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2025

**THE INTERNATIONAL YEAR OF QUANTUM
SCIENCE AND TECHNOLOGY ACROSS CANADA**

**L'ANNÉE INTERNATIONALE DE LA SCIENCE ET DE LA
TECHNOLOGIE QUANTIQUES À TRAVERS LE CANADA**

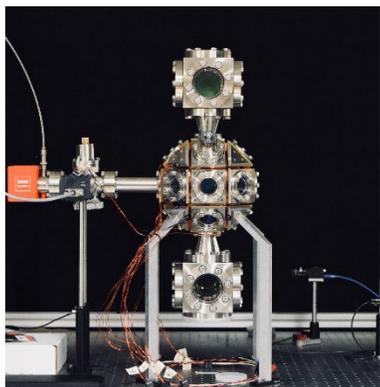


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Non-magnetic ultra-high vacuum chamber for quantum sensing

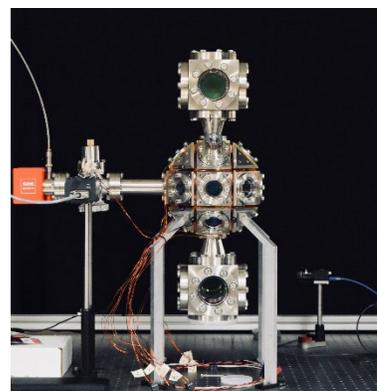
The cover photograph shows the 6.8-L sensor head of a benchtop quantum gravimeter at the Quantum-Sensing and Ultracold Matter lab (UNB, Fredericton, New Brunswick). The two main chambers are a glass cell and a central titanium “science chamber”. The glass cell houses a dispenser that produces hot rubidium vapour that is laser cooled in a 2D magneto-optical trap (MOT). These cold atoms are then optically “pushed” through a small pinhole—creating a cold atomic beam in the science chamber. The atoms are loaded into a 3D MOT (approximately 10^9 atoms in 1 s) and further cooled to a temperature of a few micro-Kelvin (10^{-6} K). An interferometry beam is aligned vertically through the science chamber and the atomic cloud is allowed to fall. Two stainless-steel cubes are fixed above and below the science chamber to provide an extended free-fall height up to 0.5 m. The gravimeter is designed to reach a sensitivity of $1 \times 10^{-8} g$ at 1 s of integration time, and an accuracy around $10^{-9} g$. The objective is to act as one of Canada’s primary gravity standards—providing uninterrupted high-accuracy time-variable gravity data for long timescales and traceability for gravimetric/geodetic heights, while also serving as an accurate calibration reference for other gravimeters/accelerometers. More details at <https://www.quantumsensing.ca/projects>.

by **Brynle Barrett**

Associate Professor, Department of Physics, University of New Brunswick

Chambre à ultra-vide non magnétique pour capteurs quantiques

La photo de couverture montre la tête de capteur de 6,8 litres d'un gravimètre quantique de paillasse au laboratoire Quantum-Sensing and Ultracold Matter (UNB, Fredericton, Nouveau-Brunswick). Les deux chambres principales sont une cellule en verre et une « chambre scientifique » centrale en titane. La cellule en verre abrite un distributeur qui produit de la vapeur de rubidium chaude, refroidie par lasers dans un piège magnéto-optique (PMO) 2D. Ces atomes froids sont ensuite « poussés » optiquement à travers un petit trou d'épingle, créant ainsi un faisceau atomique froid dans la chambre scientifique. Les atomes sont chargés dans un PMO 3D (environ 10^9 atomes en 1 s) et refroidis à une température de quelques microkelvins (10^{-6} K). Un faisceau interférométrique est aligné verticalement à travers la chambre scientifique et le nuage atomique est laissé tomber. Deux cubes en acier inoxydable sont fixés au-dessus et au-dessous de la chambre scientifique afin d'offrir une hauteur de chute libre prolongée pouvant atteindre 0,5 m. Le gravimètre est conçu pour atteindre une sensibilité de $1 \times 10^{-8} g$ à un temps d'intégration de 1 s, et une précision d'environ $10^{-9} g$. L'objectif est de servir de norme de référence en matière de gravité au Canada, en fournissant des données gravimétriques variables dans le temps, d'une grande précision et sans interruption, sur de longues périodes, ainsi que la traçabilité des hauteurs gravimétriques/géodésiques, tout en servant de référence d'étalonnage précise pour d'autres gravimètres/accéléromètres. Plus d'informations sur <https://www.quantumsensing.ca/projects>.



par **Brynle Barrett**

Professeur associé, Département de physique, University of New Brunswick



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**Canadian Association of Physicists (CAP)
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The Canadian Association of Physicists was founded in 1945 as a non-profit association representing the interests of Canadian physicists. The CAP is a broadly-based national network of physicists working in Canadian educational, industrial, and research settings. We are a strong and effective advocacy group for support of, and excellence in, physics research and education. We represent the voice of Canadian physicists to government, granting agencies, and many international scientific societies. We are an enthusiastic sponsor of events and activities promoting Canadian physics and physicists, including the CAP's annual congress and national physics journal. We are proud to offer and continually enhance our web site as a key resource for individuals pursuing careers in physics and physics education. Details of the many activities of the Association can be found at <http://www.cap.ca>. Membership application forms are also available in the membership section of that website.

L'Association canadienne des physiciens et physiciennes a été fondée en 1946 comme une association à but non-lucratif représentant les intérêts des physicien(ne)s canadien(ne)s. L'ACP est un vaste regroupement de physiciens et de physiciennes oeuvrant dans les milieux canadiens de l'éducation, de l'industrie et de la recherche. Nous constituons un groupe de pression solide et efficace, ayant pour objectif le soutien de la recherche et de l'éducation en physique, et leur excellence. Nous sommes le porte-parole des physicien(ne)s canadien(ne)s auprès du gouvernement, des organismes subventionnaires et auprès de plusieurs sociétés scientifiques internationales. Nous nous faisons le promoteur enthousiaste d'événements et d'activités mettant à l'avant-scène la physique et les physicien(ne)s canadien(ne)s, en particulier le congrès annuel et la revue de l'Association. Nous sommes fiers d'offrir et de développer continuellement notre site Web pour en faire une ressource clé pour ceux qui poursuivent leur carrière en physique et dans l'enseignement de la physique. Vous pouvez trouver les renseignements concernant les nombreuses activités de l'ACP à <http://www.cap.ca>. Les formulaires d'adhésion sont aussi disponibles dans la rubrique « Adhésion » sur ce site.



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The Editorial Board welcomes articles from readers suitable for, and understandable to, any practising or student physicist. Review papers and contributions of general interest of up to four journal pages in length are particularly welcome. Suggestions for theme topics and guest editors are also welcome and should be sent to the Editor-in-Chief, Béla Joós, at bjoos@uottawa.ca.

Le comité de rédaction invite les lecteurs à soumettre des articles qui intéresseraient et seraient compris par tout physicien, ou physicienne, et étudiant ou étudiante en physique. Les articles de synthèse d'une longueur d'au plus quatre pages de revue sont en particulier bienvenus. Des suggestions de sujets pour des revues à thème sont aussi bienvenues et peuvent être envoyées à la Redacteur-en-chef, Béla Joós, à bjoos@uottawa.ca.

FOREWORD – THE INTERNATIONAL YEAR OF QUANTUM SCIENCE AND TECHNOLOGY ACROSS CANADA

John Donohue, Ben Newling and Neil J. Ross, Guest Editors, *Physics in Canada*



The United Nations General Assembly officially declared 2025 to be the International Year of Quantum Science and Technology (IYQ) [1]. The resolution, submitted by the nation of Ghana and co-sponsored by 73 countries, represents more than 5 billion people, which is surely an indication of the breadth of the impact of all things quantum

in everyday lives. More importantly, the resolution is a call for the democratization of quantum science:

“As we press forward with quantum computing, quantum simulation and other applications of quantum technologies to help overcome current constraints and go beyond what is possible today, we should underscore how important it is for the skills in quantum science and technology to be diverse and universal, including from Africa and the developing world, and to mainstream the inclusion of women.” [1]

This special issue of *Physics in Canada* hopes to contribute by “increase[ing] public awareness of the importance of quantum science and applications” [1] and “inspire[ing] young people across the globe... to take an interest in such an exciting field of study” [1].

In 1925, Walter Heisenberg ushered in the “new” quantum mechanics with his paper “On the quantum-theoretical reinterpretation of kinematical and mechanical relationships” [2], in which he sought to establish a basis for the quantum theory using only physical quantities that could be directly observed at the time. Heisenberg drafted his paper in July of 1925 and asked his senior colleague, Max Born, to take a look, before leaving on vacation. While Heisenberg was away, Born realized that some of the mathematics suggested the use of matrices and he enlisted his assistant Pascual Jordan in writing a re-interpretation, which was also published in 1925 [3] and followed by a second part [4] in which the three scientists, together, established key pieces of the understanding upon which quantum technologies are built today [5]. At the same time, Erwin Schrödinger, inspired by an offhand remark by Peter Debye that Louis de Broglie’s matter waves should be governed by some sort of wave equation, had been developing his famous wave mechanics formulation. Schrödinger drew up his wave equation

The contents of this journal, including the views expressed above, do not necessarily represent the views or policies of the Canadian Association of Physicists.

Comments of readers on this Foreword are more than welcome.

in 1925 and published it in 1926 [6]. Shortly afterwards, Schrödinger tied the two threads together by showing that the wave and matrix approaches are equivalent.

Fast forward one hundred years and we find ourselves increasingly reliant upon a host of quantum technologies, such the atomic clocks that underpin GPS, the semiconductor electronics that are the basis for modern computing, magnetic resonance imaging in the clinic, and lasers around every corner. We also find ourselves looking ahead, in the Government of Canada’s “National Quantum Strategy” (NQS), to a “quantum-enabled future” [7]. The \$360-million investment described in the NQS is an affirmation of Canada’s strategic commitment to quantum science and technology [8], which seems increasingly necessary given optimistic forecasts, for example, of a \$139-billion industry supporting 200,000 Canadian jobs by 2045 [9].

Included in this issue is a tribute to the late Raymond Laflamme, a pioneer of quantum information science in Canada and one of the key guiding figures of the Government of Canada’s quantum strategy. A feature article from his group on responsible innovation in quantum technologies highlights the need for thoughtful development of such strategies. To explore how industry needs are accounted for in the NQS, we have included an interview with Photonic Inc founder and co-chair of the Canadian Quantum Advisory Council, Stephanie Simmons.

Exploring the foundations of quantum science led to unexpected fields like quantum computing, and continuing to explore those foundations is a major part of physics research in Canada. In an opinion piece, Gilles Brassard explores what the Nobel-prize winning Bell tests really say about non-locality, challenging the common conception that Bell tests prove nature is nonlocal. In another, Louis Marchildon shares his two major unanswered questions about quantum science.

Quantum information technologies are commonly broken up into a number of categories, which change from place to place but almost always include sensors, communication, and computers. In this issue, we are pleased to include an overview of quantum sensing work in Canada, including the physical systems explored and sectors impacted. For a specific quantum sensor, we have also included a deep dive into atomic gravimeters being developed at the University of New Brunswick. In communication and networking, near-ideal photon sources are essential, as reviewed by Dalhousie University researchers in a feature article on these flying qubits. For computation, you can find a feature article on the history of quantum error correction developments in Canada.

The modern quantum paradigm is one that not only explores how physics intersects with computer science, chemistry, mathematics, and engineering, but also one that breaks down traditional boundaries between fields of physics as its language and tools find homes in new domains. Relativistic quantum information, for example, explores the intersection of relativity, information theory, and quantum mechanics, and has grown rapidly thanks in large part to contributions from Canadian physicists, as detailed in a feature article by Robert Mann’s group. More feature articles explore how quantum computing may find uses in healthcare by improving radiotherapy techniques, how quantum phenomena influence biology, and how nanomaterials enabled by quantum mechanics could provide a

path to neuromorphic computing. You can also find a review of how quantum sensors, computation, and materials are applied in particle physics research at TRIUMF.

To realize the promise of quantum information science and technology, a new generation of keen researchers are needed. Those future workers will be educated and trained in schools, colleges, universities, internships and apprenticeships in Canada and outside Canada, in learning situations that may be very different from those we are used to, in order to mentor a diverse, “quantum-ready workforce” [10]. Welcoming new people to a topic with a public-perception problem like quantum science requires presenting the science in new, accessible ways. We have included an article on outreach efforts across Canada aiming to make quantum accessible to pre-university students, as well as an article exploring different models of introducing quantum physics at the undergraduate level. Finally, as IYQ provided a platform to promote the achievements and wonder of quantum mechanics, we have included a yearbook highlighting the numerous celebrations that brought together people across Canada in 2025, as well as the results of the Quantum Arts and IYQ Canada Logo Design competitions organized by the CAP IYQ Task Force with the generous support of NSERC. We have also included a themed crossword puzzle for a quieter sort of celebration.

The future is always (appropriately) uncertain, but we can be confident that fruitful quantum developments will require collaboration between governments, academic institutions, for-profit and not-for-profit organizations and between quantum physicists of all stripes [10]. We hope that you will see some of that variety gathered in this special issue, not as a comprehensive directory of activities across the country, but more as a sample of the diversity of contributions that are absolutely necessary for groundbreaking discovery and innovation.

No less certain is the need for collaboration between quantum scientists and quantum technologists across borders. A national strategy is an essential thing, and provincial collaborations are crucial to leverage the quantum infrastructure and expertise that Canada has nurtured with decades of investment. However, an *international* point of view has been essential in the last one hundred years of ideas freely exchanged and quantum inventions marvelously realized. It is to be hoped that those collaborations may continue to advance quantum science and technology in “its further contribution to addressing the prevailing challenges of our time” [1].

John Donohue, University of Waterloo
Ben Newling, University of New Brunswick
Neil J. Ross, Dalhousie University
Guest Editors, *Physics in Canada*

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PRÉFACE – L'ANNÉE INTERNATIONALE DE LA SCIENCE ET DE LA TECHNOLOGIE QUANTIQUES À TRAVERS LE CANADA

John Donohue, Ben Newling et Neil J. Ross, Rédacteurs invités, *La Physique au Canada*



L'Assemblée générale des Nations Unies a officiellement déclaré 2025 « L'Année internationale de la science et de la technologie quantiques » (IYQ, pour International Year of Quantum Science and Technology) [1]. La résolution, présentée par le Ghana et coparrainée par 73 pays, représente plus de 5 milliards de

personnes, ce qui témoigne sans aucun doute de l'ampleur de l'impact de tout ce qui touche au quantique dans la vie quotidienne. Plus important encore, cette résolution est un appel à la démocratisation de la science quantique :

« Alors que nous poursuivons nos efforts dans le domaine de l'informatique quantique, de la simulation quantique et d'autres applications des technologies quantiques afin de surmonter les contraintes actuelles et d'aller au-delà de ce qui est possible aujourd'hui, nous devons souligner à quel point il est important que les compétences en science et technologie quantiques soient diverses et universelles, y compris en Afrique et dans les pays en développement, et que l'inclusion des femmes soit généralisée. » [1]

Ce numéro spécial de *La Physique au Canada* espère contribuer à « sensibiliser davantage le public à l'importance de la science quantique et de ses applications » [1] et à « inspirer les jeunes du monde entier [...] à s'intéresser à ce domaine d'étude passionnant » [1].

En 1925, Walter Heisenberg inaugura la « nouvelle » mécanique quantique avec son article « Sur la réinterprétation quantique des relations cinématiques et mécaniques » [2], dans lequel il cherchait à établir une base pour la théorie quantique en utilisant uniquement des grandeurs physiques pouvant être directement observées à l'époque. Heisenberg rédigea son article en juillet 1925 et demanda à son collègue plus âgé, Max Born, de le relire avant de partir en vacances. Pendant l'absence de Heisenberg, Born se rendit compte que certaines des mathématiques suggéraient l'utilisation de matrices et il demanda à son assistant Pascual Jordan de rédiger une réinterprétation, qui fut également publiée en 1925 [3] et suivie d'une deuxième partie [4] dans laquelle les trois scientifiques établirent ensemble les

Le contenu de cette revue, ainsi que les opinions exprimées, ne représentent pas nécessairement les opinions ou les politiques de l'Association canadienne des physiciens et physiciennes.

Les commentaires des lecteurs sur cet éditorial sont toujours les bienvenus.

NOTE: Le genre masculin n'a été utilisé que pour alléger le texte.

éléments clés de la compréhension sur laquelle repose la mécanique quantique. Au même moment, Erwin Schrödinger, inspiré par une remarque désinvolte de Peter Debye selon laquelle les ondes de matière de Louis de Broglie devaient être régies par une sorte d'équation d'onde, développait sa célèbre formulation de la mécanique ondulatoire. Schrödinger élabora son équation d'onde en 1925 et la publia en 1926 [6]. Quelque temps plus tard, Schrödinger réconcilia les deux approches en prouvant que les formulations ondulatoire et matricielle sont équivalentes.

Cent ans plus tard, nous dépendons de plus en plus d'une multitude de technologies quantiques, telles que les horloges atomiques qui sous-tendent le GPS, les composants électroniques à semi-conducteurs qui sont à la base de l'informatique moderne, l'imagerie par résonance magnétique dans les cliniques et les lasers omniprésents. Nous nous tournons également vers un « avenir quantique » au travers de la « Stratégie nationale sur les technologies quantiques » (SNTQ) du gouvernement du Canada [7]. L'investissement de 360 millions de dollars décrit dans la SNTQ confirme l'engagement stratégique du Canada en faveur de la science et de la technologie quantiques [8], qui semble de plus en plus nécessaire compte tenu des prévisions optimistes, par exemple, d'une industrie de 139 milliards de dollars soutenant 200 000 emplois canadiens d'ici 2045 [9].

Ce numéro comprend un hommage à feu Raymond Laflamme, pionnier de la science de l'information quantique au Canada et l'une des figures clés de la stratégie quantique du gouvernement canadien. Un article de fond rédigé par son groupe sur l'innovation responsable dans les technologies quantiques souligne la nécessité d'élaborer ces stratégies de manière réfléchie. Afin d'explorer la manière dont les besoins de l'industrie sont pris en compte dans la SNTQ, nous avons inclus une entrevue avec Stephanie Simmons, fondatrice de Photonic Inc. et coprésidente du Conseil consultatif canadien sur la technologie quantique.

L'exploration des fondements de la science quantique a mené à des domaines inattendus comme l'informatique quantique, et la poursuite de cette exploration constitue une part importante de la recherche en physique au Canada. Dans un article d'opinion, Gilles Brassard examine ce que les tests de Bell, récompensés par le prix Nobel, révèlent réellement sur la non-localité, remettant en question l'idée répandue selon laquelle les tests de Bell prouvent que la nature est non locale. Dans un autre article, Louis Marchildon partage ses deux grandes questions sans réponse concernant la science quantique.

Les technologies de l'information quantique sont généralement divisées en plusieurs catégories, qui varient d'un endroit à l'autre, mais qui comprennent presque toujours les capteurs, les communications et les ordinateurs. Dans ce numéro, nous sommes heureux de présenter un aperçu des travaux sur la détection quantique au Canada, y compris les systèmes physiques explorés et les secteurs concernés. Pour un capteur quantique spécifique, nous avons également inclus une analyse approfondie des gravimètres atomiques en cours de développement à l'Université du Nouveau-Brunswick. Dans le domaine des communications et des réseaux, des sources de photons quasi idéales sont essentielles, comme l'ont souligné les chercheurs de l'Université Dalhousie dans un article de fond sur ces qubits volants. En ce qui concerne le calcul, vous trouverez un article de fond sur l'histoire des développements en matière de correction d'erreurs quantiques au Canada.

Le paradigme quantique moderne explore non seulement les intersections entre la physique et l'informatique, la chimie, les mathématiques et l'ingénierie, mais il abolit également les frontières traditionnelles entre les domaines de la physique, dont le langage et les outils trouvent leur place dans de nouveaux domaines. L'information quantique relativiste, par exemple, explore l'intersection entre la relativité, la théorie de l'information et la mécanique quantique, et s'est développée rapidement grâce en grande partie aux contributions de physiciens canadiens, comme le détaille un article de fond rédigé par le groupe de Robert Mann. D'autres articles explorent comment l'informatique quantique pourrait trouver des applications dans le domaine de la santé en améliorant les techniques de radiothérapie, comment les phénomènes quantiques influencent la biologie et comment les nanomatériaux rendus possibles par la mécanique quantique pourraient ouvrir la voie à l'informatique neuromorphique. Vous trouverez également une analyse de la manière dont les capteurs, les calculs et les matériaux quantiques sont appliqués à la recherche en physique des particules au TRIUMF.

Pour concrétiser les promesses de la science et de la technologie de l'information quantique, une nouvelle génération de chercheurs passionnés est nécessaire. Ces futurs travailleurs seront formés dans des écoles, des collèges, des universités, des stages et des apprentissages au Canada et à l'étranger, dans des contextes d'apprentissage qui peuvent être très différents de ceux auxquels nous sommes habitués, afin de former une « main-d'œuvre (diversifiée) prête pour le quantique » [10]. Pour intéresser de nouvelles personnes à un sujet qui souffre d'un problème d'image auprès du grand public, comme la science quantique, il faut présenter cette science sous un jour nouveau et accessible. Nous avons inclus un article sur les efforts de sensibilisation menés à travers le Canada pour rendre la physique quantique accessible aux élèves du secondaire, ainsi qu'un article explorant différents modèles d'introduction de la physique quantique au niveau du premier cycle universitaire. Enfin, comme l'IYQ a fourni une plateforme pour promouvoir les réalisations et les merveilles de la mécanique quantique, nous avons inclus un album souvenir mettant en évidence les nombreuses célébrations qui ont rassemblé des gens à travers le Canada en 2025, ainsi que les résultats des concours d'art quantique et de logo de l'ACP-IYQ organisés par le groupe de travail ACP-IYQ avec le généreux soutien du CRSNG. Nous avons également inclus des mots croisés thématiques pour une célébration plus calme.

L'avenir est toujours incertain, mais nous pouvons être convaincus que les développements fructueux dans le domaine quantique nécessiteront une collaboration entre les gouvernements, les institutions universitaires, les organisations à but lucratif et non lucratif, ainsi qu'entre les physiciens quantiques de tous horizons [10]. Nous espérons que vous découvrirez une partie de cette diversité dans ce numéro spécial, non pas comme un répertoire exhaustif des activités menées à travers le pays, mais plutôt comme un échantillon de la diversité des contributions absolument nécessaires à des découvertes et innovations révolutionnaires.

La nécessité d'une collaboration transfrontalière entre les scientifiques et les technologues quantiques ne fait aucun doute. Une stratégie nationale est essentielle, et les collaborations provinciales sont cruciales pour tirer parti de l'infrastructure et de l'expertise quantiques que le Canada a développées grâce à des décennies d'investissement. Cependant, une perspective internationale a été essentielle au

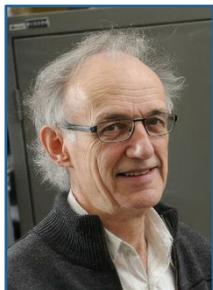
cours des cent dernières années, marquées par le libre échange d'idées et la réalisation d'inventions quantiques remarquables. Il faut espérer que ces collaborations continueront à faire progresser la science et la technologie quantiques afin qu'elles « contribuent davantage à relever les défis actuels » [1].

John Donohue, University of Waterloo
Ben Newling, University of New Brunswick
Neil J. Ross, Dalhousie University
Rédacteurs invités, *La Physique au Canada*

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RENÉ ROY (1943-2024)



Originaire de Cap-Chat au Québec, René Roy a obtenu sa scolarité classique au Séminaire de Rimouski, terminant en 1964 avec la Médaille du Gouverneur général du Canada. Il entame un baccalauréat en génie physique à l'Université Laval en 1965, puis des études doctorales en physique nucléaire de 1969 à 1973 en tant que boursier du CNRC, sous la supervision du professeur Rodolfo Slobodrian. Au cours de cette période, il réalise diverses expériences avec le Van de Graaff du laboratoire de physique nucléaire du département de physique de l'Université Laval, ainsi qu'au cyclotron 88" du Lawrence Berkeley Laboratory. La thèse de doctorat intitulée « Études des spectres continus des états non liés du ^8Be et du mécanisme des réactions $^7\text{Li}(d, n)^8\text{Be}$, $^9\text{Be}(\tau, \alpha)^8\text{Be}$ et $^{10}\text{B}(d, \alpha)^8\text{Be}$ » sera soutenue en 1973.

Il s'engagera ensuite dans une formation postdoctorale au Lawrence Berkeley National Laboratory (LBL) grâce à une bourse du CNRC, sous la direction du docteur H.E. Conzett. Il y restera jusqu'en mai 1976, mais continuera la collaboration et la réalisation d'expériences au LBL jusqu'à la fin des années 80. Les travaux porteront sur la mesure de sections efficaces de réaction, la polarisation, test de symétrie et invariance par rapport au renversement du temps et autres sujets.

Au premier juin 1976, il entre en fonction comme professeur adjoint sous octroi au département de physique de l'Université Laval, où il accomplira l'ensemble de sa carrière universitaire. Chercheur boursier en 1981, il devient professeur agrégé en 1981, puis titulaire en 1986. Son frère, Denis Roy, chercheur dans le domaine de l'état solide, a aussi été professeur du département de physique pendant toute sa carrière. Fait à noter, au cours de sa carrière, le professeur Roy a été pendant près de 25 ans le directeur du programme de génie physique et 8 ans comme directeur du département. Il aura dirigé ou codirigé la supervision de plus de soixante maîtrises et doctorats.

À travers ses activités de recherche, il a instauré de multiples collaborations et entrepris la conception de divers instruments de mesure associés à la physique des ions lourds. D'abord au National Superconducting Laboratory (NSCL) du Michigan State University dès 1985, puis de 1989 à 1997 au Tandem Accelerator Superconducting Cyclotron (TASCC) de Chalk River en Ontario. C'est à ce moment que son équipe construira le multidétecteur Héraclès constitué d'un ensemble de CsI(Tl) et de BaF₂. Le tout fut par la suite utilisé au Cyclotron Institute de College Station au Texas (1997-2004 et 2007). Le professeur Roy a aussi débuté une collaboration avec le GANIL à Caen (France) dès 1990. Il s'est impliqué, entre autres, dans la collaboration INDRA, une association fructueuse, associée à de nombreuses cotutelles. Cette collaboration s'est poursuivie jusqu'à sa retraite en 2017. Finalement, de 2008 à 2016, il a participé à des expériences associées aux faisceaux radioactifs et des faisceaux stables accélérés par l'accélérateur ISAC II de TRIUMF (UBC).

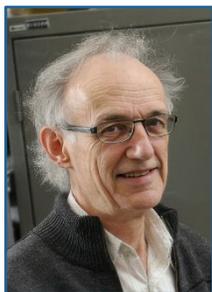
Membre actif de les communautés de physique et de physique nucléaire canadienne, le professeur Roy a notamment été secrétaire de la Division de physique nucléaire de l'Association canadienne des physiciens et physiciennes (ACP), conseiller au conseil de l'ACP, région sud et est du Québec, et

membre du Comité de rédaction de *La Physique au Canada / Physics in Canada*. Bien qu'ingénieur, il a été un grand défenseur du titre *phys. / P. Phys*, lui-même licencié, ainsi que membre actif du comité de certification de titre pendant plusieurs années. Toujours pour l'ACP, il a occupé les postes de président de la Division de physique nucléaire, de secrétaire de la Division de physique industrielle et appliquée pendant deux mandats, de président de la Division de physique industrielle et appliquée (à différents moments), et d'autres mandats comme conseiller. À ceci s'ajoutent de nombreux mandats sur divers comités du CRSNG. Ce sont notamment les subventions en physique subatomique, le Comité canadien de planification en physique subatomique, le Comité consultatif pour la physique nucléaire et la physique des particules, l'évaluation de chaires de recherche pour le programme de chaires en recherche du Canada, ainsi que la fonction de membre du Comité de décision pour remettre la première médaille d'or Gerhard Herzberg, parmi tant d'autres activités.

Érudit, grand amateur de musique classique, collectionneur de BD et excellent joueur de billard (depuis ses années au Séminaire de Rimouski), le professeur René Roy laisse une empreinte indélébile au département par sa passion pour la physique, son soutien d'un programme de génie physique côtoyant celui de physique dans un même département et un appui indéfectible pour l'établissement des activités de recherche et d'enseignement en physique médicale, qu'il voyait comme une extension naturelle de la physique nucléaire. D'ailleurs un fonds, Fonds René-Roy en physique médicale, a été établi à la Faculté des sciences et de génie de l'Université Laval en sa mémoire et a pour objectif de favoriser les études en sciences et en génie dans le programme CAMPEP en physique médicale.

LUC BEAULIEU, Université Laval

RENÉ ROY (1943-2024)



Originally from Cap-Chat, Quebec, René Roy completed his classical studies at the Séminaire de Rimouski, graduating in 1964 with the Governor General of Canada's Medal. He began a bachelor's degree in engineering physics at Université Laval in 1965, then pursued doctoral studies in nuclear physics from 1969 to 1973 as a National Research Council of Canada (NRC) scholarship holder, under the supervision of Professor Rodolfo Slobodrian. During this period, he conducted a variety of experiments using the Van de Graaff accelerator at the Nuclear Physics Laboratory of Université Laval, as well as at the 88-inch cyclotron at Lawrence Berkeley National Laboratory (LBNL). His Ph.D. dissertation, entitled "Studies of the continuum spectra of unbound states of ^8Be and of the mechanisms of the $^7\text{Li}(d,n)^8\text{Be}$, $^9\text{Be}(\tau,\alpha)^8\text{Be}$ and $^{10}\text{B}(d,\alpha)^8\text{Be}$ reactions," was defended in 1973.

He subsequently undertook postdoctoral training at LBNL, supported by an NRC fellowship, under the direction of Dr. H. E. Conzett. He remained there until May 1976 but continued his collaboration and experimental work at LBNL through the late 1980s. This research focused on the measurement of reaction cross sections, polarization, symmetry tests and invariance under time reversal, among other topics.

On June 1, 1976, he was appointed as an assistant professor (grant-funded position) in the Department of Physics at Université Laval, where he would spend his entire academic career. He became an associate professor in 1981 and a full professor in 1986. His brother, Denis Roy, a researcher in solid-state physics, was also a professor in the Department of Physics throughout his career. Notably, over the course of his career, Professor Roy served for nearly 25 years as Director of the Engineering Physics program and for eight years as Chair of the department. He supervised or co-supervised more than sixty Master's and Ph.D. students.

Through his research activities, he established numerous collaborations and led the design of several instruments associated with heavy-ion research. This work began at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University as early as 1985 and continued from 1989 to 1997 at the Tandem Accelerator Superconducting Cyclotron (TASCC) in Chalk River, Ontario. During this period, his team built the Héraclès multi-detector array, composed of an ensemble of CsI(Tl) and BaF₂ detectors. The system was subsequently used at the Cyclotron Institute in College Station, Texas (1997–2004 and 2007). Professor Roy also initiated a collaboration with GANIL in Caen (France) beginning in 1990. Among other contributions, he participated in the INDRA collaboration, a highly productive partnership associated with numerous joint doctoral supervisions. This collaboration continued until his retirement in 2017. Finally, from 2008 to 2016, he took part in experiments involving radioactive beams and stable beams accelerated by the ISAC II facility at TRIUMF (UBC).

An active member of the Canadian physics and nuclear physics communities, Professor Roy notably served as Secretary of the Division of Nuclear Physics of the Canadian Association of Physicists (CAP),

as a councillor for South and East Québec on the CAP Council, and as a member of the editorial board of *Physics in Canada / La Physique au Canada*. Although an engineer by training, he was a strong advocate of the P. Phys. / phys. professional designation—himself licensed—and served for several years as an active member of the designation’s certification committee. Within CAP, he also held the positions of Chair of the Division of Nuclear Physics; Secretary of the Division of Industrial and Applied Physics for two terms; Chair of the Division of Industrial and Applied Physics (at different times); and several other terms as a councillor. In addition, he served on numerous NSERC committees, including those related to subatomic physics grants, the Canadian Subatomic Physics Long-Range Planning Committee, the Advisory Committee for Nuclear and Particle Physics, the assessment of research chair applications for the Canada Research Chairs program, and as a member of the committee that awarded the first Gerhard Herzberg Gold Medal, among many other contributions.

A true scholar, passionate lover of classical music, collector of comic books, and excellent billiards player (since his years at the Séminaire de Rimouski), Professor René Roy left an indelible mark on the department through his passion for physics; his sustained support for an Engineering Physics program alongside Physics within the same department; and his unwavering commitment to the development of research and teaching activities in medical physics, which he viewed as a natural extension of nuclear physics. In that regard, the René-Roy Fund in Medical Physics was established within Université Laval’s Faculty of Science and Engineering, with the aim of supporting studies in science and engineering within the CAMPEP-accredited Medical Physics program.

LUC BEAULIEU, Université Laval

RAYMOND LAFLAMME (1960-2025)



On June 19, 2025, Canada lost one of its great physicists, visionary leaders, and most generous human beings. Raymond Laflamme, OC, FRSC (1960–2025), passed away peacefully at his home in Waterloo, Ontario, surrounded by his wife, Janice Gregson, and their children, Patrick and Jocelyne.

In the days that followed, tributes poured in from around the world—scientists and students, Nobel laureates and policymakers, musicians and neighbours. Some had known him for decades, others only briefly. All said the same thing: Raymond—or simply “Ray”—touched lives.

Ray’s accomplishments were remarkable. He was a pioneer of quantum computing and one of its leading voices worldwide. He was a founding faculty member of the Perimeter Institute and co-founded the Institute for Quantum Computing, guiding the latter into a world-class centre that drew researchers from every corner of the globe. He wrote more than 300 scientific papers, co-authored influential textbooks, and mentored over sixty graduate students and many postdocs who now carry his influence forward. He helped place Canada firmly at the centre of quantum research. But for those who knew him, the accolades never came first. What people remember most is the person: his generosity, his warmth, and his unmistakable joie de vivre.

No obituary can capture a life as full as Ray’s. At best, it can point toward his spirit: the curiosity of the scientist, the vision of the builder, and above all, the kindness of the man.

THE ADVENTUROUS AND CURIOUS SCIENTIST

Ray approached science much like he approached the outdoors: with curiosity and a sense of adventure. As a PhD student under Stephen Hawking, he was asked to confirm Hawking’s claim that the arrow of time would reverse at the universe’s maximum expansion—a reversal that seemed to defy the second law of thermodynamics. Instead, Ray and his collaborator Don Page challenged the idea and showed the opposite. Hawking retracted the claim, later inscribing Ray’s copy of *A Brief History of Time*: “To Raymond, who showed me the arrow of time is not a boomerang.” Soon after, with Ruth Gregory, he revealed that higher-dimensional black strings are unstable, work that became known as the Gregory–Laflamme instability and reshaped the study of spacetime horizons [1].

That same appetite for the unknown eventually pulled him into an entirely new field. While working as a quantum cosmologist at Los Alamos National Laboratory, Ray wandered into a seminar on quantum computing. “I was convinced this idea of computing with quantum mechanics would never be feasible—and I wanted to prove it,” he later recalled with a smile. “Well, we ended up showing that it was absolutely possible!” Together with his long-time collaborator Emmanuel Knill, they established the threshold theorem, demonstrating that reliable quantum computation is possible even with

imperfect components, and laid down the Knill–Laflamme conditions for error correction, tools still essential today [2]. With colleagues, he also discovered the first “perfect” quantum code [3].

For most physicists, the line between theory and experiment is a lifelong barrier. Ray ignored it. He reinvented himself as an experimentalist—a leap almost unheard of as a senior researcher. He saw promise in nuclear magnetic resonance (NMR) as a testbed for quantum computing and set about mastering the hardware. Together with his colleague David Cory, he carried out some of the first laboratory demonstrations of quantum algorithms and quantum error correction [4]. Critics doubted NMR’s legitimacy as a quantum computer, due to a lack of entanglement, but Ray refused to dismiss it. With Knill, he introduced the DQC1 model, what he liked to call “*the power of one qubit*”: proof that even a state with very little entanglement could perform a task beyond the reach of any known classical algorithm [5]. In the years since, DQC1 has echoed across quantum complexity theory, reshaping how researchers think about the structure of quantum computational power.

Having already ventured into NMR experiments, he veered further—this time into quantum optics. At a moment when photons were largely dismissed as impractical for computation, Ray, together with Emmanuel Knill and Gerard Milburn, proposed a radically different path: the KLM scheme. Instead of relying on elusive optical nonlinearities, they showed how linear optics, single-photon sources, and photon detectors could be combined to build scalable quantum computers [6]. Within a decade, the paper had become one of the most celebrated works in the field and a blueprint for today’s multi-billion-dollar photonic quantum industry.

From black holes to quantum computers, from chalkboard to laboratory, Ray’s career showed a scientist unafraid of the unknown, guided by curiosity and an eagerness to open new doors for others to walk through.

THE VISIONARY BUILDER

The same disregard for limitations that once let a cosmologist reinvent himself as a quantum computing experimentalist also made him a visionary leader. In the late 1990s, quantum computing was barely more than theory, and Canada had no foothold. To believe it could lead the world was audacious, but Ray believed it, and made it real.

In 2002, Ray co-founded the Institute for Quantum Computing (IQC) at the University of Waterloo and led it for fifteen years. He loved to tell how its blueprint was first sketched over dinner at David Johnston’s farm, with Johnston—then Waterloo’s president—and Mike Lazaridis, founder of BlackBerry. Ray agreed to return to Canada only if they would match his vision with resources, “with many, many zeros,” as he liked to joke. From those beginnings, IQC grew into one of the world’s leading centres for quantum information, home to hundreds of researchers and facilities envied worldwide. More than its size, though, it was the culture Ray built that mattered: he convinced brilliant theorists, experimentalists, engineers, mathematicians—even politicians—to take a leap together. Almost everyone in today’s global quantum community can trace a connection back to IQC, and to Ray’s belief that Canada could be a home for world-class quantum science.

Ray also knew the effort had to extend beyond one institute. As founding director of CIFAR's Quantum Information Program from 2003 to 2016 and the driving force behind QuantumWorks, he helped knit together a national network of researchers, institutions, and students. Many of the people he mentored in those years now lead quantum programs across Canada and around the world.

His reach went further still. Governments sought his advice on shaping science policy in Canada and abroad. He played a central role in the proposal that became Canada's first National Quantum Strategy, then co-chaired the advisory council guiding its future. He also chaired the expert panel that produced the Council of Canadian Academies' landmark report on the responsible adoption of quantum technologies [7]. Ray's voice helped set priorities not just for labs and universities, but for the country itself.

Through it all, Ray never stopped being a teacher. He co-authored two textbooks—*An Introduction to Quantum Computing* [8] and *Building Quantum Computers* [9]—that trained thousands of students, wrote review articles that made subfields accessible, and co-founded startups to see how research could live outside the lab. He once said he wanted to “learn how building a company works”, so he went and did it. That's how Ray operates.

To ask why Canada has long punched above its weight in quantum is to arrive, inevitably, at Raymond Laflamme. He saw further, built wider, and left behind institutions, strategies, and communities that will carry his vision forward.

THE KIND AND GENEROUS MAN

No matter how far Ray's vision stretched in building institutions, or how closely he examined the smallest details as a scientist, his true focus was always people. After his passing, tributes poured in from around the world, not of titles and awards but of the countless ways he touched lives with his kindness and generosity. They were streams of stories, admiration not for his accomplishments but for his humanity.

Ray showed up when it mattered, often quietly, always sincerely. A student who reached out distressed during their first PhD term found him ready to talk the next day, on Christmas Eve. A new postdoc, suddenly ill and alone in a new country, found him at their side on hospital visits. A colleague at Perimeter, grieving the loss of a mother, found him at the memorial, despite Ray's own chemotherapy. If someone was in need, Ray was there.

That same care extended to the broader community. When concerns were raised about how female students were being supported in STEM, he didn't deflect; he co-chaired an EDI committee, and later he and Janice created a scholarship for women in quantum information. When a young boy came to see “where the man who studied with Stephen Hawking worked,” Ray sat with him for ten minutes, asking questions, listening intently. For the boy it was unforgettable. For Ray it was simply what you did.

He carried a lightness that put people at ease. In a pickup hockey game, a student once gleefully dumped him into a snowbank. Ray got up grinning, “Finally, someone is here to play for real,” he said, already plotting his revenge.

In the classroom, no problem was too small. One instructor remembered an undergraduate’s surprise when an “older man with a French accent” sat down to help with a problem set, unaware it was the founding director of IQC, whose work they had just studied in class.

Ray made space for others to grow. He encouraged students to lead public events, even when the guest was Stephen Hawking. He stood nearby, but let them be the ones at the podium. As one student put it, “More than anything, he let us all grow.” That is the legacy of a true mentor.

And through it all, Ray never lost his humility. When praised for his leadership, he would shrug, “I just answer the phone when I am called.” When congratulated on a scientific result, he would say, “My students did it,” overlooking that the idea often began with him. He was often honoured in public, yet still grew embarrassed when singled out. Even near the end, he remained bemused to be treated as a celebrity at high schools and undergraduate events. He never stopped being surprised that others saw him that way.

Ray’s legacy lives on—in the students he mentored, the institutions and vision he built, and in his children, whom he always said were his greatest accomplishment. His imprint endures in Canada’s quantum landscape and in the lives of all who knew him.

Farewell, Ray

MARTIN LAFOREST, Quantacet, University of Waterloo PhD ’08 under Raymond Laflamme
SHAYAN MAJIDY, Harvard University, University of Waterloo PhD ’24 under Raymond Laflamme



Raymond Laflamme and his instantly recognizable camper van.

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QUI VOUS A DIT QUE LA NATURE EST NONLOCALE ?¹



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Peu de temps après que le Prix Nobel de physique ait été attribué à Alain Aspect, John Clauser et Anton Zeilinger en 2022 « pour des expériences [...] qui ont établi la violation des inégalités de Bell [...] »², les médias populaires ont foisonné d'articles pour annoncer qu'Einstein avait eu tort de croire fermement au réalisme local de la Nature, selon le *Principe de localité* qu'il avait exprimé ainsi dans son autobiographie :

Selon moi, il y a *une* hypothèse que nous devrions absolument retenir : la réalité factuelle (l'état) du système S_2 est indépendante de ce qui est fait à un système S_1 qui lui serait spatialement éloigné.³

Ce point de vue a été ébranlé lorsque John Stewart Bell a démontré en 1964 que certaines prédictions de la théorie quantique sont incompatibles avec toute théorie dite à *variables locales cachées* [2]. Quelques années plus tard, la position d'Einstein a semblé s'effondrer à la suite des expériences réalisées entre autres par les lauréats du Prix Nobel de physique de 2022, lesquelles ont confirmé ces prédictions. Faut-il vraiment en conclure que la Nature est nonlocale ? Est-ce bien ce que nous disent ces nobélisés ?

Dans une interview à l'émission radiophonique *Quirks and Quarks* sur les ondes du réseau anglais de Radio-Canada (CBC), qui a eu lieu immédiatement après l'annonce du comité Nobel, **John Clauser** a affirmé ceci : « Pour vous dire la vérité, je ne savais pas quel allait être le résultat. Je pariais sur Einstein. [...] J'ai été très triste car je croyais qu'Einstein avait raison mais, hélas, j'ai contredit son point de vue. »⁴

À l'occasion de son discours d'acceptation au mythique banquet Nobel, **Alain Aspect** a affirmé que « La conclusion est maintenant claire : la position d'Einstein sur la réalité physique ne peut pas être

¹ Une version plus longue de cet essai paraîtra ailleurs en anglais.

² « For experiments [...] establishing the violation of Bell inequalities [...] ». (Ici comme plus loin, les traductions libres en français sont de mon cru, avec la participation de Nicolas Gisin pour traduire de l'allemand.)

³ « Aber an *einer* Annahme sollten wir nach meiner Ansicht unbedingt festhalten: Der reale Sachverhalt (Zustand) des Systems S_2 ist unabhängig davon, was mit dem von ihm räumlich getrennten System S_1 vorgenommen wird. » [1]

⁴ « The truth is, I didn't know what the result was gonna be. I was betting on Einstein. [...] I was very sad because I thought Einstein was right but, unfortunately, I did disprove his point of view. » [3]

maintenue. »⁵ Dans son podcast Nobel du 7 juin 2023, il a tenu des propos similaires à ceux de Clauser : « Je ne pouvais pas imaginer comment Einstein aurait pu avoir tort [...], mais je dois accepter le résultat. »⁶ Dans son tout récent livre en français pour grand public averti *Si Einstein avait su*, il a renchéri en ces mots : « J'accepte l'idée [...] d'une interaction capable d'affecter l'état quantique à distance de façon instantanée. » [4]

Nous voyons donc que tant Clauser qu'Aspect croient que la Nature est nonlocale car c'est ce qu'ils veulent dire par « Einstein avait tort ». Qu'en est-il du troisième lauréat du Prix Nobel de physique de 2022, **Anton Zeilinger** ? Lors d'une communication personnelle, il m'a dit ceci : « Toutes les expériences nous disent que la nature ne peut pas être décrite par des propriétés locales au sens de Bell (ou de ses généralisations). »⁷ Cela est rigoureusement exact. Zeilinger a immédiatement rajouté ceci : « Mais de dire que la nature est nonlocale serait aller trop loin à mes yeux. »⁸ J'applaudis à cette opinion nuancée.

En effet, le Principe de localité d'Einstein n'a *rien à voir* avec la notion de localité de Bell, laquelle est basée sur les variables locales cachées. Par conséquent, « établir la violation des inégalités de Bell » ne peut pas servir à argumenter en faveur d'une vision nonlocale de la Nature, mais uniquement à corroborer sa nonlocalité *au sens de Bell*, ainsi que Zeilinger l'a si bien dit. Pourrait-il y avoir une autre façon pour la Nature d'être locale et réaliste, une autre façon qui ne demanderait qu'un peu plus d'imagination ?

C'est précisément ce qu'ont fait David Deutsch et Patrick Hayden au tournant du siècle : ils ont découvert comment expliquer toutes les prédictions de la théorie quantique dans un univers local-réaliste [6]. Par la suite, Paul Raymond-Robichaud a démontré l'équivalence entre le local réalisme et le principe du non-signallement que tous acceptent au sujet de la théorie quantique, pour autant que la dynamique de la physique soit réversible [7]. En conséquence, *aucune* expérience dont le but est de confirmer les prédictions de la théorie quantique ne peut servir pour conclure que la Nature est nonlocale !

En conclusion, qui vous a dit que la Nature est nonlocale ? C'est hélas une vue partagée par maints physiciens, incluant deux récents lauréats du Prix Nobel. Toutefois, leurs arguments pour en arriver à cette croyance sont des coquilles vides. Comme d'habitude, Einstein avait raison. :-)

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Je suis profondément reconnaissant à des discussions s'étant étalées sur plusieurs décennies avec (en ordre alphabétique) Alain Aspect, Charles Alexandre Bédard, David Deutsch, Nicolas Gisin, Renato Renner, Paul Raymond-Robichaud, Lev Vaidman et Anton Zeilinger, bien que certains d'entre eux ne partagent pas ma perspective. D'inspirantes discussions plus récentes ont eu lieu avec

⁵ « The conclusion is now clear: Einstein's view on physical reality cannot be upheld. »

⁶ « I could not imagine how Einstein could be wrong, [...] but I have to accept the result. »

⁷ « All the experiments tell us is that nature cannot be described by local properties in the sense of Bell (and extensions). » [5]

⁸ « But to say that nature is nonlocal is going too far in my eyes. » [5]

Samuel Kuypers et Taha Skiredj. Ce fut Paul Raymond-Robichaud qui, le premier, m'a fait réaliser qu'aucune violation des inégalités de Bell ne peut servir à conclure que la Nature est nonlocale : un jour mémorable de 2012, il lui a suffi de quelques minutes pour changer à jamais ma vision de l'Univers. Merci Paul, je t'en serai éternellement reconnaissant !

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La photographie originale, à partir de laquelle le portrait a été développé par le bureau d'architecture belge LIGNES, a été prise par Hatim Kaghat.

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WHO TOLD YOU THAT NATURE IS NONLOCAL?¹



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Shortly after the Nobel Committee awarded its 2022 Physics Prize to Alain Aspect, John F. Clauser and Anton Zeilinger “for experiments [...] establishing the violation of Bell inequalities [...]”, the popular press went abuzz with stories about Albert Einstein having been wrong in his firm conviction that Nature is both local and realistic according to his *Principle of Locality*, which he stated as follows in his autobiography:

On *one*² supposition we should, in my opinion, absolutely hold fast: the real factual situation (the state)² of the system S_2 is independent of what is done with the system S_1 , which is spatially separated from the former. [1]

Einstein's position was shaken after John Stewart Bell proved in 1964 that some predictions of quantum theory are incompatible with *local hidden variables* [3]. Soon thereafter, it appeared to be untenable after experiments, performed in particular by the 2022 Nobel Prize laureates, confirmed those predictions. Does it follow that Nature is nonlocal? Did the Nobel laureates tell you so?

In an interview with the CBC radio programme *Quirks and Quarks* immediately after the Nobel announcement, **John Clauser** said this: “The truth is, I didn't know what the result was gonna be. I was betting on Einstein. [...] I was very sad because I thought Einstein was right but, unfortunately, I did disprove his point of view.” [4]

In his Nobel banquet speech, **Alain Aspect** claimed that “The conclusion is now clear: Einstein's view on physical reality cannot be upheld.” In his 7 June 2023 Nobel podcast, he said: “I could not imagine how Einstein could be wrong, [...] but I have to accept the result.”

We see that both Clauser and Aspect believe that Nature is nonlocal since this is indeed what they mean by “Einstein was wrong”. What about **Anton Zeilinger**? In a personal communication [5], he told me that “All the experiments tell us is that nature cannot be described by local properties in the sense

¹ A full version of this version will appear elsewhere.

² The word “one” was not emphasized in Schilpp's translation [1] and the parenthetical addition “(the state)” was omitted. Yet “einer” is emphasized and “(Zustand)” appears in Einstein's original version in German [2].

of Bell (and extensions).” This is absolutely correct. Then, he added “But to say that nature is nonlocal is going too far in my eyes.” I applaud this nuanced opinion.

Indeed, Einstein's Principle of Locality has *nothing* to do with Bell's notion of locality, which is based on local hidden variables. It follows that “establishing the violation of Bell inequalities” *cannot* be used to argue that Nature is nonlocal, only that it is nonlocal *in the sense of Bell*, exactly as Zeilinger stated so aptly. Could there be another way for Nature to be local and realistic?

It turns out that David Deutsch and Patrick Hayden discovered a quarter of a century ago how to explain all the predictions of quantum theory in a local realistic universe [6]. Subsequently, Paul Raymond-Robichaud proved that local realism and nonsignalling are equivalent when the dynamics is reversible [7]. Therefore, *no* experiment whose purpose is to vindicate quantum theory can serve as evidence that Nature is nonlocal!

So, who told you that Nature is nonlocal? A great many people indeed, including two Nobel Prize laureates, but their arguments for this claim are empty. As usual, Einstein prevails. :-)

ACKNOWLEDGEMENTS

I am deeply indebted to decade-long discussions on this topic with (in alphabetical order) Alain Aspect, Charles Alexandre Bédard, David Deutsch, Nicolas Gisin, Renato Renner, Paul Raymond-Robichaud, Lev Vaidman and Anton Zeilinger, even though some of them do not share my perspective. More recent discussions with Samuel Kuypers and Taha Skiredj were also illuminating. It was Paul Raymond-Robichaud who was the first to make me aware that experimental violations of Bell inequalities cannot be used to argue that Nature is nonlocal. It was in 2012 that, in a matter of minutes, he changed my entire view of the Universe. Thank you Paul. I am forever indebted to you.

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The original photograph, from which the portrait was developed by Belgian architecture firm LIGNES, was taken by Hatim Kaghat.

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DEUX QUESTIONS POUR LE BICENTENAIRE



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La mécanique quantique est née au cours de l'été 1925, alors que le jeune physicien Werner Heisenberg se retirait dans l'île de Helgoland, au nord de l'Allemagne, pour fuir les allergies qui l'accablaient. Au cours des cent dernières années, la théorie a donné lieu à d'innombrables applications. L'électrodynamique quantique, l'une de ses généralisations, a révélé un accord entre prédictions et mesures d'une précision stupéfiante, meilleure qu'une partie dans mille milliards [1].

Et pourtant, les fondements de la théorie échappent toujours à la compréhension. Cela tient à deux propriétés qui distinguent radicalement la mécanique quantique de son pendant classique : la superposition et l'intrication. La première signifie que toute combinaison linéaire de vecteurs d'état quantiques est un état quantique ; la seconde permet des corrélations dont l'explication semble requérir une action à distance transmise instantanément. Les deux propriétés sont essentielles à l'élaboration d'ordinateurs quantiques, dont on parle abondamment depuis que Peter Shor [2] a montré leur rapidité dans la factorisation en nombres premiers.

On s'accommoderait de la superposition si elle ne s'appliquait qu'à des systèmes microscopiques, comme un électron. Mais voilà : dans la mesure où la théorie a une valeur universelle, superposition microscopique implique superposition macroscopique, comme dans le cas du chat de Schrödinger. Différentes interprétations de la mécanique quantique (l'onde pilote de Bohm et de Broglie [3], les mondes multiples d'Everett [4] ou la réalité relationnelle de Rovelli [5], par exemple) tentent de réconcilier la superposition macroscopique avec ce qu'on observe. Une solution très différente, qui remonte à Dirac et von Neumann [6], consiste à affirmer que la superposition macroscopique est impossible, c'est-à-dire qu'à partir d'une certaine échelle, la théorie quantique n'est plus valable.

La théorie quantique rend compte du monde microscopique, alors que la structure à grande échelle de l'univers est décrite par la théorie de la relativité générale. Celle-ci n'a, jusqu'à maintenant, jamais été prise en défaut. La relativité générale est une théorie classique, incompatible avec la mécanique quantique. La plupart des chercheurs estiment que l'incompatibilité sera résolue lorsqu'on aura élaboré une théorie quantique de la gravité. D'autres, comme Roger Penrose [7], croient que le principe de superposition ne s'applique pas au champ gravitationnel, et que celui-ci est le responsable de la réduction du vecteur d'état.

La construction d'un ordinateur quantique performant pose des défis colossaux. Il faut maintenir l'intrication des « qubits », malgré les perturbations dues à l'environnement. Mais le défi n'est pas que

technique. Si la mécanique quantique n'est plus valable à une certaine échelle, la taille et la puissance des ordinateurs quantiques sont limitées. Dans ce sens, la construction d'ordinateurs quantiques de plus en plus puissants constitue un test sévère de la théorie quantique.

Ces réflexions conduisent à de nombreuses interrogations, qu'on peut sans doute ramener à deux questions fondamentales :

1. Est-ce qu'un jour, le développement des ordinateurs quantiques sera freiné par une limite fondamentale de la validité de la théorie quantique ?
2. Le champ gravitationnel (Figure 1) satisfait-il au principe de superposition et, si oui, comment en donner une version quantique ?

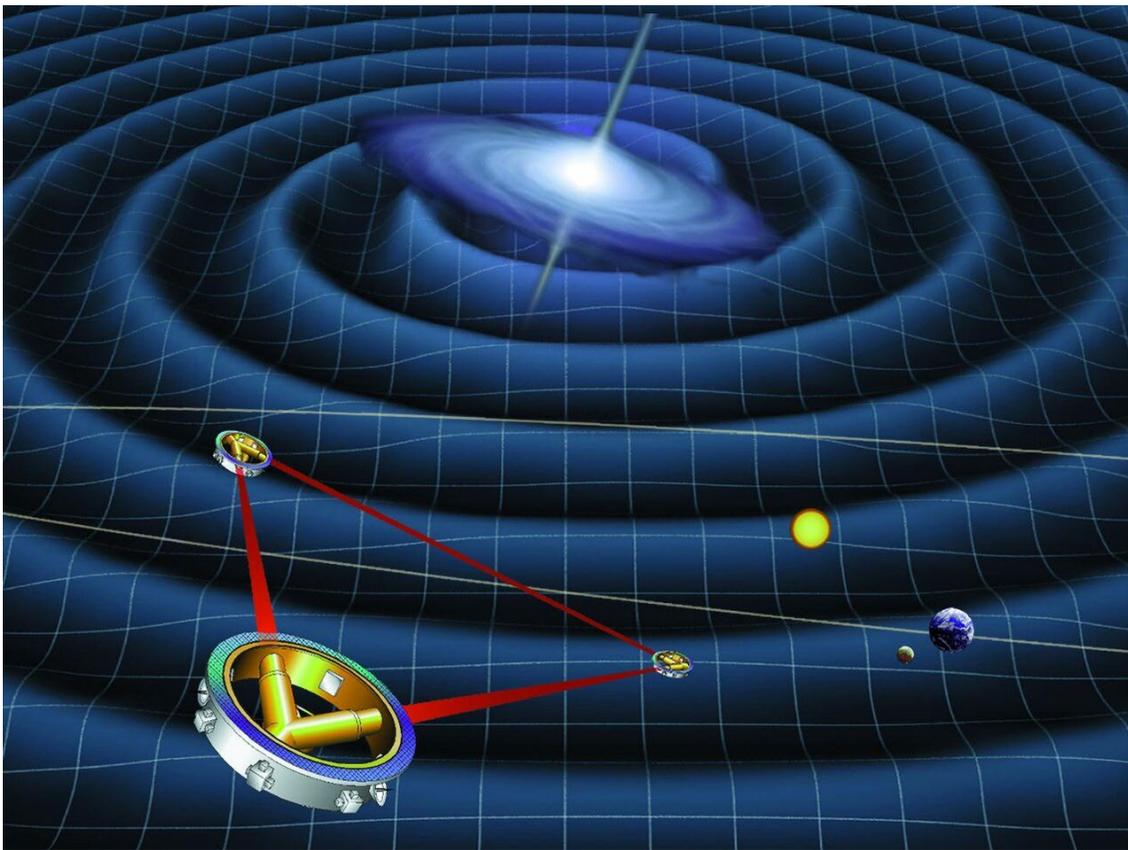


Figure 1. LISA, un interféromètre triangulaire prévu par l'Agence spatiale européenne pour 2035, pourrait détecter des signes de gravité quantique dans les ondes gravitationnelles produites lors de la fusion de trous noirs ou dans les premiers instants de l'univers. (Source : Wikimedia Commons.)

Ces questions, sous une forme ou une autre, nous accompagnent depuis plusieurs décennies. Y répondrons-nous bientôt ? En tout cas, je m'empresserais de les poser si je revenais sur terre en 2125, au moment de célébrer le bicentenaire de la théorie quantique.

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TWO QUESTIONS FOR THE BICENTENNIAL



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Quantum mechanics was born in the summer of 1925, when the young physicist Werner Heisenberg retreated to the island of Helgoland in northern Germany to escape the allergies that plagued him. Over the past hundred years, the theory has given rise to countless applications. Quantum electrodynamics, one of its generalizations, has shown an agreement between predictions and measurements of astonishing precision, better than one part in a trillion [1].

And yet, the foundations of the theory still elude understanding. This is due to two properties that radically distinguish quantum mechanics from its classical counterpart: superposition and entanglement. The first means that any linear combination of quantum state vectors is a quantum state; the second allows for correlations whose explanation seems to require instantaneous action at a distance. Both properties are essential to the development of quantum computers, which have been widely discussed since Peter Shor [2] demonstrated their speed in prime number factorization.

We could accept superposition if it only applied to microscopic systems, such as an electron. Since, however, the theory has universal value, microscopic superposition implies macroscopic superposition, as in the case of Schrödinger's cat. Different interpretations of quantum mechanics (Bohm and de Broglie's pilot wave [3], Everett's many worlds [4], or Rovelli's relational reality [5], for example) attempt to reconcile macroscopic superposition with what is observed. A very different solution, dating back to Dirac and von Neumann [6], consists in asserting that macroscopic superposition is impossible, i.e., that beyond a certain scale, quantum theory is no longer valid.

Quantum theory accounts for the microscopic world, while the large-scale structure of the universe is described by the theory of general relativity. To date, this theory has never been proven wrong. General relativity is a classical theory, incompatible with quantum mechanics. Most researchers believe that this incompatibility will be resolved once a quantum theory of gravity has been developed. Others, such as Roger Penrose [7], believe that the principle of superposition does not apply to the gravitational field, and that this field is responsible for the reduction of the state vector.

Building a high-performance quantum computer poses enormous challenges. The entanglement of "qubits" must be maintained despite disturbances from the environment. But the challenge is not only technical. If quantum mechanics no longer applies above a certain scale, the size and power of quantum computers are limited. In this sense, building increasingly powerful quantum computers is a severe test of quantum theory.

These considerations raise many questions, which can be summarized by two fundamental ones:

1. Will the development of quantum computers one day be hindered by a fundamental limitation in the validity of quantum theory?
2. Does the gravitational field (Figure 1) satisfy the principle of superposition and, if so, how can a quantum version of it be elaborated?

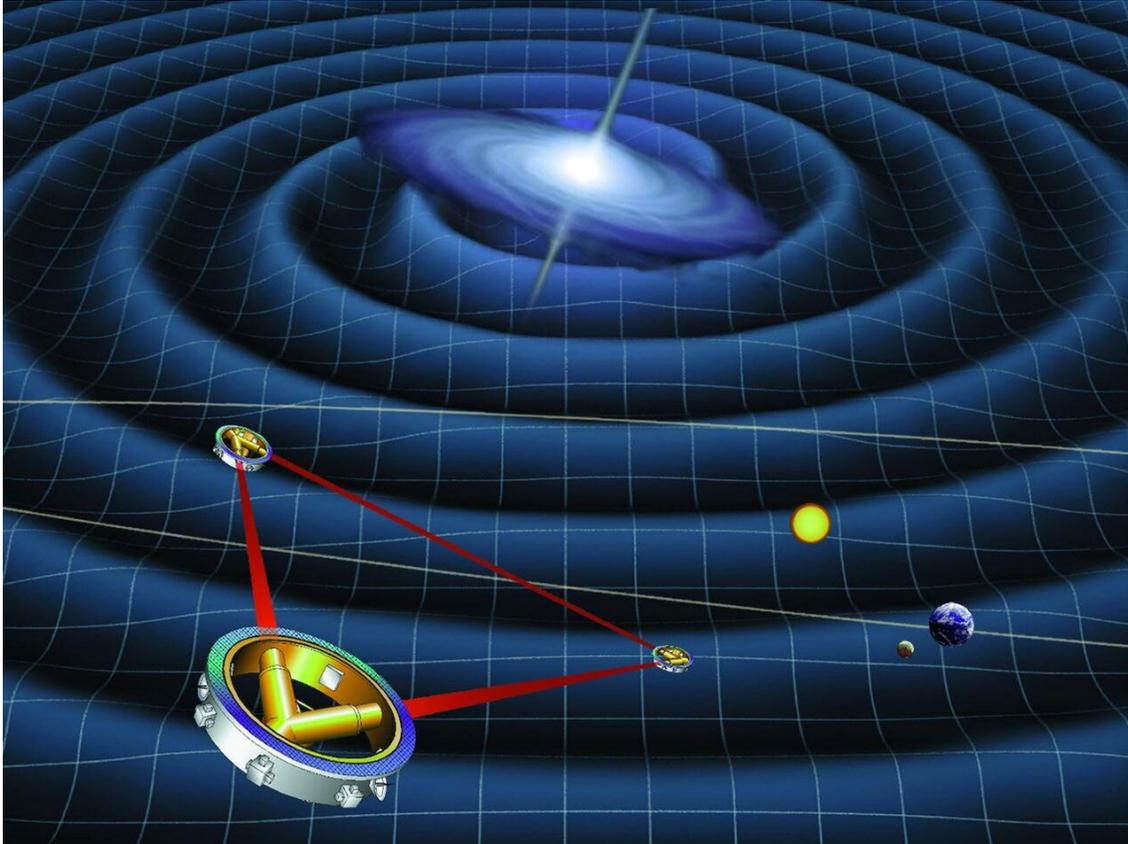


Figure 1. LISA, a triangular interferometer planned by the European Space Agency for 2035, could detect signs of quantum gravity in gravitational waves produced during the merger of black holes or in the early moments of the universe. (Source: Wikimedia Commons.)

These questions, in one form or another, have accompanied us for several decades. Will the answers come anytime soon? In any case, I would quickly ask them if I came back to Earth in 2125, celebrating the bicentennial of quantum theory.

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SPINS, PHOTONS, AND NATIONAL IMPERATIVES: AN INTERVIEW WITH DR. STEPHANIE SIMMONS



Dr. Stephanie Simmons is the Chief Quantum Officer at Photonic Inc, an Associate Professor and Canada Research Chair in Silicon Quantum Technologies at Simon Fraser University, and co-chair of the Canadian Quantum Advisory Council. As one of Canada's leaders in quantum information science and technology (QIST) across many sectors, we were delighted to interview her for this special IYQ edition of *Physics in Canada* to discuss her history in the field, moving research to the private sector, and a vision for Canada's quantum future

Interview conducted by the guest editors of the IYQ edition of Physics in Canada

You started working in quantum information science and technology as an undergraduate student. How did you find your way to quantum technology?

When I first discovered quantum technologies at 16, it was through a newspaper article about the Institute for Quantum Computing in Ontario, Canada. The potential inherent in large-scale quantum computers immediately captivated me, and I've been pursuing it ever since. I completed my undergraduate studies at the University of Waterloo in Mathematics and Mathematical Physics, my doctorate in Materials Science at Oxford University, and then went to the University of New South Wales as an Electrical Engineering research fellow in silicon-based quantum computing. I then returned to Canada to start the Silicon Quantum Technology lab at Simon Fraser University in BC.

What application of that potential grabbed your interest in those early days?

It was the concept of teleportation in quantum computing—the fact that you could harness it to do things made me really think that this would define the future. Today, I think I'm driven by just how close we are to creating the really large scale systems that will enable us to run the high impact algorithms - using teleportation, of course!

How has the field changed in Canada and globally since you got your start?

Early on there were still debates about *IF* quantum computers could ever be built. The big question now is *WHEN* we will see quantum computers that are large enough to unlock the exponential speedups that quantum can provide.

Another big change is the acceleration in the pace of progress. Across Canada and around the world, we're seeing big improvements in hardware, software, error correction – these are addressing some of the core challenges to large scale quantum systems.

The shift from curiosity to implementation is profound. It means we've crossed a threshold. Quantum is no longer just a scientific endeavor; it's a technological inevitability.

To move along that inevitability, what is the mission of your company, Photonic Inc?

Our mission is to build scalable, fault-tolerant quantum computers that can deliver real-world impact. We're focused on a distributed architecture using silicon spin qubits connected by photons, a design that allows us to *scale up* (increasing the quantity and density of components within a single unit) and to *scale out* (adding units to a network), cost-effectively.

Our vision is to unlock the transformative potential of quantum computing across industries from drug discovery and clean energy to secure communications, finance, and national security. We're not just building a computer; we're building the foundation for technologies that will shape the next century.

What has Photonic allowed you to do that would have been impossible in the context of academia?

Being in a company has allowed us to move further, faster. In academia, the focus is often on foundational research — which is essential — but building a scalable quantum system requires sustained, coordinated engineering efforts and significant resources. The private sector enables that kind of momentum. At Photonic, we've been able to bring together a multidisciplinary team of global experts, invest in infrastructure, and make long-term bets that would be difficult to support through traditional academic funding models.

What are you looking for when assembling your team at Photonic?

At Photonic, we're doing something that has never been done, and that starts with assembling a team that is fearlessly ambitious. We look for brilliant, dedicated people who are genuinely excited about making quantum computing a reality.

The physical systems used in your devices at Photonic are spin qubits connected by photons. From a birds-eye view, how do we build and interface with spin qubits?

To be able to unlock the promise of quantum computing, we need systems with so many highly connected qubits that it is not practical to be constrained to a single box. So, we focused on an efficient way to network systems using telecom infrastructure.

At Photonic, we use T-center qubits as the basic building blocks that generate entanglement. The T-center is a colour centre in silicon that can emit photons — particles of light — that are entangled with the spins left behind. And when photons from two separate T centres interact in a certain protocol, you can trigger the ability to connect or entangle the spins in T centres that emitted them, even though the T centres themselves remain physically separated. It's astonishing. These are what's called spin-photon interfaces, which means they have the compute and memory capability in the spin, but they also have the communication capabilities of photons. And that link is through telecom fibre, which is the standard fibre used to string together all of today's internet and modern data centers. It's a super lightweight connection, enabling us to get distributed entanglement and to do distributed computation using that entanglement.

Most of the attention in the media is paid to superconducting circuits as the platform for building quantum computers. Why should we be pursuing alternative platforms like silicon spins? Should we be pursuing others as well?

Superconducting qubits were among the first quantum technologies to capture widespread media and investor attention, for good reason. They enabled some of the earliest demonstrations of quantum algorithms at a few dozen qubits and helped bring quantum computing into the public imagination.

The consideration of other modalities reflects the fact that no single platform has yet proven it can scale to commercial utility. That's why initiatives like DARPA's Quantum Benchmarking Initiative (QBI) are so important. QBI was launched to rigorously assess whether any quantum modality can realistically deliver more computational value than it costs within the next decade. Crucially, it applies equal scrutiny to all platforms to determine which approaches are truly viable at scale. In that context, pursuing alternatives like our photonically-linked silicon spin qubits isn't just a hedge — it's a strategic imperative.

Can you describe your role as the co-chair of Canada's Quantum Advisory Council to the National Quantum Strategy?

The role of the Quantum Advisory Council is to bring the perspectives of academia, industry, and other quantum players to the government to inform policy and provide updates on what could be achieved and how we can keep the quantum advantage that Canada had the foresight to build with decades of research.

What makes quantum unique from a research funding perspective? Why do we need a National Quantum Strategy?

Quantum technologies are unlike most other research domains because they sit at the intersection of deep science and transformative economic potential. Quantum technologies are dual use, which means they have known defense and commercial applications, and therefore are not just a scientific endeavour; they are a platform technology that could underpin future advances in many sectors. That breadth of impact means the stakes are high, and the opportunity is enormous. A National Quantum Strategy is essential to ensure Canada doesn't just contribute to the global quantum ecosystem — but helps shape it.

What's a tangible way in which the National Quantum Strategy has started to shape the environment in Canada?

The National Quantum Strategy highlights the fact that building a strong quantum economy is important, and requires an integrated approach - it can't be created by just supporting research, or talent development, or commercialization. Doing it well requires a comprehensive understanding of the necessary inputs, supports, and desired outcomes both within the country and on the international stage. We've seen this play out in Canada including quantum as a key priority in the G7 talks this June and in the subsequent Kananaskis Common Vision for the Future of Quantum Technologies that was released from those discussions.

What would you encourage the government to do more of to support the development of QIST in Canada?

I'm thrilled to see the government taking bold, strategic action by setting a clear timeline for implementing Post-Quantum Cryptography. This signals that Canada is serious about securing its digital infrastructure and leading in quantum readiness.

We need to ensure that Canada remains a place where quantum companies can start, scale, and stay. That means supporting rigorously vetted companies, even when it involves calculated risk. Anchor firms are essential to building the ecosystems that attract and retain top talent, drive innovation, and generate long-term economic value.

We've seen this story before. Canada helped pioneer AI, but much of the economic benefit went elsewhere. We can't afford to let that happen again with quantum. Realizing our potential will depend on the choices we make today — scaling homegrown companies, securing supply chains, and anchoring quantum deployment here at home. This is a moment to lead in building the global quantum economy.

What advantages does Canada have in quantum technologies? Are there any disadvantages that we'll need to work hard to overcome?

Canada's greatest advantage in quantum is its head start. Decades of investment in research have built a deep bench of talent, world-class institutions, and a collaborative ecosystem that's already producing globally competitive companies.

The challenge? Turning that early lead into long-term economic impact. We need to overcome our risk aversion, especially when it comes to scaling deep tech. If we wait until technologies are "proven," others will be ahead in mobilizing commercially, and we risk losing the return on investment and the talent we've trained. Supporting homegrown companies now is how we turn potential into prosperity.

Looking forward, what's the biggest current bottleneck to useful quantum computers?

The biggest bottleneck to useful quantum computers today is demonstrating scalable, fault-tolerant architectures. We need robust systems that can both scale up and scale out. Scaling up improves the quality and quantity of qubits within a module, while scaling out connects those modules into a larger, networked system capable of distributed computation.

But it's not just about scale — it's about scaling cost-effectively. To deliver real-world value, quantum systems must be architected from the start to support modularity, interoperability, and efficient entanglement distribution across nodes. These are technically demanding challenges but solving them is essential to move from experimental demonstrations to commercially useful quantum computing.

What would you say to a young student interested in pursuing quantum science and technology in their future?

Go for it! Quantum is one of the most exciting areas in science and technology today and there are so many ways to contribute. Whether your interests lie in physics, engineering, computer science, or even policy, there's a place for you in this field. The skills are flexible, the problems are fascinating, and the impact could be enormous. If you're curious, there are great resources out there to help you get started and a growing community ready to welcome you in.

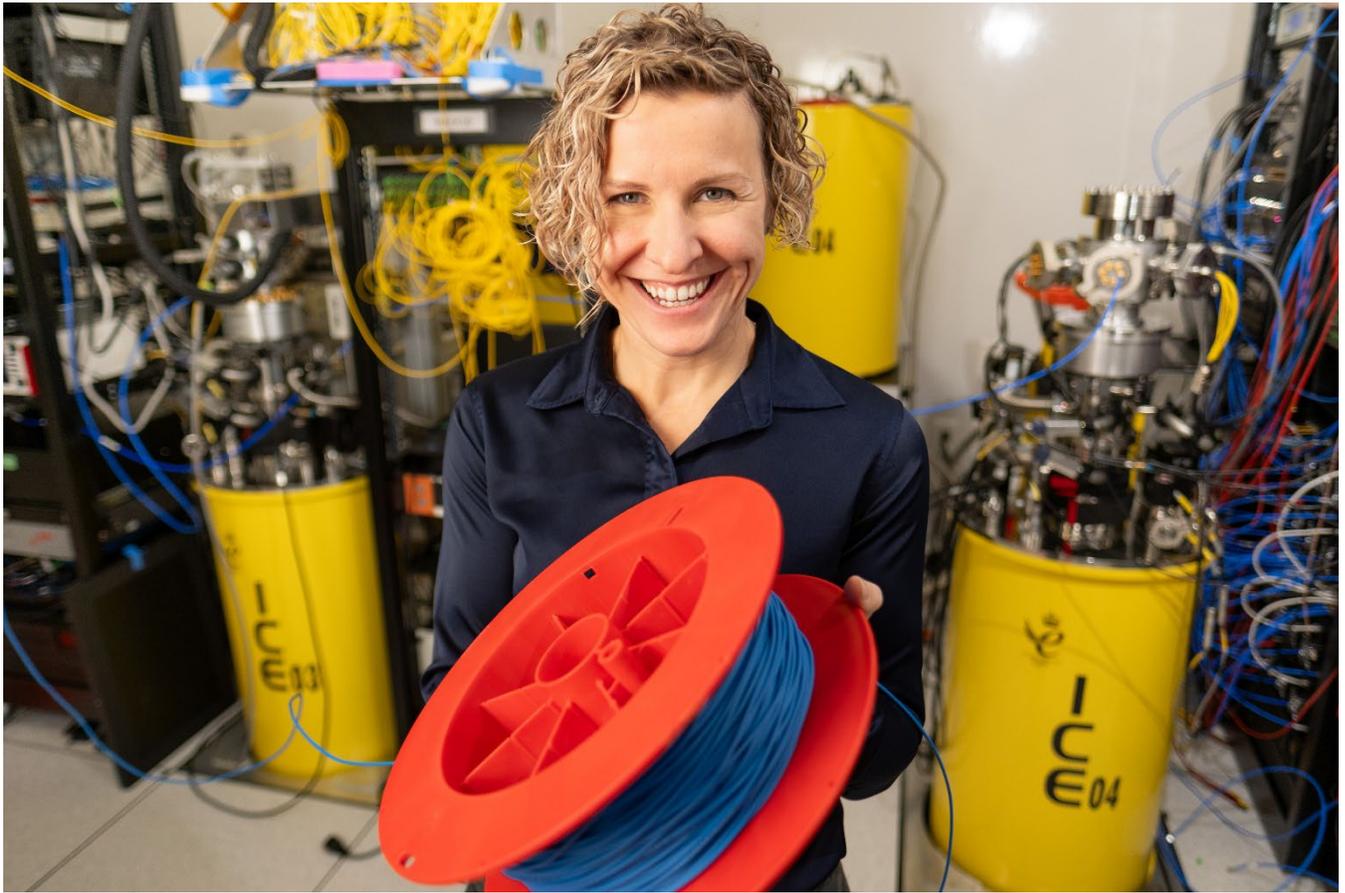


Figure 1. Dr. Simmons holds a roll of telecommunications fibre used in her work to route photons between qubits in different cryostats. Compatibility with telecommunications infrastructure like these fibres is a major advantage in networking multiple quantum devices to scale up to larger systems.

EXPLORING RESPONSIBLE QUANTUM INNOVATION EFFORTS IN CANADA AND THE WORLD

SUMMARY: We assess global quantum technologies efforts in the Responsible Innovation framework and how Canada leads or lags in development and regulations.



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The global landscape for quantum technologies (QTs) is rapidly changing, and proper understanding of their impact and subsequent regulations need to match this pace. A Responsible Innovation (RI) approach and guiding principles have been proposed to accompany this development. We examine practical efforts globally and in Canada, from industry to research to governments, and analyze the current status of quantum technological advances under the RI framework. We analyze and compare what is being done internationally, identify gaps in the Canadian strategy, propose initiatives to fill those gaps, and highlight areas where Canada is leading or where more work is needed.

The widespread real-world impact that quantum devices will have in the near future demands attention from various sectors of society, not only those interested in research and commercialization. In response to this, international efforts have started to address the needs and consequences of the use of quantum technologies [1].

An integral part of the allocation of quantum technologies in society is consideration of the ethical implications of their use, operation, and manufacture. Do countries responsible for the research and implementation of such devices take these implications into account as they lay out their roadmaps for development? How does Canada fit in this larger picture?

We review efforts from governments, private initiatives, research groups, and grants to answer these questions in the frame of responsible innovation [2,3]. Whenever possible, we highlight verifiable output displaying the efforts: events, technical papers, policy documents, etc. We use Kop *et al.*'s Ten Principles [2] to determine the grounds for comparison, and survey the relative frequency with which each of the Principles of responsibility are addressed within a National Quantum Strategy (NQS).

We search and collect in NQS documents the keywords defined in Table 1. This is followed by verifying, within context, whether the sentence containing the keyword addresses the corresponding Principle.

The accounted quotes may include similar words, e.g. "ethics" and "ethical". Finally, the mentions to each Principle are counted and compiled in Table 2.¹ We use the CIFAR report [1] to decide what document is an NQS, and we include updated references by Qureca [5] and based on other web searches. We do not attempt to define new criteria.

We refer to each of the ten Principles in an abbreviated manner: P01 (**Table 1**), for example, refers to Principle 1 (Information security). Additional remarks on the choice of NQS documents are discussed in the next section.

INTERNATIONAL

We analyze the NQS documents listed in Table 2 and display the keyword search results there.

We see that all NQS documents roughly follow the same pattern, which reflects the context and time when these documents were crafted, with the most pressing issues of information security (P01) and race to technological edge (P03) heading the counts, and with issues of Innovation (P08) following. Occupying a negligible portion of each NQS, we have Dual Use (P02), Quantum Gap (P04), and IP (P05). A possible explanation is that both Dual Use and IP regulations may be covered in more specialized documents, when contrasted with Information Security due to its national security implications. Furthermore, while the absence of mentions of the Quantum Gap may be explained by the country-specific scope of these documents, it is an example of terminology that has only been introduced recently.

We expect that growing attention to societal problems will be given when QT reaches commercial application with practical use cases. These results suggest that the Principles of Quantum Gap, Inclusion, and Education (P04, P06, P10), which can inform what problems are of Societal Relevance (P07), are lagging behind.

The development of QT happens in an effervescent ecosystem, as demonstrated by the website for the International Year of Quantum (IYQ) [6], but a lot still needs to be addressed. The Quantum Economy Blueprint [7], a report guiding responsible development, raises the problem of the Quantum Divide (P04) between developed and Majority World countries as one that needs addressing. The IYQ map gives a glimpse of this: the number of activities in North America and Europe largely outnumber the ones in Latin America, Africa, and Asia. As we will argue in the following sections, research and an active stance must be taken on this, and with regards to other Principles that received less attention in

¹ We follow the methods used in Leshner *et al.* [4] to compile Figure 2.

TABLE 1

List of principles, a short description taken directly from,^[2] and our choices of Keywords for the keyword search.

#	Principle	Description	Keywords
01	Information Security	Make information security an integral part of QT.	Security; cybersecurity; threat; attack.
02	Dual Use	Proactively anticipate the malicious use of quantum applications.	Dual use; usage; malicious; hazard; warfare; unintended.
03	Quantum Race	Seek international collaboration based on shared values.	Race; international; collaboration.
04	Quantum Gap	Consider our planet as the sociotechnical environment in which QT should function.	Gap; quantum divide; global; world; unequal; disproportionate; fair.
05	Intellectual Property (IP)	Incentivise innovation while being as open as possible and as closed as necessary.	IP; Intellectual Property; open source.
06	Inclusion	Pursue diverse R&D communities in terms of disciplines and people.	Inclusion; DEI or EDI; equity; diversity.
07	Societal Relevance	Link quantum R&D explicitly to desirable societal goals.	Social; benefit.
08	Complementary Innovation	Actively stimulate sustainable; cross-disciplinary innovation.	Innovation; adaptation; adoption; progress.
09	Responsibility	Create an ecosystem to learn about the possible uses and consequences of QT applications.	Responsible; ethics; consequences; risk.
10	Education and Dialogue	Facilitate dialogues with stakeholders to better envision the future of QT.	Education, dialogue, outreach, science communication, general public, engage

the NQS documents, as we move forward. Furthermore, in an agenda to be fulfilled by 2030, the United Nations define Sustainable Development Goals (SDGs). It has been argued that QTs have the potential to be used to address the SDGs [8-10] (P07), and governing bodies that subscribe to this agenda should adopt policies reflecting this potential [11].

TABLE 2

Assessment of the presence of Principles in National Quantum Strategies [23-32]. Numbers indicate how many quotes address each Principle, shown as a percentage of the total number of quotes in that document. These documents were chosen by referring to the countries with NQS ready or in development. We disregard NQS documents that are not in English or not publicly available.

National Quantum Strategies	01	02	03	04	05	06	07	08	09	10
Australia	10%	0%	27%	0%	4%	12%	10%	6%	16%	14%
Canada	11%	1%	40%	1%	2%	5%	14%	9%	9%	9%
Denmark	22%	2%	26%	1%	3%	2%	12%	18%	9%	4%
Ireland	23%	1%	17%	1%	2%	6%	13%	24%	7%	5%
Netherlands	19%	0%	15%	1%	0%	0%	29%	16%	7%	12%
South Africa	30%	0%	22%	0%	8%	3%	5%	15%	0%	17%
South Korea	24%	1%	19%	2%	1%	6%	13%	25%	3%	6%
United Kingdom	16%	0%	20%	0%	4%	4%	15%	22%	14%	4%
United States	32%	2%	19%	0%	6%	0%	6%	14%	5%	16%

Before focusing on Canada, we point out that an integral part of the international efforts is led by specialists and addresses a large set of problems that can be classified under the RI Principles. Some examples are QT activities in the G77² plus China (P04), a study commissioned by the Quantum Delta program [12]. Research groups are starting to tackle the field of “quantum humanities” (P07–09), with examples in Europe, Asia, and North America [13-17] and to aid in this, quantum experts must have a strong grasp of QT, which is achieved by promoting Education and Dialogue (P10) [18]. Research on resource costs for QT, and how QT can address climate change are also integrated under socially relevant problems (P07) and are being investigated [19-20]. Ultimately, QT must not be considered in isolation; its interaction with other important emerging technologies is paramount, in particular artificial intelligence, and it must ideally be done in cross-disciplinary fashion (P08) [21,22].

CANADA

The Canadian NQS aims to establish Canada as a world leader on the quantum development stage, to boost national cybersecurity with post-quantum cryptography incentives, and to support the adoption of quantum sensing technologies [24].

² The Group of 77 (G77) is an intergovernmental organization of developing countries within the United Nations framework aimed at articulating their shared economic interests. “G77 plus China” refers to the extra consideration of China.

Although all the Principles outlined in the RI framework are discussed in the NQS, our analysis (see Table 2) revealed that Canada's initiatives align primarily with Quantum Race (P03) and Societal Relevance (P07). In particular, Canada placed a stronger emphasis on P03 than any other country surveyed, demonstrating a particular focus on international collaboration for successful quantum development. In contrast, less attention was given to Inclusion (P06), Complementary Innovation (P08) and Education and Dialogue (P10) than in peer countries. To align more closely with an RI framework, greater attention must be paid to these Principles.

Bolstering one Principle often reinforces others. For example, increased commitment to Inclusion (P06) and Education (P10) is needed to properly bring Societal Relevance to light (P07). After all, it is difficult to identify the most relevant societal problems for quantum technology without first strengthening diversity and engagement in the workforce and the general public space. At the same time, it is important to consider the potential trade-offs from Principle interactions. For one, increasing open access (P05) while maintaining a competitive edge in the quantum race (P03) and preserving national cybersecurity (P01) poses a real strategic challenge. It is important to keep this balancing act in mind when making these changes.

Although still in its infancy, the Canadian responsible quantum innovation landscape has already begun to develop, with some initiatives making use of government funding. One such organization is the Centre for Responsible Quantum Innovation and Technology (CRQIT) in British Columbia. With the principal goal of nurturing responsible quantum innovation on a national and international level (P02, P03, P09), the CRQIT's efforts have a broad span. This includes advisory work on EDI policies in Canada's quantum hubs and engagement with UNESCO [33].

A project sharing similar goals is underway at the Institut Quantique. This work, created with the realities of research and entrepreneurial development in mind, aims to create tools to encourage those in the quantum ecosystem to analyze the potential societal impacts of their work throughout its process, rather than after the fact [34] (P02, P07, P09). Another important facet of the Canadian RI landscape has been enabling broader participation in technological development. For instance, Open Quantum Design is a non-profit organization in Waterloo creating an open-source quantum computer using trapped ions [35] (P09, P10).

Finally, Canadians are also contributing to the growing international conversation on responsible quantum innovation. The Centre for International Governance Innovation (CIGI), based in Waterloo, has produced a number of publications exploring Canada's quantum ecosystem through the lens of policy [36-39]. In 2025, CIGI organized the Think7 (T7) process as part of Canada's G7 presidency, bringing together experts from around the world to develop policy briefs that will inform G7 decision-making (P03) [40,41].

FUTURE PROSPECTS

Canada's evolving quantum ecosystem offers a timely opportunity to align its national initiatives with RI Principles. This section outlines recommendations for Canada to strengthen its strategic position while ensuring ethical, secure, and sustainable development of quantum technologies.

To begin, to guarantee a science-based adoption system, the government should increase efforts to educate policymakers and companies about quantum technologies (P10). Well-defined standards assessing the development, security, and effectiveness of quantum systems can only be properly defined if those creating them have sufficient technical understanding. For instance, the government could hire physicists to deliver workshops to help these professionals build their quantum knowledge [42]. Conversely, it is also crucial for researchers to consider the social consequences of their work, and one way to do this is by learning about policy. This will increase engagement between the public, private, and academic sectors, clarify security requirements, and increase trust in government regulation (P08, P09).

Partnerships with allies should continue to be nurtured to share the responsibilities of advancing quantum technology (P03). Moreover, Canada has the opportunity to improve its position as a leader in quantum development by actively pursuing inclusive relations with developing nations and pushing for a shared-values system. Building such associations gives Canada leverage in negotiations, provides a competitive edge in the Quantum Race (P03), and directly lessens the Quantum Divide (P04). Throughout this work, it is also important to remain aware of research security risks (P01).

In our analysis, we found that most NQSs placed less emphasis on social Principles like P06. In Canada's case, although the importance of social science research for quantum was discussed, no funding was assigned to it. We suggest that a portion of NQS funding should be allocated to social science research to connect the technical advancement of the quantum ecosystem to ethical and regulatory considerations [43].

It is also important to encourage private companies to share insights from real-world testing, thus fostering a more collaborative, open, and responsive quantum ecosystem (P05). Moreover, both the public and private sectors should map out supply chains for future quantum technologies and take steps to protect critical hardware from potential threats. This work protects quantum infrastructure (P01) and pushes nations to navigate dependencies and maintain competitive resilience in the global quantum landscape (P03).

Although this article focuses on Canada, an interesting generalization would be to analyze the differences in focus between the Global North and South. We also hope that the discussions in this paper will motivate physicists to become involved in ethics and policy, thus ensuring the development of directives that are both compliant with RI and scientifically accurate.

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QUANTUM SENSING IN CANADA

SUMMARY: This article examines the physical systems underlying prominent emerging quantum sensors, highlighting their achievements and opportunities across key Canadian sectors.



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Quantum sensing exploits control over the quantum states of light or matter to engineer measurement devices with capabilities surpassing those of classical hardware. For example, quantum probes can suppress noise, enable nanoscale spatial resolution, or exploit entanglement to pick out weak signals from a noisy background. Here, we examine the techniques and applications of quantum sensing from a Canadian perspective, highlighting the work of Canadian institutions and companies while focusing on the role that quantum sensing could play in sectors relevant to the Canadian economy.

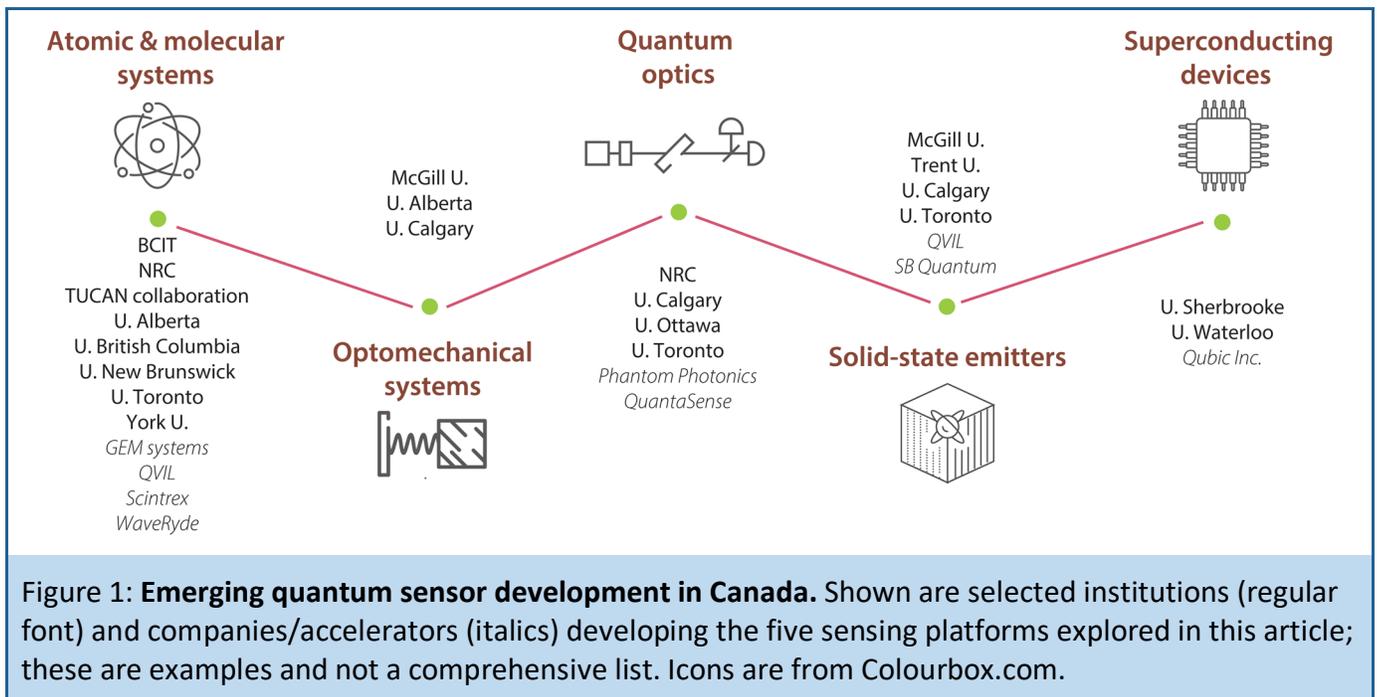
Despite strong and growing interest in the field, the definition of quantum sensing is not always clear. A recent review [1] proposed the following indicators: (1) Employing quantized energy levels, e.g., utilizing the energy shift of spin states to detect a magnetic field (2). Using quantum coherence or superposition, like in atomic matter-wave interferometry for measuring acceleration [2]. (3) Exploiting quantum entanglement, e.g., using entangled photons for improved target detection [3]. While the third category is the most unequivocally non-classical, we consider all three types of quantum sensors here. Nevertheless, this article's scope is limited to emerging quantum sensing modalities, omitting discussion of more mature platforms, such as traditional spectroscopy techniques (e.g., NMR, EPR, and optical) and scanning tunnelling microscopy.

PHYSICAL PLATFORMS

Canadian researchers and entrepreneurs are developing quantum sensors across the following physical platforms (Fig. 1).

Atomic and molecular sensors [4] exploit long-lived states of atoms or molecules whose transition frequencies can be probed with unparalleled precision (reaching below a part in 10^{18} [5]) using resonant electromagnetic fields. While unperturbed atomic transitions provide the basis for modern time standards [6], energy-level shifts induced by external electromagnetic fields permit extraordinarily sensitive magnetometry [7] and electrometry [8]. Gravitational fields, acceleration, and rotation affect the phase of atomic states and can be measured using atomic matter-wave interferometry [9]. Owing to their perfect reproducibility, long coherence times, and precision optical control techniques, atomic sensors offer promising solutions when absolute and/or ultra-high-precision measurements are required [4].

Optomechanical systems employ the radiation pressure force imparted by photons to control the quantum states of mechanical oscillators or engineer the quantum state of light interacting with the oscillator. Such systems can probe force, displacement, strain, mass, acceleration, magnetic fields, gravitational waves, and more [10]. Quantum enhancement of optomechanical sensors by squeezed light has been realized, most notably in the LIGO gravitational wave detector [11]. The ability to interact with a wide variety of targets makes optomechanical devices particularly versatile [12], for example, in using single vibrational quanta to probe microscopic electronic material phenomena [13]. Future goals include advancing classical optomechanical sensors, such as those for studying single molecules [14] and quantum materials [15], to a regime where quantum states of light are required to reach the ultimate limits in sensitivity.



Quantum optical sensors exploit quantum states of light to enhance imaging resolution or detection sensitivity, which is particularly beneficial for noisy or low-light environments. For example, by illuminating a target with photons entangled with a reference, one can exploit their quantum

correlations to isolate the signal in the presence of significant classical noise for improved imaging [16]. Alternatively, squeezed light exhibits fluctuations below the classical limit, offering enhanced signal-to-noise [17], which is especially relevant for objects that cannot tolerate intense irradiation. Ultimately, the variety of possible quantum-optical states and sensing modalities has led to a diverse range of protocols and applications.

Solid-state emitters, including atomic defects in diamond and two-dimensional materials, rare earth ions in solids, and quantum dots, can exhibit atomic-like properties and nanoscale spatial resolution that can be harnessed for sensing [18-20]. Solid-state emitters are also localized in materials amenable to device fabrication [21]. Many offer long-lived spin states, and some, such as the nitrogen-vacancy center in diamond, can operate in ambient conditions. As with atoms, external electromagnetic fields induce shifts in spin-state energies [22], but solid-state systems can also detect material properties that atoms cannot easily probe, such as temperature [23] and strain [24]. While spin ensembles provide greater sensitivity [25], individual solid-state emitters have realised spatial resolution on the 10-nm scale [26], and diamond defects have been incorporated into nanoparticles for intracellular sensing [27].

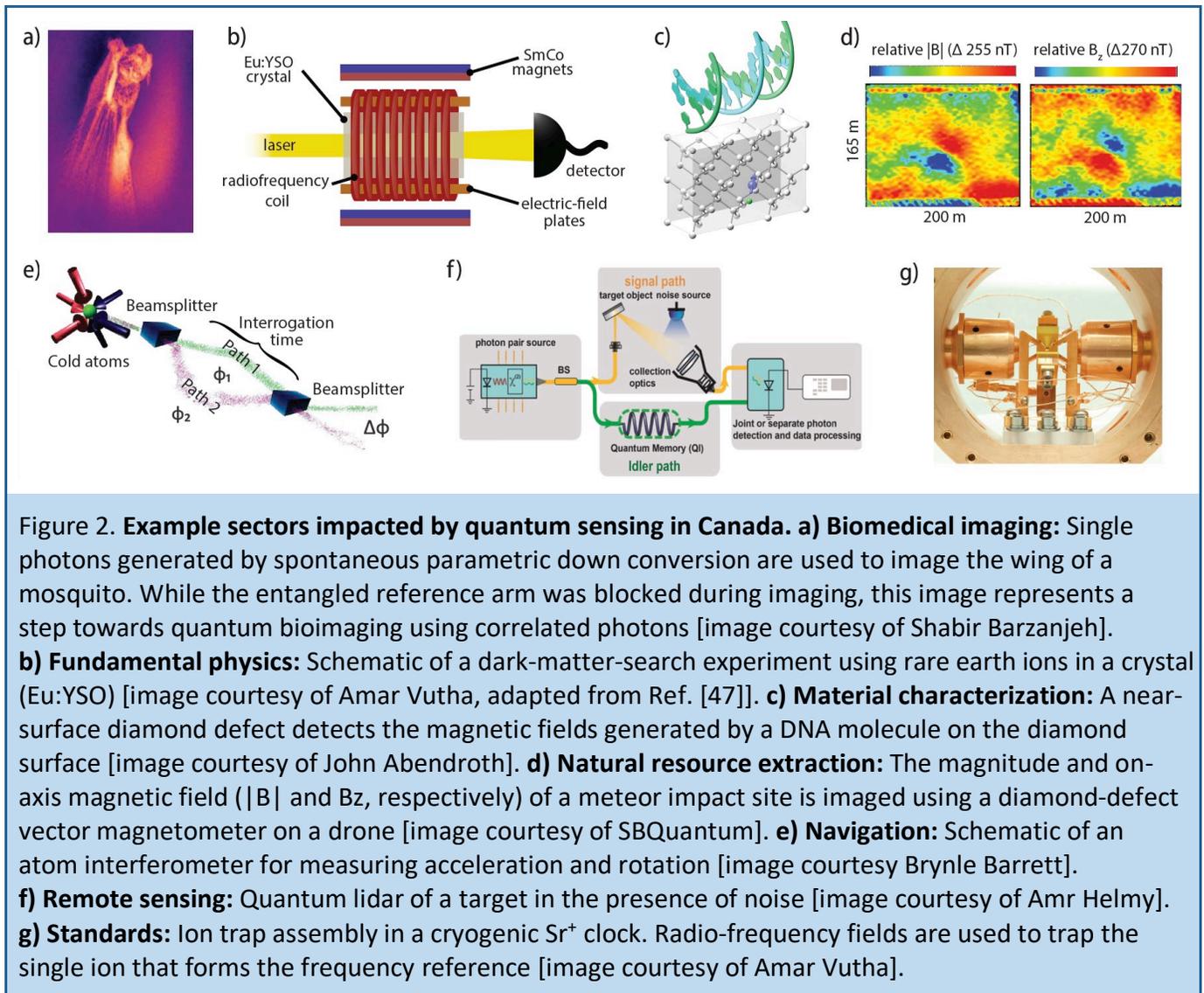
Superconducting devices leverage recent advances in superconducting materials, qubits, and resonators to offer compelling solutions for magnetometry and microwave quantum sensing when cryogenic operation is feasible. Superconducting quantum interference devices (SQUIDs) detect the magnetic flux in a superconducting ring broken by a Josephson junction [28], offering sensitive measurements from macro- to nanoscales [29]. Alternately, coherent interactions between superconducting qubits and microwave resonators can be used to engineer the quantum states of microwave fields, facilitating quantum-enhanced radar [30].

SECTORS IMPACTED

In this section, we give examples of how emerging quantum sensors offer essential capabilities for many of Canada's economic sectors and highlight efforts by Canadian institutions and companies in each area (Fig. 2).

Biomedical imaging is poised to benefit from quantum optical techniques, particularly for light-sensitive samples. Researchers at the University of Ottawa (UOttawa) and the National Research Council Canada (NRC) have used entangled photons for quantum-enhanced phase imaging to determine the thickness of transparent objects [31,32], which could be applied to biological systems such as cells. Entangled photons have also been used at the University of Calgary (UCalgary) and start-up QuantaSense to perform multilayer imaging [33], enabling complex structural analysis of biodegradable and photosensitive materials.

Fundamental physics can exploit the enhanced precision of quantum sensors to advance our understanding of physical laws. For example, ultra-high-precision quantum magnetometry at the University of Alberta (UALberta) could test theories of quantum gravity [34], while dark matter interactions could be constrained by optomechanical detection of superfluid helium acoustic modes at



McGill University and UAlberta [35] or by symmetry violations in rare earth ions in crystals at the University of Toronto (UToronto) [36]. Atomic experiments at York University (YorkU) have determined the hydrogen Lamb shift [37], the proton charge radius [37], and measured the fine structure of atomic helium [38], and a cesium magnetometer will aid measurement of the neutron electric dipole moment in the TUCAN collaboration with TRIUMF [39]. Finally, Canadian physicists have also been at the forefront of studies probing the fundamental limits to quantum measurement [40-42].

Material characterization can benefit from quantum sensors with nanoscopic resolution and sensitivity to internal material properties. For example, individual diamond defects have been used to probe nanoscale magnetic circuits at McGill [43,44], are being used for molecular [45] and material strain sensing [46] at UCalgary, and are being explored for nano-thermometry at Trent University (TrentU)

[47-48]. In addition, research at Université de Sherbrooke (USherbrooke) has contributed to thermometry in the 10-mK range using superconducting qubits [49].

Natural resource extraction relies extensively on magnetic and gravitational mapping to identify promising deposits. Commercial atomic magnetometers are produced by GEM Systems and Scintrex; magnetometers based on diamond-defect ensembles promise accurate vector-field sensing, with development at UCalgary [50] and McGill [51], and commercialization for mineral exploration by start-up SBQuantum [52] with support from USherbrooke [52]. At the same time, atomic interferometer measurements of local gravitational acceleration could provide high-precision subsurface density estimates for resource identification, aided by research at the University of New Brunswick (UNB) [2] and YorkU [54]. Finally, quantum sensors could impact post-extraction monitoring, for example, in a project on pipeline integrity monitoring from UAlberta and Synergy Aviation Inc. [53].

Navigation requires determining position and orientation with high sensitivity and accuracy. Inertial or magnetic navigation with quantum sensors could offer immunity to jamming and operation in GPS-denied or otherwise challenging environments. Several diamond-defect-based platforms are being pursued, including magnetometers from SBQuantum and gyroscopes from accelerator Quantum Valley Ideas Lab (QVIL). At the same time, researchers at UNB are developing atom interferometry for acceleration and rotation detection [2,55]. Alternately, SBQuantum's magnetometer may aid future refinements of the World Magnetic Model that underlies conventional navigation systems [56].

Remote sensing harnesses quantum techniques to enhance covert surveillance, detect sensitive objects, and image underwater or in space. While still in the proof-of-principle stage, quantum lidar [57] and radar [58] could outperform their classical counterparts in noisy or low-signal conditions [3]. Researchers at the University of Waterloo (UWaterloo) and start-up Qubic Inc. have demonstrated critical quantum radar components, including low-noise transmitters and receivers [59]. For quantum lidar, UToronto, UOttawa, and the NRC have developed correlated-photon-pair [60,61] and squeezed-light sources [62]. In combination with single-photon detectors (e.g., those from start-up Single Quantum Systems or the University of British Columbia (UBC) [63]), such sources have enabled noise-resilient target detection [64,65] and single-photon holography [66], with ongoing quantum lidar commercialization by start-up Phantom Photonics. Additionally, QVIL and start-up WaveRyde are exploring Rydberg atoms for radio-frequency electric-field monitoring in space.

Standards and metrology define and maintain accurate measurements for physical quantities, benefiting particularly from the reproducibility of atomic systems. The NRC hosts one of the world's most accurate cesium clocks [6] and novel atomic time standards are being developed by researchers at the NRC [67], UToronto [68], and QVIL. Furthermore, ultracold atoms and molecules are being leveraged for absolute pressure and particle-flux measurements at UBC and the British Columbia Institute of Technology (BCIT) [69-70]. Finally, start-up WaveRyde creates atomic vapour cells as standards for radio-frequency electromagnetic waves.

CONCLUSION

Quantum sensors are arguably the nearest-term quantum technology, with systems such as atomic clocks and SQUIDs in practical use for decades and many more on the brink of commercial adoption. Spurred by academic or government research and brought to market by start-ups, accelerators, or in collaboration with established companies, quantum sensors are finding diverse applications in sectors crucial to Canada's economy and national defence. Looking forward, as researchers and entrepreneurs refine the alignment between device capabilities and sector needs, quantum sensors are poised to drive growth and improve outcomes across a wide range of Canadian industries.

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DEVELOPING CANADA'S FIRST PORTABLE QUANTUM GRAVIMETER

SUMMARY: We discuss the development of Canada's first portable quantum gravimeter for applications in natural resource prospecting, geophysics, positioning, and navigation.



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Natural resources such as water, minerals, and petroleum can be detected passively using sensitive gravimeters that measure local variations in gravity. Gravimeters are used in mining and resource exploration to detect subsurface density variations that indicate critical mineral reserves. They are crucial for geodesists to determine geodetic heights referenced to sea level, or water levels in the Great Lakes, which strongly affect the shipping industry [1]. Gravimeters are also essential to geophysicists for detecting dynamic mass transport phenomena, including tectonic uplift due to glacial recession [2], volcanic activity [3, 4], solid-Earth tides and ocean loading effects [5]. The Canadian Geodetic Survey Division at NRCan has a vital need for precise and stable absolute gravimeters to replace its aging fleet of “classical” instruments.

Classical free-fall gravimeters operate using an optical Michelson interferometer with a free-falling corner-cube reflector as the test mass [6]. Although they have been the industry standard since the 1990s, classical gravimeters are prone to long-term drift and require periodic recalibration/repair due to mechanical wear and tear. For example, the Micro-G LaCoste FG5-X requires servicing after 10^6 drops (or after ~ 16 weeks at 10 s per drop) [7]. Quantum gravimeters have only recently emerged on the market [8, 9]. These devices are the quantum analog of classical free-fall gravimeters: they use a cloud of laser-cooled atoms instead of a macroscopic test mass. They are also self-referenced to quantum properties of the atoms; thus, they do not require recalibration, have no moving parts, consume less power, have a higher repetition rate (2 Hz or 0.5 s per drop), and can be operated remotely without intervention for years. These features make quantum gravimeters attractive for remote monitoring applications operated by non-expert users.

Canadian academics and high-tech companies continue to make important contributions to quantum sensing technologies [10], but there has been surprisingly little work on cold-atom-based gravimeters in Canada [11-13]. Several countries have developed portable atomic gravimeters (e.g., France [14], USA [15], China [16], Germany [17], United Kingdom [18], Singapore [19]), with some already offering

commercial products [9]. NRCan recently acquired an Exail AQG (model B13) as part of Canada's growing investment in quantum technology, but at \$750k CAD per unit the current cost makes widespread deployment prohibitive.

Cold-atom-based gravimeters have been operated on moving vehicles and successfully produced high-resolution gravity maps [20, 21]. Real-time gravity data is a crucial component of autonomous (GPS-free) navigation systems, which ensure robust positioning in the presence of adversarial spoofing or jamming. The Department of National Defence (DND) has identified quantum sensors as a critical technology for the defence and security of Canada and her allies. Thus, developing sovereign quantum sensing technology is both timely and necessary.

In this article, we present progress toward the development of two quantum gravimeters at the University of New Brunswick (UNB): a 1st-generation table-top instrument that will act as a high-accuracy gravity reference, and a 2nd-generation field-deployable instrument – the first portable quantum gravimeter designed and built in Canada.

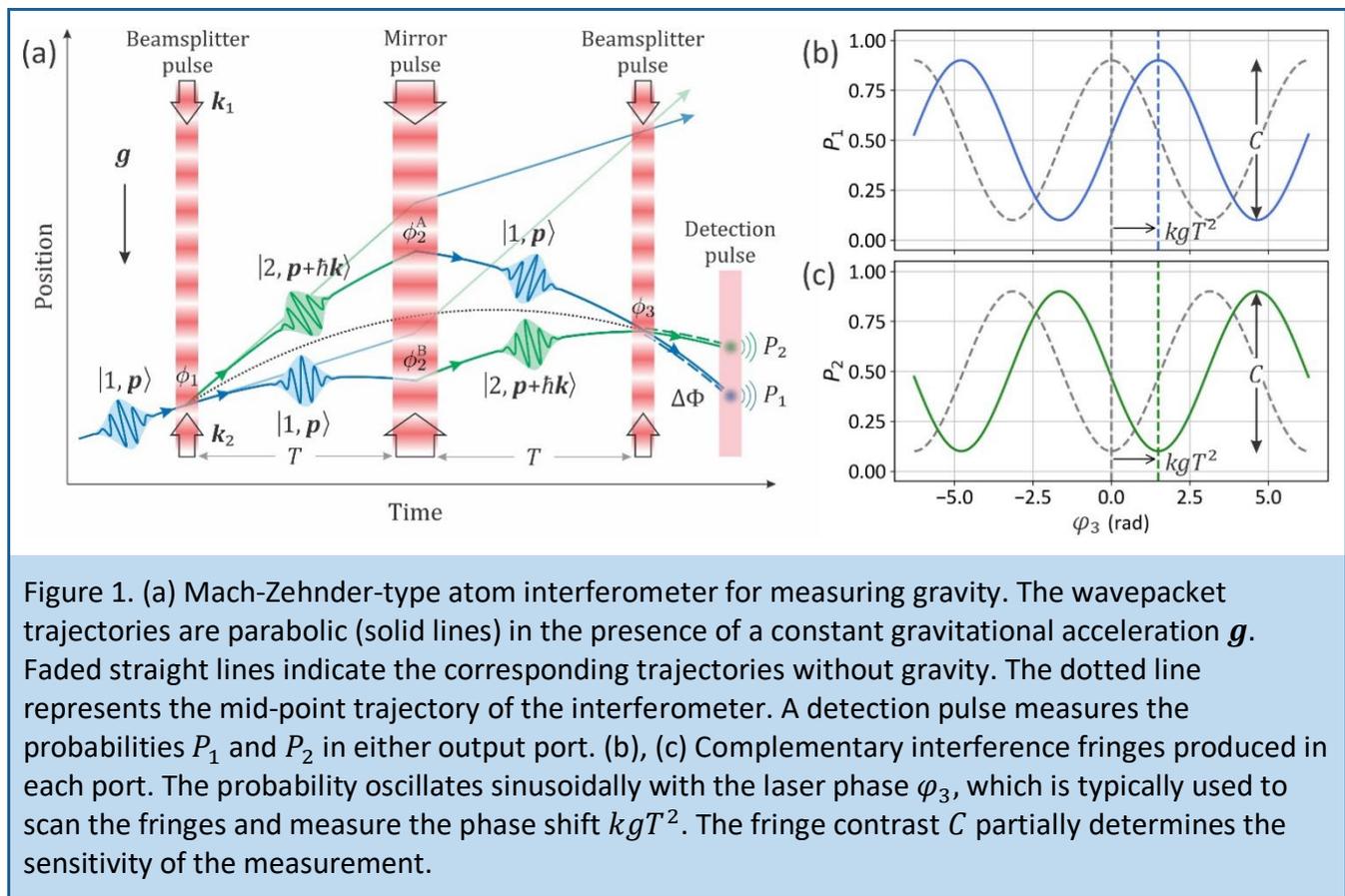
MEASURING GRAVITY WITH MATTER-WAVE INTERFEROMETRY

A cornerstone of quantum mechanics is the wave-particle duality of matter: all building blocks of matter (electrons, quarks, protons, atoms, etc.) can behave as both particles and waves. An atom moving relative to an observer can be represented as a “wavepacket” with a so-called de Broglie wavelength that is inversely proportional to its mass and velocity. Here, the amplitude of the wavepacket at any point in space represents the probability of finding the atom at that point. A quantum gravimeter relies on the interference between two atomic wavepackets in a **matter-wave interferometer**: the analog of an optical interferometer where the roles of light and matter are reversed.

Figure 1 depicts the matter-wave interferometer most widely used to measure gravity: the Mach-Zehnder configuration [22]. This atom interferometer relies on the coherent transfer of photon momentum to the atoms using optical Raman transitions between two long-lived ground states $|1\rangle$ and $|2\rangle$. Light pulses stimulate atoms in state $|1\rangle$ to absorb a photon along one direction \mathbf{k}_1 and emit a photon along the opposite direction \mathbf{k}_2 —causing a transition to state $|2\rangle$. During this process, the atom “recoils” and picks up two photons of momentum: $\hbar\mathbf{k} = \hbar(\mathbf{k}_1 - \mathbf{k}_2)$. The Mach-Zehnder configuration consists of three light pulses, each separated by a free-fall time T , as shown in Fig. 1(a). The first pulse carries out the role of a beamsplitter in an optical interferometer, which creates an equal superposition of the two states. The second light pulse acts as a mirror, exchanging the population between the two states and redirecting the wavepackets back toward one another. The final beamsplitter pulse recombines the wavepackets by “closing” the interferometer pathways—causing them to interfere. This generates two possible output “ports” where the atom can be found, one corresponding to state $|1\rangle$ with probability $P_1 = |\langle 1|\psi\rangle|^2$, and the other to state $|2\rangle$ with probability $P_2 = |\langle 2|\psi\rangle|^2$. These probabilities can be measured with a resonant detection pulse, as shown in Fig. 1(a). This leads to complementary interference fringes in the probabilities: $P_{1,2} = \frac{1}{2}(1 \pm C \cos \Delta\Phi)$, where C is the contrast of the interference fringes, as shown in Figs. 1(b) and 1(c). The total phase shift

$\Delta\Phi$ is given by the sum of the laser phases $\phi_i = \mathbf{k} \cdot \mathbf{r}(t_i) + \phi_i$ imprinted on the atoms along the mid-point trajectory of the interferometer: $\Delta\Phi = \mathbf{k} \cdot \mathbf{g} T^2$ [23], where T is the free-fall time between light pulses.

Since this phase scales as kT^2 , and $k \approx 4\pi/\lambda \sim 10^7$ rad/m for commonly used transitions in alkali-metal atoms, very precise measurements of g can be obtained by measuring this phase shift for large T [24]. Assuming a single-measurement phase uncertainty of $\delta\Phi \approx 10^{-2}$ rad at $T = 100$ ms, the corresponding relative uncertainty in gravity is $\delta g/g = \delta\Phi/kgT^2 \approx 10^{-8}$. With averaging, this precision reaches below 10^{-9} after a few hundred measurements under quiet conditions [25]. Instruments capable of this sensitivity can observe gravity signals produced by a large range of geophysical phenomena [2].



QUANTUM GRAVIMETER DESIGN

Two quantum gravimeters are being developed in the Quantum Sensing and Ultracold Matter Lab at UNB. Figure 2 depicts the sensor heads, which each consist of an ultra-high vacuum (UHV) system, various optical elements, and laser beams for cooling and manipulating rubidium atoms. Quantum

Gravimeter 1.0 (QG1) is a stationary, table-top instrument designed to reach a sensitivity of $1 \times 10^{-8} g$ at 1 s of integration time, and an accuracy around $10^{-9} g$. The objective of QG1 is to act as one of Canada's primary gravity standards—providing uninterrupted high-accuracy time-variable gravity data for long timescales and traceability for gravimetric/geodetic heights, while also serving as an accurate calibration reference for other gravimeters/accelerometers.

The 6.8-L sensor head shown in Fig. 2(a) consists of two main chambers: a glass cell, and a central titanium “science chamber”. The glass cell houses a dispenser that produces hot rubidium vapour that we laser cool in a 2D magneto-optical trap (MOT) [26]. These cold atoms are then optically “pushed” through a small pinhole—creating a cold atomic beam in the science chamber. In the science chamber, the atoms are loaded into a 3D MOT (approximately 10^9 atoms in 1 s) and further cooled to a temperature of a few micro-Kelvin (10^{-6} K). An interferometry beam is aligned vertically through the science chamber to ensure the atomic cloud maintains overlap with the laser as it falls. Two stainless-steel cubes are fixed above and below the science chamber to provide an extended free-fall height up to 0.5 m—corresponding to $T \approx 300$ ms in an atomic fountain geometry. Finally, two near-resonance light sheets at the bottom of the science chamber serve as detection beams to count the number of atoms in states $|1\rangle$ and $|2\rangle$, and hence the probabilities P_1 and P_2 in each interferometer port.

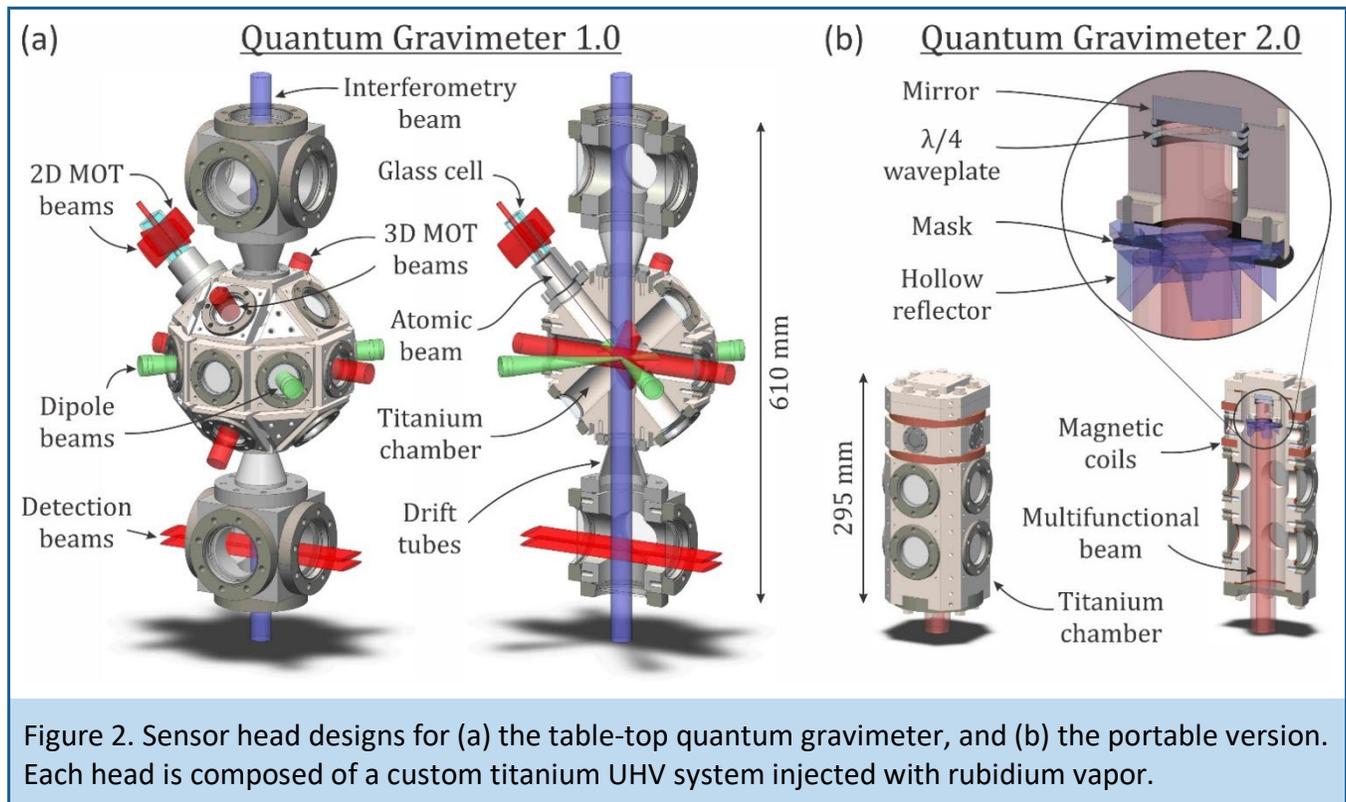


Figure 2. Sensor head designs for (a) the table-top quantum gravimeter, and (b) the portable version. Each head is composed of a custom titanium UHV system injected with rubidium vapor.

The science chamber is maintained at a lower pressure than the glass cell by virtue of differential pumping. This helps to avoid background fluorescence from rubidium vapor and will enable the use of evaporative cooling techniques [27] to reach sub-recoil temperatures. For this, we will use a high-intensity laser, red-detuned far below the D2 transitions in ^{87}Rb , to create a crossed optical dipole trap [28]. Here, atoms are attracted to the high-intensity regions of the dipole beams due to the gradient of the optical potential [29]. By gradually lowering the trap depth, faster-moving atoms escape the trap while the remained atoms re-thermalize to a lower temperature. The use of “painted” optical potentials generated by rapidly moving beams can further increase the evaporation rate [30]—making sample temperatures $< 10^{-7}$ K attainable in under 1 s of evaporation time. Ultra-cold atomic samples have been shown to dramatically improve the gravimeter’s sensitivity [31] and accuracy by reducing the dominant systematic effects due to laser wavefront distortion [32, 33].

Quantum Gravimeter 2.0 (QG2) is designed to be a compact, robust, and portable instrument. It consists of a 2.2-L all-titanium body with integrated magnetic coil frames and a 0.2-m-long drift tube. Several viewports allow for probing/imaging the atomic cloud at different positions. Central to the design is a custom in-vacuum hollow reflector that enables a single-laser-beam architecture for both cooling and interferometry [34, 8]. Figure 2(b) illustrates a large-diameter, circularly polarized laser beam incident on the reflector from the bottom. The hollow reflector consists of four right-angle prisms optically contacted to a baseplate and aligned in quadrants that reflect incident light twice by 90 degrees. The central part of the beam transmits through a square aperture at the center of the reflector. The beam then passes through a quarter waveplate and retro-reflects off a mirror fixed to the top of the chamber. This creates three mutually orthogonal pairs of counter-propagating beams within the hollow reflector. Each prism is covered with a high-reflection, zero-phase dielectric coating that maintains the direction of circular polarization at each reflection. Light propagating within the hollow reflector then creates the ideal σ^+/σ^- polarization required for a 3D MOT [35]. Below the hollow reflector, the atoms are exposed to only two counter-propagating vertical beams that have σ^+/σ^+ or σ^-/σ^- polarization, which is ideal for driving velocity-sensitive Raman transitions in the interferometer [34].

QG2 is less than 1/3 the volume of QG1 and requires 1/10 the number of laser beams, which drastically reduces the instrument’s hardware complexity, size, weight, and power consumption. The trade-off is reduced experimental flexibility and free-fall height (maximum interrogation time $T \approx 80$ ms). As a result, QG2 targets a more modest sensitivity of 4×10^{-8} g at 1 s, and an accuracy around 5×10^{-9} g. However, as a portable instrument designed to operate in relevant environments outside a climate-controlled laboratory, it will be competitive with other commercial absolute gravimeters [7, 9].

CONCLUSION

Canada’s vast and resource-rich landscape demands advanced tools for precise geophysical and geodetic measurements. While classical gravimeters have long served this role, their limitations highlight the need for next-generation solutions. Quantum gravimeters offer a transformative alternative with their enhanced stability, reduced maintenance, and suitability for remote deployment. Despite international advances, Canada has yet to fully capitalize on this technology. The development

of quantum gravimeters at the University of New Brunswick marks a critical step toward establishing domestic capability in quantum sensing, supporting both scientific exploration and national strategic priorities.

ACKNOWLEDGEMENTS

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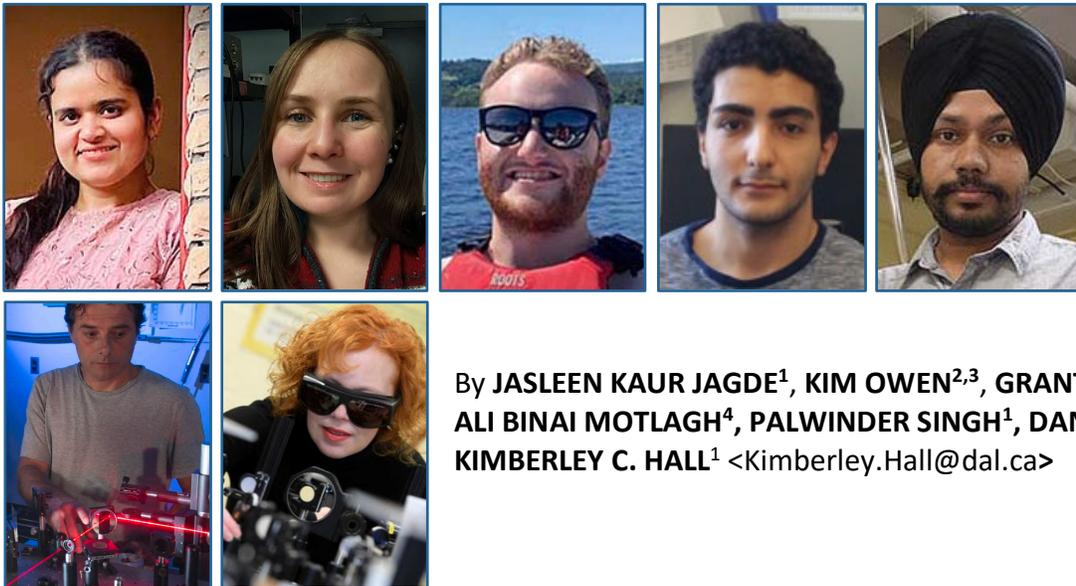
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ON-DEMAND FLYING QUBITS USING SHAPED LASER PULSES AND SCALABLE SEMICONDUCTOR EMITTERS

SUMMARY: High-performance single photon sources represent an enabling technology for a whole host of applications in quantum information science, including quantum networks and photonic quantum computers. Here we discuss made-in-Canada efforts to develop laser triggered, solid-state single photon sources, focusing on semiconductor-based approaches that offer the potential for commercial scale fabrication.



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A single photon can be used to encode quantum information (e.g. within the polarization state, time-bin or path), making it a powerful resource for applications within the field of quantum information science. On-demand single photons may be generated using atom-like transitions in a semiconductor material with confined electrons [1], combining deterministic operation, high brightness and low multiphoton probability. Such solid-state single photon sources (SPSs) may be applied to quantum key distribution for secure communication [2,3], photonic quantum computing [4], and would serve as flying qubits in quantum networks relaying information between quantum memories and simulators [5]. Due to the importance of these applications for a range of areas,

including finance, health and national security, considerable progress has been made in advancing the performance of solid-state SPS systems over the past decade [6].

Researchers at Dalhousie University and the National Research Council Canada (NRC) are pushing the envelope for the development of high-performance, on-demand SPSs based on semiconductor quantum dots (QDs) in nanowire waveguides [7] and strain-induced emitters in 2D semiconductors [8]. Due to their compatibility with semiconductor-based photonic fabrication infrastructure, both approaches offer the potential for commercial-scale fabrication. The Dalhousie group has developed laser triggering schemes for SPSs using laser pulse shaping to optimize the robustness of quantum state inversion and enable the simultaneous optimization of brightness and indistinguishability [9,10]. The NRC and Dalhousie groups are working together with the support of the NRC Quantum Sensors Challenge Program to implement these schemes on promising solid-state SPSs. This article will serve to highlight some of this work within the broader Canadian and international communities working on SPSs.

SCALABLE APPROACHES TO SINGLE PHOTON SOURCES

QUANTUM DOTS IN NANOWIRE WAVEGUIDES

Quantum dots are created within a semiconductor by confining electrons and holes to nanoscale dimensions in all three spatial directions, typically achieved through the potential step at the interface between two dissimilar semiconductors (e.g. InAsP inside of InP). Due to the resulting discrete energy level spectrum, the QD possesses a single, spectrally-isolated ground state optical transition. Following excitation of an electron-hole pair in the QD by a laser pulse, one and only one photon is emitted, resulting in a highly pure, on-demand SPS. III-V semiconductor QDs provide the current state-of-the-art for high-performance SPSs [1,6]. Traditionally, QDs are grown via strain-driven self-assembly and nucleate randomly on a semiconductor substrate, however this random positioning makes them unsuitable for large-scale integration into photonic devices. Researchers at NRC have developed a technique to produce QDs integrated within nanowire waveguides [11] (see Figs. 1(a), (b)) using vapour-liquid-solid (VLS) epitaxy [12]. Because the position of the nanowire is deterministically chosen, ordered arrays of nanowires may be produced, providing a scalable solution for QD SPSs. NRC's nanowire SPSs offer excellent single photon emission properties, including ultranarrow emission linewidths under 500 MHz [13], collection efficiencies above 80% [7], and a post-selected two-photon interference visibility over 80% [14]. The latter metric is indicative of a high degree of indistinguishability of successively emitted photons. Nanowire QDs also offer low second-order correlation ($g^{(2)}(0) < 1\%$ [7]), signifying robust antibunching, a key measure of single photon purity.

While promising, the above performance metrics are limited by the non-resonant laser excitation scheme used to trigger single photon emission. NRC and Dalhousie are currently working to apply new quantum control protocols developed by the Hall group on these quantum light sources to boost these metrics further, promising ideal, high performance SPSs. NRC is also working to integrate their nanowire SPSs into silicon nitride-based photonic integrated circuits (Fig. 1(d)-(f)). The NRC-Dalhousie

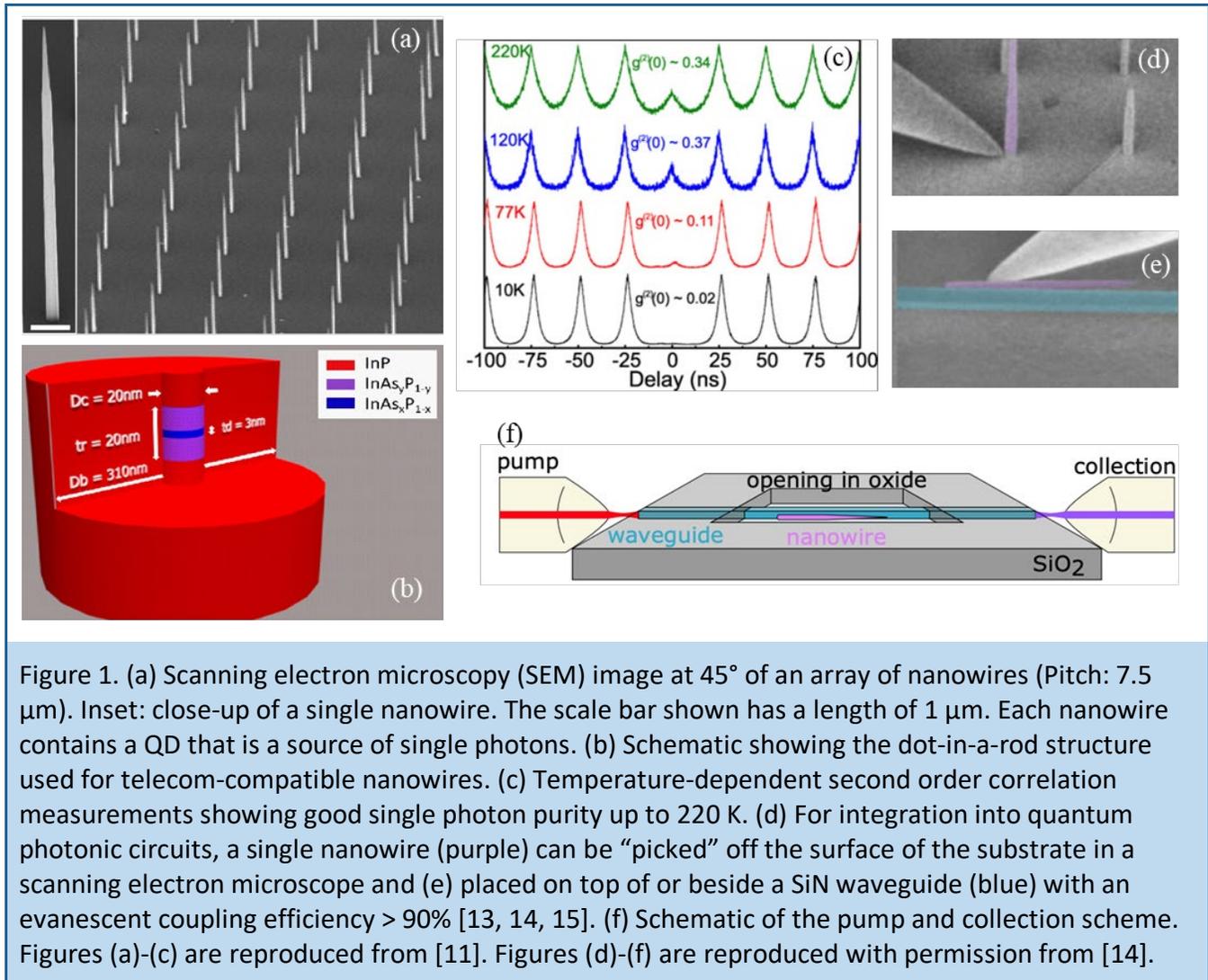


Figure 1. (a) Scanning electron microscopy (SEM) image at 45° of an array of nanowires (Pitch: 7.5 μm). Inset: close-up of a single nanowire. The scale bar shown has a length of 1 μm . Each nanowire contains a QD that is a source of single photons. (b) Schematic showing the dot-in-a-rod structure used for telecom-compatible nanowires. (c) Temperature-dependent second order correlation measurements showing good single photon purity up to 220 K. (d) For integration into quantum photonic circuits, a single nanowire (purple) can be “picked” off the surface of the substrate in a scanning electron microscope and (e) placed on top of or beside a SiN waveguide (blue) with an evanescent coupling efficiency > 90% [13, 14, 15]. (f) Schematic of the pump and collection scheme. Figures (a)-(c) are reproduced from [11]. Figures (d)-(f) are reproduced with permission from [14].

collaboration aims to implement the Hall group’s laser triggering schemes in these integrated structures, providing a pathway to a comprehensive high-performance system for quantum photonics.

EMITTERS IN 2D TRANSITION-METAL DICHALOGENIDES

Two-dimensional transition-metal dichalcogenides (TMDs), particularly in their monolayer (ML) and bilayer (BL) forms, have emerged as alternative candidates for solid-state SPSs [15]. These layered materials are composed of strong covalently bonded atomic planes held together by weak van der Waals forces, which enables the use of mechanical exfoliation to obtain pristine, atomically thin flakes from bulk crystals [16]. SPSs may be formed by inducing strain within the thin layer by transferring the exfoliated flakes onto pillars and other structures [17-20], creating an effective QD. Defects such as vacancies combine with strain-induced effects to further localize these states [20], resulting in bright SPSs exhibiting narrow emission peaks and long-term spectral stability [8]. TMDs offer a promising

alternative platform to III-V QDs because emitter site-selectivity and integration into photonic circuits is possible using conventional integrated photonic processing followed by the deposition of the ML or BL [8]. TMD SPSs also offer efficient light extraction without the need for a waveguide because the emitter is localized in the topmost layer, i.e. not embedded in a high index host where extraction is limited by total internal reflection.

The Dalhousie and NRC groups have been working to demonstrate site-selective quantum emitters in TMDs using a variety of engineered surfaces, including dielectric nanopillars (see Fig. 2(a), (b)) and the nanowire waveguides described in the preceding section oriented horizontally (Fig. 2(c)). Both structures exhibit bright, spectrally narrow emission lines and good photon purity (Fig. 2(d)-(f)), promising for the future implementation of TMD-based SPS systems. The Hall and NRC groups are working to investigate the nonlinear optical properties of these TMD emitters and to realize fully triggered SPSs using shaped laser pulses.

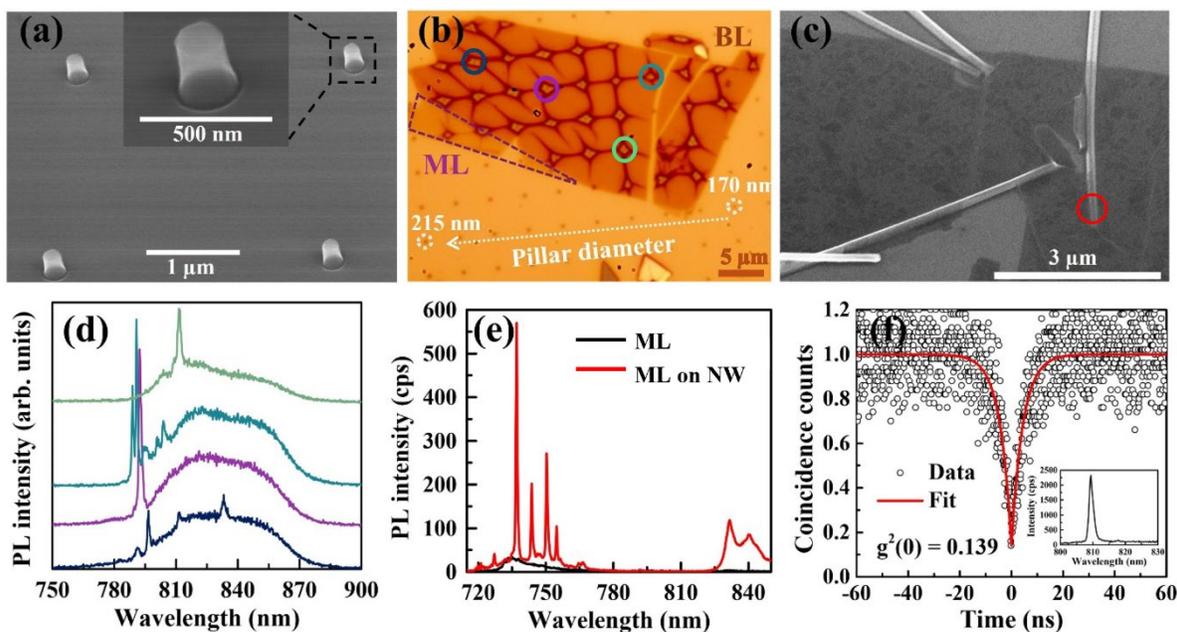


Figure 2. (a) SEM image of a SiO_2 nanopillar array (pitch: $3 \mu\text{m}$, pillar height: 275 nm). The inset shows a single nanopillar at higher magnification. (b) Optical image of ML and BL WSe_2 transferred onto the SiO_2 nanopillar array (pitch $\approx 3.67 \mu\text{m}$). (c) SEM image of ML WSe_2 on InP nanowires. (d) Photoluminescence (PL) spectra obtained from a TMD BL on nanopillars marked with circles in (b). (e) Same as (d) for an unstrained WSe_2 ML and a strained ML on a nanowire in the area marked with a circle in (c). (f) Second-order autocorrelation measurement at 809 nm collected from the bilayer covered nanopillar indicated by the light green circle in (b). Open circles represent the raw data; the solid line is a fit showing $g^{(2)}(0) = 0.139$. The inset shows the 809 nm emission line. Figures (a), (b) and (f) are reproduced from [21].

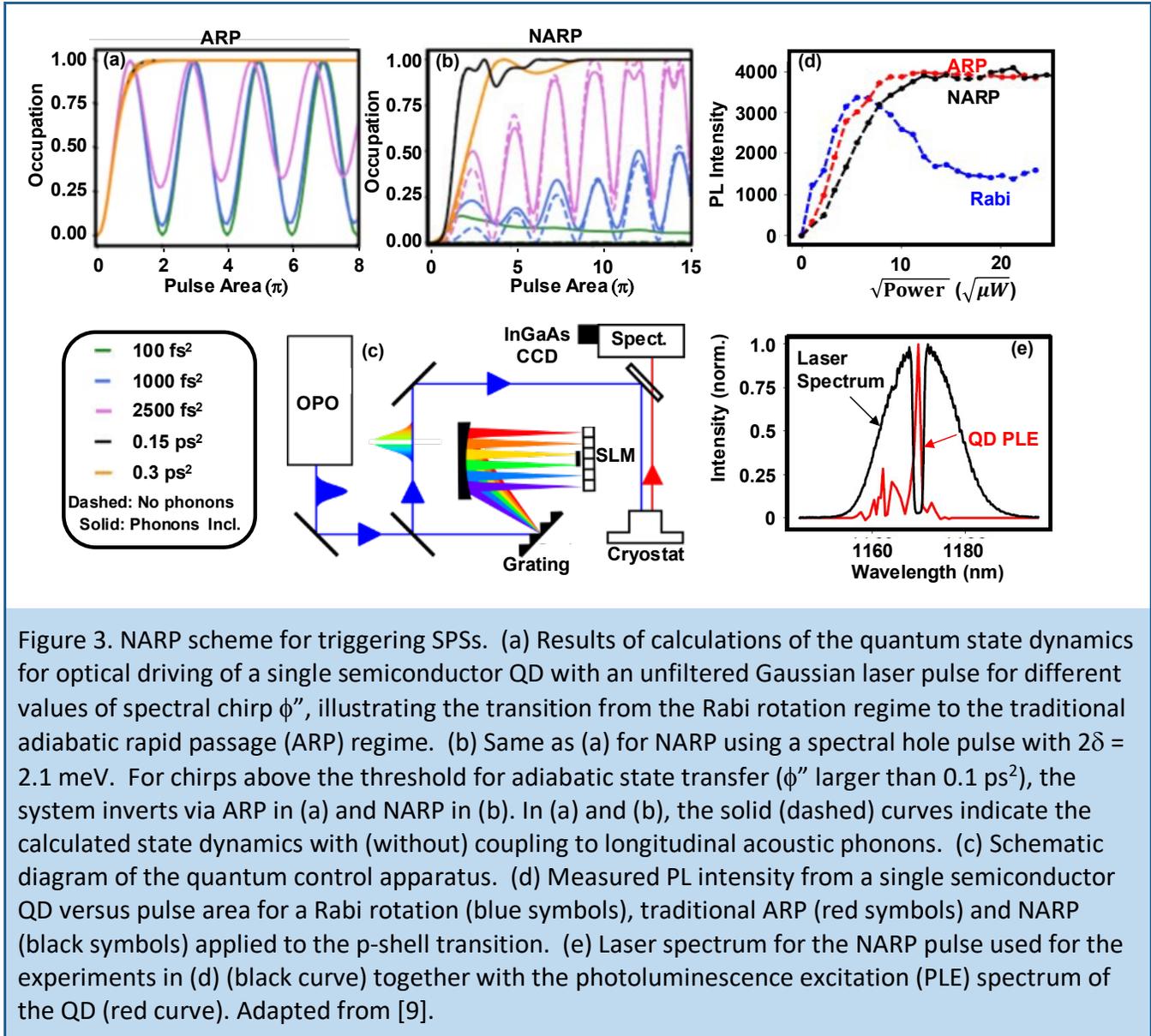
QUANTUM CONTROL FOR LASER TRIGGERED EMITTERS

The parameters of the laser pulse used to excite the QD have a dramatic impact on the quality of the emitted stream of photons [9,22-27]. Optimized values for single photon purity and indistinguishability for a QD SPS occur when the ground state exciton in the QD is pumped directly. The use of resonant pumping necessitates the development of an effective approach to separate the emitted single photons from the scattered laser light since these occur at the same wavelength. The most common approach relies on polarization-based filtering [23], but the simplicity of this approach comes at the expense of a two-fold reduction in the collection efficiency. Such high losses have the consequence that the single photon source has low brightness and is no longer deterministic. These problems have led the quantum communication community away from pure SPSs and instead towards decoy state protocols employing attenuated coherent states.

To overcome this limitation, the Hall group recently developed a new scheme for triggering SPSs called Notch-Filtered Adiabatic Rapid Passage (NARP) [9]. It utilizes a chirped trigger pulse whose spectrum has a notch resonant with the ground state exciton transition in the QD (see Fig. 3). The NARP scheme builds upon existing adiabatic control protocols for single and multiple qubit systems developed by the Hall group [9,10,22,28]. Since the photon and the pump spectrum do not overlap, the pump can be spectrally filtered, allowing for near-unity collection efficiency limited only by the quality of the spectral filters used. With this advance, QD sources of pure single photons can become competitive with the decoy state methods. The NARP scheme is also robust to experimental fluctuations, unlike many competing schemes [23-26], making it suitable for field-deployed applications outside the laboratory setting. The Hall and NRC groups are working to demonstrate the NARP protocol on both TMD-based quantum emitters and nanowire QD SPSs.

SEMICONDUCTOR EMITTERS APPLIED TO QUANTUM TECHNOLOGY

On-demand SPSs are required for a whole host of applications in quantum technology, including quantum communication, simulation and metrology. With demonstrated photon indistinguishability of 99.5% [23] and single-photon purity as low as 8×10^{-5} [29], QDs have outpaced TMDs in technological maturity and considerable progress has been made in advancing QD-based SPSs for a range of applications. The nearest-term use case for these SPSs is the development of secure communication immune to classical eavesdropping [30]. QD based SPSs are starting to become competitive with conventional quantum key distribution (QKD) sources using attenuated coherent light, with large collection efficiencies enabling higher generated key rates [31]. A telecom-compatible QD SPS was recently used to generate secure keys in a QKD experiment, achieving communication over 175 km of fiber [32]. In Canada, the quantum cryptography satellite QEYSSat is expected to launch in 2026 and could ultimately rely on quantum dot SPSs [33]. Deterministic SPSs can also be applied to quantum computing using an all-photon architecture [34-36]. Boson sampling using 20 pure single photons from a QD SPS, enough to enter the genuine sampling regime, was recently demonstrated [37]. In the area of quantum metrology, QD SPSs have been applied to intensity squeezing for sub-shot-noise measurements [38], the development of absolute calibration standards for single-photon detectors [39], and super-resolution phase measurements [40,41]. The foundational role played by SPSs in these



and other quantum technologies highlights the urgent need to develop scalable solid-state systems using a range of platforms, including the semiconductor-based SPSs being explored by the Dalhousie-NRC team.

CONCLUSION

The Dalhousie and NRC groups are making a key contribution to international efforts to develop high-performance SPSs based on solid-state platforms. By developing systems that offer compatibility with existing telecommunications and integrated photonic circuit technology, their research promises long-term scalable quantum photonic systems and will have knock-on benefits in many areas of quantum

technology where on-demand sources of quantum light are needed. This research will lead to world-leading, made-in-Canada solutions for on-demand sources of flying qubits.

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QUANTUM RESILIENCE: CANADIAN INNOVATIONS IN QUANTUM ERROR CORRECTION AND QUANTUM ERROR MITIGATION

SUMMARY: We review how quantum error correction and mitigation combat noise in quantum processes, highlighting Canadian contributions within the field's historical evolution.



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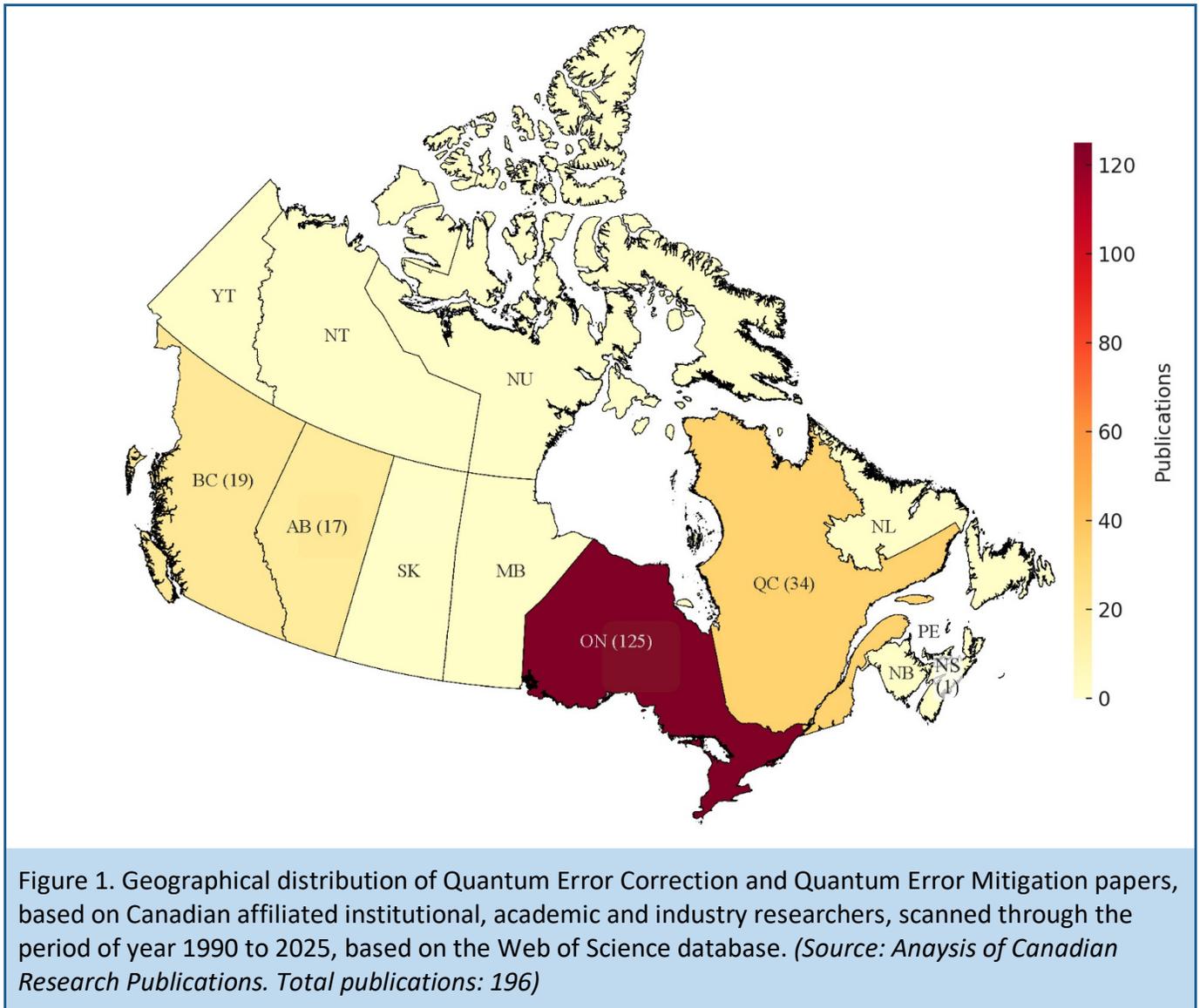
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Quantum computers promise to solve problems that are intractable even for the fastest supercomputers, from designing new materials to cracking complex optimization problems. Researchers across the globe are tirelessly developing quantum solutions to tackle complex problems, and Canada is at the forefront of these efforts. Notably, Canada is home to both the first quantum hardware company (D-Wave) and the first quantum software company (1QBit) in the world. Xanadu is another leading Canadian photonic quantum computing company driving innovation in both quantum hardware and software development. And, of course, there are so many other companies in Canada and worldwide that we do not have enough space to list them all here. Interested readers can refer to [Canadian Quantum Directory](#) and the University of Waterloo's [website](#) which are two excellent resources that offer an extensive list of many (though not all) startups and companies working on quantum technologies in Canada. Yet, despite these tremendous concerted efforts, significant challenges still stand in the way of deploying quantum computers for real-world applications.

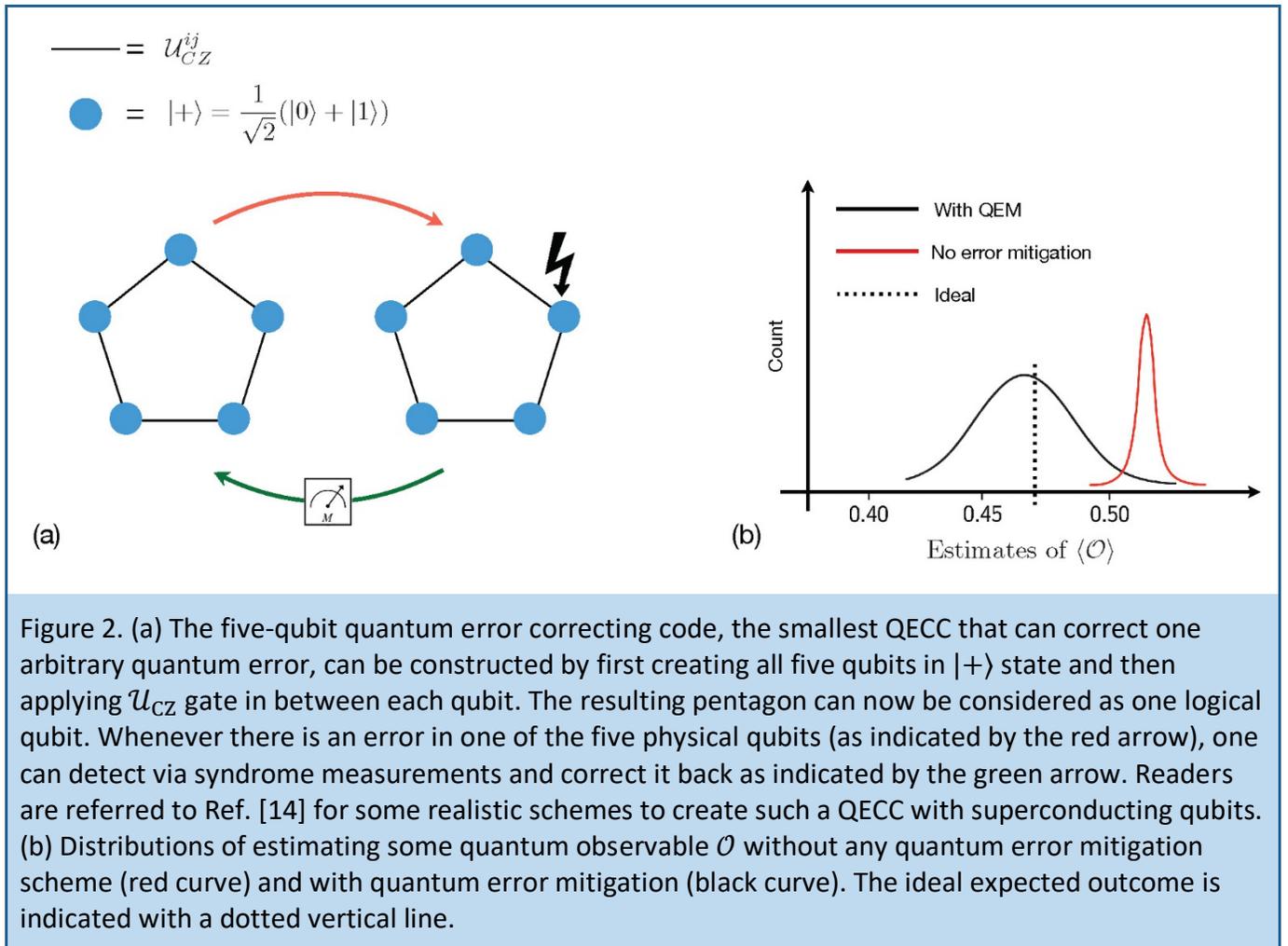
One such challenge is the extreme fragility of quantum bits (qubits). The slightest interaction with the environment or tiny imperfections in hardware can introduce errors that spoil a calculation, complicating both information storage and the scaling of quantum processing units. Even cosmic rays can deter the fate of qubits [1]! Overcoming this "noise" is essential to unlock useful quantum computing [2]. Researchers worldwide, including many in Canada, are developing two complementary strategies to tackle errors in quantum information processing. One approach is quantum error

correction (QEC): encoding information in clever ways so that errors can be detected and fixed on the fly [3,4]. The other is quantum error mitigation (QEM): finding ways to reduce or cancel errors in today’s small to intermediate-scale quantum devices without the full overhead of error correction [5]. This article briefly reviews these strategies and highlights the pivotal contributions of Canadian institutions and researchers, from pioneering theoretical codes to cutting-edge experiments and collaborations (see geographical distribution in Fig. 1).



BRIEF HISTORY OF QUANTUM ERROR CORRECTION

In 1996, Laflamme, *et al.* unveiled the five-qubit “perfect” code, the smallest possible scheme that corrects any single-qubit error [6,7] (see Fig. 2(a)). Their work produced the Knill–Laflamme conditions [8], standard criteria for deciding whether a set of states forms a valid quantum code.



Two years later, Laflamme, nuclear magnetic resonance pioneer David Cory, and collaborators delivered the first laboratory proof-of-principle demonstration of QEC, encoding information into the nuclear spins of a liquid molecule and successfully reversing an induced error [9]. Daniel Gottesman, who was affiliated with the Perimeter Institute, formalized stabilizer codes [10] and co-invented the Gottesman–Kitaev–Preskill (GKP) code for continuous-variable quantum systems [11]. This was one of the significant developments in this field and is now the main driving force behind many of the initiatives in qumode quantum information processing [12]. David Poulin (originally from Sherbrooke) developed efficient decoding algorithms and showed, via threshold theorems, that if each physical qubit’s error drops below $\sim 1\%$, scaling up will actually make logical errors rarer [13]. With the development of the theory of quantum error correction codes and the stabilizer formalism, Canadian and Canada-affiliated researchers played a pivotal role in advancing this field during the first decade of the 21st century.

This synergy between elegant theoretical insights and rigorous experimental work has catalyzed a global push toward realizing surface-code architectures—two-dimensional lattices in which local parity checks suppress the spread of error “ripples.” In 2023, Google demonstrated this principle at scale,

constructing a distance-5 surface code from 49 superconducting qubits. Crucially, the resulting logical error rate outperformed that of a smaller code, offering the first empirical confirmation of long-standing predictions about surface-code behavior [2].

BRIDGING QUBITS AND CODES: ADVANCES IN QUANTUM ERROR CORRECTION AND DETECTION

Building on its early foundational breakthroughs, Canada has quickly emerged as a global center for innovation in quantum error correction. Across industry, academia, and government laboratories, teams are advancing both the theoretical design of new codes and the engineering of hardware capable of supporting them. A common thread uniting these efforts is the pursuit of dramatically lower resource overheads compared to conventional QEC approaches such as the surface code—without compromising, and in some cases improving, error-suppression performance. Canadian researchers are contributing everything from novel error-correcting codes and advanced software toolchains to experimental milestones that bring fault-tolerant hardware closer to reality. Below is a curated, though not exhaustive, selection of these developments:

TOWARDS FAULT-TOLERANT QC

Xanadu has focused on bosonic encoding strategies, notably using GKP photonic qubits, to simplify quantum error correction requirements. In recent work, they demonstrated how universal quantum error correction could be implemented with significantly reduced qubit overhead using linear optical operations [15]. Supported by government investment, Xanadu is actively working toward a fully fault-tolerant photonic quantum computing platform, highlighting the strong integration of theoretical and hardware efforts within Canada.

ADVANCEMENTS IN QUANTUM LOW-DENSITY PARITY-CHECK CODES

One notable recent advancement from the startup Photonic Inc. in Vancouver, which introduced a new family of quantum low-density parity-check (QLDPC) codes called Subsystem Hypergraph Product Simplex codes (SHYPS) [16]. These codes can significantly reduce the number of physical qubits required for fault-tolerant quantum computing compared to conventional codes such as the surface code. Photonic Inc. further complemented their theoretical work with a specialized hardware architecture optimized for these highly connected QLDPC codes, leveraging photonic technology for efficient entanglement distribution. Such codes are optimized for use with Photonic Inc.'s hybrid photonic spin-qubit chips. In fact, local and global connectivity of physical qubits define the resulting quantum codes [17].

BOSONIC CODES ON SUPERCONDUCTING HARDWARE

In superconducting circuits, Sherbrooke-based startup Nord Quantique has made remarkable strides by experimentally demonstrating a hardware-efficient quantum error correction approach using (beyond GKP) bosonic grid states. Their pioneering experiments have shown that this method can actively extend qubit coherence times without excessive redundancy, an essential step towards

scalable quantum computing [18,19]. These developments were strongly supported by collaborations within the Sherbrooke quantum ecosystem, including the Institut Quantique and IBM Quantum Hub.

SURFACE CODES

Researchers at the University of Waterloo's Institute for Quantum Computing (IQC) and the Perimeter Institute have introduced groundbreaking QEC codes like the three-dimensional subsystem toric code. This code notably allows single-shot quantum error correction, significantly simplifying the correction process and reducing the overhead needed for practical fault-tolerant quantum computing [20]. An experimental realization of distance-three surface code using 17 physical qubits can also be found in [21].

ERROR DETECTION FOR EARLY-TERM FAULT TOLERANCE

Researchers from the BEIT group have proposed a resource-efficient framework for quantum error detection (QED) tailored to near-term quantum devices [22]. Through simulations of Grover's algorithm under a circuit-level noise model, they demonstrate that optimizing syndrome measurement schedules can enhance algorithm success probabilities. Additionally, they introduce a data-driven method to predict optimal compilation parameters based on circuit and noise characteristics. This work provides actionable guidelines for implementing QED in early-term quantum experiments and underscores its potential as a pragmatic error mitigation strategy for shallow quantum algorithms.

NEUTRAL DECODERS FOR TOPOLOGICAL CODES

Researchers at the University of Waterloo and the Perimeter Institute have pioneered the use of machine learning for quantum error correction by developing a neural network-based decoder. It was demonstrated that a restricted Boltzmann machine could efficiently decode syndrome data from topological quantum codes without requiring explicit algorithmic construction, adapting flexibly to the error distributions encountered. This method has opened a significant new avenue for scalable, adaptive decoding algorithms [23].

FLAG FAULT-TOLERANT ERROR CORRECTION

A new fault-tolerant error correction method applicable to arbitrary-distance quantum codes through the innovative use of flag qubits was introduced. By strategically employing flag qubits to signal problematic syndrome measurements, their approach effectively manages high-weight errors while significantly reducing resource overhead compared to traditional fault-tolerant ancilla techniques [24].

Collectively, these initiatives, ranging from innovative new codes and sophisticated decoding algorithms to cutting-edge hardware implementations, represent a comprehensive and cohesive approach to quantum error correction on Canadian soil. By closely aligning theoretical breakthroughs with practical experimental demonstrations, Canada is playing a crucial role in paving the way for fault-tolerant quantum computing.

FROM CODES TO QUICK FIXES: CANADIAN LEADERSHIP IN QUANTUM ERROR MITIGATION

Full quantum error correction demands thousands of physical qubits per logical qubit, a resource requirement beyond near-term capabilities. This limitation has led to *quantum error mitigation*, a technique designed to extract greater accuracy from noisy quantum devices with minimal additional resources (see Fig. 2(b)). Canadian research teams have played a key role in advancing several prominent error mitigation methods:

ZERO-NOISE EXTRAPOLATION (ZNE)

ZNE is a popular method that consists of running the same quantum circuit at different noise levels (using techniques such as stretching gate durations) and mathematically extrapolating to the zero-noise limit. Canadian researchers have been instrumental in developing and improving many error mitigation protocols based on ZNE. Digital ZNE provides a practical framework where unitary folding and parameterized noise scaling can be applied using only gate-level access common to most quantum instruction sets [25]. Another scheme, called variable-noise Clifford data regression (vnCDR), developed with the participation of the University of Waterloo, combines ZNE with Clifford data regression to mitigate errors, was shown to be more powerful than the individual methods of ZNE and CDR [26]. QEM protocols for quantum annealing using ZNE were introduced by a team comprising of researchers from D-Wave, the University of British Columbia, and Simon-Fraser University [27]. A recent study comprising of researchers from the University of Waterloo and the Vector Institute has also shown that ZNE is not the best option for mitigating errors in quantum sensing [28].

RANDOMIZED COMPILING (RC)

Conceived by researchers at the University of Waterloo, RC inserts randomly chosen gate twirls that convert coherent, bias-inducing errors into easier-to-model stochastic noise [29]. Their spin-off, Quantum Benchmark—later acquired by Keysight—made RC diagnostics widely available [30-32].

SYMMETRY-BASED POST-SELECTION AND SUPERPOSED MITIGATION

When a physical system obeys a conservation law—such as fixed particle number—any measurement outcomes that violate that constraint can simply be rejected. Extending this principle, a research team from Waterloo introduced a technique in which multiple noisy circuit executions are combined so that their quantum interference cancels specific error contributions. This idea is now advancing from theory to experiment, with early investigations exploring its practical viability [33].

QUASI-PROBABILISTIC METHODS

Error mitigation strategies such as Probabilistic Error Cancellation (PEC) based on quasi-probabilistic methods are among methods that are widely utilized and promise an unbiased result, albeit at the cost of an exponential runtime. Canadian researchers have developed quasi-probabilistic EM techniques that outperform PEC. *Pauli Error Cancellation* [34] was introduced by researchers from Keysight technologies and the University of Waterloo, and it was shown to mitigate non-local and gate-

dependent noise. A constant runtime quasi-probabilistic EM protocol, called *Error Mitigation by Restricted Evolution (EMRE)*, was recently introduced which works by restricting the evolution of the input state [35]. This constant runtime comes at the cost of a small finite bias. Another scheme called Hybrid EMRE or HEMRE was also proposed by combining EMRE with PEC. It was shown that when using HEMRE, a user can fix the maximum tolerable bias and achieve the mitigated result with a runtime not greater than that of PEC. The EMRE framework was subsequently extended to the design of a resource-efficient mitigation protocol based on noise amplification and robust extrapolation to the zero noise limit and is termed as the *Physics-Inspired Extrapolation (PIE)* method [36]. Unlike typical ZNE methods, PIE analytically justifies the extrapolation function and assigns operational meaning to the fitting parameters. The method demonstrates good accuracy and robustness in simulating quantum dynamics up to 84 qubits.

NEURAL ERROR MITIGATION

A team of researchers from 1QBit, the University of Waterloo, the Vector Institute, and the Perimeter Institute for Theoretical Physics introduced a machine learning-based framework for error mitigation in quantum simulations. By leveraging neural networks, the method achieves improved accuracy in quantum chemistry and lattice gauge theory simulations on noisy quantum devices [37]. In another work, researchers introduce a neural model that achieves quantum error mitigation without any prior knowledge of the noise and without training on noise-free data [38].

OTHER EM STRATEGIES

Other error mitigation schemes and analysis have been introduced by a team of researchers comprising of researchers from Canada. A benchmarking study to understand the application of quantum error mitigation in quantum chemistry was studied in [39]. Another work [40] introduced an error detection scheme by using the Bravyi-Kitaev superfast encoding and showed that it can be used to mitigate errors in quantum chemistry simulations. Schemes to reduce the logical error rate of Clifford circuits without the exponential sampling overhead of error mitigation were also developed with the involvement of Canadian researchers [41]. Researchers from Canadian institutions have also been involved in correctly characterizing state preparation and measurement (SPAM) errors which helped both in mitigating such errors and in designing reliable quantum processing units [42]. Lastly, *Mitiq*---a Python package, widely used in the quantum community to implement and deploy error mitigation protocols---was also developed in collaboration with Canadian researchers [43].

Thanks to these techniques, small quantum processors have already produced chemically and physically meaningful results, despite raw error rates that would otherwise swamp useful signals.

REMARKS AND WELL-WISHES

Since the late 1990s, quantum error correction has been a foundational pillar in the pursuit of building reliable quantum computers. While significant strides continue toward the ultimate goal of fault-tolerant quantum computing involving millions of physical qubits, quantum error mitigation has emerged as an invaluable complementary tool, enabling researchers to obtain trustworthy results from

today's noisy quantum hardware. In this brief review, we have highlighted notable contributions from Canadian and Canada-affiliated researchers in academia and industry in both quantum error correction and mitigation. The selected references presented here represent only a curated subset of Canada's extensive contributions to the field -- see Fig. 1.

Looking ahead, Canadian researchers are poised to play a pivotal role in achieving two key milestones. The first is the long-term goal of experimentally demonstrating quantum error correction beyond the fault-tolerance threshold *at useful scales*. While beyond-threshold computation has now been performed at small scales [2], we estimate that useful simulations in chemistry, for example, will require thousands of logical qubits to demonstrate practical usefulness. The second is a more immediate milestone in the noisy intermediate-scale quantum and early fault-tolerant quantum computing era, involving the integration of quantum error mitigation techniques with error-correcting codes on existing hardware to enable utility-scale quantum computations [44].

We find ourselves in a remarkable era, achieving a level of quantum system control and manipulation unimaginable to the pioneers of quantum mechanics, including the ability to remotely operate quantum systems from across the globe. While substantial work remains to elevate noisy quantum devices to practical, industry-relevant applications, the significant progress already made provides ample reason for optimism. To continue to be a leader in the future quantum technologies, Canada needs greater resources and top global talent committed to long-term breakthroughs. As we celebrate the 2025 International Year of Quantum Science and Technology (IYQ), it is fitting to reflect on these achievements and recognize the promising journey ahead.

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DATA AVAILABILITY

The data used to generate the Canada heatmap (Fig. 1) is available upon request.

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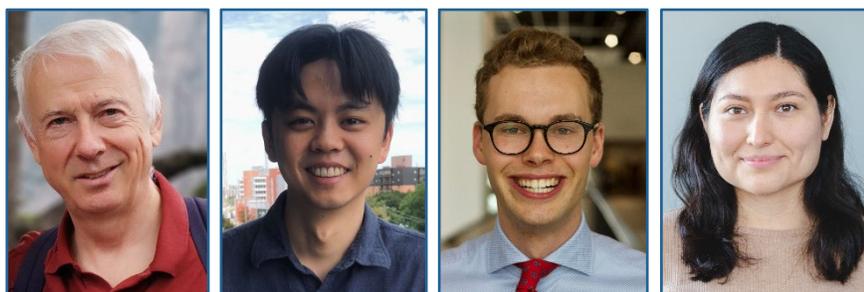
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FROM QUANTUM FOUNDATIONS TO QUANTUM GRAVITY: A BRIEF HISTORY OF RELATIVISTIC QUANTUM INFORMATION

SUMMARY: We review the history of Relativistic Quantum Information (RQI) from its antecedent roots in the 1970s, to its emergence 20 years ago, to its status as a new research field today.



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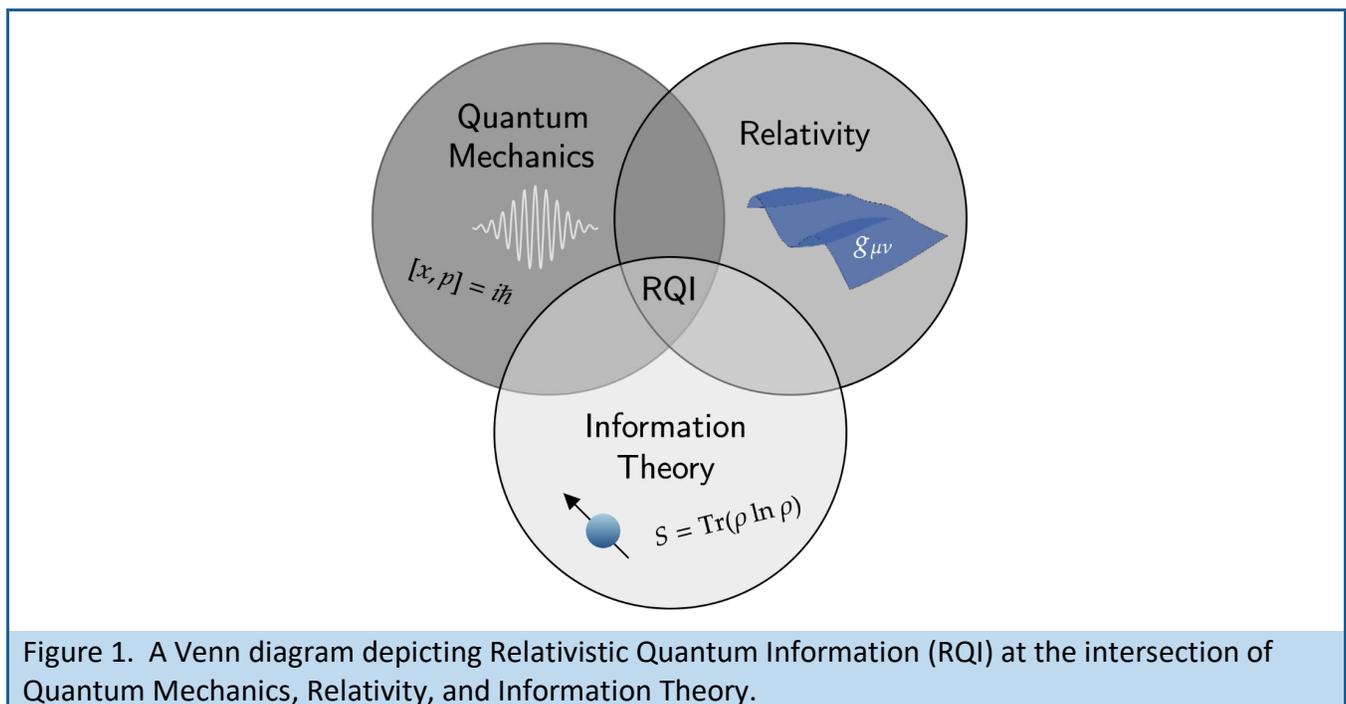
At the beginning of the 20th century, it was believed that our description of the world was complete, with the exception of a few problems like the distribution of black body radiation and Mercury's perihelion precession. However, this belief was soon overturned in the wake of two revolutions in physics: quantum theory and relativity. The former challenged the mechanistic, “classical” view of the world held since Newton, introducing notions of indeterminism and discreteness into our understanding of reality. Quantum Mechanics (QM) was formalized in 1925 by pioneers Erwin Schrödinger and Werner Heisenberg, giving rise to the so-called “first quantum revolution.” The latter, discovered by Einstein in 1905, provided a new description of space and time as two facets of a unified fabric of spacetime, allowing for consistent descriptions of events according to observers in relative motion. Ten years later, Einstein showed that gravity arises due to the curvature of spacetime in his theory of General Relativity (GR).

These two theories form the pillars of modern physics. GR predicted the existence of black holes and gravitational waves, both of which have been confirmed observationally in the past decade [1,2]. GR has also played an important role in efforts to explore space beyond our solar system, as well as in the development of the Global Positioning System here on Earth. QM, by contrast, is best suited to

describing the smallest building blocks of our universe, from molecules and atoms and even fundamental forces like electromagnetism, whilst enabling a host of modern technologies such as lasers, computers, photography, and LEDs.

In the second half of the 20th century, a new paradigm for physics emerged: information theory. Based on the work of Claude Shannon [3], the idea that information was physical became a key principle of modern physics [4,5], ranking alongside the GR notion of spacetime curvature and the QM concepts of uncertainty and discreteness. Describing information from a physical perspective naturally led to the subdiscipline of quantum information, which was founded on the insight that quantum systems like atoms and photons carry information. Storing and processing information using quantum systems allows quantum phenomena, like superposition and entanglement, to be harnessed as computational resources, paving the way towards the development of quantum computers [6].

But how do relativity, quantum mechanics, and information theory interact? Physicists seeking a unified description of the world have long wondered whether an answer may lie at the intersection of these disciplines. It turns out that Canada would serve as the breeding ground for a new interdisciplinary research field, now known as Relativistic Quantum Information (RQI), whose central motivation would be to understand this question.



EARLY DAYS OF RQI

The seeds of RQI were sown in the 1970s via the work of William Unruh and Stephen Hawking. In 1974, Hawking showed that black holes radiate particles thermally (like a blackbody), contrary to classical

intuition that they should be perfect absorbers with zero temperature [7,8]. This remarkable finding led to the infamous information loss problem, which remains controversial to this day. Specifically, the eventual evaporation of the black hole into thermal radiation (a statistical mixture¹ without any traces of the black hole's origin) eliminates all information about its initial state, contradicting the unitarity² of the quantum physics that made its radiation possible in the first place. Building on work by Steve Fulling and Paul Davies, two years later, Unruh, then faculty at McMaster University, showed [9] that this phenomenon is more general, arising even in the absence of gravity. He showed that uniformly accelerated observers in flat spacetime likewise see a “hot” bath of thermal particles, even though an inertial observer would see nothing. This demonstrated that Hawking's prediction was rooted in a more generic mechanism, namely the observer-dependence of quantum states.

In the early 2000s, information-based approaches to relativistic quantum physics took on more prominence as an exciting playground for studying new phenomena. A review article by Asher Peres and Daniel Terno (then a postdoc at the Perimeter Institute (PI) in Waterloo), set the stage for the early days of RQI research, providing examples of how quantum measurements and quantum information are affected by relativistic motion [10]. This newly-founded institute for theoretical physics proved to be fertile ground for RQI-related research. Following a seminar at PI by Gerard Milburn on relativistic quantum teleportation [11], postdoctoral fellow Ivette Fuentes and the University of Waterloo's then-Department Chair, Robert Mann, showed how relativistic acceleration degrades the entanglement between a pair of observers [12]. This work ushered in a new range of foundational questions in physics lying squarely at the intersection of relativity, quantum, and information theory. In 2012, the journal *Classical and Quantum Gravity* devoted a special issue to RQI [13]; co-edited by Mann and Tim Ralph of the University of Queensland, this became a benchmark that attracted many new researchers to the field.

At its core, RQI provides a new perspective on what is arguably the paramount goal of modern theoretical physics: unifying quantum theory with gravity. What if information theory—long regarded as a bystander in advancing our understanding of physics—was instead promoted to a main character in the quest for a quantum theory of gravity? Rather than “top-down” attempts at quantizing gravity, RQI offered a “bottom-up” approach that allowed theorists and experimentalists to investigate quantum gravity from an information-theoretic operational perspective, namely one based on “measurements” made by rods, clocks, and detectors.

¹ A statistical mixture occurs when a system is prepared in one of several states with a probability, and the observer doesn't know which state was chosen. For the black hole, the radiation is in a mixture given by a thermal probability distribution.

² Unitarity refers to the condition that the time evolution of a quantum state is mathematically represented by a unitary operator; if unitarity breaks down then quantum states do not have well-defined time-evolution.

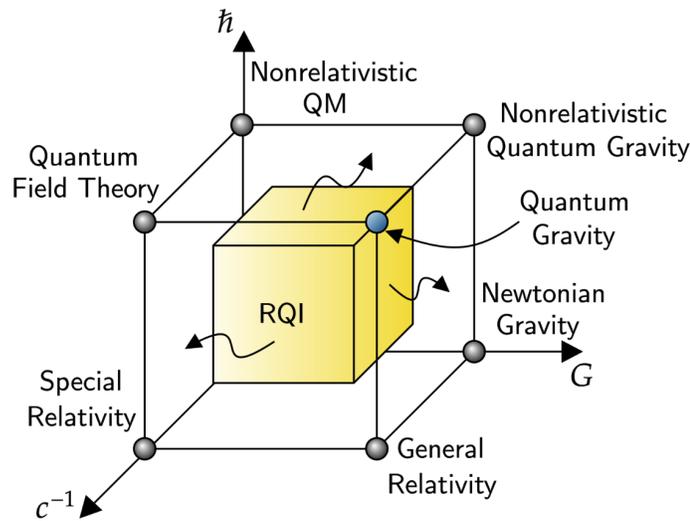


Figure 2. A Bronstein cube organizing different physical theories based on their dependence on the fundamental constants: \hbar (Planck's constant), c (speed of light in vacuum), and G (the gravitational constant). RQI research is generally interested in understanding new physics in regimes where all three constants are relevant.

RQI TODAY

The first breakthrough made by the RQI community was to provide an information-first approach to quantum field theory (QFT), which has come to define the Waterloo branch of the RQI community. Despite QFT's resounding success in the field of particle physics, its application to understanding relativity and the structure of spacetime had been limited. Then-Ph.D. student Eduardo Martín-Martínez, now a Professor at the University of Waterloo, generalized Fuentes and Mann's earlier work to account for gravitational effects [14], while Professor Achim Kempf explored the role of quantum information in cosmological settings and the emergence of spacetime itself [15,16]. Mann's group, based on early work by Benni Reznik [17,18] and Nicholas Menicucci [19], advanced investigations in extracting quantum vacuum entanglement with local probes (building on pioneering work by Jorma Louko [20]), a protocol now known as entanglement harvesting [21,22]. Recent efforts at Waterloo, spearheaded by Martín-Martínez in collaboration with Institute of Quantum Computing Professor Adrian Lupascu, has brought entanglement harvesting within reach of experimental superconducting circuit platforms [23].

European researchers in particular began asking questions about how gravity affects quantum systems like atoms, molecules, and photons. These questions were inspired by the record-breaking precision achieved in experiments in quantum optics and matter-wave interferometry. The first such proposals arose from the "Vienna School of Quantum Foundations," led by Caslav Brukner. Prior to this, probing quantum gravity in low-energy systems was not thought to be possible. Brukner's then-Ph.D. student Igor Pikovski showed that tabletop quantum optomechanical systems offered the possibility of testing

such effects in a controlled laboratory setting [24]. Concurrently, Magdalena Zych, also a Ph.D. student of Brukner’s, made new predictions about the behaviour of time according to “quantum clocks” in the presence of gravity [25]. Perhaps the most influential contribution came in 2017, when two papers including eminent quantum physicists like Sougato Bose and Vlatko Vedral proposed experiments showing that particles interacting via gravity could become entangled; its observation would provide strong evidence that gravity acts as a “quantum information channel” [26,27].

Last but not least, the RQI community has made seminal contributions to the development of a quantum information approach to causality and reference frames. These ideas are all central features of GR, but until recently had not been generalized to the quantum domain. PI scientist Lucien Hardy proposed that causal order itself was quantum mechanically indefinite [28], an idea furthered by PI postdoc Giulio Chiribella and collaborators in 2013 [29]. Concurrently, Brukner, with then-postdocs Fabio Costa and Ognjan Oreshkov, provided a new formulation of quantum mechanics without reference to time [30]. This overturned our classical understanding of causality, in which the ordering of events and their temporal relationship is fixed. Université de Montréal Professor Hlér Kristjánsson was instrumental in conducting early experiments verifying advantages that arise when performing operations without a fixed causal order—i.e., in a “superposition of causal orderings” [31]. The extension of quantum theory to reference frames (the set of coordinates used by observers to measure quantities like position and velocity) was achieved in 2019, again in a paper by Brukner and his then-students Esteban Castro-Ruiz and Flaminia Giacomini [32]—the latter of whom went on to be a Yvonne Choquet-Bruhat fellow at PI. A collaborative effort by the groups of Brukner and Mann showed that indefinite causal ordering measurably affected processes such as entanglement harvesting [33].



Figure 3. The group picture from the RQI-North 14 Conference held at Charles University, Prague, from August 5-9, 2024. Many of the authors cited in this article can be found in the picture.

CONCLUSION

Since the inaugural RQI publications and workshops in the early 2000s, the community, which now gathers bi-annually under the auspices of the International Society for Relativistic Quantum Information (ISRQI)³, has expanded far beyond what its founders envisioned. In 2023, IQC and PI Ph.D. student Tales Rick Perche began a global initiative called the RQI Circuit, leading a movement of student-led RQI-research hubs in Canada, Europe, and Australia to live-broadcast their research on YouTube⁴. In 2024, a consortium of RQI researchers secured a multi-year international grant to facilitate collaboration and cooperation in RQI research⁵. Interest in the field has grown rapidly, especially with the increased level of dialogue between theorists and experimentalists. An example of this has been the implementation of landmark analogue gravity experiments (led by Silke Weinfurter's group at the University of Nottingham) simulating phenomena ranging from black holes to early-Universe physics [34]. The community's research focuses have also diversified, with current problems including the operational description of spacetimes in superposition [35], proposals for detecting single "quanta" of gravitational radiation [36], and experimentally probing quantum vacuum entanglement [37], to name a few. The opportunities for new researchers entering the field are boundless, and the most exciting days for the community lie ahead.

ACKNOWLEDGEMENTS

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³ More information about the International Society for Relativistic Quantum Information can be found on their webpage: <https://www.isrqi.net>

⁴ The videos recorded during the RQI Circuit can be found on the ISRQI's YouTube Channel: <https://www.youtube.com/@ISRQI-gp3ci/featured>. These videos were meant to be accessible to a wider audience and are a great way to learn more about the research being done within the RQI community.

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ADVANCING FLASH RADIOTHERAPY WITH QUANTUM COMPUTING: OPPORTUNITIES AND CHALLENGES

SUMMARY: FLASH-RT advances hinge on ultra-high dose rate machines, validated dosimetry, and biology; quantum computing aids the supporting calculations.



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Radiotherapy is used in nearly half of all cancer treatments, and its precision has improved steadily to better spare healthy tissues [1]. A newer approach, FLASH radiotherapy (FLASH-RT), pushes this further by delivering radiation at ultra-high dose rates (UHDR) with the potential to reduce side effects while maintaining tumour control [2]. Today, translation is limited chiefly by non-computational barriers: (i) the lack of clinically deployable UHDR treatment machines, (ii) incomplete understanding of the biological mechanism underlying the FLASH effect [3], and (iii) the difficulty of measuring dose accurately at UHDR with conventional detectors [4]. Computation plays a supporting role: classical Monte Carlo (MC) already underpins beamline and dosimeter design and benchmarking, and prospectively, quantum computing (QC) could accelerate specific calculations (e.g., MC-adjacent studies, optimisation, and data analysis) within broader experimental and clinical programmes. QC does not replace the need for validated UHDR dosimetry, FLASH-capable hardware, or biological insights, but it may help move those efforts faster and at larger scale [5]. In this review, we explore how QC might one day help us meet demanding computational needs of FLASH-RT, and what challenges still lie ahead.

WHAT IS FLASH-RT?

FLASH-RT is a relatively new approach to deliver radiation treatment for cancer. Unlike conventional radiotherapy, which typically delivers radiation over several minutes at standard dose rates, FLASH-RT administers the entire treatment dose in a fraction of a second using dose rates of 40 Gy per second or higher. This ultra-rapid delivery has sparked interest because of a phenomenon known as the “FLASH effect” [6]. In preclinical studies, mainly in small animal models, researchers observed that FLASH-RT could damage cancer cells, similar to conventional treatments, but with reduced harm to nearby healthy tissues. This suggests a potential breakthrough: delivering effective treatment with fewer

adverse side effects [7]. Table 1 shows the differences between FLASH-RT and conventional radiotherapy (CONV-RT) in various aspects such as treatment time, dose rate and normal cell sparing [3].

TABLE 1
Comparison of FLASH-RT and conventional radiotherapy [3].

Aspect	FLASH-RT	CONV-RT
Treatment Time	Ultra-fast (milliseconds)	Typically seconds to minutes
Dose Rate	Extremely high (>40 Gy/s)	Moderate to high (0.001-0.4 Gy/s)
Normal Cell Sparing	Enhanced due to UHDR	Limited, increased risk to normal cells
Oxygen Effect	Reduced due to ultra-short exposure	Present, potential impact on tumour response
Radiobiological Effect	Increased therapeutic index	Standard radiobiological principles
Fractionation	Single or few fractions possible	Multiple fractions common
Patient Comfort	Reduced overall treatment time	Longer treatment sessions
Machine Wear and Tear	Potentially reduced	Standard wear and tear
Integration with Imaging	Compatibility with advanced imaging	Standard imaging requirements
Organ Motion during Treatment	Reduced impact due to faster delivery if the tumour position is known immediately prior to treatment	Continuous monitoring and adaptation
Patient Throughput	Potentially increased	Treatment duration may impact throughput
Clinical Trial Status	Investigational, ongoing research	Established, widely practiced
Cost and Accessibility	Potential for higher costs	Generally more accessible

Status snapshot: Clinical deployment awaits (a) machines that can reliably deliver clinically useful UHDR beams, (b) mechanistic clarity of the FLASH effect, and (c) validated dosimetry at UHDR where standard detectors face response limitations. These non-computational gaps currently dominate the translation agenda [4, 8].

The exact mechanisms behind the FLASH effect are still being investigated, but several hypotheses exist. One idea is that the extremely short duration of radiation exposure leads to different biological responses in healthy and cancerous tissues, possibly involving oxygen depletion or unique stress pathways in normal cells. While these theories remain under study, the biological promise has been compelling enough to encourage early-stage clinical trials [3].

Yet, bringing FLASH-RT into routine clinical practice is far from straightforward. The technology needed to produce such high dose rates safely and reliably is still under development. This intersection of innovation and complexity has led researchers to explore new computational tools, including QC, to support the future of FLASH-RT.

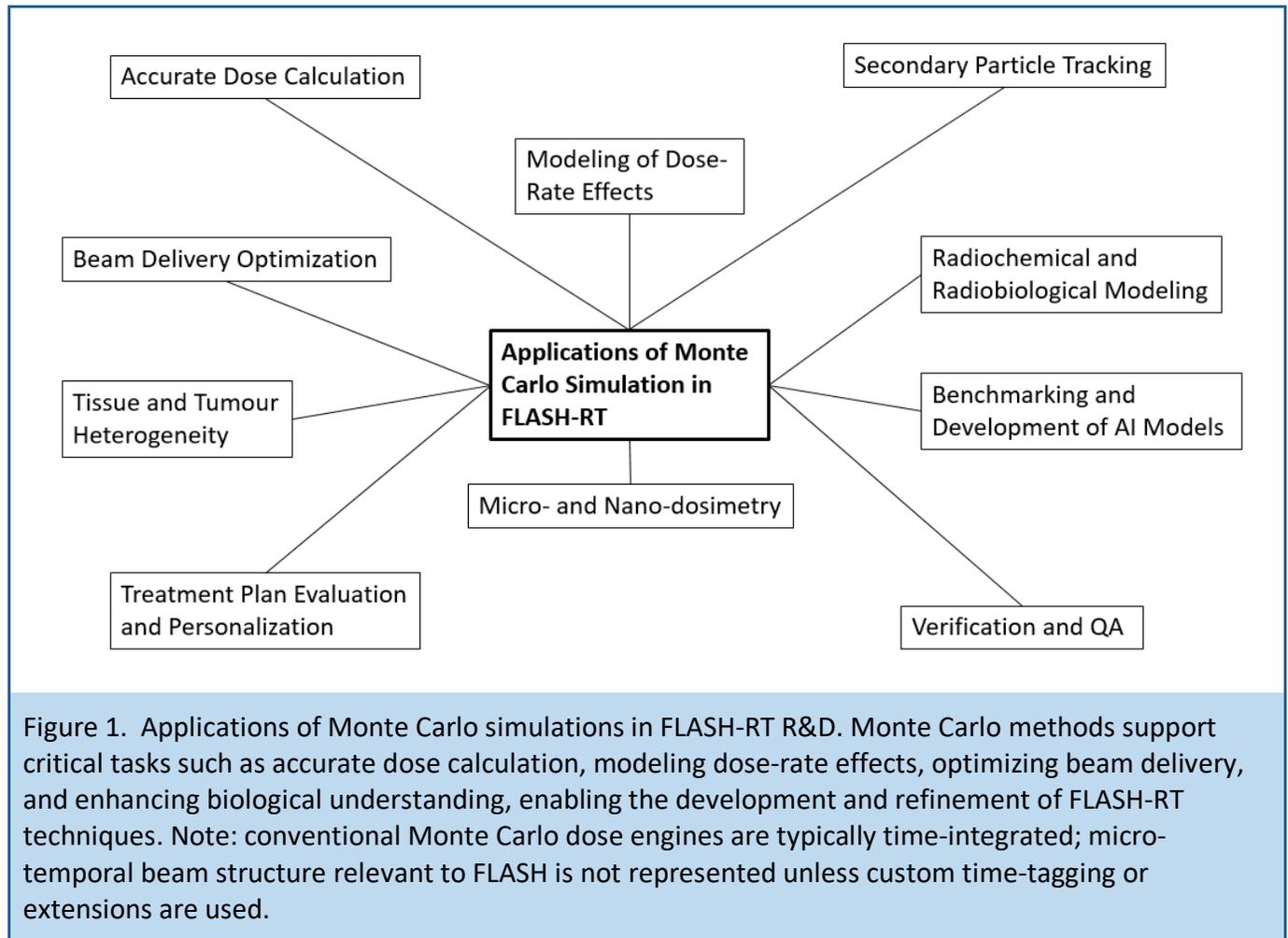
COMPUTATION'S ROLE

While FLASH-RT holds exciting potential for cancer treatment, its implementation introduces serious computational challenges. Delivering a high dose in just milliseconds leaves very little room for error. To ensure safety and effectiveness, clinicians must plan the treatment with great precision, model how the radiation interacts with tissue, and monitor delivery in real time. Each of these steps depends on intensive calculations rooted in complex medical physics and radiobiology [9].

One of the gold-standard methods for simulating radiation transport and dose distribution is the Monte Carlo method, which uses random sampling to model particle interactions with high accuracy [10]. However, this approach is computationally expensive, it can take hours or even days on classical computers to complete a full simulation. In the context of FLASH-RT, where speed is critical, these calculations remain important but are supporting tasks relative to today's hardware, dosimetry, and biology challenges.

Moreover, real-time treatment adaptation, adjusting the dose or beam in response to patient movement or changing conditions, is an emerging goal in radiotherapy. For FLASH-RT, real-time adaptation becomes even more important, and even more difficult, due to the sheer speed of dose delivery. This pushes current computing systems to their limits. Figure 1 shows key applications of Monte Carlo simulations in FLASH-RT, including dose calculation, beam optimization, biological modeling, and treatment personalization. Monte Carlo is indispensable for UHDR beamline and dosimeter design and for dose transport benchmarking. However, standard clinical Monte Carlo dose engines generally compute time-integrated dose and usually do not explicitly represent the pulsed or microsecond structure of UHDR beams; specialized time-resolved modeling or paired measurements are required when interrogating FLASH-specific dose-rate effects.

An important challenge is performing these calculations efficiently, an area where novel approaches, including QC, may help. This is where new computing paradigms, like QC, are being considered [11]. By rethinking how we process information at the most fundamental level, researchers hope to unlock faster, more efficient ways to meet the computational demands of FLASH-RT.



WHAT IS QC?

QC is a new way of thinking about computation, one that harnesses the principles of quantum mechanics to solve certain types of problems more efficiently than classical computers. At the heart of a quantum computer are qubits, the quantum counterpart to classical bits. While a classical bit can be either 0 or 1, a qubit can be in a superposition of both states at once. This allows quantum computers to process information in parallel and explore many possibilities simultaneously. Unlike classical parallelism, which distributes tasks across multiple processors, quantum parallelism leverages superposition and entanglement to evaluate many computational paths within a single quantum state, offering a fundamentally different scaling advantage for certain problems.

Another key concept is entanglement, a quantum phenomenon where the state of one qubit is linked to another, no matter how far apart they are. This connection enables qubits to work together in ways that classical bits cannot, potentially giving quantum computers an edge in solving highly complex problems, like optimizing large systems or simulating physical interactions at the atomic level.

Table 2 shows a comparison between classical and quantum computing, highlighting their fundamental differences in data representation, processing, and application. While classical computers use bits and perform deterministic operations, quantum computers use qubits and leverage quantum phenomena like superposition and entanglement to solve certain complex problems more efficiently.

TABLE 2

Comparison between classical and quantum computing. The table highlights key differences in how information is represented and processed, as well as their respective strengths, limitations, and areas of application.

Aspect	Classical Computing	Quantum Computing
Basic Unit of Information	Bit (0 or 1)	Qubit (0, 1, or both simultaneously via superposition)
Data Representation	Binary states	Quantum states (superposition and entanglement)
Processing	Sequential or parallel via multiple cores	Quantum parallelism – can explore many states at once
Computational Power	Scales linearly or polynomially	Can scale exponentially for certain problems
Key Operations	Logic gates (AND, OR, NOT)	Quantum gates (Hadamard, CNOT, etc.) manipulate probabilities
Strengths	General-purpose, reliable, good for most everyday tasks	Ideal for complex optimization, simulation, and factoring problems
Limitations	Slower for problems with vast probabilities (e.g. combinatorics, many-body simulations)	Prone to noise, requires error correction, still early-stage hardware
Memory	Deterministic and easily readable	Probabilistic outcomes that require measurement and repetition
Examples of Applications	Web browsing, spreadsheets, image processing	Drug discovery, cryptography, optimization, quantum physics simulation
Maturity	Fully developed and widely used	Emerging, in research and development phase

QC is still in its early days. Most current devices have a limited number of qubits and are prone to noise and error. But progress is moving quickly, and researchers around the world are exploring how even today's small-scale quantum devices might outperform classical computers in specific tasks.

Canada is actively contributing to the global advancement of quantum science, with leading companies such as D-Wave and Xanadu [12], as well as growing access to quantum hardware through IBM's quantum computing infrastructure in Canada [13]. Research institutions such as the Centre for Quantum Information and Quantum Control and Quantum Software Consortium at the University of Toronto are also playing a key role in exploring practical applications of quantum technologies. This expanding ecosystem positions Canada well to pursue real-world innovations in QC [14], including those in health and medical research. As FLASH-RT stretches the capabilities of classical computing, QC presents a fundamentally new approach that may help meet its unique computational demands.

HOW COULD QC SUPPORT FLASH-RT?

Applying QC to FLASH-RT is still a developing idea, but there are several promising directions where it can make a meaningful impact. One key area is dose calculation. In radiotherapy, precise knowledge of how radiation deposits energy in tissue is critical for treatment planning. The most accurate way to simulate this is through Monte Carlo methods, which model millions of particle interactions. However, these simulations are extremely time-consuming on classical computers, especially at the speed and precision needed for FLASH-RT. Quantum algorithms could one day accelerate these simulations by using quantum parallelism to explore many possible particle paths simultaneously [15]. In FLASH-RT, QC should be viewed as a complementary tool. It does not replace the need for validated UHDR dosimetry, FLASH-capable treatment hardware, or mechanistic biology. Its most credible near-term role is to speed up or improve specific calculations within larger experimental and clinical programs.

Another important challenge is treatment plan optimization. Radiation doses must be shaped and delivered to fit the patient's anatomy while avoiding sensitive structures. This involves solving large, complex optimization problems, which are often computationally intensive. QC can offer advantages here through techniques like quantum annealing or variational algorithms, which may find solutions faster or more effectively than classical methods [16].

Moreover, as researchers try to understand the biological effects of FLASH-RT, there is growing interest in quantum machine learning to help analyze large datasets and uncover patterns in biological response. Personalized FLASH-RT will require accurate models of patient-specific anatomy and tissue heterogeneity, which influence scattering and dose deposition. Quantum algorithms, particularly in optimization and machine learning, could help integrate these complex datasets into individualized treatment plans, complementing classical approaches. These tools could contribute to better models for predicting patient outcomes and tailoring treatments [17]. Though practical implementation is still a way off, these examples highlight how QC can help address some of the most pressing computational challenges in FLASH-RT. The goal is not to replace classical computers, but to augment them, offloading the most difficult parts of the problem to quantum processors, and using hybrid approaches that combine the strengths of both.

Figure 2 shows an example of a quantum deep reinforcement learning (qDRL) algorithm designed to support optimal decision-making in knowledge-based adaptive radiotherapy [11]. In this approach, a quantum AI agent interacts with a simulated radiotherapy environment (ARTE) to determine the most effective radiation dose for a given patient state. The agent uses a deep Q-network to evaluate a range of dose options, selects the dose with the highest predicted value (Q-value), and applies quantum amplification to enhance this decision on a quantum state. A quantum measurement is then performed to finalize the dose selection. This decision, along with the patient's current state, is input into ARTE, which models how the patient responds to treatment. ARTE consists of three components: a transition function that simulates state progression, an outcome estimator that predicts treatment effects, and a reward function that scores each decision. The predicted outcomes, including tumour control and risk of side effects, are used to update the agent's learning. This cycle continues until an optimal treatment strategy is learnt, and the process is repeated for new patients. The patient state is defined using five key biological features, including radiomics, radiation sensitivity, cytokine levels, and genetic markers.

CHALLENGES AND THE ROAD AHEAD

Despite its promise, QC is not yet ready to transform FLASH-RT for radiation treatment, or most other applications, overnight. Today's quantum hardware is still in a phase known as "Noisy Intermediate-Scale Quantum" (NISQ) computing [18]. This means current quantum computers have a limited number of qubits, and those qubits are prone to errors caused by noise and imperfect control. These constraints make it difficult to run large, reliable quantum programs. There are also important practical challenges in applying QC to healthcare problems. Translating a medical physics or radiobiology problem into a form that a quantum computer can process is not straightforward. It requires close collaboration between experts in quantum algorithms, medical physics, oncology, and computer science. Even for researchers, the learning curve can be steep [19].

In addition, clinical validation and safety are paramount in radiotherapy. Before any quantum-enhanced tool could be used in patient care, it would need to go through extensive testing, regulatory approval, and integration with existing clinical workflows—a process that can take years. That said, progress is happening rapidly. As quantum hardware improves and algorithms become more sophisticated, researchers are already exploring hybrid quantum-classical models that use quantum processors for specific tasks within a larger workflow [3]. This "division of labor" may be one of the first practical steps toward bringing quantum computing into radiotherapy research and, eventually, into the clinic. Canada is well-positioned to contribute to this progress. With strong research institutions, access to QC platforms like IBM's, and a growing community of interdisciplinary researchers, the foundations are being laid for innovation at the intersection of quantum science and cancer care.

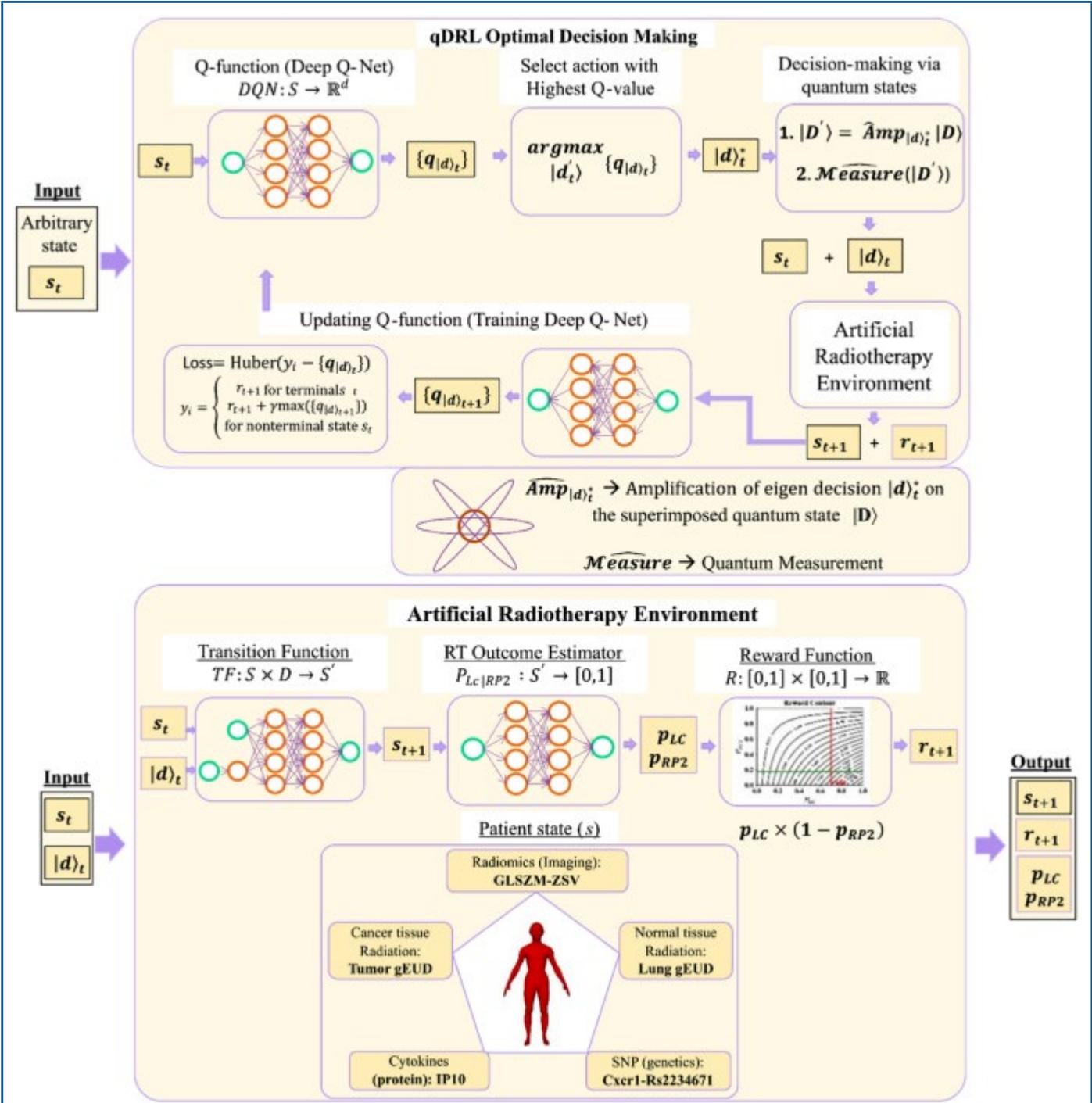


Figure 2. Schematic of a quantum deep reinforcement learning (qDRL) algorithm for adaptive radiotherapy decision-making. The quantum agent interacts with a simulated treatment environment to optimize radiation dosing based on patient-specific biological features [11].

CONCLUSION

FLASH-RT is a promising frontier in cancer treatment, with the potential to deliver highly effective radiation therapy while reducing side effects for patients. To make FLASH-RT practical and widely available, the foremost needs are engineering FLASH-capable clinical systems, establishing accurate and traceable UHDR dosimetry, and resolving key biological questions. Computation including Monte Carlo and, prospectively, quantum approaches will support these efforts by accelerating design, optimization, and analysis.

QC offers a compelling avenue for addressing the unique challenges of FLASH-RT, from speeding up dose calculations to optimizing treatment plans and improving our understanding of biological responses. While much work remains to be done, both in refining quantum technologies and adapting them to medical problems, the potential is there, and the first steps are already being taken. By fostering collaboration between physicists, computer scientists, engineers, and medical professionals, we can begin to explore how this emerging technology might one day support safer, faster, and more personalized cancer treatments. As Canada continues to build its strength in quantum science and technology, initiatives at the intersection of QC and healthcare, like those targeting FLASH-RT, represent an exciting opportunity to lead in both fields.

ACKNOWLEDGEMENTS

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QUANTUM BIOLOGY RESEARCH IN CANADA: DECODING NATURE'S SUBTLEST SECRETS

SUMMARY: Canadian researchers investigate spin- and light-related quantum effects in biological systems.



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Canada is a global leader in quantum science and technology, with quantum biology emerging as a thrilling frontier. Canadian researchers are unraveling life's deepest mysteries by exploring a key question: how can quantum mechanics, through its unique principles of superposition and entanglement, explain complex biological phenomena that classical approaches cannot?

The radical pair mechanism (RPM) — a quantum-based model that links magnetic fields to the spin dynamics of electron pairs formed transiently during biochemical reactions — has emerged as a leading explanation for magnetosensitive phenomena in biology [1]. So far, the RPM has been investigated primarily in the context of avian magnetoreception — the remarkable ability of birds to perceive and navigate using Earth's magnetic field. However, recent work by Hadi Zadeh-Haghighi and Christoph Simon at the University of Calgary has broadened the scope of this framework, arguing that the RPM may underlie a wide range of magnetic field effects across diverse biological systems, far beyond avian navigation [2]. Motivated by this hypothesis, they initiated a series of interdisciplinary experimental collaborations with research groups across Canada and internationally, aiming to test the broader applicability of the RPM in living organisms. In a recent collaboration with Western Michigan University [3], they investigated the influence of weak magnetic fields on reactive oxygen species (ROS) generation in planarian flatworms. The experimental data showed alterations in ROS levels under hypomagnetic and weak static magnetic field conditions, consistent with RPM-based predictions. These changes in ROS concentrations, particularly superoxide, directly influence tissue regeneration

and healing in flatworms, which are known for their high regenerative capacity, as well as in other organisms. In a collaborative study at the University of Calgary, researchers investigated the impact of weak magnetic fields on pigment formation in *Xenopus* tadpoles, implicating cryptochrome 4 [4,5]. Expanding the scope of their research, Zadeh-Haghighi and Simon also proposed an RPM-based model for the magnetic field effects on microtubule assembly, key components of the cellular cytoskeleton [6]. In this model, RPM influences microtubule polymerization by modulating the spin-dependent recombination of radical pairs formed in tubulin proteins, thereby altering reaction yields that affect the energy exchange processes involved in assembly. Their model predicted that isotope substitution could modulate microtubule polymerization through the RPM. In collaboration with Travis Craddock — then at Nova Southeastern University and currently at the University of Waterloo — they experimentally verified this prediction by demonstrating isotope effects on microtubule assembly consistent with RPM-based mechanisms [7]. Such effects on microtubule dynamics could have profound implications for cellular processes like mitosis, intracellular transport, and cytoskeletal reorganization, potentially linking quantum phenomena to macroscopic biological functions such as cell division or neuronal signaling. These findings further support the role of quantum spin dynamics in mediating magnetic and isotope effects in biology. They also point to microtubules as a novel and highly relevant target for quantum biological investigations, illustrating how subtle quantum effects can propagate to influence essential cellular structures and behaviors in living systems.

Microtubules, cylindrical protein polymers composed of tubulin subunits, are critical for maintaining cellular structure, enabling intracellular transport, and orchestrating chromosome segregation during cell division. Their highly ordered lattice, rich in aromatic amino acids such as tryptophan, phenylalanine, and tyrosine, exhibits striking similarities to light-harvesting complexes found in photosynthetic organisms [8], suggesting a potential role in long-range energy transfer and protection against cellular oxidative damage [9]. Research led by Jack Tuszynski at the University of Alberta, in collaboration with Travis Craddock and Gregory D. Scholes of Princeton University, has provided compelling evidence for these functions by observing tryptophan autofluorescence in microtubules. Their studies demonstrated exciton diffusion—energy transfer via excited electrons—across the microtubule lattice, mirroring mechanisms seen in photosynthetic systems [10]. Furthermore, their work revealed that anesthetics, such as propofol, disrupt this energy transfer by altering the electronic properties of aromatic residues, potentially explaining their mechanism of action in modulating conscious awareness. Conversely, certain chemicals, including psychoactive compounds, may enhance this transfer, suggesting a role for microtubules in modulating neural signaling and brain function [11]. The crucial role of microtubules and the quantum effects that govern them could therefore be an avenue for investigating scientific questions around consciousness. Additional experimental evidence from Craddock's and Alfano's lab at City College of New York has identified quantum coupling between the electronic states of aromatic amino acids and vibrational modes within the microtubule lattice, indicating that microtubules may function as quantum-like conduits for energy and information processing in cells [12]. These findings position microtubules not only as structural and transport elements but also as sophisticated optical systems with potential applications in bio-inspired technologies, such as quantum computing and nanoscale energy transfer devices. Ongoing research

continues to explore how these quantum-like properties contribute to cellular processes and neural computation, bridging biophysics, neuroscience, and quantum biology.

Lithium (Li) has been the cornerstone treatment for bipolar disorder since its efficacy was established decades ago, primarily due to its ability to stabilize mood swings. In 1986, pioneering studies on rats uncovered intriguing behavioral differences influenced by lithium isotopes, specifically lithium-6 and lithium-7, which differ in their nuclear spin properties. These findings prompted physicist Matthew P.A. Fisher of the University of California Santa Barbara to hypothesize in 2015 that lithium isotopes could play a role in quantum neural processing within the brain [13]. Fisher proposed that phosphorus nuclear spins in Posner molecules — calcium phosphate clusters potentially present in the brain — could become quantum-entangled, facilitating a form of quantum computation. He suggested that lithium ions, when substituted for calcium in Posner molecules, enhance the molecules' stability. He also posited that these ions influence neurological outcomes through isotope-specific nuclear spin effects, potentially impacting mood regulation at a quantum level. This theory posits that the nuclear spin differences between lithium-6 (spin-1) and lithium-7 (spin-3/2) could modulate the entanglement properties, thereby affecting neural signaling in ways relevant to bipolar disorder treatment. In contrast, Hadi Zadeh-Haghighi and Christoph Simon at the University of Calgary offered an alternative explanation in 2021. They invoked the RPM to account for lithium isotope effects on hyperactivity in rats [14]. They proposed that lithium isotopes differentially affect these radical pair dynamics, altering cellular processes linked to hyperactivity and potentially explaining the behavioral outcomes observed in earlier rat studies.

More recently, in 2023, an international research team — including Zoya Leonenko and Michel Gingras of the University of Waterloo — investigated lithium's isotope-specific effects on mitochondrial calcium handling. This investigation shed light on its cellular mechanisms [15]. Their study explored how lithium isotopes influence mitochondrial function, particularly calcium ion dynamics, which are critical for cellular energy production and signaling. By examining isolated mitochondria, the team found that lithium-6 and lithium-7 differentially affect calcium uptake and release. This differential effect is potentially due to variations in nuclear spin interactions with mitochondrial proteins or membranes. These findings suggest that lithium's therapeutic effects in bipolar disorder may partly stem from isotope-specific modulation of mitochondrial activity, which could influence neuronal excitability and synaptic transmission. This research bridges cellular biology with quantum effects, highlighting the multifaceted role of lithium isotopes in both clinical and theoretical contexts.

These efforts establish Canada as a leader in quantum biology, probing a key question: How deeply do quantum phenomena influence life? This research supports the 2025 International Year of Quantum Science and Technology (IYQ), highlighting quantum science's promise for sustainable health solutions, like magnetic field therapies for cancer or isotope-specific drugs designed to enhance treatment precision.

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RESISTIVE SWITCHING AND QUANTUM NANOMATERIALS AS NEUROMORPHIC SYSTEMS: TOWARDS ENERGY-EFFICIENT BRAIN-INSPIRED COMPUTING

SUMMARY: This review feature article covers a literature subset focusing on hardware strategies, solid-state learning mechanisms, theoretical descriptions, challenges, and opportunities in the cutting-edge field of (quantum) nanomaterials with a seemingly “synthetic intelligence” that can be used in future neuromorphic computing. The latter is viewed as a novel paradigm in computing hardware, inspired by energy-efficient biological neural processing, that goes beyond conventional microprocessor technology.



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Integrated circuits are semiconductor-based electronic components ubiquitous in present-day technology. Advances in miniaturization and nanofabrication strategies of integrated circuits have led to very-large-scale integration (VLSI), capable of packing billions of transistors on a single microchip, with its scalability trended by the well-known Moore’s law [1]. Key to this success is the consistent shrinking of the metal oxide semiconductor field-effect transistor, the most primitive building block in electronics, with typical length scales reaching nanometers in which quantum effects are dominant. However, such gains are starting to slow down in response to physical limitations at sub-10 nm processes. Therefore, dimensional scaling alone is insufficient to fulfil commercial expectations in the semiconductor and electronics industry, heavily pressured by the growing demands on artificial intelligence (AI) and smart/automated systems, big data cloud processing and storage, and emulation of brain-like inference beyond rigid binary/logic capabilities.

Emerging forms of computation compatible with AI-based or brain-inspired systems require diversification of electronics and their integration; this includes the search for new materials and

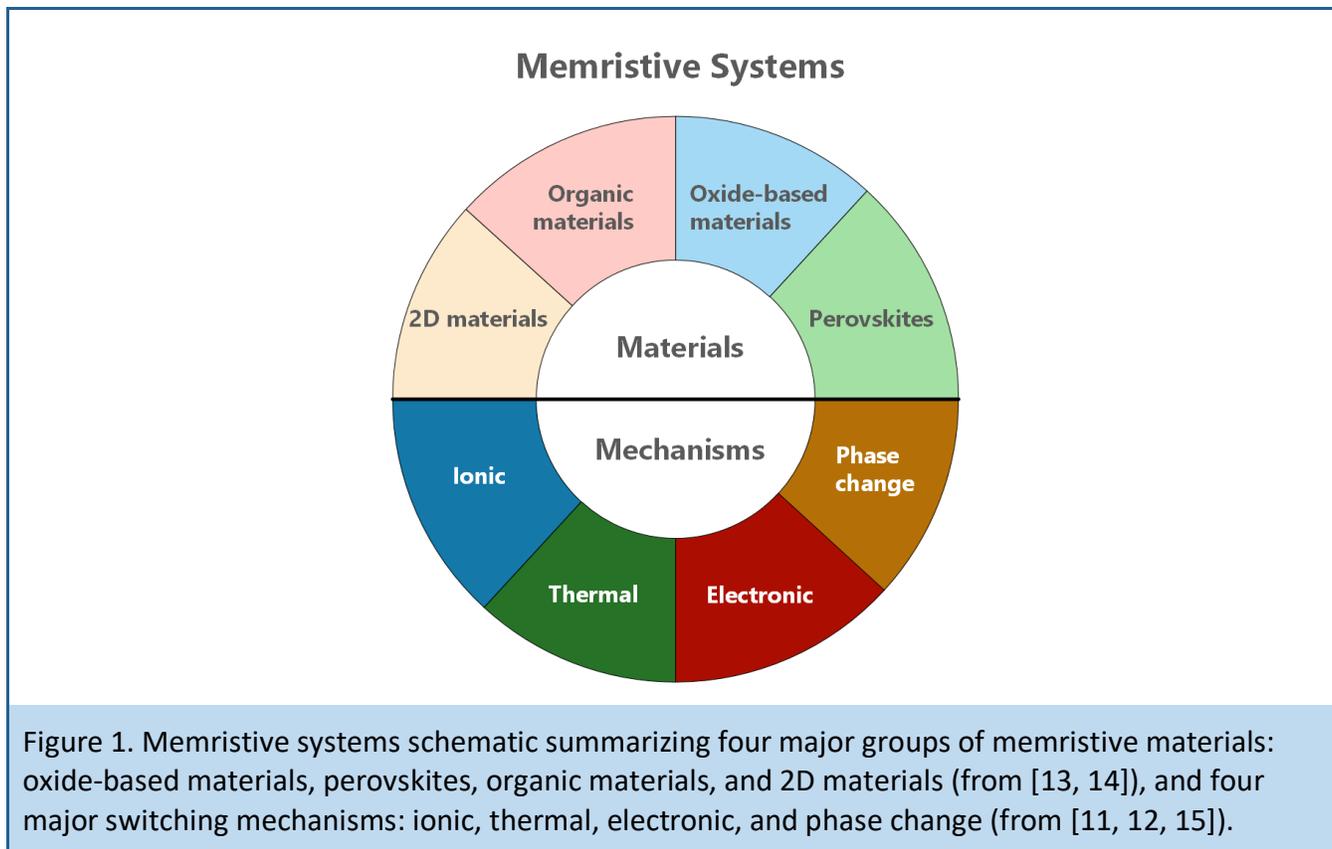
computer architectures beyond conventional complementary metal oxide semiconductor (CMOS) technology. Moreover, alternative computing paradigms and new (“green”) materials/hardware solutions could offer ways of mitigating the escalating energy demands and growing environmental footprint of large-scale digital computing infrastructure [2, 3], often associated with limitations of the von Neumann architecture -- the blueprint design for most computers -- known as the von Neumann bottleneck.

Moving highly centralized and rigid CMOS platforms to a brain-inspired lens characterizes a paradigm shift in computing, relying on adaptive, built-in learning, massively parallel/in-memory processing, and fault-tolerant operations. Brain-inspired or neuromorphic systems [4] encompass an interdisciplinary approach of overhauling conventional computer hardware with novel brain-like architectures [5, 6]. A particularly promising step toward neuromorphic design is the selection of raw materials that will constitute the bio-inspired hardware [7], leading to research on novel materials and solid-state systems, as well as ways of controlling their active particle constituents, e.g., atoms, ions, electrons, and/or spins semiclassically or at the quantum level. As of now, a wide range of “intelligent matter” [8] has been identified with the advent of resistive switching (RS) systems and memristive materials, as presented next.

MEMRISTIVE MATERIALS AND MECHANISMS

With respect to novel neuromorphic materials and devices, memristive systems [9] have been central due to their adaptive RS response to external stimuli, similar to bio-synapses, enabling energy-efficient hardware learning. Memristive systems are a generalization of the memristor [10], a two-terminal circuit unit whose “memristance” depends on the history of the input stimulus and is governed by an internal state variable (e.g., the charge) which evolves in time according to a dynamic rate equation. Memristive systems exhibit nonlinear and hysteretic behaviours with their resistance state switching discretely or continuously (analogue) between a high resistance state (HRS) and a low resistance state (LRS), representing logical bits, or OFF/ON states, respectively [11]. As a result, cutting-edge brain-like and spiking neural operations, as well as optimal memory devices, can be devised [12].

There is an immense variety of memristive materials and mechanisms highlighted in comprehensive reviews. Focusing on metal-insulator-metal stacks, RS is typically associated with the formation/dissolution of a conductive filament inside the insulator, driven by external stimuli. The state of the filament/conductive region modulates the conductance of the channel representing synaptic weights. From [13, 14], Figure 1 summarizes four major groups of memristive-based materials relevant to neuromorphic applications: oxide-based materials, perovskites, organic materials, and two-dimensional (2D) materials. Other memristive-based material specifications include chalcogenides, polymers, biomolecules, magneto-memristive materials, and ferroelectric materials. Figure 1 also features four major switching mechanism groups organized from [11, 12, 15]: ionic, thermal, electronic, and phase change, observed over a plethora of different materials and system configurations at the nanoscale.



Ionic mechanisms include anion, cation, and dual ionic switching devices [16, 17], in which the filamentary or conducting region is dominated by redox reactions and ion migration. Anion switching found in many TiO_x -based systems with mobile oxygen vacancies is also referred to as valence change memory. Cation switching involves electrochemical filament formation, often ionized Ag or Cu, also named electrochemical metallization or programmable metallization cells. Phase-change memory mechanisms are found in phase-change materials that exhibit different conduction properties at thermally driven structural phases, with $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST) being a benchmark. Examples of electronic processes, some widely governed by quantum-based transport effects, include tunnelling-assisted (de)trapping of electrons through defective localized states in filamentary-free switching. Due to ample materials interface/stack combinations, other relevant electronic conduction mechanisms [18] include space-charge limited conduction, Poole-Frenkel, Schottky-barrier emission, Fowler-Nordheim quantum-tunnelling, Mott memristors, and quantized conductance effects [19, 20]. Memristive mechanisms can also be temperature-assisted [21], optically controlled [22] and magnetic or spin-based [23], from which switching is governed by the modulation in quantum domain magnetization and spin-polarized currents, following spintronics approaches. In the context of strongly correlated quantum materials such as Mott insulators [24], they offer multiple degrees of freedom to emulate neural plasticity, such as lattice reorganization, charge density, spin and orbital states, resulting in robust metal-insulating transitions, Joule heating mechanisms, and magnetization dynamics. From such a miscellaneous of switching mechanisms [25], substantial theoretical and modelling development is

required (and summarized below) to assist comprehension and device response prediction for prominent architectures and integration.

MEMRISTIVE MODELLING AND DESIGNS

Following Chua's memristor formulation [10], various mathematical descriptions have been proposed and tested experimentally, starting with the seminal HP Labs memristor model [26] applied in TiO₂ structures, the linear ion drift model. Extensions/variations of this picture can incorporate stochasticity, diffusion and electro-thermal effects [27], coupled ionic-electronic degrees of freedom [28], short- and long-term memory [29], nonlinearities [30], quantum tunnelling [31], and other materials interface/barrier modulations to cover diverse RS conditions. At atomistic levels, first principles quantum-mechanics methods such as Density Functional Theory are often used to characterize electronic structure and correlations, charge density, optical and magnetic properties, metal-insulating transitions, and other microscopic properties relevant to memristive material design and switching [32].

In analogy to neural network connectivity, interconnection and integration of memristive units are achieved through innovative designs, such as crossbar arrays [33] and amorphous nanowire networks (NWNs) [34, 35, 36]. These realizations have demonstrated prominent learning and neuromorphic functions, including smart sensory and in-memory processing, pattern recognition, associative memory, fault-tolerant operations, (*in-materia*) reservoir computing [37, 38], and spike-timing dependent plasticity. We have been studying random memristive NWNs [39, 40] and showed that they exhibit winner-takes-all behaviour in which a unique conduction pathway is activated. This represents the lowest power consumption state of the material and the encoding of independently addressable memory/conductance states within the network mesh at the conductance quantum range. We recently developed a modular computational framework to simulate multiple memristive properties in NWNs [41], with an initial version available on [42]. Figure 2 is a result from the package depicting current potentiation for a sufficiently dense NWN made of Ag core-shell nanowires subjected to a voltage pulse train. The simulation uses the semiclassical memristive model by Chen *et al.* [29], which considers short-/long-term memory effects, but the package permits easy model alteration. Other simulations included are reservoir-based waveform transformation, bit pattern storage through selective pathways, and associative memory through multi-electrode probing. Future upgrades will include testing quantum tunnelling-based memristive models and emerging algorithms/solid-state systems following quantum neuromorphic computing (QNC) [43] for reliable quantum computing and noisy data processing.

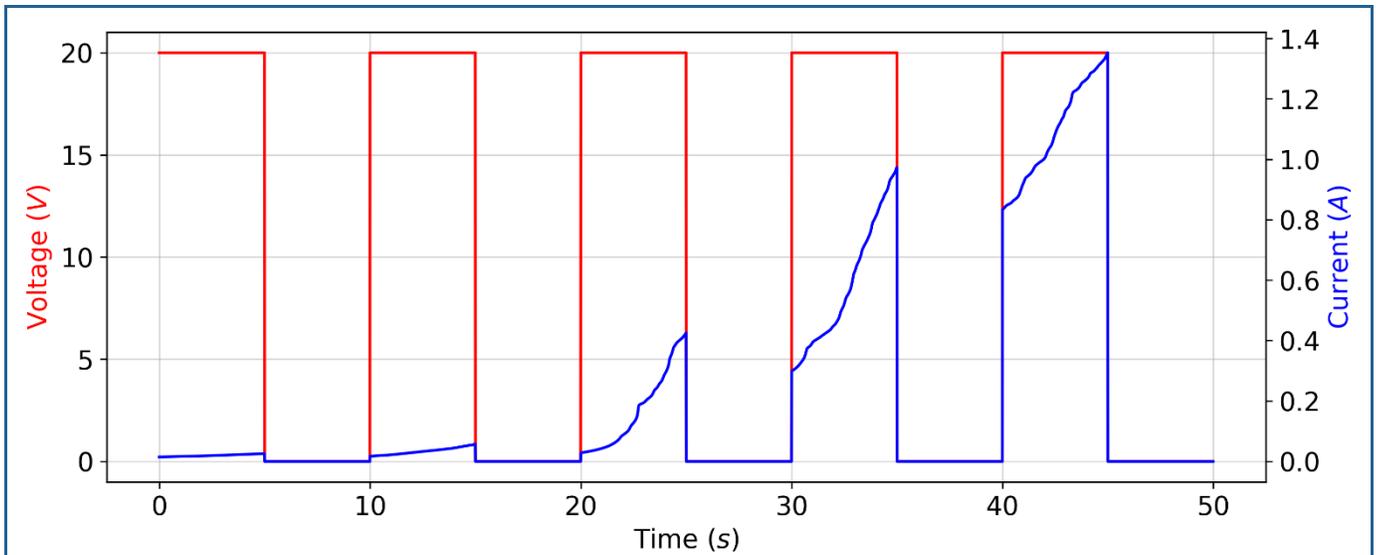


Figure 2. Current potentiation in response to a voltage pulse train simulated in Ag random NWNs using the memristive model by Chen *et al.* [29]. This is a simulation example from our modular computational package to simulate memristive responses in NWNs [41].

CONCLUSION

This contribution showcases a noteworthy literature on memristive systems and quantum platforms for neuromorphic applications. Neuromorphic hardware is not an aspiration; they are in use and early-stage commercialization. Nonetheless, the technology is not yet mainstream due to challenges hindering costs and large-scale production. These include need for noise control and device variability at the nanoscale, as well as a systematic roadmap for co-designing neuro-inspired algorithms compatible with the hardware and multi-task versatility. Moreover, many state-of-the-art neuromorphic chips still depend heavily on conventional CMOS and digital circuitry, meaning that power efficiency and footprint are still not at the human brain standards. Therefore, novel paradigms in brain-inspired computing are emerging, such as multi-terminal memristive systems [44], neuromorphic photonics [45], and QNC [43, 46]. QNC takes the best of both worlds: brain-inspired and quantum systems to accelerate innovation in intelligent quantum computing hardware. Quantum reservoir networks with rich nonlinear dynamics originating from interconnected qubits may offer advantages over existing quantum information technologies due to their superior fault-tolerance to decoherence. According to a recent report by Global Industry Analysts [47], the global market for neuromorphic computing was at US\$87.2 Million in 2024, and is projected to US\$3.6 Billion by 2030, growing at a compound annual growth rate of 85.6% over 2024-2030. Undoubtedly, the transformational impact that neuromorphic and quantum technologies will impart across multiple AI-reliant sectors, such as healthcare, security, transportation, telecommunications, energy, sensors and industry automation, and consumer electronics, is inevitable.

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QUANTUM SCIENCE AT TRIUMF

SUMMARY: TRIUMF advances quantum science through research in sensing, materials, computing, and precision experiments with applications across multiple domains.



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In its 20-year strategic vision, TRIUMF has recognized quantum technology as a cornerstone of its research agenda (see Fig. 1). By capitalizing on its accelerator-based research facilities, TRIUMF has established its role in advancing quantum research, concentrating on areas such as quantum-enabled science, quantum sensing technologies, quantum materials, and quantum computing.

This short article highlights TRIUMF-led initiatives across these domains, encompassing all departments within the Physical Sciences Division. TRIUMF's interdisciplinary expertise in precision measurements with quantum objects (including radioactive ions, atoms, molecules, neutrons, muons, and antimatter) is driving the development of innovative quantum measurement techniques for discoveries in fundamental physics. Quantum algorithms are being exploited to solve quantum many-body problems in nuclear theory and accelerate detector simulations at the high energy frontier. Additionally, TRIUMF leverages its expertise in radiation detector systems, originally developed for advanced nuclear and particle physics experiments, for the advancement of quantum technologies. Particularly, single photon sensors have a broad spectrum of potential applications, including environmental monitoring, quantum communication and autonomous transportation.

Through these efforts, TRIUMF contributes significantly to the global quantum research landscape, fostering innovation and collaboration across disciplines.



Figure 1. Quantum Technologies are a cornerstone of TRIUMF's research agenda [1].

TUCAN

The TUCAN collaboration is developing a new ultracold neutron (UCN) source to test the Standard Model through precision measurements, including searches for a neutron electric dipole moment (nEDM) and improved determinations of the neutron lifetime. The nEDM is predicted in the Standard Model to be smaller than 10^{-31} e-cm, and any measurement yielding a larger value would be a remarkable discovery that requires a new theory beyond the Standard Model. The UCN source (Fig. 2) is in its commissioning phase, to be completed in 2025, with the goal of enabling the nEDM experiment to reach the sensitivity of 10^{-27} e-cm, which is one order of magnitude smaller than the latest result from the nEDM experiment at the Paul Scherrer Institute (PSI) in Switzerland [2].

UCN production benefits from two quantum effects. The first is quantum cooling, which slows neutrons to velocities below 5 m/s. This is achieved by using superfluid helium as the thermalizing medium, where neutrons lose energy through the emission of quantized excitations in the superfluid [3]. The second is quantum confinement, whereby UCNs can be "trapped" once their kinetic energy is low enough that they undergo total internal reflection from the trap walls, effectively behaving as waves confined within a potential well.

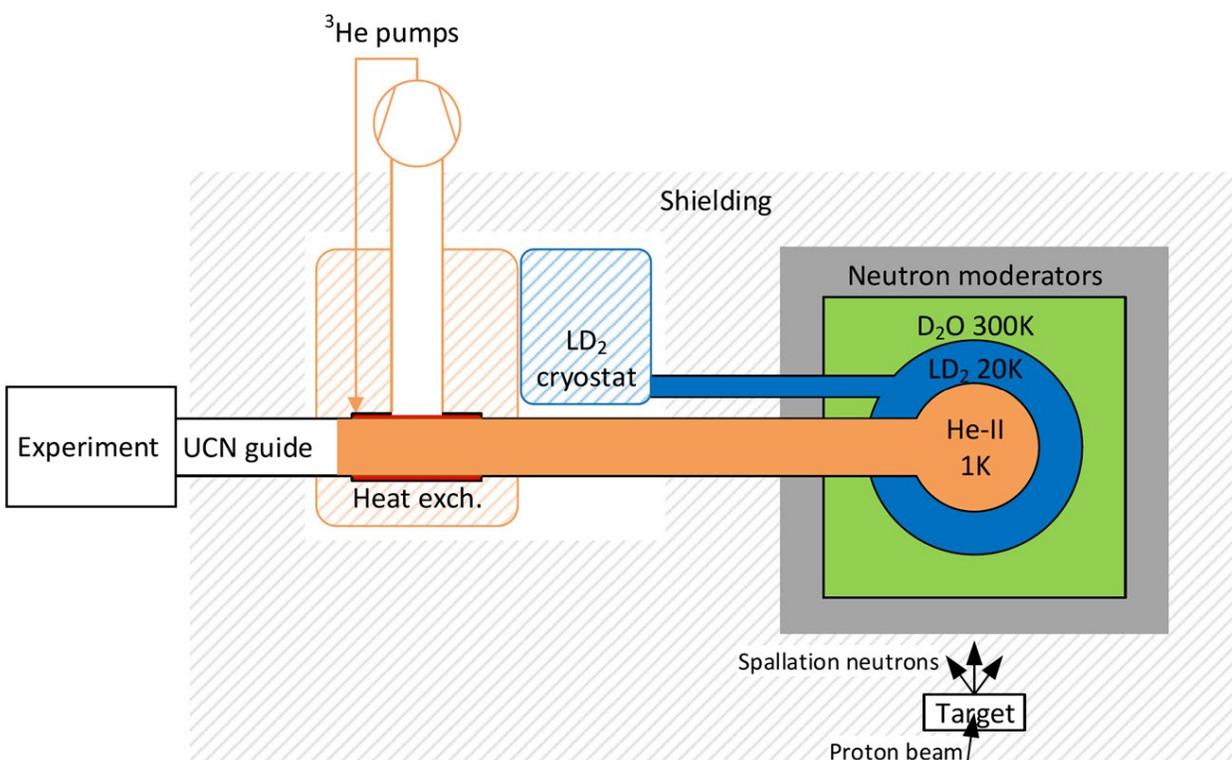


Figure 2. Schematic of the TUCAN source.

The core of nEDM experiments relies on precisely measuring the precession frequency of the neutron's spin in combined magnetic and electric fields. This is achieved using Ramsey's method of separated oscillatory fields [4], a technique rooted in quantum mechanics, which precisely manipulates the quantum spin state of the neutrons using radio-frequency pulses. Maintaining quantum coherence, i.e., the ability of particles to exist in a superposition of states (enabling wave-like interference and unique quantum behaviors), over long durations is paramount for this method to work [5].

nEDM experiments require exceptionally stable and uniform magnetic fields, monitored with high precision. Extremely sensitive quantum magnetometers are employed to distinguish the true EDM signal from magnetic field noise. TUCAN's magnetic field stability criterion requires that temporal variations remain below 10 femtotesla (10^{-15} T) over a 100-second interval, while the field uniformity standard demands that spatial fluctuations stay below 100 picotesla (10^{-12} T) per meter. This extraordinary level of control is precisely where the following advanced quantum techniques excel.

- Atomic Co-magnetometers: The spin precession frequency of the atoms is precisely measured and directly related to the magnetic field. By comparing their precession with that of the neutrons, systematic errors due to magnetic field drifts can be cancelled [6].

- Nitrogen-Vacancy (NV) Diamond Sensors: These are emerging quantum sensors, where a nitrogen atom replaces a carbon atom in the diamond lattice, and an adjacent site is vacant. These impurities form a quantum system whose spin states can be initialized and read out, providing information about the local electric and magnetic fields.
- SQUIDs (Superconducting Quantum Interference Devices): They exploit quantum interference in superconductors to detect small magnetic fields.

In essence, the TUCAN experiment is a prime example of "quantum metrology".

ALPHA AT CERN AND HAICU AT TRIUMF

Laboratory studies of antihydrogen provide a direct means of probing the fundamental laws of physics. They hold the potential to challenge the very foundations of the Standard Model and the theory of General Relativity, and to unravel one of the open questions in contemporary cosmology – the dominance of baryons over antibaryons.

The ALPHA experiment at CERN has achieved major breakthroughs, such as the confinement of thousands of antihydrogen atoms in a magnetic trap for several hours at the time [7], the establishment of an extensive spectroscopic program [8], and the initiation of antihydrogen gravity studies with the ALPHA-g apparatus [9].

The next leap forward towards measurements with increasingly higher precision, both in the electromagnetic and gravitational sector, requires developing new techniques to engineer the quantum states of antihydrogen, and exploit quantum effects, such as superposition.

The HAICU project, in preparation at TRIUMF [10], is developing new quantum techniques with hydrogen that can be exported to antihydrogen experiments, e.g., ALPHA. The atomic manipulation proposed by HAICU are compatible with the storage of antimatter and are geared towards the development of a hydrogen atomic fountain, where cold atoms are launched upwards with a velocity of few meters per second, so they travel a short distance before falling back down due to gravity. This technique allows to interrogate the atoms for long periods of time, in a region that can be shielded from external perturbations.

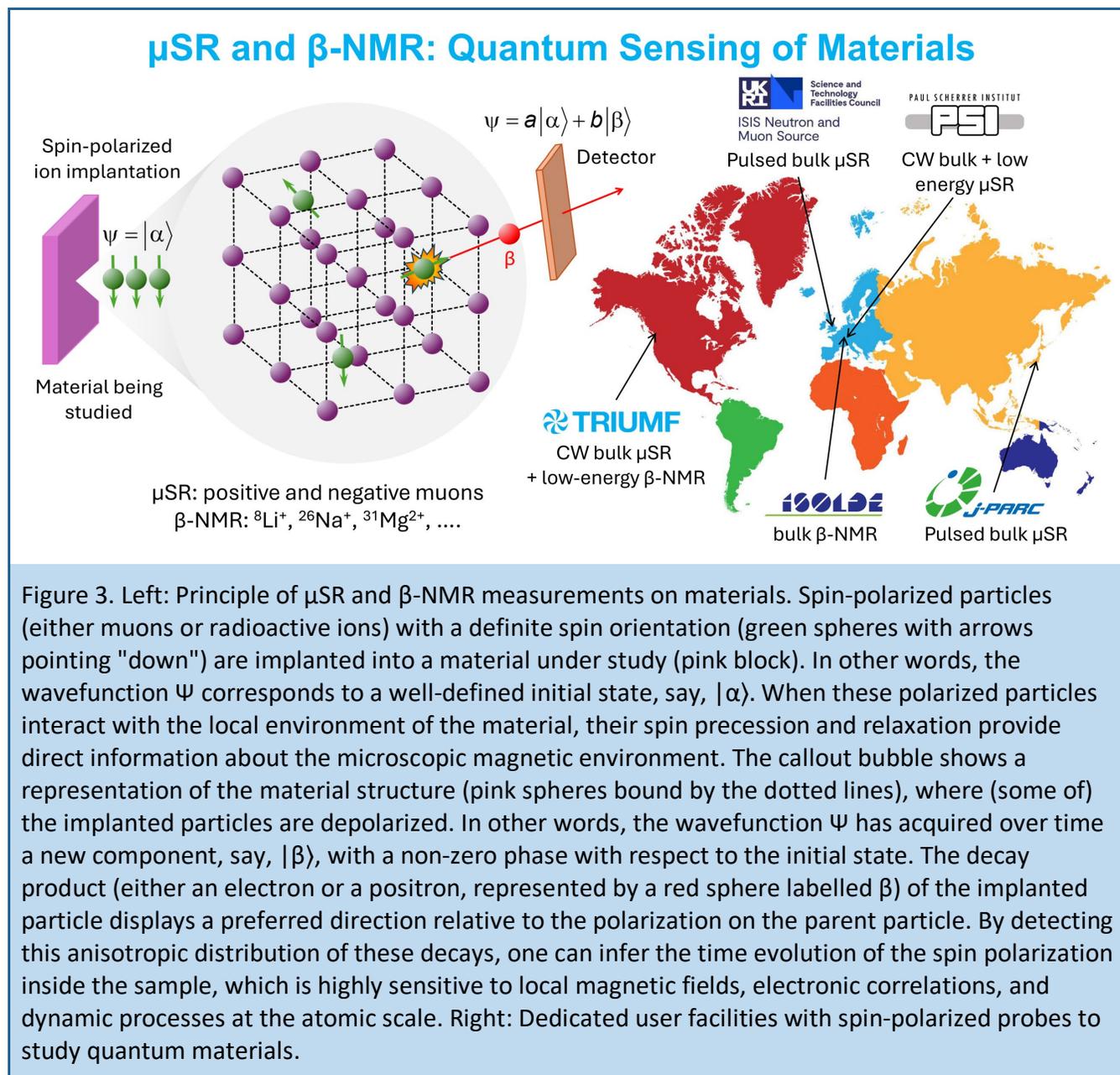
HAICU's primary goal is to magnetically trap hydrogen atoms and to cool them below the recoil limit, as to enable the creation of an atomic fountain. Several measurements can be performed in a hydrogen fountain. Extremely narrow lines can be measured using Ramsey spectroscopy. Atoms can be prepared in the long-lived 2S state using the STIRAP technique [11]. In this metastable state, Raman interferometry can be exploited to build a hydrogen gravimeter.

These efforts represent a transformative step toward precision antimatter research, leveraging quantum manipulation of hydrogen to unlock new frontiers in fundamental physics.

MATERIALS SCIENCE

Muon spin rotation, relaxation and resonance (μ SR) [12] and β -detected NMR (β -NMR) [13] are quantum sensing techniques that use spin-polarized local probes – muons in the case of μ SR, and radioactive ions

such as ${}^8\text{Li}^+$ for β -NMR – that can be considered qubits. These probes allow the evaluation of the decoherence of quantum information injected into the environmental spin system (Fig. 3 left).



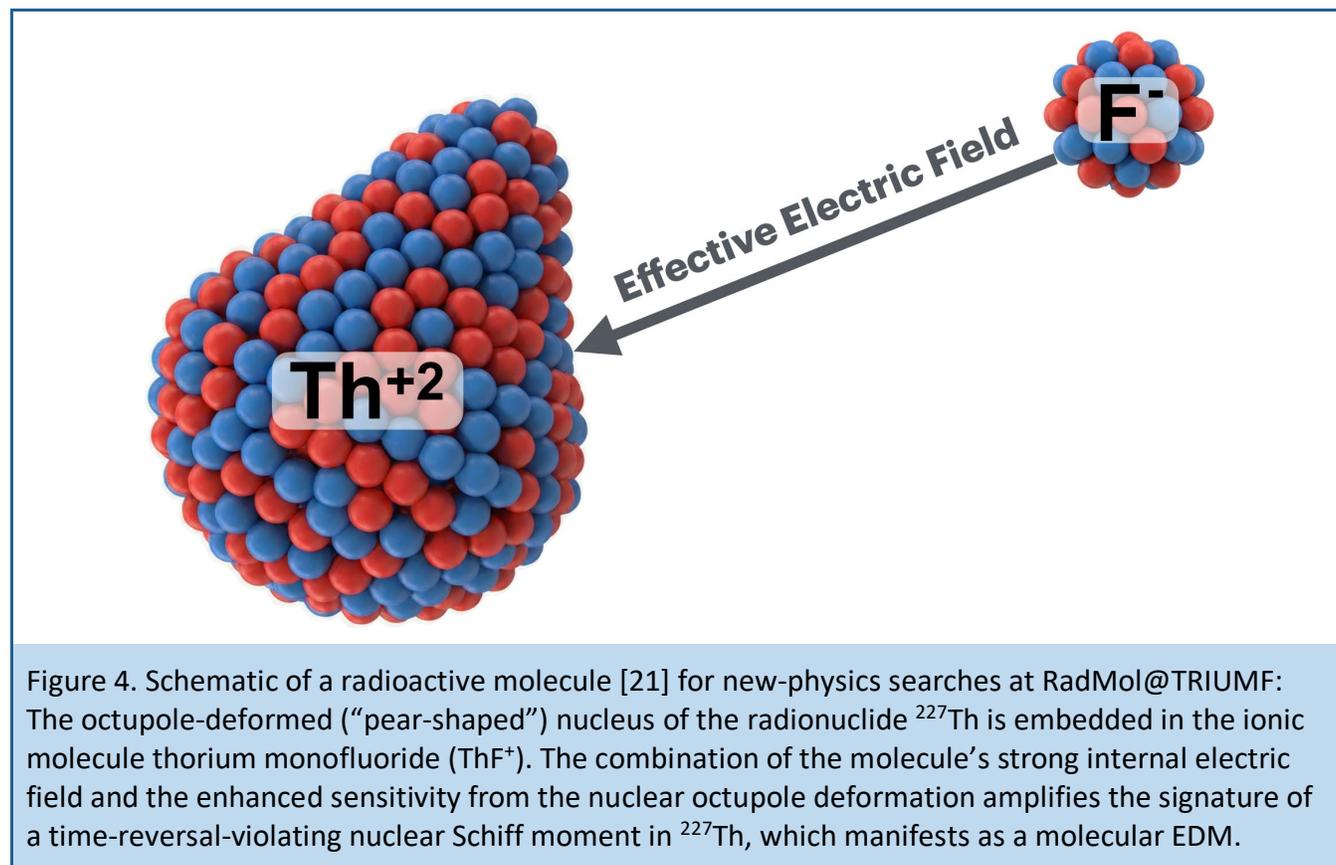
TRIUMF is one of only four μ SR facilities in the world (Fig. 3 right) and the only β -NMR facility capable of depth-resolved studies of near-surface phenomena over the range of about 2–200 nm. μ SR and β -NMR are used to study a wide range of topics in condensed matter physics and chemistry such as quantum materials (frustrated magnetic systems, superconductors, topological insulators, etc. [14]),

defects in semiconductors, ionic diffusion in battery materials, dynamics in soft matter, and short-lived intermediates in chemical reactions [13]. Scientists come from across Canada and around the world to make use of these unique characterization tools. TRIUMF has three surface muon beamlines with several μ SR spectrometers and cryostats that allow for measurements from 15 mK to 1000 K and magnetic fields up to 7 T. A new high - momentum muon beamline is nearing completion and will enable studies of materials under high pressure. There are two β -NMR beamlines for low - and high-magnetic field measurements.

In summary, TRIUMF's world-class quantum sensing facilities offer scientists powerful tools to explore the unresolved properties of quantum and other novel materials.

RADMOL

Radioactive molecules are molecules containing a short-lived radioactive atom. Their scientific potential has recently been demonstrated through precision laser spectroscopy of radium monofluoride [16-19], produced at ISOLDE, the CERN's radioactive ion beam (RIB) facility. Their wide-ranging research opportunities include, among others, fundamental symmetries studies, nuclear structure, astrophysics, or radiochemistry, see discussions in Ref. [20].



With the advent of the Advanced Rare Isotope Laboratory (ARIEL) [22], TRIUMF will offer a unique environment for the study of radioactive molecules, enabled by a significantly expanded availability and variety of short-lived radionuclides. Seizing these emerging opportunities, the newly formed RadMol collaboration aims to establish a dedicated laboratory for quantum-enabled precision studies with radioactive molecules, supporting a diverse and ambitious research program. Its first scientific objective is the exploitation of polar molecules containing octupole-deformed ('pear-shaped') radionuclides (Fig. 4) for measurements of molecular electric dipole moments (EDMs) with unprecedented sensitivity for time-reversal violating phenomena inside the atomic nucleus. Indeed, the unique ability of (quasi-)stable molecules to probe fundamental symmetry violations is, for example, well-illustrated by their pivotal role in the latest bound on the electron EDM [23-25]. The ambition of the RadMol collaboration is to translate and advance the quantum state control and manipulation techniques, central to molecular EDM measurements, into the environment of (accelerator-based) RIB facilities such as ARIEL@TRIUMF where these octupole-deformed radionuclides can uniquely be produced.

BEEST AND SALER

BeEST (Beryllium Electron-capture in Superconducting Tunnel junctions) and SALER (Superconducting Array for Low-Energy Radiation) are novel precision nuclear-recoil spectroscopy experiments that use rare-isotope-doped superconducting tunnel junction (STJ, see Fig. 5) quantum sensors to precisely search for Beyond the Standard Model (BSM) physics at the eV–TeV scale. These experiments are the leading edge of a new revolution in precision subatomic physics and have a strong Canadian contribution (led at TRIUMF), with key components and leadership in the US and Europe.



Figure 5. 128-pixel Ta-STJ detector array fabricated by Starcryo Electronics.

The primary objective of these experiments is to search for new BSM physics effects in weak nuclear decay of the ^7Be isotope (BeEST) and short-lived rare isotopes (SALER) implanted into STJs. These include world-leading laboratory search for Heavy Neutral Leptons (HNLs) in the keV mass range, the only direct measurements of the neutrino wavepacket size [26], exotic particle searches, applied nuclear science, and weak nuclear structure observables.

The experiments implant radioisotopes into the active absorber of STJ sensor arrays and measures the eV-scale nuclear recoil that gets a kick from the emission of a neutrino or other exotic particles. These are model-independent searches for BSM physics, as they only rely on energy and momentum conservation in weak nuclear decay. Precision spectral fits are used to search for excess or shifted peaks corresponding to beyond-Standard-Model physics.

QUANTUM COMPUTING: MACHINE LEARNING

Canadian scientists are key contributors to the ATLAS experiment at the CERN LHC, leading efforts in machine learning (ML) applications among other activities. The LHC and its experiments are undergoing substantial upgrades and will commence the High Luminosity run (HL-LHC) in 2030 – a broad-reaching science program projected to run for over a decade.

Interpretation of the data collected by experiments like ATLAS requires a vast body of simulated data, which is used for the statistical interpretation of the experimental data. The calorimeters of the ATLAS detector are devices that measure the energy of a particle by fully absorbing it. The simulation of the calorimeters is a particularly CPU-intensive task and the overall cost of running such simulations is expected to become prohibitive for current methods [27], resulting in the consumption of millions of CPU years. For this reason, significant research and development is required to accelerate detector simulation.

One direction that is being explored is the use of Deep Learning, with further advancements potentially enabled by Quantum Computing (QC) [28]. TRIUMF Scientists, together with partners at the National Research Council (NRC), Perimeter Institute (Waterloo, Ontario) and universities worldwide, have been developing a quantum assisted generative method, where a D-Wave quantum annealing processor [29] is used as a sampler.

Our architecture [30] is broadly based on a Variational Autoencoder (VAE) concept [31]. During training, the data are transformed into a compressed representation known as the latent space, which captures their essential features, and then decoded back into their original form. During deployment the latent space is sampled and decoded to create new synthetic data.

Canonical VAE models do not perform very well [32] due to the simple Gaussian nature of the latent space. However, our model (based on [33]) implements a Restricted Boltzmann Machine (RBM) [34] where two layers of binary-valued nodes are connected to each other – but no connections are present within each layer. This model is a universal approximator to arbitrary, binary valued distributions [35]. Notably, the 2024 Nobel Prize in Physics was jointly awarded to Canadian researcher Geoffrey Hinton for the development of this model. As opposed to a canonical VAE the latent space implemented by the RBM is trainable.

While RBMs are generally avoided in practice due to the computational cost of sampling via long Markov Chain Monte Carlo processes, deploying the model on a quantum annealer accelerates the data generation process by several orders of magnitude compared to first-principles simulations and classical deep generative models. The energy efficiency of the quantum-assisted generation is vastly improved with respect to the first principles simulation, competitive against best deep generative models and expected to improve with further technology advancements.

QUANTUM COMPUTING: DEVELOPING QUANTUM ALGORITHMS FOR NUCLEAR MANY-BODY PROBLEM

Solving the quantum many-body problem is a challenge for modern theoretical physics. Quantum computers have a potential of enabling many-body solutions for number of particles well beyond current capabilities. Development of suitable quantum algorithms is critical for achieving this goal.

When simulating quantum many-body systems on a quantum computer, straightforward encodings that transform many-body Hamiltonians into qubit Hamiltonians use N of the available basis states of an N -qubit system, whereas 2^N are in theory available. TRIUMF nuclear theorists explored an efficient encoding that uses the entire set of basis states, where terms in the Hamiltonian are mapped to qubit operators with a Hamiltonian that acts on the basis states in Gray code order, so that only one qubit changes between successive states. In a proof-of-principle study [36], this encoding was applied to the problem of finding the ground-state energy of a deuteron with a simulated variational quantum eigensolver (VQE). It has been shown that the resulting energy distribution of VQE solutions has smaller variance compared to the standard encoding. The reduced number of qubits and a shorter-depth variational Ansatz in the proposed algorithm enables the encoding of larger problems on current-generation quantum machines. Quantum algorithms are being further explored at TRIUMF in the context of *ab initio* nuclear theory.

PHOTONICS

Photonics plays a crucial role in the advancement and implementation of the Canadian National Quantum Strategy (NQS). A particularly key aspect in this area is the development of high-speed and high-detection efficiency, single-photon detectors. This technology, if properly advanced, can proportionally impact both the quantum computing and quantum-enabled cryptography fields, both strong pillars of NQS.

TRIUMF is at the forefront of single photon detector development, with multiple facilities at our disposal to study and further develop new devices. The photonics R&D efforts at TRIUMF are focused primarily on Si-based solid-state devices, with developments in two distinct directions. First, is the development of novel analog sensors with enhanced vacuum ultraviolet (wavelength greater than 200 nm) sensitivity, as reported in [37,38]. And secondly, is the design of a digitally integrated single photodetector, with a high-speed signal, as described in [39].

Moreover, the infrastructure at TRIUMF enables the working groups to study and characterize new devices directly on-site, by investigating their performances at different temperatures (spanning from

room temperature to 4K), as well as their response to single photons of specific monochromatic wavelengths, ranging from vacuum ultraviolet to infrared (wavelength greater than 700 nm and approximately smaller than 1 mm). These capabilities, coupled with laboratory-strong expertise in electronics and data-acquisition system developments, ensure that TRIUMF can be at the vanguard of the global development of these photonics developments, to the benefit of the Canadian ecosystem at large.

CONCLUSION

TRIUMF plays an important role as a national asset in the Canadian research ecosystem, with expertise and infrastructure centered around particle accelerators and detectors. Like other nuclear and particle physics laboratories around the world, TRIUMF not only pushes the frontiers of fundamental physics but is also deeply involved in the development of emerging technologies, including AI and medical applications. This short article has highlighted some of our activities in the area of Quantum Science.

The key message is twofold: (1) TRIUMF has been engaged in what is now considered Quantum Science for many years; and (2) building on this longstanding expertise and infrastructure, TRIUMF is well positioned to make significant contributions to Canadian Quantum Science. A Centre for Quantum Science at TRIUMF, proposed by the authors of this article, represents a major step in this direction, and we look forward to collaborating with the Quantum Science community in Canada and beyond.

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BRINGING QUANTUM SCIENCE AND TECHNOLOGY TO THE PUBLIC AND YOUTH ACROSS CANADA

SUMMARY: Building trust among the public and opportunities for youth from diverse backgrounds in quantum science and technology requires a multi-faceted approach. In this article, we review a selection of outreach efforts taking place across Canada to build a quantum-aware public and quantum-curious next generation.



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Quantum science is often qualified to be hard to understand, counter-intuitive, and even spooky or weird [1]. It is often seen in pop culture as very technical and reserved for an elite group of scientists. With quantum science taking more and more space in technology development and public investment, how can we build trust with the public and ask them to care about quantum? How do we get teenagers and young adults from a range of backgrounds to consider this field of studies? Providing positive contact with quantum science through thoughtful and inclusive outreach can go a long way towards engaging students of all levels [2]. Many centres dedicated to studying quantum science and technology in Canada are engaged in this essential outreach work.

ACTIVITIES FOR PRE-UNIVERSITY STUDENTS

Introducing quantum science and technology to different groups does not have a one-size-fits-all strategy. Just as some practitioners are more drawn to the philosophical aspects of quantum and others to the technological potential, pre-university students can be engaged with a variety of approaches, including lectures, hands-on experiments, puzzles, virtual games, exhibits, and more. Many groups across Canada have developed novel ways to approach students and other interested learners on a level that works for them, whether in a classroom, museum, library, or online.



Figure 1. Participants in the 2025 [Avantage quantique](#) program at the Institut Quantique de l'Université de Sherbrooke in Sherbrooke, QC attempt a quantum escape game, where they must solve quantum-themed puzzles to release padlocks on the backpack.

[The Quantum Enigmas](#), a series of videos produced by Institut quantique de l'Université de Sherbrooke (IQ), introduces the viewer to quantum programming key concepts via funny paradoxes. It is accompanied by two levels of online exercises to help the viewer understand. To introduce people to the series, IQ also developed the *2-Qubit Dance*, a game inspired by classic arcade dance games. In addition to getting participants on their feet and active, the [2-Qubit Dance](#) introduces them to fundamental ideas in quantum computers like logic gates and the Bloch sphere. By gamifying the theory, we can achieve a positive and fun first contact with the subject.

IQ also partnered with Freemick Aventure, a company that designs escape games, to build an activity for high school students inspired by escape games and involving quantum physics. The escape game component of the activity attracts a lot of attention from the teachers but also from other groups of people as well. For example, without really knowing they are playing with quantum concepts, players must solve an equation by finding numbers made from polarized filters. A science mediator explains those concepts at the end of the game to make sure students understand what they did and link the activity with the science curriculum. Quantum science in the game is seen as a bonus to their experience. Outreach activities with Let's Talk Science / Parlons Sciences, exhibitions like [QUANTUM:](#)

The Exhibition from the Institute for Quantum Computing (IQC), video series like *Quantum 101* from the Perimeter Institute for Theoretical Physics (PI), and online games like those featured *The Quantum Arcade* from UBC Geering Up Engineering Outreach (Geering Up) have also demonstrated a positive impact on participants. Bringing people into a research environment can also improve how people see the value of and opportunities in quantum science. In the nation-wide Quantum Canada Open Doors event in 2025, people had the chance to see labs across Canada: the people, the machines, the effort. Taking people where they can't usually go and taking the time to show them how quantum science is done creates this positive feeling of being part of something special and (ironically for quantum physics) bigger than us! This feeling is empowering and creates that sparkle that makes you want to know more about quantum after the visit. It also inspires the younger generation to be interested in science and to look for other ways to get involved and pursue this path for their future.



Figure 2. Students in Moncton, NB play Quantum 2048, a game on Geering Up's Quantum Arcade introducing quantum concepts like tunnelling to a familiar desktop game.

EFFECTIVELY ENGAGING YOUNG LEARNERS

If you have ever tried to give a child vegetables or medication to a sick pet, there is one simple rule: It cannot taste like vegetables or medicine. The broccoli must be utterly undetectable. The pill must be deceptively enveloped in cheddar. Learning, particularly after-school learning, should be a cleverly

made, captivating game wrapped around a core rich with foundational knowledge. Geering Up thinks of this as the Spinach Smoothie approach.

The question then becomes: what's the recipe to make learning feel like playing?

- 1 heaping scoop of cool science facts
- A healthy pour of inquiry-based approach
- 2-3 spoonfuls of wow-factor
- Two handfuls of supported STEM Identity
- And little to no barrier to entry

A few fruit snacks never hurt either.

What does this look like in practice? At Geering Up, programs are delivered in many formats to accommodate a wide variety of learners. Through in-school workshops, summer camps, weekend events, after-school clubs, online courses, and presentations, we are focused on ensuring that learners feel safe, supported, and importantly — that they're having fun. At the University of Victoria's [HighTechU](#), students spend three weeks in the summer deep diving into quantum through either electrical or software engineering. At the IQC's [Quantum School for Young Students \(QSYS\)](#), students from across the globe learn the fundamentals from experts, conduct labs with real quantum systems, and build a network of like-minded quantum champions [3].

A big part of this is explicitly championing groups that have been systemically excluded from STEM spaces. All Girls* (inclusive of cis and trans girls, genderqueer or non-binary people, and those who identify as other gender minorities), Indigenous STEM, Black Youth, and subsidized programming are all crucial for a diverse future. The University of Toronto's *Girls in STEM* programming, for example, provides this opportunity. Quantum mechanics carries a mystique and sci-fi connotation that can be intimidating, and pop-culture references have only added to this. Contrarily, quantum mechanics is as core to our existence as breathing, eating, or the water cycle. So why can we easily show one to a young learner and not the other? The answer is in the Spinach Smoothie approach- it's up to educators to make quantum mechanics a positive, approachable topic. As an example: superposition is a fundamental mechanic of the natural world but is often presented in complex math. Geering Up succeeded in engaging classes of grade 6/7s by developing a game of quantum battleship, where players solve for the probability of hitting their opponents' ships. When learning is gamified, students will wholeheartedly dive into complex topics and keep learning.

QUANTUM SCIENCE FOR TEACHERS

To reach students across Canada at scale, outreach efforts through even large educational and research institutions will struggle. One possible way to introduce more students to the excitement and opportunities of quantum science is by providing teachers with tools for their classrooms. While quantum science is part of the high-school curriculum in many provinces, usually in the final-year physics class, this is not the case nation-wide. When quantum science is present in the curriculum, it is often with a historical perspective focused on phenomena like wave-particle duality and the photoelectric effect [4] but not features like entanglement and coherence considered key for current

research directions in quantum information science [5]. It is usually the final topic in the course when present and is therefore at risk of being skipped due to time constraints. However, students often consider it one of the most interesting topics in the course [6], indicating that spending more time on it could lead to higher interest in pursuing physics and related disciplines at the post-secondary level.



Figure 3. Participants at the 2024 Quantum for Educators (QEd) workshop in Waterloo, ON test a 3D-printed quantum key distribution teaching tool designed for high-school classrooms.

In addition to struggling to fit it into a packed course schedule, teachers' comfort and confidence with quantum topics can also be a challenge. In a survey taken of high-school teachers participating in IQC's 2023 and 2024 [Quantum for Educators \(QEd\)](#) workshops, only a minority responded that they felt knowledgeable about (19/49) or confident teaching (9/49) quantum concepts. Workshops focused on quantum science and how it can fit into existing curriculum may help educators build this confidence.

In QEd, rather than taking a historical approach, modern quantum technologies are built up by introducing new ideas to familiar concepts. For example, vector components and light polarization are usually familiar concepts in the high-school physics classroom. By introducing a wrinkle to this idea, namely that the polarization of a photon would be found probabilistically depending on the way in which it is measured, key concepts about quantum bits and measurement bases can be explored in a hands-on way. From this backbone, participants can then explore future quantum technologies like

quantum communication and quantum computing, as well as technologies that have been making an impact for decades like atomic clocks and MRI. In addition to developing the theory in a way that connects to the curriculum, a variety of options for hands-on lab activities are presented, many of which require little to no budget. These include using diffraction from a human hair to demonstrate interference, using dice with removable faces to explain trade-offs in the uncertainty principle, and coins and boxes to role-play the quantum key distribution protocol.

After the workshops, most participants felt knowledgeable about (40/41) and confident teaching (37/41) these concepts. Other opportunities for teachers in Canada include the [EinsteinPlus](#) workshop and various others by PI and *Classe quantique* by IQ. There is certainly an appetite for quantum support among educators, with QEd participants over the years consistently ranking videos and hands-on lab activities as the most in-demand resources.

CONCLUSION

Our understanding of quantum science has impacted lives across the globe for the past 100 years. It is no longer considered niche or radical by scientists, but still is considered as especially abstract and difficult by most of the public. Breaking that perception and empowering the next generation to seriously consider studying quantum science necessitates a variety of approaches and working closely with students, teachers, and our community more broadly. With quantum research happening from coast-to-coast and multiple internationally recognized initiatives to engage students and the public, it is possible to make quantum ideas and opportunities accessible to all Canadians.

ACKNOWLEDGEMENTS

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SPINS FIRST? WAVE-FUNCTIONS FIRST? QUBITS FIRST!

SUMMARY: I discuss strengths and shortcomings of the “waves first” and “spins first” strategies for teaching introductory quantum mechanics and advocate for what I call “qubits first”.



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Quantum Mechanics is taught in two or three courses in typical physics programs, often starting with a “Modern Physics” course in second year that presents historical experiments before introducing wave mechanics. Students find it interesting, instructors enjoy teaching it, researchers apply (more advanced) quantum mechanics skillfully and successfully. But in the end, “what it all means” remains mysterious to many physicists at all levels, despite them being fully comfortable with “the math” [1].

Why is that? Part of the reason is certainly that quantum phenomena are detached from everyday experience. Second-year students have just learned how to use an abstract language to express concepts much closer to their experience, such as forces, momentum, or energy, but are probably not ready for the jump in abstraction required to think about wave functions as probability amplitudes. Finding suitable in-class demos is also a challenge, and the introductory quantum course may look like an exercise in solving differential equations to many students.

But I believe the more important reason - and one that we should address now that we celebrate quantum mechanics’ approximately 100th birthday in this International Year of Quantum Science and Technology - is the sequence of content that is typically chosen for quantum courses. The usual approach is to present historical experimental insights starting from the Bohr model (quantization of energy levels), the photoelectric effect (photons as energy packets) and the Compton effect (photons have momentum, emphasizing particle-wave duality), and then follow the historical timeline by introducing the wave function to describe simple systems. Some textbooks, including the widely used one written by Griffiths, even start with the Schrödinger equation and wave function without any prior motivation. This approach requires the students to accept new, abstract and counterintuitive concepts that are typically not stated explicitly (the waves-first approach often does not introduce the postulates at the beginning) while discussing physical variables (position and momentum) that are deceptively close to classical ones. At the same time, students must apply relatively advanced mathematical tools that they have typically just learned, such as the theory of ordinary differential

equations. This curriculum increases the cognitive load unnecessarily. Not only does this approach make it harder for the students to learn quantum mechanics, but it also blurs the distinction between actual quantum mysteries and confusion due to the mathematical description. Even worse, this approach obfuscates core quantum concepts such as uncertainty: a student who learns to “explain” position-momentum uncertainty in terms of Fourier analysis will likely view quantum uncertainty as a side-effect of the mathematical description instead of a fundamental feature of quantum systems, including discrete ones.

For other physics courses, we have long abandoned the historical approach: for example, we do not teach Newtonian mechanics using geometry. Instead, we simplify it using “modern” mathematics, in the form of calculus. We also use a more intentional pedagogical approach using simplified models: we start introducing mechanics with point masses instead of rigid bodies, and electricity and magnetism with point charges before introducing electric fields - so why should we introduce the wave function first instead of using a simple two-level system (which we can call a qubit to illustrate its generic nature and its use in current technical applications)?

One reason is probably tradition, combined with reluctance to change something that appears to be working fine if one doesn't look too closely. Another reason might be a desire to avoid thinking about “philosophy” (more on that below). While these sentiments should not be strong reasons to avoid updating the curriculum, there is a real obstacle: workload. Fundamentally rethinking how we teach quantum mechanics means redesigning not only the introductory course, but also adjusting the whole sequence of quantum courses, with possible effects on other parts of the program. This can affect many instructors in a department, who may simply not have the bandwidth to deal with such changes. Fortunately, the redesign of any course after the introductory one requires essentially only a rearrangement of the order in which topics are taught, and clarifying the learning outcomes.

Given these nontrivial obstacles, is it worth the effort? Student difficulties with traditionally taught quantum mechanics are well documented in the Physics Education Research (PER) literature [2], and reducing the extraneous cognitive load for our students is certainly a worthy goal. Starting with two-level systems like spin-1/2 particles allows them to focus on understanding the new concepts while using very simple linear algebra. Introducing the postulates of quantum mechanics with two-level systems requires only that students think of two-dimensional (complex) vectors and their representations in different bases, 2x2 matrices, and probabilities, as opposed to infinite-dimensional Hilbert spaces, square-integrable functions, and probability densities. When students learn about wave mechanics later, they can identify the wave function as the position representation of an object they are familiar with, the ket. This connection represents a crucial insight that often gets lost in the waves-first approach.

In addition to reducing the extraneous cognitive load, the spins-first approach gets to the core of quantum concepts like states, measurement, probabilistic outcomes and uncertainty right away. Starting from the experimental results of a Stern-Gerlach experiment, it emphasizes the fact that physics is an experimental science (which sometimes gets lost for students struggling with what they see as “just math”), and that the probabilistic nature of quantum mechanics is a fact of life. In the

waves-first approach, this probabilistic nature is much less clear because it is often introduced as “smearing out” the location of a particle, which can appear as artificially imposing fuzziness on a perfectly adequate classical variable. Using a spin-1/2 system also introduces uncertainty as a fundamental feature of quantum mechanics based on experimental observations of e.g. two spin components, as opposed to using the Fourier transform relating position and momentum.

For some instructors, switching to a spins-first approach might feel uncomfortable because it implies taking a more deliberate stance on what many would dismiss as “philosophy”, the so-called interpretations of quantum mechanics. Describing a spin-1/2 system with a two-dimensional vector requires introducing the concept of the state of a system as a container for all we can know about it.

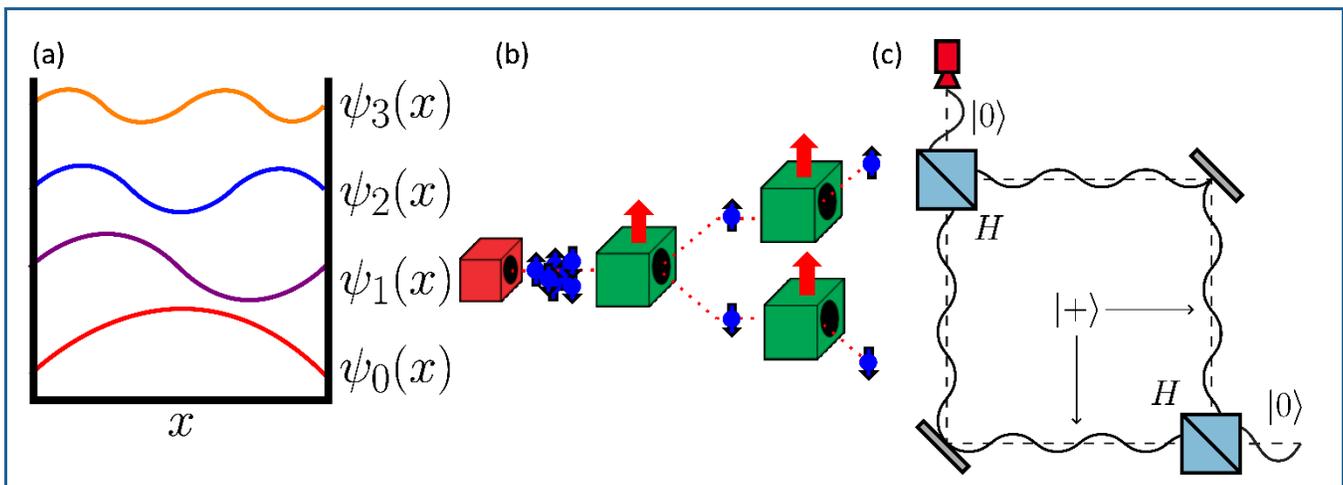


Figure 1. These images show the model systems we use for teaching quantum mechanics: The bound states in a potential well (a) are typical for the waves-first approach. They don't show the physical system, just the mathematical solution which reminds the students of standing waves on a string - good for illustrating quantization, but bad for interpreting the amplitude. The Stern-Gerlach experiment (b) is at the core of the spins-first approach. While the image is a very simplified presentation of the experiment, it does relate to physics the students have seen before (charged particles in a magnetic field) and explicitly shows the quantization of the new (to them) quantity spin. The Mach-Zehnder Interferometer (c) plays a crucial role for the qubits-first approach. Similar to the Stern-Gerlach sketch, it shows a simplified representation of physics familiar to the students (lasers, interferometry), and a simple description using 2x2 matrices will allow them to obtain the correct result. It can also be used to illustrate the use and meaning of different bases.

This is not too far from the original Copenhagen interpretation, which treats physics epistemologically, as theory of what we can say about nature, as opposed to an ontological theory of what nature is. (Note that this is very different from the popular “shut up and calculate” that is often presented as Copenhagen interpretation). Anton Zeilinger beautifully clarified this epistemological view even further in terms of information:

"If we accept that the quantum state is no more than a representation of the information we have, then the spontaneous change of the state upon observation, the so-called collapse or reduction of the wave packet, is just a very natural consequence of the fact that, upon observation, our information changes and therefore we have to change our representation of the information, that is, the quantum state." [3]

The waves-first approach does not require this epistemological clarification of what a state vector is, although it could be done. I believe that the origin of much confusion when students learn quantum mechanics is the combination of a naive "shut up and calculate" interpretation with an emphasis on variables that are familiar from classical physics, such as position and momentum. In contrast, it is much easier to proceed from the general concept of a state vector (as is done in the spins-first approach) to a specific representation (the wave function) than backwards. It is also much easier to go from 2 dimensions to infinitely many.

There are more advantages to teaching quantum mechanics in this order: Decoupling the quantum concepts from more advanced mathematical formalism frees up class time to address exciting aspects of quantum mechanics that students likely have encountered already on YouTube or social media - but doing it properly. One only needs two-level systems to illustrate entanglement. One can even introduce density matrices and discuss decoherence, which - although it does not solve the measurement problem - provides deeper insight into the quantum-classical transition. Learning these concepts early provides a big advantage in upper-level courses.

Starting with two-level systems also provides an opportunity to talk about modern developments in quantum technology, including quantum communication and quantum computing. These are fascinating topics that engage students and provide opportunities to learn about current research, a rare opportunity in undergraduate courses. In the quantum computing context, students can practice their coding skills and might even get an opportunity to program a real quantum computer (or a simulation).

The spins-first approach (see [4] for textbooks) provides many advantages over the waves-first approach - but my own favorite approach is actually "qubits first", motivated by the textbook by Pieter Kok [5]. Using a Mach-Zehnder interferometer as the first model system, one can introduce two-level systems (with a basis of paths, not polarizations) and call them qubits to illustrate that they can be described with states in an abstract space that is fundamentally different from 3-dimensional physical space. The interferometer can easily be described with vectors, matrices and probabilities, but still feels somewhat familiar to students because they have seen lasers before (as opposed to spin-1/2 particles). Even the transition from classical interference with a laser to quantum interference with a single-photon source is sufficiently intuitive for the students, although one needs to rely on simulations to "show" results.

Is this approach working? PER on the topic is only starting (see [6]), with a major hurdle being the scarcity of research tools and the difficulty of comparing student populations from different institutions. We have implemented the qubits-first approach in our introductory quantum course at SFU since 2022, with very positive feedback from our students [7], and we are continually updating and

evaluating. Introducing topics like quantum information and quantum technology allows us to include hands-on demos such as those from the Quantum Explorations Student Toolbox (QuEST) kits developed by the Institute for Quantum Computing (IQC) at the University of Waterloo [8]. Some of our students have even started developing their own demos.

The spins-first (or qubits-first) approach does not try to play down or hide the quantum mysteries that make the topic challenging – on the contrary, it places them at the core of teaching and learning. By decoupling them from advanced math and historical confusion, it allows the students to focus on the fundamental quantum concepts and “what it all means”. Building on these solid foundations allows the students to dig deeper into more advanced and mathematically challenging topics in upper-level courses, but they don’t have to wait until then to learn about entanglement, quantum teleportation, and other exciting topics from current quantum information research.

ACKNOWLEDGEMENTS

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QUANTUM SCIENCE ACROSS CANADA IN 2025

By THE CAP INTERNATIONAL YEAR OF QUANTUM SCIENCE AND TECHNOLOGY TASK FORCE*

In February 2025, the United Nations Educational, Scientific and Cultural Organization (UNESCO) officially declared 2025 as the International Year of Quantum Science and Technology (IYQ), recognizing 100 years since the development of quantum mechanics. The mission of IYQ was to broaden public understanding of quantum science and technology, including its impact on our lives today and potential for the future. Celebrations and activities were held across Canada to mark this moment, a small number of which are captured in this article.

YEAR OF QUANTUM OPENING CEREMONIES



The Canadian delegation to the opening ceremonies of IYQ at UNESCO Headquarters in Paris, France. 2025 February 4. (Photo source: Angela Olano)

In February, University of Guelph Professor Martin Williams, then President of the CAP, represented the CAP at the official launch of the International Year of Quantum Science and Technology at UNESCO headquarters in Paris [1]. A delegation of over 20 representatives from Canada's quantum community were in attendance. Diplomats, academic representatives, and even students took part in various panels and conferences during the two-day celebration, including three Canadians on-stage to discuss education, ethics, and the frontiers of quantum research. A main takeaway was that quantum technology must be developed with a view to its potentially far-reaching societal impact.



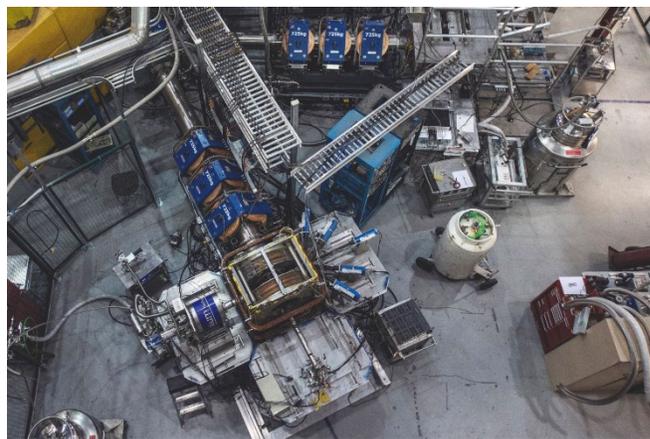
The International Year of Quantum Science and Technology opening ceremonies at UNESCO headquarters in Paris were held February 4th and 5th and featured lectures from Nobel laureates and expert panels. Dr. Stephanie Simmons from Simon Fraser University (SFU) and founder of Photonic Inc. spoke on *Pushing the Frontiers of Quantum Science and Technology*. Dr. John Donohue from the Institute for Quantum Computing at the University of Waterloo (UWaterloo) participated in a discussion on *Public Engagement and Education in Quantum Science and Technology*. Dr. Shohini Ghose of Wilfrid Laurier University and the Quantum Algorithms Institute (QAI) enlivened a panel on the *Ethics of Quantum Technology*. (Photo source: © UNESCO/Marie ETCHEGOYEN.)

BUILDING QUANTUM INFRASTRUCTURE ACROSS CANADA

On June 17 in Kananaskis, the Leaders of the G7, including Prime Minister Mark Carney, formally recognized a common vision to collaborate and support quantum technologies [2]. Investments in the infrastructure to research quantum technology in many locations across Canada are essential to realize this global vision.



Research students Ayesha Iqbal and Yusuf Ahmed install qubits inside the CUTE (Cryogenic Underground Test facility) cleanroom at SNOLAB. CUTE is being used to host a new collaboration between researchers from the Institute for Quantum Computing (IQC) at the University of Waterloo, Chalmers University of Technology in Sweden, and SNOLAB to test the effects of ionizing radiation on superconducting qubits 2 kilometres underground at the SNOLAB deep underground laboratory. *(Photo source: Mike Whitehouse, SNOLAB)*



The M20 beamline at TRIUMF, housing the LAMPF and Omni-Prime spectrometers. As an international user facility, TRIUMF enables researchers worldwide to study quantum and functional materials using muon spin spectroscopy (μ SR), where the precession and relaxation of implanted muon spins reveal static and dynamic properties of the local magnetic environment. *(Photo source: TRIUMF)*



On March 21, 2025, the University of Calgary officially opened Quantum City's qHub, a 17,400 sq. ft. collaborative space designed to connect research, development and adoption of quantum technologies and solutions implementation. Located in the Alastair Ross Technology Centre (ARTC) within the University Innovation Quarter (UIQ), qHub is a key step in building Alberta's quantum-enabling infrastructure within the growing ecosystem by bringing together experts, industry partners and emerging quantum talent. *(Photo source: University of Calgary)*

STUDENT QUANTUM OPPORTUNITIES



At the UBC Quantum Club's 2025 Career Fair, students, researchers, and professionals explored career pathways in quantum science and technology, including an Academia vs. Industry panel highlighting the differences and similarities between pursuing academic research and building careers in quantum-focused companies. *(Photo source: QAI)*



The 17th annual Undergraduate School for Experimental Quantum Information Processing (USEQIP), including a lab in the nanofabrication facility, was held in May for 25 undergrads at the University of Waterloo. *(Photo source: Fiona Thompson and Michael Grabowecy, Institute for Quantum Computing, UWaterloo)*



This summer, UToronto graduate students Byung Ha, Max Bridgewater, and Nicholas Sullivan organized Quantum Research Day 2025, a student-led conference featuring student talks, posters, and a panel with speakers from academia, industry, and research institutes discussing career pathways in quantum information and control. *(Photo source: Eva Cheung, University of Toronto)*



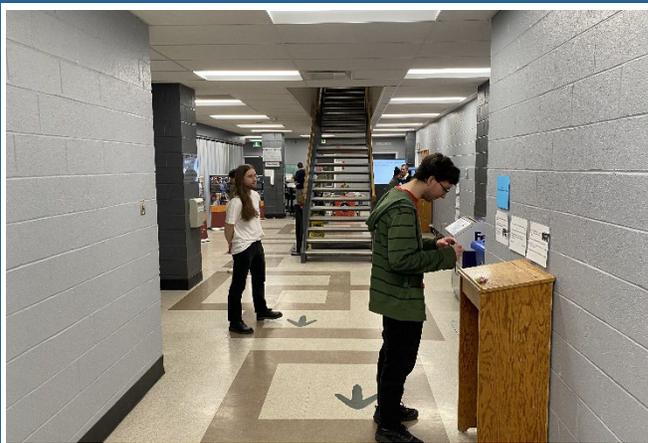
Première édition de l'École d'été en informatique quantique de l'Institut quantique de l'Université de Sherbrooke pour le premier cycle universitaire. 29 personnes participantes issues d'universités canadiennes se sont rassemblées à Sherbrooke du 5 au 9 mai 2025. *(Source de la photo : Martin Blache, Université de Sherbrooke)*

OPEN DOORS ACROSS CANADA

On May 3rd, institutions at 11 locations across Canada opened their doors to visitors to explore quantum science and technology as part of the CAP's Quantum Open Doors initiative.



Polarization Art was a fantastically engaging activity at both our STEAM school and our Saturday morning STEAM drop-in program for the local community. (Photo source: Mary McDonald, Ampere Makerspace, Lindsay, ON)



Visitors to the qUNB Quantum Open Doors were treated to hands-on demonstrations with Stern-Gerlach simulations, quantum dots, probability experiments and a personal tour of the QSUM Quantum Sensing research laboratory. (Photo source: Ben Newling, University of New Brunswick)



The Physics Department at Simon Fraser University (SFU) celebrated with two public lectures including high voltage experiments and the quantum internet, hands-on activities on quantum key distribution (see picture), quantum communication in space, lab tours and quantum memes. (Photo source: Daria Ahrensmeier, SFU)

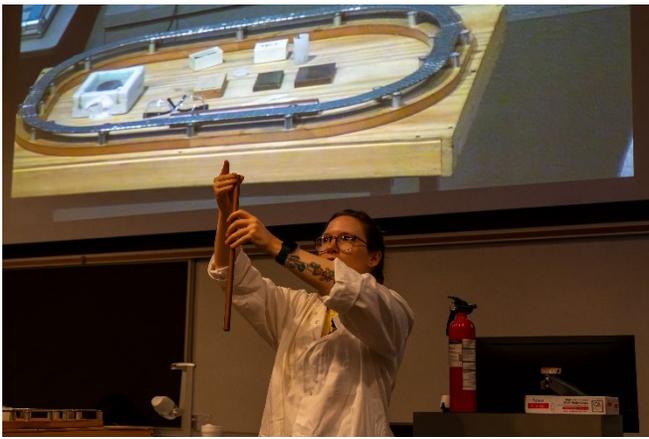


Jaimie Greasley from the University of Victoria (UVic) talks to interested community members at the Royal BC Museum about the International Year of Quantum while Eliza Partridge, Dominic Largoza, and Aaron Dayton helped run a booth at the International Astronomy Day. (Photo source: Thomas E. Baker, UVic)

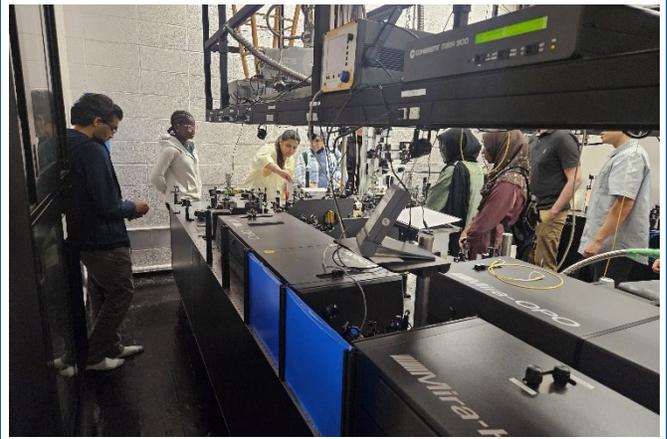


More from the University of Victoria and Let's Talk Science at the Royal BC Museum, hosted by the Royal Astronomical Society of Canada with support from the CAP.

QUANTUM FOR YOUNG STUDENTS



UBC Geering Up Engineering Outreach and the Stewart Blusson Quantum Matter Institute collaborated to bring live superconducting demonstrations to students in the weekly Science Show at summer camp. *(Photo source: David Yoon, UBC Geering Up Engineering Outreach)*



The "Quantum Hacking a Better Future" summer camp was held at Dalhousie University in the summer of 2025. The camp was geared toward high-school students in NS and included a visit to the Ultrafast Quantum Control Lab. *(Photo source: Scott Wesley, Dalhousie University)*

Melissa Valdez

Your Quantum Future: Opportunities in Canada

May 20, 2025



As part of the NSERC Chairs for Inclusion in Science and Engineering program, a series of talks were hosted remotely for students in remote and rural schools in Atlantic Canada. Speakers included Melissa Valdez, who talked about career opportunities in the quantum field. *(Photo source: Svetlana Barkanova, Memorial University and Chitra Rangan, UWindsor)*

Quantum-mania indeed! School-aged children learned about quantum bits and polarization in a workshop at the University of Windsor (UWindsor) co-hosted by the Institute of Quantum Computing and the Canadian Association for Girls in Science (CAGIS). *(Photo source: Chitra Rangan, UWindsor)*

High-school students generate quantum-secure keys at the Quantum School for Young Students (QSYS) at UWaterloo.



Students in Newfoundland playing quantum games on the Quantum Arcade, built by UBC Geering Up.

QUANTUM CONFERENCES ACROSS CANADA



The Manitoba Materials Conference centered around material science that invites students, academic researchers and industry users in the local and prairie region to enjoy the day of learning, sharing knowledge and collaboration. *(Photo source: Manitoba Institute for Materials)*



Dr. Jasneet Kaur from Brock University presents her group's recent work on 2D materials based solid-state electrolytes for clean energy applications at 14th Nano Ontario conference held at Toronto Metropolitan University. On the right, you can see the accordion-like structure of titanium carbide MXene, being studied for applications in clean energy and sensing. *(Photo source: Jasneet Kaur and Pritish Kumar Behura, Brock University)*

The QSTATE symposium at the 2025 CAP Congress saw the first public demonstration of a Quantum Key Distribution outreach experiment built by the Quantum Photonics Lab at SFU, with prior work at IQC in Waterloo. Participants took the roles of Alice and Bob to send and receive qubits. The photo shows Wilson Wu and Thomas Jennewein, SFU. *(Photo source: CAP)*



Workshop on Programmable Quantum Simulators based on 2D Materials (PQS2D) & Quantum Theory of Materials, Nanostructures and Devices (QTMND), University of Ottawa.

The Quantum Horizons Symposium, co-hosted by the U. Alberta, U. Calgary, and U. Lethbridge and hosted at the Banff Centre for Arts and Creativity.

Julien Chosson of IBM Quantum gave a keynote lecture at the second annual Windsor Quantum Applications Symposium (WiQAS.org) in July. *(Photo source: Chitra Rangan, UWindsor)*

MORE QUANTUM CONFERENCES



Centre for Quantum Information and Quantum Control (CQIQC) director Dvira Segal welcoming attendees to UToronto for the Quantum Days conference organized by Deep Tech Canada, focused on building and strengthening the Canadian quantum community. *(Photo source: Deep Tech Canada)*



The inaugural Satellite Series of Quantum Days took place in June at the University of Saskatchewan (USask). During the DQI Entanglement Social, Graeme Dyck (left) display Quantum Gates, an interactive demonstration where participants build quantum circuits with sound. *(Jae Kim Photography c/o Steven Rayan, quanTA, USask)*



In June, Quantum Industry Canada, with partner Distriq, hosted QUANTUM NOW | ICI QUANTIQUE — an executive forum on the quantum economy in Montreal, where over 375 decision-makers explored what many see as the most significant technological shift since the digital revolution. *(Photo source: Angela Olano, Quantum Industry Canada)*



This summer, faculty and students from the University of Toronto and the University of Waterloo met for a CQIQC-IQC Workshop, aimed at strengthening ties between Toronto and Waterloo's quantum ecosystems. *(Photo source: Anna Dyring, CQIQC, UToronto)*



The conference, “Year of Quantum Across Canada: From Fundamental Science to Applications”, jointly hosted by the Perimeter Institute for Theoretical Physics (PI) (left) and the Institute for Quantum Computing (right) and, celebrated 100 years of quantum science and technology. *(Photo sources: PI and IQC)*

BUILDING THE CANADIAN QUANTUM COMMUNITY



During a fierce Saskatoon snowstorm on the evening of January 31, the Centre for Quantum Topology and Its Applications (quanTA) kicked off its celebration of all things quantum with a reading of Michael Frayn's Copenhagen featuring Elizabeth Nepjuk, Skye Brandon, and Kris Bratton. (Photo source: Steven Rayan, quanTA Centre, USask)



Les 14 et 15 mai derniers, l'Institut quantique a souligné les 10 ans de l'obtention de la subvention Apogée Canada — un moment fondateur qui a permis de bâtir un institut de recherche de calibre international. Pour souligner cette étape marquante, l'IQ a réuni sa communauté et ses partenaires dans un moment fort de célébration. (Source de la photo: Institut quantique de l'Université de Sherbrooke)



QAI's Vancouver Quantum Mixer brought together BC's quantum community for networking, collaboration, and to commemorate UBC Geering Up's 5th anniversary in advancing STEM and quantum education. (Photo source: QAI)



"A Quantum of Hope" had its debut performance by Perimeter alumni and researchers. The play provides insight into researchers and their lively scientific debates by putting quantum science and technology on stage. (Photo source: PI)



Jaimie Greasley presents on quantum computing to at the Vancouver Island Star Party in August. (Photo source: UVic)

A teacher tests quantum dots using LEDs in a workshop with the Quantum Technology educational resource. (Photo source: PI)





Physicists from UNB, UToronto, and UWaterloo introduced hundreds of young students to quantum science at the Canada-Wide Science Fair's IYQ booth co-hosted by CAP. Activities included the Quantum Cats arcade game, the Institut Quantique's Two-Qubit Dance, and demonstrations of interferometry and QKD. The photo shows Matthew Robbins, UToronto and Taylor Pacholko, UWaterloo.



The CNRS Science Mediation Ambassador for Quantum Physics, Dr. Charles Antoine from Sorbonne University, visited BC, Ontario, and New Brunswick on an outreach mission organized by the Institut français du Canada. He presented EquiQuanto (pictured in Moncton, NB), a live lecture paired with equestrian art exploring the fundamental mysteries of quantum mechanics.



SFU, the Consulates of Switzerland and France, Mitacs and GESDA organized "Creating the Quantum Future" in Vancouver. Participants engaged in Quantum Diplomacy, exploring the societal, ethical, and governance aspects of quantum technologies. (Photo source: Consulate General of France, Vancouver)

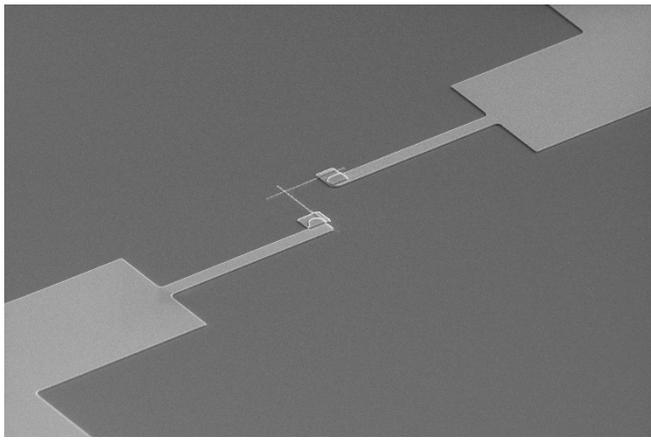


Quantum Meets Poetry at the University of Windsor. Organized by the Science Meets Art group and the English Undergraduate Students Association, the event featured readings of original poetry by students, and an interpretive dance to the poem 'A Quantum Love Story' by Ann Druyan. (Photo source: Chitra Rangan, UWindsor)



The Web Summit 2025 featured a keynote talk by Quantum Algorithms Institute (QAI) CEO Louise Turner and a panel on Quantum & AI organized by QAI, SFU VentureLabs, and Mitacs, connecting startups, enterprises, researchers, and policymakers. (Photo source: QAI)

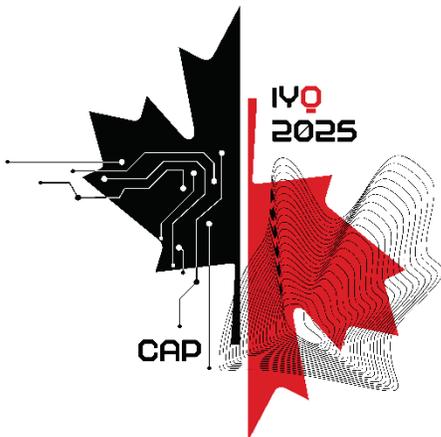
EVEN MORE QUANTUM IN CANADA



Intitulée «Quantum Bridge: Where Election Dance», cette photo s'est vue attribuée la première place de la catégorie «Beyond our eyes» du concours de photos de la International Union of Pure and Applied Physics (IUPAP). La photo fut captée par un microscope électronique à balayage et montre une jonction Josephson, une structure délicate au coeur d'un qubit supraconducteur. (Photo source: Alexandra Roy, Institut quantique, U. Sherbrooke)



Kerr-instability amplification is a nonlinear optical process extending four-wave mixing to extreme intensities, where two pump photons are destroyed to create seed and idler. Conservation of energy and momentum dictate non-collinear intensity-dependent phase matching. As amplification saturates, cascaded mixing leads to higher-order beams spanning from the infrared to the ultraviolet. (Photo source: Nathan Drouillard and T.J. Hammond, UWindsor)



The CAP logo for IYQ was designed by Jasmine Zhang, a PhD student at UBC. Their design represents a superposition of quantum-driven technological advancements and the fundamental physics underlying the natural world. The orientation of the two halves of the Canadian maple leaf is a nod to the familiar orthonormal basis for the spin-1/2 particle.



The Quantum Photonic Devices Lab members and Waterloo Warrior hit the ice to welcome a quantum dot single-photon source from Berlin in their Waterloo lab as part of QuanTour. The source had previously been tested at labs across Europe and next went to NRC in Ottawa. (Photo source: Michael Reimer, IQC, UWaterloo)

ACKNOWLEDGEMENTS

The CAP IQ Task Force are grateful for support from NSERC through the Special Opportunities Fund SOF-601917-2024. We are also grateful for financial support from SNOLAB, TRIUMF, the Perimeter Institute for Theoretical Physics, the Quantum Algorithms Institute, and the Institute for Quantum Computing. The events celebrated in this yearbook took place on the traditional and unceded territories of diverse Indigenous peoples (First Nations, Inuit, and Métis) across what is now known as Canada (Turtle Island). We are grateful to celebrate quantum science and technology across these lands.

REFERENCES

* The CAP International Year of Quantum Science and Technology Task Force consisted of over 30 representatives from across Canada and was chaired by Daria Ahrensmeier (Simon Fraser University) and Oliver Stelzer (TRIUMF). For more details and a complete list of members, visit the [CAP IQ website](#).

1. UNESCO IQ 2025 Opening Ceremony. 2025 February 3. <https://quantum2025.org/iq-event/iq-2025-opening-ceremony>
2. Kananaskis Common Vision for the Future of Quantum Technologies. 2025 June 17. <https://g7.canada.ca/en/news-and-media/news/kananaskis-common-vision-for-the-future-of-quantum-technologies/>

RESULTS OF THE CAP-IYQ 2025 “QUANTUM ARTS” AND CAP-IYQ LOGO DESIGN COMPETITIONS / RÉSULTATS DES CONCOURS ACP-IYQ 2025 « QUANTUM ARTS » ET CONCOURS DE DESSIN DE L’ACP-IYQ 2025

By THE CAP INTERNATIONAL YEAR OF QUANTUM SCIENCE AND TECHNOLOGY TASK FORCE / PAR L’ÉQUIPE DE L’ACP DE L’ANNÉE INTERNATIONALE DE LA SCIENCE ET DE LA TECHNOLOGIE QUANTIQUES

THE CAP-IYQ 2025 “QUANTUM ARTS” COMPETITION / CONCOURS ACP-IYQ 2025 « QUANTUM ARTS »

As part of the International Year of Quantum Science and Technology celebration, the CAP invited participation in the **CAP-IYQ 2025 “Quantum Arts” Competition**, a Canada-wide showcase of creativity inspired by quantum themes. The competition was open to everyone in Canada, with prizes of up to \$500 available in three categories: visual arts, performing arts, and literature. The artwork could be literal or abstract; scientific, humorous, or poetic.

Thirty-four submissions were received from the general call, and we are delighted to announce the winners in each category:

	Literature	Performing Arts	Visual Arts
1 st Prize (\$500)	Cristian Ramirez Rodriguez <i>Pauli Matrices with Scaling Factors</i>	Stefanos Kourtis <i>Windchime #13</i>	Julie Bélanger <i>Quantum Bloom</i>
2 nd Prize (\$300)	Abiy Nedie <i>Superposition</i>	Graeme Dyck <i>Quantum Gates</i>	Sareen Sabra <i>Schrodinger’s Stereogram</i>
3 rd Prize (\$200)			Elham Zohari <i>Untitled Diamond</i>
Honourable Mentions	Richard Germain <i>Oh Quanta!</i>		Ruvé Staneke <i>Untitled Butterflies</i> Amelia Alcock-White <i>Entanglement</i> Hansima Keppetiyawa <i>Untitled SEM</i>

The main results are reproduced in this article; please see the [IYQ website](#) for further details.

PAULI MATRICES WITH SCALING

By Cristian Ramirez Rodriguez of the University of New Brunswick, Fredericton, New Brunswick
1st Prize Winner, Literature

Identity, σ_0

$$I = C_0 \sigma_0$$

$$I = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$C_0 = 1$$

An electron from a complex molecule
in a Rydberg state
sees itself as a hydrogen atom
with a rapidly rotating core structure.

The present holds heartbreak,
an incidental product of excited separation
across a well-defined boundary
and the measurement of time.

Far from home
a tendency to simplify
the old home ground arises
while the past holds presence.

Identity can be defined
as the distance between
perception and measurement.
Interferometric precision comes from the cold.

Ex, σ_x

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$A = C_1 \sigma_1$$

$$A = \begin{pmatrix} 0 & -1 \\ -1 & 0 \end{pmatrix}$$

$$C_1 = -1$$

An atomic physicist told me
“disarmament is the sign of a mature civilization”
and that any worthwhile measurement
is worth measuring twice.

As troops surround the nation
where all my grandparents lived
I watch Maria win a Nobel prize for her attempts
to achieve “a peaceful transition” to democracy.

The two classical idioms assume
measurement does not irrevocably alter the state
when even the suspicion of WMDs
may lead to regime change.

She shares the name of an ex-girlfriend who gave
me an oversized sweater for winter mornings
before the border crossing and the breakup.
When I grew into the sweater, how disarming it was.

Why, σ_y

$$\sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$M = C_2 \sigma_2$$

$$M = \begin{pmatrix} 0 & -mi \\ mi & 0 \end{pmatrix}$$

$$C_2 = m$$

Lightning bugs produce circularly polarized light. In northwestern Venezuela the Barí peoples claim lightning storms come from the ancestors who return to the earth as celestial fireflies.

This year I learned cyclic variables depend on the reference frame and the life cycle of a relationship depends on whether it survives a migration.

Grief is also circular. I remember fireflies and dancing with abuelita when the Aurora arrives. In Cree, the Northern Lights are "wâwâhtêwak," or "kâ-nîmihitocik," they who dance in a circle.

If entangled observables are translation independent why does a lightwave collapse upon measurement with no memory of previous states?

Rest, σ_z

$$\sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$T = C_3 \sigma_3$$

$$A = \begin{pmatrix} e & 0 \\ 0 & -e \end{pmatrix}$$

$$C_3 = e$$

Mistranslation is an art form amplified by notation. To the one who split the atom entropy's arrow becomes death.

Evaporative cooling carries a macroscopic analogy: eight million Venezuelans left the country including every major opposition leader.

Semiclassically, cooling bosons to a phase space density that produces a new state of matter requires the removal of the most energetic elements in an atomic ensemble following a MB distribution.

How could I translate the dream of returning to a forgotten home when the precisely defined energy levels lead to greater uncertainty in the destroyer of worlds?

$$I = AMTi(me)^{-1}$$

DESCRIPTION BY AUTHOR:

The poem, "Pauli Matrices With Scaling Factors" refers to the set of 2x2 matrices which can represent the polarization states of light. I wrote the poem in the Quantum Sensing and Ultracold matter lab in Fredericton, New Brunswick, Canada while thinking about my family in Venezuela and working on improving our atom interferometer through an evaporative cooling stage.

SUPERPOSITION: FOR THOSE WHO DREAM IN PROBABILITIES

By Abiy Nedia of MacEwan University, Edmonton, Canada
2nd Prize Winner, Literature

I walk where light decides,
a boundary of maybe ...
half-step in the world that is,
half-step in the world that might be.

My shadow collapses first,
choosing a single truth
while I wander the branching paths
like a rumor of myself.

In the hush between wave and particle
I feel the pulse of possibility ...
the quiet electricity
of a universe that has not yet made up its mind.

Here, uncertainty is not a flaw
but a doorway:
a promise that even the smallest thing
can rewrite the cosmos.

So, I breathe in the quantum dawn
where reality shimmers uncommitted ...
and for a moment
I, too, am infinite.

DESCRIPTION BY AUTHOR:

This pairing brings the reader into a world poised between certainty and possibility. In the image, a lone figure stands at the threshold of a glowing portal, facing a spiraling cosmos that feels both distant and intimately connected by thin, red threads of light. The figure becomes an observer whose act of perception will crystallize their fate, echoing the poem's meditation on superposition; the space where reality hesitates, where every step is both taken and not yet taken. The warm light behind them evokes the solidity of the known world, while the swirling galaxy ahead embodies Hilbert space "ghost-selves," a realm where identity softens into probability. This quiet contrast of gold and deep blue amplifies the poem's sense of shadow, branching paths, and truths waiting to collapse into form. Together, image and text create an atmosphere of soft wonder; a gentle invitation to inhabit uncertainty not as a fear, but a doorway into infinite potential.

Disclaimer: I wrote the poem. I used AI for the image. I also polished a few of my words using AI.



OH QUANTA!

Par Richard Germain, Pointe-des-Cascades, Québec
Mention honorable, littérature

Ma conscience s'éveille
Je suis observateur du Soleil
Il m'envoie son rayonnement chaleureux
Mais était-il dans cet état avant mon regard curieux?

Dans cet Univers où règne l'incertitude innée
Le déterminisme a fait place à la probabilité
Je voudrais faire la lumière sur cette nature voilée
Alors que la nature de la lumière est une dualité

En quête d'un modèle standard, toujours je sonde
J'observe l'effondrement des fonctions d'ondes
Ainsi que les actions fantômes à distance qui me confondent

Mon esprit spin en rêvant d'intrication
Et je suis en décohérence en songeant à des chats vivants et non

Je sens venir en moi une catastrophe ultraviolette
Quand le monde me confronte à un corps noir à énergies discrètes
Par principe, pas d'exclusion simplette
Je dois laisser le quantique me prendre dans ses bra-kets

J'ai l'impression d'être sur le BOHR du puits de potentiel
Lorsque la vérité me frappe; PLANCK!! Enfin la beauté du réel!
Transistors, qubits, lasers, IRM, CMOS et DEL
Les quantas donnent à ma vie un ASPECT sensationnel.

WINDCHIME #13

By Stefanos Kourtis, Université de Sherbrooke
1st Prize, Performing Arts

Listen online: <https://iyqcda.cap.ca/wp-content/uploads/2026/02/QuantumWindchime-Windchime13Exposition-Stefanos-Kourtis.mp3>

DESCRIPTION BY ARTIST:

Windchime #13 is inspired by the theory of quantum magnetism. "Snapshots" of a wavefunction modeling magnetically interacting electrons (Hubbard model) are taken during its time evolution and translated into a musical score.

QUANTUM GATES

By Graeme Dyck of the University of Saskatchewan, Saskatoon, Saskatchewan
2nd Prize, Performing Arts

View on YouTube: <https://youtu.be/BQXQarihKw> .

DESCRIPTION BY ARTIST:

'Quantum Gates' was an interactive audio installation that explored the logic of gate-based quantum computing through electronic music. Participants wandered through the soundscape created by a ring of four speakers and modulated it using buttons in the centre of the space. Each speaker corresponded to one qubit in a quantum computer model and produced sound according to the state of the qubit in the system, moving between musical sound (1) and textural noise (0). A pad labelled with quantum gate diagrams allowed users to apply gates to the system and hear its state change around them. With 16 different gates available and a faithful Hilbert space model of the 4-qubit system, participants could hear phenomena like entangled Bell states and build circuits such as Feynman's 1986 quantum adder. Different operations and post-measurement states revealed varied musical textures that participants could explore while building a sonic intuition for quantum logic.

QUANTUM BLOOM

By Julie Bélanger of Université de Sherbrooke, Sherbrooke, Québec
1st Prize, Visual Arts



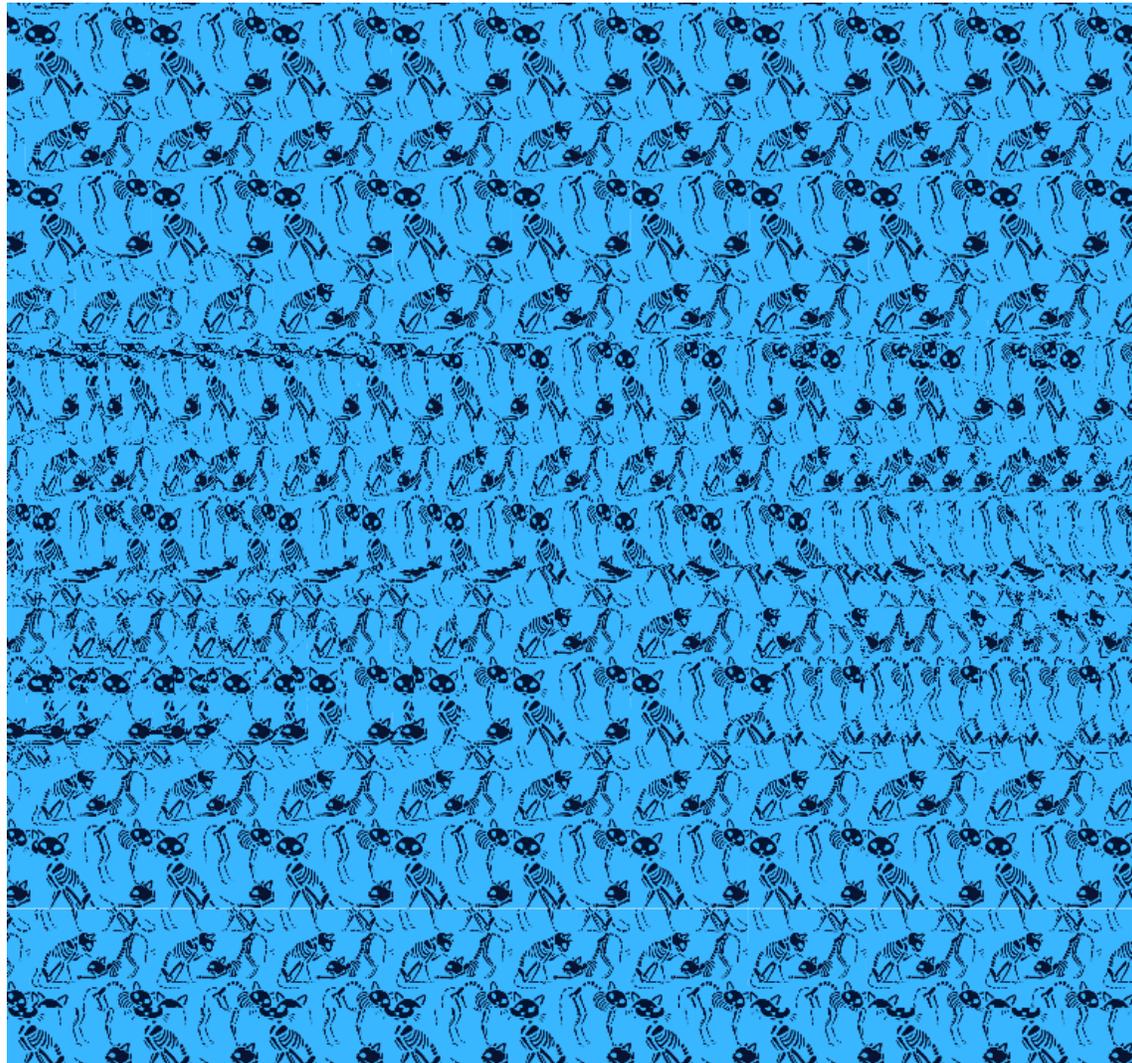
DESCRIPTION BY ARTIST:

Quantum Science is a constantly growing field nourished by scientists such as physicists, engineers and mathematicians all over the world. It is composed of three major schemes: the foundation concepts (i.e. the roots) such as quantum hardware and linear algebra, the core concepts (i.e. trunk) like quantum information, quantum computation and software developments, and finally the numerous possible applications (i.e. the branches). If you take a closer look, you will notice that each part of the tree is composed of quantum lexicon related to the respective scheme. In principle, each terminology appears only once; a word can appear many times since it can be used in a different expression. For instance, the roots section contains: Josephson junction, orbit and ion trap. The trunk section contains among others: Deutsch's algorithm, Hamiltonian and tomography. Examples of words in the branches section include quantum finance, DNA computing and cryptography.

Disclaimer: This project is created with the help of Canva, an online design platform. Each word has been meticulously and individually added and scaled to form a tree pattern. No artificial intelligence has been used.

SCHRÖDINGER'S STEREOGRAM

By Sareen Sabra of the University of Windsor, Windsor, Ontario
2nd Prize, Visual Arts



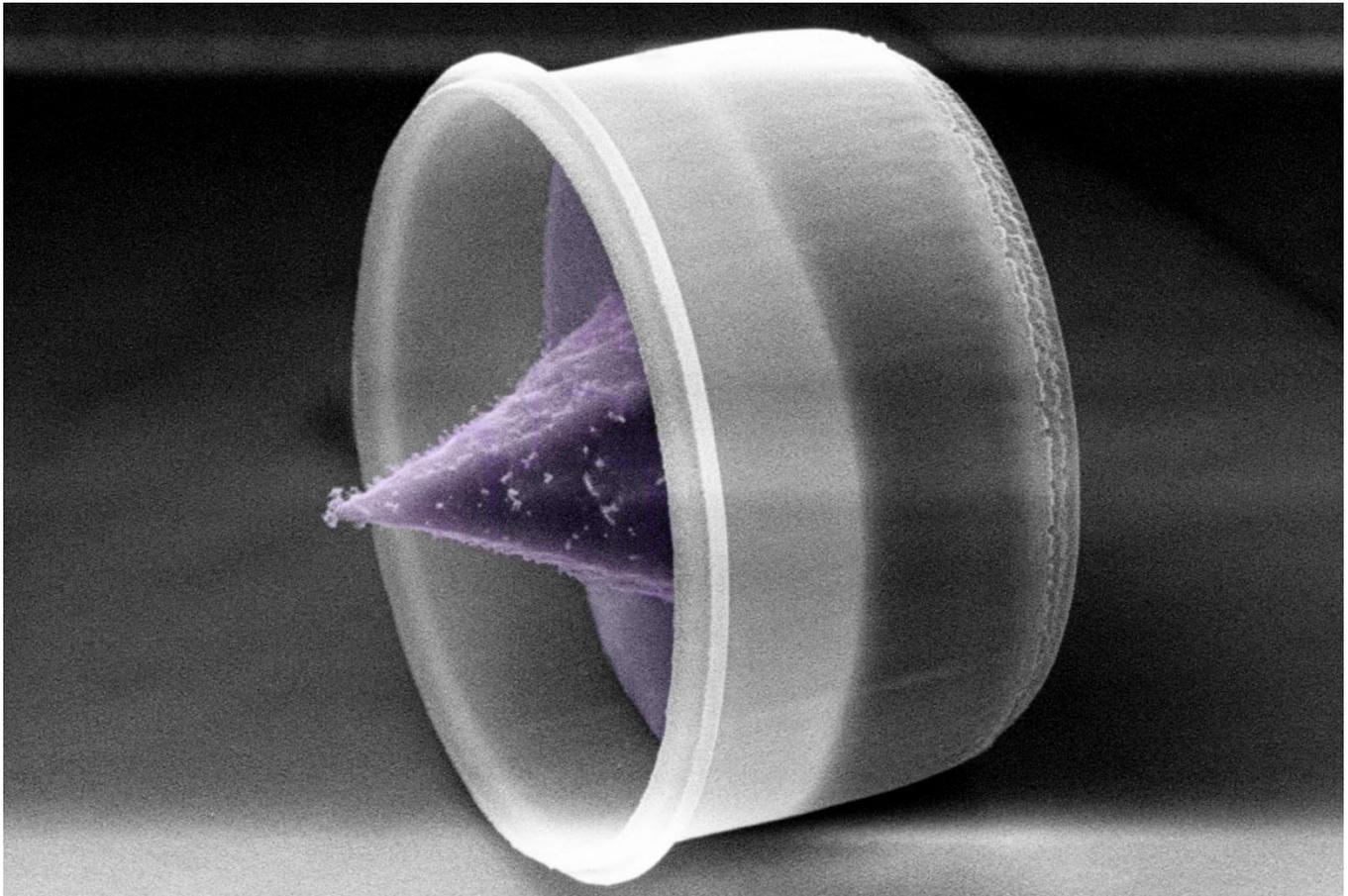
DESCRIPTION BY ARTIST:

Cross your eyes and focus on the image to reveal a hidden surprise. A stereogram is a two-dimensional image that creates the illusion of depth through binocular disparity, allowing a three-dimensional form to emerge only when viewed in a specific way. Just as in quantum systems, the noisy background suggests multiple possibilities coexisting simultaneously as we see in superposition and quantum mechanics' probabilistic nature. Yet, beneath this apparent randomness lies hidden information, highly sensitive to how it is observed. When you uncross your eyes, the image collapses, but cross them just right, and the concealed pattern emerges, capturing the true essence of quantum mechanics. Finally, the choice of a dead cat as the background and a living cat as the depth image pays homage to Schrödinger's famous thought experiment!

NANOSCALE DIAMOND MICROLINK RESONATOR

By Elham Zohari of the University of Alberta, Edmonton, Alberta.

3rd prize, Visual Arts



DESCRIPTION BY ARTIST:

This image shows nanoscale diamond microdisk resonator, a structure engineered to confine and control light for quantum technologies. While diamonds are most commonly associated with jewelry, they also possess exceptional properties at the quantum level. Embedded within the crystal lattice of this microdisk are nitrogen-vacancy (NV) centers, atomic-scale defects formed when nitrogen atoms replace carbon. These defects can store and manipulate quantum information, making diamond a platform for quantum memory applications. The microdisk is false-colored pink to reference the natural hue of pink diamonds, which arises from nitrogen-related defects in the crystal. This visual choice connects a familiar gemstone aesthetic to the same atomic features that enable quantum functionality. By highlighting this shared origin of color and information storage, the image bridges everyday intuition and advanced quantum science, inviting viewers to see diamonds not only as objects of beauty, but as engineered materials shaping the future of quantum technologies

VISUAL ARTS HONOURABLE MENTIONS

Untitled by Ruvé Staneke of the University of British Columbia

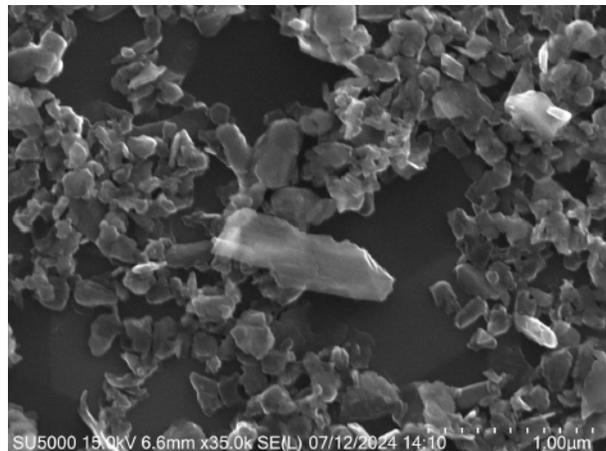


Entanglement by Amelia Alcock-White, Vancouver, BC (<https://ameliawhite.net>)



Untitled by Hansima Keppetiyyawa of Brock University

This SEM image flips into a pixelated pond party! Accumulated Titanium Carbide MXene flakes bloom into leafy aquatic plants, while a long, layered flake struts through the scene as a goldfish, surrounded by smaller companions. The untouched silicon substrate resembles crystal-clear water, unveiling a peaceful world imagined at the nanoscale. The original SEM image is shown on the right.



THE CAP-IYQ 2025 LOGO DESIGN COMPETITION / CONCOURS DE DESSIN DE L'ACP-IYQ 2025

The CAP invited all physics students in Canada to create a design for the Canada-wide celebration of the International Year of Quantum Science and Technology (IYQ) – and to compete for the prize of \$1000, and see their design on t-shirts, mugs, and more distributed across the country in 2025.

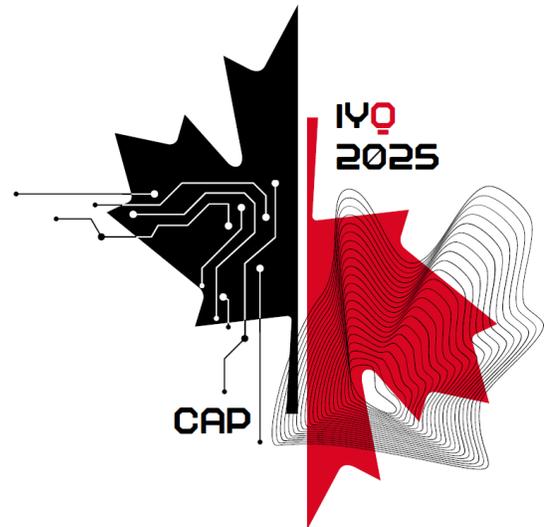
1ST PLACE WINNER CAP-IYQ 2025 LOGO DESIGN

Congratulations to the IYQ Design Competition winner – Jasmine Zhang of the University of British Columbia – whose striking design was used for pins, stickers, and buttons that have been brought to events celebrating IYQ across Canada and the world, including the UNESCO Opening Ceremony in Paris, France.

Jasmine Zhang is a first-year PhD student at the University of British Columbia working with the T2K/Hyper-K group at TRIUMF. They are honoured to have their design chosen for the CAP IYQ 2025 competition. Their design represents a superposition of quantum-driven technological advancements and the fundamental physics underlying the natural world.

The orientation of the two halves of the Canadian maple leaf is a nod to the familiar orthonormal basis for the spin-1/2 particle.

This design superimposes quantum science and the iconic Canadian maple leaf. The leaf is split into two halves, oriented oppositely to evoke the familiar orthonormal basis for the spin-1/2 particle (spin-up and spin-down). One half of the leaf is interwoven with circuit patterns, representing the technological advancements driven by quantum mechanics. The other half features a flowing waveform, symbolizing the natural phenomena and foundational principles of quantum mechanics. Together, these elements reflect the balance between innovation and the deeper understanding of the natural world fostered by quantum research.



CAP-IYQ 2025 LOGO DESIGN COMPETITION HONOURABLE MENTIONS



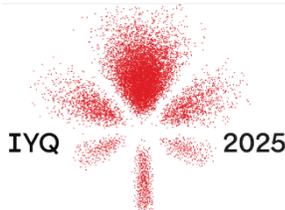
Pierre Lefloïc from the University of Sherbrooke uses their design to highlight the work Canada has contributed to the international field of quantum physics. The focus of this design in particular is on quantum information, qubits, and current research in reducing quantum errors in computing fields.



Sareen Sabra, an undergraduate at the University of Windsor, chose to do a diffraction pattern in the shape of a Canadian maple leaf as a nod to the quantum-physical nature of particles. Sareen chose to draw out the diffraction lines to highlight how the current understanding of the quantum mechanical nature of the world is still incomplete, and the future of our understanding that Canada will contribute to.



Isaac Bahler from Dalhousie University was inspired by Louis Taillefer, the first Canadian winner of the Simon Memorial Prize in 2017. Isaac nods to the lattice structure of cuprate superconducting materials, as well as the superpositional nature of particles according to quantum theory. Isaac also used the DALL-E 3 generative engine to aid in the design process, drawing inspiration from various related scientific papers.



Shane Ackerley, who holds a B.Sc. in Astrophysics from Western University, submitted this design as a versatile, minimal, and meaningful design for the International Year of Quantum in Canada. The maple leaf, an icon of Canada, is re-imagined through the lens of quantum physics. Shane made the design with Python using a custom script to plot solutions to the Schrödinger equation of a Hydrogen 4fz orbital and modified it slightly to represent the stem of the maple leaf.

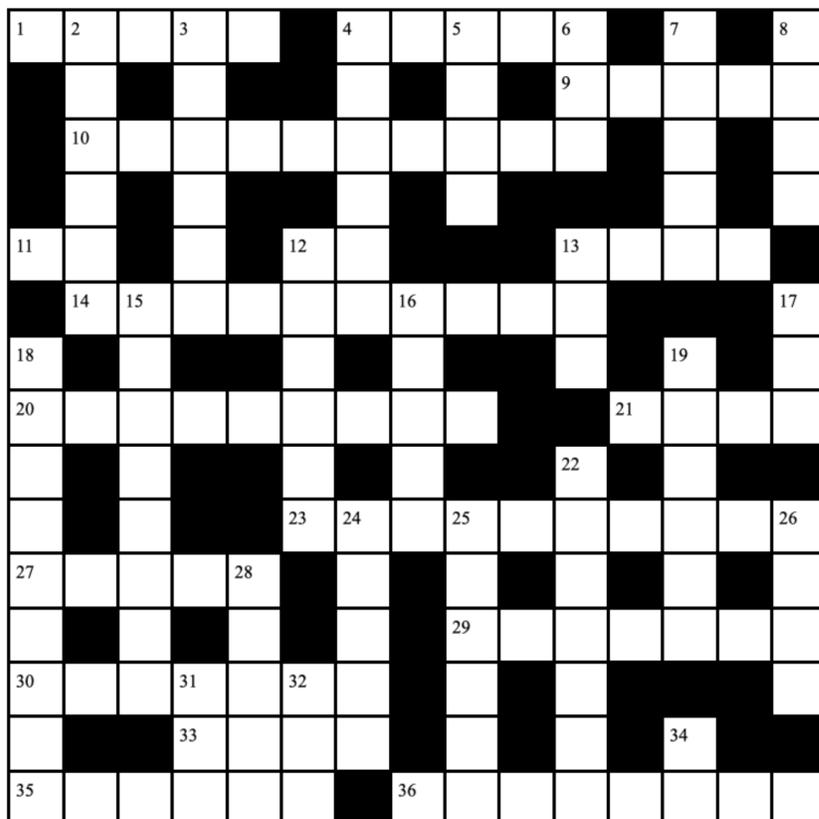


Ryan Naderi at Simon Fraser University produced a design which prominently features the Canadian Flag, as well as the classical model of an atom devised by Ernest Rutherford. Although newer and more accurate models of atomic interactions have been developed, this design outlines that it is important to understand the steps physics has made to get where we are today.

ACKNOWLEDGEMENTS

The CAP International Year of Quantum Science and Technology Task Force consisted of over 30 representatives from across Canada and was chaired by Daria Ahrensmeier (Simon Fraser University) and Oliver Stelzer (TRIUMF). For more details and a complete list of members, visit the [CAP IYQ website](#). The CAP IYQ Task Force are grateful for support from NSERC through the Special Opportunities Fund SOF-601917-2024. We are also grateful to financial support from SNOLAB, TRIUMF, the Perimeter Institute for Theoretical Physics, the Quantum Algorithms Institute, and the Institute for Quantum Computing.

Quantum Cryptic Crossword Puzzle *by Donero*



SCRIBBLE ZONE of UNCERTAINTY

ACROSS

1. Dad and I encapsulate the heads of university life in quantum pioneer (5)
4. To boast, say, of father/son laureates (5)
9. Particles are home with Georg, but missing the start of holiday (5)
10. Need for a radio confines new right-angle in quantum phenomenon (10)
11. Cher's heart is periodically in the right place (2)
12. Solemn opera openings to such a great extent (2)
13. Capri-cious? (4)
14. The type of freedom that leads, as so you might perceive, to one time in confinement (10)
20. Her first letter wrecked Legoland anniversary location (without me) (9)
21. Billy is one endless doll (4)
23. Re-use copious pieces and leave nothing in showing distrust (10)
27. Places headless mite in snake's skin (5)
29. Being in agreement takes the edge off being criticized (7)
30. Quantum pioneer sounds most supported (3,4)
33. I'm to admit holding amphibian (4)
35. In suspense: short, holy man had called... (6)
36. Hastily drawn! We hear half of Dirac's duel at the speed of light blew outhouse asunder (8)

DOWN

2. A girl's three articles (6)
3. Madness lies in final unacylization (6)
4. Dance on, extra hours, say the votes cast (6)
5. Even hair tied is dry (4)
6. Silence reflex (3)
7. Aggregate blend to a tee on hand (5)
8. Requests? Like the outskirts of Knossos? (4)
12. Magical intervals? (6)
13. Cold water is almost pleasant (3)
15. Lax seats made extra cost at checkout (5,3)
16. Sounds like nothing writes (5)
17. Pedro's photon source begins shutting off loudly (3)
18. This crams confusion into holiday (9)
19. Sit next to Hermitian conjugate (almost) (6)
22. Electricity slightly disrupted robbery - most uncomfortable! (7)
24. Overtum Ivy League school reduction to 500 (5)
25. Tiny scale for isometric exercise, say (6)
26. Also dark hides fizzy drink (4)
28. Faint from curtailed swim with nothing on (5)
31. Tops of both torn umbrellas measure energy (3)
32. Make fun of endless fury (3)
34. Dehydrogenation of water creates exclamation of surprise (2)

2026 CAP CONGRESS PROGRAM HIGHLIGHTS, JUNE 22-26 HOSTED BY UNIVERSITY OF OTTAWA AND CARLETON UNIVERSITY

All events to be held at the University of Ottawa, unless otherwise specified

(Please visit <https://www.cap.ca/congress-conference/congress2026/> for speakers' abstracts and bios and symposia details)

HERZBERG PUBLIC LECTURE



NEIL TUROK, Higgs Chair of Theoretical Physics, University of Edinburgh and Roger Penrose Distinguished Visiting Chair, Perimeter Institute for Theoretical Physics

“A Simpler Cosmology”

Monday, June 22, 2026, 20h00-21h00, Carleton University

PLENARY SPEAKERS



JOHN DONOHUE, Scientific Outreach Manager, Institute for Quantum Computing, University of Waterloo

“Quantum for Educators and Young Students”

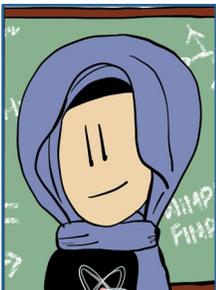
Monday, June 22, 2026, 9h00-9h45



NORMAND MOUSSEAU, Professor of Physics at the Université de Montréal, Scientific Director of the Trottier Energy Institute at Polytechnique Montreal, and co-Scientific Director of the Energy Modeling Hub.

“What can physicists contribute to the climate challenge?”

Tuesday, June 23, 2026, 9h00-9h45



SANIYA HEEBA, Institute of Particle Physics Connect Fellow, Carleton University

“The Universe as a Dark Matter Laboratory”

Thursday, June 25, 2026, 9h00-9h45

SYMPOSIA DAY WEDNESDAY JUNE 24, 2026

FUTURE PARTICLE PHYSICS ENERGY FRONTIERS FACILITIES

Researchers working on new facilities that will enable exploration of the energy frontier will discuss theory motivations, experimental developments, and accelerator technologies that enable the next generation of experiments. *Organizers: Max Swiatlowski (TRIUMF), Jesse Heilman (Carleton University), Dag Gillberg (Carleton University), Alison Lister (University of British Columbia), Thomas Koffas (Carleton University), Luise Poley (TRIUMF).*

BIG DATA IN MATTER, MATERIALS, AND BEYOND

This symposium will draw together physicists working across disciplinary borders to forge new approaches to empirical science in the 21st century. Topics to be discussed include machine learning and artificial intelligence, information geometry, big data, and applications in materials, condensed matter, biophysics, and the physics of medicine. *Organizers: Bill Atkinson (Trent University), Greg van Anders (Queen's University).*

ADVANCING QUANTUM SIMULATION BASED ON 2-DIMENSIONAL MATERIALS THROUGH CANADIAN COLLABORATION

Presenting recent advances and ongoing challenges of the Programmable Quantum Simulators Based on 2-Dimensional (2D) Materials initiative, supported by the Natural Sciences and Engineering Research Council of Canada (NSERC), this symposium aims to highlight potential industrial and academic impacts and foster new collaborations within the Canadian quantum research ecosystem. *Organizers: Adina Luican-Mayer (University of Ottawa, University of Illinois Chicago), Pawel Hawrylak (University of Ottawa), Louis Gaudreau (University of Ottawa, National Research Council Canada (NRC)), Didier Guignard (University of Ottawa).*

NOVEL IMAGING OF THE RETINA OF THE EYE

This special memorial Symposium will recognize the research and training in the area of retinal imaging and their impact on the diagnosis of eye diseases undertaken by Prof. Kostadinka Bizheva, of the Department of Physics and Astronomy, University of Waterloo. *Organizer: Melanie Campbell (University of Waterloo).*

PRIVATE SECTOR PHYSICS

Physicists interested in learning about physics career paths outside academia are encouraged to attend this interactive symposium, which will provide insights into the careers of private sector physicists and offer insights and advice into the possible pathways and training needed to transition your physics training into an engaging and rewarding career beyond academia. *Organizers: Ian D'Souza (CAP Director of Private Sector Relations), Daniel Cluff (CanMIND Associates), and Steffon Luoma (SNOLAB).*

FUSION ENERGY IN CANADA

Growth in fusion energy supports national aims in research, technological diversification, defense, and national technological sovereignty in addition to energy independence. This meeting will showcase the potential of fusion energy, identify and highlight Canadian expertise in academia, and on-going work in associated industries in Canada. *Organizers: Émile Carbone (emile.carbone@inrs.ca) and Amina Hussein (aehussein@ualberta.ca).*

Q-STATE: QUANTUM SCIENCE, TECHNOLOGY, APPLICATIONS, TRAINING, AND EDUCATION

Learn about current directions in the field and the unique Canadian quantum landscape across research, education and industry. *Organizers: Daria Ahrensmeier (Simon Fraser University) and Olivia Di Matteo (University of British Columbia).*

TRANSFORMING PHYSICS: EDIT-STEM TOOLS TO ADVANCE EQUITY, DIVERSITY, AND INCLUSION

Practical tools to support physicists in learning about how they can address challenges to equity, diversity, and inclusion (EDI) in their professional activities. *Organizers: Rowan Thomson (Carleton University), Alisha Szozda (Carleton University). Sponsored by: Carleton University, IVADO, and the Perimeter Institute.*

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FAITS SAILLANTS DU PROGRAMME DU CONGRÈS DE L'ACP 2026

ORGANISÉ PAR L'UNIVERSITÉ D'OTTAWA ET CARLETON UNIVERSITY

Tous les événements auront lieu à l'Université d'Ottawa, sauf indication contraire.

(Visiter le <https://cap.ca/fr/congres-de-lacp/congres-2026/> pour les résumés et biographies des conférenciers et détails des symposiums)

CONFÉRENCE PUBLIQUE COMMÉMORATIVE HERZBERG



NEIL TUROK, Higgs Chair of Theoretical Physics, University of Edinburgh and Roger Penrose Distinguished Visiting Chair, Perimeter Institute for Theoretical Physics

“A Simpler Cosmology”

Lundi, le 22 juin 2026 20h00-21h00, Carleton University

CONFÉRENCIERS PLÉNIERS



JOHN DONOHUE, Scientific Outreach Manager, Institute for Quantum Computing, University of Waterloo

“Quantum for Educators and Young Students”

Lundi, le 22 juin 2026, 9h00-9h45



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“The Universe as a Dark Matter Laboratory”

Jeudi, le 25 juin 2026, 9h00-9h45

JOURNÉE DES SYMPOSIUMS MERCREDI LE 24 JUIN 2026

FUTURES INSTALLATIONS EN PHYSIQUE DES PARTICULES AUX FRONTIÈRES DE L'ÉNERGIE

Les chercheurs travaillant sur de nouvelles installations qui permettront d'explorer les frontières de l'énergie discuteront des motivations théoriques, des développements expérimentaux et des technologies d'accélérateurs qui rendront possible la prochaine génération d'expériences.

Organisateurs : Max Swiatkowski (TRIUMF), Jesse Heilman (Carleton University), Dag Gillberg (Carleton University), Alison Lister (University of British Columbia), Thomas Koffas (Carleton University), Luise Poley (TRIUMF).

LES MÉGADONNÉES DANS LA MATIÈRE, LES MATÉRIAUX ET AU-DELÀ

Ce symposium réunira des physiciens travaillant au-delà des frontières disciplinaires afin de forger de nouvelles approches de la science empirique au XXI^e siècle. Parmi les thèmes abordés figureront l'apprentissage automatique et l'intelligence artificielle, la géométrie de l'information, le big data et ses applications dans les domaines des matériaux, de la matière condensée, de la biophysique et de la physique médicale. *Organisateurs : Bill Atkinson (Trent University), Greg van Anders (Queen's University).*

FAIRE PROGRESSER LA SIMULATION QUANTIQUE BASÉE SUR DES MATÉRIAUX BIDIMENSIONNELS GRÂCE À LA COLLABORATION CANADIENNE

Présentant les avancées récentes et les défis actuels de l'initiative « Simulateurs quantiques programmables basés sur des matériaux bidimensionnels (2D) », soutenue par le Conseil de recherches en sciences naturelles et en génie du Canada (CRSNG), ce symposium vise à mettre en lumière les répercussions potentielles dans les milieux industriel et universitaire et à favoriser de nouvelles collaborations au sein de l'écosystème canadien de recherche quantique. *Organisateurs : Adina Luican-Mayer (Université d'Ottawa, University of Illinois Chicago), Pawel Hawrylak (Université d'Ottawa), Louis Gaudreau (Université d'Ottawa, Conseil national de recherche du Canada (CNRC)), Didier Guignard (Université d'Ottawa).*

IMAGERIE NOVATRICE DE LA RÉTINE DE L'ŒIL

Ce symposium commémoratif spécial rendra hommage aux travaux de recherche et à la formation dans le domaine de l'imagerie rétinienne et à leur impact sur le diagnostic des maladies oculaires menés par le professeur Kostadinka Bizheva, du département de physique et d'astronomie de l'université de Waterloo. *Organisatrice : Melanie Campbell (University of Waterloo).*

LA PHYSIQUE DANS LE SECTEUR PRIVÉ

Les physiciens intéressés par les carrières dans le domaine de la physique en dehors du milieu universitaire sont invités à participer à ce symposium interactif, qui leur permettra de découvrir les carrières des physiciens du secteur privé et leur fournira des informations et des conseils sur les parcours possibles et la formation nécessaire pour transformer leur formation en physique en une

carrière passionnante et enrichissante en dehors du milieu universitaire. *Organisateurs : Ian D'Souza (CAP Director of Private Sector Relations), Daniel Cluff (CanMIND Associates), et Steffon Luoma (SNOLAB).*

L'ÉNERGIE DE FUSION AU CANADA

La croissance dans le domaine de l'énergie de fusion soutient les objectifs nationaux en matière de recherche, de diversification technologique, de défense et de souveraineté technologique nationale, en plus de l'indépendance énergétique. Cette réunion mettra en valeur le potentiel de l'énergie de fusion, identifiera et soulignera l'expertise canadienne dans le milieu universitaire et les travaux en cours dans les industries connexes au Canada. *Organisateurs : Émile Carbone (INRS) and Amina Hussein (University of Alberta).*

Q-STATE : SCIENCE, TECHNOLOGIE, APPLICATIONS, FORMATION ET ÉDUCATION QUANTIQUES

Découvrez les orientations actuelles dans ce domaine et le paysage quantique unique du Canada dans les domaines de la recherche, de l'éducation et de l'industrie. *Organisatrices : Daria Ahrensmeier (Simon Fraser University) et Olivia Di Matteo (University of British Columbia).*

TRANSFORMER LA PHYSIQUE : LES OUTILS EDIT-STIM POUR PROMOUVOIR L'ÉQUITÉ, LA DIVERSITÉ ET L'INCLUSION

Outils pratiques destinés à aider les physiciens à apprendre comment relever les défis liés à l'équité, à la diversité et à l'inclusion (EDI) dans leurs activités professionnelles (Outils se traduit Tools en anglais, ce qui explique l'acronyme EDIT). *Organisatrices : Rowan Thomson (Carleton University), Alisha Szozda (Carleton University). Commandité par : Carleton University, IVADO, et le Perimeter Institute.*



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The Canadian Association of Physicists: *A Physics Community*

l'Association canadienne des physiciens et physiciennes : La Physique, une communauté

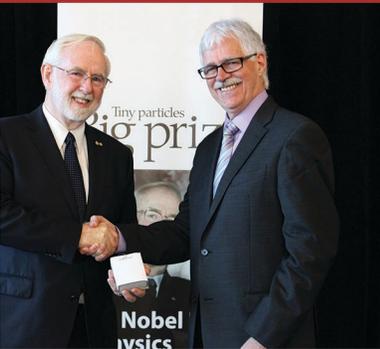


How are we a community?

Focus on Equity, Diversity & Inclusion in Physics
Annual Congress - Community Partnerships
Lecture Tours - Professional certification
Networking - Conferences - Scholarships
Awards and Medals - Science Policy and Advocacy
Resources - Read & Publish in *Physics in Canada*
Employment Board Postings - Advertising
Recognitions Program - Art of Physics
Reciprocal Agreements - Group Insurance

Comment sommes-nous une communauté ?

Priorité à l'équité, à la diversité et à l'inclusion en physique
Congrès annuel - Partenariats communautaires
Tournée de conférenciers - Certification professionnelle
Mise en réseau - Conférences - Bourses
Prix et médailles - La politique scientifique et du plaidoyer
Ressources - Lire et publier dans *La Physique au Canada*
Offres d'emploi - Publicité
Reconnaisances professionnelles - L'Art de la physique
Accords de réciprocité - Assurance collective



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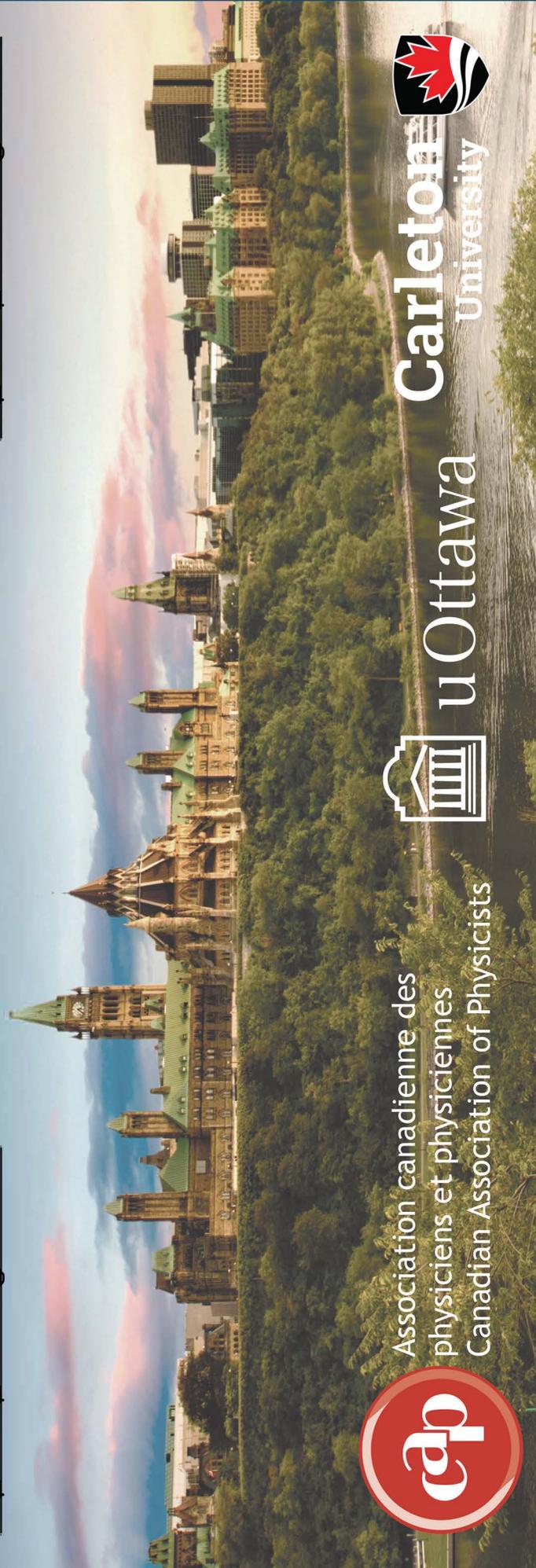
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