

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.

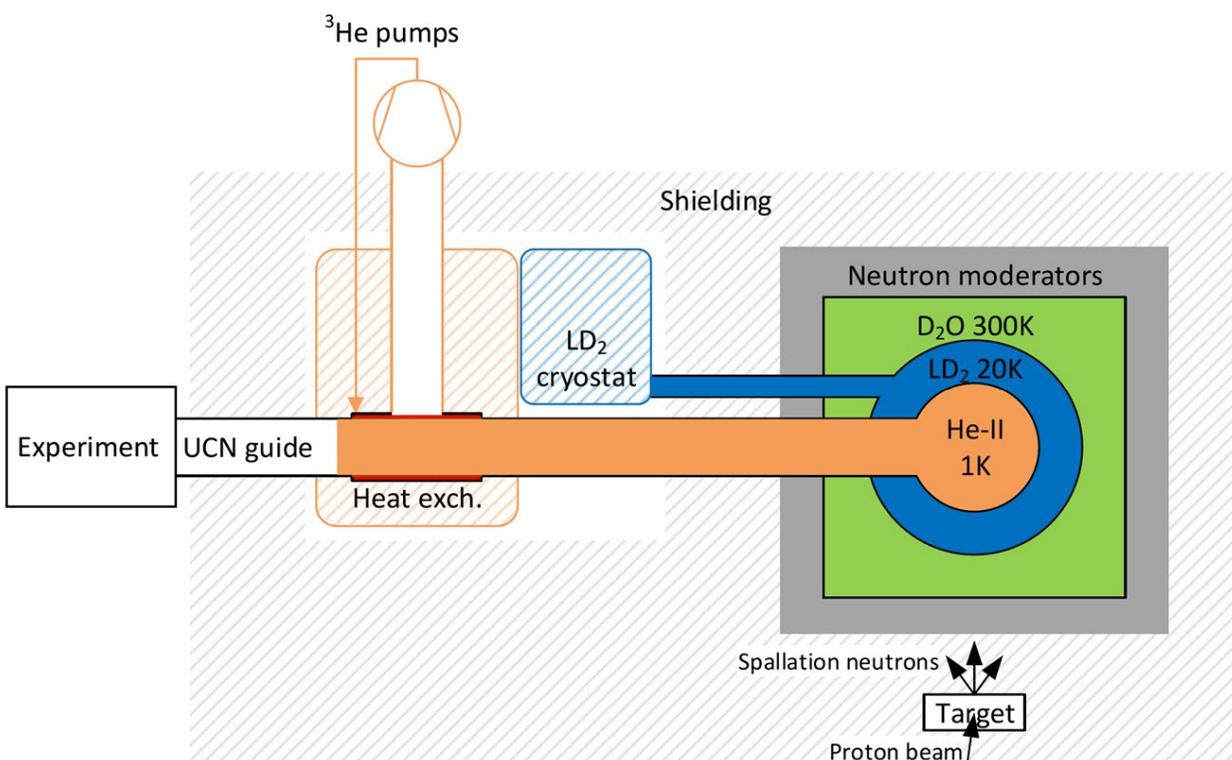


Figure 2. Schematic of the TUCAN source.

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.

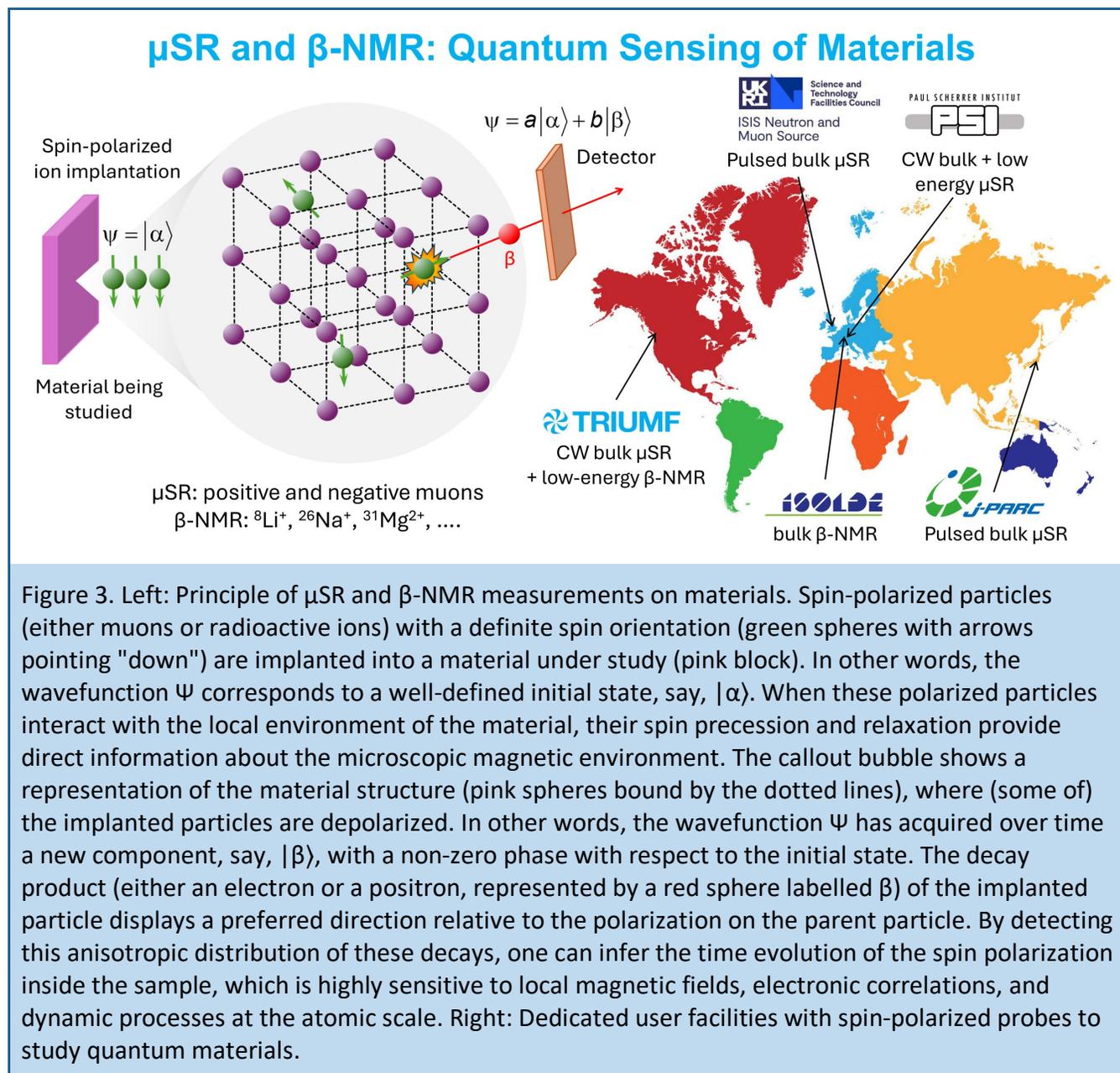
HAICU's primary goal is to magnetically trap hydrogen atoms and to cool them below the recoil limit, as to enable the creation of an atomic fountain. Several measurements can be performed in a hydrogen fountain. Extremely narrow lines can be measured using Ramsey spectroscopy. Atoms can be prepared in 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).



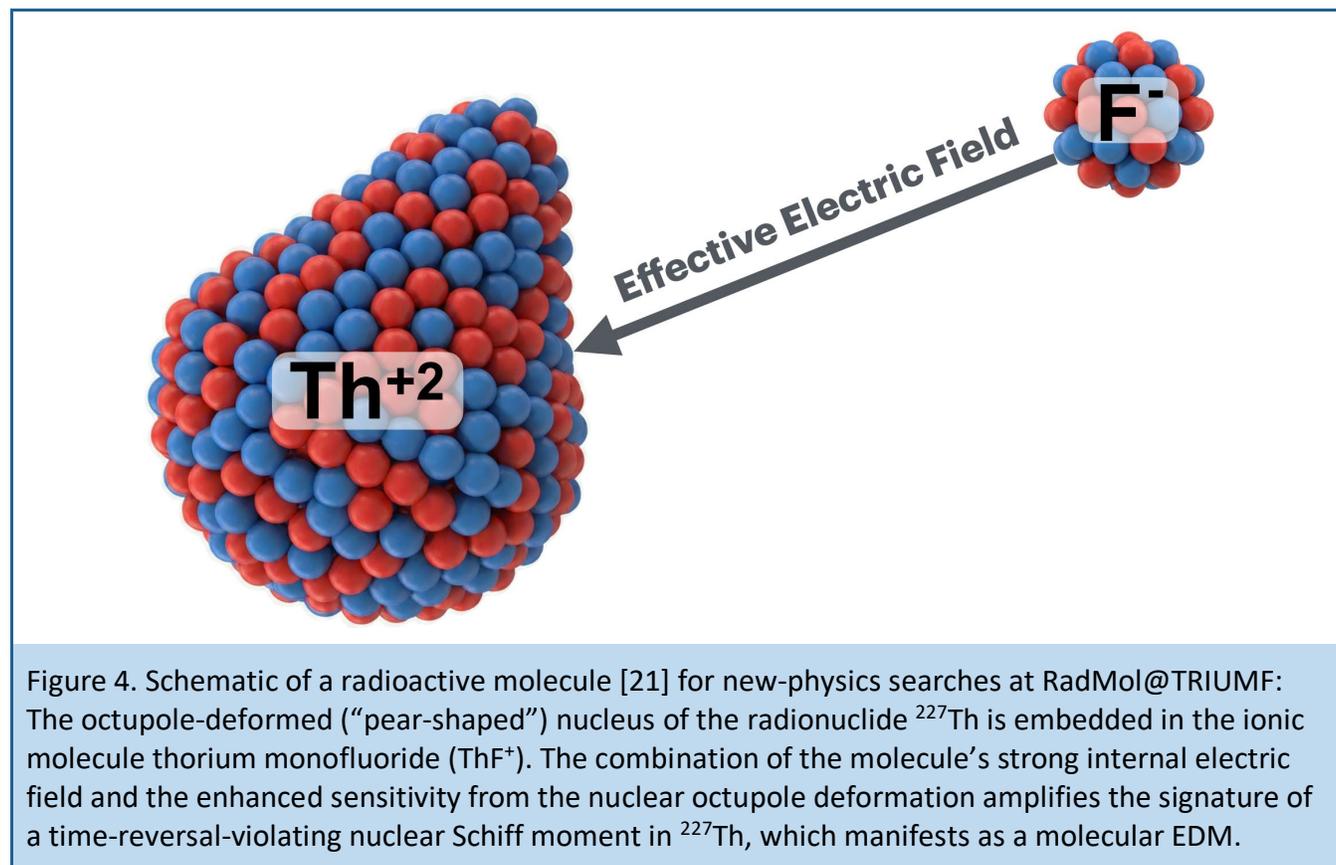
TRIUMF is one of only four μ SR facilities in the world (Fig. 3 right) and the only β -NMR facility capable of depth-resolved studies of near-surface phenomena over the range of about 2–200 nm. μ SR and β -NMR are used to study a wide range of topics in condensed matter physics and chemistry such as 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.

REFERENCES

1. TRIUMF 20-Year Vision (2022). Available online: <https://triumf.ca/wp-content/uploads/2025/01/2022-TRIUMF-20YV-Web-Vertical.pdf>
2. C. Abel *et al.*, Phys. Rev. Lett. **124**, 081803 (2020).
3. S. Sidhu, *Improving the statistical sensitivity reach of the TUCAN neutron electric dipole moment experiment* (Simon Fraser University, 2023).
4. N. F. Ramsey, Phys. Rev. **78**, 695 (1950).
5. S. Sidhu *et al.*, EPJ Web Conf. **282**, 01015 (2023).
6. W. Klassen *et al.*, Eur. Phys. J. C **84**, 110 (2024).
7. R. Akbari *et al.*, Nucl. Instrum. Methods Phys. Res., A **1072**, 170194 (2025).
8. C. J. Baker *et al.*, Nat. Phys. **21**, 1 (2025).
9. E. K. Anderson *et al.*, Nature **621**, 716 (2023).
10. A. Capra, in *APS Division of Atomic, Molecular and Optical Physics Meeting*, Y03-001 (2024).
11. K. Amer *et al.*, Phys. Rev. A **112**, 043111 (2025).
12. D. Hillier *et al.*, Nat. Rev. Methods Primers **2**, 4 (2022).
13. W. A. MacFarlane, Solid State Nucl. Magn. Reson. **68–69**, 1 (2015).
14. B. Keimer and J. E. Moore, Nat. Phys. **13**, 1045 (2017).
15. G. Fleming, I. McKenzie, and P. W. Percival, *Muon spin spectroscopy: Methods and applications in chemistry and materials science* (Wiley-VCH, 2024).
16. R. F. Garcia Ruiz *et al.*, Nature **581**, 396 (2020).
17. S. M. Udrescu *et al.*, Phys. Rev. Lett. **127**, 033001 (2021).

18. S. M. Udrescu *et al.*, *Nat. Phys.* **20**, 202 (2024).
19. M. Athanasakis-Kaklamanakis *et al.*, *Nat. Commun.* **16**, 2139 (2025).
20. G. Arrowsmith-Kron *et al.*, *Rep. Prog. Phys.* **87**, 084301 (2024).
21. Illustration in part generated using Google Gemini.
22. J. Dilling, R. Krücken, and L. Merminga, eds., *ARIEL overview* (Springer, Dordrecht, 2014), pp. 253–262.
23. V. Andreev *et al.*, *Nature* **562**, 355 (2018).
24. J. J. Hudson *et al.*, *Nature* **473**, 493 (2011).
25. T. S. Roussy *et al.*, *Science* **381**, 46 (2023).
26. J. Smolsky *et al.*, *Nature* **638**, 640 (2025).
27. ATLAS Collaboration, *ATLAS Software and Computing HL-LHC Roadmap*, CERN Report No. CERN-LHCC-2022-005, LHCC-G-182 (CERN, Geneva, 2022).
28. S. Hoque *et al.*, *Eur. Phys. J. C* **84**, 1244 (2024).
29. M. Johnson *et al.*, *Nature* **473**, 194 (2011).
30. J. Q. Toledo-Marín *et al.*, *npj Quantum Inf.* **11**, 114 (2025).
31. D. P. Kingma and M. Welling, *Auto-encoding variational Bayes*, arXiv:1312.6114 [stat.ML] (2013).
32. ATLAS Collaboration, *Comput. Softw. Big Sci.* **8**, 7 (2024).
33. W. Winci *et al.*, *Mach. Learn.: Sci. Technol.* **1**, 045028 (2020).
34. G. E. Hinton and R. R. Salakhutdinov, *Science* **313**, 504-507 (2006).
35. G. Montúfar and N. Ay, *Neural Comput.* **23**, 1306 (2011).
36. O. Di Matteo *et al.*, *Phys. Rev. A* **103**, 042405 (2021).
37. G. Gallina *et al.*, *Eur. Phys. J. C* **82**, 1125 (2022).
38. H. Lewis *et al.*, *Eur. Phys. J. C* **85**, 214 (2025).
39. K. Raymond *et al.*, *IEEE Trans. Electron Devices* **71**, 10 (2024).