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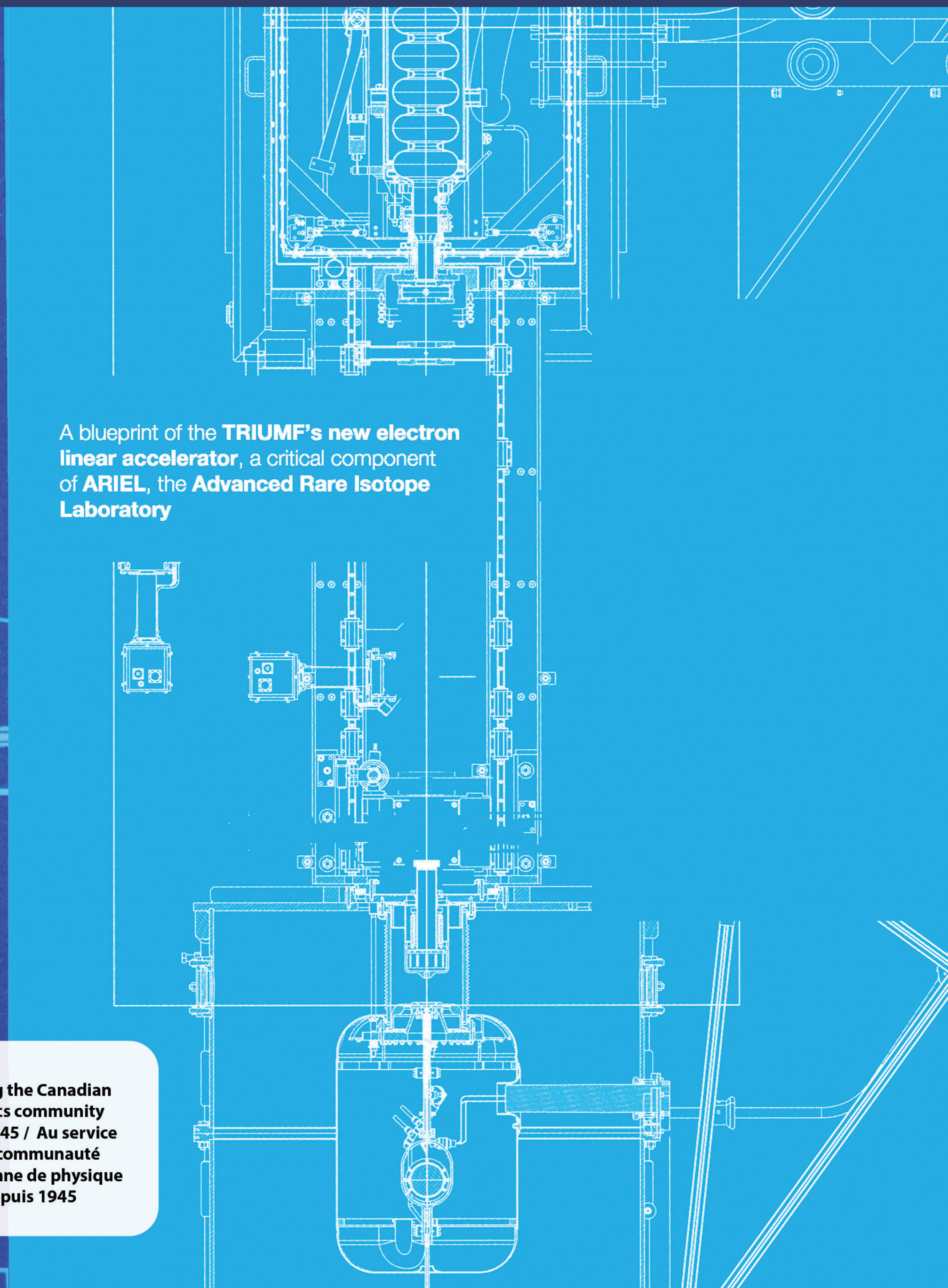
Physics in Canada
La Physique au Canada

Volume 75, No. 2
2019

THE HISTORY OF TRIUMF's FUTURE / L'HISTOIRE DE L'AVENIR DE TRIUMF

A cyanotype depiction of **TRIUMF's 520 MeV cyclotron** *(design credit: Jenny Oakley)*



A blueprint of the **TRIUMF's new electron linear accelerator**, a critical component of **ARIEL**, the **Advanced Rare Isotope Laboratory**

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Physics in Canada
La Physique au Canada

Volume 75 No. 2 (2019)

Canadian Association of Physicists
Association canadienne des physiciens et physiciennes
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Articles de fond

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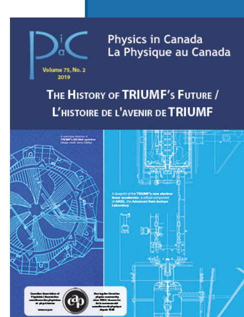

The left side of the front cover shows a reproduction of an original cyanotype depiction of the TRIUMF main cyclotron, while the right shows a blueprint of the ARIEL electron linear accelerator.

Le côté gauche de la couverture montre une reproduction d'un cyanotype original du cyclotron principal de TRIUMF, tandis que le côté droit montre un plan de l'accélérateur linéaire d'électrons ARIEL.

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PHYSICS IN CANADA LA PHYSIQUE AU CANADA

The Journal of the Canadian Association of Physicists
La revue de l'Association canadienne des physiciens et physiciennes

ISSN 0031-9147

ANNUAL SUBSCRIPTION / ABONNEMENT ANNUEL:
$46.00 Cdn + GST or HST (Cdn addresses),
$46.00 US (US addresses); $51.00 US (other/foreign addresses)

Advertising, Subscriptions, Change of Address/
Publicité, abonnement, changement d'adresse:
Canadian Association of Physicists /
Association canadienne des physiciens et physiciennes,
3rd Floor, 555 King Edward Ave. / 3e étage, ave. 555 King Edward,
Ottawa, Ontario K1N 7N6
Phone/ Tél: (613) 562-5614; Fax/Téléc. : (613) 562-5615
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Numéro de convention pour les envois de publications canadiennes : 0484202

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THE HISTORY OF TRIUMF'S FUTURE

If one thing has remained constant for TRIUMF, it has been change.

Founded in April 1968, TRIUMF was proposed to appeal to both the nuclear and the particle physicists at the founding universities. The facility's core was a wonderfully versatile cyclotron, still the physically largest of its kind, that would supply the necessary beams. Nevertheless, even before the first experiments were performed, visionaries saw the potential for this machine to facilitate experiments in material science and radioisotope physics, as well as its ability to advance developments in nuclear medicine. Thus began a virtuous cycle of development and reinvention that has defined TRIUMF to this day.

52 years later, TRIUMF is striding through middle age stronger than ever. It has grown into a multidisciplinary laboratory attracting thousands of researchers from every corner of the globe. Last year the federal government funded TRIUMF's current five-year plan (https://fiveyearplan.triumf.ca) which lays the groundwork for programs and infrastructure that readies the laboratory for decades to come. TRIUMF's future is based around the three 'pillars' of Science and Technology, People and Skills, as well as Innovation and Collaboration. The research will focus on rare isotope applications in nuclear physics, molecular and materials and the life sciences, as well on particle physics both at home and abroad, with continued development of accelerator technology, including exploitation of TRIUMF's new made-in-Canada superconducting electron linear accelerator. The future is already well underway, with the construction of the Advanced Rare Isotope Laboratory (ARIEL) and the Institute for Advanced Medical Isotopes (IAMI) both scheduled for completion in the coming years.

But how did we get here, from there? This issue is about historical developments that led up to TRIUMF's reinvention into a rare isotope and innovation facility—the history of TRIUMF's future.

It begins with the story of the birth of TRIUMF and the development of its iconic cyclotron, from conception in 1965 to the celebration of the first beam in December 1974, by Michael Craddock, who was a key figure through it all. Sadly, Michael passed away in November 2015, but his story lives on here through a slight abridgement of his 'Forty Years On' historical series written for TRIUMF newsletters.

The story moves to the fascinating history of the Centre for Molecular and Material Sciences (CMMS). Not even on the radar when TRIUMF was first proposed, its potential was envisioned even before the first beam came out of the cyclotron and has since grown to be a cornerstone of the lab's science. Many thanks to the 'keepers of the secrets' at the CMMS for helping us piece together a wonderful tale that combines the best of serendipity, perseverance, and thrift which characterized TRIUMF in its early days.

At first TRIUMF focused on nuclear physics utilizing the primary proton beam and secondary beams of pions. Very soon after commissioning, the potential was recognized for TRIUMF to develop a rare (or radioactive) isotope program with applications in medicine and physics. Small and then medium-scale efforts through the 1970s and into the 1980s grew and succeeded, ultimately leading to the ISAC (I and II) and ARIEL facilities which are now cornerstones of TRIUMF's science landscape. The history of TRIUMF's emergence as a rare isotope laboratory is here told with the help of those that created it, including the ISAC pioneer John D'Auria in his final interview with his journalist son Geoff just prior to John's death in the fall of 2017.

Part of the founding science duopoly in the early days, particle physics was, at the start, a home-grown affair, yielding impressive results in such areas as precision measurements of pion and muon decay, with parallel contributions to detector technology with construction of the world's first time-projection chamber used in an experiment. Starting in the 1980s TRIUMF's particle physics reach went global, with collaborations at HERA and Brookhaven, later starting a close association with CERN with contributions to the LHC accelerator, ATLAS detector, and Tier-1 computing, which continues to this day with contributions to the ATLAS and High Luminosity LHC upgrades. TRIUMF's history in global particle physics is here represented by Dean Karlen's article on the

Marcello Pavan <marcello@triumf.ca>, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3

history of Canada's involvement in the Japanese T2K experiment, where the lab made crucial contributions to the project, including the idea for off-axis neutrino beams discovered by a TRIUMF undergraduate student during a summer placement!

TRIUMF's life sciences (formerly nuclear medicine) program started soon after commissioning, with radioisotope production for nuclear medicine using low-energy beams from the cyclotron — a fabulous demonstration of the machine's versatility. The program always has been smaller but exceedingly important part of TRIUMF's scientific repertoire, and with the emergence of IAMI and other important initiatives, it is now a centerpiece of the lab's scientific future. The fascinating story of life science's development is told here by the program's primary architect over the decades, Tom Ruth.

This issue is rounded out by an interview with long-time TRIUMF Associate Director and Head of the Science Division, Jean-Michel Poutissou, and an article by Jenasee Mynerich on the application of strontium-119 in targeted radionuclide therapy that she wrote while an undergraduate student at TRIUMF, two articles that neatly frame TRIUMF's storied past and bright future. We hope you will find all these articles both informative and enjoyable.

Marcello M. Pavan, Ph.D.
Head, Academic and User Programs, TRIUMF
Guest Editor, *Physics in Canada*

Comments of readers on this Editorial are more than welcome.

L'histoire de l'avenir de TRIUMF

Il y a une constante chez TRIUMF, et c'est le changement.

Fondé en avril 1968, TRIUMF visait à intéresser tant les physiciens nucléaires que ceux des particules au sein des universités fondatrices. Le cœur de l'installation était un cyclotron étonnamment polyvalent, encore le plus grand en son genre, qui fournirait les faisceaux nécessaires. Néanmoins, avant même la réalisation des premières expériences, des visionnaires ont vu le potentiel de cet instrument pour faciliter les expériences en sciences des matériaux et en physique des radioisotopes, et pour faire progresser les avancées en médecine nucléaire. Ainsi, s'est amorcé le cycle efficace de développement et de réinvention qui a défini TRIUMF à ce jour.

Quelque 52 années plus tard, TRIUMF connaît un âge moyen plus fort que jamais, étant devenu un laboratoire multidisciplinaire qui attire des milliers de chercheurs de tous les coins du monde. L'an dernier, le gouvernement fédéral a financé l'actuel plan quinquennal de TRIUMF (https://fiveyearplan.triumf.ca), qui jette les bases des programmes et infrastructures préparant le laboratoire pour les décennies à venir. L'avenir de TRIUMF repose sur trois « piliers » : sciences et technologie, personnes et compétences, ainsi qu'innovation et collaboration. La recherche sera axée sur les applications d'isotopes rares en physique nucléaire, sciences des molécules, des matériaux et de la vie, et aussi sur la physique des particules tant au pays qu'à l'étranger, tout en poursuivant le développement de la technologie des accélérateurs, y compris l'exploitation du nouvel accélérateur linéaire électronique supraconducteur qui a vu le jour au Canada. L'avenir est bien amorcé par la construction du laboratoire avancé d'isotopes rares (ARIEL) et de l'Institut des isotopes médicaux avancés (IAMI), tous deux censés être achevés au cours des prochaines années.

Mais comment tout cela nous a-t-il amenés là? Il s'agit d'avancées historiques qui ont conduit TRIUMF à se devenir une installation d'isotopes rares et d'innovation—l'histoire de son avenir.

Ça commence par l'histoire de la naissance de TRIUMF et la création de son cyclotron iconique, de la conception en 1965 à la célébration du premier faisceau en décembre 1974 par Michael Craddock, figure de proue tout au long de l'aventure. Michael nous a malheureusement quittés en novembre 2015, mais son histoire perdure grâce à un abrégé de sa série historique « Forty years On » (Quarante années d'efforts) écrite pour les bulletins TRIUMF.

L'histoire se poursuit par l'ère fascinante du Centre for Molecular and Material Sciences (CMMS). Le potentiel de celui-ci, absent du radar lors de la première ébauche de TRIUMF, était envisagé avant même que le cyclotron n'émette son premier faisceau et devienne une pierre angulaire des sciences du laboratoire. Mille mercis aux « gardiens des secrets » du CMMS de nous avoir aidés à reconstituer un conte merveilleux combinant le meilleur de la sérendipité, de la persévérance et de la vigueur qui caractérisaient TRIUMF à ses débuts.

TRIUMF s'est tout d'abord concentré sur la physique nucléaire en utilisant le faisceau primaire de protons et les faisceaux secondaires de pions. Dès sa mise en service, on a reconnu que TRIUMF pourrait élaborer un programme d'isotopes rares (ou radioactifs) comportant des applications en médecine et en physique. Des entreprises à petite puis à moyenne échelle ont foisonné et connu du succès au fil des années 1970 et jusqu'en 1980, aboutissant finalement aux installations de l'ISAC (I et II) et de l'ARIEL, pierres angulaires du paysage scientifique de TRIUMF. L'histoire de l'émergence de TRIUMF à titre de laboratoire d'isotopes rares est brossée ici avec l'aide de ses créateurs, dont le pionnier de l'ISAC, John D'Auria, dans sa dernière entrevue avec son fils journaliste Geoff, juste avant la mort de John à l'automne 2017.

La physique des particules, volet du duopole scientifique fondateur au début, fut d'abord une affaire maison aux résultats impressionnants dans des domaines tels que la mesure précise de la décroissance de pions et de muons, avec des apports parallèles à la technologie des détecteurs par la construction de la première chambre de projection temporelle utilisée dans une expérience. Depuis les années 1980, la physique des particules de TRIUMF a gagné une portée mondiale grâce à des collaborations chez HERA et Brookhaven, amorçant par la suite une étroite association avec la CERN en contribuant à l'accélérateur LHC, au détecteur ATLAS et à l'informatique de niveau 1, qui se poursuit encore aujourd'hui grâce aux contributions à l'ATLAS et aux mises à niveau de haute luminosité LHC. L'histoire de TRIUMF en physique mondiale des particules est exposée ici dans l'article de Dean Karlen sur l'histoire de la participation du Canada au projet japonais T2K auquel le laboratoire a fait des apports cruciaux, y compris l'idée des faisceaux de neutrinos hors axe découverte par un étudiant de premier cycle TRIUMF lors d'un stage d'été!

Le programme des sciences de la vie (de médecine nucléaire auparavant) de TRIUMF a débuté peu après sa mise en service par la production de radioisotopes destinés à la médecine nucléaire au moyen des faisceaux à faible consommation d'énergie du cyclotron — démonstration fabuleuse de la polyvalence de l'appareil. Le programme a toujours été un volet moindre mais extrêmement important du répertoire scientifique de TRIUMF et, l'émergence de l'IAMI et d'autres initiatives importantes en fait maintenant une pièce maîtresse de l'avenir scientifique du laboratoire. L'histoire fascinante de l'essor des sciences de la vie est racontée ici par l'architecte principal du programme au fil des décennies, Tom Ruth.

Le présent numéro est complété par une entrevue de Jean-Michel Poutissou, depuis longtemps directeur associé et chef de la division sciences de TRIUMF, et par un article rédigé par Jenasee Mynerich à titre d'étudiante de premier cycle à TRIUMF sur l'application du strontium-119 au traitement isotopique ciblé, deux documents qui balisent bien les volets du passé et du brillant avenir de TRIUMF. Nous espérons que vous trouverez ces documents à la fois instructifs et agréables à lire.

Marcello M. Pavan, Ph.D.
Directeur, Programmes d'études et d'utilisateurs, TRIUMF
Rédacteur honoraire, *La Physique au Canada*

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

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

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 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 particular bienvenus. Des suggestions de sujets pour des revues à thème sont aussi bienvenues et peuvent être envoyées à bjoos@uottawa.ca.

Michael Plischke (1945-2020)

We are deeply saddened to inform you that Michael Plischke, Professor Emeritus, Department of Physics, Simon Fraser University (SFU), passed away Wednesday April 29, 2020 after an extended illness.

Michael (Mike) was born in January 1945 in Czechoslovakia; shortly after, his family moved to Würzburg, Germany. He was 9 years old when they settled in Montreal QC where he did all his schooling up to a BSc Physics from Loyola College.

He pursued graduate studies in the United States, first at Yale University, New Haven (CT) where he completed a MPhil. He then moved to Yeshiva University in New York City NY., where he completed a PhD under the supervision of Daniel Mattis, who is well known for his work on magnetism and statistical mechanics, and the author of many well-known textbooks on those subjects.

Mike graduated in 1970 at a time when there were very few openings in academia. But he hung in there, working in various short term positions from 1970 to 1976, at Yeshiva University, McGill University, University of Leuven and the University of Alberta, producing first rate work at each posting.

Mike joined SFU in January 1976 as an Assistant Professor and was quickly promoted to Associate Professor (1978) and Full Professor (1983). In his forties, he decided that he was interested in becoming Chair of the Department of Physics and eventually served two terms; from 1988-1993 and again from 1998-2003.

He went on to serve as Dean of Science from 2003 until 2010. He was valued as an insightful and effective Chair and Dean, who promoted excellence in teaching and research. As Chair, he fostered young faculty members, sharing his NSERC grant to support a joint postdoctoral fellow, or sharing lecture notes to help with teaching. As Dean, he was a strong advocate for science, he consistently promoted quality research and teaching, and he effectively mentored new Chairs.

Mike had a successful and rewarding research career as a condensed matter theorist; he published over 100 papers, and mentored many graduate students and postdoctoral fellows. In 2006, he was named a Fellow of the American Physical Society in recognition of his “seminal work on the statistical mechanics of complex systems, including alloys, random magnets, classical fluids, aggregation, random surfaces, interface growth and deposition, and vulcanization.” He co-authored with Birger Bergersen (UBC) a well-regarded advanced textbook on Equilibrium Statistical Physics that had three editions (1988, 1994, and 2006).

In the words of his colleagues - he was an insightful man of science, an amazing theorist, a great teacher, a wonderful colleague, a dedicated administrator and a close friend. He will be missed.

Barbara Frisken, *Simon Fraser University*
Béla Joós, *University of Ottawa*

In Memoriam

A BRIEF HISTORY OF THE MOLECULAR AND MATERIALS SCIENCE PROGRAM AT TRIUMF

BY MARCELLO M. PAVAN

SUMMARY

A brief history of the 45 year development of the materials science program at TRIUMF, from its serendipitous beginning in 1975 through to the Centre for Molecular and Material Science today.

THE EARLY DAYS AND SERENDIPITY

TRIUMF and the other so-called 'meson factories' of the era were planned primarily for conducting research in particle and nuclear physics. These plans were dramatically affected by the pioneering work of Ken Crowe and collaborators at Lawrence Berkeley Laboratory (LBL) demonstrating the promising capabilities of muons to probe the fundamental chemistry and physics of materials. And so TRIUMF's fortunes took an unexpected turn in 1972 when Donald Fleming, then a new Assistant Professor in the Department of Chemistry at the University of British Columbia (UBC), received a phone call from Joe Cerny, his former PhD supervisor at LBL, who had just come from a colloquium given by Crowe on the subject of 'Muonium Chemistry'. Cerny thought that might be something Fleming could get started at TRIUMF, since TRIUMF promised the world's most intense beam of continuous-wave pion beams in the world, and this type of research (later dubbed μSR for 'Muon Spin Rotation, Relaxation or Resonance') would ideally capitalize on the prolific availability of the required polarized muons arising from pion decay.[1] So, Fleming went back to LBL to meet Crowe and his group, including his graduate student, Jess Brewer. Brewer was tremendously enthusiastic, and Fleming soon became enmeshed in the μSR program underway at the (now defunct) 184" synchrocyclotron.

Serendipity struck again. On a neighboring beam line, a University of Tokyo group — Toshimitsu ('Toshi') Yamazaki, Shoji Nagamiya (later a Director of the JPARC Laboratory in Japan), Kanetada ('Ken') Nagamine, and their graduate student, Ryugo ('Ryu') Hayano — were conducting research using negative muon (μ^-) capture to probe nuclear radii. Yamazaki was a postdoctoral fellow (PDF) at LBL when Fleming was a graduate student, and they reconnected at that time.

Soon after in 1974-76, Yamazaki, Nagamime, and Hayano came to TRIUMF to participate in the commissioning of the original 'M20' μSR beam line. Hayano would later play a pivotal role developing the data acquisition system for the embryonic μSR program, and in fact submitted TRIUMF's first Ph.D. thesis on March 29, 1979. Brewer came to TRIUMF around the same time, driven by his desire to develop a world-class μSR program, and to partake in the world-class steelhead fly-fishing scene on the Cheakamus river near Squamish. He soon became faculty at the UBC Physics Department after a stint as a Killam Postdoctoral Fellow. This early complement of people — joined soon after by Fleming's first graduate student, Dave Garner, who played a very significant role in the beginning and would go on to become TRIUMF's second Ph.D. — formed the nucleus for the original μSR group at TRIUMF.

Marcello Pavan <marcello@triumf.ca>, TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3

THE M20 μSR BEAM LINE AT TRIUMF

The cyclotron designer, Reg Richardson, was TRIUMF's Director in 1974 during the machine's construction phase. The "T2" pion-production target station was being installed, with one port for pions for cancer therapy ('M8'), and one for μ^- beams ('M9') for muonic X-ray (and related) studies. Brewer urged the Director to install a port for a dedicated μSR beamline before the shielding blocks were put in. Richardson agreed. A 'President's Emergency Grant' from UBC, strongly supported by Chemistry head Charles McDowell, provided \$25,000 in funding — meagre, but enough to get a program started.

The first M20 beam line was not a budget item at TRIUMF, so it was 'home-made' using surplus magnets and power supplies from other laboratories. See Fig. 1 for a photo of its installation in 1974. Key players in constructing M20 were Ken Crowe and David Measday at UBC Physics, both helping to procure magnets and power supplies from their network of international contacts. Thanks to Measday, the first bending magnet ('Patty Jane') came from Harvard University. Crowe helped procure the subsequent string of five quadrupole magnets from the

[1] Please refer to Ref. [1] for an introduction to μSR.

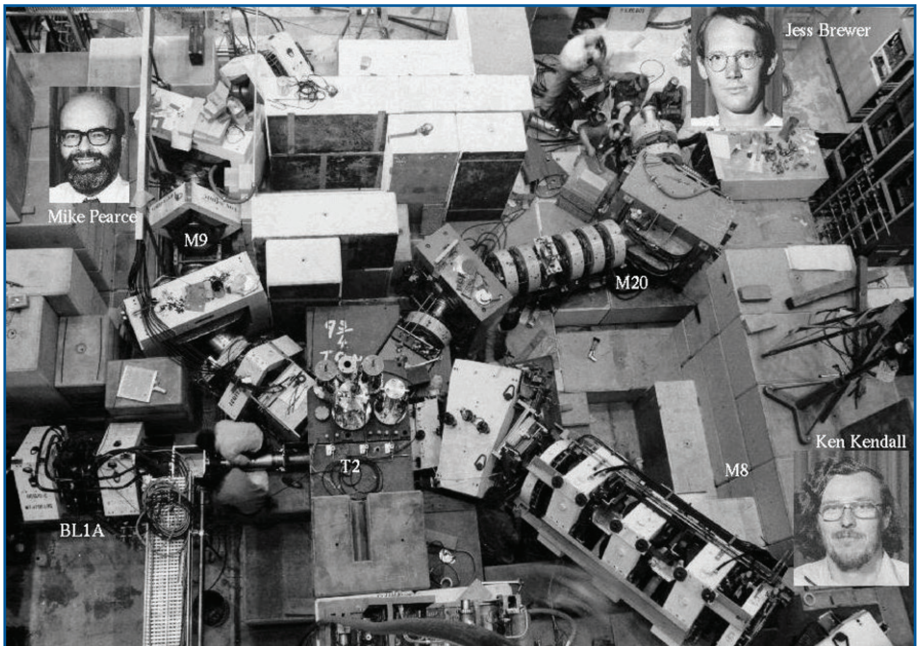

Fig. 1 Beamline 1A at the T2 production target shortly before first beam in 1974, showing its three original secondary channels (M9, M20 and M8) and photos of their respective designers: Mike Pearce, Jess Brewer, and Ken Kendall. The proton beam (BL1A) is coming from the bottom left in this photo.

probing the dynamics of quantum phase transitions, see e.g., Ref. [6].

The original M9 channel was upgraded in 1979-80 with a DC separator to remove unwanted e^+ contamination. A test with surface muons on M9 demonstrated that the particle separator could also rotate the muon spins transverse to their momenta, allowing injection into strong magnetic fields. Such a "spin rotator" was incorporated into plans for an M20 upgrade in 1983, which enabled muon spin precession measurements in high magnetic fields parallel to the muons' momenta but transverse to their spins, a big advantage essential for (e.g.) Knight shift measurements. Spin rotation with surface muons was a global first and had a game changing impact on μ^+SR worldwide.

M20 underwent a second refurbishment at the end of 2010, with major funding from the Canadian Foundation for Innovation (CFI).

University of Chicago, as well as the 2nd bending magnet, eponymously named 'Cal-Tech', followed by more 'Chicago' quads to focus the μ^+ beam.

The cyclotron proton beam was first extracted on December 15, 1974 (see article by Michael Craddock, this issue). The μSR era at TRIUMF was born just 7 months later on July 11, 1975, when the first μ^+ beam was delivered from the M20 channel (see Fig. 2). In those early days the M20 channel was tuned for 'forward muons', where the μ^+ produced from pion decay is emitted in the same direction as the pion momentum. The muon flux was minimal at first, gradually increasing with development of the cyclotron proton beam current, but nonetheless sufficient to initiate a robust molecular and materials science program (see e.g., Ref [2]).

The first published papers from M20 were in the field of magnetism, exemplified by Nishida *et al.* in Ref. [3]. Soon the first muonium chemistry papers began to appear, such as Ref. [4]. Muonium chemistry in low pressure gases was greatly facilitated by low energy "surface muons" (from pion decay at rest in the skin of the production target) — while these were observed initially on the M8 medical pion beamline, their widespread use at TRIUMF in μ^+SR had to wait for the M20 channel. It was during this early period that arguably the most influential paper in μSR (to this day) was produced by the Japanese collaboration of Hayano *et al.* [5] using M20, which established the zero-field μ^+SR technique which is to date a bulwark of μSR, e.g., in

The new design features a fast electrostatic kicker which can deliver a muon to one of two final legs independently (so-called "muons on demand" MOD), or deliver continuous beam to each leg simultaneously. Work was largely completed in August 2012, though kicker procurement issues have delayed implementation of the MOD capability. When commissioned, MOD will allow low-background μ^+SR measurements on M20 out to many muon lifetimes — conferring to the heretofore continuous wave-only beamline a capability now enjoyed mainly by pulsed muon facilities.

Over the years, M20 has witnessed a multitude of groundbreaking experiments. Of particular relevance (beyond zero-field μSR) is an entirely new μSR experimental technique, called "Avoided Level Crossing Resonance" [7], whose muonium analog has become the mainstay of μSR's applicability in the chemistry of radicals.

THE BEAM LINE THAT CLIMBS THE WALL: M15

The 'T1' target station on BL1A upstream from T2 initially had two beam ports: 'M11' for studies in pion physics; and 'M13' for studies using both pion and muon beams. M13 was suitable for some μ^+SR experiments, but had an appreciable e^+ contamination, making it less popular than M20. For some years M13 was used for numerous short trial μ^+SR experiments, many of which led to new programs of research. Meanwhile, more and

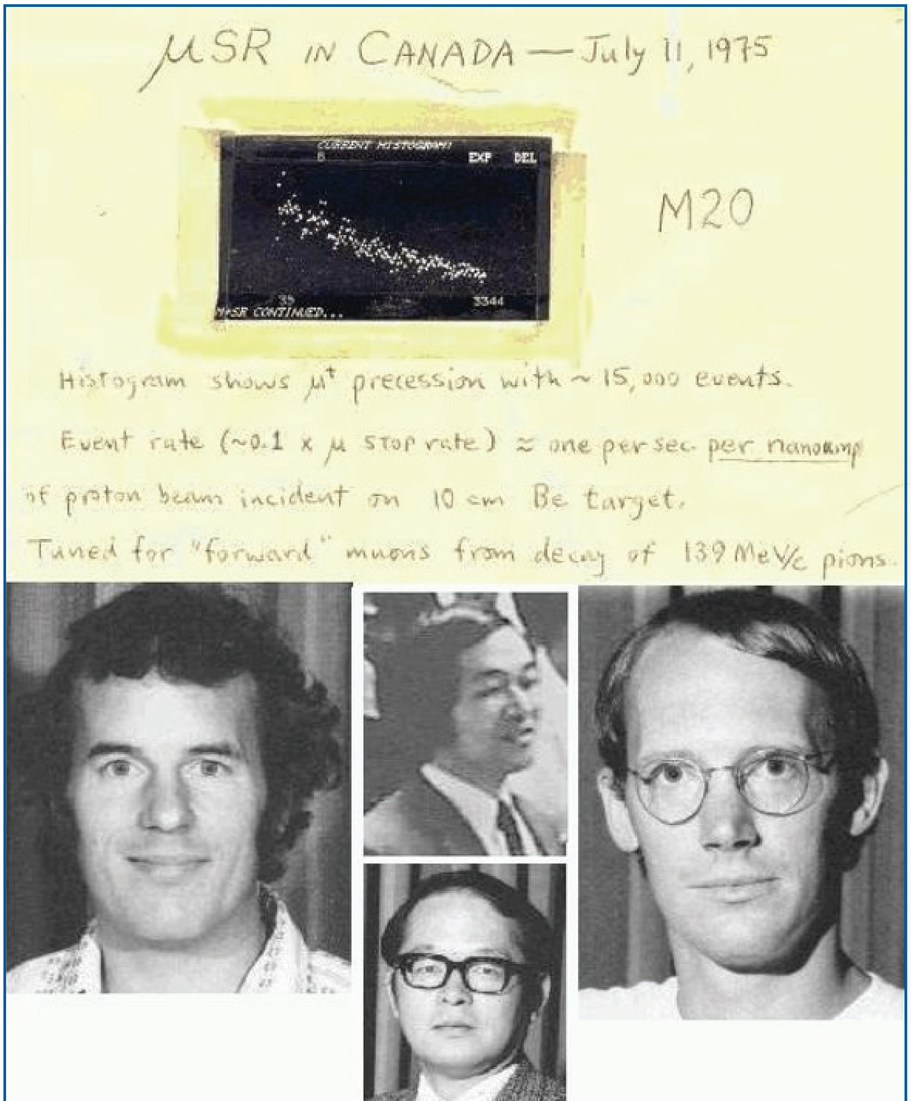

Fig. 2 Top: The first μ^+SR spectrum in Canada. Bottom: Key people in the realization of this achievement: Left: Don Fleming. Right: Jess Brewer. Middle, top: Toshi Yamazaki. Middle, bottom: Ken Nagamine.

more users from Canada and abroad began asking for spin-rotated surface muon beams on M20, which made it apparent that another such beam line was needed at TRIUMF.

Meanwhile, UBC physics Professor John Warren's group was anxious to search for spontaneous conversion of muonium (μ^+e^-) to antimuonium (μ^-e^+), and so (then Director) Erich Vogt ordered construction of the world's best dedicated surface μ^+ beamline. There was insufficient real estate to accommodate a new beamline and experimental area on the floor of the Meson Hall, hence the new beamline (dubbed 'M15') had to go vertical (as shown in Fig. 3) and then south to a new purpose-built experimental area, two stories above. Warren's experiment [8] was the first to use M15, but the channel has since been used mainly as a μ^+SR facility.

THE M9 DECAY-MUON CHANNEL

Though surface μ^+ beams are most in demand from the μSR community at TRIUMF, an initial kinetic energy of only 4.1 MeV limits their usefulness in probing dense materials. Forward muon beams are too energetic and have high e^+ contamination; consequently, 'backward muons' (where the muon is emitted opposite to the pion momentum) with momenta typically 70-90 MeV/c remain essential for many experiments. Backward muons were also provided by the M20 channel, but more capacity was desired, particularly μ^- beams for muon-catalyzed fusion studies.

Due to a strong commitment from the U. of Tokyo, who provided a superconducting solenoid with additional beam line components, a second "B" leg to the original M9 beam line was installed and became operational in 1988. It was commissioned by two founding fathers of μSR at TRIUMF, Ken Nagamine and Toshi Yamazaki, for their program of muon-catalyzed fusion studies (see e.g., Ref. [9]). The M9B leg would deliver backward muons from 40 MeV/c to 100 MeV/c, facilitating measurements on high-pressure solids, liquids and even gases in thick-walled vessels. An official dedication for the M9B beamline was held in 1989 (see Fig. 4).

The backward $\mu^\pm$ beams of M9B were first used for liquid-phase muonium chemistry experiments [10] and solid state samples in high-pressure cells [11], where surface muons could not penetrate the target containers.

After a serendipitous magnet coil failure, it was discovered that M9B could be tuned to produce transversely-polarized $\mu^\pm$ beams by extracting them off-centre as they exited the solenoid, thus approximating the important advantages of (μ^+ only) spin-rotated surface muon beams. In a landmark experiment this capability was used to make high precision measurements of

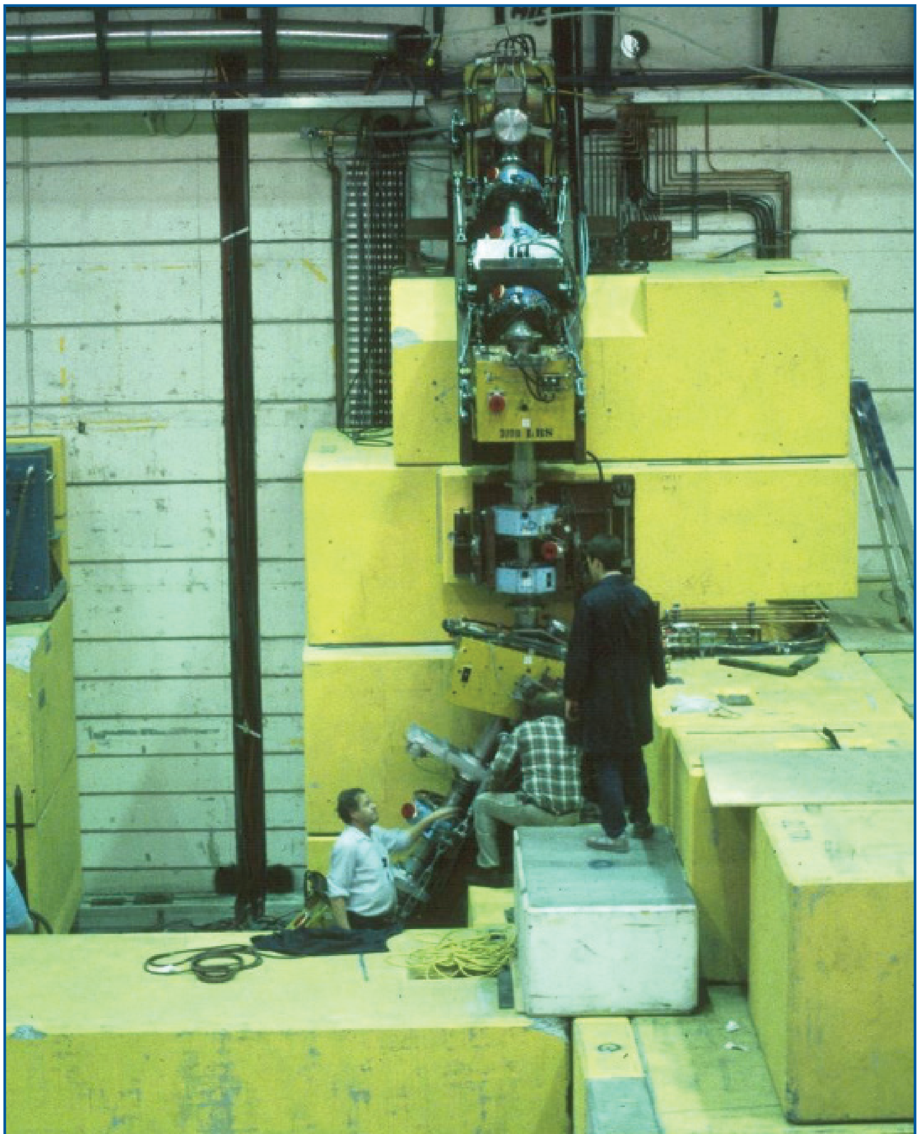

Fig. 3 The vertical section of the M15 surface muon channel, installed and commissioned in 1984. At the top, M15 turns 90 degrees to pass horizontally through the wall and into the M15 Hall, which houses its dual DC Separators and a quadrupole triplet field lens for the world's only achromatic spin rotator.

relativistic shifts in muonic atoms, which illustrated the fact that the μ^- wave function is essentially completely inside the nucleus for nuclei heavier than tin [12].

Most recently the negative muons from M9B were used to make the first measurement [13] of the chemical reaction rate of the heaviest isotope of the H atom, muonic helium (He++ $\mu^- e^-$), with a mass 4.1 times that of hydrogen, in a gas target at 500 bar pressure.

Eventually, age caught up with M9B's original infrastructure and it became impractical to operate and maintain. However, given M9B's worldly unique capability to produce a spin-rotated decay beam, the beamline's loss could not be long tolerated. In 2012, Simon Fraser University (SFU) Professor Paul Percival penned a letter (signed by 54 other molecular and materials scientists from around the world) making the case for the important and varied scientific program at M9B. This led to a CFI Innovation Fund proposal submitted by SFU Professor Jeff Sonier in 2016, which was eventually funded and dubbed 'M9H'. As of 2020 this project is actively underway and will eventually provide transversely spin polarized $\mu^\pm$ beams into a variety of extreme physics and chemistry environments, supporting a broad program in quantum materials, green chemistry, energy storage devices, and even potentially, archaeological materials characterization.

HIGH TC SUPERCONDUCTIVITY AND OTHER RESEARCH HIGHLIGHTS

Without question the emergence of the field of high temperature superconductivity (HTSC) brought the TRIUMF μ^+SR program to the next level of prominence. In 1986, Bednorz & Muller discovered that Sr-doped lanthanum cuprate could be superconducting at the highest temperatures then recorded. By January 1987 a sample was brought to TRIUMF by Gabe Aeppli of Bell Labs to be measured with μ^+SR (see Ref. [14]). Within a few months the even higher-*Tc* "YBCO" superconductor ($YBa_2Cu_3O_{7-\delta}$) was discovered and samples from various groups around the world were brought to TRIUMF for testing with μ^+SR, which had unique capabilities ideally suited for these materials.

Over the next several decades a huge variety of new HTSC materials passed through TRIUMF's μ^+SR facilities, partly as a result of the establishment of a Superconductivity Program (later renamed "Quantum Materials") in the Canadian Institute for Advanced Research in 1987-8. From the outset the μ^+SR technique was paired with microwave and other techniques at UBC, where the group of Hardy,

Fig. 4 (from right) Japanese Prime Minister Toshiki Kaifu, (then) TRIUMF Director Erich Vogt (red tie), BC Premier Bill van der Zalm, and BC Minister Stan Hagen, at the official M9B beamline dedication in 1989.

Bonn, and Liang eventually developed the world's most perfect single crystals of YBCO, after an initial sample prepared for a UBC Physics Open House display. This led to the demonstration [15] of the *d*-wave character of the superconductivity in YBCO, a breakthrough contribution to the field. To this day HTSC is one of the bread-and-butter staples of TRIUMF's μ^{+}SR program.

TRIUMF'S *β* -NMR PROGRAM

In the early 1990s TRIUMF was in friendly competition with other μSR facilities around the globe, in particular the Paul Scherrer Institute (PSI) in Switzerland. PSI's very high intensity proton cyclotron enabled the practical realization of very low energy (LE) muons, the proof-of-principle having first been demonstrated at TRIUMF [16]. The LE muon flux at TRIUMF was far too low to compete, so a different approach to probing thin films and surfaces was needed. In 1995, (then) TRIUMF Director Alan Astbury approached UBC Physics Professor Robert Kiefl about the potential for a materials science program at the radioisotope production facility, ISAC, that was being proposed at the time (see ISAC History article, this issue). Discussions in the fall of 1995 led to the idea of using an ISAC-produced polarized ^{8}Li isotope beam coupled with beta-detected nuclear magnetic resonance (βNMR) to realize a new probe of materials on the nano-scale. βNMR was well established — e.g., for characterizing states of impurity atoms implanted in bulk materials — but applications in materials research had languished due to the lack of dedicated infrastructure. Like the muon, ^{8}Li nuclei decay asymmetrically, so the nuclear spin can be monitored via the anisotropy of the decay products. Unlike muons, which are created fully polarized as a consequence of pion decay, the ^{8}Li must be polarized by in-flight laser excitation, which was the most challenging part of the βNMR installation, ably realized under the leadership of TRIUMF's polarized beam expert Phil Levy. The combination of a large nuclear spin polarization, shallow depth, and signal detection via nuclear decay would enable NMR experiments complementary to LE μSR. In December 1995 the TRIUMF Experiments Evaluation Committee agreed with the argument for such a facility, so in 1996 Kiefl and others investigated ^{8}Li-βNMR's potential, finding applications in a variety of areas, including the nature of magnetism in thin films, multilayer structures, and interfaces where conventional NMR would be unable to obtain a signal from such tiny amounts of material.

The "Workshop on Experiments and Equipment at Isotope Separators", held in Harrison Hot Springs, B.C. in April 1997 with presentations from several leading European βNMR experts marked the transition of this concept into reality. The promise built momentum in the community and spurred a dedicated effort to quickly realize the new facility. Several key aspects differed from all previous implementations of βNMR — in particular, drawing on the model of the μSr facility at TRIUMF, it was envisioned as a permanent user facility expected to provide a new capability to a wide community of researchers on an ongoing basis.

In 1997, designs were initiated by Kiefl and a newly-hired post-doc, Gerald Morris, and the first βNMR experiments were approved. Construction began in early 1999 and by May 2000 the first experiment with polarized beam was performed — with a ^{8}Li beam rate of just 10^{7}/sec, a huge resonance with a 50:1 signal-to-noise ratio was seen after a single 1-second pulse of beam! This made it clear that βNMR could accumulate high-quality data as quickly and efficiently as its more established μSR big brother and fill the LE μSR niche that TRIUMF was missing. The facility (Fig. 5) was commissioned in 2001 and during that year resonance and spin relaxation measurements on thin metallic films and

Fig. 5 UBC Professor Rob Kiefl in the cage of the ^{8}Li-βNMR facility he helped conceive.

insulators were performed, and the ^{8}Li-βNMR program was off and running.

Subsequent facility improvements included a second spectrometer for beta-detected nuclear quadrupole resonance βNQR in zero magnetic field and low field βNMR was commissioned in 2003, with the high voltage systems for variable implantation energy added later in 2007.

Two of the earliest applications of βNMR studying metals and insulating perovskite oxides (related to the cuprate high Tc superconductors) remain some of the most important and clearly illustrate the unique power of the technique. In the first, the Tesla-range magnetic field available for the first time in a βNMR experiment allowed the first reliable measurements of the Knight shift, a resonance shift in metals due to the weak polarization of the conduction electron spins. Remarkably, the "Korringa" relaxation of the initially highly-polarized spin towards thermal equilibrium could also be measured in metals, which, in combination with the Knight shift, offered all the power of conventional NMR in metals, but now in thin films and as a function of depth [17]. In contrast, the muon lifetime is so short that this type of relaxation is almost never observable. This clearly demonstrated that ^{8}Li, as a probe of solids, was not simply a heavier version of the muon, but a complementary modality sensitive to different phenomena by virtue of its million times longer lifetime.

The ^{8}Li nucleus is spin-2, enabling a coupling between the ^{8}Li nuclear spin and the gradient of the electric field at the ^{8}Li site. The resulting splitting provides a useful fingerprint of the specifc crystallographic site of the ^{8}Li when its symmetry is lower than cubic. In contrast, the muon is spin 1/2, a pure magnetic probe which doesn't feel this interaction at all. The quadrupole splitting in $SrTiO_3$ was by far the largest seen using ^{8}Li, enabling a number of novel investigations, including a study of magnetism in mutlilayer structures of $SrTiO_3$ with $LaAlO_3$ [18]. Remarkably, the interfaces of these two *nonmagnetic insulators* exhibits both *superconductivity* and a form of weak magnetism!

THE TRIUMF CENTRE FOR MOLECULAR AND MATERIAL SCIENCES (CMMS)

Prior to 1990, the μSR facilities at TRIUMF were not oriented towards being true 'user facilities', even though they were developing future Canadian leaders in material science (e.g., Rob Kiefl at UBC and Graeme Luke at McMaster). But demand from visitors was increasing, prompting a new operational model. So in 1990, thanks to generous support from NSERC, TRIUMF, UBC, and SFU, the TRIUMF μSR User Facility was created to provide the most productive environment possible for visitors doing μSR at TRIUMF. The change had the desired effect of attracting many new users from across the globe, and gaining new prominence at TRIUMF, where it assumed a more significant role in the development of the lab's 2005 Five-Year Plan, specifically the intent to build a new (3rd) surface muon beamline in M9A.

The program's ambitions were growing with its prominence. After years of being dispersed around TRIUMF, the program finally gained a 'home' in 2002 when the former 'Batho' biomedical facility was turned into laboratory and office space for local facility scientists, grad students, and post-docs, as well as national and international visitors. The emergence of the βNMR program necessitated a name change, so in 2003 the "Centre for Molecular and Materials Science" (CMMS) was born. This was coincident with a major CFI application that led to a drastically enhanced infrastructure, including the two new surface muon beamlines, M20 and M9A, described above. The CMMS provided the umbrella for an improved organizational structure in concert with TRIUMF Management for both μSR and βNMR science that led to even further growth, culminating most recently in the M9H CFI project. A critical measure of TRIUMF's support was its response to the ongoing world-wide helium supply crisis, which threatened the life-liquid of the CMMS. In 2013 a dedicated liquefier was purchased and commissioned, thereby rescuing the CMMS and its Ultra Cold Neutron experimental neighbour from oblivion.

Today, the CMMS at TRIUMF is composed of a dedicated and experienced group of seven permanent scientists (all experts in specific aspects of the art of μSR/βNMR) and three technicians. The scientists are variously involved in managing the day-to-day operations of the Centre in parallel with a renewed emphasis in engaging their own and/or collaborative research initiatives. As such, these efforts support a wide range of visiting scientists (including 5 CAP prize winners [19]) from practically everywhere in the world. About 100 peer-reviewed research papers are published each year in such diverse areas as atomic, molecular and chemical physics, reaction rate and free-radical chemistry, condensed matter physics, and nanoparticle science, with a small but important number of applied science efforts for industry thrown into the mix. With the deployment of the full capabilities of the M20, M9A, M9H and a significant increase of βNMR beam availability all on the horizon, the CMMS is looking forward to a long and ever more prosperous future.

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HISTORY OF TRIUMF'S TRANSFORMATION INTO A RARE ISOTOPE LABORATORY

BY MARCELLO M. PAVAN

Marcello Pavan
<marcello@triumf.ca>,
TRIUMF, 4004
Wesbrook Mall,
Vancouver,
BC V6T 2A3

SUMMARY

A brief account of the people and events that led TRIUMF's transformation from a meson factory into a rare isotope laboratory.

For over 50 years, the TRIUMF cyclotron has spurred the growth of a diverse and multidisciplinary community whose ideas continue to coax new uses from the decades-old accelerator. These new applications served to continuously redefine TRIUMF as a laboratory, from its roots in the 1970s as a nuclear and low-energy particle physics lab utilizing mesons and protons, to a more multidisciplinary laboratory in the 1980s by adding molecular and material science with muons and then life sciences with radioisotopes. At each stage the inherent flexibility of the cyclotron's design and the management philosophy has allowed TRIUMF to overcome challenges and exploit new opportunities as they arose. Today, TRIUMF has transformed into a world-leading rare isotope factory utilizing a unique suite of particle accelerators to create isotopes for science, medicine, and business.

TRIUMF's transformation into a rare-isotope facility began soon after the cyclotron turned on in the early 1970s, though it was nowhere near apparent at the time. In those days there were a number of ISOL (**I**sotope **S**eparator **O**n-**L**ine) facilities in the world, including the ISOLDE facility at CERN in Geneva. ISOL is a method to create beams of rare isotopes: a solid target is bombarded with a driver beam (protons, neutrons, etc.), which creates an array of rare isotopes through fission, spallation, or fragmentation that escape the very hot target through diffusion and effusion for later ionization and mass separation. In 1975-76, SFU professor John D'Auria went on sabbatical to ISOLDE, where he became interested in the ISOL technology and its potential at TRIUMF. John brought his trademark enthusiasm back to TRIUMF and began a two-decade long campaign to realize an ISOL facility at the lab. The concept was met favourably at TRIUMF and ultimately a small group generated a proposal in the late 1970s for a facility similar to that at ISOLDE. But with TRIUMF in full swing exploiting the nuclear and particle physics capabilities of the lab, this was viewed as a niche project and placed on the back burner.

But by the 1980s, the TRIUMF research community was looking for new opportunities. Planning had begun on the much more ambitious KAON project, which would have seen the cyclotron become the injector for a new 30 GeV synchrotron complex. This was a huge effort led by then TRIUMF Director Erich Vogt as the project soaked up most of the resources at the lab throughout the 80s. Nevertheless, with support from the TRIUMF Cyclotron and Experimental Facilities Divisions, led by Gerardo Dutto and Ewart Blackmore, respectively, a small group with modest funding and much resourcefulness continued work on an ISOL proposal, which included rare isotope post-acceleration, a unique proposition for the time. TRIUMF's transformation into a premiere radioactive isotope beam facility can be traced to a pivotal workshop in Mont Gabriel, Quebec in June 1984. Workshop participants concluded that there was a strong scientific case for a next-generation ISOL facility at TRIUMF and recommended construction of a test facility (**T**RIUMF **ISOL** or TISOL). A second workshop at Parksville, British Columbia in September 1985 focused on nuclear astrophysics applications using rare isotope beams. This led to an internal report for an ISAC (**I**sotope **S**eparation and **Ac**celeration) facility, coupling an ISOL target with post-acceleration in the proton hall at TRIUMF.

These background efforts led to a proposal before the TRIUMF Board of Management in 1985 which recommended post-accelerated rare isotope beams (RIB's) up to energies <1.5 MeV/A (see Fig. 1) to induce nuclear reactions for nuclear astrophysics experiments, as well as standard experimental stations for stopped rare isotope beam studies. The TISOL test facility went ahead quickly after TRIUMF approval. It was built at the end of the BL4A proton beam line (see Fig. 2) over a five-year period by a very creative and experienced group of scientists and engineers, largely using equipment repurposed from other laboratories and TRIUMF experiments. At TISOL, targets were irradiated with a 1 μA 200-500 MeV proton beam, producing a wide range of short-lived (milliseconds to seconds) rare isotopes. TISOL became operational in 1986 and ran until 1999. It was originally envisioned to be a low-power test area to gain R&D and operational experience for a more complete ISAC facility, but with target and ion source advancements, a science program

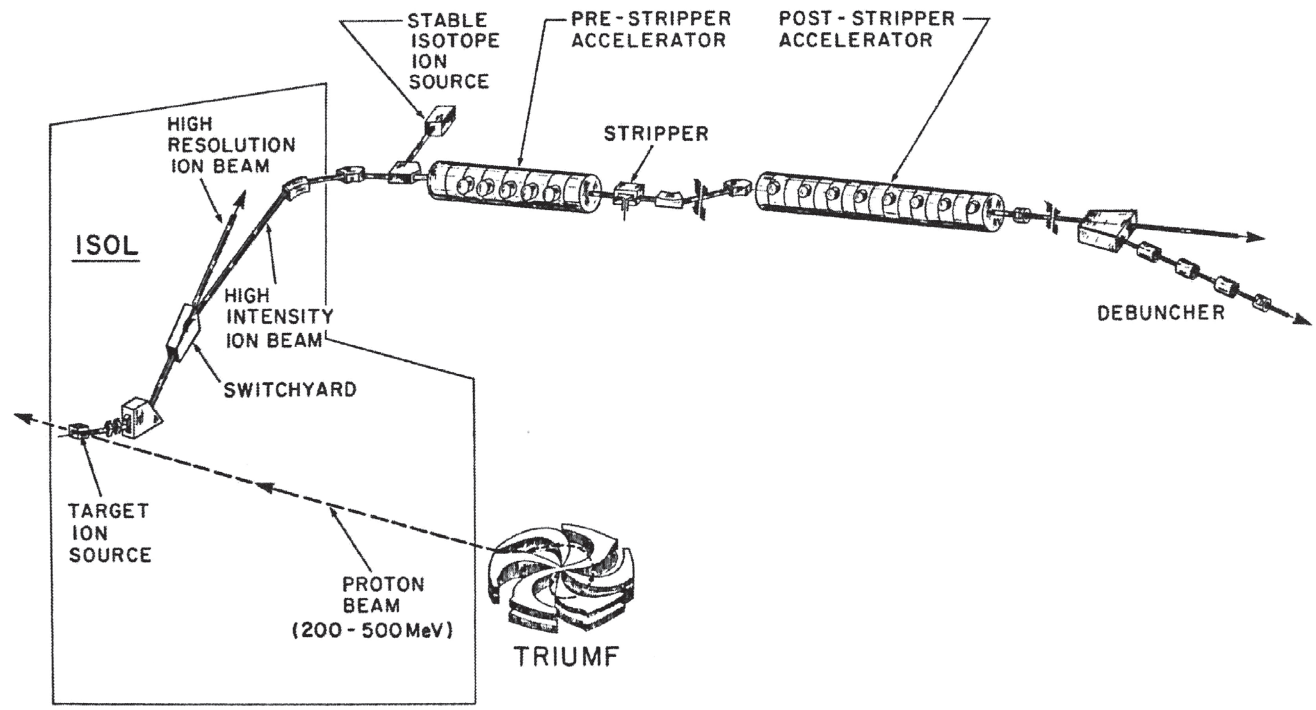


Fig. 1 From the 1985 Annual report, an early conceptual design for a TRIUMF-ISOL facility in the TRIUMF Proton Hall west of the main cyclotron, a decade before ISAC.

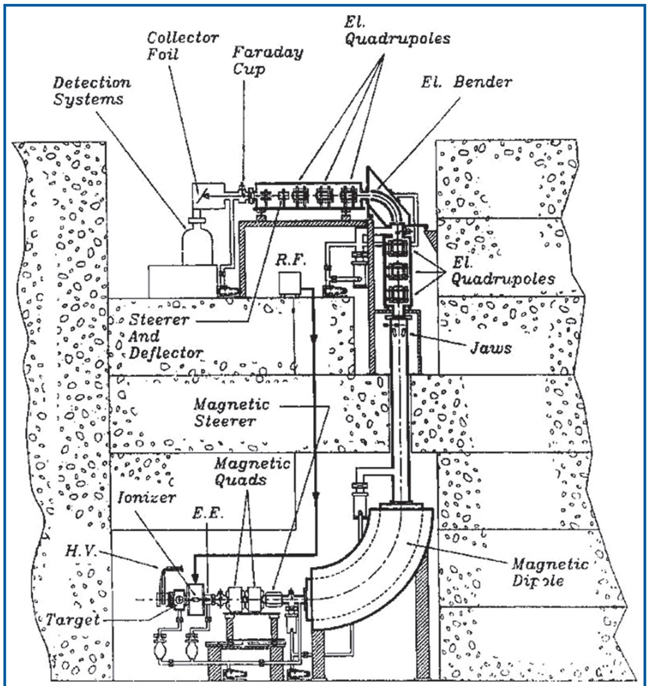


Fig. 2 An elevation view of the TISOL test facility *circa* 1987.

developed that made important contributions to nuclear astrophysics and fundamental symmetries.

TISOL's scientific impact is best illustrated by a key experiment and a ground-breaking facility. In 1992 scientists undertook an indirect measurement of the ^{12}C(alpha, gamma)^{16}O reaction, which is believed to be the mechanism for creating oxygen from carbon and helium in red giant stars. In fact, this "Red Giant" experiment studied the reaction in reverse, where the unstable isotope ^{16}N (1.6 second half life) was produced in TISOL, which then decayed to ^{16}O, and in a miniscule fraction of the time, followed by a decay into an alpha particle (helium) and ^{12}C. The experiment successfully threw light on the origin of the carbon to oxygen elemental abundance ratio observed throughout the universe.

In the early 1990s, Simon Fraser University professor Otto Hausser led the development of a magneto-optical trap for neutral atoms that would exploit the novel properties of rare isotopes produced at TISOL. The facility was envisioned initially to study atomic parity violation, which is greatly enhanced in high-Z rare isotopes (like Francium), and new classes of beta decay correlation measurements. The effort bore fruit in 1997 with a measurement of the optical isotopic shifts and nuclear radii differences between the radioactive isotopes ^{37}K and ^{38m}K. The success of Red Giant and TRINAT gave TRIUMF confidence in its ability to develop a world-class rare isotope program.

Background work on the TRIUMF ISAC proposal continued during the end stages of the KAON proposal in the early 1990s. In 1993, when it was becoming clear that the KAON proposal might not be approved, efforts redoubled on developing the ISAC proposal, which included recruiting a dedicated development team pursuing target and accelerator technology. These efforts led to a number of submissions to the TRIUMF Long Range Planning Committee meeting in summer 1993, and to the creation of an ISAC Steering Committee in September 1993, chaired by (then) Science Director Jean-Michel Poutissou.

The wisdom of pursuing the TISOL programme and the parallel ISAC study became evident in February 1994, when the federal government chose not to pursue the KAON proposal. From then events moved very quickly — University of Victoria professor Alan Astbury was appointed to succeed Erich Vogt as TRIUMF Director in April 1994, with the task of mapping out TRIUMF's future. Initial plans called for an upgraded TISOL facility in the Proton Hall area, but feedback from the nuclear physics community called for a facility with post-acceleration, so Astbury took the courageous decision to pursue the more expensive ISAC option, leading to the submission of TRIUMF's first Five-Year Plan (5YP) in July 1994. Work on the detailed ISAC design began immediately. The proposal to government envisioned a modest ISAC facility where TISOL was located, but after more detailed studies the location was moved to the present site as it offered better opportunities for future expansion, a decision that would become prescient. The breakneck effort was rewarded in June 1995, when the federal government awarded TRIUMF funding over five years, including ~\$18M for a new ISAC facility. In March 1996, the Province of British Columbia followed with funds for new civil construction. The period between the 5YP submission and the budget approval was a time of great uncertainty at TRIUMF, but the time allowed for careful planning which has since served the lab well. Thus dawned the isotope era at TRIUMF.

Work soon began under the project leadership of TRIUMF scientist Paul Schmor. It included provisions for facilities for modular ISOL targets, stopped rare-isotope beams, and one 1.5 MeV/A accelerated beam (up to $A = 30$) utilizing a radiofrequency quadrupole (RFQ) and drift tube linac (DTL) linear accelerator chain. The lab's existing expertise in remote handling of high-current production targets facilitated development of a modular target system able to withstand 100 μA of proton beam, advances which were unique to TRIUMF. The accelerators also were designed at TRIUMF from scratch and were unique in the world at that time. TRIUMF had excellent contacts with the Vancouver construction community as a result of KAON, so design and construction proceeded rapidly and was completed on budget and on schedule. The building permit was received in September 1996, and by 1998 the ISAC building, isotope production target, transport beam line, and mass separation components were completed (see Fig. 3). The first radioactive beam (^{38m}K) was delivered to TRINAT, now relocated to the new ISAC building, in November 1998. This was followed by the first physics with unaccelerated beam for a precision measurement of the ^{74}Rb lifetime, in 2000, the same year that the facility was declared commissioned by federal Industry Minister John Manley in an on-site ceremony. The linear post-accelerator chain also became operational by 2000, and the first accelerated beam, ^{21}Na, was delivered to the DRAGON and TUDA nuclear astrophysics experiments in 2001. In 2002 two other key facilities became operational: (1) the 8π spectrometer (built in 1985 by a Canadian consortium for in-beam reaction studies at Chalk River) was relocated from Lawrence Berkeley Laboratory and reconfigured for use with stopped radioactive beams; and (2) the beta-NMR facility for material science studies. In 2003, funding was announced for the TITAN facility for precision isotope mass measurement, and in 2004, the laser ion source became operational, allowing a wide array of rare isotopes to become available for ISAC experiments. So in just under a decade, ISAC went from an idea to a fully operational facility doing world-class science in nuclear astrophysics, nuclear structure, fundamental symmetries, and materials science, remarkably transforming TRIUMF into an isotope science laboratory.

At the outset, ISAC-I was purposely overdesigned to permit upgrades and future expansion. Soon after construction on ISAC-I started, thoughts turned toward preparing a proposal for an upgrade. At the Dunsmuir Workshop in February 1998, discussion swirled around "doing ISAC properly" to put "TRIUMF on the international map". These efforts culminated in the ISAC-II proposal, which planned for an increase in beam energy from 1.5 MeV/A in ISAC up to 6.5 MeV/A for masses up to $A = 150$, opening up new capabilities in nuclear structure research. The ISAC-II proposal was included in the 2000-2005 5YP, which was funded by the federal government in February 2000, with additional funding for civil construction released by the Province of British Columbia in June 2001. A key feature of the ISAC-II proposal was a third stage of isotope post acceleration utilizing superconducting radio-frequency (SRF) cavities, developed with a laboratory in Legnaro, Italy and sourced from Italian Industry with cryomodules and cryogenics systems designed and built at TRIUMF.

Federal funds allowed work to begin on the first of three planned SRF accelerator sections, with support for completing a second ISAC-II SRF accelerator section and the high-energy experimental beamlines being received in the 2005-2010 5YP budget. The ISAC-II building was completed in 2003, and by 2005 SRF module acceleration was demonstrated with a beam of ^{4}He^{2+}. In April 2006, a ^{40}Ca^{10+} beam was accelerated through both ISAC-I linear accelerators and the first ISAC-II superconducting section to a final energy of 220 MeV (5.5 MeV/A). The second section featuring 'Made In Canada' SRF cavities was completed in 2010. The experimental facilities were to be anchored by two flagship facilities for nuclear reaction studies: TIGRESS, a gamma-ray detection array with provision for auxiliary detection of charged particles and neutrons, and EMMA, a next-generation mass analyzer designed to be used stand-alone or in conjunction with TIGRESS. The ISAC-II era began in earnest when the first production radioactive ion beam (^{11}Li) was

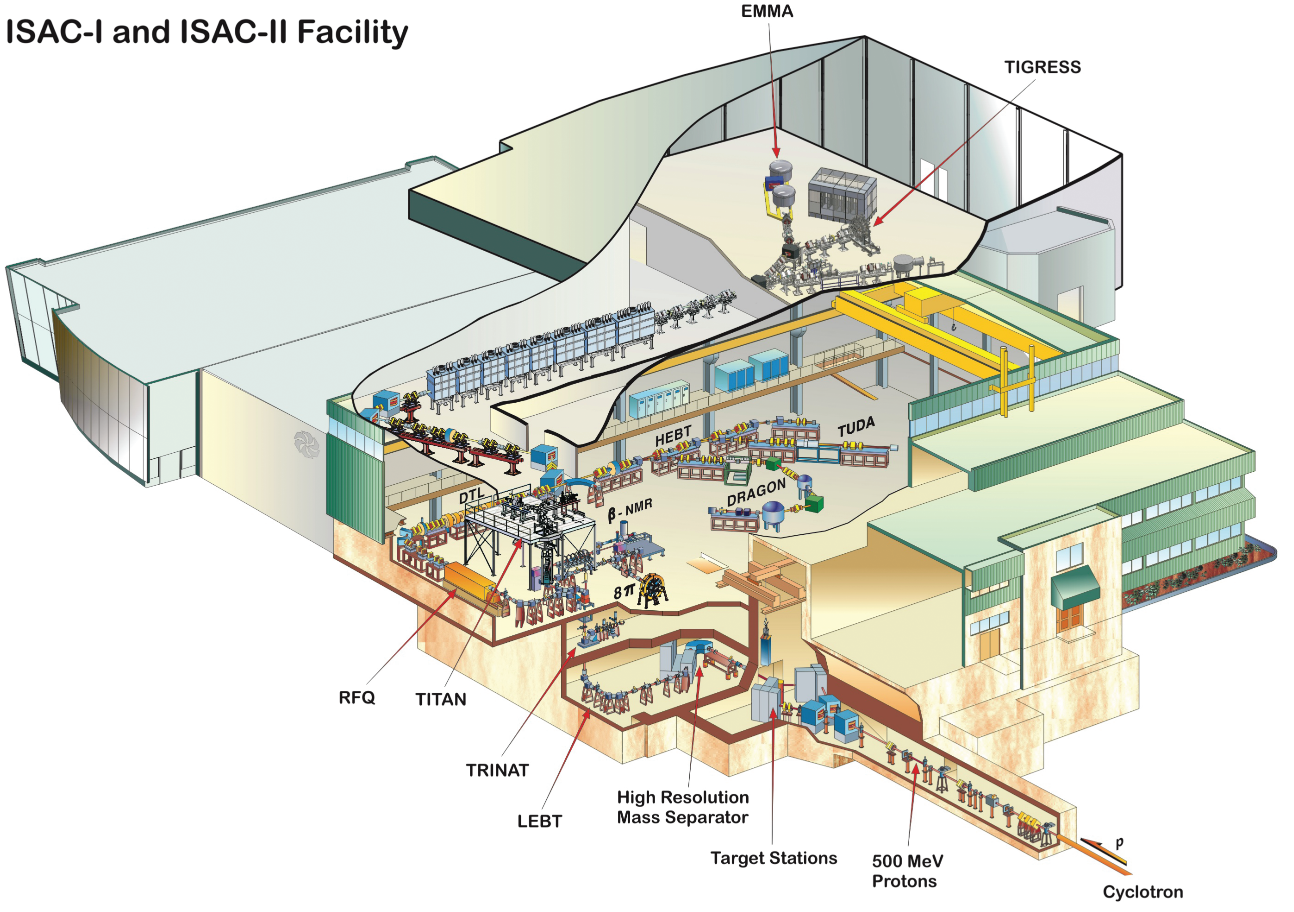


Fig. 3 Cutaway graphic of the ISAC I and II facilities as they appeared in March 2012. These purpose-built buildings are located north of the main cyclotron.

delivered to the MAYA experiment (from GANIL in France) in the ISAC-II experimental hall on January 05, 2007.

ISAC's success did not satiate TRIUMF's ambitions to become a truly multi-user RIB "factory". There were plans extant to provide additional "driver" beams for isotope production in addition to the single proton beam line from the main cyclotron, and the decisive step was taken by (then) TRIUMF Director Nigel Lockyer in 2008 to pursue the ARIEL project (**A**dvanced **R**are **I**sotop**e** **L**aboratory). The centrepiece of ARIEL is a new superconducting electron linear accelerator (e-linac) for isotope production via photoproduction and photofission which promise a complementary class of neutron-rich isotopes created completely independently of the main cyclotron. The proposal also envisioned a second proton beam line from the cyclotron, resulting in ultimately three independent rare isotope beams into the ISAC I and II experimental facilities, thereby tripling the scientific output potential.

ARIEL was the centrepiece of the 2010-15 5YP, with construction beginning in March 2011. In contrast to the way ISAC was funded, ARIEL funding has come in stages from a combination of Canadian Foundation for Innovation (CFI), provincial, and TRIUMF federal operating funding. The University of Victoria is the primary CFI stakeholder for the e-linac, with professor Dean Karlen as principal investigator for two successive CFI projects. The e-linac, developed at TRIUMF in partnership with local industry, demonstrated electron acceleration in September 2014. The first stage of ARIEL, which included the building and e-linac, was declared completed in November 2014 (see Fig. 4). The second stage, which includes completion of the beam transport lines, target hall, ion sources, and second proton beamline, received funding in June 2017. At time of writing, TRIUMF is working with great effort on ARIEL, with first post-accelerated beams utilizing the new ARIEL CANREB charge-breeding facility (itself a CFI project) anticipated in 2020. Beams utilizing the e-linac and second proton beamline drivers are anticipated in 2023 and 2026, respectively. Ultimately, ARIEL will deliver three independently produced rare radioisotope beams to the many experimental facilities at ISAC I and II, strengthening and growing research programs in nuclear structure, nuclear

Fig. 4 Drone's-eye view of the present TRIUMF site, with the ARIEL building (orange trim) visible in the centre, and the ISAC-I and II buildings in behind it. The long main cyclotron building is visible on the right.

astrophysics, fundamental symmetries, materials science, as well as the life sciences.

While TRIUMF began as a "meson factory" primarily for nuclear and particle physics, the laboratory has transitioned over the last 30 years into a laboratory where rare radioisotopes have taken centre stage. This transition was set in motion with the construction of the TISOL facility in the 1980s, which led in turn to ISAC I and II. The new ARIEL facility will greatly augment the capabilities of both these facilities.

The visionary design of the TRIUMF cyclotron, and in particular the (up to) four simultaneously available very intense proton beams at energies up to 500 MeV, has ensured that the laboratory, as a world-class facility, could transition smoothly into this new role. That a cyclotron designed in 1967 could have such an exciting and forefront future in international science 50 years later is a testament to the laboratory Directors and the scientists, engineers, and technical and support staff who have contributed over the years to this continuing development.

MORE INFORMATION

For more information on the facilities and experimental program developed to exploit the rare isotope beams at ISAC and ARIEL, as well as the many talented people who worked on the projects, please refer to the following publication and presentations:

"Canada's Radioactive Beam Facility – At the Nexus of Past and Future Triumphs", John D'Auria, Jens Dilling, Paul Schmor, *Nuclear Physics News*, **20**, 2010.

ISAC and ARIEL: The TRIUMF Radioactive Beam Facilities and the Scientific Program, ed. J. Dilling, R. Kruecken, L. Merminga, *Hyperfine Interactions*, **225**, 1-282, 2014.

G.C. Ball, G. Hackman, R. Kruecken, *Physica Scripta*, **91**(2016), 093002.

Presentation on the 10th Anniversary of ISAC, by John D'Auria, https://www.triumf.ca/sites/default/files/TRIUMF_ISAC_10th_jd'auria.pdf.

Presentation on the 20th Annivesary of ISAC, by Gordon Ball, https://meetings.triumf.ca/indico/event/75/session/2/contribution/2/material/slides/0.pdf.

A BRIEF HISTORY OF THE LIFE SCIENCE PROGRAM AT TRIUMF

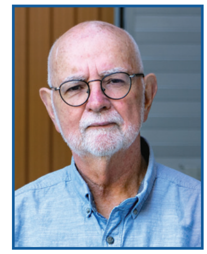
BY TOM RUTH

SUMMARY

A short history of nuclear medicine (now life sciences) at TRIUMF, through the eyes of one of the founding fathers and driving forces behind the program.

The story of the Life Science program at TRIUMF starts in the mid 1970s, when the first real images related to glucose function in the living human brain were taken with the positron emission tomography (PET) technique, and the (then) TRIUMF Director, Jack Sample, asked Associate Director Brian Pate to develop a program to make use of the nuclear chemistry capabilities at TRIUMF for the production of radiotracers for medicine. While the use of positron decay to create images of in-vivo biological function had been discussed for decades, in 1976 a collaboration involving Brookhaven National Lab in NY, where the radioactive tracer (^{18}F-fluoro-deoxyglucose, FDG) was developed, the University of Pennsylvania, where the detector was installed, along with the medical and technical staff and the National Institutes of Health, where the basic concept of using autoradiography using ^{14}C-deoxyglucose, was developed to study glucose function in rodent brains. Around the same time, a collaboration was negotiated between TRIUMF and Atomic Energy of Canada, Limited (AECL) to establish laboratories for accelerator-based radioisotope production. Initially the program made use of the main 500 MeV cyclotron, where the main interest for AECL was the 500 MeV beam dump where a target system was developed to produce radioisotopes from the spallation of various targets. In parallel, John Vincent was developing a target system to produce I-123 and have it shipped to different hospitals for testing. I-123 was seen as a potential safer radioisotope than I-131 for imaging.

With the success in the US of using the glucose analog, ^{18}F-fluoro-deoxyglucose, for imaging brain function, scientists at TRIUMF and UBC pursued a PET program in Vancouver. Pate along with Pat McGeer, a neuroscientist, William Webber, Dean of Medicine, and Bernard Riedel, Dean of Pharmaceutical Sciences, sought $675,000 (the sum quoted by AECL) in funding from the Medical Research Council to construct a PET camera, using a design already in operation by Lucas Yamamoto at McGill University. At that time commercial scanners were not widely available.



Almost simultaneously, AECL decided to purchase a cyclotron for the production of medical radioisotopes at lower proton energies (30 MeV) to provide isotopically purer commercial products such as Tl-201, Ga-67, In-111 and I-123. It was to be installed at TRIUMF to take advantage of existing accelerator expertise and infrastructure.

The next phase in the PET program development was to hire experts in radiochemistry and radionuclide production. To this end a collaboration was established with Professor Laurie Hall, a (sugar) chemist at UBC, who enlisted his most recent PhD graduate, Mike Adam. The other position was filled by the recruitment of Tom Ruth from Brookhaven National Lab where FDG had been developed. It was felt this tandem could tackle the issues in producing FDG — while Mike had no radiochemistry experience, Tom brought expertise in radiochemistry and radionuclide production. The Chemistry team was completed with the hiring of Salma Jivan, who worked closely with Mike and Tom for more than 20 years, helping with the development of all the tracers (^{18}F-fluorodopa, ^{11}C-raclopride, etc.) used in the program over that period.

Initially the only source of F-18 for labeling research was from a gas target (loaded with a mixture of 0.1% F_2 and Ne) inserted at the beam dump of the 500 MeV beam, just ahead of the AECL spallation targets. While the yields were not very high, it allowed the development of a number of labeling techniques and production of FDG labeled with F-18. It was not until the AECL cyclotron, the CP-42, was purchased (1982) from the Cyclotron Corporation in Berkeley that the PET program could begin producing FDG in sufficient quantities to be used in the scanning of subjects. The TRIUMF PET users had 10 hours of beam available per week for their development and production for scanning. The beam quality only allowed for the production of ^{18}F as F_2.

Meanwhile, in mid-1980, AECL in Chalk River informed Brian that the scanner that they had contracted to build could not meet the specifications outlined in the purchase agreement. The principal problem was the fraction of the events measured in an image that resulted from scattered radiation. AECL informed the TRIUMF team that they

Tom Ruth <truth@triumf.ca>, Emeritus Senior Scientist TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3

would need at least 6 months and an additional $250,000 funding. TRIUMF did not have the extra funds and needed urgently to fulfill the terms of the MRC grant. So, the contract was broken and TRIUMF recovered its deposit, but was left without a scanner.

Brian then went to the new Director of TRIUMF, Erich Vogt, and recommended that TRIUMF build its own scanner. Brian had previously been a faculty member at Washington University in St. Louis, MO which had successfully built several PET scanners. The most recent version at that time was called the PETT VI and had been installed in several US locations. Brian's contacts at Washington University were John Hood, a Mechanical Engineer with the cyclotron group and a Physicist, Michel Ter Pogossian, who had been instrumental in designing and building all of the PETT scanner versions. The Washington U group willingly allowed TRIUMF scientists and engineers to visit and bring back mechanical drawings, as well as suggested improvements for the scanner. The team that went to St. Louis included Don Haywood, an electronic expert, and Joop Burgerjon, an engineer.

Upon their return, a team of about a dozen scientists, engineers and electronic and mechanical technicians was assembled to build the TRIUMF version of the PETT VI (see Fig. 1). As part of the agreement with TRIUMF Management, the funds from the MRC grant would be spent on the material costs and TRIUMF would supply the personnel, similar to other TRIUMF experiments. This was late 1981. The mechanical aspects of the Wash U. scanner were basically kept but the electronics from the detectors downstream were totally modified to improve the timing and coincidence characteristics.

Over the next 18 months, the scanner was put together, commercially available components were ordered, and the physical gantry was constructed in the TRIUMF machine shop. The new electronics design led to the assembly and disassembly of the detectors and electronic components a number of times to deal with the various complications associated with a near prototype machine. By late 1982, the scanner was assembled and basic tests were performed. After this success, the scanner was disassembled and shipped to the UBC hospital where the PET program had offices and labs for the research activities.

During this time, a 2.7 km pneumatic pipeline, consisting of a bundle of 4 polyethylene tubes encased in concrete about one meter below grade, was installed to transport the scanning agents from the TRIUMF chemistry labs to the UBC hospital PET scanning laboratory (see Fig. 2). The route went from the PET chemistry lab in the AECL building, through the TRIUMF property, and then north parallel to Wesbrook Mall. The pipeline was installed in sections with access holes at approximately 300-meter intervals. To transport the radioisotopes, plastic bullets were designed with a plug at the rear end sealed with an "o"-ring. Into this bullet, a multi-injection vial with the desired radioactivity would be placed for shipment. The pipeline was connected to a large ballast tank held at 90 psi, so that the bullet was transported to the hospital by air pressure in less than 2 minutes. This pipeline delivery system is still in operation after more than 35 years, although modifications of all aspects of the system have been made over the years.

Fig. 1 Development group posing in 1982 with the newly TRIUMF-built positron emission tomograph (PETT VI). Standing behind the centre of the PETT VI is (then) TRIUMF Director Erich Vogt (left, with suit) and Associate Director Brian Pate (right, with sweater).

With the availability of production and labeling FDG with F-18, a means of transporting the tracer to the hospital, and a scanner to image with, TRIUMF was set to begin an imaging program by early 1983. Initially, FDG PET was developed to perform human functional studies of the brain, *in vivo*. Thus, the cameras being used during these early days were designed to optimize brain imaging. It was not until the mid 1990s that FDG begin to be used in the diagnoses of cancer, principally in Europe and the US.

Establishing a brain research program required recruiting neurologists and psychiatrists. The challenge was that the large number of interested parties were, for the most part, clinicians, not researchers. The attempts at acquiring funding from the MRC (the CIHR predecessor) acknowledged the strength of the physical infrastructure while pointing out the weakness in the proposed

Fig. 2 Erich Vogt, Brian Pate, and Lloyd Detwiller, UBC Health Sciences Centre administrator, standing next to the radiopharmaceutical-transporting pneumatic pipeline to be installed between TRIUMF and UBC.

Fig. 3 Brian Pate showing off the PETT VI to Queen Elizabeth II in 1983 during the opening of the UBC Brain Research Center.

brain studies. Things changed in 1981 with the recruitment of Donald Calne, a world-renowned Parkinson's disease research scientist, who arrived emphatically stating that he intended to use PET as his primary tool for understanding the origins, progression and complications of Parkinson's disease (PD).

Our first PET scan with FDG was on a normal subject, one of the participating neurologists, on February 24, 1983. Just over two weeks later, Her Majesty, the Queen of Canada, came to UBC to participate in the opening of the UBC Brain Research Center (see Fig. 3). This included PET scanning and Canada's first clinical MRI scanner (acquired through the efforts of Laurie Hall who was an NMR expert in addition to his research in carbohydrate chemistry) at the Koerner Pavilion, UBC Hospital.

Later that year a new tracer, ^{18}F-fluorodopa, first developed at McMaster University, was introduced to the UBC program by the PET chemists. This L-Dopa analog allowed for the study of the dopamine system in PD patients.

With the support of (then) TRIUMF Director Erich Vogt and Bob Miller (VP Research, UBC), Tom Ruth became PET Director in 1989 after Brain Pate stepped down in late 1987 to pursue PET studies of dopamine metabolism in non-human primates. During the one-year gap between Brian's stepping down and Tom's assuming the role of PET Director, Andy Eisen served as the Acting Director during the search for a Full Time Director.

During the first 15+ years numerous studies were performed to demonstrate preclinical changes in the dopamine system that lead to PD. In addition, we were able to observe that asymptomatic patients progress to PD, that early signs of compensation can be detected, that singular events can cause PD, and that there exist clusters of PD, all of which led to the "event" hypothesis.

In the early 1990s, Dick Johnson, serving as Head of the Life Science Program within the Science Division, worked with EBCO Industries to build a small cyclotron suitable for hospitals. The TR13 prototype (see Fig. 4), built with TRIUMF support, utilized localized shielding so that it could be placed in an open area within a fenced safety zone, obviating the need for a special shielded vault. The TR13 cyclotron allowed the PET program to schedule their productions runs according to the needs of the medical program. In addition, the cyclotron opened the possibility to produce C-11 radiotracers.

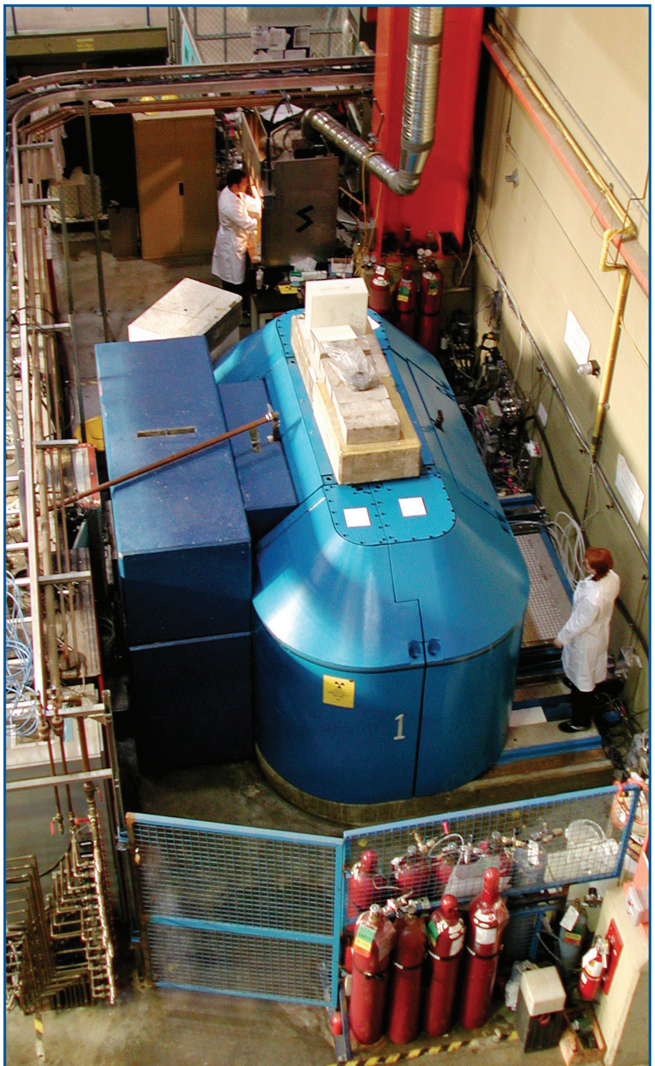


Fig. 4 Overhead view of the TR13 medical-isotope cyclotron at TRIUMF.

The tracers developed were ones that had been previously published elsewhere. The unique aspect of the UBC/TRIUMF PET program was applying them to address significant fundamental questions in the living human brain, especially as related to Parkinson's disease. The availability of C-11 tracers provided the opportunity to explore the dopamine system in a very dramatic fashion. The leadership of the Parkinson's disease program changed hands in the 1990s with Jon Stoessl leading the research efforts. All told, the UBC/TRUMF PET program in Movement Disorders became a recognized world class effort.

While the PET program was moving forward with gusto, collaborations were established amongst local university researchers which demonstrated that radiotracers could be used to address questions in a variety of fields. Probably the most successful collaboration was with Tony Glass, a Botanist at UBC, who made use of $^{13}NO_3^-$ to investigate nitrogen incorporation in various plant systems. Over the next 20 years Tony and his colleagues published nearly 50 papers using ^{13}N, fifteen of which each had more than 100 citations.

Other studies involved the pulp and paper industry with Mark Martinez, a Chemical Engineer at UBC, who used the PET scanner to monitor the settling of ^{18}F-labeled pulp fibers. He devised a mathematical term that he called the *Crowding* number which related to the quality of paper. These studies determined the optimal conditions for operating a paper mill, optimizing the tradeoff between cost efficiency and environmental safety. Mark's further work explored the mathematics of fluids undergoing sudden expansion, a phenomenon observed in many industrial processes. Recently, Mark has been helping develop heat transfer models to better understand the operation of gas targets for radioisotope production.

UBC oceanographer Maite Maldonado used isotopes of Cu to study the use of copper by phytoplankton in iron-poor regions of the ocean, work impacting the study of CO_2 sequestration in the oceans. She brought radioactive copper on sea cruises to enable the investigation of copper uptake in various regions of the North Pacific Ocean.

Also, in the 1993, John Vincent, Tom Ruth and Mike Cackette published a process for the production and isolation of Sr-82 that has been adopted by a number of centers for the production of Sr-82 for use in supplying $^{82}Sr/^{82}Rb$ generators. Rb-82 is used in cardiac PET studies.

During this period, the TR13 was used to support the University of Alberta PET program before they acquired their own cyclotron, which involved shipping F-18 to Edmonton once a week. Even with the long transit time (8-10 hours including clearing transport requirements), they were able to begin their clinical program in cancer research and diagnoses.

Throughout the 1990s and early 2000s the Life Science program was organized within the Science Division Headed by Jean-Michel Poutissou who provided support and guidance for all aspects of the Life Science endeavors. As part of the succession plan, Paul Schaffer was recruited to assume the leadership of the Life Science program in 2010. The (then) Director Nigel Lockyer created a Nuclear Medicine Division, which was then led by Paul.

Collaborations with the Chemistry Departments at UBC and SFU led to many graduate student theses based on new techniques in the development of radiotracers. The principle UBC Chemistry professors were Chris Orvig (metal chelates), Steve Withers (β-Glucosidase inhibitors), David Perrin (Boron, silicon facilitated fluorinations), and at SFU with John D'Auria (Tracers for ISAC, Mass Separator), David Li (microfluidics), Tim Storr (fluorination of large molecules, click chemistry), Rob Britton (aqueous photocatalytic fluorinations of amino acids), and David Vocadlo (^{18}F — cerebrosidase inhibitors for Alzheimer's research). Each of these collaborations involved students at all levels of training. And for nearly 30 years, the PET group involved Coop students from the University of Victoria Chemistry Department. Many of these students went on to pursue graduate studies at one of the TRIUMF member universities.

Probably the most significant non-UBC PET collaboration developed was with the BC Cancer Agency in helping to establish their clinical PET program. This relationship established a working plan for the design of a PET facility, the writing of a grant proposal to establish a Chair in Functional Imaging, the recruitment of a lead Clinician Scientist to fill that chair, the delivery of FDG to the Cancer Agency while their program was being expanded, and the assistance with establishing the research laboratories for radiochemistry and the GMP facility (see Fig. 5). Francois Benard became the Chair and has since established a strong cancer research imaging program. This relationship has continued with TRIUMF serving as a back-up for when the Cancer Agency cyclotron is down for maintenance.

This close relationship led to a collaboration to develop a cyclotron approach to the production of Tc-99m. Following the worldwide shortage of $^{99}Mo/^{99m}Tc$ caused by outages at the two largest reactor producers (NRU at Chalk River and the HFR in the Netherlands), the Government of Canada put out a series of Request for Proposals for which TRIUMF and the BC Cancer Agency teamed up to lead one effort. Leadership for the various grants rotated between Ruth, Benard, and Schaffer. The success of this effort resulted in NSERC awarding the team the Brockhouse Award for interdisciplinary research, honouring team leaders Ruth, Schaffer, Benard, Anna Celler (UBC Radiology), Mike Kovacs (Lawson Health Research Institute in London) and John Valliant (Centre for Probe Development and Commercialization in Hamilton).

Fig. 5 (from left) Ken Buckley, Christine Takhar, Kathleen Genge, Mike Adam, Salma Jivan, Tom Ruth, and Paul Schaffer in the newly-commissioned GMP lab in 2016.

In an additional research effort to address the Mo-99 shortage, a team led by the late John D'Auria and Tom Ruth sought to improve the specific activity of neutron capture Mo-99 by performing post-irradiation mass separation. This effort built on the success of a graduate student Suzanne Lapi, whose thesis explored mass separation of Re-186 as a means to increase specific activity of this potential therapeutic radionuclide.

The Division's latest research thrust is into the production of alpha emitting isotopes for therapy. The use of the TRIUMF ISAC facility made it possible to prepare $^{210/211}At$ and ^{211}Rn to create a $^{211}Rn/^{211}At$ generator. Now the focus has extended to include ^{225}Ac.

For nearly 30 years the Life Science program operated with just two TRIUMF faculty, Mike Adam and Tom Ruth. Then Paul Schaffer was hired and the program became its own Division. With this new status, more personnel have been appointed. Conny Hoehr is pursuing targetry research, Valery Radchenko has expertise in actinium production and applications, and Monika Stachura is involved in Metallo-Biochemical studies.

There are many, many individuals over the years that have contributed to the success of the program. That said, there are two individuals that provided expertise and dedication over the years, Salma Jivan, a magician chemist who could make just about anything, and Ken Buckley (since retired) who has worn many hats from cyclotron manager, PET camera manger (these two at the same time), program manager for the Tc-99m project, and then Deputy Division Head for Life Sciences.

The Life Science program is poised to install a new cyclotron, the TR24, which will expand the isotope production capabilities, forming the center of the new Institute for Advanced Medical Isotopes (IAMI) program (see Fig. 6). The IAMI program led by Paul Schaffer reflects the continued support of TRIUMF management. In fact, TRIUMF's ability to reinvent itself and expand programs has been due to the continued support of its Directors over the years, most recently with the latest Director, Jonathan Bagger.

Fig. 6 Concept rendering of the new Institute for Advanced Medical Isotopes (IAMI) at TRIUMF. Construction of the new building began in spring 2019.

40 YEARS ON – REFLECTIONS ON THE HISTORY OF TRIUMF FROM CONCEPTION TO THE FIRST BEAM

BY MICHAEL CRADDOCK

This retrospective is a compendium of a ten-article series entitled "40 Years On" written by Michael Craddock between 2006 and 2015. Michael passed away on November 11, 2015, five months after penning the last article

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SUMMARY

This article is a collection of articles meant to reflect the history of TRIUMF from its first beam. Beginning in 1965 through to 1974, it provides an insider's look at how TRIUMF came to be.

FORTY YEARS ON - TRIUMF'S BEGINNINGS IN 1965

By the 1960s, under the inspired leadership of John Warren and George Griffiths, the UBC Nuclear Physics Group had produced more than half the Canadian Ph.D.s in that field. But the 3 MeV van de Graaff accelerator, built by John and his students in 1948, no longer provided the exciting research opportunities of higher energy machines being built at universities across the country. Ottawa was believed to be sympathetic, but tight-fisted, as its rejection of a 1960 UBC proposal for a 12 GeV proton synchrotron had shown. John therefore proposed a joint project with B.C.'s two new universities, Victoria (1963) and Simon Fraser (1965). But was it to be aimed at nuclear structure or particle physics? There was a wide split between low and high energy enthusiasts — with John writing in March 1965, "I would not settle for less than 3 GeV". As the junior dogsbody, I was then delegated to look at some recent U.S. proposals. It became clear that such energies were too costly, but that a meson factory might not be, and could satisfy both camps.

Astonishingly this notion was approved unanimously at a meeting of the UBC nuclear physicists in May 1965. The name TRIUMF (Tri-University Meson Facility) was coined soon after, and the TRIUMF Study Group was formed, with University of Victoria (UVic) and Simon Fraser University (SFU) members, to formulate a request for funds to produce a full proposal. A fully-fledged meson factory seemed too ambitious, particularly the shielding challenges, so we aimed only at a stripped-down 500 MeV, 20 mA "Meson Workshop". A powerful new UBC arrival was Erich Vogt, and with John away on sabbatical, he led the Group in compiling *The TRIUMF Project* report.

Of the various designs extant, I had recommended Reg Richardson's UCLA H^- cyclotron as potentially the most flexible and least expensive. Extensive consultations confirmed that it was a safe choice, and we persuaded Reg that we were competent to foster his baby — the deal sealed by a visit to UCLA by George Griffiths, Karl Erdman, and myself on December 15th, where we also negotiated the loan of their 1/20 scale model magnet. Oddly enough, this was *nine years to the day* prior to achieving the first 500 MeV beam at TRIUMF!

1966: ASSEMBLING THE TEAM

The newly formed TRIUMF Study Group spent the fall of 1965 compiling their initial *Report on the TRIUMF Project,* and early in January 1966 it was submitted to the Atomic Energy Control Board (AECB), the agency then responsible for funding university nuclear physics research. In April a $100,000 grant from Ottawa was obtained, enabling us to hire staff and purchase equipment for model design and cost studies.

The first TRIUMF employee was Joop Burgerjon, who brought considerable experience from building cyclotrons in Amsterdam, Pretoria, and Winnipeg. One of his first contributions was designing the original TRIUMF logo. In September he was joined by Ed Auld to work on the cyclotron magnet design. The loan of a 1/20-scale model magnet by Reg Richardson and his UCLA colleagues and the purchase of a 150 kW, 3000 A power supply enabled a complete test setup to be assembled by the end of the year. Orbit studies of the sensitive central region were initiated with the help of a computer analyst, David Scott. Additional civil and mechanical design was provided by Terry Creaney *et al.* of Shawinigan Engineering, who also compiled the initial cost estimate — $22 million in 1966 dollars (at least $140 million today).

The end result was the *TRIUMF Proposal and Cost Estimate,* edited by Erich Vogt and Joop Burgerjon, submitted to the AECB in November, which recommended a full 100 μA meson "factory". This required a larger machine: orbit radius now 271″ from 230″, and magnet weight now 2800 from 1470 tons. The initial plan was for one extracted beam with all experiments in one hall at the proposed site on the south end of the UBC campus.

A crucial advance in 1966 was the informal involvement of the University of Alberta. Several members, led by Jack Sample and Croy Nielsen, joined the TRIUMF Study Group, and the *Proposal* included a statement from the UoA's Board of Governors approving in principle the university's participation. Interestingly, one of the conditions set was that "The name of the project would need to reflect the University of Alberta's place as a founding partner". I recall giving a talk in Toronto at that time entitled "The TRIUMF-AL Project" — but somehow the suggestion didn't catch on!

1967 — WORKING ON THE TECHNICAL DESIGN

With the *TRIUMF Proposal and Cost Estimate* submitted in November 1966, TRIUMF's small team of physicists and engineers, guided by the TRIUMF Steering Committee (John Warren, Erich Vogt, Joop Burgerjon, Brian Pate, Mike Pearce, and Jack Sample), was able to concentrate on optimizing the design through calculations and model studies. The $100,000 grant received from the AECB in 1966 was renewed in April 1967 but didn't provide much for increasing manpower, though we were able to hire our first summer ("Miss I. Hor and Miss J. Argyle") and first graduate (Sherman Oraas, Robin Louis, and N. Al-Qazzaz) students.

The major effort, led by Ed Auld, focused on the cyclotron magnet, the largest and most expensive component. The equipment built to survey the UCLA model magnet worked smoothly, and tests were made of various shapes for two neighbouring sectors and different coil configurations. But no arrangement seemed capable of providing sufficient magnetic field drop-off between the sectors to maintain vertical focusing at the highest energies, leaving only one solution — increase the 500 MeV radius from 271" to 302".

The radiofrequency (RF) effort, led by Karl Erdman, centred on the construction and testing of a ¼-scale resonator section model — the first in TRIUMF's cost-effective tradition of plywood and copper-sheet RF cavities. One important result confirmed that the coupling between top and bottom resonators was strong enough that feeding RF into one was sufficient to excite the desired standing waves in both.

My studies on the central region focussed on the spiral inflector and the RF accelerating gaps — the latter because their strong focusing effect in a region with minimal magnetic focusing is crucial in determining how much of the incoming beam will be captured. Field computation codes were still primitive, so a copper model was constructed and shipped to the Maryland cyclotron for measurement. Thankfully, orbit studies based on the fields obtained showed that ions passing through the first gap would make it around the centre post, though centring was difficult.

Led by Mike Pearce, studies into the design of the extracted proton beams were initiated at UVic. This involved developing a hybrid analog computer and writing their own tracking and optimizing codes!

Perhaps the most significant development for the future was the UBC Board of Governors' approval of the present 6.6 acre site, in place of the 4 acre one across the road previously assigned.

1968: FEDERAL FUNDING APPROVED!

On April 16th, 1968, federal funding for the TRIUMF project — about $20 million over six years — was announced by the Hon. Jean-Luc Pepin, Minister of Energy, Mines and Resources. Discussions in Ottawa through the winter raised expectations and in January the AECB indicated (unofficially) that the $1.3 million first-year construction funding was to be approved, and so a Board of Management with members appointed by the four universities could be set up.

The Board first met on March 2nd, when it appointed a Director (John Warren), Associate Director (Erich Vogt), and Chief Engineer (Joop Burgerjon), and established a monthly Operating Committee meeting to represent the interests of the university users. We considered ourselves very fortunate to have succeeded within three years of the project's conception, given the economic downturn at that time, and that Chalk River's $150-million proposal for a 65 mA 1 GeV Intense Neutron Generator was turned down.

Funding for the buildings was a local responsibility, and when the B.C. government refused to provide direct support, we were again fortunate that the three B.C. universities agreed to allocate a significant fraction of their building funds — around $4 million — to TRIUMF. The University of Alberta contributed $1.25 million in experimental equipment.

Meanwhile, the detailed design was progressing: the latest magnet model had extended the stable orbit region up to 440 MeV; tracking showed that ions emerging from the spiral inflector over a wide range of initial energies could be steered into centred orbits; measurements on a ¼-scale model cavity provided important data on RF power loss; a model vacuum chamber was under construction; and the engineering consultants provided draft design reports on the buildings and the magnet support structure. But the best news was undoubtedly the arrival of the first cheque ($650,000) by surface mail!

1969: TRIUMF MOVES INTO HIGH GEAR

In April 1969, TRIUMF began a period of rapid expansion. In one year, 22 new hires joined the original 9 staff (see Fig. 1 for a staff photo in spring 1968). A Project Management Office led

Fig. 1 The TRIUMF staff on the site of the future TRIUMF laboratory, June 1968.

by Terry Creaney was set up with staff from the Shawinigan and Montreal Engineering Companies. Building and Safety Committees were created, and engineering firms contracted for detailed design of the buildings, cyclotron, and ancillary equipment. User Groups (Proton, Meson, Slow Neutron, Radiochemistry, Radiobiology & Radiotherapy) were formed to represent the experimenters' interests.

Design modifications to the magnet model had extended the focused-beam region out to the full 500 MeV, and a special model had been built to study the central-region field. A new tape-controlled milling machine in UBC's Mechanical Engineering Department confirmed that the spiral inflector electrodes could actually be built. RF studies were performed on ¼-, ½- and (partial) full-scale models of the resonators, tests of 20K cryopumping began, and a 1/20-scale vacuum chamber model was built for outgassing and other studies. A beam transport system was designed for the extracted proton beam allowing pion-production targets up to 20 g/cm^2 thick.

A critical step was completing TRIUMF's first physics experiment — a measurement at the Rutherford High Energy Laboratory in England of the H^- ion's lifetime in the electric fields induced by passing through magnetic fields at relativistic speeds. The lifetime was found to be only one-third of the theory prediction and previous less-accurate measurements! To keep high-energy beam losses below 6% as planned required a 4% reduction in magnetic field strength, increasing the outer 500 MeV orbit radius to 312" — and raising the cyclotron's cost by about $430,000.

Twelve months of intense activity culminated in the official dedication of TRIUMF on May 5th, 1969 by federal Minister Jean-Luc Pépin (see Fig. 2). The site remained an empty field but for the office building's skeleton, so the ceremony was held at the traffic circle outside. The proceedings ended with the planting of a scion of the apple tree from Isaac Newton's home, a symbol to inspire TRIUMF scientists to equally great insights. After forty years, there are now seven trees thriving there and anyone is welcome to pick "Newton apples" in the Fall.

1970: EXCAVATIONS COMPLETE AND CRM CYCLOTRON TAKING SHAPE

The year following the official dedication saw tangible progress across the lab. By June 1970 the staff had grown to 43, not

Fig. 2 UBC Chancellor John Buchanan looks on as federal Minister Jean-Luc Pepin plants a scion of a Newton apple tree at the official TRIUMF dedication, May 5, 1969.

counting university people, with another 12 at UVic, 5 at SFU, and 6 at Alberta. The skeletal Office & Laboratory Building was completed over the summer and fully occupied by November.

Outside, the muddy field was transformed by heavy earth-moving equipment, and employees enjoyed the spectacle of great fountains of water shooting into the air from hole boring for the perimeter well-point system. Excavations for the cyclotron and experimental halls were completed in June, by which time 60,000 cubic metres of glacial till had been removed to leave a 120 m by 30 m by 13 m deep hole.

Several major contracts were also let over this period. Davie Shipbuilding in Québec won for the cyclotron magnet fabrication ($1.94 million), for which Stelco ($0.4 million) and Lukens Steel ($0.6 million) were to provide the steel plate — overall 75% Canadian content. Commonwealth Construction were awarded a $2.2 million contract for the concrete substructure — but were then delayed nearly three months by a construction strike/lockout.

The Central Region Model (CRM) — a 2.5 MeV cyclotron with the same magnetic and RF fields, 300 kV ion source, and injection line as the big machine — was taking shape in the office building. The huge vacuum tank (2 m wide by 10 m long) built by EbCo Industries arrived in April and was quickly pumped down to the required 5×10^{-7} Torr. The resonator panels, also built by EbCo, arrived soon after.

1971: CYCLOTRON BUILDING COMPLETE AND THE FIRST H- ION BEAM

In the year up to June 1971, construction of the main cyclotron building was the most visible progress at TRIUMF. The previous summer's enormous hole in the ground had been filled — first with a forest of rebar, then 25,500 cubic yards of concrete. Finally, the walls were crowned with the steel superstructure and roof, and the two 50-ton cranes were installed by June.

More major equipment and building contracts were awarded, with around 90% of the 1,970 contracts going to Canadian companies. Notably, TRIUMF's first Ph.D. was awarded to Robin Louis by UBC for his beam dynamics studies of the cyclotron's central region.

As well, the design vacuum of 3×10^{-7} Torr had been reached in the CRM, and the RF Group achieved their goal of 100 kV on the resonators in February 1971. Following this the magnet was installed and field measurements begun. The H^- ion source had arrived from the Cyclotron Corporation in October and was soon producing a 2.3 mA beam — the first particle beam at TRIUMF. The source was then tested at 300 kV and construction of the injection line started.

1971-72: CYCLOTRON CONSTRUCTION BEGINS

With the cyclotron building complete, assembling the cyclotron magnet and vacuum tank was the main activity from mid-1971 to mid-1972. The first of the six magnet sectors arrived in July 1971 from Davie Shipbuilding in Quebec. By January all had arrived and the lower sectors had been installed in the vault, allowing the entire staff to pose for an iconic photo (see Fig. 3).

Meanwhile, Ebco was busy in the Meson Hall assembling the gigantic (15 m diameter) stainless-steel vacuum tank, with its myriad field-adjustment and water-cooling coils. Tests showed that there were no leaks, and a vacuum of 2×10^{-7} Torr was achieved on the first pump down — a real tribute to the welders' skill. In February the tank and lid were lifted over the vault wall and lowered onto the lower magnet sectors, allowing the upper sectors to be installed in March. The 664 tie rods (supporting the 2660 tonne atmospheric load on the tank) were also installed, followed in April by the massive spider-web support structure.

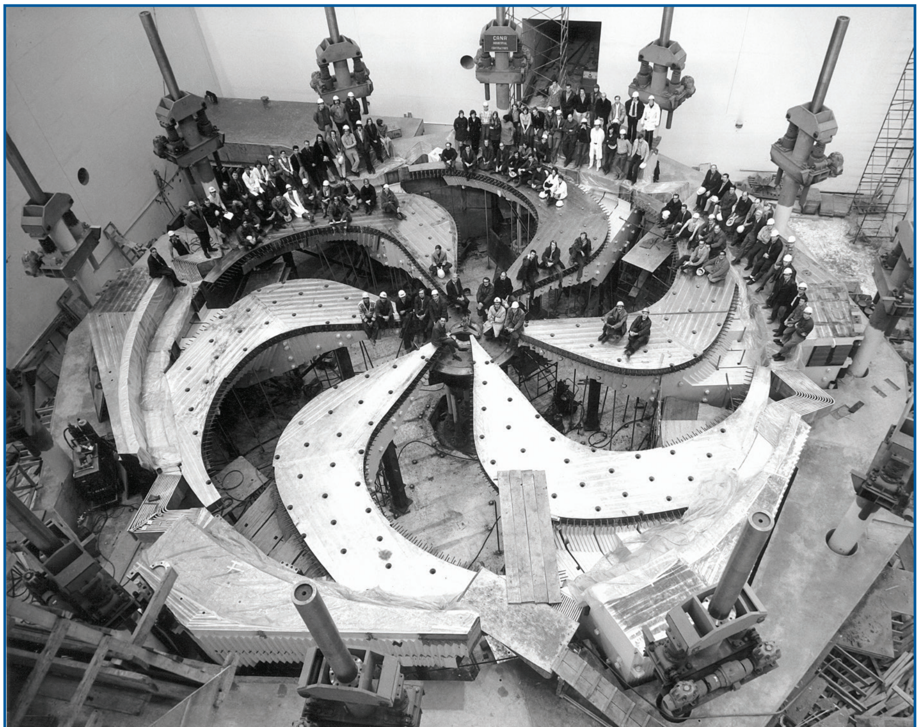


Fig. 3 The TRIUMF staff posing proudly in 1971 on the completed lower magnet sectors of the cyclotron.

RF tests on the CRM led to improvements of the resonator design, the fine-tuning mechanism, and the amplifier's control circuitry. Optimization of the injection gap required redesign of the spiral inflector, a prototype of which was then manufactured using UBC's novel computer-controlled milling machine and successfully tested to full voltage in vacuum. These efforts were crowned by the first successful beam injection into the CRM on May 12th.

John Warren completed his term as Director in September 1971 and was succeeded by Reg Richardson. September saw the first meeting of the Experiments Evaluation Committee, where 29 proposals were considered, an enthusiastic initial response by the user community that augured well for the future!

1972-74: TWO DIFFICULT YEARS

May 1972 until April 1974 was a period of great difficulties and delays, beginning with a 3 month-long general labour dispute in BC that delayed completion of the main cyclotron's magnet — the jacking system could not be finished until July 1972 and the six sectors of each magnet coil could not be welded together until August. Afterward, the 27,000 amp magnet power supply was commissioned and by mid-December the survey arm had been installed and ready to take magnetic field strength data inside the cyclotron (see Fig. 4).

But the first results were alarming! The mean field strength was 3% too high over the inner region and 3% too low at the outside, far outside the ~±0.01% design tolerances! Although the 1/10 scale model was built of plates from the same steel melt as the full-scale magnet, the rolling process had affected the surface magnetic properties, lowering the overall permeability more for thin plates than for thick ones. Moreover, in January the isolating transformer was destroyed by fire, delaying further measurements by three months.

Drastic surgery was required on the main cyclotron magnet. Over the spring and summer, 100 tons of steel were added to the outer return yokes and 16 tons cut away from the inner ones. This brought the field error down to ±0.1%, close enough to achieve the desired accuracy using just pole shims. As well, the magnetic field's azimuthal variation had to be adjusted to ensure vertical focusing and to eliminate harmonics, and any field asymmetry between the upper and lower magnets removed. In all there were 15 parameters to be corrected at each of 103 radii by adding or removing shims at up to 666 locations — a massive undertaking. Computer programs were devised to calculate the shim changes required, but the physical changes had to be made by hand.

In that era, codes demanded hours of dedicated overnight running on UBC's IBM360 mainframe. During the day teams laboured to implement the changes — very many iterations were needed, as crosstalk between the field parameters meant that improvement was slow. It took from September until April and the volunteer efforts of nearly everyone on site before the magnetic field was deemed accurate enough to commission the beam with trim coils alone.

Meanwhile the CRM was making good progress. The measured orbits agreed with computations and by October 1972 the beam reached the full 3 MeV energy while confirming its sensitivity to RF cavity misalignment and magnetic field asymmetries across the large pole gap. But with central correction electrodes, steel shims, and trim coils, the beam could be brought sufficiently close to the mid-plane, and by June 1973 the design 100 μA beam intensity had been achieved.

1974: CYCLOTRON COMPLETED AND BROUGHT TO LIFE!

With the Herculean task of reshaping the cyclotron magnet completed in April 1974, the lab's efforts shifted to installing the equipment needed to inject, accelerate and extract the beam.

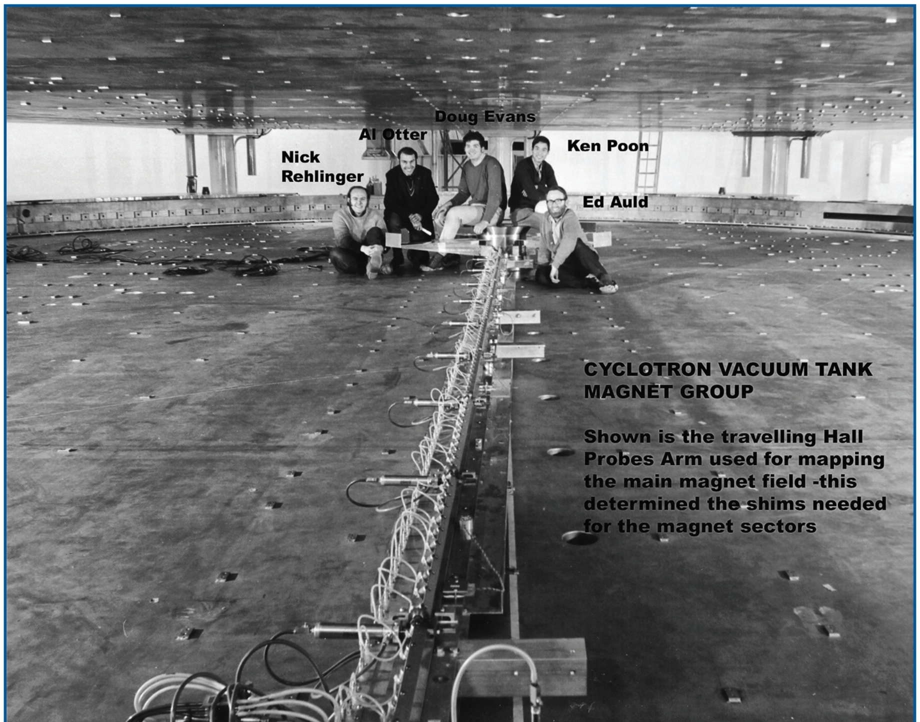


Fig. 4 The magnet survey group circa 1973, led by UBC Professor Ed Auld, inside the cyclotron tank.

First, the vacuum tank was carefully aligned (by adjusting some 500 tie rods) and turned into a clean area. 80 RF resonator sections (each about 5 m × 0.8 m) that had already been carefully assembled, washed, baked, and leak tested were installed, followed by seven weeks on a 14 shift/week schedule to align them! Electrical tests started with connection of the 30 cm-diameter transmission line from the 2 MW RF amplifier to the coupling loop. The resonator Q value was found to be 6400, very close to that expected. Resonator vibrations induced by the cooling water were damped by a combination of mechanical dampers at the tips and "Chore Girl"-brand copper-mesh kitchen cleaners under the header lines.

Meanwhile, the turbo pumps, sublimation pumps, and 20K cryopanels were installed, and by early September a tank vacuum of 5×10^{-7} Torr was achieved. But RF power tests led to unacceptable hydrogen outgassing, so the sublimation pumps, with their low capacity for hydrogen, were replaced by oil diffusion pumps. This allowed 50 kV RF operation and eventually 90 kV by October, sufficient to accelerate H^- beam around the centre post.

As a 100 µA H^- beam had already been achieved in April through the injection line's horizontal section, the summer was devoted to installing and commissioning the vertical section. This was followed in October by installing the spiral inflector, allowing injection of a 6 µA H^- beam into the cyclotron. By this time at least one each of the centring, low-energy, and high-energy beam probes were in place and operational, along with a variety of correction plates and collimating devices in the central region and the extraction foil for Beam Line 4. Outside the cyclotron a host of activities crucial to its successful operation were under way: developing an effective control system, building an external beam line, providing electrical services and water cooling, laying cables, and so on.

By November 16th all was ready for the task of coaxing the H^- beam through the cyclotron by fine adjustments to the magnetic field — a daunting proposition due to the large number of orbits, high RF harmonics, weak vertical focusing, and a large pole gap. Fortunately, the Director himself, Reg Richardson, was a champion cyclotron tuner — dubbed a "ten-knob man" at Berkeley for his dexterity at the controls. His office armchair was moved into the Control Room, where he installed himself to manually adjust the 54 circular trim coils and 78 harmonic coils.

On that first day, good progress was made through the tricky first turns, and two days later the beam had been guided to a 2 m-radius orbit at an energy of 22 MeV, with the excited entry in the logbook, "Radiation in vault!!". Steady progress was made and in spite of losing 7 days to breakdowns, 295 MeV was reached by December 1st. But the orbits crowd closer together at high energies, making tuning very difficult, and 6 days were lost to breakdown of the ISIS 300 kV power supply, so that by December 14th we were still only at 363 MeV.

Fig. 5 TRIUMF Director Reg Richardson (seated) at the controls when the first beam was extracted from the cyclotron December 15, 1974. The author (Mike Craddock) is seen directly behind Richardson in the black shirt and vest.

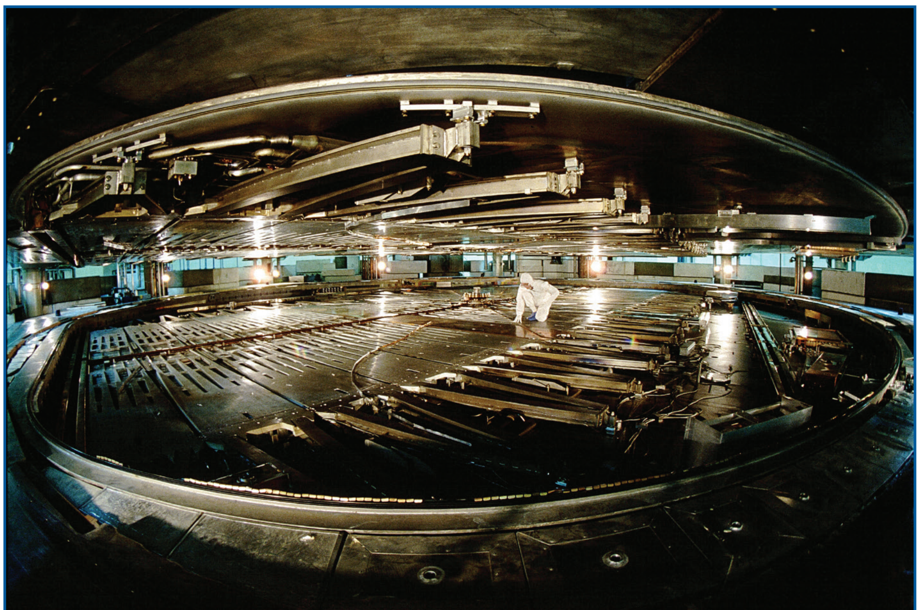


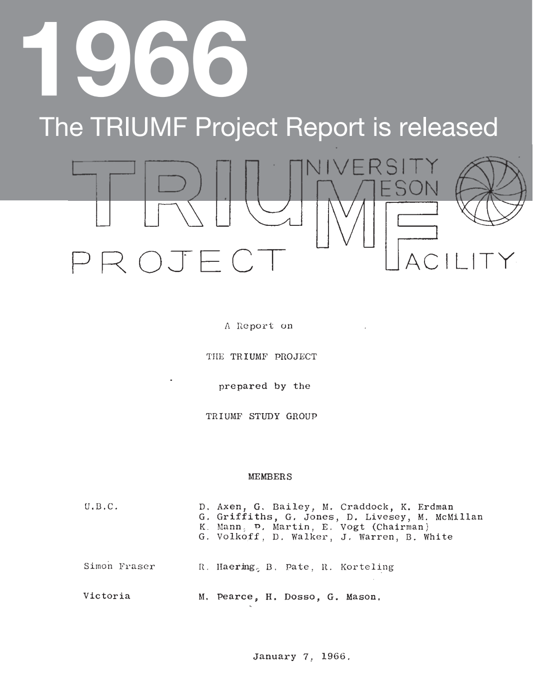
Fig. 6 Inside view of the completed TRIUMF cyclotron.

However, the next day it took Reg only an hour to bring the ions to the long-awaited goal of 500 MeV. Beam line 4V magnets were then turned on and when the H^- ions were allowed to hit a stripper foil, protons were immediately detected in the vault. It then took just over an hour to steer and focus the beam to a 1 cm-diameter spot on a scintillator screen — a great demonstration of the simplicity of extraction by stripping (see Fig. 5).

It would be hard to exaggerate the relief and exhilaration everyone felt at having finally achieved the goal we had worked towards for so many years. The news spread like wildfire and the Control Room was soon inundated with visitors from both inside and outside the lab, many of them bringing refreshments for an impromptu celebration.

For the TRIUMF users of course this was just the beginning, their challenge was to put this powerful tool (see Fig. 6) to effective use, as it was the staff's challenge to develop the facility's full potential. Happily, over 40 years of highly productive research in a wide variety of fields show how well both groups have succeeded.

Article has been edited for brevity by Marcello Pavan.


A Report on

THE TRIUMF PROJECT

prepared by the

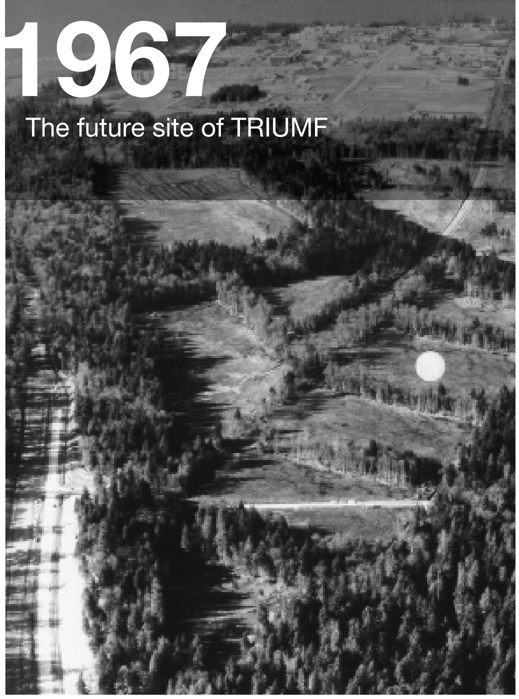
TRIUMF STUDY GROUP

MEMBERS

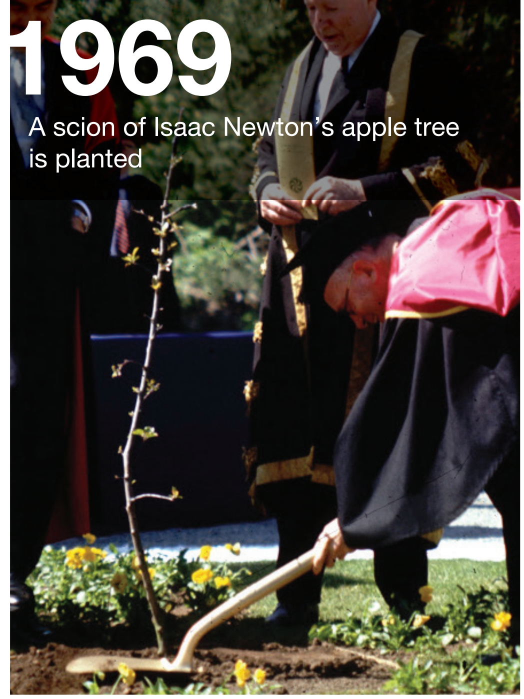
U.B.C.	D. Axen, G. Bailey, M. Craddock, K. Erdman, G. Griffiths, G. Jones, D. Livesey, M. McMillan, K. Mann, P. Martin, E. Vogt (Chairman), G. Volkoff, D. Walker, J. Warren, B. White
Simon Fraser	R. Haering, B. Pate, R. Korteling
Victoria	M. Pearce, H. Dosso, G. Mason.

January 7, 1966.

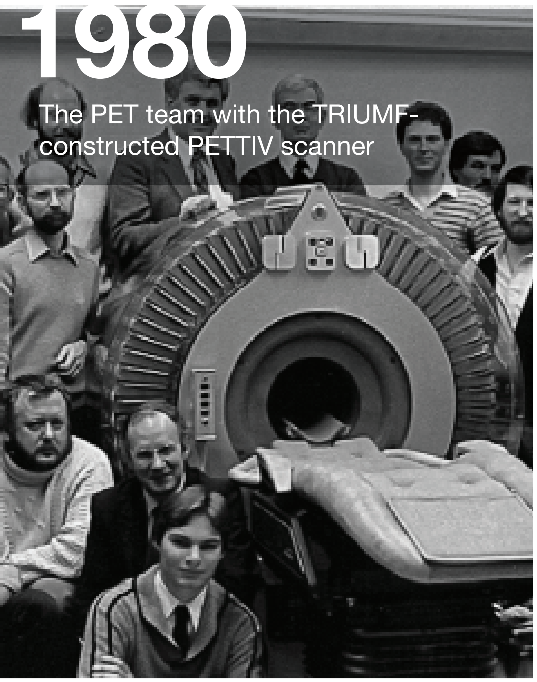
1966
The TRIUMF Project Report is released



1967
The future site of TRIUMF



1969
A scion of Isaac Newton's apple tree is planted

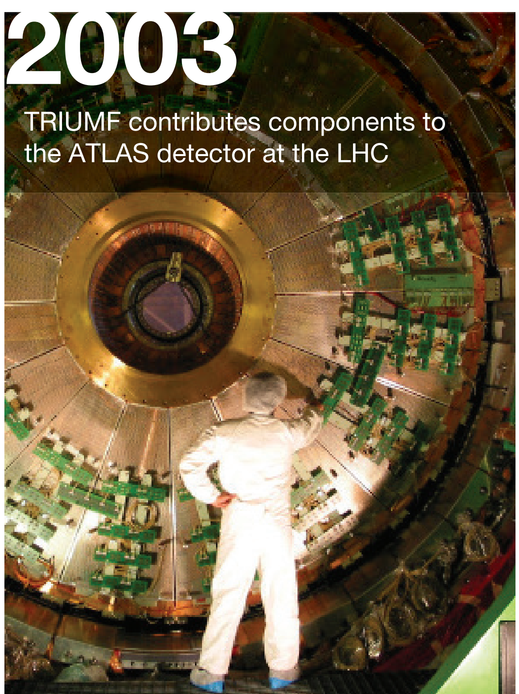


1980
The PET team with the TRIUMF-constructed PETTIV scanner

1983
Queen Elizabeth II visits TRIUMF

1986
TRIUMF provides beamline equipment to DESY

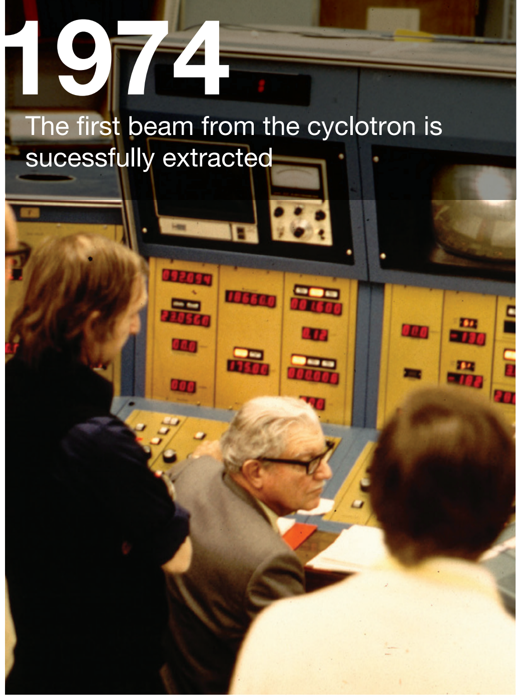
1999
The new ISAC RFQ accelerator



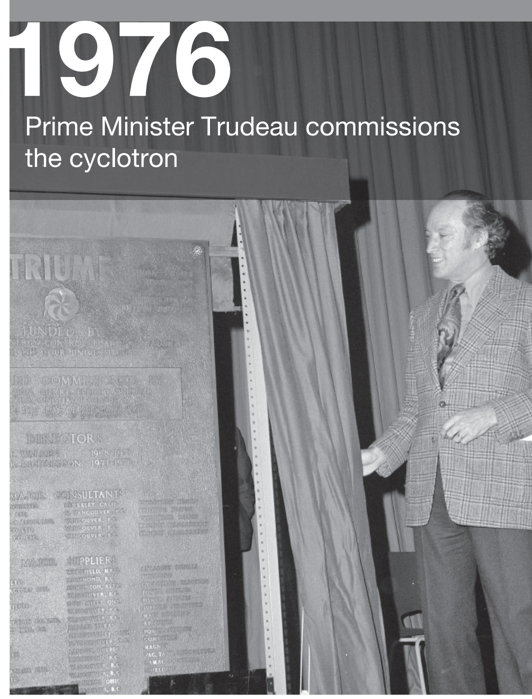
2003
TRIUMF contributes components to the ATLAS detector at the LHC

2008
The superconducting linac at ISAC II

1972
TRIUMF staff gather for a photo on top of the cyclotron

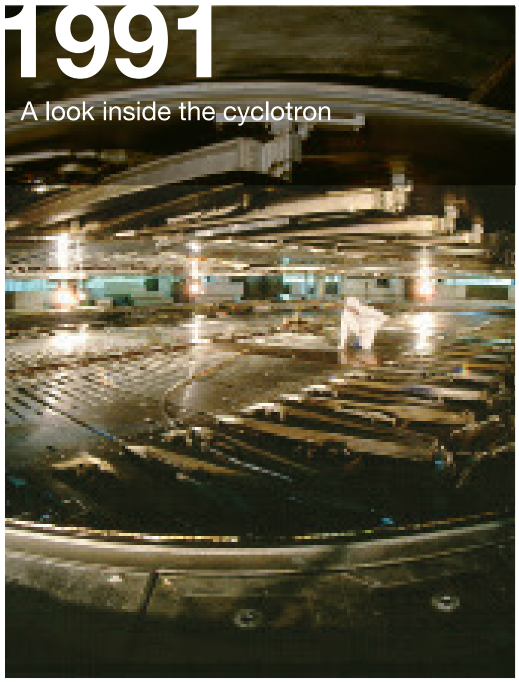


1974
The first beam from the cyclotron is sucessfully extracted

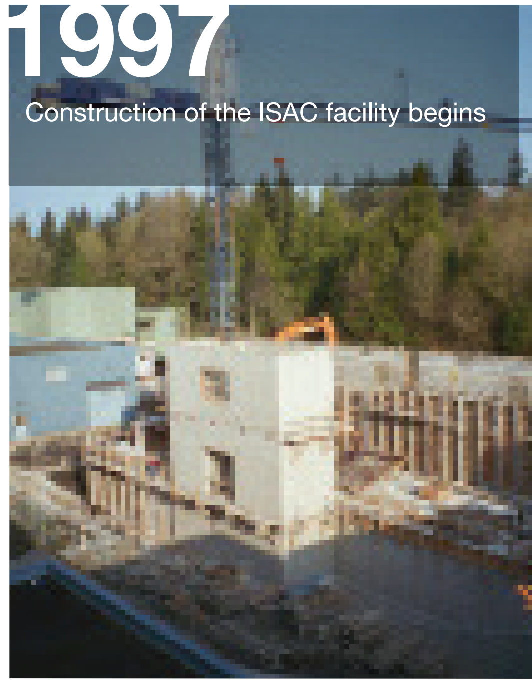


1976
Prime Minister Trudeau commissions the cyclotron

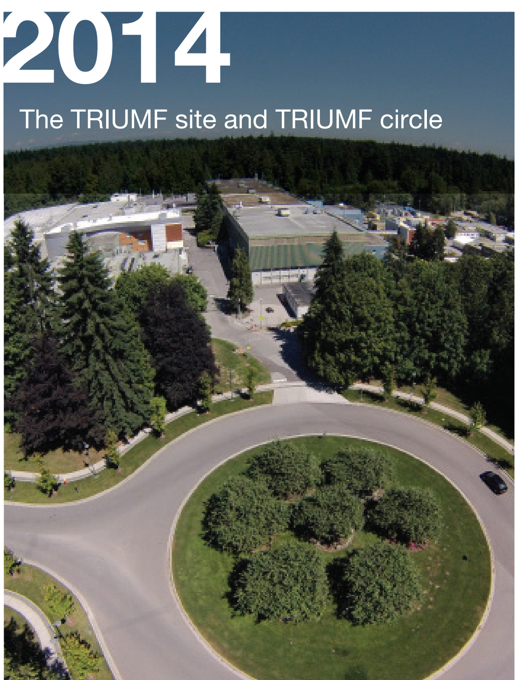
1989
Japanese Prime Minister Toshiki Kaifu visits TRIUMF for the M9 upgrade



1991
A look inside the cyclotron



1997
Construction of the ISAC facility begins



2014
The TRIUMF site and TRIUMF circle

2015
The ARIEL team in front of the e-linac

2018
Prime Minister Justin Trudeau visits TRIUMF to announce the establishment of IAMI

TRIUMF NEUTRINO PROGRAM

BY DEAN KARLEN

The Canadian effort in the Tokai-to-Kamiokande (T2K) experiment at the Japanese Hadron Facility (JHF), now known as the Japan Proton Accelerator Research Complex (J-PARC), was initiated by TRIUMF scientist, Akira Konaka. He was the only contributor outside Japan on the Letter of Intent (LOI) for the "JHF-Kamioka neutrino project" released in June 2001. The proposal was to build a neutrino beamline at the new proton accelerator facility under construction in Tokai to produce an intense neutrino beam directed towards the Super-Kamiokande detector, 295 km away. The discovery of oscillation of atmospheric and solar neutrinos by earlier experiments (in particular Super-Kamiokande and Sudbury Neutrino Observatory, recognized by the 2015 Nobel Prize in Physics) provided the physics justification. The distance between Tokai and Super-Kamiokande happened to be ideal for fully exploring the oscillation of muon neutrinos and muon anti-neutrinos. The highly ambitious LOI concluded with the statement, "The first phase experiment is planned to start in 2007."

The project would require significant international participation to be a success. Akira Konaka convinced several TRIUMF scientists to join the effort, forming a nucleus that attracted many other scientists from across Canada. In 2003, 20 Canadian scientists signed the pre-collaboration LOI, with 45 from Japan and 80 from other nations, and later that year the Japanese government approved the proposal.

TRIUMF had a significant impact on the neutrino beamline design, including the deliberate misdirection by a few degrees from the Super-Kamiokande direction, to improve beam properties for oscillation studies. The latter "off-axis beam" concept was first investigated by a (then) undergraduate student working at TRIUMF, Jared Anderson. TRIUMF contributed to the beam kicker, beamline optics, hot cell, and the beamline technical advisory committee. The hot cell has been invaluable in repairing equipment impossible to access directly due to radioactivity. TRIUMF proposed to use an optical transition radiation (OTR) detector to monitor the proton beam properties immediately in front of the neutrino production target. The OTR system was successfully completed by Canadian collaborators at York University and University of Toronto. Former T2K spokesperson, Takashi Kobayashi remarked "Without the collaboration with TRIUMF, the T2K beam facility would not have been completed".

A complex of near detectors was necessary to measure the neutrino beam properties prior to their oscillation. TRIUMF's technical resources and experience in detector design led to the Canadian group taking responsibility for the most critical elements of the near detectors, the Fine Grained Detectors (see Fig. 1) and the Time Projection Chambers (see Fig. 2). Following a period of 5 years to design, prototype, construct, and test, the detector systems were installed in Japan in 2009. These systems were completed as a collaboration between TRIUMF, UBC, University of Victoria, University of Regina, and international partners.

The far detector, Super-Kamiokande (SK), was in operation prior to the formation of T2K. Some members of the

SUMMARY

A brief history of the T2K project in Canada, a pillar of Canada's involvement in global neutrino physics, as presented at the TRIUMF 50th Anniversary Science Symposium.

Fig. 1 Fine grained detectors under construction in the cleanroom at TRIUMF. From left to right: Joanna Zalipska (NCBJ, Warsaw), Robert Henderson (TRIUMF), Hiro Tanaka (SLAC), Scott Oser (UBC), Daniel Brook-Roberge (Rival Tech).

Dean Karlen
<karlen@uvic.ca>,
on behalf of the T2K-Canada group

Department of Physics, University of Victoria, 3800 Finnerty Rd, Victoria, BC V8P 5C2

and

TRIUMF 4004 Wesbrook Mall, Vancouver, BC V6T 2A3

Fig. 2 Time projection chamber under construction in clean-room at TRIUMF under the watchful eye of Robert Henderson (TRIUMF).

Fig. 3 Canadian group members visiting J-PARC during neutrino beamline construction. From left to right: Akira Konaka (TRIUMF), Peter Kitching (TRIUMF and U Alberta, ret.), John Martin (IPP and U Toronto, ret.), Richard Helmer (TRIUMF, ret.), Dean Karlen (UVic and TRIUMF), Jean-Michel Poutissou (TRIUMF, ret.), Slavic Galymov (IPN Lyon), Thomas Kutter (LSU)

Canadian group joined the SK group and introduced new methods to analyze SK data, significantly improving the detector performance. Under Akira's leadership, Canada had significant involvement in all aspects of the T2K experiment (see Fig. 3).

A special seminar was scheduled for March 11, 2011, at 3:00 pm, at the Japanese laboratory, KEK, to reveal the first results from the T2K experiment. At 2:46 pm, a magnitude 9 earthquake struck Japan, followed by devastating tsunami waves on the east coast. At the J-PARC laboratory, 200 km from the epicentre, there was significant upheaval of roads, but the buildings and accelerator were not severely damaged. The accelerator was brought back into operation before the end of 2011, and the T2K experiment was collecting data again within one year of the earthquake. The data collected by 2011 showed evidence (at the 3-sigma level) that all three types of neutrino oscillation occur. One additional year of data was required to make that conclusion definitive (i.e., more than 5 sigma), during which time the observation was confirmed by other experiments studying the oscillation of neutrinos from reactors. For this discovery, T2K shared the 2016 Breakthrough Prize in Fundamental Physics with 5 other collaborations. The experiment continues to collect data to measure possible difference between neutrino and anti-neutrino oscillation and to determine the mass ordering of the neutrino mass states.

T2K has been a great training ground for the future scientists in Canada and around the world. There have been more than 120 Canadians involved since its inception, and several students and postdocs now hold faculty positions in Canada, the US, and abroad.

Canadian participation in T2K has been a tremendous success. Only with a laboratory like TRIUMF could a large group be established and accomplish so much in such a short time. The combination of excellent technical resources and highly knowledgeable and enthusiastic staff at TRIUMF allows Canadian scientists to come together and lead major international projects at the forefront of science.

The former T2K spokesperson, Takashi Kobayashi, asked to summarize the role of TRIUMF in T2K said, "Long and extremely fruitful collaboration with TRIUMF has been essential for the success of the T2K experiment. We really appreciate the essential contribution from TRIUMF on many aspects of the T2K experiment and we would like to continue and further strengthen our collaboration toward the next generation experiment, Hyper-Kamiokande."

^{119}Sb: Production, Radiochemical Separation, and Chelation of a Promising Candidate for Targeted Radionuclide Therapy

by Jenasee Mynerich[1], Thomas I. Kostelnik, Aeli P. Olson, Atanaska Marinova, Dmitry Filosofov, Paul Schaffer, Jonathan W. Engle, Cornelia Hoehr, and Valery Radchenko

Summary

Cyclotron production, separation chemistry, and proof-of-principle chelation applicable to the Auger-electron emitter ^{119}Sb ($t_{1/2}$ 38.1 h) has been explored to promote further development of this radionuclide as a candidate for targeted radionuclide therapy for cancer.

TRIUMF, Canada's national accelerator centre located in Vancouver, B.C., is home to the world's largest cyclotron as well as multiple smaller cyclotrons, advanced laboratories, and equipment. With these resources at hand, the Life Science Division at TRIUMF has developed a research program centred on the production and medical application of various radioisotopes including the treatment of cancer.

Cancer incidence continues to increase globally, with a staggering projection of 26 million new cases and 17 million cancer deaths per year by 2030 [1-3]. Clearly, there is a need for improvements to current treatments and development of new ones to address limitations. For the most common cancers, including prostate cancer in men and breast cancer in women, surgery is the primary method of treatment, often supported by radiotherapy or chemotherapy [4]. Surgery and traditional radiotherapy (external beam therapy) are most effective when the tumour is large or localised; however, as metastases form elsewhere in the body, these treatment options are rendered ineffective — not to mention impractical. In these cases, the use of Targeted Radionuclide Therapy (TRT) can be extremely effective.

TRT is based on the idea of selectively delivering dose to target cells while minimizing radiation exposure to healthy tissues [5]. This is commonly achieved by "radiolabeling" a targeting vector (e.g., peptide or antibody) with a therapeutic radionuclide. The direct radiolabeling of unmodified targeting vectors is seldom permissible for subsequent *in vivo* use, thus small organic molecules known as "bifunctional chelators" are typically attached to targeting vectors to permit safe delivery of the radioactive cargo [5]. Since the therapeutic capacity of so-called "radiopharmaceuticals" is directly linked to the decay properties of the employed radionuclide, selecting the ideal therapeutic nuclide is imperative. The choice is based on a number of factors including its emission type, range/energy of emission, and half-life [6,7].

For TRT, useful emissions include alpha particles, beta particles, and Auger electrons. Each of these interact differently in the body based on their Linear Energy Transfer (LET), or the amount of energy deposited per unit length (keV/µm). Alpha particles and Auger electrons have a high LET, meaning they deposit their energy over a short tissue range, ultimately producing dense regions of ionization capable of inducing cell death [7]. In contrast, beta particles have a much lower LET and are less likely to cause irreparable damage to target cells (via double-strand DNA breaks).

Particle energy and LET will determine how far the particle travels in biological medium. Beta particles have a typical range of 1-10 mm in media, while alpha particles will travel no more than 100 µm, or a few cell widths, as depicted in Fig. 1 [7]. Accordingly, beta particles are better suited to treat larger tumours, while alpha particles will be more effective in treating smaller tumours (notably metastases). Of current interest are Auger electrons, which have an even shorter tissue range of just 0.01-10 µm [8]. This extremely short tissue range promises targeting specificity at the scale of a single metastatic cell's nuclear DNA, which could prevent the spread of solid tumours elsewhere in the body.

1 Jenasee was the winner of the TRIUMF Student Symposium (X2). She received a travel bursary to attend the Targeted Alpha Theory Symposium (TAT11), April 1-4, 2019, in Ottawa, ON. She also presented this work as an invited talk at the Canadian Organization of Medical Physicists conference in Kelowna, BC, Sept. 24-27, 2019.

Jenasee Mynerich <mynericj@mcmaster.ca>
Nuclear Medicine Research Assistant, Life Science Division, TRIUMF/ Honours Medical & Health Physics Co-op Student, McMaster University, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3

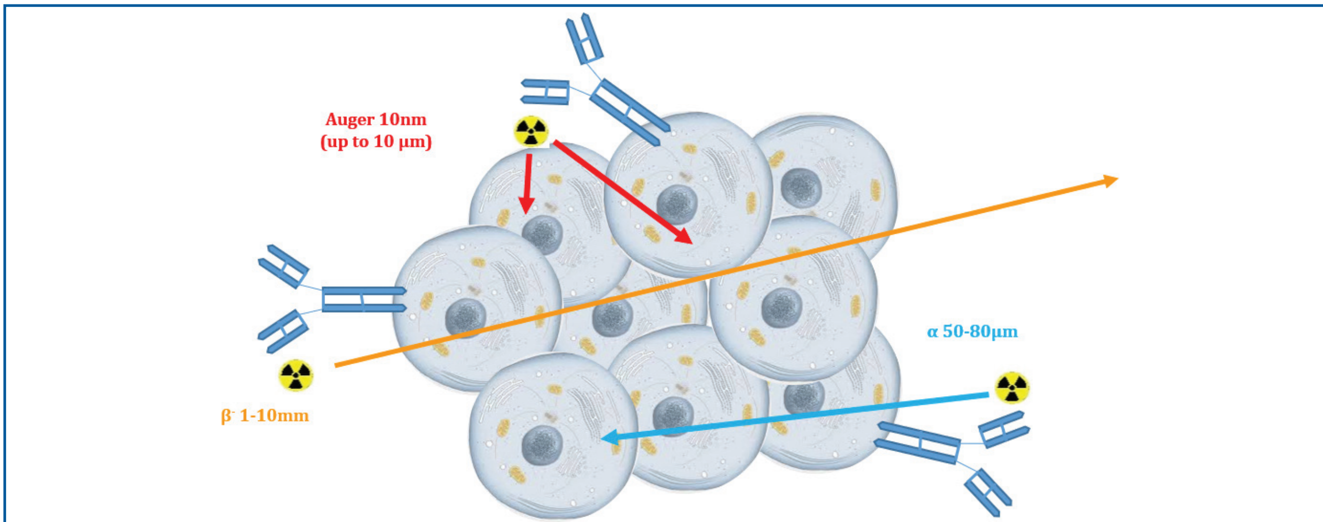


Fig. 1 Representation (not to scale) of the range of various charged particles in tissue.

Despite the therapeutic potential of Auger emitters, they have been the focus of limited research. The major deterrent is the common belief that their short decay range necessitates transport inside the cell to exert a significant therapeutic effect. Furthermore, initial calculations predicted only one single-strand DNA break per decay of most Auger emitters [8]. More recent work, however, has shown through Monte Carlo simulations that multiple single strand and double strand DNA breaks are possible due to indirect effects of Auger cascades, including creation of radical species that can damage DNA [9].

In 2001, Bernhardt *et al.* identified five Auger-emitting radionuclides as ideal candidates for TRT, based on their low photon-to-electron ratio, electron energy, half-lives, production capabilities, and chemical properties [10]. Among these candidates was ^{119}Sb, with a half-life of 38.1 h and 100% decay through electron capture. This enables ample time for delivery of the radionuclide and the lack of photon emission reduces dose to surrounding tissue [11]. Antimony-119 can be easily produced via the ^{119}Sn(p,n)^{119}Sb reaction on small medical cyclotrons with proton energies between 6-13 MeV. Estimated cross-sections are 400-600 mb for 10-13 MeV protons [11]. Despite favourable decay properties and a feasible production route, little research has been focused on the use of ^{119}Sb.

This article will briefly describe the recent efforts of a collaboration between the Life Sciences Division at TRIUMF, the Medicinal Inorganic Chemistry Group at the University of British Columbia (UBC) Chemistry Department, the University of Wisconsin-Madison, and the Joint Institute for Nuclear Research (JINR, Dubna) on the production of Sb isotopes from natural Sn targets, subsequent separation chemistry, and proof-of-principle chelation (radiolabeling).

TABLE 1

NATURAL ABUNDANCES OF STABLE ISOTOPES OF TIN. [12]

Isotope	Natural abundances (%)
Sn-112	0.900(3)
Sn-114	0.61(1)
Sn-115	0.350(6)
Sn-116	14.07(8)
Sn-117	7.54(3)
Sn-118	23.98(3)
Sn-119	8.620(3)
Sn-120	33.03(12)
Sn-122	4.78(1)
Sn-124	6.110(6)

METHODS

Cyclotron Production

Antimony radioisotopes were produced by a 60 min irradiation of a 0.1 mm thick natural Sn foil with approximately 13 MeV protons and 5 μA current. The natural abundance of Sn isotopes is shown above in Table 1 [12]. This leads to the production of a variety of radio-Sb isotopes including ^{117}Sb ($t_{1/2}$ 2.8 h), ^{118}Sb ($t_{1/2}$ 5.0 h), ^{119}Sb ($t_{1/2}$ 38.1 h), and ^{120m}Sb ($t_{1/2}$ 5.76 d). Of interest to us were ^{117}Sb which decays to ^{117m}Sn ($t_{1/2}$ 14 d) and ^{120m}Sb, which we used as tracers of Sb and Sn in radiochemical processes. These radionuclides have longer half-lives, enabling more time to work with produced material and better gamma emissions for detection with a high-purity

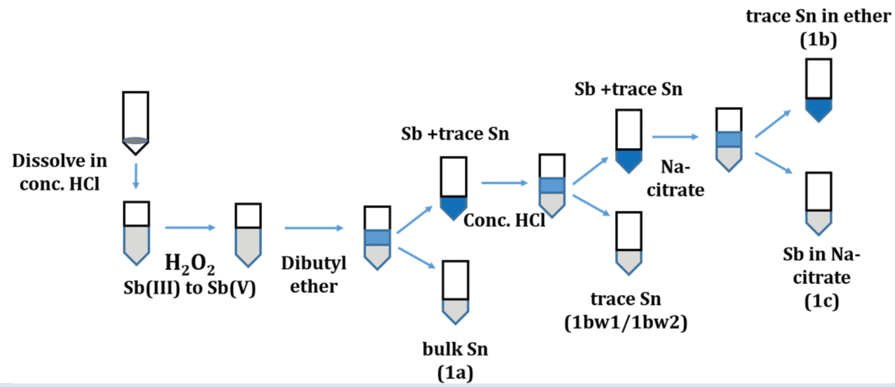


Fig. 2 Schematic of liquid-liquid extraction procedure to separate Sb from Sn target material after dissolution in concentrated hydrochloric acid.

germanium (HPGe) detector. A typical run produced about 1.5 MBq of ^{120m}Sb at end of bombardment (EOB).

While irradiation of natural tin targets is sufficient for research purposes, an enriched ^{119}Sn target would be ideal in future production of ^{119}Sb radiopharmaceuticals, to maximise ^{119}Sb yield and minimise the presence of impurities. Our collaborators at the University of Wisconsin-Madison have been investigating the production of thick enriched ^{119}Sn targets through electrodeposition from simple acidic solutions, as well as recovery of target material post-irradiation. At present, they have achieved successful deposition of natural tin with mass exceeding 500 mg/cm^2 [13]. Targets of this mass are thick enough to stop a 16 MeV proton beam, which is important for maximising production, and have withstood up to 40 µA of current. For these irradiation parameters, a 95% enrichment of ^{119}Sn is expected to produce a tenfold increase in the yield of ^{119}Sb, a significant amount suitable for radiopharmaceutical production [13].

Chemical Separation

To chemically separate the radio-Sb from bulk Sn, our process requires dissolution of the foil target in concentrated hydrochloric acid (HCl). Initial work involved establishing and standardizing a liquid-liquid extraction procedure, whose groundwork was developed by collaborators at the JINR in Dubna, Russia. Later work involved transferring to an ion-exchange separation strategy to improve reproducibility of separations and reduce the amount of hands-on work (and thus hand dose) involved.

Liquid-Liquid Extraction

Liquid-liquid extraction is a routine separation technique in chemistry. The general principle is to separate substances based on their solubility in two immiscible liquids (i.e., an organic (non-polar) and aqueous (polar) solvent). Non-polar substances will be more soluble in the organic solvent while polar substances will be soluble in the aqueous solvent. This was the basis for the liquid-liquid extraction procedure developed. It should be noted that while our current understanding of this established process has allowed us to form a number of hypotheses around the observed phenomenon, we have yet to empirically confirm exact chemical speciation. Below is an account of our current understanding based on qualitative observations.

In this procedure, Sb was extracted from the HCl target solution first into an ether solution, then back-extracted into an aqueous solution, as subsequent radiolabeling is preferred in aqueous solvents over organic solvents. Figure 2 shows a schematic of the separation procedure. To begin, hydrogen peroxide (H_2O_2) was added to the target solution to oxidize Sb from Sb(III) to Sb(V), and Sn from Sn(II) to Sn(IV). After oxidation, dibutyl ether was added in equal volume to the target solution. After sufficient mixing, the phases were allowed to settle so that the ether rested above the HCl. The ether, containing Sb(V) and trace Sn(IV), was transferred to another vial. Two washes with equal volumes of concentrated HCl removed the remaining Sn(IV). After the second wash, dilute sodium citrate (Na-citrate) was added in equal volume to the ether to back-extract Sb(V) into aqueous Na-citrate, with any trace Sn(IV) remaining in the ether.

To track the movement of Sb and Sn during the separation, aliquots were taken from the target solution, the first HCl extract (1a), the first HCl wash (1bw1), the second HCl wash (1bw2), the ether after back-extraction (1b), and Na-citrate after back-extraction (1c). These aliquots were each placed in a HPGe detector and counted to identify which radionuclides were present. The 197.3 keV gamma line from ^{120m}Sb (γ = 0.87) and 158.6 keV gamma line from ^{117m}Sn (γ = 0.86) were used to quantify the amount of each isotope present. Five sequential runs resulted in an average yield of 81.7 ± 0.1% of ^{120m}Sb in the final product.

Ion-Exchange Extraction

While the liquid-liquid extraction resulted in several successful separations, the process relied heavily on the user and the distinction between the organic and aqueous phases, which was often inconsistent. If there was greater overlap in the phases, less of the Sb-containing phase was taken to prevent additional contamination with removed Sn, resulting in a reduced activity of ^{120m}Sb in the final product. Ion-exchange extraction offered a more reproducible and robust method of separation.

Solid-phase extraction involves passing the initial solution through a resin upon which the desired compound is absorbed while all other contaminants pass through. Once adsorbed, the desired compound can then be eluted from the column with another solvent. A particular type of solid-phase extraction is ion-exchange chromatography, in which the resin adsorbs certain species based on their charge. In cation-exchange chromatography, the resin adsorbs positively charged species, while anion-exchange does the opposite.

For the separation of Sb from Sn, a cation-exchange resin was used based on results reported by Kraus *et al.* [14]. This method requires the oxidized states of Sb and Sn, as Sb(V) will be slightly better retained than Sn(IV) on the resin. Figure 3a shows a schematic of the separation using cation exchange. All solutions passing through the column were collected in 1 mL fractions that were later counted in the HPGe detector to follow the movement of ^{120m}Sb and ^{117m}Sn. Similar to the liquid-liquid extraction procedure, H_2O_2 was used to oxidize Sb(III) to Sb(V) and Sn(II) to Sn(IV). The target solution was then loaded onto the cation exchange column which was preconditioned with various concentrations of HCl and deionized distilled water. The loaded target solution was allowed to drip through by gravity. The column was then washed with concentrated HCl to remove any trace Sn(IV) from the resin. Finally, the Sb(V) was eluted with sodium hydroxide (NaOH). The results of one run are shown in the elution curve in Figure 3b. Initial runs were very promising with greater than 95% of ^{120m}Sb in the NaOH fractions, and no detectable ^{117m}Sn.

Chelation

As mentioned previously, TRT relies on the chelation of a radioisotope with an organic molecule, known as the (bifunctional) chelator or ligand, which can then be attached to a bio-molecule of some kind. Identifying a chelator that can securely bind the radioisotope can be difficult, and depends on the charge, size, and chemical properties of the radioisotope, as well as reaction conditions such as time, temperature, pH, and concentration. To quantify radiolabeling yields, radio-thin-layer-chromatography can be used. Radio-TLC is similar to solid-phase extraction where a thin sheet (usually aluminum or paper) with a thin layer of adsorbent material (usually silica gel) is spotted with a small amount of a mixture solution and placed in a developing solvent. The components of the mixture will migrate different distances up the sheet based on their interaction with the adsorbent material and solvent. In radio-TLC migration of the radioisotope is tracked using a gas-proportional counter that can scan the plate and detects any betas/gammas emitted as a function of distance on the plate. The complexed radioisotope will often remain at the baseline whereas the free radioisotope will be carried up the plate.

To attempt to chelate Sb, a trithiol ligand (provided by Dr. Sylvia Jurisson and Yutien Feng from the University of Missouri) was used. This ligand had been used to successfully complex As(III), which sits just above Sb on the periodic table. For testing of chelation, the final back-extract from the liquid-liquid extraction containing radio-Sb(V) in a Na-citrate solution was used. Initial experiments in which Sb(V) was directly labelled were unsuccessful. Radiolabeling following reduction of Sb(V) to Sb(III) produced promising results. The first run yielded 66% complexed ^{120m}Sb, calculated by dividing the counts under the complexed peak by the total counts in the spectrum.

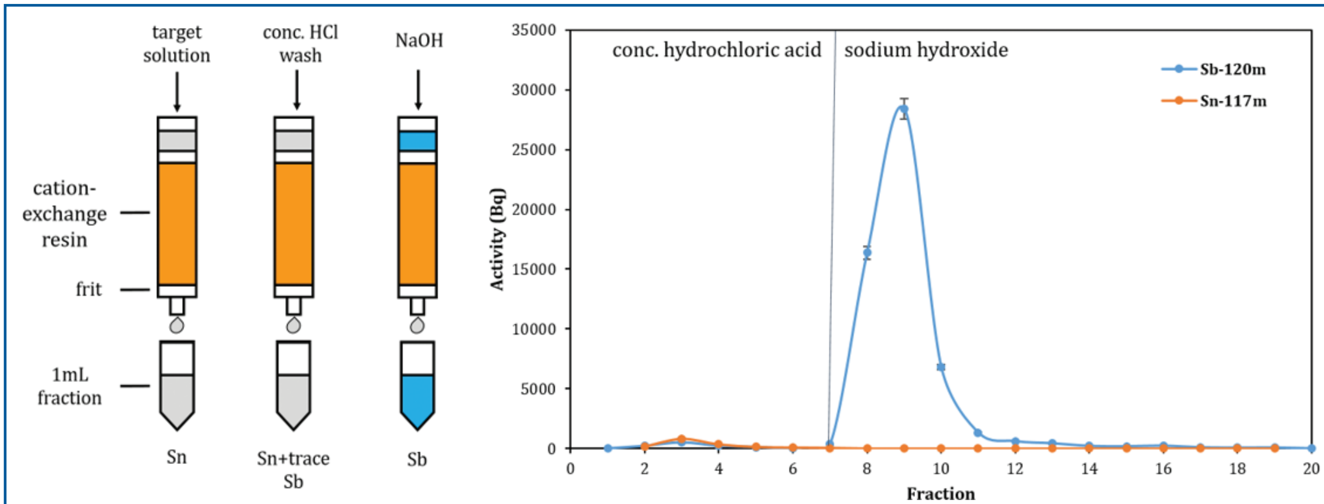


Fig. 3(a) Schematic of separation of Sb from Sn using a cation exchange resin after dissolution of target in concentrated hydrochloric acid. Sb was eluted with sodium hydroxide. (b) Elution curve showing activity of tracers ^{117m}Sn and ^{120m}Sb in each fraction collected. Fractions 1-6 contained the target solution and washes in hydrochloric acid. Fractions 7-20 contained the sodium hydroxide elutions.

FUTURE DIRECTION

After demonstrating production, various potential separation strategies, and chelation of ^{120m}Sb as a tracer of ^{119}Sb, future work will focus on optimizing these procedures. Work on the electrodeposition and recycling of Sn for future enriched ^{119}Sn targets continues as a priority at the University of Wisconsin-Madison to increase yields of ^{119}Sb. Experiments for the separation of Sb from Sn via cation exchange will look towards establishing a system that elutes the majority of the Sb from the column in a small volume of a solvent that is suitable for radiolabelling. While initial tests were encouraging, there is much work to be done on the chelation front, in terms of optimizing radiolabeling parameters (pH, time, temperature) with the trithiol ligand and exploring other potential chelators. Stability of the labelled complex and bi-functionalization of chelators can be examined for eventual *in vitro* and *in vivo* studies. This work will be the foundation to potentially bring ^{119}Sb radiopharmaceuticals into the clinic for cancer treatment.

ACKNOWLEDGEMENTS

Thanks to Prof. Silvia Jurisson and Yutian Feng from the University of Missouri for providing the trithiol ligand. Thanks to Linda Graham and David Prevost, the TR13 operators, for the irradiation and removal of countless targets.

TRIUMF receives funding from the National Research Council of Canada.

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TRIUMF: FROM MESONS TO RARE RADIOISOTOPES

BY JOHN D'AURIA AND GEOFF D'AURIA

John M. D'Auria, professor emeritus, Simon Fraser University, Fellow of the American Physical Society. John D'Auria completed this interview three months before his death.

SUMMARY

Three months before his death, Simon Fraser University Professor (Emeritus) John D'Auria dictated the following recollection on the history of rare isotope science at TRIUMF to his son Geoff. John is considered one of the "founding fathers" of the rare isotope program at TRIUMF, which is now the primary research focus of the laboratory.

AN INTERVIEW WITH JOHN M. D'AURIA BY HIS SON GEOFF

Tell me about the transition TRIUMF made from its early scientific program to what it has become today.

Usually a facility has a lifespan of about 20 years and is dedicated to one main type of science or physics. The TRIUMF facility, built in the early '70s, was constructed to study and use mesons in different types of physics and non-physics experiments. After 20 years, and a good program of scientific results, it was considered time to close.

An attempt was made to upgrade the facility, to improve its production capabilities at higher energy, and it was called KAON. But the price tag proved too high for Canada.

However, scientists at the lab pulled a switcheroo, a major change in focus.

What happened?

Using the high proton production capabilities of the intense proton beam, the facility decided to make rare (radioactive) isotopes.

But it wanted to do something unique.

It was known from locations in Europe — CERN — that one could produce rare isotopes on an ISOL (isotope separator online) device.

Luckily, a small group at TRIUMF studied and learned how to use the 500 MeV intense proton beam to make rare isotopes. This resulted in a new prototype facility called TISOL.

At the TISOL facility, some key experiments were performed.

[This was the Red Giant experiment]

The experiment was important. There was a reaction: alphas plus carbon to make O16. They needed to know where this reaction took place, what was the resonance energy. Since we couldn't use alphas because of the Coulomb barrier, we did the reaction in reverse. Alphas plus carbon-12 make nitrogen-16; nitrogen-16, when it decays, gives you carbon-12 and alphas. So we studied the reaction in reverse. That was unique.

What effect did TISOL have on the future direction of TRIUMF?

TISOL showed there were good experiments you could do [with this approach].

You have to remember, TRIUMF was a meson facility. Now they were showing we can also do rare isotope experiments.

With the anticipated demise of TRIUMF on the horizon, the director of TRIUMF switched the focus of the science at TRIUMF to the science of rare isotopes.

But the unique feature added was to then accelerate these rare isotopes to energies of importance to studying reactions occurring in exploding stars.

It turns out there were four major components of this: spectroscopy, fundamental physics testing the Standard Model, condensed-matter physics, and the most important — the initial driving force — the use of an accelerator with the rare isotopes to study key reactions occurring in exploding stars.

In order to achieve this important goal, which drove the facility, one needed an ISOL device, one needed an appropriate low-velocity accelerator, and one needed a facility in which to measure the reaction of interest.

[No one knew how to build the low-velocity accelerator of the variety required to reach this goal. So, the TRIUMF team built it.]

And so ISAC was born. The name "ISAC" refers to the combination of an ISOL device with an accelerator.

And the many scientists at TRIUMF had to start learning a new language.

The first reaction we studied was sodium-21 plus a proton to make magnesium-22.

How is that experiment performed?

The half-life of sodium-21 is, I don't know, minutes. So you can't study that reaction with a proton beam, right? So, you study it with a sodium-21 beam on a hydrogen target.

Now, how do you get sodium-21?

You take 500 MeV protons hitting a silicon target. One of the products is sodium-21. You diffuse it out, you ionize it. Once you've ionized it, you can control it. You [then] take it through your low-velocity RFQ accelerator to give it the right velocity to match the velocity of the stellar reaction.

So, you've got this sodium-21 hitting hydrogen, picking up the proton, and becoming magnesium-22.

How do you separate the magnesium-22 produced from the sodium-21 in the beam?

We built the so-called very elaborate mass separator device called DRAGON.

It separates mass. You're separating mass 21 from 22, [which is] very hard. You have a beam of about, let's say, 15,000 beams/second. How do you pull out one reaction from that? You have to take advantage of the mass difference between 21 and 22. That's all DRAGON is.

With the success of the first Dragon experiment on sodium-21, other experiments followed. With the successful production of rare isotopes at ISOL, the other major areas of research profited with major results.

A fifth group that joined was the TITAN mass measurement group, measuring all sorts of exciting masses of very short[-lived] isotopes [very exotic isotopes].

The bottom line was this 20-year old accelerator lab, TRIUMF, was given a new life and can now live another 30 years.

What resulted from the success at ISAC1?

Ultimately, with the success of ISAC1, ISAC2 was built.

The accelerator for ISAC1 accelerated particles below the Coulomb barrier to match stellar reactions. ISAC2 was built to accelerate these rare isotopes to above the Coulomb barrier.

[Nuclear reactions that happen above the Coulomb Barrier are those that happen in super nova and create the very heavy elements in the universe.]

Finally, given the large number of facilities built to receive beams of rare isotopes at TRIUMF, but with the availability of only one beam, they decided to make another facility to make more beams. This was called ARIEL. And they also developed new ways of making these beams.

Are ISAC1, ISAC2, and ARIEL limited to physics research?

[No.] In addition, methods were found to allow large production of medical isotopes for commercial purposes in the new facility.

Think of a pencil. That's what the target for an ISOL looks like, a pencil. A beam goes through it. It gets heated. Stuff comes out. But you're only using about 30 per cent of the beam. You put another pencil behind it and use that for medical isotope production, independently.

[So, for every experiment, you're also creating medical isotopes as a byproduct.]

So, what is TRIUMF today?

[In short,] TRIUMF was built to do meson and proton physics studies, nuclear physics. What we did was converted it into a device to make rare isotopes, which are studied.

In this transition from mesons to rare isotopes, a facility has been created that is essentially unique in the world using old technology to do new science.

John D'Auria passed away on October 22, 2017 at the age of 78. At the time of his passing he was still active in developing a program to produce at TRIUMF the therapeutic medical isotope 225Ac, the "Rarest Drug on Earth". The project recently achieved a major success with the first joint production run of the isotope.

-John D'Auria and Geoff D'Auria, October 2019

Interview de Jean-Michel Poutissou, Récipiendaire de la Médaille de l'ACP 2018 pour Contributions exceptionnelles de carrière à la physique (par Béla Joós, 12 juin 2018)

B. Joós: Félicitations d'abord pour votre prix.

J.-M. Poutissou: Merci beaucoup. Oui. Je dois dire que c'est quelque chose qui me fait très plaisir en ce sens qu'avoir la reconnaissance des personnes avec qui on travaille et des collègues physiciens canadiens — cette évaluation par mes pairs — est une référence très importante.

B. Joós: Oui. Ils vous ont mis de l'avant aussi. Donc c'est déjà un signe d'estime. Vous êtes d'origine française ?

J.-M. Poutissou: Oui.

B. Joós: Et votre parcours ? Comment êtes-vous arrivé au Canada ?

J.-M. Poutissou: Lorsque je finissais mes études d'ingénieur en France, j'étais dans la filière scientifique des années 60 qui visait à former des ingénieurs pour développer le Programme des réacteurs nucléaires français. Après l'école d'ingénieurs, (j'ai fait INSA Lyon) je devais aller à l'Institut de Grenoble qui formait les ingénieurs en techniques nucléaires pour le Commissariat à l'Energie Atomique (CEA) et je serais rentré dans la filière CEA. Mais mon professeur de mécanique quantique (Professeur Davoine) connaissait très bien le professeur Paul Lorrain — celui du livre d'électromagnétisme D. Corson et P. Lorrain — qui était le directeur du département de physique à l'Université de Montréal, et voulait monter un programme de physique nucléaire autour d'un accélérateur Tandem Van de Graff.

Ils m'ont donc suggéré de faire une demande de bourse auprès du Conseil des Arts du Canada. J'ai obtenu cette bourse qui m'offrait un séjour de deux ans au Canada.

B. Joós: Pour un diplôme spécifique ?

J.-M. Poutissou: Pour faire ma maîtrise en physique nucléaire à l'Université de Montréal. J'ai donc échappé au courant en France où tout le monde partait faire du réacteur nucléaire pour venir à Montréal et y faire une maitrise et de la recherche. Mais en arrivant, j'ai alors découvert que le laboratoire n'était encore pas complètement établi. Il y avait un grand trou et on commençait la construction des bâtiments. P. Lorrain essayait de trouver justement du personnel pour faire marcher le laboratoire de physique nucléaire attaché au Département de physique de l'Université.

B. Joós: Quelle année ?

J.-M. Poutissou: 1965. L'Université de Montréal venait d'acquérir l'accélérateur tandem de AECL à Chalk River qui était disponible et a fait construire un laboratoire autour de ce système. Quand je suis arrivé, il a fallu déballer tous les morceaux du Tandem, nettoyer tous les éléments et remonter l'accélérateur. Il fallait aussi construire des lignes de faisceaux vers les positions d'expérience (celles de Chalk River ne venaient pas dans le contrat). Donc c'est comme ça que j'ai commencé à utiliser mes connaissances d'ingénieur. Je suis venu pour deux ans au début. Et après, ça s'est enchaîné. Au bout de deux ans, j'ai eu une autre bourse qui venait des accords France-Québec pour finir ma maitrise. A l'époque, on nous avait promis que grâce à ces bourses, les diplômes obtenus au Canada seraient reconnus en France. Donc on pouvait facilement réintégrer les centres de recherche français. Ça, ne s'est jamais fait. Ce n'est toujours pas fait d'ailleurs. C'est très difficile à faire. Entre-temps, j'ai rencontré ma femme qui est Québécoise et qui faisait aussi sa maitrise dans le même laboratoire.

B. Joós: Donc elle est physicienne ?

J.-M. Poutissou: Elle est physicienne. Oui, On a fait toute notre carrière ensemble. Elle faisait sa maîtrise aussi à ce moment-là et éventuellement, on s'est marié. Etant français, j'ai du faire mon service militaire français que j'ai fait en coopération en restant au labo, en faisant ma thèse de Ph.D. Donc tous les deux, on a fait notre doctorat, moi avec le professeur Del Bianco et elle avec H. Jeremie. A ce moment-là, le laboratoire était dirigé par le professeur René Lévesque qui avait succédé à P. Lorrain et était un très bon physicien. Quand il a pris sa retraite du département de Physique, Pierre Depommier, qui est aussi Français, est venu diriger le laboratoire de Physique nucléaire.

B. Joós: Oui, le Professeur Pierre Depommier.

J.-M. Poutissou: Oui. Donc j'ai commencé à travailler avec lui. Pierre Depommier, qui terminait une expérience fondamentale au CERN, avec entre autre C.Rubbia et V.Soergel, a donné un cours sur les interactions faibles qui était absolument fantastique. Essentiellement, c'est là que j'ai décidé que c'était ce que je voulais faire, c'est-à-dire que je suis passé de la physique nucléaire traditionnelle à essentiellement la physique des particules et à l'étude des interactions faibles. Donc ça, c'était le déclencheur.

Quand j'ai fini mon Ph. D. en 72. je cherchais où faire des études postdoctorales. J'avais une offre à Heidelberg et aussi une offre à Saskatoon avec Bill Shin. Pierre Depommier avait proposé deux expériences à TRIUMF sur les désintégrations de pions et des muons, qui ont été approuvées. Pierre Depommier m'a dit : « non, non, tu viens dans mon groupe. Tu vas aller à TRIUMF et tu seras le représentant de notre groupe là-bas. Et tu vas monter nos expériences là-bas ». Donc c'est comme ça que je suis venu à TRIUMF. C'était en 1972. Je suis venu avec un titre de boursier postdoctoral pour deux ans qui a été renouvelé une fois. Entre-temps, ma femme a fini son Ph. D. … après avoir eu deux enfants. Elle aussi cherchait un poste et Pierre Depommier lui a offert un poste à temps partiel dans son groupe, ce qui était idéal pour nous pour pouvoir gérer la famille. Éventuellement, on a fait toute notre carrière à TRIUMF tous les deux.

B. Joós: Très bien. Alors, TRIUMF célèbre son 50e anniversaire.

J.-M. Poutissou: 50e anniversaire. C'est-à-dire que c'était, je pense, le 16 avril 1968 que le premier chèque pour la construction du cyclotron est arrivé.

B. Joós: Donc vous étiez au tout début de l'aventure de TRIUMF ?

J.-M. Poutissou: Oui ou presque , de la même façon que j'étais arrivé à Montréal…

B. Joós: Devant un trou ?

J.-M. Poutissou: Quand je suis arrivé à Vancouver, le trou de TRIUMF était déjà couvert. Il y avait une partie de l'accélérateur qui était prête, mais il fallait obtenir le champ magnétique correct pour pouvoir faire marcher le cyclotron. C'était l'élément le plus critique et cela a retardé le démarrage de l'accélérateur. Donc j'ai passé effectivement mes deux premières années de travail à TRIUMF à construire la ligne de faisceau 1A, la ligne à haute intensité, puis la ligne de muons pour pouvoir enfin monter les expériences pour lesquelles j'étais venu. Mais finalement, quand on regarde en arrière, ça m'a permis d'avoir une connaissance très détaillée du laboratoire que peu de gens ont maintenant. Je connaissais absolument tout le monde, tous les techniciens, les spécialistes des accélérateurs, les gens des sources d'ions, les systèmes de contrôle ... tout. Et donc j'ai eu une compréhension et aussi une relation avec le personnel de TRIUMF qui m'a aidé beaucoup par la suite puisque je faisais partie intégrale de la famille TRIUMF.

B. Joós: Et vous vous sentiez encore ingénieur-physicien ? Parce que vous construisiez quelque chose.

J.-M. Poutissou: Bon. Quand on rentre dans le domaine de la physique des particules, il y a de très grandes variétés de qualification qui sont requises pour monter des expériences. Je dirais que je me qualifierais plus comme expérimentateur et plus précisément un spécialiste en instrumentation, technologie, prise de données, systèmes de détection etc… Je me qualifie plus comme un instrumentaliste finalement. Au début, comme j'avais travaillé à l'Université de Montréal sur la détection des photons d'assez haute énergie à l'aide de cristaux d'iodure de Sodium (NaI), j'ai joint le groupe du Professeur D. Measday à UBC qui voulait pouvoir détecter des photons de beaucoup plus haute énergie avec de très gros cristaux de NaI et cela était aussi nécessaire pour les expériences de Montréal. Donc nous avons joint nos compétences et acheté deux gros cristaux de NaI, TRIUMF Iodure de Sodium (TINA) et Montréal Iodure de Sodium (MINA). Par la suite, j'ai travaillé avec d'autres types de spectromètre gamma, spectromètre électrons etc..

B. Joós: Donc vous avez vu l'évolution de toutes ces méthodes de détection qui prennent des particules chargées et des photons et les convertissent en signal électrique ?

J.-M. Poutissou: Oui. Tandis que ma femme elle, elle s'est mise dans le système d'acquisition de données en ligne pour ces détecteurs.

B. Joós: Est-ce qu'on peut avoir son nom ?

J.-M. Poutissou: Oui, Renée Poutissou.

J.-M. Poutissou: Nous avons fait notre carrière ensemble et elle a participé presque à toutes les expériences dans lesquelles j'étais impliqué. On a fait partie de grandes collaborations aux États-Unis, au Japon et à TRIUMF bien sûr. Il fallait donc gérer la famille parce que...

B. Joós: Ah oui, parce que vous partiez ensemble.

J.-M. Poutissou: On partait généralement l'un après l'autre car il fallait toujours avoir quelqu'un avec la jeune famille.

B. Joós: Mais c'était quand même spécial de pouvoir partager des recherches semblables.

J.-M. Poutissou: Oui. Dans ce cas-là, ça a très bien marché en ce sens que ça nous a permis à chacun de savoir ce qui était nécessaire pour pouvoir faire ce qu'on avait à faire et donc il y n'avait pas de questions. Quand on disait : « moi, il faut que je travaille toute cette nuit et je ne peux pas être là ce soir », on comprend.

B. Joós: Elle va comprendre, oui.

J.-M. Poutissou: Et elle fait la même chose. Elle dit : « je suis appelée à 2 h du matin, il faut que je parte ». « D'accord. OK. » Bon, il faut tout changer. Donc il y a cette compréhension qui nous a permis de survivre. On a vécu vraiment en symbiose tout le temps.

B. Joós: Oui, parce que c'est une source de stress.

J.-M. Poutissou: Oui. Quand le partenaire n'est pas du tout dans le domaine, c'est difficile d'imaginer quelles sont les contraintes qui sont nécessaires ...

B. Joós: Mais oui.

J.-M. Poutissou: On a travaillé pendant 20 ans au Brookhaven National Laboratory (BNL) sur Long Island près de New York à partir de Vancouver. Après, cela fait 20 ans qu'on travaille au Japon à partir de Vancouver. Donc ce n'est pas facile à gérer tout le temps avec la vie de la famille.

B. Joós: Je comprends. Maintenant, juste pour votre carrière et votre reconnaissance de ce prix, je ne suis pas un expert dans le domaine. Et ceux qui vont lire ceci ne seront pas non plus experts. Donc est-ce qu'on peut résumer les thèmes ou ce qui a justifié qu'on vous ait accordé ce prix ?

J.-M. Poutissou: Oui. Alors, il y a deux grands volets, en fait. L'un comme physicien expérimental, l'autre comme administrateur « scientifique ». En 1988, ma carrière a changé brutalement lorsqu' Erich Vogt voulait absolument faire l'usine de KAON à TRIUMF. Et donc en 88, il obtient un financement de 11 millions de dollars pour faire une proposition technique détaillée, c'est-à-dire développer toutes les études pour s'assurer qu'on comprenne bien la validité des coûts de ce qu'il fallait construire et estimer quelle participation des pays étrangers pouvaient être obtenues .Il crée à l'intérieur du laboratoire une sous-section, KAON Factory, et il appelle Alan Astbury pour la diriger et a demandé à celui qui dirigeait la division scientifique de TRIUMF, qui était Peter Kitching à l'époque, d'aller épauler Alan et de développer le programme scientifique de KAON. Et il me demande de prendre en charge le laboratoire existant.

B. Joós: Le reste du laboratoire ?

J.-M. Poutissou: Donc je deviens directeur de la division Sciences et en même temps il me nomme aussi directeur adjoint parce que Erich voyageait beaucoup pour trouver des fonds à l'étranger. Il était rarement là. Donc il fallait quelqu'un qui fasse marcher…

B. Joós: Le jour le jour.

J.-M. Poutissou: Ma connaissance du labo et de son personnel m'a beaucoup aidé pour rentrer dans mon rôle. Cela a changé un peu ma fonction parce que là je suis devenu directeur adjoint du labo. Eventuellement KAON n'a pas été supporté par le gouvernement en 93. Alan Astbury est devenu directeur pour réorienter le laboratoire mais il m'a demandé de rester dans mes fonctions.

Par la suite, chaque fois que le directeur changeait, je donnais ma démission mais, le nouveau directeur me demandait de continuer. Et donc j'ai passé 21 ans à faire la direction du labo essentiellement.

Par contre, j'ai toujours insisté pour ne pas devenir un administrateur à plein temps. J'ai toujours eu une partie de mon temps qui était attaché à des expériences. Et donc, j'ai continué ce travail de recherche sur les interactions faibles que j'avais commencé avec les désintégrations des pions et des muons à TRIUMF, pour aller après à la désintégration des kaons au BNL (USA), puis ensuite on est passé aux neutrinos au Japon, mais toujours dans la même perspective.

B. Joós: Donc l'interaction faible est ce qui contrôle la séparation ...

J.-M. Poutissou: Par exemple, en physique nucléaire traditionnelle aux basses énergies, c'est la désintégration bêta des noyaux, qui est due au changement d'un proton en un neutron ou vice et versa. En fait, toutes les particules subissent la désintégration faible. Avec l'amélioration des accélérateurs, des lignes de faisceau et des systèmes de détection, on est passé des études avec des particules chargées comme les muons et les électrons au neutrino qui est la particule la plus élémentaire et qui subit seulement l'interaction faible. Donc là, vous n'avez pas à vous inquiéter des autres intéractions, l'intéraction électromagnétique ni l'intéraction forte. Donc c'est beaucoup plus simple. C'est le système le plus simple, sauf que ... ils sont très difficiles à détecter…

B. Joós: Donc la théorie n'a pas changé ? Il n'y a pas eu besoin de repenser la théorie de…

J.-M. Poutissou: Non. Exactement. C'est seulement le fait qu'on ait des accélérateurs beaucoup plus performants et qu'on a pu faire des faisceaux de neutrinos tellement intenses qu'on est capable de faire de la physique avec ces particules qui normalement n'étaient pas visibles. Il faut des détecteurs comme SNO (1 000 tons) pour pouvoir en détecter quelques uns par mois. Notre détecteur SK est une piscine de 50 000 t d'eau qui se trouve à 300 km de la source de neutrino.

B. Joós: Attendez. Là, vous parlez de votre collaboration avec…

J.-M. Poutissou: L'expérience T2K au Japon.

B. Joós: OK. Donc ça, justement, avant de sauter là-dessus, en parallèle avec toute l'entreprise de SNO, TRIUMF vise à développer une collaboration avec Kamiokande et les Japonais. Comment cela s'est-il produit ?

J.-M. Poutissou: Pendant les études pour le KAON Factory, on avait étudié comment produire assez de neutrinos à TRIUMF–KAON pour faire une expérience d'oscillation du genre de celles que nous faisons au Japon, avec des détecteurs qui auraient été mis dans la mine de cuivre désaffectée à Britannia Beach (BC). Ça, c'était pendant les années 88-90.

B. Joós: Donc l'idée d'oscillation des neutrinos remonte déjà à ...

J.-M. Poutissou: Ça remonte à 1948, à un papier qui a été publié au Canada par Ted Hincks et Bruno Pontecorvo. Et Bruno Pontecorvo est le premier qui a suggéré l'idée que si les neutrinos avaient une masse, ils pourraient possiblement faire des oscillations. Ça, c'était en 1948. Personne n'a relevé cette hypothèse car cela était en contradiction totale avec le Modèle Standard des particules qui suppose que les neutrinos ont une masse nulle.

B. Joós: Donc l'objectif était juste de résoudre la question de la masse ou non-masse du neutrino?

J.-M. Poutissou: Exactement, oui. J'étais président du comité du CRSNG qui monitorait la construction de SNO. SNO essentiellement essayait de montrer que la possibilité de faire des oscillations entre le soleil et la terre pouvait expliquer le fait que l'expérience de Ray Davis qui mesurait le flux de neutrinos émis par le soleil, trouvait toujours moins de la moitié de ce qui était attendu.

B. Joós: Exactement, mais vous avez un autre point de vue…

J.-M. Poutissou: Oui, mais c'est le même principe.

B. Joós: Même question, même principe.

J.-M. Poutissou: Dans les expériences de Ray Davis et de SNO, ou de Kamiokande, on utilise des sources de neutrinos qu'on ne contrôle pas : le soleil, le cosmos, les neutrinos atmosphériques. Par contre on est capable de faire des faisceaux de neutrinos nous-mêmes par accélérateur de très haute puissance, où on contrôle la source. C'est nous qui décidons quand les neutrinos partent, quelles sortes de neutrinos sont faits. Et donc on peut faire une expérience d'oscillation beaucoup plus précise.

B. Joós: Ça, c'est le T2K? Donc les Japonais ont un KAON Factory?

J.-M. Poutissou: Oui. Quand le Canada a décidé de ne pas construire une usine de KAON à Vancouver, il y avait une proposition américaine à Los Alamos, une proposition au Japon et une moins avancée en Europe. En 2002, les Japonais ont commencé à dire : «bon, c'est nous qui allons faire KAON». Comme nous avions travaillé beaucoup sur toutes les expériences qu'on pourrait y faire, nous nous sommes joints à leur effort.

Pour reprendre l'histoire — quand on a commencé à sentir que KAON ne serait pas supporté, en 93, notre groupe à TRIUMF s'est dit : «pourquoi est-ce qu'on n'essaie pas de faire cette expérience neutrino qu'on voulait faire à Brittania Beach, à Brookhaven où il y a un accélérateur (l'AGS) qui, bien que n'étant pas aussi performant que KAON, avait déjà des faisceaux de neutrinos?» Et donc, on a travaillé sur une proposition à Brookhaven qui nous permettait de faire une expérience d'oscillation en utilisant des détecteurs espacés sur Long Island, depuis Brookhaven jusqu'au bout de Long Island.

B. Joós: Donc 70 km?

J.-M. Poutissou: Oui. Nous avons développé une très, très belle proposition d'expérience avec A. Mann de l'Université de Pennsylvanie, BNL889. Durant la préparation de ce projet, un de nos étudiants coop travaillant sur la simulation de l'expérience eu comme projet d'été d'évaluer la précision avec laquelle on devait aligner les 4 détecteurs proposés le long de Long Island. Ce faisant, il a découvert que si on déplaçait un peu (qq degrés) les détecteurs par rapport à l'axe du tunnel d'ou sont émis les neutrinos, on obtenait moins de neutrinos détectés au total mais ceux qui l'étaient, avaient une dispersion en énergie bien meilleure, ce qui améliore beaucoup l'expérience. C'est ce qui est maintenant connu sous le nom de Off-axis neutrino beam. En parallèle, le laboratoire Fermilab à Chicago développait aussi une proposition mais qui utilisait, conventionnellement, des détecteurs sur l'axe.

En 1995, le Department Of Energy (USDOE) décide de financer seulement une des deux expériences et demande un duel (*shootout aux USA)* entre les deux groupes. C'est l'expérience MINOS à Fermilab qui a gagné en partie parce que notre faisceau Off-Axis n'avait encore jamais était prouvé expérimentalement. Et donc notre groupe a été dissous.

Plus tard, quand les Japonais ont dit : «OK, on fait le KAON Factory», nous avons vite fait une proposition basée sur notre idée des faisceaux neutrino Off-Axis. C'est Akira KONAKA qui a pris sur lui d'aller convaincre les Japonais qu'il fallait utiliser cette technique « *off-axis* » car cela améliorait grandement la sensibilité de notre expérience aux oscillations des neutrinos.

B. Joós: Alors, *off-axis,* ça veut dire que vous ne détectez pas le…

J.-M. Poutissou: Et en choisissant l'angle auquel vous mettez vos détecteurs par rapport à la direction principale des pions qui émettent les neutrinos, vous voyez une distribution des neutrinos qui devient de plus en plus piquée en énergie. Les pics se recentrent sur une énergie bien particulière. Donc, c'était une façon intelligente de faire un faisceau qui est presque mono-énergétique.

J.-M. Poutissou: Et donc ça a pris du temps à convaincre les gens.

B. Joós: Pourquoi? Parce qu'il y avait une crainte qu'il n'y aurait pas suffisamment de signal?

J.-M. Poutissou: Parce que personne ne l'avait jamais fait. Et puis, quand on engage 156 millions de dollars pour faire un faisceau de neutrinos, on veut être sûr que ça va marcher. Entre temps plusieurs physiciens avaient confirmé la validité de ce processus (qui n'est rien d'autre que dû à la transformation de la cinématique de la réaction entre le référentiel du laboratoire et celui du centre de masse). C'était donc une bonne façon de faire les choses. Donc ce sont des concours de circonstances qui ont guidé ma carrière du point de vue expérimental.

B. Joós: Donc quand tout s'est placé, vous avez obtenu le résultat que vous vouliez?

J.-M. Poutissou: Alors, peut être ! Oui. Dans l'expérience de J-PARC au Japon, on commence avec un faisceau neutrino composé de neutrino muoniques avec une toute petite contamination de neutrino électroniques, que nous pouvons mesurer à

280m de la source. Quand on regarde 300km plus loin dans la grande piscine SK dont j'ai parlé plus haut, la composition du faisceau neutrino change. Le nombre de neutrinos muoniques que vous espérez trouver à 300 km n'est pas directement proportionnel au nombre que vous avez à la source. Il a changé parce que certains des neutrinos muoniques ont changé d'état et sont devenus des neutrino électroniques (ou tauoniques).

B. Joós: Oui, ça, c'est l'oscillation.

J.-M. Poutissou: Ce qu'on voulait voir vraiment, c'est : est-ce qu'on peut détecter des neutrinos électroniques à 300 km qui sont dus au changement d'un neutrino muonique, et non pas à la contamination du faisceau original ? Il y avait des limites supérieures sur la probabilité que cela arrive, qui étaient données par les expériences neutrino sur les réacteurs nucléaires comme à Chooz en France. Il y avait une limite supérieure mais aucune prédiction théorique. On a donc conçu l'expérience pour trouver des oscillations ayant une probabilité d'au moins un ordre de grandeur plus faible que ce qui était donné par la limite supérieure à l'époque. En six mois d'opération en 2010-11, avec le super faisceau bien mono-énergétique que le Canada avait proposé, nous avions déjà observé 6 événements de neutrinos électroniques qui normalement n'auraient pas dû être là. Il ne devait y avoir que des neutrinos muoniques. On s'attendait à une contamination de 1 événement.

On a donc été très chanceux parce que la probabilité s'est avérée très près de la limite supérieure que les autres expériences avaient mise. Alors que nous étions prêts à marcher pendant 5 ou 6 ans ou même 10 ans avant de trouver cette évidence d'oscillation. Cela voulait dire que l'angle de mélange était assez grand qu'on a puisse le voir très vite. C'est ça qui a été vraiment excitant pour nous…

C'était en 2011 juste avant le terrible tremblement de terre et le désastre à Fukushima qui se trouve à 80km de notre expérience à J-PARC. Ensuite après les réparations, en 2014, on a confirmé avec de meilleures statistiques qu'on avait vraiment bien découvert une apparition de neutrino électronique dans un faisceau de neutrino muonique. Et en parallèle, deux nouvelles expériences neutrinos qui ont été faites sur des réacteurs en Chine (Daya Bay) et en France (Double CHOOZ) ont éventuellement trouvé une évidence de ce même phénomène d'oscillation. Et là, il y a un truc intéressant. C'est que les expériences qu'on fait avec des réacteurs sont faites avec des anti-neutrinos et pas avec des neutrinos, et ne peuvent mesurer que la perte du nombre de anti-neutrinos du aux oscillations.

J.-M. Poutissou: C'est ce qu'on appelle une expérience de disparition. Alors que nous, nous avions mesuré une apparition.

B. Joós: Apparition d'un autre type. Voilà.

J.-M. Poutissou: En comparant les deux résultats, on peut trouver une source d'asymétrie entre la matière et l'anti-matière, qui pourrait être responsable de l'existence de notre univers (qui ne contient plus d'anti-matière alors que le Big Bang avait produit autant de matière que d'anti-matière).

On sait qu'il y a une asymétrie de ce genre-là dans le système des quarks, mais on sait qu'elle est trop petite pour expliquer la dominance de la matière sur l'antimatière dans notre univers. Il se peut donc que dans le système neutrino il y ait un effet assez important pour expliquer pourquoi nous existons.

Trouver quelque chose de nouveau, de complètement nouveau, cela mérite bien des heures de labeur. C'est pour cela que toutes ces expériences neutrinos de notre génération ont obtenu le prix Breakthrough, *Breakthrough Prize* en 2016.

B. Joós: *Breakthrough Prize*. Après le Prix Nobel, oui.

J.-M. Poutissou: C'était à cause de l'importance de ces résultats. Mais c'est pour ça que je suis très fier d'avoir pu combiner, si vous voulez, mes tâches administratives, qui n'étaient pas négligeables, avec une participation dans ce courant de la physique fondamentale. C'est très motivant.

B. Joós: Donc vos journées étaient pleines parce que vous n'avez pas fait du 8 à 5. Qu'est-ce que vous faites pour vous déstresser ou rester équilibré ?

J.-M. Poutissou: Alors, une activité que nous faisions tous les deux ensemble, encore une fois tous les deux, c'était de la voile, en compétition de dériveur dans les années 80 puis en croisière dans les fjords de Colombie Britannique sur un plus gros voilier.

B. Joós: Vous êtes membres d'un club à Vancouver ?

J.-M. Poutissou: Oui, membres d'une coopérative car nous n'avions pas beaucoup de temps à y consacrer. Donc on partageait le bateau entre cinq familles et comme ça, j'avais deux semaines chaque été où on partait sur le voilier. Là, il n'y avait pas d'Internet ni de téléphone cellulaire dans les années 90. Et donc on s'échappait comme ça. Les enfants disaient toujours qu'on avait des *quality times*. On était organisés avec certaines périodes de *quality time.*

B. Joós: Vous débranchiez ?

J.-M. Poutissou: Oui, on débranchait. Les enfants sentaient ça. Ils sentaient bien que là, on était beaucoup plus disponibles avec eux. Donc ils appréciaient beaucoup. Ce n'était pas souvent, mais il y avait ces moments spéciaux.

B. Joós: Alors, vous saviez couper. Parce qu'ils disent qu'on doit recharger ses batteries, on doit se déconnecter complètement.

J.-M. Poutissou: Oui. Ce n'était pas toujours possible.

Surtout pour Renée. Elle, comme elle était en charge des systèmes d'acquisition de données qui marchent 24 heures par jour, elle recevait souvent des appels du Japon : « Il y a un truc qui ne marche pas, il faut réparer tout de suite ».

B. Joós: Oui. Parce qu'on ne veut pas perdre des données. Donc c'est ça, la vie de physicien.

J.-M. Poutissou: Ce n'est pas tout le monde qui peut supporter ça.

B. Joós: Cela aide beaucoup si vous êtes à deux sur la même longueur d'onde.

J.-M. Poutissou: Oui, c'est exactement ça. Ç'a été extrêmement, extrêmement important. Je ne pense pas qu'on aurait pu faire ce qu'on a fait si on n'avait pas eu cette combinaison.

B. Joós: Je pense qu'on peut bientôt conclure. Parce que ça, c'était un grand pas en avant. Où voyez-vous maintenant cette discipline ? SNO a fait SNOLAB maintenant.

J.-M. Poutissou: Oui.

B. Joós: Où vont les Japonais ?

J.-M. Poutissou: En ce moment, on fait une expérience avec un accélérateur sur la côte est du Japon au J-PARC, un faisceau de neutrino, un détecteur à 280 m et un détecteur sur la côte ouest à 300 km qui s'appelle Super-Kamiokande (SKI).

Maintenant on va faire Hyper-Kamiokande (HK). L'idée, c'est que, comme l'accélérateur de J-PARC peut augmenter en puissance jusqu'à 1 mégawatt et probablement même plus, on peut au moins doubler l'intensité du faisceau actuel, possiblement même le tripler. En décuplant aussi la taille du détecteur à 300 km., on va augmenter de beaucoup les statistiques et contrôler les erreurs systématiques qui limitent la précision des mesures.

B. Joós: Mais tout ça, c'est encore pour comprendre l'oscillation des neutrinos?

J.-M. Poutissou: Oui. C'est pour avoir le détail exact de comment la violation de la charge et de la parité intervient dans le système neutrino. Les Américains aussi ont des expériences sur les oscillations en projet, mais eux, c'est…

B. Joós: À Fermilab?

J.-M. Poutissou: À Fermilab, on propose un système qui s'appelle DUNE (Deep Underground Neutrino Experiment) avec un faisceau très puissant à Fermilab qui va envoyer les neutrinos 1500 km plus loin. Ils ont une plus grande distance et un faisceau de plus haute énergie. Donc ils ne sont pas tout à fait dans le même créneau que l'expérience japonaise et sont en fait très complémentaires.

Donc ça, c'est le futur.

B. Joós: Que retenez vous de l'autre volet de votre activité ?

J.-M. Poutissou: Le laboratoire TRIUMF est géré par des universités à travers un conseil d'administration. Le directeur change régulièrement et ça, c'est très important. Un nouveau directeur peut affecter la direction générale de développement tout en maintenant la continuité (c'était mon rôle en fait), c'est-à-dire qu'on pouvait changer le directeur, mais on ne changeait pas tout le laboratoire. On est passé de Reg Richardson, physicien des accélérateurs qui a construit le cyclotron, à Jack Sample qui a démarré le programme expérimental, puis Erich Vogt qui a vraiment lancé le laboratoire internationalement, ensuite Alan Astbury, très réputé dans le monde de la physique des particules et surtout au CERN qui a entrainé le Canada dans l'expérience ATLAS au CERN et dans ISAC, Alan Shotter qui a géré le nouveau programme de physique nucléaire autour de ISAC, ensuite Nigel Lockyer a développé le laboratoire dans une autre direction basée sur la superconductivité et la médecine nucléaire. C'est ça qui a fait la vitalité de ce laboratoire qui arrive à se redéfinir, à adapter son programme selon les avancées scientifiques…

B. Joós: Se recréer, se redéfinir à toutes les ...

J.-M. Poutissou: Maintenant, il y a 21 universités qui utilisent le laboratoire. Cela a unifié le Canada du point de vue de la physique subatomique en ayant un laboratoire vraiment national. C'est parti d'un laboratoire régional, un laboratoire en fait même de la Colombie-Britannique, à un laboratoire canadien où tout le monde utilise les facilités pour faire des expériences soit à TRIUMF ou bien à l'extérieur.

Donc c'est une infrastructure nationale, mais gérée par les universités. Cela permet de rester en contact très étroit avec les étudiants qui produisent la génération des future chercheurs. Et en fait, dans mon rôle d'administrateur, ce dont je suis le plus fier, c'est d'avoir pu engager la relève des jeunes chercheurs qui sont aujourd'hui aux commandes du laboratoire. Et donc je pense qu'après 50 ans de succès, le laboratoire TRIUMF a des nombreuses années devant lui. Probablement plus que moi-meme, c'est même certain.

B. Joós: Bon, très bien, merci.

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December 2017 to December 2018 / Décembre 2017 à Décembre 2018

Carleton University

CUDDY, S., "The impact of pinhole collimation on SPECT image noise and spatial resolution", (G. Wells), November 2018.

DI VALENTINO, D., "Constraining Standard Model and Beyond Standard Model Higgs boson couplings in the four lepton decay channel with the ATLAS detector", (T. Koffas), April 2018.

DUNFORD, M., "A search for Neutrinoless Double Electron Capture of ^{36}Ar and a Measurement of Specific Activity of ^{39}Ar in Atmospheric Argon with the DEAP-3600 Detector", (K. Graham), August 2018.

MALKOV, V., "Charged particle transport in magnetic fields in the EGSnrc Monte Carlo code system", (D. Rogers), December 2017.

OLIVER, P., "Computational cell dosimetry for cancer radiotherapy and diagnostic radiology", (R. Thomson), April 2018.

Concordia University

BAHRAMI, M., "Transport and Many-Body Effects in Novel Nanostructures", (P. Vasilopoulos), June 2018, now a Postdoctoral Fellow of Computational Physics in Novel Nanostructures at Nippising University, North Bay, ON, Canada.

MCRAE, A.C., "Graphene Quantum Strain Transistors and Two-In-One Carbon Nanotube Quantum Transistors", (A. Champagne), August 2018, now a Software Developer at Trihedral Engineering Limited, Bedford, NS, Canada.

SON, T.-V., "Ultrafast, Broadband Light Polarization Properties of Vanadium Dioxide Thin Films on Insulating and Metallic Substrates", (T. Vo-Van & A. Haché), December 2018, now a Research Associate at Concordia University and Université de Montreal, Québec, Canada.

Dalhousie University

CAMPBELL, J., "Measurement of the elastic form factor ratio μGE/GM using electron scattering spin asymmetries", (A. Sarty), July 2018, now transitioned into Data Science.

GLAZIER, S., "Isothermal Micro calorimetry as a Tool to Probe Parasitic Reactions in Lithium-ion Cells", (J. Dahn), July 2018, now a Research Scientist at Novonix, Bedford, NS, Canada.

KAUR, S., "Determination of Proton radii of Neutron-rich Oxygen Isotopes from Charge-changing Cross section Measurements", (R. Kanungo), July 2018, now searching for employment.

LI, C., "Trends and Sources of Atmospheric Aerosols Inferred from Surface Observations, Satellite Remote Sensing and Chemical Transport Modeling", (R. Martin), November 2018, now pursuing a Postdoctoral Fellowship at Berkeley, California, USA.

MACDONALD, R., "Development and Implementation of Trajectory Optimization Technologies for Cranial Stereotactic Radiation Therapy", (C. Thomas), July 2018, now doing clinical medical physics residency at Sunnybrook Health Sciences, Toronto, ON, Canada.

MARCH, S., "Four-wave mixing solution-processed methylammonium lead iodide ($CH_3NH_3PBI_3$) perovskite thin films", (K. Hall), December 2018, now pursuing a Postdoctoral Fellowship at Dalhousie University, Halifax, NS, Canada.

XU, J., "Interpreting satellite remote sensing, AIRCRAFT and ground-based observations of aerosol using a chemical transport model", (R. Martin), November 2018, now pursuing a Postdoctoral Fellowship at Dalhousie University, Halifax, NS, Canada.

Memorial University

AYOUB, S., "Understanding Intermolecular Interactions in Organic Heterojunction devices with the Use of Density Functional Theory", (J. Lagowski), October 2018, now an Assistant Professor at the Physics Department, King Abdulaziz University, Jeddah, Saudi Arabia.

KHAJEHPOUR TADAVANI, S., "Electro-hydrodynamics: A Study of Collective Behavior and Self-organization of an Oil-in-Oil Emulsion", (A. Yethiraj), October 2018, now pursuing a Postdoctoral Research Fellow at the Department of Physics and Physical Oceanography, Memorial University, NL, Canada.

MALEK, S., "Thermodynamic and Structural Anomalies of Water Nanodroplets from Computer Simulations", (I. Saika-Voivod & P. Poole), October 2018, now an Instructional Assistant at the Department of Physics and Physical Oceanography, Memorial University, NL, Canada.

PALIT, S., "Macromolecular Dynamics and Structure in Crowded and Confined Environments", (A. Yethiraj), October 2018, now an Assistant Professor at the Department of Mathematics and Physics, North South University, Bashundhara, Dhaka, Bangladesh.

SBEIH, S., "Deuterium Nuclear Magnetic Resonance (NMR) and Rheology of Microgel Colloids at Ambient and High Pressure", (M. Morrow & A. Yethiraj), June 2018, now an Assistant Professor at the Physics Department, School of Basic Sciences and Humanities, German Jordanian University, Amman, Jordan.

Polytechnique Montréal

BEJAOUI, N., "Adaptation du modèle FEEDBACK pour évaluer les propriétés neutroniques d'un nouveau cœur CANDU SCWR en géométrie hexagonale", (G. Marleau), Novembre 2018, maintenant à la recherche d'un emploi.

CHAGNON, D., "Encapsulation hermétique de microbolomètres pour pour caméras infrarouges : optimisation et étude in situ de l'instabilité des infrafaces", (O. Moutanabbir), Janvier 2018, maintenant à la recherche d'un emploi.

LAMBIN IEZZI, V., "Conception de laser et capteur distribué de température par cascade d'ondes Stokes Brillouin stimulées", (R. Kashyap), Avril 2018, maintenant associé de recherche à Polytechnique Montréal, Montréal, Québec, Canada.

LAVOIE, P., "Croissance et caractérisation de l'alliage $GaAs_{1-x}Bi_x$ par épitaxie par jets moléculaires", (P. Desjardins/S. Francoeur), Novembre 2018, maintenant à la recherche d'un emploi.

LORANGER, S., "Discovery and Correction of Spatial Non-Uniformity in Optical Fibers: Towards the Fabrication of Perfect Ultra- Long Fiber Bragg Gratings for Applications in Non-Linear Optics", (R. Kashyap), Janvier 2018, maintenant suis une Postdoctorale à Max Planck Institute, Erlangen, Germany.

LU, X., "Piezoelectric Fibers for Sensing and Energy Generation", (M. Skorobogatiy), Septembre 2018, maintenant à la recherche d'un emploi.

POUGOUM, F., "Development of Fe_3Al-Based HVOF Coatings for Wear Resistant

*This list includes all information submitted to the CAP office up to 21 January 2019.

**La liste comprend l'information reçue au bureau de l'ACP jusqu'au 21 janvier 2019.*

Applications", (J.-E. Klemberg-Sapieha, L. Martinu & R. Schulz), Février 2018, maintenant suis une Postdoctorale à Polytechnique Montréal, Montréal, QC, Canada.

SOUZA BARACHATI, F., "Optical Nonlinearities in the Strong Light-Matter Coupling Regime", (S. Kéna-Cohen), Novembre 2018, maintenant à la recherche d'un emploi en Allemagne.

Queen's University

CHAUDHURI, A., "Nanoelectromechanical Studies of Suspended Resonators using Graphene grown by Chemical Vapour Deposition", (R. Knobel), December 2017, now a Semiconductor Physics Specialist, Avalon Holographics, St. John's, NL, Canada.

CHEQUERS, M., "The Evolution of Star Formation Activity in Cluster Galaxies Over $0.15 < z < 1.5$", (L. Widrow), July 2018, now a Data Science Intern, Shopify, Waterloo, ON, Canada.

CLARK, M., "Cryogenic Alkali Halide Scintillators for Rare-Event Searches", (P. Di Stefano), August 2018, now a Postdoctoral Researcher (Xenon experiment), Purdue University, Lafayette, IN, USA.

MAZAHERI, L., "Self-organization and Light-induced Chirality in Azoglass Material", (J.-M. Nunzi), April 2018, now a Postdoctoral Researcher, Western University, ON, Canada.

MIRZAEE, S., "Studies on Optically Induced DC-Voltage in Thin Film Structures", (J.-M. Nunzi), December 2018, now a Postdoctoral Researcher, Queen's University, ON, Canada.

NORTHEAST, D., "Investigating electromechanical coupling between membrane crystal materials and superconducting microwave resonators", (R. Knobel), July 2018, now a Postdoctoral Researcher, National Research Council of Canada, Ottawa, ON, Canada.

SICK, J., "The Andromeda Optical and Infrared Disk Survey", (S. Courteau), January 2018, now a Research Associate, Large Synoptic Survey Telescope, Tucson, AZ, USA.

WAGNER, C., "The Quenching of Cluster Galaxies", (S. Courteau), August 2018, now a Research Associate, Bruyère Research Institute, Ottawa, ON, Canada.

Simon Fraser University

ARORA, M, "Origin of perpendicular magnetic anisotropy in Co/Ni multilayers and their use in STT-RAM", (E. Girt), December 2017, now a PREP Scientist in the Quantum Electromagnetic Division at The National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.

FARRÉ PÉREZ, P., "Predictive models for chromatin folding: connecting sequence to structure", (E. Emberly), April 2018, now an applied algorithm researcher at D-Wave Systems, Burnaby, BC, Canada.

HORTON, A.J., "In-situ measurement of the jet energy scale and studies of jet structure at ATLAS", (M. Vetterli), December 2017.

NIROOMAND, D., Spin transport in an ultra-cold trapped non-condensed ^{87}Rb gas, (J. McGuirk), September 2018.

TAVAKOLI DINANI, R., "Observation of critical spin dressing", (M. Hayden), April 2018, now pursuing a Postdoctoral Fellowship at Institute for Nuclear and Radiation Physics, Leuven, Flemish Brabant, Belgium.

VAHDANI, P., "Morphological studies of bulk heterojunction films made of polymers showing stable photovoltaic properties", (B. Frisken), August 2018.

Trent University

AMIRI, N., "Tracking the fate of ambient SO_2 using sulfur isotopes, oxidant mixing ratios, and hydrocarbon mixtures", (A.-L. Norman), June 2019.

KHALID, A., "Multi-Mode Multi-Photon Interferometry Applications for Quantum Information Processing", (B. Sanders), November 2018.

MAYER, A., "Study of the decay of Zr-96 by isotope geochemistry and Penning trap mass spectrometry", (R.I. Thompson), June 2018.

MILLER, K., "Study of the decay of Zr-96 by isotope geochemistry and Penning trap mass spectrometry 'Application of copper isotope abundance measurements to study copper trafficking *in vivo*'", (M. Wieser), November 2018, now pursuing a Postdoctoral Fellowship at the University of Calgary, Calgary, AB, Canada.

OUYED HERNANDEZ, A., "The neutrino sector in hadron-quark combustion: physical and astrophysical implications", (R. Ouyed), June 2019.

PALITTAPONGARNPIM, P., "Reinforcement Learning for Adaptive Quantum-channel Control", (B. Sanders), June 2019.

RASLAN, AMANY, K., "The Role of Dielectric Screening in $SrTiO_3$-Based Interfaces", (B. Atkinson), December 2018, now a Sessional Instructor at University of Ontario Institute of Technology, Oshawa, ON, Canada.

TAHANI, K., "Characterizing Star Forming Clumps in the Galaxy: A Comparison of JCMT and Herschel Observations", (R. Plume), November 2018, now an Instructor at Kwantlen Polytechnic University, Surrey, BC, Canada.

University of Calgary

WATT, E., "Development of post-implant analysis methodologies for permanent breast seed implant", (W. Smith), November 2018.

Université Sherbrooke

ACHECHE, S., "Effets des corrélations électroniques et du champ magnétique dans les semi-métaux de Weyl", (A.-M. Tremblay), Janvier 2019, maintenant à la recherche d'un emploi.

COLLIGNON, C, "De la densité des fluides électroniques dans deux oxydes supraconducteurs", (L. Taillefer & K. Behnia), Janvier 2018, maintenant suis une Postdoctorale au Collège de France, Paris, France.

HARVEY-COLLARD, P., "Qubits de spin composés de boîtes quantiques et de donneurs dans le silicium", (M. Pioro-Ladrière), Mai 2018, maintenant suis une Postdoctorale à l'Université de technologie de Delft, Delft, Pays-Bas.

IYER SRIDHARAN, P., "A critical analysis of quantum error correction methods for realistic noise processes", (D. Poulin), Novembre 2018, maintenant suis une Postdoctorale à IQC de l'Université de Waterloo, Waterloo, Ontario et à Quantum Benchmark, Kitchener, ON, Canada.

LACHANCE-QUIRION, D., "Dispositifs quantiques hybrides basés sur les systèmes de spins et les circuits supraconducteurs", (M. Pioro-Ladrière), Mars 2018, maintenant suis une Postdoctorale à l'Université de Tokyo, Tokyo, Japon.

MICHON, B., "Point critique quantique de la phase pseudogap dans les cuprates supraconducteurs", (T. Klein, C. Marcenat & L. Taillefer), Janvier 2018, maintenant suis une Postdoctorale à l'Université de Genève, Genève, Suisse.

RINKEL, P, "Dynamique du réseau dans les semi-métaux de Weyl sous champ magnétique", (I. Garate), Janvier 2019, maintenant à la recherche d'un emploi en industrie.

VERRET, S., "Rôle des ondes de densité dans les modèles théoriques pour cuprates supraconducteurs", (A.-M. Tremblay), Avril 2018, maintenant suis une Postdoctorale à Mila (Université de Montréal), Montréal, QC, Canada.

University of Alberta

BARTHWAL, H., "Integrated Microseismic Analysis: From Relocation to Advanced Geomechanical Interpretation", (M. van der Baan), June 2018.

BELTAOS, A., "Optoelectronic Properties of Graphene: Light Interaction and Emission", (A. Meldrum, A Bergren), June 2018.

CHEN, K., "Elastic Least-squares Reverse Time Migration and Elastic Gauss-Newton Full-waveform Inversion", (M. Sacchi), November 2018.

CHEN, Y., "Seismic imaging of lithosphere structures of the Western Canada Sedimentary Basin", (Y. Gu), November 2018.

FIRDOUS, T., "Nanomechanical and Optomechanical Torque Magnetometry of Isolated Nanomagnetic Assemblies", (D. Potter), November 2018.

ISLAM, M.S., "Piezoelectric and Dielectric Properties of LiNbO3, PMN-PT, and PZT-5A Materials at Cryogenic Temperatures", (J. Beamish), November 2018.

MCELROY, T., "Dark Matter Search With The First Year Of Data From The DEAP-3600 Experiment", (D. Grant, A. Hallin), November 2018.

MCPHEE, K., "Relaxometry in the Human Brain Using High Field Magnetic Resonance Imaging", (A. Wilman, J. Tuszynski), June 2018.

MEKARSKI, P., "Electron Antineutrinos in the Water Phase of the SNO+ Experiment", (C. Krauss), November 2018.

MITRA, P., "PICO-60: A Dark Matter Search Experiment with C3F8 in a Bubble Chamber", (C. Krauss), June 2018.

PETROV, P., "Characterization of Magnetic Nanoparticles as Contrast Agents and Their Application for Quantitative Magnetic Susceptibility Monitoring of the Waterflooding of Heavy Oil in Real Time", (D. Potter), June 2018.

RABBANI, A., "Ultrasonic Characterization of Bitumen with Pressure and Temperature: Implications for Seismic Monitoring of the Grosmont Formation", (D. Schmitt), November 2018.

TETARENKO, A., "Constraining the Physics of Relativistic Jets with Radio Through (Sub-) Millimetre Properties of X-Ray Binaries", (G. Sivakoff), November 2018.

TETARENKO, B., "Constraining the Physics of the X-ray Irradiated Accretion Discs in Low-mass X-ray Binaries with Observations", (G. Sivakoff), November 2018.

WANG, C., "Numerical Modeling of Drift Resonance and Drift-Bounce Resonance Between Ultra-Low Frequency Waves and Energetic Particles in the Inner Magnetosphere", (R. Rankin), November 2018.

WANG, R., "Source Analysis of Induced Earthquakes in the Western Canada Sedimentary Basin", (Y. Gu), November 2018.

WOOD, T., "Characterizing the Atmospheric Neutrino Spectrum with the IceCube Neutrino Observatory", (D. Grant), November 2018.

University of British Columbia

BALANDEH, S., "Experimental and theoretical study of the electronic structure of single-crystal $BaBiO_3$", (G. Sawatzky), August 2018.

BERKMAN, S., "$\nu\mu$ CC1π+ Events Produced in the T2K Beam at Super-Kamiokande", (H. Tanaka), April 2018.

BERNIER, N., "Decay spectroscopy of neutron-rich cadmium around the N = 82 shell closure", (R. Kruecken), December 2018.

CHAURETTE, L., "Infrared quantum information", (G. Semenoff), August 2018.

CONTRERAS, D., "Searching for hemispheric asymmetry and parity violation with the cosmic microwave background", (D. Scott), August 2018.

GORDON, J., "Applications of path integral localization to gauge and string theories", (G. Semenoff), April 2018.

GRANADOS CONTRERAS, A., "Orbital outcomes of STIPs and consequences for hot-Jupiter formation and planet diversity", (A. Boley), November 2018.

HENKELMANN, S., "Searches for heavy vector-like quarks decaying to high transverse momentum W bosons and top- or bottom-quarks and weak mode identification with the ATLAS detector", (A. Lister), August 2018.

KIM, J., "Searching for multi-nucleon processes in neutrino interactions by proton identification in the fine-grained detectors for T2K", (H. Tanaka), August 2018.

MANNING, A., "T1 relaxation and inhomogeneous magnetization transfer in brain: physics and applications", (C. Michal), December 2018.

MARCHETTO, M., "Magnetic field study for a new generation high resolution mass separator", (L. Merminga), December 2017.

MIORELLI, M., "Electromagnetic properties of medium-mass nuclei from coupled-cluster theory", (R. Kruecken), December 2017.

PARKER, A., "Microscopic origins of the mechanical response of nanostructured elastomeric materials", (J. Rottler), December 2017.

POLOVY, G., "Optical synthesis and ultracold reactions of triplet ^{6}Li molecules", (K. Madison), August 2018.

SOUS, J., "Peierls bipolarons and localization in solid-state and molecular systems", (M. Berciu), December 2018.

WANG, Q., "Gravity of quantum vacuum and the cosmological constant problem", (W. Unruh), July 2018.

WHITE, J., "Characterizing debris discs in the late stages of planet formation", (A. Boley), July 2018.

YEH, H-C., "Emergent spacetime in matrix models", (J. Karczmarek), December 2018.

ZHU, Z., "Excitonic Modes and Phonons in Biological Molecules", (P. Stamp), April 2018.

University of Guelph

DUNLOP, M., "High-Precision Half-Life Measurements for the Super allowed Fermi β+ Emitters ^{10}C and ^{22}Mg", (C.E. Svensson), September 2018.

University of Lethbridge

HASHEMI, R, "Remote Sensing (Spectroscopy): High Resolution Spectroscopic Study of Atmospheric Trace Gases with Climate Research Application", (B.Billinghurst), November 2018.

University of Ottawa

BART, G. "Bridging the Microscopic and Macroscopic Realms of Laser Driven Plasma Dynamics", (T. Brabec), October 2018.

CHAGNON-LESSARD, S. "Cellular responses to complex strain fields studied in microfluidic devices", (M. Godin & A. Pelling), October 2018.

CHERITON, R. "Design and Characterization of InGaN/GaN Dot-in-Nanowire Heterostructures for High Efficiency Solar Cells", (K. Hinzer), October 2018.

DING, X. "Increasingly complex systems in intense laser fields", (P. Corkum), December 2018.

GULLEKSON, C. "Effect of Cell-Substrate Interactions on Epithelial Cell Mechanics", (J. Harden & A. Pelling), October 2018.

KUCHAR, J. "How water, ice, and sediment deform the Earth: Novel developments and applications of models of glacial isostatic adjustment", (G. Milne), December 2018.

University of Regina

KOLACEKE, A., "Application of Synchrotron Radiation Techniques to the Study of Taphonomic Alterations and Preservations in Fossils", (M. Barbi), December 2018, now a Quantitative Analyst at BNP Paribas, Lisbon, Portugal, Spain.

PAUDYAL, D., "Spin Polarizability of a Proton Using Polarized Photon Beam and Polarized Butanol Target at Mainz Microtron", (G. Huber), September 2017.

University of Saskatchewan

GOODWIN, L., "The Consequences of Electric Field Variability and Strength on the High-Latitiude Ionosphere", (J.P. St-Maurice), March 2018, now a Postdoctoral Associate at Boston University, Boston, Massachusetts, USA.

KOSHKAROV, O., "Instabilities, Anomalous Transport, and Nonlinear Structure in Partially and Fully Magnetized Plasmas", (A. Smolyakov), February 2018, now a Postdoctoral Research Associate at Los Alamos National Laboratory, Los Alamos, New Mexico, USA.

LEEDAHL, B., "The Electronic and Magnetic Effects of 3d External Transition Metal

Impurities in Semi Conductors", (A. Moewes), August 2018, Now pursuing a Postdoctoral Fellowship at Max Planck Institute for Chemical Solids, Dresden, Germany.

MAJUMDAR, A., "Theoretical Study of Structural Transformations and Properties and Selected Materials at Extreme Conditions", (J. Tse & Y. Yao), August 2018, now a Postdoctoral Researcher at Uppsala University, Uppsala, Uppsala County, Sweden.

REIMER, A., "Improved SuperDARN Radar Signal Processing: A First Principles Statistical Approach for Reliable Measurement Uncertainties", (G. Hussey), February 2018, now a Research Engineer at SRI International, Menlo Park, California, USA.

ZAWADA, D., "Tomographic Retrievals of Stratospheric Ozone Mapping and Profiler Suite Limb Profiler", (A. Bourassa & D. Degenstein), September 2018, now a Postdoctoral Researcher at University of Saskatchewan, Saskatoon, SK, Canada.

University of Victoria

AL-HAKEEM, E., "Dosimetry at extreme non-charged particle equilibrium conditions using Monte Carlo and specialized dosimeters", (A. Jirasek & S. Zavgorodni), September 2018, now searching for employment.

BERG, T., "Probing galaxy evolution with quasar absorption lines", (S. Ellison), June 2018, now pursuing a postdoctoral fellowship at the European Southern Observatory, Chile.

DRAPER, Z., "Understanding the Liveliness and Volatility of Debris Disks: from the microscopic properties to causal mechanisms", (B. Matthews & K. Venn), August 2018, now a Scientist at Delta-X Research Inc., Victoria, BC, Canada.

FRADETTE, A., "From Gas and Dust to Protostars: Addressing the Initial Stages of Star Formation Using Observations of Nearby Molecular Clouds", (M. Pospelov), December 2017, now a Consultant at the Boston Consulting Group, Montreal, QC, Canada.

MAIRS, S., "From Gas and Dust to Protostars: Addressing the Initial Stages of Star Formation Using Observations of Nearby Molecular Clouds", (D. Johnstong & F. Herwig), December 2017, now a Support Astronomer at East Asian Observatory (James Clerk Maxwell Telescope), Hilo, Hawaii, USA.

MAYNARD, E., "Applications of x-ray computed tomography polymer gel dosimetry", (A. Jirasek & M. Hilts), December 2018, now pursuing Medical Physics residencies.

SPENGLER, C., "Nuclear Star Clusters in the Virgo Cluster of Galaxies", (P. Côté & J. Willis), November 2018, now a Postdoctoral researcher at Instituto de Astrofisica, Pontifical Catholic University of Chile, Chile.

VAN NEST, S., "Applications of Raman Spectroscopy in Radiation Oncology: Clinical Instrumentation and Radiation Response Signatures in Tissue", (A. Jirasek), August 2018, now a Postdoctoral Associate at the Department of Radiation Oncology at Weill Cornell Medicine, New York, NY, USA.

University of Waterloo

AL-DAWSARI, S., "Comprehensive Theoretical Studies of Guided Modes in Multilayer Hybrid Plasmonic Waveguides", (L. Wei & D. Strickland), April 2018, now an Assistant Professor, Physics Department, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia.

ALTAMIRANO, N., "The quantum and the gravity: Newtonian and Cosmological Applications", (R. Mann & N. Afshordi), July 2018, now a Data Analyst at Birch Hill Equity Partners, Toronto, ON, Canada.

ANISIMOVA, E., "Single-photon detectors for long distance quantum communications", (T. Jennewein), January 2018, currently unemployed.

BEDNIK, G., "Topological and superconducting properties of Weyl and Dirac metals", (A. Burkov), August 2018, now a Postdoctoral Fellow at the University of California, Santa Cruz, CA, USA.

BHARDWAJ, L., "Classifications of Quantum Field Theories", (D. Gaiotto & R. Myers), June 2018, now pursuing a Postdoctoral Fellowship at Harvard University, Cambridge, MA, USA.

CHAMBERLAND, C., "New methods in quantum error correction and fault-tolerant quantum computing", (R. Laflamme), October 2018, now a Research staff member, at IBM Thomas J Watson Research, Yorktown Heights, NY, United States.

DELCAMP, C., "Gauge models of topological phases and applications to quantum gravity", (B. Dittrich & L. Smolin), June 2018, now a Postdoctoral Fellow at the Max Planck Institute for Quantum Optics, Garching bei München, Germany.

GUNTHER, A., "PPLN-based photon pair sources toward biphoton quantum frequency conversion", (T. Jennewein), August 2018, now currently pursuing a Mitacs Science Policy Postdoctoral Fellowship at Defence Research and Development Canada, Ottawa, ON, Canada.

HAURU, M., "Tensor Networks and the Renormalization Group", (G. Vidal), August 2018, now a Postdoctoral Researcher at Ghent University, Ghent, Belgium.

HENNIGAR, R., "Explorations in black hole chemistry and higher curvature gravity", (R. Mann), August 2018, now currently holding a Banting Postdoctoral Fellowship at Memorial University of Newfoundland, St. John's, NF, Canada.

KARAMI, M., "Probing the dark universe with gravitational lensing", (N. Afshordi & A. Broderick), September 2018, now a Manager, Market Risk Measurement, Scotiabank, Toronto, ON, Canada.

MAZUREK, M., "Testing classical and quantum theory with single photons", (K. Resch), January 2018, now a Postdoctoral Associate at CU Boulder, Boulder, CO, USA.

MCRAE, C.R., "Indium Thin Films in Multilayer Superconducting Quantum Circuits", (M. Mariantoni & R. Laflamme), January 2018, now pursuing a Postdoctoral Fellowship at the National Institute of Standards and Technology, Boulder, CO, USA.

MORADI, H., "Topological Order and Universal Properties of Gapped Quantum Systems", (X.-G. Wen & R. Melko), November 2018, now a Postdoctoral Researcher at The University of Cambridge, Cambridge, United Kingdom.

NIKNAM, M., "Dynamics of Quantum Information of the Central Spin Problem", (D. Cory), January 2018, now a Postdoctoral Researcher in transformative quantum technologies (TQT), University of Waterloo, Waterloo, ON, Canada.

OTHMAN, A., "Control of Light-Matter Interactions in Classical and Quantum Optics", (D. Yevick), January 2018, now an Assistant Professor, Physics Department, Taibah University, Medina, Saudi Arabia.

PANSRI, S., "Spherically Confined Polymers: Monte Carlo Simulations with Expanded Ensemble Density-of-States Method", (J. Chen), February 2018, now a Lecturer and Researcher at Ubon Ratchathani University, Thailand.

POMARANSKI, D., "Precision Low Temperature Calorimetry and Susceptibility of Magnetic Pyrochlores", (J. Kycia), September 2018, now searching for employment.

PONTE, P., "Periodically-driven quantum many-body systems, many-body localization and machine learning", (R. Melko), March 2018, now an Associate Data Scientist, Trading Products at Bank of Montreal, Toronto, Ontario, Canada.

SARENAC, D., "Structured Beams as Quantum Probes", (D. Cory), June 2018, now a Technical Lead, Quantum Early Adopters, Transformative Quantum Technologies, Institute for Quantum Computing, University of Waterloo, Waterloo, ON, Canada.

SINAMULI MUSEMA, C., "On the robustness of Holographic Dualities: AdS Black Holes and Quotient Spaces", (R. Mann), August 2018, now a Research Assistant in Quantum field and String theory, Perimeter Institute for Theoretical Physics, Waterloo, ON, Canada.

TORLAI, G., "Augmenting Quantum Mechanics with Artificial Intelligence", (R. Melko), December 2018, now a Research Fellow at the Flatiron Institute (Simons Foundation), New York, NY, United States.

VANTYGHEM, A., "An ALMA View of Molecular Gas in Brightest Cluster Galaxies", (B. McNamara), September 2018, now pursuing a Postdoctoral Fellowship at the University of Manitoba, Winnipeg, MB, Canada.

UNIVERSITY OF WESTERN ONTARIO

ARNASON, R., "Improved techniques for atmospheric ozone retrievals from lidar measurements using the Optimal Estimation Method and Machine Learning", (P. Barmby), December 2018, now a Senior Scientist at Interface Fluidics in Edmonton, AB, Canada.

AUDDY, S., "From large-scale molecular clouds to filaments and cores: Unveiling the role of the magnetic fields in star formation", (S. Basu), July 2018, now pursuing a Postdoctoral at Academica Sinica Institute for Astronomy and Astrophysics (ASIAA) in Taipei, Taiwan.

BROCKLEBANK, M., "High Resolution Ion Beam Investigations of the Mechanism of Titanium Anodization", (L. Goncharova), October 2018, now pursuing a Postdoctoral in the School of Physics at the University of Melbourne in Victoria, Australia.

BRUZZONE, S., "Mapping debris disk at extreme contrast: Near-IR Differential Polarimetric Imaging with the Gemini Planet Imager", (S. Metchev), September 2019, now pursuing a Postdoctoral at NASA Goddard in Greenbelt, Maryland, USA.

CADOGAN, C., "Properties of Silicon quantum dots", (L. Goncharova & P.J. Simpson), December 2018, now an Optical Test Engineer at ScienceTech Inc. in London, ON, Canada.

DICARLO, A., "Investigation of flow disturbances and multi-directional wall shear stress in the stenosed carotid artery bifurcation using particle image velocimetry", (T. Poepping), December 2018, now pursuing a Medical Physics Postdoctoral at the University of Chicago, USA.

FARHANI, G., "Investigations of the X-ray Binary Population in 3 Local Group Galaxies", (R.J. Sica), November 2018, now employed at The Globe and Mail doing machine learning and data science in Toronto, ON, Canada.

GUAN, J., "Effects of High Pressure on Photochemical Reactivity of Organic Molecular Materials Probed by Vibrational spectroscopy", (Y. Song), July 2018, now pursuing a Postdoctoral at the Institute of Physics at the University of Freiburg, Germany.

HOPKINS, C., "Vibrating-wire Rheometry", (J. de Bruyn), August 2018, now pursuing a Postdoctoral at the Okinawa Institute of Science and Technology (OIST) in Okinawa, Japan.

JALALI, A., "Validating and highlighting the advantages of the Optimal Estimation Method for Rayleigh lidar middle atmospheric temperature retrievals", (R.J. Sica), December 2018, now pursuing a postdoctoral at the University of Toronto, ON, Canada.

LIU, Y., "Three Experiments on Complex Fluids", (J. de Bruyn), December 2017, now pursuing a Postdoctoral at the Institute of Mechanics in Beijing, China.

MARTINEZ, A., "High Resolution Spectroscopy of the Hyades Giants", (D.F. Gray), April 2018, now searching for employment.

PARK, J., "Copper-nanoparticle decorated graphene thin films: Applications in metal-assisted etching and synthesis of next-generation graphene-based nanomaterials", (G. Fanchini), October 2018, now pursuing a Postdoctoral in the Engineering Department at the University of Windsor, ON, Canada.

SUBASINGHE, DA3:E14., "Physical properties of faint meteors through high-resolution observations", (M. Campbell-Brown), December 2017, now interviewing and searching for employment in Industry in Southwestern Ontario, Canada.

UNIVERSITY OF TORONTO

AL RASHID, M., "Design Principles for Lab-in-a-Photonic-Crystal Biosensors", (S. John), November 2018, now a Data Scientist, BitSight Technologies, Boston, MA, U.S.A.

BYRNE, B., "Monitoring the Carbon Cycle: Evaluation of Terrestrial Biosphere Models and Anthropogenic Greenhouse Gas Emissions with Atmospheric Observations", (K. Strong), November 2018, now pursuing a Postdoctoral fellowship at NASA Jet Propulsion Laboratory, Pasadena, California, U.S.A.

FONG, H., "From Simulations to Signals: Analyzing Gravitational Waves from Compact Binary Coalescences", (H. Pfeiffer), November 2018, now pursuing a Postdoctoral fellowship at The University of Tokyo, Tokyo, Japan.

GOERKE, R., "A New Formalism for Soft Collinear Effective Theory with Applications", (M.E. Luke), June 2018, now a Data Scientist at ICBC (Insurance Corporation of British Columbia), Vancouver, BC, Canada.

GOLARAEI, A., "Polarimetric Second-Harmonic Generation Microscopy for Histopathology", (V. Barzda), November 2018, now pursuing a Postdoctoral fellowship at University Health Network, Toronto, ON, Canada.

GRANSTROM-ARNDT, C., "Probing Topological Insulators and Itinerant Magnets at the Nono- and Atomic-scale with Andreev Reflection Spectroscopy", (J.Y.T. Wei), November 2018, now searching for employment.

HU, Y., "X-ray Spectroscopy and Scattering Studies on Thermoelectric Skutterudities", (Y.J. Kim), November 2018, now a Senior Consultant, YE, Toronto, ON, Canada.

LEWIS, A., "Orbital Resonances and GPU Acceleration of Binary Black Hole Inspiral Simulations", (H.P. Pfeiffer) , June 2018, now pursuing a Postdoctoral fellowship at Perimeter Institute, Waterloo, ON, Canada.

LI, Y., "Insane in the Membrane: The Functional Assembly of a G Protein Coupled Receptor at the Single-Molecule Level", (C.C. Gradinaru), March 2018, now a course Instructor at University of Toronto Mississauga, Mississauga, ON, Canada.

PIMENTA SILVEIRA, H., "Simulating One-Dimensional Physics with Stationary Dark Polaritons", (D.F.V. James), November 2018, now a Data Scientist at Scotia Bank, Toronto, ON, Canada.

PRANAI, V., "Room-Temperature Bose-Einstein Condensation of Excition-Polaritons in Photonic Crystal Architectures", (S. John), November 2018, now a Teacher, Toronto, ON, Canada.

SADEQ, Z.N., "The Electronic and Optical Properties of Graphene Flakes and Similar System", (J. Sipe), November 2018, now an Associate at McKinsey & Company, Toronto, ON, Canada.

SALAZAR GONZALEZ, J. C., "Effective Models for Optical Properties: A Study on 1D, 2D and 3D Materials", (J.E. Sipe), March 2018, now pursuing a Postdoctoral fellowship at University of Warwick, U.K.

STANEVICH, I., "Variational Data Assimilation of Satellite Remote Sensing Observations for Improving CH4 Simulation in Chemical Transport Models", (K. Strong), June 2018, now a Data Scientist at Layer 6 AI, Toronto, ON, Canada.

TIBBO, M., "A True-Triaxial Laboratory Seismic Velocity Experiment under in Situ Stress Conditions: A Comparison with in Situ 3D Stress and Velocity", (R.P. Young), November 2018, now searching for employment.

ZHANG, H., "Novel Phases in Hetero-Epitaxial and Super-Oxygenated Thin Films of Complex Oxides", (J.Y.T. Wei), June 2018, now an Associate Director, Counterparty Credit Risk at Royal Bank Canada, Toronto, ON, Canada.

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En plus des titres mentionnés ci-dessous, les lecteurs sont invités à soumettre des revues sur des ouvrages récents, ou des revues thématiques comparées sur des sujets particuliers. Celles-ci pourraient par exemple porter sur des ouvrages de nature pédagogique, ou des textes de référence destinés à des professionnels.

GENERAL LEVEL

Introduction to Graphene-Based Nanomaterials: From Electronic Structure to Quantum Transport, Luis E. F. Foa Torres, Stephan Roche & Jean-Christophe Charlier, Cambridge University Press, 2020; pp. 476; ISBN: 978-1108476997; Price: 116.08.

Radiative Transfer in Stellar and Planetary Atmospheres, Lucio Crivellari, Sergio Simón-Díaz & María Jesús Arévalo, Cambridge University Press, 2020; pp. 246; ISBN: 978-1108499538; Price: 149.95.

UNDERGRADUATE LEVEL

Damn Particles: Physics Cartoons by Sidney Harris, Sidney Harris & Arthur W Wiggins, Science Cartoons Plus, 2019; pp. 153; ISBN: 978-0989068529; Price: 19.58.

Lectures on Astrophysics, Steven Weinberg, Cambridge University Press, 2019; pp. 226; ISBN: 978-1108415071; Price: 51.95.

SENIOR LEVEL

Effective Field Theories for Nuclei and Compact-Star Matter [v], Yong-Liang Ma, Mannque Rho, World Scientific, 2018; pp. 330; ISBN: 978-981-3273-31-3; Price: 146.85.

Formation of the First Black Holes, Edited By: Muhammad Latif and Dominik Schleicher, World Scientific, 2019; pp. 376; ISBN: 978-081-3227-94-1; Price: 149.88.

Heavy Ion Collisions at Intermediate Energy, Subal Das Gupta, Swagata Mallik, Gargi Chaudhuri, World Scientific, 2019; pp. 184; ISBN: 978-981-3277-95-9; Price: 111.84.

Book Reviews / *Critiques de livres*

A Student Manual for "A First Course in General Relativity", by Robert B. Scott, Cambridge University Press, 2016, pp. 310, ISBN 9781139795449, price 29.95.

This is an excellent companion volume for anyone contemplating teaching a first course in General Relativity. Ideally the course manual should be the corresponding book by Bernard Schutz called "A first course in general relativity" also published by Cambridge University Press. The book by Schutz is an excellent first course in General Relativity, which presents the subject by first explaining in detail special relativity in the first 4 chapters followed by 8 chapters which gently lead the student into the complexity of General Relativity where it starts with the definition of curved manifolds followed by physics in curved spacetime, to Einstein's equations and then followed by applications to gravitational radiation, spherical solutions for stars, black holes and ending with a short introduction to cosmology.

Scott's Student Manual follows Schutz' book exactly, chapter by chapter, indeed the chapter headings in the two books are identical. There are according to Scott, 388 exercises in Schutz's book. Scott suggests that the interested learner do each and every one of them. In Scott's book, he does give the solution of most of the exercises of Schutz and he gives many more solved supplementary exercises, in addition to some exercises for which the solutions are not provided. Scott uses the notation Eq. (n.m) to denote the exercises/equations in Schutz's book while the notation eqn. (n.m) to denote exercises/equations in the Student Manual. The solutions are always placed in a grey background so that it is clear when one is reading a solution as opposed to the exercises themselves. Scott goes into significant detail in explaining the solution, hence some might find the solutions a bit laborious, however, they are very pedagogic. Scott does this expressly, his aim being "to be complete, to spell it all out". Scott also has provided an accompanying Maple worksheet, which is available for download from the Cambridge University Press website.

The first 4 chapters of Scott's book are on special relativity. The subject is presented to the reader through many exercises that are based on very fundamental aspects, starting with exercises on the basic definition of natural units, then the principles of special relativity: that no observer can measure the absolute velocity of any other observer and that the speed of light is universal, invariant for all inertial observers. These are followed by two chapters of exercises on the notions of vectors and tensors in Minkowski spacetime and ending with a chapter on the definition of a perfect fluid in special relativity.

Then come the exercises on the heart of the matter, General Relativity. The next four chapters, 5 through 8, give exercises on the mathematical structure and the notions of differential geometry leading to the Einstein equations. I have done several of the problems in each of the chapters and I find some of them quite challenging. I compared my solutions to those offered by Scott and I am happy and relieved to know that they compare pretty well with those provided, the difference being largely that Scott gives far more details! There are in depth exercises on the first corrections to the Newtonian theory and how they arise in Einstein's theory, which is very educative.

The final four chapters, 9 through 12, are exercises on the fundamental applications of Einstein's theory, to gravitational radiation, solutions (spherical) for stars, black holes and cosmology. These chapters capture the essence of the excitement of General Relativity. They correspond to predictions of Einstein's theory that go beyond the Newtonian theory, including time dependent phenomena, strong gravity and gravitational collapse, event horizons and a first exposure to cosmology. The exercises are again very detailed and expose the various pedagogical aspects of the rather theoretical analyses in Schutz's book.

Thus, in summation, this book is a perfect companion to a textbook for teaching a first course in General Relativity. Ideally, it goes hand in glove with the book by Schutz. However, it could be used as a source book of exercises to accompany any similar course based on another book (like that of Hartle or Carrol). The instructor could use the book to assign solved problems and unsolved problems suitable for homework problems.

Manu Paranjape,
Université de Montréal

A Well-Ordered Thing, by Michael Gordin, Princeton University Press, 2019, ISBN:978-0-691-17238-5, pp. 351, price 22.58.

Michael Gordin's "A Well-Ordered Thing" is a carefully researched and scholarly account of the life and surroundings of Dmitrii Mendeleev, the late 19th century co-inventor of the periodic table. Gordin covers Mendeleev's academic beginnings, his famous work on the periodic table, and takes time to discuss the lesser-known pursuits of Medeleev: his economic and political thought, his work in industry and in service to the Russian empire, and his investigation into the Spiritualism movement. Mendeleev's diverse interests are used to explore the setting Mendeleev lived in; indeed, Gordin emphasizes that the book is not so much the story of Mendeleev as it is an examination of imperial St. Petersburg.

Due to its emphasis on St. Petersburg, the book is a biography of a scientist without being a scientific biography. With the exception of the famous periodic law, to which Gordin devotes a chapter, Mendeleev's scientific thought is presented in an incidental way. Further, the scientific context in which Medeleev worked is never discussed in detail. Consequently, Gordin's priorities may not align with those of a scientist-reader. Nonetheless, the book contains some interesting scientific details. Gordin stresses that Medeleev's thinking on the periodicity of properties of the elements stemmed from a pedagogical need: to organize the known elements into a form suitable for a first-year chemistry textbook. I also found Medeleev's views on the ether to be of interest. Medeleev believed the ether was composed of particles which could be placed in the periodic table and attempted to predict properties of the ether by using his periodic law, just as he had predicted the existence and properties of unknown elements.

Gordin explores in depth Mendeleev's economic and political thought, and his role in shaping imperial policy. Gordin stresses how, to Mendeleev, scientific societies were models for how technical expertise could be employed by the empire. The book emphasizes Medeleev's "Imperial Turn", a transition from a focus on local affairs in St. Petersburg to a top-down approach to enacting reform. In Gordin's analysis, this turn was initiated by Mendeleev's rejection from the St. Petersburg Academy of Sciences, as Mendeleev had taken the Academy to be a model of how reform could be organized locally. Gordin also argues that the ensuing outrage in the popular press made Mendeleev's reputation.

"A Well-Ordered Thing" aims to explore imperial St. Petersburg through one of its great citizens. In his writing, Gordin has emphasized analysis over narrative. In some places the analysis felt stretched or obvious. For instance, Gordin draws a parallel between Mendeleev's work on gases and his meteorological work, noting that in both cases he was "amassing data on irregularities in order to determine laws", but the parallel could have been made to nearly any scientific work. As well, the lack of narrative left me without a clear sense of Mendeleev as a person. In general, though the historical analysis makes interesting points, especially regarding Mendeleev's rejection from the Academy and consequent Imperial Turn, and the book largely succeeds in its aim.

Alex May, PhD student,
University of British Columbia

Fearful Symmetry: The Search for Beauty in Modern Physics, by A. Zee, Princeton University Press, 2016, ISBN 9780691173269, pp. 376, price 31.99.

There are few popular physics books which are worth recommending to a student beginning a new subject. Tony Zee's "Fearful symmetry" is one of them. This book should be productive reading for students studying particle physics or group theory in physics. This is not only because the book presents technical material honestly, but also because the book reads easily. To achieve this, Zee maintains the unusual writing style he is known for in his textbooks - short and pointed sections colored with references to art, literature and anecdote.

Zee covers some of the usual ground for a popular physics book, for instance quantum mechanics, relativity, and the Standard Model. Additionally, however he reaches topics rarely touched: groups, non-abelian gauge theory, spontaneous symmetry breaking and supersymmetry. By presenting these topics and tying them to a unifying theme of symmetry and the aesthetic sense of the theorist, Zee presents one of the most recognizable portraits of work as a theoretical physicist available in popular work.

To Zee, beauty, largely as expressed through symmetry, is a powerful guiding force in theoretical physics. Also running throughout the work is a persistent reference to God or a Designer. Usually among theorists such references are linguistic conveniences or metaphors (as was the case for Einstein, a frequent source of such usages), though this subtlety is an inevitable point of confusion. In Zee's case however the references are more than metaphor, as he believes in a presence of some kind responsible for creating the universe. Indeed, Zee views the aesthetics of the universes design, as evidenced through the role of symmetry, along with the basic fact of the universe's comprehensibility as evidence for this deistic view.

Zee's views on deism and aesthetics contribute much of the uniqueness of the book. At times though Zee risks portraying theoretical physics as a mystic art, and it is worth emphasizing a counterbalancing view. My own view is that theoretical physics is not at all divorced from observation - and so not at all a mystic art - even in a case such as string theory. In that case, theorists have chosen to focus on the core principles of quantum mechanics and gravity and work mathematically to tie them together into a consistent theory. Those principles however are well grounded in experiment. Momentarily ignoring some details and beginning from basics is sometimes necessary to make conceptual jumps. In fact, Zee makes a similar point in the context of general relativity - Einstein did not arrive at his theory by studying observations of the orbit of Mercury, but by revisiting long known simple observations.

While Zee's views may not align precisely with my own, he has written an excellent book. It will be of interest not only to the new student, but also to any artist or layperson interested in beauty. Zee has made great progress in making the beauty of symmetry in physical law accessible for a wide audience.

Alex May,
University of British Columbia

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