RESEARCH TRACK RECORDS

ACCELERATOR SCIENCE

A PATHWAY TO OPTIMIZING THE PERFORMANCE OF SRF CAVITIES

SRF

Superconducting radio-frequency acceleration involves creating strong electromagnetic fields inside a cryogenically cooled superconducting vessel that can be used to accelerate charged particles. The superconducting state is limited by the ability of the material to repel magnetic flux penetration from the strong surface fields. New materials or new material treatments are being developed to allow higher fields and more efficient acceleration before flux penetrates the material. Recent experiments at the TRIUMF muSR facility have shown that coating niobium with a high Tc material (like Nb^3Sn or MgB^2) of variable coating thickness can increase the field of first flux penetration by 40% with respect to a non-coated sample. **The measurements** suggest a path forward to increase the performance of niobium SRF resonators through modification to the surface.

Superheating in coated niobium
T. Junginger, R. Laxdal, W. Wasserman, SUST, 3012 (2017)

CHARACTERIZATION AND MODELING OF RARE ISOTOPE PRODUCTION AT ISAC

Rare Isotope Beam Delivery, Targets and Ion Sources

A computer simulation using the GEANT4 nuclear transport toolkit was developed to model the production of isotopes from rare isotope beam targets used at ISAC. In combination with in-depth isotope beam characterization (via nuclear spectroscopy) at the ISAC yield station, the simulation data is a pivotal foundation for the development of better targets and the production of new and more intense isotope beams. Using simulation and yield results, the average release time of francium from uranium carbide targets was determined, providing a better understanding of the dynamics that govern the extraction of isotopes from the target. Yield and simulation results are accessible in a database, helping researchers to devise and plan experiments.

FIRST WAKE-FIELD ACCELERATION OF ELECTRONS

e-linac: Electron Linear Accelerator, AWAKE

On May 26th, 2018, the AWAKE collaboration (to which TRIUMF has been an active contributor of beam instrumentation since 2014) **successfully accelerated witness-electrons for the first time**. AWAKE has demonstrated that these low energy electrons can gain energy while "riding" waves generated in plasma (ionized gas) by a proton beam, at a rate of around 200 MV/m (million volts per meter) over a distance of just 10 m. This represents current-day state-of-the-art technology in particle accelerators, for the overall distance over which acceleration can be sustained and ensuring intensity and quality of accelerated beams. These results are an important step towards the future development of smaller high-energy particle accelerators.

Acceleration of electrons in the plasma wakefield of a proton bunch

E. Adli et al., Nature, 561, 363 (2018)

INVESTIGATIONS OF BEAM-BEAM EFFECTS IN HL-LHC

SRF

Around the experimental regions of the Large Hadron Collider (LHC), beams travel in a common vacuum chamber and therefore experience the fields of the opposing beams - so-called 'long-range interactions'. These are unavoidable and, being nonlinear, limit the LHC's luminosity. Studies of this effect are essential for designs crucial for the ongoing high-luminosity upgrade (or HL-LHC; a program to bring a factor-of-10 performance improvement to the LHC), due to begin operating in 2025. The usual method of investigating the effect is by multiparticle simulations, and TRIUMF is part of the international collaboration charged with these calculations. These are compute-power limited, so it is highly desirable that an alternative analytic model be found. Recently, we have **discovered such a model**. This has the potential of making beam-beam calculations more tractable.

Fourier Coefficients of Long-Range Beam-Beam Hamiltonian via Two-Dimensional Bessel functions
D. Kaltchev, Proc. Int. Particle Accelerator Conf., Vancouver, Canada (2018)

ISOL TARGET MATERIAL R&D

Targets and Ion Sources

Via nuclear reactions induced by a high-energy primary beam of particles, porous uranium carbide with excess graphite is the international benchmark material for the production of exotic isotopes via the isotope on-line (ISOL) method. This process enables a broad range of science programs with increasing interest in the **development of cancer imaging and treatment agents** [1]. While the production rate for a specific isotope is determined by the primary beam and the target nucleus, the amount of available isotopes can fall a million times below the production yield, caused by losses inside the target material. De-novo engineered material nanostructures **show significantly enhanced performance** [2]. Combined with **new production methodologies**, TRIUMF is aiming to meet the future demand in terms of material availability and isotope yields [3].

[1] *Medical isotope production at TRIUMF – from imaging to treatment*
C. Hoehr et al., Physics Procedia 90, 200 (2017)
[2] *Target materials for exotic ISOL beams*
A. Gottberg, Nuclear Instruments and Methods-B, 376, 8 (2016)
[3] *A New Production Process for UCx Targets for Radioactive Isotope Beams at TRIUMF*
M. S. Cervantes, A. Gottberg, P. Kunz, A. Mjos, J. Wong, P Fouquet-Métivier, Proc. 9th Int. Particle Accelerator Conf., Vancouver, BC, Canada 4990 (2018)

MODEL-SUPPORTED ACCELERATOR BEAM TUNING

e-linac: Electron Linear Accelerator

An efficient but accurate beam dynamics model for linear accelerators has been developed and is being used in our control rooms, and in particular to commission the electron linear accelerator (e-linac). Other labs use simulations of up to ond million particles and then distill these down to only the 3 size parameters of the beam bunches. These multi-particle simulations are too slow to be used in online tuning of an accelerator. We have developed a technique that tracks bunch sizes, including space charge, instead of individual particles. Such applications have existed for many years but only for beam transport, not for linear accelerators. Our application allows operators to calculate new linac tunes online. It has generated international interest and an invited talk at the 2016 Linac Conference.

Fast Envelope Tracking for Space Charge Dominated Injectors

R. Baartman, LINAC 2016 conference proceedings, East Lansing, MI, USA, **1017** (2016)

PURE RADIOACTIVE ION BEAMS AND RARE ISOTOPE SPECTROSCOPY FROM TRIUMF'S LASER ION SOURCE TRILIS

Targets and Ion Sources

Virtually contamination-free radioactive ion beams can now be provided at ISAC from a new ion-guide laser ion source (IG-LIS) [1]. This IG-LIS allows for experiments on isotopes that for decades have been overwhelmed by contamination from surface-ionized isobars. TRILIS now routinely provides isotopes from 37 different elements. Laser ionization schemes for an additional 24 elements are ready for off-line testing. TRILIS also supports an in-source laser spectroscopy program that investigates fundamental properties of the rarest isotopes such as atomic energy levels and elemental ionization potentials have been determined for the first time [2] or improved significantly [3].

[1] *An ion guide laser ion source for isobar-suppressed rare isotope beams*
S. Raeder et al., Rev. Sci. Instr., 85, 03309 (2014)
[2] *Measurement of the first ionization potential of astatine by laser ionization spectroscopy*
S. Rothe et al., Nat. Commun., 4, 1835 (2013)

[3] *Determination of the first ionization energy of polonium by resonance ionization spectroscopy – part I: Measurement of even-parity Rydberg states at TRIUMF-ISAC*
S. Raeder et al., Spectrochimica Acta B (2018)

SUCCESSFUL PROOF OF PRINCIPLE TEST OF NOVEL BALLOON RESONATOR

SRF

Superconducting radiofrequency (SRF) technology is the enabling advances in a new generation of proton linacs for discovery science or industrial application. Strong electromagnetic fields created in specially designed resonators are used to accelerate the protons. A class of resonators, termed spoke cavities, is efficient in acceleration but suffers from a phenomenon called 'multipacting' wherein a cascade of electrons is released from the surface by the high fields, which can limit the cavity performance. The TRIUMF SRF team has invented a new type of spoke resonator called the `balloon cavity' with a special shape that virtually eliminates multipacting as an issue for single spoke resonators. A prototype cavity was fabricated and tested at TRIUMF and recent tests confirm the unique capabilities of the new variant.

Fabrication and Test of a β=0.3 325MHz Balloon Single Spoke Resonator

Z. Yao et al., 9th Int. Particle Accelerator Conf., Vancouver, BC, Canada (2018)

THE ARIEL FRONT-END AND SEPARATOR SYSTEM

Rare Isotope Beam Delivery

The ARIEL front-end is a complex switchyard consisting of more than 200 m of electrostatic beam lines designed to transport two rare isotope beams simultaneously from the new target stations to the ISAC experimental facilities in a vacuum of eleven orders of magnitude smaller than atmospheric pressure (10^{-8} Torr). The switchyard includes a new generation high resolution separator (HRS) system engineered to differentiate between two beams with a mass difference of only one part in twenty thousand. The HRS system, which is part of the CANREB project, includes two state-of-the art, 16-tonne magnetic dipoles manufactured with a field flatness of the order of one part in one hundred thousand and a unique multipole corrector that will remove any imperfection stemming from aberrations from a beam thinner than a sheet of paper (or 100 mm).

The ARIEL radioactive Ion Beam Transport system
M. Marchetto et al., LINAC 2016 conference proceedings, East Lansing, MI, USA (2016)

New design studies for TRIUMF's ARIEL High Resolution Separator

J.A Maloney, R. Baartman, M. Marchetto, Nuclear Instruments and Methods-B, 376, 135 (2016)

Magnetic Field Study for a New Generation High Resolution Mass Separator

M. Marchetto, Ph.D. thesis, University of British Columbia (2017)

APPLIED ION BEAMS

A NEW DOSIMETER TO IMPROVE CHARACTERIZATION OF TRIUMF PROTON AND NEUTRON BEAMS

PIF & NIF

A new dosimeter to improve characterization of TRIUMF proton and neutron beams: With collaborators at the **University of Waterloo**, TRIUMF's PIF & NIF group has invented a new dosimeter that's proven incredibly valuable at characterizing the proton and neutron test beams available at TRIUMF's irradiation facilities. Neutron radiation effects testing, usually for single event effects (SEE), uses accelerator produced neutrons with a broad energy spectrum to simulate the cosmic ray or terrestrial spectrum at ground level or aircraft altitudes. The energies that are of interest are above 1 MeV, with most testing to date using the fluence of > 10 MeV neutrons for determining acceleration factors between accelerator neutrons and the terrestrial environment. The new PIF-NIF dosimeter is based on an array of SRAMs (Static Random-Access Memories) with thirty, 16 Mbit Cypress SRAMs arranged in a close-packed 5x6 array to cover an area of 36 x 36 mm. This SRAM has several key features. It does not latch-up, and the ECC can be removed and the single event upset (SEU) cross section with ECC removed is large enough at about 10^{-13} cm^2 per bit for good sensitivity. The total error rate at a flux of 10^6 protons or neutrons/cm^2/s is about 2500-3000/minute so good statistics can be achieved very quickly even at much lower fluxes. The new dosimeter will allow for improvements to TRIUMF's testing facilities and methods benefiting both scientific researchers and industrial engineers in their understanding and quantification of radiation effects.

(citation forthcoming; IEEE Transactions)

BIO-BETANMR: A NEW TOOL TO UNDERSTAND BIOLOGY AT THE MOLECULAR LEVEL

Radiochemistry Laboratories

bio-betaNMR: A new tool to understand biology at the molecular level Although bNMR has been applied to nuclear physics and condensed matter for the past five decades, its application to biology, wet chemistry, and medicine are still fairy uncommon, mainly due to technical difficulties of maintaining liquid solutions under vacuum. Over the past three years, TRIUMF has not only pioneered technology that overcomes that barrier, but also carried out first experiments on liquids and biological samples, moving from proof-of-feasibility to first applications. In April 2017, we recorded the first-ever bNMR signals originating from oxygen and nitrogen coordinating Mg^{2+} in typical Mg complexes, illustrating that bNMR can discriminate between different structures. In July 2018, we carried out first bNMR measurements on Mg coordination to ATP. This achievement marks a milestone in applications of bNMR into biologically-relevant samples and opens new opportunities in the fields of wet chemistry, biology, and medicine.

Direct observation of Mg^{2+} complexes in ionic liquid solutions by ^{31}Mg-bNMR spectroscopy
D. Szunyogh et al., Dalton Trans. (2018), in press.

On the use of ^{31}Mg for beta-detected NMR studies of solids
R. McFadden et al., . JPS Conf. Proc. 21, 011047 (2018)

Towards ^{31}Mg beta-NMR resonance line widths adequate for applications in magnesium chemistry
M. Stachura et al., Hyperfine Interact., 238, 32 (2017)

NOVEL ACCELERATOR TARGET TECHNOLOGY FOR IMPROVED PRODUCTION OF MEDICAL ISOTOPES

Radiochemistry Laboratories

Novel accelerator target technology for improved production of medical isotopes: Historically, research within TRIUMF's Life Science division has focused on the world's more common PET isotopes: ^{11}C, ^{13}N and ^{18}F. However, through new target development in recent years, this list has been dramatically expanded to include new isotopes through new target development: ^{68}Ga, ^{44}Sc, ^{86}Y, ^{89}Zr, ^{192}Ir, ^{52}Mn, $^{61,64}Cu$, ^{99m}Tc and ^{119}Sb. One of these new target systems is the so-called solution target, modelled after the remotely-controlled ^{18}F production process currently used in medical cyclotrons. In lieu of a traditional solid target station, this technique allows for the irradiation of solutions (for example: nitrate solutions of metals of interest) in a cost-efficient, simple, and safe manner.

Radiometals from liquid targets: Tc-94m production using an adapted water target on a 13 MeV cyclotron

C. Hoehr et al., Applied Radiation and Isotopes, 70, 2308 (2012)

Sc-44g production using a water target on a 13 MeV cyclotron

C. Hoehr et al., Nuclear Medicine and Biology, 41, 401 (2016)

Production of Y-86 and other radiometals for research purposes using a solution target system
E. Oehlke et al., Nuclear Medicine and Biology, 42, 842 (2015)

REDEFINING THE GLOBAL ISOTOPE SUPPLY PHILOSOPHY

Radiochemistry Laboratories

Redefining the global isotope supply philosophy: In 2009, the world was recovering from widespread shortages of ^{99m}Tc - an isotope used in ~40 million nuclear medicine scans around the world every year - when the Canadian federal government announced the imminent cessation of isotope production activities at the Chalk River reactor. In response, TRIUMF (along with BC Cancer, the Centre for Probe Development and Commercialization, and Lawson Health Research) teamed together to develop a novel, high-powered target hardware solution capable of enabling the production of commercial-scale quantities of ^{99m}Tc using local, hospital-based cyclotrons. This technology has been licensed to a new spin-off company, ARTMS Products, Inc., which obtained US$3M in venture funding from Quark Ventures in December 2017. Cyclotron-produced ^{99m}Tc is now being implemented in the United Kingdom, with additional jurisdictions soon to follow. This same hardware has since been adapted to allow for the production of ^{68}Ga, ^{64}Cu, ^{89}Zr and other isotopes of interest.

Implementation of multi-Curie production of ^{99m}Tc by conventional medical cyclotrons

F. Bénard et al., Journal of Nuclear Medicine, 55, 1017 (2014)

Direct Production of Tc-99m via 100Mo(p,2n) on Small Medical Cyclotrons

P. Schaffer et al., Physics Procedia, 66, 383 (2015)

Imaging study of using radiopharmaceuticals labelled with cyclotron-produced Tc-99m

X. Hou et al., Physics in Medicine and Biology, 61, 8199 (2016)

APPLIED RADIOISOTOPES

BETANMR REVEALS NANOSCALE SURFACE DETAILS IN TOPOLOGICAL INSULATORS

bNMR

bNMR reveals nanoscale surface details in topological insulators: Wolfgang Pauli said, "God made the bulk; surfaces were invented by the devil", a recognition of the fact that theories and experimental measurements of near-surface properties are very difficult. Surfaces may be difficult to study, but it is where much interesting physics arise. Topological insulators (TI) are materials where the bulk is an insulator but whose surface contains conducting states, which means that electrons can only move along the surface of the material. Topologically protected states could act as a source of spin-polarized electrons with properties relevant to spintronics applications including quantum computing. As published in the ***Proceedings of the National Academy of Sciences*** (2015) researchers at CMMS used bNMR spectroscopy as a nano-scale depth-resolved probe of magnetism and conductivity within about 10 nm of the free surface of $(Bi,Sb)_2Te_3$. This depth-dependent study of electronic and magnetic properties of TI epitaxial layers using implanted, spbin-polarized $^{8}Li^{+}$ ions reveals differences in the band structure between the near-surface and deeper into the bulk material.

Nanoscale β-nuclear magnetic resonance depth imaging of topological insulators

D. Koumoulis et al., PNAS, 11228 (2015)

EXPANDING TRIUMF'S ISOTOPE TOOLKIT: THERAPEUTIC ISOTOPES

TRIUMF's accelerator infrastructure and expertise provides for a unique and fertile ecosystem for the development of isotopes for new medical applications. Over the past 5 years, the Life Sciences division has been working to expand its portfolio of isotopes beyond the traditional repertoire of positron- and gamma-emitting imaging isotopes to include a number of alpha-, beta- and Auger-emitting isotopes that can be used in therapeutic applications. Examples of isotopes recently produced for further study include ^{211}At, $^{212,213}Bi$, ^{225}Ac, ^{212}Pb and ^{212}Bi. Interests also include ^{227}Th, ^{149}Tb, ^{119}Sb, ^{105}Rh and ^{67}Ga. To obtain these isotopes, the Life Sciences program at TRIUMF continues to exploit production capabilities on legacy (BL1A, TR-13 and ISAC) as well as future (ARIEL proton and electron beamlines, IAMI) infrastructure. With ready access to a broad repertoire of isotopes, TRIUMF scientists, along with their collaborators, will enable the production of new radiopharmaceuticals for Targeted Radionuclide Therapy (TRT).

Development of a preclinical Rn-211/At-211 generator system for targeted alpha therapy research with At-211

J.R. Crawford et al., Nuc. Med. Biol., 48, 31 (2017)

Development of ^{225}Ac Radiopharmaceuticals: TRIUMF Perspectives and Experiences
A.K.H. Robertson et al., Curr. Radiopharm, 3, 156 (2018)

An Eighteen-Membered Macrocyclic Ligand for Actinium-225 Targeted Alpha Therapy\
N.A. Thiele et al., Angew. Chem, 56, 14712 (2017)

NEW AQUEOUS FLUORINATION TECHNIQUES

Radiochemistry Laboratories

New aqueous fluorination techniques: ^{18}F is a key isotope for the production of many radiopharmaceuticals. For decades, the addition of ^{18}F to radiopharmaceutical precursors required harsh (high temperature, anhydrous) chemical conditions in order to provide adequate yields of the desired products. These conditions typically degrade more sensitive biomolecules, such as antibodies, peptides and proteins. Over the past 5 years, TRIUMF has worked collaboratively with scientists at the University of British Columbia and Simon Fraser University to develop two novel aqueous fluorination methods. Efforts with Dr. David Perrin (UBC, Chemistry) enabled the development of aqueous aryltrifuloroborate chemistry for rapid, 1-step incorporation of ^{18}F onto peptides and other biomolecules; while those with Dr. Robert Britton have resulted in a novel method that uses a light-activated catalyst to place fluorine atoms on very specific locations of certain amino acids. These methods give radiopharmaceutical chemists new tools by which to produce radiopharmaceuticals that have been, until now, inaccessible or too difficult to produce.

Stoichiometric Leverage: Rapid ^{18}F-Aryltrifuloroborate Radiosynthesis at High Specific Activity for Click Conjugation

Z. Liu et al., Angewandte Chemie International Edition, 52, 2303 (2013)

F-18-Fluorination of Unactivated C-H Bonds in Branched Aliphatic Amino Acids: Direct Synthesis of Oncological Positron Emission Tomography Imaging Agents
M. B. Nodwell et al., J. Am. Chem. Soc., 13910, 3595 (2017)

Site-Selective, Late-Stage C-H 18F-Fluorination on Unprotected Peptides for Positron Emission Tomography Imaging
Z. Yuan et al., Angewandte Chemie International Edition, 130, 12915 (2018)

NOVEL RADIOPHARMACEUTICALS FOR IMAGING UNIQUE METABOLIC PATHWAYS IN CANCER

Radiochemistry Laboratories

Novel radiopharmaceuticals for imaging unique metabolic pathways in cancer: Amino acids play an important role in many biological processes, serving a key role in protein synthesis and as substrates for important intermediary metabolic processes and cell signaling pathways. This makes them prime candidates for templates for new medical imaging probes – substances that can be used to diagnose and track the development of diseases. To this end, TRIUMF has developed novel tracers toward two molecular systems: x_C- and LAT1. System x_C- helps to maintain homeostasis via antioxidant/free radical management at the cellular level, while the LAT1 transporter is an important component of protein synthesis in cells. TRIUMF has developed ^{18}F-fluoroaminosuberic acid ($^{18}FASu$) as a specific positron-emitting substrate of system x_C-; and via collaborative efforts with scientists at SFU, a series of leucine-like radiolabeled amino acids as substrates of LAT1. Studies are ongoing to establish the utility of both tracers in the detection, staging and treatment monitoring of a number of different cancers.

Functional Imaging of Oxidative Stress with a novel PET imaging agent, ^{18}F-5-fluoro-L-aminosuberic acid

J.M. Webster et al., Journal of Nuclear Medicine, 55, 657 (2014)

^{18}F-5-fluoro-aminosuberic acid (FASu) as a potential tracer to gauge oxidative stress in breast cancer models

H. Yang et al., Journal of Nuclear Medicine, 58, 367 (2017)

Addressing Chirality in the Structure and Synthesis of [F-18]5-Fluoroaminosuberic Acid ([18F]FASu)

H. Yang et al., Chemistry, A European Journal, 23, 11100 (2017)

PURE RADIOACTIVE ION BEAMS AND RARE ISOTOPE SPECTROSCOPY FROM TRIUMF'S LASER ION SOURCE TRILIS

Targets and Ion Sources

Virtually contamination-free radioactive ion beams can now be provided at ISAC from a new ion-guide laser ion source (IG-LIS) [1]. This IG-LIS allows for experiments on isotopes that for decades have been overwhelmed by contamination from surface-ionized isobars. TRILIS now routinely provides isotopes from 37 different elements. Laser ionization schemes for an additional 24 elements are ready for off-line testing. TRILIS also supports an in-source laser spectroscopy program that investigates fundamental properties of the rarest isotopes such as atomic energy levels and elemental ionization potentials have been determined for the first time [2] or improved significantly [3].

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S. Raeder et al., Spectrochimica Acta B (2018)

TOWARDS MORE DATA-DENSE HARD DRIVES

bNMR

bNMR Investigation of the Depth-Dependent Magnetic Properties of an Antiferromagnetic Surface Hard drives use disks made of magnetic material to store information, and an electromagnet in the read/write head writes information to the disk by magnetizing small sections of the disk. Increasing the information on a hard drive requires shrinking the size of the magnetic sections and this means the near-surface regions are increasingly important. The prototypical antiferromagnet α-Fe_2O_3 has a first-order transition known as the Morin transition at 260 K, where the orientation of antiferromagnetic order with respect to the crystal lattice undergoes an abrupt change. In this work the static spin orientation and dynamic spin correlations within nanometers from the surface of a single crystal was studied via the nuclear spin polarization of implanted ^{8}Li ions and detected via bNMR spectroscopy. As reported in ***Physical Review Letters*** (2016), the experiment found that the Morin transition temperature was independent of depth from 1 to 100 nm from the free (110) surface but the fluctuations of the electronic spins are faster near the crystal surface and decay into the bulk over a characteristic length of 11 nm. The results suggest the magnetic order parameter undergoes a continuous gradient rather than a phase separation of bulk vs. surface magnetism. Whereas previous studies made use of nanoparticles to achieve sufficient near-surface volume fraction to extract a signal, bNMR spectroscopy allowed a depth-resolved characterisation of the magnetic order parameter into a macroscopic single crystal of α-Fe_2O_3, differentiating free-surface and finite-size effects on magnetic order.

β-NMR Investigation of the Depth-Dependent Magnetic Properties of an Antiferromagnetic Surface

D.L. Cortie et al., Phys. Rev. Lett., 11610 (2016)

HIGH ENERGY FRONTIER

2013 NOBEL PRIZE IN PHYSICS AND THE CHARACTERIZATION OF THE HIGGS BOSON

ATLAS

2013 Nobel Prize in Physics and the characterization of the Higgs boson: The 2013 Nobel Prize in Physics was awarded jointly to François Englert and Peter Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider". The 2012 discovery paper constituted the "Observation of a new particle in the search of the Standard Model Higgs boson". The scientific justification from the Nobel Prize Committee cited in addition two ATLAS papers in *Physics Letters B* (2013). The **first** and **second** papers showed the consistency with the spin-0 and even parity characteristics of the discovered particle as well as couplings to bosons that were as expected for a Higgs boson.

Evidence for the spin-0 nature of the Higgs boson using ATLAS data

ATLAS Collaboration, Physics Letters B, 726, 120 (2013)

Measurement of Higgs boson production and couplings in diboson final states with the ATLAS detector at the LHC

ATLAS Collaboration, Physics Letters B, 726, 88 (2013)

COMBINATION OF SEARCHES FOR HEAVY RESONANCES DECAYING INTO BOSONIC AND LEPTONIC FINAL STATES

ATLAS

Combination of searches for heavy resonances decaying into bosonic and leptonic final states: A generic prediction of many extensions of the Standard Model (SM) is the existence of heavy bosons decaying into pairs SM gauge bosons, as well as WH, ZH, or a pair of fermions. Specific searches for diboson resonances in several decay channels were combined to set constraints, using simple benchmark models, on the existence of a heavy hypothetical scalar, vector, or tensor particle. Analyses of leptonic final states and were further combined with the diboson searches. Limit contours were obtained on the couplings of a heavy vector triplet (HVT) to quarks, leptons and the Higgs boson. The data exclude an HVT boson with mass below 5.5 (4.5) TeV in a weakly-coupled (strongly-coupled) scenario. Limits are also set on a Kaluza-Klein graviton.

CONSTRAINTS ON NEW PHENOMENA VIA HIGGS BOSON COUPLINGS AND INVISIBLE DECAYS

ATLAS

Constraints on new phenomena via Higgs boson couplings and invisible decays: A crucial question in particle physics is whether the Higgs boson discovered in 2012 is truly the fundamental scalar predicted by the Standard Model (SM). Strong theoretical arguments suggest that the SM is only an approximation to a more fundamental theory such as supersymmetry or composite Higgs models, which predict modified properties of the Higgs with respect to SM expectations. As published in the ***Journal of High Energy Physics*** (2015), the results of several analyses of production and decay rates of the Higgs boson in different channels were combined to determine how the couplings scale with mass and hence put constraints on various extensions of the SM. Vector boson processes and associated WH/ZH production set an upper limit on the Higgs boson decay branching ratio to invisible particles, such as dark matter, of 25%.

Constraints on new phenomena via Higgs boson couplings and invisible decays with the ATLAS detector

The ATLAS collaboration et al., Journal of High Energy Physics, 206 (2015)

ELUSIVE DARK MATTER AND OTHER EXOTIC PHENOMENA

ATLAS

Elusive dark matter and other exotic phenomena: A number of astrophysical measurements point to the existence of a new form of matter. For instance, the rotational speed of stars and observation of gravitational lensing effects strongly indicate the presence of so-called dark matter, in addition to our ordinary matter, that would compose a large fraction of our universe. Dark matter particles can be directly produced at the Large Hadron Collider, and one striking event signature would be the presence of an energetic jet of ordinary particles (called a monojet) and large missing energy due to dark matter particles escaping the ATLAS detector. As reported in the ***Journal of High Energy Physics*** (2018), a monojet final state constitutes a distinctive signature of beyond-Standard Model physics, and is also used to search for extra spatial dimensions and supersymmetry. Constraints have been set on various models.

Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector

The ATLAS Collaboration et al., Journal of High Energy Physics, 126 (2018)

EXCLUSION OF OBVIOUS AND ACCESSIBLE SUPERSYMMETRY

ATLAS

Exclusion of Obvious and Accessible Supersymmetry: The key feature of a proton collider is copious pair production of strongly interacting particles. The ATLAS collaboration scoured the entire dataset collected in the 8 TeV Large Hadron Collider run for an excess of events containing only particle jets, with an imbalance of transverse momentum. This would be the signature of strongly-produced supersymmetric particles decaying to Standard Model particles and the stable lightest supersymmetric particle, a weakly interacting particle detectable only by the hole it would leave, and thus an excellent candidate for dark matter. As published in the ***Journal of High Energy Physics*** (2015), no excess was found, and lower limits on masses of a large number of supersymmetric particles were obtained in a wide variety of benchmark and simplified models. These were in excess of one TeV for most strongly produced particles.

Summary of the searches for squarks and gluinos using $\sqrt{s} = 8$ TeV pp collisions with the ATLAS experiment at the LHC

The ATLAS Collaboration et al., Journal of High Energy Physics, 54 (2015)

OBSERVATION OF HIGGS BOSON PRODUCTION IN ASSOCIATION WITH A TOP QUARK PAIR

ATLAS

Observation of Higgs boson production in association with a top quark pair: A probe of fundamental interest to further explore the nature of the Higgs boson is to measure its interaction with the top-quark, the most massive particle in the Standard Model. Indirect measurements of this interaction were previously made assuming no contribution from unknown particles. A more direct test of this coupling can be performed through the direct production of the Higgs boson in association with a top-quark pair, *ttH*. Measuring this process is challenging, because it is extremely rare: only one percent of Higgs bosons are expected to be produced this way. As submit to ***Physics Letters B*** (2018), using advanced analysis techniques, several independent searches for ttH production have been performed and combined, yielding the first observation of ttH production with a significance of 6.3 standard deviations relative to the background-only hypothesis.

Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector

The ATLAS Collaboration et al., Physics Letters B, 784, 173 (2018)

PIONS, MUONS AND POSITRONS

M11 beamline

Pions, muons and positrons: The M11 beam channel provides low intensity beams of pions, muons and positrons for testing and calibrating detectors for particle physics experiments world-wide. Three notable examples from the period 2013-2018 are described here. TREK The TREK experiment is searching for new physics beyond the standard model in the rare decay modes of kaons. In November 2013 and June 2014, a group led by Mike Hasinoff (UBC) **tested the scintillating fibre target to establish the bias voltage offsets for each individual MPPC detector/scintillating fibre combination**. Muon and positron tracks through the detector were measured to compute individual fibre efficiencies. This target was subsequently used for data taking in Experiment 36 at J-PARC in Tokai, Japan. Previous to this, in November 2012, the TREK group tested TOF counter time resolution and e-mu discrimination using a polyethylene block placed in front of a Lead-Glass-Counter to change the shower development. ATLAS Polycrystalline chemical vapor deposition (pCVD) diamond detectors are a candidate for forward calorimetry in the high luminosity environment of the CERN LHC. One such detector was exposed to particles delivered by M11 to quantify the variation in signal response across the surface of such a detector. A discrepancy was observed in the diamond detector's response to beam particles at different bias polarities. This study was documented in a Carleton MSc thesis, "**Characterization of diamond sensors for use in ATLAS calorimetry upgrades**", by Joshua Turner, 2012, Super-B and BELLE The Super-B drift chamber group undertook two tests of drift chamber prototypes in the M11 beam line in 2013. These tests were the first to **demonstrate that the particle identification capabilities of drift chambers could be significantly improved** by counting individual ionization events in the gas ("cluster counting"), rather than just measuring the total energy deposited in each cell. The results were published as NIM A735, 169-183 (2014), and formed a key component of the PhD thesis of Jean-Francois Caron (UBC, 2015). After the merging of the Super-B and BELLE-II collaborations, the Belle II Canada group used the M11 beamline to test pure and thallium CsI crystals with various readout options in the summer of 2015. The group subsequently decided not to pursue pure CsI. The thallium-doped CsI data have been used, along with data collected at the proton irradiation facility at TRIUMF, to develop a new method of distinguishing hadronic from electromagnetic energy deposits using pulse shape discrimination. This technique is being implemented for the Belle II calorimeter, and will form an important component of the PhD thesis of S. Longo (Victoria).

Performance test of a lead-glass counter for the J-PARC E36 experiment

Y. Miyazaki, S. Shimizu et al., Nuclear Instruments and Methods in Physics Research, 779, 13 (2015)

Characterization of diamond sensors for use in ATLAS calorimetry upgrades

J. Turner, Thesis (M.Sc.), Carleton University (2012)

Improved particle identification using cluster counting in a full-length drift chamber prototype

J.F. Caron, C. Hearty, P. Lu, R. So, R. Cheaib, J.P. Martin, W. Faszer, A. Beaulieu, S. de Jong, M. Roney et al., Nuclear Methods in Physics Research, 735, 169 (2014)

VACUUM STABILITY AND THE MSSM HIGGS MASS

Theory

Vacuum stability and the MSSM Higgs mass: Supersymmetry is a leading candidate for beyond-Standard Model physics. A crucial requirement for supersymmetry to be realized is that it does not lead to the catastrophic destruction of the universe, which can occur if the theory contains new lowest-energy vacuum states that are deeper than the one that we live in. As reported in the ***Journal of High Energy Physics*** (2014), TRIUMF theorists investigated the implications of this vacuum stability condition on the minimal supersymmetric extension of the Standard Model (MSSM) by studying the vacuum structure of the theory as well as the quantum transition rates between vacuum states. A close connection was found between the stability of the Universe, the observed mass of the Higgs boson, and the properties of the supersymmetric partner particles of the top quarks which are currently being searched for with CERN's Large Hadron Collider.

Vacuum stability and the MSSM Higgs mass

N. Blinov and D.E. Morrissey, Journal of High Energy Physics, 106 (2014)

MOLECULAR AND MATERIALS SCIENCE

A NEW, TUNABLE QUANTUM SPIN LIQUID OFFERS NEXT-GENERATION TECHNOLOGY PROMISE

muSR

A new, tunable quantum spin liquid offers next-generation technology promise: Research at CMMS has demonstrated that it's possible to tweak a magnetic materials' overall electron structure in a new way to create novel states that could have numerous technological applications, including for improved magnetic information storage. As reported in ***Physical Review Letters*** (2018), using TRIUMF's μSR probe it was discovered that a material's magnetic ground state can be tuned by changing its charge order. A quantum spin liquid (QSL) is a strange ground state of a magnetic material with long-range entanglement and emergent excitations. The usual ingredients required to make a QSL are small spins and competing interactions that create geometric frustration. CMMS added an additional ingredient to generate QSL physics: charge order. The materials $Li_2In_{1-x}Sc_xMo_3O_8$ have an asymmetric lattice and the electrons are dilute, with only a third of the sites occupied. As the ratio of scandium (Sc) to indium (In) atoms in the material is altered, the lattice becomes more symmetric and the electrons form a particular “plaquette” charge order which generates more frustration and induces a new, tunable QSL ground state.

Tunable Quantum Spin Liquidity in the 1/6th-Filled Breathing Kagome Lattice

A. Akbari-Sharbaf, R. Sinclair, A. Verrier, D. Ziat, H.D. Zhou, X.F. Sun, and J.A. Quilliam, Phys. Rev. Lett., 12022 (2018)

BETANMR REVEALS NANOSCALE SURFACE DETAILS IN TOPOLOGICAL INSULATORS

bNMR

bNMR reveals nanoscale surface details in topological insulators: Wolfgang Pauli said, “God made the bulk; surfaces were invented by the devil”, a recognition of the fact that theories and experimental measurements of near-surface properties are very difficult. Surfaces may be difficult to study, but it is where much interesting physics arise. Topological insulators (TI) are materials where the bulk is an insulator but whose surface contains conducting states, which means that electrons can only move along the surface of the material. Topologically protected states could act as a source of spin-polarized electrons with properties relevant to spintronics applications including quantum computing. As published in the ***Proceedings of the National Academy of Sciences*** (2015) researchers at CMMS used bNMR spectroscopy as a nano-scale depth-resolved probe of magnetism and conductivity within about 10 nm of the free surface of $(Bi,Sb)_2Te_3$. This depth-dependent study of electronic and magnetic properties of TI epitaxial layers using implanted, spbin-polarized $^8Li^+$ ions reveals differences in the band structure between the near-surface and deeper into the bulk material.

Nanoscale β-nuclear magnetic resonance depth imaging of topological insulators

D. Koumoulis et al., PNAS, 11228 (2015)

TOWARDS MORE DATA-DENSE HARD DRIVES

bNMR

bNMR Investigation of the Depth-Dependent Magnetic Properties of an Antiferromagnetic Surface Hard drives use disks made of magnetic material to store information, and an electromagnet in the read/write head writes information to the disk by magnetizing small sections of the disk. Increasing the information on a hard drive requires shrinking the size of the magnetic sections and this means the near-surface regions are increasingly important. The prototypical antiferromagnet α-Fe_2O_3 has a first-order transition known as the Morin transition at 260 K, where the orientation of antiferromagnetic order with respect to the crystal lattice undergoes an abrupt change. In this work the static spin orientation and dynamic spin correlations within nanometers from the surface of a single crystal was studied via the nuclear spin polarization of implanted ^{8}Li ions and detected via bNMR spectroscopy. As reported in ***Physical Review Letters*** (2016), the experiment found that the Morin transition temperature was independent of depth from 1 to 100 nm from the free (110) surface but the fluctuations of the electronic spins are faster near the crystal surface and decay into the bulk over a characteristic length of 11 nm. The results suggest the magnetic order parameter undergoes a continuous gradient rather than a phase separation of bulk vs. surface magnetism. Whereas previous studies made use of nanoparticles to achieve sufficient near-surface volume fraction to extract a signal, bNMR spectroscopy allowed a depth-resolved characterisation of the magnetic order parameter into a macroscopic single crystal of α-Fe_2O_3, differentiating free-surface and finite-size effects on magnetic order.

β-NMR Investigation of the Depth-Dependent Magnetic Properties of an Antiferromagnetic Surface

D.L. Cortie et al., Phys. Rev. Lett., 11610 (2016)

VOLUME-WISE DESTRUCTION OF THE ANTIFERROMAGNETIC MOTT INSULATING STATE THROUGH QUANTUM TUNING

muSR

Volume-wise destruction of the antiferromagnetic Mott insulating state through quantum tuning: Mott insulators are materials that should conduct electricity under conventional band theories but are actually insulators due to electron–electron interactions. They have applications in thin-film magnetic heterostructures and high-temperature superconductivity. Published in ***Nature Communications*** (2016), the work presents μSR results from the CMMS combined with X-ray, neutron and μSR data from other laboratories in a study of metal-insulator transitions of prototypical Mott insulators. The composition of $RENiO_3$ with various fractions of rare earths RE=La, Pr, Ni and Sm, provides a tuning parameter in the temperature-composition phase diagram, controlling a phase transition between an antiferromagnetic Mott insulating state and a paramagnetic metallic state, terminating in a quantum critical point at T=0. Being a sensitive probe of magnetism, μSR is the ideal tool to measure the magnetic field distribution, the magnetic volume fraction and excitations from the ordered magnetic ground state. This experiment produced evidence that the quantum phase transition (QPT) in RENiO3 is first order: the magnetically ordered volume fraction decreases continuously to zero at the QPT, while the ordered magnetic moment retains essentially its full value until it abruptly vanishes at the QPT. These results unambiguously demonstrate that the QPT in these materials proceeds in a distinctly first-order fashion. Studies of antiferromagnetic Mott insulators, as well as emergent quantum phenomena in other kinds of materials, are useful to elucidate both the system-specific and more universal roles of first-order behaviour in quantum phase evolution.

Volume-wise destruction of the antiferromagnetic Mott insulating state through quantum tuning

B.A. Frandsen, L. Liu, S.C. Cheung, Z. Guguchia, R. Khasanov, E. Morenzoni, T.J.S. Munsie, A.M. Hallas, M.N. Wilson, Y. Cai et al., Nature Communications, 7 (2016)

NEUTRINOS AND DARK MATTER

A SUCCESSFUL SNO+ START-UP

SNO+

A successful SNO+ start-up: SNO+ has successfully completed the first water phase of the experiment. During this phase the expected levels of background were verified; in particular, the goals for uranium and thorium contamination in the water were met, and all sources of external backgrounds were measured. The external background measurements are directly transferable to the upcoming scintillator and tellurium-loaded second and third phases of the experiment. An underwater camera system was deployed and commissioned, used to monitor the hold-down rope system of the acrylic vessel, and the location of calibration sources inside the vessel. The SNO+ team also commissioned the new electronics and data acquisition systems, upgraded to handle the higher event rates in SNO+.

COMMISSIONING OF THE DATA ACQUISITION SYSTEM AND FIRST LIQUID ARGON SIGNAL

DEAP-3600

In August 2016, the DEAP-3600 experiment was finally completed with the filling of the acrylic vessel with 3.6 tonnes of liquid argon. This milestone marked the beginning of the physics operation for this experiment. The DAQ and the Science & Technology groups at TRIUMF worked extensively to ensure that the data acquisition system was ready for the data intake upon filling. One of the biggest challenges for the scientists at TRIUMF who drove this part of the project was to ensure that the experiment could keep up with the high rate of the intrinsic argon beta-emitter ^{39}Ar, of the order of ~3.6 kHz, while never missing any possible dark matter-argon interaction. The commissioning period was brief and smooth, and the data acquisition system operated to specification due primarily to the efforts of the TRIUMF team.

COMPLETION OF THE DEAP-3600 ACRYLIC VESSEL INNER SURFACE SANDING

DEAP-3600

To listen for interactions between DEAP's argon detector and dark matter, the collaboration had to create one of the most radiogenically clean environments in the entire universe. To do this, the collaboration fabricated its inner detector, a sphere of radius 85 cm, from ultra-pure acrylic, and designed and implemented an 18 feet tall sanding robot (the Resurface) capable of removing the innermost layer of the acrylic sphere in a contained environment (with the aim of removing any contamination introducted during installation). This never-before-attempted, large-scale robot, a true experiment within the experiment, was deployed at the center of the DEAP vessel in October 2014 and after a month of operation, had **successfully removed 500 microns uniformly from the detector surface**, thus returning the purity levels of the acrylic back to production standards.

In-situ surface contamination removal and cool-down process of the DEAP-3600 experiment

P. Giampa and DEAP Collaboration, J. Phys.: Conf. Ser., 71804 (2016)

CONSTRAINTS ON NEW PHENOMENA VIA HIGGS BOSON COUPLINGS AND INVISIBLE DECAYS

ATLAS

Constraints on new phenomena via Higgs boson couplings and invisible decays: A crucial question in particle physics is whether the Higgs boson discovered in 2012 is truly the fundamental scalar predicted by the Standard Model (SM). Strong theoretical arguments suggest that the SM is only an approximation to a more fundamental theory such as supersymmetry or composite Higgs models, which predict modified properties of the Higgs with respect to SM expectations. As published in the ***Journal of High Energy Physics*** (2015), the results of several analyses of production and decay rates of the Higgs boson in different channels were combined to determine how the couplings scale with mass and hence put constraints on various extensions of the SM. Vector boson processes and associated WH/ZH production set an upper limit on the Higgs boson decay branching ratio to invisible particles, such as dark matter, of 25%.

Constraints on new phenomena via Higgs boson couplings and invisible decays with the ATLAS detector

The ATLAS collaboration et al., Journal of High Energy Physics, 206 (2015)

DARK MATTER FROM A NEW DARK STRONG FORCE

Theory

Dark matter from a new dark strong force: Most of the matter in the Universe seems to be a new form that gives off very little light, called dark matter (DM). While the evidence for DM is very strong, very little is known about what it is made of. As reported in ***Physical Review D***, TRIUMF theorists showed that DM can arise from a new strong force that interacts only very feebly with regular matter. In this realization, DM consists of glueballs consisting of a conglomeration of the mediators of the new force. Implications of glueball dark matter and decays on the formation of light elements in the early Universe, the cosmic microwave background radiation, and astronomical gamma rays seen today were also studied.

Cosmological bounds on non-Abelian dark forces

L. Forestell, D.E. Morrissey, and K. Sigurdson, Phys. Rev. D, 977 (2018)

DIRECT MEASUREMENT OF SPIN POLARIZATION OF DECAYING ATOMS

TRINAT

Direct measurement of spin polarization of decaying atoms: In 2016, TRINAT demonstrated a direct atomic-physics probe of the spin polarization of potassium-37 (^{37}K) nuclei as they decayed. Many spin-polarized decay experiments disturb the polarization or must measure it separately. As reported in the ***New Journal of Physics*** (2016), the high accuracy of the polarization achieved (99.1% +/- 0.1%) enabled a sensitive search for wrong-handed neutrinos. The result also demonstrates the potential to measure the polarization to a level of precision which would be competitive in searches for new physics. The paper was selected as one of the journal's 2016 Highlights.

Precision measurement of the nuclear polarization in laser-cooled, optically pumped ^{37}K

B. Fenker, J.A. Behr, D. Melconian et al., New Journal of Physics, 1807 (2016)

ELECTRON DRIFT VELOCITY AND TRANSVERSE DIFFUSION MEASUREMENTS IN LIQUID XE WITH EXO-200

nEXO

Electron drift velocity and transverse diffusion measurements in liquid Xe with EXO-200: EXO-200 is using a liquid xenon (LXe) time projection chamber to search for 0nbb. This measurement relies on modeling the transport of charge deposits produced by interactions in the LXe to allow discrimination between signal and background events. As reported in ***Physical Review C*** (2017), by varying the electric field of the EXO-200 TPC, we measured the transverse diffusion constant and drift velocity of electrons at drift fields between 20 V/cm and 615 V/cm using EXO-200 data. At the operating field of 380 V/cm EXO-200 measures a drift velocity of $1.705^{+0.014}_{-0.010}$mm/μs and a transverse diffusion coefficient of 55±4cm^2/s. This measurement provide information for liquid xenon dark matter detectors such as LZ and XENON, as well as for the future nEXO detector.

Measurement of the drift velocity and the transverse diffusion of electrons in liquid xenon with the EXO-200 detector

J.B. Albert et al. (EXO-200 Collaboration), Phys. Rev. C, 9502 (2017)

ELUSIVE DARK MATTER AND OTHER EXOTIC PHENOMENA

ATLAS

Elusive dark matter and other exotic phenomena: A number of astrophysical measurements point to the existence of a new form of matter. For instance, the rotational speed of stars and observation of gravitational lensing effects strongly indicate the presence of so-called dark matter, in addition to our ordinary matter, that would compose a large fraction of our universe. Dark matter particles can be directly produced at the Large Hadron Collider, and one striking event signature would be the presence of an energetic jet of ordinary particles (called a monojet) and large missing energy due to dark matter particles escaping the ATLAS detector. As reported in the ***Journal of High Energy Physics*** (2018), a monojet final state constitutes a distinctive signature of beyond-Standard Model physics, and is also used to search for extra spatial dimensions and supersymmetry. Constraints have been set on various models.

Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector

The ATLAS Collaboration et al., Journal of High Energy Physics, 126 (2018)

EXPERIMENTAL OBSERVATION OF NEUTRINO FLAVOUR TRANSFORMATION

T2K: Tokai to Kamioka

Experimental observation of neutrino flavour transformation: As reported in ***Physical Review Letters*** (2014) as an Editor's Suggestion and since then cited almost 600 times, the T2K experiment for the first time experimentally observed neutrino flavour transformation. Muon neutrinos were produced at the J-PARC facility on Japan's east coast and sent 295 km through the ground to the Super-Kamiokande (SK) neutrino detector in western Japan. SK recorded a decreased number of muon neutrinos and the appearance of electron neutrinos, demonstrating flavour transformation. The discovery of an explicit oscillation confirms the neutrino oscillation mechanism (first observed with solar neutrinos) and opens the door to the use of neutrino oscillation as a probe of CP symmetry violation in leptons.

Observation of Electron Neutrino Appearance in a Muon Neutrino Beam

K. Abe et al. (T2K Collaboration), Phys. Rev. Lett., 11206 (2014)

FIRST EXCLUSION OF CP CONSERVATION IN NEUTRINO OSCILLATION AT 90% CONFIDENCE LEVEL

T2K: Tokai to Kamioka

First exclusion of CP conservation in neutrino oscillation at 90% confidence level: The observation of muon to electron-neutrino oscillation opens the possibility of using neutrino oscillation to study CP violation by comparing neutrino flavour transformations between neutrinos and anti-neutrinos. CP violation has been observed in quarks but not yet measured in leptons (particles, including neutrinos, that do not undergo strong interactions). The size of quark CP violation is not enough to explain the matter anti-matter asymmetry of the universe, and as such, leptons' role may be significant. As reported in ***Physical Review Letters*** (2017) as an Editor's Suggestion, T2K performed a combined analysis of neutrino and anti-neutrino oscillations and notably excluded CP conservation at the 90% confidence level.

Combined Analysis of Neutrino and Antineutrino Oscillations at T2K

K. Abe et al., Phys. Rev. Lett., 11815 (2017)

FIRST RESULTS ON DARK MATTER CROSS-SECTION WITH LIQUID ARGON

DEAP-3600

In July 2017, the DEAP-3600 collaboration published its first paper reporting on the search for Weakly Interacting Massive Particles (WIMPs) using four days of data collected during the commissioning phase. While the data showed no interactions between the liquid argon atoms and WIMPs (as expected based on the short exposure time), the result showed the true power of DEAP’s Pulse-Shape Discrimination (PSD), a methodology that differentiates electronic interactions (backgrounds) to nuclear interactions (signal). In **Physics Review Letters**, the collaboration showed that the experiment is performing to specifications and PSD can discriminate electronic recoils from nuclear recoils with an unprecedented measured power of $1.2x10^{-7}$.

First Results from the DEAP-3600 Dark Matter Search with Argon at SNOLAB

P.A. Amadruz et. al (DEAP-3600 Collaboration), Phys. Rev. Lett., 12107 (2018)

HALO DEVELOPMENT

HALO

HALO development: The HALO supernova neutrino detector in SNOLAB is unique among neutrino detectors in that it is primarily sensitive to electron-type neutrinos, rather than electron-type antineutrinos. As such, it has an important role to play in understanding the neutrino flavour content of the neutrino burst from the next galactic core-collapse supernova. The period 2013-2018 had several highlights for HALO:

1. The completion of the construction of the HALO detector and its water shielding
2. The calibration of the detector with a neutron source inserted at multiple locations within the lead matrix
3. HALO joining the international SuperNova Early Warning System (SNEWS) in October 2015

The HALO collaboration has recently expanded to become the HALO-1kT collaboration, to include new collaborators from the USA and Italy. The collaboration is currently designing a much larger detector, using the 1000 tonnes of lead from the decommissioned OPERA detector at the Gran Sasso laboratory in Italy, and making plans to measure the neutrino-lead cross section at the Spallation Neutron Source at Oak Ridge National Laboratory, Tennessee. **TRIUMF's role in the construction of the detector:** TRIUMF's electronics shop fabricated the electrical cables that supply the neutron detectors with high voltage, and carry the signals from the neutron detectors to the amplifiers and then onto the data acquisition computers. TRIUMF's machine shop built the test stand that was used to test the neutron detectors one by one before installation inside the lead matrix of HALO. A substantial part of the manpower for design and assembly of the detector was supplied by TRIUMF. **TRIUMF's role in the calibration of the detector:** The neutron detectors count the number of neutrons emitted when supernova neutrinos hit the mass of lead. But not all neutrons are counted; some are absorbed by the lead itself, and others escape out the surface of the lead mass. To relate the number of neutrinos arriving from the supernova to the number of neutrons counted, it is necessary to know the efficiency with which neutrons are counted. We do this by inserted a radioactive source that injects a known number of neutrons at various locations in the lead matrix, and compare this with the number of neutrons that are counted).

SEARCHING FOR NEW DARK FORCES AT LOWER-ENERGY EXPERIMENTS

Theory

Searching for new dark forces at lower-energy experiments: New forces may exist beyond those described by the Standard Model. The characteristic energy of a new force can be much smaller than that of the weak force provided it interacts only very feebly with regular matter. One of the most promising ways to discover such new dark forces is in lower-energy beam dump experiments in which a very intense beam is directed at a material target. As reported in the ***Journal of High Energy Physics*** (2014), TRIUMF theorists investigated new ways to apply existing beam dump experiments (usually designed for other scientific objectives) to look for dark forces and new particles associated with them. They also connected theories of dark forces with limits from cosmology and direct searches for dark matter.

New limits on light hidden sectors from fixed-target experiments

D.E. Morrissey and A.P. Spray, Journal of High Energy Physics, 83 (2014)

SENSITIVITY AND DISCOVERY POTENTIAL OF THE PROPOSED NEXO EXPERIMENT

nEXO

Sensitivity and discovery potential of the proposed nEXO experiment: nEXO is a future 0nbb decay experiment searching for this weak process in the decay of ^{136}Xe. nEXO is building on the experience gained and the success of the EXO-200. As reported in ***Physical Review C*** (2018), the sensitivity of nEXO, which is anticipated to deploy 5x10^3 kg of liquid xenon enriched in the isotope ^{136}Xe to 90%, has been investigated under demonstrated and realizable background rates. The projected sensitivity of nEXO after 10 years of operation reaches 10^{28} years, which is an improvement of almost two orders of magnitude compared to current experiments.

Sensitivity and discovery potential of the proposed nEXO experiment to neutrinoless double-β decay

J.B. Albert et al. (nEXO Collaboration), Phys. Rev. C, 9706 (2018)

THE CASE OF THE MISSING NEUTRINOS

TITAN

The Case of the Missing Neutrinos: After 15 years of solar-neutrino measurements, 13% of the theoretically expected flux, or number, of neutrinos is unobserved. This is leading physicists to explore a variety of possible reasons, from the underlying nuclear physics to detector design. One proposed reason is the energetic cost of the detector material to capture a neutrino. To explore this, TITAN deployed its high-accuracy, high-precision Penning trap, the only one in the world coupled to a charge breeder. The charge breeder's removal of electrons boosted the precision of the measurements with gallium and germanium isotopes and allowed for a novel radioactive-beam purification. As reported in ***Physical Letters B*** (2013), TITAN measurements validate the final piece of the nuclear physics underpinning the predicted neutrino flux, and thus the cause of the missing neutrinos remains an open case.

Penning-trap Q-value determination of the ^{71}Ga (ν, e^-) ^{71}Ge reaction using threshold charge breeding of on-line produced isotopes

D. Frekers, M.C. Simon et al., Physics Letters B, 722, 233 (2013)

NUCLEAR ASTROPHYSICS

A NEW PATH TO ELEMENT FORMATION

IRIS

A new path to element formation: IRIS' first results give astrophysicists and nuclear physicists a deeper understanding of the nuclear states and pathways involved in element formation. As reported in ***Physical Review Letters*** (2015), the results provide the experimental evidence for a new kind of nuclear excitation, soft dipole resonance. IRIS researchers identified this resonance in neutron-rich lithium-11 (^{11}Li), the heaviest bound lithium isotope, with three protons and eight neutrons, two of which orbit, barely held, in a halo, far from the nuclear core. Oscillation of the halo neutrons, the experiment revealed, leads to an extremely brief, quasi-bound nuclear resonance state, significantly changing the potential for neutron capture, as occurs in stars during element formation. The results confirm theoretical predictions and provide an important path for developing new nuclear models to predict the properties of neutron-rich isotopes.

Evidence of Soft Dipole Resonance in ^{11}Li with Isoscalar Character

R. Kanungo et al., Phys. Rev. Lett., 11419 (2015)

CLARIFYING A KEY STEP IN THE ORIGIN OF THE ELEMENTS

GRIFFIN

Clarifying a key step in the origin of the elements: As reported in ***Physical Review C*** (2016) researchers using GRIFFIN have produced the highest-precision measurement ever of the half-life of cadmium-130 (^{130}Cd), a rare isotope that's a cornerstone for understanding cosmic element formation. Astrophysical observations are providing mounting evidence that heavy elements are forged in the merger of neutron stars. However, to understand and accurately simulate this element formation process (r-process), it's necessary to experimentally characterize the key rare isotopes involved. This is especially the case for the half-lives of isotopes with masses of about 130 since theoretical models have been tuned to reproduce the half-life of ^{130}Cd and then predict half-lives in the entire region. Thus, scientists used GRIFFIN to produce a ^{130}Cd half-life measurement three-times more precise than the previously adopted world average, a result which will help astrophysicists more clearly see our stardust origins.

High-precision half-life measurement for the superallowed Fermi β^+ emitter ^{22}Mg

M.R. Dunlop et al., Phys. Rev. C, 9604 (2017)

EMMA SET TO HELP REVEAL THE HEARTS OF STARS AND ATOMS

EMMA

EMMA set to help reveal the hearts of stars and atoms: In 2018, the coupling of the EMMA and TIGRESS spectrometers will mark the beginning of EMMA's scientific program to probe the deep nature of nuclear reactions in stars and the subtleties of extreme nuclear structure. EMMA's arrival is the culmination of a multi-year series of commissioning steps successfully demonstrating the spectrometer's enormous potential for TRIUMF's rare isotope beam program. In December 2016, commissioning of the spectrometer as a whole began with a test beam of argon-36 (^{36}Ar) bombarding a very thick gold (Au) foil. The spectrometer was initially tuned for elastically scattered Ar ions and its first mass/charge spectrum was collected. As shown in *figure A*, both the 13^{+} and 14^{+} charge states were detected simultaneously, the dispersion–the key ability to distinguish between states–agreed exactly with calculations. In September 2017 an argon-40 (^{40}Ar) beam bombarded a very thin Au target and elastically back-scattered Au ions were detected in two charge states simultaneously and used to measure the energy, angular, and mass/charge acceptances; substantially improved resolving power was observed. In November 2017, EMMA accepted its first radioactive beam, sodium-24 (^{24}Na) which was used to induce fusion evaporation reactions on a copper target. Various fusion products with atomic masses from 80 to 85 were clearly detected and resolved in a single spectrometer setting. EMMA will use of both the light, neutron-deficient beams from ISAC and the future heavy, neutron-rich beams from ARIEL to explore radiative capture and transfer reactions that are central to astrophysical research, and fusion reactions important to the study of nuclear structure.

EXPLAINING ANOMALIES IN THE SPECTRA OF CLASSICAL NOVAE

DRAGON

Explaining anomalies in the spectra of classical novae: The optical, ultraviolet and infrared spectra of the debris left over after nova explosions – thermonuclear detonations on the surface of accreting white dwarves in stellar binary systems – contain important fingerprints of the chemical elements synthesized and ejected during these cataclysmic events. However, for some elements, namely argon and calcium, much more than expected seems to be present. This flies in the face of theoretical models of nova explosions which say that nucleosynthesis in novae effectively stops at calcium, with around the same amount of calcium being present after the explosion as before the explosion. The volume of elements from Ar-Ca produced in these scenarios depends sensitively on the strengths of nuclear reactions around that region, in particular proton-induced *radiative capture* reactions. One of these, p (^{38}K $,\gamma$)^{39}Ca has **now been experimentally measured for the first time using TRIUMF's DRAGON facility**, previously impossible because if the short lifetime of ^{38}K, but accessible to the *inverse kinematics* technique of DRAGON using an intense ^{38}K beam made at ISAC. This makes p (^{38}K$,\gamma$)^{39}Ca the highest mass reaction ever measured using this technique with radioactive beams.

Direct measurement of astrophysically important resonances in ^{38}K(p,γ)^{39}Ca

G. Christian, G. Lotay, C. Ruiz et al., Phys. Rev. C, 9702 (2018)

Synopsis: Intel on Stellar Element Production from Accelerator Data (APS Physics Editor's Highlight)

M. Rini, Physics (2018)

Direct Measurement of the Astrophysical ^{38}K(p,γ)^{39}Ca Reaction and Its Influence on the Production of Nuclides toward the End Point of Nova Nucleosynthesis

G. Lotay, G. Christian, C. Ruiz et al., Phys. Rev. Lett., 11613 (2016)

HOW OLD ARE THE OLDEST STARS?

DSL

How old are the oldest stars? Using DSL, scientists have helped astrophysicists narrow-in on a key cosmic mystery: the age of the oldest stars in the Milky Way. To infer a star's age from its starlight, astrophysicists need to know the rates of nuclear reactions powering it, in particular the rate of the reaction when ^{14}N captures a proton to become ^{15}O. It's the slowest reaction, and thus determines the overall pace, of the carbon-nitrogen-oxygen cycle of hydrogen burning in stars. As reported in ***Physical Review C*** (2014), using the DSL facility, scientists measured the 6.79 MeV energy state and others in ^{15}O and constrained its lifetime to be less than 1.8 femtoseconds, or quadrillionths of a second. The researchers believe that even more precise reaction rates could come from coupling the DSL facility to TRIUMF's new recoil spectrometer EMMA.

Lifetime measurements of states in ^{15}O

N. Galinski, S.K.L. Sjue et al., Phys. Rev. C, 903 (2014)

MEASUREMENT OF THE MOST EXOTIC NEUTRON EMITTERS AT BRIKEN

BRIKEN

Measurement of the most exotic neutron emitters at BRIKEN: The BRIKEN (Beta-delayed neutron measurements at RIKEN for nuclear structure, astrophysics, and applications) project started in 2016 at the RIKEN Nishina Center in Japan. As reported in the ***Journal of Instrumentation*** (2017) the ambitious goal of the collaboration is to design the most efficient neutron detector array for the measurement of the most exotic nuclei that can be produced today. With TRIUMF research collaboration, so far 268 nuclei have been measured, and for 180 of them the neutron branching ratio and for 60 the decay half-life has been measured for the first time. The neutron-branching ratio of the doubly-magic isotope nickel-78 has been measured for the first time, and will help to pinpoint theoretical predictions of neutron-magic nuclei.

Conceptual design of a hybrid neutron-gamma detector for study of β-delayed neutrons at the RIB facility of RIKEN

A. Tarifeño-Saldivia, J.L. Tain, C. Domingo-Pardo, F. Calviño, G. Cortés, V.H. Phong, A. Riego et al., Journal of Instrumentation, 12 (2017)

NEUTRON-SKIN AS A PORTAL TO NEUTRON STAR PROPERTIES

Theory

Neutron-skin as a portal to neutron star properties: With the new era opened up by the LIGO and VIRGO observation of neutron-star mergers, multi-messenger astronomy will provide us with new ways to constrain the equation of states of neutron-rich matter. Stronger constraints will be obtained by combining such future data with observations on finite nuclei. Indeed, neutron-rich nuclei provide a portal to study neutron-rich matter, in that they form a neutron-skin around their surface which is directly related to the equation of state of nuclear matter. As reported in ***Nature*** (2016), TRIUMF theorists and international collaborators provided the first *ab initio* computation of calcium-48 (^{48}Ca), a nucleus with 20 protons and 28 neutrons. It was predicted that a neutron-skin is formed, though much smaller than previously thought, calling for new experimental investigations.

Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen, A. Ekström, C. Forssén, G.R. Jansen, W. Nazarewicz, T. Papenbrock, K.A. Wendt et al., Nature Physics, 12, 186 (2016)

RARE ISOTOPE SHEDS LIGHT ON HOW DEAD STARS RE-IGNITE

DSL

Rare isotope sheds light on how dead stars re-ignite: Novae are stellar element-making explosions caused when a white dwarf, the carbon-cinder of a once giant star, accretes hydrogen-rich material onto its surface from a companion star. A key to help astrophysicists better understand novae is through determining the rates of reactions that create and destroy the key rare isotopes they're observed to produce, including sodium-22 (^{22}Na). As reported in ***Physical Review C*** (2016) scientists used DSL to determine, for the first time using the Doppler-shift attenuation method, the lifetimes of several energetic states magnesium-23 (^{23}Mg) the rare isotope that dominates the destruction of ^{22}Na. The researchers' more precise lifetime measurements of related states help explain the structure and behaviour of these rare isotopes and thus the underlying nuclear physics driving novae.

Measurement of Lifetimes in ^{23}Mg

O.S. Kirsebom et al., Phys. Rev. C, 9302 (2016)

RELATING HUBBLE OBSERVATIONS TO THE INSIDE OF A NOVAE EXPLOSION

DRAGON

Relating Hubble observations to the inside of a novae explosion: Several years ago, fluorine was observed in the spectrum of a nova explosion for the first time by a joint exercise between the Hubble Space Telescope and the Nordic Optical Telescope. This provides a powerful tool to compare astronomical observations with theoretical stellar models, because only one stable isotope of fluorine exists, ^{19}F, and its quantity is extremely sensitive to the nuclear reactions that create and destroy it as well as the temperature & density conditions in the explosion. One such reaction, *p* (^{19}Ne,*γ*)^{20}Na, **was measured for the first time at the DRAGON facility**, using a beam of short-lived ^{19}Ne produced at ISAC. This long sought-after reaction cross section was previously inaccessible to direct measurement. The results reduce the uncertainties resulting from nuclear physics inputs to negligible levels when comparing theoretical stellar models to the HST observations.

Direct Measurement of the Key $E_{c.m.} = 456 keV$ Resonance in the Astrophysical ^{19}Ne(p,γ) ^{20}Na Reaction and Its Relevance for Explosive Binary Systems.

R. Wilkinson, G. Lotay, A. Lennarz, C. Ruiz, G. Christian et al., Phys. Rev. Lett., 11924 (2017)

SOLAR FUSION AND BIG BANG NUCLEOSYNTHESIS FROM AB INITIO THEORY

Theory

Solar fusion and Big Bang nucleosynthesis from ab initio theory: The ^{3}He(α,γ)^{7}Be and ^{3}H(α,γ)^{7}Li radiative-capture processes hold great astrophysical significance. Their reaction rates between ~20 and 500 keV are essential to calculate the primordial ^{7}Li abundance in the universe. In addition, standard solar model predictions for the fraction of pp-chain branches resulting in ^{7}Be versus ^{8}B neutrinos depend critically on the ^{3}He(α,γ)^{7}Be astrophysical *S* factor at about 20 keV. These capture cross sections are strongly suppressed at such low energies and thus hard to measure in a laboratory. As reported in ***Physics Letters B*** (2016), TRIUMF nuclear theorists investigated these reactions *ab initio* using a chiral nucleon–nucleon interaction. Our calculated ^{3}He(α,γ)^{7}Be cross sections agree reasonably with the higher-energy experimental data including those measured at TRIUMF while the ^{3}H(α,γ)^{7}Li ones are overestimated. Our low-energy predictions help reduce uncertainty of nuclear data evaluations for astrophysics**.**

^{3}He(α,γ)^{7}Be and ^{3}He(α,γ)^{7}Li astrophysical S factors from the no-core shell model with continuum

J. Dohet-Eraly, P. Navrátil, S. Quaglioni et al., Physics Letters B, 757, 430 (2016)

STUDYING THE ALUMINIUM PRODUCED IN MASSIVE STARS

TUDA

Studying the aluminium produced in massive stars: As reported in ***Physical Review Letters*** (2015), TUDA performed a direct measurement of the *α* (^{23}Na *,p*)^{26}Mg reaction, whose strength influences the amount of aluminum-26 (^{26}Al) produced in convective burning in giant stars. Considerable disagreement existed in the literature as to its strength of this reaction, leading to large uncertainties in the predictions of the synthesis of ^{26}Al by massive stars. The TUDA measurement resolved the discrepancy, showcasing TUDA's ability to directly measure a reaction of astrophysical interest at the energies inside the stars.

Measurement of ^{23}Na(α,p)^{26}Mg at Energies Relevant to ^{26}Al Production in Massive Stars

J.R. Tomlinson, J. Fallis, A.M. Laird, S.P. Fox et al., Phys. Rev. Lett., 1155 (2015)

TRIUMF HELPS PROVIDE IAEA WITH EVALUATION OF BETA-DELAYED NEUTRON EMITTERS

BRIKEN

TRIUMF helps provide IAEA with evaluation of beta-delayed neutron emitters In a coordinated research project under the auspices of the International Atomic Energy Agency (IAEA), Canadian researchers from TRIUMF and **McMaster University** have evaluated all existing beta-delayed neutron emitters and provided recommended values for their decay half-lives and neutron-branching ratios. These new recommendations, released as an IAEA **report**, together with the new data from ongoing experiments, will be integral part of a newly created database. Among a variety of applications, the data will be a key input in astrophysical studies for a better understanding of the heavy element production in explosive stellar events including core-collapse supernovae and binary neutron star mergers. Such a reliable and regularly updated database is essential for a better understanding of these important physical properties, especially for benchmarking theoretical predictions of yet unmeasured nuclei.

Development of a Reference Database for Beta-Delayed Neutron Emission

I. Dillmann, P. Dimitriou, and B. Singh, INDC International Nuclear Data Committee, Vienna, Austria (2017)

TUDA HELPS LEAD ASTROPHYSICISTS TO SOURCES OF COSMIC ALUMINUM

TUDA

TUDA Helps Lead Astrophysicists to Sources of Cosmic Aluminum: The rare isotope aluminum-26 (^{26}Al) with a lifetime of roughly a million years is one of the most important sources of information about galactic nucleosynthesis and has been carefully studied using the most advanced telescopes. However, what's highly uncertain in stellar models are certain nuclear reactions that produce and destroy ^{26}Al. As reported in ***Physical Review Letters*** (2015) scientists using TUDA achieved precise new measurements for one of these difficult to experimentally explore reactions, ^{26}Al(*p,γ*)^{27}Si. The results provide astrophysicists more precise estimates about the destruction of ^{26}Al in massive stars, and about the contributions of various cosmic sources to ^{26}Al production.

Inverse Kinematic Study of the ^{26g}Al (d, p) ^{27}Al Reaction and Implications for Destruction of ^{26}Al in Wolf-Rayet and Asymptotic Giant Branch Stars

V. Margerin, G. Lotay, P.J. Woods et al., Phys. Rev. Lett., 1156 (2015)

UNDERSTANDING GAMMA-RAY EMISSION FROM NOVA EXPLOSIONS

DRAGON

Understanding gamma-ray emission from nova explosions: One of the first signals to emanate from a nova explosion is an intense burst of X- and gamma rays, long before the peak of the optical brightness is reached. At such a time, the 511 keV gamma-ray line is directly linked to the amount of radioactive ^{18}F synthesized in the explosion. Thus, observing the 511 keV gamma ray intensity in a nova explosion would give astronomers a direct “thermometer” in the heart of the explosion. The problem is that the rates of nuclear reactions that create and destroy ^{18}F in this environment are highly uncertain, including specifically the ^{18}F(p,α)^{15}O and ^{18}F(p,γ)^{19}Ne reactions. Complementary to work on the ^{18}F(p,α)^{15}O reaction performed at TUDA, DRAGON has measured a key resonance in ^{18}F(p,γ)^{19}Ne for the first time, finding it to be much weaker than previously thought, and reducing the uncertainties in the amount of ^{18}F produced in these scenarios.

Measurement of Radiative Proton Capture on ^{18}F and Implications for Oxygen-Neon Novae

C. Akers, A.M. Laird, B. R. Fulton, C. Ruiz et al., Phys. Rev. Lett., 11026 (2013)

Measurement of radiative proton capture on ^{18}F and implications for oxygen-neon novae re-examined

C. Akers, A.M. Laird, B. R. Fulton, C. Ruiz et al., Phys. Rev. C, 946 (2016)

NUCLEAR CHEMISTRY

BIO-BETANMR: A NEW TOOL TO UNDERSTAND BIOLOGY AT THE MOLECULAR LEVEL

Radiochemistry Laboratories

bio-betaNMR: A new tool to understand biology at the molecular level Although bNMR has been applied to nuclear physics and condensed matter for the past five decades, its application to biology, wet chemistry, and medicine are still fairy uncommon, mainly due to technical difficulties of maintaining liquid solutions under vacuum. Over the past three years, TRIUMF has not only pioneered technology that overcomes that barrier, but also carried out first experiments on liquids and biological samples, moving from proof-of-feasibility to first applications. In April 2017, we recorded the first-ever bNMR signals originating from oxygen and nitrogen coordinating Mg^{2+} in typical Mg complexes, illustrating that bNMR can discriminate between different structures. In July 2018, we carried out first bNMR measurements on Mg coordination to ATP. This achievement marks a milestone in applications of bNMR into biologically-relevant samples and opens new opportunities in the fields of wet chemistry, biology, and medicine.

Direct observation of Mg^{2+} complexes in ionic liquid solutions by ^{31}Mg-bNMR spectroscopy
D. Szunyogh et al., Dalton Trans. (2018), in press.

On the use of ^{31}Mg for beta-detected NMR studies of solids
R. McFadden et al., . JPS Conf. Proc. 21, 011047 (2018)

Towards ^{31}Mg beta-NMR resonance line widths adequate for applications in magnesium chemistry
M. Stachura et al., Hyperfine Interact., 238, 32 (2017)

NOVEL ACCELERATOR TARGET TECHNOLOGY FOR IMPROVED PRODUCTION OF MEDICAL ISOTOPES

Radiochemistry Laboratories

Novel accelerator target technology for improved production of medical isotopes: Historically, research within TRIUMF's Life Science division has focused on the world's more common PET isotopes: ^{11}C, ^{13}N and ^{18}F. However, through new target development in recent years, this list has been dramatically expanded to include new isotopes through new target development: ^{68}Ga, ^{44}Sc, ^{86}Y, ^{89}Zr, ^{192}Ir, ^{52}Mn, $^{61,64}Cu$, ^{99m}Tc and ^{119}Sb. One of these new target systems is the so-called solution target, modelled after the remotely-controlled ^{18}F production process currently used in medical cyclotrons. In lieu of a traditional solid target station, this technique allows for the irradiation of solutions (for example: nitrate solutions of metals of interest) in a cost-efficient, simple, and safe manner.

Radiometals from liquid targets: Tc-94m production using an adapted water target on a 13 MeV cyclotron

C. Hoehr et al., Applied Radiation and Isotopes, 70, 2308 (2012)

Sc-44g production using a water target on a 13 MeV cyclotron

C. Hoehr et al., Nuclear Medicine and Biology, 41, 401 (2016)

Production of Y-86 and other radiometals for research purposes using a solution target system
E. Oehlke et al., Nuclear Medicine and Biology, 42, 842 (2015)

REDEFINING THE GLOBAL ISOTOPE SUPPLY PHILOSOPHY

Radiochemistry Laboratories

Redefining the global isotope supply philosophy: In 2009, the world was recovering from widespread shortages of ^{99m}Tc - an isotope used in ~40 million nuclear medicine scans around the world every year - when the Canadian federal government announced the imminent cessation of isotope production activities at the Chalk River reactor. In response, TRIUMF (along with BC Cancer, the Centre for Probe Development and Commercialization, and Lawson Health Research) teamed together to develop a novel, high-powered target hardware solution capable of enabling the production of commercial-scale quantities of ^{99m}Tc using local, hospital-based cyclotrons. This technology has been licensed to a new spin-off company, ARTMS Products, Inc., which obtained US$3M in venture funding from Quark Ventures in December 2017. Cyclotron-produced ^{99m}Tc is now being implemented in the United Kingdom, with additional jurisdictions soon to follow. This same hardware has since been adapted to allow for the production of ^{68}Ga, ^{64}Cu, ^{89}Zr and other isotopes of interest.

Implementation of multi-Curie production of ^{99m}Tc by conventional medical cyclotrons

F. Bénard et al., Journal of Nuclear Medicine, 55, 1017 (2014)

Direct Production of Tc-99m via 100Mo(p,2n) on Small Medical Cyclotrons

P. Schaffer et al., Physics Procedia, 66, 383 (2015)

Imaging study of using radiopharmaceuticals labelled with cyclotron-produced Tc-99m

X. Hou et al., Physics in Medicine and Biology, 61, 8199 (2016)

NUCLEAR STRUCTURE AND DYNAMICS

A BETTER VIEW OF THE STRONG FORCE

Theory, IRIS

A better view of the strong force: An IRIS experiment discovered that using rare isotopes to scatter protons can reveal subtle, new characteristics of the nuclear strong force which binds protons and neutrons, the building blocks of all matter. The strong force appeared well understood for explaining simple nuclei, such as hydrogen isotopes, but its extension to complex, many body systems has exposed important gaps. Theorists have proposed new models, but many strong force characteristics in these models can only be constrained with experiments. As reported in ***Physical Review Letters*** (2017), using the rare isotope carbon-10 (^{10}C), IRIS's researchers showed that the intensity distribution of scattered protons by rare isotope is highly sensitive to different theoretical models of the strong force, providing a key new way to constrain them.

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

A. Kumar et al., Phys. Rev. Lett., 11826 (2017)

A CLEARER VIEW OF THE STRUCTURE OF EXOTIC LITHIUM

TUDA

A clearer view of the structure of exotic lithium: The study of the transfer of a single neutron during a nuclear reaction from the target to a rare isotope from a beam provides crucial information on the structure of the nucleus created in the reaction. While most of the nuclei studied in this way are bound, some, such as lithium-10 (^{10}Li), are not; when formed via the $d(^{9}Li,p)$ reaction, ^{10}Li breaks up promptly into ^{9}Li and a neutron. As reported in ***Physical Review Letters*** (2017), detecting the protons and ^{9}Li breakup products of this reaction in coincidence, TUDA experimenters have provided important new information on the much debated structure of ^{10}Li.

Investigation of the ^{10}Li shell inversion by neutron continuum transfer reaction

M. Cavallaro, M. De Napoli, F. Cappuzzello, S.E.A. Orrigo et al., Phys. Rev. Lett., 11801 (2017)

A NEW PATH TO ELEMENT FORMATION

IRIS

A new path to element formation: IRIS' first results give astrophysicists and nuclear physicists a deeper understanding of the nuclear states and pathways involved in element formation. As reported in ***Physical Review Letters*** (2015), the results provide the experimental evidence for a new kind of nuclear excitation, soft dipole resonance. IRIS researchers identified this resonance in neutron-rich lithium-11 (^{11}Li), the heaviest bound lithium isotope, with three protons and eight neutrons, two of which orbit, barely held, in a halo, far from the nuclear core. Oscillation of the halo neutrons, the experiment revealed, leads to an extremely brief, quasi-bound nuclear resonance state, significantly changing the potential for neutron capture, as occurs in stars during element formation. The results confirm theoretical predictions and provide an important path for developing new nuclear models to predict the properties of neutron-rich isotopes.

Evidence of Soft Dipole Resonance in ^{11}Li with Isoscalar Character

R. Kanungo et al., Phys. Rev. Lett., 11419 (2015)

A NEW TOOL TO EXPLORE EXOTIC NUCLEAR STRUCTURE

A new tool to explore exotic nuclear structure: Forty years of after the discovery of magnesium- 31 (^{31}Mg), TRIUMF's ability to produce the world's highest spin-polarization for rare nuclei has successfully enabled Japanese and Canadian researchers to clarify this rare isotope's exotic structure. High spin polarization makes it possible to efficiently measure a rare nuclei's basic, but hard-to-know, quantum numbers–the spins and parities of the ground and excited states of a resulting nucleus from the b-decay of the polarized nucleus. As reported in ***Physics Letters B*** (2017), one of the highlights from this new method is the finding of “shape coexistence” in ^{31}Mg. Here, states with various types of shape coexist in a narrow and low excitation energy region. Shape coexistence can be seen as a result of subtle competition between a persistent spherical shape due to the neutron magic number 20, and prevalence of deformation due to nuclear correlations.

Shape coexistence in the N=19 neutron-rich nucleus ^{31}Mg explored by β-γ spectroscopy of spin-polarized ^{31}Na

H. Nishibata, T. Shimoda, A. Odahara, S. Morimoto, S. Kanaya, A. Yagi, H. Kanaoka, M.R. Pearson, C.D.P. Levy, and M. Kimura, Physics Letters B, 767, 81 (2017)

AN ISOMERIC STATE IN RUBIDIUM-98

Laser spectroscopy

An isomeric state in rubidium-98: Several elements around rubidium undergo a dramatic change in the nuclear shape when they cross 60 neutrons within the nucleus. ^{98}RB is the first isotope in the Rb chain above this number and had been postulated to contain a long-lived isomeric state. This was c**onfirmed for the first time using laser spectroscopy measurements at ISAC,** where not only was the state confirmed but also the shape, size and spin of both nuclear states were determined. Using this information it could be shown that both states were built on the same on the same basic structure and the isomer was not, as was previously thought, based on the shape of the light nuclei.

Direct observation of an isomeric state in ^{98}Rb and nuclear properties of exotic rubidium isotopes measured by laser spectroscopy.

T.J. Procter et al., Eur. Phys. J. A, 5123 (2015)

CLARIFYING A KEY STEP IN THE ORIGIN OF THE ELEMENTS

GRIFFIN

Clarifying a key step in the origin of the elements: As reported in ***Physical Review C*** (2016) researchers using GRIFFIN have produced the highest-precision measurement ever of the half-life of cadmium-130 (^{130}Cd), a rare isotope that's a cornerstone for understanding cosmic element formation. Astrophysical observations are providing mounting evidence that heavy elements are forged in the merger of neutron stars. However, to understand and accurately simulate this element formation process (r-process), it's necessary to experimentally characterize the key rare isotopes involved. This is especially the case for the half-lives of isotopes with masses of about 130 since theoretical models have been tuned to reproduce the half-life of ^{130}Cd and then predict half-lives in the entire region. Thus, scientists used GRIFFIN to produce a ^{130}Cd half-life measurement three-times more precise than the previously adopted world average, a result which will help astrophysicists more clearly see our stardust origins.

High-precision half-life measurement for the superallowed Fermi β^+ emitter ^{22}Mg

M.R. Dunlop et al., Phys. Rev. C, 9604 (2017)

COEXISTING SHAPES IN STRONTIUM

TIGRESS

The shape of an atomic nucleus is a result of a delicate interplay between macroscopic, liquid drop-like and microscopic shell structure effects. Nuclei with a closed shell configuration are spherical in their ground states, but away from magic numbers deformed ground states are observed. Small changes in the nucleon number can lead to rapid changes in deformation and states of different deformation can coexist at close excitation energies. In the first ISAC experiment with a post-accelerated heavy beam, recently published in **Physics Letters B**, the shape coexistence in ^{96}Sr was studio with **TIGRESS** and **SHARC** by means of the d(^{95}Sr,p) transfer reaction. These results suggest coexistence of three different configurations in ^{96}Sr and strong shape mixing of two excited 0^+ states.

Shape coexistence and mixing of low-lying 0^+ states in ^{96}Sr

S. Cruz, P.C. Bender, R. Krücken, K. Wimmer et al., Physics Letters B, 786, 94 (2018)

ELECTRON JUMPS REVEAL SUBTLE CHANGES IN SHAPE OF FRANCIUM NUCLEI

Francium Trapping Facility

Electron jumps reveal subtle changes in shape of francium nuclei: As part of the commissioning process for the Francium Trapping Facility, precise measurements were carried out on the isotopic dependence of the 7s – $7p_{1/2}$ electronic transition in a chain of different francium isotopes. As reported in ***Physical Review A*** (2014) these data were combined with previously measured isotope shifts in the 7s - $7p_{3/2}$ transition. Isotope shifts are a sensitive measure of changes in the nuclear charge radius, or size of the nucleus, between isotopes of the same atom. Comparison of the two data sets provides insights into the change of electron behaviour as the number of neutrons in the nucleus varies. The results provide a sensitive gauge of the ability of the atomic many-body calculation to describe the francium atom at a level necessary for the interpretation of the Facility's future atomic-parity violation measurements with francium.

Isotope shifts in francium isotopes $^{206\text{-}213}$Fr and ^{221}Fr

R. Collister, G. Gwinner, M. Tandecki et al. (FrPNC Collaboration), Phys. Rev. A, 9005 (2014)

EMMA SET TO HELP REVEAL THE HEARTS OF STARS AND ATOMS
EMMA

EMMA set to help reveal the hearts of stars and atoms: In 2018, the coupling of the EMMA and TIGRESS spectrometers will mark the beginning of EMMA's scientific program to probe the deep nature of nuclear reactions in stars and the subtleties of extreme nuclear structure. EMMA's arrival is the culmination of a multi-year series of commissioning steps successfully demonstrating the spectrometer's enormous potential for TRIUMF's rare isotope beam program. In December 2016, commissioning of the spectrometer as a whole began with a test beam of argon-36 (^{36}Ar) bombarding a very thick gold (Au) foil. The spectrometer was initially tuned for elastically scattered Ar ions and its first mass/charge spectrum was collected. As shown in *figure A*, both the 13^+ and 14^+ charge states were detected simultaneously, the dispersion–the key ability to distinguish between states–agreed exactly with calculations. In September 2017 an argon-40 (^{40}Ar) beam bombarded a very thin Au target and elastically back-scattered Au ions were detected in two charge states simultaneously and used to measure the energy, angular, and mass/charge acceptances; substantially improved resolving power was observed. In November 2017, EMMA accepted its first radioactive beam, sodium-24 (^{24}Na) which was used to induce fusion evaporation reactions on a copper target. Various fusion products with atomic masses from 80 to 85 were clearly detected and resolved in a single spectrometer setting. EMMA will use of both the light, neutron-deficient beams from ISAC and the future heavy, neutron-rich beams from ARIEL to explore radiative capture and transfer reactions that are central to astrophysical research, and fusion reactions important to the study of nuclear structure.

EXTENDING FIRST PRINCIPLES OF NUCLEAR STRUCTURE TO ALL OPEN-SHELL NUCLEI
Theory

Extending first principles of nuclear structure to all open-shell nuclei: The breadth of first-principles nuclear structure calculations in medium- and heavy-mass nuclei has largely been limited to closed-shell and neighboring nuclei or spherical even-even systems. As reported in ***Physical Review Letters*** (2017), TRIUMF nuclear theorists developed a new approach for calculating virtually any property of the atomic nucleus. It generalizes the ideas of the nuclear shell model to capture the effects of three-nucleon forces among valence nucleons with a valence-space Hamiltonian specifically targeted to each nucleus of interest. Predicted ground-state energies from carbon through nickel agree with results of other large-space *ab initio* methods, generally to the 1% level. This approach then effectively extends the reach of ab initio nuclear structure calculations to essentially all medium- and many heavy-mass nuclei.

Nucleus-Dependent Valence-Space Approach to Nuclear Structure

S.R. Stroberg, A. Calci, H. Hergert, J.D. Holt et al. Phys. Rev. Lett., 11803 (2017)

FIRST MEASUREMENT AND AB INITIO CALCULATION OF RARE EXCITED NUCLEUS' ENERGY LOSS

Theory, GRIFFIN

First measurement and ab initio calculation of rare excited nucleus' energy loss Using GRIFFIN, researchers confirmed the existence of a very rare state of energy loss from excited scandium-50 (^{50}Sc) nuclei and the TRIUMF theory group produced the first *ab initio* calculation of this transition rate. Nuclei in hot excited states become more stable by emitting radiation in the form of gamma (γ) rays, high energy photons, that carry away both energy and angular momentum. Usually, the gamma rays carry away one or two units of angular momentum and do not change the parity. As reported in ***Physical Review C*** (2017), scientists used the GRIFFIN spectrometer to identify the angular momentum of states in ^{50}Sc using γ-γ angular correlations. The existence of a transition (magnetic octupole) was confirmed which carries away three units of angular momentum at once. This decay is so rare that the parent state lives for a full half a second instead of the typical one- trillionth of a second.

Spectroscopy of ^{50}Sc and ab initio calculations of B(M3) strengths

A.B. Garnsworthy, M. Bowry, B. Olaizola, J.D. Holt, S.R. Stroberg et al., Phys. Rev. C, 9604 (2017)

HOW MAGIC ARE THE MAGIC NUMBERS?: TRACKING SINGLE-PARTICLE LEVELS IN SODIUM-26

TIGRESS

How magic are the magic numbers?: Tracking single-particle levels in sodium-26: The standard shell model explains tightly bound nuclei in terms of magic numbers associated with large energy gaps between quantum mechanical single-particle levels. These magic numbers are well understood in nearly stable nuclei, but the magic numbers change in nuclei with a large neutron excess. As published in ***Physics Letters B*** (2014), a TIGRESS-SHARC experiment measured reactions of radioactive sodium-25 (^{25}Na) beams on targets containing deuterium (one proton, one neutron). In particular, reactions where one neutron was taken out of the deuterium, measured the single-particle wave function composition of ^{26}Na. The results showed that the neutron single-particle levels are already starting to be squeezed together by a complicated feature of the neutron-proton interaction, an effect which ultimately leads to the breakdown of the neutron magic number 20 in the so-called “island of inversion” around magnesium-32 (^{32}Mg).

Shell evolution approaching the N=20 island of inversion: Structure of ^{26}Na

G.L. Wilson, W.N. Catford, N.A. Orr, C.Aa. Diget, A. Matta, G. Hackman, S.J. Williams, I.C. Celik et al., Physics Letters B, 759, 417 (2016)

ISOMERIC STATES IN LIGHT FRANCIUM NUCLEI

Laser spectroscopy

Isomeric states in light francium nuclei: Francium is the heaviest alkali element. In addition to its simple atomic structure, it also possesses a fairly simple nuclear structure based on what has been observed to be an inert lead core with 5 additional protons. This combination makes francium one of the leading candidates upon which to perform high precision experiments to test both nuclear and atomic theories as well as to perform fundamental tests of the standard model. A precursory experiment to investigate the nuclear structure of very light francium isotopes confirmed for the first time that several isotopes contain long-lived isomeric states. The nuclear structure of these states has been **determined via laser spectroscopy**, providing invaluable input and tests of both nuclear and atomic theories.

Nuclear moments and charge radii of neutron-deficient francium isotopes and isomers

A. Voss et al., Phys. Rev. C, 9104 (2015)

LITHIUM MOMENTS

Laser spectroscopy

Lithium moments: ^{11}Li is one of the most extreme cases of nuclear structure that can be produced at ISAC. With a nuclear containing 8 neutrons and only 3 protons, it has long been known that the final 2 neutrons form a halo outside of a nuclear core. A collaboration between nuclear and condensed matter scientists at TRIUMF has developed a unique method with which to probe the distribution of charge within the nucleus with hitherto unachievable precision. This measurement, combining nuclear detection methods within a zero magnetic field nuclear quadrupole resonance spectrometer, **showed that the 2 outer neutrons have very little influence on the shape of the nucleus' core**, instead causing it to oscillate around a common centre of mass.

High precision measurement of the^{11}Li and ^{9}Li quadrupole moment ratio using zero-field β-NQR

A. Voss, M.R. Pearson et al., Journal of Physics G: Nuclear and Particle Physics, 4101 (2013)

MASS CARTOGRAPHY OF THE ISLAND OF INVERSION POINTS TO STRONG CORRELATION ENERGY

TITAN

Mass cartography of the island of inversion points to strong correlation energy: Analogous to electron shells in chemistry, neutrons and protons occupy similar, exceptionally stable configurations, which are seen as sharp ridges in mass cartography. As the ratio of protons to neutrons changes, this stability can disappear, for example around sodium-31 (^{31}Na). The neighbourhood is difficult to examine due to low production rates and half-lives, too short for a typical Penning-trap mass spectrometer. TITAN, however, routinely measures isotopes with half-lives below 50 ms, or thousands of a second. TITAN's ongoing survey reveals a singularity: The energy, or mass cost, of two neutrons is higher for magnesium-33 (^{33}Mg) than for aluminum-34 (^{34}Al). As reported in ***Physical Review C*** (2015) investigating with premier shell-model calculations points to gains in correlation energy as the cause.

Observation of a crossover of S_{2n} in the island of inversion from precision mass spectrometry

A.A. Kwiatkowski, C. Andreoiu, J.C. Bale, A. Chaudhuri, U. Chowdhury, S. Malbrunot-Ettenauer, A.T. Gallant, A. Grossheim, G. Gwinner, A. Lennarz et al., Phys. Rev. C, 9206 (2015)

MEASUREMENT OF THE MOST EXOTIC NEUTRON EMITTERS AT BRIKEN

BRIKEN

Measurement of the most exotic neutron emitters at BRIKEN: The BRIKEN (Beta-delayed neutron measurements at RIKEN for nuclear structure, astrophysics, and applications) project started in 2016 at the RIKEN Nishina Center in Japan. As reported in the ***Journal of Instrumentation*** (2017) the ambitious goal of the collaboration is to design the most efficient neutron detector array for the measurement of the most exotic nuclei that can be produced today. With TRIUMF research collaboration, so far 268 nuclei have been measured, and for 180 of them the neutron branching ratio and for 60 the decay half-life has been measured for the first time. The neutron-branching ratio of the doubly-magic isotope nickel-78 has been measured for the first time, and will help to pinpoint theoretical predictions of neutron-magic nuclei.

Conceptual design of a hybrid neutron-gamma detector for study of β-delayed neutrons at the RIB facility of RIKEN

A. Tarifeño-Saldivia, J.L. Tain, C. Domingo-Pardo, F. Calviño, G. Cortés, V.H. Phong, A. Riego et al., Journal of Instrumentation, 12 (2017)

NEUTRON-SKIN AS A PORTAL TO NEUTRON STAR PROPERTIES

Theory

Neutron-skin as a portal to neutron star properties: With the new era opened up by the LIGO and VIRGO observation of neutron-star mergers, multi-messenger astronomy will provide us with new ways to constrain the equation of states of neutron-rich matter. Stronger constraints will be obtained by combining such future data with observations on finite nuclei. Indeed, neutron-rich nuclei provide a portal to study neutron-rich matter, in that they form a neutron-skin around their surface which is directly related to the equation of state of nuclear matter. As reported in ***Nature*** (2016), TRIUMF theorists and international collaborators provided the first *ab initio* computation of calcium-48 (^{48}Ca), a nucleus with 20 protons and 28 neutrons. It was predicted that a neutron-skin is formed, though much smaller than previously thought, calling for new experimental investigations.

Neutron and weak-charge distributions of the ^{48}Ca nucleus

G. Hagen, A. Ekström, C. Forssén, G.R. Jansen, W. Nazarewicz, T. Papenbrock, K.A. Wendt et al., Nature Physics, 12, 186 (2016)

PURE RADIOACTIVE ION BEAMS AND RARE ISOTOPE SPECTROSCOPY FROM TRIUMF'S LASER ION SOURCE TRILIS

Targets and Ion Sources

Virtually contamination-free radioactive ion beams can now be provided at ISAC from a new ion-guide laser ion source (IG-LIS) [1]. This IG-LIS allows for experiments on isotopes that for decades have been overwhelmed by contamination from surface-ionized isobars. TRILIS now routinely provides isotopes from 37 different elements. Laser ionization schemes for an additional 24 elements are ready for off-line testing. TRILIS also supports an in-source laser spectroscopy program that investigates fundamental properties of the rarest isotopes such as atomic energy levels and elemental ionization potentials have been determined for the first time [2] or improved significantly [3].

[1] *An ion guide laser ion source for isobar-suppressed rare isotope beams*
S. Raeder et al., Rev. Sci. Instr., 85, 03309 (2014)
[2] *Measurement of the first ionization potential of astatine by laser ionization spectroscopy*
S. Rothe et al., Nat. Commun., 4, 1835 (2013)

[3] *Determination of the first ionization energy of polonium by resonance ionization spectroscopy – part I: Measurement of even-parity Rydberg states at TRIUMF-ISAC*
S. Raeder et al., Spectrochimica Acta B (2018)

RARE ISOTOPE SHEDS LIGHT ON HOW DEAD STARS RE-IGNITE

DSL

Rare isotope sheds light on how dead stars re-ignite: Novae are stellar element-making explosions caused when a white dwarf, the carbon-cinder of a once giant star, accretes hydrogen-rich material onto its surface from a companion star. A key to help astrophysicists better understand novae is through determining the rates of reactions that create and destroy the key rare isotopes they're observed to produce, including sodium-22 (^{22}Na). As reported in ***Physical Review C*** (2016) scientists used DSL to determine, for the first time using the Doppler-shift attenuation method, the lifetimes of several energetic states magnesium-23 (^{23}Mg) the rare isotope that dominates the destruction of ^{22}Na. The researchers' more precise lifetime measurements of related states help explain the structure and behaviour of these rare isotopes and thus the underlying nuclear physics driving novae.

Measurement of Lifetimes in ^{23}Mg

O.S. Kirsebom et al., Phys. Rev. C, 9302 (2016)

ROLE OF THE CONTINUUM IN BERYLLIUM-11

TIGRESS

Role of the continuum in Beryllium-11: The exotic nucleus beryllium-11 (^{11}Be) is a one-neutron halo nucleus, one in which the last proton or neutron appears to be in a large, extended orbit around an otherwise normal core. The extent to which ^{11}Be truly behaves as a lone neutron in a large orbit around a ^{10}Be core has been the subject of two important TIGRESS experiments, both of which employed scattering of ^{11}Be off of heavy metal thin foil targets. The first, also using TRIUMF's Bambino, as measured the ratio of elastic scattering to Coulomb excitation, the process in which energy is transferred to a nucleus from the electric field of another, and (in most cases) re-emitted as a gamma ray. As reported in ***Physical Review Letters*** (2017), this high-precision measurement revealed the influence of coupling to the continuum, the role of virtual states corresponding to unbound, free neutrons interacting with ^{10}Be. A second experiment with TIGRESS, published in ***Physics Letters B*** (2014), also identified breakup reactions, those in which enough energy is transferred to break ^{11}Be into ^{10}Be and a free neutron, a “continuum” state. The first measurement was accurate enough to validate a first-principles calculation of the gamma-decay rate, which revealed the influence of the coupling of virtual, continuum states to the overall structure of the bound states of ^{11}Be. The second showed that the overall reaction dynamics depended not just on the continuum but also on highly excited states in the ^{10}Be core itself.

Scattering of the Halo Nucleus ^{11}Be on ^{197}Au at Energies around the Coulomb Barrier

V. Pesudo et al., Phys. Rev. Lett., 11815 (2017)

SEEING FRANCIUM NUCLEI AS TINY MAGNETS

Francium Trapping Facility

Seeing francium nuclei as tiny magnets: The ratio of the hyperfine splittings of *s* and *p* states is not constant across isotopes due to the isotope-dependent distribution of nuclear magnetization, a phenomenon called the hyperfine anomaly. By carrying out measurements of the hyperfine splitting of the excited electronic $7p_{1/2}$ state at the 100-ppm level, and comparing to previously known ground state 7s splittings, the hyperfine anomaly in six isotopes of francium (Fr) was experimentally determined. As reported in ***Physical Review Letters*** (2015) the measured magnetic distributions behave regularly from ^{213}Fr through ^{207}Fr, but ^{206}Fr stops behaving like a spherical nucleus with valence nucleons. The results are valuable input for future calculations of both the anapole moments and the neutron radii needed for small corrections to Francium Trapping Facility measurements of atomic-parity violation for $^{207-213}$Fr.

Hyperfine Anomalies in Fr: Boundaries of the Spherical Single Particle Model

J. Zhang (张颉颃), M. Tandecki, R. Collister, et al., Phys. Rev. Lett, 11504 (2015)

TESTING MODERN NUCLEAR STRUCTURE THEORIES

TIGRESS

Testing modern nuclear structure theories: As published in ***Physics Letters B*** (2018), this recent TIGRESS result measured the gamma-ray excitation transition rate in magnesium-22 (^{22}Mg) and its mirror sodium-22 (^{22}Ne). Mirror nuclei are pairs of nuclei where there are as many protons in one as neutrons in the other and vice versa. Based on “isospin symmetry”, the relative transition rates in mirror pairs ought to be well understood. However, in selected nuclei around atomic mass 21 to 24, there appears to be a much higher transition rate in the proton-rich pair compared to the neutron-rich mirror partner. This discrepancy cannot be explained within the phenomenological shell model, the standard model for nuclear structure, but for gamma-ray transition rates, it invokes an empirical “effective charge” parameter. The ^{22}Mg experiment was two-fold: 1) measure the transition rate in ^{22}Mg with high enough precision to determine if the anomalous proton-rich transition rate was an anomaly in selected nuclei or a trend across the whole mass region; and, 2) compare results to modern calculations that do not use effective charges but that calculate transition rates from first principles. The results clearly showed that, indeed, ^{22}Mg’s transition rate is anomalously high compared to ^{22}Ne, and furthermore, the first principles also were also unable to reproduce it.

Testing microscopically derived descriptions of nuclear collectivity: Coulomb excitation of ^{22}Mg

J. Henderson, G. Hackman, P. Ruotsalainen, S.R. Stroberg, K.D. Launey, J.D. Holt et al., Physics Letters B, 782, 468 (2018)

THE CASE OF THE MISSING NEUTRINOS
TITAN

The Case of the Missing Neutrinos: After 15 years of solar-neutrino measurements, 13% of the theoretically expected flux, or number, of neutrinos is unobserved. This is leading physicists to explore a variety of possible reasons, from the underlying nuclear physics to detector design. One proposed reason is the energetic cost of the detector material to capture a neutrino. To explore this, TITAN deployed its high-accuracy, high-precision Penning trap, the only one in the world coupled to a charge breeder. The charge breeder's removal of electrons boosted the precision of the measurements with gallium and germanium isotopes and allowed for a novel radioactive-beam purification. As reported in ***Physical Letters B*** (2013), TITAN measurements validate the final piece of the nuclear physics underpinning the predicted neutrino flux, and thus the cause of the missing neutrinos remains an open case.

Penning-trap Q-value determination of the ^{71}Ga (ν, e^-) ^{71}Ge reaction using threshold charge breeding of on-line produced isotopes

D. Frekers, M.C. Simon et al., Physics Letters B, 722, 233 (2013)

TIN-100: A GATEWAY TO AB INITIO CALCULATIONS IN HEAVY NUCLEI
Theory

Tin-100: A gateway to ab initio calculations in heavy nuclei: For many years Tin-100 (^{100}Sn) has stood as a distant milestone of first-principles calculations of atomic nuclei, a gateway to modeling nuclei in the heavy-mass region above atomic mass 100. ^{100}Sn is the heaviest self-conjugate nucleus, it exhibits the largest known β-decay strength, and is close to the proton dripline. As reported in ***Physical Review Letters*** (2017), TRIUMF nuclear theorists linked the structure of nuclei around ^{100}Sn, the heaviest doubly magic nucleus with equal neutron and proton numbers, to nucleon-nucleon and three-nucleon forces constrained only by data of few-nucleon systems. The results provide the first *ab initio* prediction that ^{100}Sn is indeed doubly magic, paving the way for *ab initio* calculations to the heaviest nuclei.

Structure of the Lightest Tin Isotopes

T.D. Morris, J. Simonis, S.R. Stroberg, C. Stumpf et al., Phys. Rev. Lett., 12015 (2018)

TITAN REVEALS SHELL MODEL BREAKDOWN AT THE EXTREME
TITAN

TITAN reveals shell model breakdown at the extreme: Certain combinations of protons and neutrons form exceptionally stable nuclei. While these closed-shell configurations are well understood in stable nuclei, they change in exotic nuclei. Previous mass determinations with TITAN found a closed shell for calcium (Ca) with 32 neutrons. Now, as reported in ***Physical Review Letters*** (2018), TITAN's measurements of neighbouring titanium isotopes shows that the shell weakens more quickly than predicted by state-of-the-art nuclear theory. The results are also noteworthy as TITAN's first measurements with its Multi-Reflection Time-Of-Flight mass separator (MR-TOF). The MR-TOF has a remarkable sensitivity, able to make precise measurements with just a single radioactive nucleus.

Dawning of the N=32 Shell Closure Seen Through Precision Mass Measurements of Neutron-Rich Titanium Isotopes

E. Leistenschneider et al., Phys. Rev. Lett., 12006 (2018)

TRIUMF HELPS PROVIDE IAEA WITH EVALUATION OF BETA-DELAYED NEUTRON EMITTERS

BRIKEN

TRIUMF helps provide IAEA with evaluation of beta-delayed neutron emitters In a coordinated research project under the auspices of the International Atomic Energy Agency (IAEA), Canadian researchers from TRIUMF and **McMaster University** have evaluated all existing beta-delayed neutron emitters and provided recommended values for their decay half-lives and neutron-branching ratios. These new recommendations, released as an IAEA **report**, together with the new data from ongoing experiments, will be integral part of a newly created database. Among a variety of applications, the data will be a key input in astrophysical studies for a better understanding of the heavy element production in explosive stellar events including core-collapse supernovae and binary neutron star mergers. Such a reliable and regularly updated database is essential for a better understanding of these important physical properties, especially for benchmarking theoretical predictions of yet unmeasured nuclei.

Development of a Reference Database for Beta-Delayed Neutron Emission

I. Dillmann, P. Dimitriou, and B. Singh, INDC International Nuclear Data Committee, Vienna, Austria (2017)

UNDERSTANDING THE PHENOMENON OF PARITY INVERSION IN BERYLLIUM-11

Theory

Understanding the phenomenon of parity inversion in beryllium-11: It has been known since 1960s that the spectrum of beryllium-11 (^{11}Be) has peculiar features, namely, its weakly bound ground state has positive parity contrary to the standard shell model picture. Yet, a first-principles explanation of this phenomenon has been lacking. As reported in ***Physical Review Letters*** (2016), TRIUMF nuclear theorists investigated this nucleus *ab initio* and demonstrated that the inclusion of continuum effects is crucial for a description of the ^{11}Be system. The results showed that the spectrum is extremely sensitive to the details of the nuclear two- and three-nucleon interactions and constitutes an important benchmark for future forces. In particular, the parity inversion of the bound states could be achieved only by a nuclear force that provides accurate predictions of nuclear radii and matter saturation properties.

Can Ab Initio Theory Explain the Phenomenon of Parity Inversion in ^{11}Be?

A. Calci, P. Navrátil, R. Roth, J. Dohet-Eraly, S. Quaglioni, and G. Hupin, Phys. Rev. Lett., 11724 (2016)

UNIFIED AB INITIO APPROACH TO BOUND AND UNBOUND STATES

Theory

Unified ab initio approach to bound and unbound states: Theoretical understanding of weakly bound and unbound atomic nuclei produced and investigated at TRIUMF and other rare isotope facilities requires quantum mechanical description that includes continuum effects, in other words, the nuclear bound and unbound states must be treated on the same footing. As reported in ***Physical Review Letters C*** (2013), TRIUMF nuclear theorists achieved such a description by introducing a novel *ab initio* approach called no-core shell model with continuum capable of predicting properties of exotic nuclei from basic interactions between nucleons. As the first demonstration of this approach we calculated the properties of resonances of the unbound exotic ^{7}He nucleus that was subject of several experimental investigations contradicting each other especially in properties of a low-lying ½- resonance. Our results clearly discriminated among three experiments agreeing with only one of them.

Unified ab initio approach to bound and unbound states: No-core shell model with continuum and its application to ^{7}He

S. Baroni, P. Navrátil, and S. Quaglioni, Phys. Rev. C, 873 (2013)

PRECISION TESTS OF FUNDAMENTAL INTERACTIONS

A NEW LOW-STRESS ELASTOPOLYMER VIEWPORT SEAL COMPATIBLE WITH ULTRA-HIGH VACUUM

TRINAT

A new low-stress elastopolymer viewport seal compatible with ultra-high vacuum: As reported in ***Review of Scientific Instruments*** (2014), a TRINAT co-op student developed a technique for a vacuum viewport seal that minimizes stress-related birefringence while maintaining ultra-high vacuum. One of many systematic effects that alters atomic polarization is imperfect circularly polarized light, and a common well-known difficulty is stress-induced birefringence (the same effect that produces the appearance of colors in stressed, otherwise clear and colourless, Scotch tape. The new technique keeps the circular polarization almost perfect.

PCTFE as a solution to birefringence in atom trap viewports

C.L. Warner, J.A. Behr, and A. Gorelov, Review of Scientific Instruments, 8511 (2014)

A NEW PRIMARY PROTON BEAMLINE AT TRIUMF FOR PRODUCTION OF SPALLATION NEUTRONS

UCN

A new primary proton beamline at TRIUMF for production of spallation neutrons: BL1U is a new primary proton beamline commissioned in TRIUMF's Meson hall in Fall 2016. The beamline ends in a target made of tungsten and provides spallation neutrons for fundamental neutron research to the Ultracold Neutron Facility. BL1U is unique in that it shares the proton beam provided by TRIUMF's 520 MeV cyclotron with BL1A, the other primary beamline in the Meson hall. This is facilitated by a special, very fast-kicker magnet which ramps its field on-and-off during the 100 microsecond gap between two proton pulses, and thus diverts single proton pulses out of BL1A into BL1U. Since the Centre for Material and Molecular Science instruments rely on BL1A proton beam, this innovative beam sharing enables the simultaneous operation of both facilities.

A NEW TOOL FOR LOW-ENERGY FUNDAMENTAL PARTICLE TRANSPORT INVESTIGATIONS

UCN

A new tool for low-energy fundamental particle transport investigations: As reported in ***Nuclear Instruments and Methods in Physics Research Section A*** (2017) researchers from TRIUMF and Technical University of Munich have developed PENTrack, a tool for simulating proton, electron and neutron paths in low-energy particle transport research. Knowledge of detailed particle behaviour has a large impact on systematic studies of experimental data, and simulations are key to accounting for such phenomena as complex apparatus geometries and electromagnetic fields. The simulation tool will in particular support simulations of trajectories and spins with ultra-cold neutrons at the new TRIUMF Ultracold Advanced Neutron source.

PENTrack- a simulation tool for ultracold neutrons, protons, and electrons in complex electromagnetic fields and geometries

W. Schreyer, T. Kikawa, M.J. Losekamm, S. Paul, and R. Picker, Nuclear Instruments and Methods in Physics Research, 858, 123 (2017)

CANADIAN LASER BREAKTHROUGH TOWARDS LASER-COOLING OF ANTIMATTER

ALPHA

Canadian laser breakthrough towards laser-cooling of antimatter: In ***Nature*** (2018), the ALPHA collaboration reports the first-ever observation of a key atomic transition in antihydrogen, the so-called Lyman-alpha transition. In ordinary hydrogen, this is one of the most important transitions in the Universe, responsible for first light produced after the Big Bang when the electrons and the protons combined to form hydrogen atoms. However, the transition is notoriously difficult to observe in antimatter, partly because of the technical challenges with producing laser light to drive the transition. The observation of the Lyman-alpha transition in antihydrogen was made possible by the development of an innovative laser system by a team from TRIUMF and the University of British Columbia. The Lyman-alpha transition not only provides important information of the structure of the anti-atom, but also can be used to control the motion of antihydrogen. In particular, the laser cooling of antihydrogen will enable the creation of ultra-cold antihydrogen, essential for future spectroscopy and the gravity studies of antimatter.

Observation of the 1S-2P Lyman-α transition in antihydrogen

M.C. Fujiwara, J.S. Hangst, T. Momose et al., Nature, 561, 211 (2018)

DIRECT MEASUREMENT OF SPIN POLARIZATION OF DECAYING ATOMS

TRINAT

Direct measurement of spin polarization of decaying atoms: In 2016, TRINAT demonstrated a direct atomic-physics probe of the spin polarization of potassium-37 (^{37}K) nuclei as they decayed. Many spin-polarized decay experiments disturb the polarization or must measure it separately. As reported in the ***New Journal of Physics*** (2016), the high accuracy of the polarization achieved (99.1% +/- 0.1%) enabled a sensitive search for wrong-handed neutrinos. The result also demonstrates the potential to measure the polarization to a level of precision which would be competitive in searches for new physics. The paper was selected as one of the journal's 2016 Highlights.

Precision measurement of the nuclear polarization in laser-cooled, optically pumped ^{37}K

B. Fenker, J.A. Behr, D. Melconian et al., New Journal of Physics, 1807 (2016)

ELECTRON JUMPS REVEAL SUBTLE CHANGES IN SHAPE OF FRANCIUM NUCLEI

Francium Trapping Facility

Electron jumps reveal subtle changes in shape of francium nuclei: As part of the commissioning process for the Francium Trapping Facility, precise measurements were carried out on the isotopic dependence of the 7s – $7p_{1/2}$ electronic transition in a chain of different francium isotopes. As reported in ***Physical Review A*** (2014) these data were combined with previously measured isotope shifts in the 7s - $7p_{3/2}$ transition. Isotope shifts are a sensitive measure of changes in the nuclear charge radius, or size of the nucleus, between isotopes of the same atom. Comparison of the two data sets provides insights into the change of electron behaviour as the number of neutrons in the nucleus varies. The results provide a sensitive gauge of the ability of the atomic many-body calculation to describe the francium atom at a level necessary for the interpretation of the Facility's future atomic-parity violation measurements with francium.

Isotope shifts in francium isotopes $^{206-213}$Fr and ^{221}Fr

R. Collister, G. Gwinner, M. Tandecki et al. (FrPNC Collaboration), Phys. Rev. A, 9005 (2014)

FIRST PRODUCTION OF ULTRACOLD NEUTRONS AT TRIUMF

UCN

First production of ultracold neutrons at TRIUMF: In fall 2017, the Japanese-Canadian TUCAN (TRIUMF Ultra Cold Advanced Neutron source) collaboration **succeeded for the first time** in producing ultracold neutrons (UCN). This was a major milestone towards the search for the elusive neutron electric dipole moment (nEDM). UCN move so slowly, about 5 meters per second compared to about 500 meters per second for air molecules, and with such low energy that they can be contained and observed. Thus, UCN are ideal for determining the nEDM, which TUCAN aims to measure with the highest-ever precision. The nEDM is predicted to be vanishingly small, but if it is measured to be larger than expected, the TUCAN results could aid in solving a key cosmic puzzle: why there is much more matter than antimatter in the universe.

First ultracold neutrons produced at TRIUMF

S. Ahmed et al., the TUCAN Collaboration, arXiv Physics: Instrumentation and Detectors (physics.ins-det) (2018)

HALF-LIFE MEASUREMENT PROVIDES CLEARER VIEW OF THE WEAK FORCE

GRIFFIN

Half-life measurement provides clearer view of the weak force: Scientists using GRIFFIN achieved a half-life measurement of magnesium-22 (^{22}Mg) three times more precise than the previously adopted world average. As reported in ***Physical Review C*** (2017), this high-precision measurement provides a clearer view of the dynamics of the weak force. Precision measurements of the *ft* values for superallowed Fermi β-decay transitions between isobaric analog states provide fundamental tests of Standard Model's description of electroweak interaction. These transitions provide a stringent test of the conserved vector-current (CVC) hypothesis, and in combination with other values, they also provide the most precise determination of V_{ud}, the most precisely determined element of the Cabibbo-Kobayashi-Maskaw quark-mixing matrix. Researchers used a 4π proportional gas counter and the GRIFFIN spectrometer to make the ^{22}Mg half-life measurement, resolving a discrepancy between the two previously published ^{22}Mg half-life measurements.

High-precision half-life measurement for the superallowed Fermi β^+ emitter ^{22}Mg

M.R. Dunlop et al., Phys. Rev. C, 9604 (2017)

IMPROVED MEASUREMENT OF THE Π→EN BRANCHING RATIO

PIENU

Improved measurement of the π→ev branching ratio: In ***Physical Review Letters*** (2015), the PIENU collaboration announced an interim result (based on 10% of the data set) which improved knowledge of the branching ratio, and consequently of the equivalence of electron and muon couplings to the weak force, by a factor of two. Since the result agreed well with the Standard Model (SM) prediction assuming universality, it serves to deepen the lepton universality puzzle. It also further constrains hypothetical non-SM theories by increasing the mass-scale limitation on those theories. The subject is highly topical since tentative measurements in B-meson decays are indicating possible deviations from universality involving the third flavor or generation of particles. This work is the latest in a long series of TRIUMF experiments on pion decay, improving the precision by more than an order of magnitude. The final results are expected in late 2018.

Improved Measurement of the π → ev Branching Ratio

A. Aguilar-Arevalo et al. (PIENU Collaboration), Phys. Rev. Lett., 11507 (2015)

IMPROVED SEARCH FOR HEAVY NEUTRINOS IN THE DECAY Π→EN

PIENU

Improved search for heavy neutrinos in the decay π→ev: Using the complete data set, PIENU has improved the exclusion limits for heavy neutral leptons coupled to electrons by an order of magnitude for masses less than the pion mass (139.6 MeV). As reported in *Physical Review D* (2018), so far only three neutrinos have been found, corresponding to the three electron-type particles. The tiny values of the neutrino masses have stimulated theoretical speculation that additional heavy neutral leptons may exist which, if verified, could have important consequences for the origin and composition of the universe. However the mass range for those new particles is relatively unconstrained. PIENU could directly observe evidence for heavy neutral leptons such as sterile neutrinos in the 2-body decays of pions $\pi^+ \rightarrow e^+ v_h$ where v_h is a massive neutrino, by observing an extra peak in the positron energy spectrum. After suppressing backgrounds by five orders of magnitude, the search came up empty allowing new more sensitive limits to be obtained; these results give the best limits in any mass region so far studied. In future, PIENU expects to have new results on heavy neutrinos coupled to muons by studying $\pi^+ \rightarrow \mu^+ v_h$. In addition, the comparison of the measured and predicted $\pi^+ \rightarrow e^+ v$ branching ratio also constrains the presence of non-SM neutrinos in the lowest energy region.

Improved search for heavy neutrinos in the decay π→ev

PIENU Collaboration, Phys. Rev. D, 977 (2018)

ISOMERIC STATES IN LIGHT FRANCIUM NUCLEI

Laser spectroscopy

Isomeric states in light francium nuclei: Francium is the heaviest alkali element. In addition to its simple atomic structure, it also possesses a fairly simple nuclear structure based on what has been observed to be an inert lead core with 5 additional protons. This combination makes francium one of the leading candidates upon which to perform high precision experiments to test both nuclear and atomic theories as well as to perform fundamental tests of the standard model. A precursory experiment to investigate the nuclear structure of very light francium isotopes confirmed for the first time that several isotopes contain long-lived isomeric states. The nuclear structure of these states has been **determined via laser spectroscopy**, providing invaluable input and tests of both nuclear and atomic theories.

Nuclear moments and charge radii of neutron-deficient francium isotopes and isomers

A. Voss et al., Phys. Rev. C, 9104 (2015)

KEY STEP TOWARDS HISTORIC MEASUREMENT OF ATOMIC PARITY VIOLATION IN FRANCIUM

Francium Trapping Facility

Key step towards historic measurement of atomic parity violation in francium: Francium Trapping Facility scientists made the first excitation of the highly forbidden 7s-8s transition on which future atomic-parity violation measurements will be based. As reported in *Physical Review A* (2018) the researchers scrutinized the accuracy of theoretical predictions of the overlap of the valence electron wavefunction with the nucleus (field shift) and electron-electron correlations (specific mass shift) in francium was carried out, another critical test towards understanding atomic theory in francium.

Hyperfine Anomalies in Fr: Boundaries of the Spherical Single Particle Model

J. Zhang (张颉颃), M. Tandecki, R. Collister et al. (FrPNC Collaboration), Phys. Rev. Lett., 11504 (2015)

LASER SPECTROSCOPY OF ANTIHYDROGEN

ALPHA

Laser spectroscopy of antihydrogen: In a series of the papers published in ***Nature***, the ALPHA collaboration reported the first-ever laser spectroscopy of antimatter atoms. Over the past several decades, laser spectroscopy of the ordinary hydrogen atom has reached exceedingly high accuracies to the level of 4×10^{-15} level. Now ALPHA has achieved laser measurements in antihydrogen, with an initial precision of 2×10^{-10}, which was subsequently improved to 2×10^{-12}. The latter is the most precise direct measurement of antimatter properties, and represents a test of matter-antimatter symmetry, known as CPT symmetry, with a parts-per-trillion precision. The results attracted significant attention both from the scientific community and the general public.

Characterization of the 1S–2S transition in antihydrogen

J.S. Hangst et al., Nature, 557, 71 (2018)

PIONS, MUONS AND POSITRONS

M11 beamline

Pions, muons and positrons: The M11 beam channel provides low intensity beams of pions, muons and positrons for testing and calibrating detectors for particle physics experiments world-wide. Three notable examples from the period 2013-2018 are described here. TREK The TREK experiment is searching for new physics beyond the standard model in the rare decay modes of kaons. In November 2013 and June 2014, a group led by Mike Hasinoff (UBC) **tested the scintillating fibre target to establish the bias voltage offsets for each individual MPPC detector/scintillating fibre combination**. Muon and positron tracks through the detector were measured to compute individual fibre efficiencies. This target was subsequently used for data taking in Experiment 36 at J-PARC in Tokai, Japan. Previous to this, in November 2012, the TREK group tested TOF counter time resolution and e-mu discrimination using a polyethylene block placed in front of a Lead-Glass-Counter to change the shower development. ATLAS Polycrystalline chemical vapor deposition (pCVD) diamond detectors are a candidate for forward calorimetry in the high luminosity environment of the CERN LHC. One such detector was exposed to particles delivered by M11 to quantify the variation in signal response across the surface of such a detector. A discrepancy was observed in the diamond detector's response to beam particles at different bias polarities. This study was documented in a Carleton MSc thesis, "**Characterization of diamond sensors for use in ATLAS calorimetry upgrades**", by Joshua Turner, 2012, Super-B and BELLE The Super-B drift chamber group undertook two tests of drift chamber prototypes in the M11 beam line in 2013. These tests were the first to **demonstrate that the particle identification capabilities of drift chambers could be significantly improved** by counting individual ionization events in the gas ("cluster counting"), rather than just measuring the total energy deposited in each cell. The results were published as NIM A735, 169-183 (2014), and formed a key component of the PhD thesis of Jean-Francois Caron (UBC, 2015). After the merging of the Super-B and BELLE-II collaborations, the Belle II Canada group used the M11 beamline to test pure and thallium CsI crystals with various readout options in the summer of 2015. The group subsequently decided not to pursue pure CsI. The thallium-doped CsI data have been used, along with data collected at the proton irradiation facility at TRIUMF, to develop a new method of distinguishing hadronic from electromagnetic energy deposits using pulse shape discrimination. This technique is being implemented for the Belle II calorimeter, and will form an important component of the PhD thesis of S. Longo (Victoria).

Performance test of a lead-glass counter for the J-PARC E36 experiment

Y. Miyazaki, S. Shimizu et al., Nuclear Instruments and Methods in Physics Research, 779, 13 (2015)

Characterization of diamond sensors for use in ATLAS calorimetry upgrades

J. Turner, Thesis (M.Sc.), Carleton University (2012)

Improved particle identification using cluster counting in a full-length drift chamber prototype

J.F. Caron, C. Hearty, P. Lu, R. So, R. Cheaib, J.P. Martin, W. Faszer, A. Beaulieu, S. de Jong, M. Roney et al., Nuclear Methods in Physics Research, 735, 169 (2014)

SEARCH FOR K+→ Π+N¯N AT NA62

NA62

Search for K+→ π+ν¯ν at NA62: Recently, NA62 (in talks at conferences, and soon to be published) announced its first results based on a small initial data set, with the **observation of one event compatible with K+→ π+ν¯ν** decay. An upper limit on the branching ratio of <14x the SM expectation was set demonstrating that the experiment basically works a planned (after 10 years of development). Since data with about 30x the sensitivity has been already acquired, the experiment is on track to meet its goals of improving the measurement sensitivity by an order of magnitude compared the work done at BNL where **K+→ π+ν¯ν** was initially discovered with a few events observed at the one in 10 billion level. The precise measurement of this tiny branching ratio will severely test the predictions of the SM and reveal or limit the prospects for certain new avenues of theoretical speculation which go beyond the SM.

Search for K+→ π+ν¯ν at NA62
R. Volpe, the NA62 Collaboration, Nuclear and Particle Physics Proceedings, 282, 101 (2017)

SEARCH OF HEAVY NEUTRAL LEPTON PRODUCTION IN K+ DECAYS

NA62

Using the first small data set, NA62 improved the exclusion limits for heavy neutral leptons coupled to electrons and muons by an order of magnitude for masses less than the kaon mass (200 - 495 MeV); this study is similar to that done by PIENU in a lower mass region. As reported in ***Physical Letters B*** (2018), so far only three neutrinos have been found, corresponding to the three electron-type particles. The tiny values of the neutrino masses have stimulated theoretical speculation that additional heavy neutral leptons may exist which, if verified, could have important consequences for the origin and composition of the universe; however, the mass range for those new particles is relatively unconstrained. NA62 could directly observe heavy neutral leptons coupled to electrons and muons such as sterile neutrinos in the 2-body decays of kaons $\mathbf{K^+ \to e^+ \nu_h}$ and $\mathbf{K^+ \to \mu^+ \nu_h}$ (where $\mathbf{\nu_h}$ is a massive neutrino) by observing an extra peak in the positron or muon energy spectrum. After suppressing backgrounds by several orders of magnitude, the search came up empty, allowing new order of magnitude more sensitive limits to be obtained. NA62 expects to continue improving these results with more data.

Search for heavy neutral lepton production in K+ decays
The NA62 collaboration, Physics Letters B, 778 (2018)

SEEING FRANCIUM NUCLEI AS TINY MAGNETS

Francium Trapping Facility

Seeing francium nuclei as tiny magnets: The ratio of the hyperfine splittings of *s* and *p* states is not constant across isotopes due to the isotope-dependent distribution of nuclear magnetization, a phenomenon called the hyperfine anomaly. By carrying out measurements of the hyperfine splitting of the excited electronic $7p_{1/2}$ state at the 100-ppm level, and comparing to previously known ground state 7s splittings, the hyperfine anomaly in six isotopes of francium (Fr) was experimentally determined. As reported in ***Physical Review Letters*** (2015) the measured magnetic distributions behave regularly from ^{213}Fr through ^{207}Fr, but ^{206}Fr stops behaving like a spherical nucleus with valence nucleons. The results are valuable input for future calculations of both the anapole moments and the neutron radii needed for small corrections to Francium Trapping Facility measurements of atomic-parity violation for $^{207–213}$Fr.

Hyperfine Anomalies in Fr: Boundaries of the Spherical Single Particle Model

J. Zhang (张颉颃), M. Tandecki, R. Collister, et al., Phys. Rev. Lett, 11504 (2015)

SUCCESSFUL CONSTRUCTION OF THE ALPHA-G ANTIMATTER GRAVITY DETECTOR

ALPHA

Successful construction of the ALPHA-g antimatter gravity detector: In July 2018, the construction at TRIUMF of the time-projection chamber (TPC) for the new antimatter gravity experiment, ALPHA-g, was completed. The TPC detector has been shipped to CERN, where it is currently being tested. The detector is a key component for the ALPHA-g project, whose goal is to measure the gravitational property of antimatter by dropping antihydrogen atoms inside a detector. The TPC will measure the location of the antihydrogen annihilations, from which the effect of gravity will be inferred. According to the equivalence principle in Einstein's theory of gravity, matter and antimatter should behave identically under the force of gravity. However, no one has ever seen how antimatter falls. The ALPHA-g experiment is set to be the first to do just that.

THE MOST ACCURATE BETA ASYMMETRY IN NUCLEAR OR NEUTRON DECAY

TRINAT

The most accurate beta asymmetry in nuclear or neutron decay: As reported in ***Physical Review Letters*** (2018), scientists using TRINAT measured the asymmetry in the average direction of beta particles with respect to the nuclear spin of potassium-37 (^{37}K), achieving the best fractional accuracy of any nuclear or neutron decay. Since C.S. Wu's discovery of parity violation using this observable in 1957, steadily improving experiments have shown no evidence for right-handed neutrinos. When compared to other nuclear beta decay experiments, the 37K result shows a possible 2.2 sigma discrepancy in the strength of the weak interaction in different nuclei, empirically and suggestively correlated with the density of nuclear magnetism.

Precision Measurement of the β Asymmetry in Spin-Polarized ^{37}K Decay

B. Fenker, A. Gorelov, D. Melconian, J.A. Behr et al., Phys. Rev. Lett., 12006 (2018)

WHILE SOME FRANCIUM ATOMS ESCAPE, MOST STAY TRAPPED

Francium Trapping Facility

While some francium atoms escape, most stay trapped: As reported in the ***Canadian Journal of Physics*** (2017), laser-trapped francium atoms were irradiated with blue laser light, causing some of them to be photoionized (lose an electron) and lost from the francium trap. The probability of photoionization was in line with the general trend exhibited by the other alkali atoms. Photoionization losses from the laser trap are one of the most serious limitations for a trap-based tests of atomic parity violation, and the results of this experiment importantly support the feasibility of such experiments.

Photoionization of the francium $7P_{3/2}$ state

R. Collister, J. Zhang, M. Tandecki, et al., Canadian Journal of Physics, 953, 234 (2017)