Introduction to TRIUMF

Workshop on Progress in *Ab Initio* Nuclear Theory

TRIUMF, Vancouver, Canada

February 27 – March 1, 2024

Petr Navratil

TRIUMF Theory Department

Interim Director, Physical Sciences

TRIUMF is located on the traditional, ancestral, and unceded territory of the xwməθkwəy̓əm (Musqueam) People, who for millennia have passed on their culture, history, and traditions from one generation to the next on this site.

2024-02-27

Discovery, accelerated

In memory of Rupert Machleidt

- Pioneer of high-precision nuclear forces
  - Meson-exchange & chiral EFT based
  - Passed away in December 2023
- Frequent participant of TRIUMF workshop series
- Everlasting impact on *ab initio* nuclear theory

PHYSICAL REVIEW C, VOLUME 63, 024001

High-precision, charge-dependent Bonn nucleon-nucleon potential

R. Machleidt*

RAPID COMMUNICATIONS

PHYSICAL REVIEW C **68**, 041001(R) (2003)

Accurate charge-dependent nucleon-nucleon potential at fourth order of chiral perturbation theory

D. R. Entem[1,2,*] and R. Machleidt[1,†]

Recent advances in chiral EFT based nuclear forces and their applications

R. Machleidt[a], F. Sammarruca[a,*]

[a] *Department of Physics, University of Idaho, Moscow, Idaho 83844, USA*

Abstract

During the past two decades, chiral effective field theory has evolved into a powerful tool to derive nuclear forces from first principles. Nearly all two-nucleon interactions have been worked out up to sixth order of chiral perturbation theory, while, with few exceptions, three-nucleon forces, which play a subtle, but crucial role in microscopic nuclear structure calculations, have been derived up to fifth order. We review the current status of these forces as well as their applications in nuclear many-body systems. While the *ab initio* description of light nuclei is generally very successful, we point out and analyze problems encountered with medium-mass nuclei. We also survey the construction of equations of state for symmetric nuclear matter and neutron-rich matter based on chiral forces. A focal point is the symmetry energy and its impact on neutron skins and systems of astrophysical relevance. The physics of neutron-rich systems, from nuclei to compact stars, is essentially determined by the density dependence of the symmetry energy. We review the status of predictions in comparison with latest empirical constraints, with particular attention to those extracted from parity-violating electron scattering.

Keywords: Chiral effective field theory, nucleon-nucleon scattering, three-nucleon forces, *ab initio* calculations of nuclei, nuclear-matter theory, neutron-rich systems, neutron skin

Physics Reports 503 (2011) 1–75

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ELSEVIER

Chiral effective field theory and nuclear forces

R. Machleidt [a,*], D.R. Entem [b]

PHYSICAL REVIEW C **96**, 024004 (2017)

High-quality two-nucleon potentials up to fifth order of the chiral expansion

D. R. Entem,[1,*] R. Machleidt,[2,†] and Y. Nosyk[2]

Our vision is for Canada to lead in science, discovery, and innovation, improving lives and building a better world.

TRIUMF is Canada's particle accelerator centre.

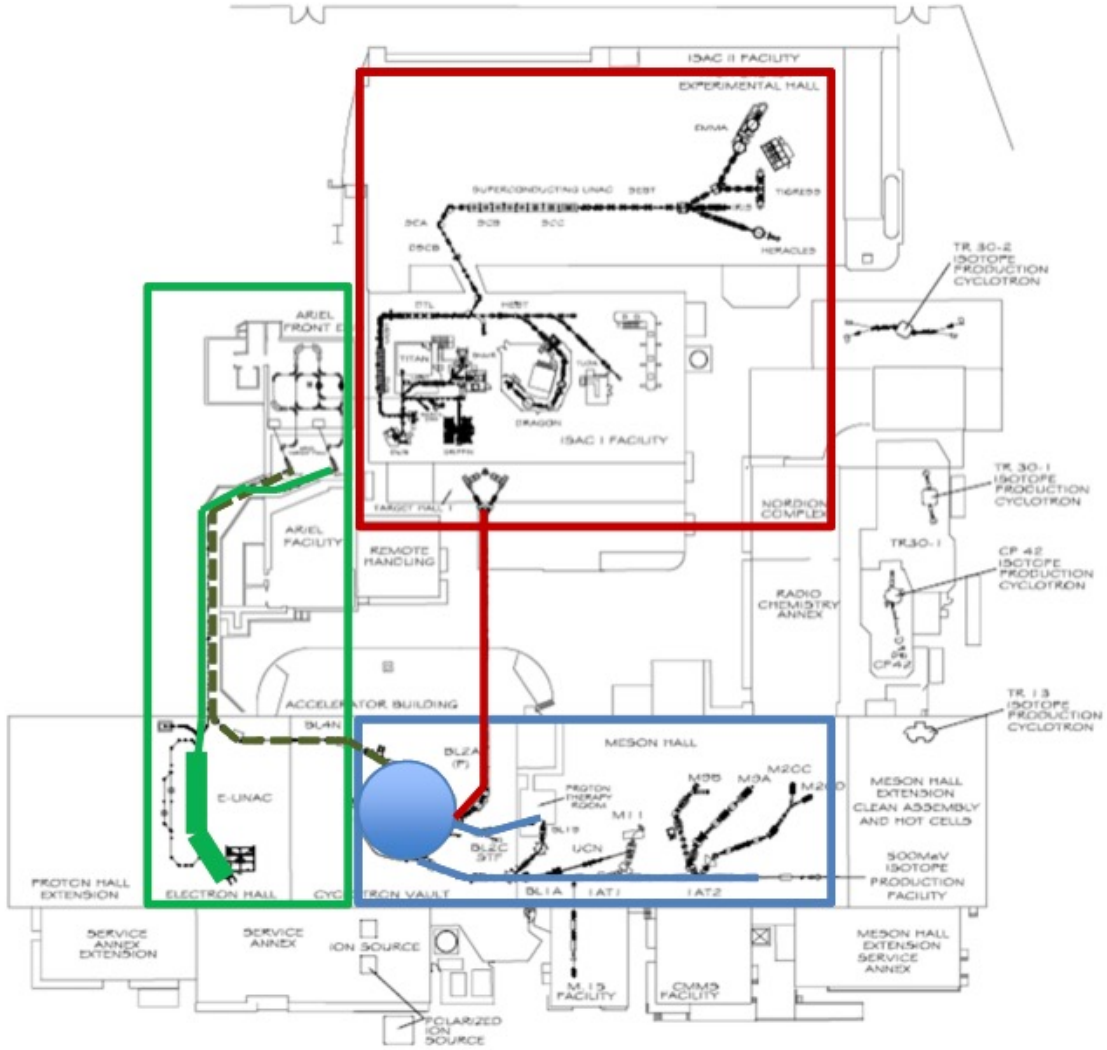
- We advance isotope science and technology, both fundamental and applied.
- We collaborate across communities and disciplines, from nuclear and particle physics to the life and material sciences.
- We discover and innovate, inspire and educate, creating knowledge and opportunity for all.

- Home to ~600 staff and students from 30 countries
- > 200 students & post-doctoral researchers

TRIUMF

TRIUMF history

- **500 MeV cyclotron** since 1974
  - One of the three Meson factories built at the same time – including LAMPF and PSI
- **Isotope Separator and ACcelerator (ISAC)** since 1995
  - Radioactive ion beam (RIB) facility
  - Driven by 500 MeV protons from cyclotron
- **Advanced Rare Isotope Facility (ARIEL)** in progress since 2010



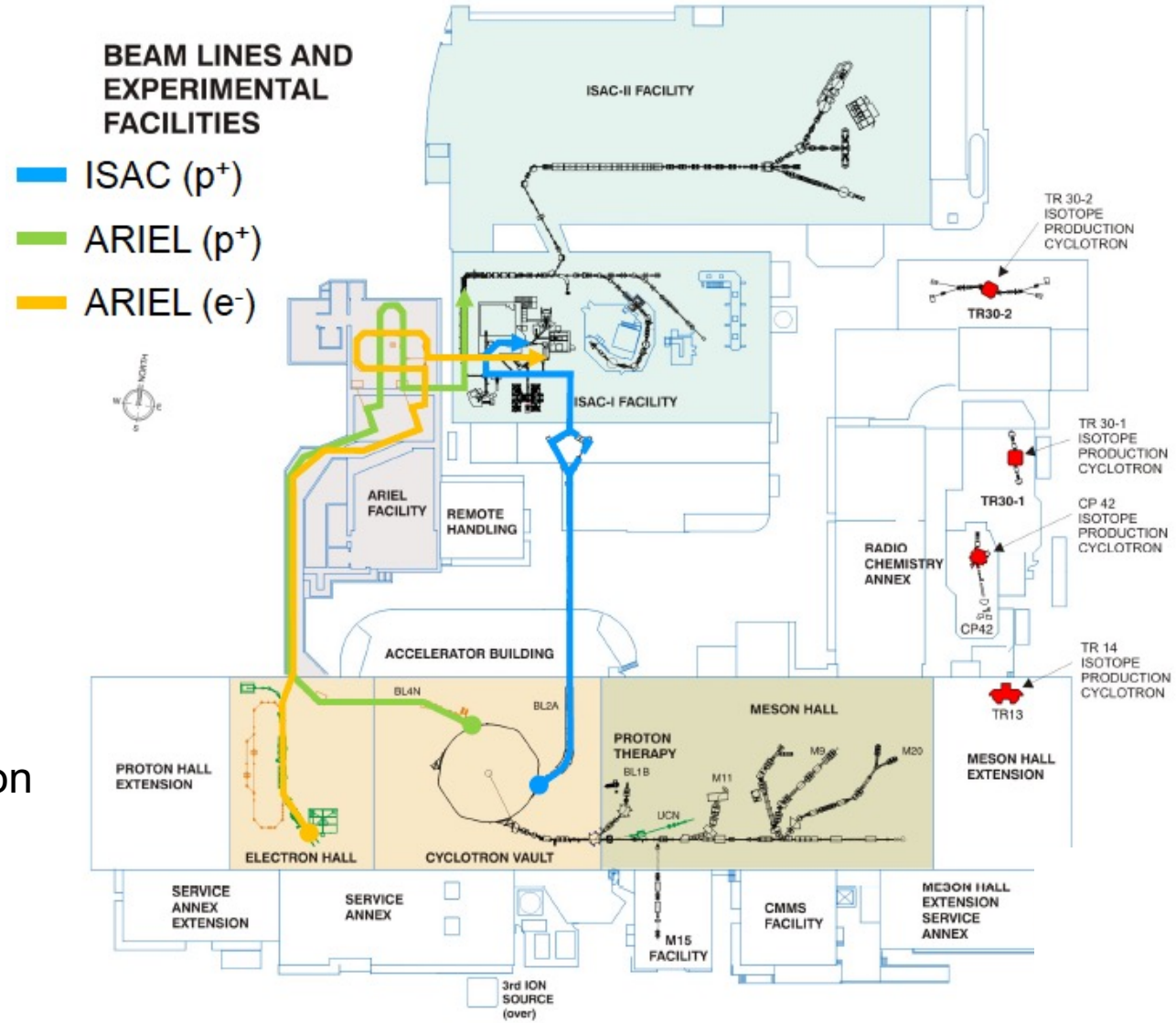
Advanced Rare Isotope Facility (ARIEL)

TRIUMF's flagship project

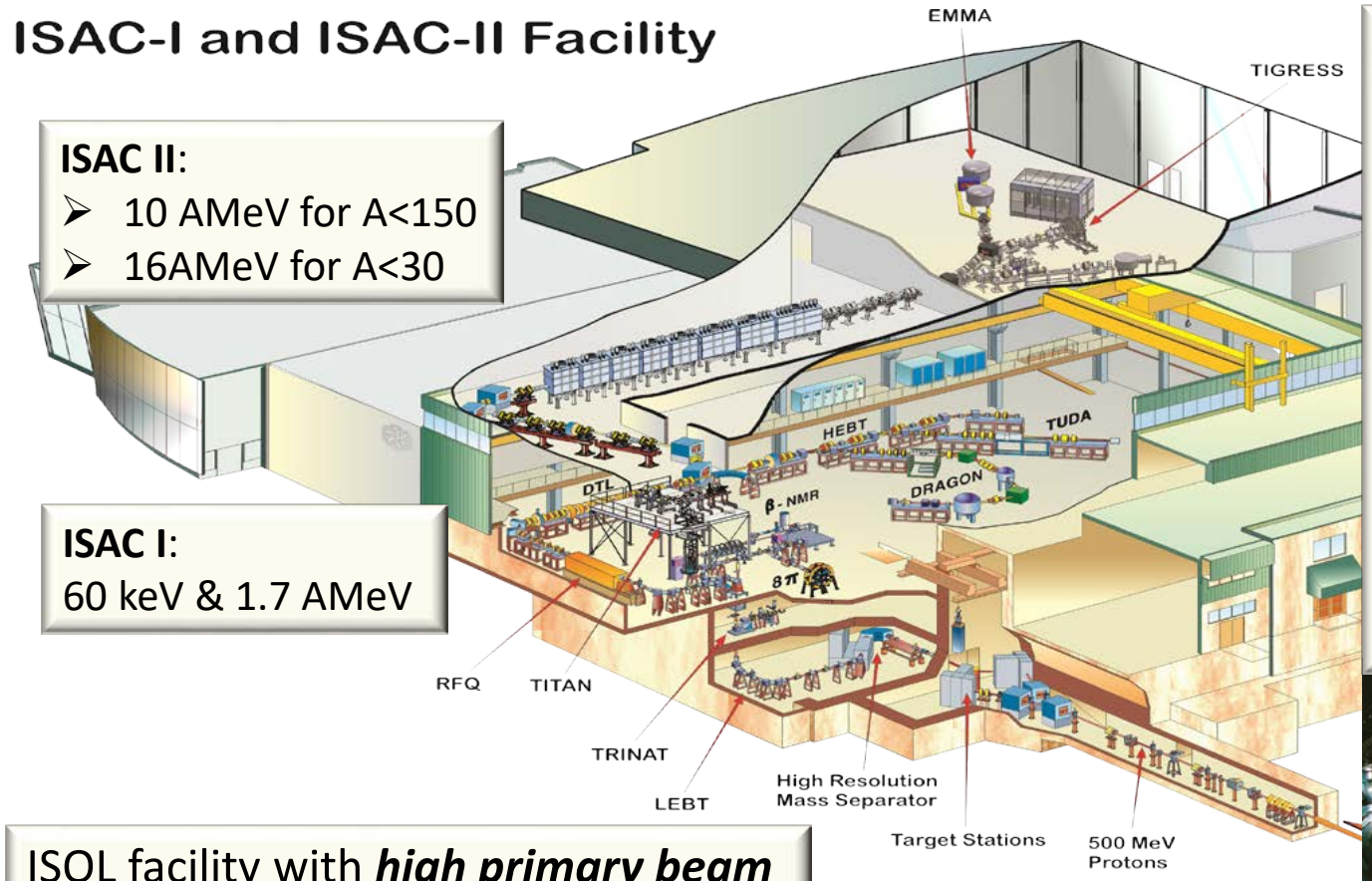
Substantially expands RIB capabilities:

- Simultaneous RIB production from 3 targets
  - 50 kW existing ISAC proton target
  - 50 kW new ARIEL proton target
  - 100 kW new ARIEL electron target
- More beam hours for science
- Multi-user capability with more and new isotopes for
  - Nuclear Physics (Structure, Nucl. Astro, Fund. Sym.)
  - Materials Science, Life Sciences
- Project completion in 2026 with phased implementation, interleaving science with construction

TRIUMF accelerator complex



TRIUMF ISAC/ARIEL Experiments

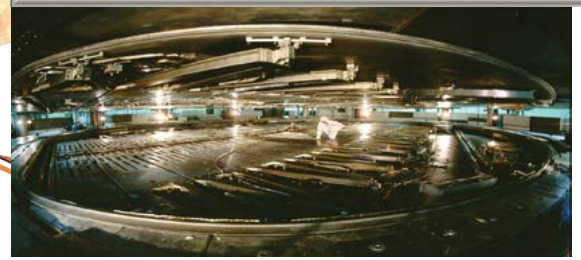


ISAC II:
- 10 AMeV for A<150
- 16AMeV for A<30

ISAC I:
60 keV & 1.7 AMeV

ISOL facility with ***high primary beam intensity*** (100 μA, 500 MeV, p)

Programs in
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science
- 16 permanent experiments



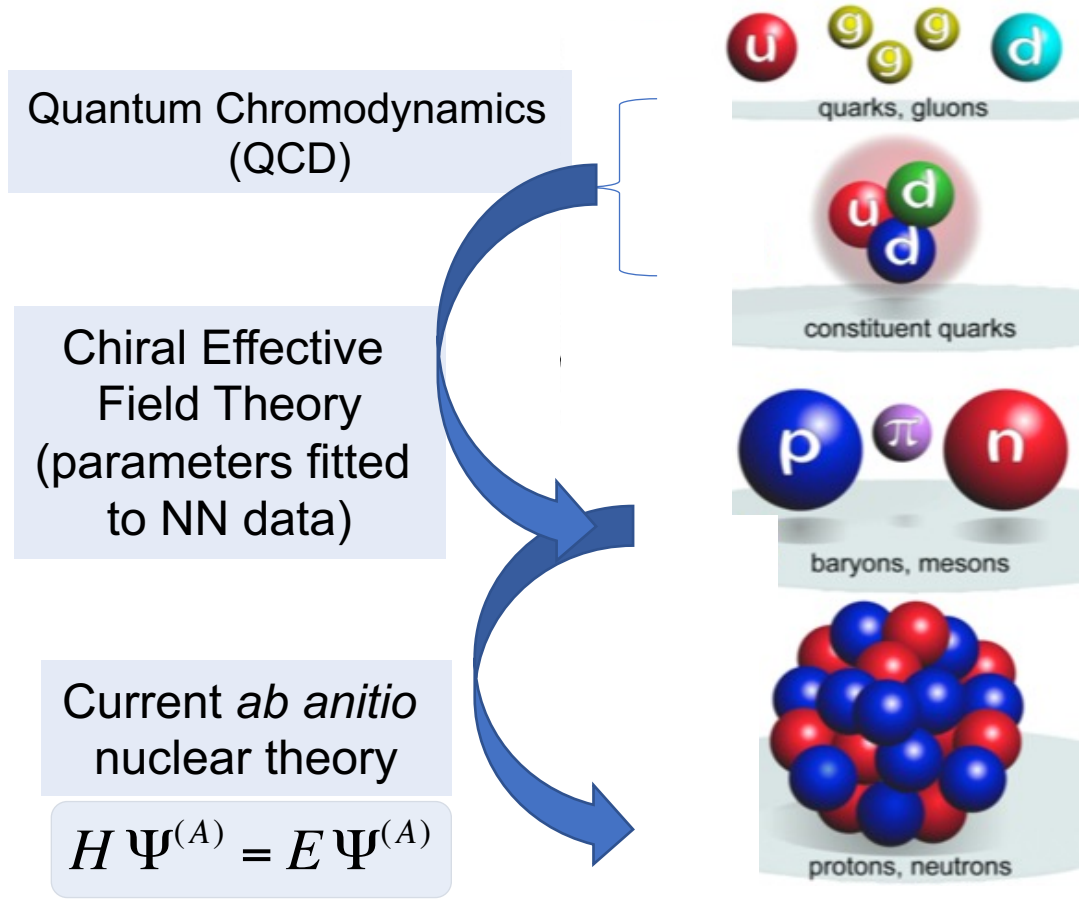
TRIUMF

TRIUMF Theory

- First principles or *ab initio* nuclear theory
  - Input NN+3N interactions from chiral EFT
  - Solving many-nucleon Schrodinger equation
    - Quantum many-body problem

- Unique to TRIUMF nuclear theory:
  - Unified approach to nuclear structure and reactions for light nuclei: No-Core Shell Model with Continuum (NCSMC)
  - Powerful valence-space method for medium mass nuclei: Valence-Space In-Medium Similarity Renormalization Group (VS-IMSRG)

- Large-scale high-performance computation
  - Massively parallel codes
  - Frontier@ORNL, Quartz@Livermore Computing, Niagara@Compute Canada

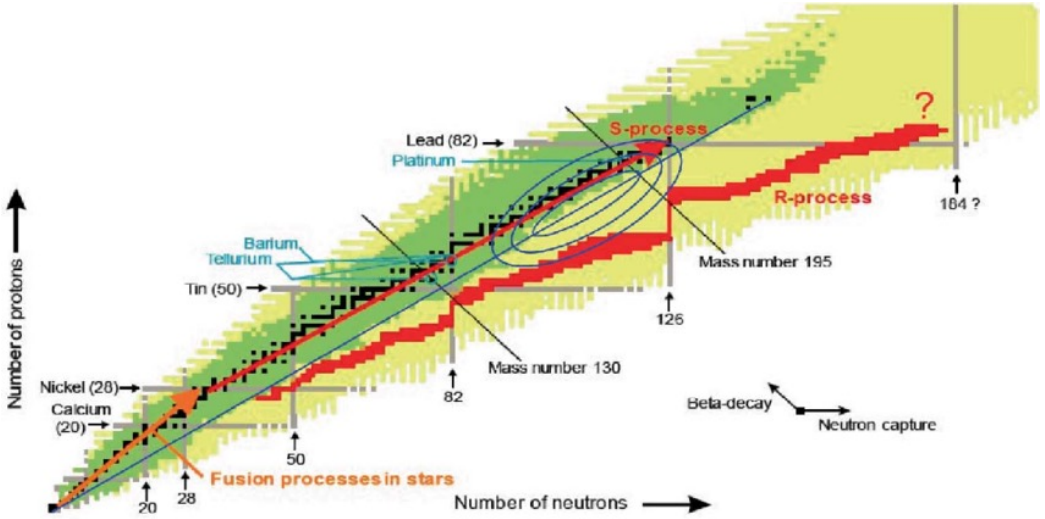


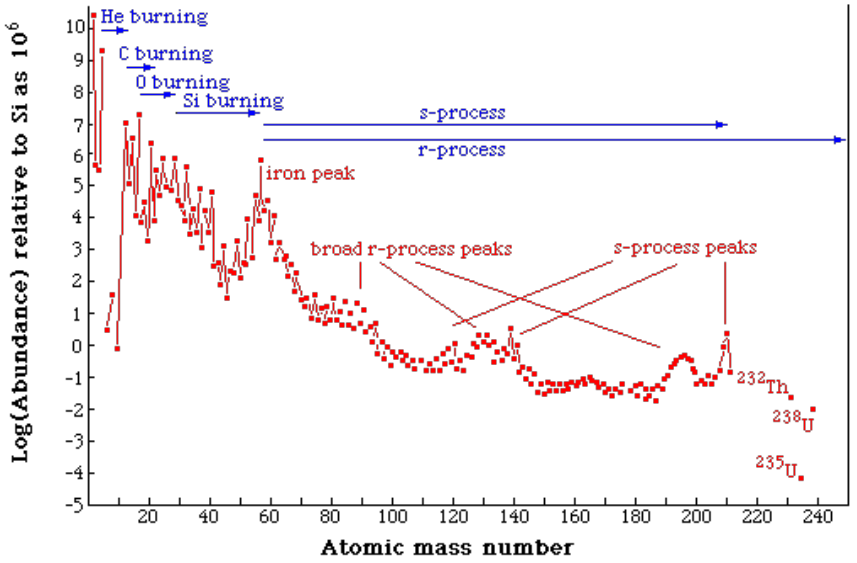
TRIUMF Theory

- Nuclear astrophysics
  - r-process nucleosynthesis

- Particle physics
  - Dark matter physics, collider phenomenology, neutrino physics, particle cosmology, hadronic physics

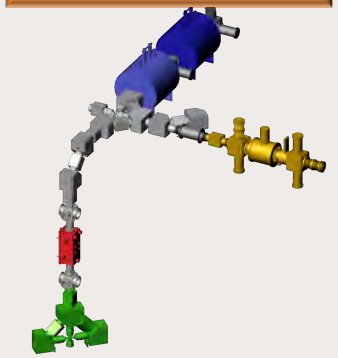
$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\bar{\psi}\not{D}\psi + \bar{\psi}_i y_{ij}\psi_j\phi + h.c. + |D_\mu\phi|^2 - V(\phi)$$



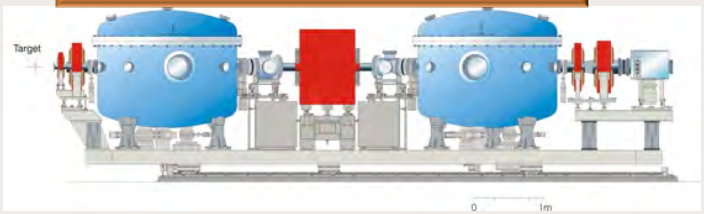


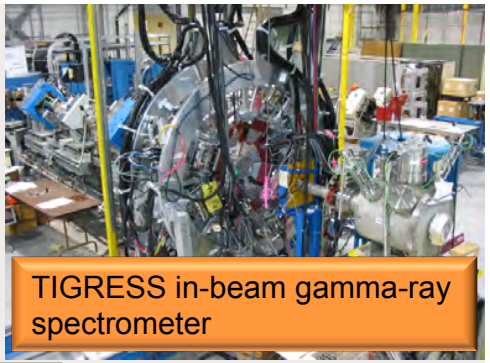
Leading edge ISAC experiments

TITAN Penning Trap facility



EMMA recoil mass analyzer (2015)



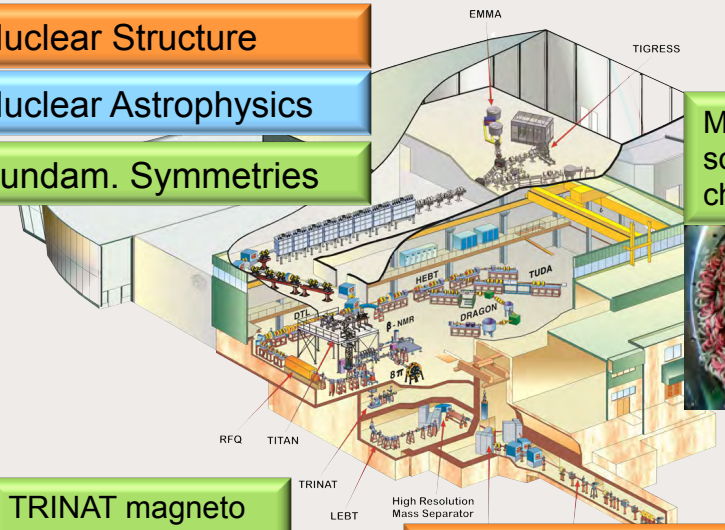


TIGRESS in-beam gamma-ray spectrometer

Nuclear Structure

Nuclear Astrophysics

Fundam. Symmetries

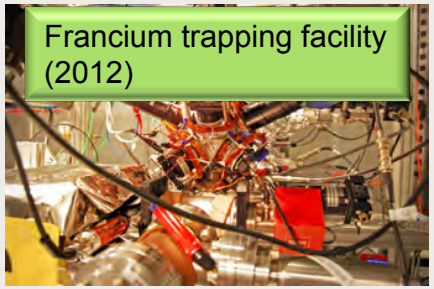


MTV Mott scattering drift chamber

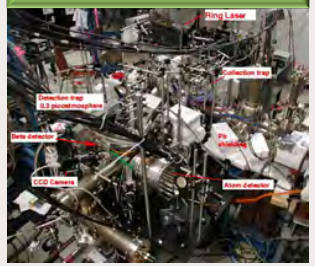
IRIS solid hydrogen reaction set-up (2012)

Laser polarizer line

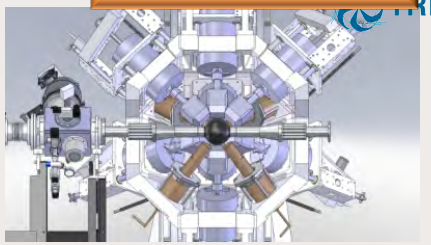
Francium trapping facility (2012)

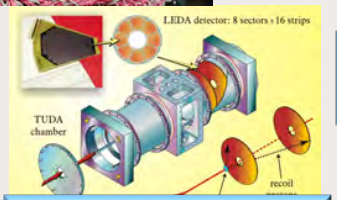


TRINAT magneto optical trap



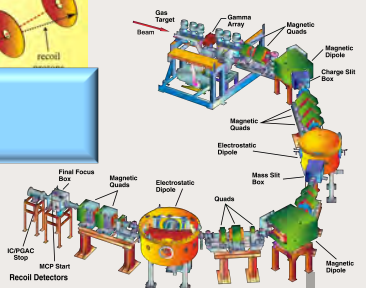
GRIFFIN gamma-ray decay spectrometer





TUDA reaction setup

DRAGON recoil separator



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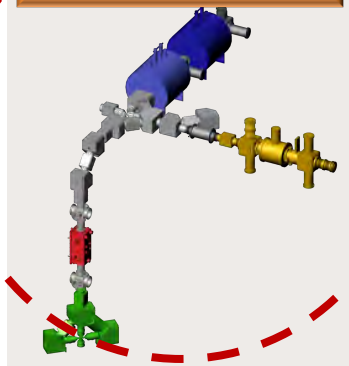

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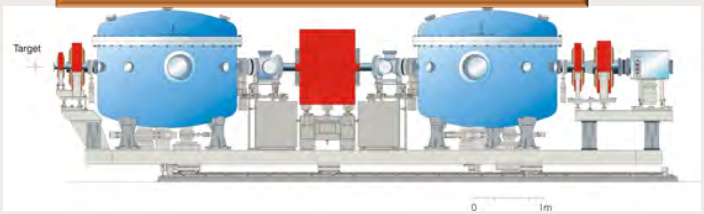

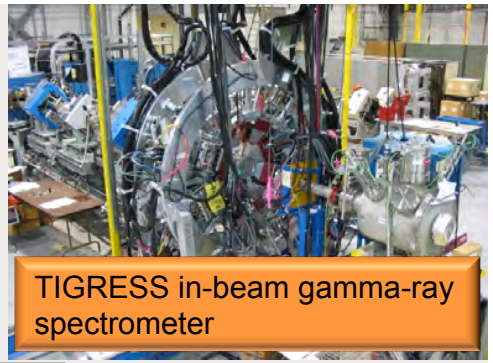

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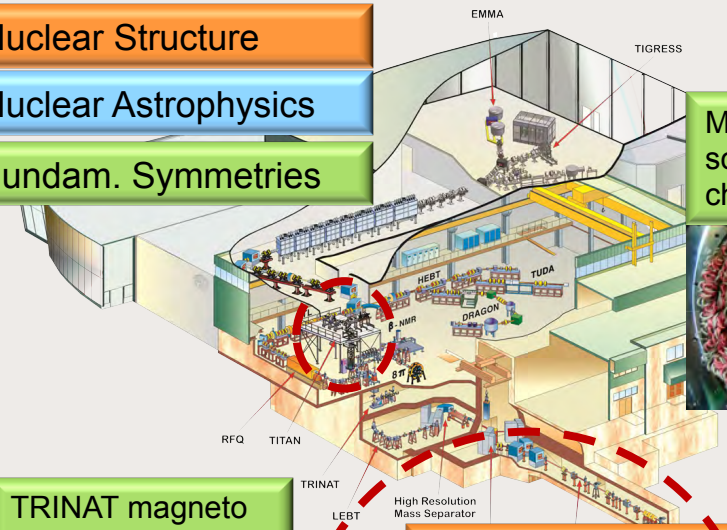

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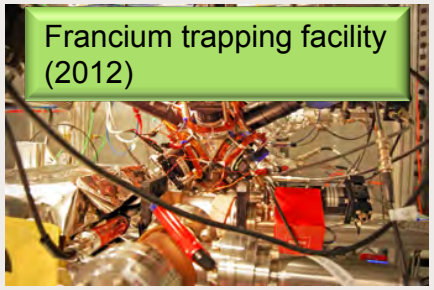

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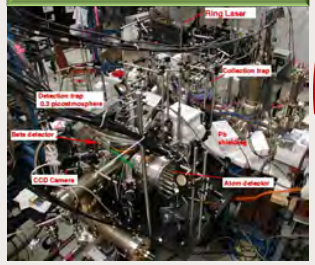

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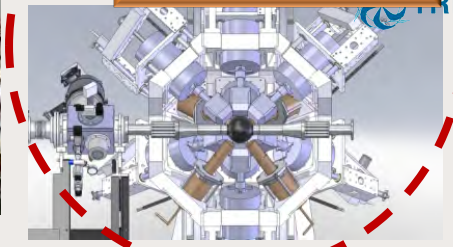

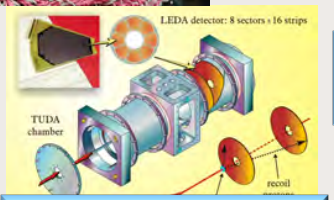

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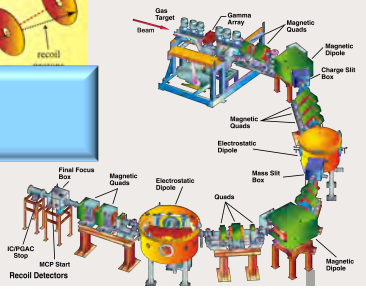


Decay Spectroscopy & Mass Measurements: Structure & Fund. Symmetries

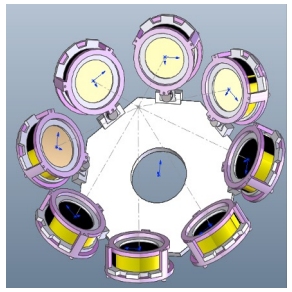
GRIFFIN Decay Spectrometer

- Wide-ranging and active science program in nuclear structure, nuclear astrophysics and fundamental symmetries → continue with ISAC and further ramp up with ARIEL. → New n-rich isotopes, higher yields, cleaner beams
- New upgrades will ensure competitive edge over worldwide competition + enable new science opportunities.
  - Upgrade SCEPTAR beta-tagging array to ARIES.
  - Upgrade PACES conversion electron spectrometer to CEDAR.
  - New RCMP detector (DSSD box built by Uni. of Regina) to enable charge-particle spectroscopy (eg. β-delayed proton and alpha)

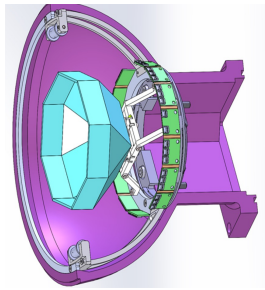
"Everything except the neutrino!"

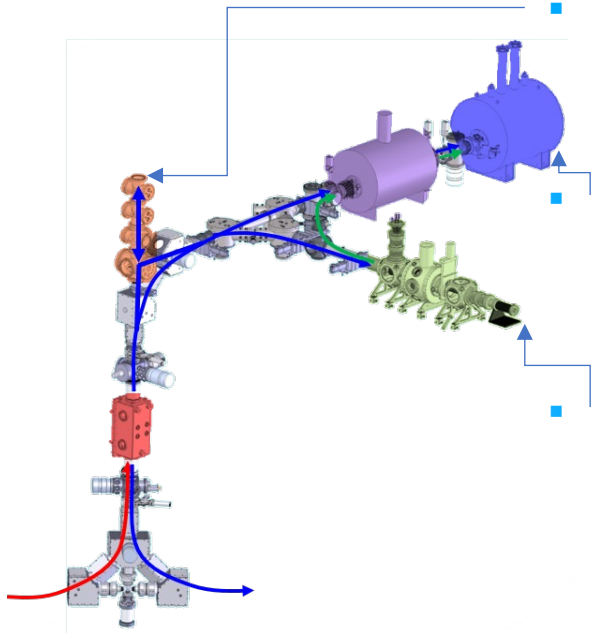
New capability (2025-2030):
Delivery of spin-polarized beams to GRIFFIN

CEDAR

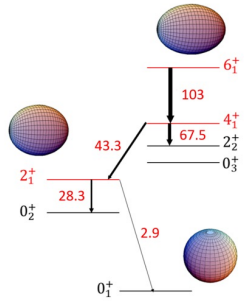


ARIES





Shape coexistence

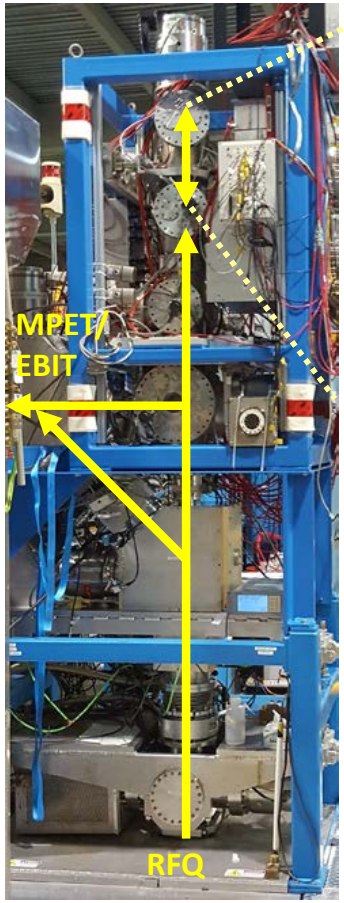


TITAN Ion Trap Facility

- MR-TOF: Program of measuring r-process nuclei for astrophysics (masses), plus instrument of standard for measuring low intensities from ARIEL
- MPET (Penning Trap): Precision mass measurements, v. high precision (1:1E+10) of heavy superallowed β-emitters → V_{ud}
- EBIT (highly-charged ions)
  - In-trap decay spectroscopy: nuclear structure & Astro
  - Extreme UV spectroscopy → absolute charge radii of heavies (e.g. Fr, Ra) for EDMs
  - Highly-charged radioactive molecules: establishing existence → RadMol facility

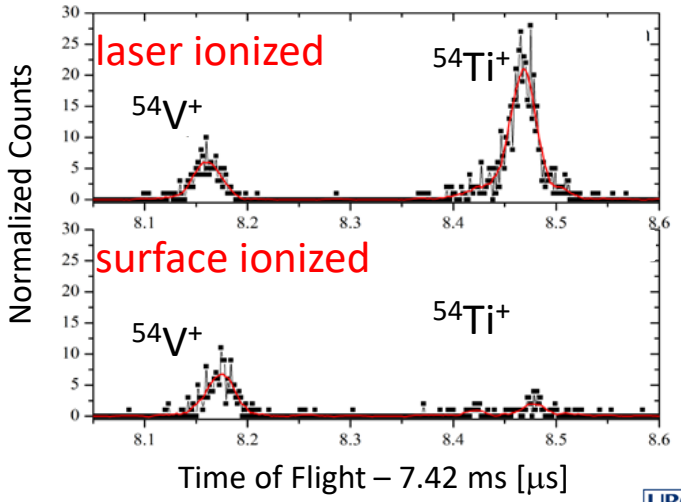
TRIUMF's Ion Trap for Atomic & Nuclear science (TITAN)

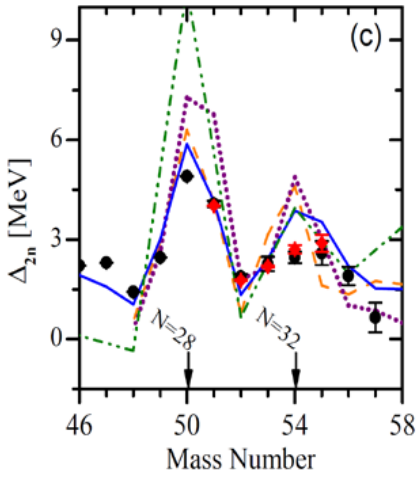
Recent research highlight



TITAN: precision mass measurement to test fundamental nuclear physics

- MR-TOF successfully commissioned on-line
- 3 successful RIB experiments
- Verified accuracy w/ Penning trap mass spectrometry
- Investigation of N=32 shell closure in Ti isotopes





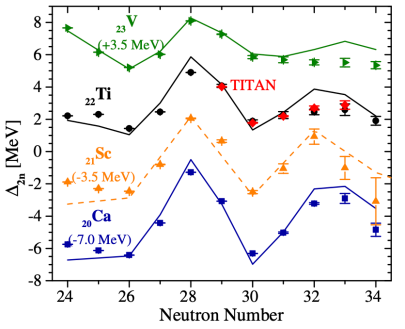
PHYSICAL REVIEW LETTERS 120, 062503 (2018)

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

E. Leistenschneider,[1,2,*] M. P. Reiter,[1,3] S. Ayet San Andrés,[3,4] B. Kootte,[1,5] J. D. Holt,[1] P. Navrátil,[1] C. Babcock,[1] C. Barbieri,[6] B. R. Barquest,[1] J. Bergmann,[3] J. Bollig,[1,7] T. Brunner,[1,8] E. Dunling,[1,9] A. Finlay,[1,2] H. Geissel,[3,4] L. Graham,[1] F. Greiner,[3] H. Hergert,[10] C. Hornung,[3] C. Jesch,[3] R. Klawitter,[1,11] Y. Lan,[1,2] D. Lascar,[1,†] K. G. Leach,[12] W. Lippert,[3] J. E. McKay,[1,13] S. F. Paul,[1,7] A. Schwenk,[11,14,15] D. Short,[1,16] J. Simonis,[17] V. Somà,[18] R. Steinbrügge,[1] S. R. Stroberg,[1,19] R. Thompson,[20] M. E. Wieser,[20] C. Will,[3] M. Yavor,[21] C. Andreoiu,[16] T. Dickel,[3,4] I. Dillmann,[1,13] G. Gwinner,[5] W. R. Plaß,[3,4] C. Scheidenberger,[3,4] A. A. Kwiatkowski,[1,13] and J. Dilling[1,2]

theory and experiment

- TITAN
- AME
- 1.8/2.0 (EM) VS-IMSRG
- NN+3N (lnl) GGF
- N^2LO_{sat} GGF
- N^2LO_{sat} MR-IMSRG



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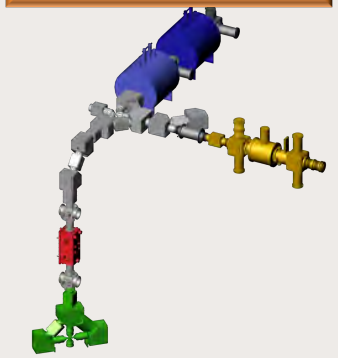
Leading edge ISAC experiments

TITAN Penning Trap facility



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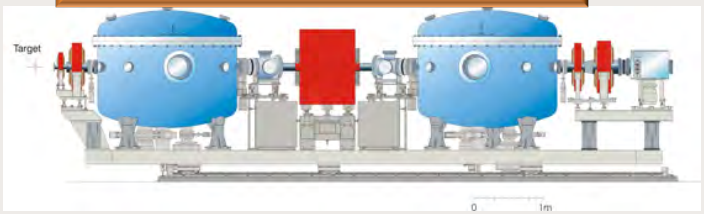
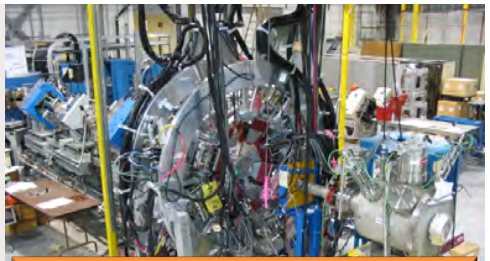


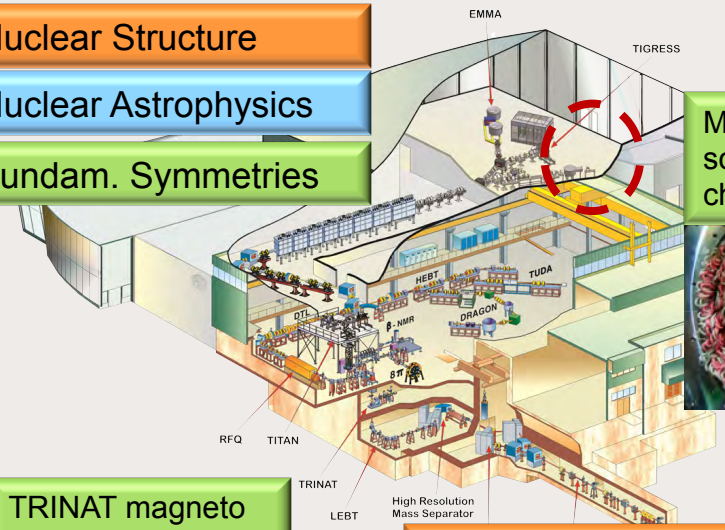


TIGRESS in-beam gamma-ray spectrometer

Nuclear Structure

Nuclear Astrophysics

Fundam. Symmetries



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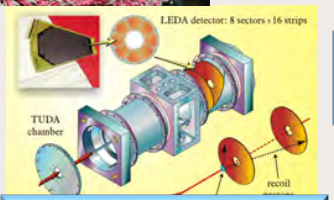

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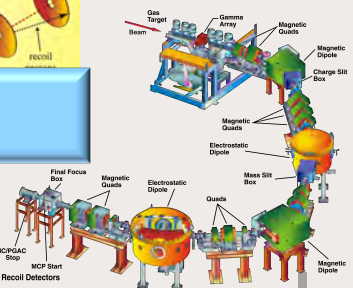

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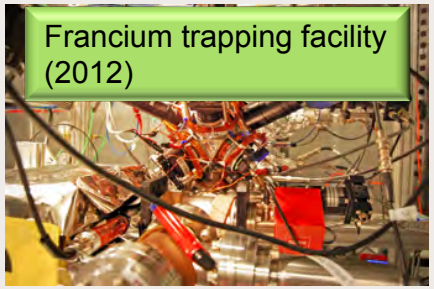

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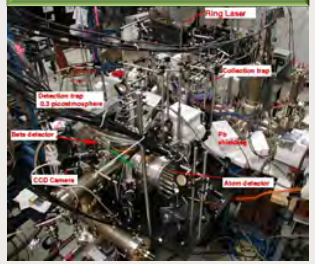
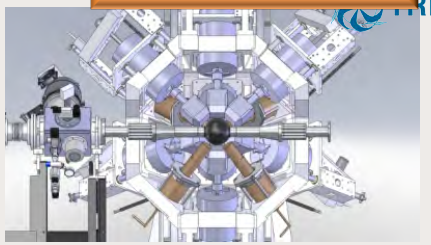
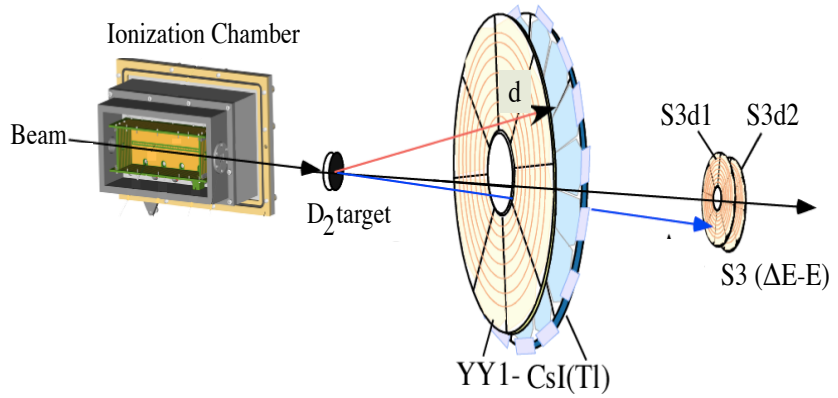


GRIFFIN gamma-ray decay spectrometer



IRIS Innovative Rare Isotope reaction Spectroscopy facility

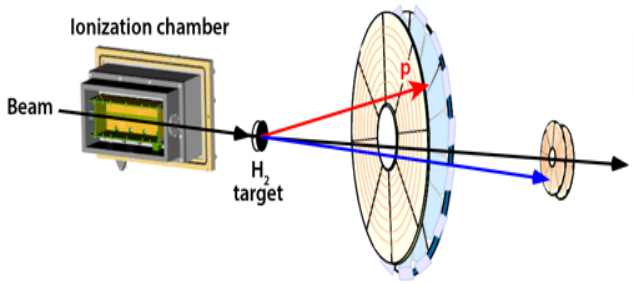
- Rare isotope reaction spectroscopy station
  - Lead by St. Mary's University
  - Commissioned in 2012
- Reactions with a frozen (solid) windowless hydrogen or deuterium target
- Charged particle spectrometer
  - Silicon strip detectors and CsI(Tl) detectors



IRIS reaction spectroscopy facility – recent research highlight

Testing fundamental nuclear physics theory:
Led by R. Kanungo, St. Mary's University

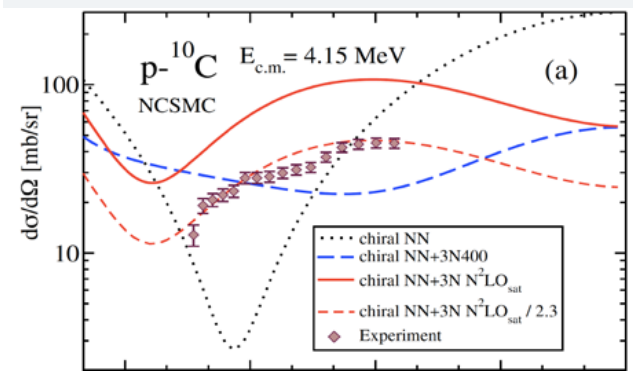
- **IRIS charged particle spectrometer**
- **Windowless solid hydrogen target**
- ^{10}C beam, 4.5 MeV/u from TRIUMF-ISAC-II



PRL 118, 262502 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

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

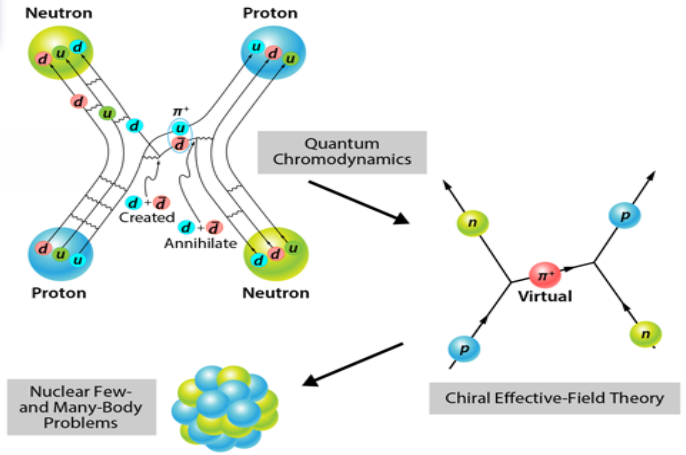
A. Kumar,[1] R. Kanungo,[1*] A. Calci,[2] P. Navrátil,[2†] A. Sanetullaev,[1,2] M. Alcorta,[2] V. Bildstein,[3] G. Christian,[2] B. Davids,[2] J. Dohet-Eraly,[2,4] J. Fallis,[2] A. T. Gallant,[2] G. Hackman,[2] B. Hadinia,[3] G. Hupin,[5,6] S. Ishimoto,[7] R. Krücken,[2,8] A. T. Laffoley,[3] J. Lighthall,[2] D. Miller,[2] S. Quaglioni,[9] J. S. Randhawa,[1] E. T. Rand,[3] A. Rojas,[2] R. Roth,[10] A. Shotter,[11] J. Tanaka,[12] I. Tanihata,[12,13] and C. Unsworth[2]



Theory from TRIUMF
- Ab initio with modern two- and three-nucleon forces

NN alone wrong – overpredicts fringe contrast

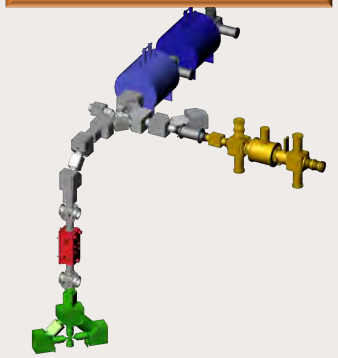
NN and 3N fit simultaneously : **shape correct** but fails to reproduce magnitude



SAINT MARY'S UNIVERSITY SINCE 1802 — One University. One World. Yours.
UNIVERSITY of GUELPH
McMaster University
SFU SIMON FRASER UNIVERSITY
KEK-JAPAN
RCNP
THE UNIVERSITY OF EDINBURGH
TRIUMF
GANIL GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

Leading edge ISAC experiments

TITAN Penning Trap facility



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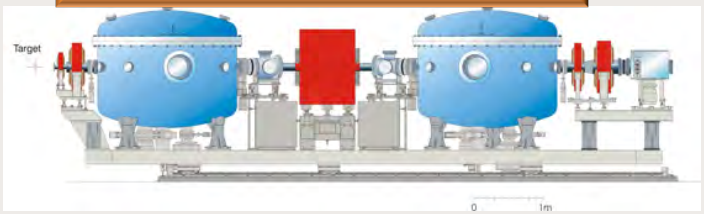
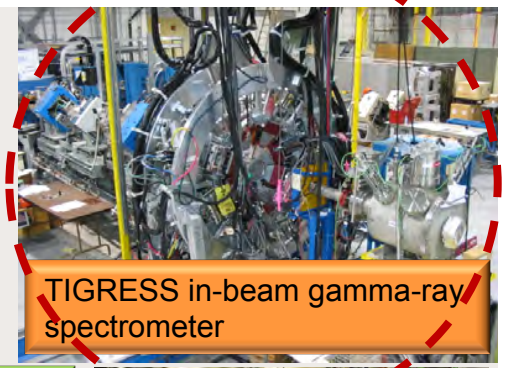


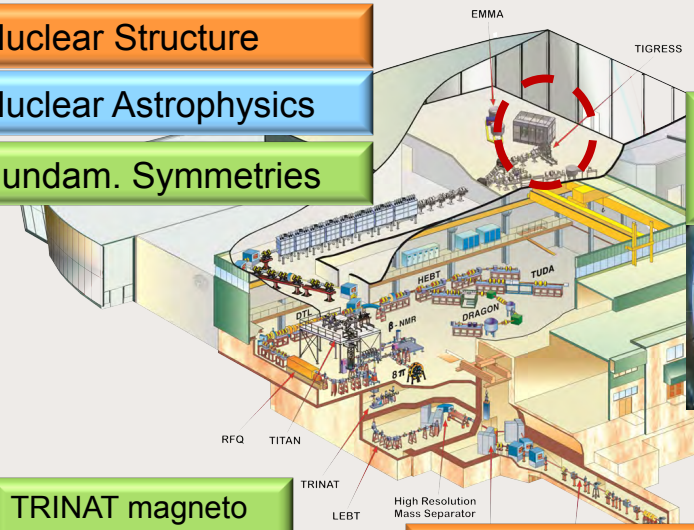


TIGRESS in-beam gamma-ray spectrometer

Nuclear Structure

Nuclear Astrophysics

Fundam. Symmetries



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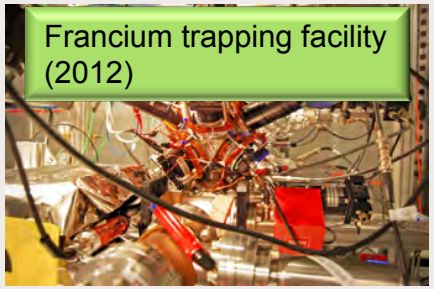

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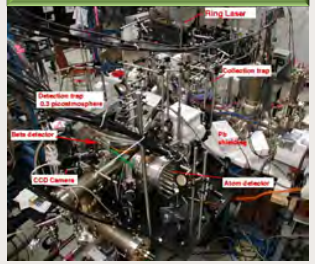

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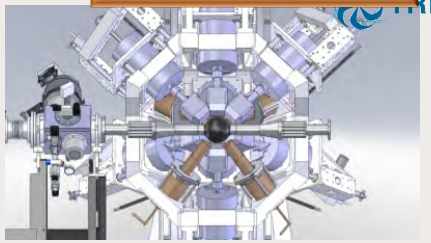

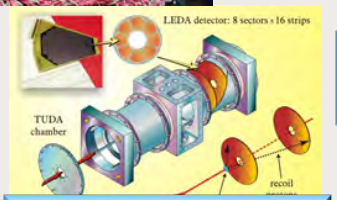

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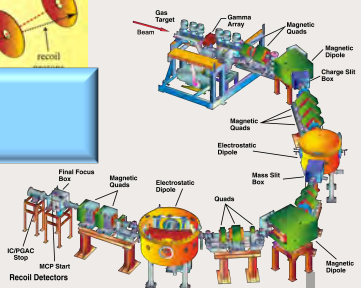
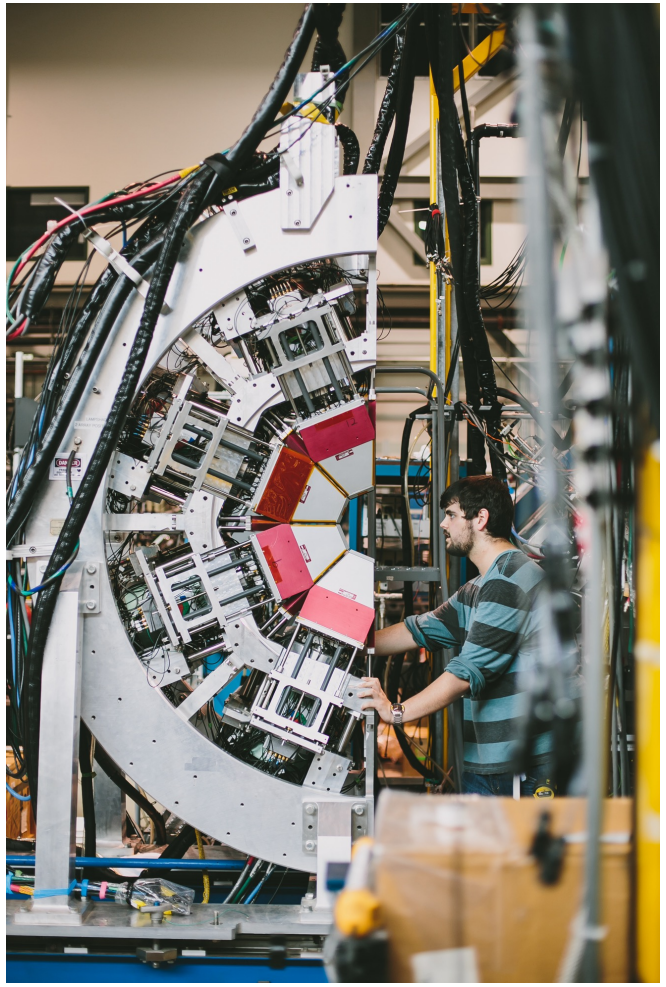
DRAGON recoil separator



TIGRESS: High efficiency and high energy-resolution gamma ray spectrometer

- TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS)
- Array of 32-fold segmented high-purity germanium (HPGe) gamma-ray detectors
- The ability to determine gamma-ray interaction locations within the TIGRESS detectors enables accurate correction of the measured gamma-ray energies for the Doppler shifts
- Excellent gamma-ray energy resolution
- Very high gamma-ray detection efficiency
- Compton suppression shields from scintillator crystals bismuth germanate (BGO) and cesium iodide (CsI).



To work towards a complete theory of nuclear matter, we study shapes and modes of excitation of exotic nuclei

To understand heavy element nucleosynthesis, we study reaction and structure properties of exotic nuclei

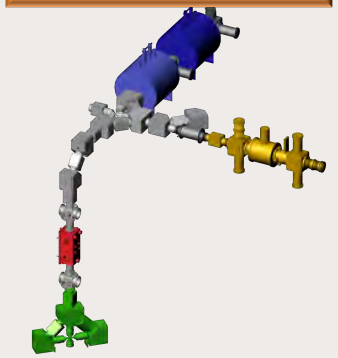
We study these inner workings of exotic nuclei by measuring de-excitation gamma rays following high energy collisions

TIGRESS: High efficiency and high energy-resolution gamma ray spectrometer

Designed for experiments with exotic nuclei at ~10% speed of light

Leading edge ISAC experiments

TITAN Penning Trap facility



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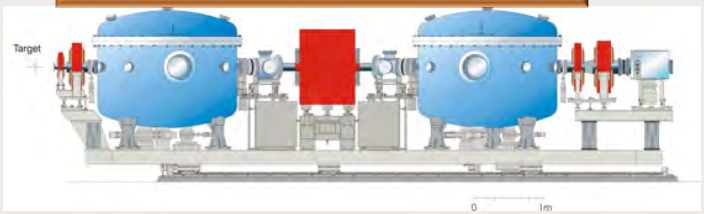

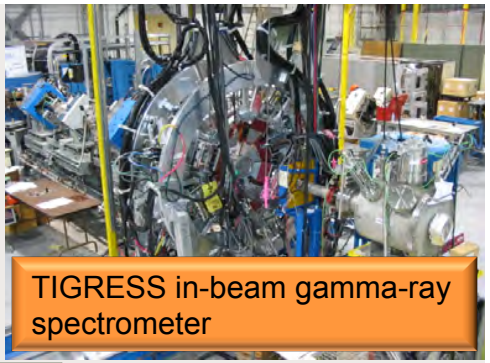

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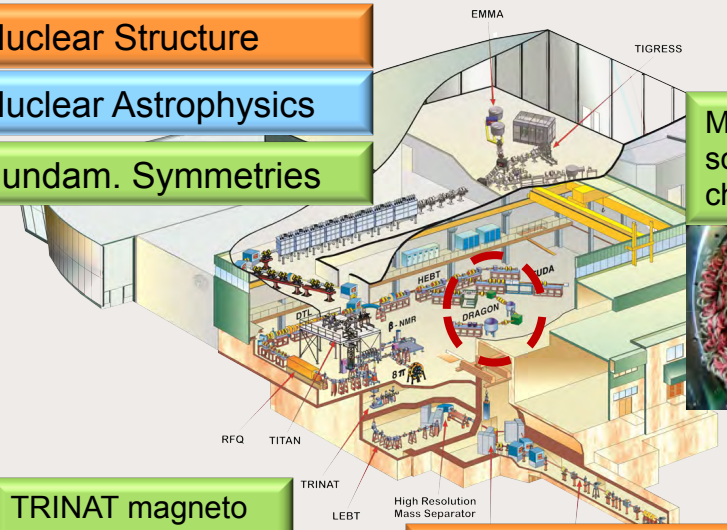

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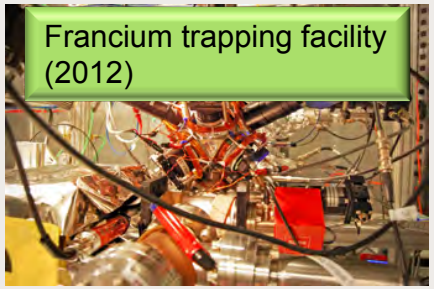

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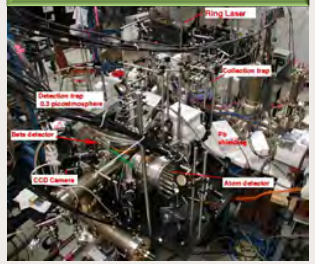

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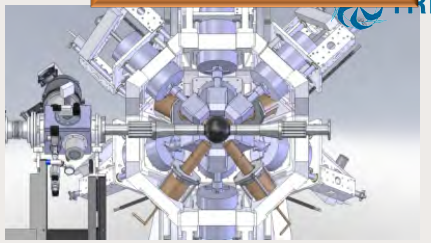

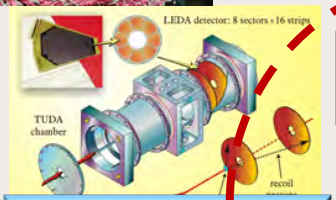

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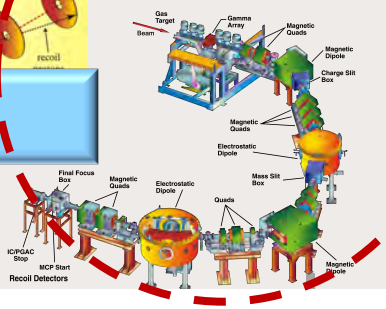
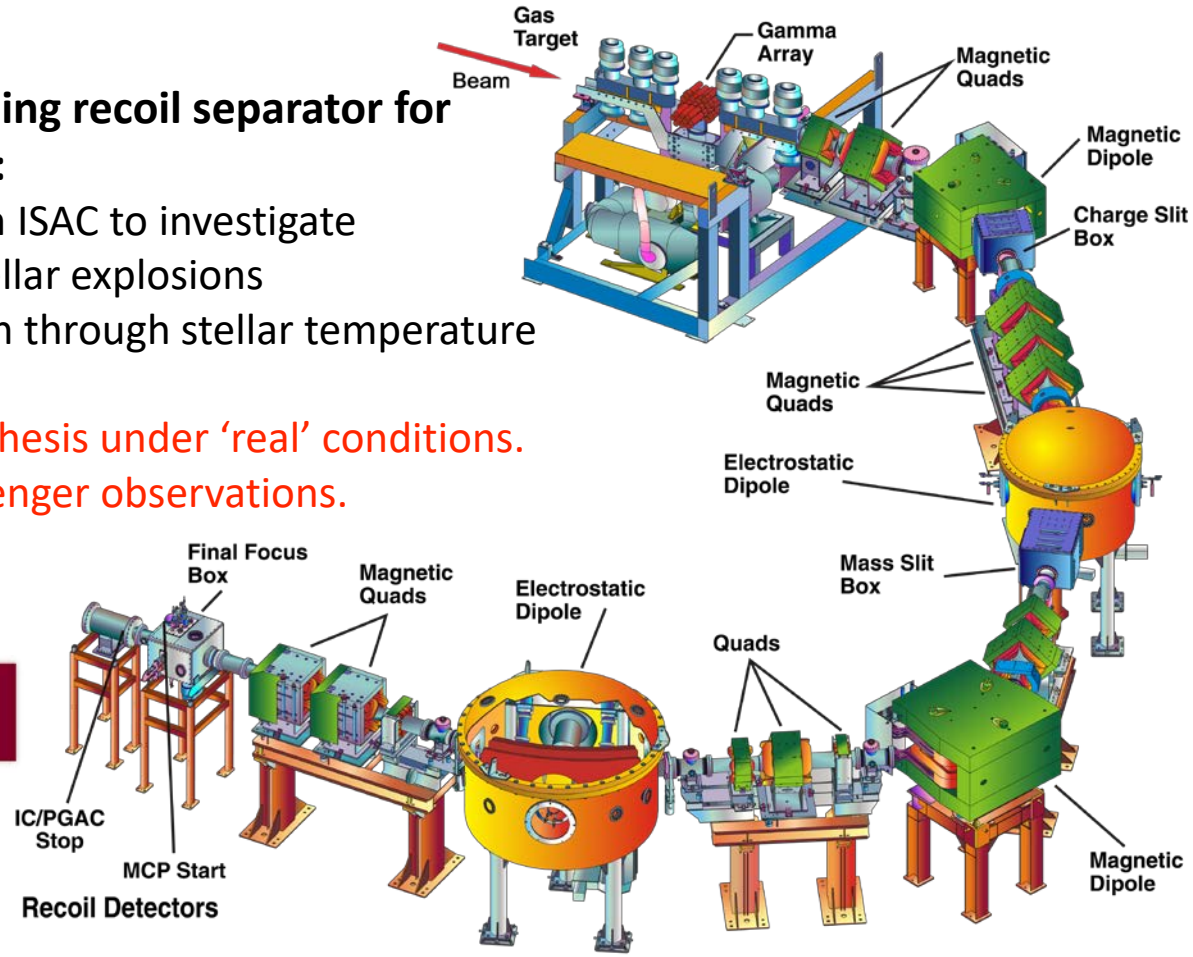


DRAGON – Detector of Recoils And Gammas Of Nuclear reactions

DRAGON: world's highest performing recoil separator for measuring stellar fusion reactions:

- Uses exotic short-lived beams from ISAC to investigate nucleosynthesis & behaviour of stellar explosions
- Vary incoming beam energy to scan through stellar temperature and observe reactions.
- Stepwise re-creation of nucleosynthesis under 'real' conditions.
- Compare outcomes to multi-messenger observations.



UNIVERSITY OF SURREY
THE UNIVERSITY OF EDINBURGH
McMaster University
TRIUMF
Colorado School of Mines
UNIVERSITY of York

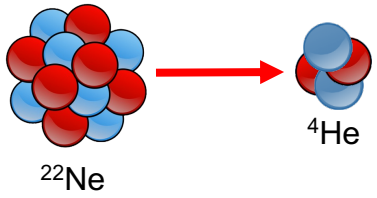
S2230: Pioneering direct measurements of (α,n) reactions using a recoil separator: Proof of principle measurement of the E_x = 11.83 MeV resonance in ^{22}Ne(α,n)^{25}Mg

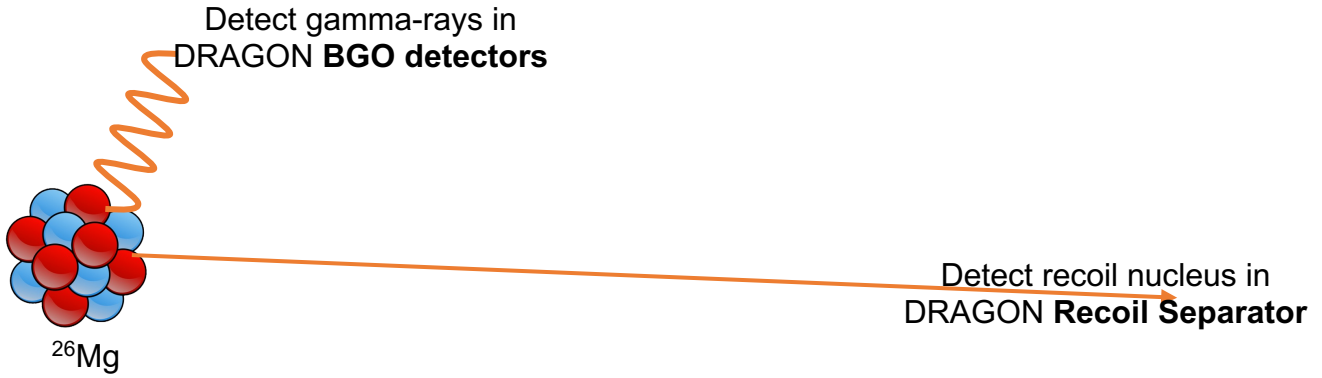
The ^{22}Ne(α,n)^{25}Mg reaction is an **important source of neutrons** for the astrophysical 's-process' (which makes about half of the e.g. iron in the universe in AGB stars)

It's difficult to measure! Usually use ^{4}He beam on ^{22}Ne target, but neutrons are notoriously difficult to measure + lots of background.

What if could also detect the reaction product, ^{25}Mg? → Use DRAGON in inverse kinematics!

Normal DRAGON Experiment:
^{22}Ne(α,γ)^{26}Mg





DEMAND-DRAGON Experiment:
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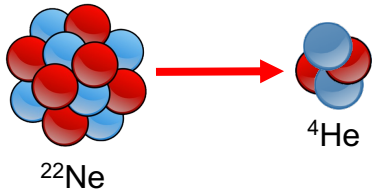

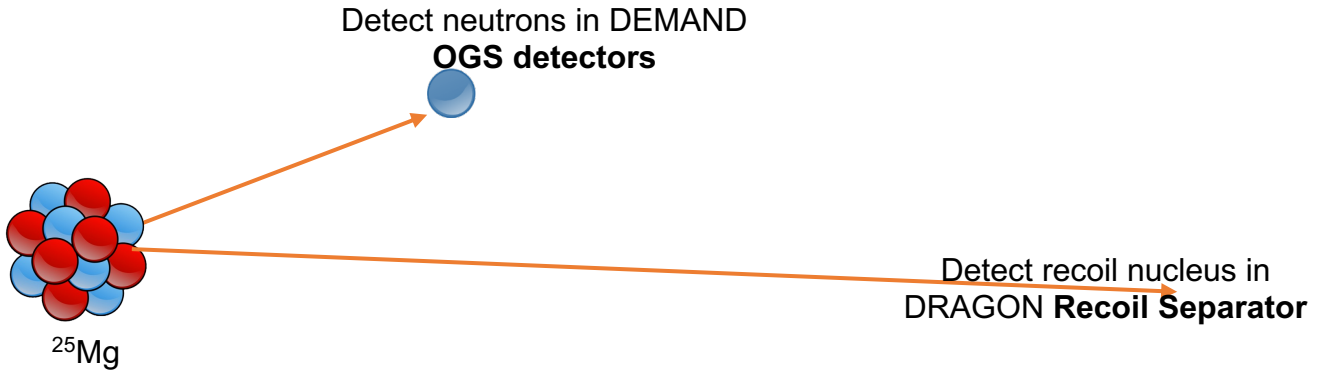

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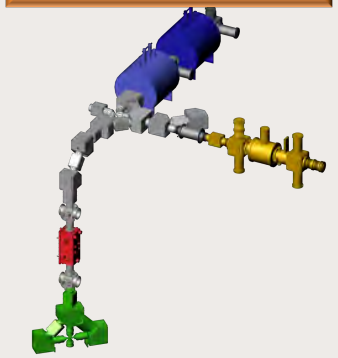

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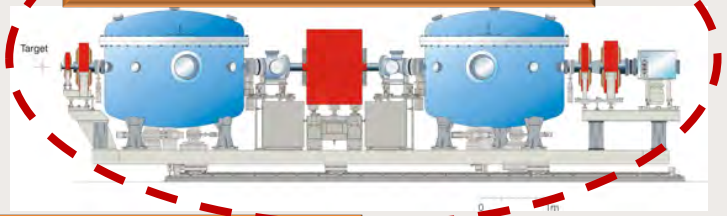

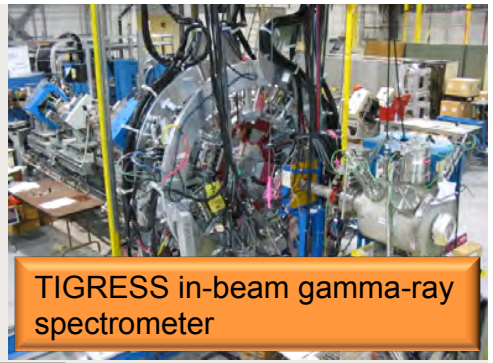

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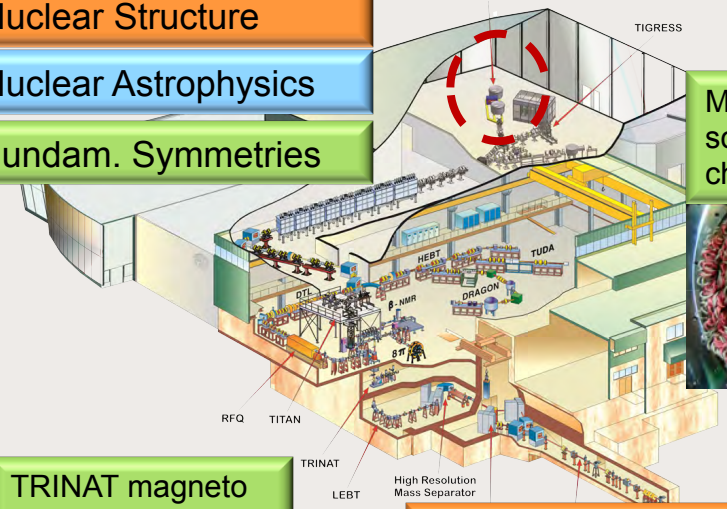

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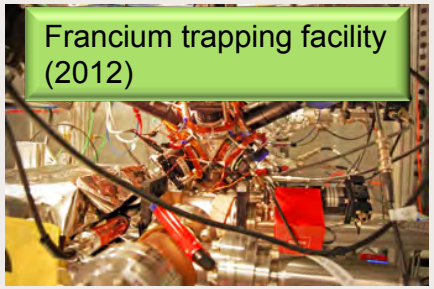

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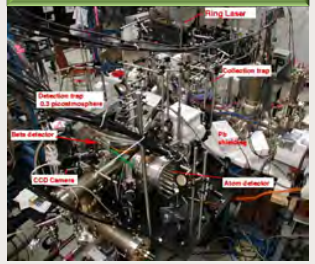

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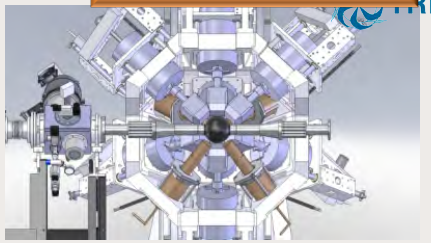

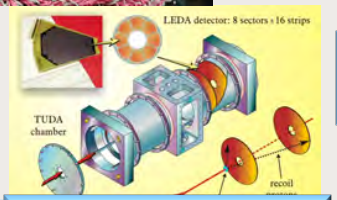

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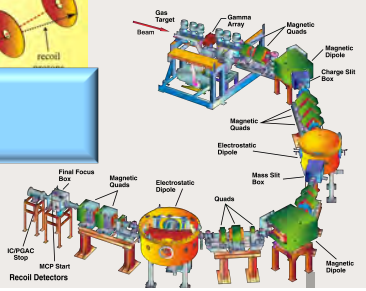
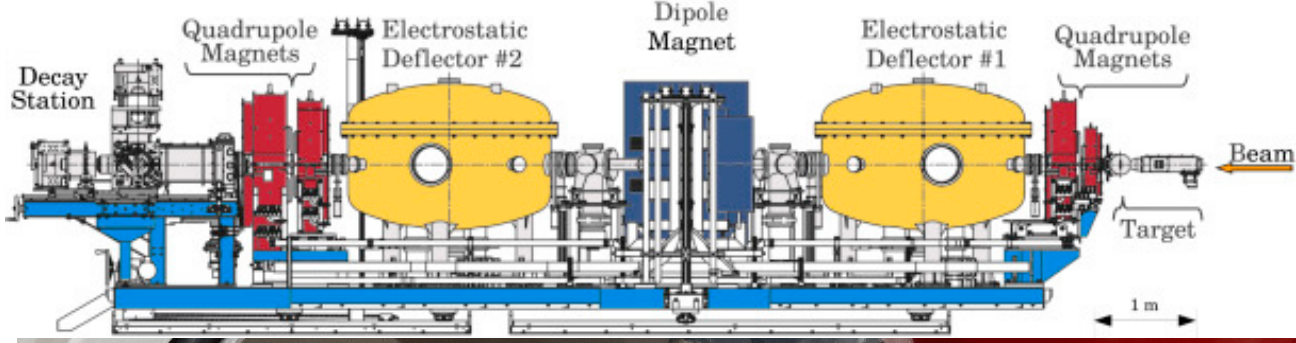
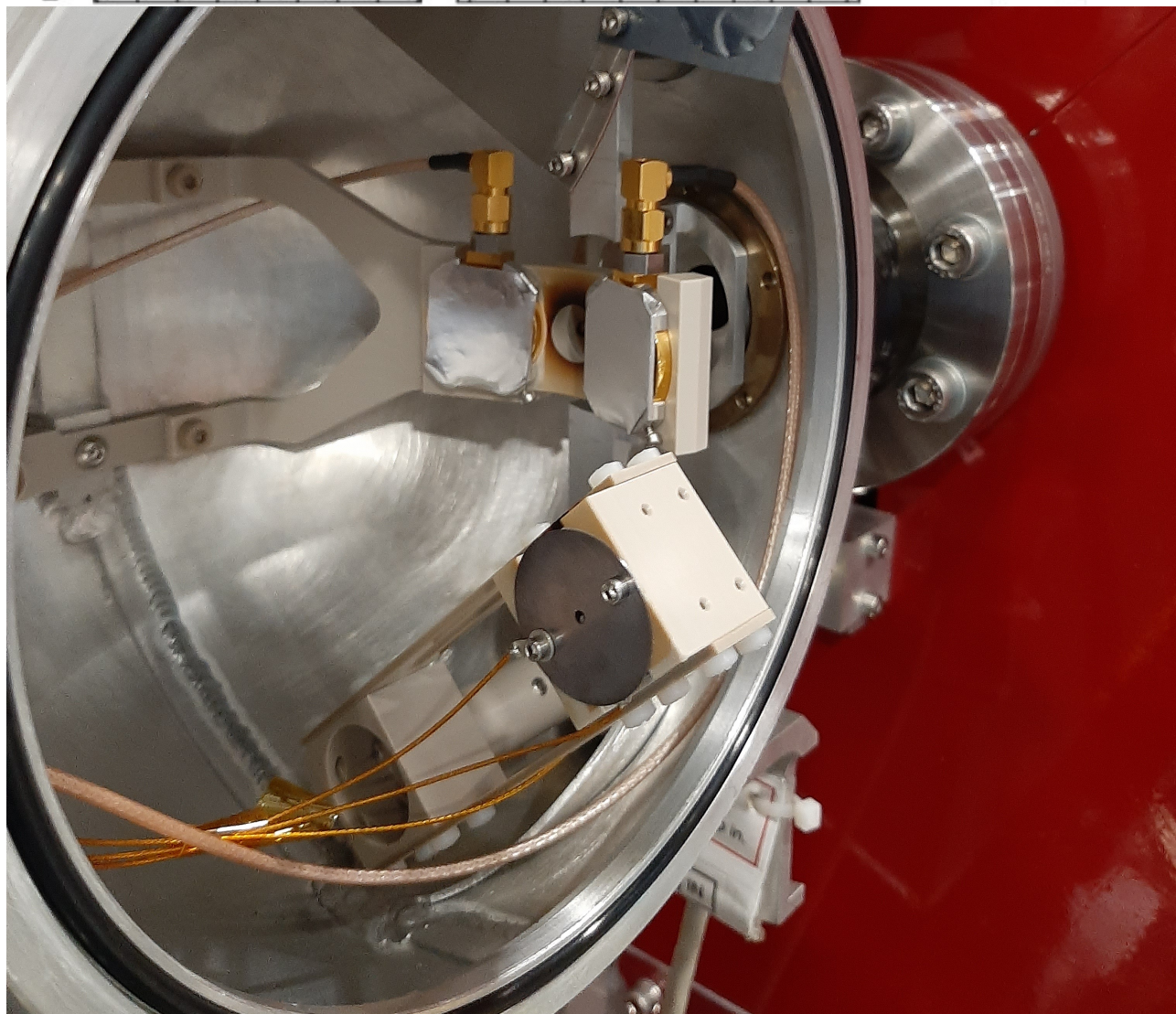


EMMA: S2037 - First cross-section measurement of the $^{94}Sr(\alpha,n)^{97}Zr$ reaction at relevant energies for the weak r-process





- EMMA (ElectroMagnetic Mass Analyser) in operation since 2017
- Measurement of the $^{94}Sr(\alpha,n)^{97}Zr$ cross section in inverse kinematics with a solid He target made by depositing a thin film of silicon and helium onto an aluminum foil
- → Important for astrophysical “weak r-process” occurring in core collapse supernovae (nucleosynthesis)
- γ rays detected in TIGRESS surrounding target in coincidence with ^{97}Zr recoils at EMMA focal plane
- After several failed attempts, this represents the first successful measurement of an (α,n) reaction induced by a radioactive ion beam

The BeEST Experiment

TRIUMF

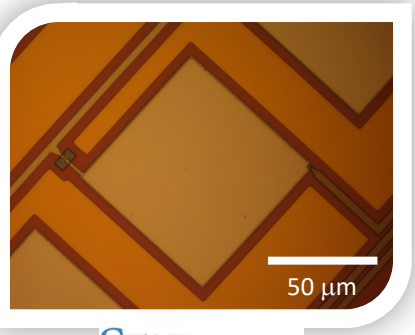
Rare-isotope implantation at TRIUMF-ISAC

THE BeEST

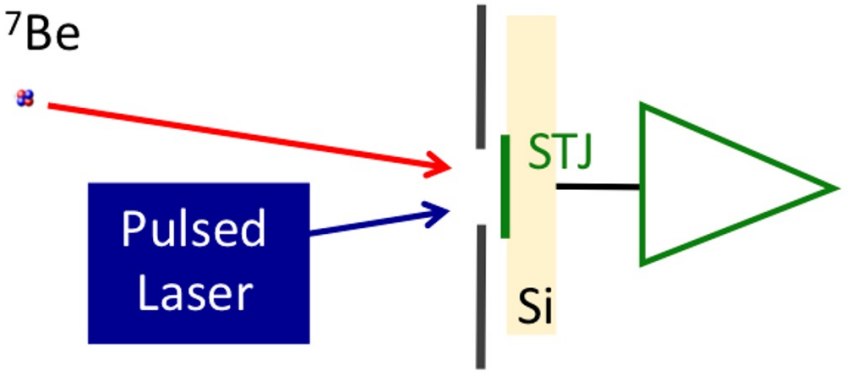
Beryllium Electron capture in Superconducting Tunnel junctions

K.G. Leach and S. Friedrich, arXiv:2112.02029 (2021)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS



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EMPIR EURAMET

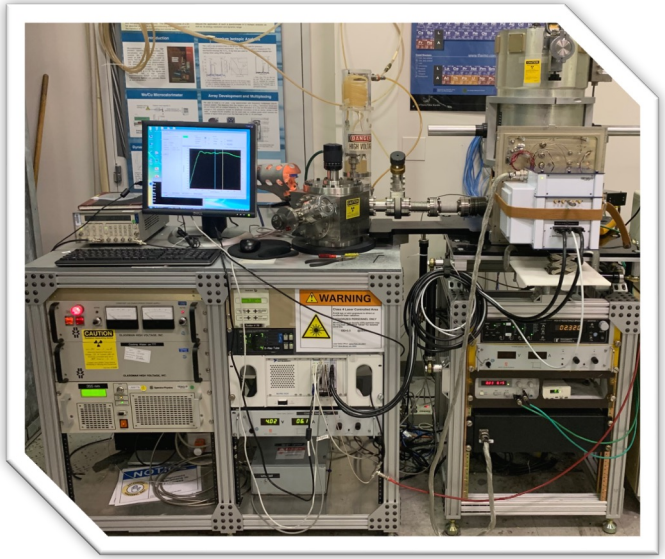
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

NNSA National Nuclear Security Administration

APS physics

GORDON AND BETTY MOORE FOUNDATION

High-precision *In-situ* calibration and characterization



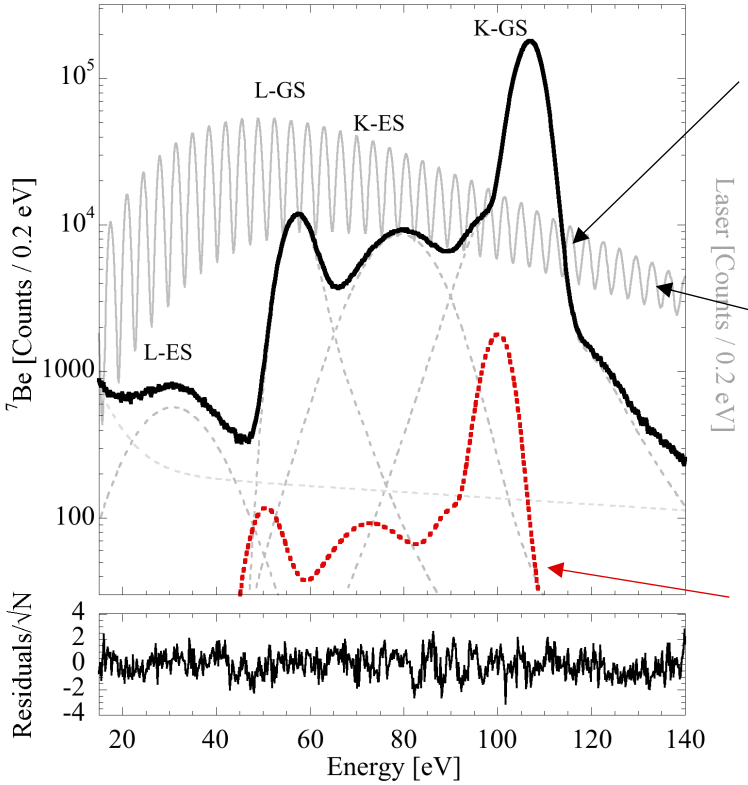
Lawrence Livermore National Laboratory

Cooling (<0.1 K) and measurement in ADR at LLNL

Courtesy of K. G. Leach

First Limits from BeEST Phase-II Data

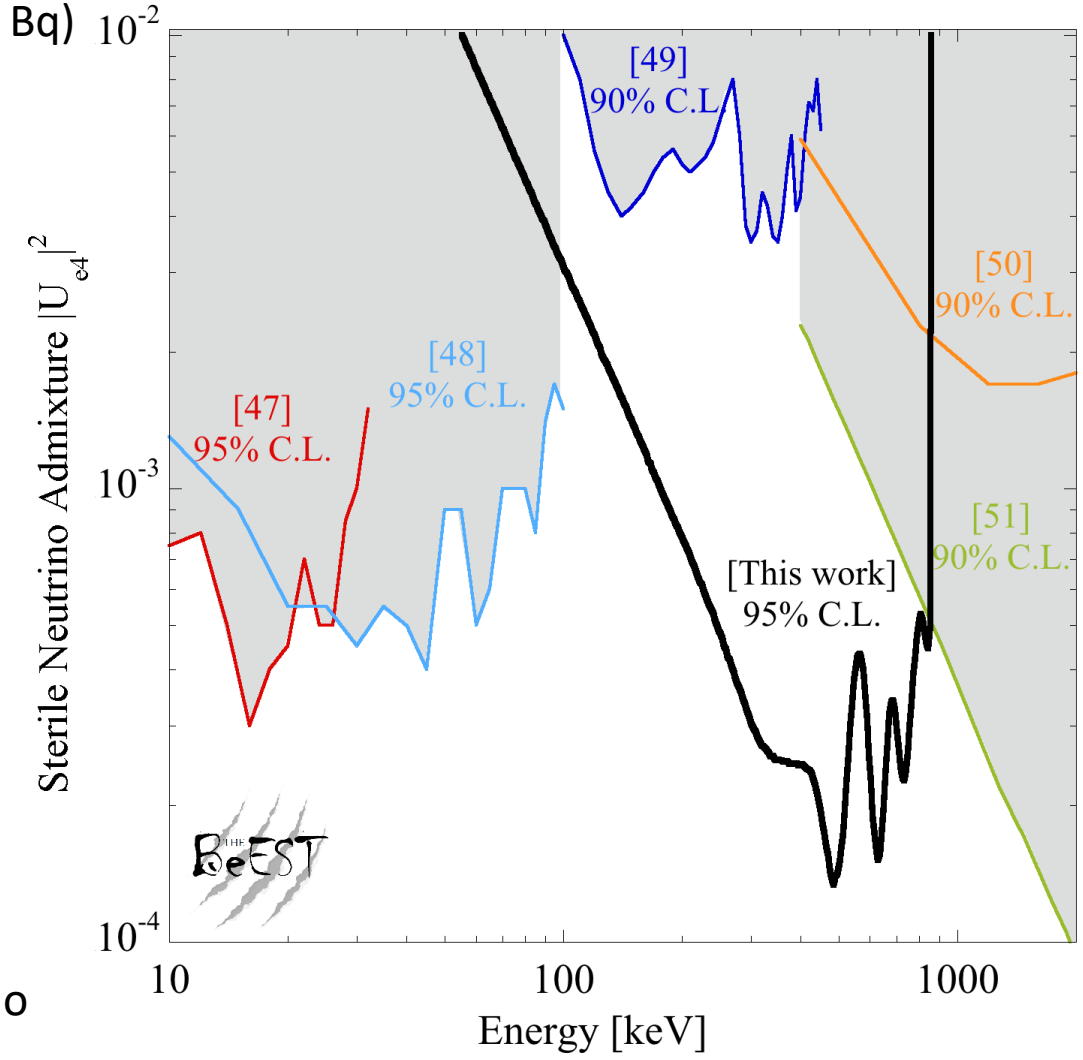
- Phase-II data from a single 138x138 μm² STJ counting at low rate (~10 Bq)



Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Simultaneously acquired laser calibration spectrum

Example of signal that would be generated by 300 keV neutrino with 1% mixing



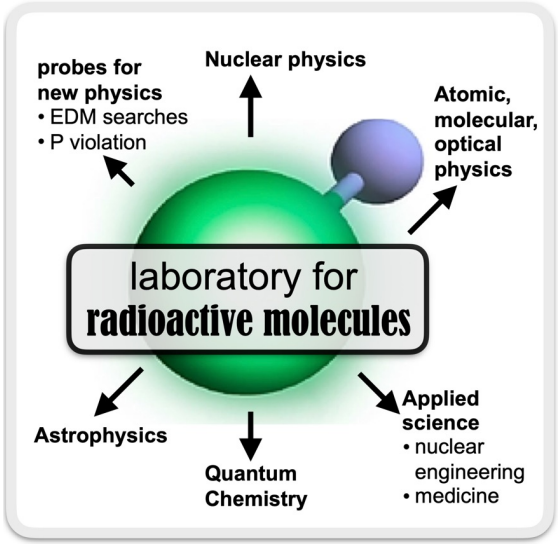
- Up to an order of magnitude improvement for limits on heavy neutrino admixtures to ν_e for masses of 100 – 850 keV

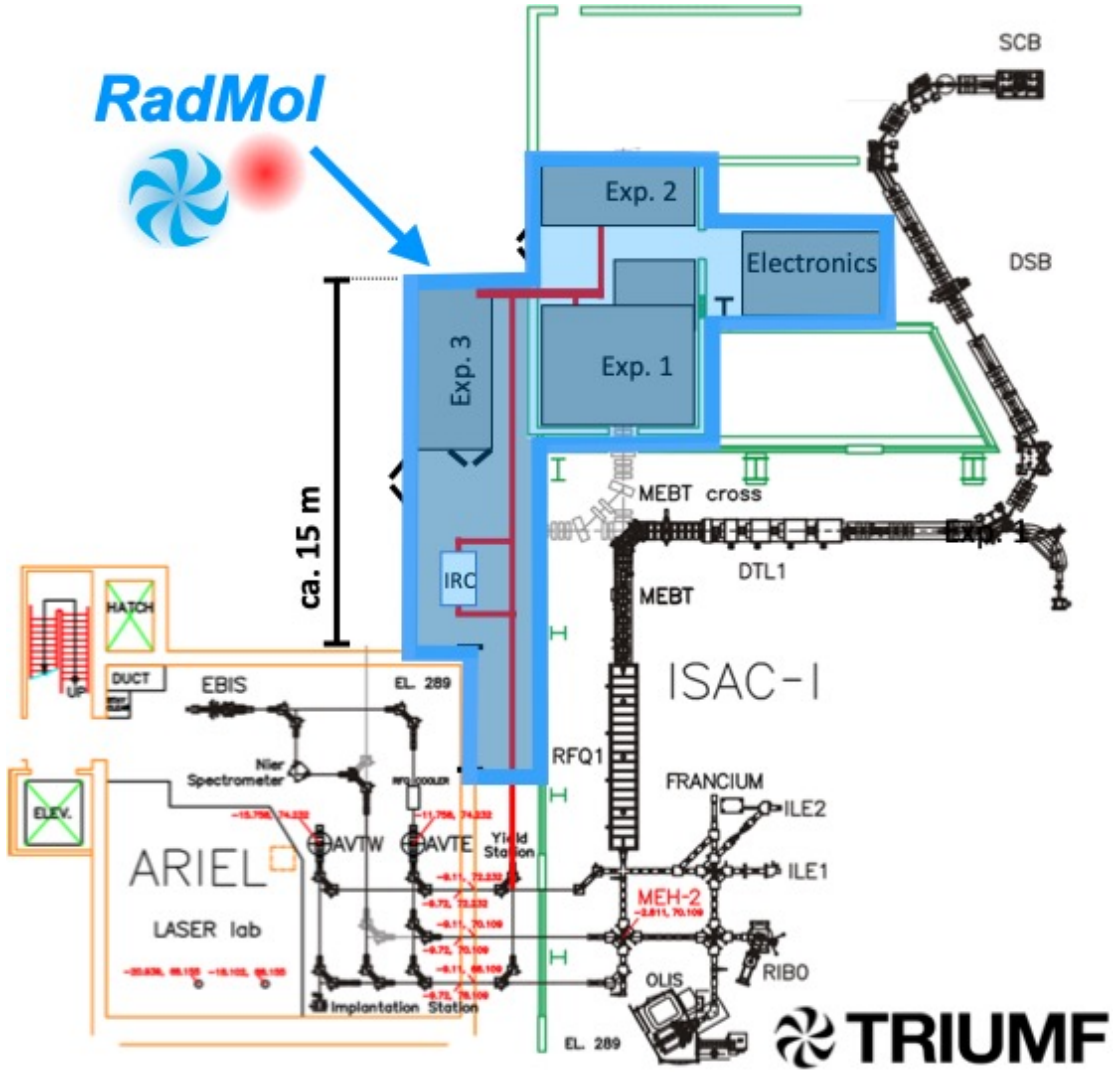
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

Courtesy of K. G. Leach

Future Radioactive Molecule (RadMol) Laboratory

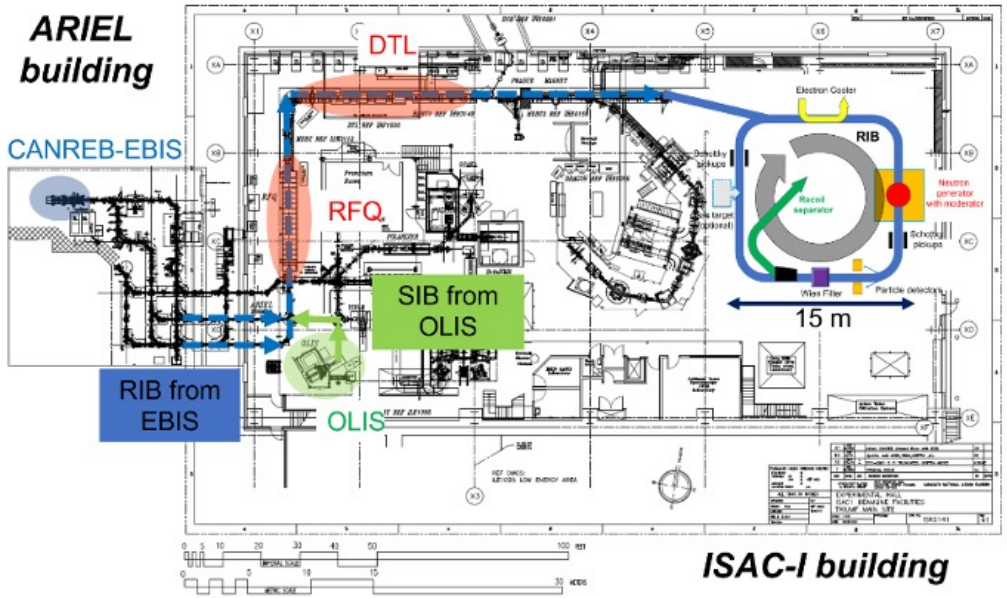
- Radioactive molecules as novel precision probes for fundamental physics
- Initial physics program:
  - Octuple-deformed nuclei incorporated into polar molecules ⇒ unmatched sensitivity for nuclear EDM
  - Access nuclear anapole moments via diatomic molecules
- Provision for expansions into other fields





Future TRIUMF Storage Ring (TRISR)

- TRISR – a storage ring for neutron capture on radioactive nuclei
  - Direct measurement in inverse kinematics
  - Coupled to ISAC radioactive beam facility
  - High-flux neutron generator – “neutron target” that intersects with orbiting ion beam
  - Nuclear astrophysics applications – r-process



Workshop series on progress in *ab initio* nuclear theory

- Annual international workshops at TRIUMF on Progress of *Ab Initio* Nuclear Theory
  - Workshop series started in 2011
  - The 11th edition held in last year & the 12th edition is now (Feb 27-March 1, 2024)

- The 11th Workshop on Progress in *Ab Initio* Nuclear Theory held at TRIUMF from Feb 28th to Mar 3rd, 2023
  - 46 participants (16 students), 37 international
  - Students presented posters introduced by jamboree talks
  - Included well-attended TRIUMF Colloquium on March 2nd by Chloe Hebborn (MSU/LLNL)

2018

2017

2015

TRIUMF

Thank you!
Merci!

Discovery, accelerated