TRIUMF

Welcome to TRIUMF

2nd Joint Canada-APCTP Meeting on Nuclear Theory

TRIUMF, Vancouver, Canada

August 8-12, 2022

Petr Navratil

TRIUMF Theory Department

Interim Director, Physical Sciences

Discovery, accelerated

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.

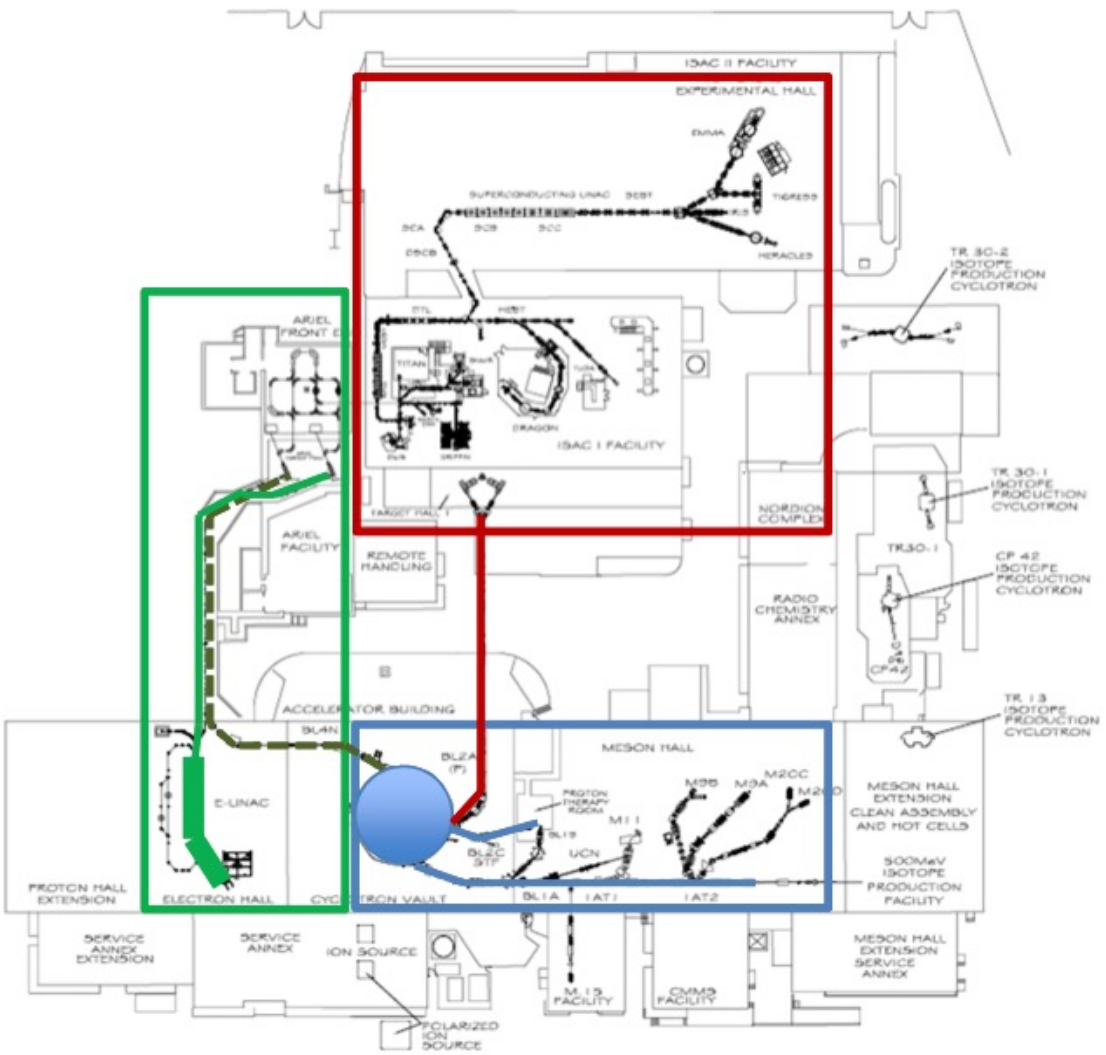
- We advance isotope science and technology, both fundamental and applied.
- We collaborate across communities and disciplines, from nuclear and particle physics to the life and material sciences.
- We discover and innovate, inspire and educate, creating knowledge and opportunity for all.

- 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



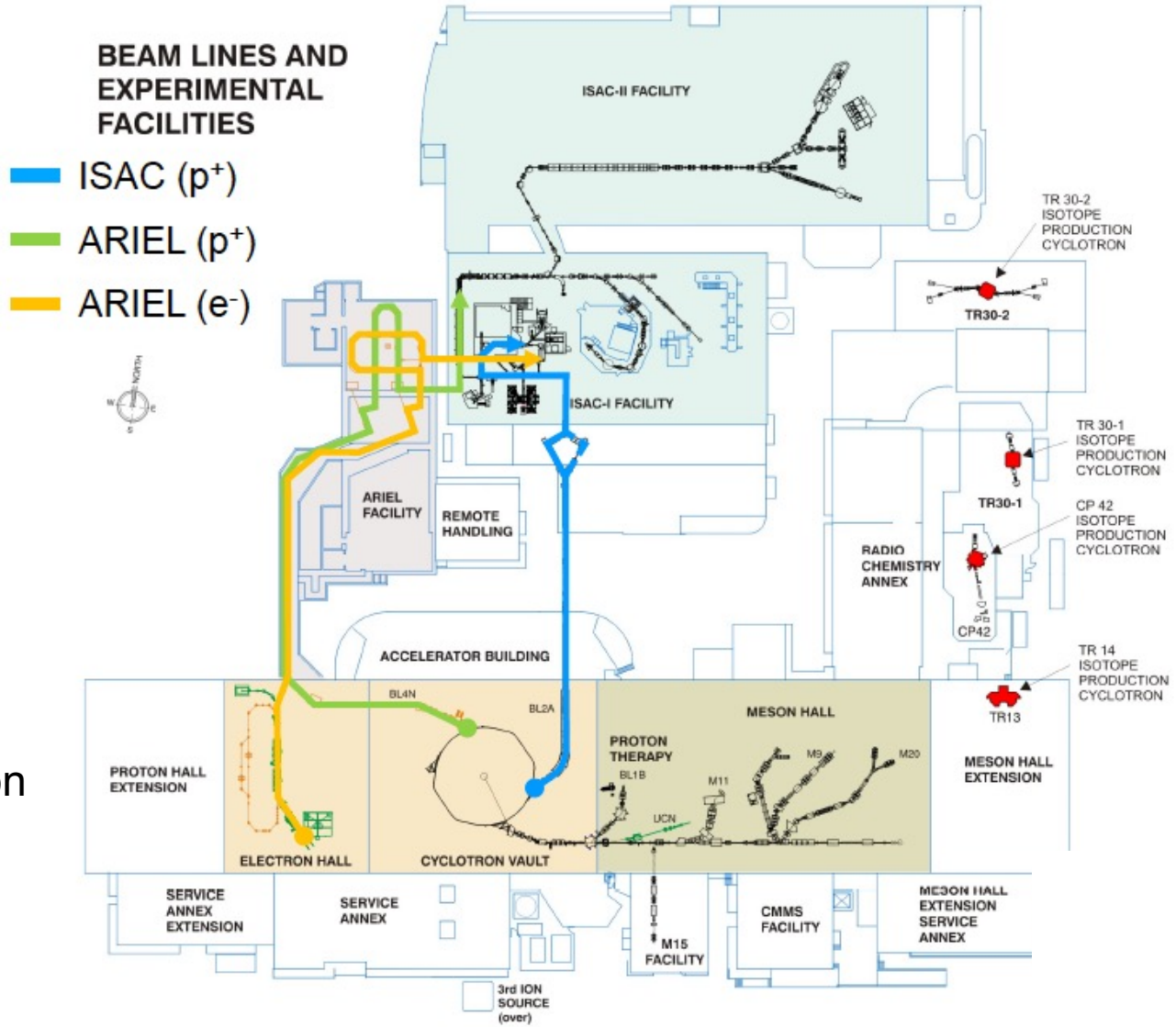
Advanced Rare Isotope Facility (ARIEL)

TRIUMF's flagship project

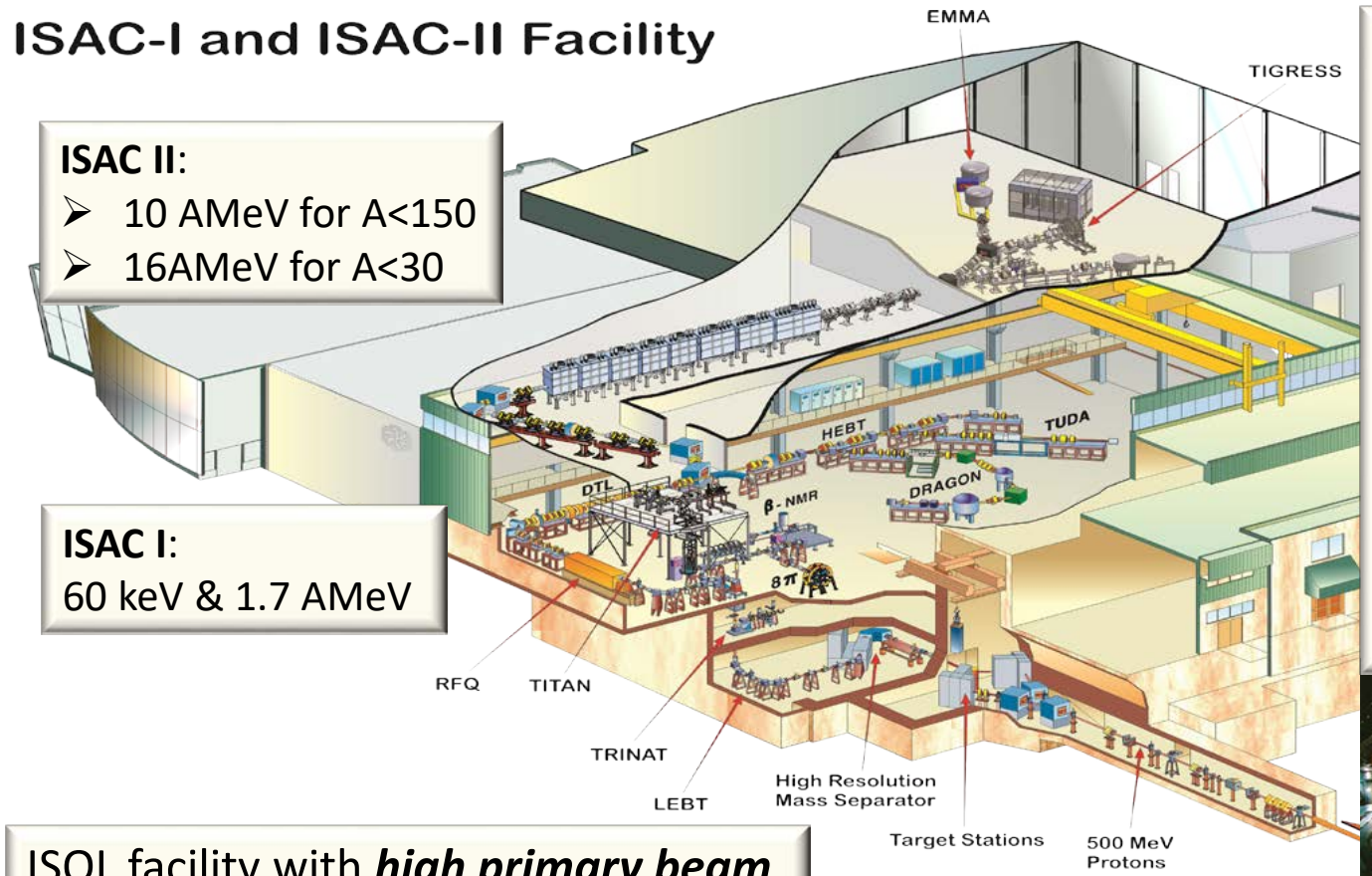
Substantially expands RIB capabilities:

- 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

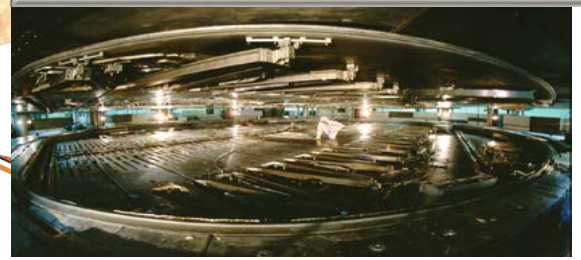


ISAC II:
- 10 AMeV for A<150
- 16AMeV for A<30

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)

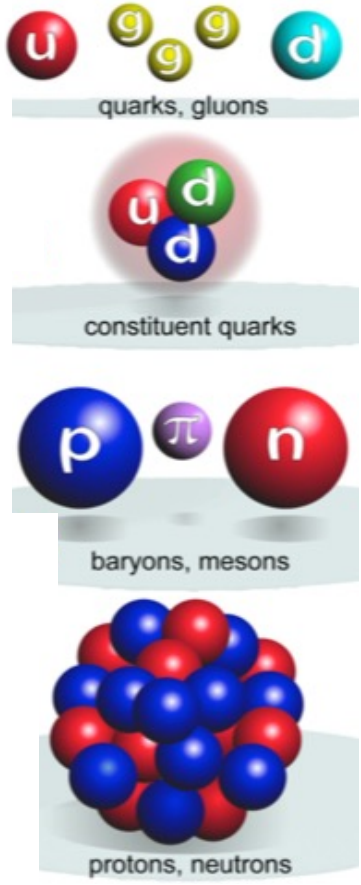
- Large-scale high-performance computation
  - Massively parallel codes
  - Summit@ORNL, Quartz@Livermore Computing, Cedar@Compute Canada

Quantum Chromodynamics (QCD)

Chiral Effective Field Theory (parameters fitted to NN data)

Current *ab anitio* nuclear theory

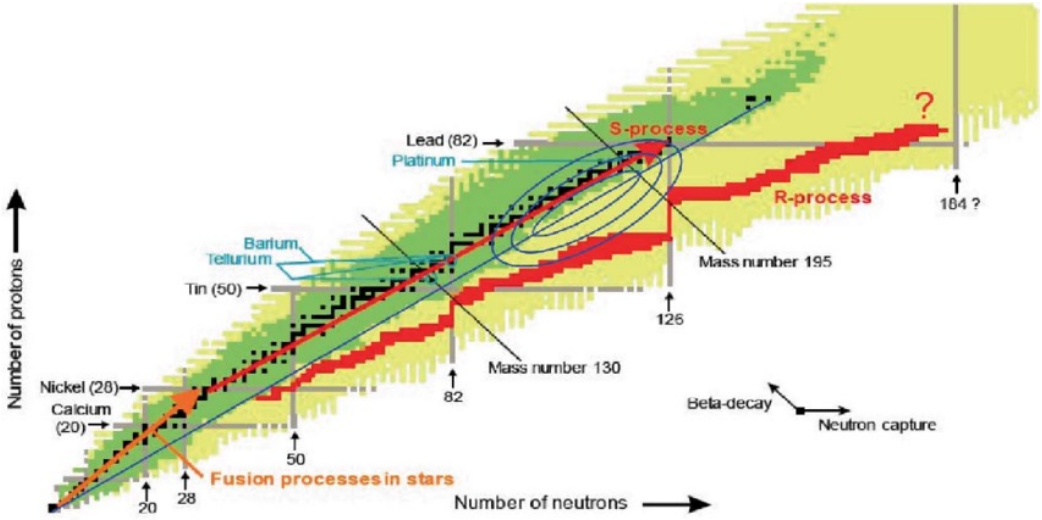
$$H\,\Psi^{(A)} = E\,\Psi^{(A)}$$

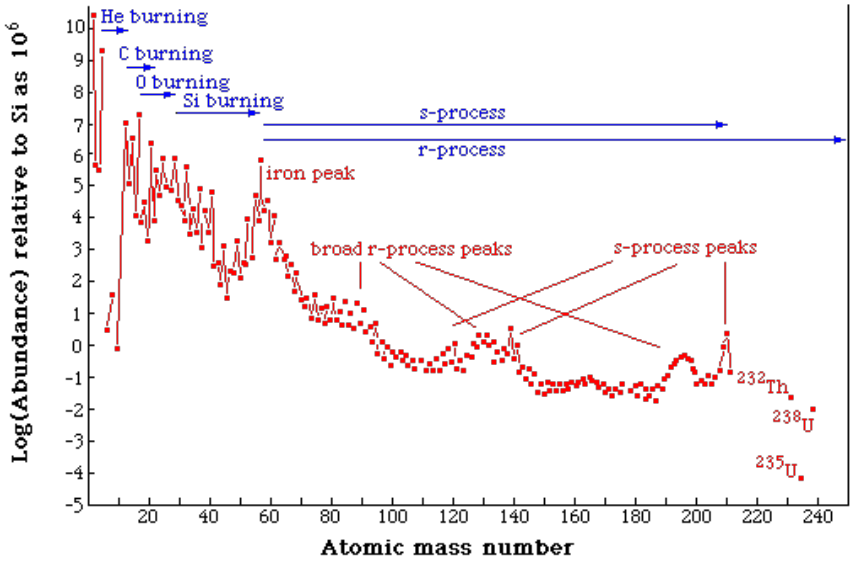


TRIUMF Theory

- Nuclear astrophysics
  - r-process nucleosynthesis
- Particle physics
  - Dark matter physics, collider phenomenology, neutrino physics, particle cosmology, hadronic physics

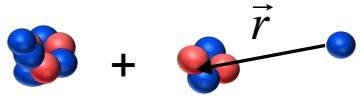
$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + i \bar{\Psi} \not{D} \Psi + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



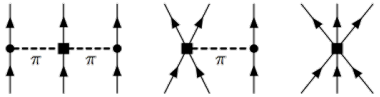


Ab initio nuclear theory at TRIUMF Theory Department

- Unified approach to nuclear structure and reactions for light nuclei: No-Core Shell Model with Continuum (NCSMC)

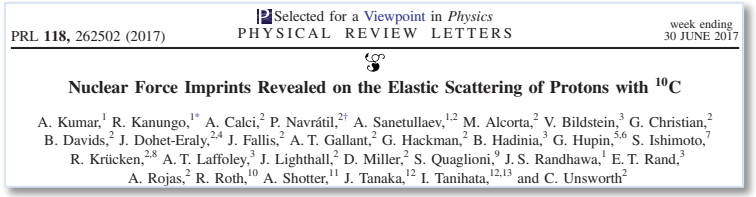


  - Applications to
    - Properties of exotic nuclei – prediction of near threshold *S*-wave resonance in ^{6}He+p → TUDA experiment
    - Nuclear reactions important for astrophysics - ^{7}Be(p,γ)^{8}B, ^{11}C(p,γ)^{12}N → DRAGON experiments
    - Tests of fundamental symmetries – CKM unitarity tests (superallowed β-decays), β-decay electron spectra, anapole moments, nuclear EDM
- Properties of chiral three-nucleon interaction



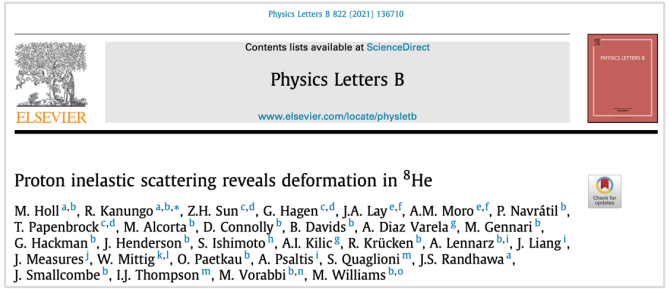
- Large-scale high-performance computation - massively parallel codes
  - Summit@ORNL, Quartz@Livermore Computing, Cedar & Niagara@Compute Canada
- **Synergy with ISAC RIB experiments**
- Petr Navratil + 2 PhD students + 1.5 postdocs (+ co-op students)

See talk by Peter Gysbers


Selected for a Viewpoint in *Physics*
PRL **118,** 262502 (2017) 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]


Physics Letters B 822 (2021) 136710

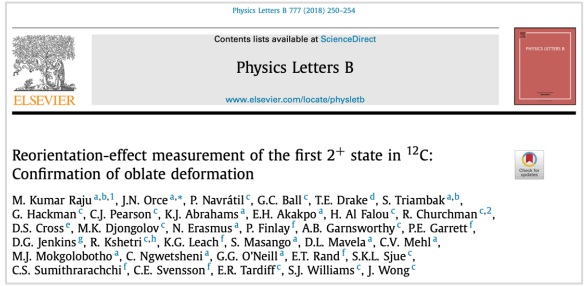
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Proton inelastic scattering reveals deformation in ^{8}He

M. Holl[a,b], R. Kanungo[a,b,*], Z.H. Sun[c,d], G. Hagen[c,d], J.A. Lay[e,f], A.M. Moro[e,f], P. Navrátil[b], T. Papenbrock[c,d], M. Alcorta[b], D. Connolly[b], B. Davids[b], A. Diaz Varela[g], M. Gennari[b], G. Hackman[b], J. Henderson[b], S. Ishimoto[h], A.I. Kilic[g], R. Krücken[h], A. Lennarz[b,i], J. Liang[i], J. Measures[j], W. Mittig[k,l], O. Paetkau[b], A. Psaltis[i], S. Quaglioni[m], J.S. Randhawa[a], J. Smallcombe[b], I.J. Thompson[m], M. Vorabbi[b,n], M. Williams[b,o]


Physics Letters B 777 (2018) 250–254

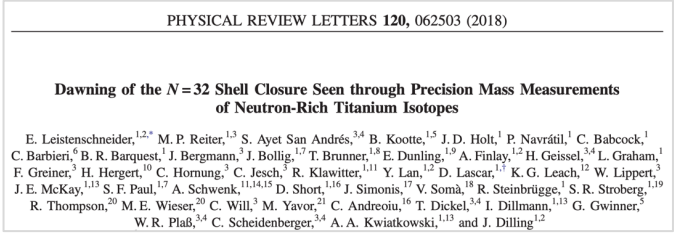
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Reorientation-effect measurement of the first 2^{+} state in ^{12}C: Confirmation of oblate deformation

M. Kumar Raju[a,b,1], J.N. Orce[a,*], P. Navrátil[c], G.C. Ball[c], T.E. Drake[d], S. Triambak[a,b], G. Hackman[c], C.J. Pearson[c], K.J. Abrahams[a], E.H. Akakpo[a], H. Al Falou[c], R. Churchman[c,2], D.S. Cross[c], M.K. Djongolov[c], N. Erasmus[a], P. Finlay[f], A.B. Garnsworthy[c], P.E. Garrett[f], D.G. Jenkins[g], R. Kshetri[c,h], K.G. Leach[f], S. Masango[a], D.L. Mavela[a], C.V. Mehl[a], M.J. Mokgolobotho[a], C. Ngwetsheni[a], G.G. O'Neill[a], E.T. Rand[f], S.K.L. Sjue[c], C.S. Sumithrarachchi[f], C.E. Svensson[f], E.R. Tardiff[c], S.J. Williams[c], J. Wong[c]


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,[1,7] 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]


PHYSICAL REVIEW C **103,** 035801 (2021)

Microscopic investigation of the ^{8}Li(n, γ)^{9}Li reaction

Callum McCracken*
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada and University of Waterloo, 200 University Avenue, Waterloo, Ontario N2L 3G1, Canada

Petr Navrátil† and Anna McCoy‡
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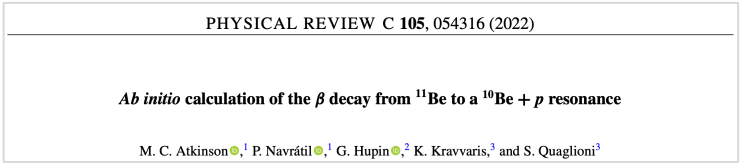
Sofia Quaglioni§
Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA

Guillaume Hupin‖
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

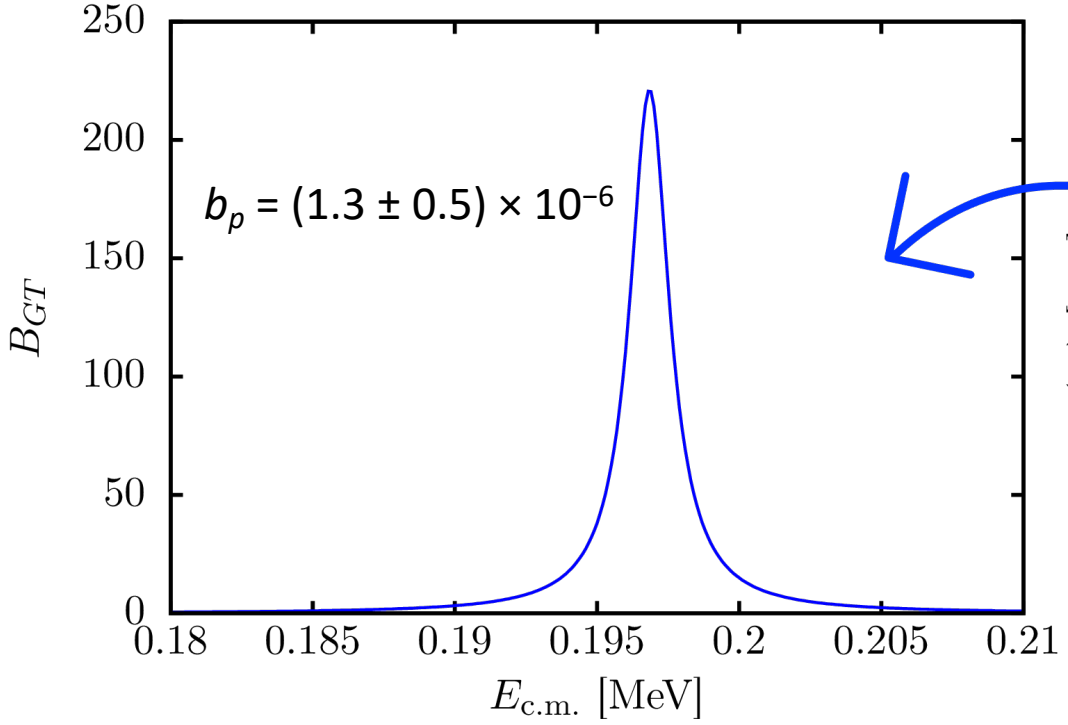

PHYSICAL REVIEW C **105,** 054316 (2022)

***Ab initio* calculation of the β decay from ^{11}Be to a ^{10}Be + p resonance**

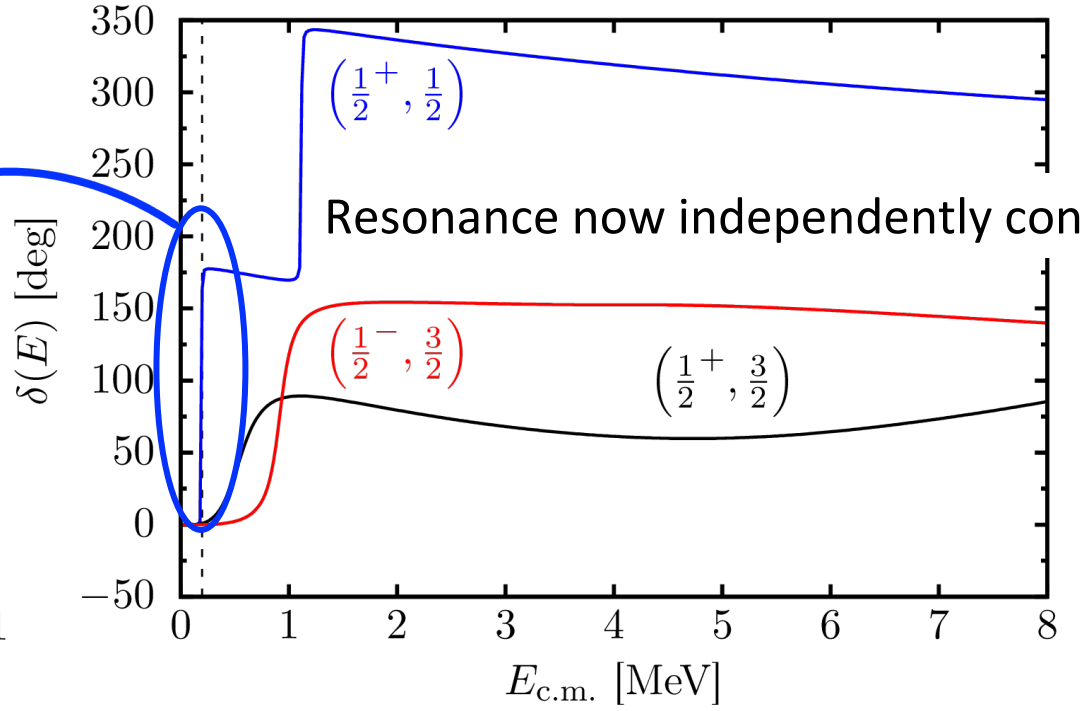
M. C. Atkinson,[1] P. Navrátil,[1] G. Hupin,[2] K. Kravvaris,[3] and S. Quaglioni[3]

NCSMC extended to describe exotic ^{11}Be βp emission, supports large branching ratio due to narrow ½$^+$ resonance (TRIUMF experiment by Ayyad *et al.*, Phys. Rev. Lett. 123, 082501 (2019))

^{11}Be → (^{10}Be+p) + β^- + $\bar{\nu}_e$ GT transition



p+^{10}Be Scattering Phase Shifts



Resonance now independently confirmed!

PHYSICAL REVIEW C **105**, 054316 (2022)

***Ab initio* calculation of the β decay from ^{11}Be to a ^{10}Be + p resonance**

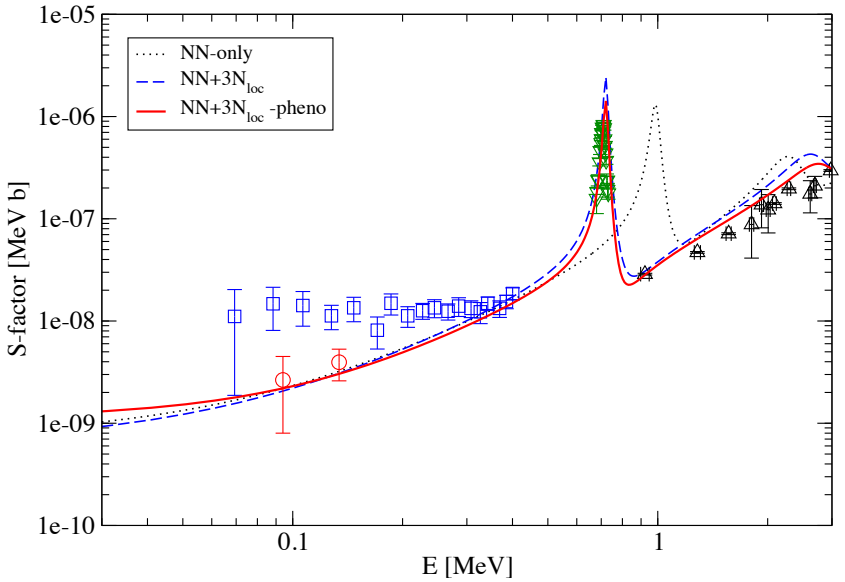
M. C. Atkinson,[1] P. Navrátil,[1] G. Hupin,[2] K. Kravvaris,[3] and S. Quaglioni[3]

Ab initio calculations of radiative capture reactions important for astrophysics

PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

***Ab Initio* Prediction of the ^{4}He$(d,\gamma)^6$Li Big Bang Radiative Capture**

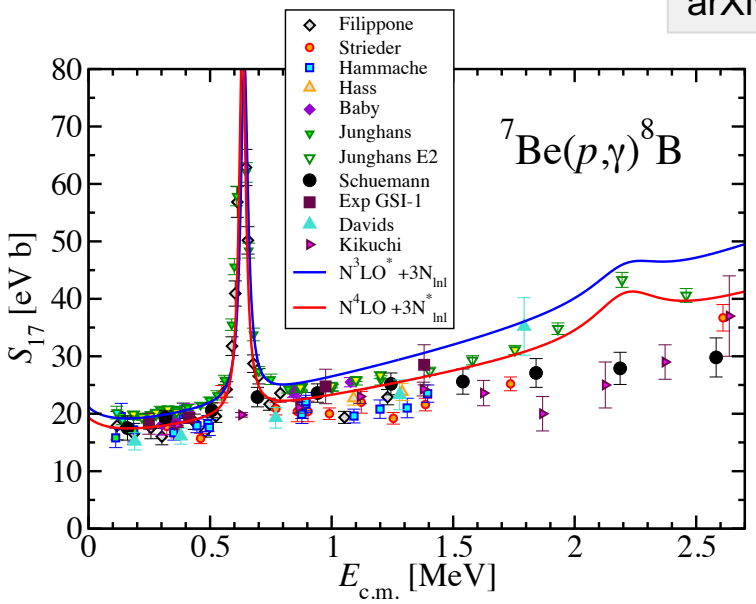
C. Hebborn,[1,2,*] G. Hupin,[3] K. Kravvaris,[2] S. Quaglioni,[2] P. Navrátil,[4] and P. Gysbers[4,5]



Ab initio prediction for the radiative capture of protons on ^{7}Be

K. Kravvaris,[1] P. Navrátil,[2] S. Quaglioni,[1] C. Hebborn,[3,1] and G. Hupin[4]

arXiv: 2202.11759



PHYSICAL REVIEW C **103**, 035801 (2021)

Microscopic investigation of the ^{8}Li$(n,\gamma)^9$Li reaction

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TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada and University of Waterloo, 200 University Avenue, Waterloo, Ontario N2L 3G1, Canada

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Sofia Quaglioni[§]
Lawrence Livermore National Laboratory, P.O. Box 808, L-414, Livermore, California 94551, USA

Guillaume Hupin[‖]
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

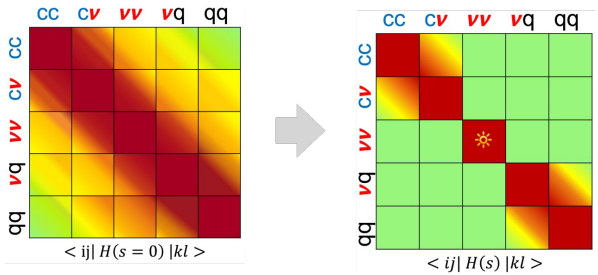
To be measured at TRISR?

Precision Mass Measurements of Neutron-Rich Scandium Isotopes Refine the Evolution of $N = 32$ and $N = 34$ Shell Closures

E. Leistenschneider, E. Dunling, G. Bollen, B. A. Brown, J. Dilling, A. Hamaker, J. D. Holt, A. Jacobs, A. A. Kwiatkowski, T. Miyagi, W. S. Porter, D. Puentes, M. Redshaw, M. P. Reiter, R. Ringle, R. Sandler, C. S. Sumithrarachchi, A. A. Valverde, and I. T. Yandow (The LEBIT Collaboration and the TITAN Collaboration)
Phys. Rev. Lett. **126**, 042501 – Published 26 January 2021

Ab initio nuclear theory at TRIUMF Theory Department

- Novel approach to calculate **essentially all open-shell medium/heavy mass nuclei**: Valence-Space in-medium similarity renormalization group (VS-IMSRG)
  - Applications to
    - Exotic nuclei: nuclear driplines, continuum, shell structure, r-process
    - BSM Physics: $0\nu\beta\beta$ decay, dark matter detection, neutrino scattering
    - Fundamental symmetries: CKM unitarity, anapole moments, EDM
- Properties to constrain nuclear EOS: neutron skin and dipole polarizability in ^{208}Pb
- Extension to atomic systems in progress, e.g., for laser spectroscopy
- Large-scale high-performance computation: Cedar@Compute Canada
- **Synergy with ISAC and worldwide RIB experiments + Art McDonald Institute/SNOLAB**
- Jason D. Holt + 2 PhD students + 2 MSc student + 2 postdocs (+ many co-op students)



PHYSICAL REVIEW LETTERS **120,** 062503 (2018)

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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]

Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

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

J. Henderson[a,b,*], G. Hackman[a], P. Ruotsalainen[c], S.R. Stroberg[a,1], K.D. Launey[d], J.D. Holt[a], F.A. Ali[e,f], N. Bernier[a,g], M.A. Bentley[b], M. Bowry[a], R. Caballero-Folch[a], L.J. Evitts[a,1], R. Frederick[a], A.B. Garnsworthy[a], P.E. Garrett[f], B. Jigmeddorj[f], A.I. Kilic[f], J. Lassen[a], J. Measures[a,1], D. Muecher[f], B. Olaizola[a,f], E. O'Sullivan[a], O. Paetkau[a], J. Park[a,g,2], J. Smallcombe[a], C.E. Svensson[f], R. Wadsworth[h], C.Y. Wu[b]

Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

Identification of significant $E0$ strength in the $2_2^+ \rightarrow 2_1^+$ transitions of ^{58,60,62}Ni

L.J. Evitts[a,b], A.B. Garnsworthy[a,*], T. Kibédi[c], J. Smallcombe[a], M.W. Reed[c], B.A. Brown[e,f], A.E. Stuchbery[c], G.J. Lane[c], T.K. Eriksen[c], A. Akber[c], B. Alshahrani[c,d], M. de Vries[c], M.S.M. Gerathy[c], J.D. Holt[a], B.Q. Lee[c,1], B.P. McCormick[c], A.J. Mitchell[c], M. Moukaddam[a,2], S. Mukhopadhyay[g], N. Palalani[c], T. Palazzo[c], E.E. Peters[g], A.P.D. Ramirez[g], S.R. Stroberg[a,3], T. Tornyi[c], S.W. Yates[g]

Featured in Physics Editors' Suggestion

Ab Initio Limits of Atomic Nuclei

S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis
Phys. Rev. Lett. **126**, 022501 – Published 12 January 2021

Physics See synopsis: Predicting the Limits of Atomic Nuclei

Ab Initio Structure Factors for Spin-Dependent Dark Matter Direct Detection

B. S. Hu, J. Padua-Argüelles, S. Leutheusser, T. Miyagi, S. R. Stroberg, and J. D. Holt
Phys. Rev. Lett. **128**, 072502 – Published 17 February 2022

Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for ^{48}Ca, ^{76}Ge, and ^{82}Se

A. Belley, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt
Phys. Rev. Lett. **126**, 042502 – Published 29 January 2021

See talks by Baishan Hu, Antoine Belley

Ab initio nuclear theory at TRIUMF Theory Department

- Novel approach to calculate **essentially all open-shell medium/heavy mass nuclei**: Valence-Space in-medium similarity renormalization group (VS-IMSRG)
  - Applications to
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ARTICLE

https://doi.org/10.1038/s41586-019-1155-x

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

R. Taniuchi[1,2], C. Santamaria[2,3], P. Doornenbal[2*], A. Obertelli[2,3,4], K. Yoneda[2], G. Authelet[3], H. Baba[2], D. Calvet[3], F. Château[3], A. Corsi[3], A. Delbart[3], J.-M. Gheller[3], A. Gillibert[3], J. D. Holt[5], T. Isobe[2], V. Lapoux[3], M. Matsushita[6], J. Menéndez[6], S. Momiyama[1,2], T. Motobayashi[2], M. Niikura[1], F. Nowacki[7], K. Ogata[8,9], H. Otsu[2], T. Otsuka[1,2,6], C. Péron[3], S. Péru[10], A. Peyaud[3], E. C. Pollacco[3], A. Poves[11], J.-Y. Roussé[3], H. Sakurai[1,2], A. Schwenk[4,12,13], Y. Shiga[2,14], J. Simonis[4,12,15], S. R. Stroberg[5,16], S. Takeuchi[2], Y. Tsunoda[6], T. Uesaka[2], H. Wang[2], F. Browne[17], L. X. Chung[18], Z. Dombradi[19], S. Franchoo[20], F. Giacoppo[21], A. Gottardo[20], K. Hadyńska-Klęk[21], Z. Korkulu[19], S. Koyama[1,2], Y. Kubota[2,6], J. Lee[22], M. Lettmann[4], C. Louchart[4], R. Lozeva[7,23], K. Matsui[1,2], T. Miyazaki[1,2], S. Nishimura[2], L. Olivier[20], S. Ota[6], Z. Patel[24], E. Şahin[21], C. Shand[24], P.-A. Söderström[2], I. Stefan[20], D. Steppenbeck[6], T. Sumikama[25], D. Suzuki[20], Z. Vajta[19], V. Werner[4], J. Wu[2,26] & Z. Y. Xu[22]

12

nature physics LETTERS
https://doi.org/10.1038/s41567-021-01326-9
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Mass measurements of $^{99-101}$In challenge ab initio nuclear theory of the nuclide ^{100}Sn

M. Mougeot[1,2], D. Atanasov[2], J. Karthein[1,2,17], R. N. Wolf[3], P. Ascher[4], K. Blaum[1], K. Chrysalidis[2], G. Hagen[5,6], J. D. Holt[7,8], W. J. Huang[1,18], G. R. Jansen[9], I. Kulikov[10], Yu. A. Litvinov[10], D. Lunney[11], V. Manea[2,11], T. Miyagi[7], T. Papenbrock[5,6], L. Schweikhard[12], A. Schwenk[1,13,14], T. Steinsberger[1], S. R. Stroberg[15], Z. H. Sun[5,6], A. Welker[2], F. Wienholtz[2,12,13], S. G. Wilkins[2] and K. Zuber[16]

Article

Nuclear moments of indium isotopes reveal abrupt change at magic number 82

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Received: 10 June 2021
Accepted: 28 April 2022
Published online: 13 July 2022
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A. R. Vernon[1,2,3], R. F. Garcia Ruiz[2,4], T. Miyagi[5], C. L. Binnersley[1], J. Billowes[1], M. L. Bissell[1], J. Bonnard[6], T. E. Cocolios[3], J. Dobaczewski[6,7], G. J. Farooq-Smith[3], K. T. Flanagan[1,8], G. Georgiev[9], W. Gins[3,10], R. P. de Groote[3,10], R. Heinke[4,11], J. D. Holt[5,12], J. Hustings[3], Á. Koszorús[3], D. Leimbach[11,13,14], K. M. Lynch[4], G. Neyens[3,4], S. R. Stroberg[15], S. G. Wilkins[1,2], X. F. Yang[3,16] & D. T. Yordanov[4,9]

LETTERS
https://doi.org/10.1038/s41567-020-0868-y
nature physics
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Measurement and microscopic description of odd–even staggering of charge radii of exotic copper isotopes

R. P. de Groote[1,2], J. Billowes[3], C. L. Binnersley[3], M. L. Bissell[3], T. E. Cocolios[1], T. Day Goodacre[4,5], G. J. Farooq-Smith[1], D. V. Fedorov[6], K. T. Flanagan[3], S. Franchoo[7], R. F. Garcia Ruiz[3,8,9], W. Gins[1,2], J. D. Holt[5,10], Á. Koszorús[1], K. M. Lynch[9], T. Miyagi[5], W. Nazarewicz[11], G. Neyens[1,9], P.-G. Reinhard[12], S. Rothe[3,4], H. H. Stroke[13], A. R. Vernon[1,3], K. D. A. Wendt[14], S. G. Wilkins[3,4], Z. Y. Xu[1] and X. F. Yang[1,15]

Featured in Physics Editors' Suggestion

Ab Initio Limits of Atomic Nuclei

S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis
Phys. Rev. Lett. **126**, 022501 – Published 12 January 2021

Physics See synopsis: Predicting the Limits of Atomic Nuclei

Ab Initio Structure Factors for Spin-Dependent Dark Matter Direct Detection

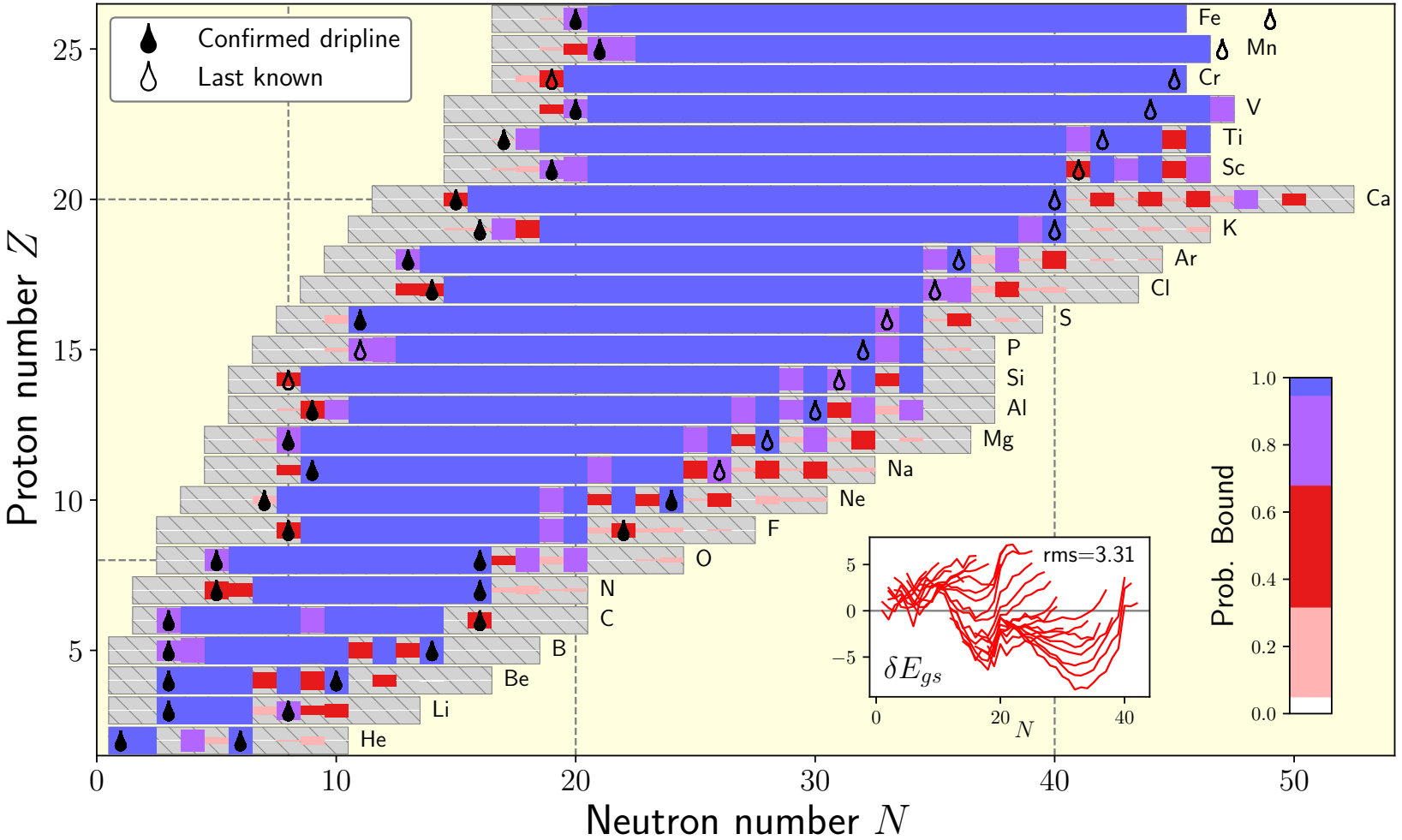
B. S. Hu, J. Padua-Argüelles, S. Leutheusser, T. Miyagi, S. R. Stroberg, and J. D. Holt
Phys. Rev. Lett. **128**, 072502 – Published 17 February 2022

Ab Initio Neutrinoless Double-Beta Decay Matrix Elements for ^{48}Ca, ^{76}Ge, and ^{82}Se

A. Belley, C. G. Payne, S. R. Stroberg, T. Miyagi, and J. D. Holt
Phys. Rev. Lett. **126**, 042502 – Published 29 January 2021

Dripline Predictions to Fe Isotopes

First predictions of proton and neutron driplines from first principles



From **few body** data only:

$$\mathcal{P}_{1n} = \frac{1}{\sqrt{2\pi}\sigma_{1n}} \int_0^\infty \exp \frac{(x - S_n^{th.corr})^2}{2\sigma_{1n}^2} dx$$

$$\mathcal{P}_{\text{bound}} = (\mathcal{P}_{1n}\mathcal{P}_{2n} + \xi_{1n,2n})(\mathcal{P}_{1p}\mathcal{P}_{2p} + \xi_{1p,2p})$$

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S. R. Stroberg, J. D. Holt, A. Schwenk, and J. Simonis
Phys. Rev. Lett. **126**, 022501 – Published 12 January 2021

Physics See synopsis: Predicting the Limits of Atomic Nuclei

Known drip lines largely predicted within uncertainties (artifacts at shell closures)

Provide ab initio predictions for neutron-rich region

Nuclear Astrophysics Theory

- **Research program focuses on the origin of heavy elements with an emphasis on the impact of unknown nuclear physics on observables**

PHYSICAL REVIEW C **105**, L052802 (2022)

Letter

Searching for the origin of the rare-earth peak with precision mass measurements across Ce–Eu isotopic chains

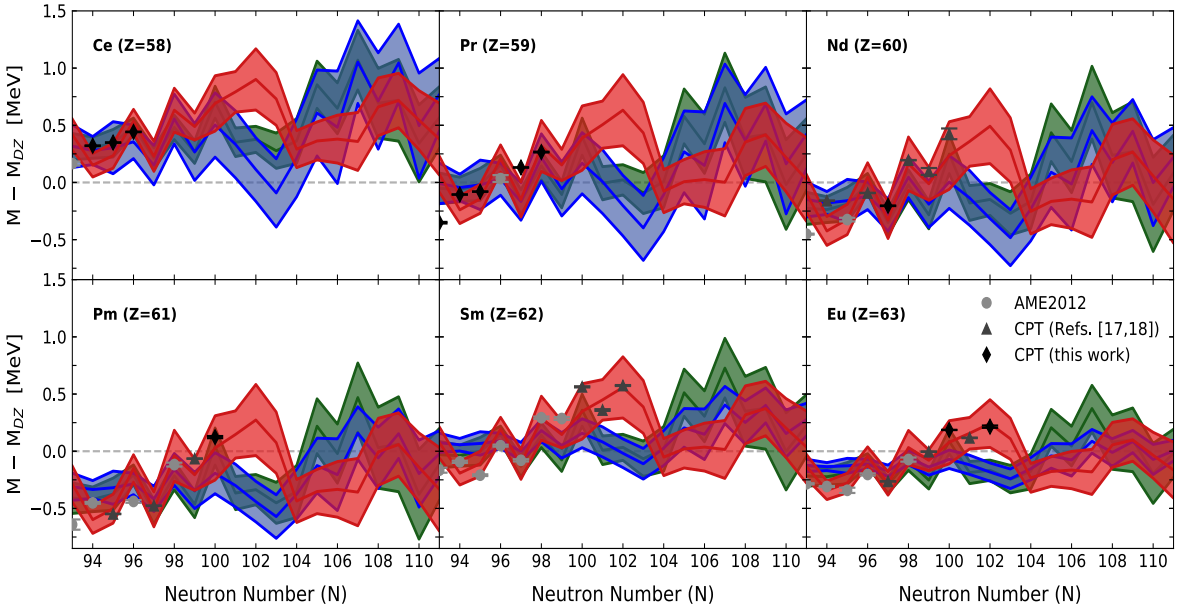
R. Orford,[1,2,3,*] N. Vassh,[4,†] J. A. Clark,[2,5] G. C. McLaughlin,[6] M. R. Mumpower,[7] D. Ray,[2,5] G. Savard,[2,8] R. Surman,[4] F. Buchinger,[1] D. P. Burdette,[2,4] M. T. Burkey,[2,8,‡] D. A. Gorelov,[2,5] J. W. Klimes,[2,§] W. S. Porter,[2,∥] K. S. Sharma,[5] A. A. Valverde,[2,5] L. Varriano,[2,8] and X. L. Yan[2,9]

[1]*Department of Physics, McGill University, Montréal, Québec H3A 2T8, Canada*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkleley, California 94720, USA*
[4]*Department of Physics, University of Notre Dame, Notre Dame, Indiana 46556, USA*
[5]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*
[6]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[7]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[8]*Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*
[9]*Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China*

(Received 28 September 2021; accepted 29 March 2022; published 18 May 2022)

A nuclear mass survey of rare-earth isotopes has been conducted with the Canadian Penning Trap mass spectrometer using the most neutron-rich nuclei thus far extracted from the CARIBU facility. We present a collection of 12 nuclear masses determined with a precision of $\leqslant 10$ keV/c^2 for $Z = 58$–63 nuclei near $N = 100$. Independently, a detailed study exploring the role of nuclear masses in the formation of the r-process rare-earth abundance peak has been performed. Employing a Markov chain Monte Carlo (MCMC) technique, mass predictions of lanthanide isotopes have been made which uniquely reproduce the observed solar abundances near $A = 164$ under three distinct astrophysical outflow conditions. We demonstrate that the mass surface trends thus far mapped out by our measurements are most consistent with MCMC mass predictions given an r process that forms the rare-earth peak during an extended $(n, \gamma) \rightleftarrows (\gamma, n)$ equilibrium.

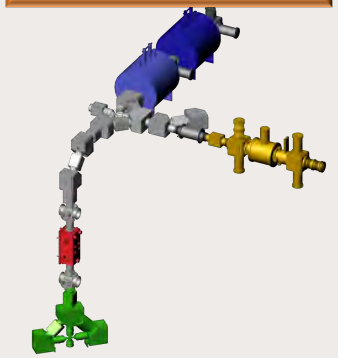
DOI: 10.1103/PhysRevC.105.L052802



*Statistical methods work motivated measurements which pushed to previously unknown neutron-rich lanthanide masses across several isotopic chains

Leading edge ISAC experiments

TITAN Penning Trap facility



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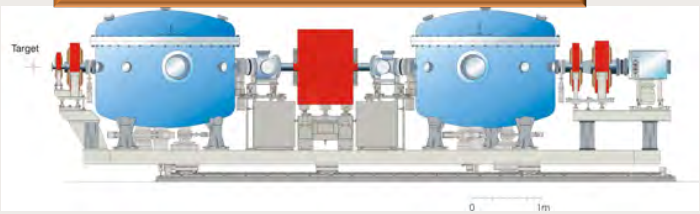
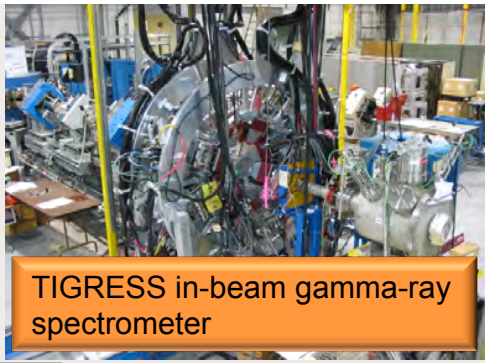


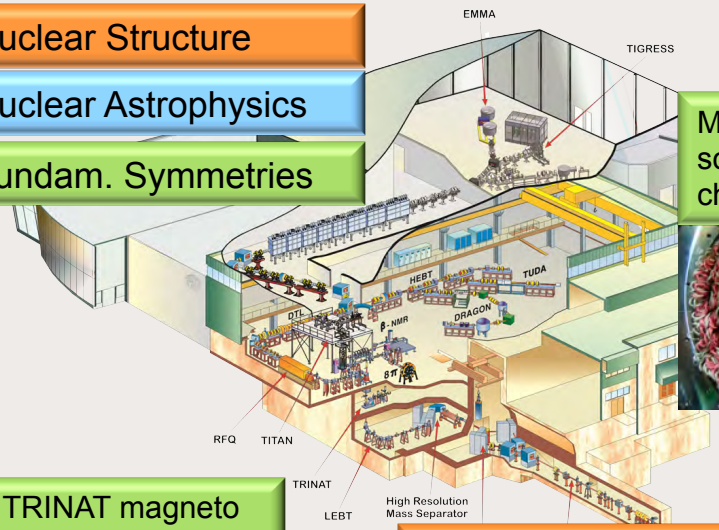


TIGRESS in-beam gamma-ray spectrometer

Nuclear Structure

Nuclear Astrophysics

Fundam. Symmetries



MTV Mott scattering drift chamber

IRIS solid hydrogen reaction set-up (2012)

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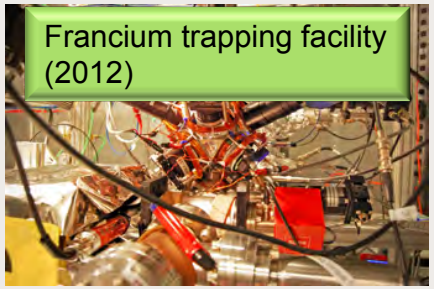
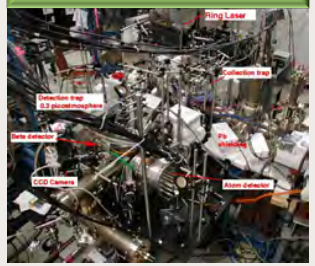
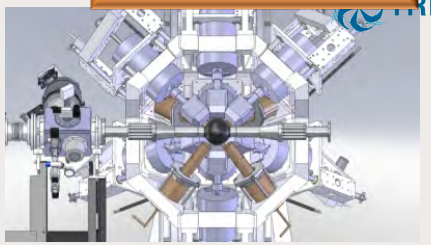
Francium trapping facility (2012)

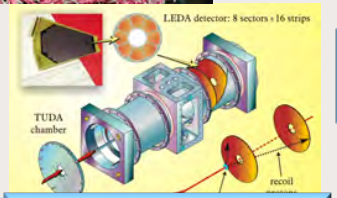


TRINAT magneto optical trap



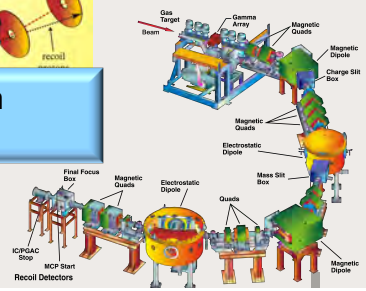
GRIFFIN gamma-ray decay spectrometer



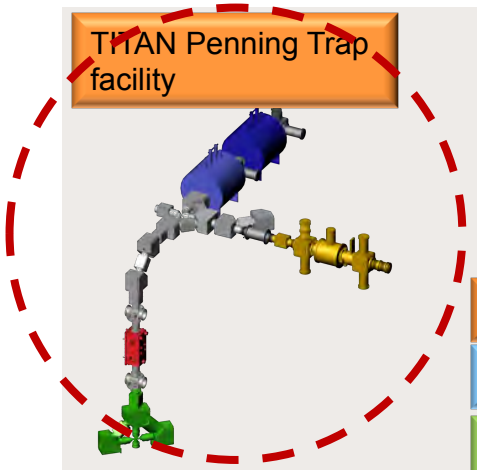


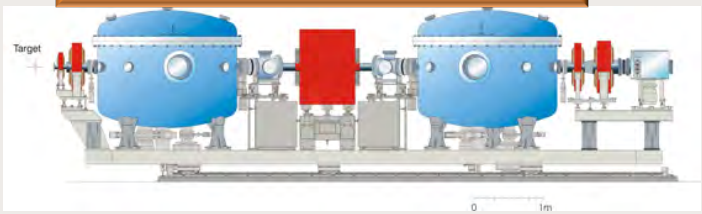
TUDA reaction setup

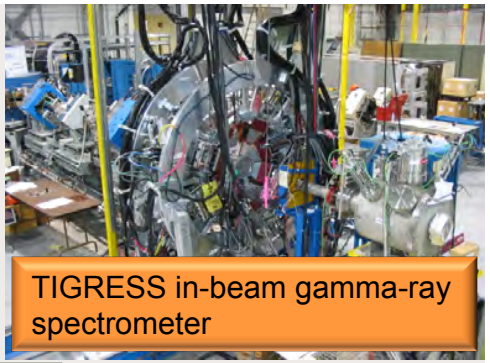
DRAGON recoil separator



Leading edge ISAC experiments







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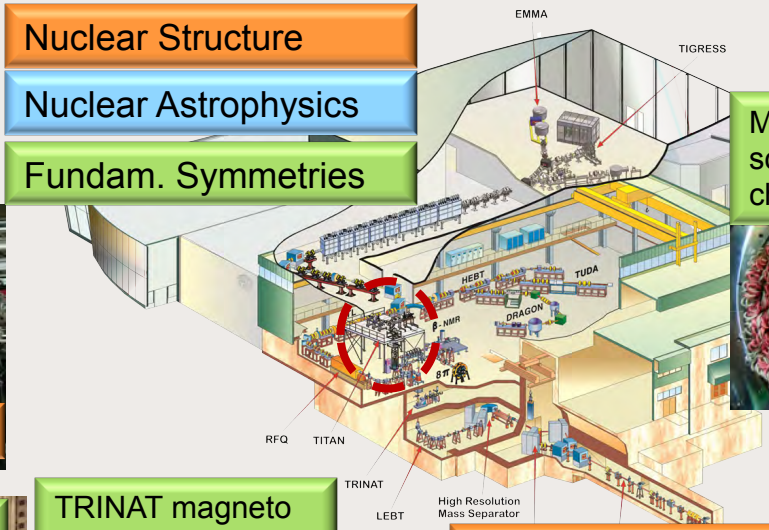
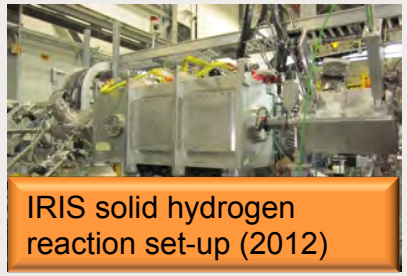
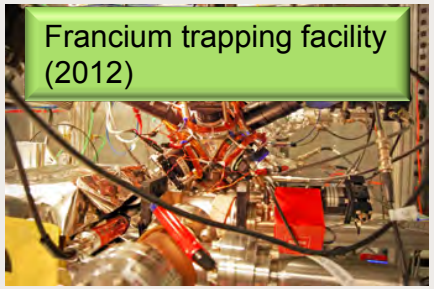
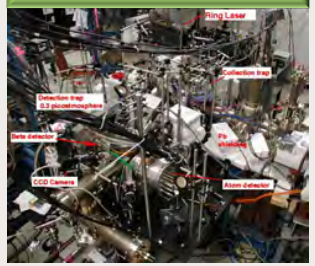
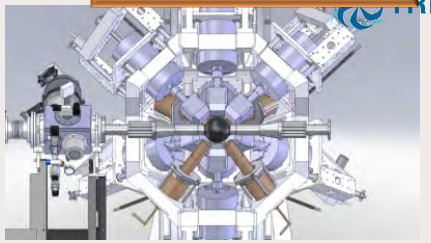
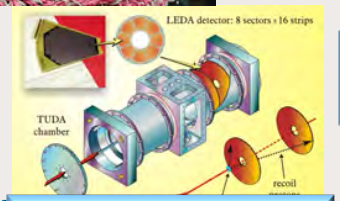


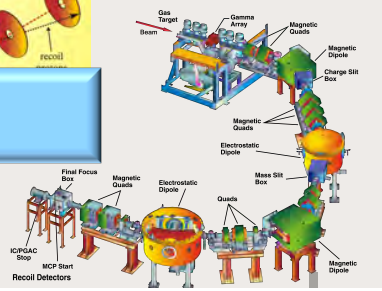












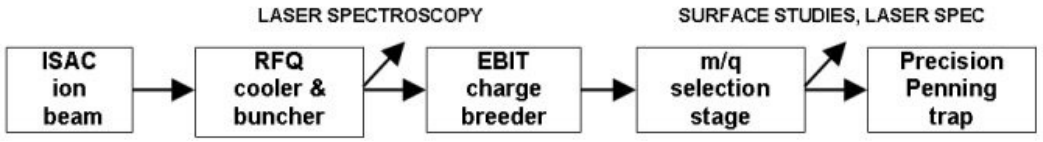
TRIUMF's Ion Trap for Atomic & Nuclear science (TITAN)

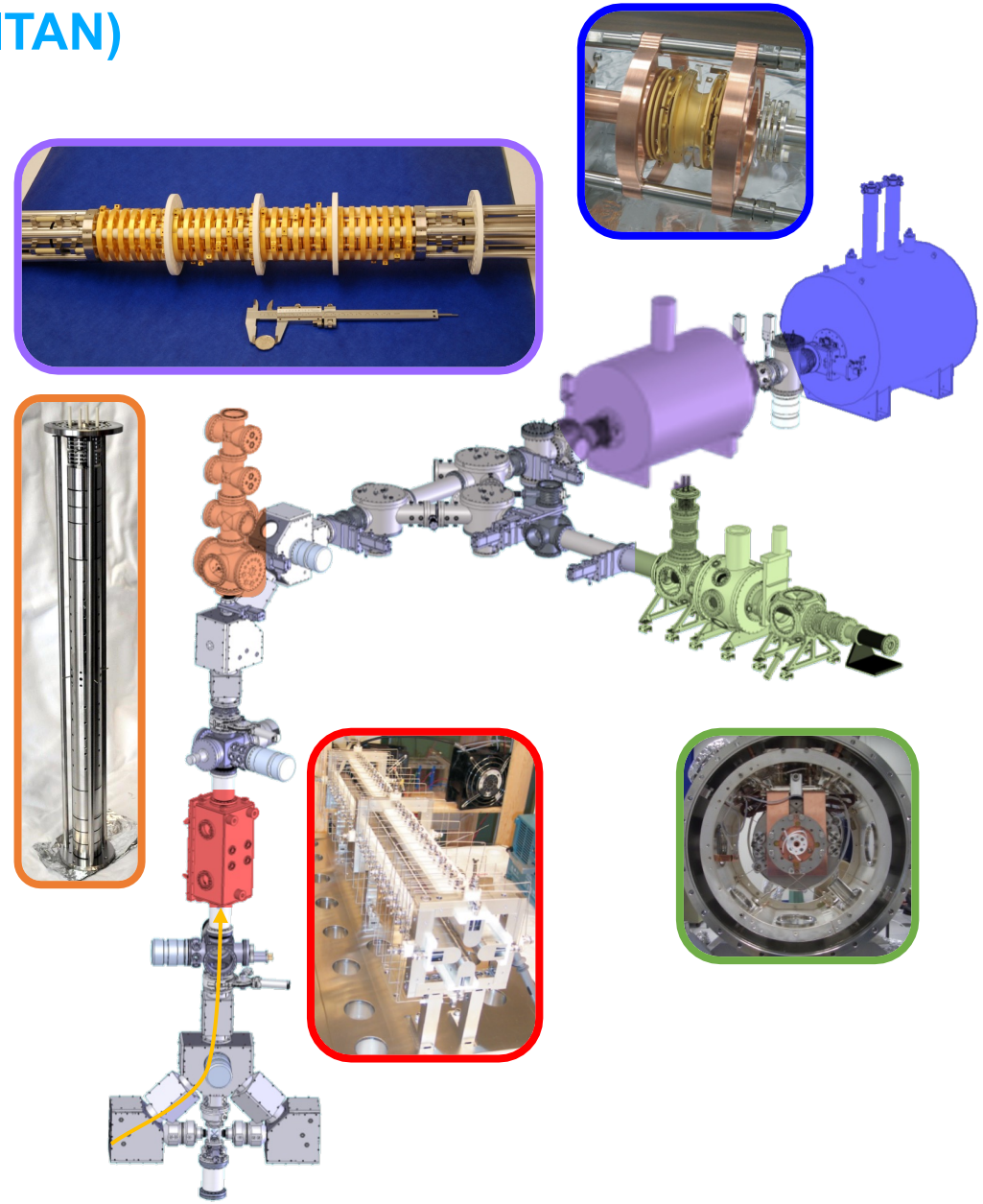
Scientific goals rely on access to radioactive beams.

- Evolution of nuclear shells away for rare isotopes
- Exotic nuclear structure like halo nuclei
- Nuclear astrophysics and nucleosynthesis
- High-precision tests of the Standard Model

Atomic-physics techniques executed in ≥5 ms

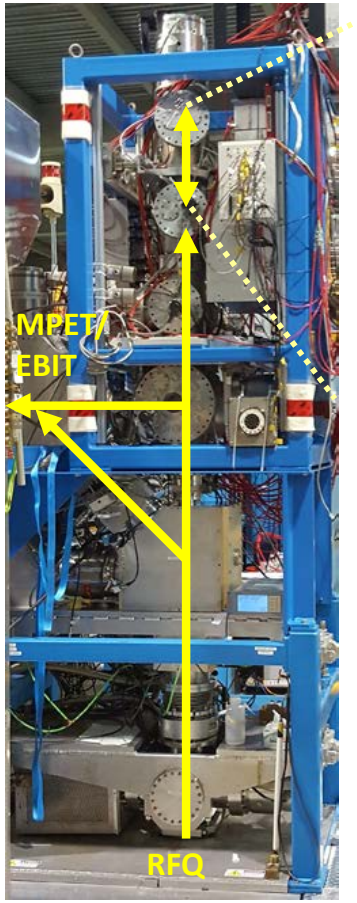
- High-precision Penning trap mass spectrometry
- Precision mass determinations through Multi-Reflection Time-of-Flight measurements
- In-ion-trap decay spectroscopy





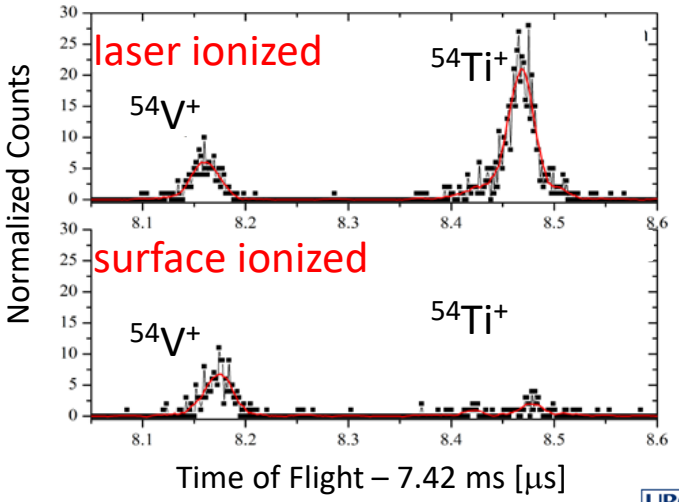
TRIUMF's Ion Trap for Atomic & Nuclear science (TITAN)

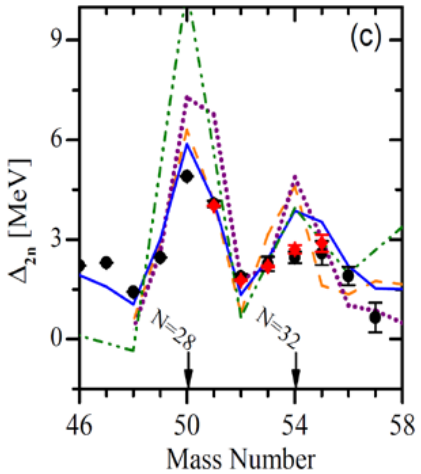
Recent research highlight



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





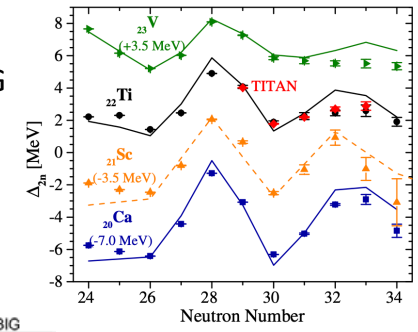
PHYSICAL REVIEW LETTERS **120,** 062503 (2018)

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



TRIUMF · UBC · University of Manitoba · Max-Planck-Institut für Kernphysik Heidelberg · University of Calgary · Justus-Liebig Universität Giessen · Colorado School of Mines · McGill University · Westfälische Wilhelms-Universität Münster · SFU · university of groningen · University of Notre Dame

Leading edge ISAC experiments

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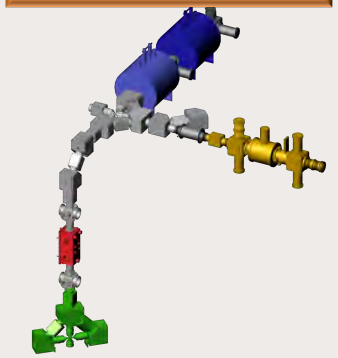

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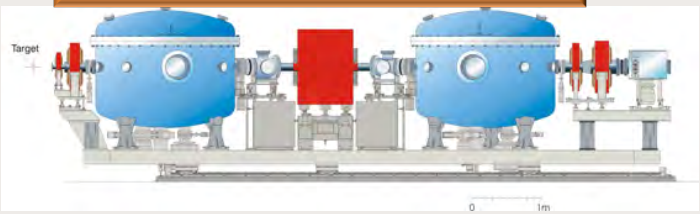

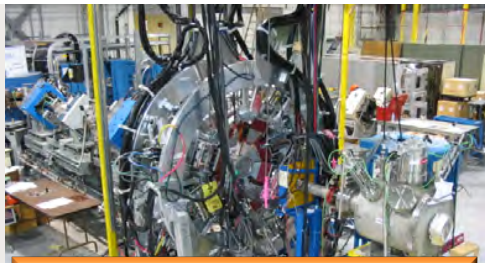

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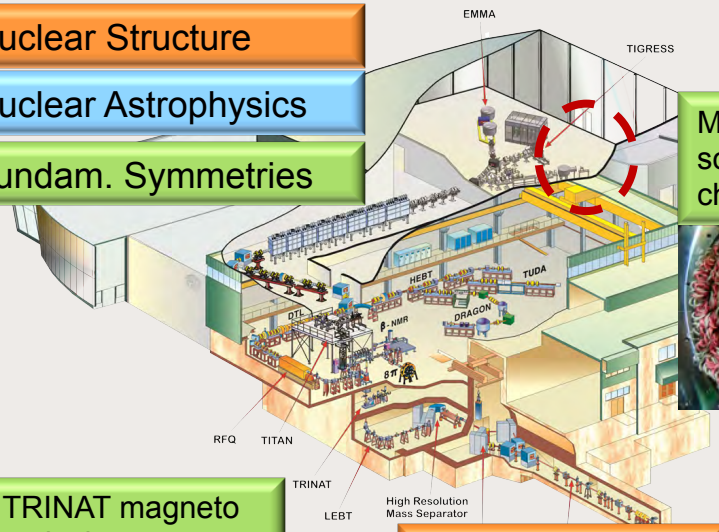

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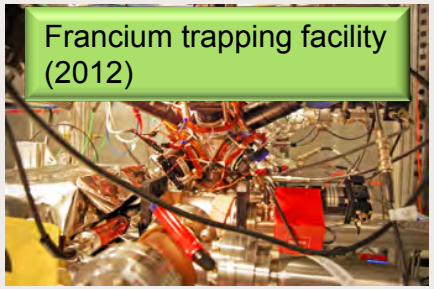

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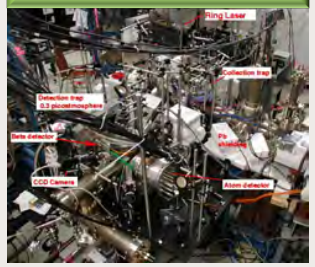
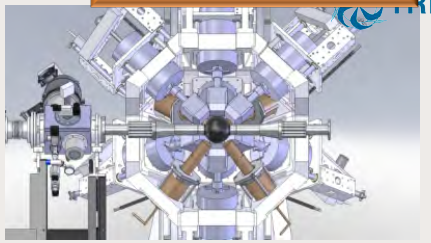
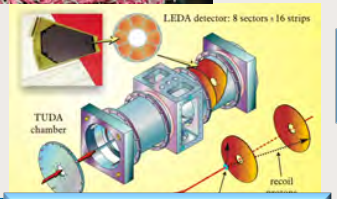


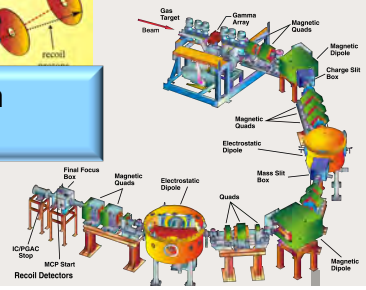
GRIFFIN gamma-ray decay spectrometer





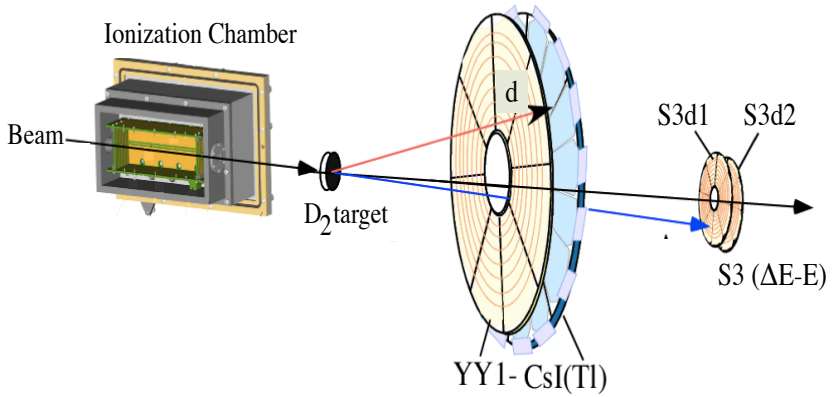
TUDA reaction setup

DRAGON recoil separator



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

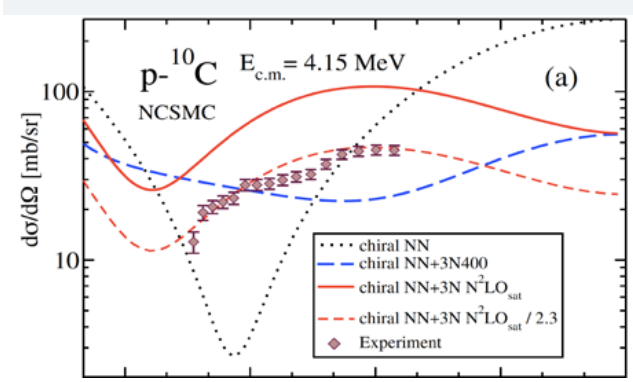
PRL 118, 262502 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

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]

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

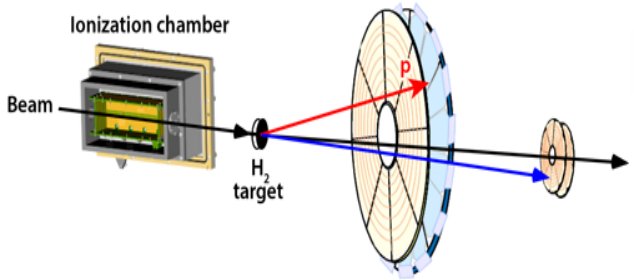
- **IRIS charged particle spectrometer**
- **Windowless solid hydrogen target**
- ^{10}C beam, 4.5 MeV/u from TRIUMF-ISAC-II

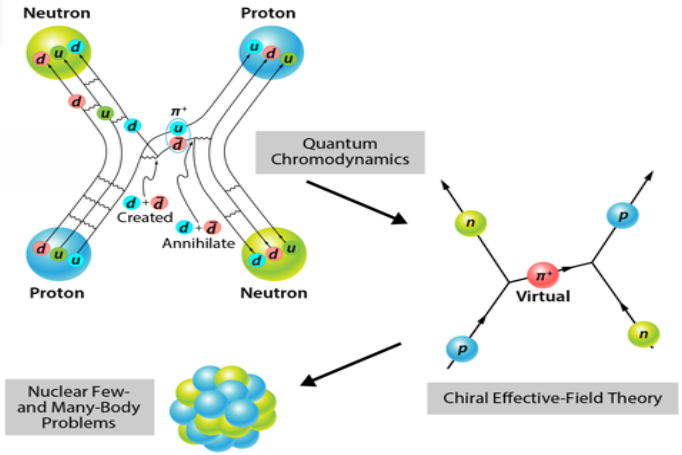


Theory from TRIUMF
- Ab initio with modern two- and three-nucleon forces

NN alone wrong – overpredicts fringe contrast

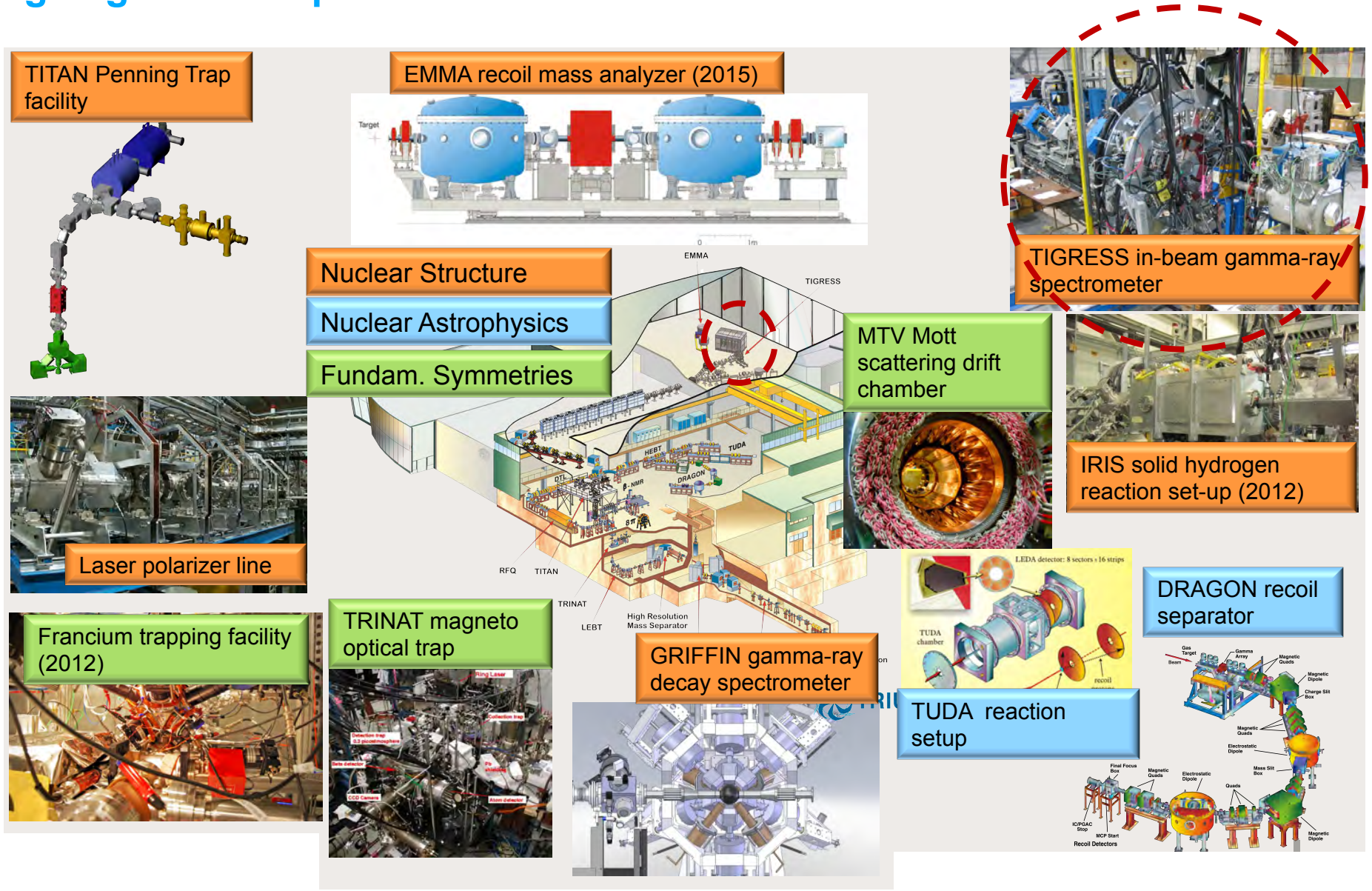
NN and 3N fit simultaneously : **shape correct** but fails to reproduce magnitude





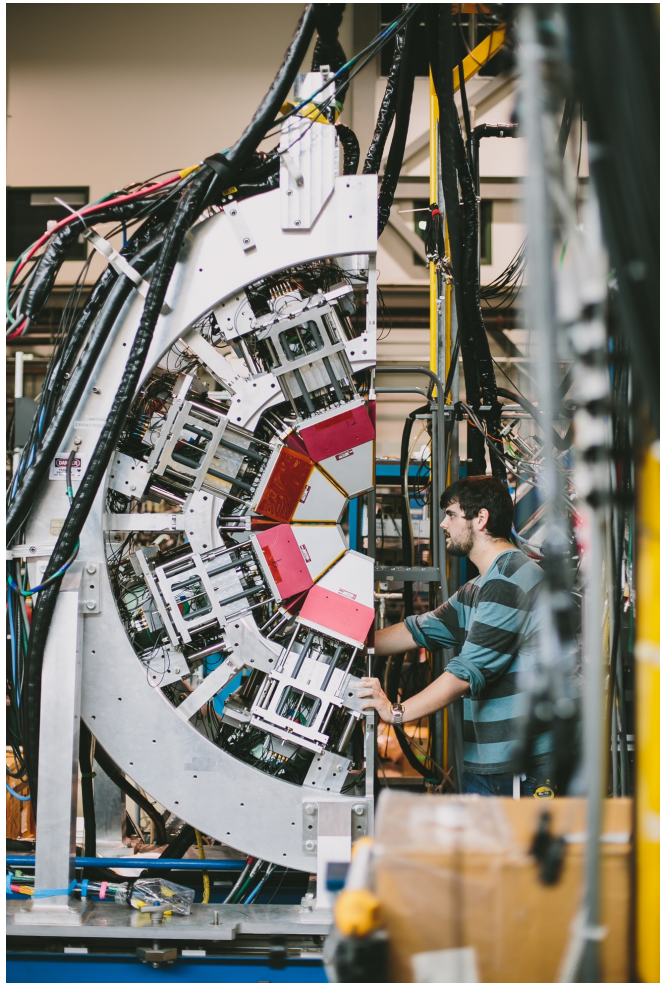
SAINT MARY'S UNIVERSITY SINCE 1802 One University. One World. Yours. · UNIVERSITY of GUELPH · McMaster University · SFU SIMON FRASER UNIVERSITY · KEK-JAPAN · RCNP · THE UNIVERSITY OF EDINBURGH · TRIUMF · GANIL GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

Leading edge ISAC experiments



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

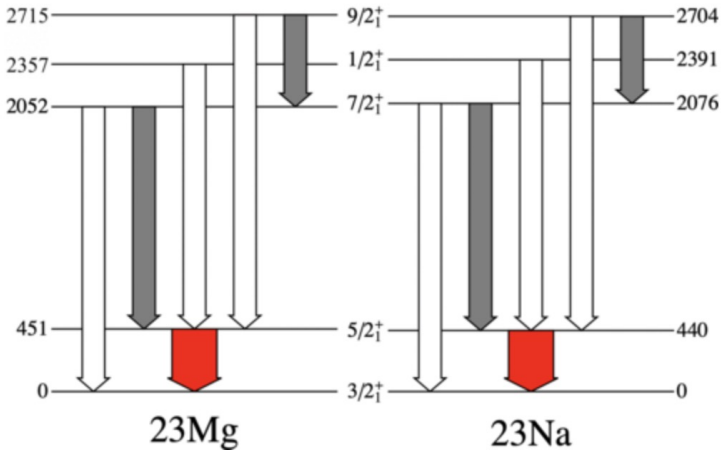
Research highlights – Nuclear Physics: TIGRESS Standalone Experiment – Coulex of ^{23}Mg & ^{23}Na

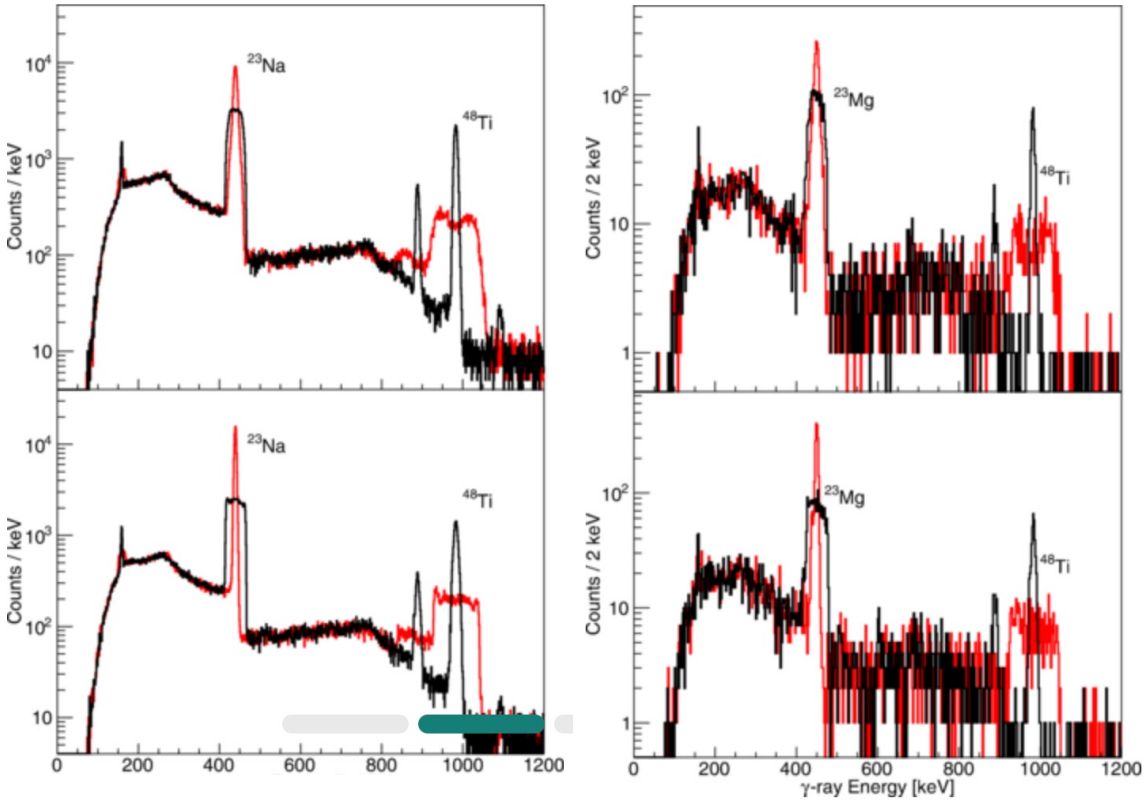
PHYSICAL REVIEW C
covering nuclear physics

Highlights Recent Accepted Collections Authors Referees Search Press About Staff

Coulomb excitation of the $|T_z| = \frac{1}{2},\ A = 23$ mirror pair

J. Henderson *et al.*
Phys. Rev. C **105**, 034332 – Published 28 March 2022

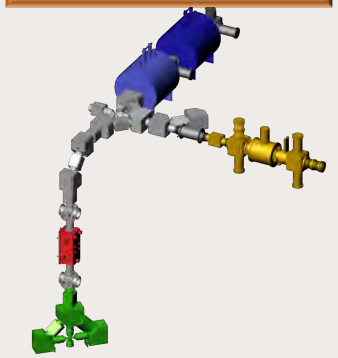




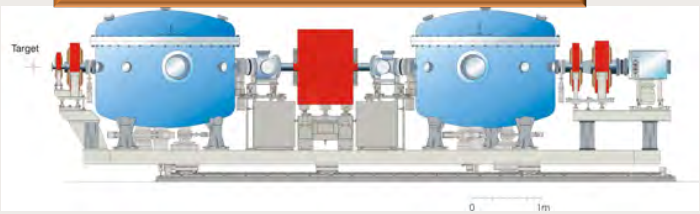
- Coulomb-excitation measurements of ^{23}Mg and ^{23}Na were performed at the TRIUMF-ISAC facility using the TIGRESS spectrometer. They were used to determine the E2 matrix elements of mixed E2/M1 transitions.
- Uncertainties from E2 strengths are some of largest in literature. Need to improve precision for better comparison with theory.
- Reduced E2 transition strengths, B(E2), were extracted for ^{23}Mg and ^{23}Na. Their precision was improved by factors of approximately 6 for both isotopes, while agreeing within uncertainties with previous measurements.
- **Conclusions:** A comparison was made with both shell-model and *ab initio* valence-space in-medium similarity renormalization group calculations. Valence-space in-medium similarity renormalization group calculations were found to underpredict the absolute E2 strength, in agreement with previous studies.

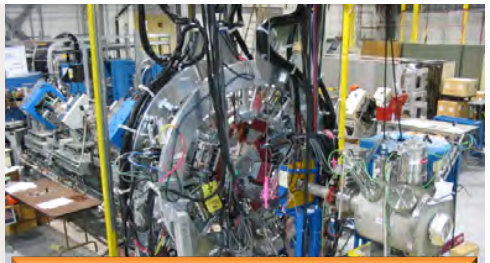
Leading edge ISAC experiments

TITAN Penning Trap facility



EMMA recoil mass analyzer (2015)



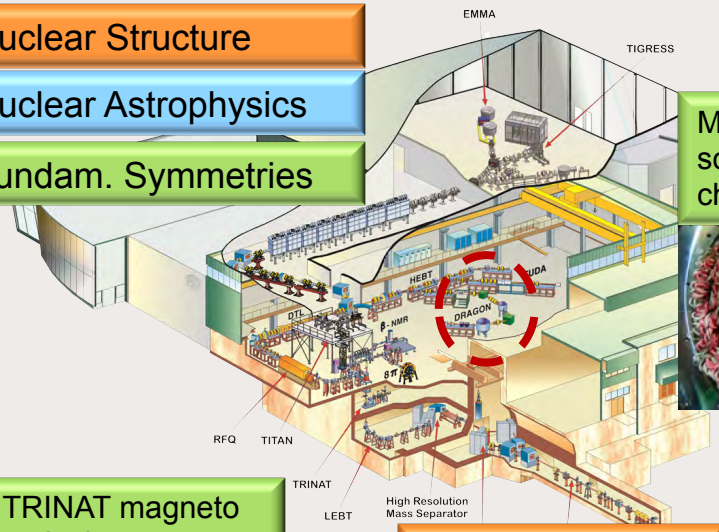


TIGRESS in-beam gamma-ray spectrometer

Nuclear Structure

Nuclear Astrophysics

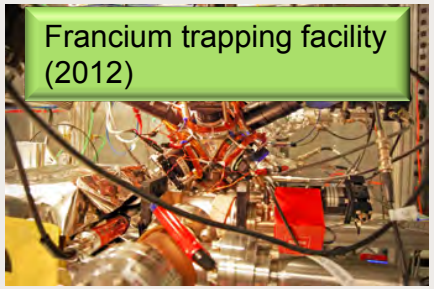
Fundam. Symmetries



MTV Mott scattering drift chamber

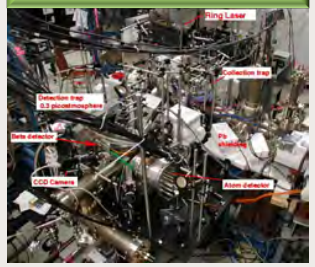
IRIS solid hydrogen reaction set-up (2012)

Laser polarizer line

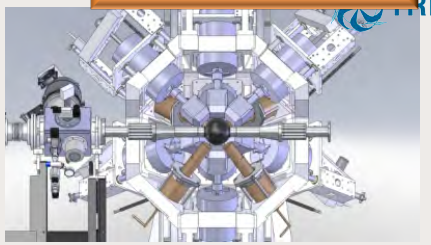


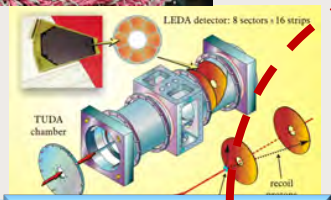
Francium trapping facility (2012)

TRINAT magneto optical trap



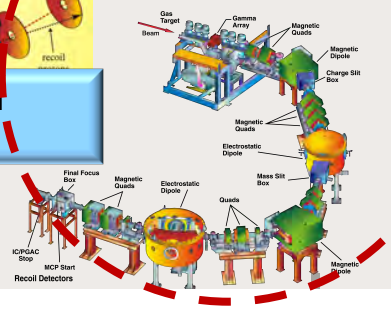
GRIFFIN gamma-ray decay spectrometer





TUDA reaction setup

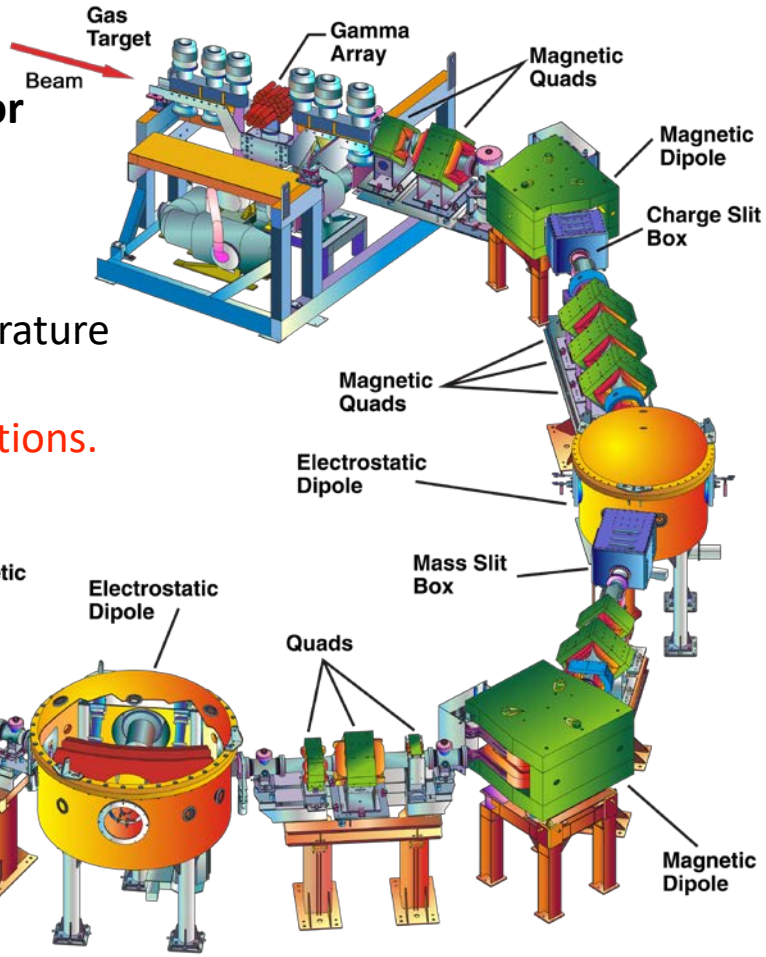
DRAGON recoil separator



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

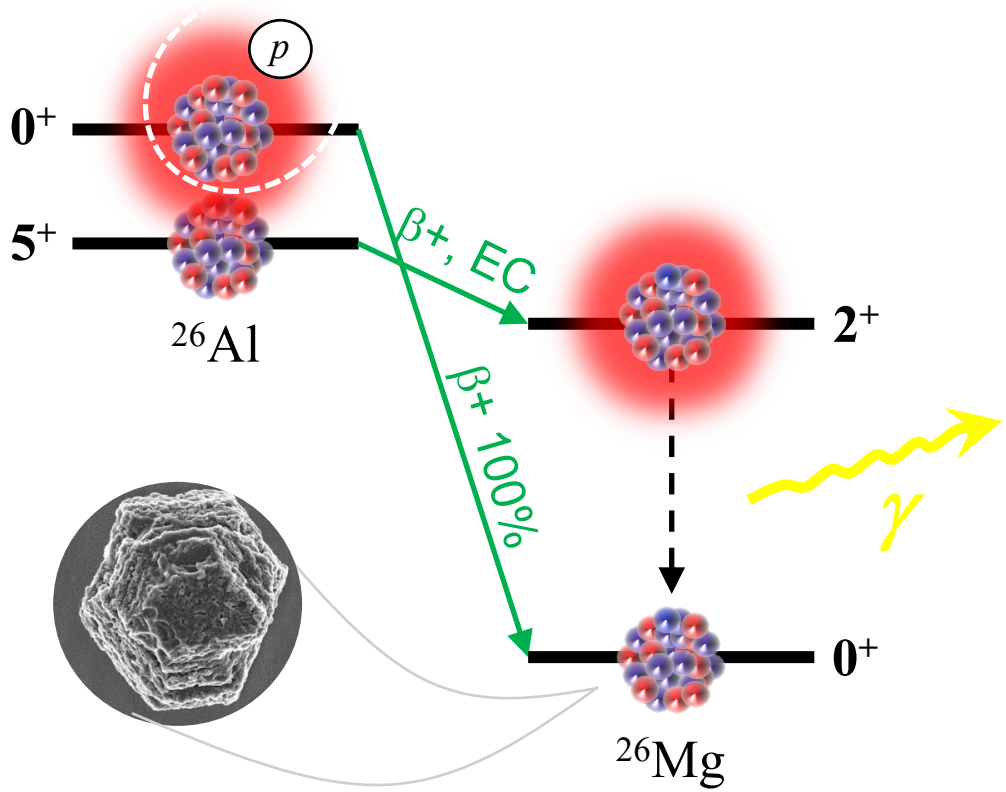
The astrophysical origin of ^{26}Al

Need to understand production & destruction of ^{26}Al in stellar scenarios!

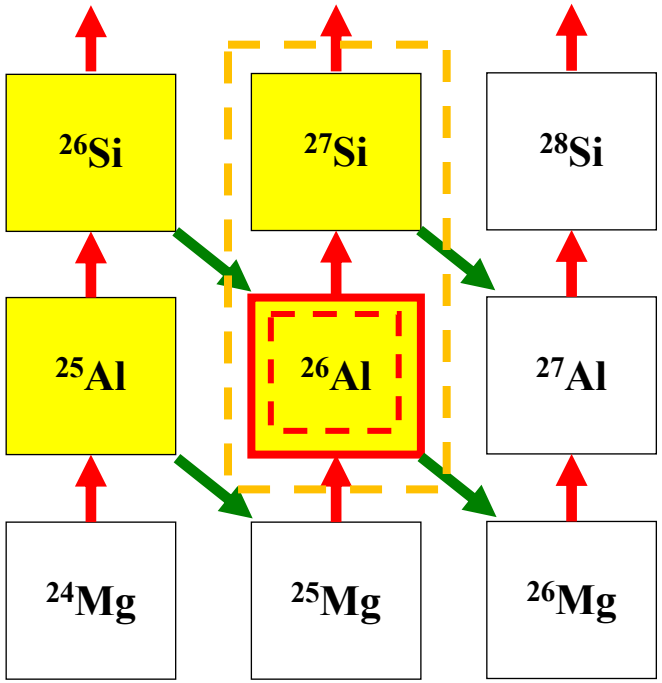
Nucleosynthesis of ^{26}Al is complicated by the presence of an isomer (E_x = 228.31(3) keV)

- Experimental physics has focused on

^{26m}Al(p,γ) nuclear ground states

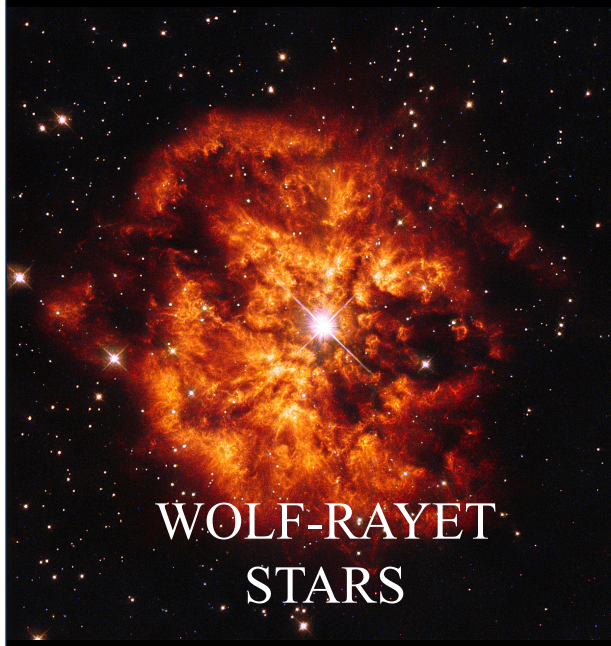


Courtesy of A. Lennartz



➔ Need to measure proton capture on excited quantum state of ^{26}Al

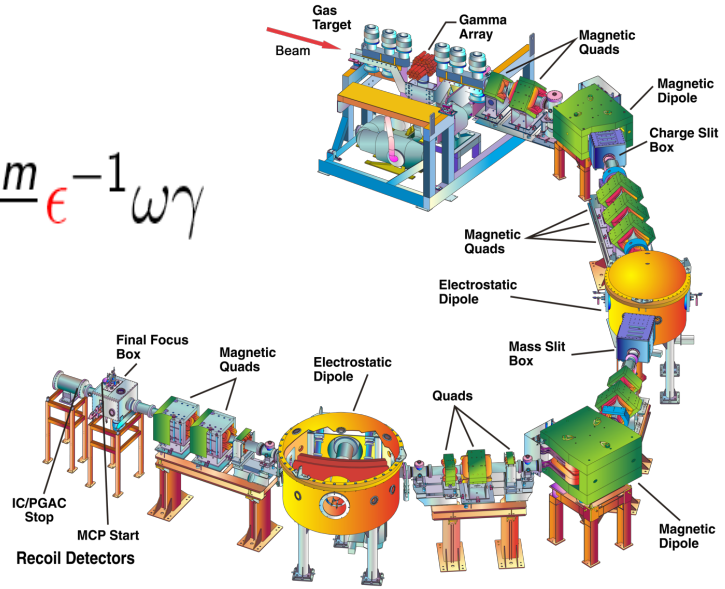
EXTREME EXPERIMENTAL CHALLENGE



DRAGON – Detector of Recoils and Gammas of Nuclear Reactions

$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

#reactions per incident ion



$$N_A\langle\sigma\upsilon\rangle = 1.54\times10^{11}(\mu T)^{-3/2}\,\omega\gamma\cdot\exp\left(-11.605\frac{E_R}{T_9}\right)$$

- Incoming beam composed of ^{26m}Al, ^{26g}Al, ^{26}Na
- **Isomeric component was identified** by its associated β+ decay to the ^{26}Mg g.s.

<u>Total beam on target:</u>

- 6.21(2)E+14 incident ^{26}Al g.s. beam ions
- 7.5(2)E+10 incident ^{26m}Al beam ions

Present result for ωγ: **$E_{c.m.}$ = 447 keV resonance** governs the entire ^{26m}Al(*p*,γ) stellar reaction rate over the peak temperature range of classical novae and supernovae

PHYSICAL REVIEW LETTERS

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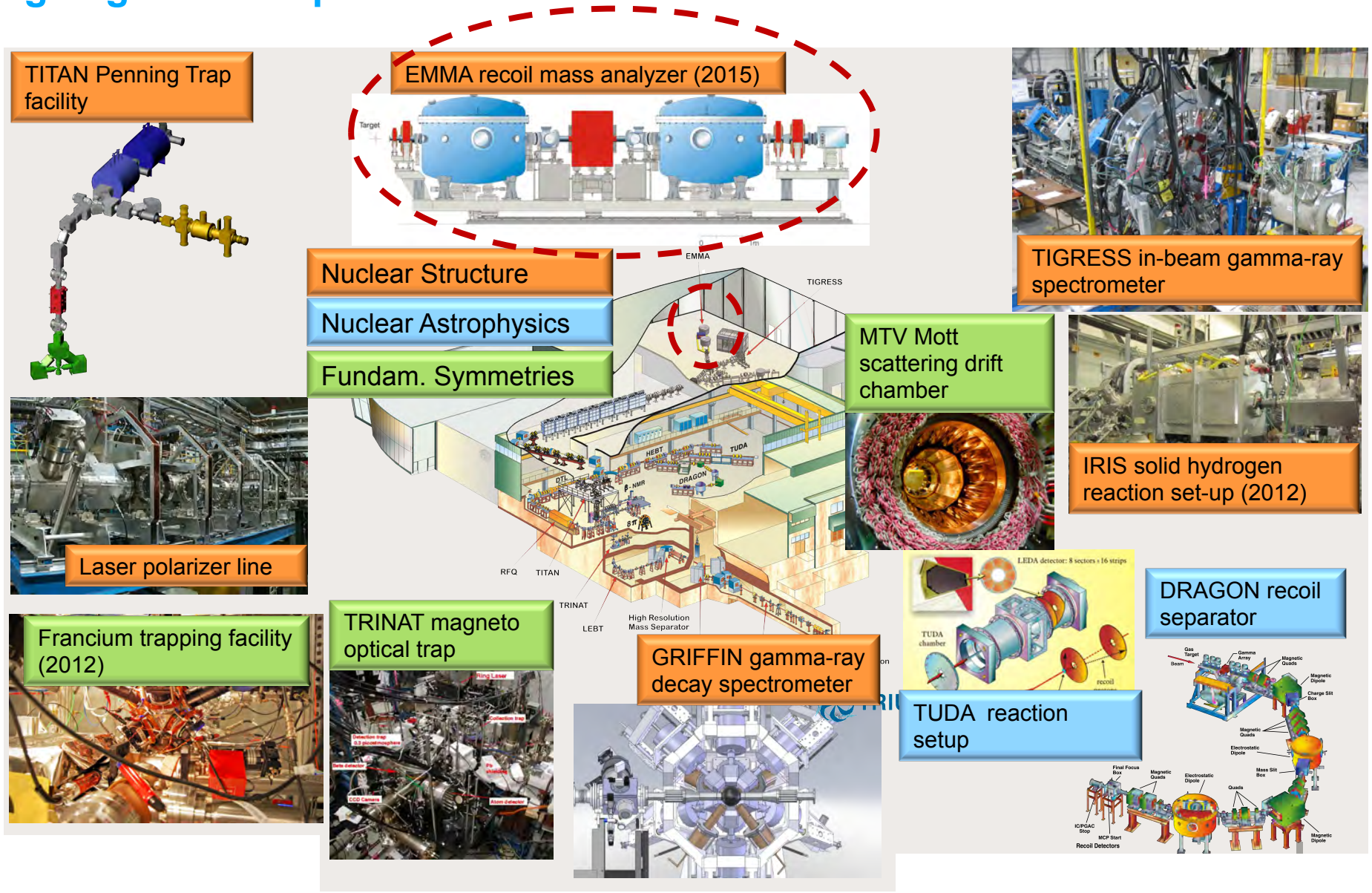
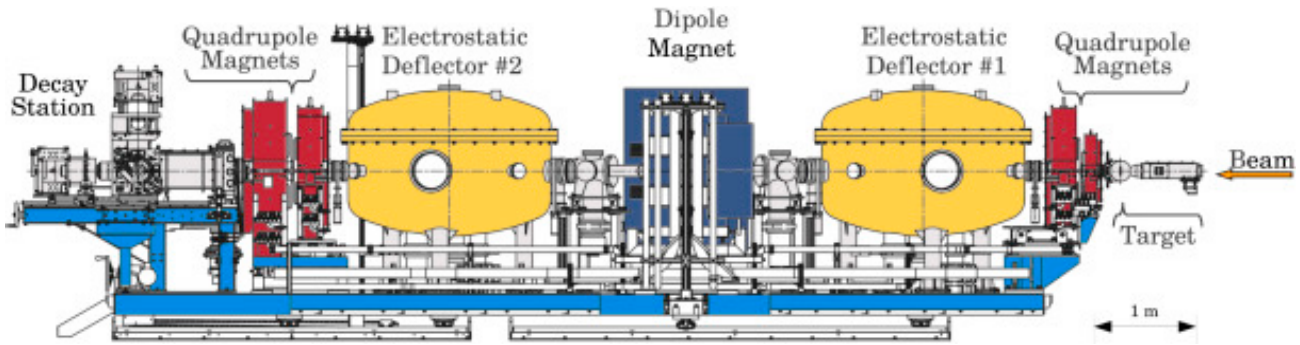
Radiative Capture on Nuclear Isomers: Direct Measurement of the ^{26m}Al$(p,\gamma)^{27}$Si Reaction

G. Lotay, A. Lennarz, C. Ruiz, C. Akers, A. A. Chen, G. Christian, D. Connolly, B. Davids, T. Davinson, J. Fallis, D. A. Hutcheon, P. Machule, L. Martin, D. J. Mountford, and A. St. J. Murphy
Phys. Rev. Lett. **128**, 042701 – Published 27 January 2022

Leading edge ISAC experiments

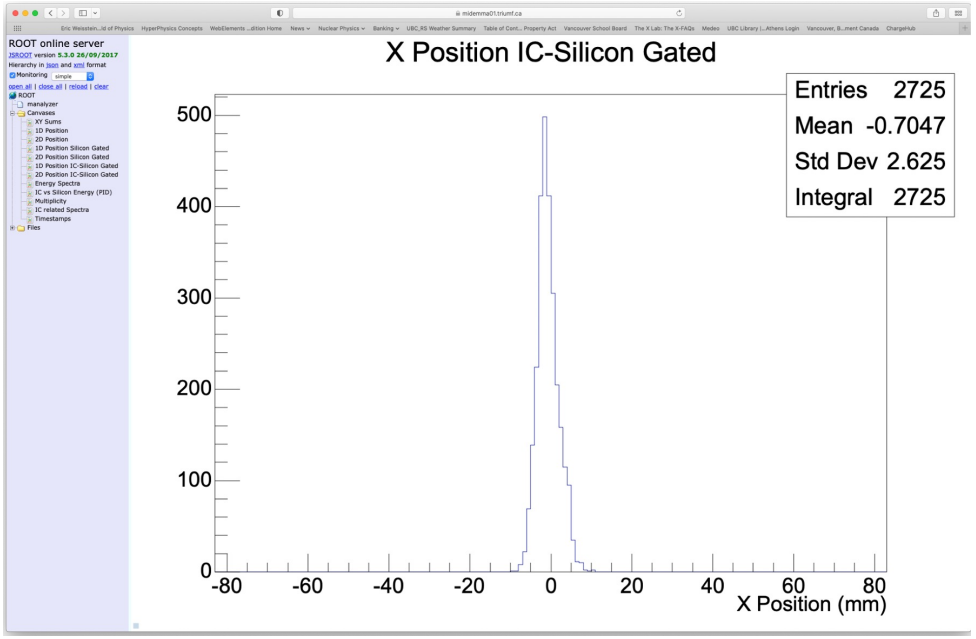


EMMA: Recoil Mass Spectrometer at ISACII



- EMMA (ElectroMagnetic Mass Analyser) in operation since 2017
- Study of transfer and fusion-evaporation reactions
  - Identify products of reactions by measuring their charge & mass
- 2nd EMMA+TIGRESS RIB experiment last fall
  - 84 MeV ^{21}Na RIB bombarded deuterated polyethylene target at 10^7 s^{-1}
  - EMMA transmitted ^{22}Na and ^{22}Mg recoils from (d,p) and (d,n) transfer reactions
  - > 10^5 recoils detected from a RIB induced reaction, a world record

^{22}Mg recoil position spectrum (1h of data)



The BeEST Experiment

TRIUMF

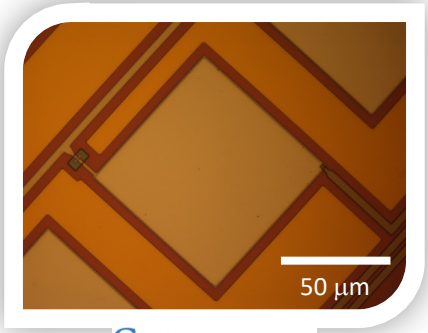
Rare-isotope implantation at TRIUMF-ISAC

THE BeEST

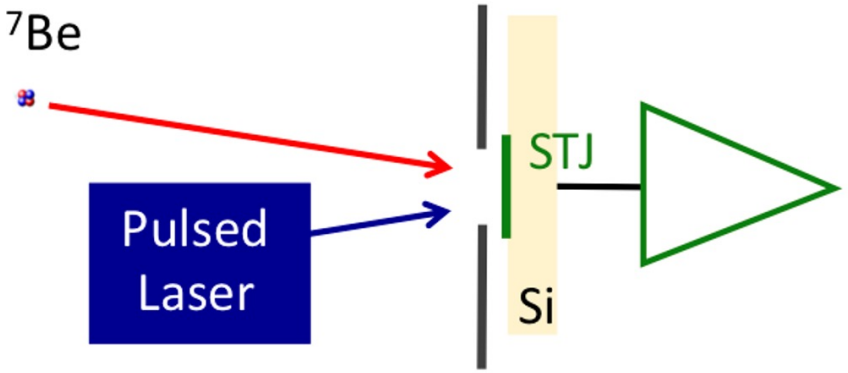
Beryllium Electron capture in Superconducting Tunnel junctions

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)

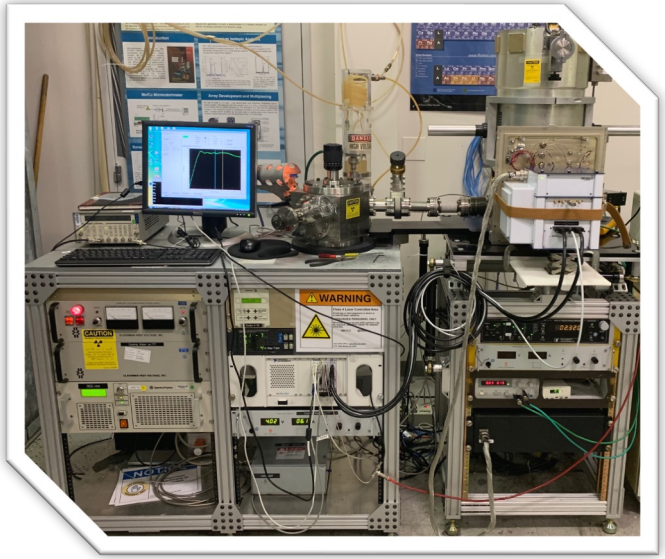
Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS



High-precision *In-situ* calibration and characterization



Lawrence Livermore National Laboratory

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

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EARTH • ENERGY • ENVIRONMENT

U.S. DEPARTMENT OF ENERGY | Office of Science

Lawrence Livermore National Laboratory

TRIUMF

NSERC CRSNG

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

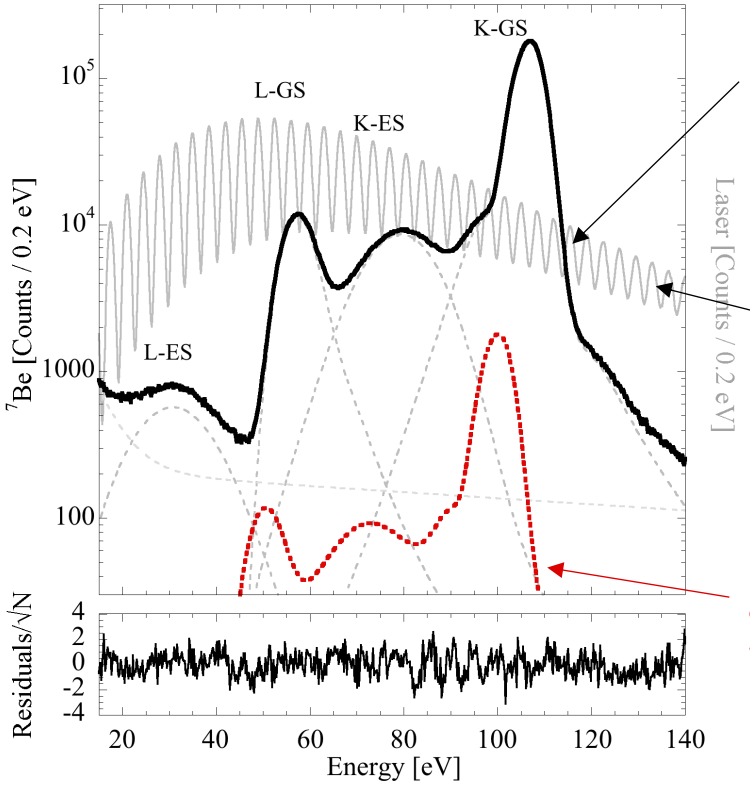
APS physics

GORDON AND BETTY MOORE FOUNDATION

Courtesy of K. G. Leach

First Limits from BeEST Phase-II Data

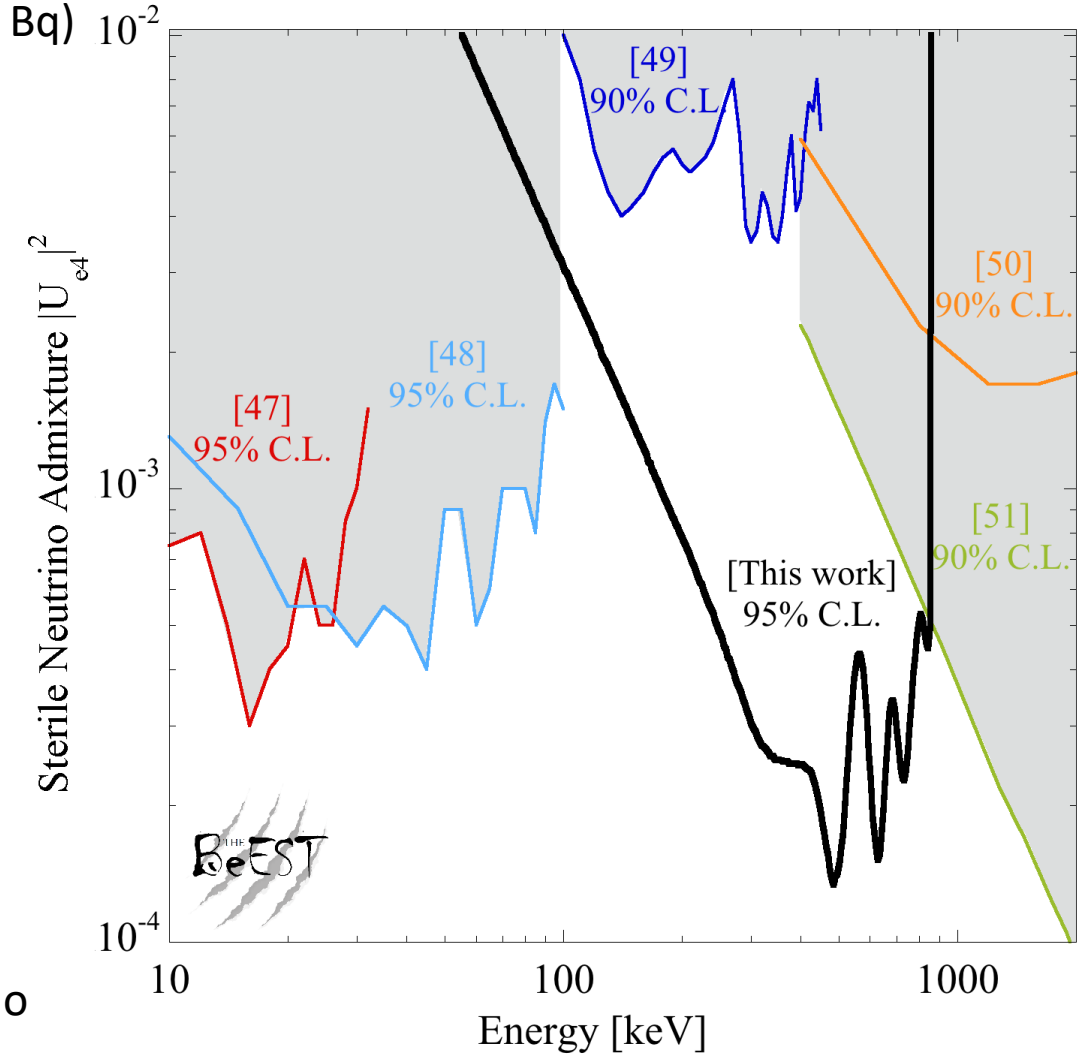
- Phase-II data from a single 138x138 μm² STJ counting at low rate (~10 Bq)



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

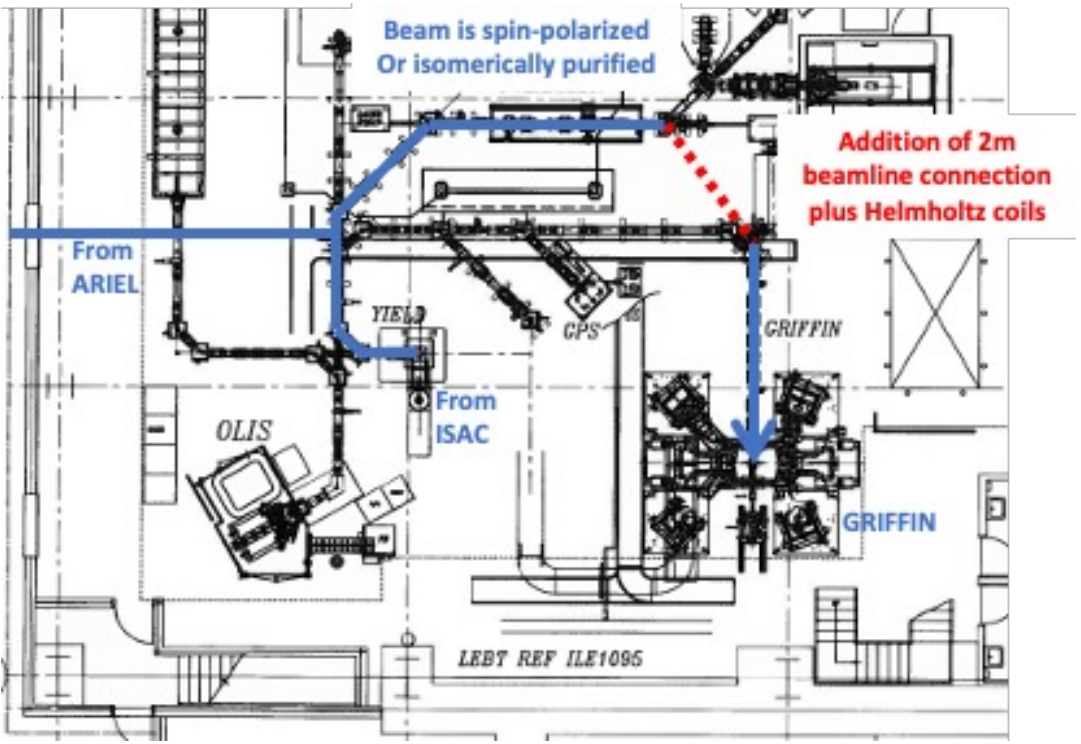
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

Courtesy of K. G. Leach

Delivery of spin-polarized beams to GRIFFIN

NEW INITIATIVES

Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei (GRIFFIN) is a state-of-the-art high-efficiency gamma-ray spectrometer for decay spectroscopy research with the low-energy RIBs



Decay spectroscopy with **β-γ** and **γ-γ** coincidences of spin-polarized beams:

- High initial polarization can improve sensitivity over PAC by ~ 10
- gamma-tagged beta asymmetry for firm assignment of spins, parities;
- isospin mixing measurements relevant to V_{ud};
- searches for time-reversal breaking

Decay spectroscopy of Isomerically pure beams by resonant photoionization:

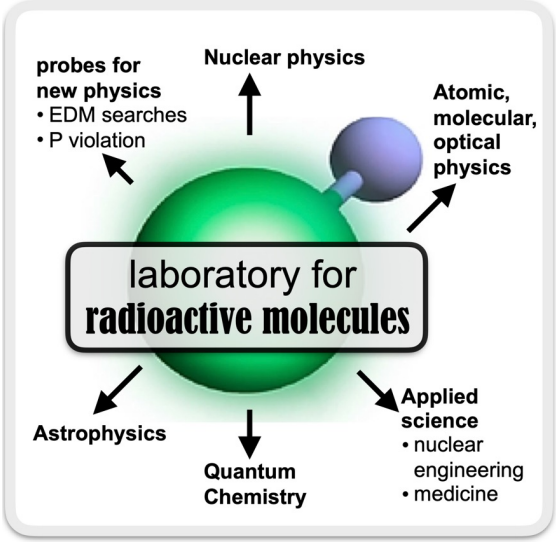
- Detailed nuclear structure investigations in regions such as ^{132}Sn with important implications for nuclear astrophysics

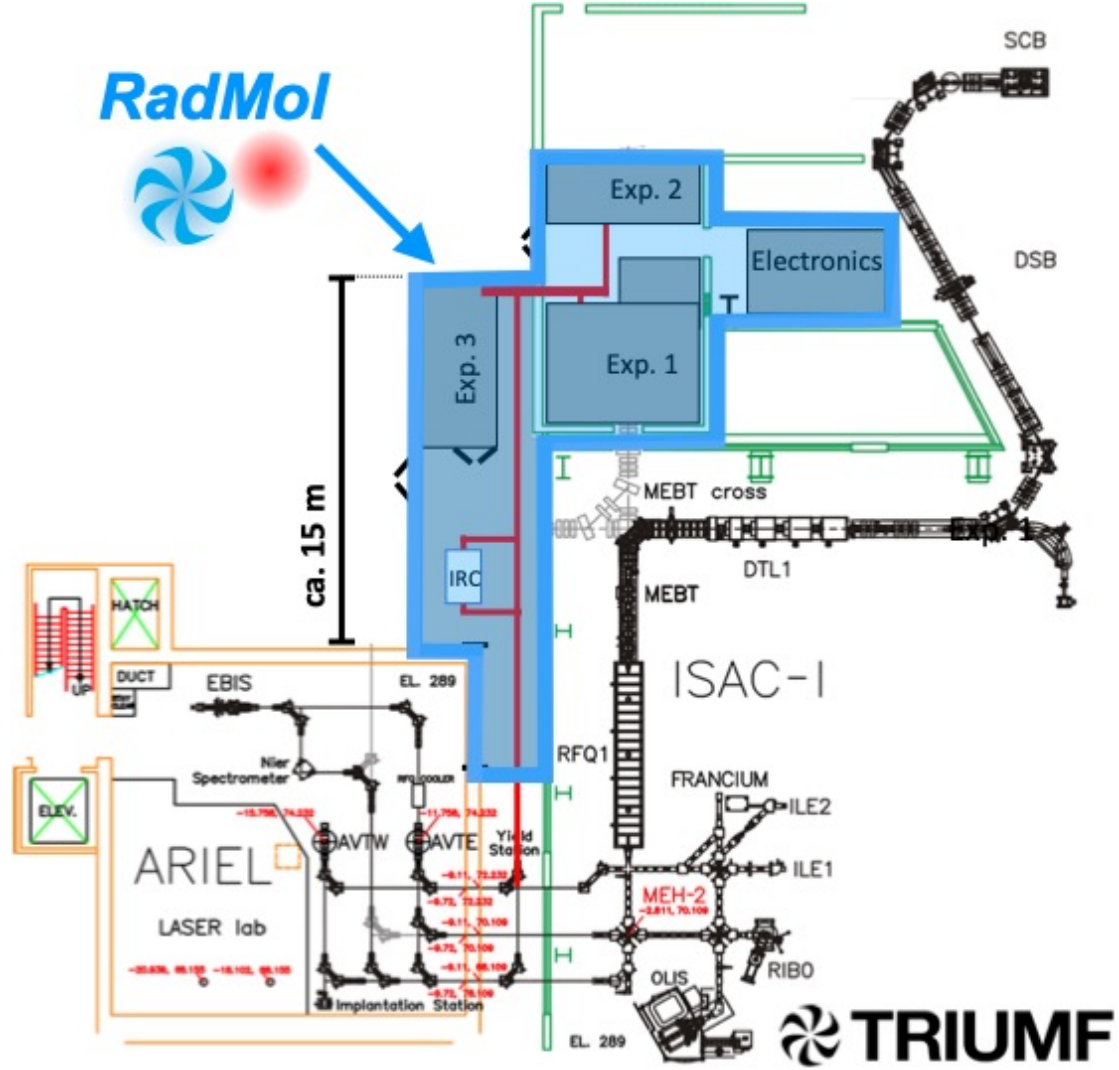
Needs: development of high-power photoionization laser for last step

A new 2-meter section of beamline is needed to join the Polarizer beamline to the GRIFFIN gamma-ray spectrometer

Future Radioactive Molecule (RadMol) Laboratory

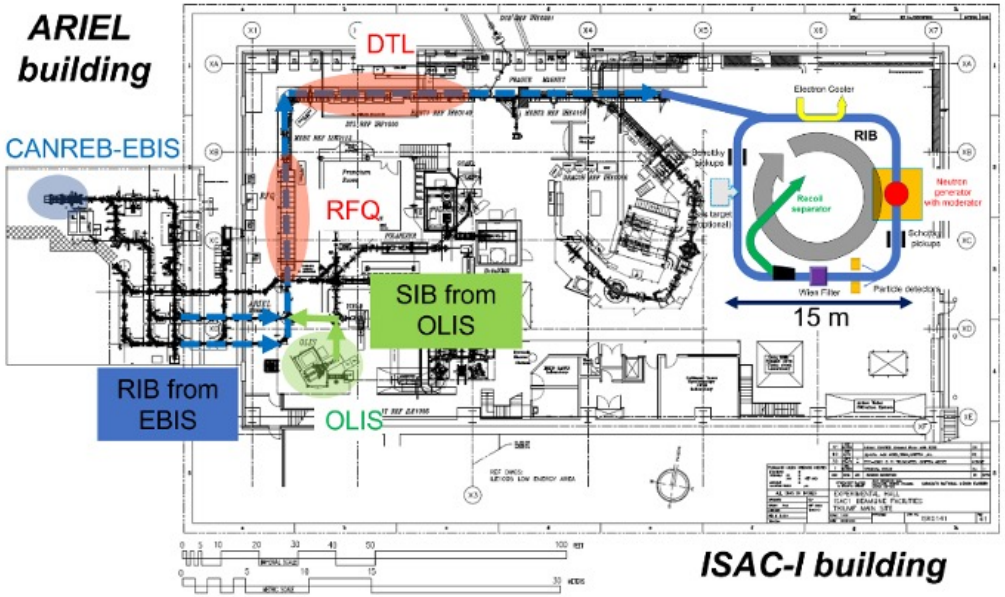
- Radioactive molecules as novel precision probes for fundamental physics
- Initial physics program:
  - Octuple-deformed nuclei incorporated into polar molecules ⇒ unmatched sensitivity for nuclear EDM
  - Access nuclear anapole moments via diatomic molecules
- Provision for expansions into other fields





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



TRIUMF

Thank you!
Merci!
고맙습니다!

Discovery, accelerated