TRIUMF

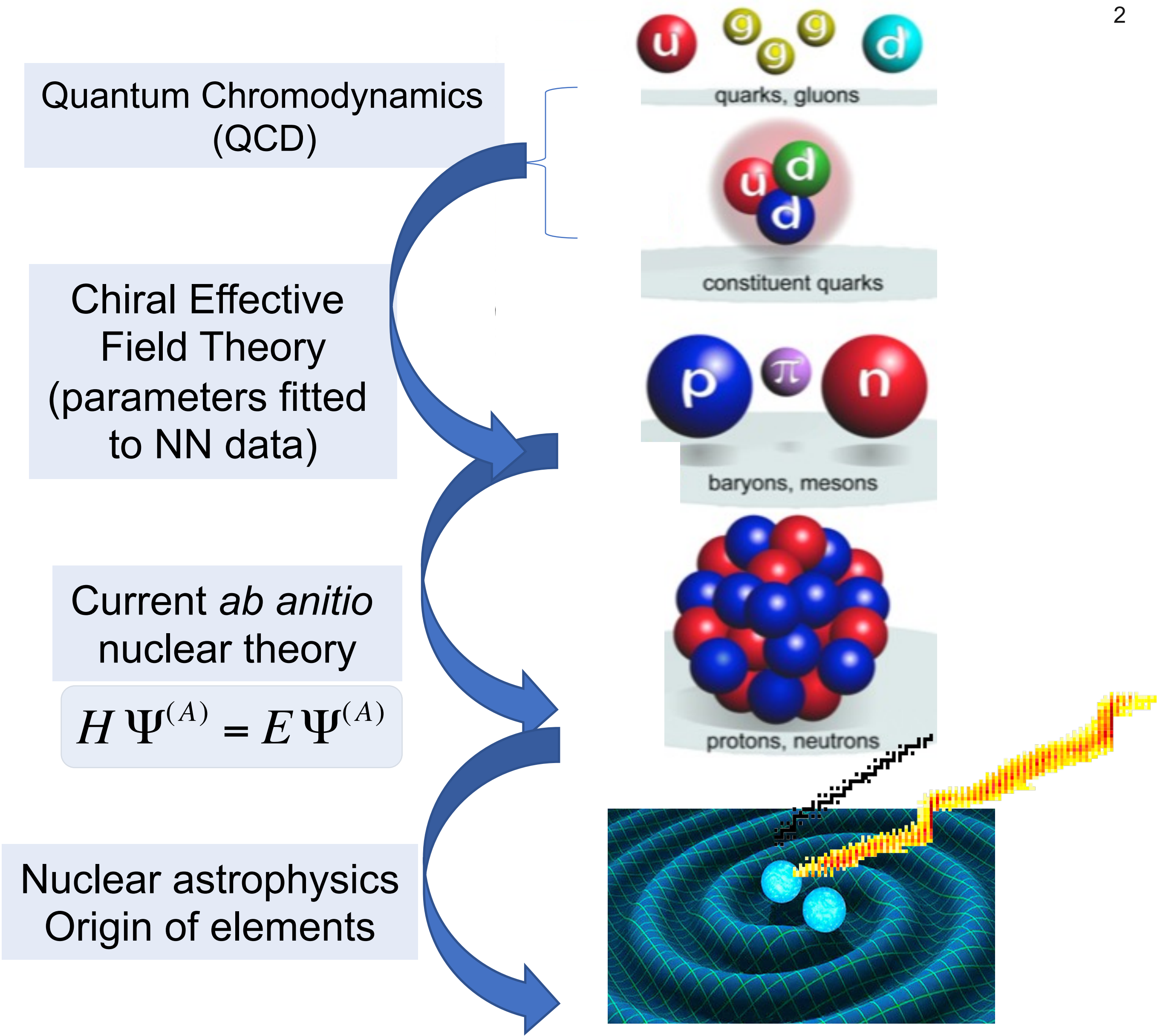
Nuclear Theory at TRIUMF

Jason D. Holt
Scientist, Theory Department
Science Week
July 20, 2022

Discovery, accelerated

TRIUMF Nuclear Theory

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

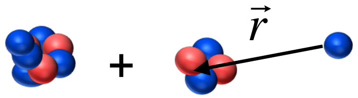
Current *ab anitio* nuclear theory

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

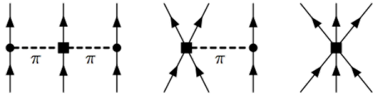
Nuclear astrophysics Origin of elements

Ab initio nuclear theory at TRIUMF Theory Department

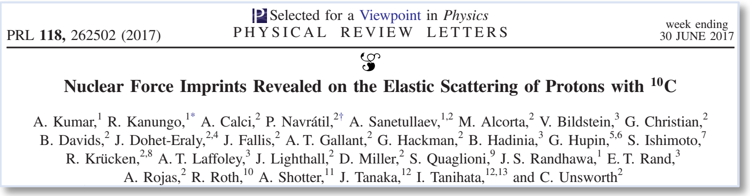
- Unified approach to nuclear structure and reactions for light nuclei: No-Core Shell Model with Continuum (NCSMC)
  - Applications to
    - Properties of exotic nuclei – prediction of near threshold *S*-wave resonance in ^{6}He+p → TUDA experiment
    - Nuclear reactions important for astrophysics - ^{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



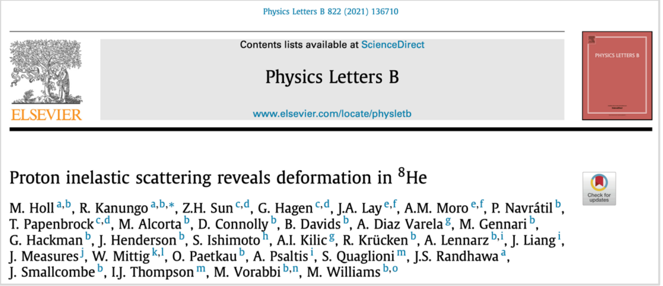
- Large-scale high-performance computation - massively parallel codes
  - Summit@ORNL, Quartz@Livermore Computing, Cedar & Niagara@Compute Canada
- **Synergy with ISAC RIB experiments**
- Petr Navratil + 2 PhD students + 1.5 postdocs (+ co-op students)



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
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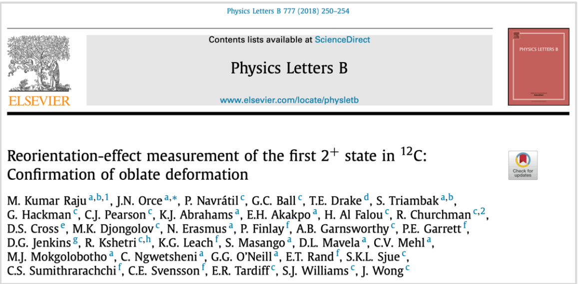
Proton inelastic scattering reveals deformation in ^{8}He

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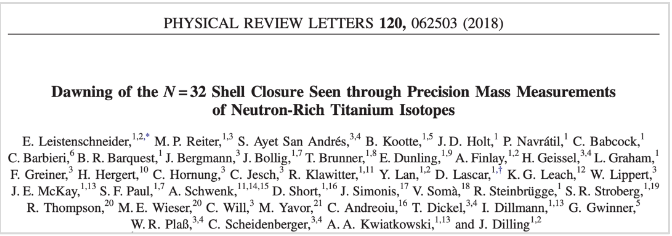
Reorientation-effect measurement of the first 2^+ state in ^{12}C: Confirmation of oblate deformation

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[e], 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]

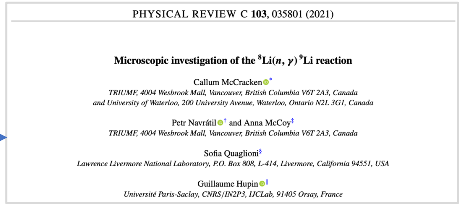


PHYSICAL REVIEW LETTERS **120,** 062503 (2018)

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,†] 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]

To be measured at TRISR?



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

Microscopic investigation of the ^{8}Li$(n, \gamma)^9$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[‡]
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

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

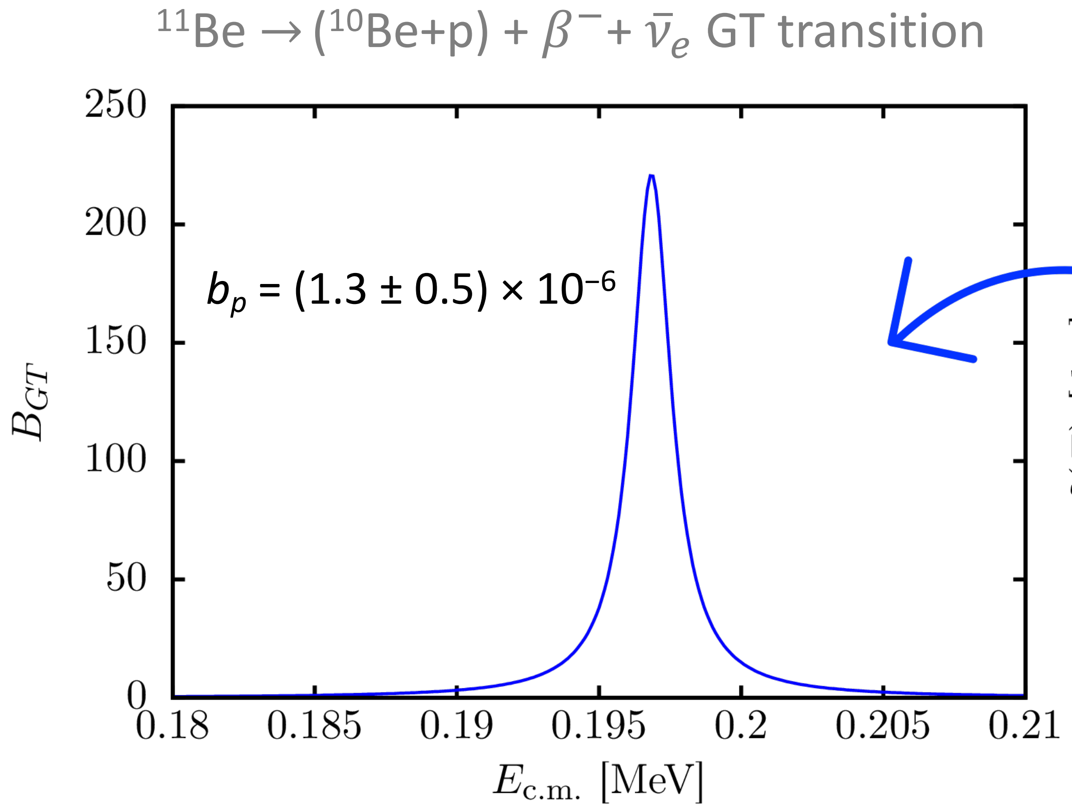
Guillaume Hupin[‖]
Université Paris-Saclay, CNRS/IN2P3, IJCLab, 91405 Orsay, France

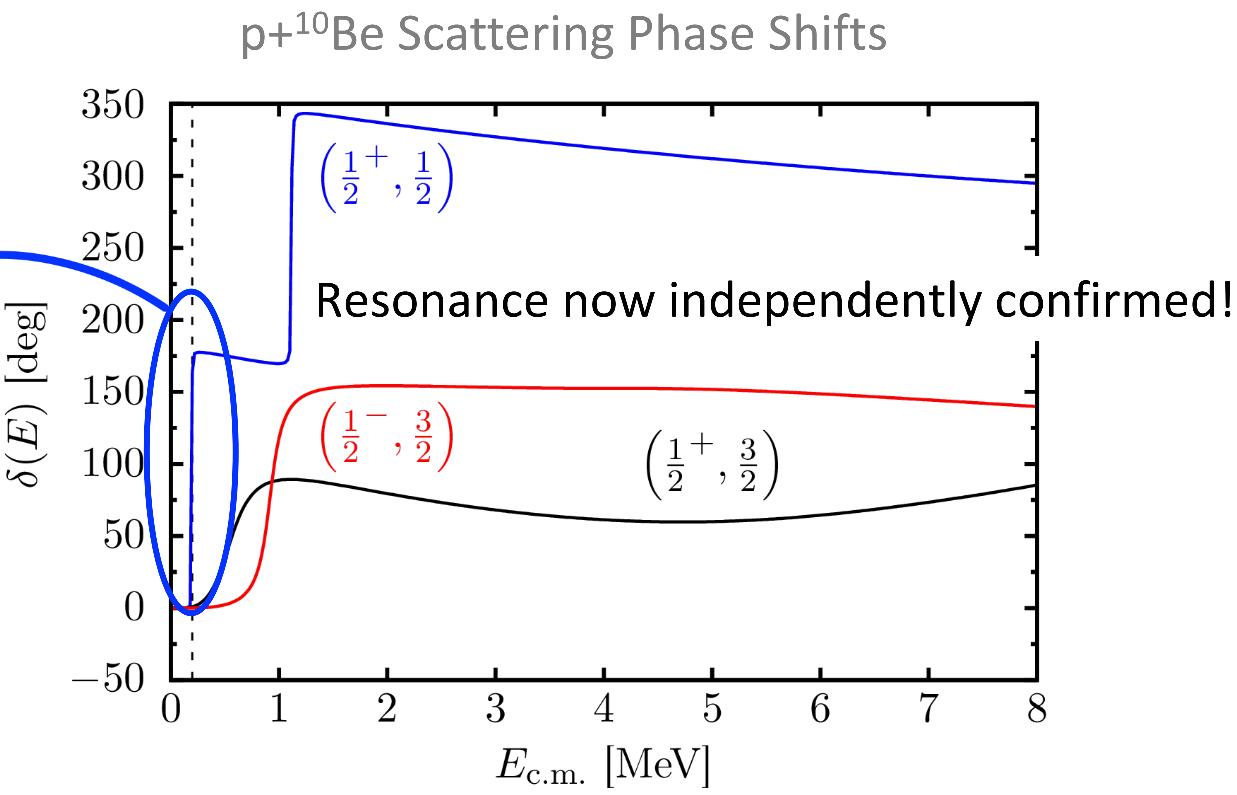
PHYSICAL REVIEW C **105**, 054316 (2022)

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

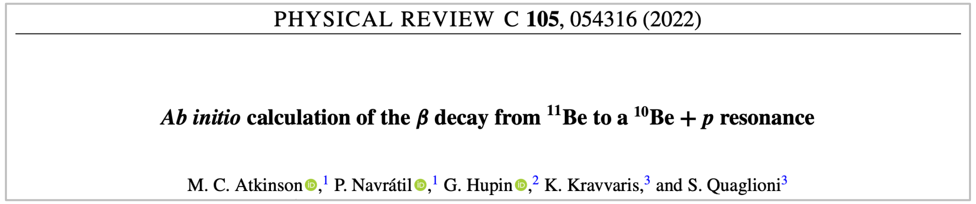
M. C. Atkinson,[1] P. Navrátil,[1] G. Hupin,[2] K. Kravvaris,[3] and S. Quaglioni[3]

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))





Resonance now independently confirmed!

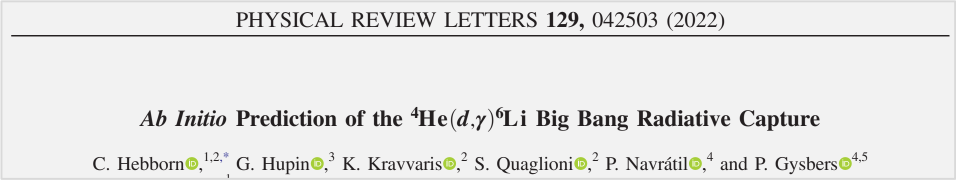


PHYSICAL REVIEW C **105**, 054316 (2022)

***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]

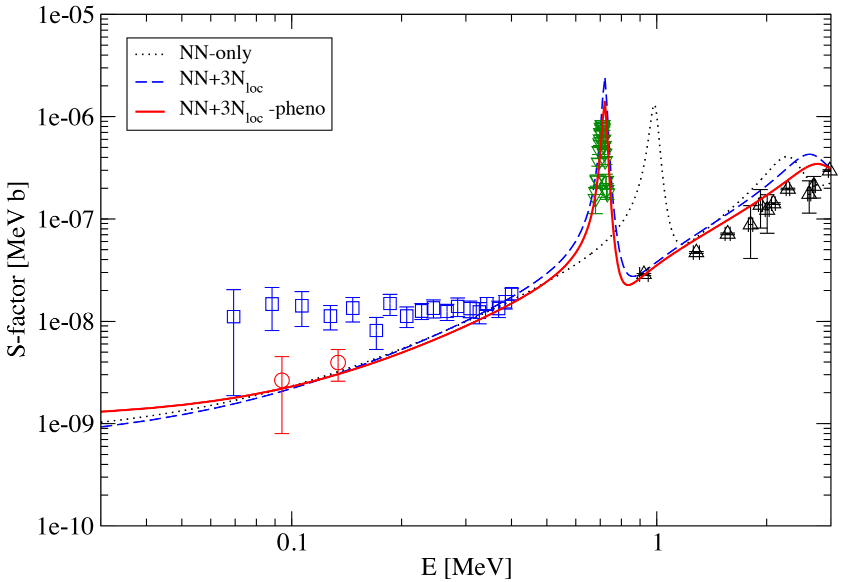
Ab initio calculations of radiative capture reactions important for astrophysics

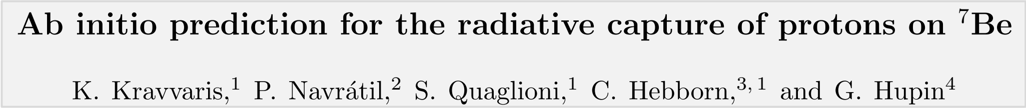


PHYSICAL REVIEW LETTERS **129,** 042503 (2022)

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]

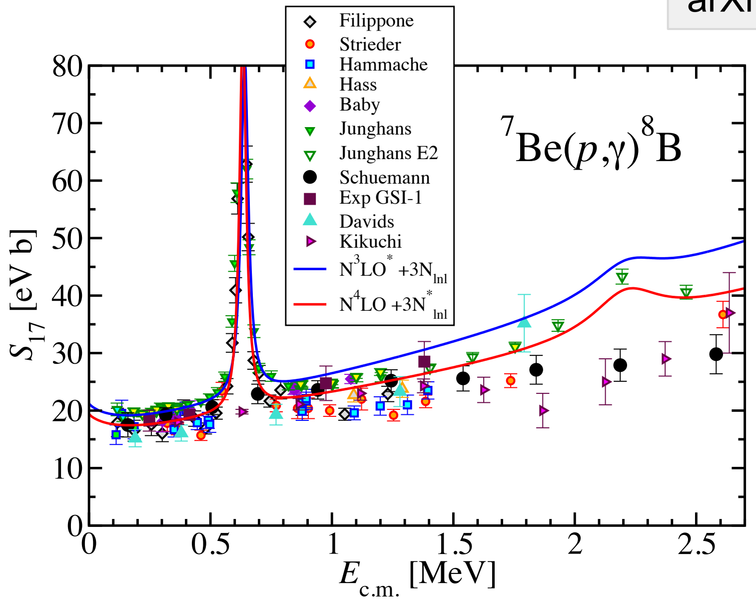


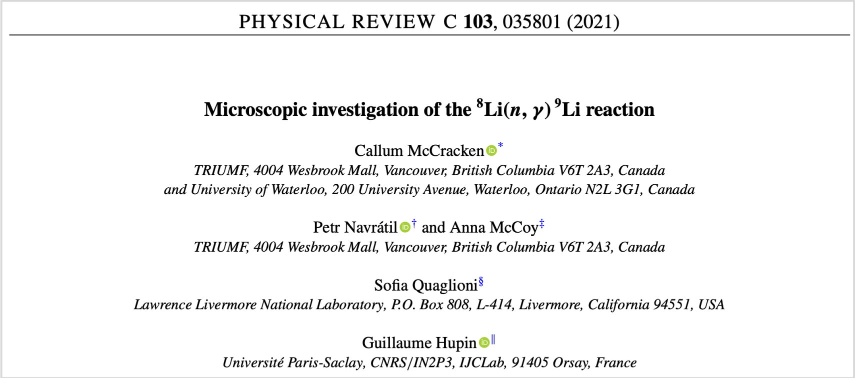


Ab initio prediction for the radiative capture of protons on ^{7}Be

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

Callum McCracken[*]
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and University of Waterloo, 200 University Avenue, Waterloo, Ontario N2L 3G1, Canada

Petr Navrátil[†] and Anna McCoy[‡]
TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada

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?

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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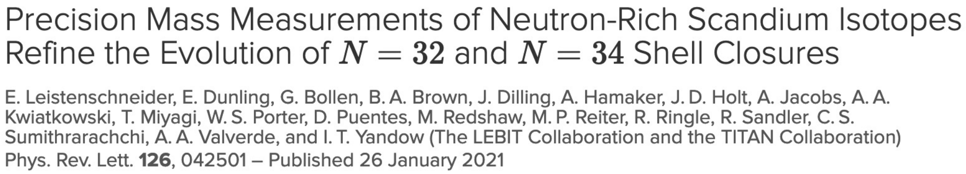
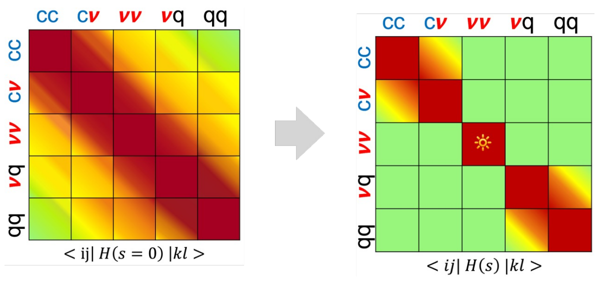
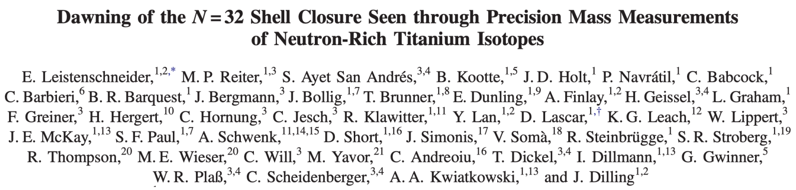
    - Fundamental symmetries: CKM unitarity, anapole moments, EDM
- Properties to constrain nuclear EOS: neutron skin and dipole polarizability in ^{208}Pb
- Extension to atomic systems in progress, e.g., for laser spectroscopy
- Large-scale high-performance computation: Cedar@Compute Canada
- **Synergy 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)


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

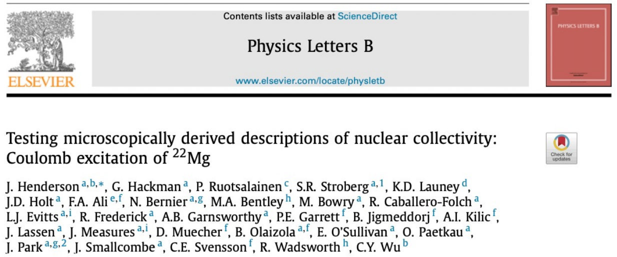
E. Leistenschneider, E. Dunling, G. Bollen, B. A. Brown, J. Dilling, A. Hamaker, J. D. Holt, A. Jacobs, A. A. Kwiatkowski, T. Miyagi, W. S. Porter, D. Puentes, M. Redshaw, M. P. Reiter, R. Ringle, R. Sandler, C. S. Sumithrarachchi, A. A. Valverde, and I. T. Yandow (The LEBIT Collaboration and the TITAN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



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]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Physics Letters B

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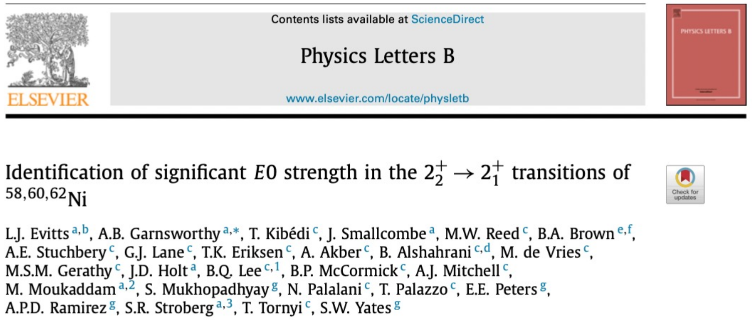
Testing microscopically derived descriptions of nuclear collectivity: Coulomb excitation of ^{22}Mg

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[h], M. Bowry[a], R. Caballero-Folch[a], L.J. Evitts[a,i], R. Frederick[a], A.B. Garnsworthy[a], P.E. Garrett[f], B. Jigmeddorj[f], A.I. Kilic[f], J. Lassen[a], J. Measures[a,i], 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]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Physics Letters B

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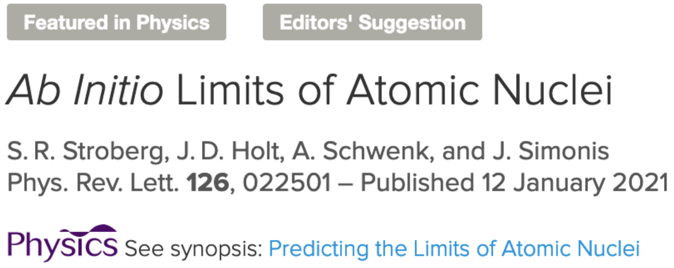
Identification of significant $E0$ strength in the $2_2^+ \rightarrow 2_1^+$ transitions of ^{58,60,62}Ni

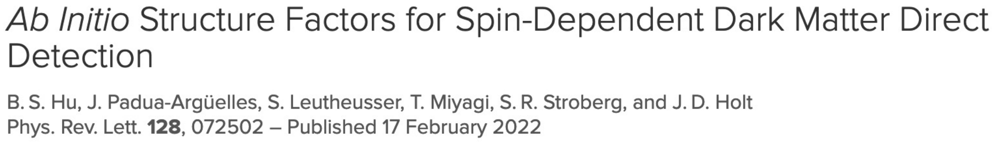
L.J. Evitts[a,b], A.B. Garnsworthy[a,*], T. Kibédi[c], J. Smallcombe[a], M.W. Reed[c], B.A. Brown[e,f], A.E. Stuchbery[c], G.J. Lane[c], T.K. Eriksen[c], A. Akber[c], B. Alshahrani[c,d], M. de Vries[c], M.S.M. Gerathy[c], J.D. Holt[a], B.Q. Lee[c,1], B.P. McCormick[c], A.J. Mitchell[c], M. Moukaddam[a,2], 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

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
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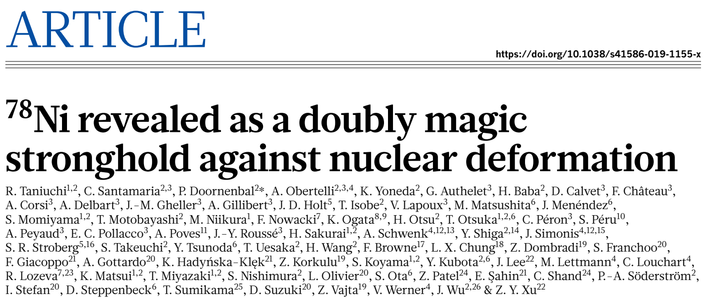
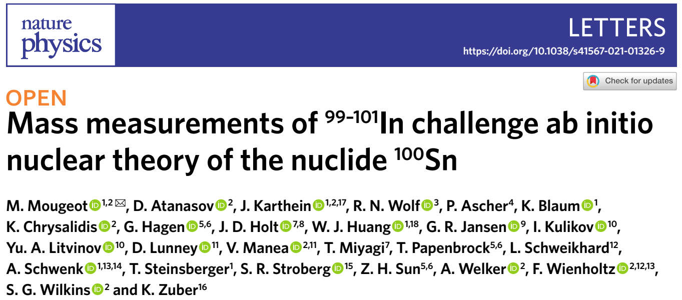

ARTICLE

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]



LETTERS

https://doi.org/10.1038/s41567-021-01326-9

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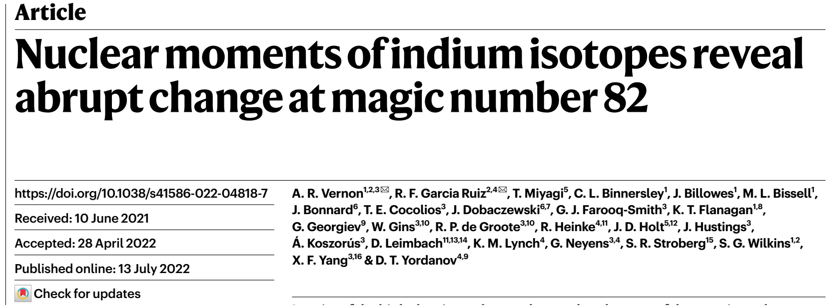
Mass measurements of $^{99-101}$In challenge ab initio nuclear theory of the nuclide ^{100}Sn

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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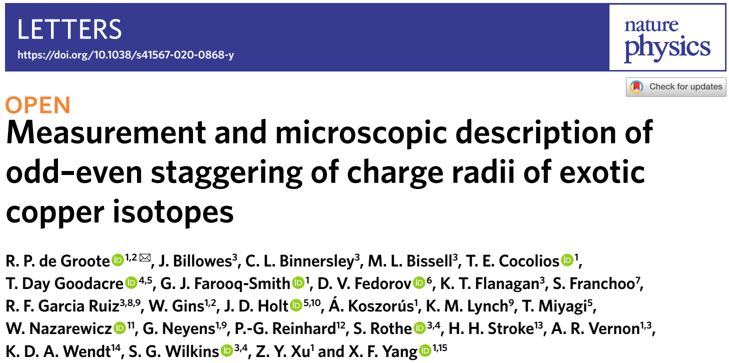
A. R. Vernon[1,2,3], R. F. Garcia Ruiz[2,4], T. Miyagi[5], C. L. Binnersley[1], J. Billowes[1], M. L. Bissell[1], J. Bonnard[6], T. E. Cocolios[3], J. Dobaczewski[6,7], G. J. Farooq-Smith[3], K. T. Flanagan[1,8], G. Georgiev[9], W. Gins[3,10], R. P. de Groote[3,10], R. Heinke[4,11], J. D. Holt[5,12], 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

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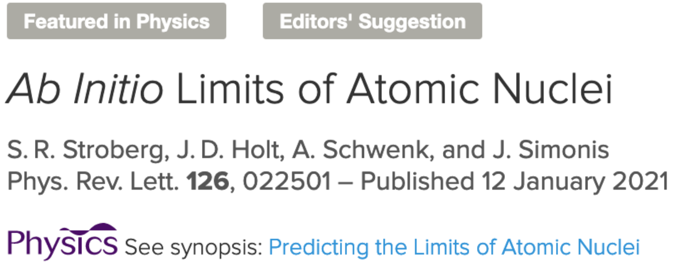
OPEN

Measurement and microscopic description of odd–even staggering of charge radii of exotic copper isotopes

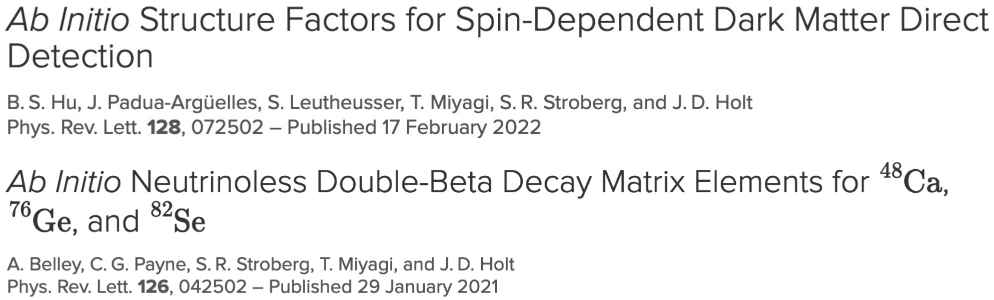
R. P. de Groote[1,2], J. Billowes[3], C. L. Binnersley[3], M. L. Bissell[3], T. E. Cocolios[1], T. Day Goodacre[4,5], G. J. Farooq-Smith[1], D. V. Fedorov[6], K. T. Flanagan[3], S. Franchoo[7], R. F. Garcia Ruiz[3,8,9], W. Gins[1,2], J. D. Holt[5,10], Á. Koszorús[1], K. M. Lynch[9], T. Miyagi[5], W. 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]



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

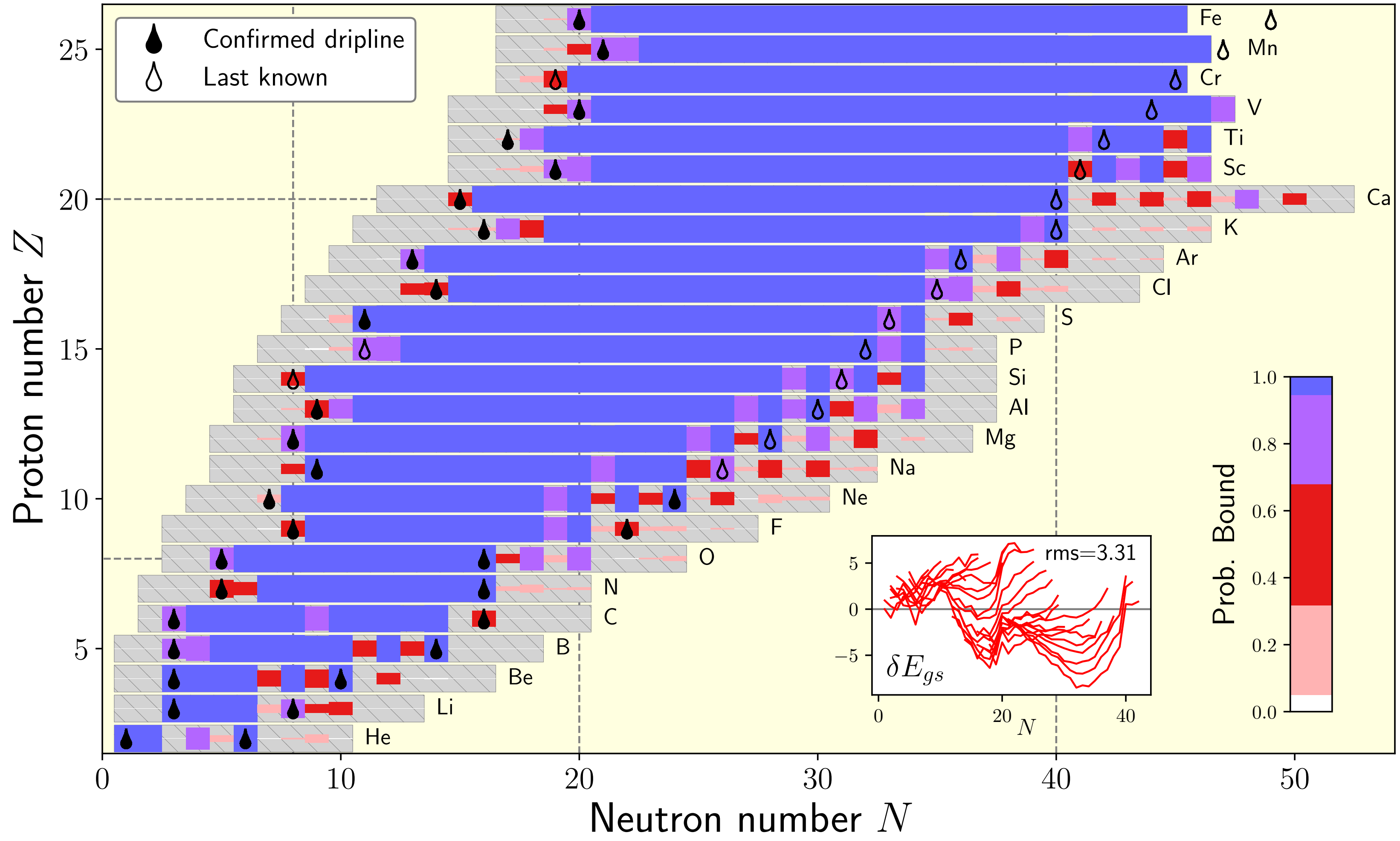
B. S. Hu, J. Padua-Argüelles, S. Leutheusser, T. Miyagi, S. R. Stroberg, and J. D. Holt
Phys. Rev. Lett. **128**, 072502 – Published 17 February 2022

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

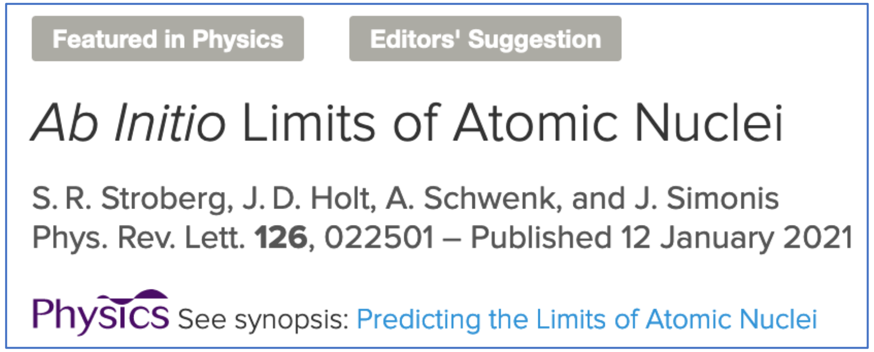
First predictions of proton and neutron driplines from first principles



From **few body** data only:

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

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



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

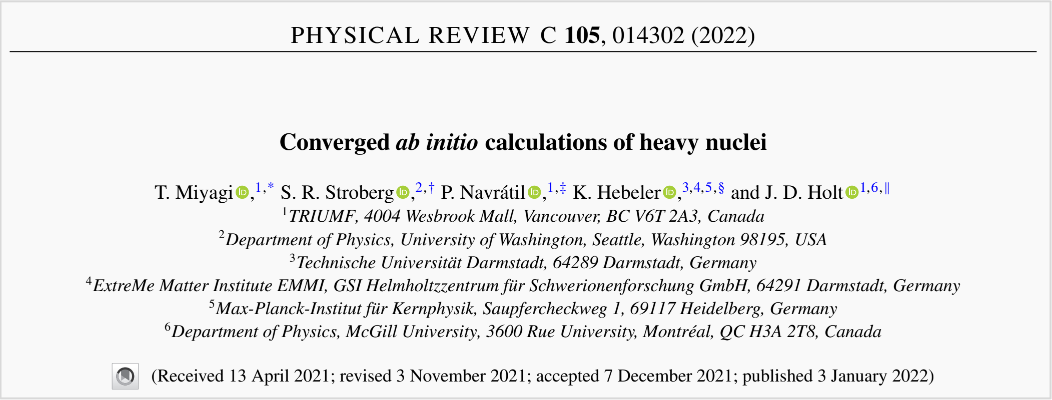
Physics See synopsis: Predicting the Limits of Atomic Nuclei

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

Provide ab initio predictions for neutron-rich region

Ab initio calculations for heavy nuclei

- Challenge: Convergence with respect to the number of three-nucleon (3N) force matrix elements
- Breakthrough in storage achieved
- Opens possibilities for calculations of ^{132}Sn, ^{208}Pb, … superheavy isotopes?!?

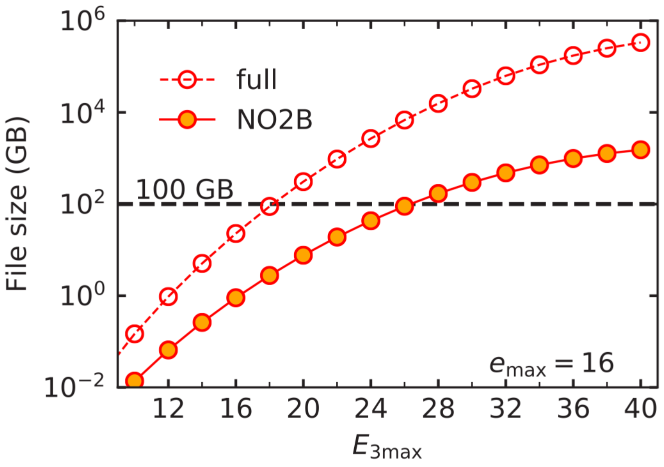


PHYSICAL REVIEW C **105**, 014302 (2022)

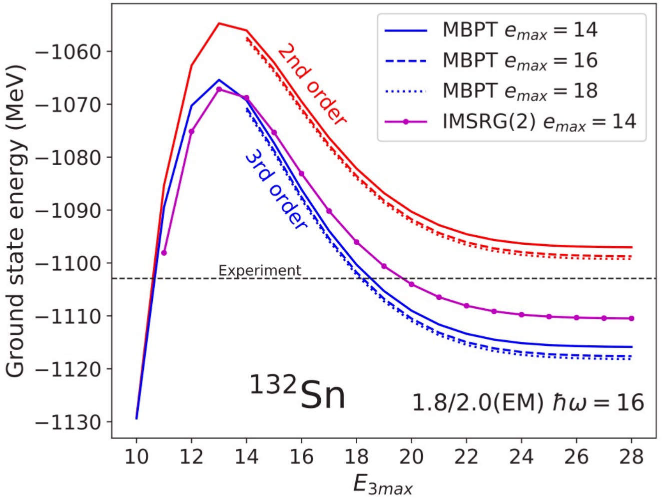
Converged *ab initio* calculations of heavy nuclei

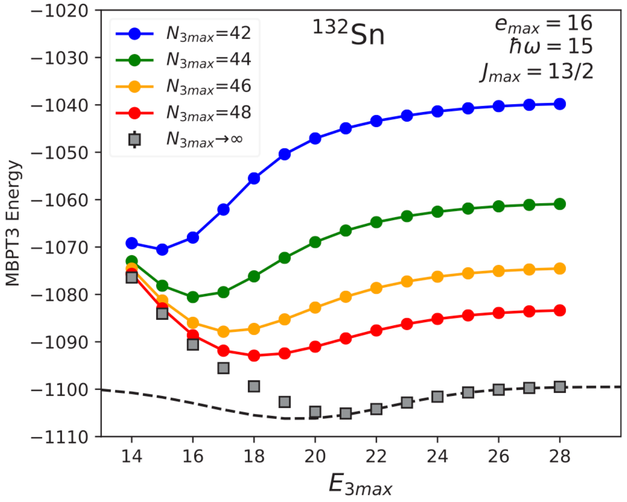
T. Miyagi[1,*] S. R. Stroberg[2,†] P. Navrátil[1,‡] K. Hebeler[3,4,5,§] and J. D. Holt[1,6,∥]
[1]*TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[2]*Department of Physics, University of Washington, Seattle, Washington 98195, USA*
[3]*Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[4]*ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[5]*Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*
[6]*Department of Physics, McGill University, 3600 Rue University, Montréal, QC H3A 2T8, Canada*

(Received 13 April 2021; revised 3 November 2021; accepted 7 December 2021; published 3 January 2022)



Ground-state energy of ^{132}Sn with chiral NN+3N 1.8/2.0 (EM) & NN N^{3}LO+3N$_{lnl}$





Neutron Skin of ^{208}Pb

TRIUMF/ORNL/Chalmers collaboration

Machine learning: calibrate on light nuclei (**green**)

10^8 calculations spanning EFT parameter space

34 non-implausible NN+3N interactions (with uncertainties)

Validate for ^{48}Ca (**blue**) + ^{208}Pb predictions (**pink**)

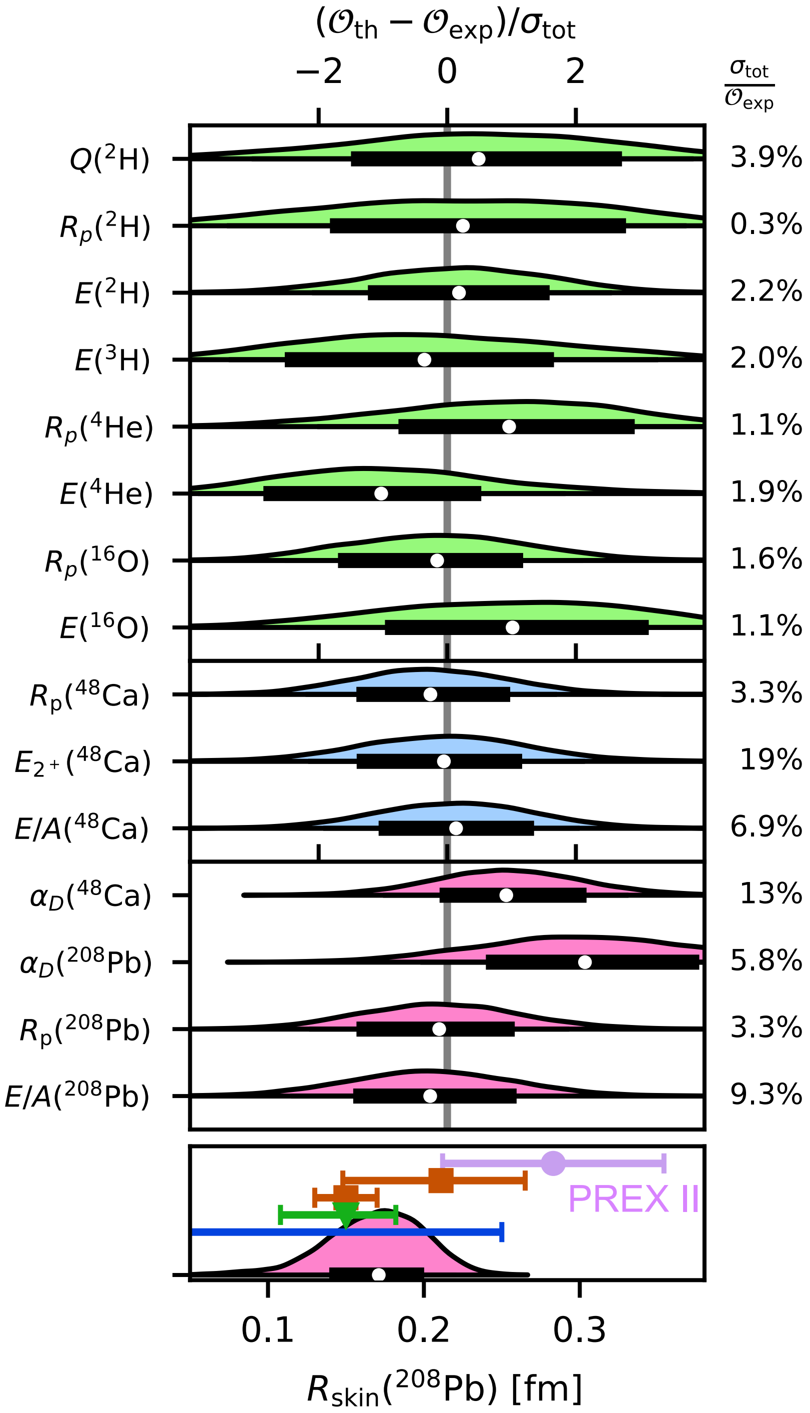
E/A, 2^+, radii, dipole polarizability

Final prediction for neutron skin with systematic uncertainty

$R_{skin}(^{208}Pb) = 0.15\text{-}0.19$ fm

Mild tension with new PREX measurement

B. Hu, W. Jiang, T. Miyagi, Z. Sun et al., Nature Phys. (in press)



TRIUMF

Large-Scale Efforts for Ab Initio GT Transitions

Calculate **large GT matrix elements**

$$M_{\mathrm{GT}} = g_A \langle f | \mathcal{O}_{\mathrm{GT}} | i \rangle$$

$$\mathcal{O}_{\mathrm{GT}} = \mathcal{O}^{1\mathrm{b}}_{\sigma\tau} + \mathcal{O}^{2\mathrm{b}}_{2BC}$$

- Light, medium, and heavy regions
- Benchmark different ab initio methods
- Wide range of NN+3N forces
- Consistent inclusion of 2BC

LETTERS
https://doi.org/10.1038/s41567-019-0450-7
nature physics

Discrepancy between experimental and theoretical β-decay rates resolved from first principles

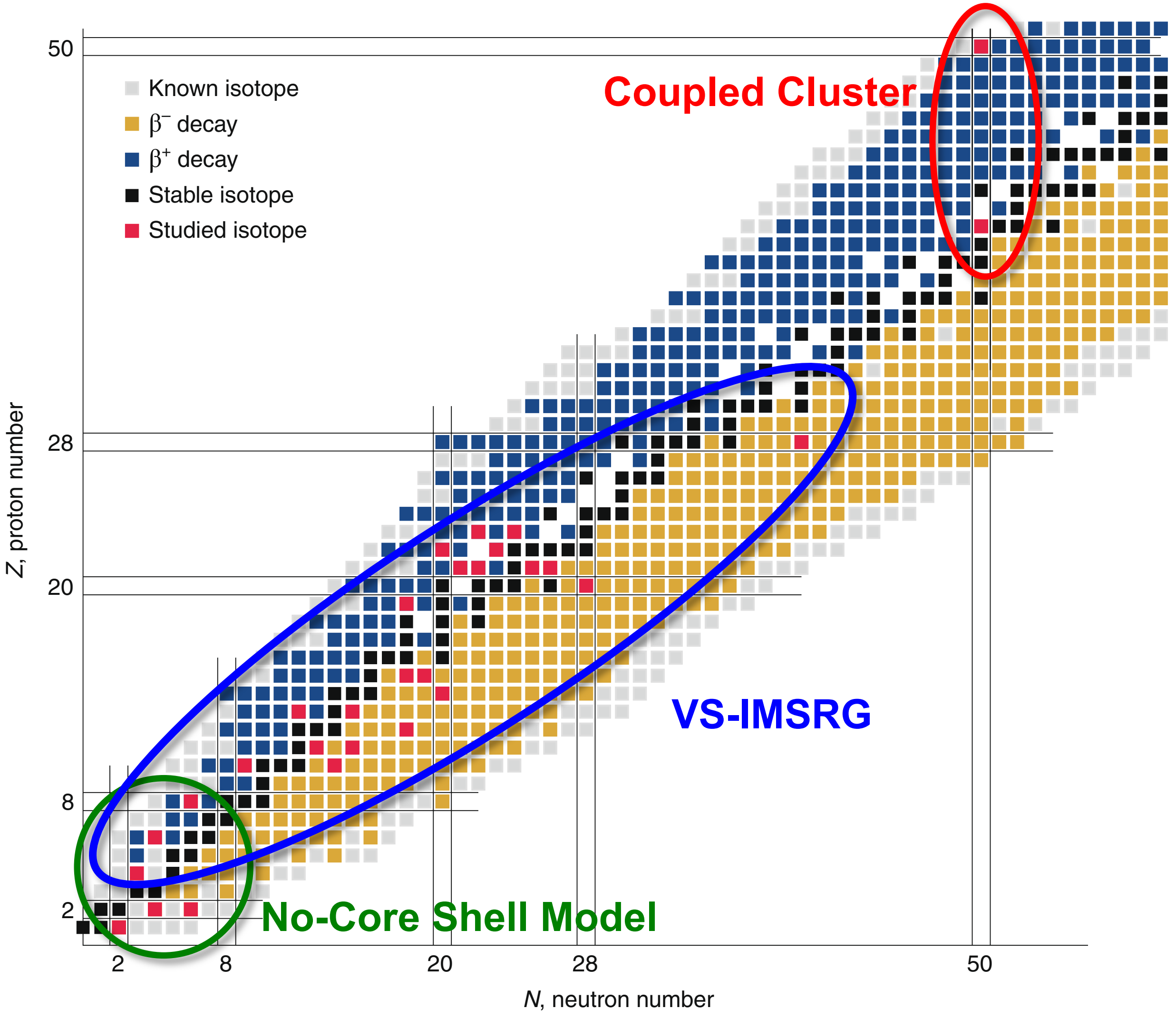
P. Gysbers[1,2], G. Hagen[3,4]*, J. D. Holt[1], G. R. Jansen[3,5], T. D. Morris[3,4,6], P. Navrátil[1], T. Papenbrock[3,4], S. Quaglioni[7], A. Schwenk[8,9,10], S. R. Stroberg[1,11,12] and K. A. Wendt[7]

0

NUCLEAR PHYSICS

Beta decay gets the ab initio treatment

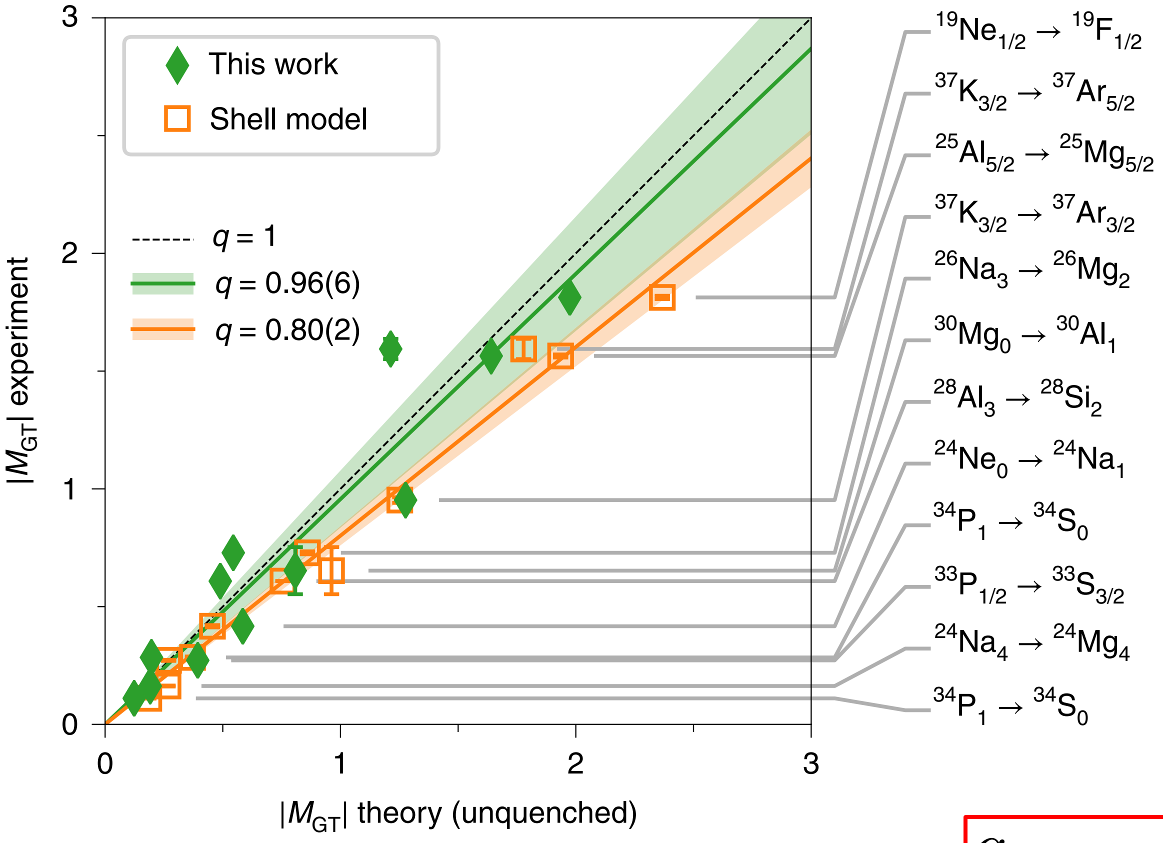
One of the fundamental radioactive decay modes of nuclei is β decay. Now, nuclear theorists have used first-principles simulations to explain nuclear β decay properties across a range of light- to medium-mass isotopes, up to ^{100}Sn.

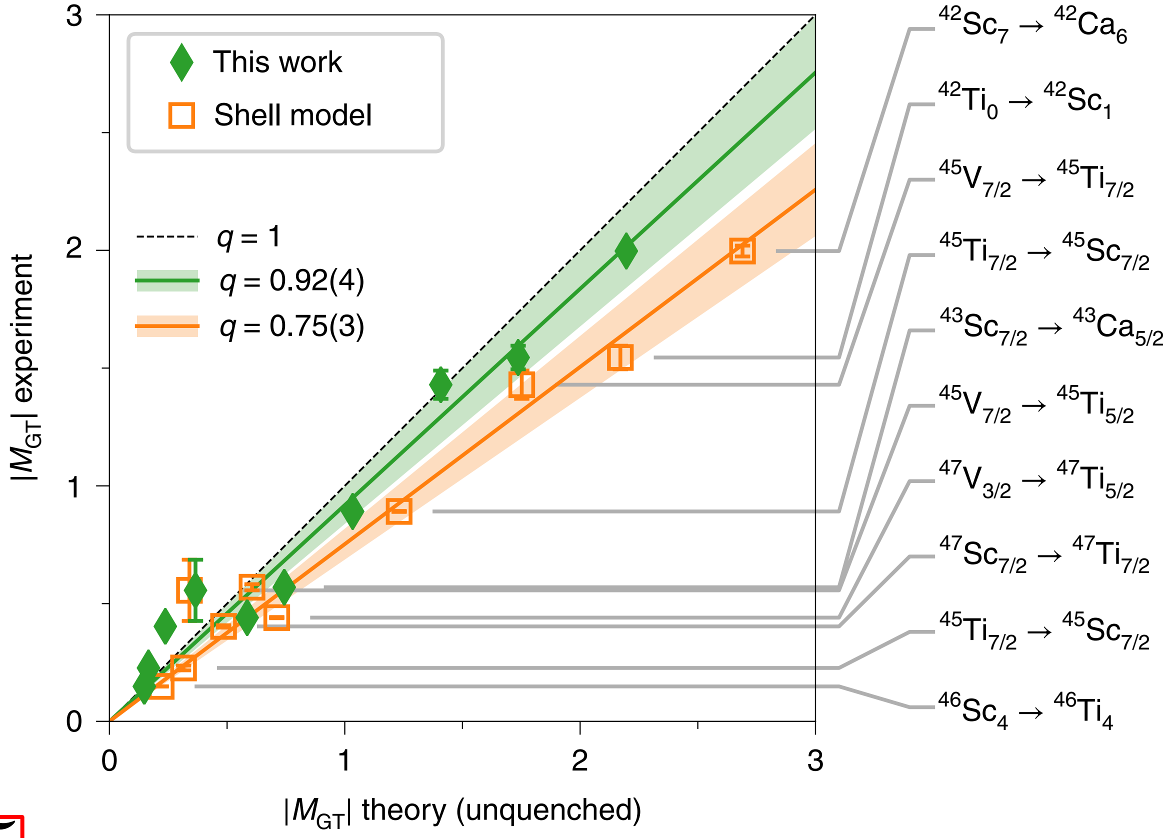


Solution to g_A-Quenching Problem

Comparison to standard phenomenological shell model

Ab initio calculations across the chart explain data with unquenched g_A





$$\boxed{g_A = 1.25}$$

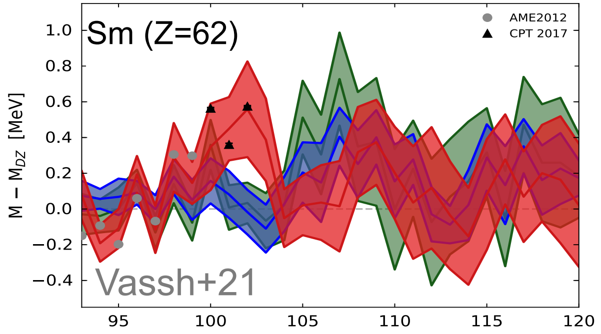
Gysbers et al., Nature Phys. (2019)

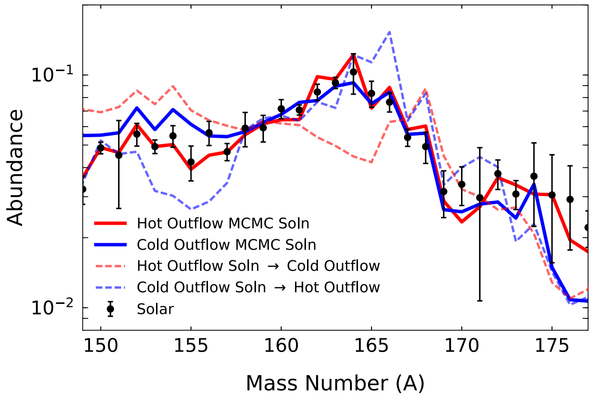
Refine results with improvements in forces and many-body methods

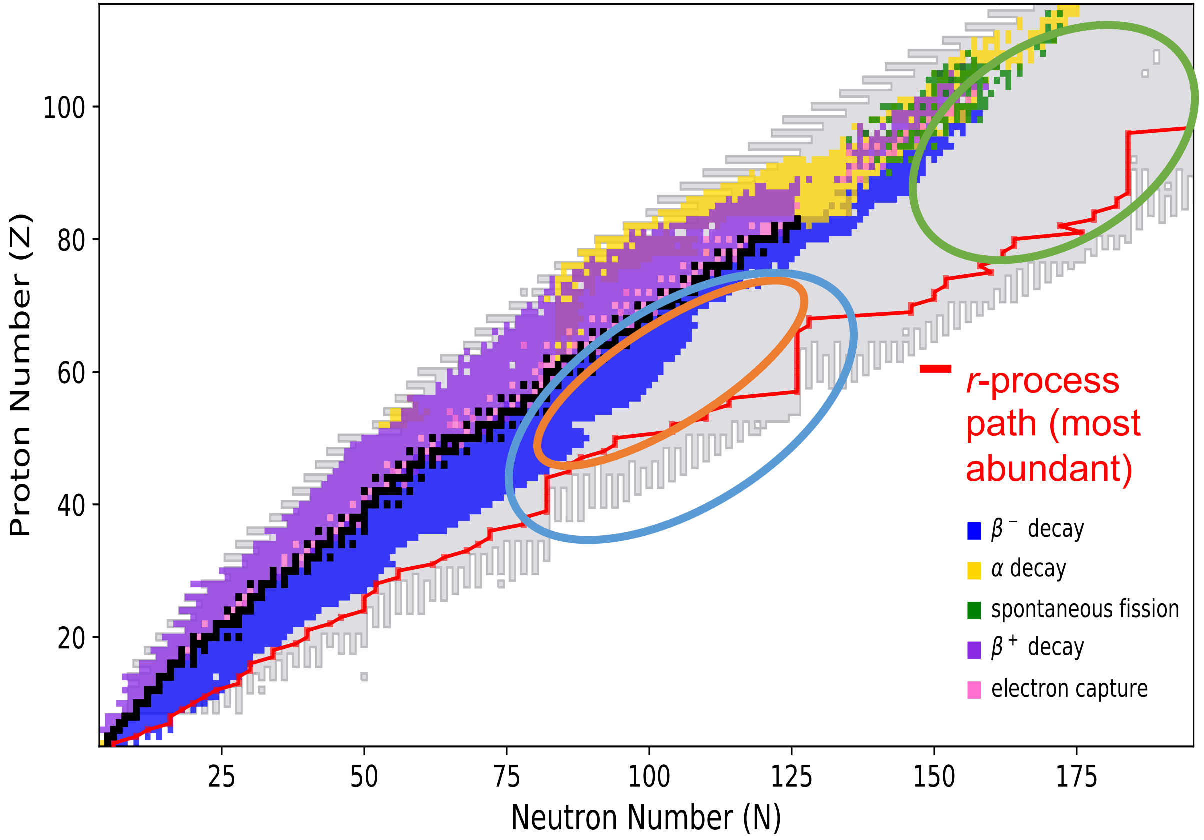
Nuclear Astrophysics Theory

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

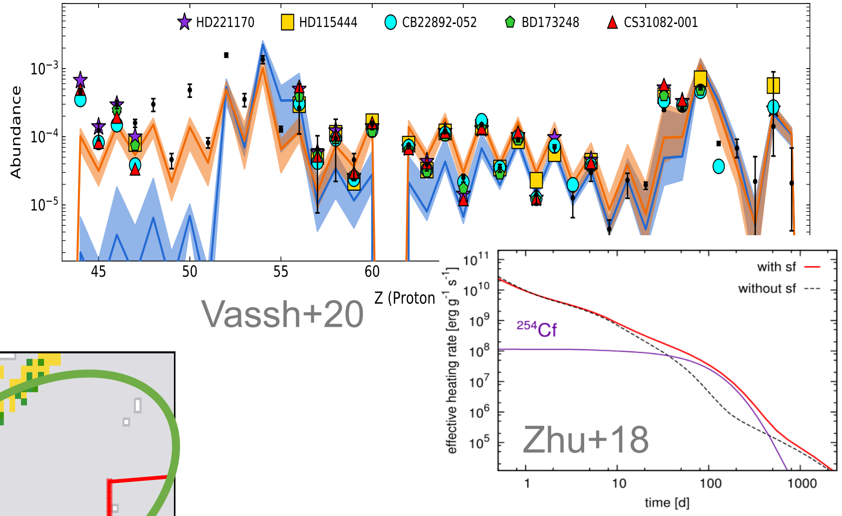
Statistical methods to predict masses of neutron-rich rare-earths using Solar abundances



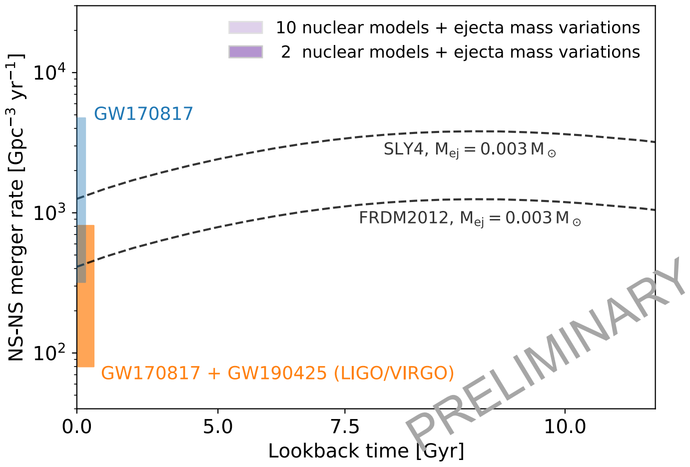




Studies of possible fission signatures: universality of *r*-process abundances? ^{254}Cf and actinide heating in neutron star merger kilonova light curves?



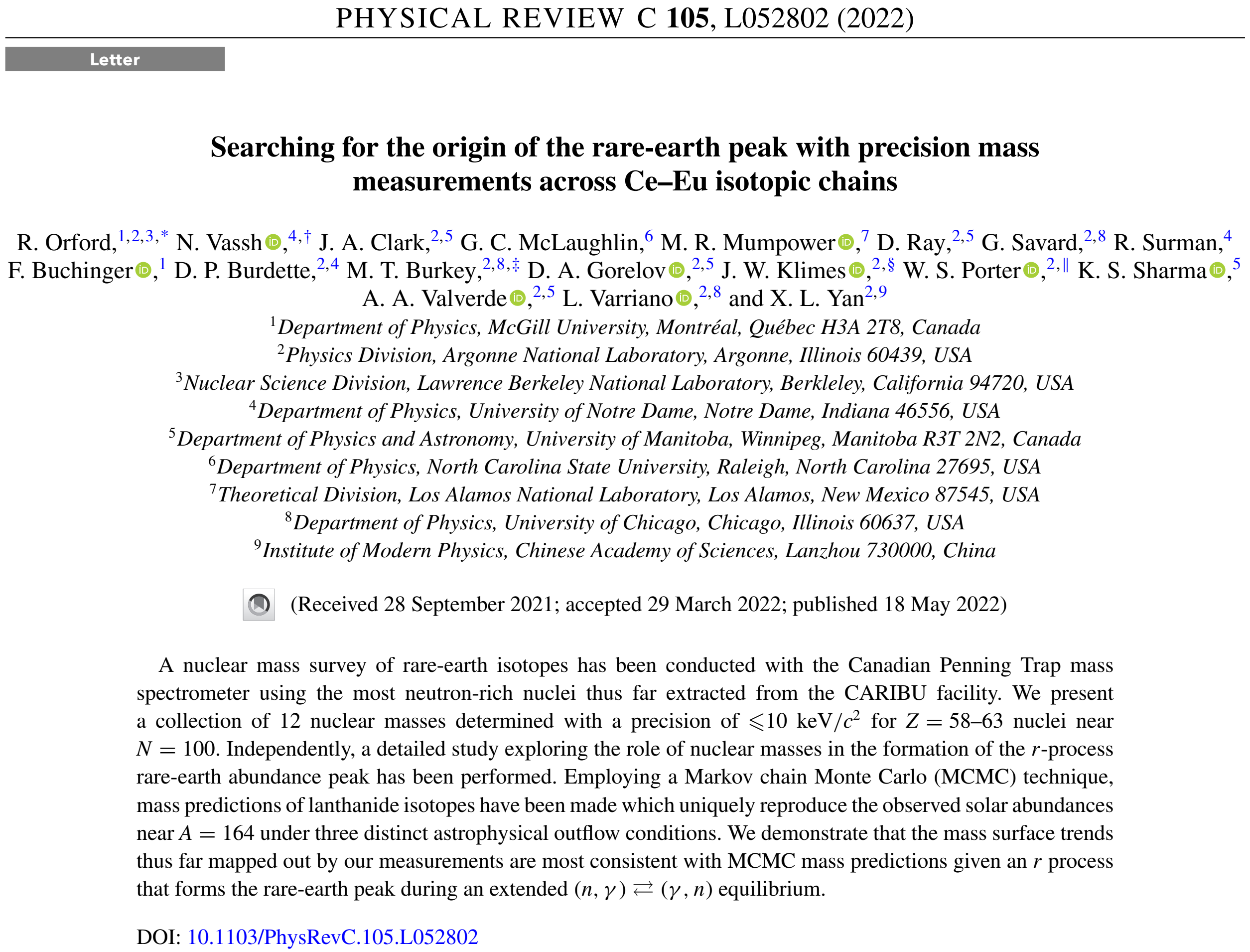
LIGO merger rate + nuclear physics uncertainties: are NSNS mergers the source of Solar system heavy elements? Can LIGO disfavor some nuclear models?



See Côté+18

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*

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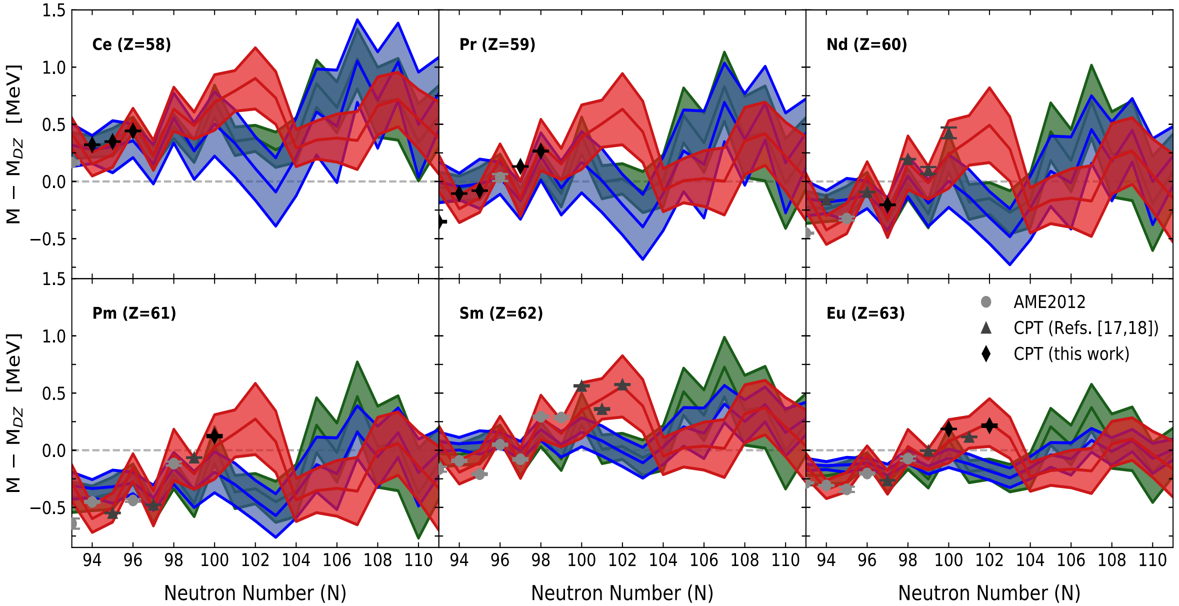
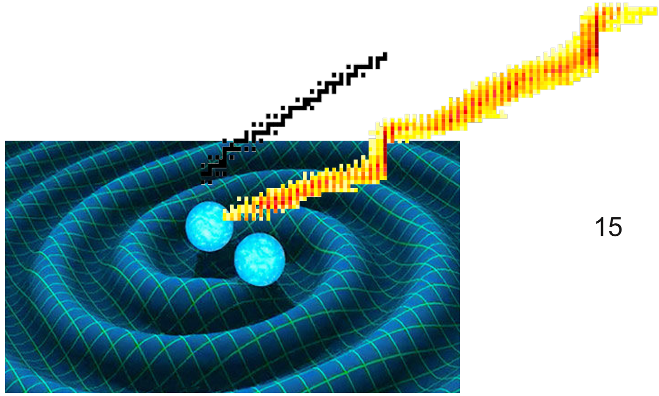
A nuclear mass survey of rare-earth isotopes has been conducted with the Canadian Penning Trap mass spectrometer using the most neutron-rich nuclei thus far extracted from the CARIBU facility. We present a collection of 12 nuclear masses determined with a precision of $\leqslant 10$ keV/c^2 for $Z = 58$–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



Nuclear Astrophysics Theory

- **Research program focuses on the origin of heavy elements with an emphasis on the impact of unknown nuclear physics on observables**
  - Statistical methods + rare-earth nuclei work ongoing (in prep work exploring impact of Solar data uncertainties; theory support for two accepted proposals at ANL to measure more n-rich rare-earth masses (ex ^{164}Nd))
  - Work on the impacts and signatures of fission in nucleosynthesis ongoing (in prep sensitivity study for neutron-induced fission; theory support for accepted Hubble Space Telescope proposal to measure abundances of possible fission products in metal-poor stars)
  - Work to use LIGO data to pin down heavy element origins and search for disfavored nuclear models ongoing (in prep work extending NSNS merger study to elements other than Eu, in prep work incorporating NSBH mergers)
- **Future directions and synergies with the TRIUMF team**
  - Interest in reducing nuclear data uncertainties near N=82 to pin down predicted shape of 2nd *r*-process peak (connection to TITAN capabilities)
  - Interest in expanding program to other processes such as supernova nucleosynthesis and *i*-process (connections with DRAGON and future TRISR neutron storage ring)
  - Interest in the strength of the N=126 shell closure to refine predictions for 3rd peak element (ex gold) production in NSMs (connection with ab initio nuclear theory (newly started N=126 project w/ J. Holt))
  - Interest in dark matter and neutrino physics in explosive events such as NSMs and SN (connection with particle theorists (newly started dark neutron project w/ D. McKeen))

New initiatives: Establishment of Theory Centres

- **Ab Initio Nuclear Theory Centre** Strengthen TRIUMF nuclear *ab initio* program
  - Require additional nuclear theorist with associated postdoc position
    - Quantum many-body theory (in the future quantum computing?)
    - Intersection of nuclear and quantum chemistry *ab initio* theory
    - Increasing reach to heavy nuclei – connection to r-process modeling, Radioactive Molecules
  - Increase synergy with ARIEL program and the newly proposed AMO/Precision/Quantum centre
  - **Build on existing strength → bigger impact**
- **TRIUMF Workshop/Visitor/Education Centre**
  - Model based on very successful centres such as the Institute for Nuclear Theory (INT)
  - Host multiple in-house workshop and collaboration programs year-round – cover all lab topics!
  - Program proposals would be submitted externally and reviewed by an evaluation committee
  - True workshop format: office space for participants, 2-week timeline, limited presentations.
  - Allow extended student and scientist visits from member universities/expand outreach

Future of Theory @ TRIUMF: Unified first-principles approach to all nuclei

- **Key recent/future applications in structure and reactions**
  - Nuclear reactions important for astrophysics and fusion energy generation such as
    - ^{7}Be(p, γ)^{8}B, ^{3}He(α,γ)^{7}Li, ^{12}C(α, γ)^{16}O, ^{13}C(α,n)^{16}O, ^{3}H(d,n)^{4}He
  - Alpha clustering in nuclei and nuclear deformation
  - Structure of exotic nuclei like ^{11}Li studied extensively at TRIUMF ARIEL
  - Further dripline studies, nuclear shell evolution and shape coexistence
  - Extension to heavy nuclei: ^{208}Pb skin, input for r-process simulations, superheavy region(?!)
- **Ab initio theory for beyond-standard-model physics**
  - gA quenching → Neutrinoless double beta decay matrix elements for all key nuclei
  - WIMP-nucleus and neutrino-nucleus scattering for dark matter/neutrino
  - Calculations for nuclei in searches for symmetry-violating moments (eg, anapole, EDM…)
  - Superallowed beta decay for isospin mixing correction δ_C
- **Key applications of nuclear astrophysics**
  - Guide future ARIEL/worldwide RIB experiments for interpreting astrophysical observables
  - Advance applications of statistical methods/machine learning for nuclear astrophysics
  - Leverage multi-messenger/gravitational wave era capabilities to inform fundamental nuclear physics

In synergy with experiments, *ab initio* nuclear theory is the leading approach to understand low-energy properties of atomic nuclei