NUCLEAR PHYSICS OVER THE YEARS: FROM THE HIGH SPIN ERA TO RARE ISOTOPES

SEPTEMBER 19-20, 2025

TRAPPED AT ARGONNE

JASON CLARK
PHYSICS DIVISION

U.S. DEPARTMENT of ENERGY

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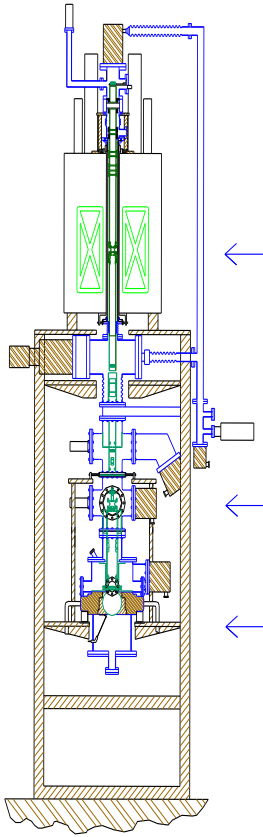
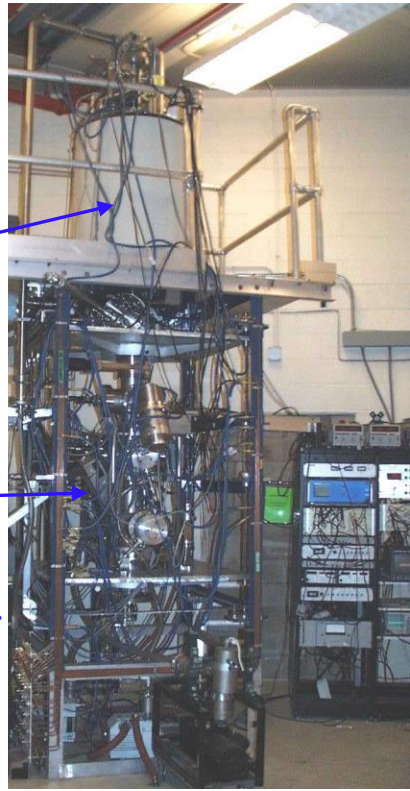
EARLY DAYS: MOVE OF CPT TO ANL

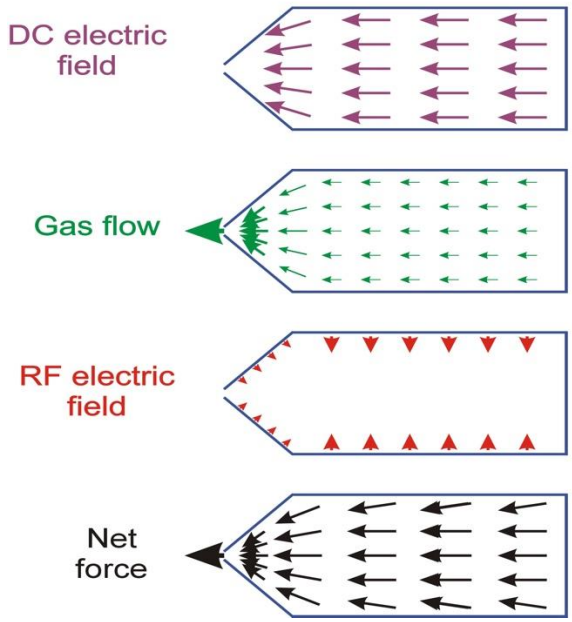
- Following shutdown of TASCC (Chalk River), a budding scientist (Guy Savard) was searching for a new home that could accommodate the Canadian Penning Trap (CPT)
- I worked on the CPT in 1996 at Chalk River, and came to Argonne in summer of 1997 (undergraduate research assistant) to help rebuild the CPT
- Collaboration between McGill U., U. Manitoba, and ANL began

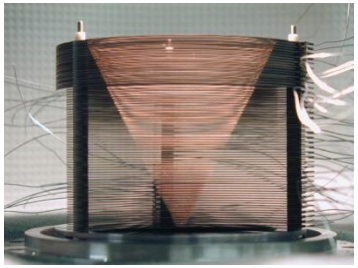




EARLY DAYS: GAS CATCHER DEVELOPMENT

- Guy had proposed new way to collect rare, short-lived isotopes and deliver them to the CPT: gas catcher
- Gas catcher uses gas, DC, and RF fields to thermalize and transport isotopes that enter it
- Years of development of gas catchers from handheld ones to the large ones of today
- Meanwhile, studies of systematic uncertainties with CPT underway (I joined as a Ph.D student)

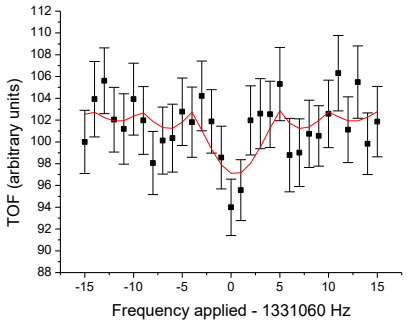


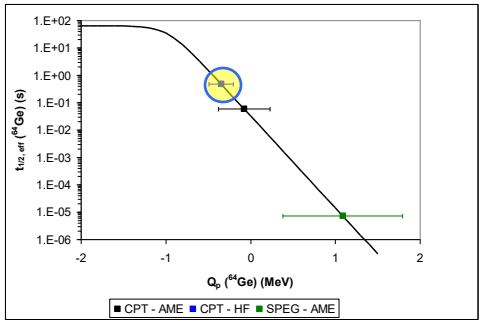


EARLY DAYS: FIRST MEASUREMENTS

- Originally planned to measure ^{38m}K (superallowed 0^+ to 0^+ beta decay), but later learned of importance of mass measurement of rp-process waiting point ^{68}Se which promised to be easier

- My thesis experiments of waiting-point nuclides ^{68}Se and ^{64}Ge were the kick-start to the CPT measurement program of short-lived rare isotopes collected by a gas catcher





J.A. Clark *et al.,* Phys. Rev. Lett **92,** 192501 (2004).

J.A. Clark *et al.,* Phys. Rev. C **75,** 032801® (2007).

AME: G. Audi *et al.,* Nucl. Phys. **A729,** 337 (2003).
HF: B. A. Brown *et al.*, Phys. Rev. C **65**, 045802 (2002).
SPEG: G.F. Lima *et al.*, Phys. Rev. C **65,** 044618 (2002).

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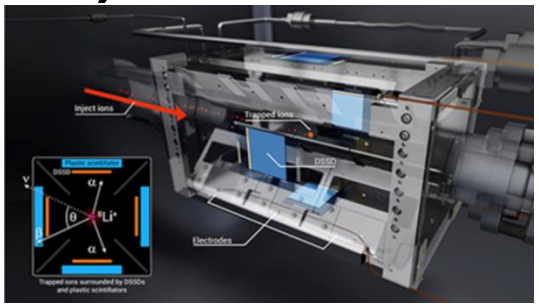
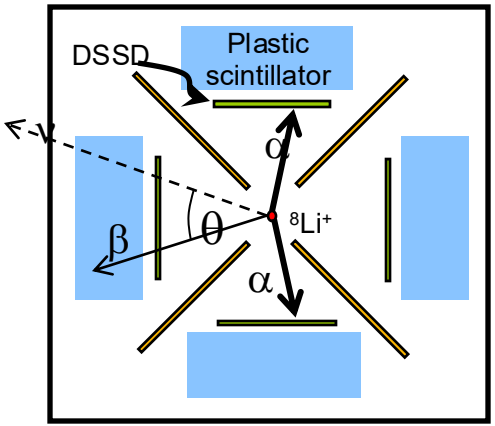
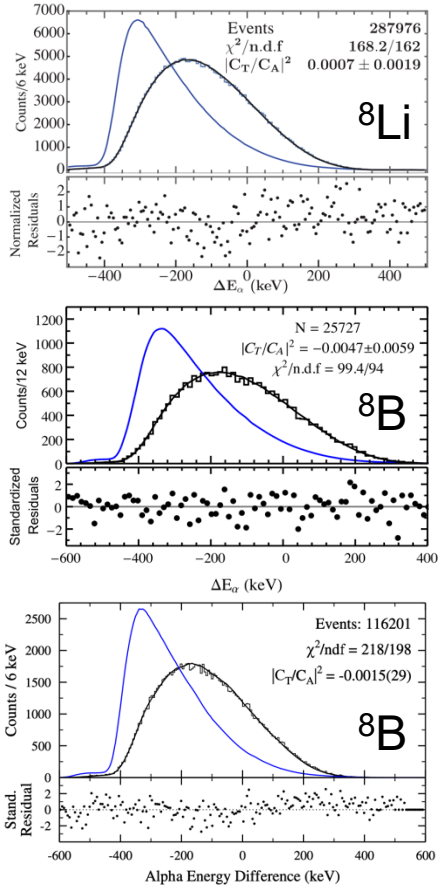
MEANWHILE … DEVELOPMENT OF THE BETA-DECAY PAUL TRAP (BPT)

- Paul trap was developed to study weak interaction (beta-neutrino correlation)
- Open volume Paul trap, surrounded by DSSDs, permitted study of ^{8}B, ^{8}Li decay
- Much improved limits on the contribution of the tensor component to the weak interaction
- Improved limits continue to show agreement with Standard Model predictions
- 8B: $a_{\beta\nu}$ = −0.3345+-0.0019 (stat)+-0.0021 (syst), consistent with the SM prediction of −1/3.



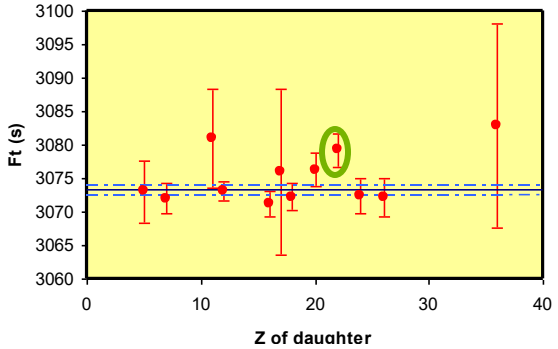


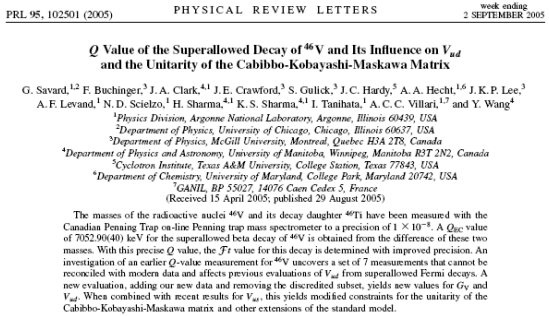


Burkey [ANL] PRL **128** (2022), Gallant [LLNL] PRL **130** (2023), Longfellow [LLNL] PRL **132** (2024)

EARLY DAYS: FIRST MEASUREMENTS

- Measurements of interest for rp-process nucleosynthesis continued, along with measurements of interest for CKM matrix unitarity
- More advanced gas catchers developed to optimize collection and transfer of more exotic and low mass ions
- Started program of measurements with ^{252}Cf fission fragments



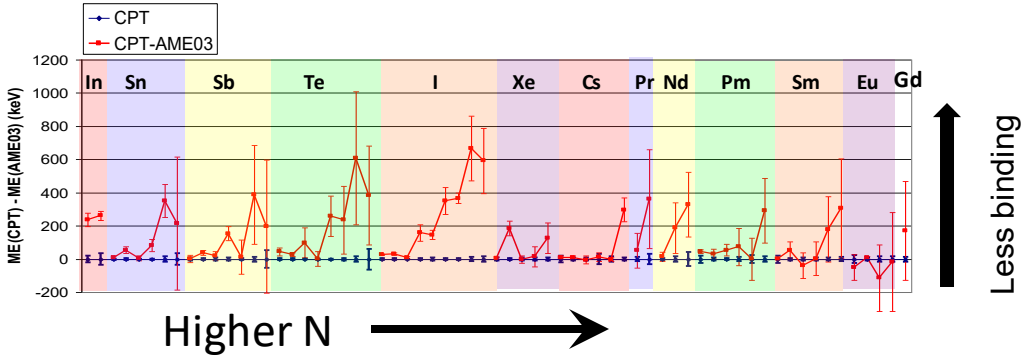

PRL 95, 102501 (2005) PHYSICAL REVIEW LETTERS week ending 2 SEPTEMBER 2005

Q Value of the Superallowed Decay of ^{46}V and Its Influence on V_{ud} and the Unitarity of the Cabibbo-Kobayashi-Maskawa Matrix

G. Savard,[1,2] F. Buchinger,[3] J. A. Clark,[4,1] J. E. Crawford,[3] S. Gulick,[3] J. C. Hardy,[5] A. A. Hecht,[1,6] J. K. P. Lee,[3] A. F. Levand,[1] N. D. Scielzo,[1] H. Sharma,[4,1] K. S. Sharma,[4,1] I. Tanihata,[1] A. C. C. Villari,[1,7] and Y. Wang[4]

[1]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2]*Department of Physics, University of Chicago, Chicago, Illinois 60637, USA*
[3]*Department of Physics, McGill University, Montreal, Quebec H3A 2T8, Canada*
[4]*Department of Physics and Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*
[5]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
[6]*Department of Chemistry, University of Maryland, College Park, Maryland 20742, USA*
[7]*GANIL, BP 55027, 14076 Caen Cedex 5, France*
(Received 15 April 2005; published 29 August 2005)

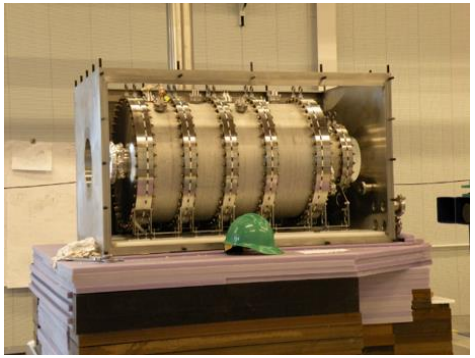
The masses of the radioactive nuclei ^{46}V and its decay daughter ^{46}Ti have been measured with the Canadian Penning Trap on-line Penning trap mass spectrometer to a precision of 1×10^{-8}. A Q_{EC} value of 7052.90(40) keV for the superallowed beta decay of ^{46}V is obtained from the difference of these two masses. With this precise Q value, the $\mathcal{F}t$ value for this decay is determined with improved precision. An investigation of an earlier Q-value measurement for ^{46}V uncovers a set of 7 measurements that cannot be reconciled with modern data and affects previous evaluations of V_{ud} from superallowed Fermi decays. A new evaluation, adding our new data and removing the discredited subset, yields new values for G_V and V_{ud}. When combined with recent results for V_{us}, this yields modified constraints for the unitarity of the Cabibbo-Kobayashi-Maskawa matrix and other extensions of the standard model.

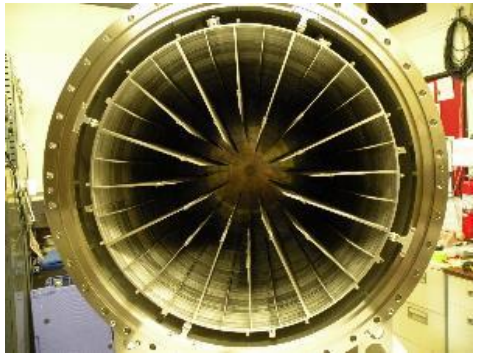


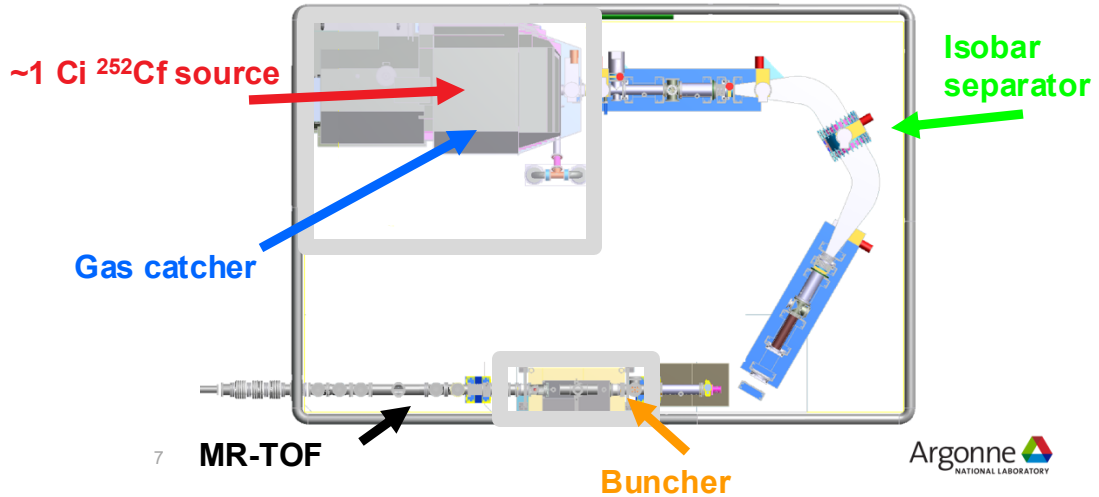
J. Van Schelt *et al.*, Phys. Rev. C **85**, 045805 (2012)

THE RIA YEARS: NEW FACILITIES

- Competition for the next generation facility included Argonne's proposal utilizing gas catcher technology
- While waiting for a decision to go ahead with a new facility and the site for the new facility, CARIBU was proposed, and started delivering beams in 2010
- CPT moved to CARIBU and started taking beams

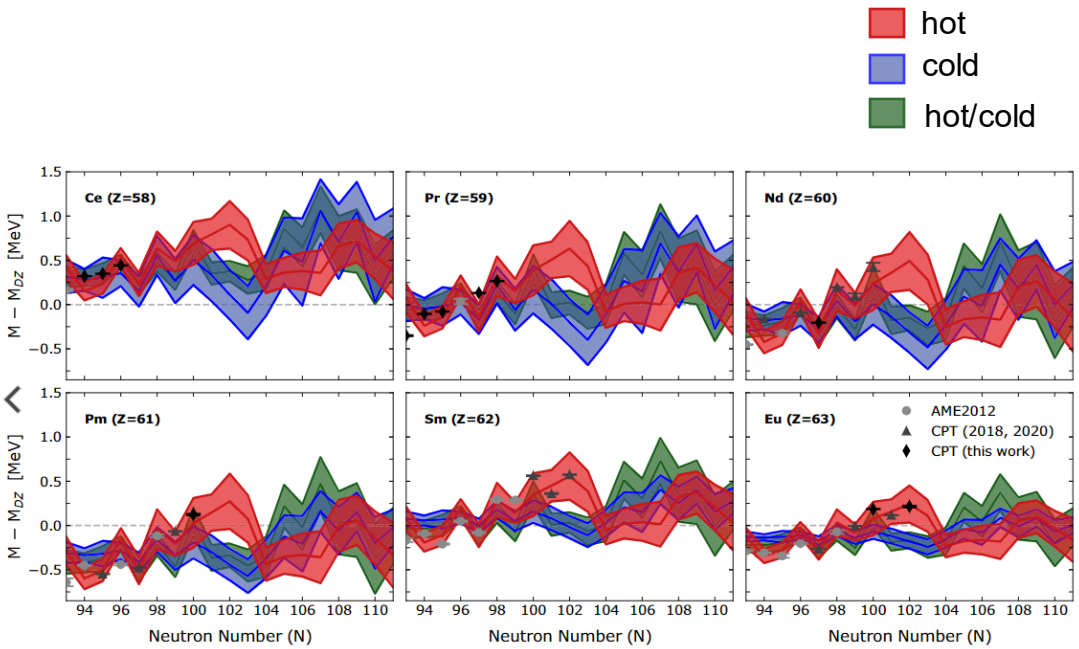




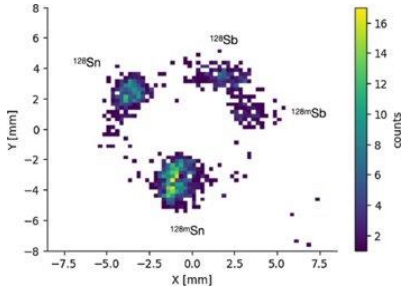


THE CARIBU YEARS

- Large number of ^{252}Cf fission fragments measured with the CPT
- Measurements helped to determine possible sites of the astrophysical *r* process
- Converted mass measurement technique from TOF-ICR to PI-ICR
- Measurements also used to examine nuclear structure, improve mass models, and determine relevance of “astromers”



R. Orford, N. Vassh *et al.*, Phys. Rev. C, **105**, L052802 (2022).

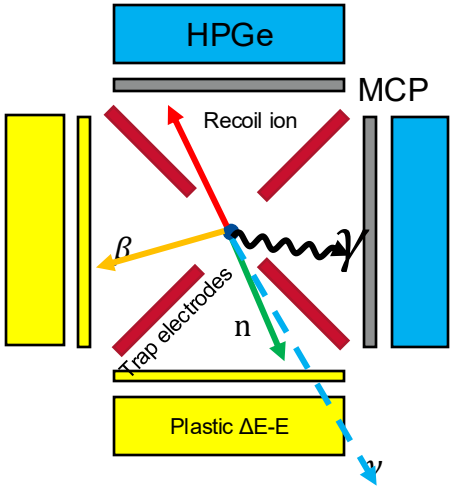


D. Hoff et al, Phys. Rev. Lett. **131** (2023) 262701

THE CARIBU YEARS

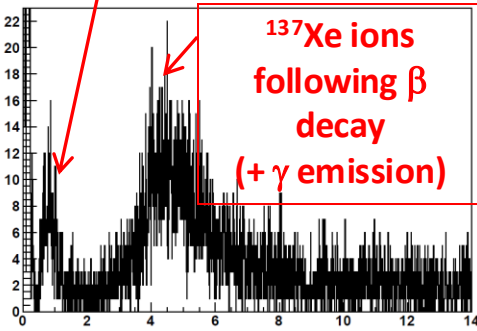
- Beta-decay Paul Trap (BPT) moved to CARIBU in 2013 for series of measurements of beta-delayed neutron (BDN) emission
- BDN program had started in 2010 by outfitting BPT with MCPs, plastic scintillators, and Ge detectors to look at ^{137}I decay
- Success of program in 2013 led to development of trap dedicated to studying BDN in new CARIBU hall (ex Tandem hall) with BEARtrap

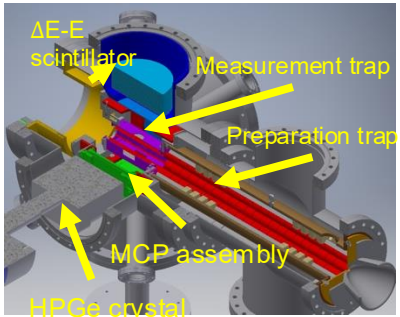
N.D. Scielzo *et al.*, NIM A **681**, 94 (2012).

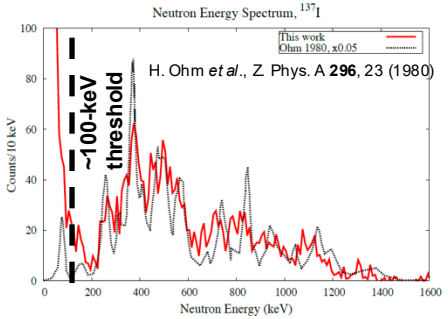


^{136}Xe ions following β-delayed neutron emission

^{137}Xe ions following β decay (+ γ emission)

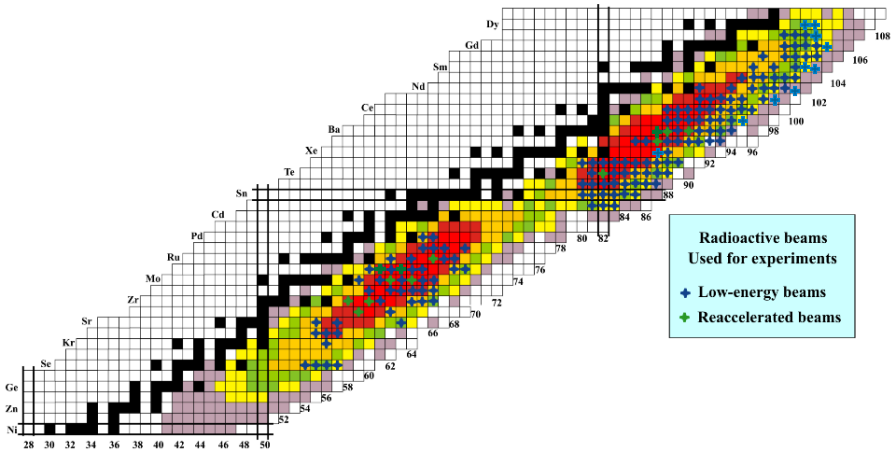






THE CARIBU YEARS

- Tandem removed and space became the new experimental hall for CARIBU low-energy (stopped) beams
- X-array, SATURN, MTAS, SuN, implantation station, ATLANTIS, BEARtrap, …



X-array and SATURN

MTAS

SuN

THE CARIBU YEARS

- Papers with R.V.F. Janssens and J.A. Clark as co-authors primarily with CARIBU beams (low energy …)

PHYSICAL REVIEW C **93**, 014306 (2016)

γ-soft ^{146}Ba and the role of nonaxial shapes at $N \approx 90$

A. J. Mitchell,[1,*] C. J. Lister,[1] E. A. McCutchan,[2] M. Albers,[3,†] A. D. Ayangeakaa,[3] P. F. Bertone,[3,‡] M. P. Carpenter,[3] C. J. Chiara,[3,4,§] P. Chowdhury,[1] J. A. Clark,[3] P. Copp,[1] H. M. David,[3,‖] A. Y. Deo,[1,¶] B. DiGiovine,[3] N. D'Olympia,[1,#] R. Dungan,[5] R. D. Harding,[1,6,**] J. Harker,[3,4] S. S. Hota,[1,††] R. V. F. Janssens,[3] F. G. Kondev,[7] S. H. Liu,[8,9,‡‡] A. V. Ramayya,[10] J. Rissanen,[11,§§] G. Savard,[3,12] D. Seweryniak,[3] R. Shearman,[1,6,‖‖] A. A. Sonzogni,[2] S. L. Tabor,[5] W. B. Walters,[4] E. Wang,[10] and S. Zhu[3]

PHYSICAL REVIEW LETTERS **120,** 182502 (2018)

Masses and β-Decay Spectroscopy of Neutron-Rich Odd-Odd ^{160,162}Eu Nuclei: Evidence for a Subshell Gap with Large Deformation at $N = 98$

D. J. Hartley,[1] F. G. Kondev,[2] R. Orford,[2,3] J. A. Clark,[2,4] G. Savard,[2,5] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] F. Buchinger,[3] M. T. Burkey,[2,5] M. P. Carpenter,[2] P. Copp,[2,6] D. A. Gorelov,[2,4] K. Hicks,[1] C. R. Hoffman,[2] C. Hu,[7] R. V. F. Janssens,[2,‡] J. W. Klimes,[2] T. Lauritsen,[2] J. Sethi,[2,8] D. Seweryniak,[2] K. S. Sharma,[9] H. Zhang,[7] S. Zhu,[2] and Y. Zhu[7]

PHYSICAL REVIEW C **101**, 044301 (2020)

High-K, two-quasiparticle states in ^{160}Gd

D. J. Hartley,[1] F. G. Kondev,[2] G. Savard,[2] J. A. Clark,[2] A. D. Ayangeakaa,[2,*] S. Bottoni,[2,†] M. P. Carpenter,[2] P. Copp,[2,3] K. Hicks,[1] C. R. Hoffman,[2] R. V. F. Janssens,[4,5] T. Lauritsen,[2] R. Orford,[6,‡] J. Sethi,[2,7] and S. Zhu[2,§]

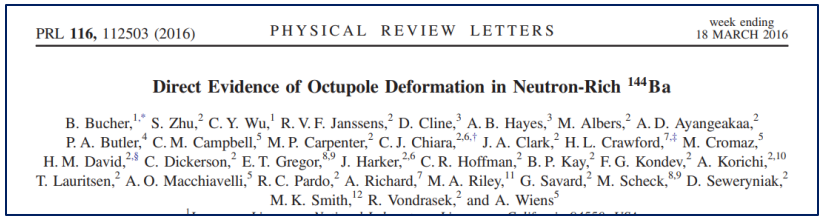
PHYSICAL REVIEW C **103**, 024323 (2021)

Ground-state and decay properties of neutron-rich ^{106}Nb

A. J. Mitchell,[1,*] R. Orford,[2,3,†] G. J. Lane,[1] C. J. Lister,[4] P. Copp,[4,‡] J. A. Clark,[3] G. Savard,[3,5] J. M. Allmond,[6] A. D. Ayangeakaa,[7,8] S. Bottoni,[3,§] M. P. Carpenter,[3] P. Chowdhury,[4] D. A. Gorelov,[3,9] R. V. F. Janssens,[7,8] F. G. Kondev,[3] U. Patel,[1,‖] D. Seweryniak,[3] M. L. Smith,[1,¶] Y. Y. Zhong,[1] and S. Zhu[3,#]

THE CARIBU YEARS

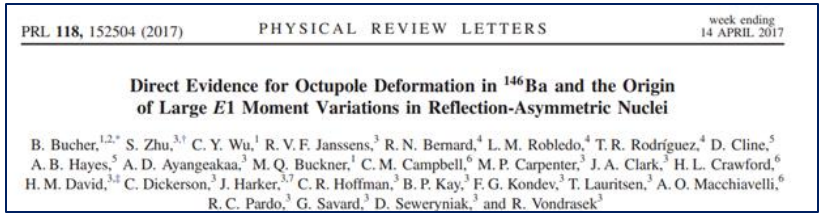
- Papers with R.V.F. Janssens and J.A. Clark as co-authors primarily with CARIBU beams (… and reaccelerated)



PRL **116,** 112503 (2016) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2016

Direct Evidence of Octupole Deformation in Neutron-Rich ^{144}Ba

B. Bucher,[1,*] S. Zhu,[2] C. Y. Wu,[1] R. V. F. Janssens,[2] D. Cline,[3] A. B. Hayes,[3] M. Albers,[2] A. D. Ayangeakaa,[2] P. A. Butler,[4] C. M. Campbell,[5] M. P. Carpenter,[2] C. J. Chiara,[2,6,†] J. A. Clark,[2] H. L. Crawford,[7,‡] M. Cromaz,[5] H. M. David,[2,§] C. Dickerson,[2] E. T. Gregor,[8,9] J. Harker,[2,6] C. R. Hoffman,[2] B. P. Kay,[2] F. G. Kondev,[2] A. Korichi,[2,10] T. Lauritsen,[2] A. O. Macchiavelli,[5] R. C. Pardo,[2] A. Richard,[7] M. A. Riley,[11] G. Savard,[2] M. Scheck,[8,9] D. Seweryniak,[2] M. K. Smith,[12] R. Vondrasek,[2] and A. Wiens[5]



PRL **118,** 152504 (2017) PHYSICAL REVIEW LETTERS week ending 14 APRIL 2017

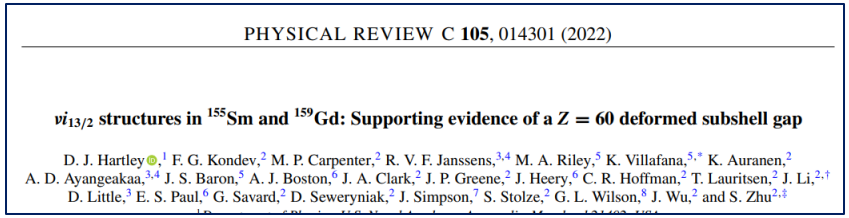
Direct Evidence for Octupole Deformation in ^{146}Ba and the Origin of Large $E1$ Moment Variations in Reflection-Asymmetric Nuclei

B. Bucher,[1,2,*] S. Zhu,[3,†] C. Y. Wu,[1] R. V. F. Janssens,[3] R. N. Bernard,[4] L. M. Robledo,[4] T. R. Rodríguez,[4] D. Cline,[5] A. B. Hayes,[5] A. D. Ayangeakaa,[3] M. Q. Buckner,[1] C. M. Campbell,[6] M. P. Carpenter,[3] J. A. Clark,[3] H. L. Crawford,[6] H. M. David,[3,‡] C. Dickerson,[3] J. Harker,[3,7] C. R. Hoffman,[3] B. P. Kay,[3] F. G. Kondev,[3] T. Lauritsen,[3] A. O. Macchiavelli,[6] R. C. Pardo,[3] G. Savard,[3] D. Seweryniak,[3] and R. Vondrasek[3]

PHYSICAL REVIEW C **103**, 034322 (2021)

Possible quenching of static neutron pairing near the $N = 98$ deformed shell gap: Rotational structures in ^{160,161}Gd

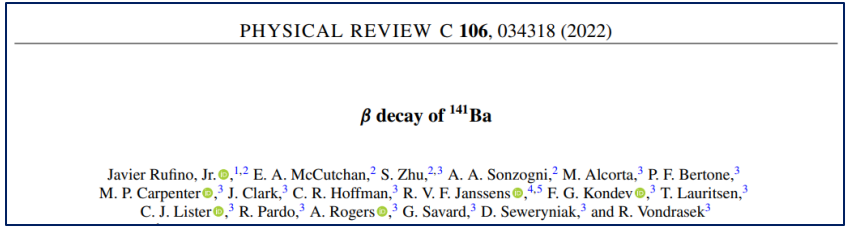
D. J. Hartley,[1] K. Villafana,[2,*] F. G. Kondev,[3] M. A. Riley,[2] R. V. F. Janssens,[4,5] K. Auranen,[3] A. D. Ayangeakaa,[1,†] J. S. Baron,[2] A. J. Boston,[6] M. P. Carpenter,[3] J. A. Clark,[3] J. P. Greene,[3] J. Heery,[6] C. R. Hoffman,[3] P. Jackson,[1] T. Lauritsen,[3] J. Li,[3,‡] D. Little,[4] E. S. Paul,[6] G. Savard,[3] D. Seweryniak,[3] J. Simpson,[7] S. Stolze,[3] G. L. Wilson,[8] J. Wu,[3] S. Zhu,[3,§] and S. Frauendorf[9]



PHYSICAL REVIEW C **105**, 014301 (2022)

$vi_{13/2}$ structures in ^{155}Sm and ^{159}Gd: Supporting evidence of a $Z = 60$ deformed subshell gap

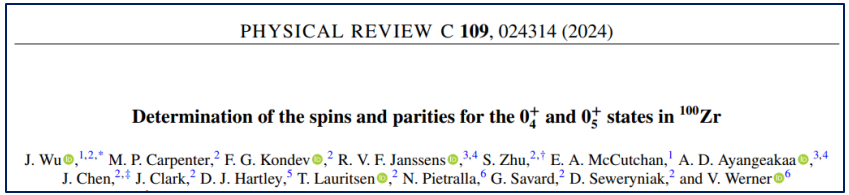
D. J. Hartley,[1] F. G. Kondev,[2] M. P. Carpenter,[2] R. V. F. Janssens,[3,4] M. A. Riley,[5] K. Villafana,[5,*] K. Auranen,[2] A. D. Ayangeakaa,[3,4] J. S. Baron,[5] A. J. Boston,[6] J. A. Clark,[2] J. P. Greene,[2] J. Heery,[6] C. R. Hoffman,[2] T. Lauritsen,[2] J. Li,[2,†] D. Little,[3] E. S. Paul,[6] G. Savard,[2] D. Seweryniak,[2] J. Simpson,[7] S. Stolze,[2] G. L. Wilson,[8] J. Wu,[2] and S. Zhu[2,‡]



PHYSICAL REVIEW C **106**, 034318 (2022)

β decay of ^{141}Ba

Javier Rufino, Jr.,[1,2] E. A. McCutchan,[2] S. Zhu,[2,3] A. A. Sonzogni,[2] M. Alcorta,[3] P. F. Bertone,[3] M. P. Carpenter,[3] J. Clark,[3] C. R. Hoffman,[3] R. V. F. Janssens,[4,5] F. G. Kondev,[3] T. Lauritsen,[3] C. J. Lister,[3] R. Pardo,[3] A. Rogers,[3] G. Savard,[3] D. Seweryniak,[3] and R. Vondrasek[3]



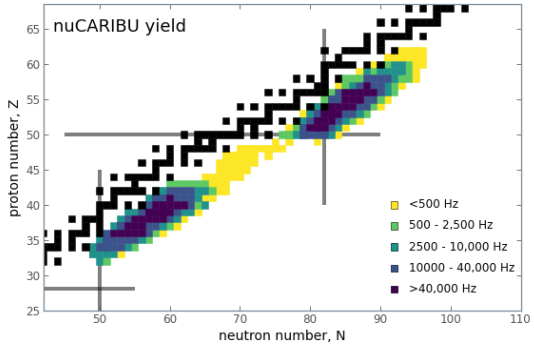
PHYSICAL REVIEW C **109**, 024314 (2024)

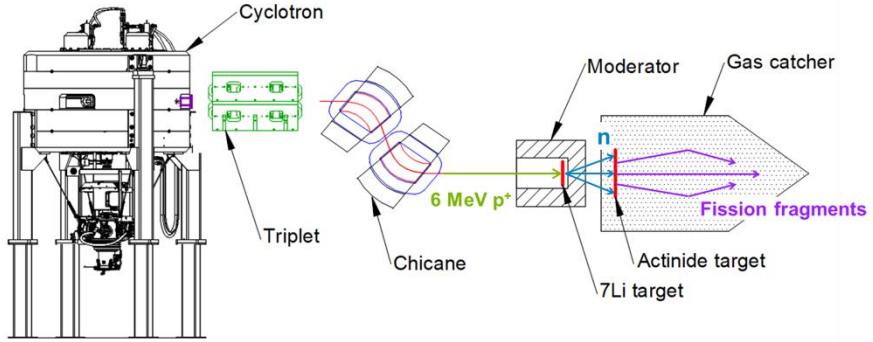
Determination of the spins and parities for the 0_4^+ and 0_5^+ states in ^{100}Zr

J. Wu,[1,2,*] M. P. Carpenter,[2] F. G. Kondev,[2] R. V. F. Janssens,[3,4] S. Zhu,[2,†] E. A. McCutchan,[1] A. D. Ayangeakaa,[3,4] J. Chen,[2,‡] J. Clark,[2] D. J. Hartley,[5] T. Lauritsen,[2] N. Pietralla,[6] G. Savard,[2] D. Seweryniak,[2] and V. Werner[6]

FROM CARIBU TO nuCARIBU

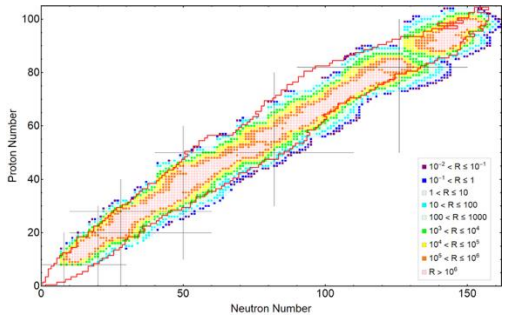
- Source of neutron-rich nuclides from ^{252}Cf replaced with n-induced fission of ^{235}U
- Beams first extracted in June of 2025
- In coming months, beams to be delivered to low-energy area, and reaccelerated through ATLAS
- First at 10% power; full power expected sometime in 2026

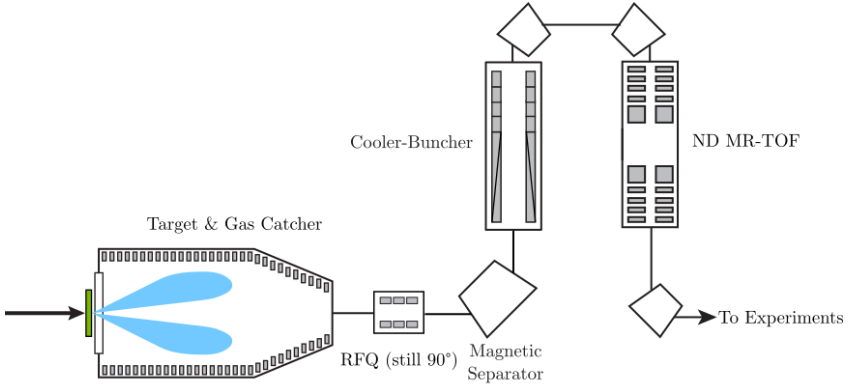




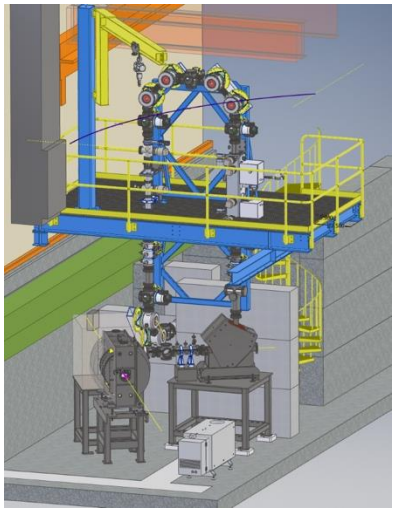
N=126 FACTORY

- Building upon the developed gas catcher technology, short, fat gas catcher optimal to capture products from multi-nucleon transfer (MNT) reactions
- CPT, laser spectroscopy station, and decay station to take first beams at N=126 Factory

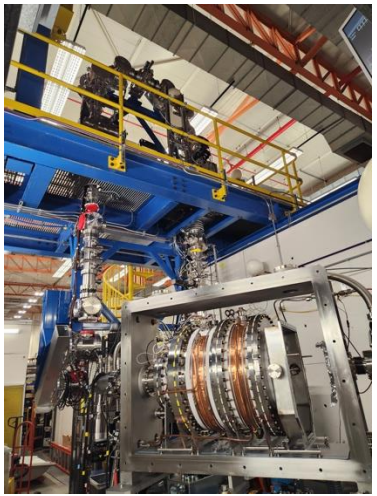




Schematic of N=126 Factory



Picture taken June, 2024



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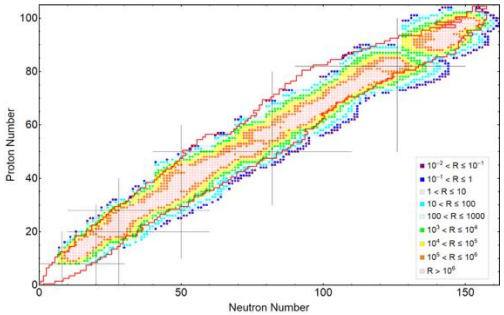
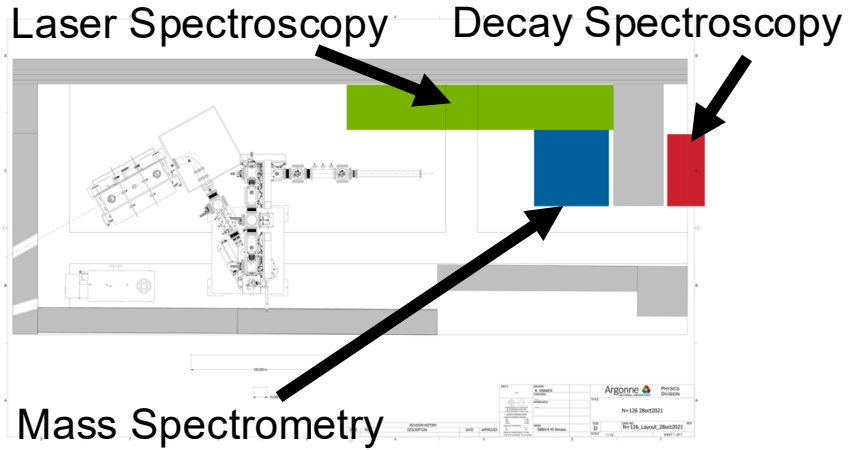
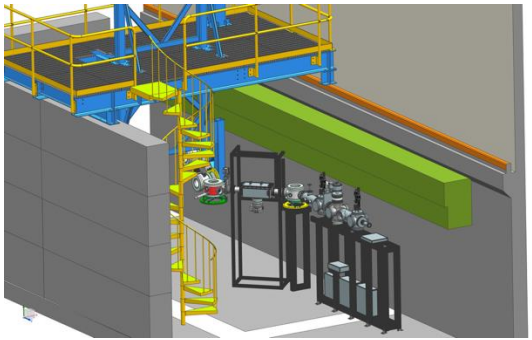




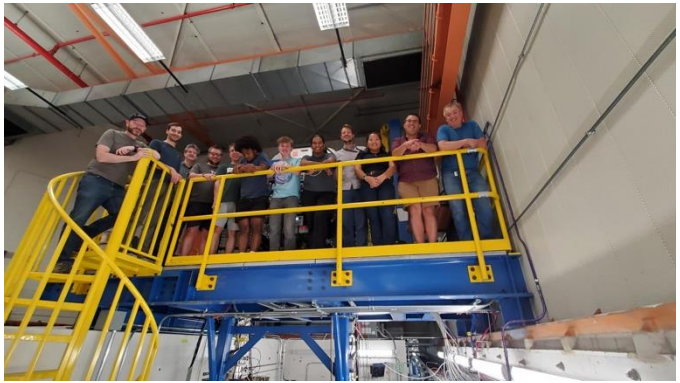


Laser spectroscopy beamline design

CPT tower

SUMMARY, ACKNOWLEDGEMENTS, AND THANKS

- Ion trapping program at ANL started in 1997 with the CPT, and has since led to the development of the BPT, BEARtrap, CARIBU (nuCARIBU), and the N=126 Factory, providing new insight into nuclear structure, nucleosynthesis, and the weak interaction
- So, so, so many people to thank and it's impossible to list them all here



- Special thanks to Robert for all the discussions, advice, counseling, leadership, mentoring, and friendship over the years.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