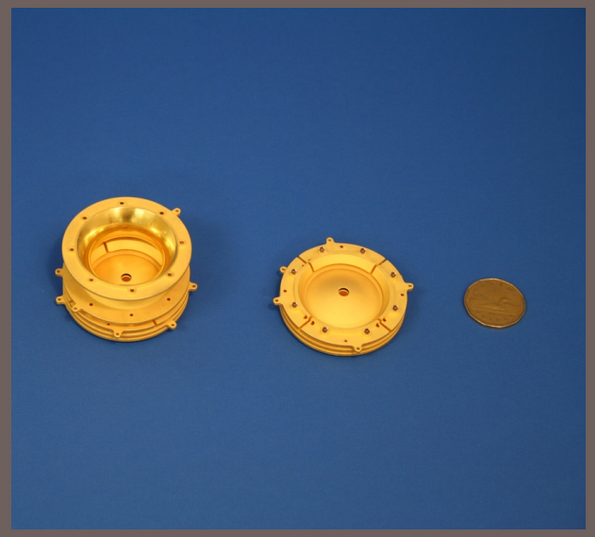
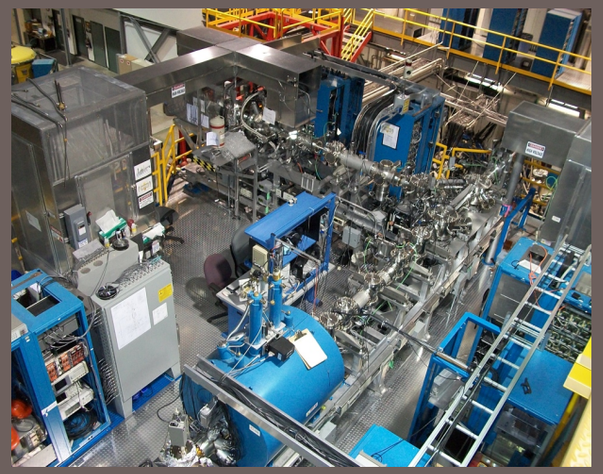
TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules





3N forces Near N = 32

Precision Mass Measurements at TITAN

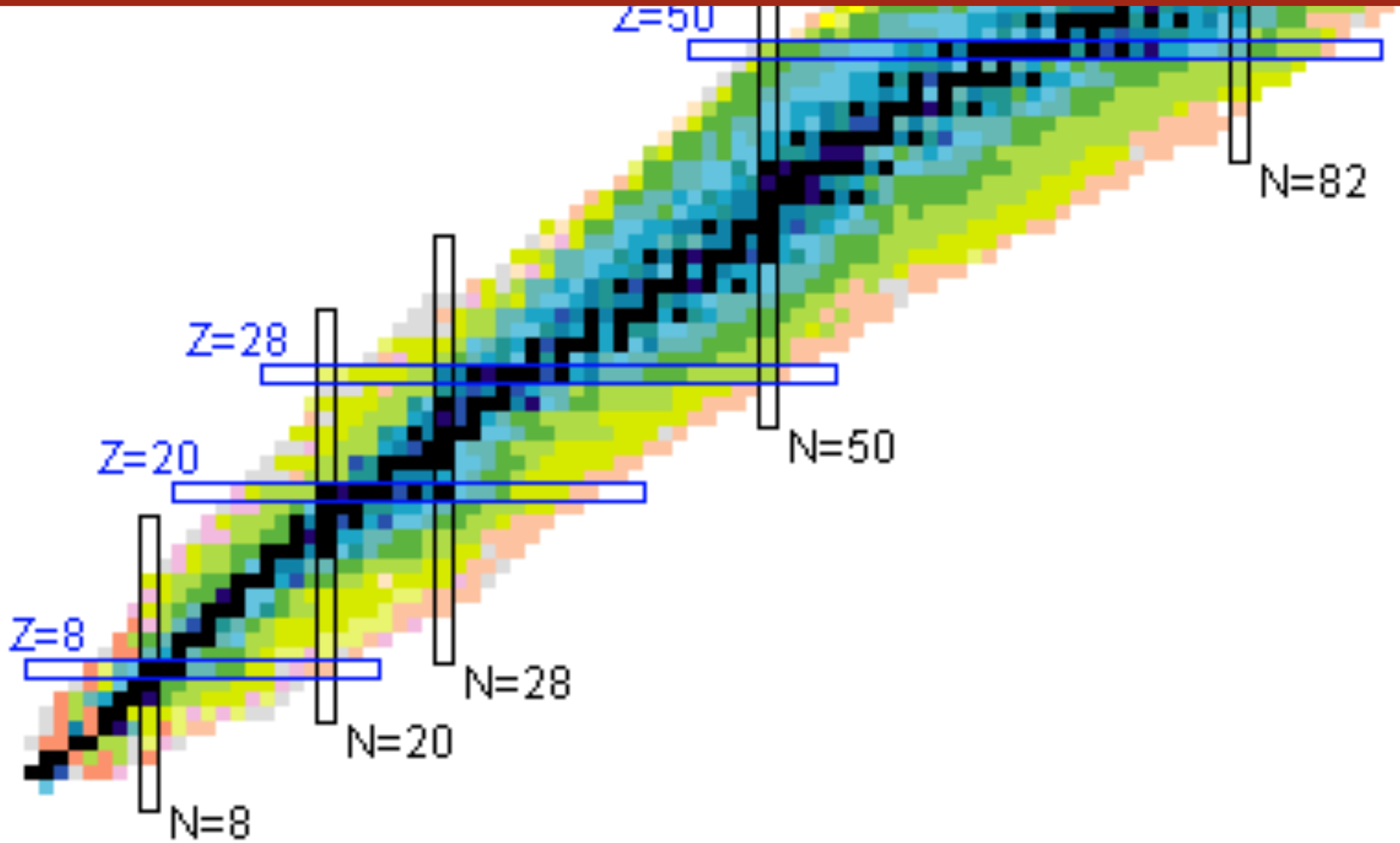
Aaron Gallant for the TITAN Collaboration

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA

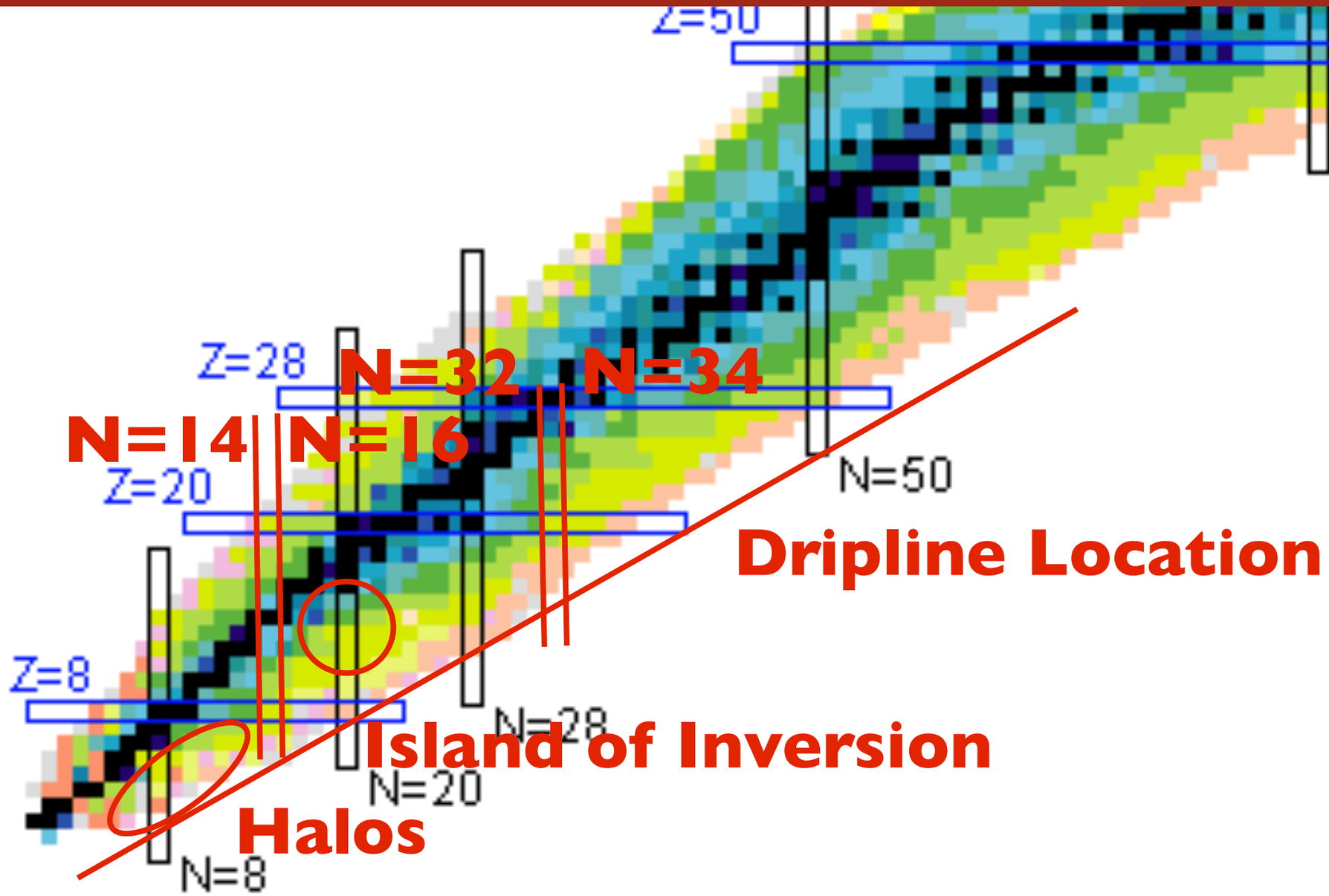
Owned and operated as a joint venture by a consortium of Canadian universities via a contribution through the National Research Council Canada
Propriété d'un consortium d'universités canadiennes, géré en co-entreprise à partir d'une contribution administrée par le Conseil national de recherches Canada

TRIUMF

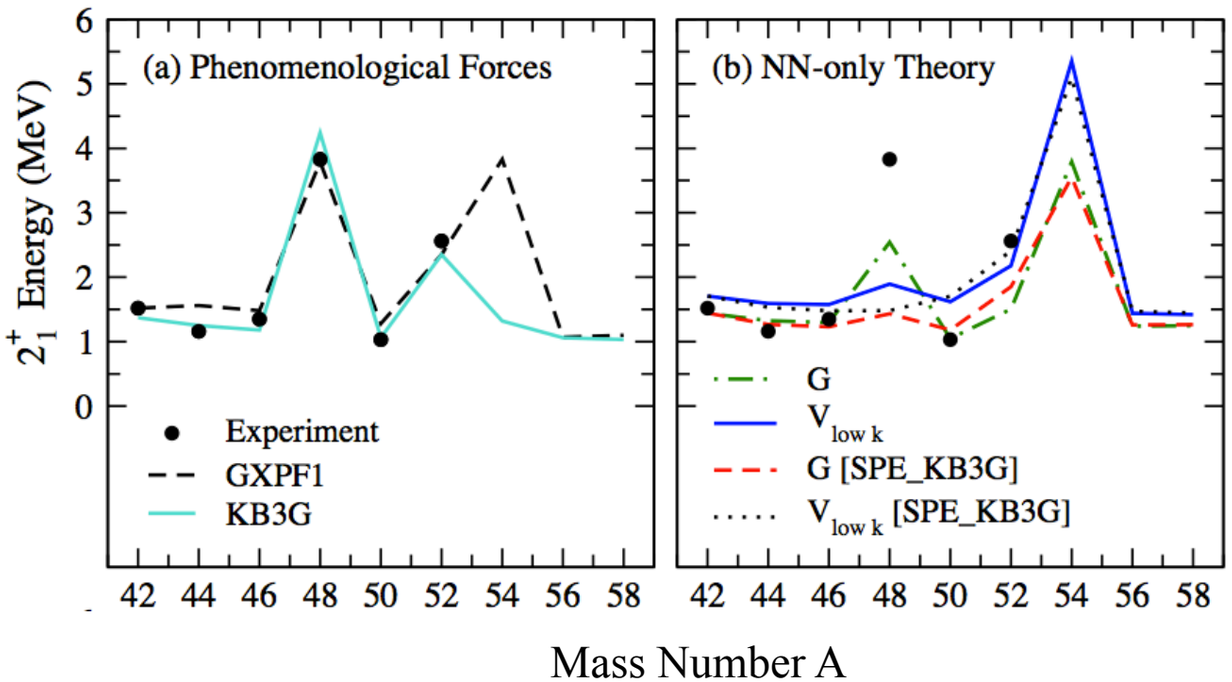
Frontiers of Nuclear Science

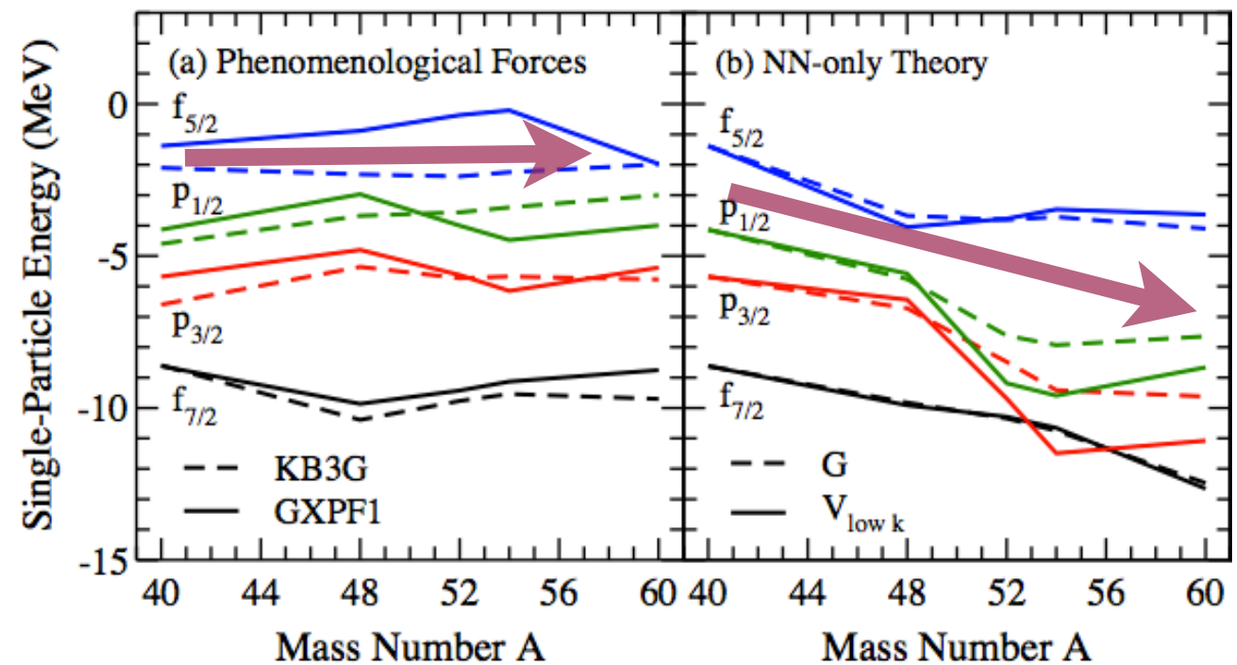


Frontiers of Nuclear Science



NN and 3N Forces





J. D. Holt *et al.*, J. Phys. G: Nucl. Part. Phys. 39, 085111 (2012)

Phenomenological Forces:

- Predict N=28 closure
- Disagree on N=34

NN-only Forces:

- NN predict large N=32 closure
- No N=28 shell closure!

- NN-only interactions greatly overbind!
- Need repulsive 3N contribution

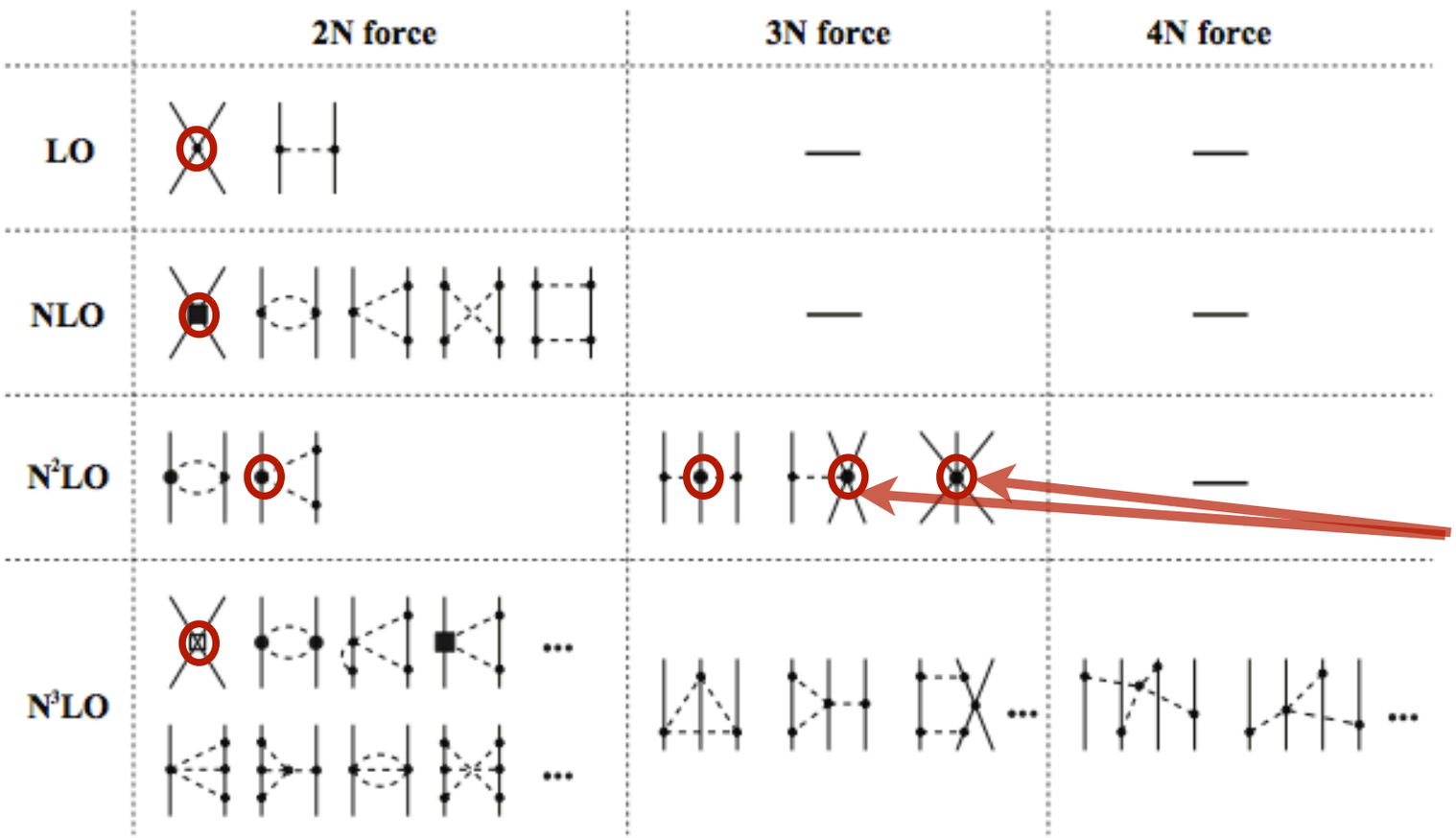
Chiral EFT

$$H(\Lambda) = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + V_{4N}(\Lambda) + \ldots$$

resolution scale / cut-off

3 body forces!

Explains Hierarchy: $V_{NN} > V_{3N} > V_{4N}$ ➡ systematic expansion in Q/Λ



Excellent agreement with experiment in <u>light systems</u>

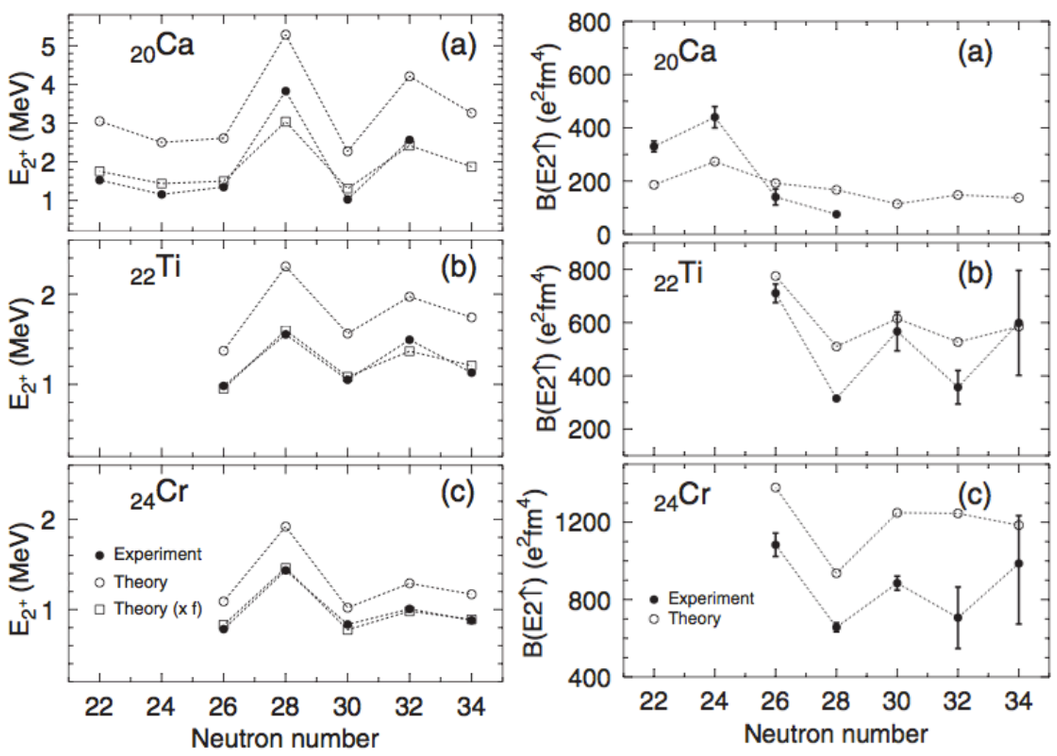
Short range couplings; fit to experiment once in A=3,4 systems

E. Epelbaum *et al.*, Rev. Mod. Phys., 81, 1773 (2009)
S.K. Bogner *et al.*, Prog. Par. Nuc. Phys., 65, 94, (2010)

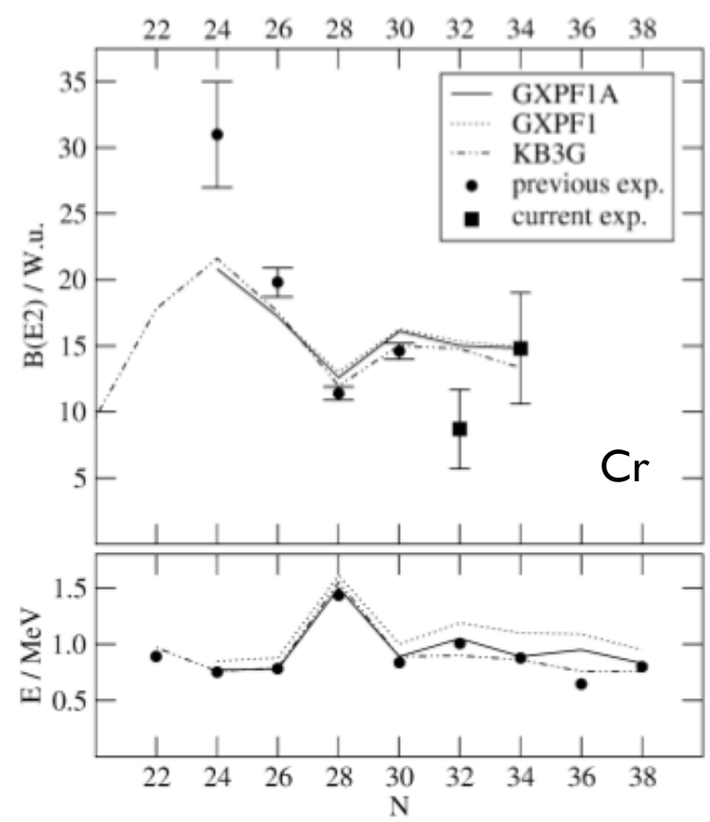
Previous Work at N=32,34

Selection of results:

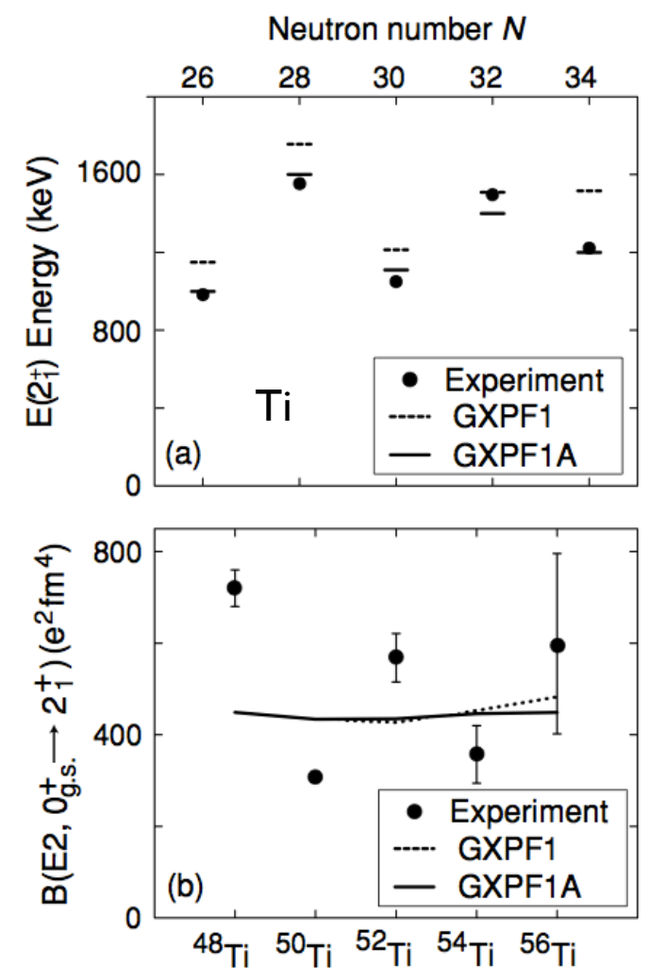
- Good agreement on excitation energies
- B(E2)'s leave something to be desired



T. Rodríguez and J. Egido, Phys. Rev. Lett. 99, (2007)

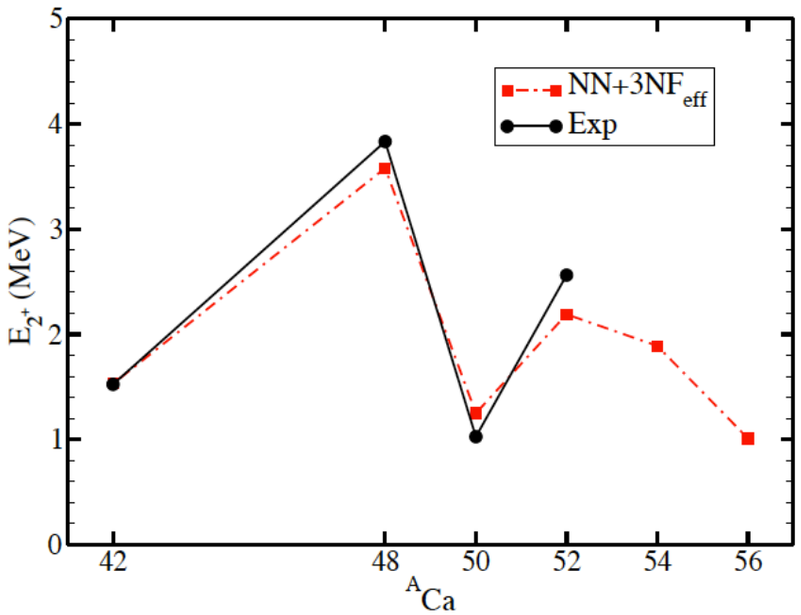


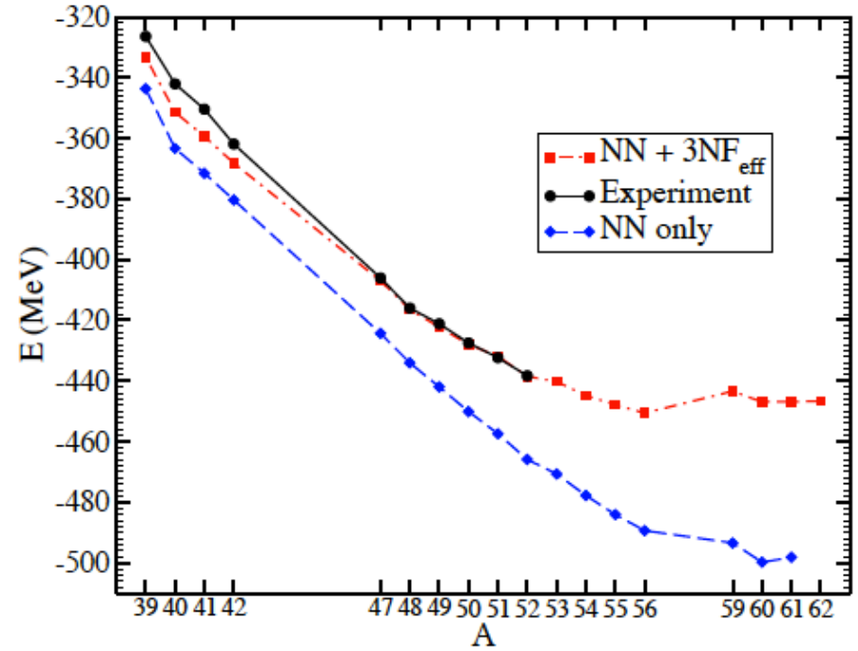
A. Bürger *et al.*, Physics Letters B 622, 29 (2005)



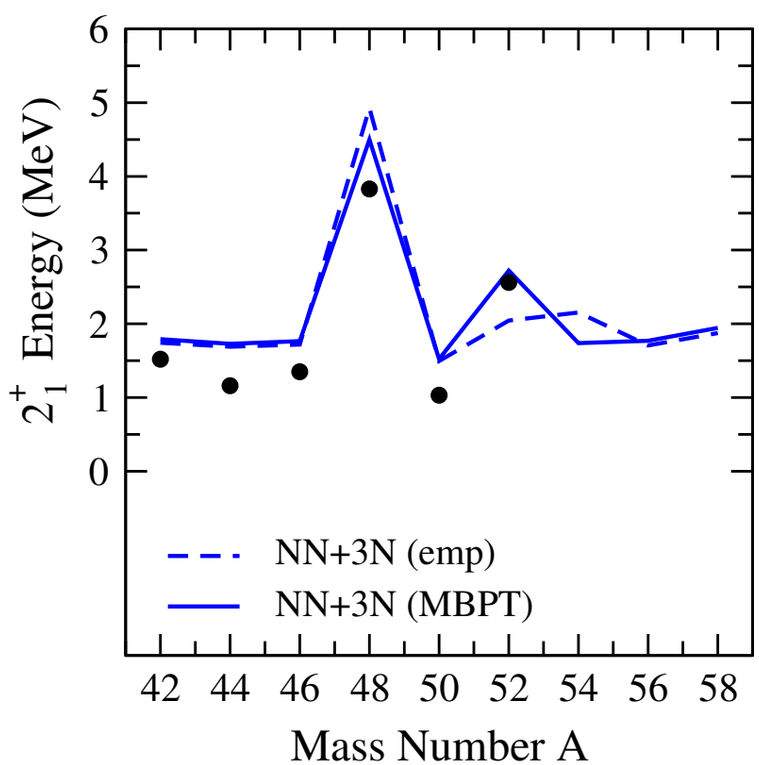
D. C. Dinca *et al.*, Phys. Rev. C 71, (2005)

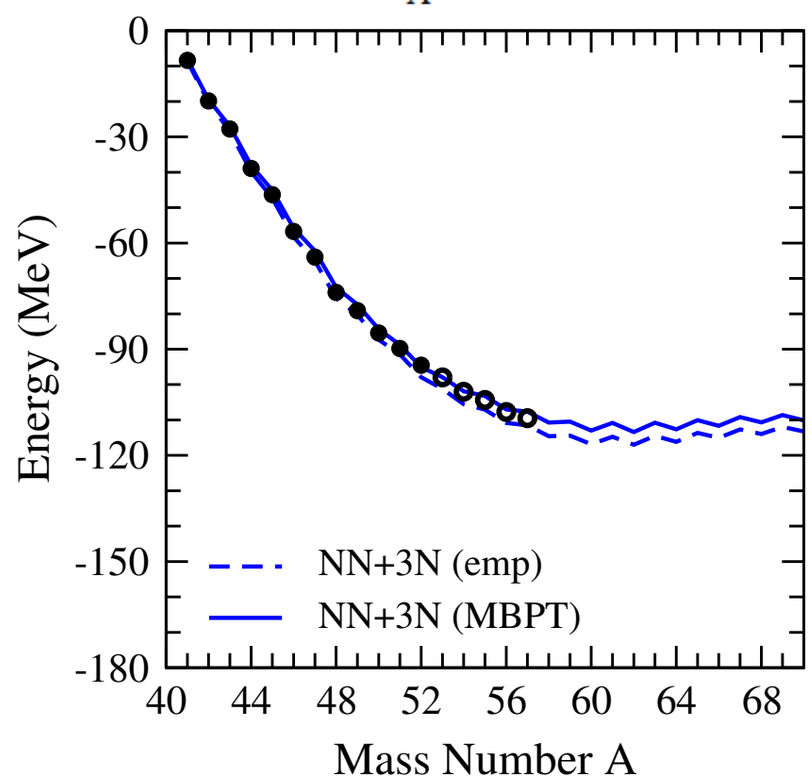
Previous Work at N=32,34





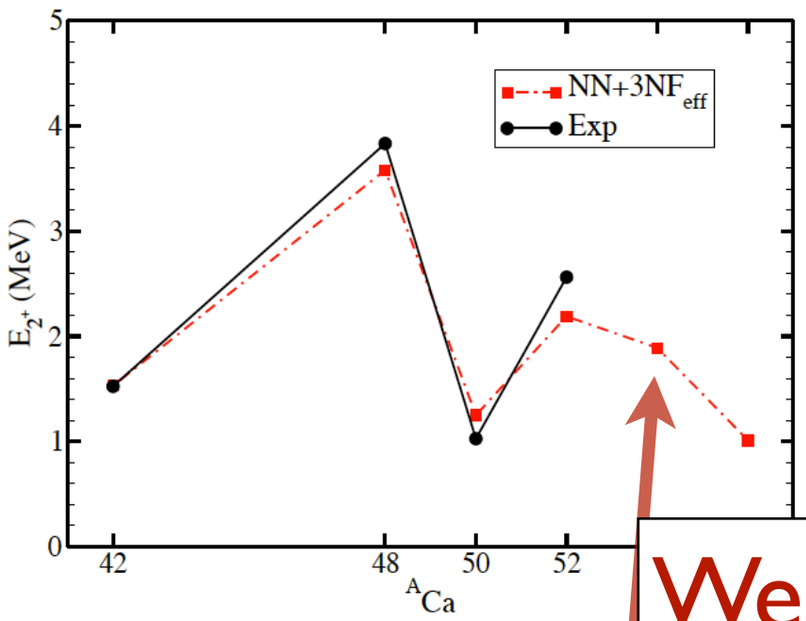
G. Hagen *et al.*, Phys. Rev. Lett. 109, 032502 (2012)

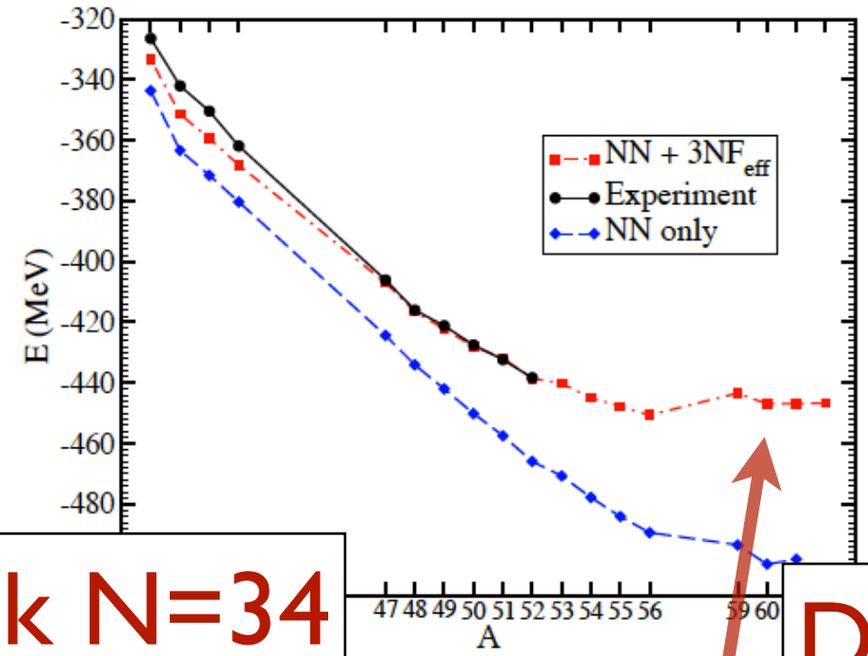




A. Schwenk, priv. comm., 2012

Previous Work at N=32,34

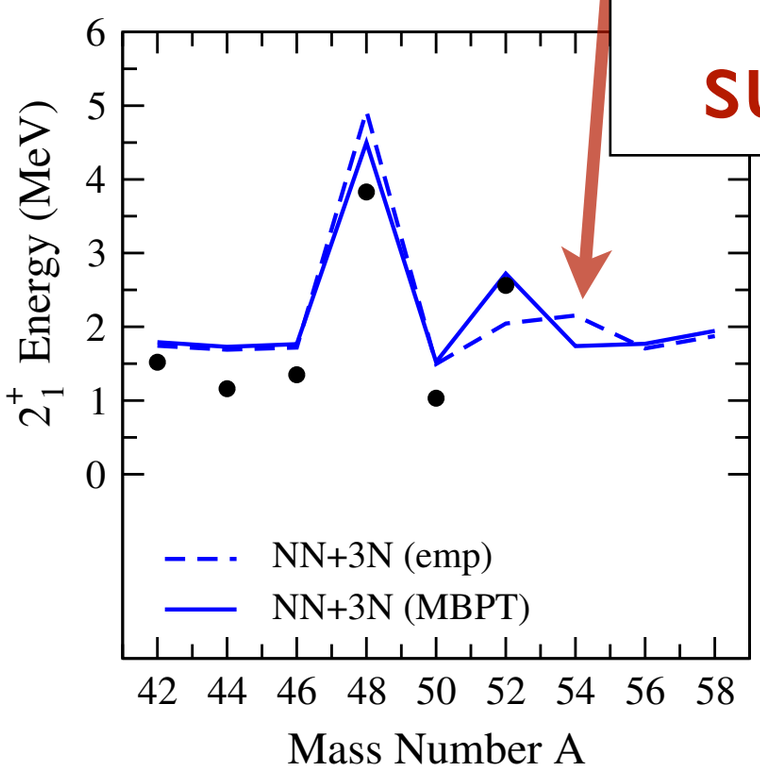


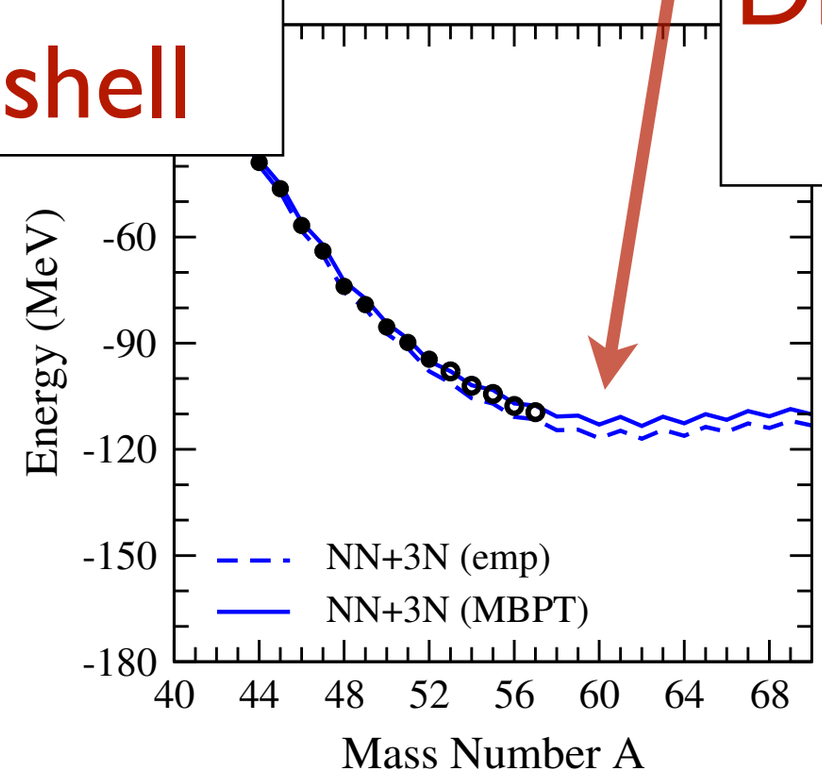


G. Hagen *et al.*, Phys. Rev. Lett. 109, 032502 (2012)

Weak N=34 sub-shell

Drip-line near N=60?





A. Schwenk, priv. comm., 2012

Recent Ca + 3N Forces

PRL 109, 032502 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

Evolution of Shell Structure in Neutron-Rich Calcium Isotopes

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[2]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[3]*Department of Physics and Center of Mathematics for Applications, University of Oslo, N-0316 Oslo, Norway*
[4]*National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
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(Received 16 April 2012; published 17 July 2012)

We employ interactions from chiral effective field theory and compute the binding energies and low-lying excitations of calcium isotopes with the coupled-cluster method. Effects of three-nucleon forces are included phenomenologically as in-medium two-nucleon interactions, and the coupling to the particle continuum is taken into account using a Berggren basis. The computed ground-state energies and the low-lying $J^\pi = 2^+$ states for the isotopes ^{42,48,50,52}Ca are in good agreement with data, and we predict the excitation energy of the first $J^\pi = 2^+$ state in ^{54}Ca at 1.9 MeV, displaying only a weak subshell closure. In the odd-mass nuclei ^{53,55,61}Ca we find that the positive parity states deviate strongly from the naive shell model.

DOI: 10.1103/PhysRevLett.109.032502 PACS numbers: 21.10.−k, 21.30.−x, 21.60.−n, 27.40.+z

G. Hagen *et al.*,
Phys. Rev. Lett. 109, 032502 (2012)

PRL 109, 032506 (2012) PHYSICAL REVIEW LETTERS week ending 20 JULY 2012

New Precision Mass Measurements of Neutron-Rich Calcium and Potassium Isotopes and Three-Nucleon Forces

A. T. Gallant,[1,2,*] J. C. Bale,[1,3] T. Brunner,[1] U. Chowdhury,[1,4] S. Ettenauer,[1,2] A. Lennarz,[1,5] D. Robertson,[1] V. V. Simon,[1,6,7] A. Chaudhuri,[1] J. D. Holt,[8,9] A. A. Kwiatkowski,[1] E. Mané,[1] J. Menéndez,[10,11] B. E. Schultz,[1] M. C. Simon,[1] C. Andreoiu,[3] P. Delheij,[1] M. R. Pearson,[1] H. Savajols,[12] A. Schwenk,[11,10] and J. Dilling[1,2]
[1]*TRIUMF, University of British Columbia, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[2]*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
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[8]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*
[9]*Physics Division, Oak Ridge National Laboratory, P.O. Box 2008, Oak Ridge, Tennessee 37831, USA*
[10]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
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[12]*GANIL, Boulevard Henri Becquerel, Boîte Postale 55027, F-14076 Caen Cedex 05, France*
(Received 4 April 2012; revised manuscript received 3 June 2012; published 20 July 2012)

We present precision Penning trap mass measurements of neutron-rich calcium and potassium isotopes in the vicinity of neutron number $N = 32$. Using the TITAN system, the mass of ^{51}K was measured for the first time, and the precision of the ^{51,52}Ca mass values were improved significantly. The new mass values show a dramatic increase of the binding energy compared to those reported in the atomic mass evaluation. In particular, ^{52}Ca is more bound by 1.74 MeV, and the behavior with neutron number deviates substantially from the tabulated values. An increased binding was predicted recently based on calculations that include three-nucleon (3N) forces. We present a comparison to improved calculations, which agree remarkably with the evolution of masses with neutron number, making neutron-rich calcium isotopes an exciting region to probe 3N forces.

DOI: 10.1103/PhysRevLett.109.032506 PACS numbers: 21.10.Dr, 21.30.−x, 21.60.Cs, 27.40.+z

A.T. Gallant *et al.*,
Phys. Rev. Lett. 109, 032506(2012)

PRL 109, 052501 (2012) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 2012

Medium-Mass Nuclei with Normal-Ordered Chiral $NN+3N$ Interactions

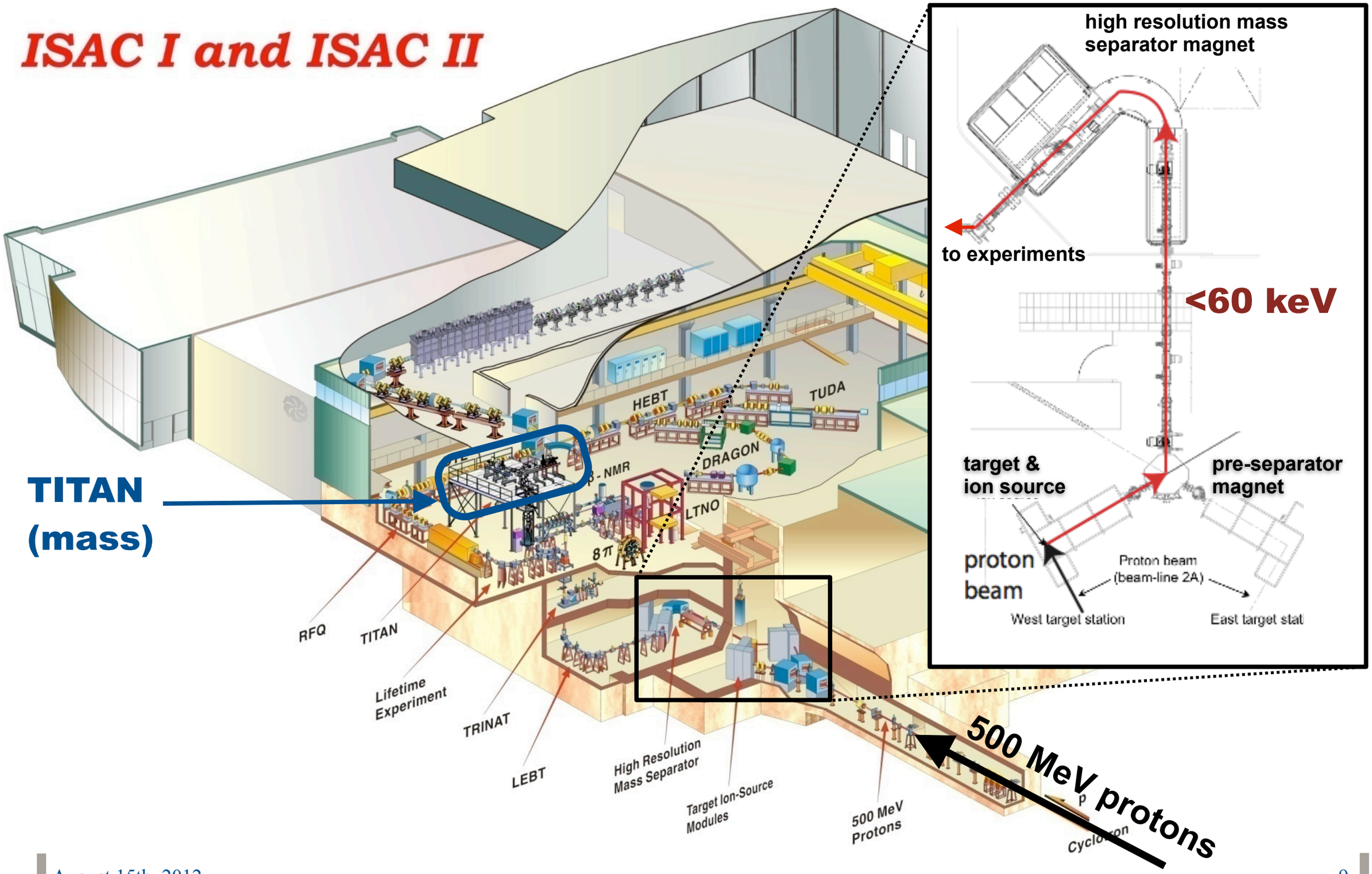
Robert Roth,[1,*] Sven Binder,[1] Klaus Vobig,[1] Angelo Calci,[1] Joachim Langhammer,[1] and Petr Navrátil[2]
[1]*Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[2]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, V6T 2A3, Canada*
(Received 1 December 2011; published 31 July 2012)

We study the use of truncated normal-ordered three-nucleon interactions in nuclear structure calculations starting from chiral two- plus three-nucleon Hamiltonians evolved consistently with the similarity renormalization group. We present three key developments: (i) a rigorous benchmark of the normal-ordering approximation in the importance-truncated no-core shell model for ^{4}He, ^{16}O, and ^{40}Ca; (ii) a direct comparison of the importance-truncated no-core shell model results with coupled-cluster calculations at the singles and doubles level for ^{16}O; and (iii) first applications of similarity renormalization group-evolved chiral $NN+3N$ Hamiltonians in coupled-cluster calculations for medium-mass nuclei ^{16,24}O and ^{40,48}Ca. We show that the normal-ordered two-body approximation works very well beyond the lightest isotopes and opens a path for studies of medium-mass and heavy nuclei with chiral two- plus three-nucleon interactions. At the same time we highlight the predictive power of chiral Hamiltonians.

DOI: 10.1103/PhysRevLett.109.052501 PACS numbers: 21.60.De, 21.30.−x, 05.10.Cc, 21.45.Ff

R. Roth (P. Navrátil) *et al.*,
Phys. Rev. Lett. 109, 052501 (2012)

ISAC @ TRIUMF


ISAC I and ISAC II
TITAN
(mass)
HEBT
TUDA
DRAGON
LTNO
8π
RFQ
TITAN
Lifetime
Experiment
TRINAT
LEBT
High Resolution
Mass Separator
Target Ion-Source
Modules
500 MeV
Protons
500 MeV protons
high resolution mass
separator magnet
to experiments
<60 keV
target &
ion source
pre-separator
magnet
proton
beam
Proton beam
(beam-line 2A)
West target station
East target stat

Isotope Yields

HP Ta (Laser + Surface):

Ca-39 5.1/s

Ca-49 6.3e5/s

Ca-50 9.1e4/s

Ca-51 1.4e4/s

Ca-52 1.3e3/s

Laser ON/OFF Yield Ratios

Ca-50 6.8 (eff. 8.6%)

Ca-51 5.2 (eff. ~6.3%)

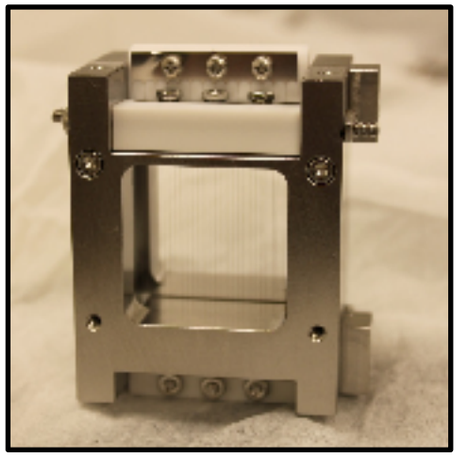
UC_x (Surface):

K-51 50-100 /s

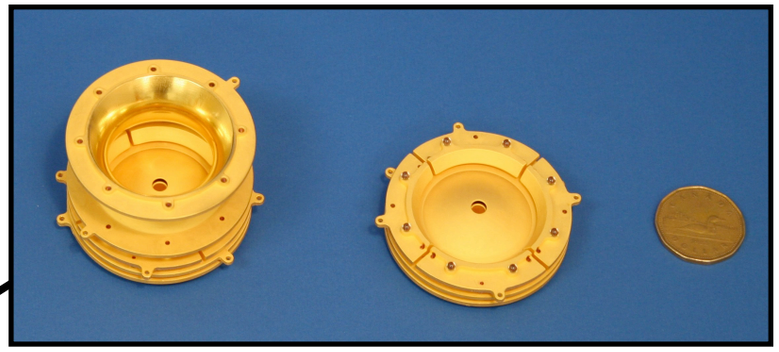
K-52 3-4 /s

No Sc's

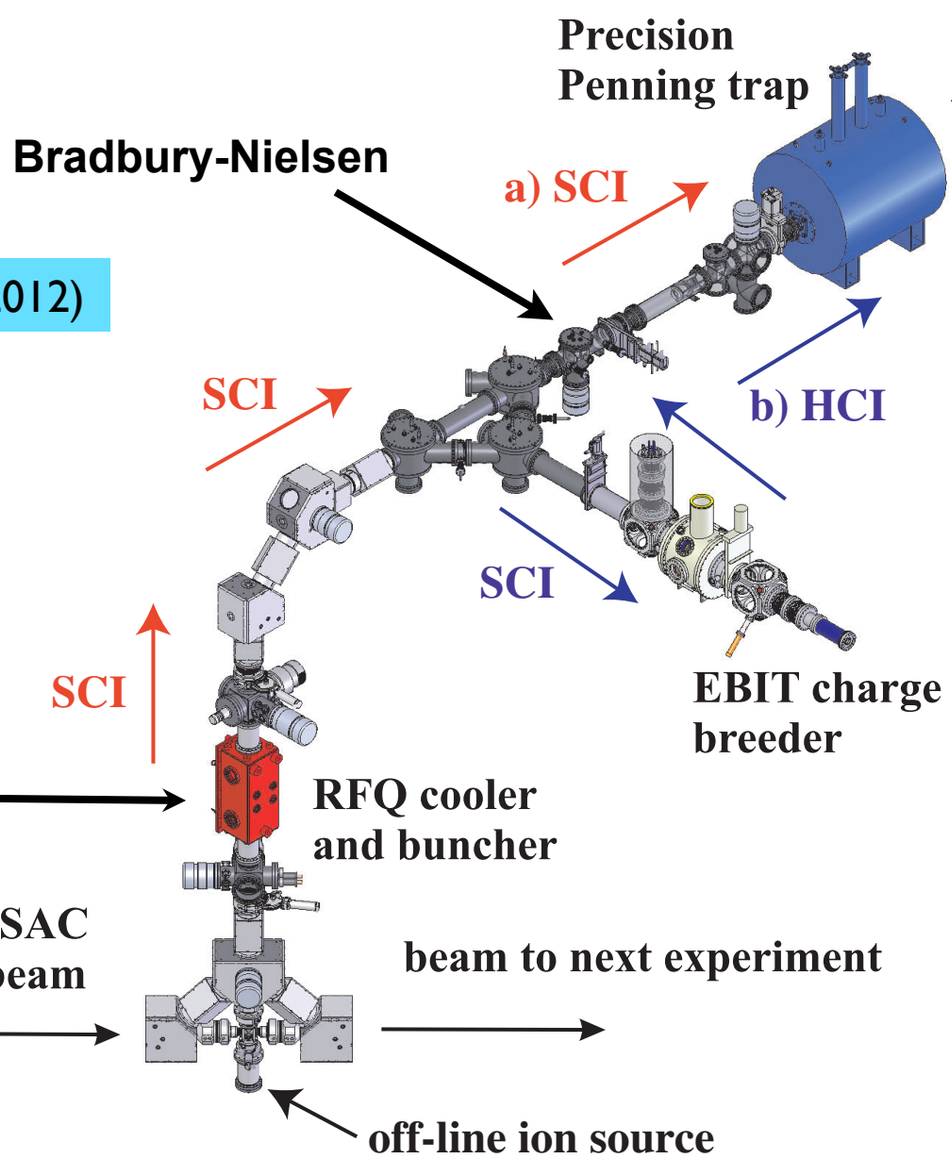
TITAN



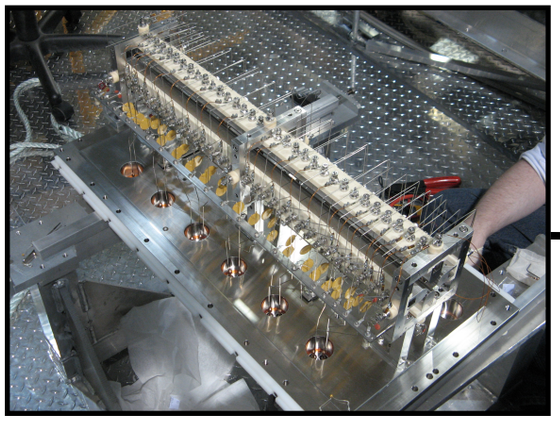
T. Brunner *et al.*, IJMS 309, 97 (2012)



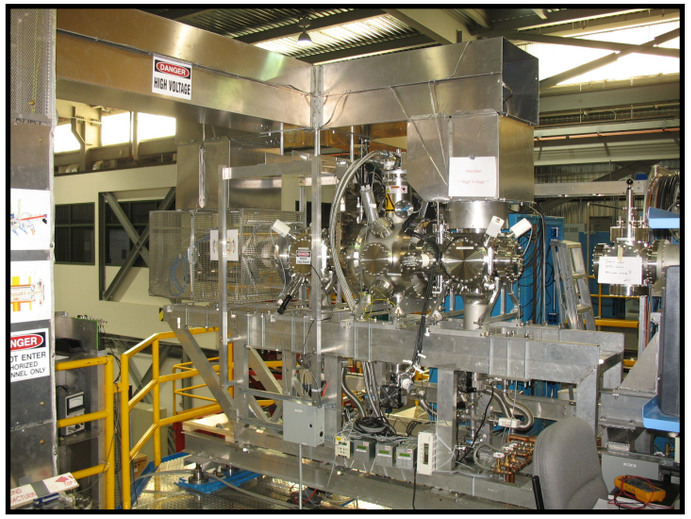
M. Brodeur *et al.*, IJMS 310, 20 (2012)



J. Dilling *et al.*, IMJS 251, 198–203 (2006)



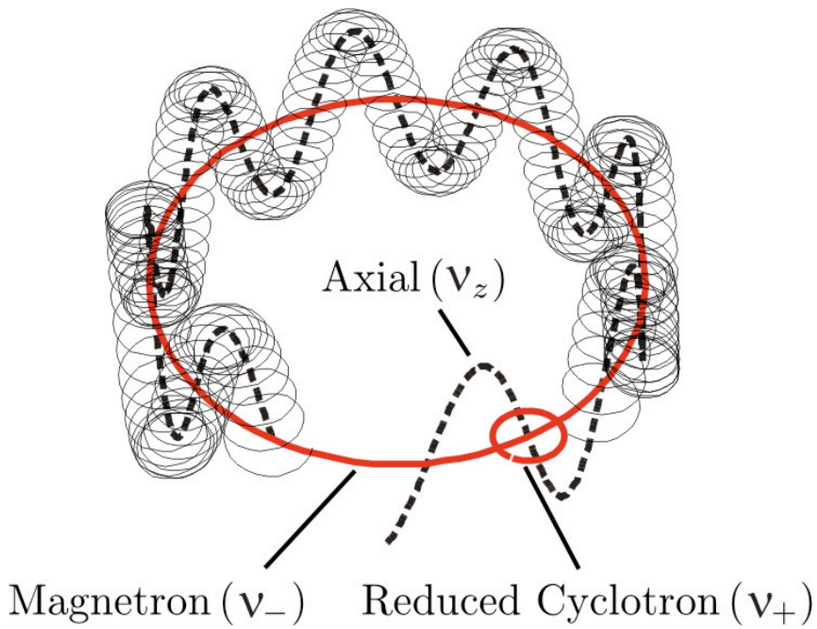
T. Brunner *et al.*, NIMA 676 32 (2012)



A. Lapierre *et al.*, NIMA 624, 54 (2010)

$$\frac{\delta m}{m} \propto \frac{m}{q} \frac{1}{BT\sqrt{N}}$$

Penning Traps



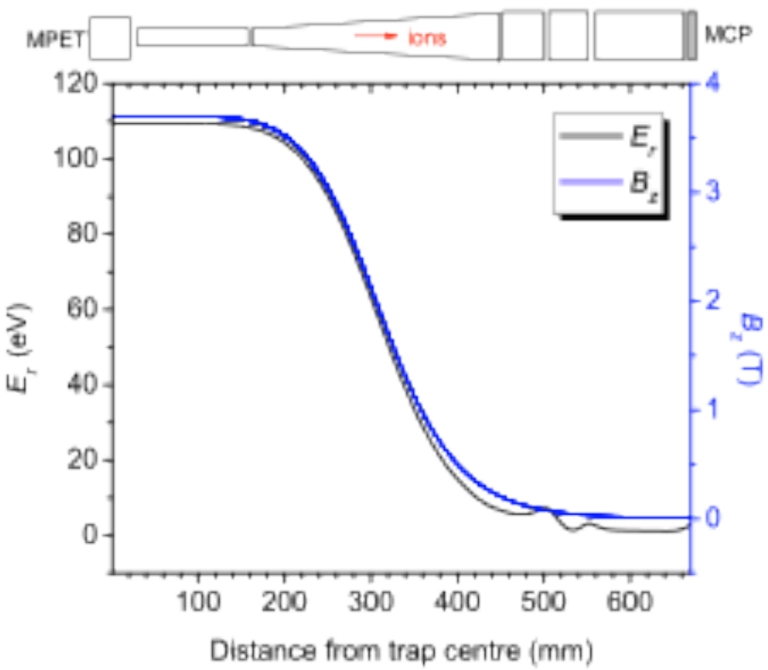
Relevant frequencies

$$\nu_c = \nu_+ + \nu_- = \frac{1}{2\pi}\frac{q}{m}B$$

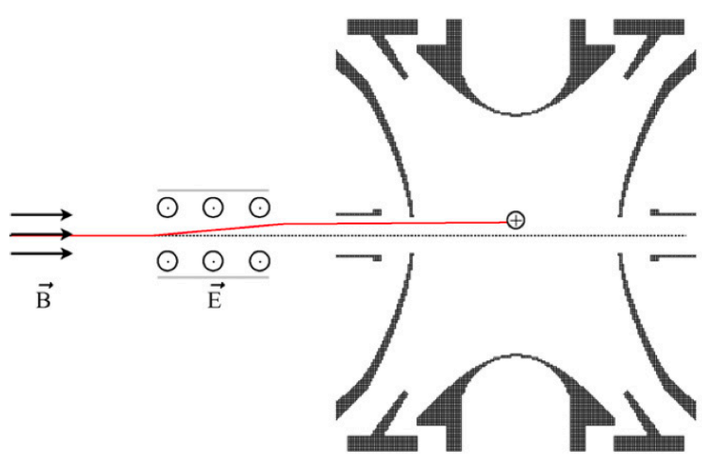
$$\nu_+ >> \nu_z >> \nu_-$$

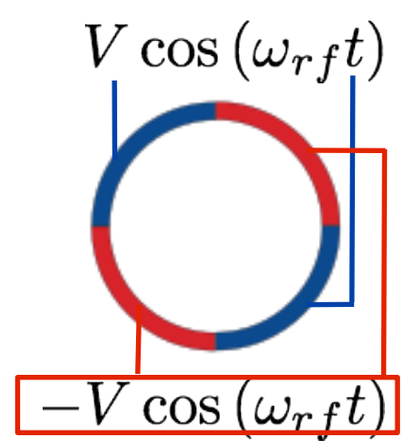
Radial energy:

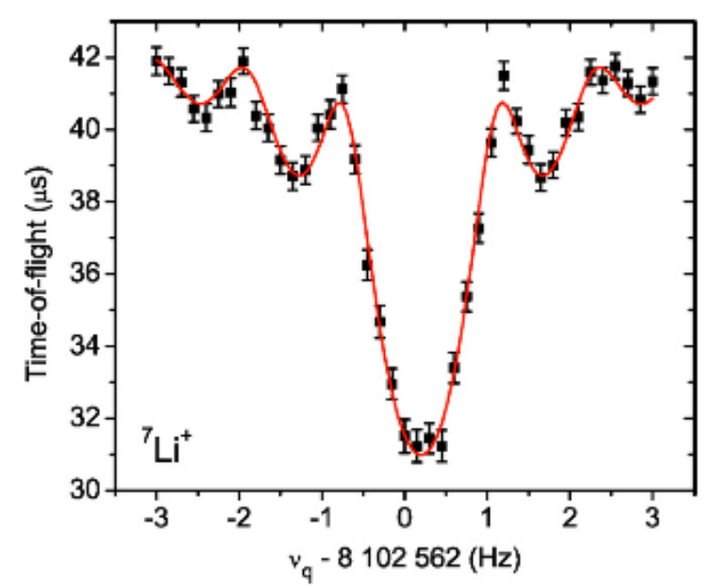
$$E_r \propto \nu_+^2\rho_+^2 + \nu_-^2\rho_-^2$$
$$\approx \nu_+^2\rho_+^2$$



Lorentz-steerer
=> pure magnetron motion

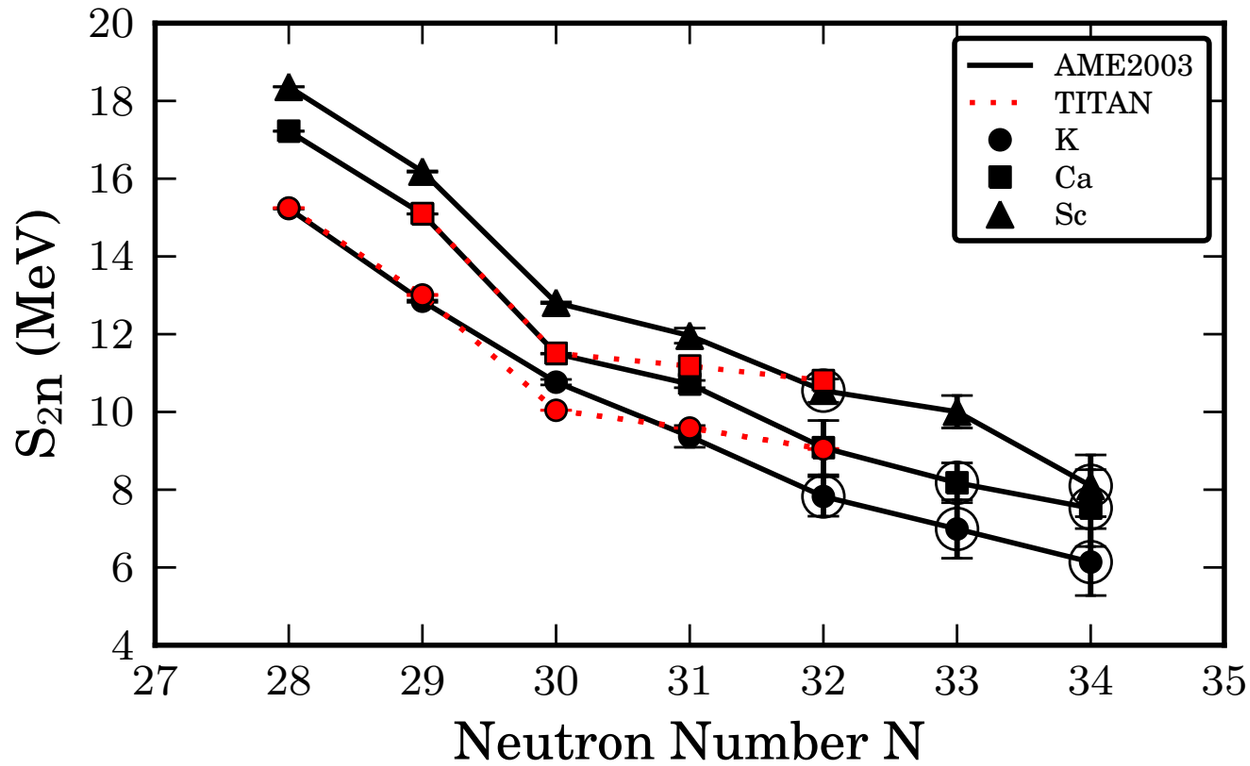


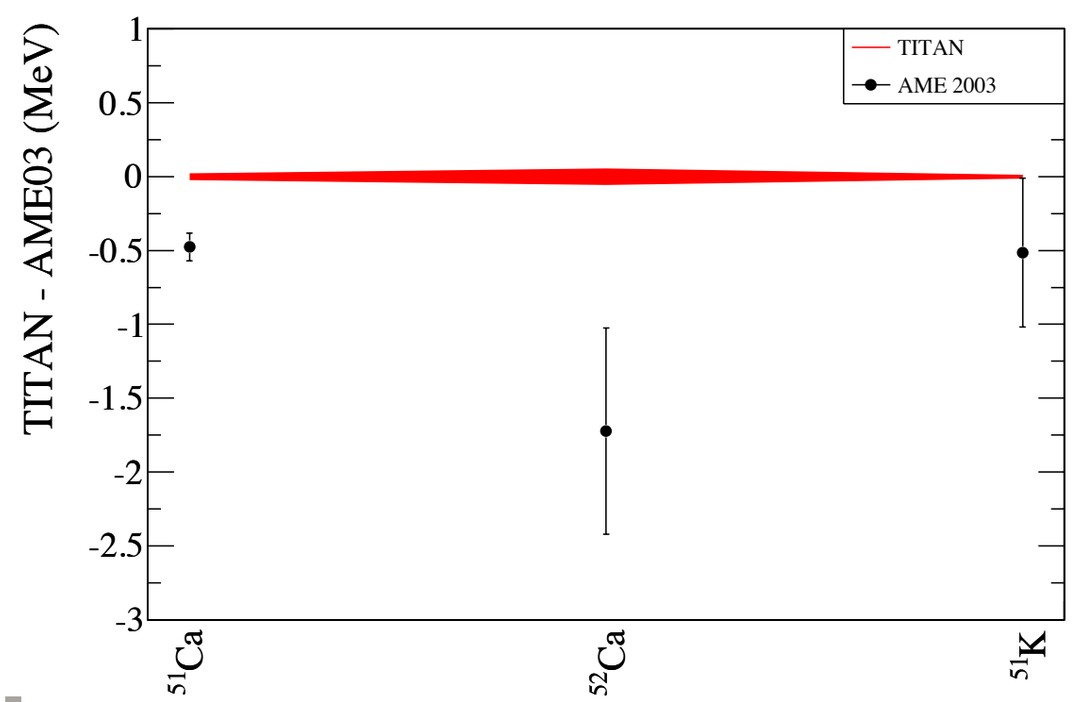


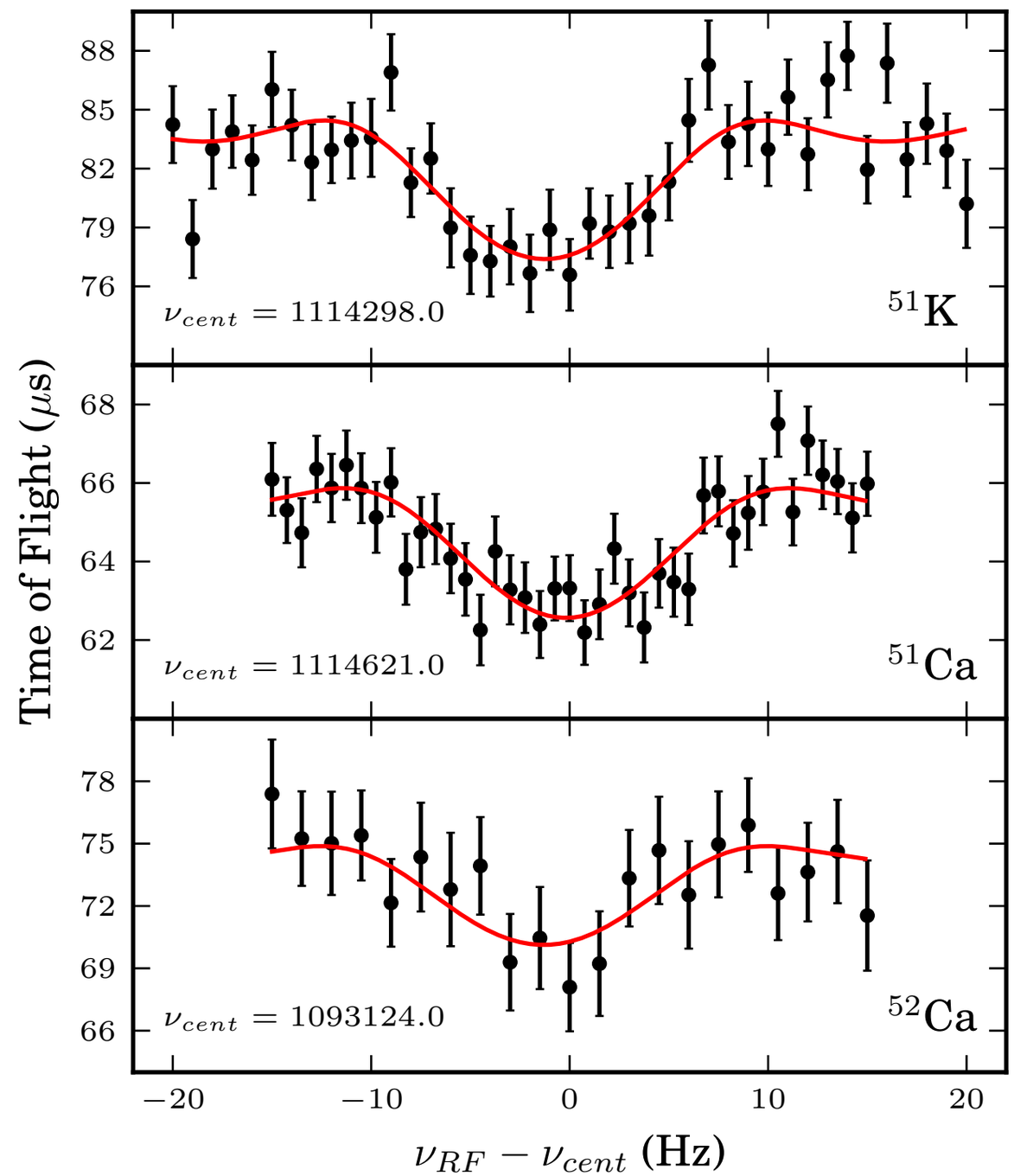


Convert magnetron motion to reduced cyclotron motion

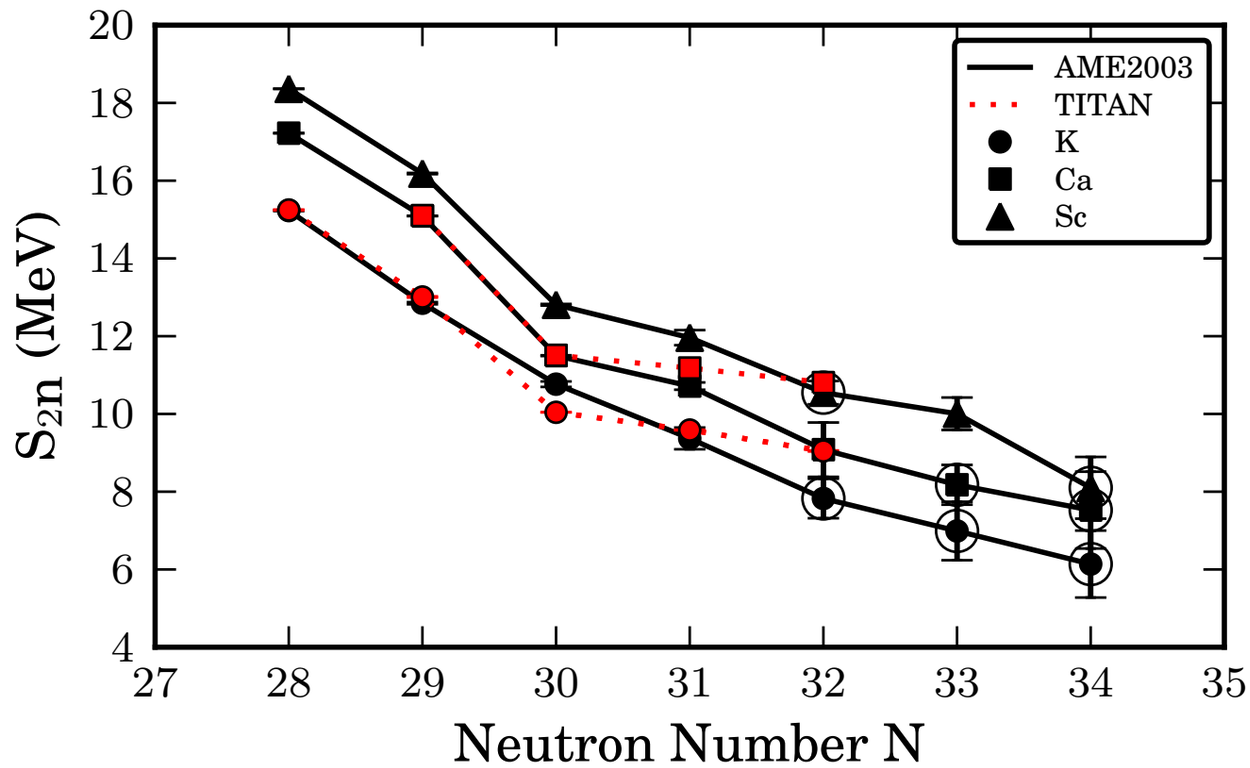
Results - Experiment

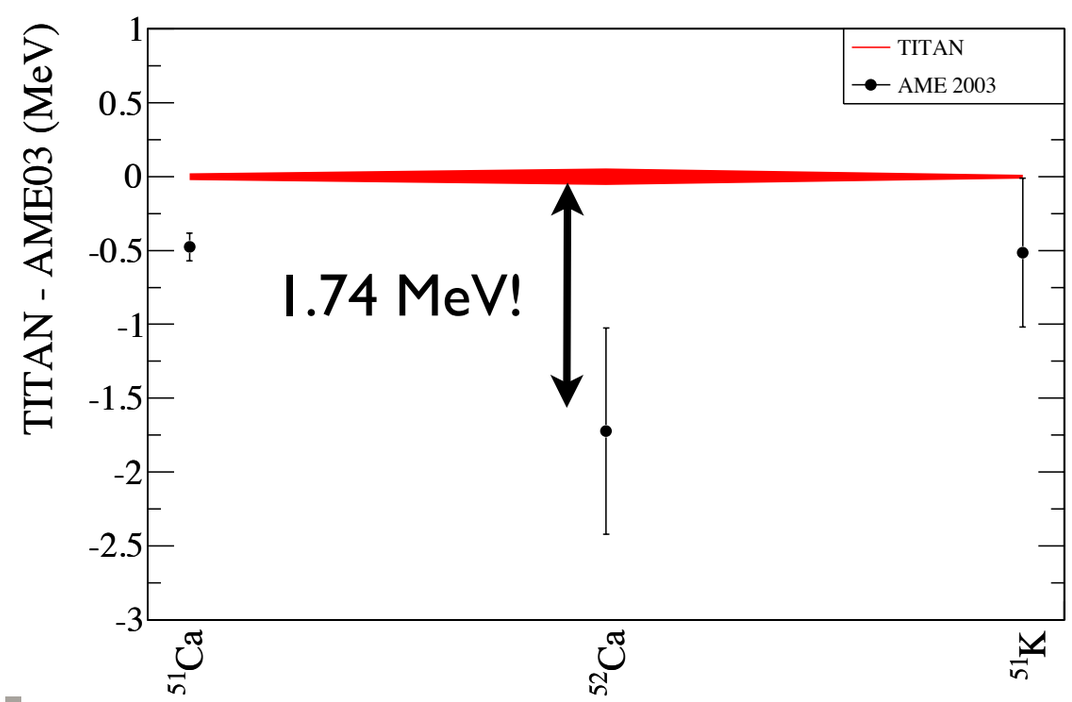


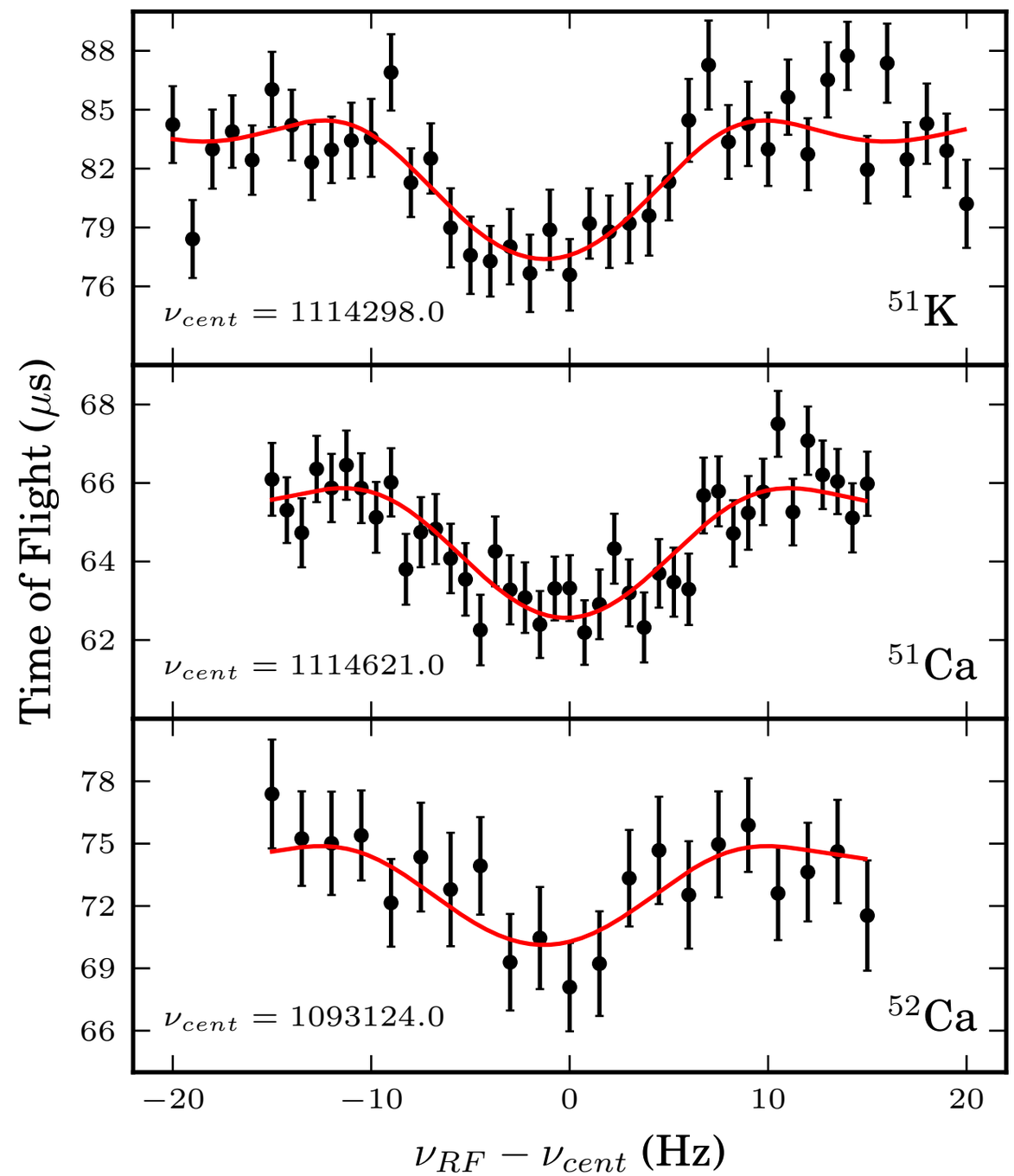




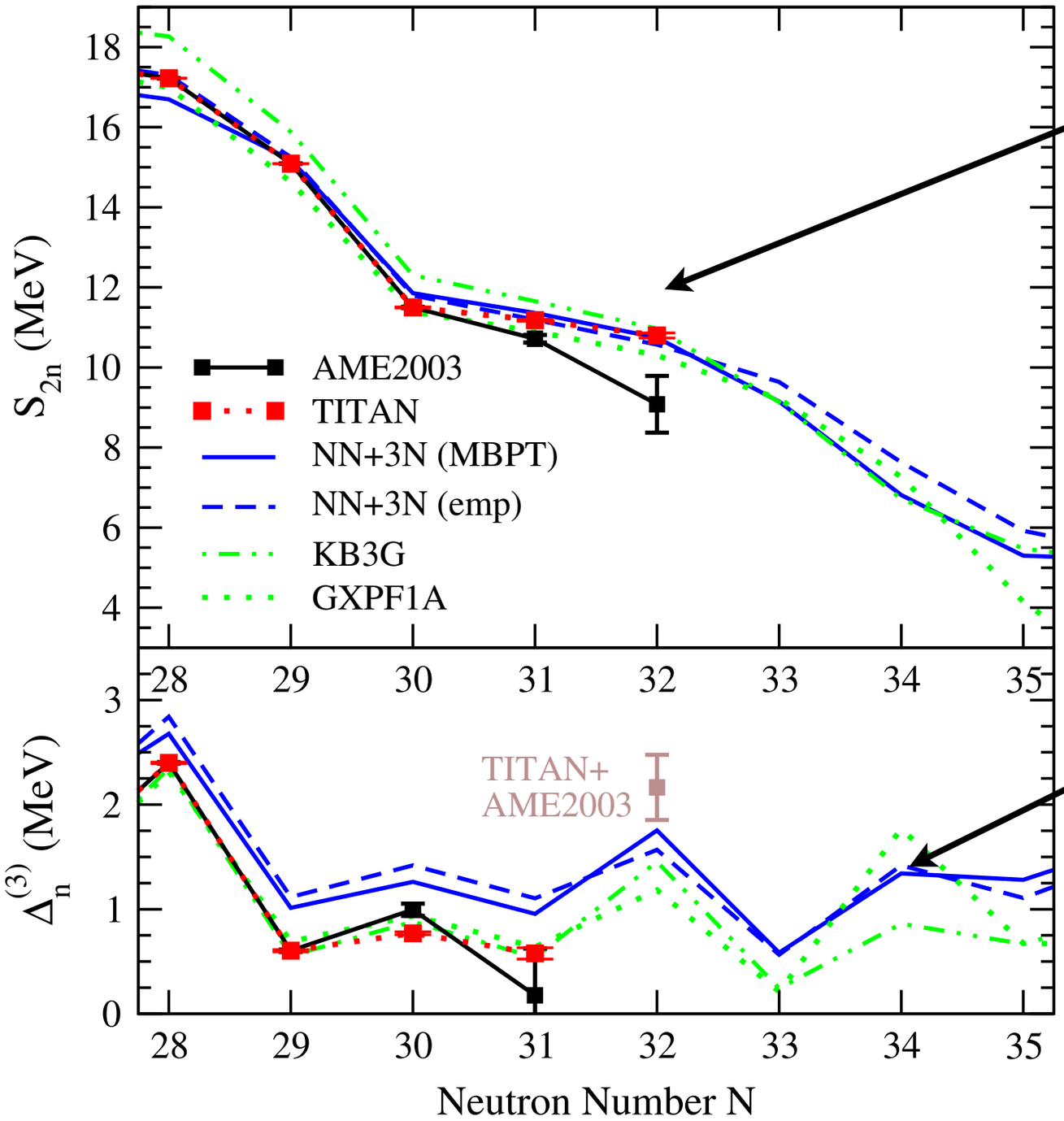
Results - Experiment







Results - Theory



Flattening well reproduced by theory

Weak sub-shell closure predicted. Similar to CC calculation

Summary

- Large deviations found to AME2003
  - Potentially large impact on predicted location of drip-line
- Continue campaign out to N=34
  - Mass measurements of Sc
- 3N forces reproduce the experimental results
  - Further experiments will provide stringent tests of 3N forces in medium mass nuclei
  - Same 3N forces are important for neutron matter

TRIUMF

Thank you!

The TITAN Group:

A.T. Gallant, J.C. Bale, T. Brunner, U. Chowdhury, S. Ettenauer, A. Lennarz, D. Robertson, V.V. Simon, A. Chaudhuri, A.A. Kwiatkowski, E. Mané, B.E. Schultz, M.C. Simon, C. Andreoiu, P. Delheij, M.R. Pearson, H. Savajols, and J. Dilling

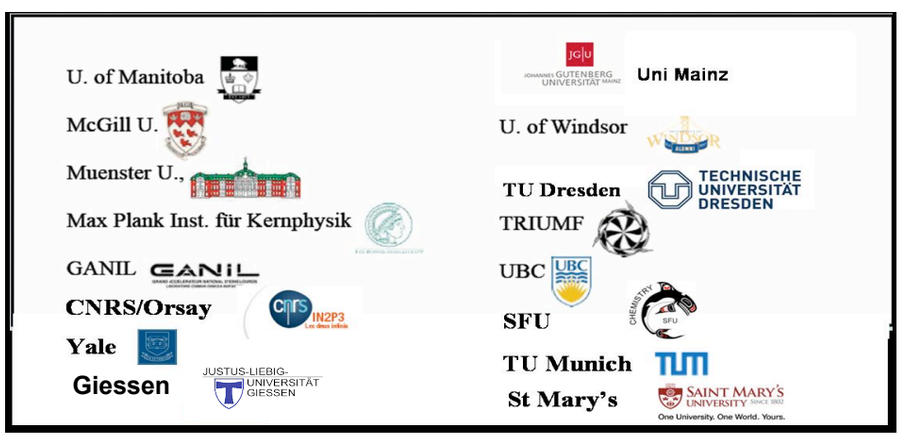
TRIUMF Staff:

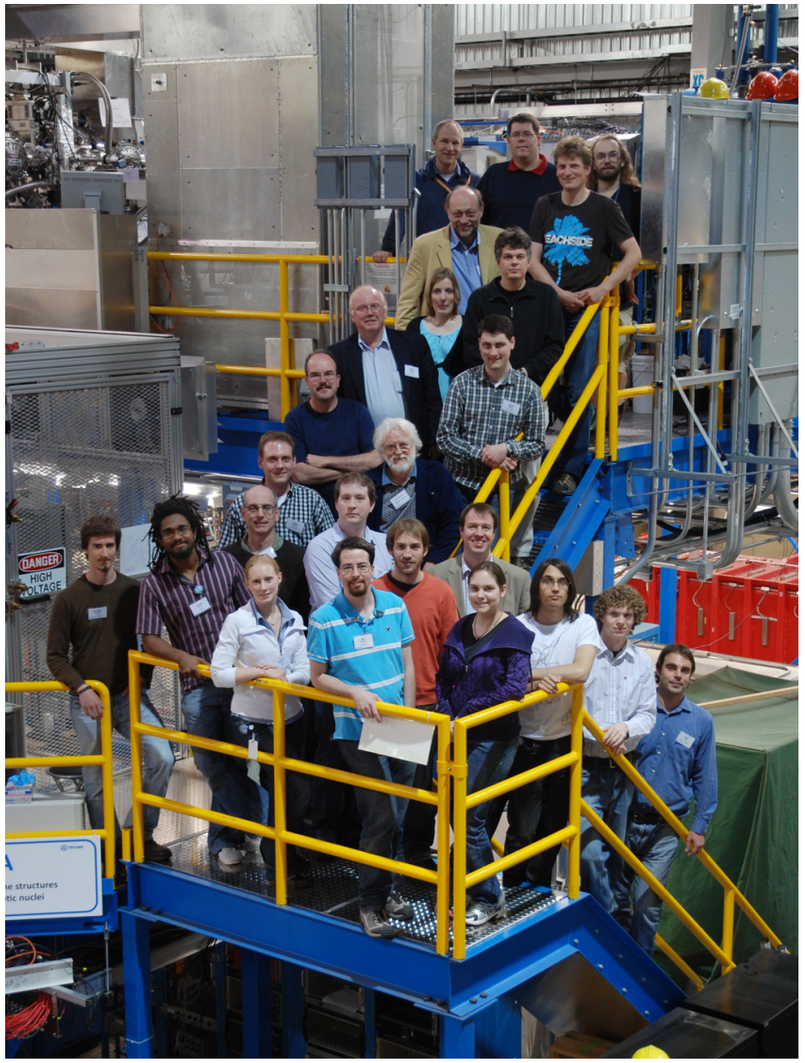
Jens Lassen & the TRILIS Team, Marik Dombsky, Peter Kunz & the yields team, TRIUMF Operators

Theory:

Achim Schwenk, Jason Holt, Javier Menéndez

And the rest of the TITAN collaboration....





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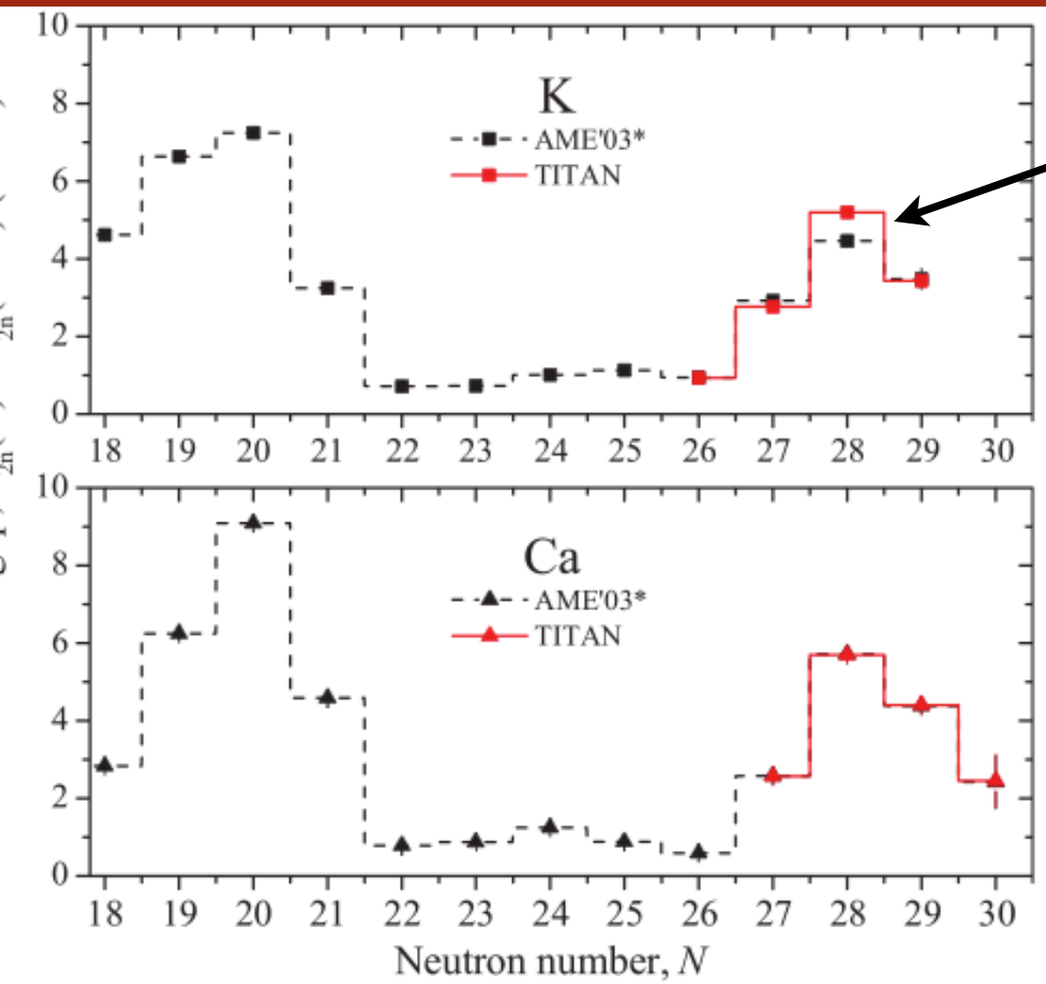
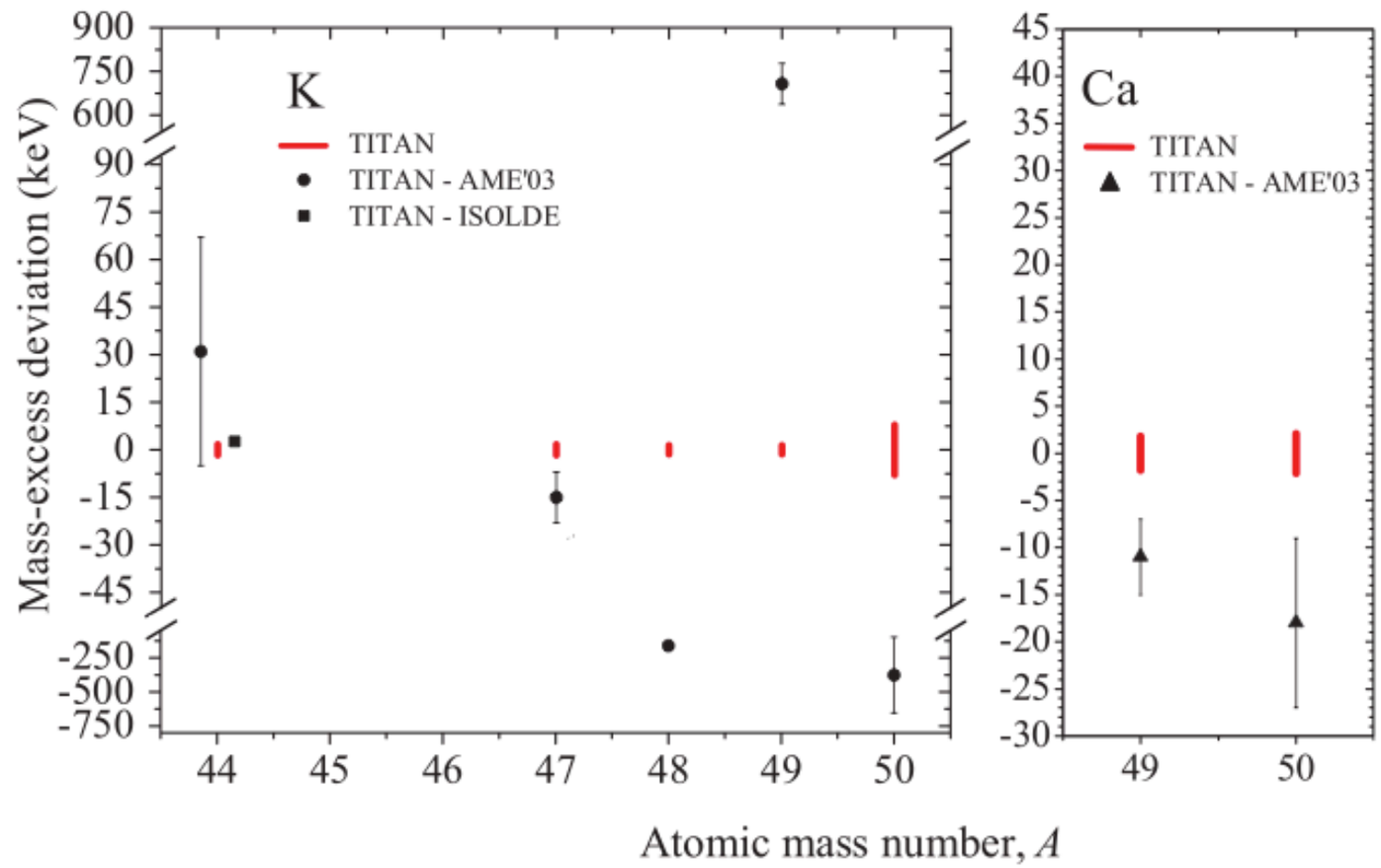
Back-up Slides

Resurgence of N=28



Stronger N=28 Shell Gap



Large Deviations from tabulated values

Much stronger neutron shell gap at N=28

A. Lapierre *et al.*, Phys. Rev. C, 85, 024317 (2012)