Evolution of the N=32 shell closure through mass observables

Erich Leistenschneider

FRIB / NSCL
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NSCL FRIB

NUSTAR Annual meeting 2021

U.S. DEPARTMENT OF ENERGY | Office of Science

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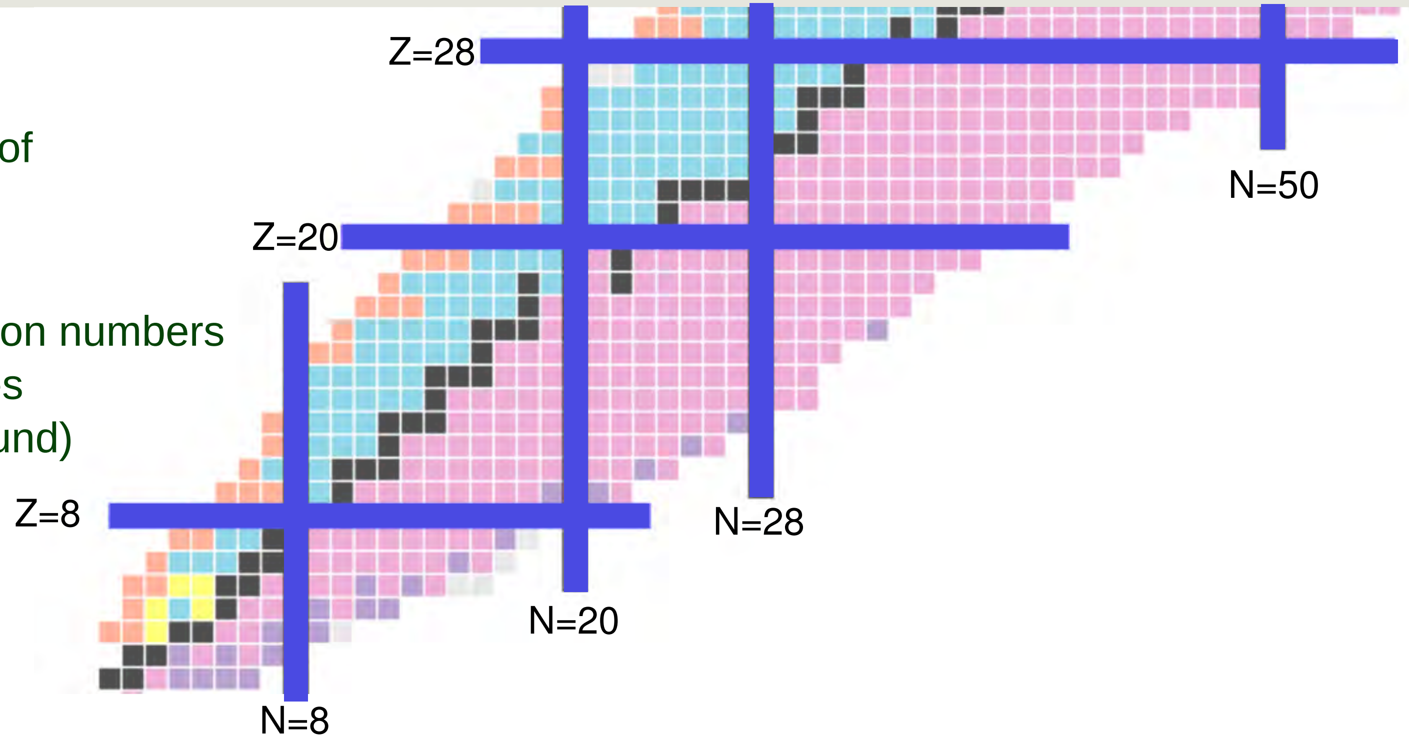
Nuclear Shells

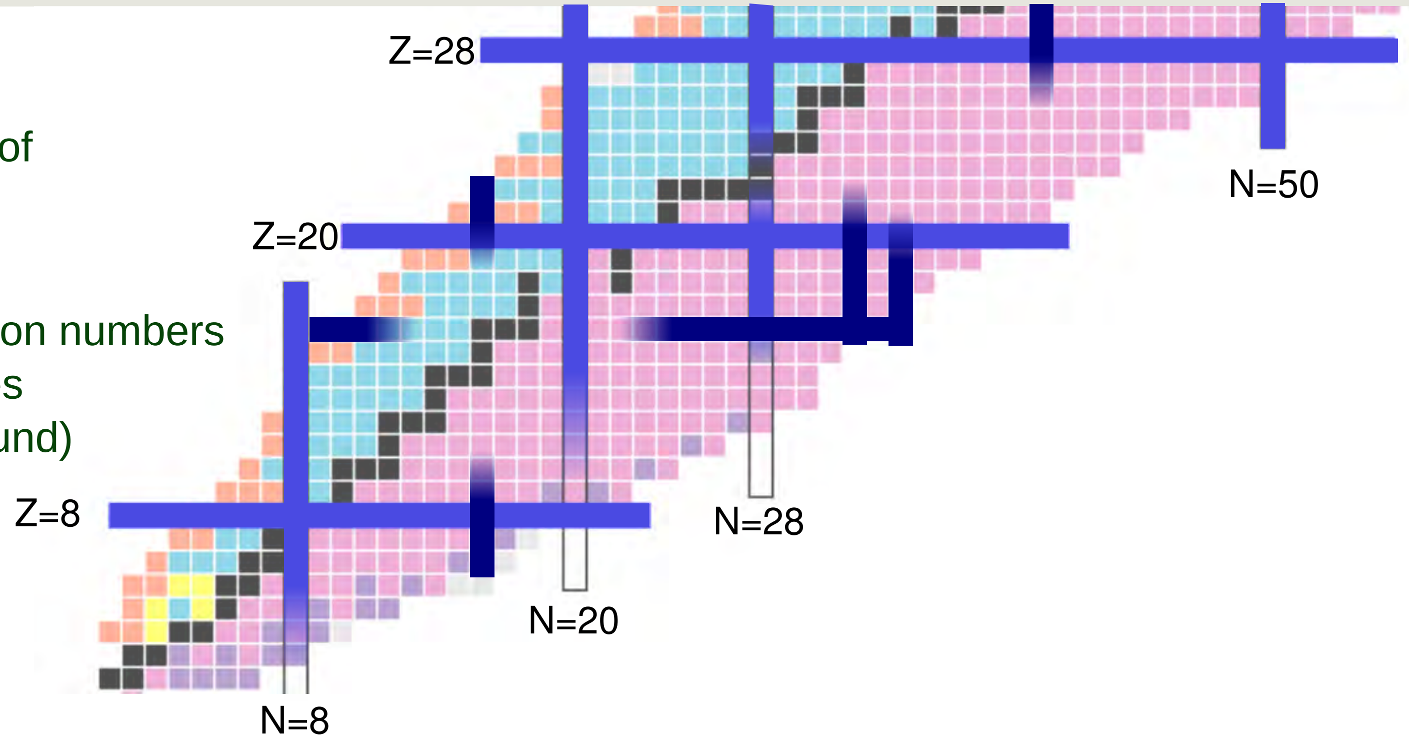
Backbone of models of nuclear structure

Nuclei at **magic** nucleon numbers have special properties (*e.g.* exceptionally bound)

Discovered well over half century ago!



Nuclear Shells



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Discovered well over half century ago!

Shells are **not immutable!**

Several instances of "non-canonical" behavior

Shell evolution is currently one of the most active fields in nuclear structure.

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Backbone of models of nuclear structure

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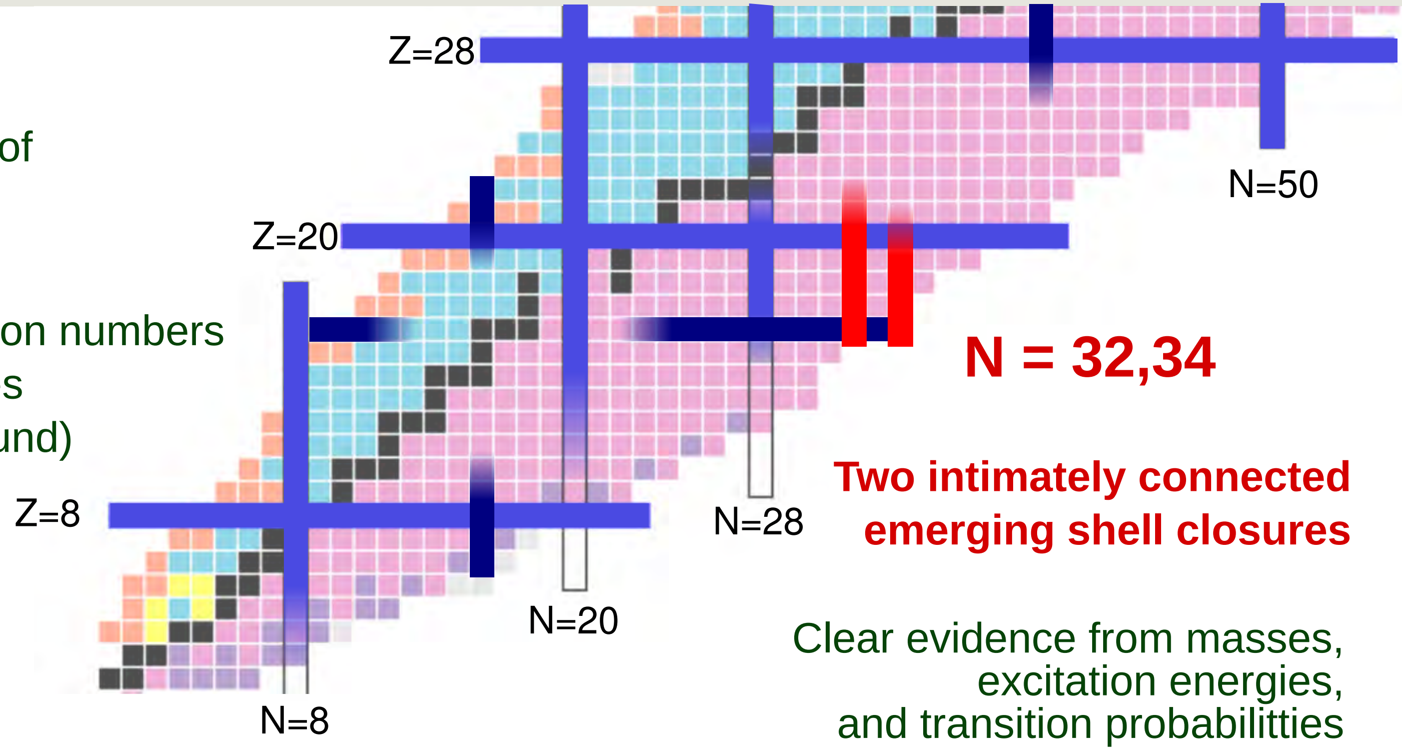


Two intimately connected emerging shell closures

Clear evidence from masses, excitation energies, and transition probabilitties

A rich test bench for nuclear theories

Shells are **not immutable!**

Several instances of "non-canonical" behavior

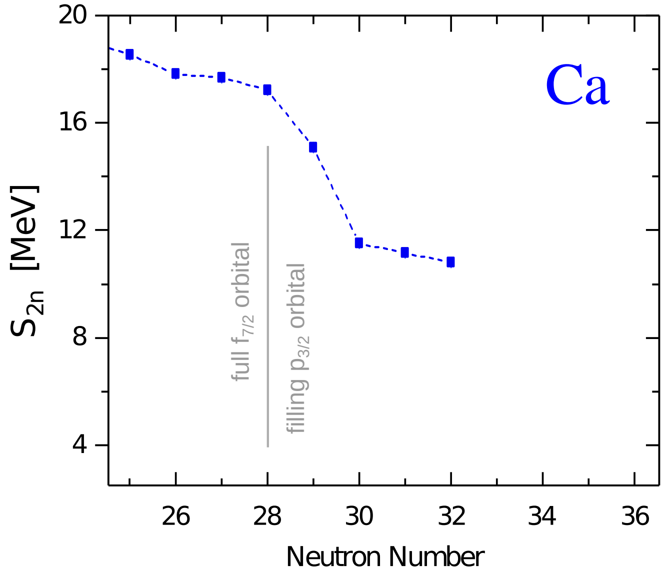
Shell evolution is currently one of the most active fields in nuclear structure.

Shell Closures in the Mass Surface

How to spot: systematic changes in the binding energy surface

A common signature: sudden decreases in 2-neutron separation energy

$$S_{2n}(N,Z) = B(\mathbf{N},Z) - B(\mathbf{N-2},Z)$$



Mass data from AME16

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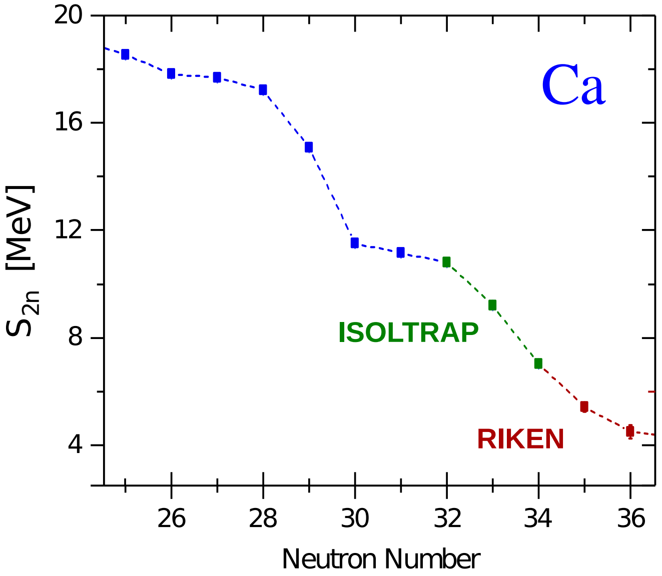

$$S_{2n}(N,Z) = B(\mathbf{N},Z) - B(\mathbf{N-2},Z)$$

First evidence of N=32 shell closure in the mass surface: **ISOLTRAP - ^{52}Ca**

F. Wienholtz *et al.* - Nature (London) 498, 346 (2013).

First evidence of N=34 shell closure in the mass surface: **RIKEN - ^{54}Ca**

S. Michimasa *et al.*, -Phys. Rev. Lett. 121, 022506 (2018)

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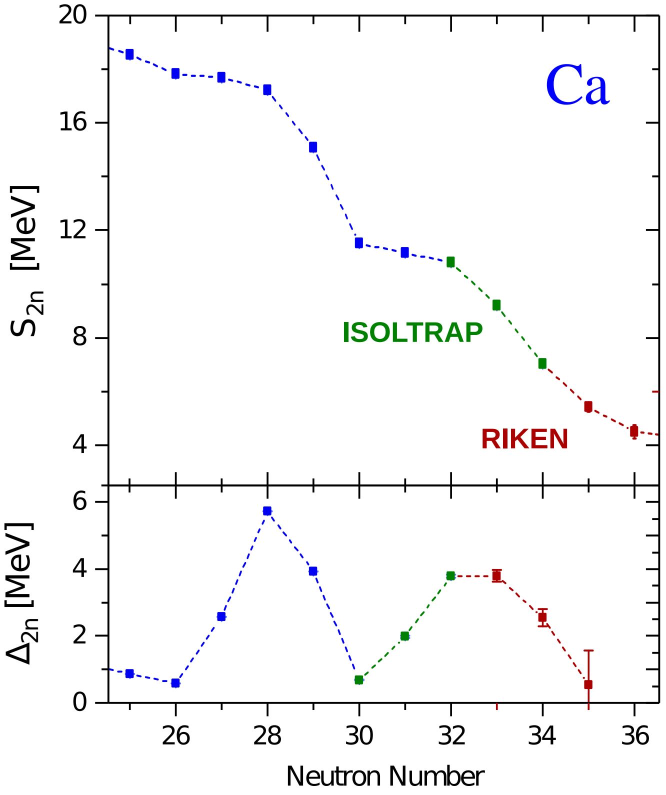

$$S_{2n}(N,Z) = B(N,Z) - B(N-2,Z)$$

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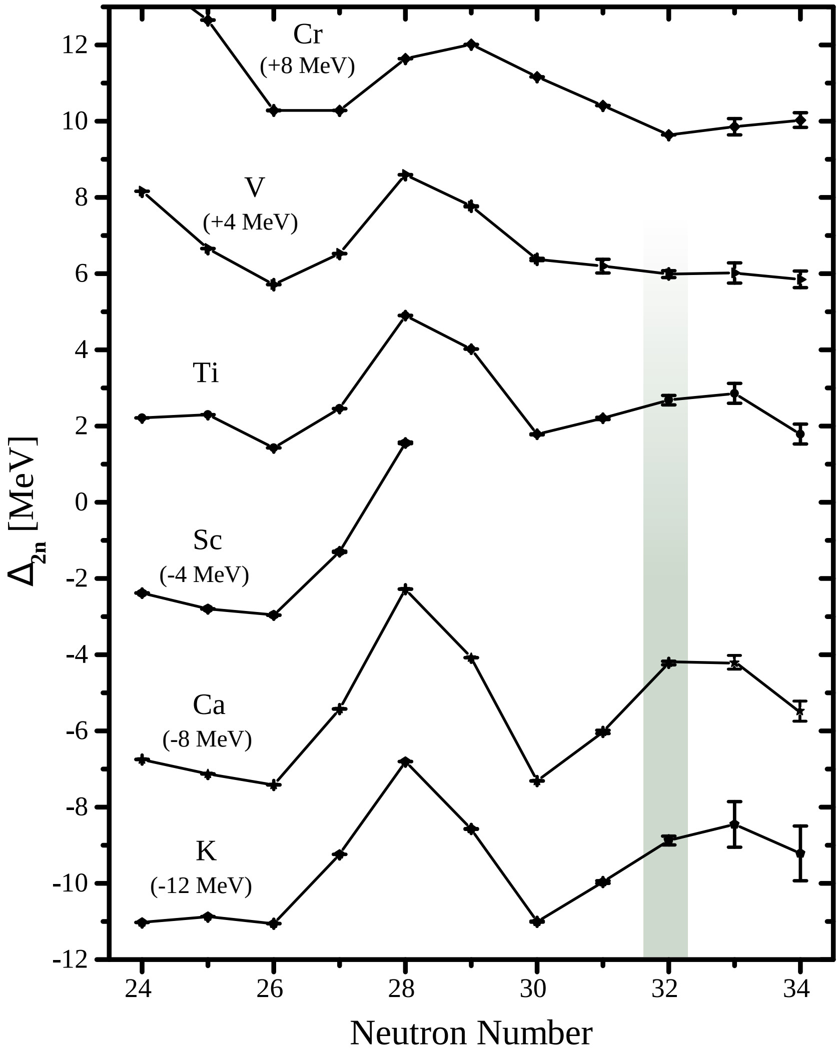
Clearer view:

$$\Delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$

Mass data from AME16

Evolution of N=32 Shell Closure



Cr: absent

V: absent

TITAN / TRIUMF - M. P. Reiter *et al.*, Phys. Rev. C 98, 024310 (2018)

Ti: weak / transitional

TITAN / TRIUMF - E. Leistenschneider *et al.*, Phys. Rev. Lett. 120, (2018).

Ca: doubly-magic

ISOLTRAP / CERN - F. Wienholtz *et al.* - Nature (London) 498, 346 (2013).

K: strong

ISOLTRAP / CERN - M. Rosenbusch *et al.*, Phys. Rev. Lett. 114,202501 (2015)

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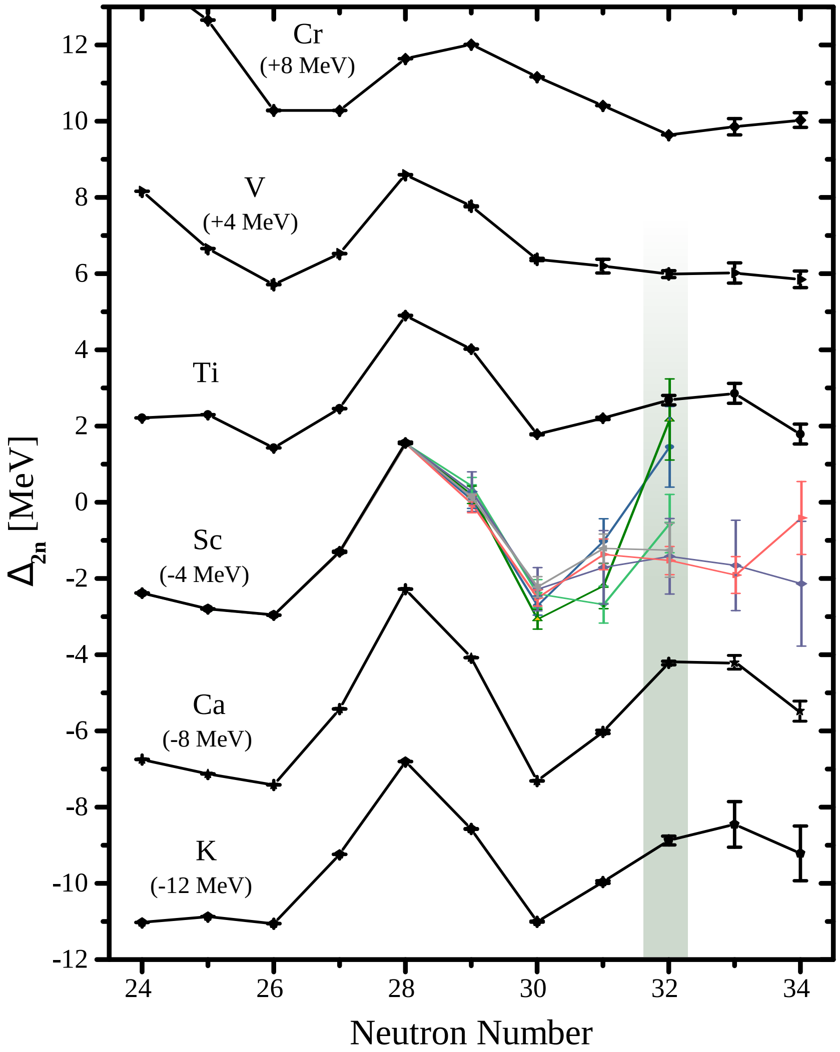
Evolution of N=32 Shell Closure



TOFI Los Alamos 1990
X. L. Tu et al., Z. Phys. A: At. Nucl. 337, 361 (1990)

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TOF-Bρ NSCL 2011
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Z. Meisel et al., Phys. Rev. Lett. 115, 162501 (2015).

TOF-Bρ NSCL 2020 (re-evaluation)
Z. Meisel et al., Phys. Rev. C 101, 052801(R) (2020)

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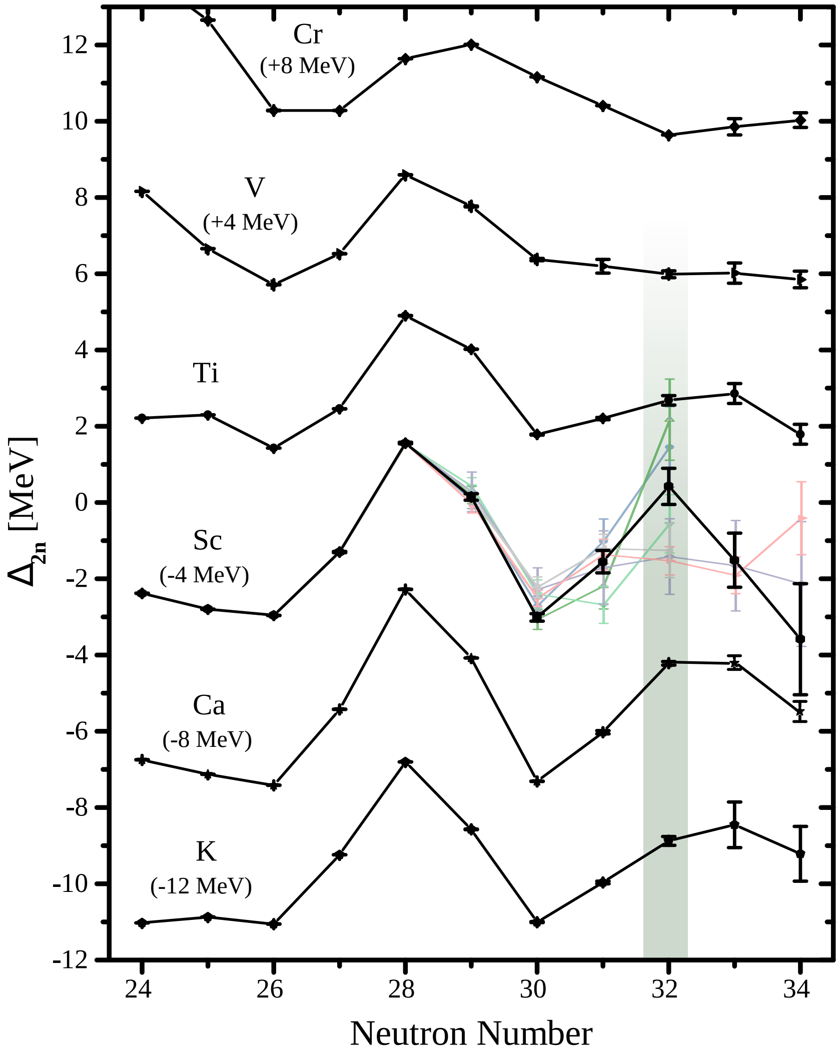

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Isochronous Mass Spectrometry at CSRe (Lanzhou)

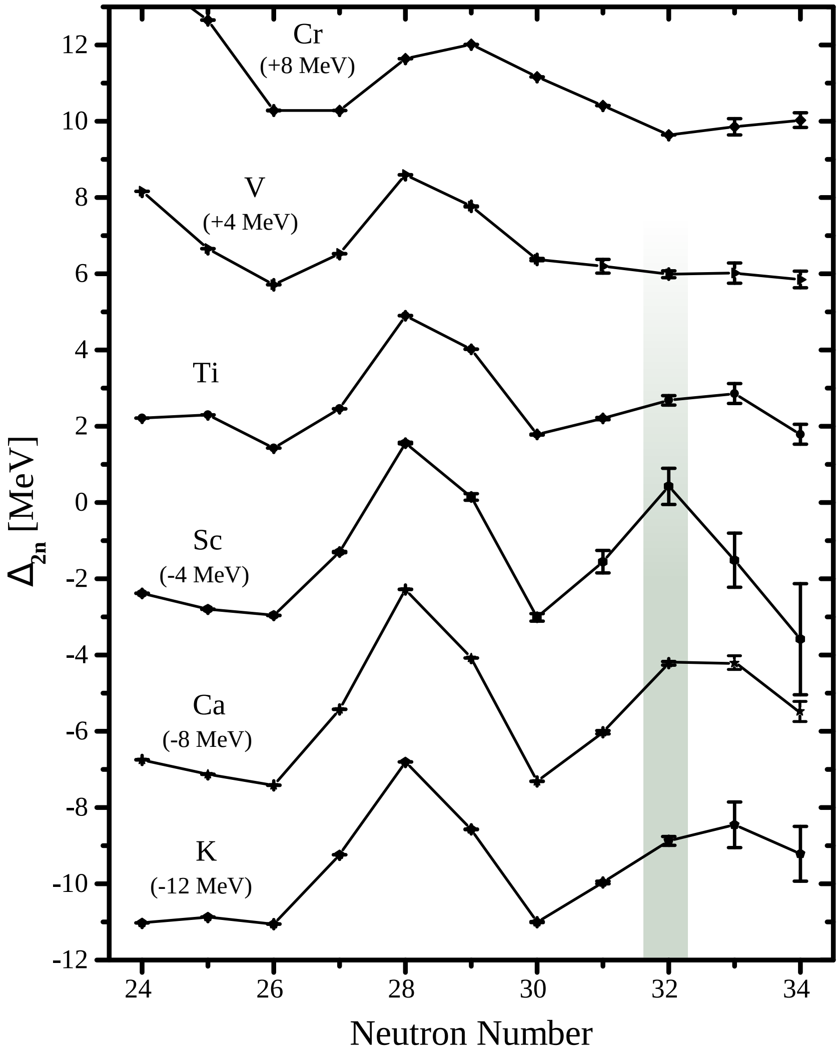
X. Xu *et al.*, Phys. Rev. C 99, 064303 (2019).

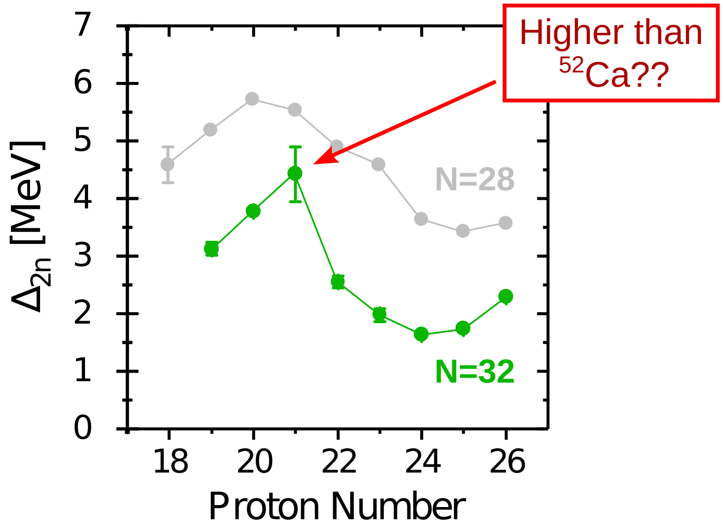
Strong shell closure in ^{53}Sc!

... But how strong?

Mass data from AME16

Evolution of N=32 Shell Closure





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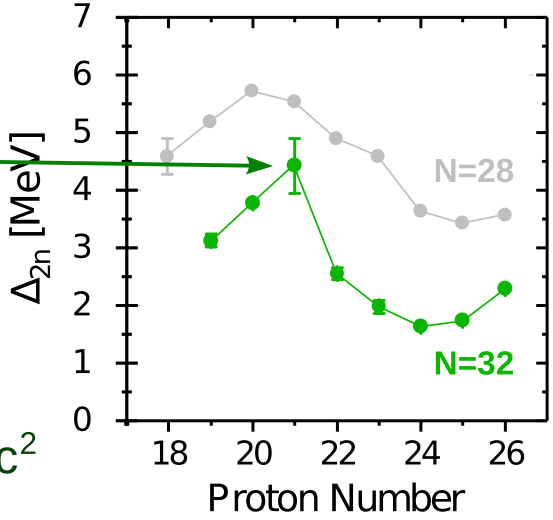
GOAL: measure Δ_{2n} in ^{53}Sc (N=32) using precision mass spectrometry to refine shell evolution.



REQUIRES: masses of neutron-rich ^{51}Sc to ^{55}Sc to a precision much better than 100 keV/c^2

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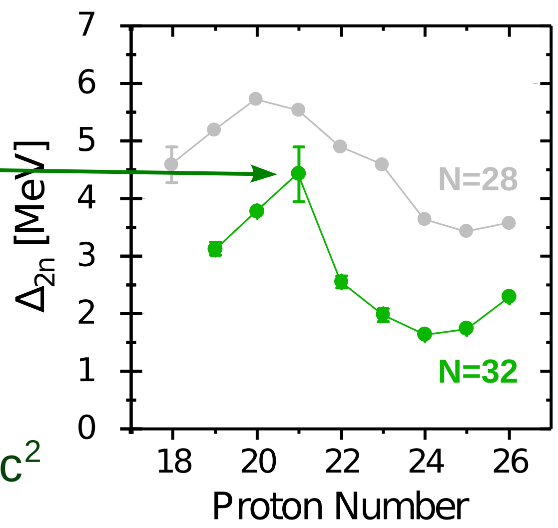

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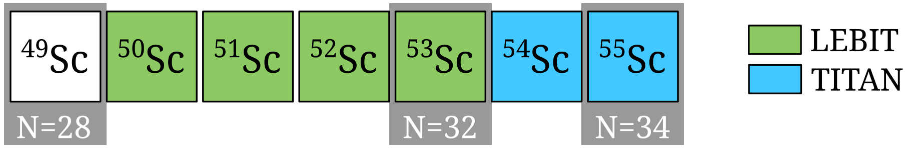
Two experiments performed at different facilities and employing distinct techniques: **LEBIT** at NSCL (Penning traps) and **TITAN** at TRIUMF (MR-TOF-MS)



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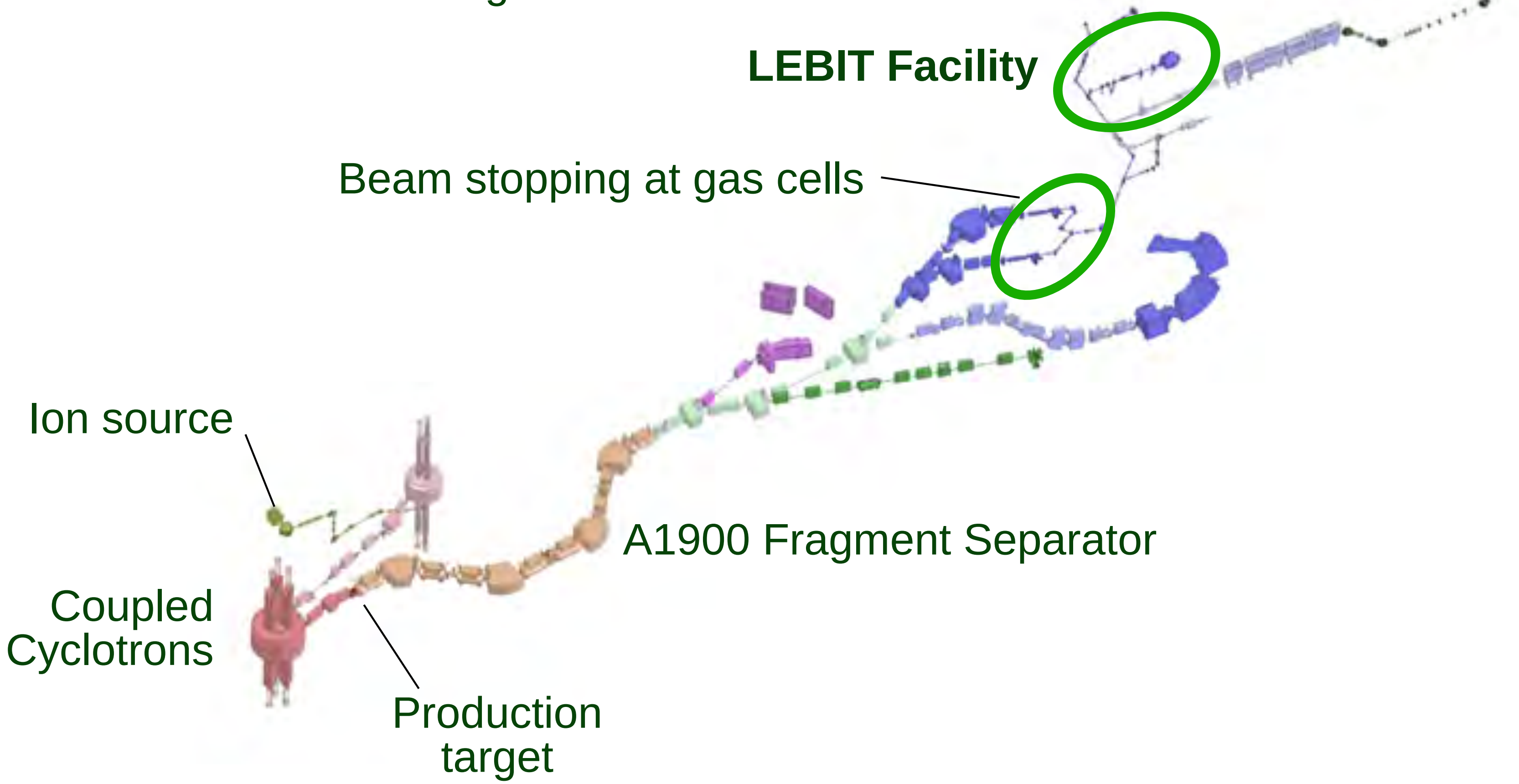
The Experiment at LEBIT (NSCL)

Production: in flight, nuclear fragmentation of 130 MeV/u ^{76}Ge into Be target



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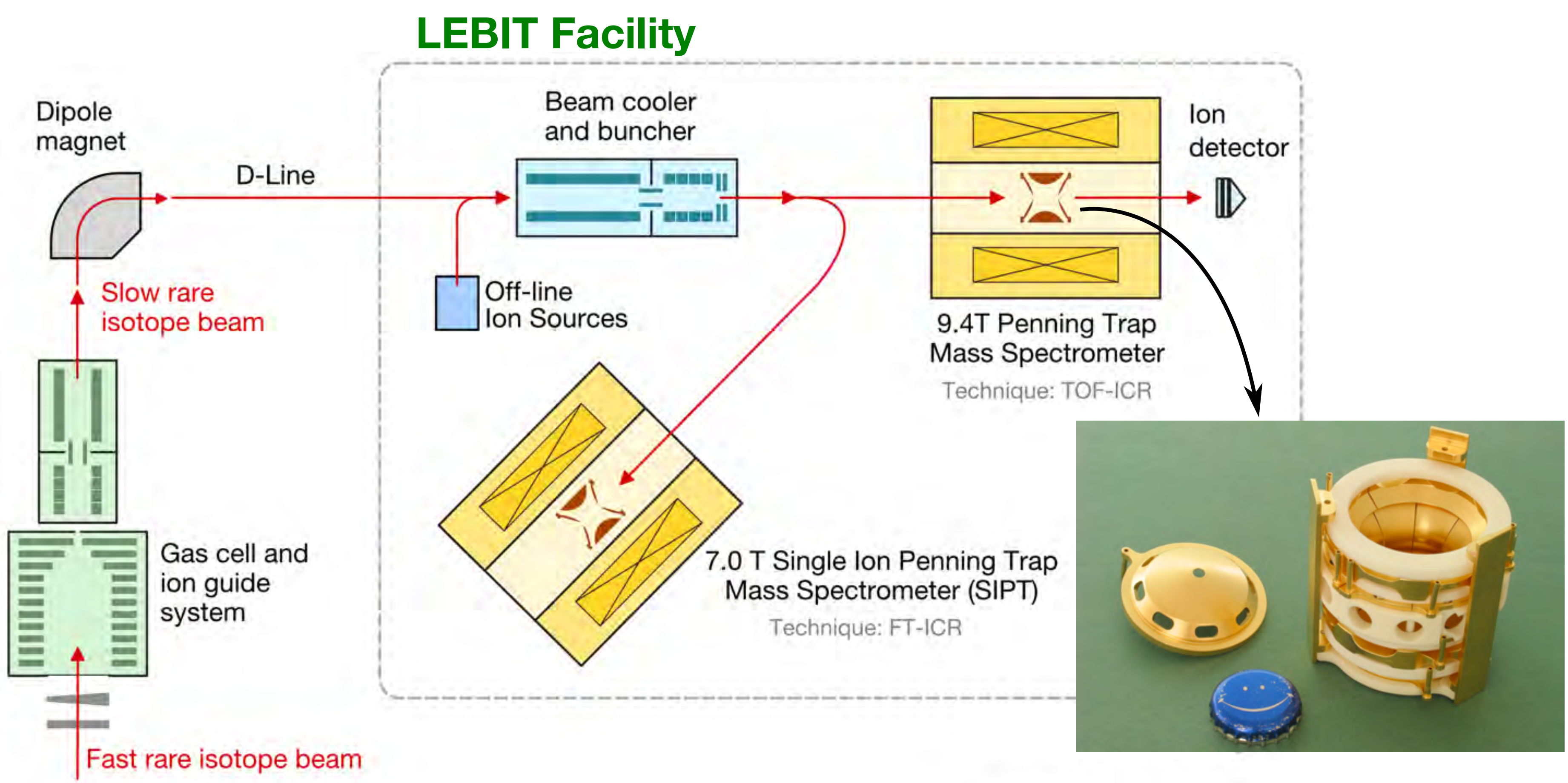

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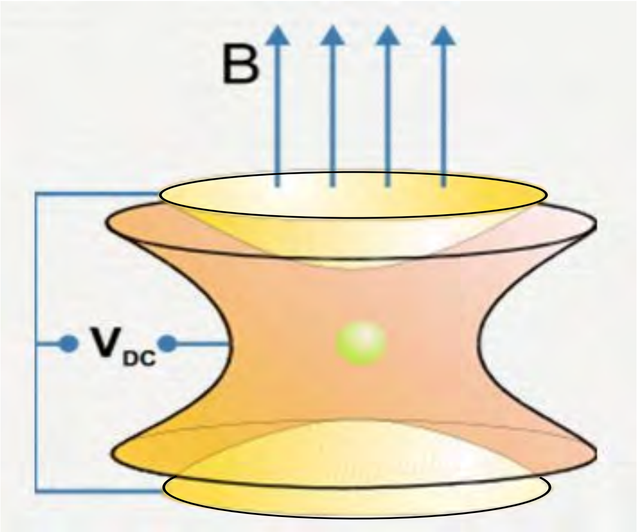
The Experiment at LEBIT (NSCL)

Penning Trap Mass Spectrometry



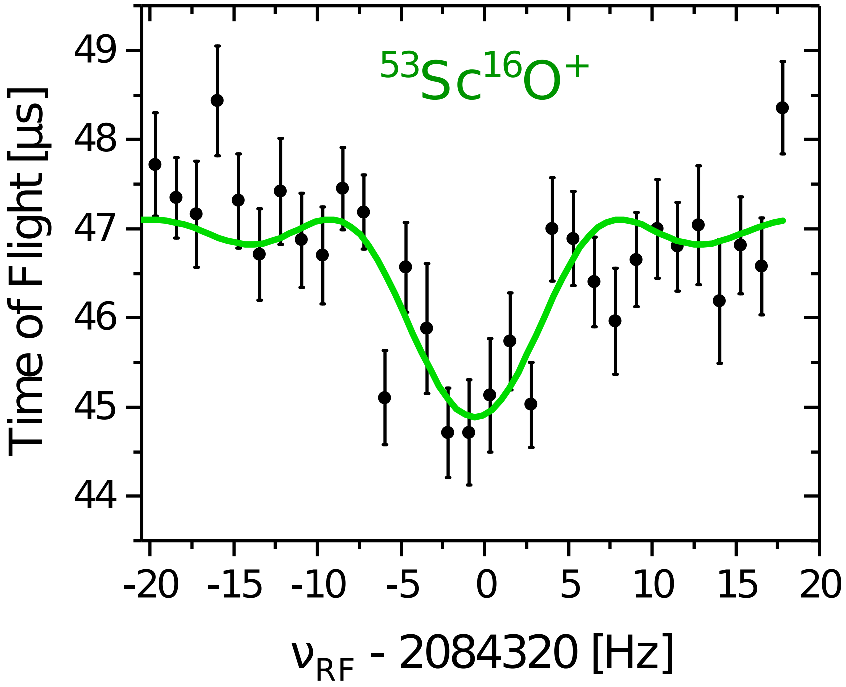
Confinement: strong B field (**9.4 T**)
+ weak E field

Mass meas. through cyclotron frequency:

$$\nu_c = \frac{q\,B}{2\pi\,m}$$

The Experiment at LEBIT (NSCL)

Penning Trap Mass Spectrometry



Cyclotron frequency: $\nu_c = \frac{q\,B}{2\pi\,m}$

Time-of-Flight Ion Cyclotron Resonance:

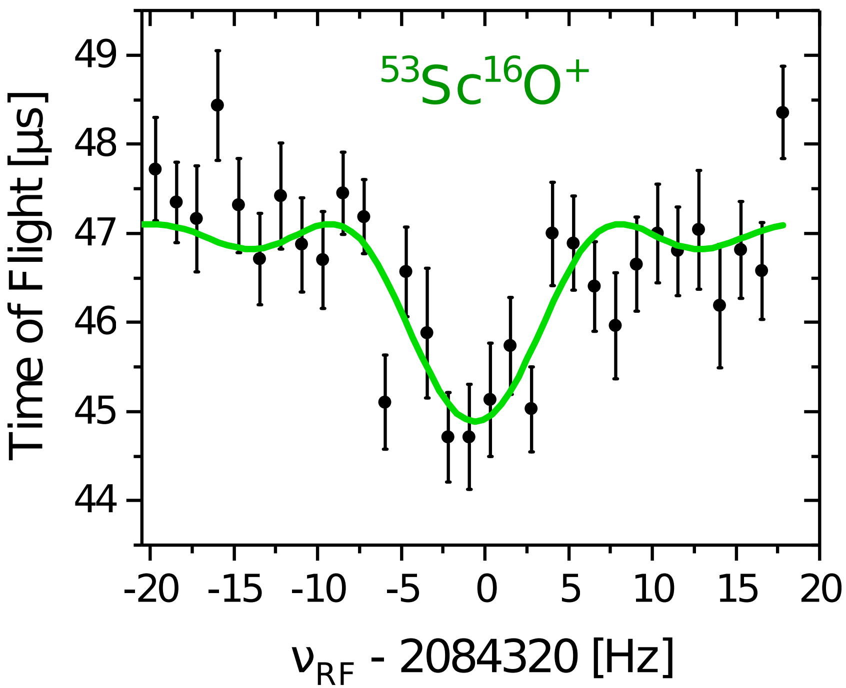
External driving field applied with frequency ν_{rf}

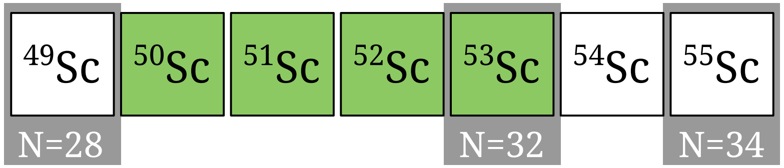
On resonance if $\nu_{rf} = \nu_c$

Gain in energy translates into a faster time-of-flight to detector

The Experiment at LEBIT (NSCL)

Penning Trap Mass Spectrometry





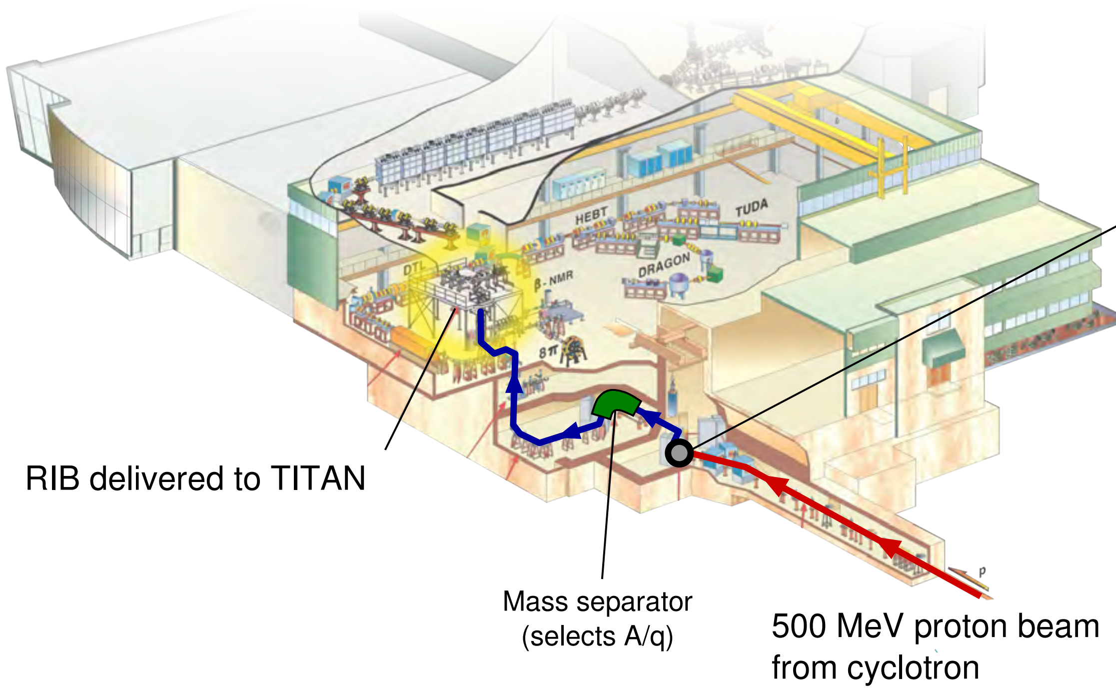
Measurement possible up to ^{53}Sc

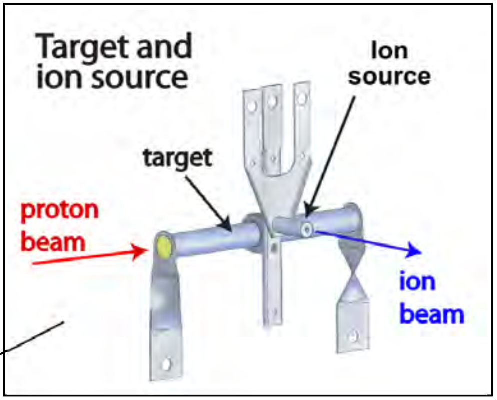
Contaminants were too abundant at $^{54,55}Sc$

The Experiment at TITAN (TRIUMF)

ISAC Facility at TRIUMF

Production: ISOL method, proton beam on Ta target aiming Ti and V isotopes (Sc came as a contaminant)





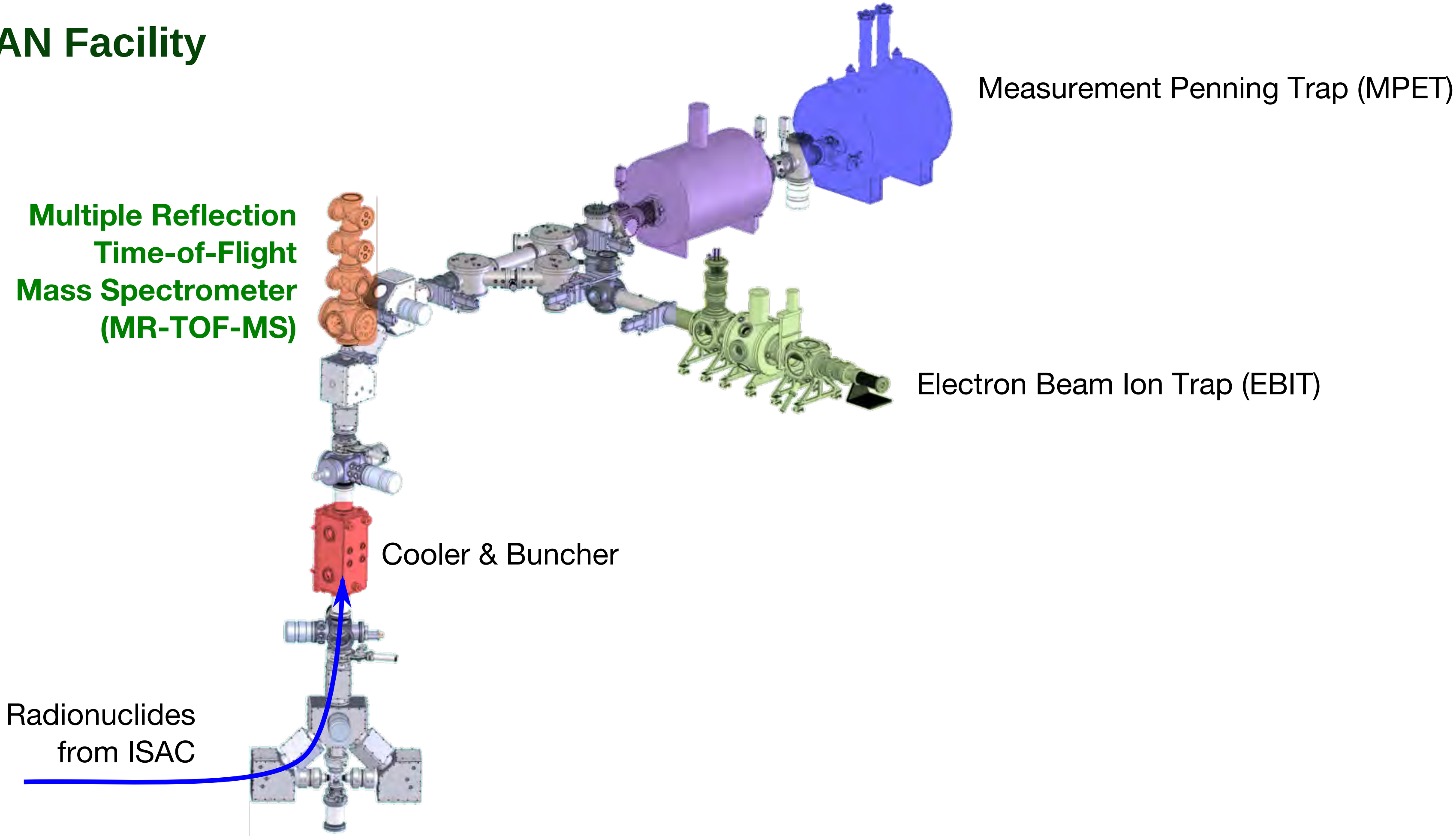
In flight: reaction products are separated, then stopped

ISOL: products are stopped, then separated

Completetely different final beam composition

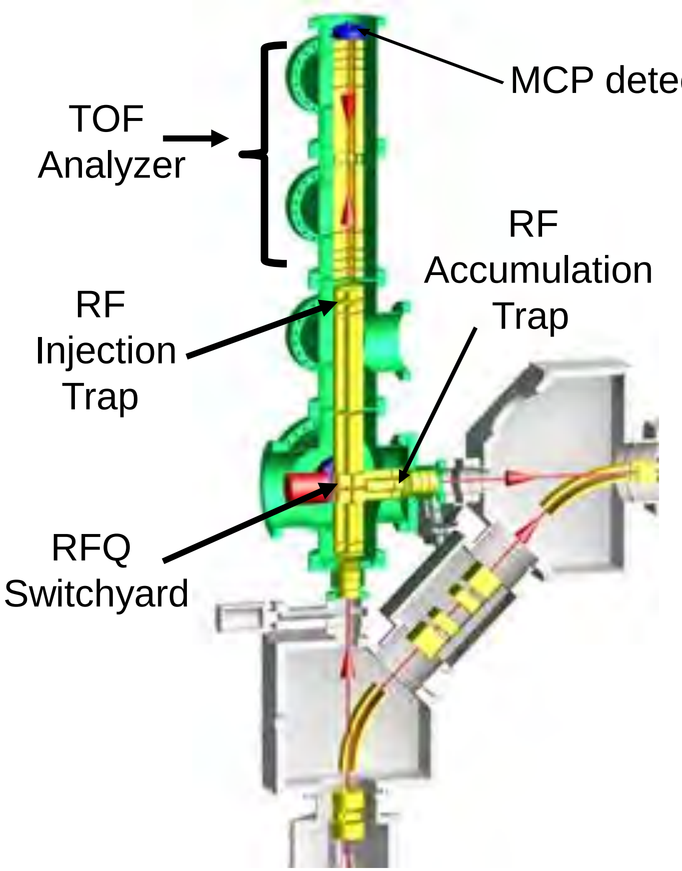
The Experiment at TITAN (TRIUMF)

TITAN Facility



The Experiment at TITAN (TRIUMF)

Multiple-Reflection Time-Of-Flight Mass Spectrometer (MR-TOF-MS)



Mass analyzer

- Two gridless, electrostatic mirrors
- Time-of-flight separation
- Over 200 000 resolving power

  (well enough to separate most isobars)

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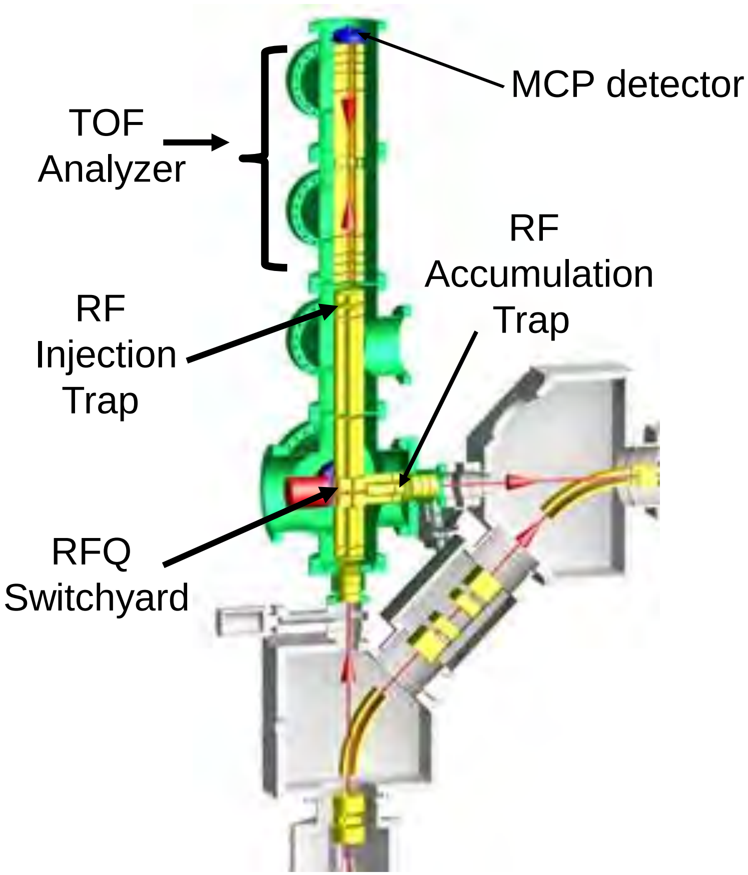

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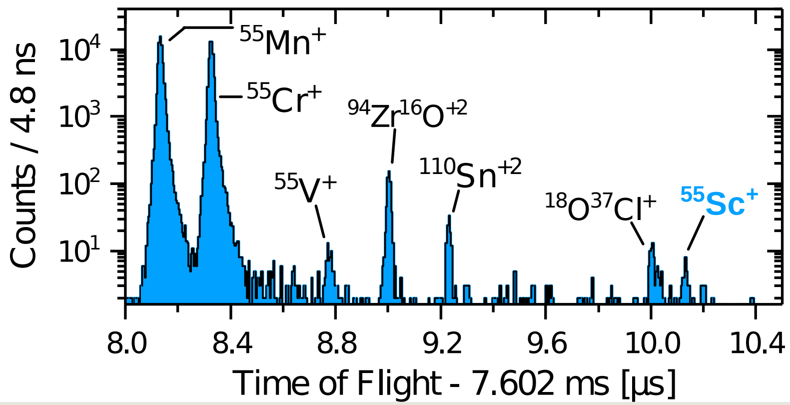

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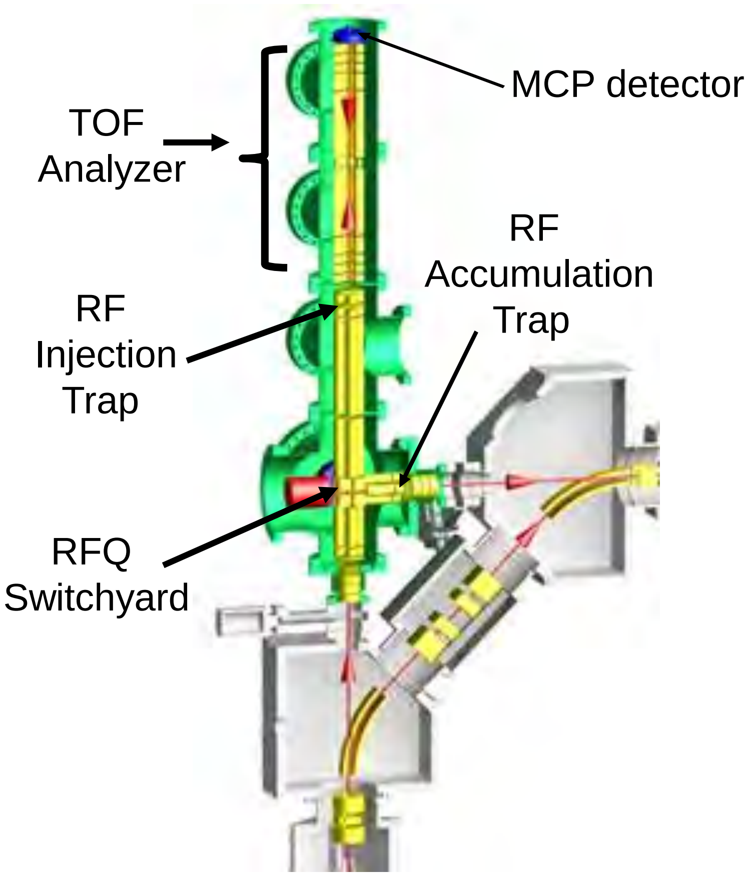
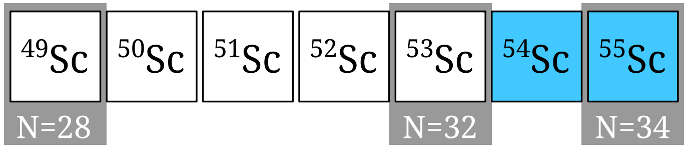
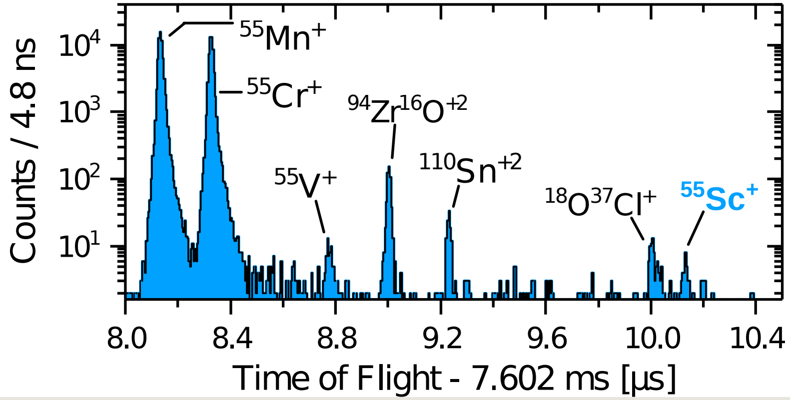


- Fast technique
- Non-scanning and sensitive
- Only 35 counts of ^{55}Sc were sufficient

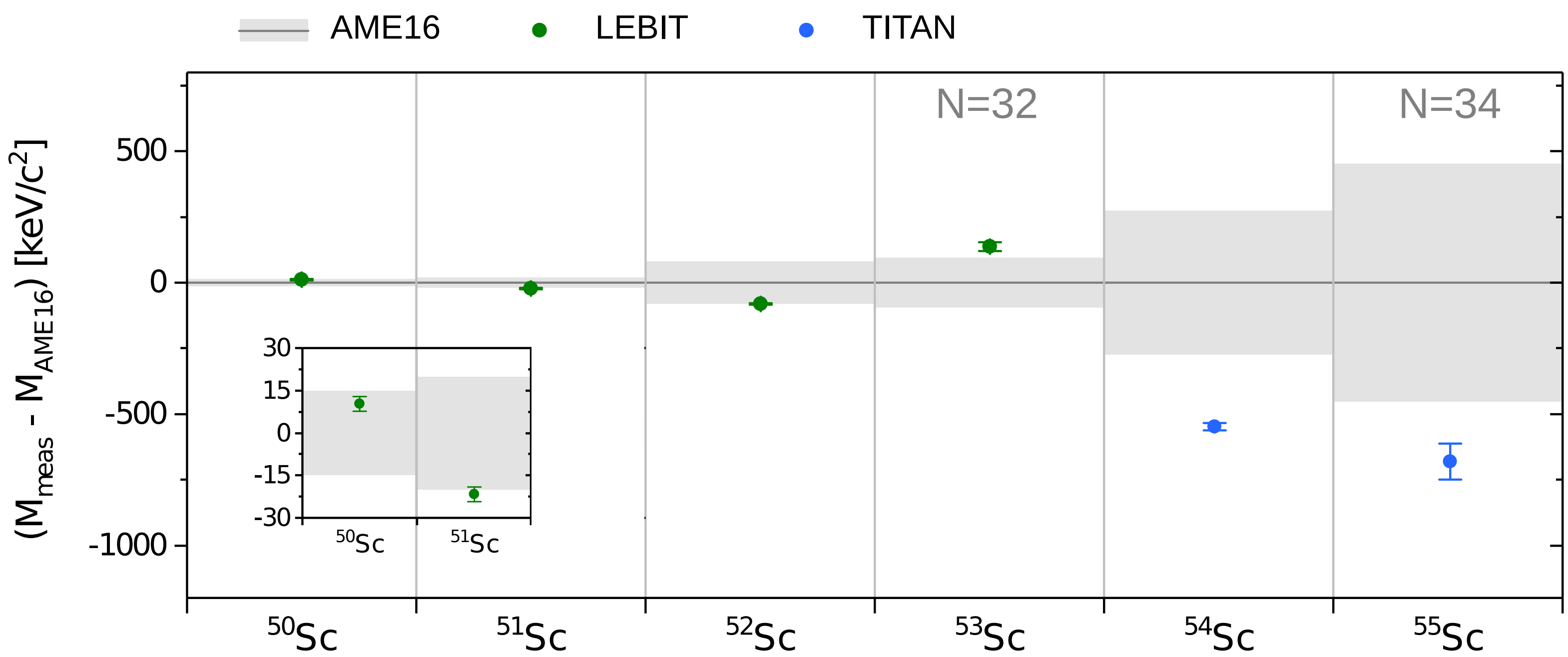


$$M_a = [C(t_{ion} - t_0)^2 + m_e]\,q$$



Results

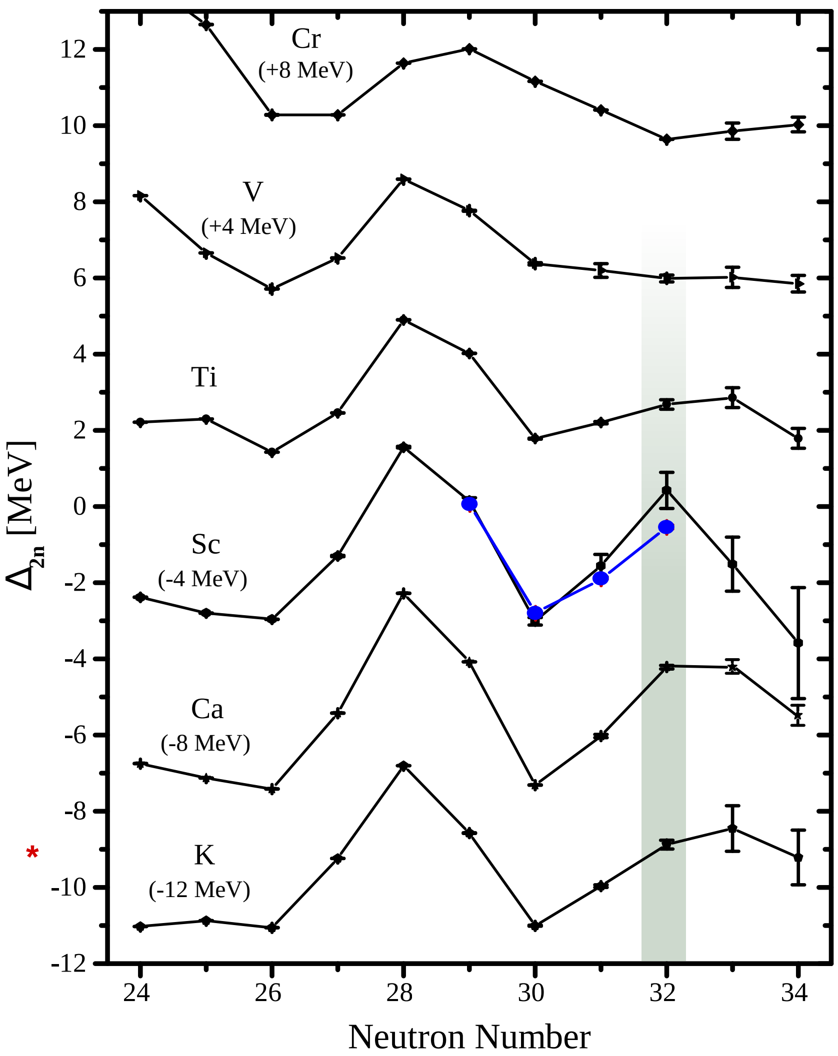
Our results compared to the literature:



Uncertainties improved in all cases

Over 0.5 MeV deviation

Results



Cr: absent

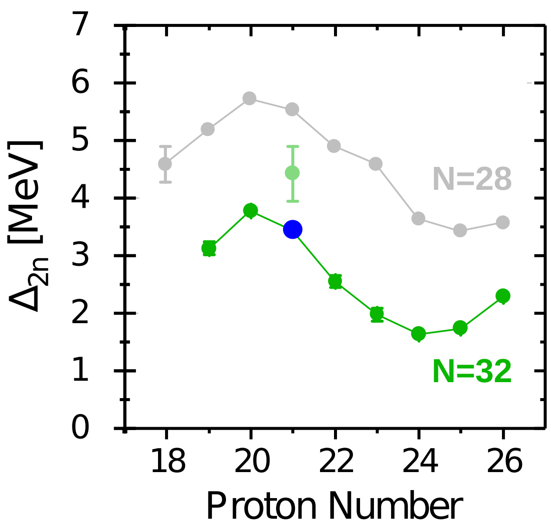
V: absent

Ti: weak

Sc: this work

Ca: doubly-magic

K: strong



Δ_{2n}(N=32) presents a smooth evolution through ^{53}Sc

Δ_{2n}(N=32) seems to mirror Δ_{2n}(N=28), but ~2 MeV lower

Results

PHYSICAL REVIEW LETTERS **126**, 042501 (2021)

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

E. Leistenschneider,[1,2,*] E. Dunling,[3,4] G. Bollen,[1,2,5] B. A. Brown,[1,2,5] J. Dilling,[3,6] A. Hamaker,[1,2,5] J. D. Holt,[3,7] A. Jacobs,[3,6] A. A. Kwiatkowski,[3,8] T. Miyagi,[3] W. S. Porter,[3,6] D. Puentes,[1,2,5] M. Redshaw,[9,2] M. P. Reiter,[3,10,11] R. Ringle,[1,2] R. Sandler,[9] C. S. Sumithrarachchi,[1,2] A. A. Valverde,[12] and I. T. Yandow[1,2,5]

The LEBIT Collaboration and the TITAN Collaboration

[1]*Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA*
[2]*National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA*
[3]*TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Canada*
[4]*Department of Physics, University of York, York YO10 5DD, United Kingdom*
[5]*Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*
[6]*Department of Physics & Astronomy, University of British Columbia, Vancouver, British Columbia V6T 1Z1, Canada*
[7]*Department of Physics, McGill University, 3600 Rue University, Montréal, Quebec H3A 2T8, Canada*
[8]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 5C2, Canada*
[9]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*
[10]*II. Physikalisches Institut, Justus-Liebig-Universität, 35392 Gießen, Germany*
[11]*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom*
[12]*Department of Physics & Astronomy, University of Manitoba, Winnipeg, Manitoba R3T 2N2, Canada*

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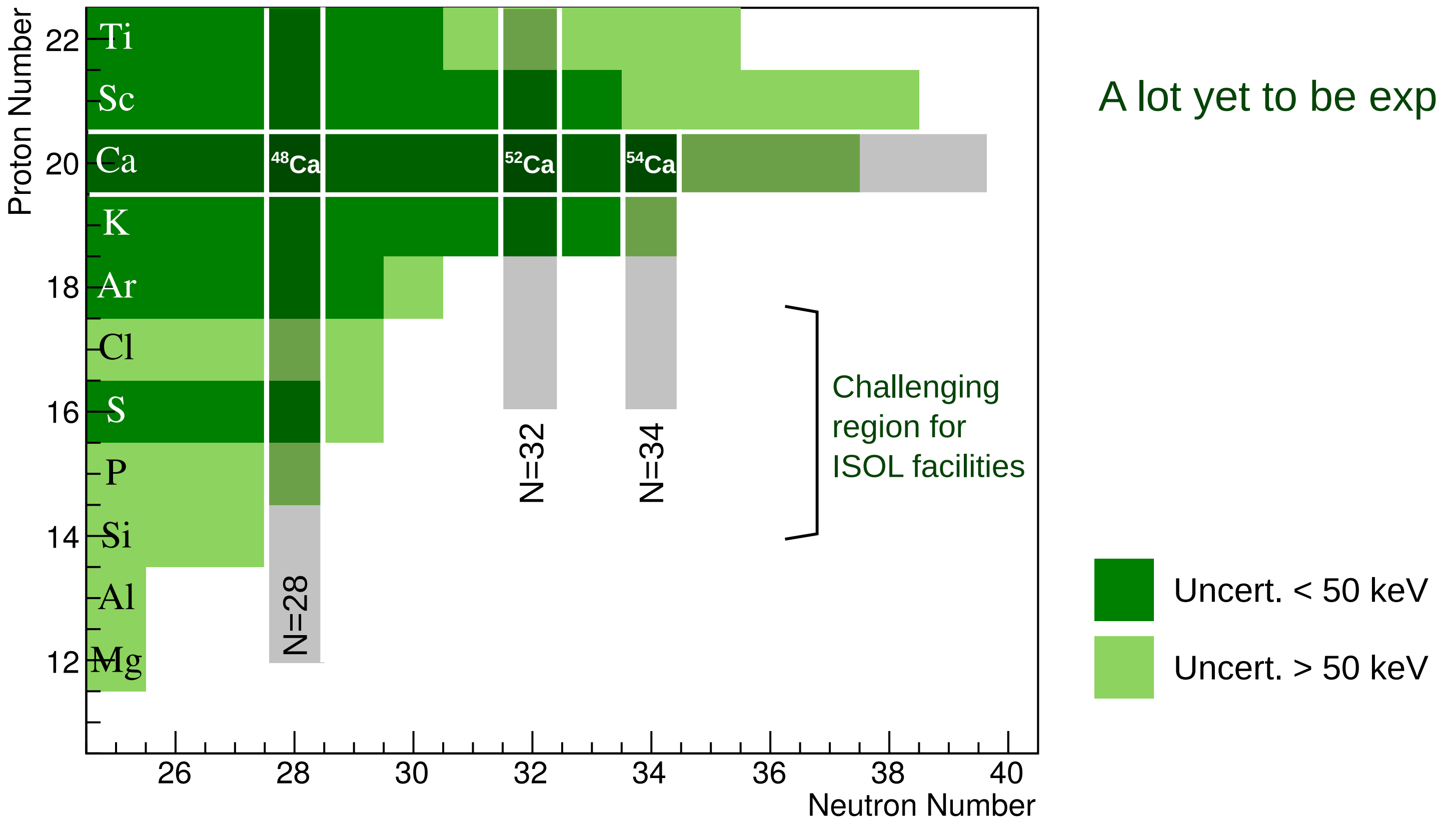
We report high-precision mass measurements of $^{50-55}$Sc isotopes performed at the LEBIT facility at NSCL and at the TITAN facility at TRIUMF. Our results provide a substantial reduction of their uncertainties and indicate significant deviations, up to 0.7 MeV, from the previously recommended mass values for $^{53-55}$Sc. The results of this work provide an important update to the description of emerging closed-shell phenomena at neutron numbers $N=32$ and $N=34$ above proton-magic $Z=20$. In particular, they finally enable a complete and precise characterization of the trends in ground state binding energies along the $N=32$ isotone, confirming that the empirical neutron shell

Further discussion on:

Implications for a possible N=34 shell gap in Sc

Conjoint theoretical descriptions of N=32,34

Future



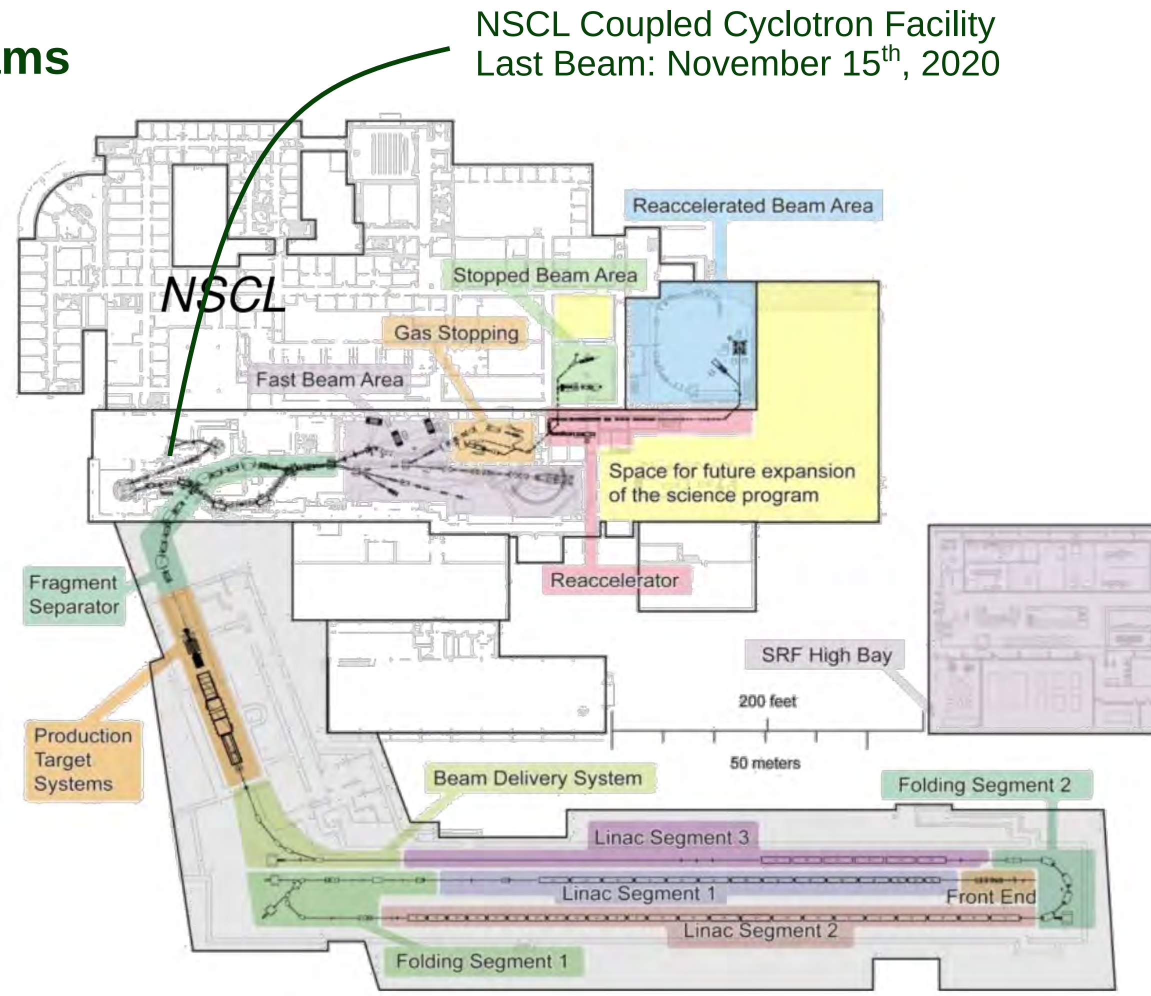
A lot yet to be explored!

Towards higher yields: FRIB

Facility for Rare Isotope Beams

Rare isotope production via in-flight technique with intense primary beams up to 400 kW

First PAC proposals received last Monday for experiments to run in **2022**.



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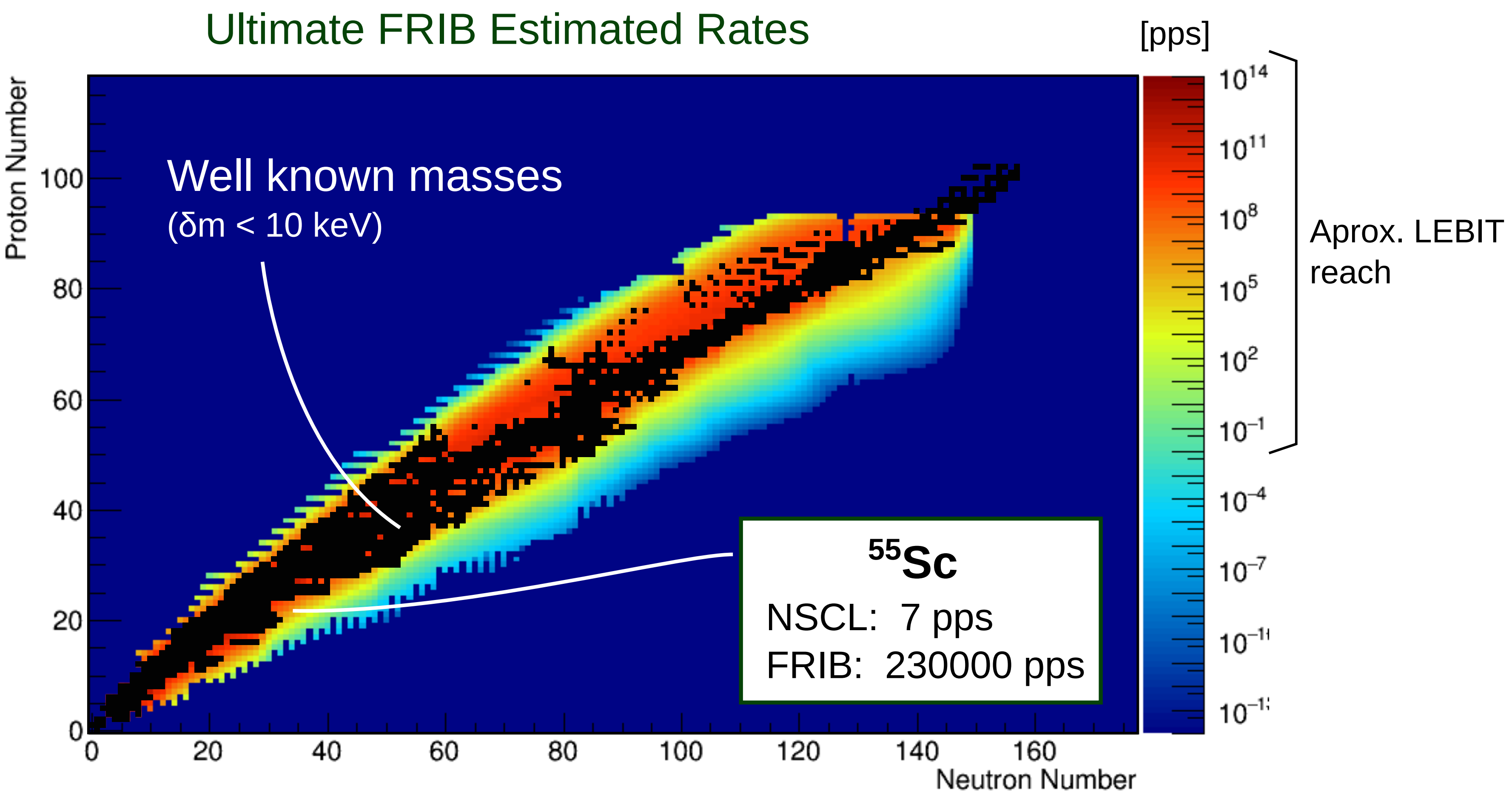
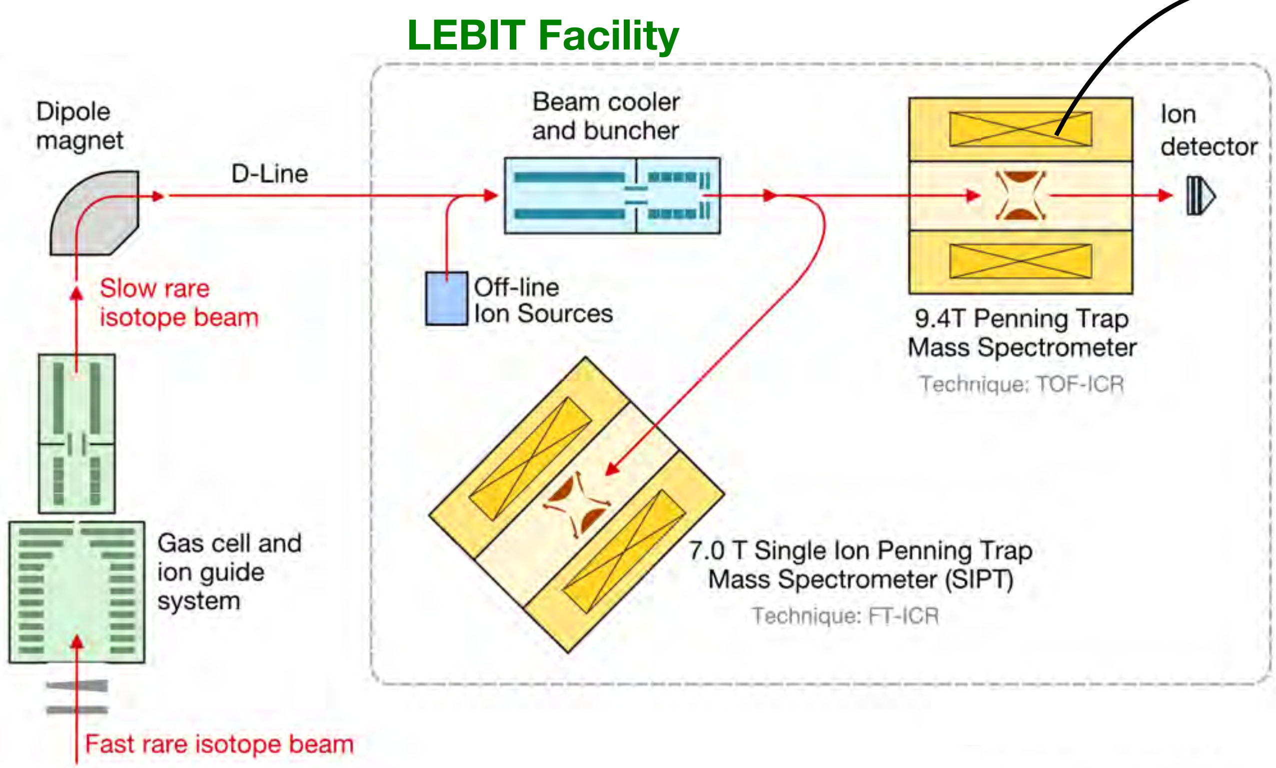
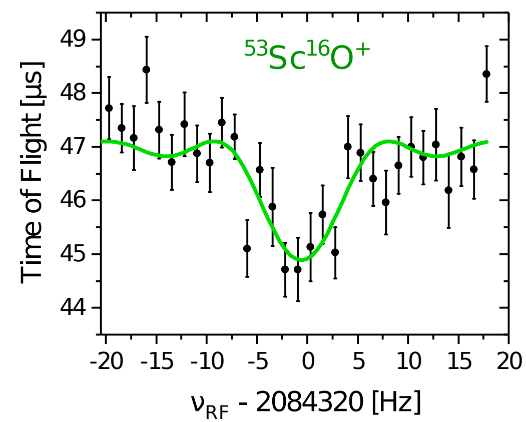


Towards Ultimate Sensitivity: SIPT

Single Ion Penning Trap



TOF-ICR



Scanning technique, Requires ~400 ions for a measurement

Towards Ultimate Sensitivity: SIPT

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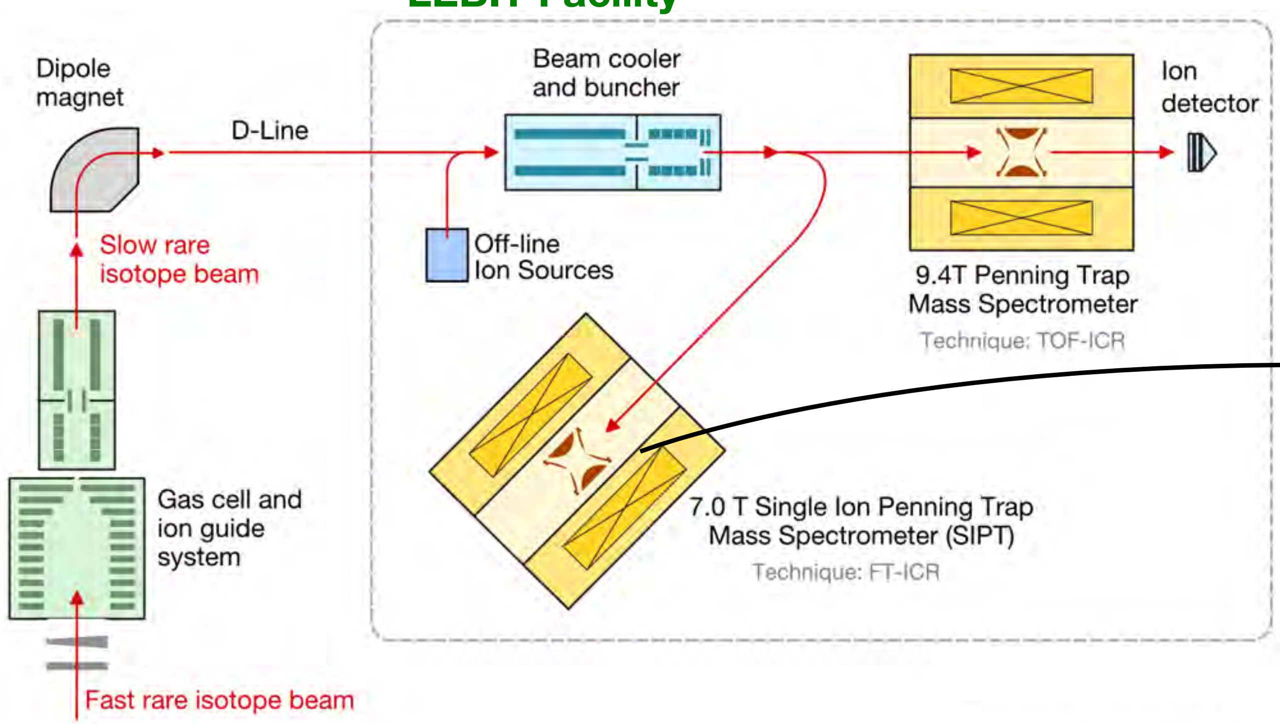
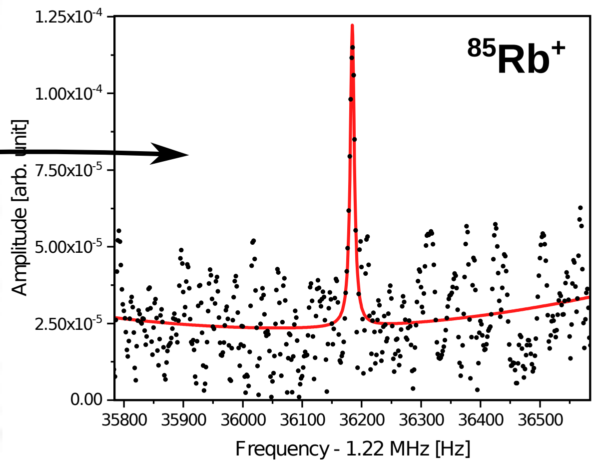


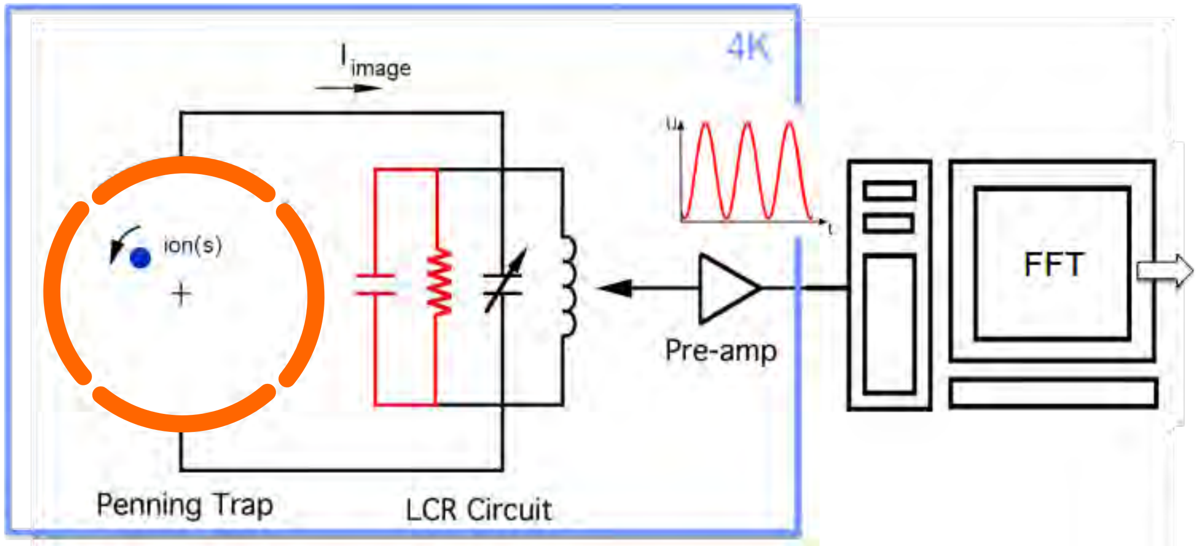
Fourier Transform -ICR



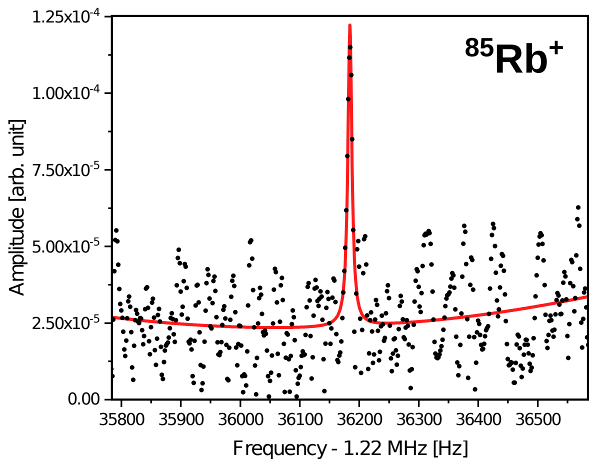
Non-Scanning technique, Ultimately requires 1 ion for a measurement

Towards Ultimate Sensitivity: SIPT

Fourier-Transform Ion-Cyclotron-Resonance Technique



Single ion signal!



1. Ion induces a weak (fA) signal into trap electrodes

2. Signal amplification and noise suppression (Cryogenic circuit)

3. Signal processing

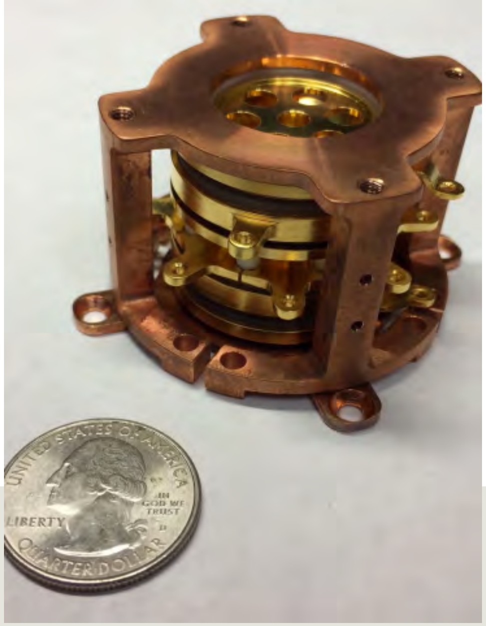
4. Frequency determination

* Can perform the measurement of many species at once

Towards Ultimate Sensitivity: SIPT

Current status

- Commissioned with stable beam
- Mass spectra from external beams acquired (2020)
- Signals from single ions detected (2021)
- **Currently:** improving signal quality to reach ultimate performance



PhD thesis work of A. Hamaker

U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Summary

- Performed precision mass spectrometry of $^{50-53}$**Sc** at LEBIT (NSCL) and of ^{54,55}**Sc** at TITAN (TRIUMF)

- Results help refine the evolution of N=32 shell closure at $Z \geq 20$

  Smooth raise of Δ_{2n}(N=32) through ^{53}Sc

- New state-of-the-art techniques will make best use of the intense FRIB beams

Thank you!

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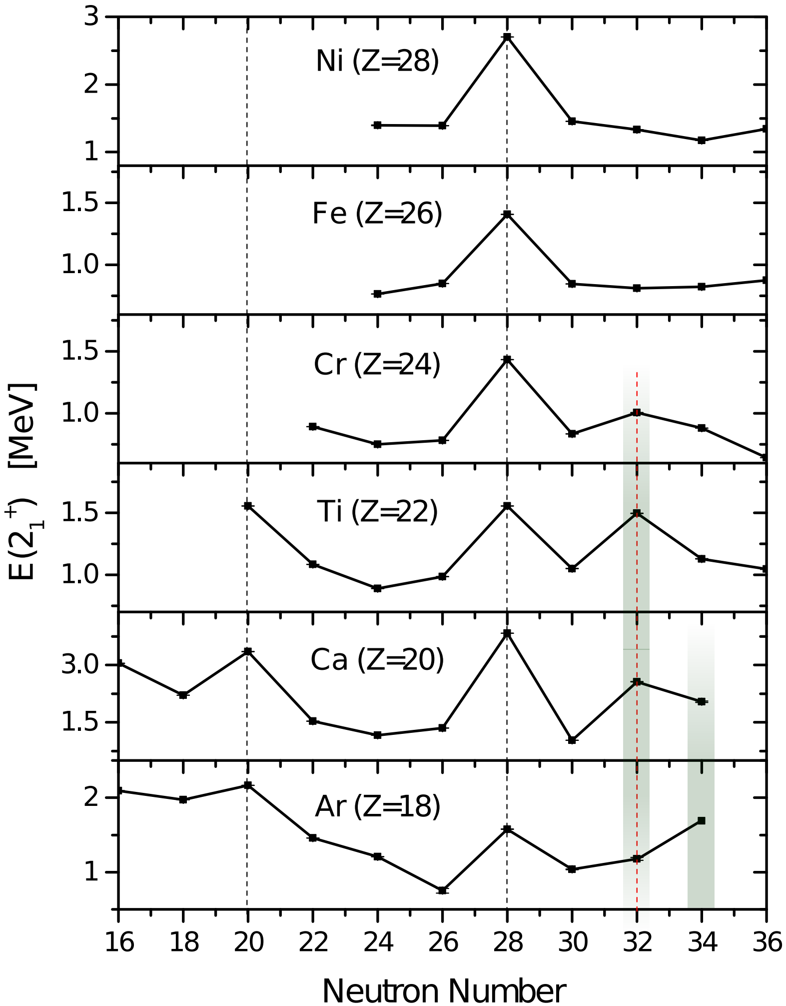
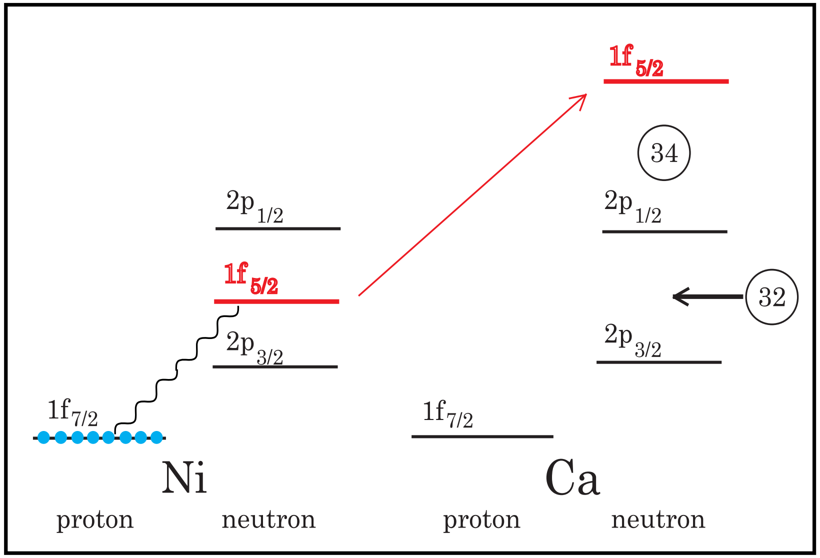
The emerging magic number 32 (and 34)



First signatures: excitation energies of 2^+ states of even-even nuclei

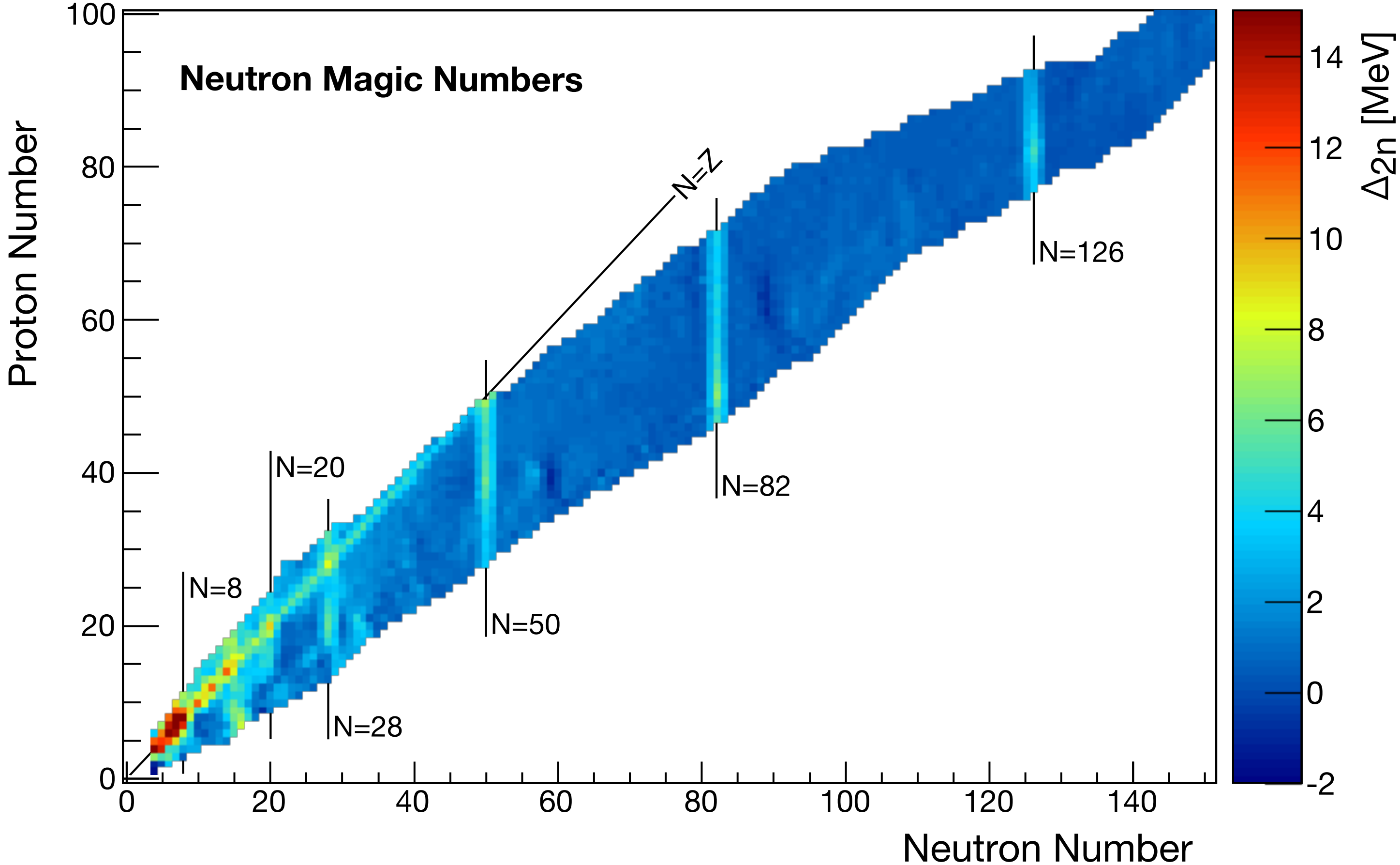
Mechanism: weakening of $\pi f_{7/2}$ - $\nu f_{5/2}$ interaction drives level inversion and appearance of energy gaps



T Otsuka and Y Tsunoda J. Phys. G: Nucl. Part. Phys. 43 024009 (2016)

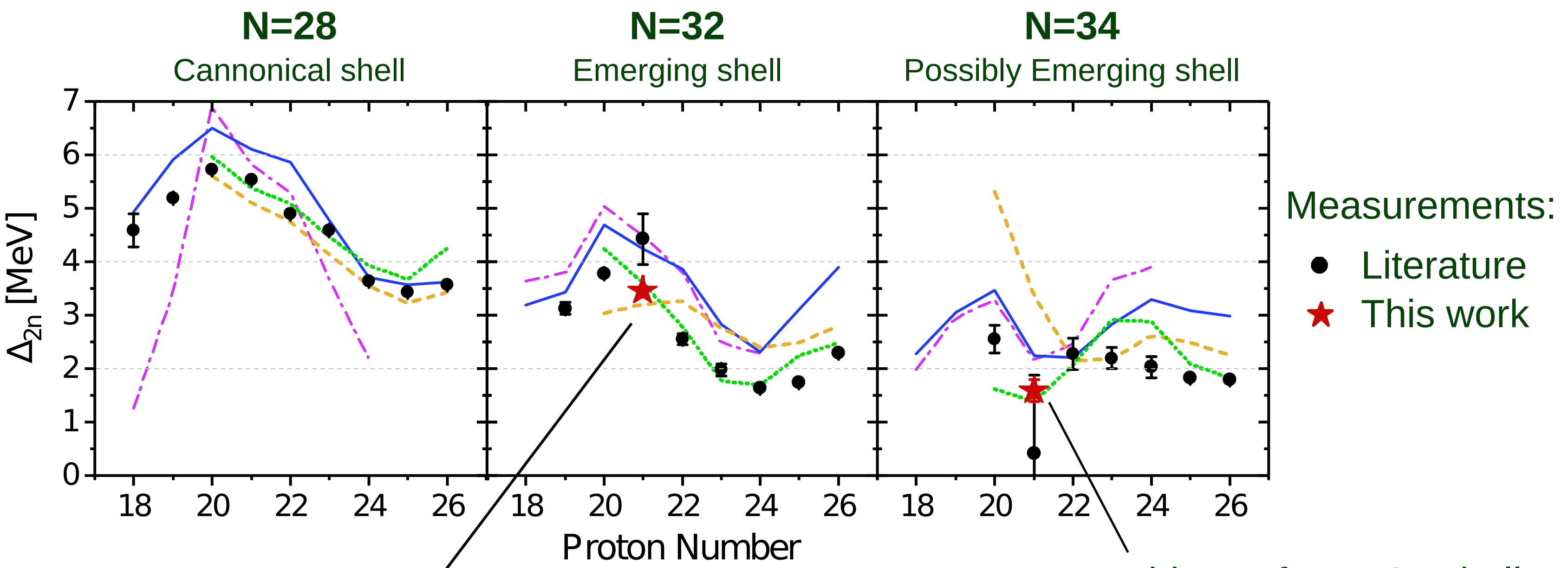
Shell Closures in the Mass Surface

$$\Delta_{2n}(N,Z) = S_{2n}(N,Z) - S_{2n}(N+2,Z)$$



Mass data from AME16

N=32 Shell Closure in Scandium



Smooth evolution of N=32

No evidence for N=34 shell effects above Z=20

Predictions:

- 1.8/2.0(EM) } χEFT
- NN+3N(lnl) } χEFT
- GX1A } Phenomenological
- KB3G } Phenomenological

Theories have good success at describing N=32, but deficiencies are found in the description of N=34

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