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The Emergence of nuclear-shell-model studies

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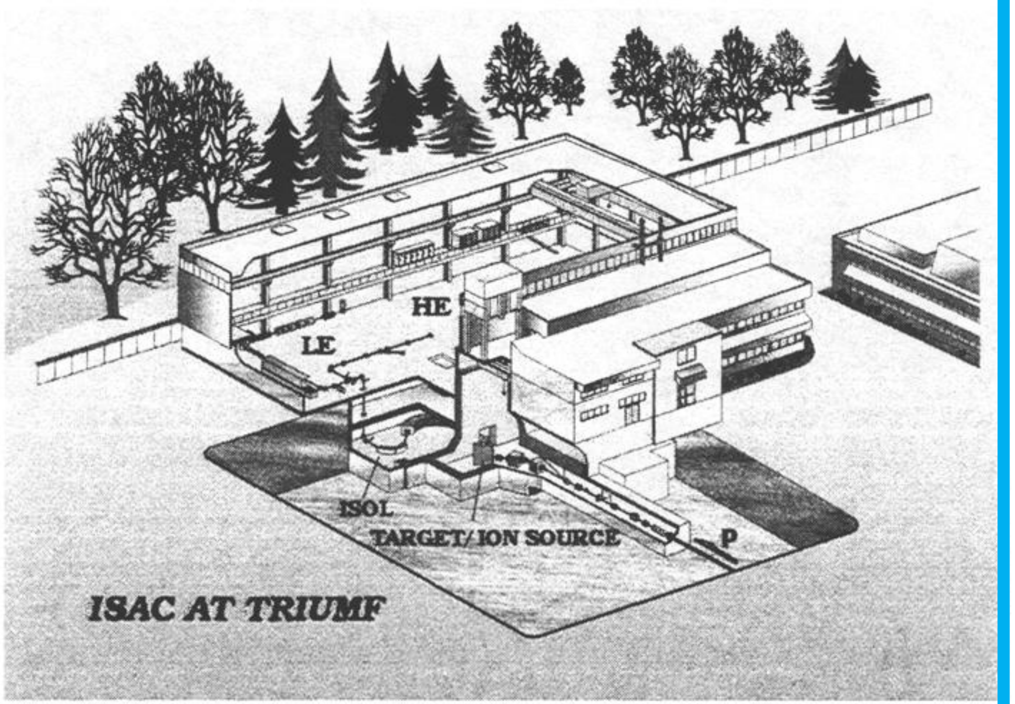
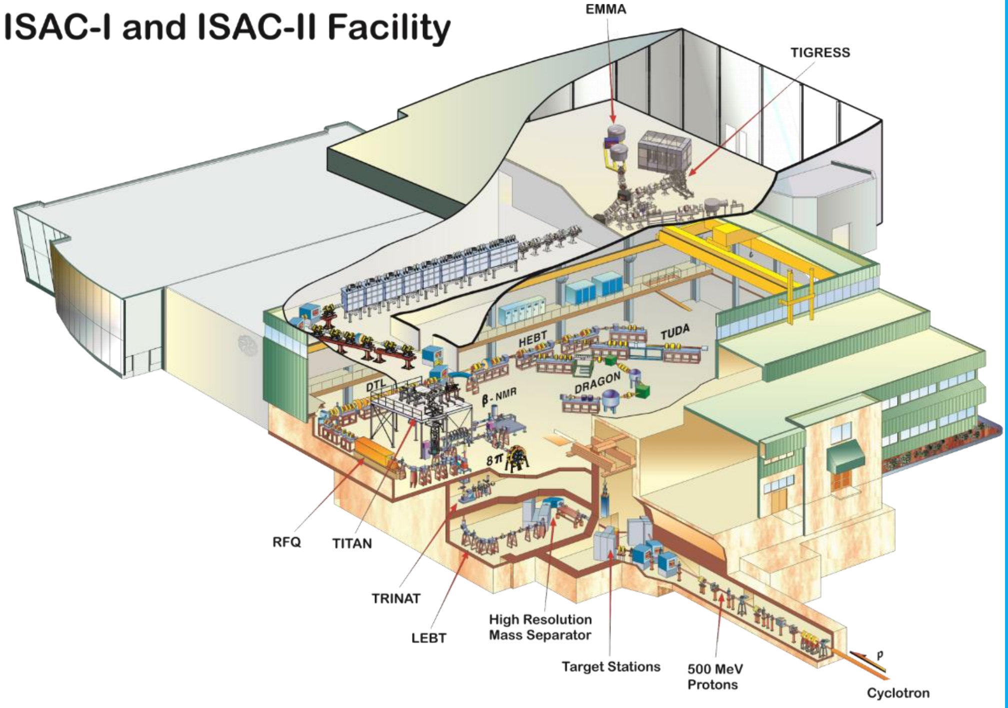
2019-08-21





Discovery, accelerated

A structure
can be observed across the chart of nuclides.

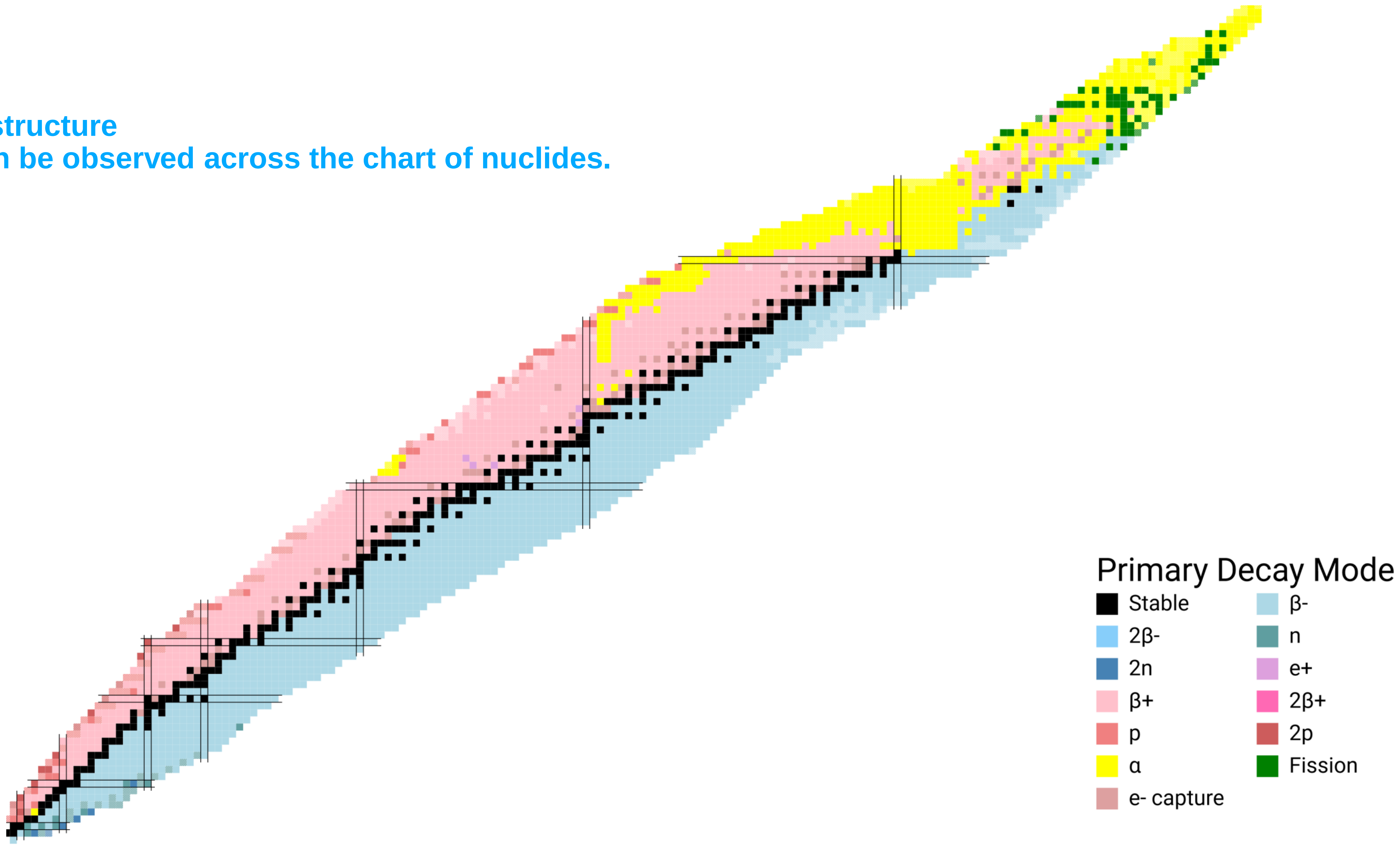


Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

A structure
can be observed across the chart of nuclides.

neutron separation energy S_n
binding energy $B(\mathrm{N},\mathrm{Z})$

$$S_n = B(N,Z) - B(N-1,Z)$$
$$= -M(N,Z) + M(N-1,Z) + m_n$$

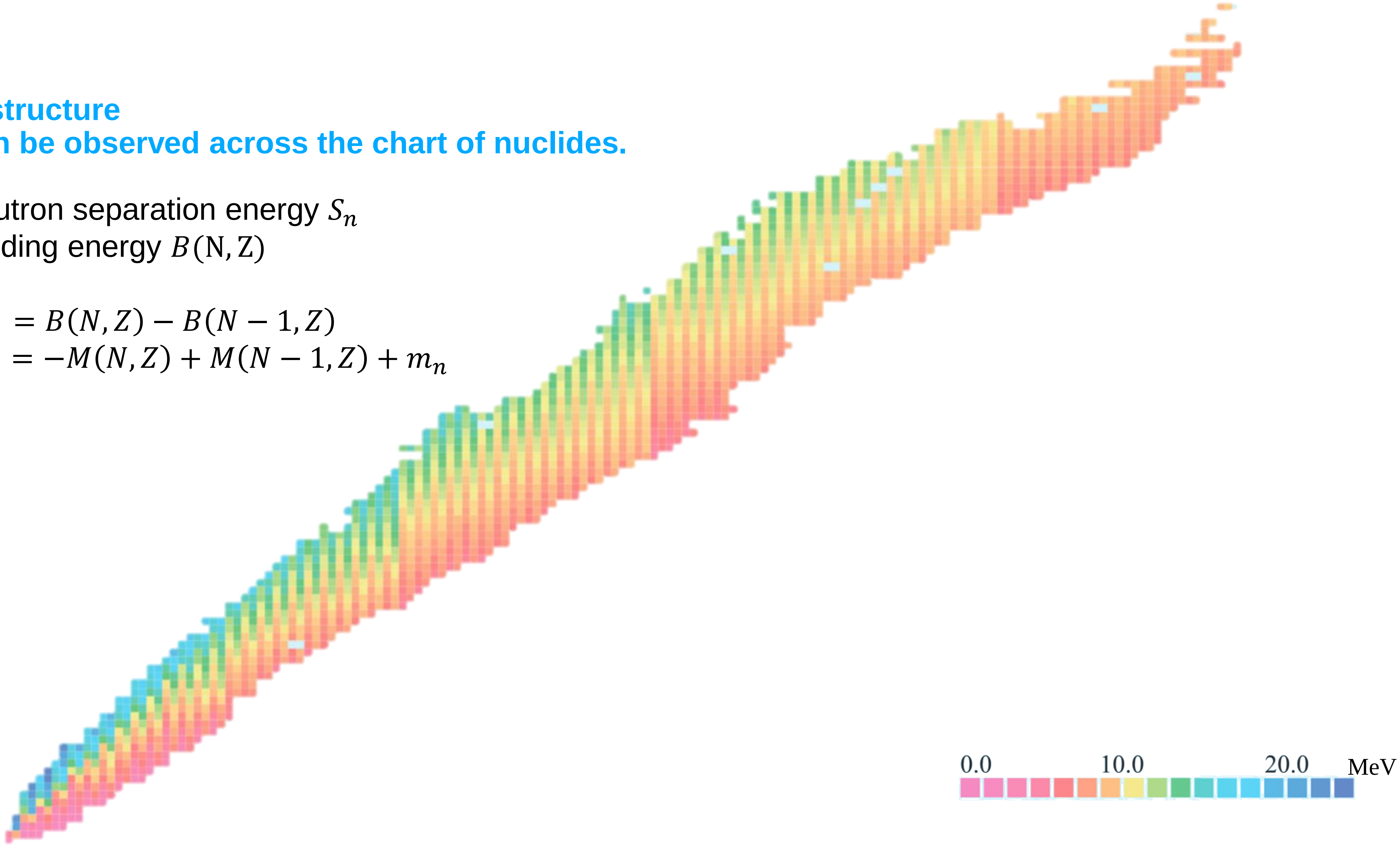
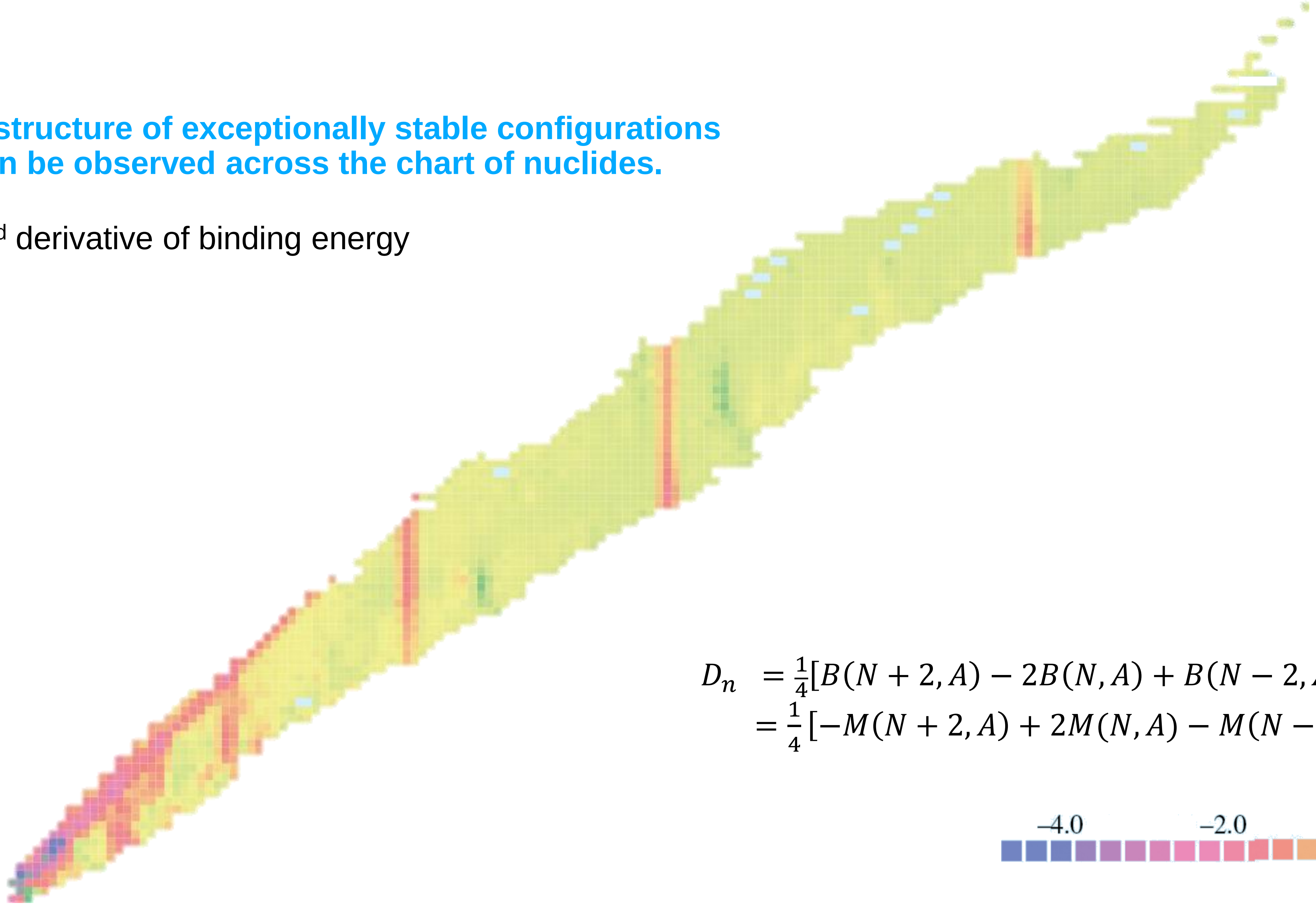


Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

A structure of exceptionally stable configurations can be observed across the chart of nuclides.

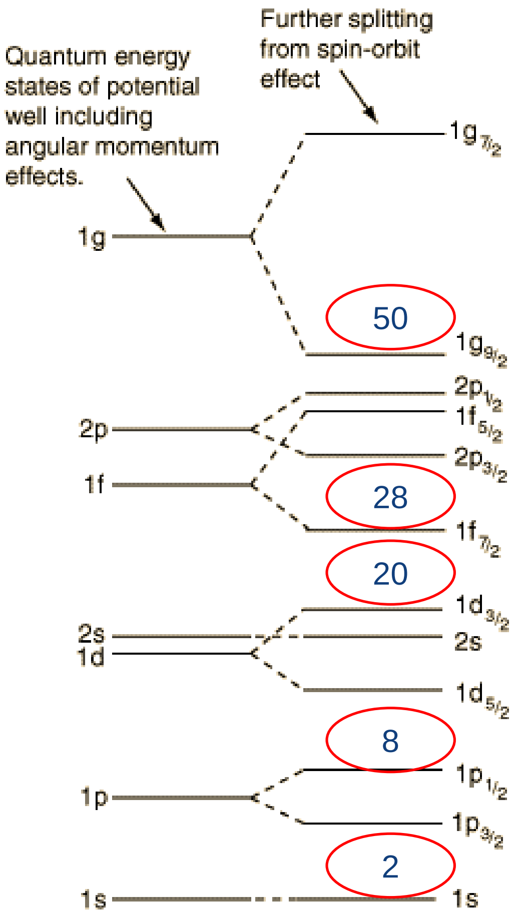
2nd derivative of binding energy



$$D_n = \frac{1}{4}[B(N+2,A) - 2B(N,A) + B(N-2,A)]$$
$$= \frac{1}{4}[-M(N+2,A) + 2M(N,A) - M(N-2,A)]$$

Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

These shells or “magic numbers” could be derived from a harmonic oscillator.

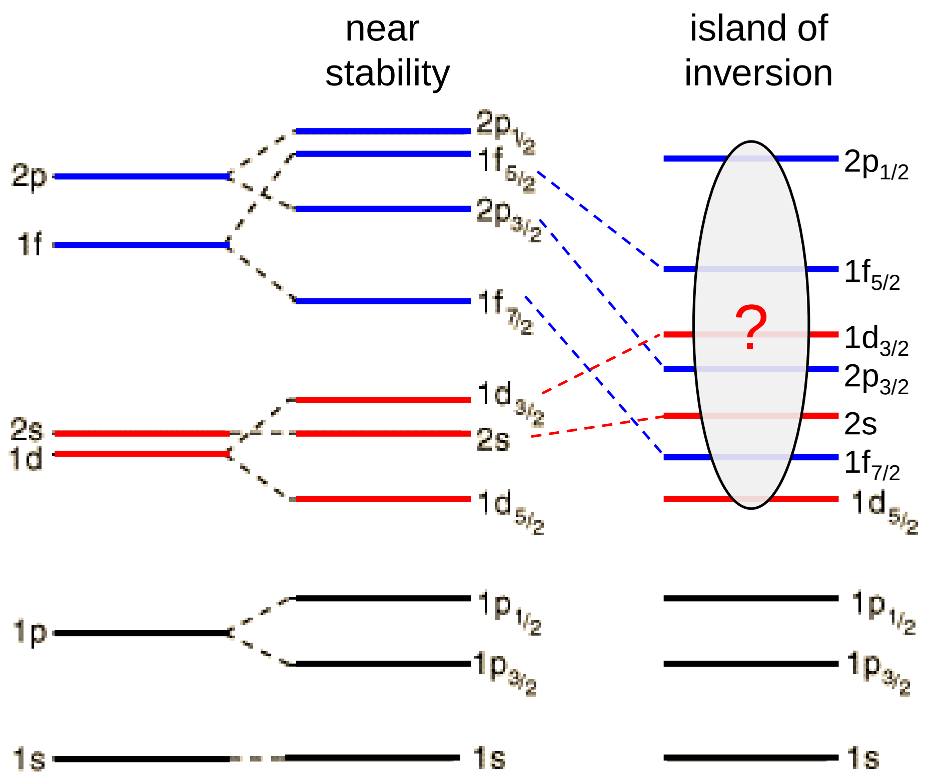


Maria Goeppert-Mayer 1963

Hans D. Jensen 1963

Images: nobelprize.org

The disappearance of expected and the emergence of new shells has been observed for several ratios of N/Z.



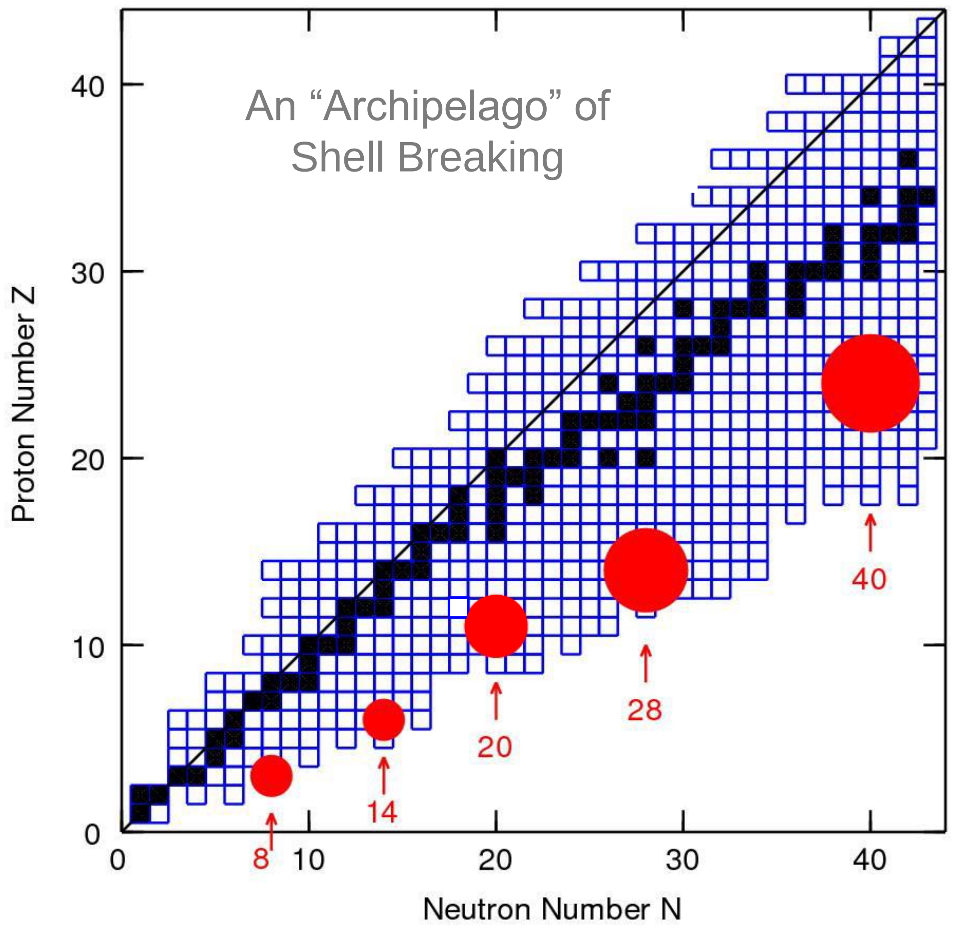
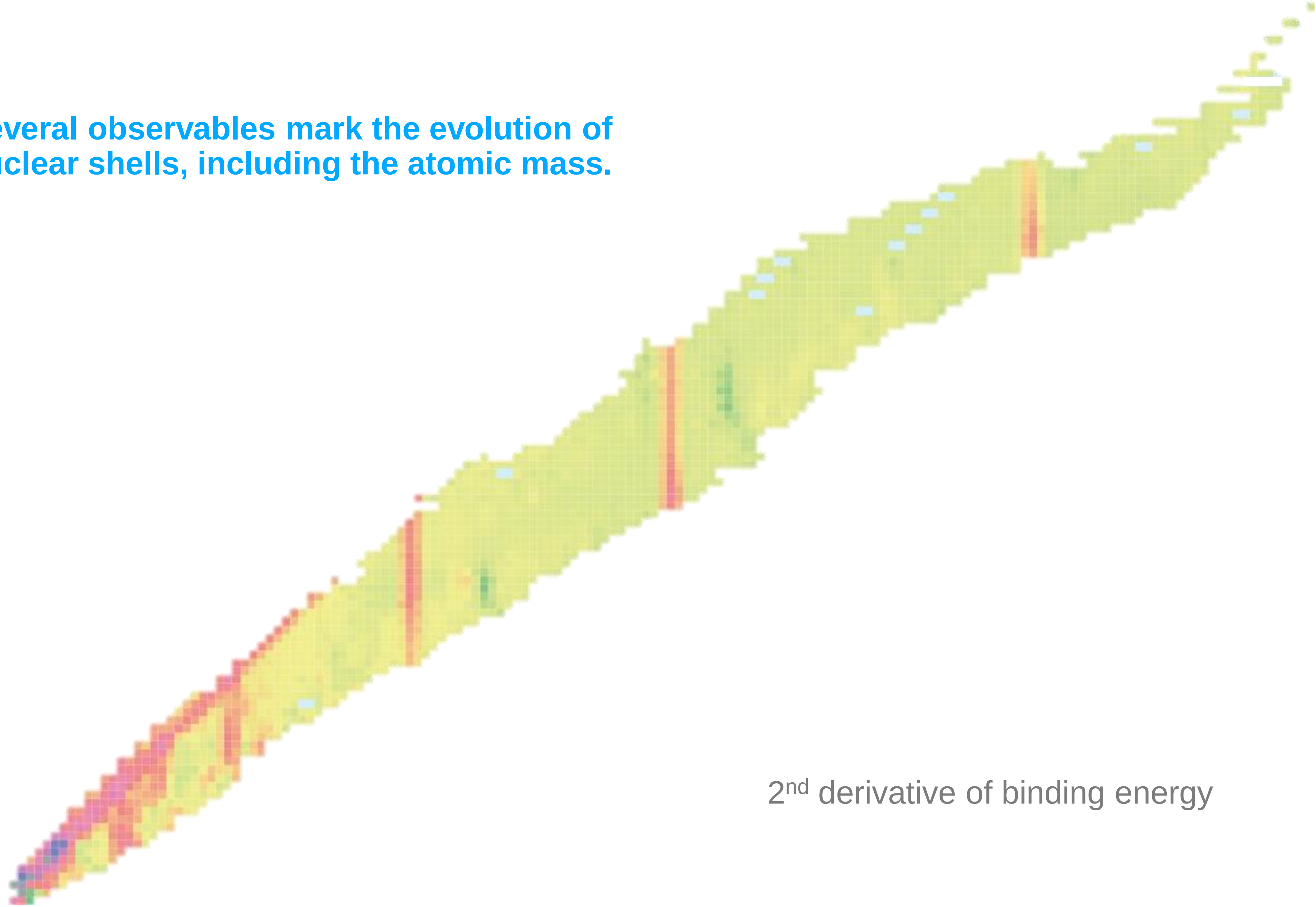


Figure: B.A. Brown, *Physics* 3 (2010) 104

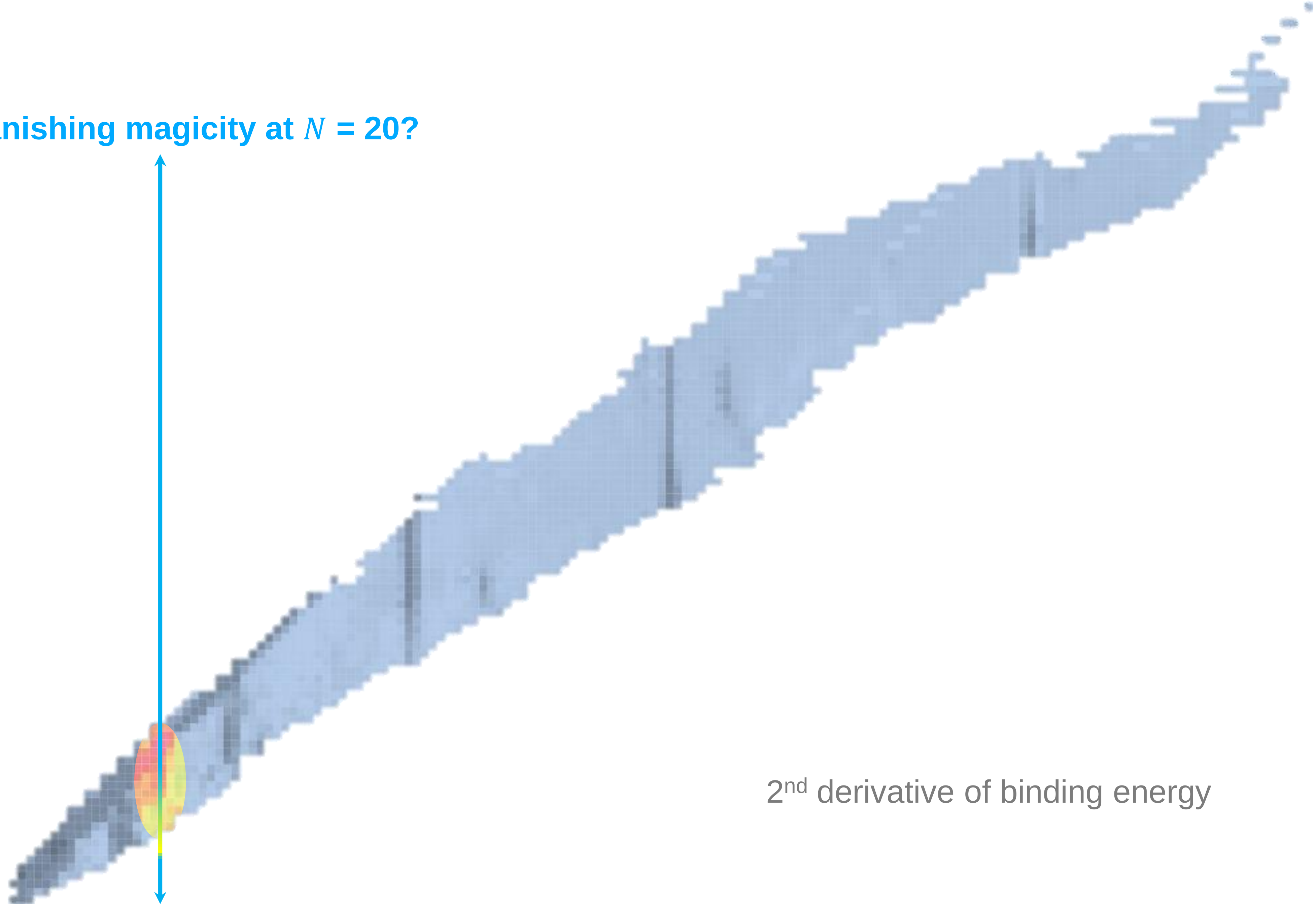
Several observables mark the evolution of nuclear shells, including the atomic mass.



2nd derivative of binding energy

Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

Vanishing magicity at N = 20?



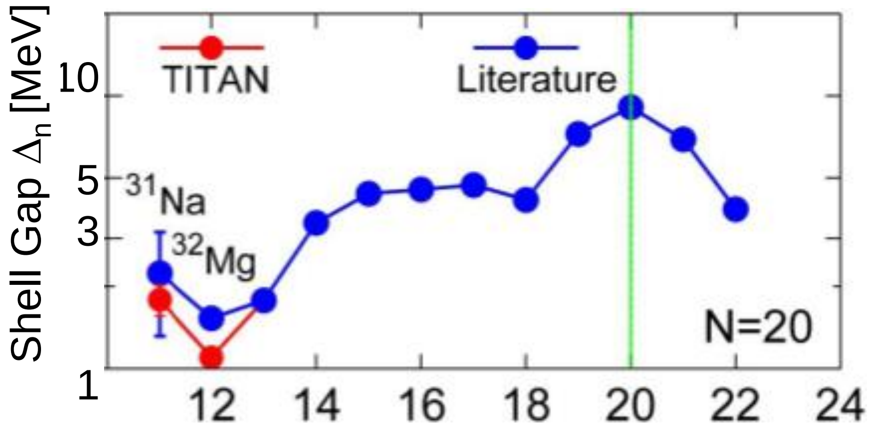
2[nd] derivative of binding energy

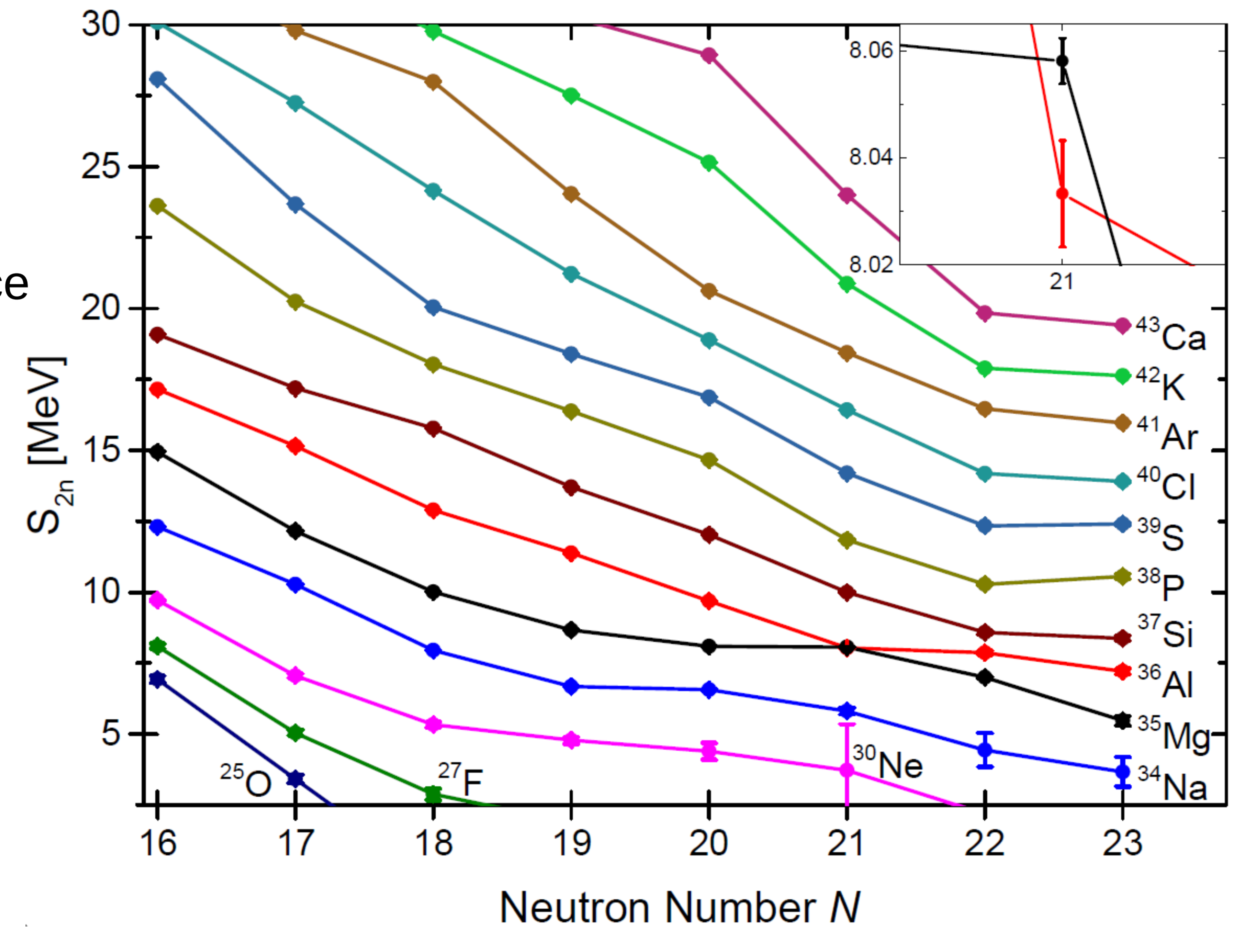
Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

TITAN's mass campaign revealed the smallest shell closure for an expected magic number.

Measured $^{29-32}Na$, $^{30-34}Mg$, $^{29-35}Al$

Shell model calculations revealed strong correlation energy manifests in S_{2n} surface





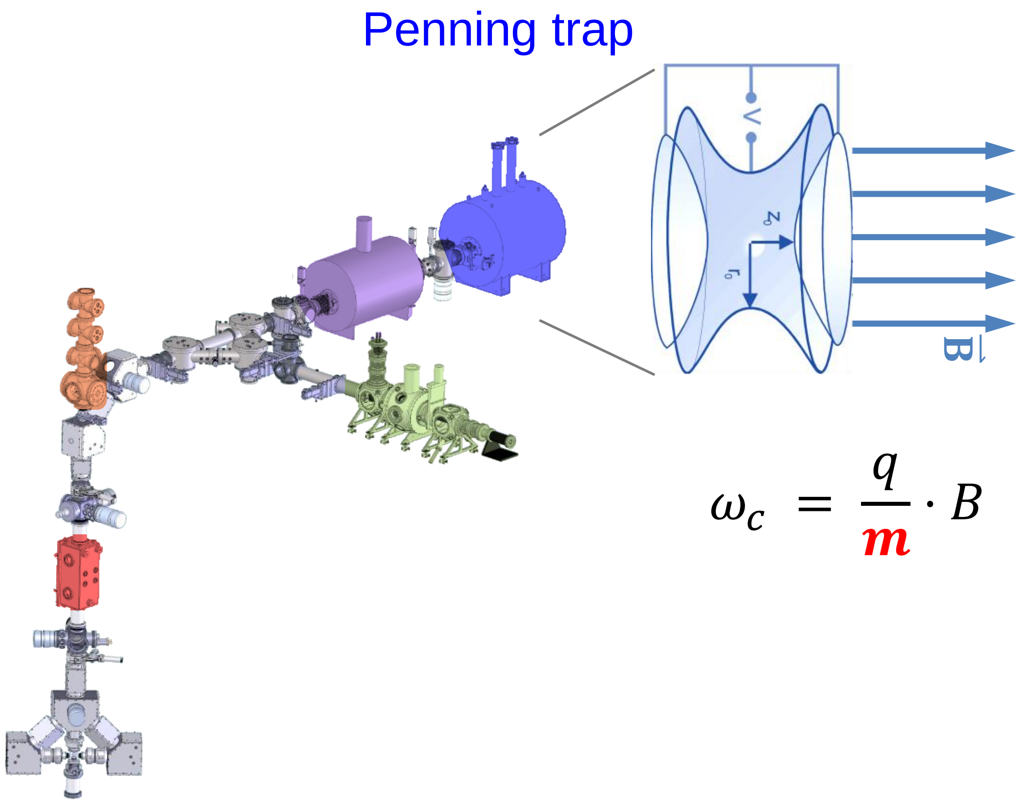
A. Chaudhuri *et al*, PRC 88 (2013) 054317; AAK *et al*, *PRC* 92 (2015) 061301; A.T. Gallant, *et al*, PRC 96 (2017) 024325

TITAN-ISAC is the only Penning trap mass spectrometer capable to survey the "Island of Inversion".

- Accuracy: calibrations with stable species
  - vs. spread of TOF measurements

- High Precision: frequency measurement (≥ 5×10^{-9})
  - uncertainty improved ≤10x

- Short $T_{1/2}$: fast beam preparation (world record 9 ms)
  - $\geq T_{1/2}\ (^{32}Na)$ =12.9 ms

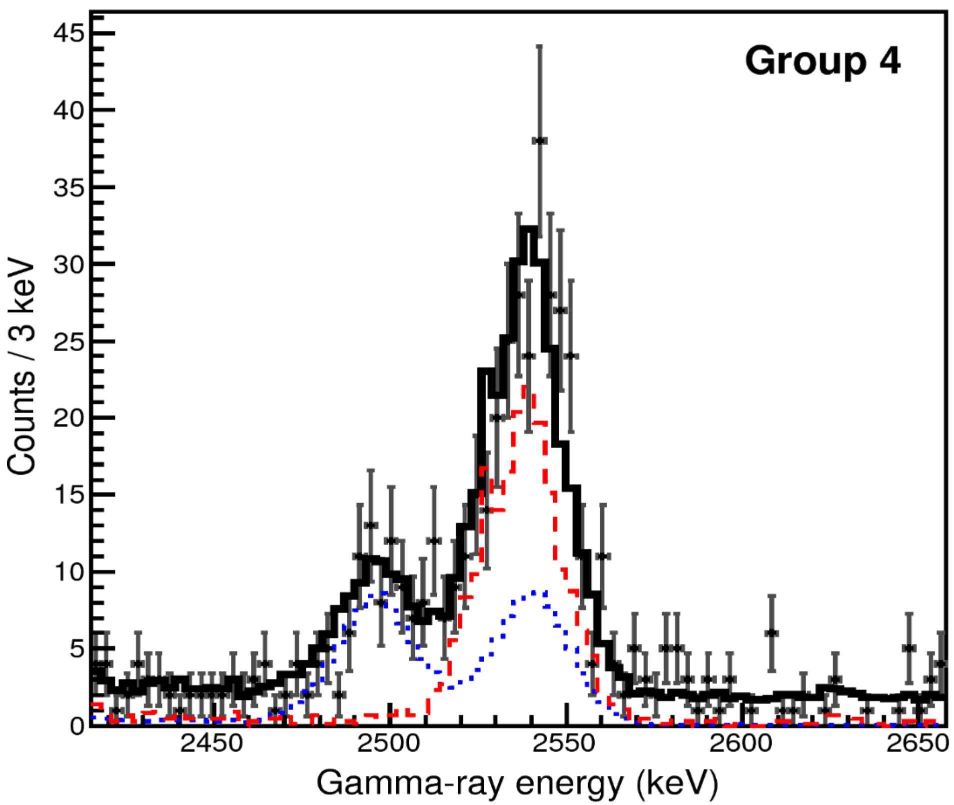


$$\omega_c = \frac{q}{m} \cdot B$$

J Dilling *et al.*, NIMB 204 (2003) 492; M. Smith *et al.*, PRL 101 (2008) 202501; A.A. Kwiatkowski *et al.*, PRC 89 (2014) 045502

At TIGRESS, ^{28}Mg was studied through γ-γ coincidence, Doppler shift lifetime, & comparison to theory.

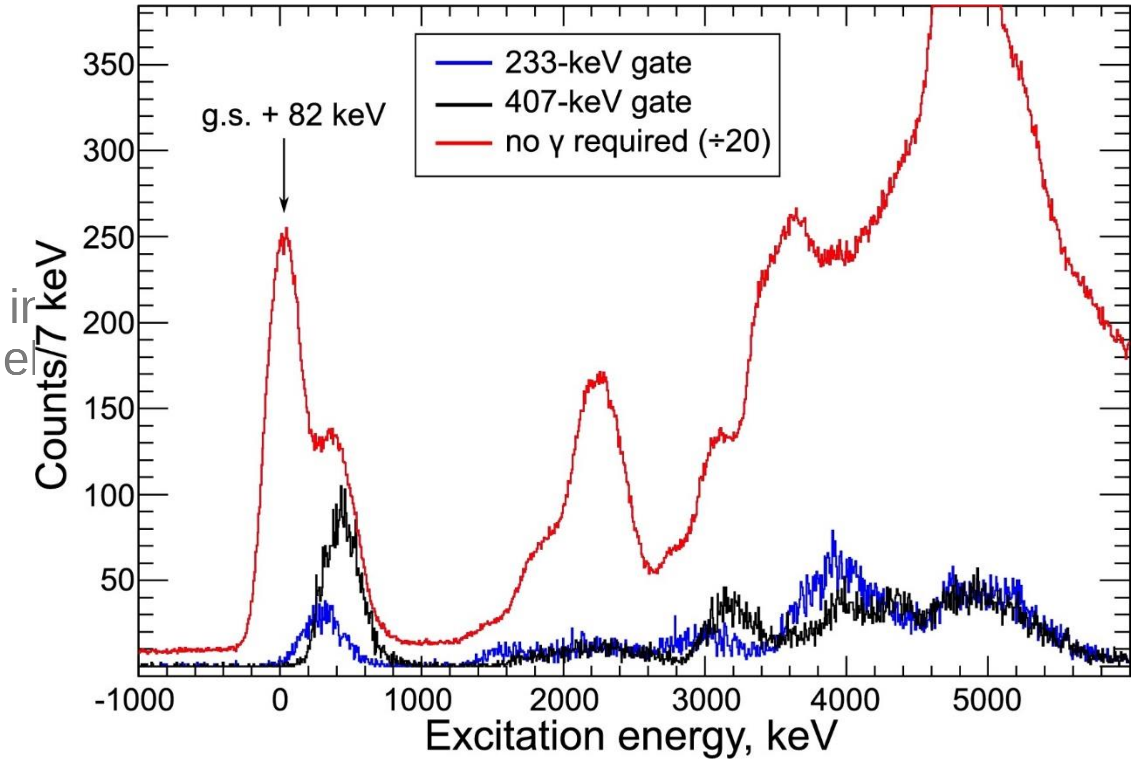
- Symmetry-adapted No Core Shell Model can describe enhanced deformation & B(E2) values
- Positive-parity states dominated by *sd* configurations
- Negative-parity states understood with SPDF-MU interaction as single neutron excitation into *pf* shell



J. Williams *et al.*, PRC, 100 (2019) 014332

First observation of ^{26}Na levels with single-particle character were performed at TIGRESS.

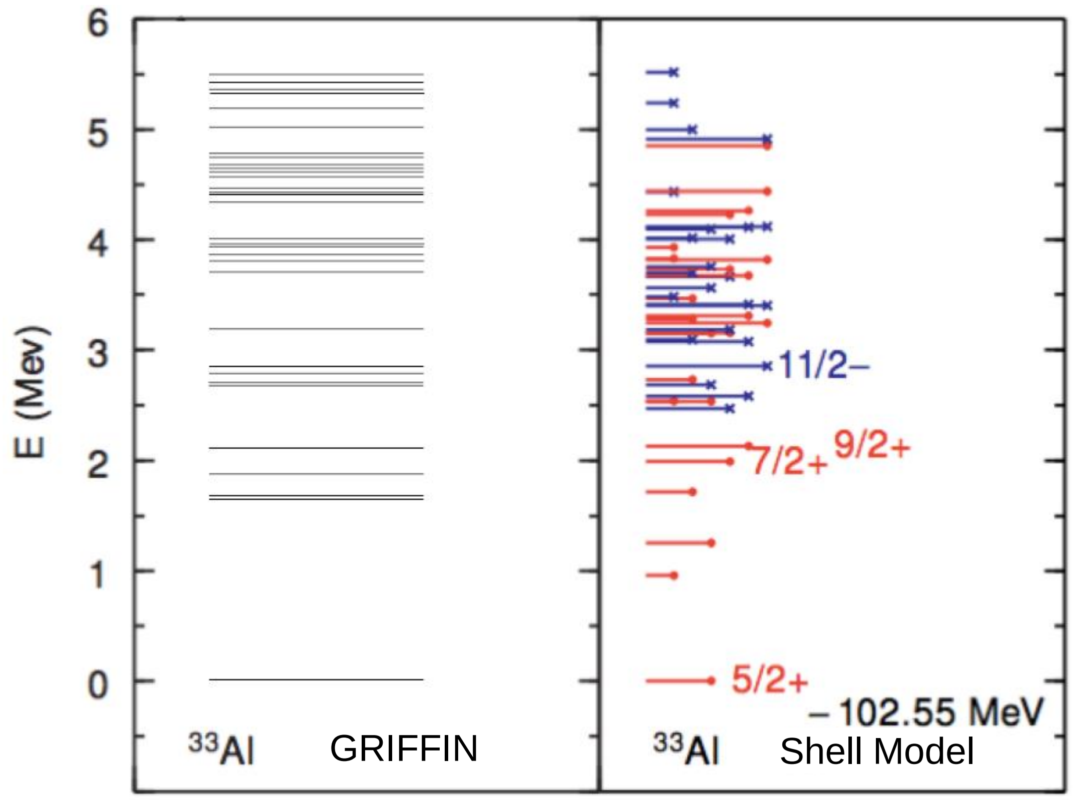
- ^{25}Na(d,pγ)^{26}Na measured with TIGRESS + SHARC
- Excitation energies & spectroscopic factors in good agreement with (0+1)\hbar \omega shell model calculations in full *spsd pf* basis
- Enhanced role of $\nu 1p_{3/2}$ configuration in structure of low-lying negative parity states (relative to ^{28}Al)



G.L. Wilson, *et al.*, PLB 759 (2015) 417

Spectroscopic information of $^{33\text{-}35}Mg$, the center of the "Island of Inversion", is forthcoming from GRIFFIN

- Decay scheme of ^{33}Al measured with GRIFFIN + SCEPTAR:
  - 32 states & 100 transitions clarified
  - half-lives of ^{33}Mg, $^{32,33}Al$, ^{33}Si determined
- Decay of $^{34,35}Mg$ under analysis
- Experiment S1367 will be continued with higher statistics



T. Zidar, MSc Thesis 2019, Univ. Guelph; M. Rajabali, *et al.*, in preparation

The Dawning of a new shell, $N = 32$?

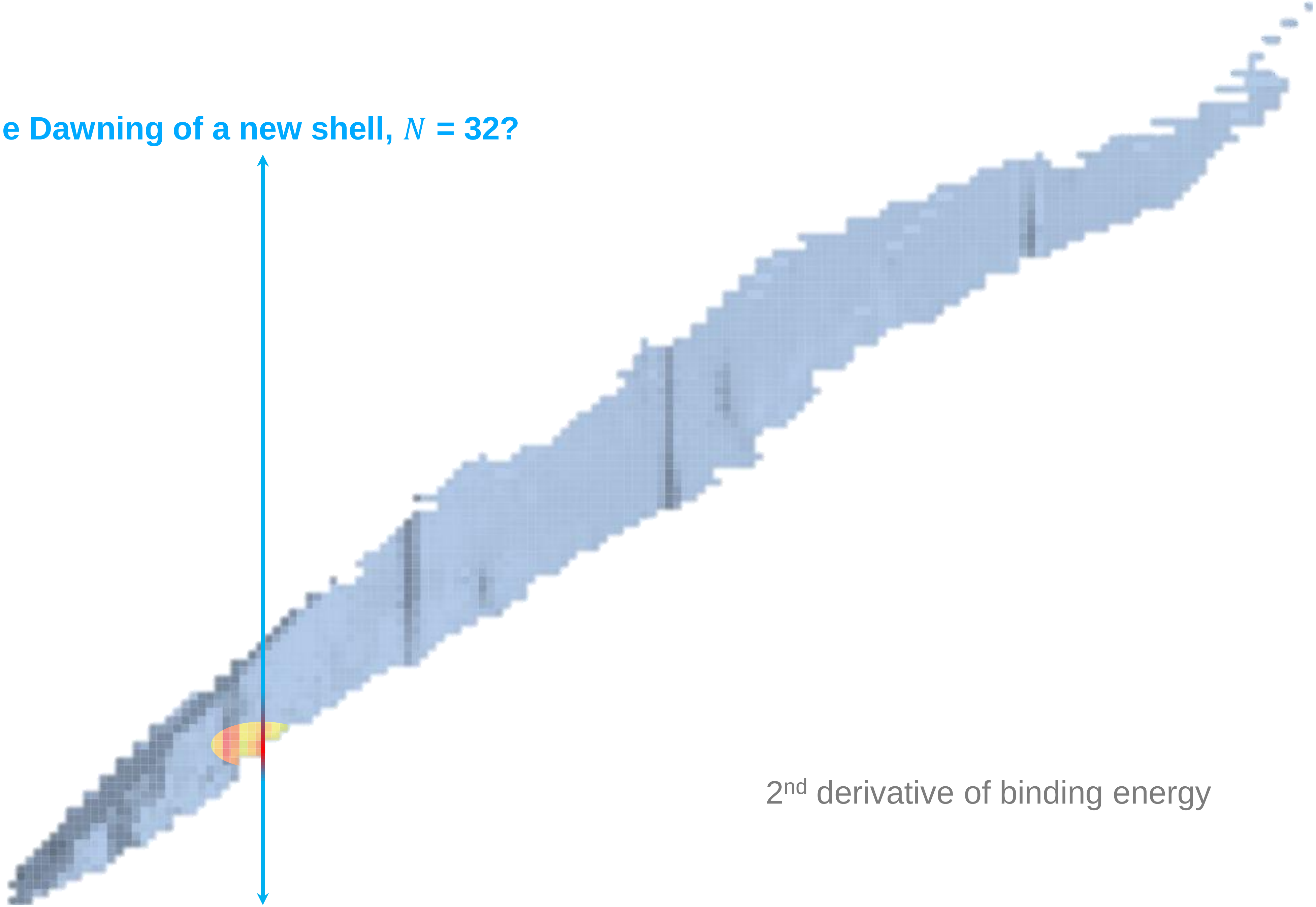
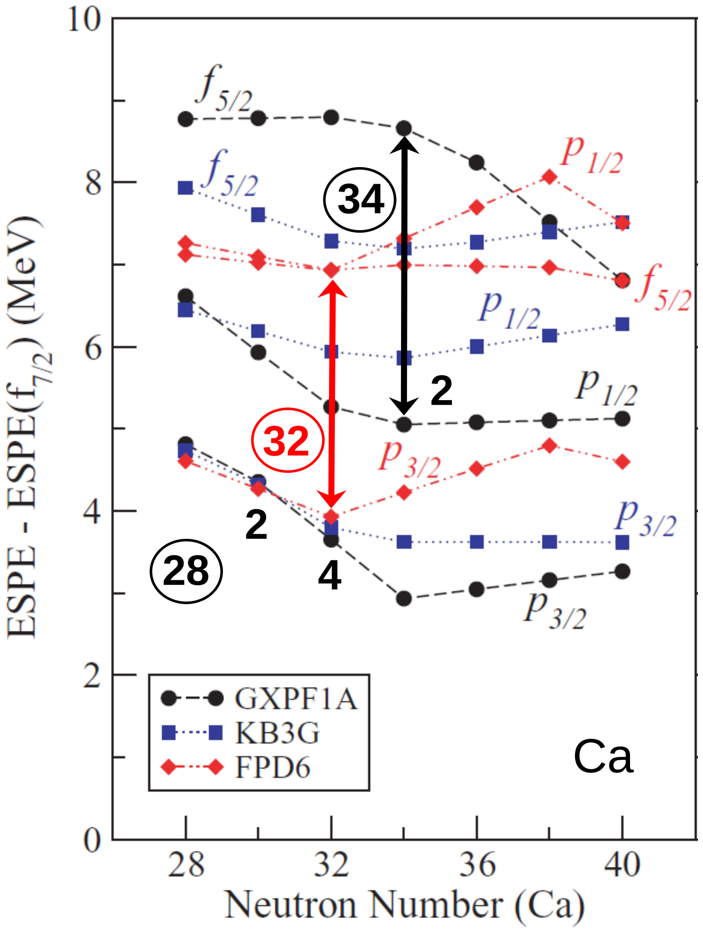


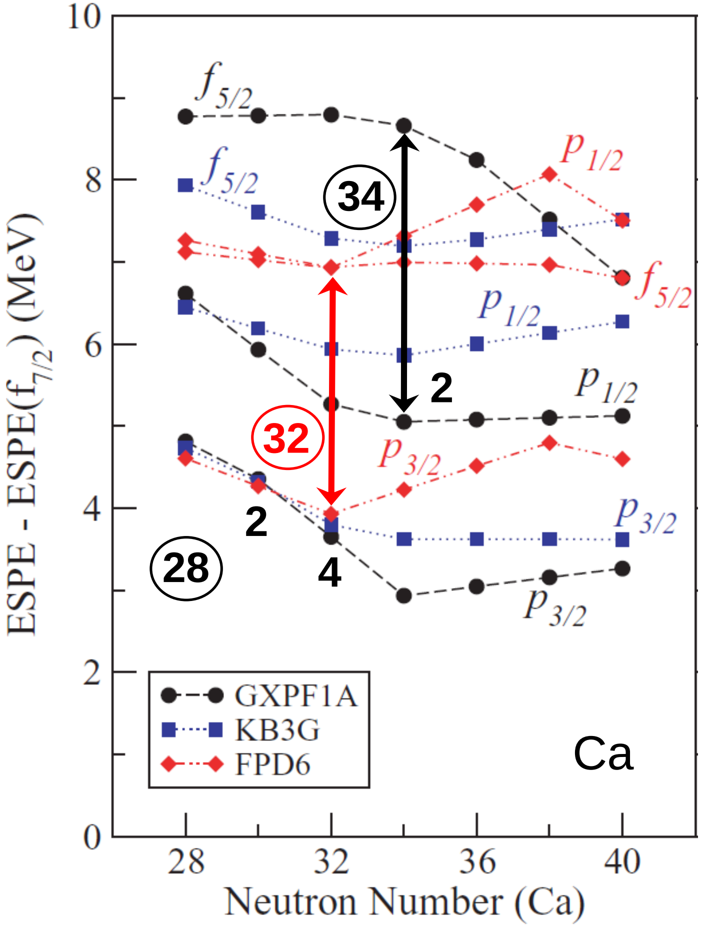
Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

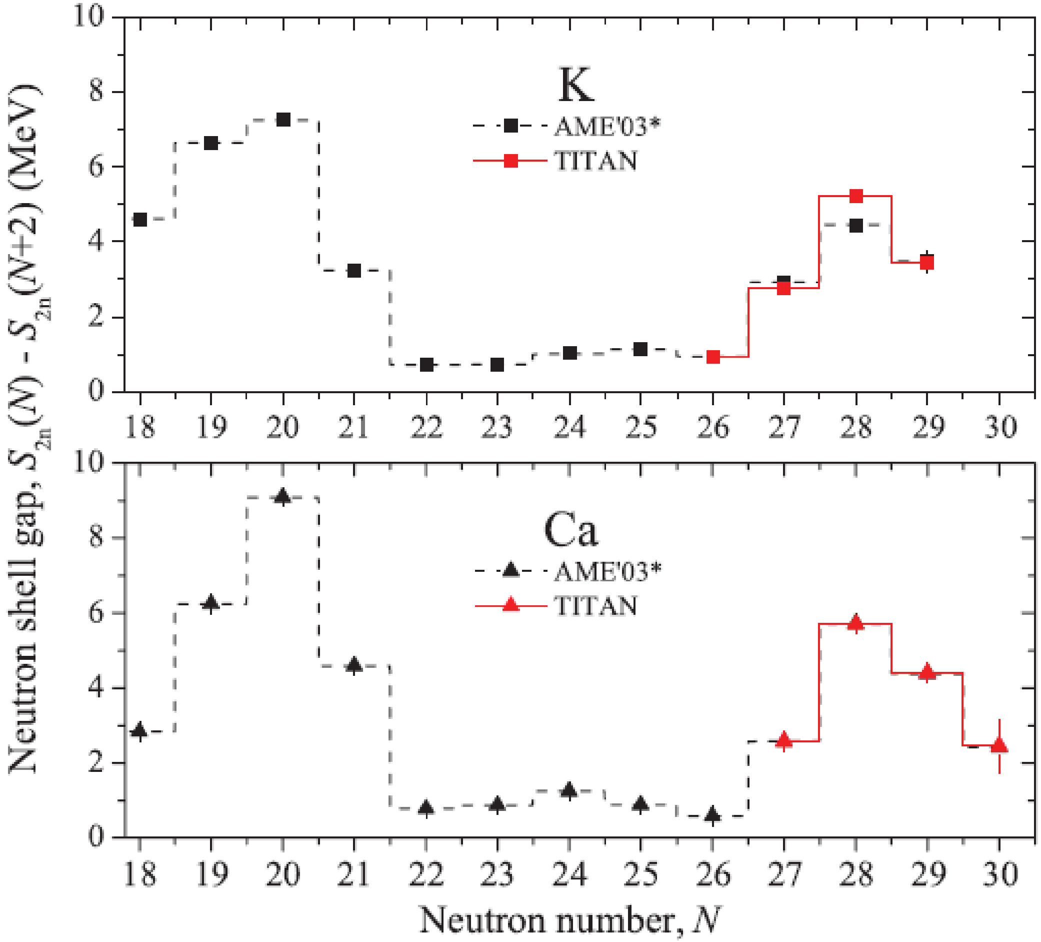
The question of magicity at N = 32 was unclear from phenomenological calculations.



S. Zhu *et al.*, PRC 80 (2009) 024318

Strategy was to approach from N = 28, which was validated through TITAN's mass measurements of K & Ca isotopes.





S. Zhu *et al.*, PRC 80 (2009) 024318; A. Lapierre *et al.*, PRC 85 (2012) 024317

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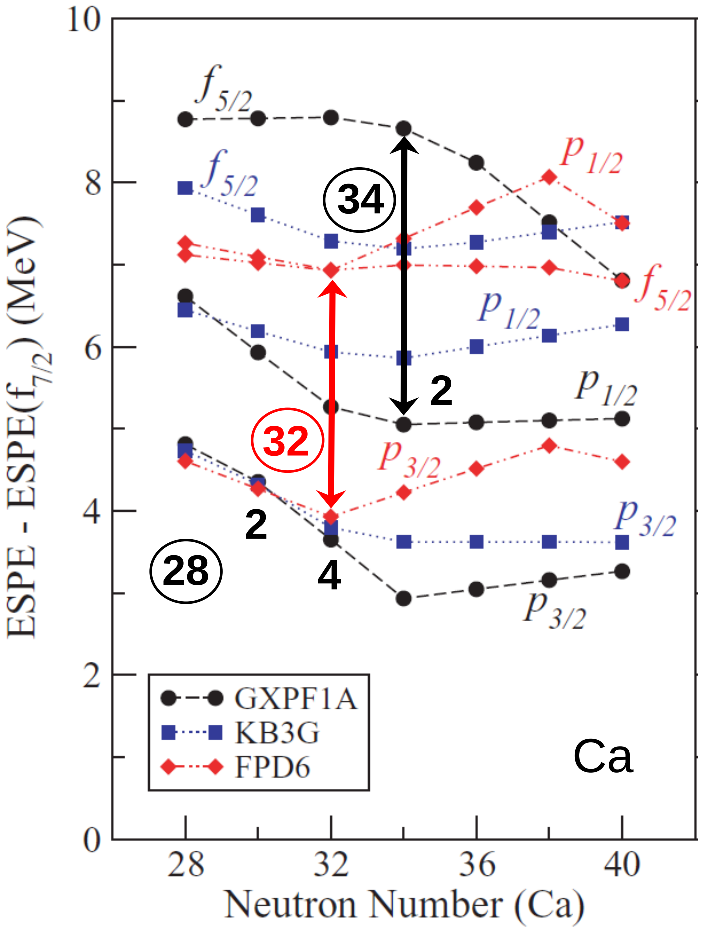
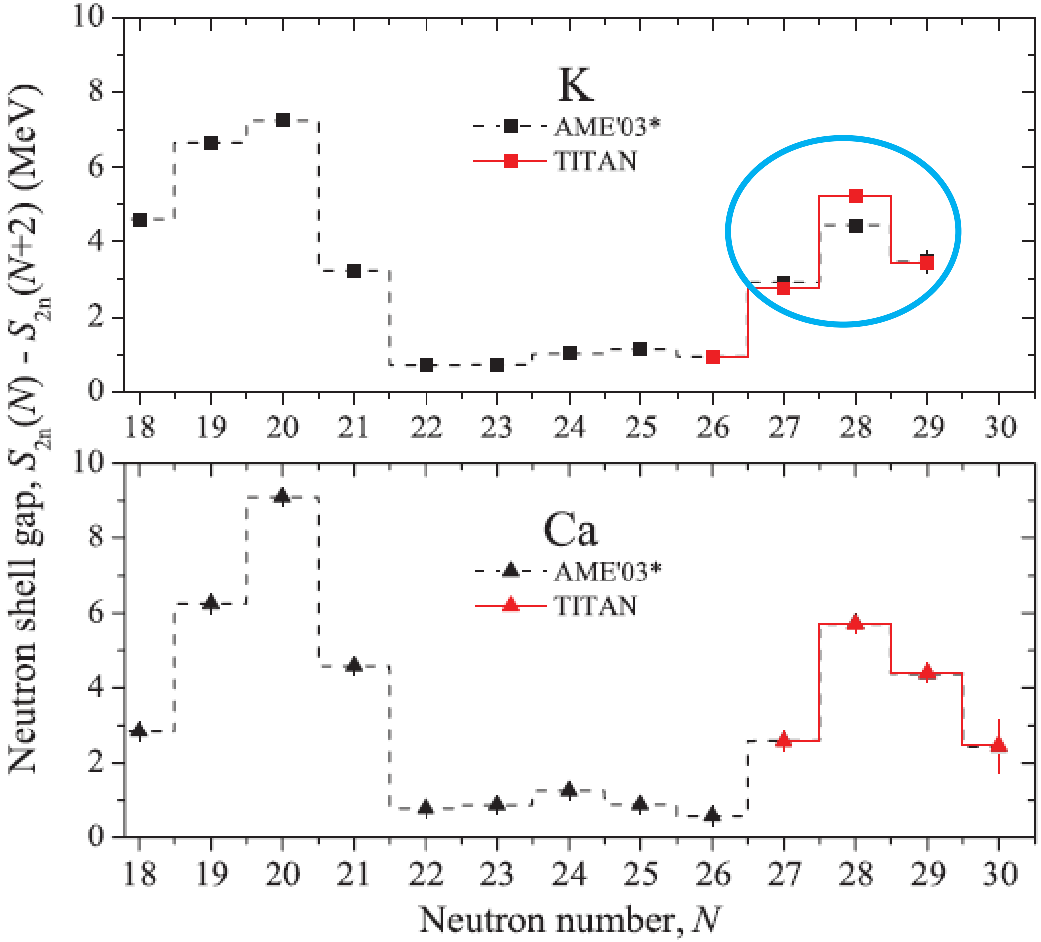
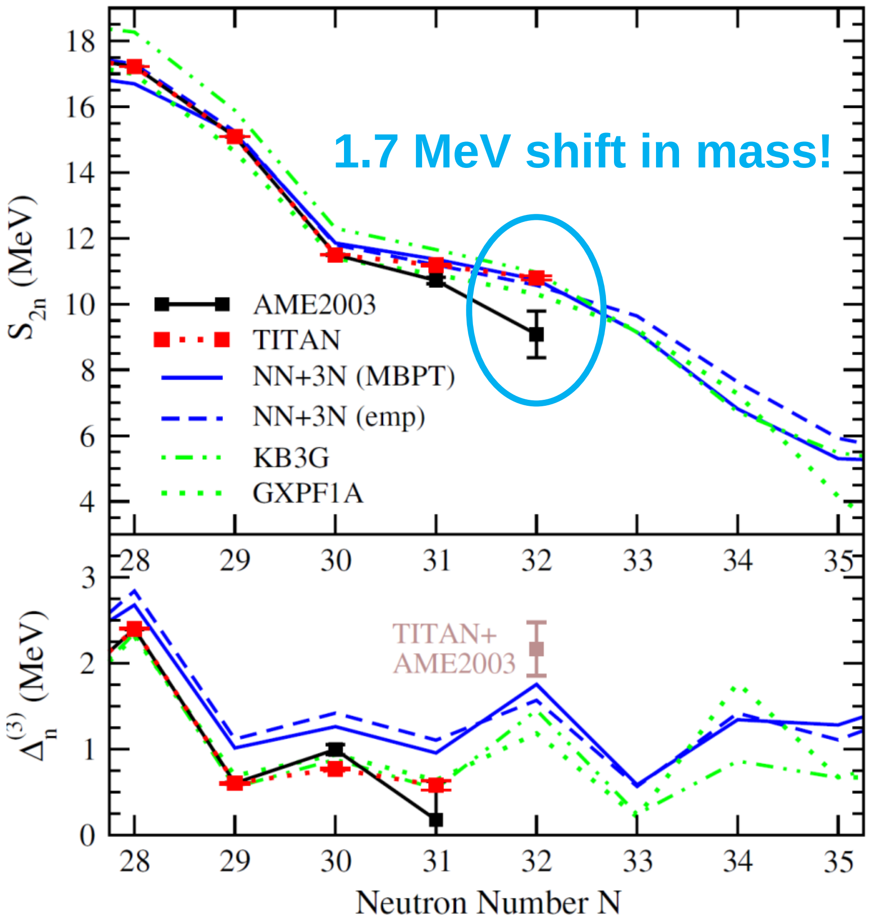




≤10σ deviation!

S. Zhu *et al.*, PRC 80 (2009) 024318; A. Lapierre *et al.*, PRC 85 (2012) 024317

With UCx targets, TITAN reached ^{52}Ca and confirmed magicity of N=32.



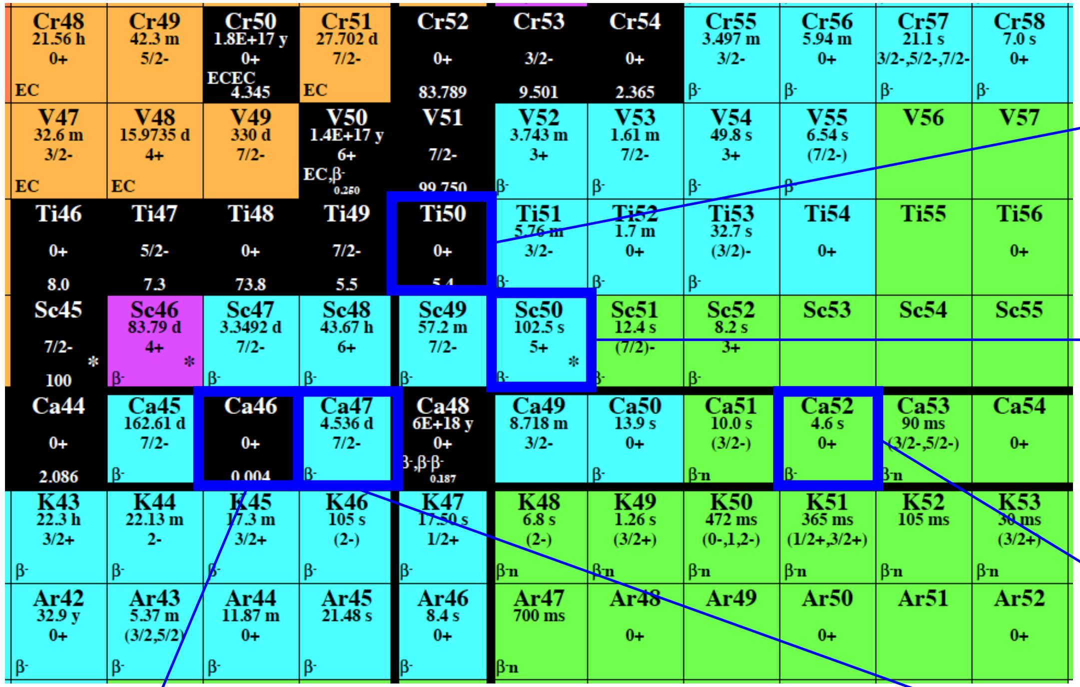
- A 1.7 MeV deviation in M(^{52}Ca) observed!
- Shift confirmed by ISOLTRAP, which measured masses up to ^{54}Ca
- Support of nascent NN and 3N calculations

A.T. Gallant *et al.*, PRL 109 (2012) 032506; F. Weinholtz *et al.*, Nature 493 (2013) 346

Systematics of Ca structure can be observed through decay of K isotopes observed at GRIFFIN spectrometer.

Three beamtime periods with GRIFFIN
1 publication (2017), 4 expected in 2019

- **1 PhD thesis, 2 Masters thesis**
- **1 Masters thesis in progress**



^{50}Sc - ^{50}Ti, Nov 2016, 1x10^{6}pps, ~5hrs
"Search for particle-hole excitations across the *N*=28 shell closure", C. Jones, **Masters thesis (Jan 2018)**, *Submitted to Phys. Rev. C (2019).*

^{50}Ca - ^{50}Sc, Nov 2016, 1x10^{6}pps, ~2hrs
"Spectroscopy of ^{50}Sc and the first calculation of *B(M3)* strengths using *ab initio* methods",
A.B. Garnsworthy, Phys. Rev. C 96, 044329 (2017).

^{52}K – ^{52}Ca, Jul 2018, 300pps, ~48hrs
"Evolution of Shell Structure in Neutron-Rich Calcium Isotopes", R. Coleman, Masters thesis Univ. of Guelph, in preparation for Phys. Rev. C (2019).

^{46}K – ^{46}Ca, Dec 2014, 4x10^{5}pps, ~40hrs
"Detailed spectroscopy of ^{46}Ca: The investigation of the β decay of ^{46}K with the GRIFFIN γ-ray spectrometer",
J.L. Pore, **PhD thesis (2016) SFU**, *submitted to Phys. Rev. C (2019).*

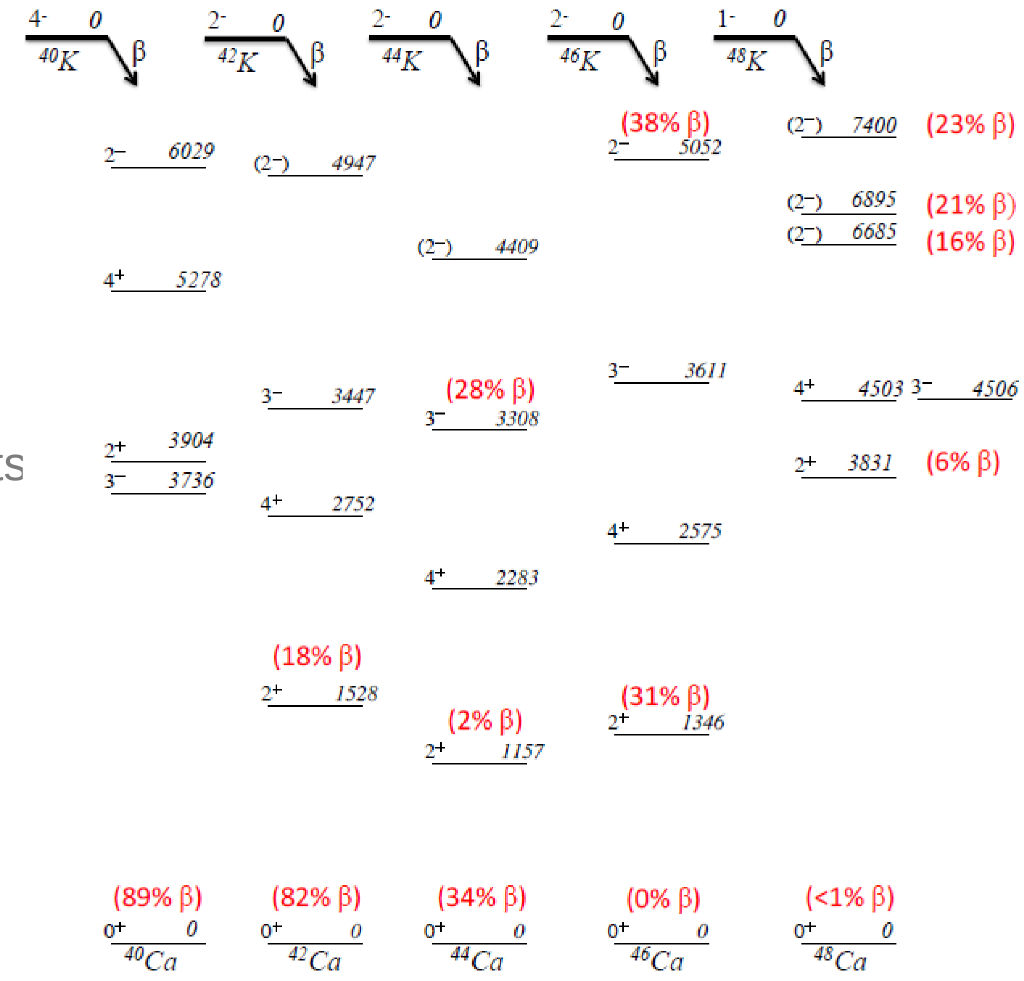
^{47}K – ^{47}Ca, Dec 2014, 1x10^{5}pps, ~90hrs
"Detailed decay spectroscopy of ^{47}Ca",
J.K. Smith, in preparation for Phys. Rev. C (2019).

Slide courtesy of A. Garnsworthy

J. L. Pore, PhD Thesis, SFU 2016; A.T. Gallant *et al.*, PRL 109 (2012) 032506; F. Weinholtz *et al.*, Nature 493 (2013) 346

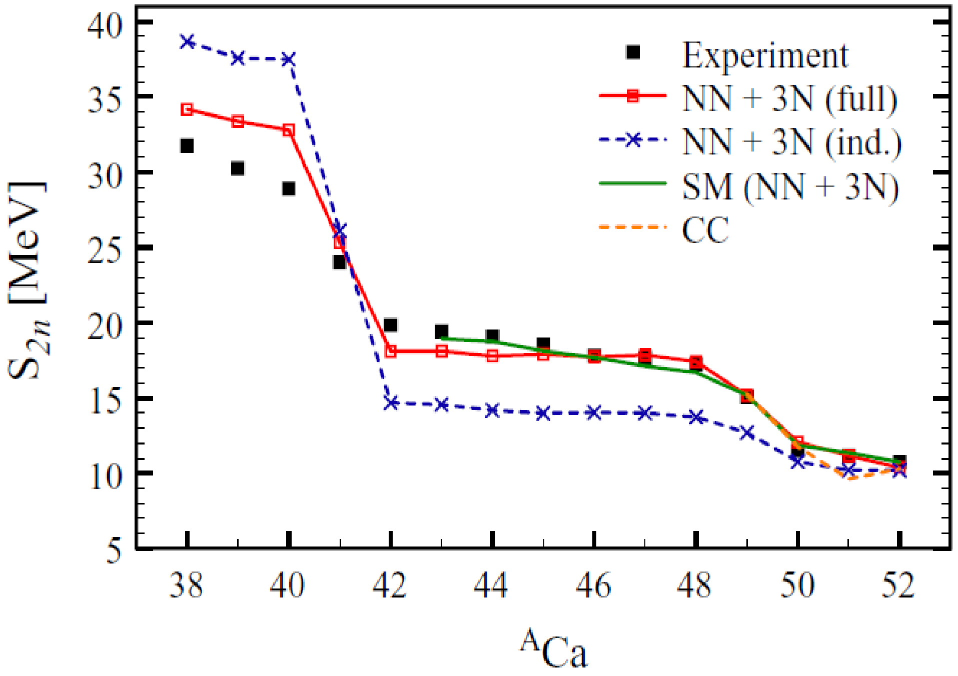
The ground state of ^{46}K exhibits more $\pi s_{1/2}$ character than previously believed.

- 150 new γ-ray transitions and 12 new excited states observed
- Angular correlations allowed for spin assignments
- Based on β feeding intensities ^{46}K may be more strongly dominated by $\pi s_{1/2}$ (mixed with $\pi d_{3/2}$)



J. L. Pore, PhD Thesis, SFU 2016; *et al.*, submitted to PRC

Validated, *ab initio* theory surpassed experiment, reaching the Ca dripline.



Predictions of dripline near ^{60}Ca are beyond present experimental reach.

J.D. Holt private communication;

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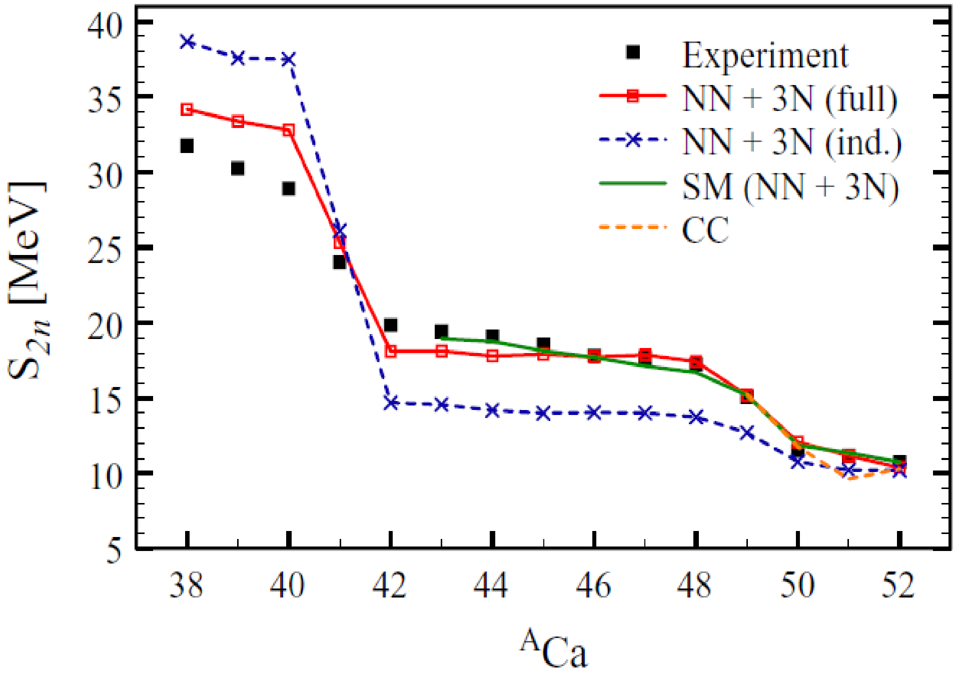

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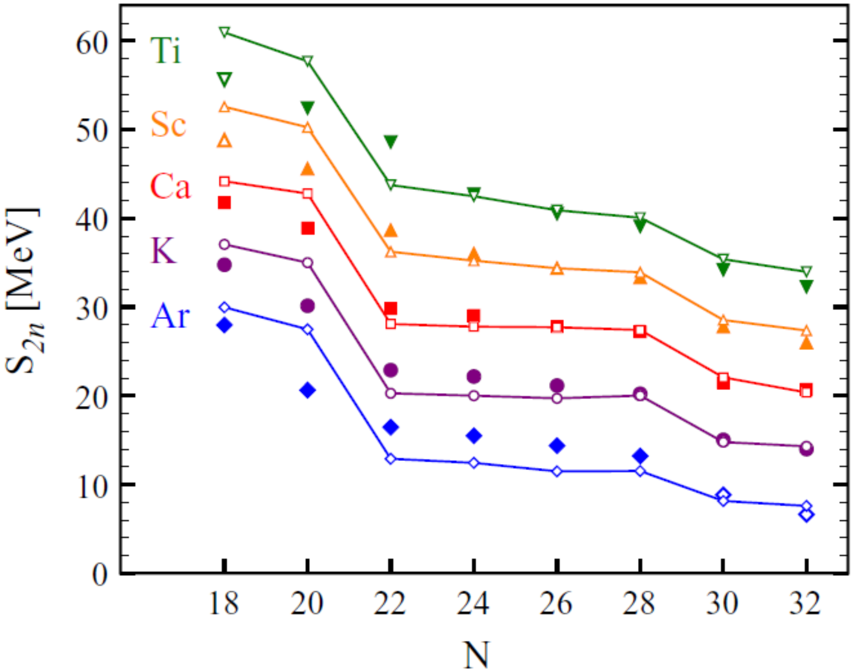
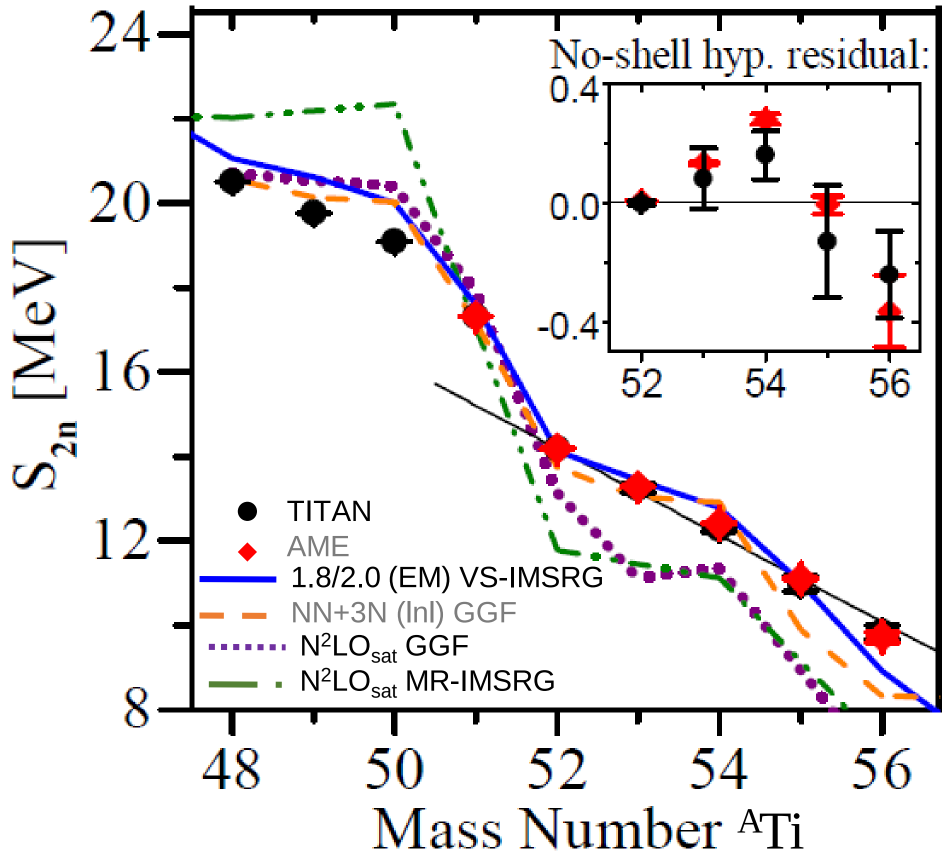


First *ab-initio* predictions for open shells in mid-mass regime from P. Navrátil & collaborators.

J.D. Holt private communication; V. Soma *et al.*, PRC 89 (2014) 061301R

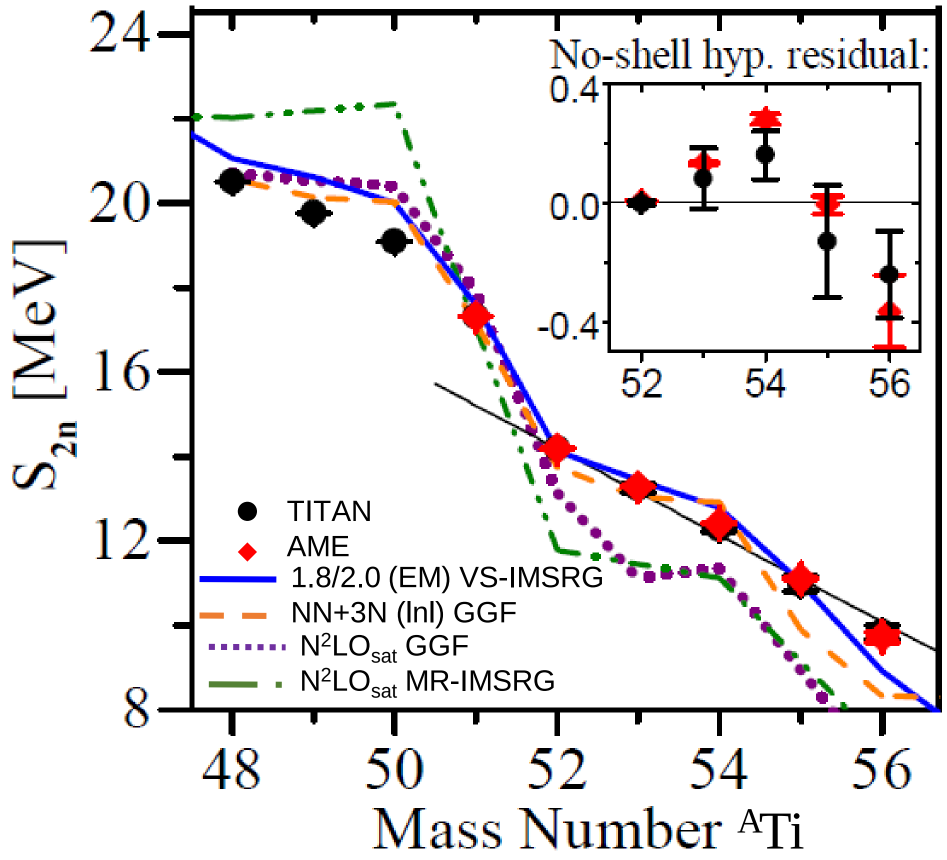
TITAN masses of Ti & V demonstrate the transitional role of Ti and were compared to TRIUMF *ab initio* predictions.

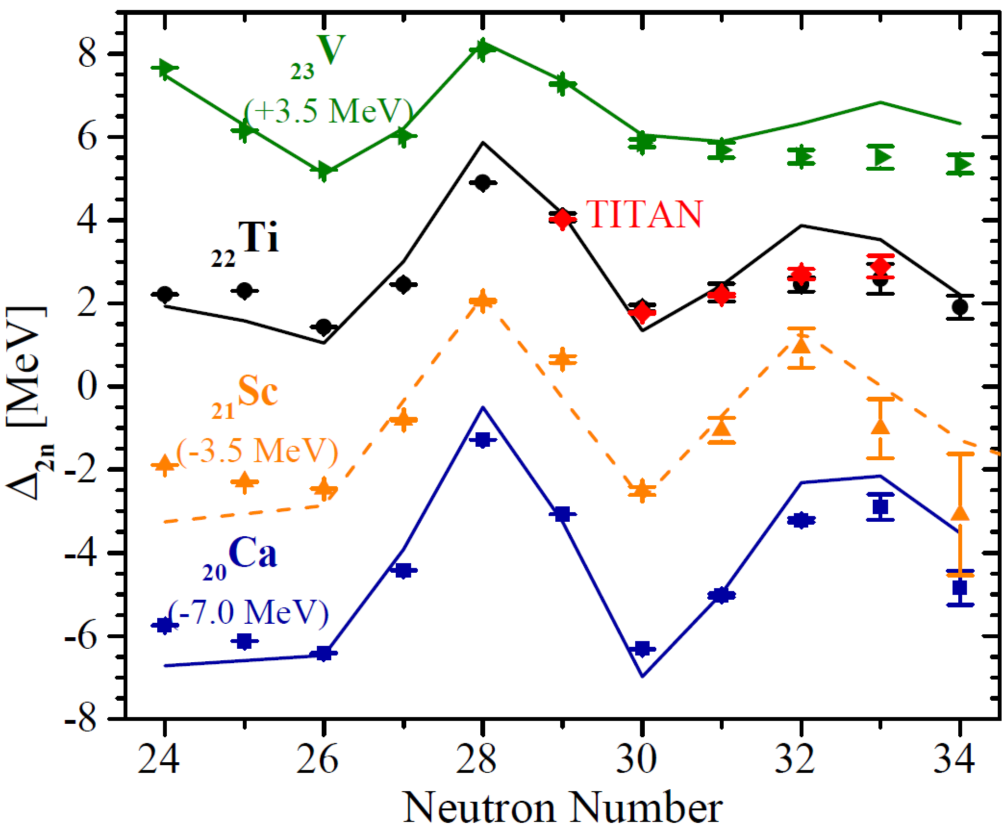


- *Ab initio* calculations from
  - Peter Navrátil & collaborators
  - Jason Holt & collaborators
  - Heiko Hergert

E. Leistenschneider *et al.*, PRL 120 (2018) 062503; M.P. Reiter *et al.*, PRC 98 (2018) 024310

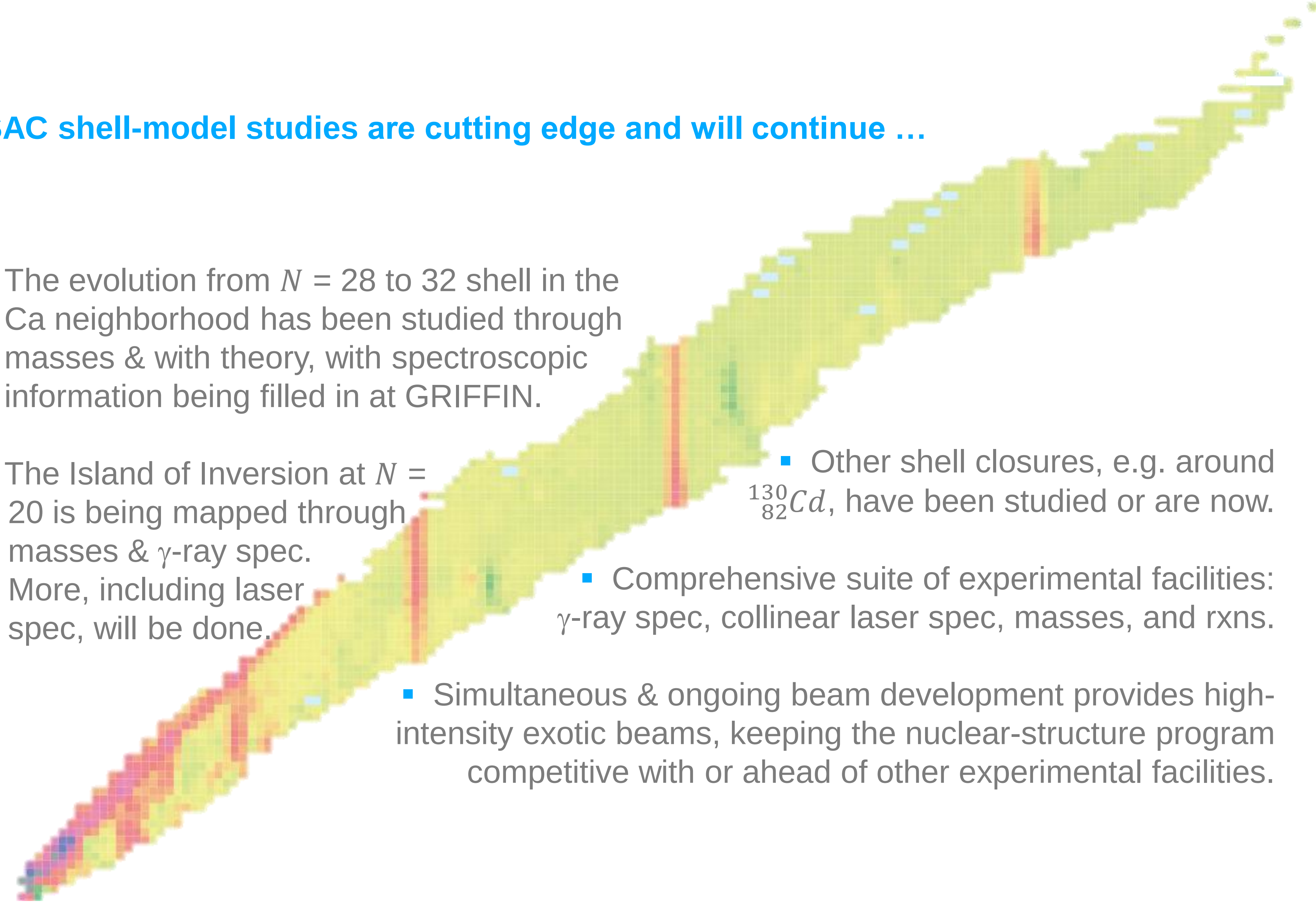
TITAN's mass measurements of Ti & V demonstrate the transitional role of Ti.





E. Leistenschneider *et al.*, PRL 120 (2018) 062503; M.P. Reiter *et al.*, PRC 98 (2018) 024310

ISAC shell-model studies are cutting edge and will continue …



- The evolution from N = 28 to 32 shell in the Ca neighborhood has been studied through masses & with theory, with spectroscopic information being filled in at GRIFFIN.

- The Island of Inversion at N = 20 is being mapped through masses & γ-ray spec. More, including laser spec, will be done.

- Other shell closures, e.g. around $^{130}_{82}Cd$, have been studied or are now.

- Comprehensive suite of experimental facilities: γ-ray spec, collinear laser spec, masses, and rxns.

- Simultaneous & ongoing beam development provides high-intensity exotic beams, keeping the nuclear-structure program competitive with or ahead of other experimental facilities.

Image: E.C. Simpson and M. Shelley, *Phys Ed* 52 (2017) 064002

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Thank you
Merci

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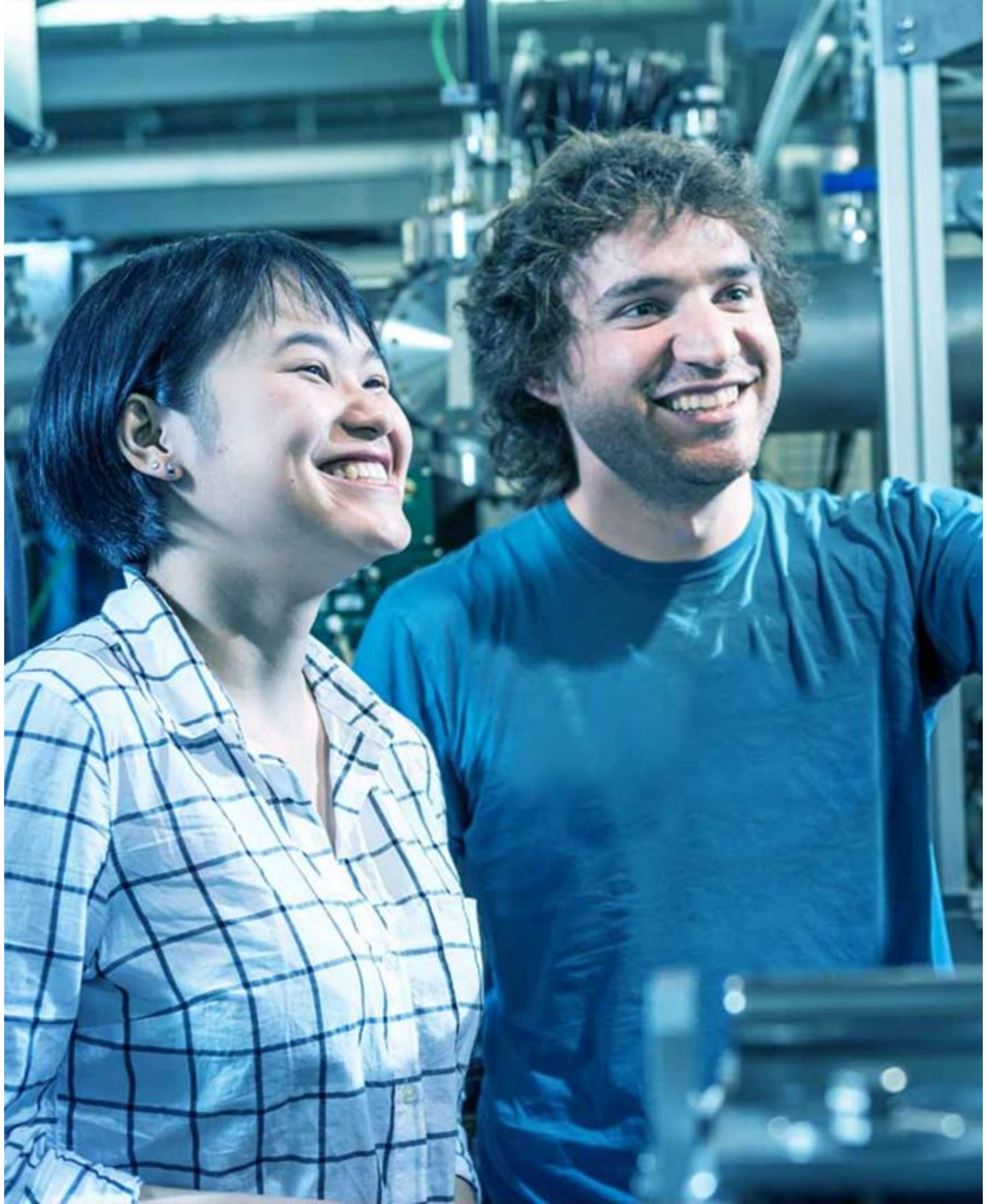

Discovery,
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