Proton-neutron interaction strength towards the N=Z line

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Talk Outline

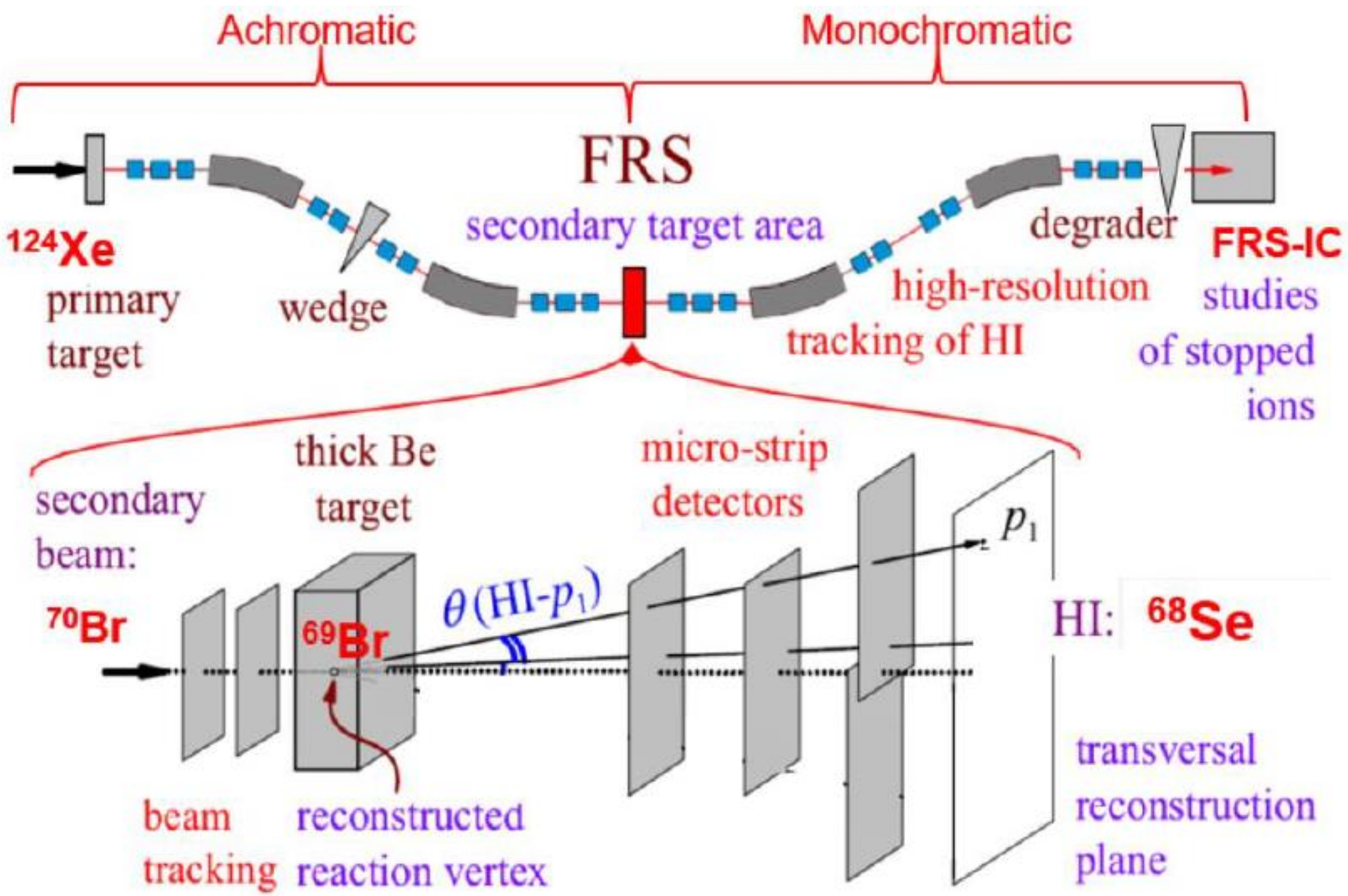
- S459+ technical and mass measurement results
- Extraction of the proton-neutron interaction strength from masses
- Physics significance of our results
- Outlook
  - More measurements around the N = Z line
  - Extension to neutron-rich nuclei, around $N_{val} \approx Z_{val}$ lines

S459+: One beam, Two experiments

- Experiment **S472** of the FRS Ion Catcher Group and experiments **S459** and **S443** of the EXPERT group ran **jointly** in March 2020 (coined **S459+**)

- The two groups used **simultaneously the same primary beam** (^{124}Xe), impinging on ^{9}Be, to measure properties of exotic isotopes near and beyond the proton dripline

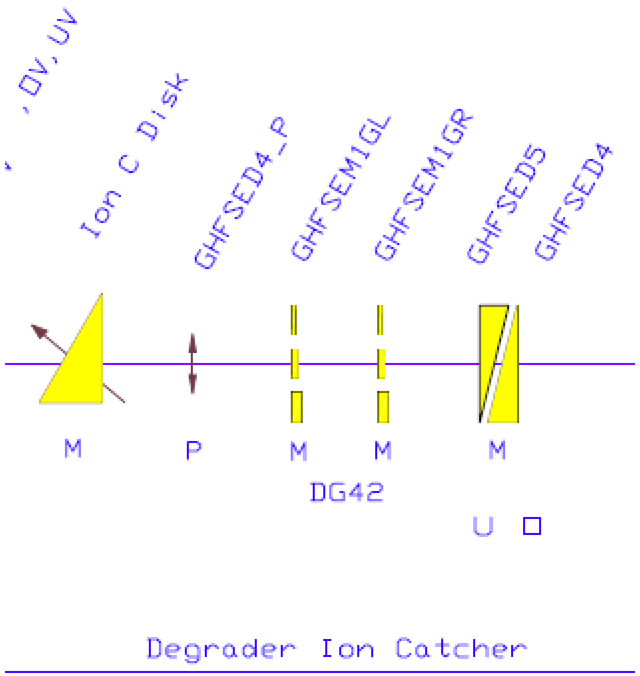
- The **FRS Ion Catcher** setup is at the final focus plane of the FRS (**S4**) whereas the **EXPERT** detectors are at its mid-focus (**S2**)



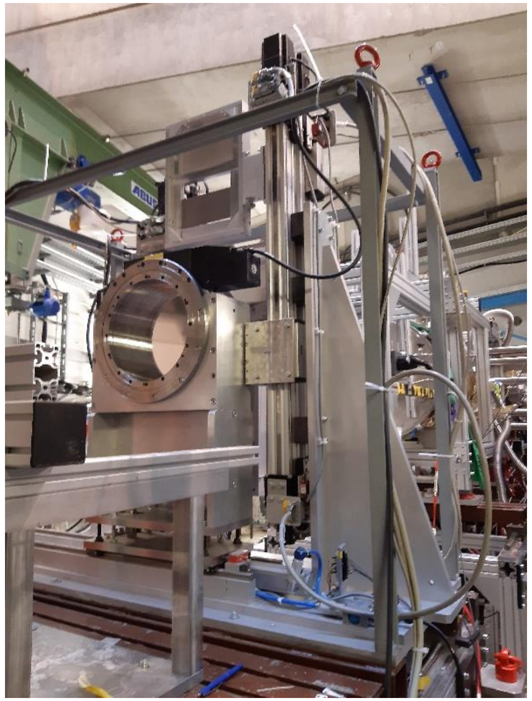
Technical achievements

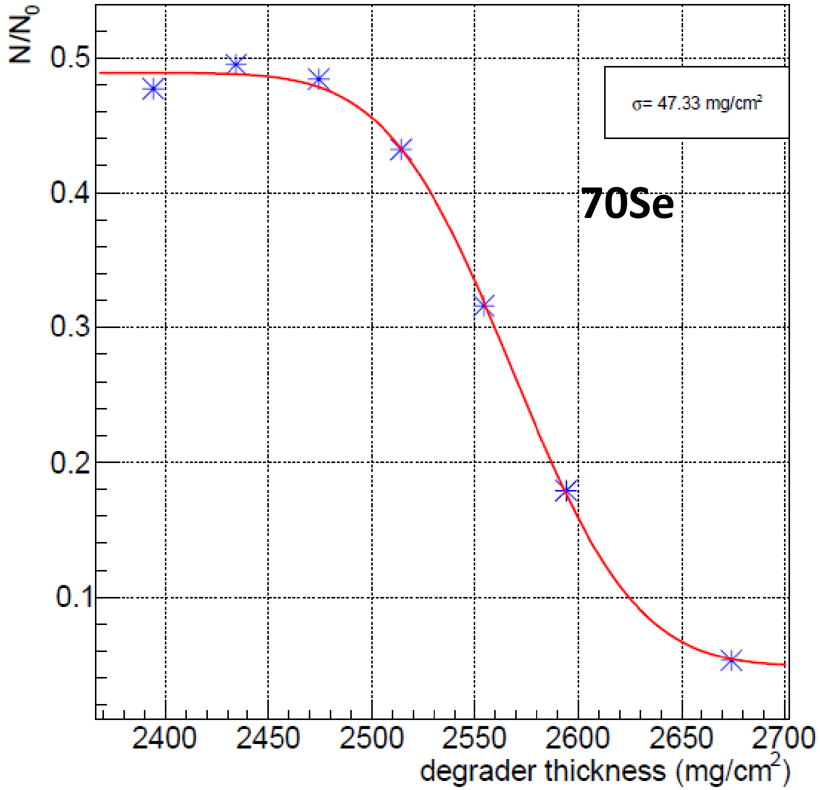
- Successful execution of two simultaneous experiments at the FRS, ‘re-using’ part of the beam that went through EXPERT for technical and physics studies at the FRS Ion Catcher
- First **range bunching at S4** with the new degrader system *C. Hornung talk tomorrow*

S4 degrader layout



S4 degrader ladder



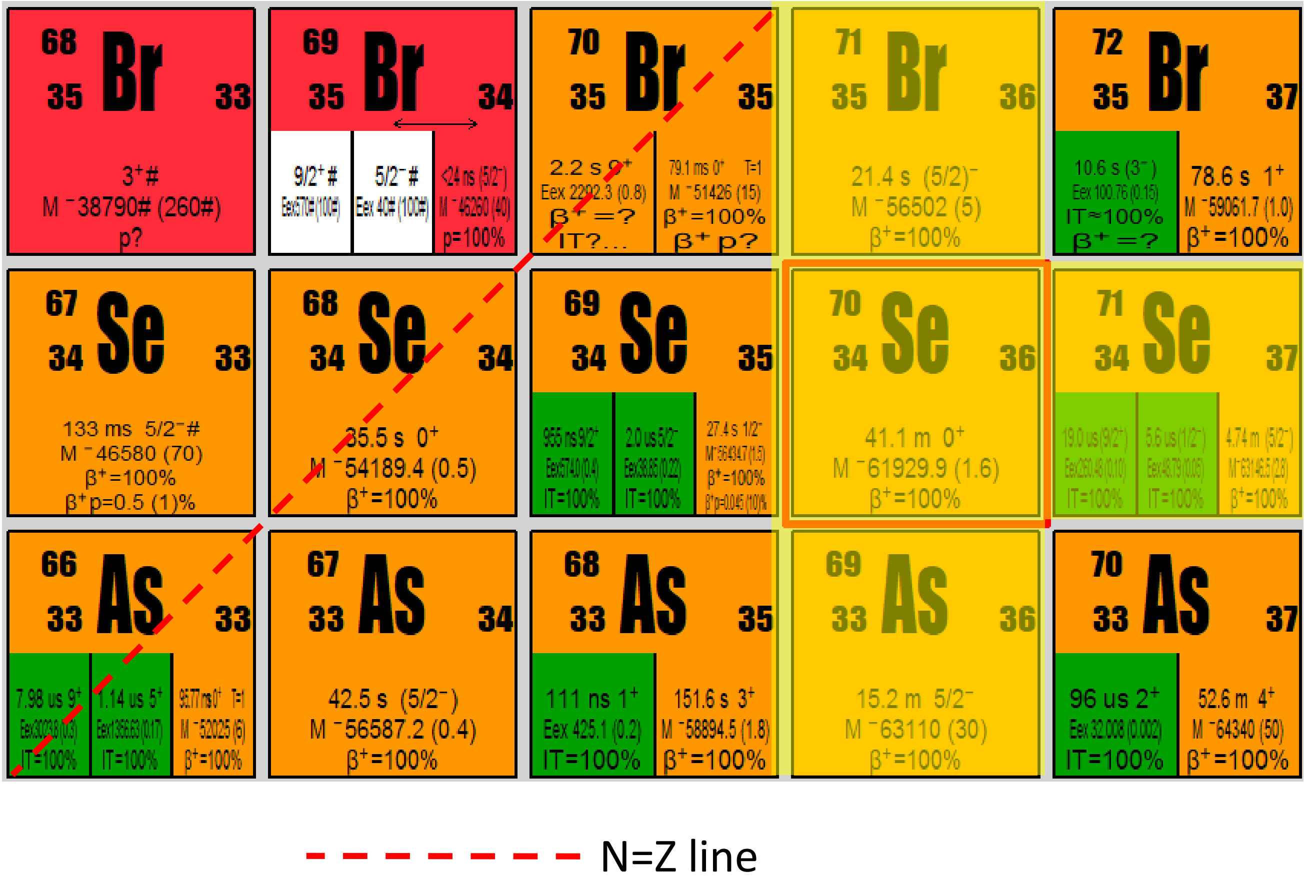


L. Gröf M.Sc. Thesis

- **Mass tagging** at **A~70**, confirming particle ID system of the FRS and EXPERT
- Extension of Ion Catcher range down to **A~70 region** (Previous low was 94)

Mass measurements

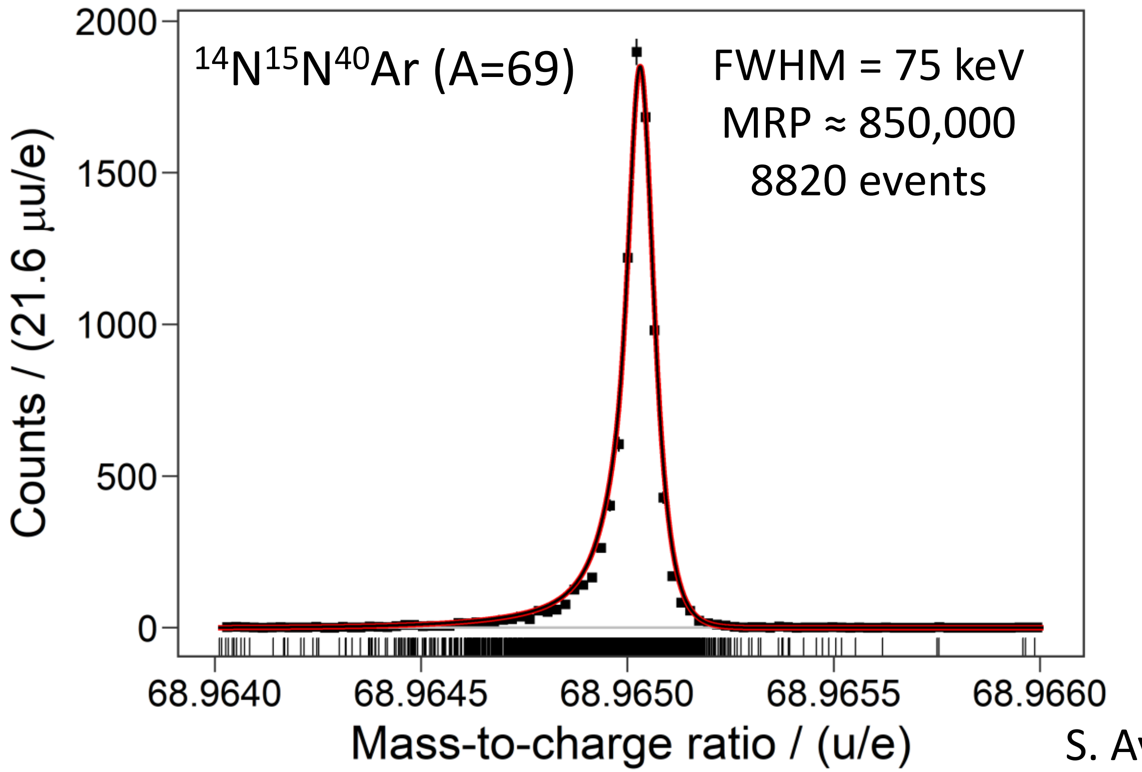
- Measured the masses of
  ^{69}As, ^{70,71}Se, ^{71}Br
- The N→Z A~70 area is important for
  - The rp-process
  - Nuclear structure (isospin symmetry, Wigner energy, p-n interaction)
  - Nuclei in this region have rapidly changing varying shapes (the “Wild West”[1])



[1]W. Nazarewicz, High Spin Physics and Gamma-soft Nuclei, 1991

Mass calibrations with stable molecules

- 4 stable molecules for same- and different-turn number with respect to ion-of-interest:
  - $^{12}C_5{}^1H_{10}$ (A=70)
  - $^{12}C_5{}^1H_9$ (A=69)
  - $^{14}N^{15}N^{40}Ar$ (A=69)
  - $^{12}C^{19}F_3$ (A=69) *(most abundant)*
- Used $^{12}C^{19}F_3$ (A=69) and 2 others to calibrate 4th molecule's mass
- Literature mass values ~ 10^{-11} level



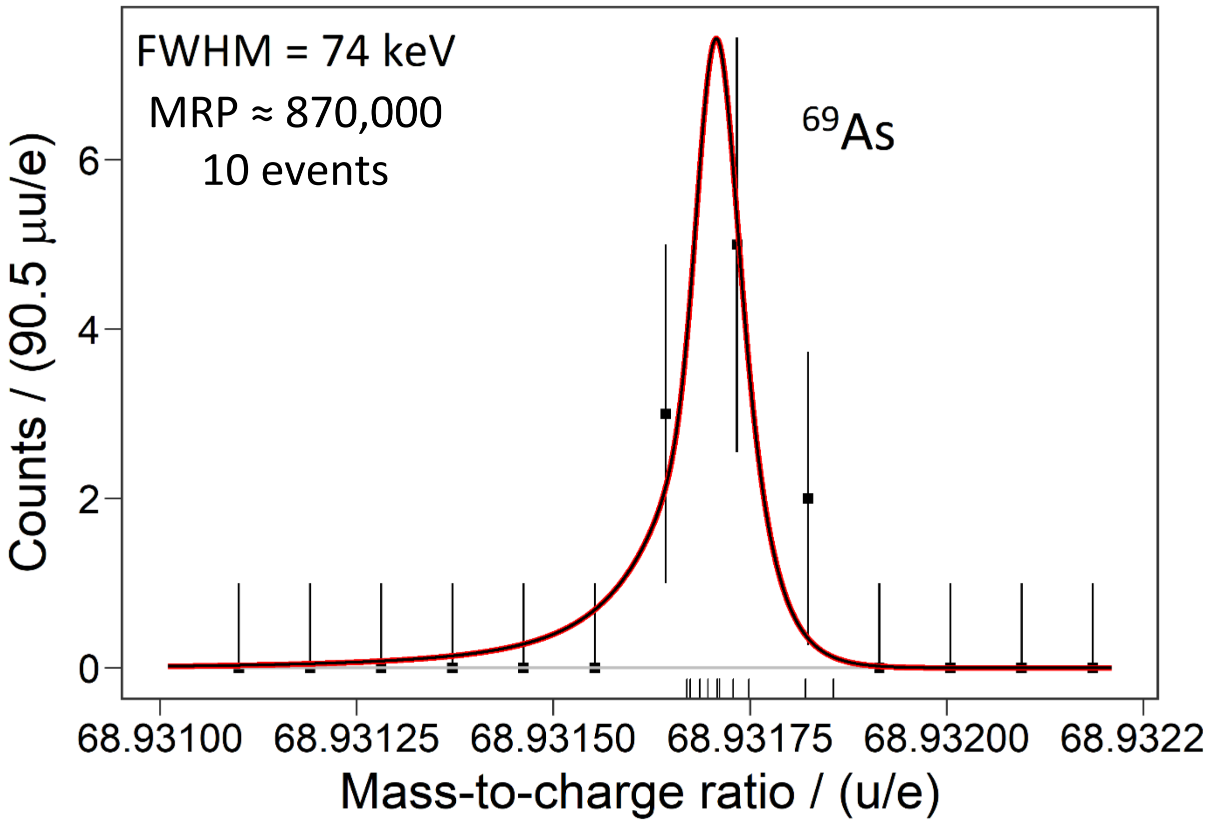
S. Ayet

Molecule	Lit. Deviation [keV]	Relative unc. $\delta m/m$
$^{12}C_5{}^1H_9$	0.9 ± 2.9	4.5×10^{-8}
$^{12}C_5{}^1H_{10}$	-1.2 ± 2.9	4.4×10^{-8}
$^{14}N^{15}N^{40}Ar$	***0.1 ± 1.1***	***1.7×10^{-8}***

World record for MR-TOF-MS!

Mass measurement of ^{69}As

- First **direct** mass measurement of ^{69}As
- Previously : 3 indirect measurements (positron end-point), with ±50 keV uncertainties, and inconsistencies amongst them
- Our value obtained with **10 events**
- Agreement with AME16, with improved uncertainty ±22 keV ($\delta m/m = 2.8\times10^{-7}$)
  - AME16 is a weighted average of the 3 previous indirect measurement
  - Origin of the selected weights is not clear



S. Ayet

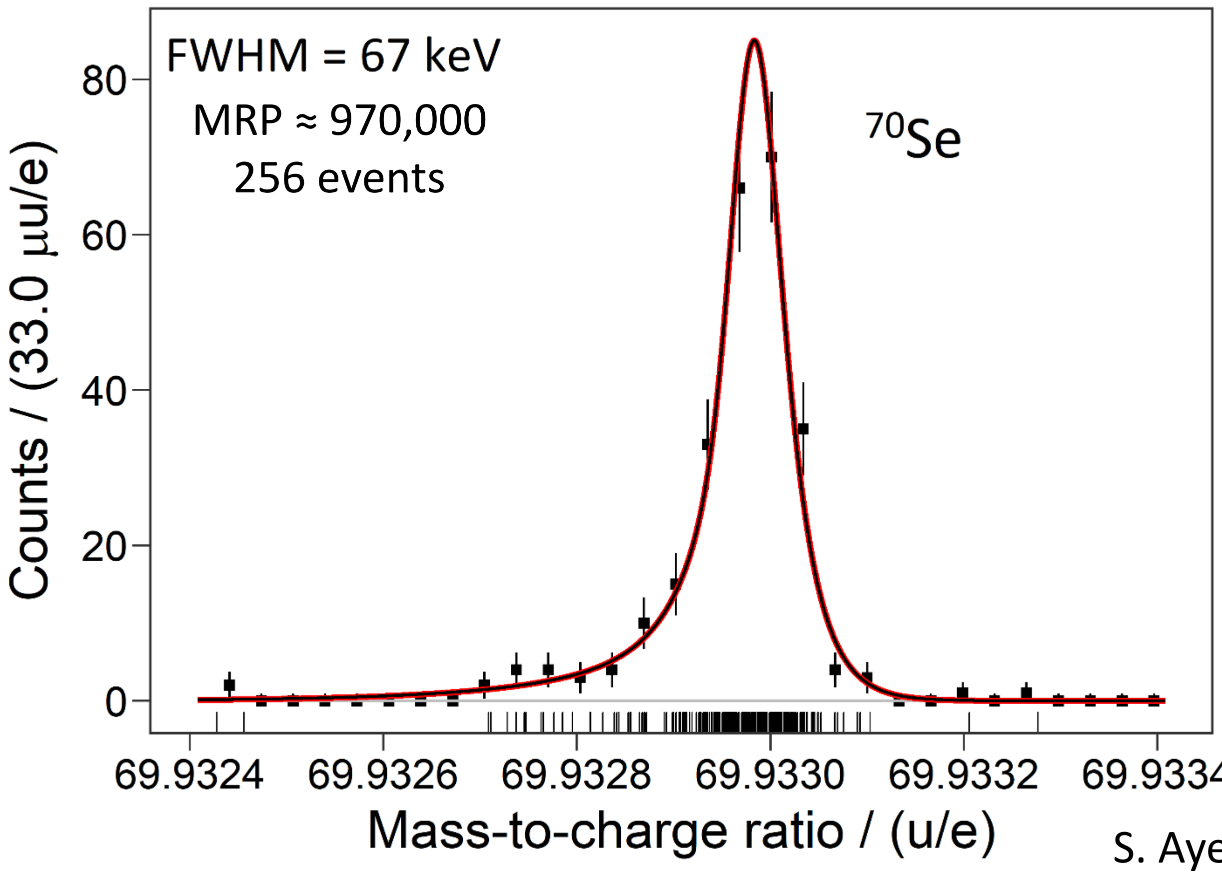
- Same turn-number calibration: $^{12}C^{19}F_3$ (A=69)
- Total ToF: 23.1 ms

For all measurements: **~900 turns** in MR-TOF-MS

Mardor, Ayet, Dickel et al., 2011.13288 (2020)

Mass measurement of ^{70}Se

- 485 events collected
- Mass uncertainty **2.6 keV** ($\delta m/m$ = **4.0×10^{-8}**), second only to MR-TOF-MS world record of **3.5×10^{-8}** (for unstable nuclei)
- World record is with 19,000 events
- Agreement with AME16
- AME16 is based on one Penning trap measurement (others are with much higher uncertainty)
- Our result is the only high-accuracy confirmation



S. Ayet

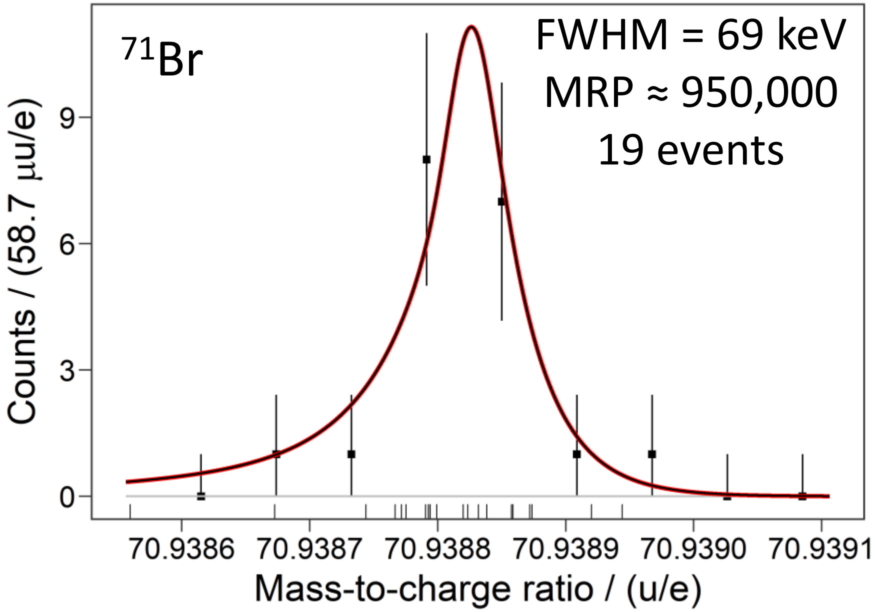
- Same- and multi-turn calibrations with four molecules
- Total ToF: 21.9 and 23.1 ms

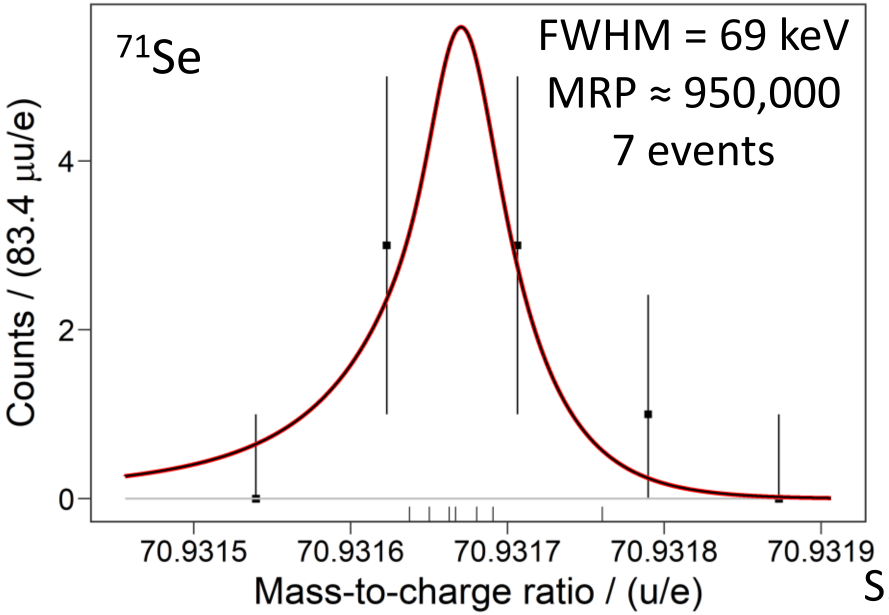
Mardor, Ayet, Dickel et al., 2011.13288 (2020)

Mass measurements of ^{71}Se, ^{71}Br

- Obtained mass values with only **19 (^{71}Br)** and **7 (^{71}Se)** events, in the same measurement
- Mass uncertainties of **16** and **23 keV**
- Both results agree with AME16
- For both nuclei, AME16 values are based on one Penning trap result. Our result is the only high-accuracy confirmation

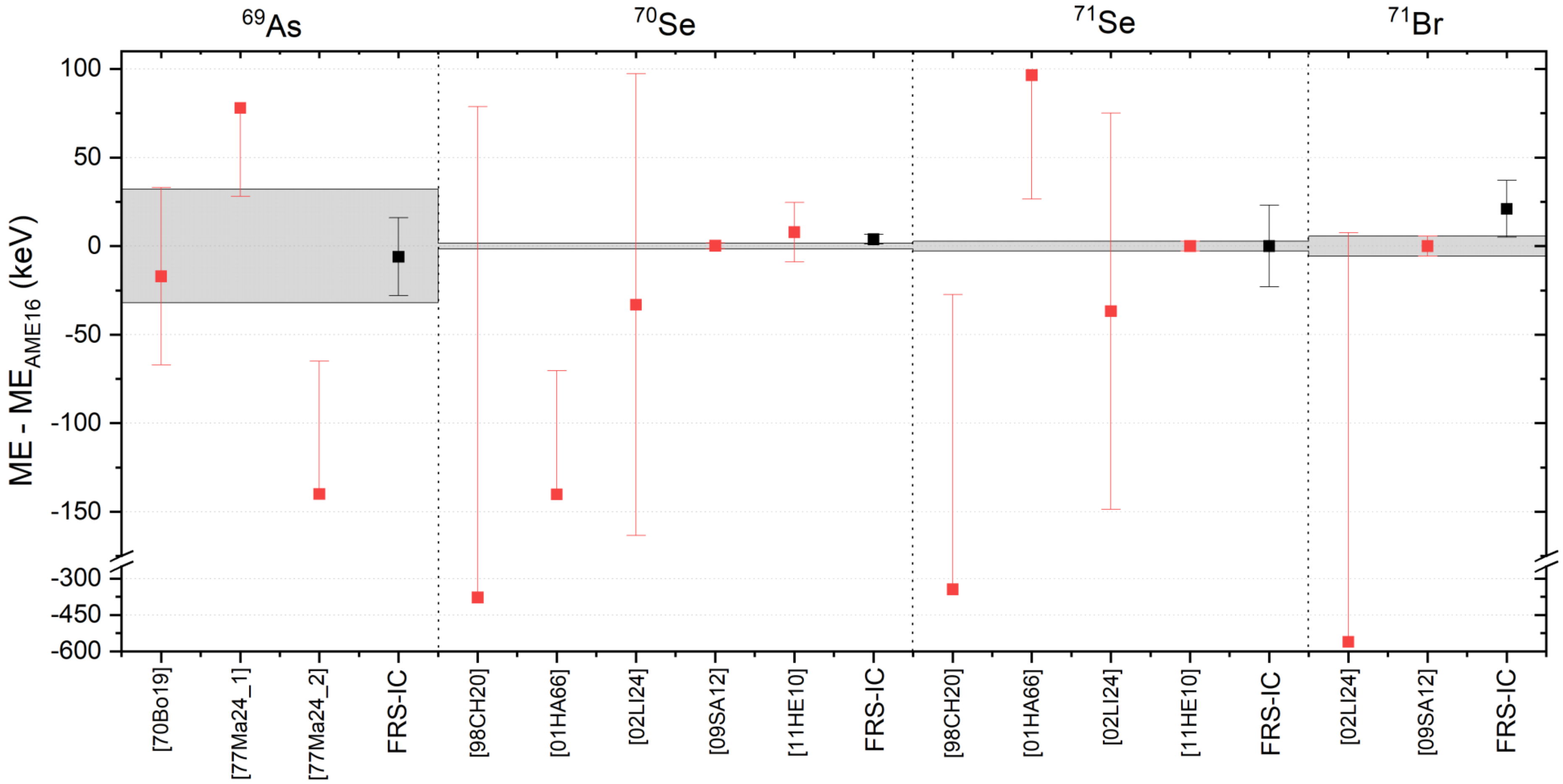
> - Multi turn-number calibration: $^{13}C^{19}F_3$ (A=70)
> - Total ToF: 23.1 ms





S. Ayet

Mass measurements summary



Mardor, Ayet, Dickel et al., 2011.13288 (2020)

Nuclei	Half-Life	ME_{FRS-IC} [keV]	ME_{AME16} [keV]	ME_{FRS-IC} - ME_{AME16} [keV]	Events
^{69}As	15.2 ± 0.2 min	$-63\,116 \pm 22$	$-63\,110 \pm 30$ †	-6 ± 37	10
^{70}Se	41.1 ± 0.3 min	$-61\,926.0 \pm 2.6$	$-61\,929.9 \pm 1.6$	3.9 ± 3.0	485
^{71}Se	4.74 ± 0.05 min	$-63\,147 \pm 23$	$-63\,146.5 \pm 2.8$	0 ± 23	7
^{71}Br	21.4 ± 0.6 s	$-56\,481 \pm 16$	$-56\,502 \pm 5$	21 ± 17	19

Technical significance of our mass resolving power

- In principle, mass uncertainty could be improved indefinitely by accumulating more and more events, even with mediocre mass resolving power
- In practice, mass uncertainty is hindered by:
  - Unresolved overlapping peaks of isobars and isomers
  - Limited number of events for rare isotopes
- We achieved excellent uncertainties at low number of events due to the **FRS-IC MR-TOF-MS** unprecedented mass-resolving-power (MRP) of ***1,000,000***

The "physics story" - proton-neutron interaction strength

- Average interaction strength the 'last' (valence) proton(s) and neutron(s):

$$\delta V_{np}^{ee} = \frac{1}{4}\{[B(N,Z) - B(N-2,Z)] - [B(N,Z-2) - B(N-2,Z-2)]\}$$ last two n + two p (4 combinations)

$$\delta V_{np}^{eo} = \frac{1}{2}\{[B(N,Z) - B(N-2,Z)] - [B(N,Z-1) - B(N-2,Z-1)]\}$$ last two n + one p (2 combinations)

$$\delta V_{np}^{oe} = \frac{1}{2}\{[B(N,Z) - B(N,Z-2)] - [B(N-1,Z) - B(N-1,Z-2)]\}$$ last one n + two p (2 combinations)

$$\delta V_{np}^{oo} = \{[B(N,Z) - B(N-1,Z)] - [B(N,Z-1) - B(N-1,Z-1)]\}$$ last one n + one p (1 combination)

Assuming that the **nuclear core remains essentially unchanged** for the four nuclei in each equation,

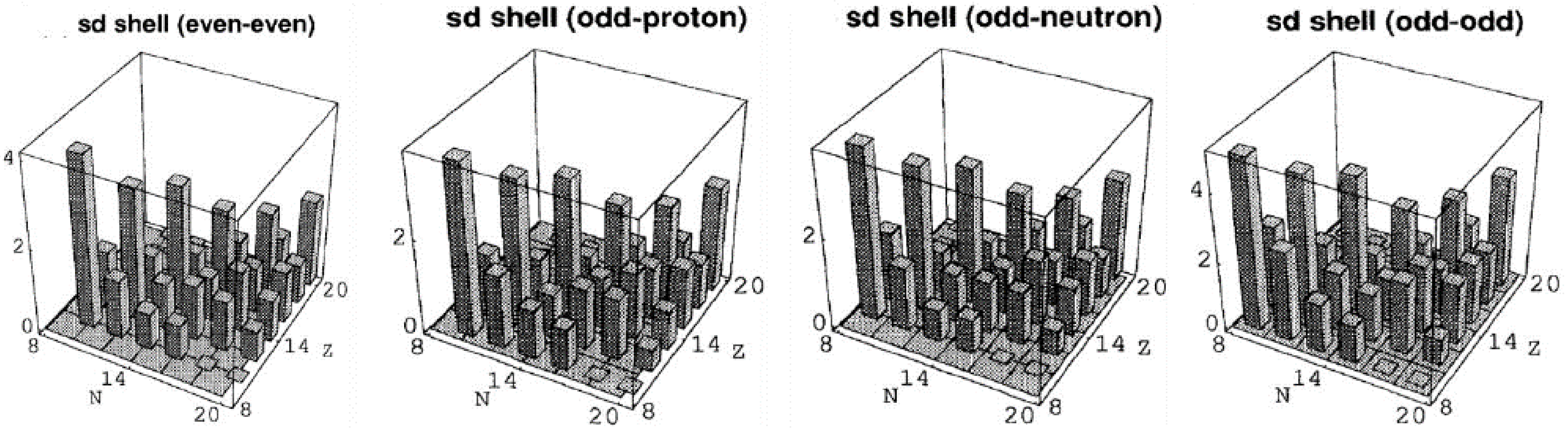
these double differences **cancel out** the **p-p and n-n pairing** interactions and the **mean field component** of the binding energy,

isolating the empirical p-n interaction strength

J.-Y. Zhang et al., Phys. Lett. B, 227, 1 (1989)
R. B. Cakirli et al., Phys. Rev. Lett., 94, 092501 (2005)
R. B. Cakirli, et al., Phys. Rev. Lett., 96 132501 (2006)
M. Stoitsov, et al., Phys. Rev. Lett., 98, 132502 (2007)

Expected trends of δV_{pn}

- δV_{pn} has been related to the spatial overlap between the last p and n wave functions
  - N≈Z nuclei should have much higher δV_{pn} values than neighbors



P. Van Isacker et al., PRL 74, 4607 (1995)

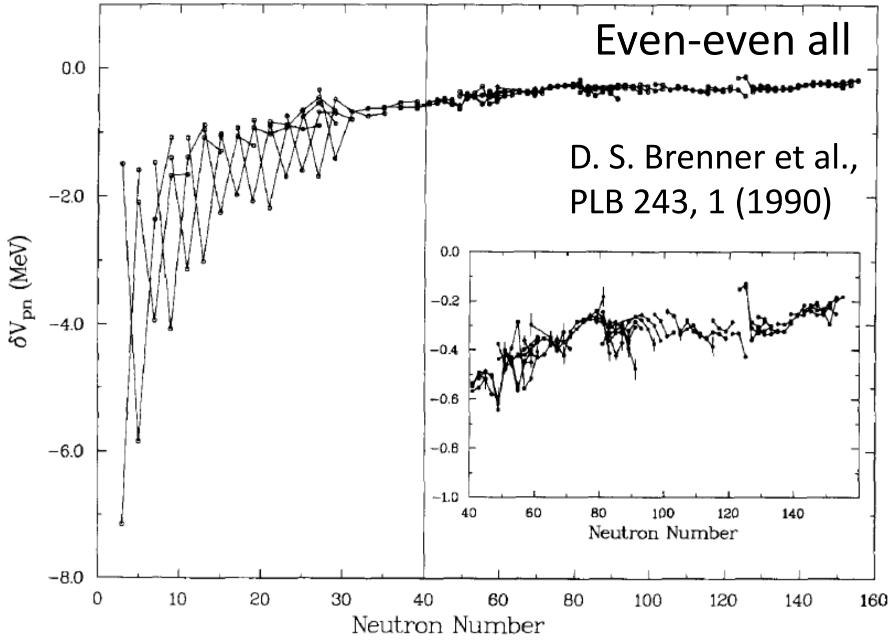
Expected trends of δV_{pn}

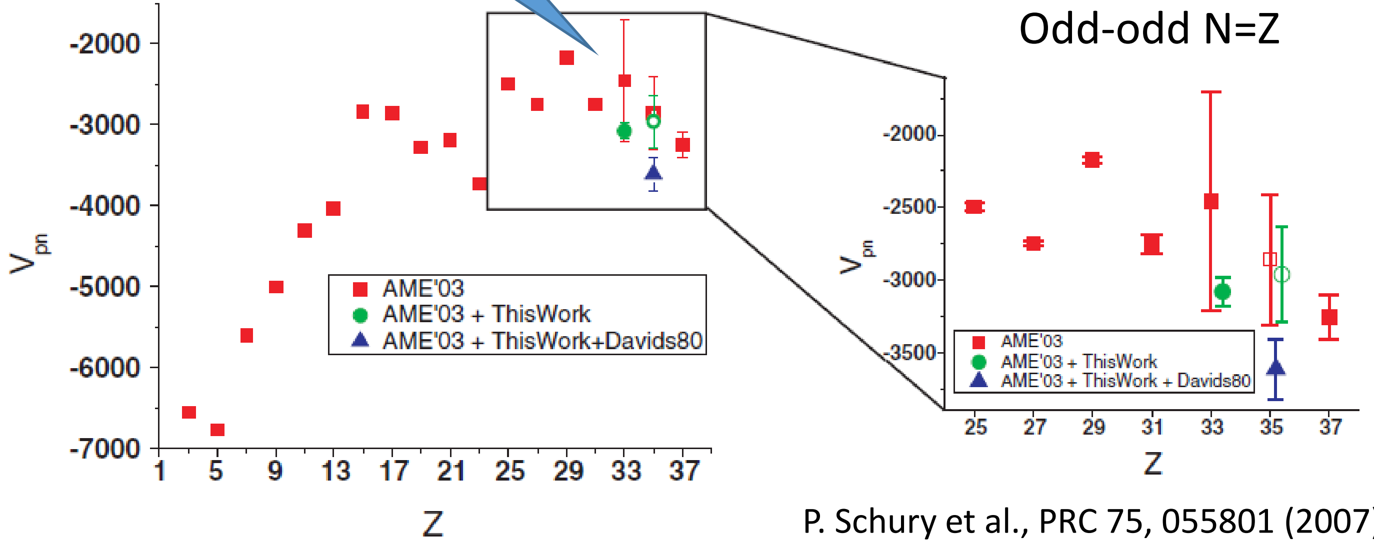
- δV_{pn} has been related to the spatial overlap between the valence p and n wave functions

- δV_{pn} should decrease with increasing mass because:

  1. Distance between p and n wave functions increase with nuclear radii
  2. Coulomb forces increase with Z, differentiating p and n wave functions
  3. Spin-orbit interaction increases, breaking spin-isospin SU(4) symmetry

"indication of a trend toward the re-strengthening of δV_{np}"

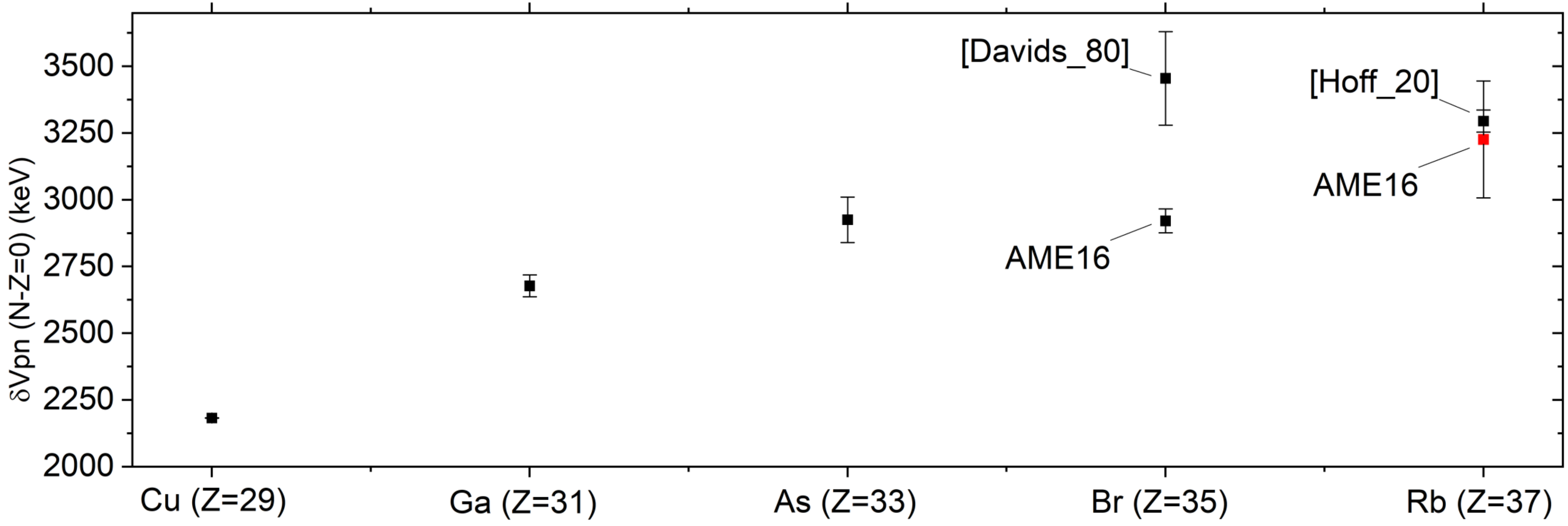




P. Schury et al., PRC 75, 055801 (2007)

Odd-Odd N=Z δV_{pn} from Z=29 to Z=37

Use recent standard of positive δV_{pn}

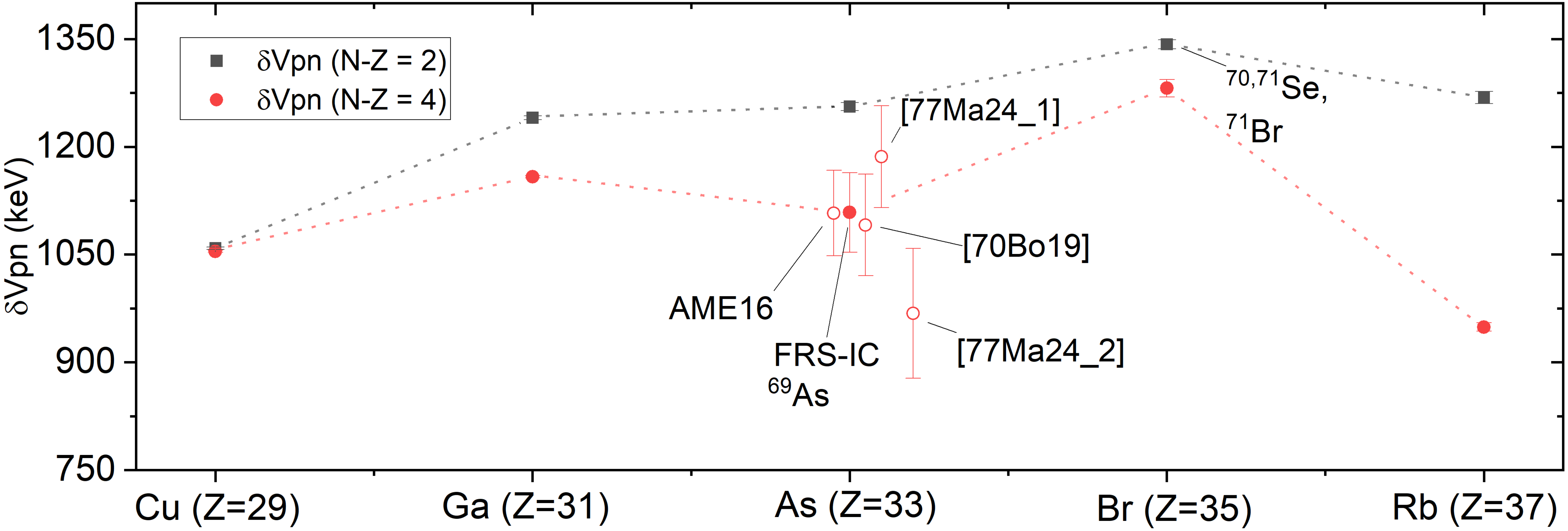


- Br: Included values from both ^{70}Br mass measurements.
  [Davids_80] is from the value that is consistent with the *Ft* world average
- Rb: Included values from AME16 evaluation of ^{73}Rb mass (red) and very recent (October 2020) indirect measurement [Hoff_20] (PRC 102, 045810 (2020), published 20 October 2020)
- **The δV_{pn} re-strengthening trend may be confirmed**

Mardor, Ayet, Dickel et al., 2011.13288 (2020)

Contribution of our measurements (goals)

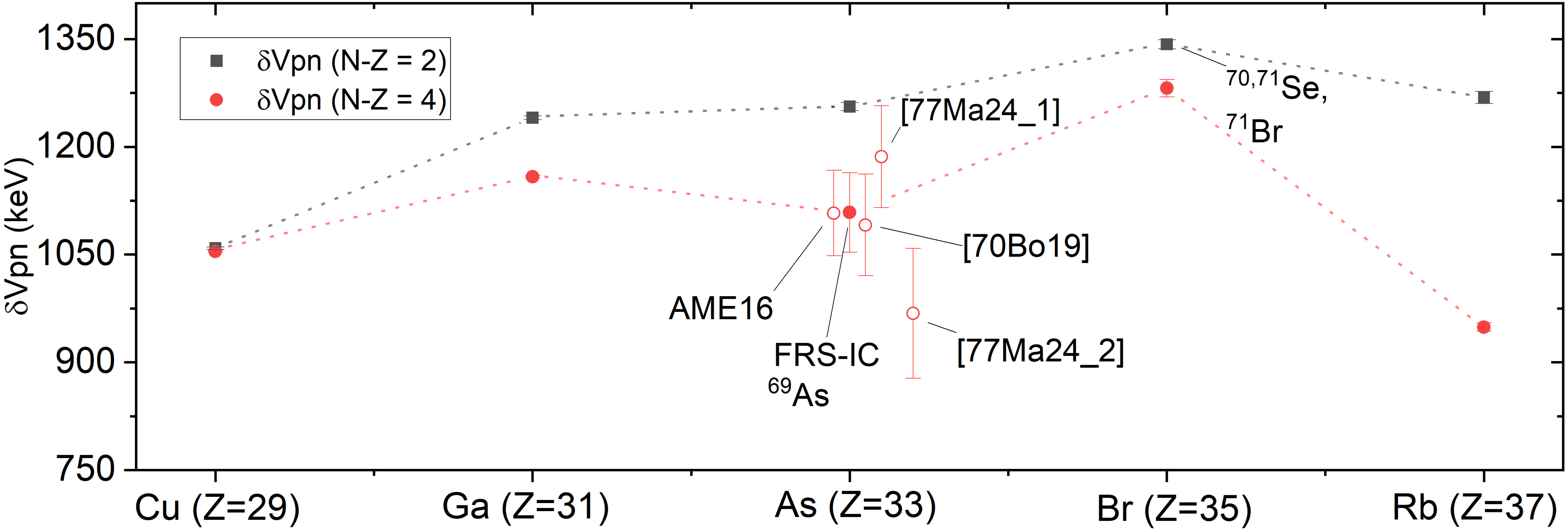
- Investigate whether δV_{pn} restrengthening occurs also for odd-odd N-Z=2 and N-Z=4 nuclei
- Study detailed trends of N=Z+2 and N=Z+4 to obtain hints on ^{70}Br discrepancy



Mardor, Ayet, Dickel et al., 2011.13288 (2020)

Contribution of our measurements (results)

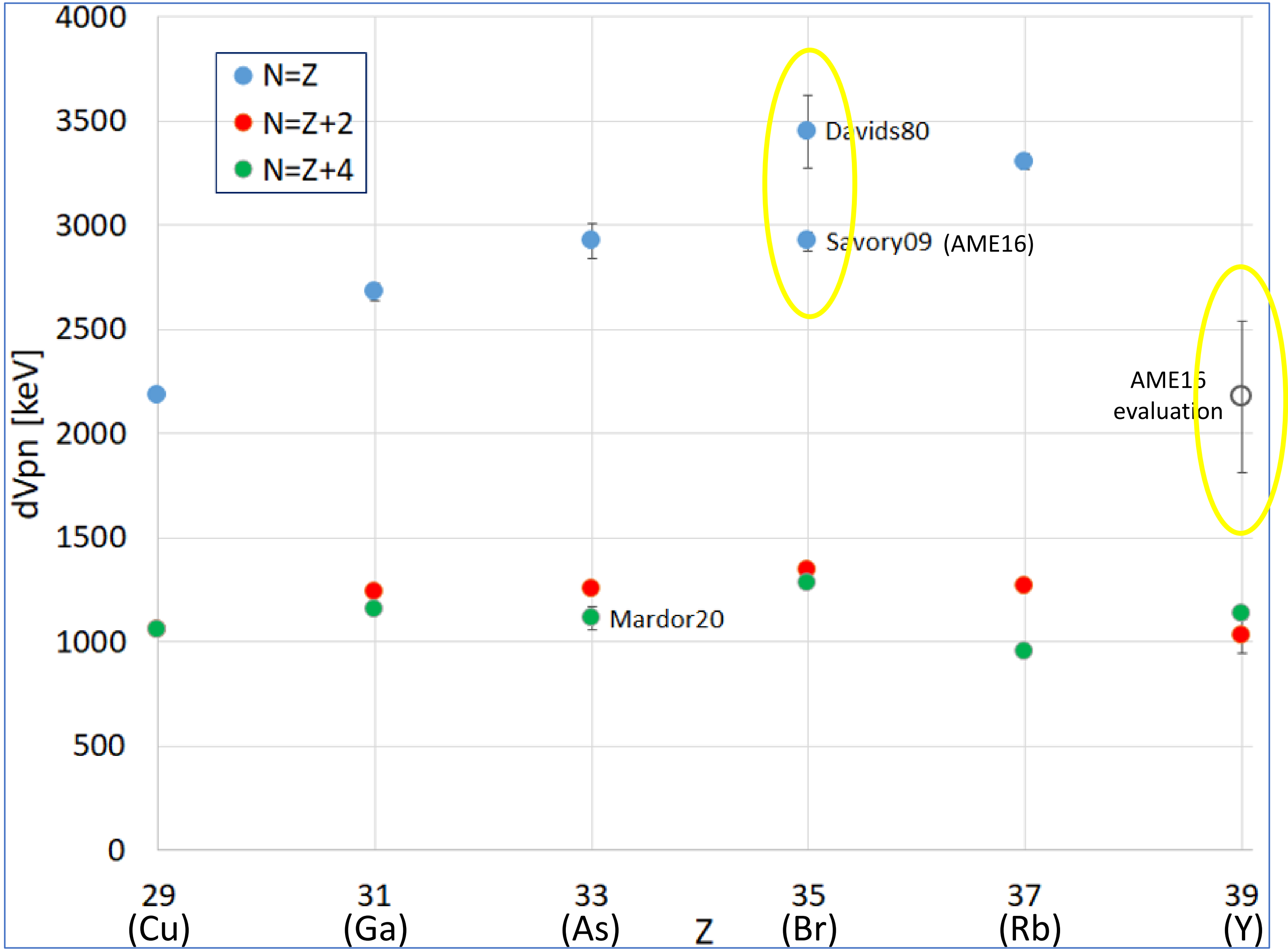
- ^{69}As measurement sets As(N-Z=4) value. $^{70,71}Se$ and ^{71}Br measurements confirm Br(N-Z=2) value.
- N-Z=2 and N-Z=4 δV_{pn} values much lower than N=Z. Restrengthening is hardly (non) evident at N-Z=2 (4)
- Restrenghtening is a sole property of the N=Z odd-odd nuclei



Mardor, Ayet, Dickel et al., 2011.13288 (2020)

Physics conclusions and outlook

- δV_{pn}(N=Z) increase may be due to partial restoration of a symmetry that is unique to these nuclei
- It has been proposed that protons and neutrons occupying the pf-shell above the magic number 28 exhibit a **pseudo-SU(4) symmetry**. Perhaps this data supports this
- δV_{pn}(N=Z+2) and δV_{pn}(N=Z+4) peak at Br. This may suggest that δV_{pn}(N=Z) should also peak at Br, meaning that **m(^{70}Br) is closer to [Davids80]**
- **S526** measurements include **^{70}Br** and **^{77,78}Y**. Will 'straighten out' this plot
- **^{78}Y** especially interesting, due to uncertainty in g.s. – isomer assignment

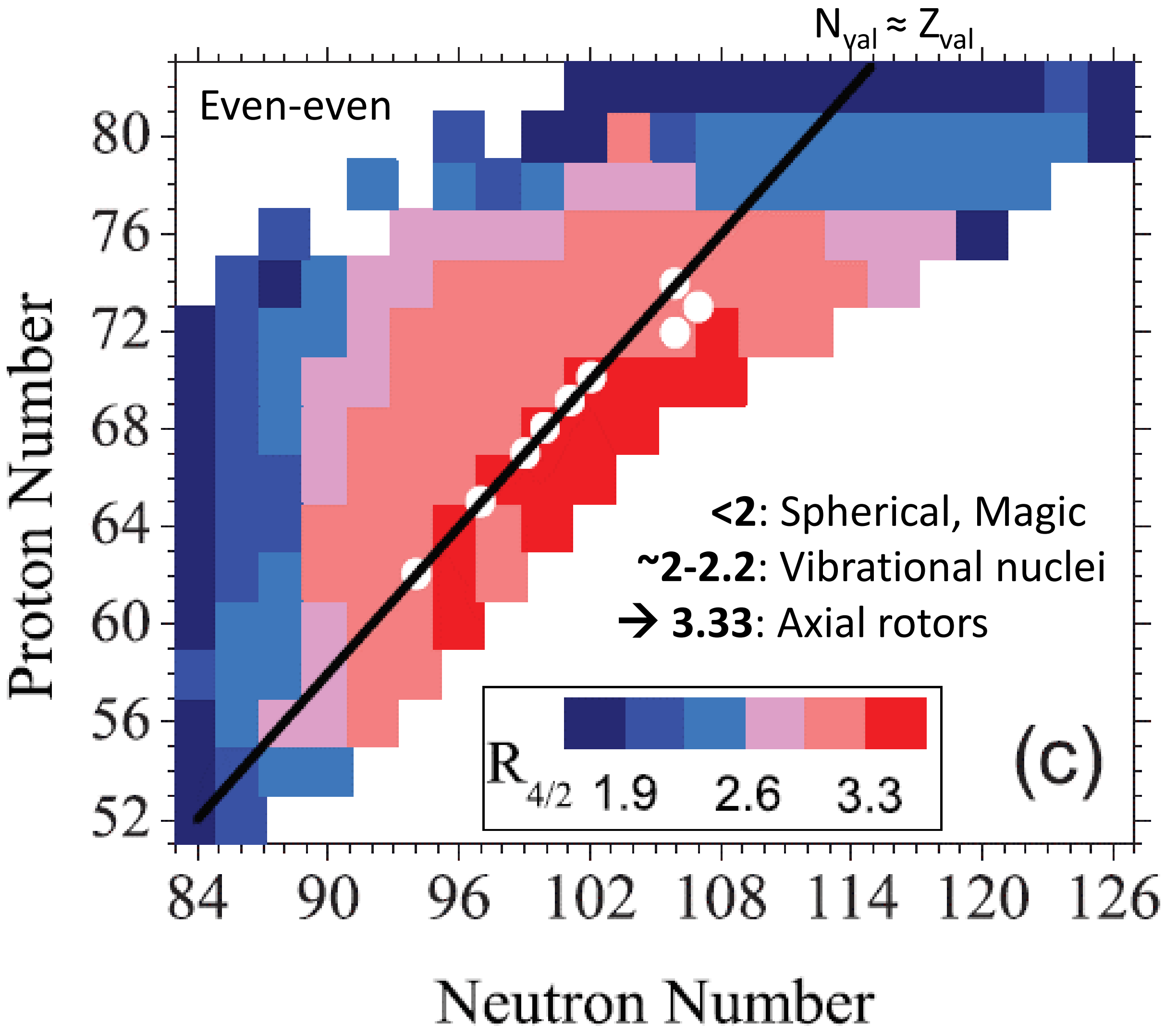


δV_{pn} measurements of n-rich nuclei

- It has been proposed that δV_{pn} should be enhanced also in neutron-rich nuclei with $\mathbf{N_{val} \approx Z_{val}}$ (above doubly-magic cores)

- Emergence of a reduced form of Wigner-like energy and SU(4) symmetry and/or onset of nuclear deformation

- related to the spatial overlap of the last neutron(s) and proton(s) wave functions



○ Highest δV_{pn} value in isotope chain

D. Bonatsos et al., PRC88, 054309 (2013)

δV_{pn} measurements of n-rich nuclei

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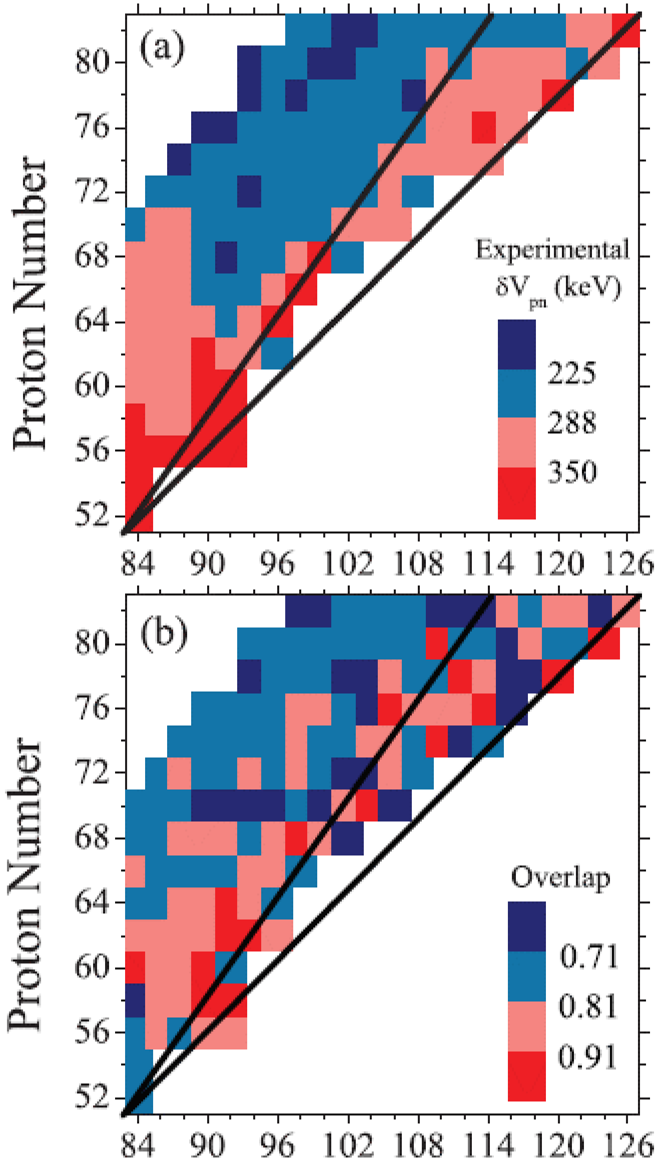
- Emergence of a reduced form of Wigner-like energy and SU(4) symmetry and/or onset of nuclear deformation
- related to the spatial overlap of the last neutron(s) and proton(s) wave functions

Even-even nuclei

- Overlaps of Nilsson wave functions
- Deformation parameter chosen for each nucleus via its $R_{4/2}$ value
- Theoretical extension to nuclei with unmeasured R4/2

$N_{val} \approx Z_{val}$

Equal partial filling

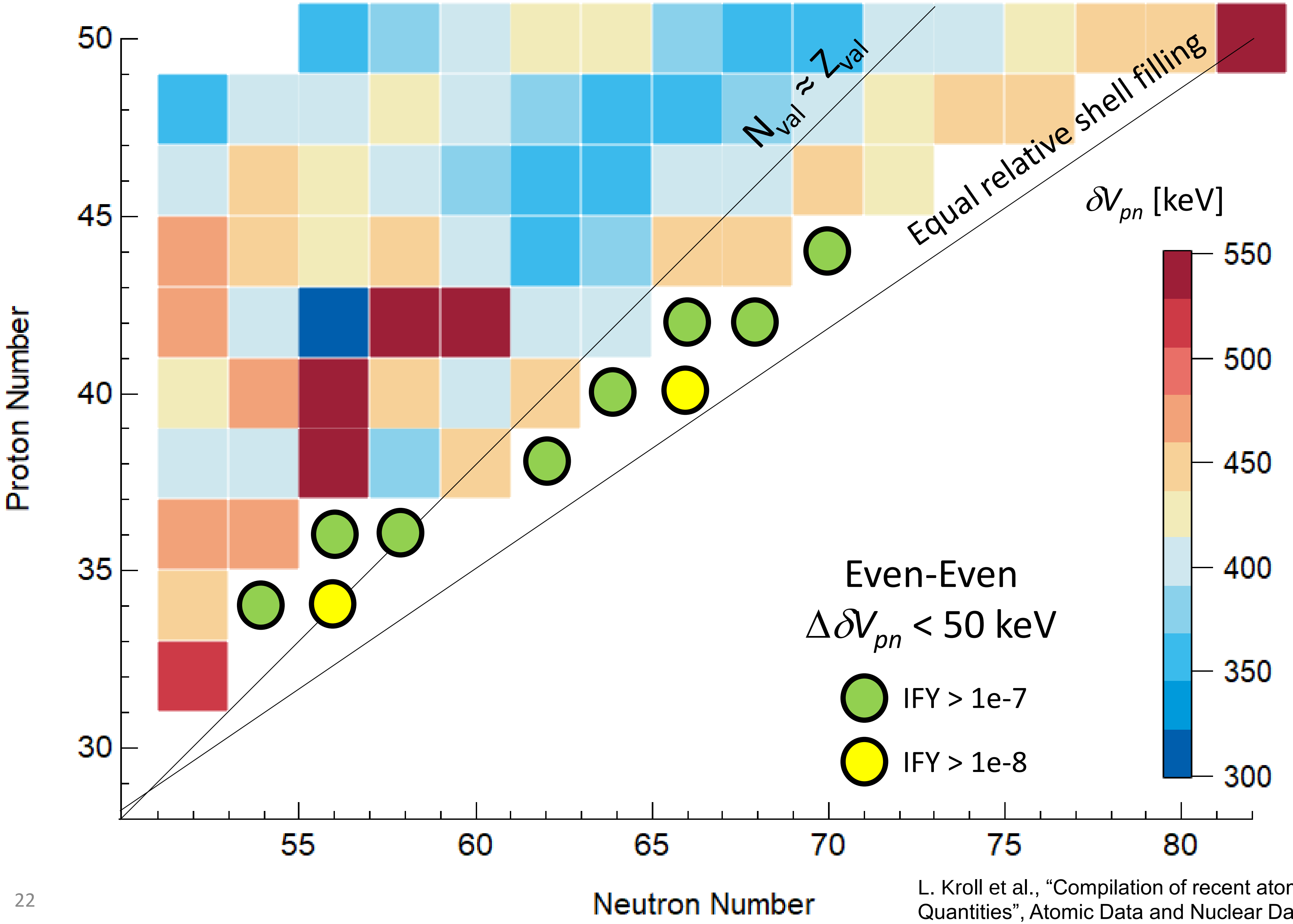


D. Bonatsos et al., PRC88, 054309 (2013)

δV_{pn} of n-rich nuclei at FRS Ion Catcher and IGISOL

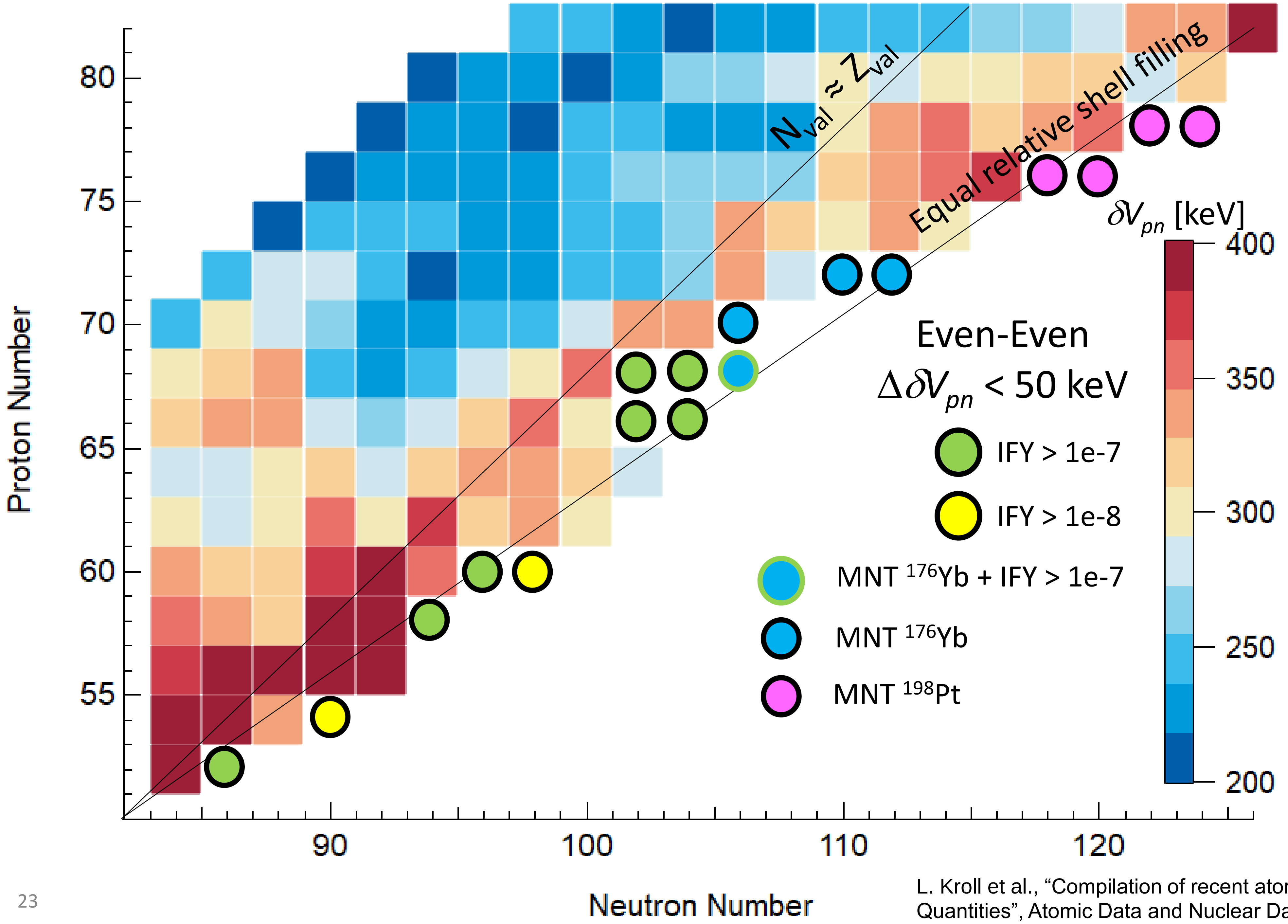
- We plan to use spontaneous fission sources at the FRS Ion Catcher to measure more δV_{pn} values above **Z=50, N=82** and **Z=28, N=50** Magic shells
- Meaningful measurements are possible with fission yields of IFY ~ $10^{-6,7}$
- (Challenging) extension to IFY ~ 10^{-8} adds only a few more δV_{pn} values
- Values of heavier nuclei will be available from the proposed MNT experiments at IGISOL @ JYFLTRAP
- Following slides show most updated δV_{pn} experimental values, and our potential contributions

N=50, Z=28 Shell



Masses from AME16 (experimental)
+
updates from [Kroll20]

L. Kroll et al., "Compilation of recent atomic mass measurements and deduced Quantities", Atomic Data and Nuclear Data Tables 133–134 (2020) 101336



N=82, Z=50 Shell

Masses from AME16 (experimental) + updates from [Kroll20]

L. Kroll et al., "Compilation of recent atomic mass measurements and deduced Quantities", Atomic Data and Nuclear Data Tables 133–134 (2020) 101336

Summary (1/2)

- Demonstrated possibility of **simultaneous experiments** with the **same FRS beam**
- Performed the **first range bunching** at the final focus of the **FRS** (S4)
- Reached a **mass resolving power** of **1,000,000** with an MR-TOF MS 
  - **Mass uncertainty** of **1.7×10^{-8}** for a **stable** molecule (≈9,000 events) 
  - **Mass uncertainty** of **4.0×10^{-8}** for an **unstable** nuclide (≈500 events) 
- First direct mass measurement of ^{69}As, resolving discrepancies in indirect ones
- First MR-TOF-MS mass measurements of ^{70,71}Se, ^{71}Br, consistent with AME16
- Our results indicate a rise with mass of δV_{pn} of odd-odd N=Z nuclei from Z = 29
- Overall trends of δV_{pn} at N≤Z suggests a resolution to the ^{70}Br mass discrepancy (towards 1980 end-point energy measurement, versus 2009 Penning Trap)

Summary (2/2)

- δV_{pn} values provide an interesting physics motivation for mass measurements of n-deficient nuclei around N=Z and also of n-rich nuclei around $N_{val} \approx Z_{val}$
- Systematic surveys of δV_{pn} may point at emergence of
  - nuclear symmetries
  - collectivity / deformation
- They can also indicate
  - erroneous mass measurements and/or evaluations (δV_{pn} fluctuates or unphysical)
  - rapid nuclear shape changes (δV_{pn} interpretation relies on four nuclei having similar cores)
- More double differences of binding energies that exhibit the p-n interaction have been suggested (W. Satula et al., PLB 407, 103 (1997), Z. Wu et al., PRC 93. 034334 (2016), and more)
  - May further differentiate mean-field and residual contributions to the p-n interaction
  - Will analyze our present and future measurements according to these expressions as well

Acknowledgement – The FRS Ion Catcher Collaboration

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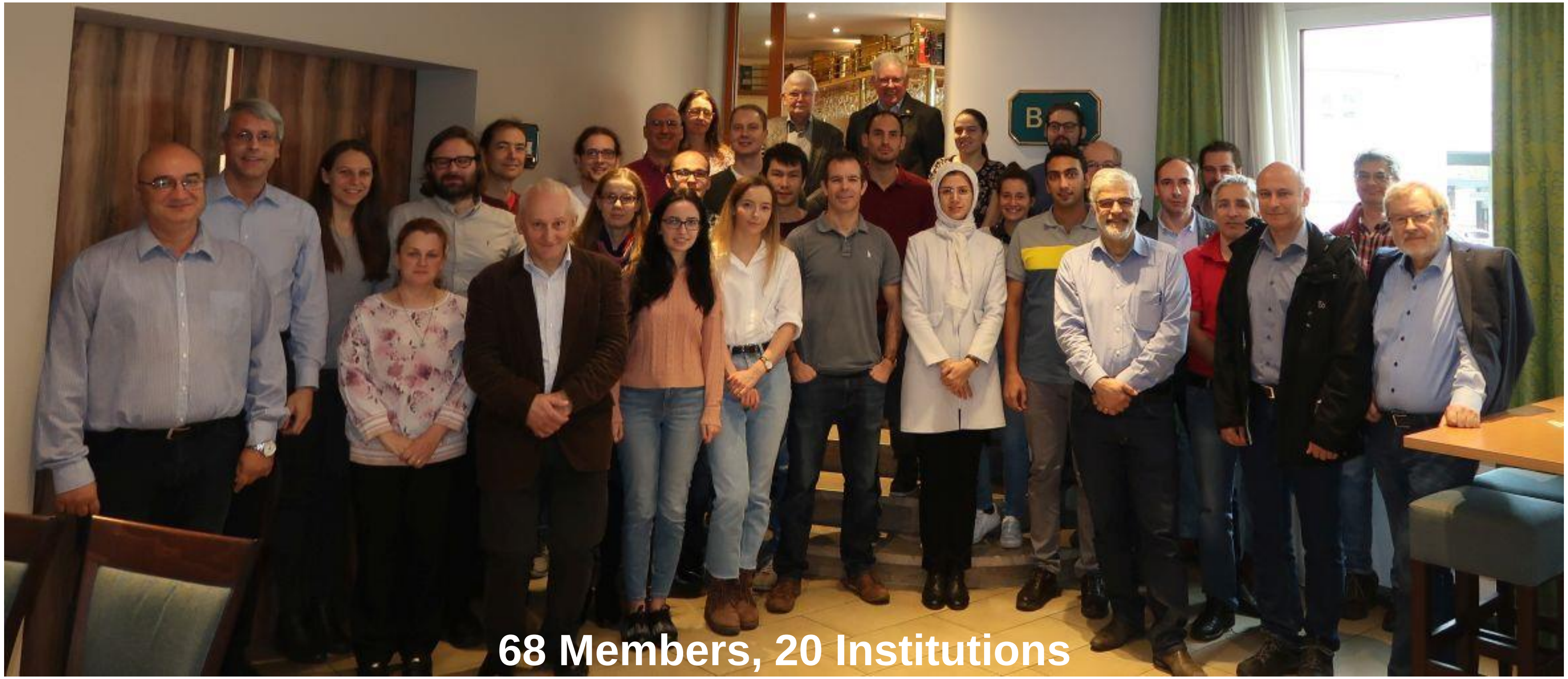

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