磁気剛性・飛行時間法を用いた中性子過剰核の直接質量測定
Direct mass measurements of $^{55\text{-}57}$Ca

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Contents

- Introduction
  - Motivation of mass measurement
- Experimental method (in detail)
- Result and Discussion

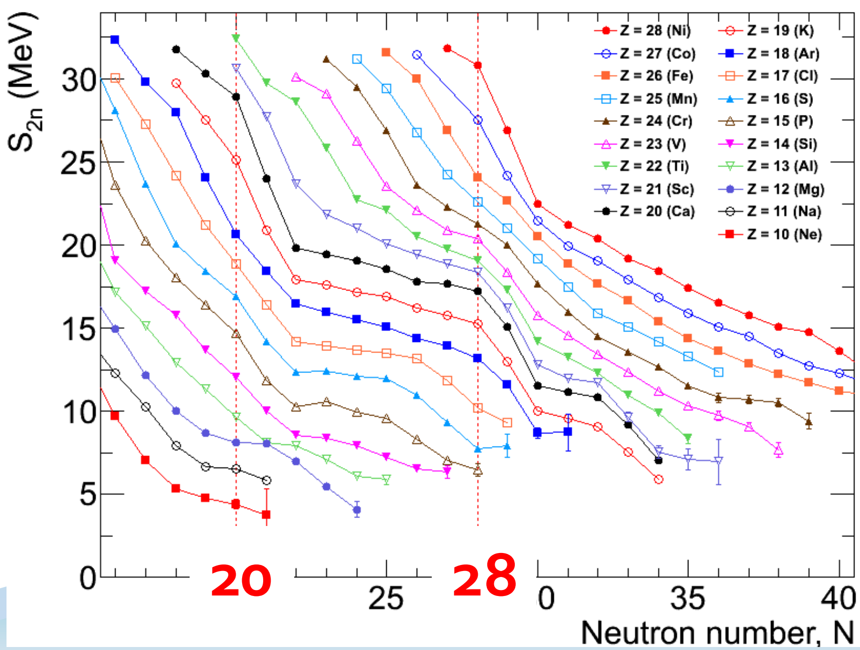
  ☞ Evolutions of S_{2n} and n shell gap in n-rich Ca
- Summary

Nuclear mass & shell evolution

- **Nuclear mass reflects the sum of all interactions within atomic nucleus**
  - Nuclear mass measurements provide fundamental information on nuclear stability

➡ **Shell evolution can be probed by nuclear masses**
- **Mass differences** are employed as a signature for **the presence of a shell gap**

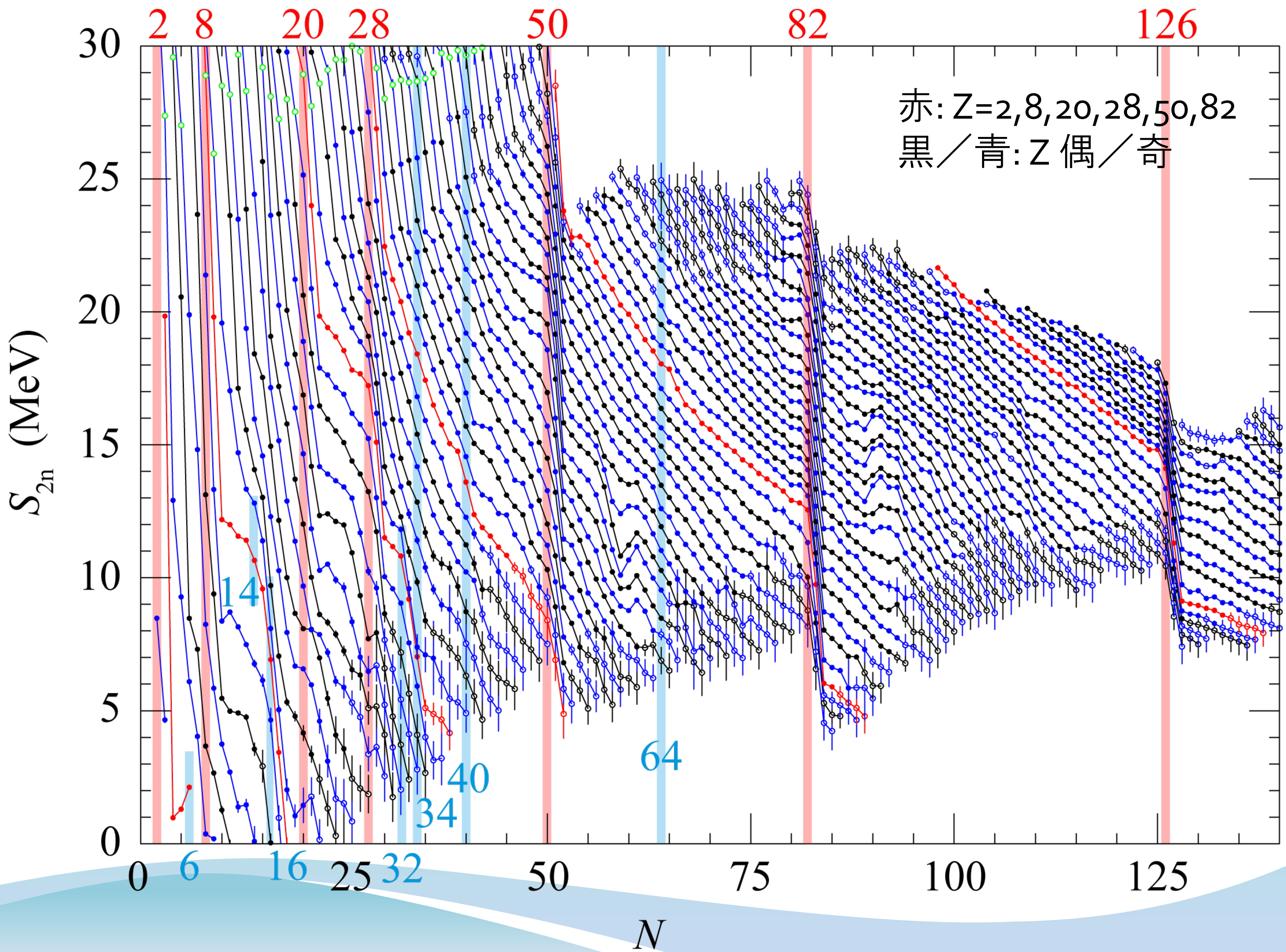
- **Changes in the shell structure in nuclei far from stability ("shell evolution") have been intensively investigated**
  - Some of the traditional magic numbers disappear, while other new ones arise



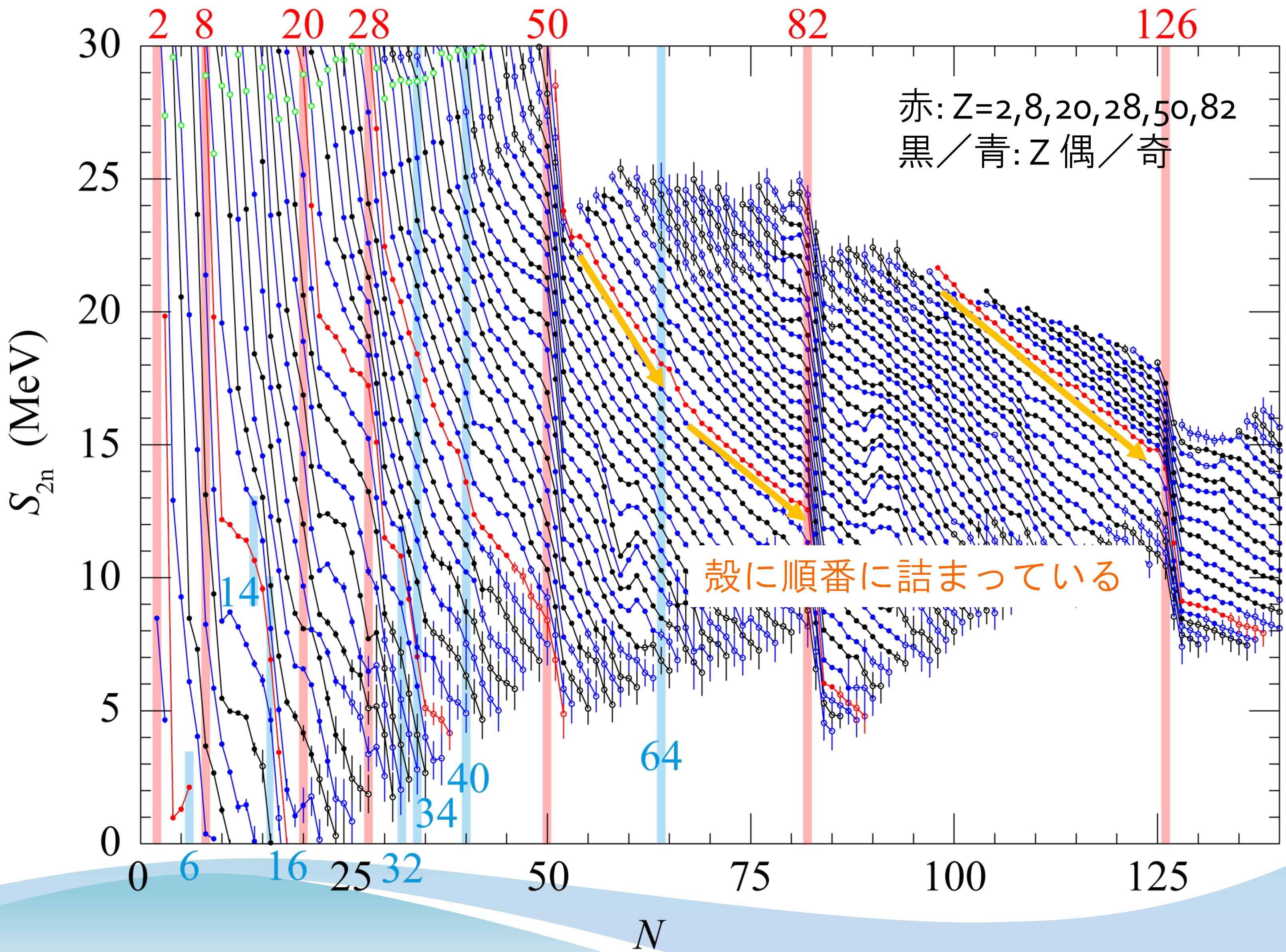
e.g. Two-neutron separation energy

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

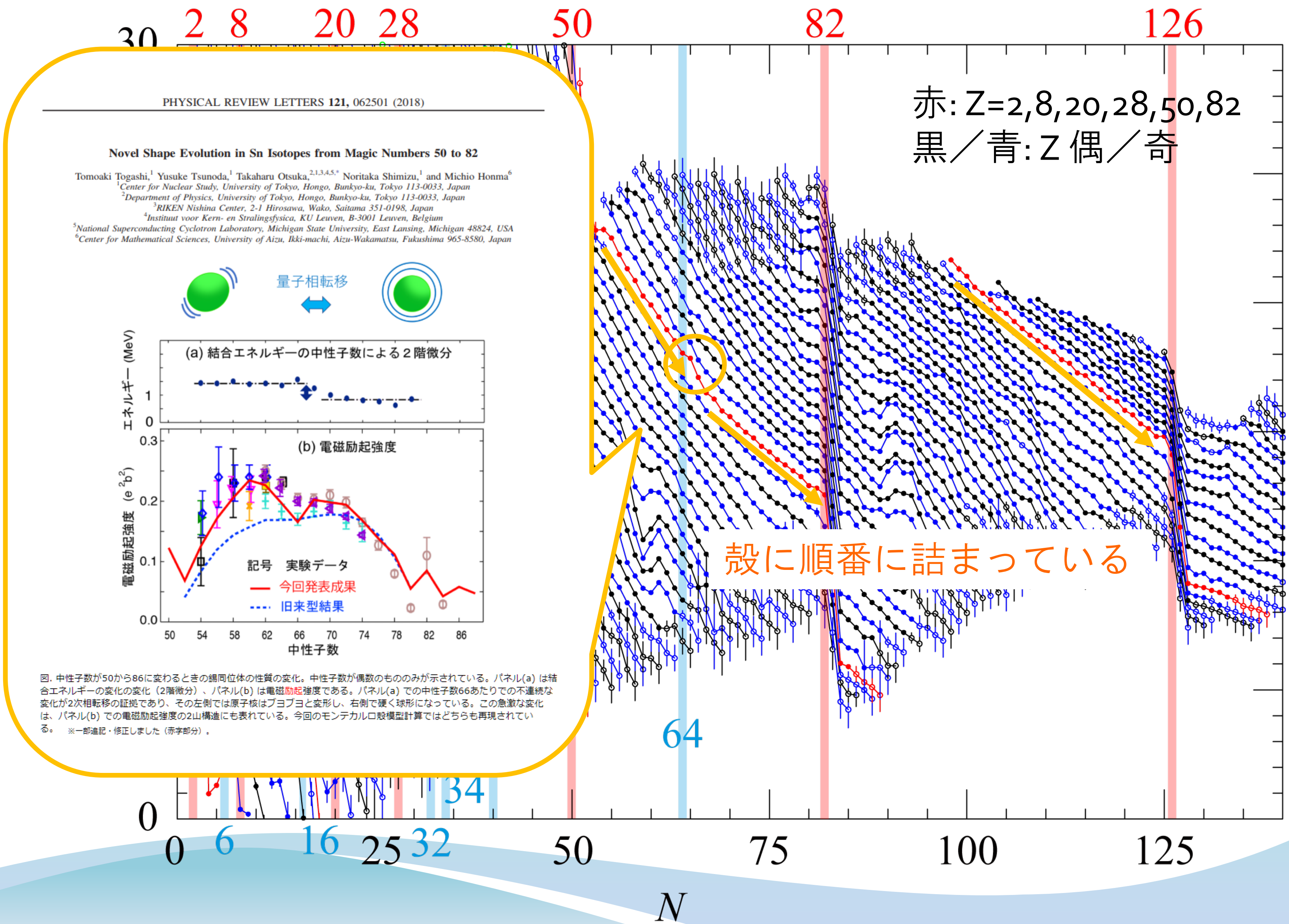
S_{2n} Systematics in Nuclei



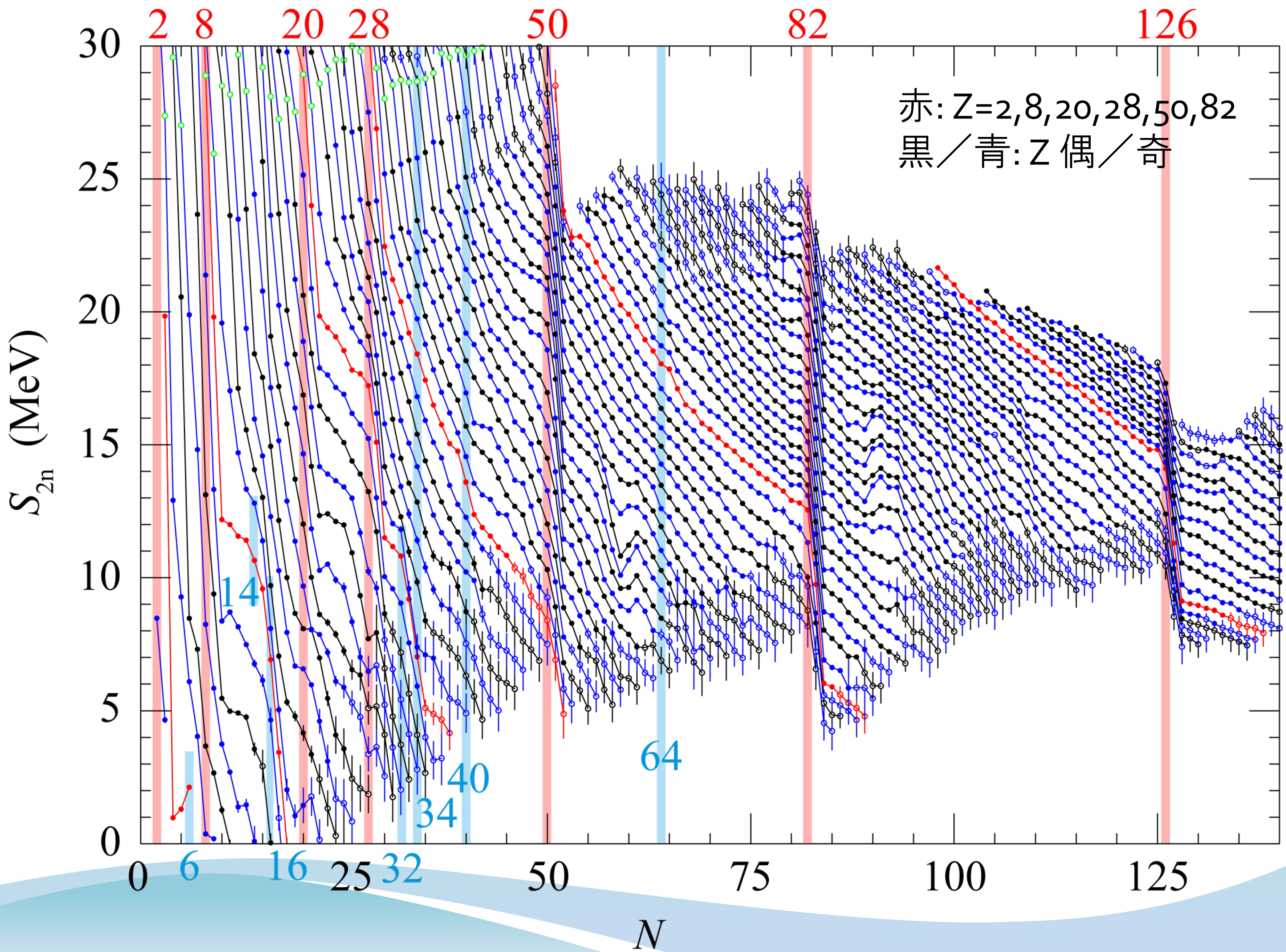
S_{2n} Systematics in Nuclei



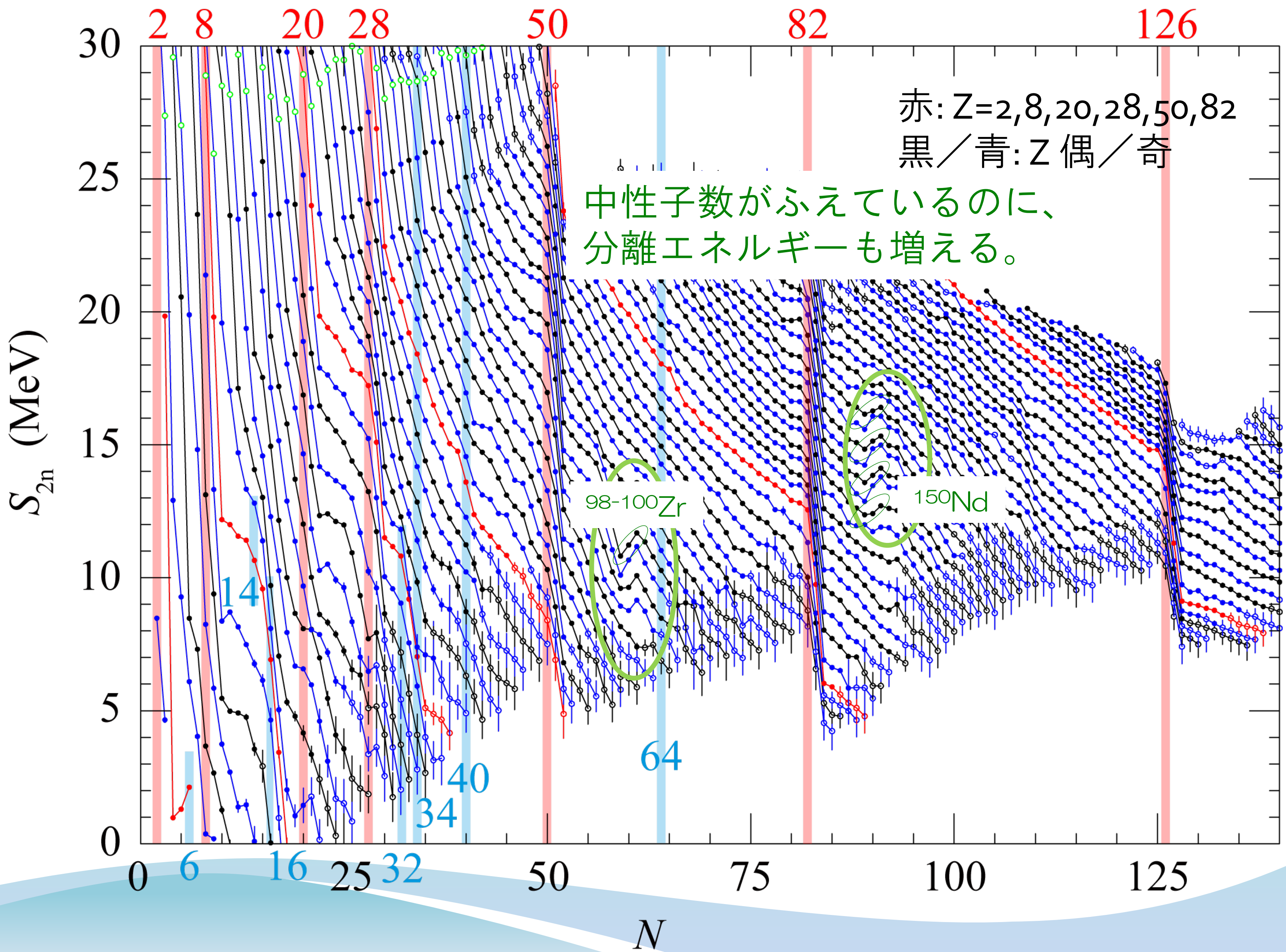
S_{2n} Systematics in Nuclei



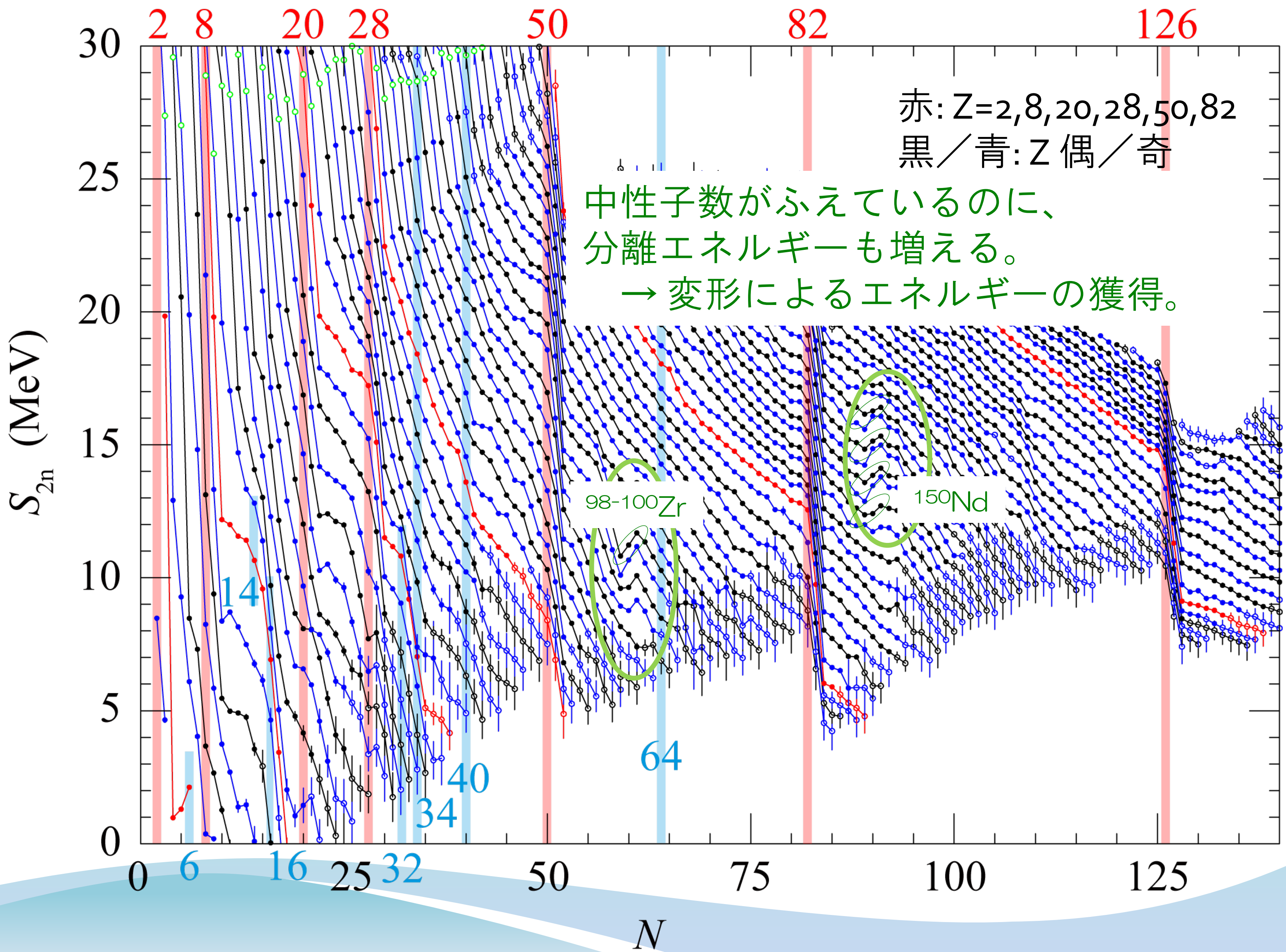
S_{2n} Systematics in Nuclei



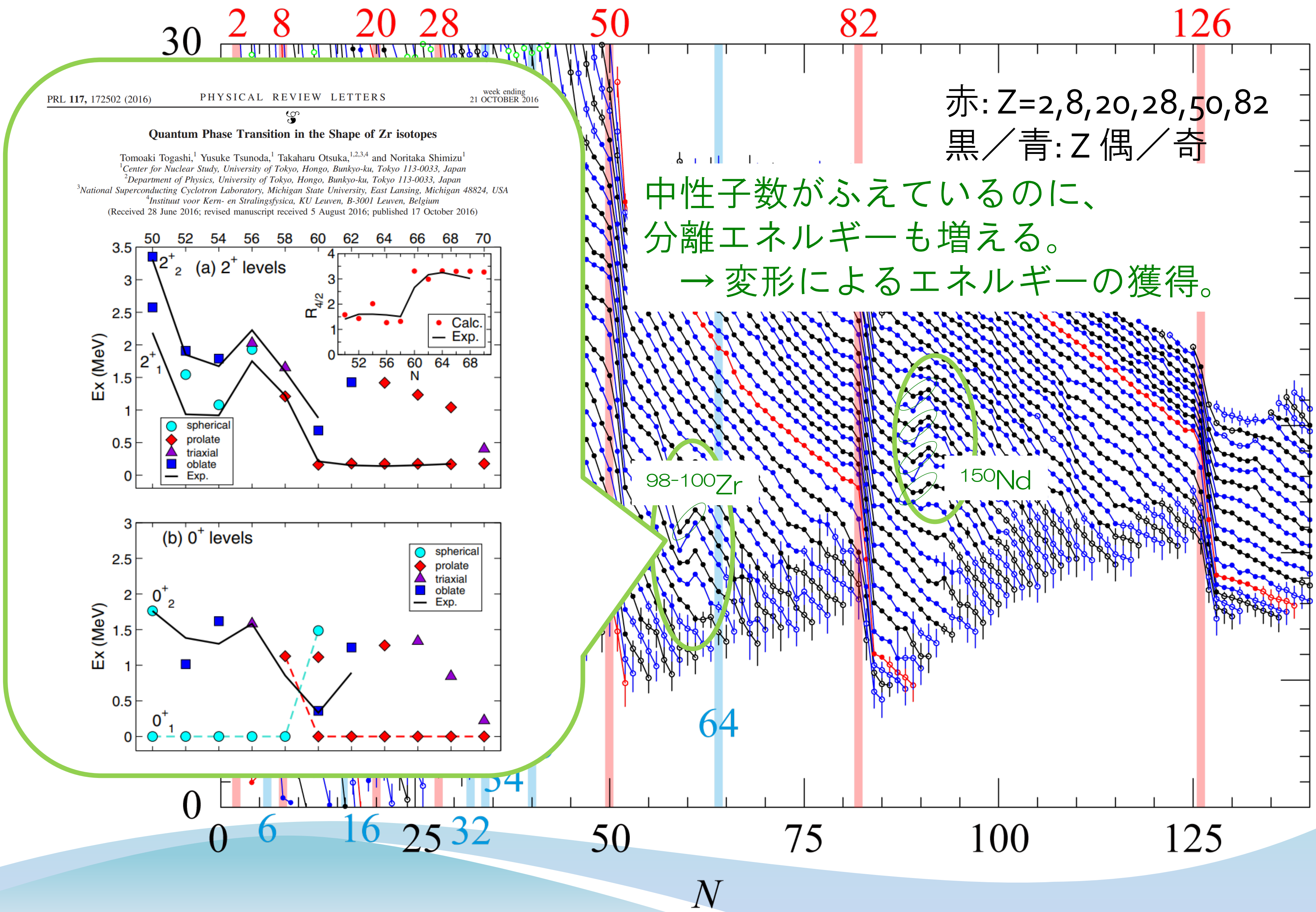
S_{2n} Systematics in Nuclei



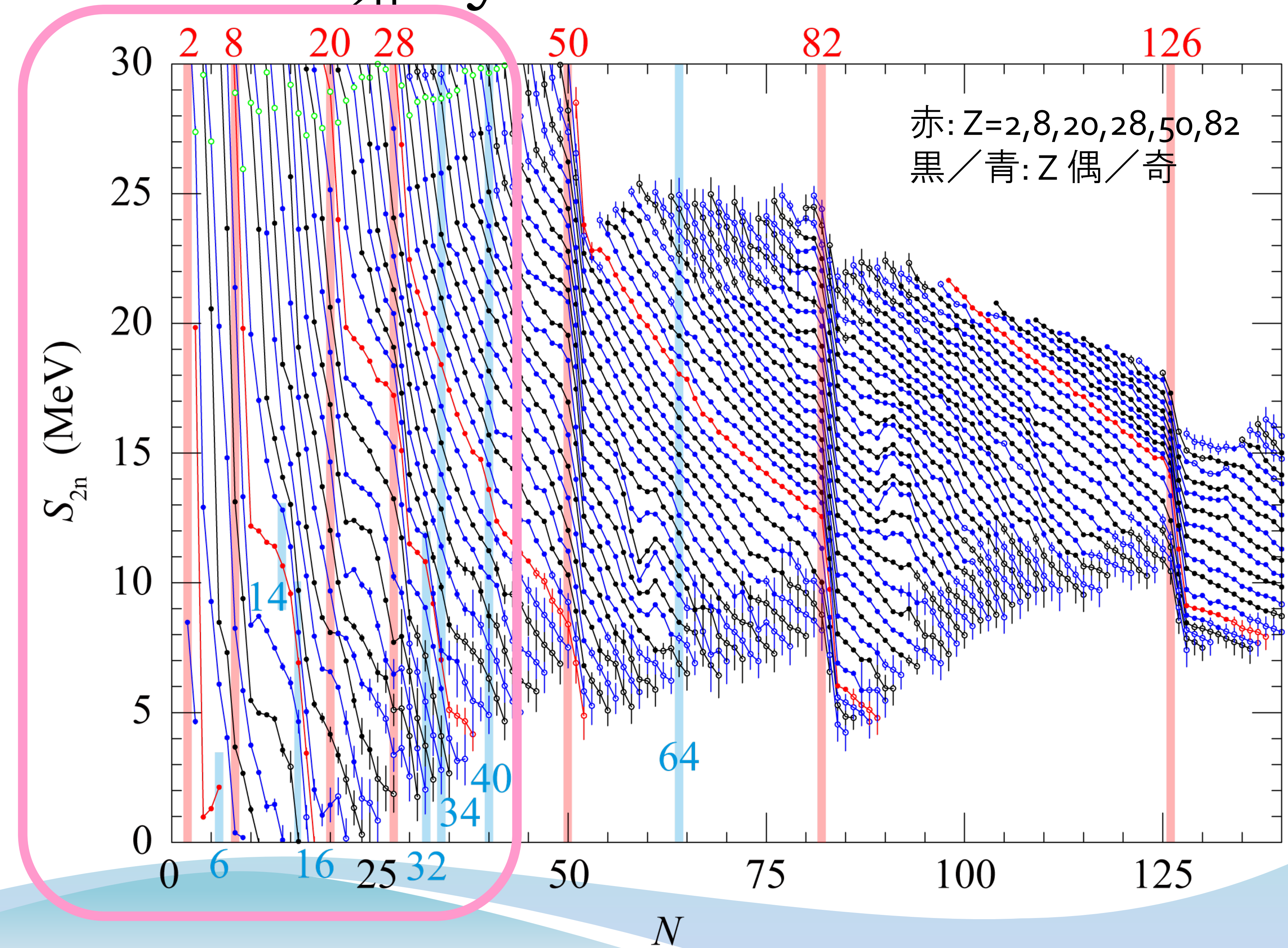
S_{2n} Systematics in Nuclei



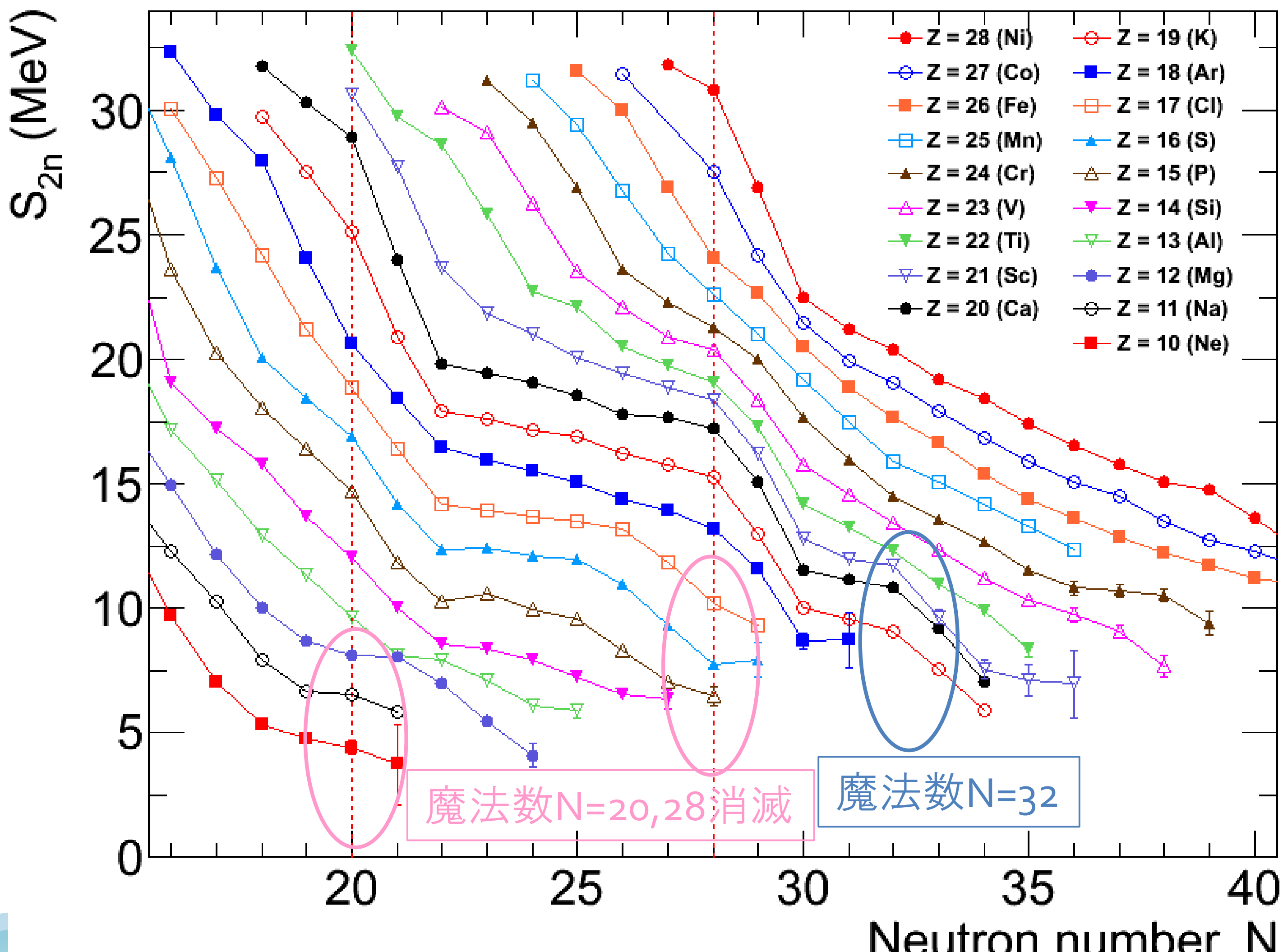
S_{2n} Systematics in Nuclei



S_{2n} Systematics in Nuclei



S_{2n} Systematics in Nuclei

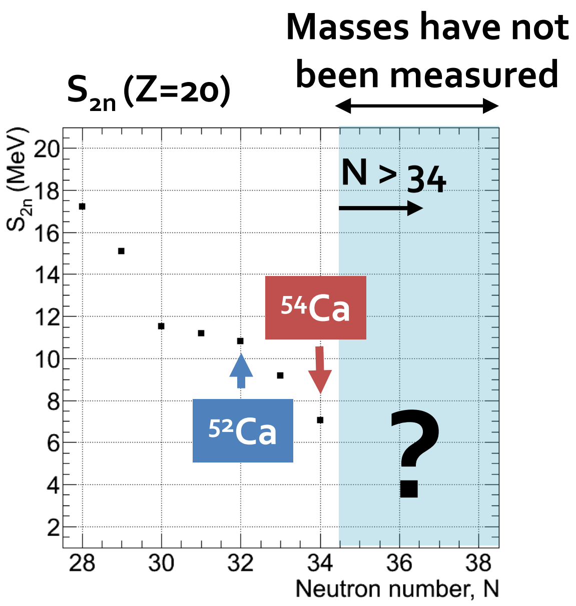


New magic numbers $N = 32, 34$

<u>*N* = 32 and 34 are candidates of new magic numbers in Ca isotopes</u>

- Wienholtz *et al.* Nature **498**, 349 (2013)
  - Mass of ^{54}Ca was measured by the Penning ion-trap method
  - Steep decrease in S_{2n} from ^{52}Ca to ^{54}Ca
  - **Established prominent shell closure at *N* = 32**
- Steppenbeck *et al.* Nature **502**, 207 (2013)
  - $E_x(2^+_1)$ in ^{54}Ca was measured
  - **Suggested the existence of an *N* = 34 shell closure in ^{54}Ca**
  - $E_x(2^+_1)$ in ^{54}Ca was found to be ~500 keV below that in ^{52}Ca

A critical evidence on the shell closure at $N = 34$
→ **Masses beyond *N* = 34 (^{55}Ca, ^{56}Ca, ...)**



<u>This work</u>
Study the nuclear shell evolution at $N = 34$
by **direct mass measurements of neutron-rich Ca nuclei beyond ^{54}Ca**

Techniques of direct mass measurements

Technique	Accessible half-life	Typical Mass precision (δm/m)
Frequency-based mass spectrometry		
Penning trap	a few 100 ms	10^{-7}
Storage ring (Schottky)	10 sec	5×10^{-7}
TOF mass spectrometry		
TOF-Bρ	**1 μs**	**10^{-5}**
Storage ring (Isochronous)	a few 10 μs	5×10^{-6}
MR-TOF	a few 10 ms	10^{-7}

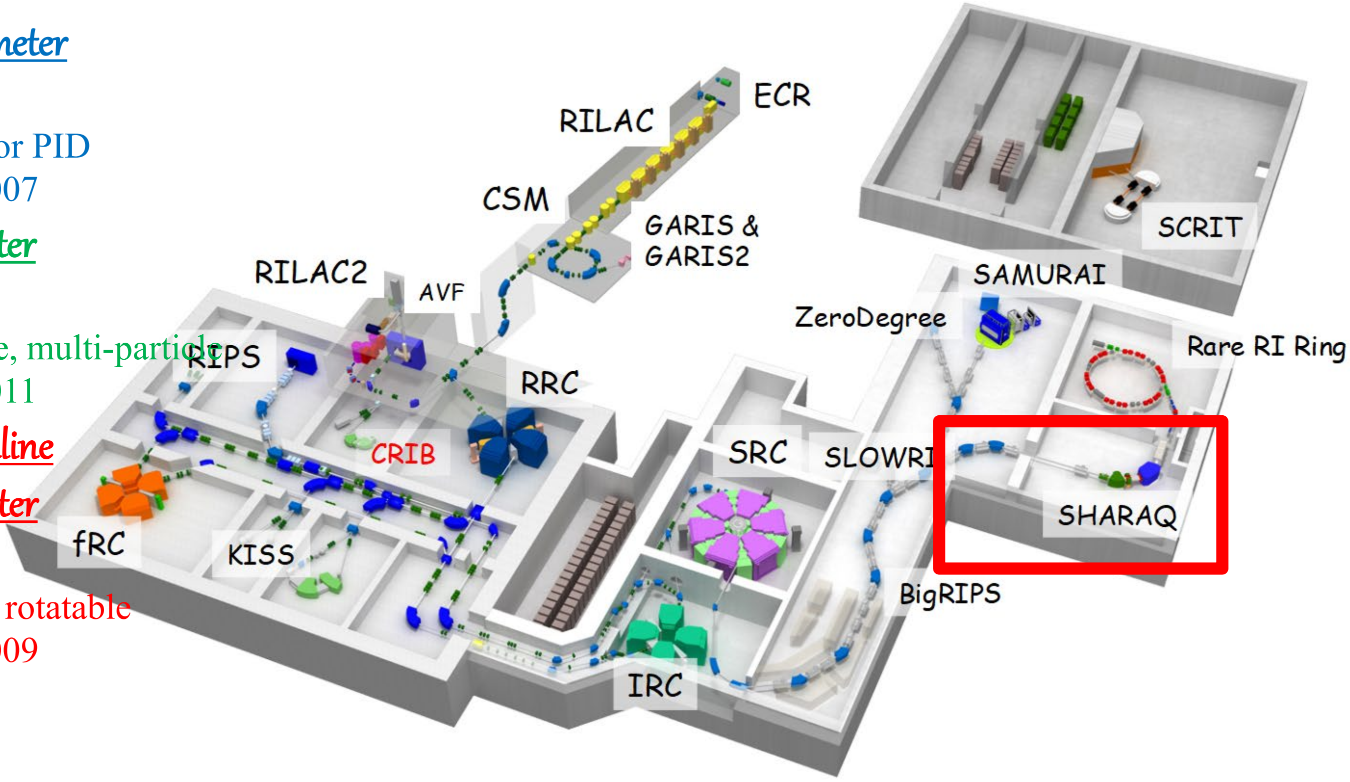
TOF-Bρ technique $\frac{m}{q} = \frac{B\rho}{\gamma L/t}$

- **can access the short-lived nuclei very far from stability**
  - but moderate mass precisions
- **can provide masses of a large number of isotopes in a single measurement**
  - allows us to map a wide region of the nuclear mass surface

RIBF facility

RIBF was equipped with 3 spectrometers for RI beams:

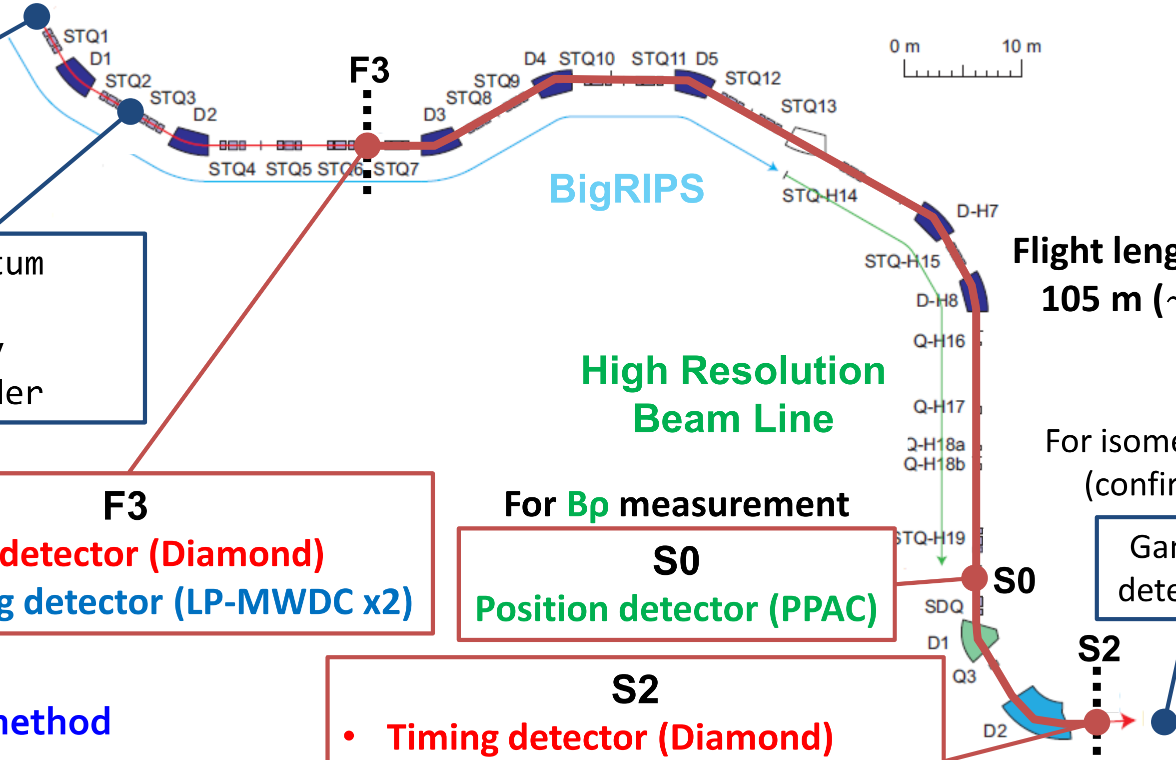
- ZeroDegree spectrometer
  (RIKEN)
  - multi-purpose for PID
  - completed in 2007
- SAMURAI spectrometer
  (Tohoku Univ.)
  - large acceptance, multi-particle
  - completed in 2011
- High resolution beamline +SHARAQ spectrometer
  (Univ. of Tokyo)
  - high resolution, rotatable
  - completed in 2009



Experimental setup

Primary beam:
^{70}Zn (345 MeV/u), I = 150 pnA

@RIKEN RI Beam Factory (RIBF) - SHARAQ



Production target (^{9}Be)

- Momentum slit
- Energy degrader

F3
- **Timing detector (Diamond)**
- **Tracking detector (LP-MWDC x2)**

For Bρ measurement

S0
Position detector (PPAC)

S2
- **Timing detector (Diamond)**
- **Tracking detector (LP-MWDC x2)**
- **ΔE detector (SSD x2)**

Flight length (F3-S2)
105 m (~540 ns)

For isomer tagging (confirm PID)

Gamma detectors

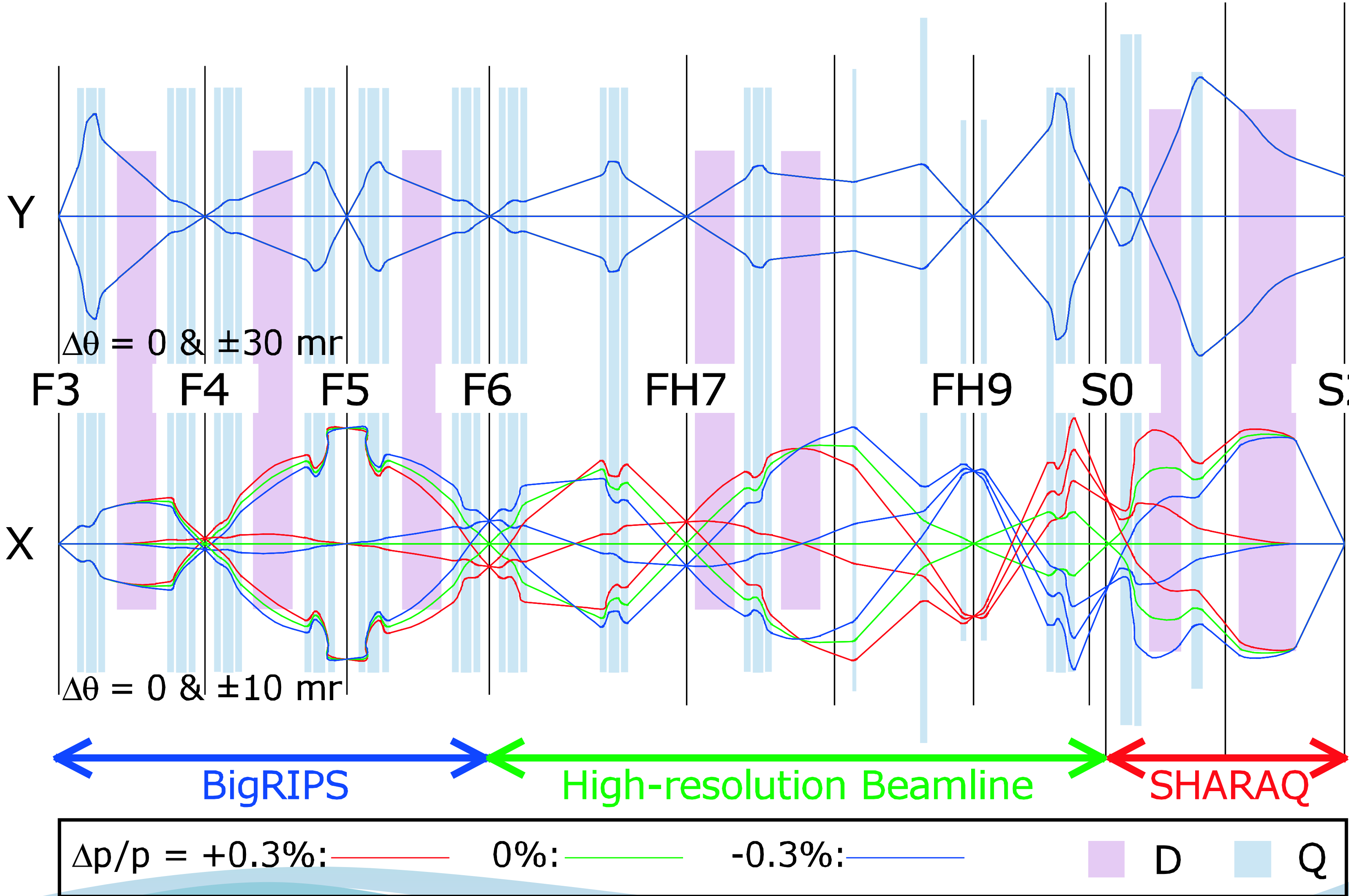
Dispersion matching mode (p/δp = 14700)

- **TOF-Bρ method**

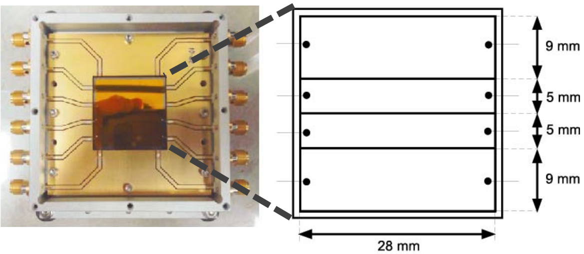
$$\frac{m_0}{q} = \frac{B\rho}{\gamma L/t}$$

➜ Precise measurement of TOF and Bρ

Dispersion Matching Optics



Time resolution of Diamond detector



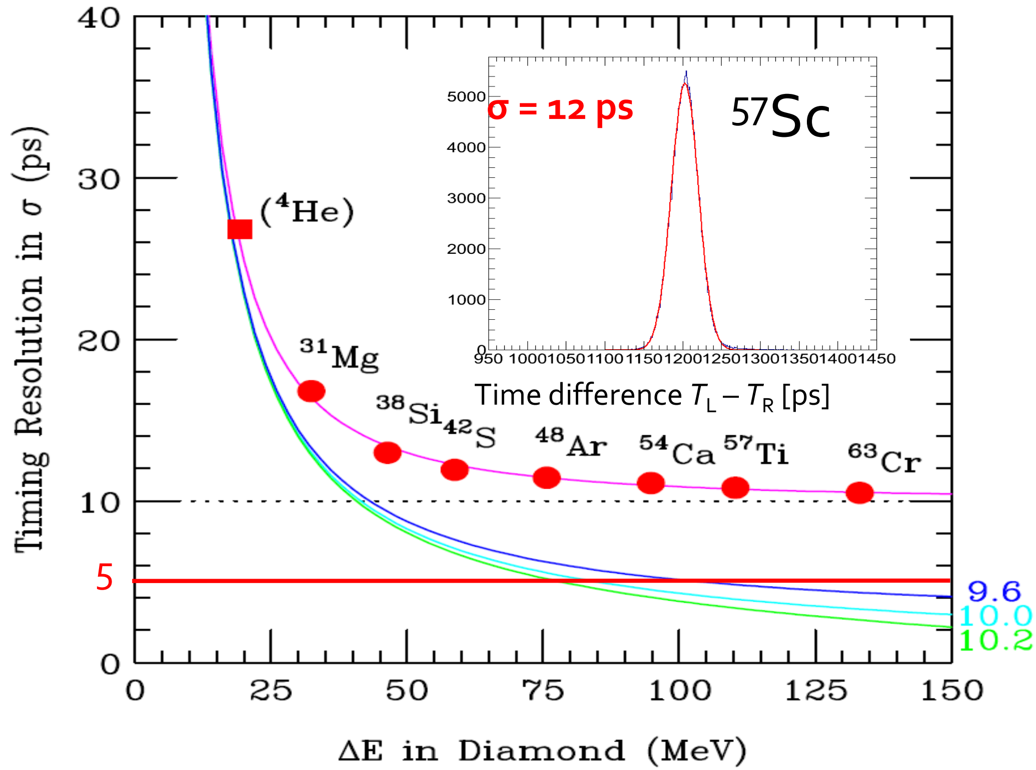
Diamond

Fast response →very good timing resolution!

Specification:

- Developed by CNS-MSU collaboration
- Polycrystalline CVD diamond

- Crystal size : 30 × 30 × 0.2 mm^3
- Pad design
  - Effective area: 28 × 28 mm^2
  - Side A: 1 pad (4 readouts)
  - Side B: 4 strips (8 readouts)
    - for correction of position dependence

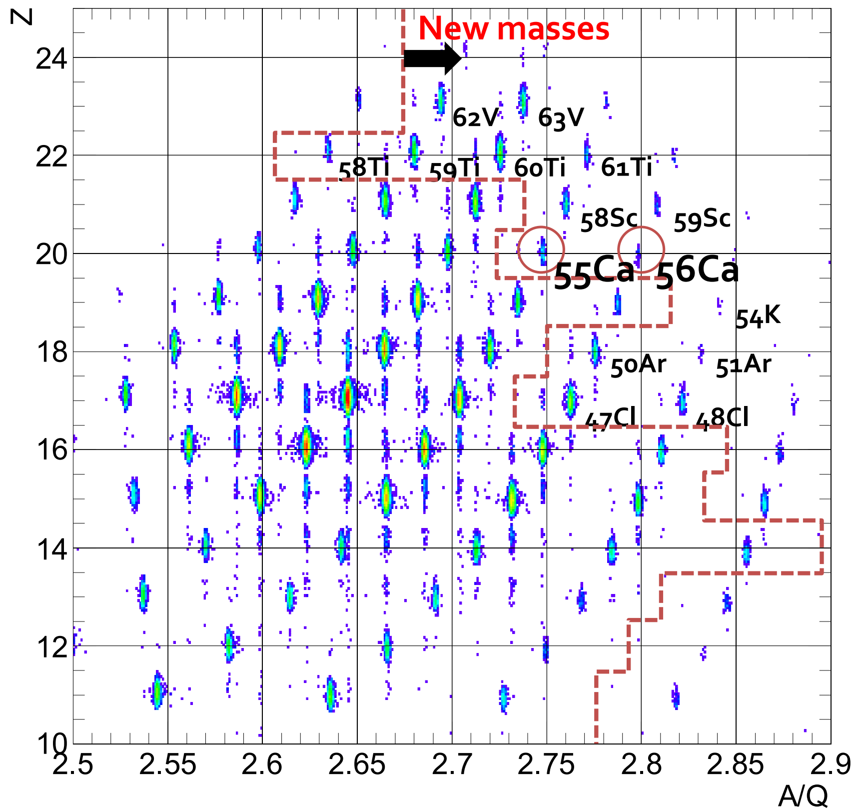


◎ Time resolution incl. DAQ system **～10ps(σ)**

⇒ Intrinsic resolution : **5 ps(σ) @ΔE=100MeV**

Particle identification

PID spectrum after rough mass calibration



- **Total yield of ^{55}Ca: ~3000**
- Many species of reference nuclei over a broad range of *A* and *Z* are observed.
  - These nuclei are used in the mass calibration.
- **Nuclei whose masses have not been measured:**

Z	Nuclei (Yield > 1000)
17	^{47}Cl, ^{48}Cl
18	^{50}Ar
19	--
20	^{55}Ca
21	^{58}Sc, ^{59}Sc
22	^{58}Ti, ^{59}Ti, ^{60}Ti
23	^{62}V, ^{63}V

Masses of these nuclei will be determined with the precision of several hundreds keV

Reference nuclei & fitting function

- Reference nuclei
  - $^{52\text{-}54}$Ca, $^{49,51\text{-}53}$K, $^{46\text{-}48}$Ar, $^{43\text{-}46}$Cl, ^{41,42}S, $^{38\text{-}42}$P, $^{36\text{-}40}$Si
  - Mass uncertainties < 320 keV
  - No known long-lived ($T_{1/2}$ > 100 ns) isomeric states

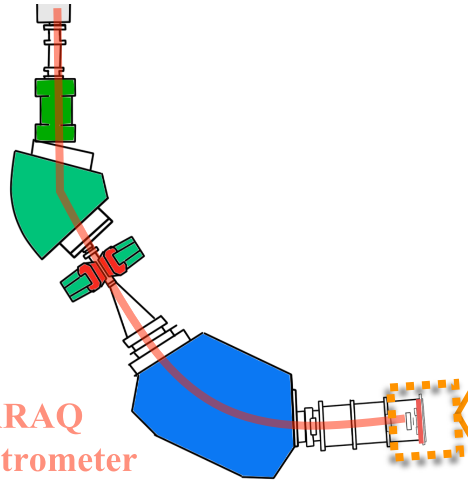
- Fitting function

$$\frac{m}{q} = f(t, \mathbf{x}) = \sum_{j_0+\cdots+j_9 \le 4} C_{(j_0,\ldots,j_9)} \cdot \tilde{t}^{j_0} x_3^{j_1} a_3^{j_2} y_3^{j_3} b_3^{j_4} \tilde{x}_0^{j_5} x_2^{j_6} \tilde{a}_2^{j_7} \tilde{y}_2^{j_8} b_2^{j_9}$$

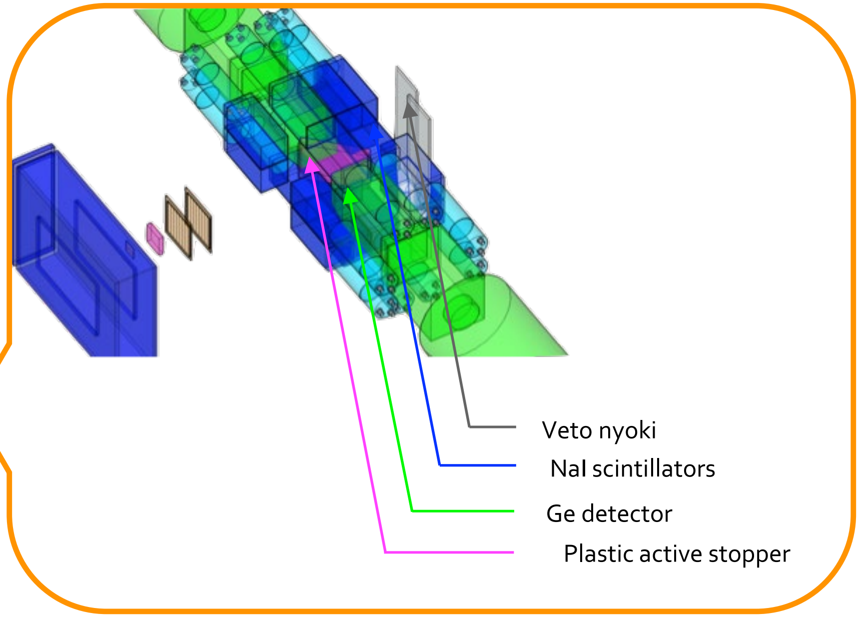
- t: TOF (between F3 and S2)
- x, y: beam position
- a, b: beam angle

  - Beam profile at S2 is essential to evaluate scattering at the S0 PPAC
  - Up to the 4th order aberrations are considered
  - Parameters are determined by the least-squares method

Gamma-ray detectors for PID



SHARAQ Spectrometer



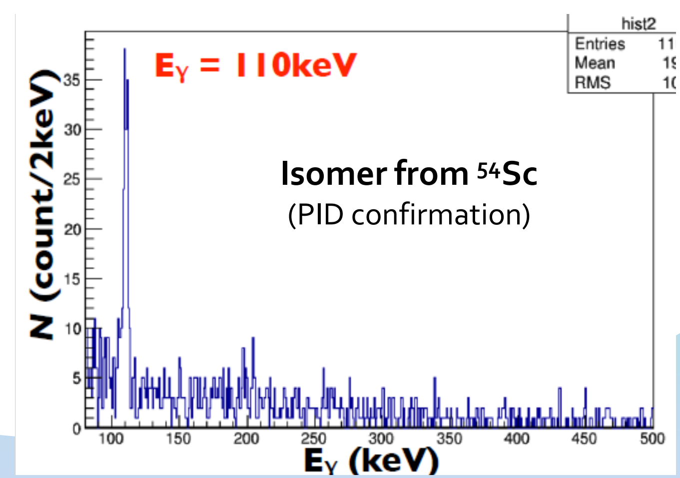
Gamma-ray detector array
- 2 clover-type Ge detectors
- 16 NaI scintillators
- Active stopper

Downstream of array
- veto scintillator

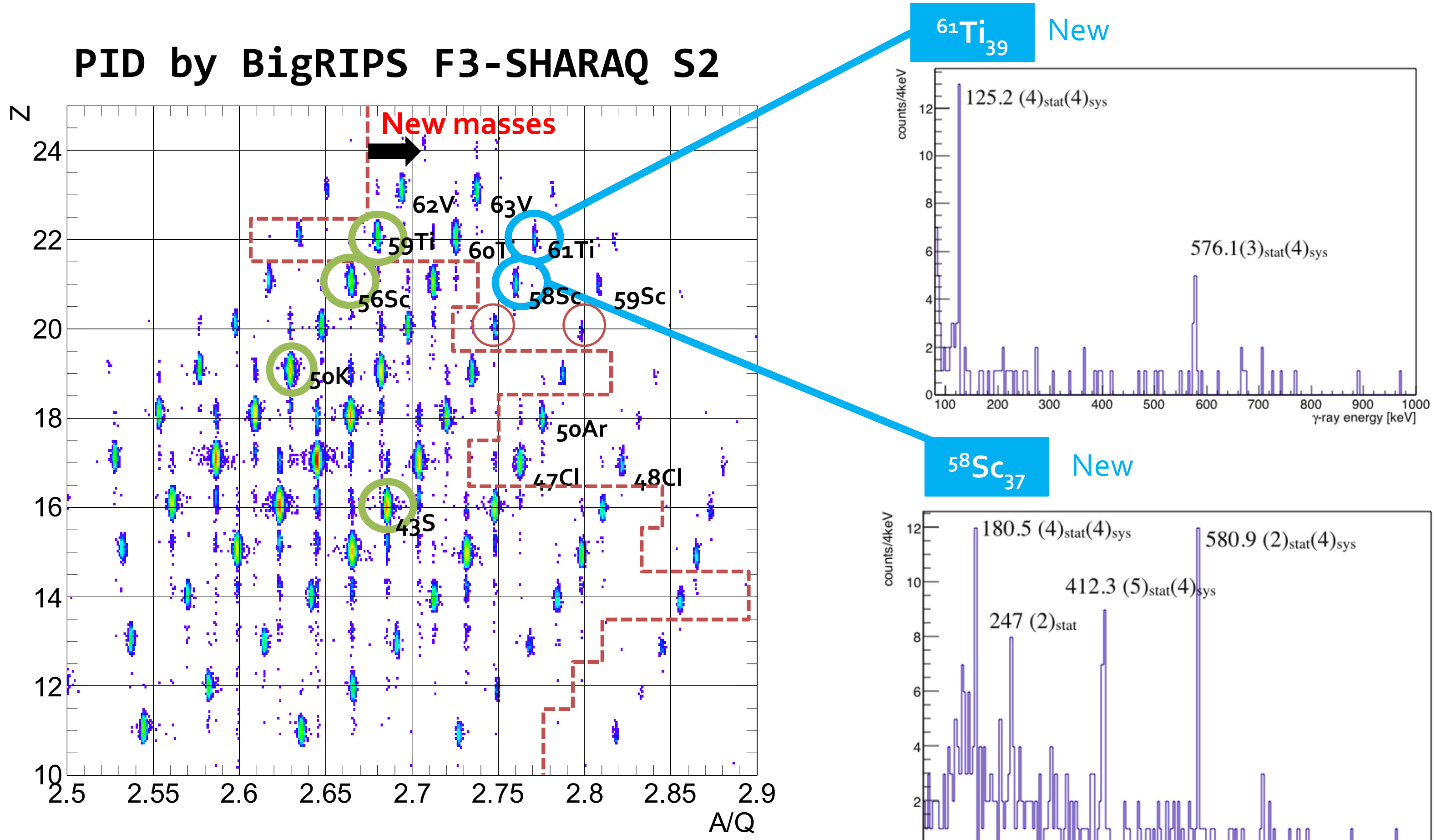
Al degrader
- Al plate 14-18mm

Energy Resolution

HPGe: 3.8 keV at 1333 keV



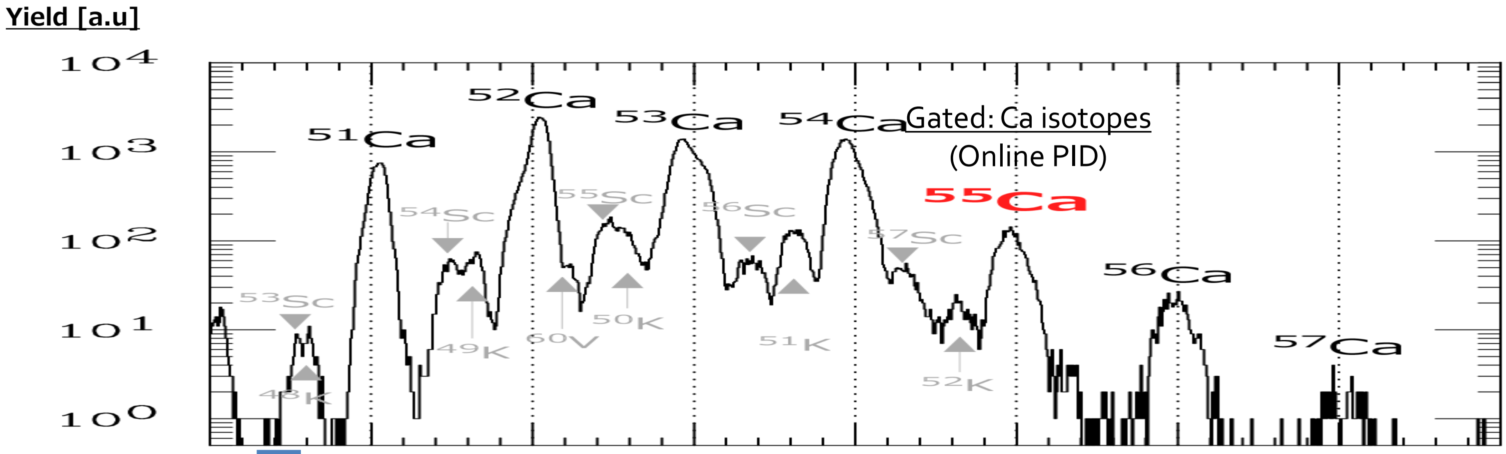
Property of Secondary Beam



Primary beam: ^{70}Zn (345 MeV/u), I = 130 pnA

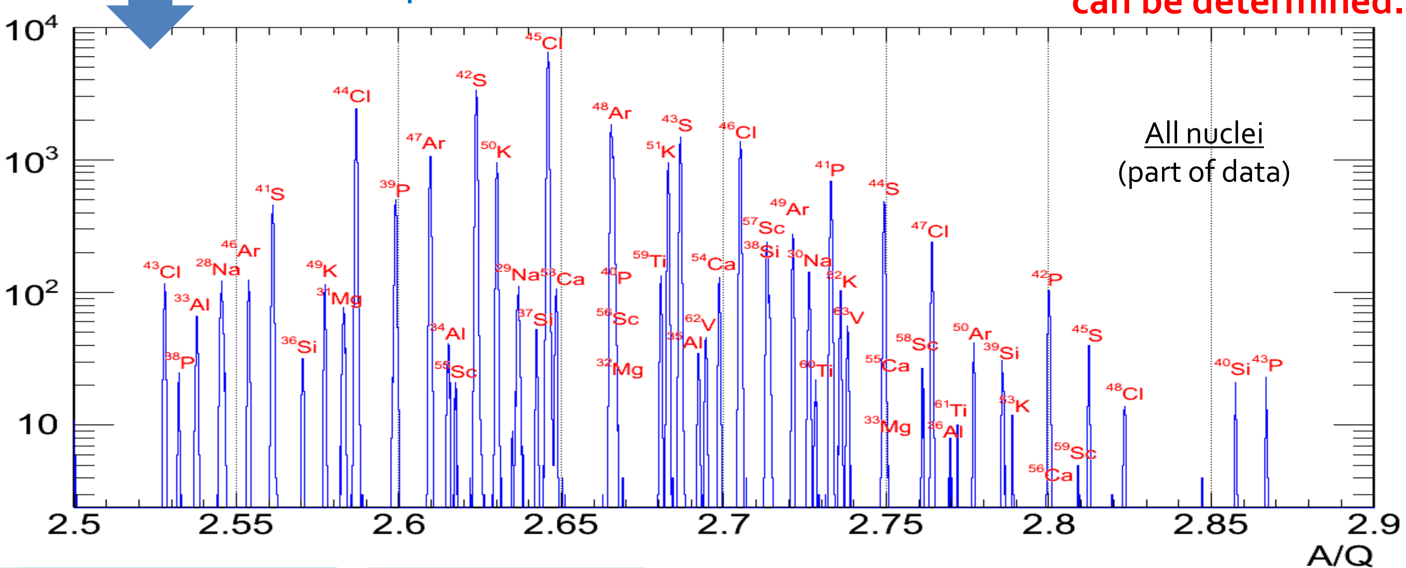
⇒ Properties of those isomers are open questions.
Those isomers will be connect to nuclear structure at N=40.
We expect theory can help us...

Ion Optical Corrections

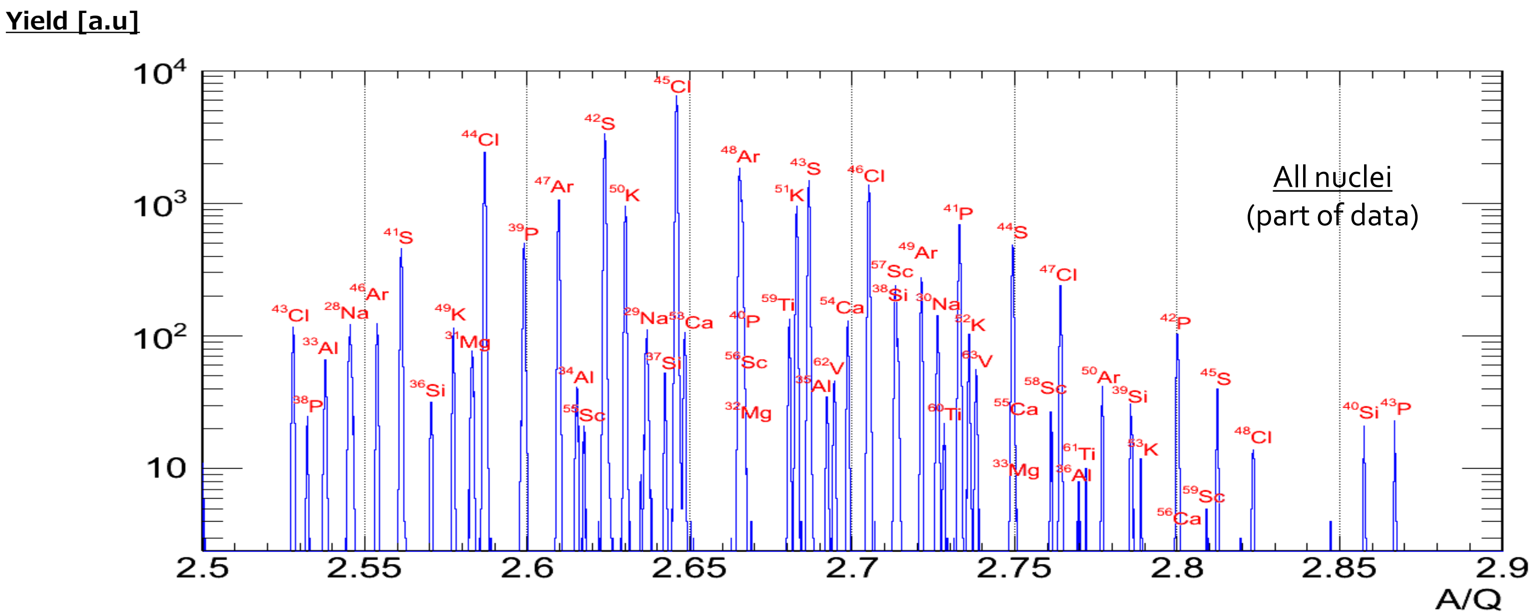


made ion optical correction

^{55}Ca, ^{56}Ca and ^{57}Ca masses can be determined.



Ion Optical Corrections



◎ We found 3 important corrections through the analysis

1. Higher order correction and Effect of scattering at S0 PPAC.
2. Stability of ion optical parameters (magnet setting)
3. Atomic number dependence to mass shift

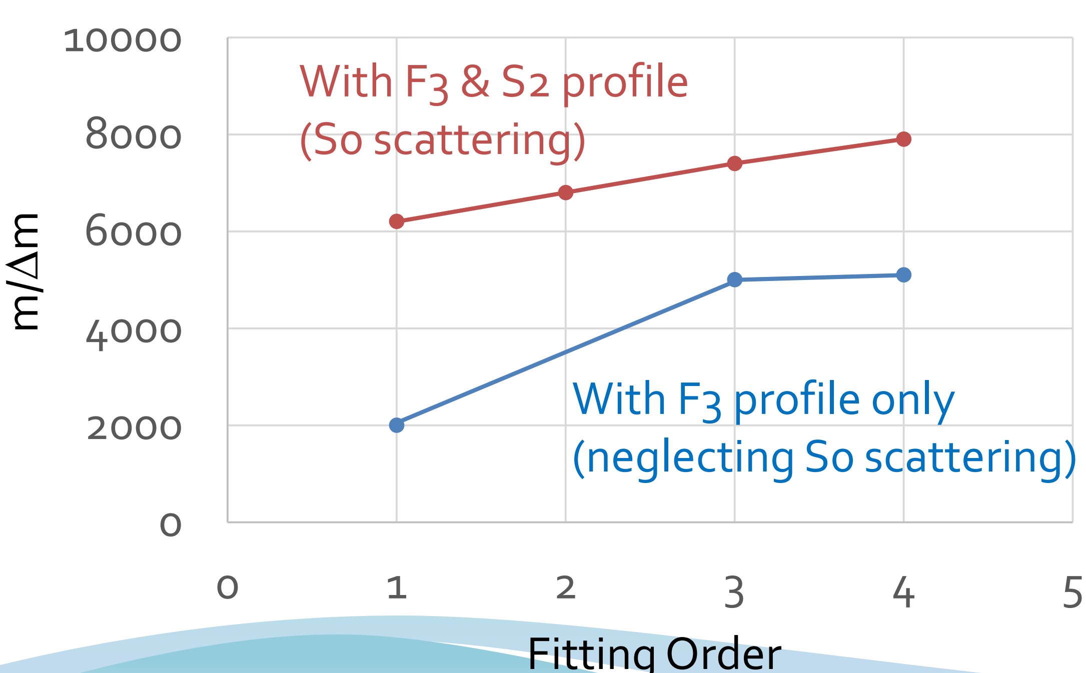
Ion Optical Correction (1)

↓ determine

$$\frac{m}{q} = f(t, \mathbf{x}) = \sum_{j_0+\cdots+j_9\le 4} \boxed{C_{(j_0,\ldots,j_9)}} \cdot \tilde{t}^{j_0} x_3^{j_1} a_3^{j_2} y_3^{j_3} b_3^{j_4} \tilde{x}_0^{j_5} x_2^{j_6} \tilde{a}_2^{j_7} \tilde{y}_2^{j_8} b_2^{j_9}$$

$$\chi^2 = \sum_{i=1}^{N_{\mathrm{event}}} \frac{\left[(m/q)^{(i)}_{\mathrm{ref}} - f(t_0^{(i)}, \mathbf{x}^{(i)})\right]^2}{(\sigma^{(i)}_{\mathrm{ref}})^2 + (\sigma^{(i)}_{\mathrm{stat}})^2 + \sigma^2_{\mathrm{syst}}},$$ → minimization

<u>How do we need of higher order correction?</u>

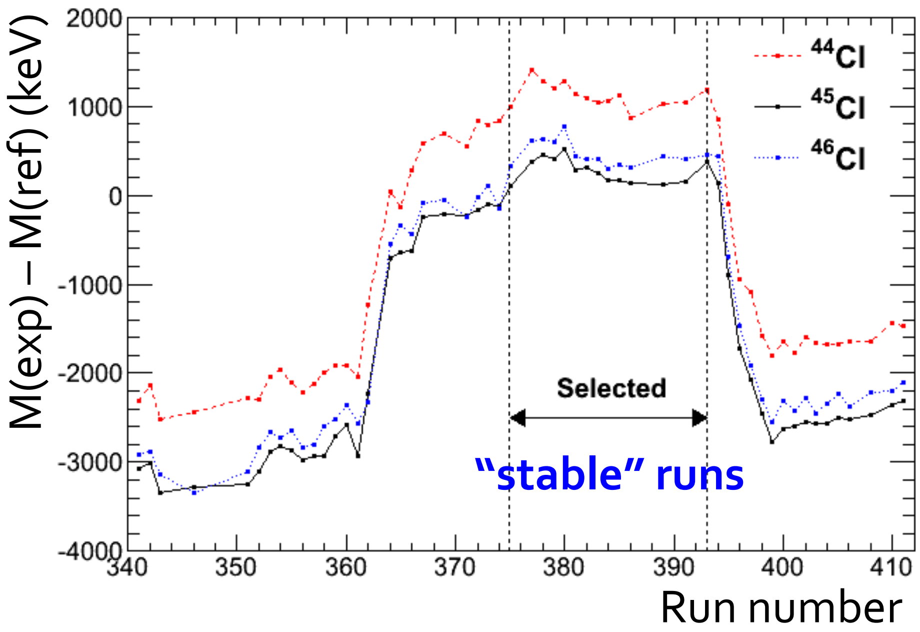


★ Measurement of scattering at S0 PPAC is critical for mass resolution.

★ Higher order correction seems better but the number of fitting coefficients easily increases.

Stability of ion optical parameters

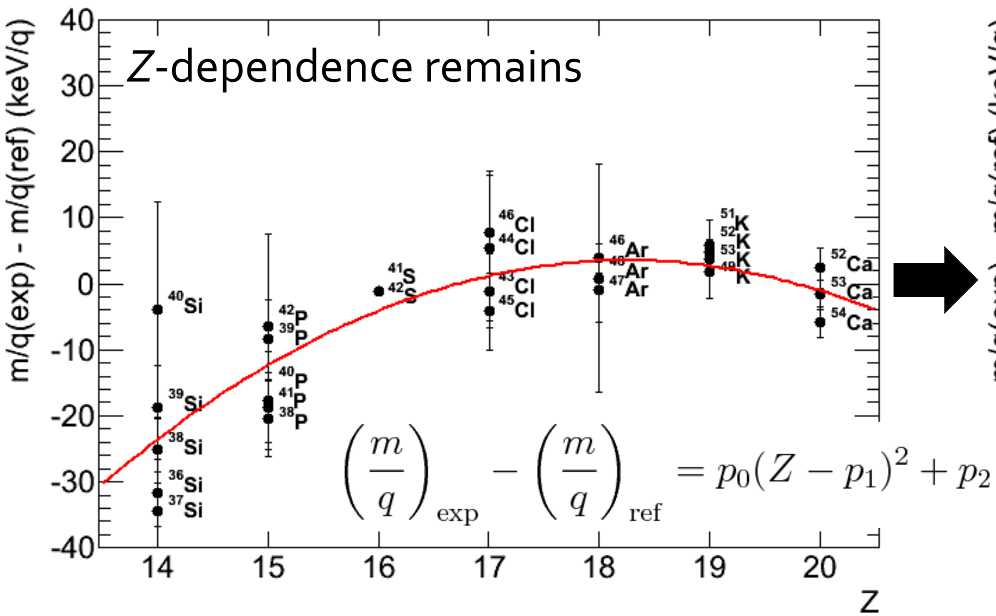
Shift of the deduced masses as a function of run number (1 run ～ 1 hour)

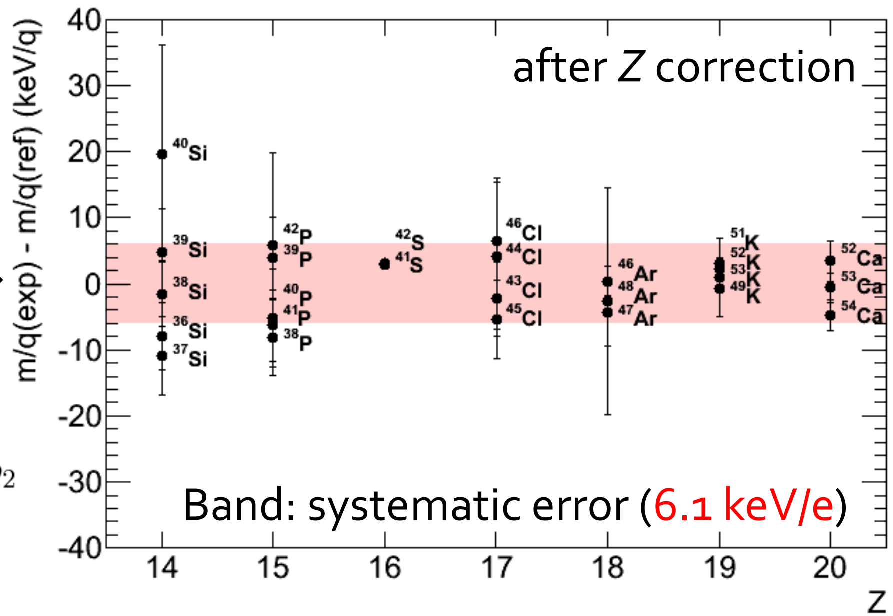


- Deduced masses show the run-number dependence
- Δm of 1 MeV ⇔ mass shift of 2×10^{-5}
  cf. magnet power supply stability: 10^{-5} / 8h
- Shift of 3×10^{-5} corresponds to
  ⇒ 3 mm of 105 m flight path
  ⇒ 15 ps of 500 ns flight time
- Shift for each nuclide has the similar trend
  → treat as shift of central ray
  (= central path length)
  and correct using ^{45}Cl trend
  [^{45}Cl is most intense nuclei of ～ 1 cps]

Correction for Z dependence

Mass calibration using all the runs to deduce the final mass values





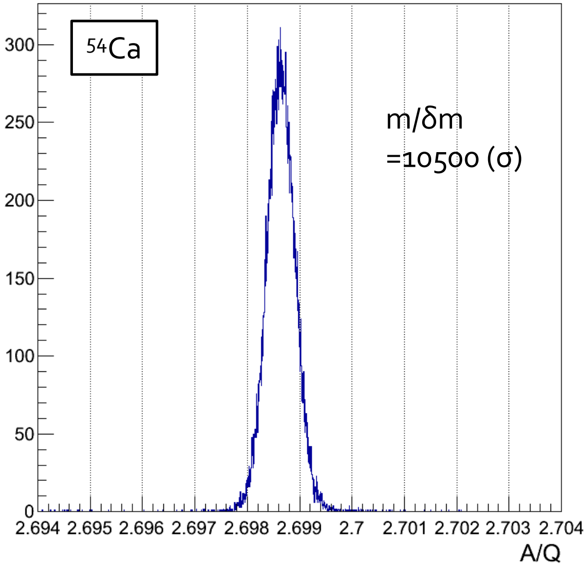
Fitting function does not explicitly contain Z (i.e. ΔE in detectors)
→ Z-dependence remains

Errors related to the Z correction

Z = 20 → δ(Zcor) = 3.3 keV/e

Evaluation of Mass resolution

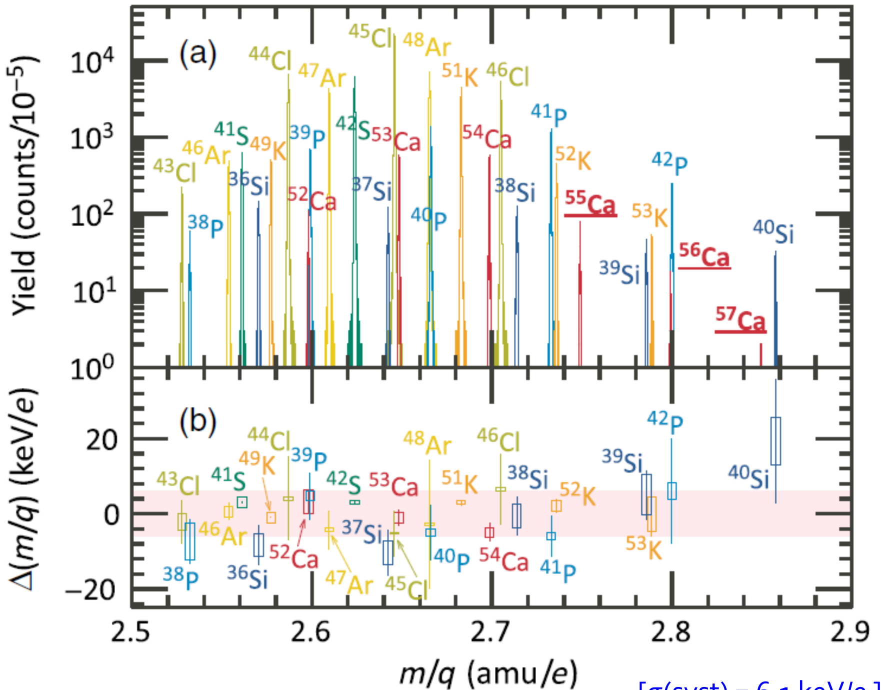
1. Statistical error



- **Mass resolution of 10500 (σ) has been achieved for Ca isotopes**
  - ^{55}Ca: σ(stat) = 90 keV (3000 events)
  - ^{56}Ca: σ(stat) = 200 keV (600 events)
  - ^{57}Ca: σ(stat) = 980 keV (30 events)

2. Systematic error

(evaluated from known masses)



[σ(syst) = 6.1 keV/e]

σ(syst) = 122 keV for Ca

Achieved masses resolution:

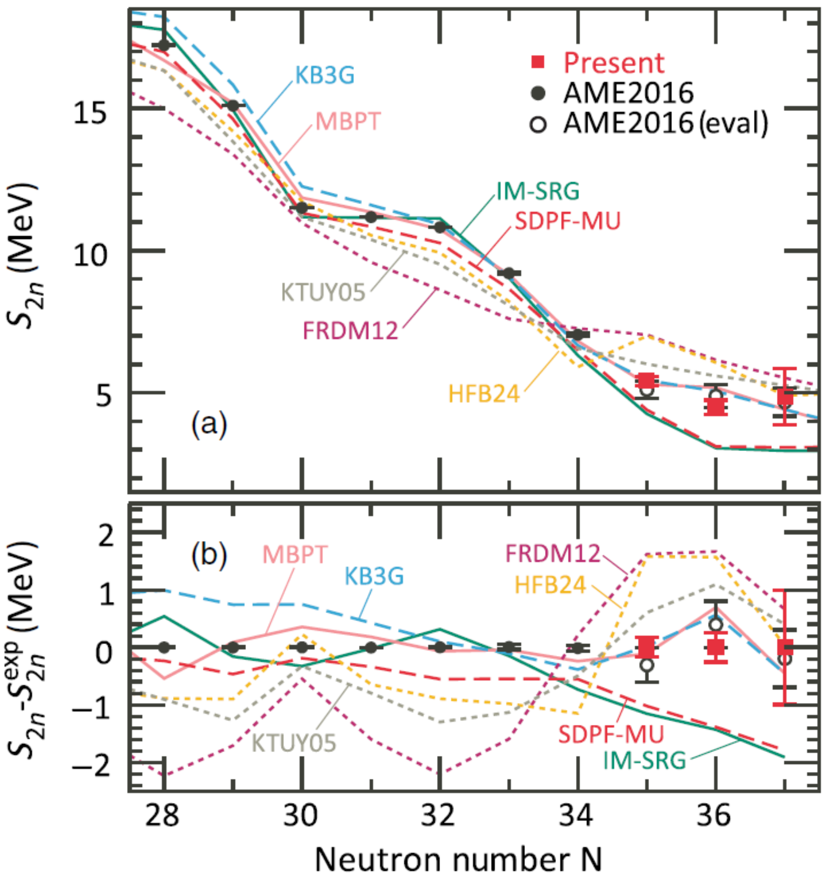
σ(mass) ~ 150 keV for ^{55}Ca

~ 250 keV for ^{56}Ca

~ 990keV for ^{57}Ca

Neutron shell evolution in Ca isotopes

S_{2n}



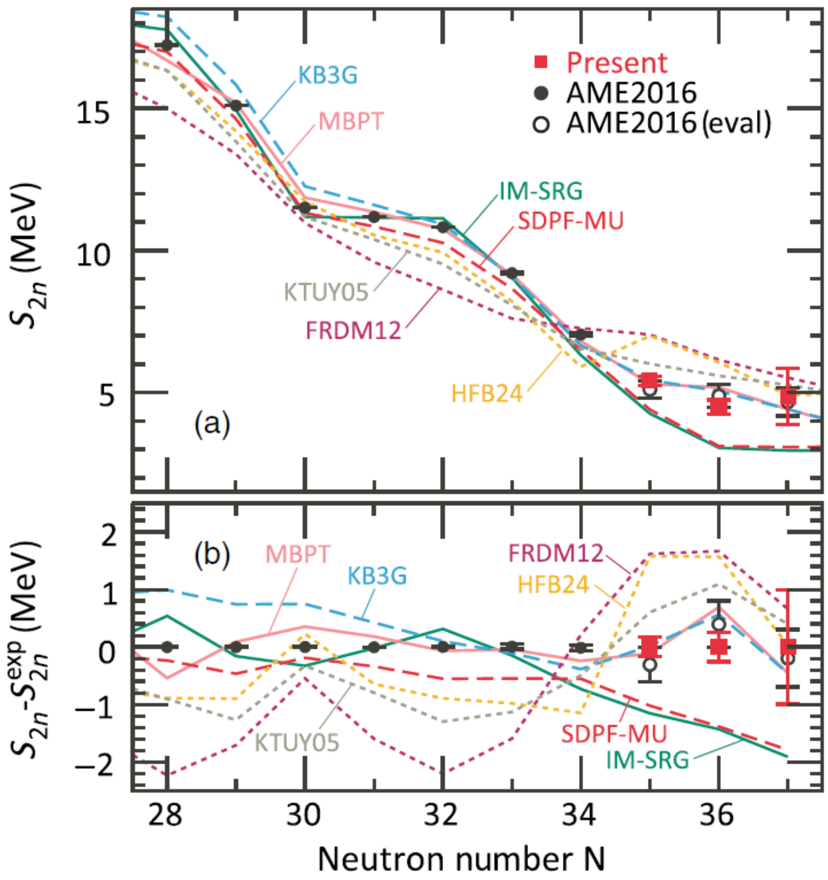
$$S_{2n} = -M(A, Z) + M(A-2, Z) + 2M_n$$

Newly determined mass excesses

Nucleus	Present (keV)	AME2016 (keV)
^{57}Ca	−7370(990)	...
^{56}Ca	−13 510(250)	...
^{55}Ca	−18 650(160)	...
^{48}Ar	−22 330(120)	−22 280(310)
^{46}Cl	−13 700(110)	−13 860(210)
^{44}Cl	−20 540(110)	−20 380(140)
^{42}P	+1100(100)	+1010(310)
^{40}P	−8150(100)	−8110(150)
^{40}Si	+5700(130)	+5430(350)

Neutron shell evolution in Ca isotopes

S_{2n}



$$S_{2n} = -M(A,Z) + M(A-2,Z) + 2M_n$$

Neutron shell gap

Estimation of Shell gap from S_{2n}.

1. Empirical Shell gap [1]

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

2. Shell gap from Δ3 indicators [2]

$$\delta e(N) = S_{2n}(N) - S_{2n}(N+1)$$

We use δe indicator in discussion:

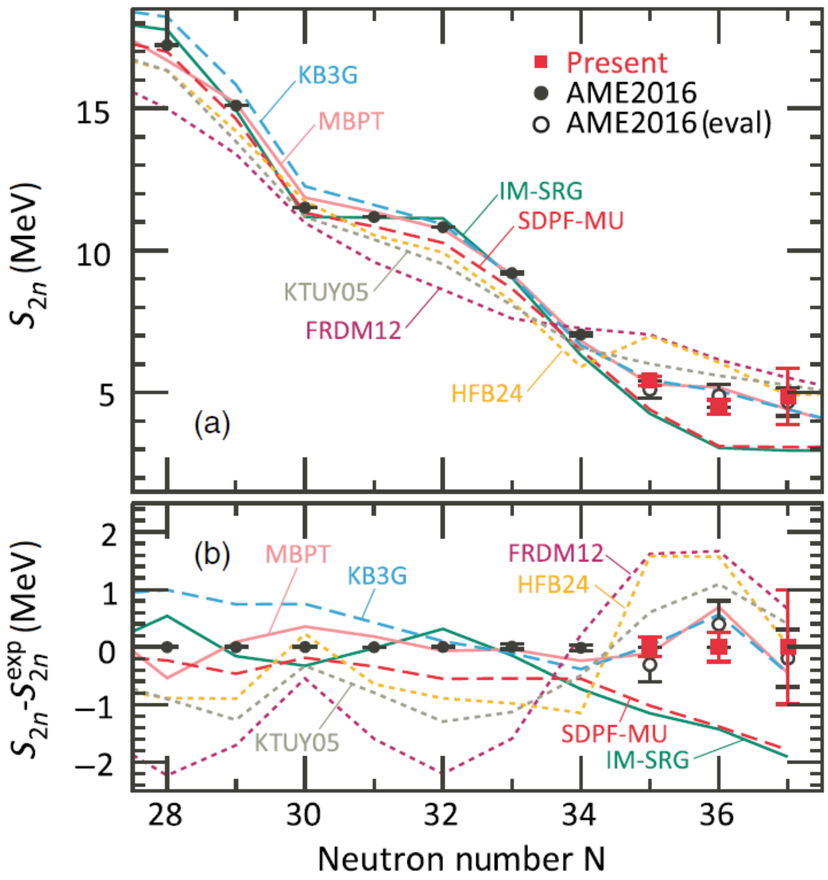
★ Taking into account neutron paring effect.

★ Can discuss more neutron-rich nuclei

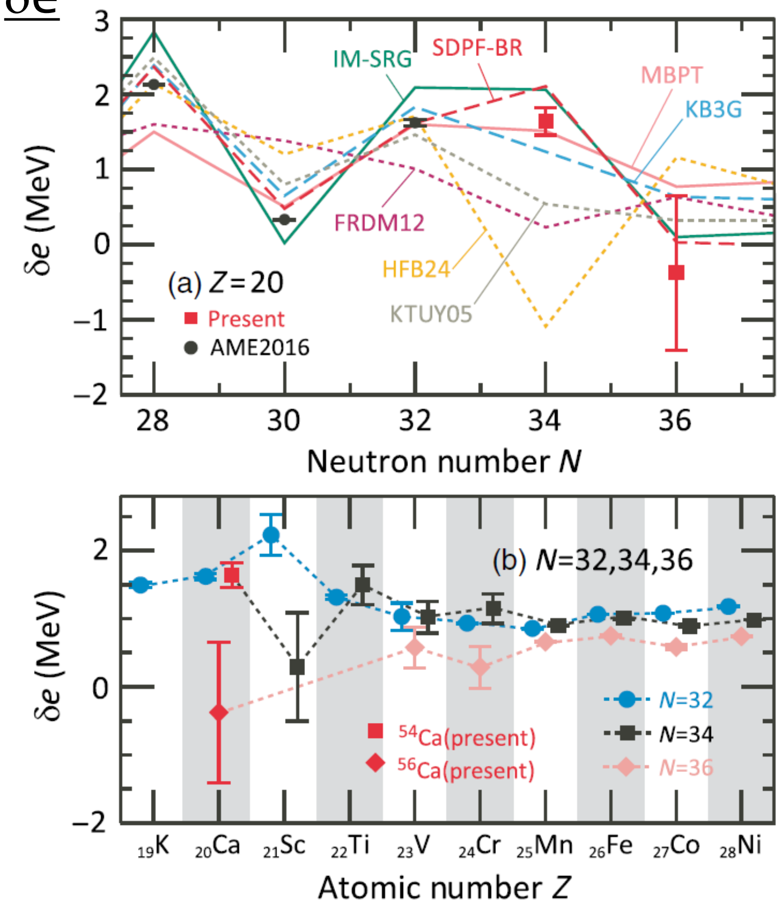
[1] D. Lunney et al., Rev. Mod. Phys. **75** 1021 (2003).
[2] W. Satula et al., Phys. Rev. Lett. **81**, 3599 (1998).

Neutron shell evolution in Ca isotopes

S_{2n}



δe



$$S_{2n} = -M(A,Z) + M(A-2,Z) + 2M_n$$

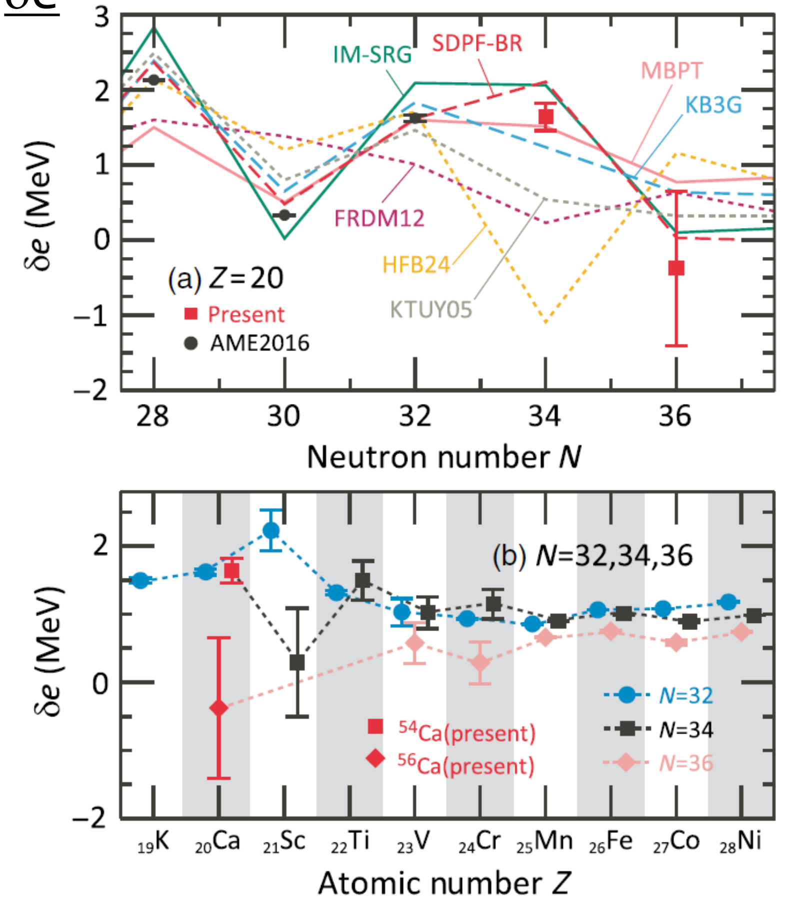
Neutron shell evolution in Ca isotopes

Trend along the neutron number

The δe shell gap in ^{54}Ca is similar value to that in ^{52}Ca but smaller than ^{48}Ca, and then it has a property of shell closure.

The δe in ^{56}Ca is weaker than ^{54}Ca and similar value to ^{50}Ca. Therefore, shell ordering $p_{3/2}$-$p_{1/2}$-$f_{5/2}$ is consistent with occurring of shell closures in ^{52}Ca and ^{54}Ca.

δe



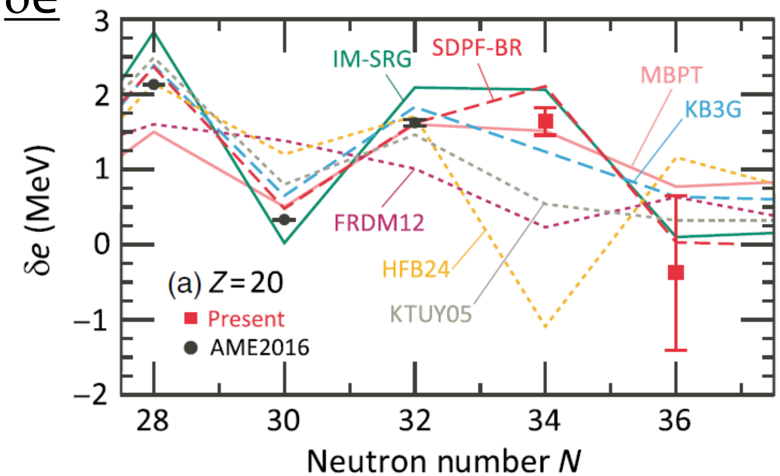
Neutron shell evolution in Ca isotopes

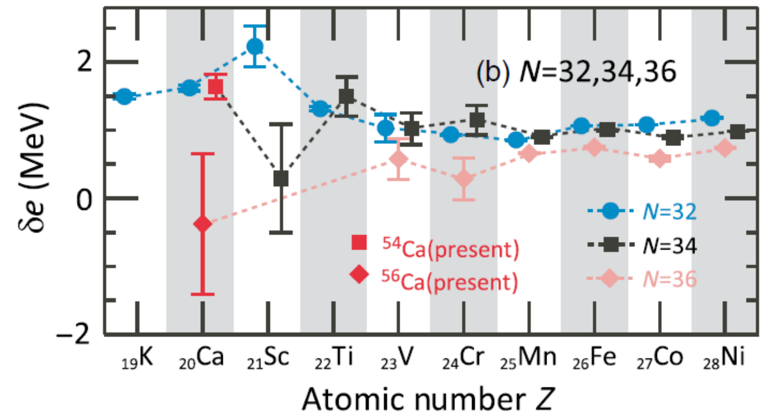
Trend along the atomic number

The shell evolution of N=32, 34 are very similar in the region from Z=28 (Ni) to 22 (Ti). The N=32 gap grow up between Ti-Sc isotopes, while the N=34 gap increases between Sc-Ca isotopes.

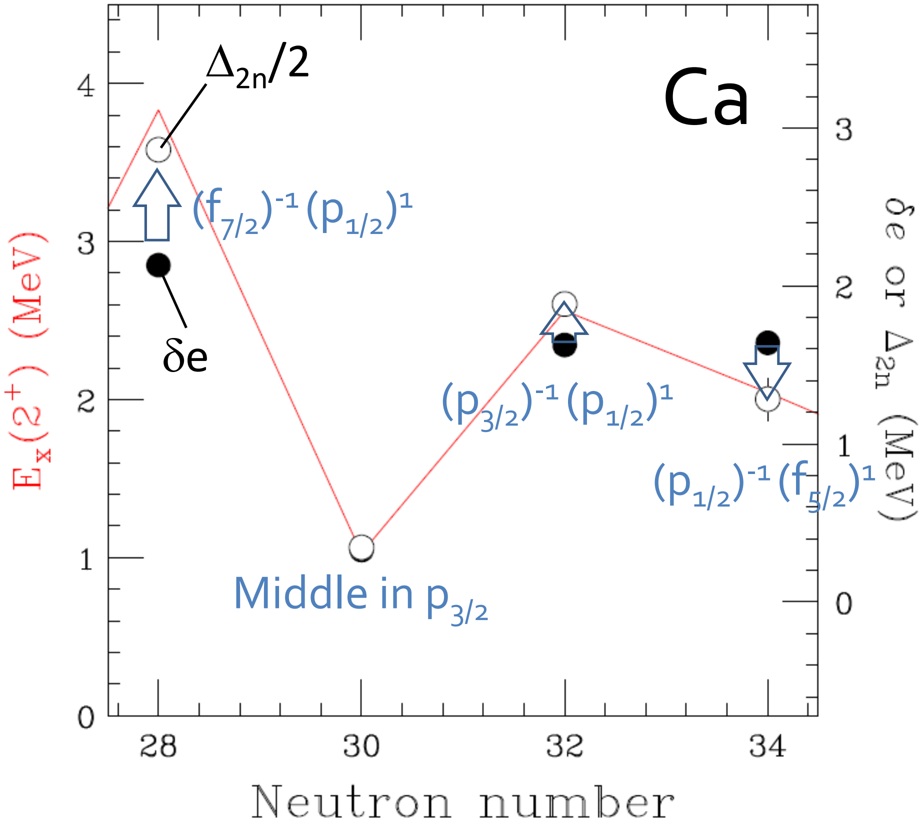
The N=36 isotones are flat trend with small δe values and have open-shell properties.

δe





Comparison to the trend of $E_x(2^+)$



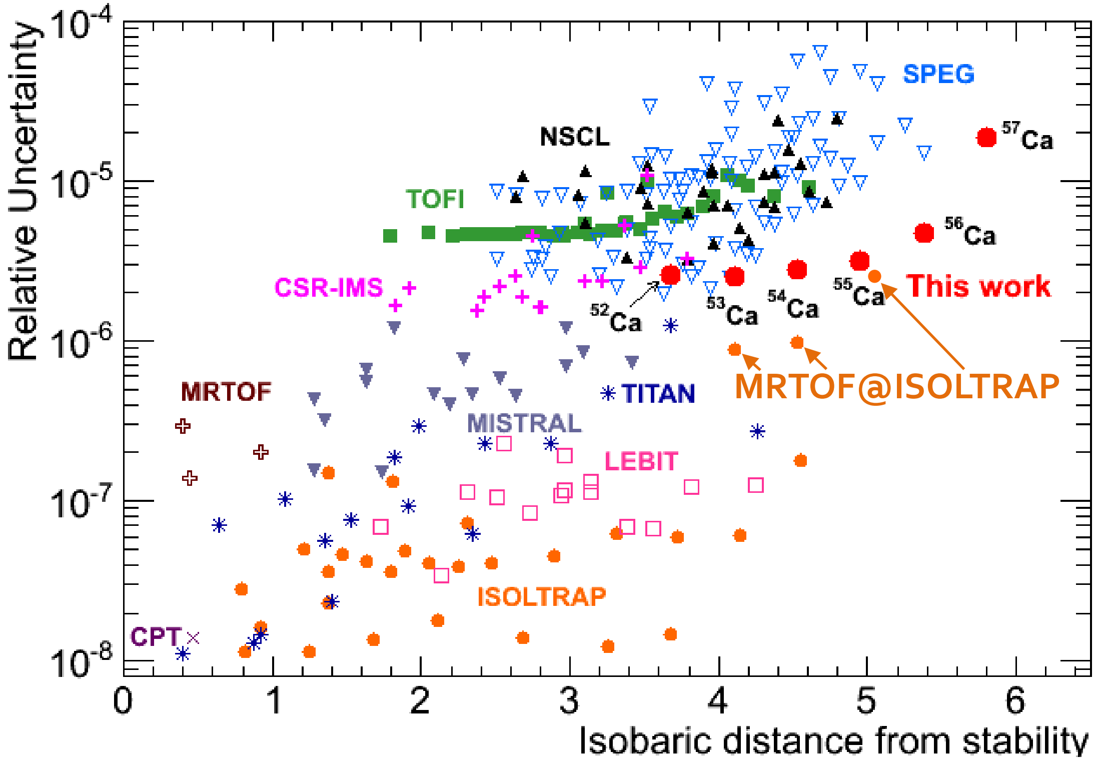
In this n-rich Ca region,
trend of Ex(2+) energies is
similar to that of the Δ_{2n} gaps
rather than δe gaps

It is reasonable that
difference of pairing energies
between lower and upper orbitals
affects the 2^+ excitation energies.

$$\Delta_{2n} = 2[\delta e - \Delta_3(N+1) + \Delta_3(N-1)],$$

Through the present measurement, we also obtain the energy differences of pairing gaps.
Based on the values, we reasonably understand that the Ex(2+) difference in ^{52,54}Ca
is mainly originated from the pairing energy differences in $p_{3/2}$, $p_{1/2}$ and $f_{5/2}$ orbitals.

Performance of the present mass measurements



Isobaric distance from stability

- defined by $Z_o - Z$
- Z_o: proton number of the most stable isotope in the isobaric chain with mass number A
- A measure of difficulty to access the nucleus

- achieved the almost highest mass precisions ever reached in the TOF mass measurement technique
  - ^{53,54}Ca: comparable to uncertainties in MRTOF at ISOLTRAP
- accessed more neutron-rich region far from stability than those in the other TOF mass measurement facilities

Summary

- We demonstrated that TOF-Br method by using BigRIPS+SHARAQ with Diamond detector is effective to measure the masses of short-lived nuclei extremely far from the beta stability.
- Successful mass measurements of $^{55-57}$Ca were done. Achieved mass resolutions are:
  - 160 keV(σ) (^{55}Ca: ~3300 events)
  - 250 keV(σ) (^{56}Ca: ~600 events)
  - 990 keV(σ) (^{57}Ca: ~30 events)
- The neutron shell gap in ^{54}Ca has a property of shell closure and that in ^{56}Ca is weaker.
- The shell evolution of N=32, 34 make difference at Sc isotopes. The shell closure at N=34 increase significantly at ^{54}Ca.