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Isospin symmetry in the $T = 1$, $A = 62$ triplet

UK Nuclear Physics Early Career Research Workshop 16.-17.1.2025

Panu Ruotsalainen, University of Jyväskylä, Department of Physics

JYFL

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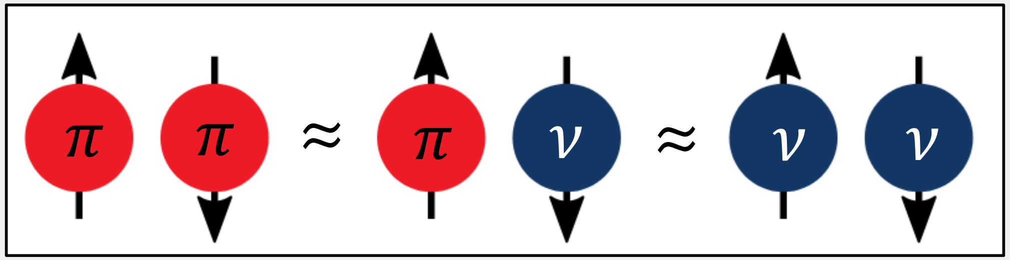
  - Isospin symmetry
  - Isospin symmetry breaking and triplet energy differences (TED)
- In-beam γ-ray spectroscopy of the A=62 triplet (^{62}Ge, ^{62}Ga, ^{62}Zn):
  - Experimental tools/techniques and results from the JYFL-ACCLAB experiment
  - Experimental tools/techniques and results from the RIKEN experiment
- Conclusions

Isospin symmetry

- The strong nuclear force is known to be approximately:

1) charge independent: $V_{pn} = \frac{V_{pp}+V_{nn}}{2}$
2) charge symmetric: $V_{pp} = V_{nn}$



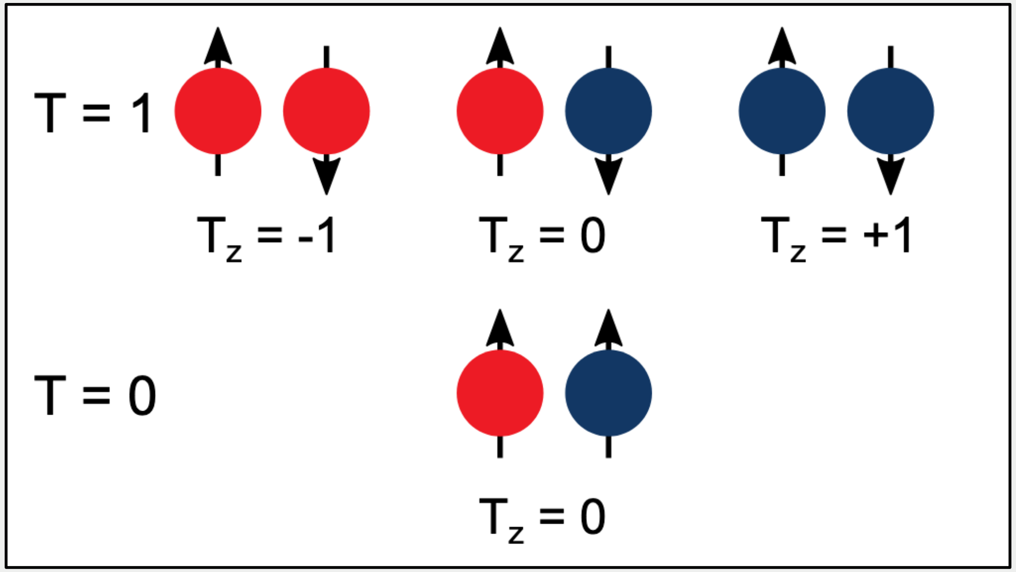
V_{pp} V_{pn} V_{nn}

- Treat protons and neutrons as two different states of a nucleon.
- The proton and neutron differ in isotopic spin (isospin) quantum number:

$$t_z^n = +\frac{1}{2} \quad \text{and} \quad t_z^p = -\frac{1}{2}$$

Isospin symmetry

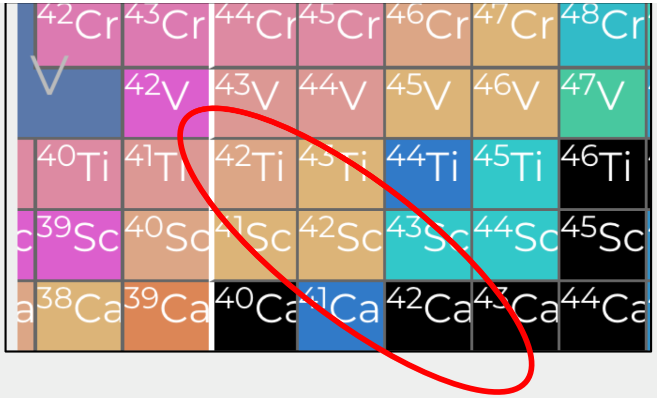
- Representation of the nucleons with isospin: $t_z^n = +\frac{1}{2}$ and $t_z^p = -\frac{1}{2}$
- "Rules": $T_z = \sum_i^A t_{z,i}$ and $T \geq T_z$ and $T_z = T, T\text{-}1, 0, \ldots \text{-}T$
  $T_z = (N\text{-}Z)/2$
- For "two-nucleon" system:
  - n-n -> $T_z = +\frac{1}{2} + \frac{1}{2} = +1$, $T = 1$
  - p-p -> $T_z = -\frac{1}{2} - \frac{1}{2} = -1$, $T = 1$
  - n-p -> $T_z = +\frac{1}{2} - \frac{1}{2} = 0$, $T = 0$ or 1



The $T = 1$ configurations form <u>isospin triplet</u> of states, which should be identical in terms of excitation energy and have identical wave functions.

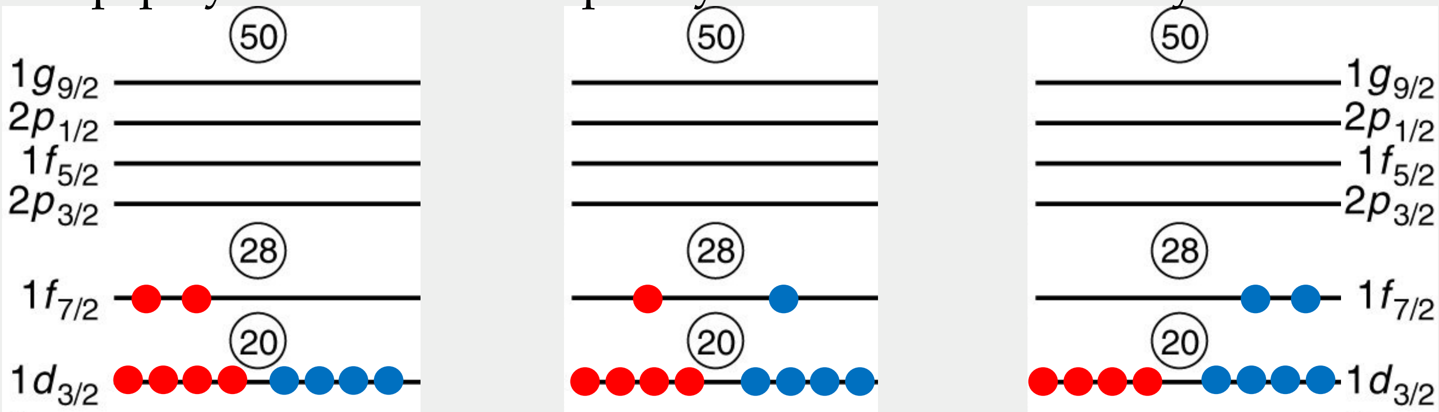
Note: deuteron (the n-p system) has only one bound state $J^\pi = 1^+$ corresponding to the $T = 0$ configuration as there are no bound states in ^{2}He and 2n.

Isospin symmetry



Example: *A*=42 triplet

"p-p system" "p-n system" "n-n system"

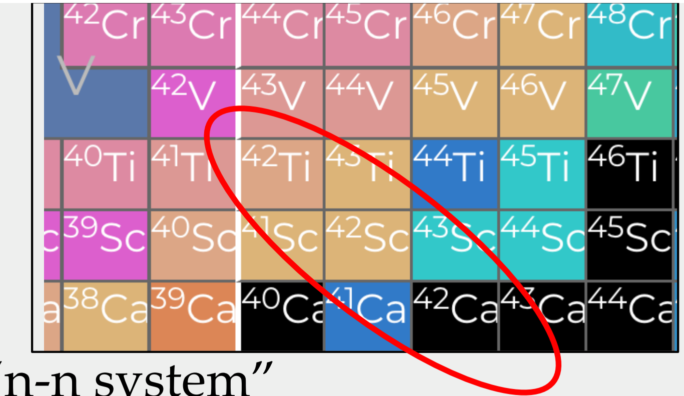


$^{42}_{22}Ti_{20}$ | $^{42}_{21}Sc_{21}$ | $^{42}_{20}Ca_{22}$

N=*Z*-2 (T_z = -1) | *N*=*Z* (T_z = 0) | *N*=*Z*+2 (T_z = +1)

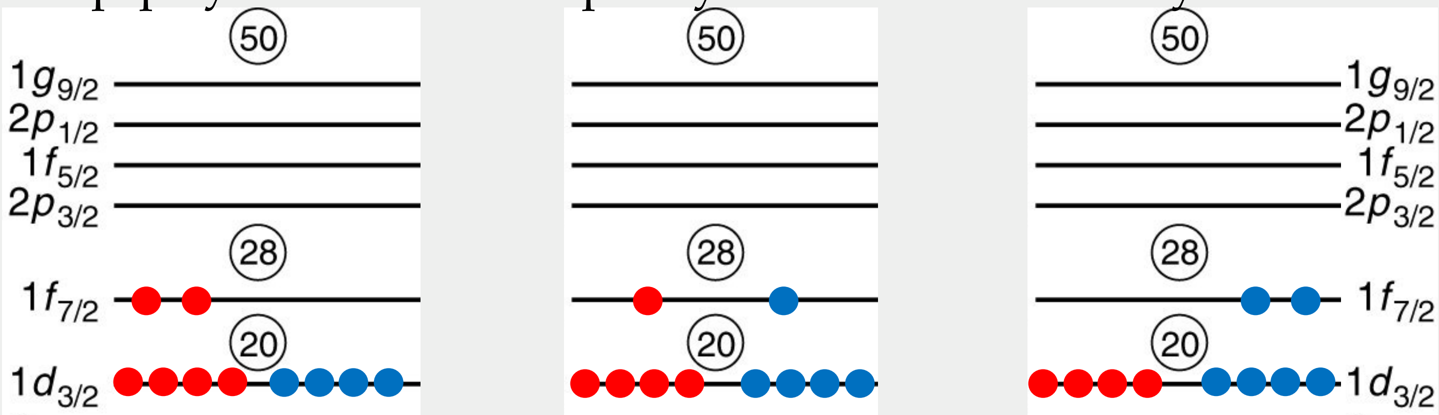
- Expect to find isobaric analog *T*=1 excited states in each member of the triplet.
- ^{42}Sc contains also *T*=0 states, which are not present in the other members.
- Experimental identification of the excited states in the T_z = -1 and T_z = 0 members of the triplet is commonly challenging.

Isospin symmetry



Example: *A*=42 triplet

"p-p system" "p-n system" "n-n system"

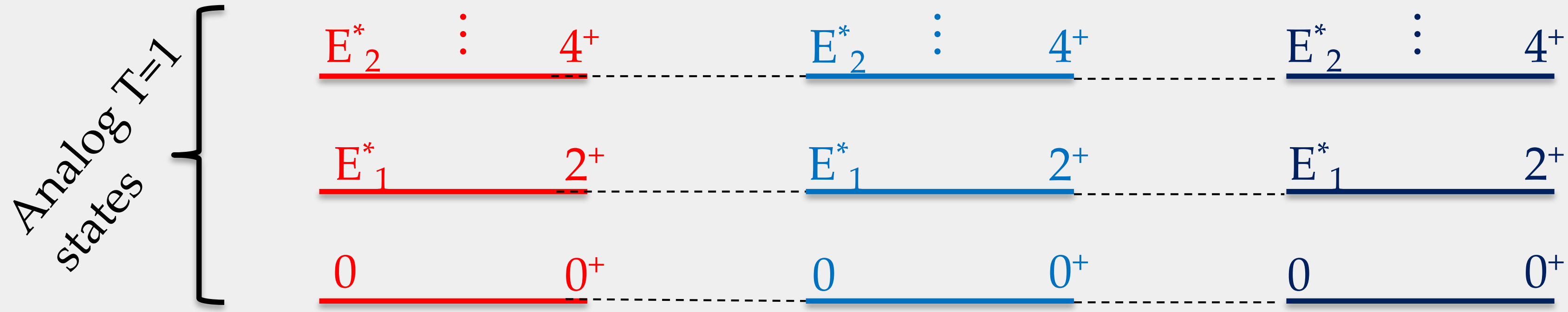


$^{42}_{22}Ti_{20}$ N=Z-2 (T_z = -1)

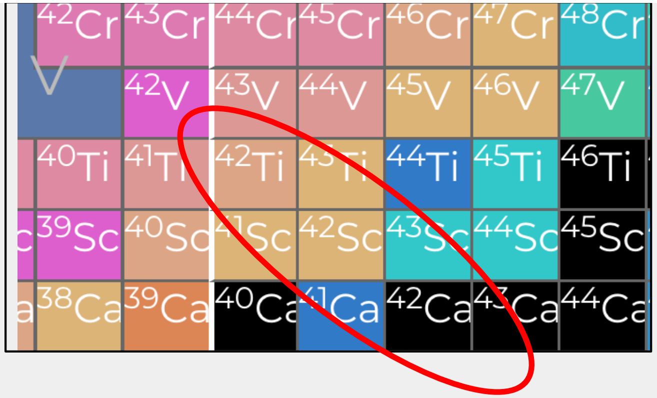
$^{42}_{21}Sc_{21}$ N=Z (T_z = 0)

$^{42}_{20}Ca_{22}$ N=Z+2 (T_z = +1)

In the absence of electromagnetic interaction (the Coulomb interaction between protons), the *T*=1 analog states in isobaric triplets should be degenerate.

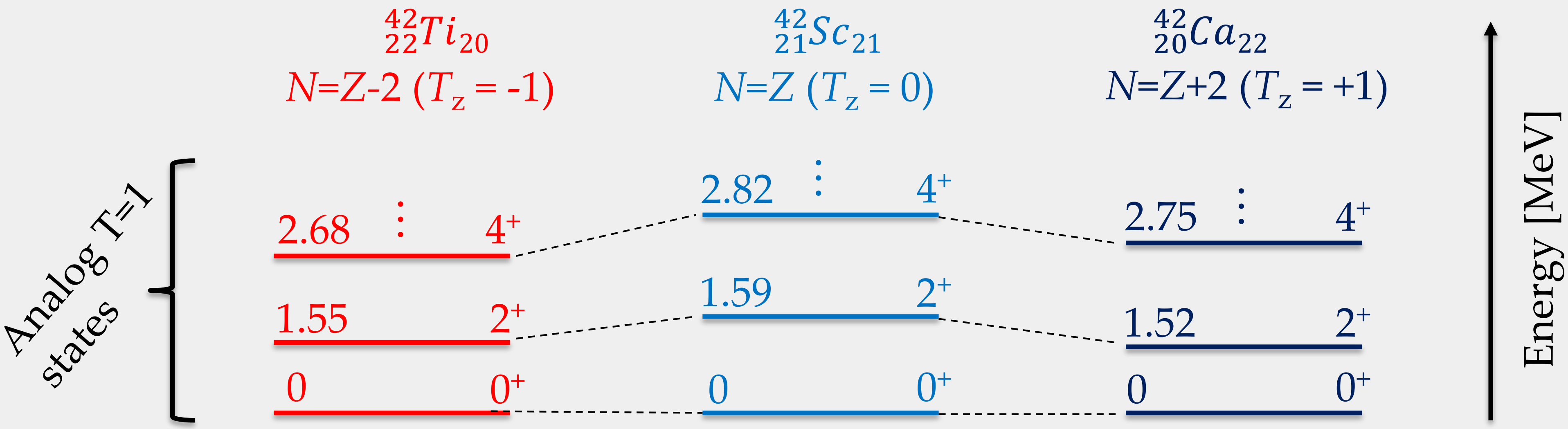


Isospin symmetry



Example: *A*=42 triplet

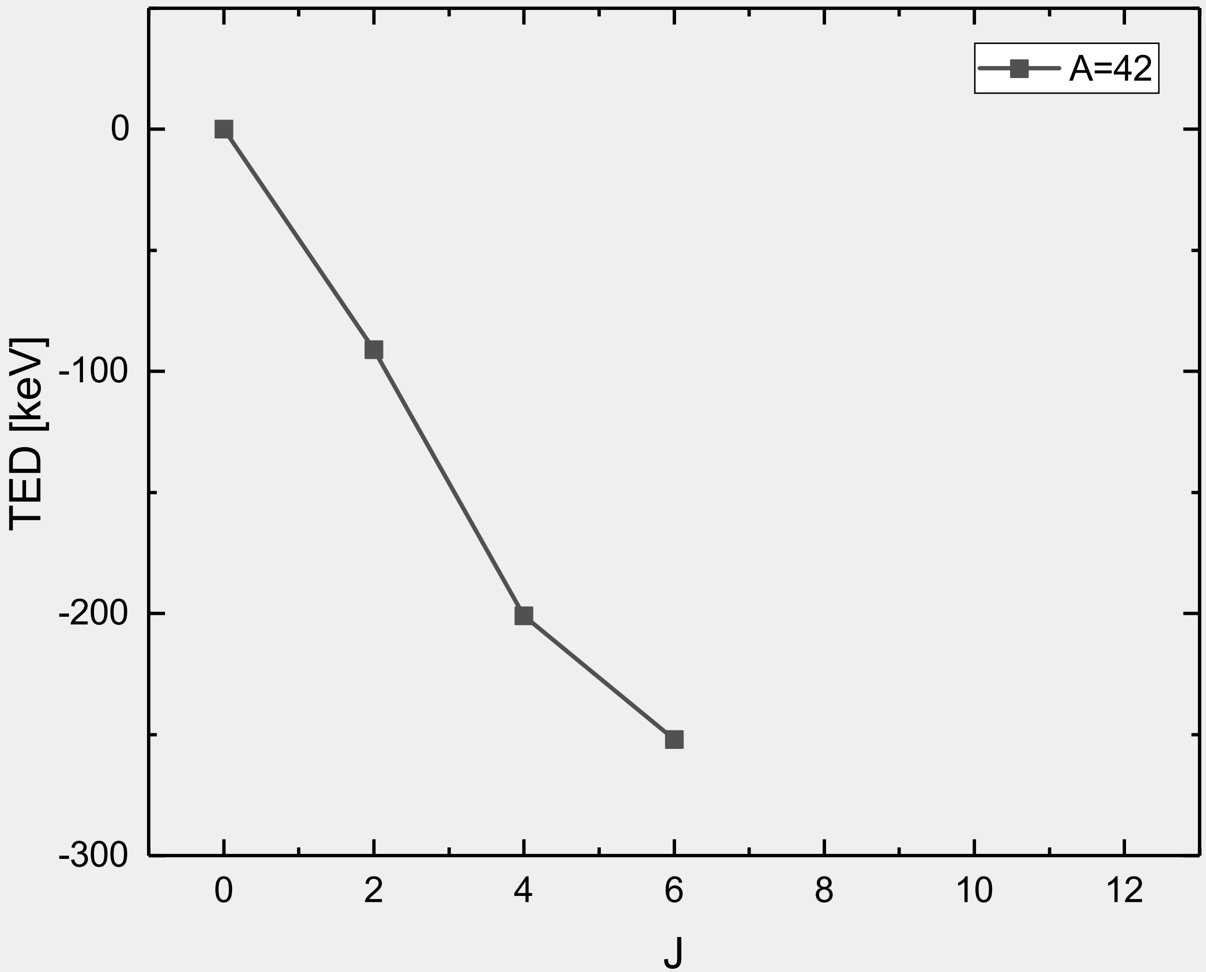
The Coulomb force between protons breaks the degeneracy in excitation energies
→ **Coulomb energy differences → CED**

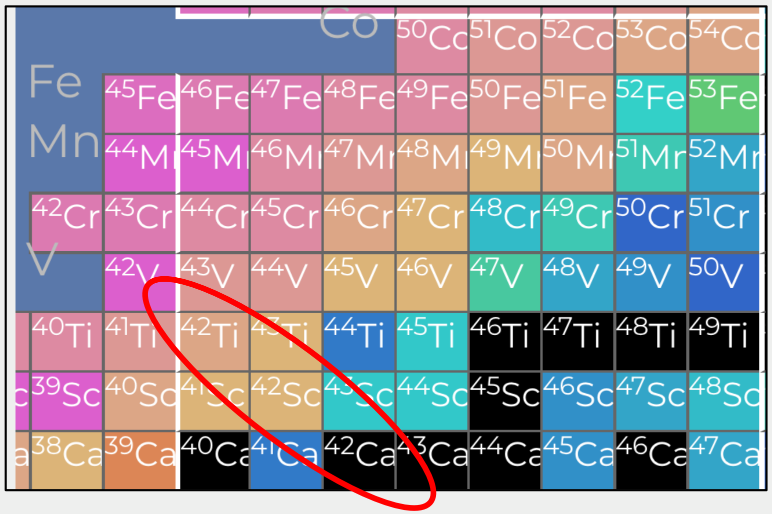


- Investigate **triplet energy differences → TED**
- **TED**(J) = $E^*(J, T_z = -1) + E^*(J, T_z = +1) - 2 \cdot E^*(J, T_z = 0)$
- **TED** tests the charge independency $(V_{pp} + V_{nn})/2 = V_{pn}$ of the nuclear interaction

Isospin symmetry breaking - TED

- $\textbf{TED}(J) = E^*(J, T_z{=}{-1}) + E^*(J, T_z = +1) - 2 \cdot E^*(J, T_z = 0)$
- Available experimental data:





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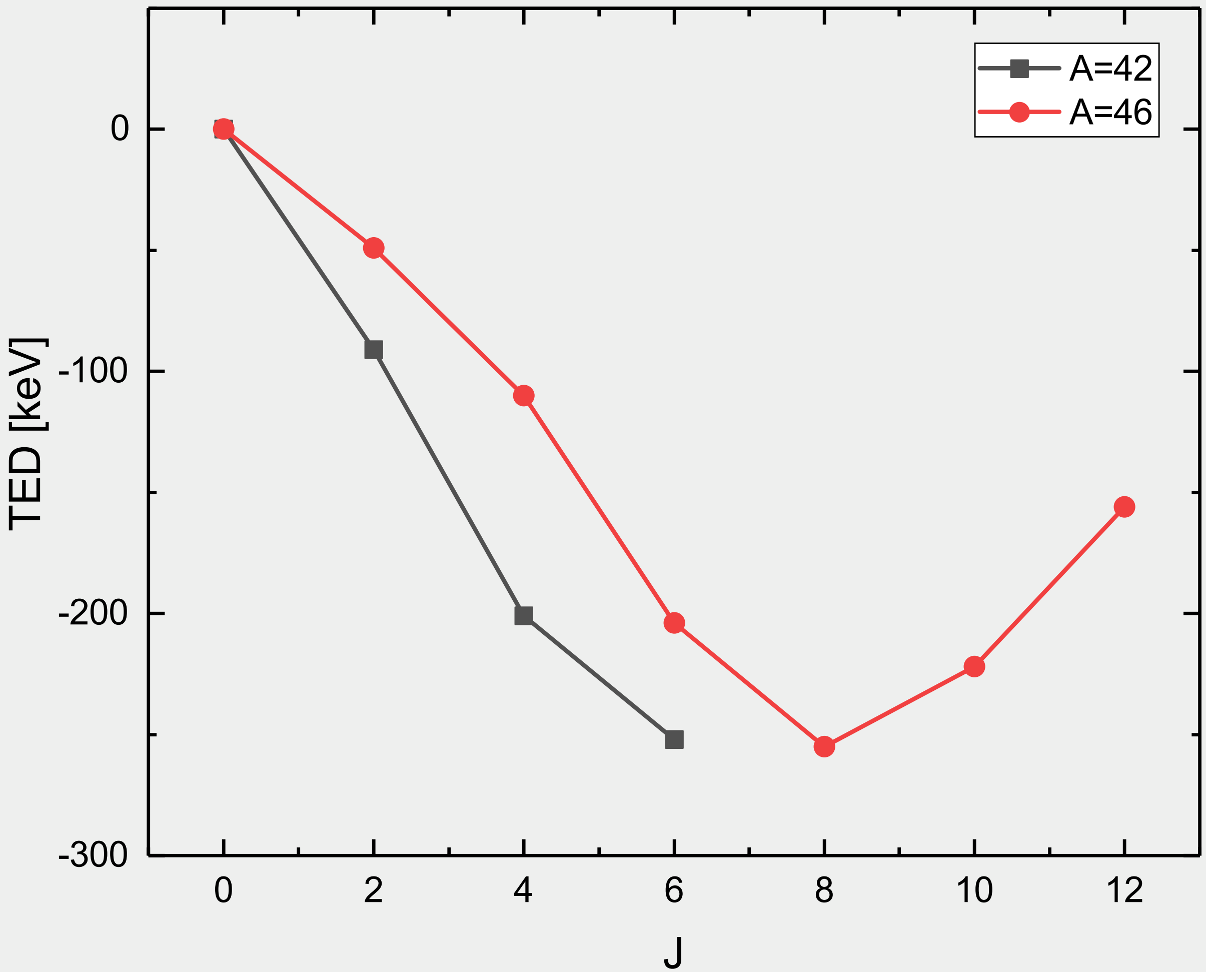

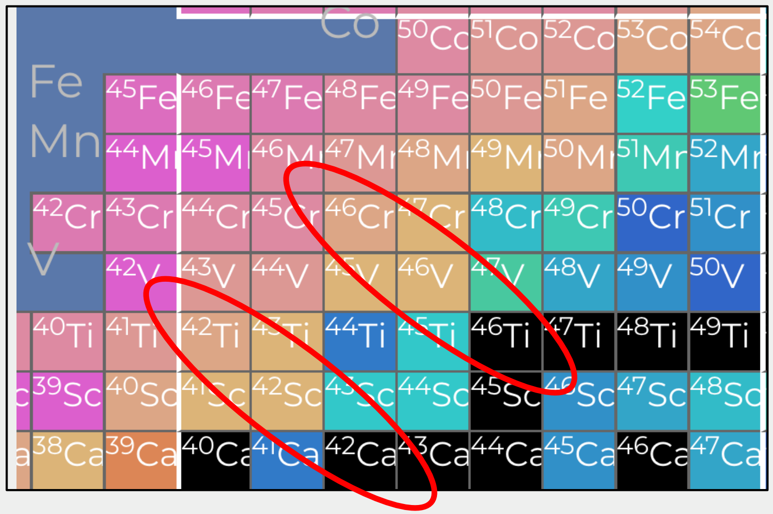

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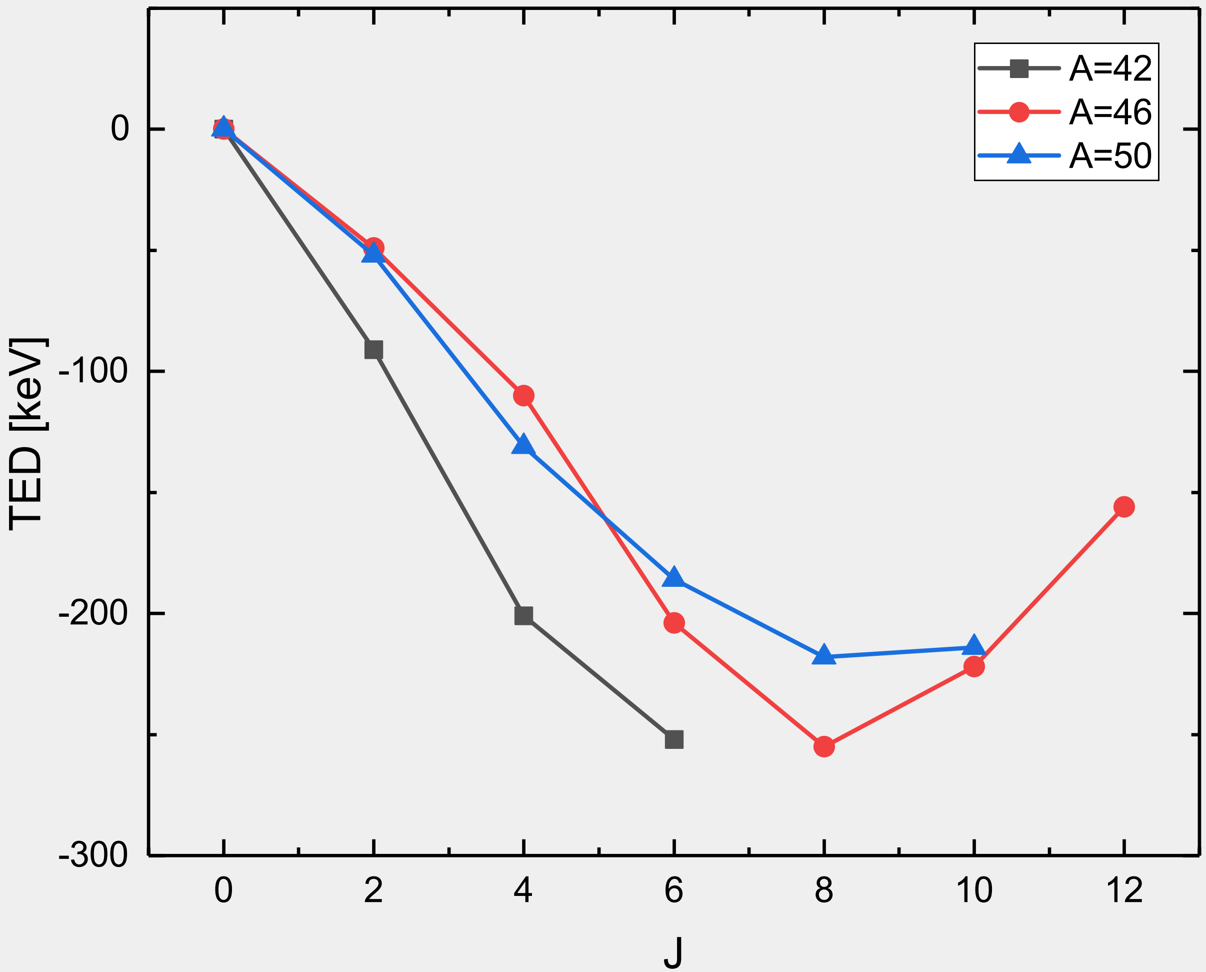

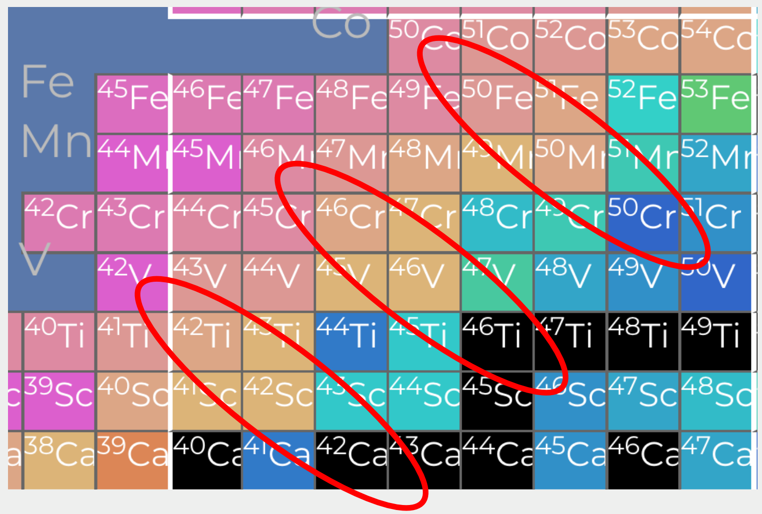

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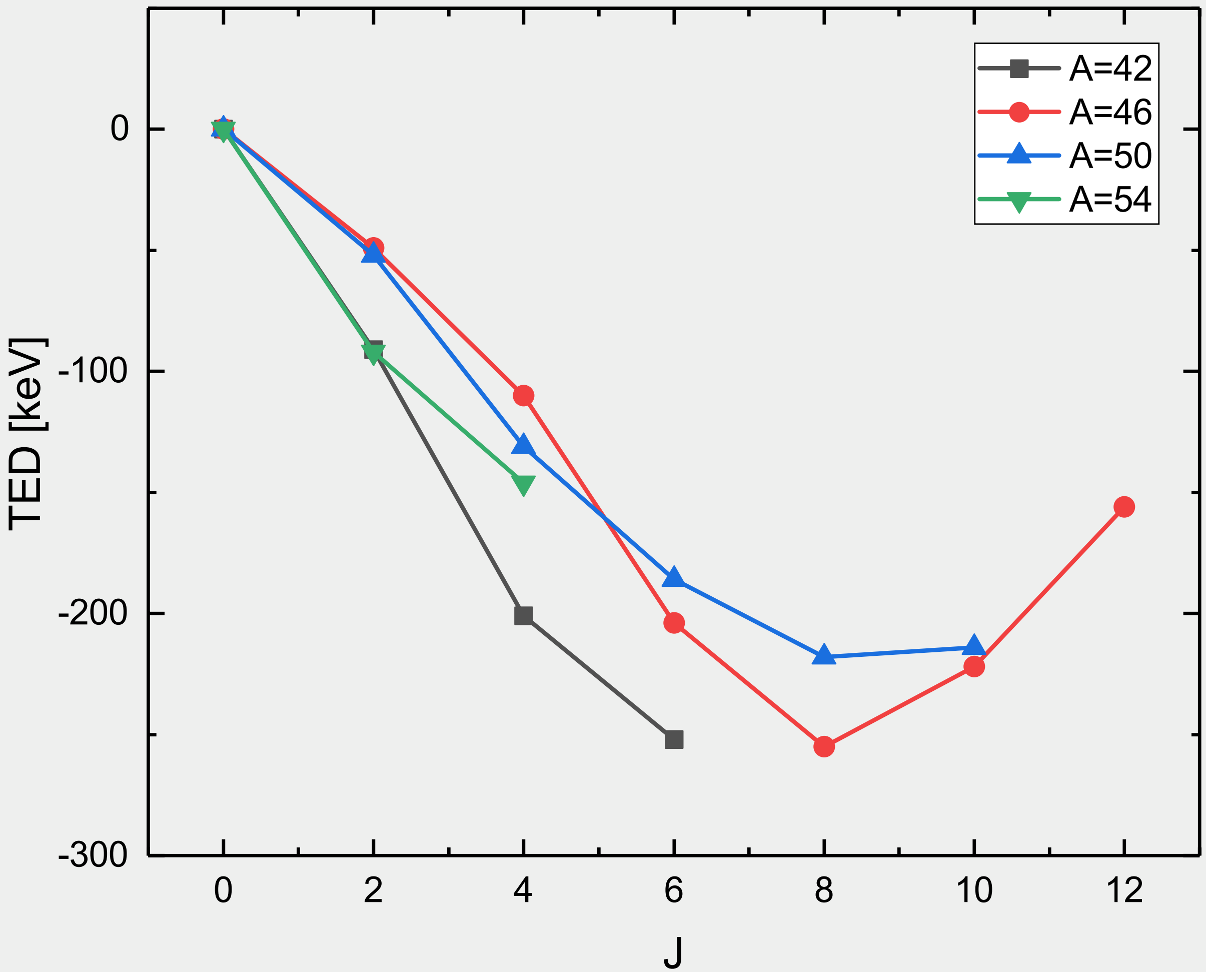

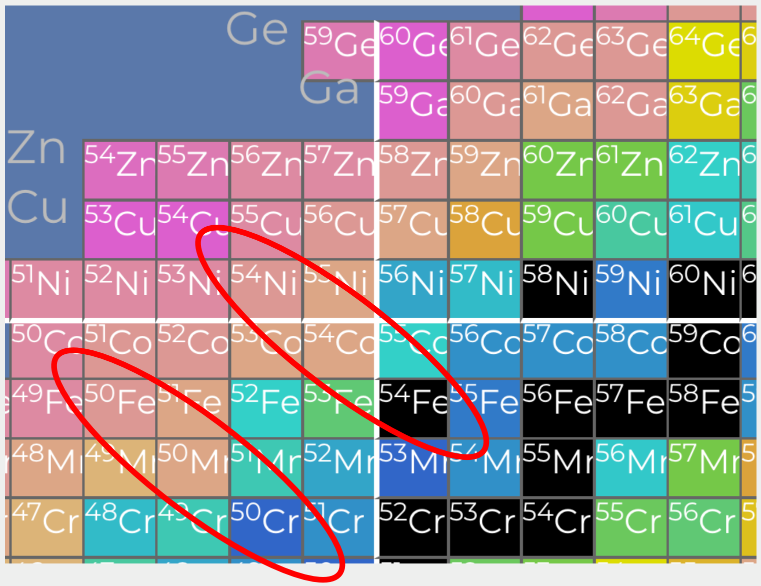

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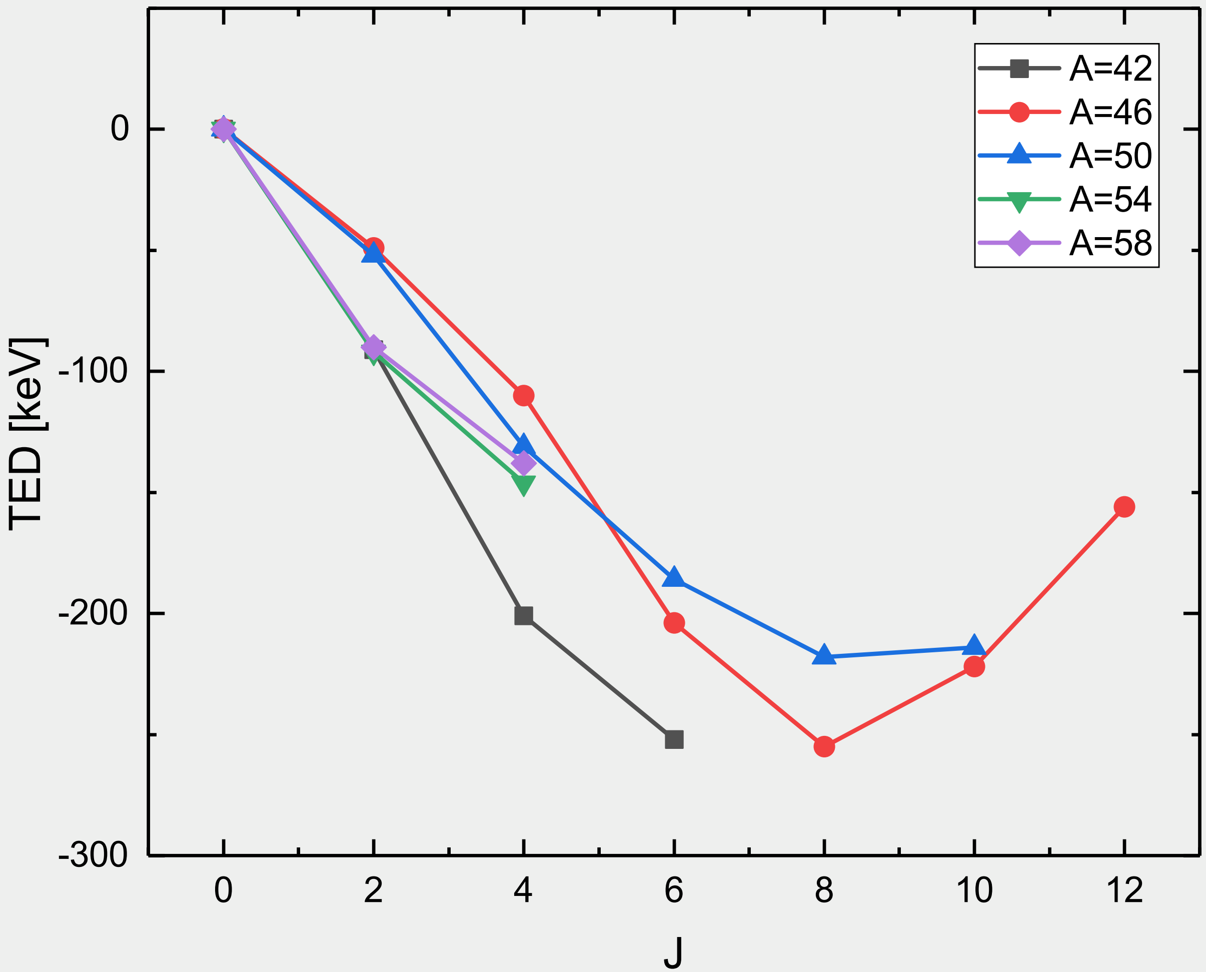

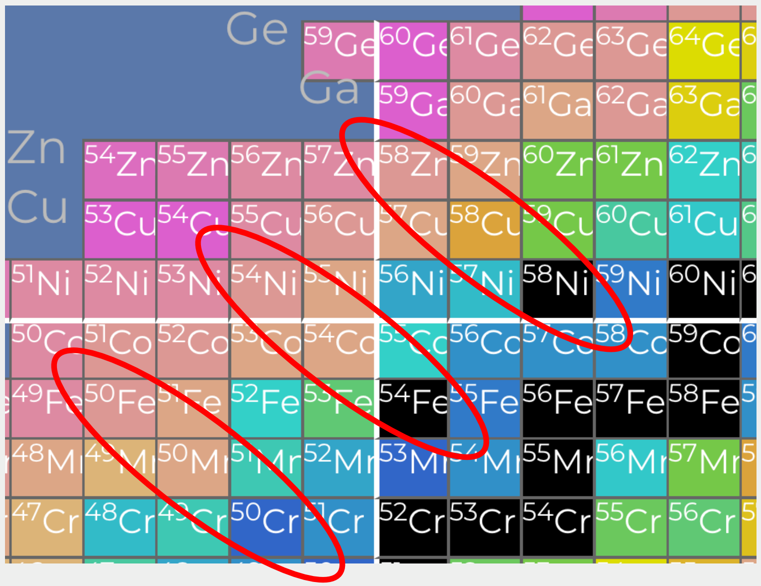

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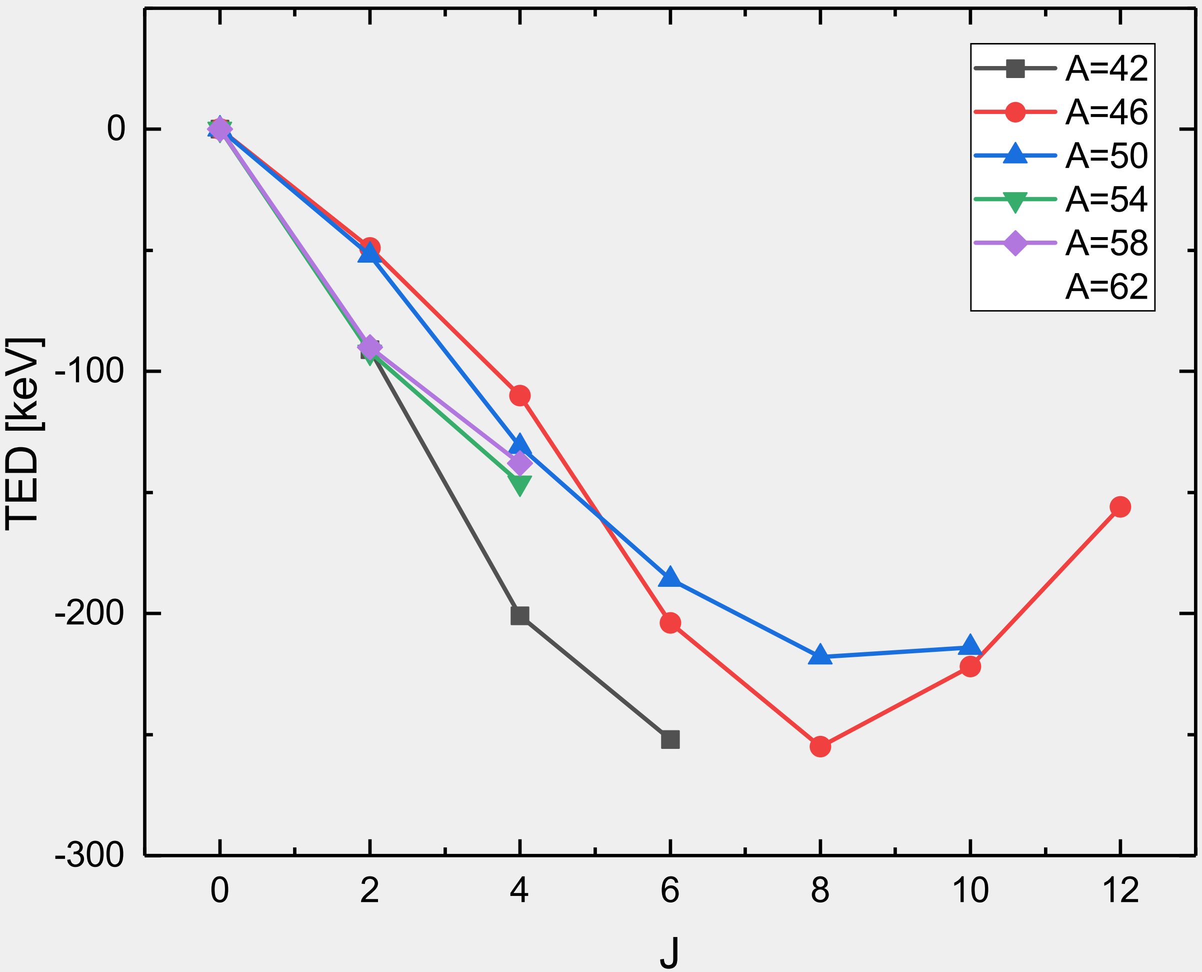

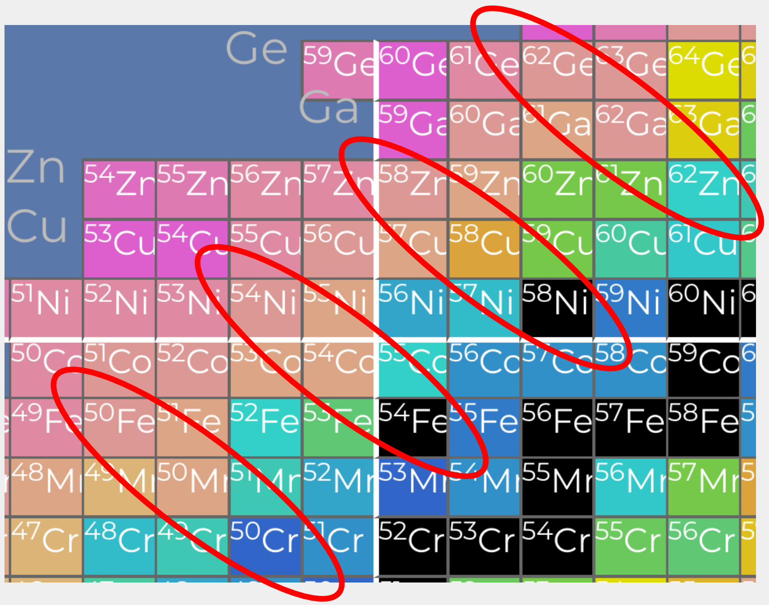

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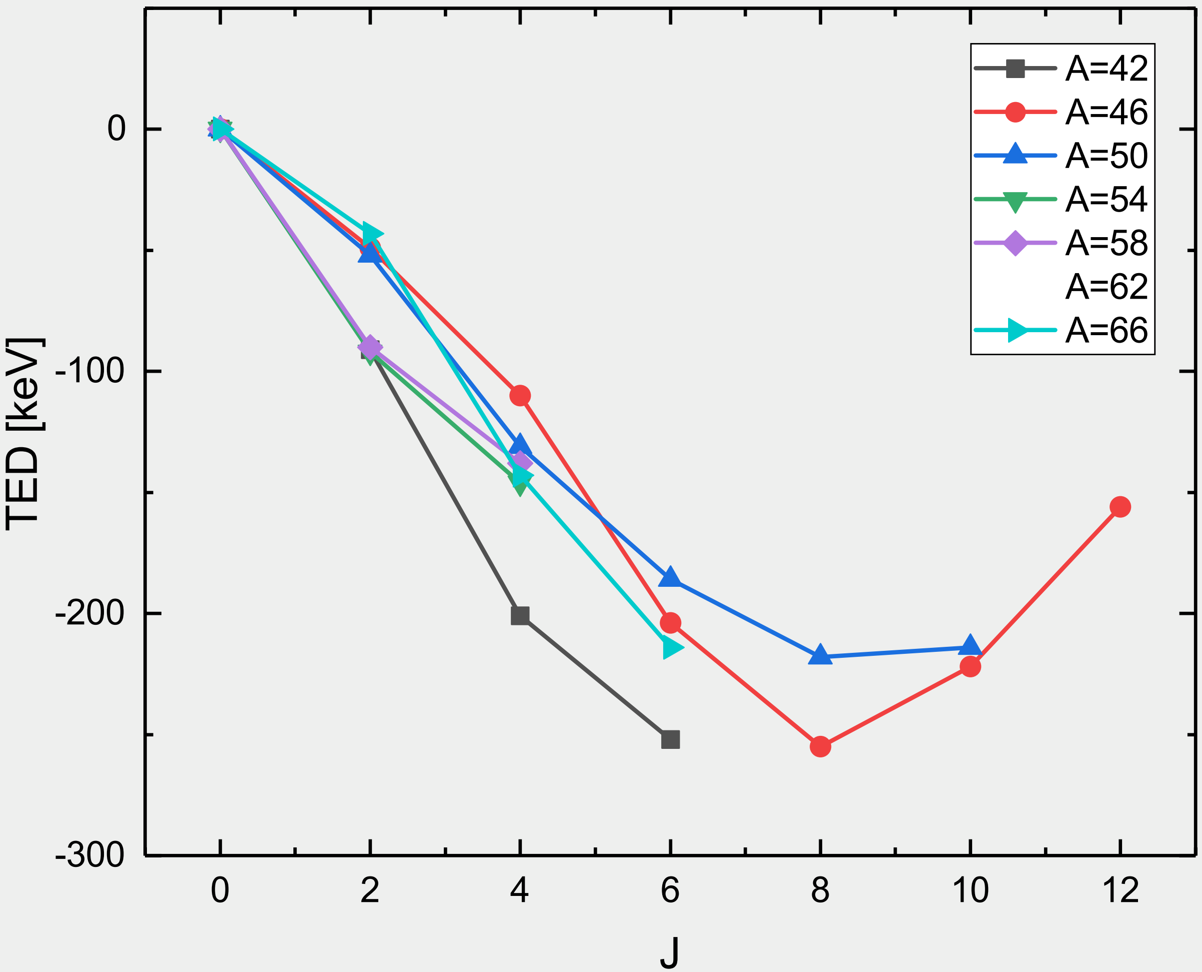

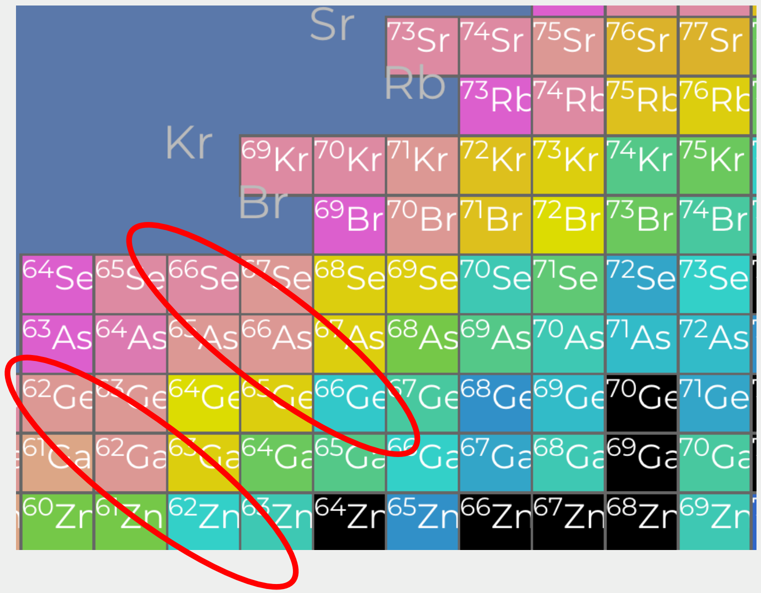

Isospin symmetry breaking - TED

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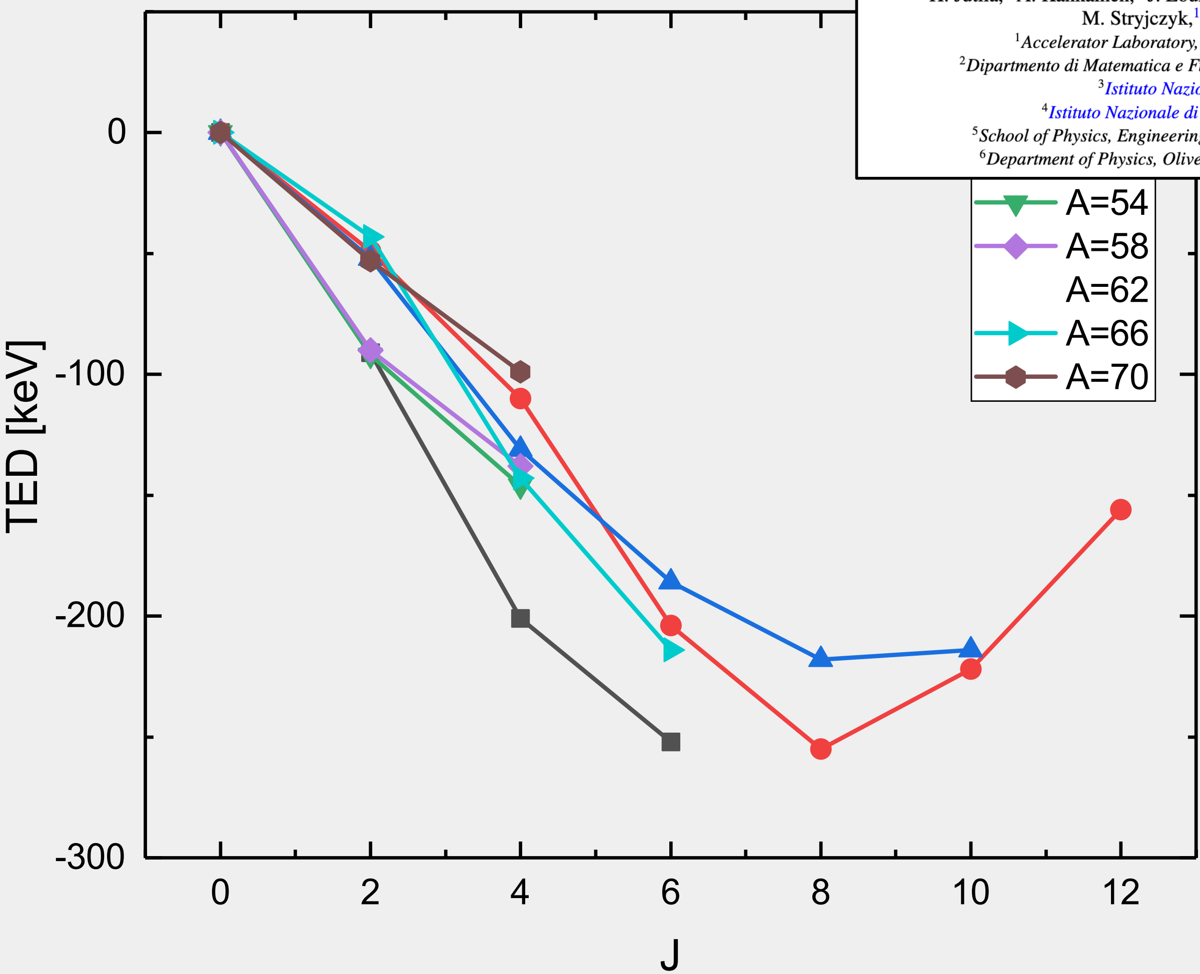
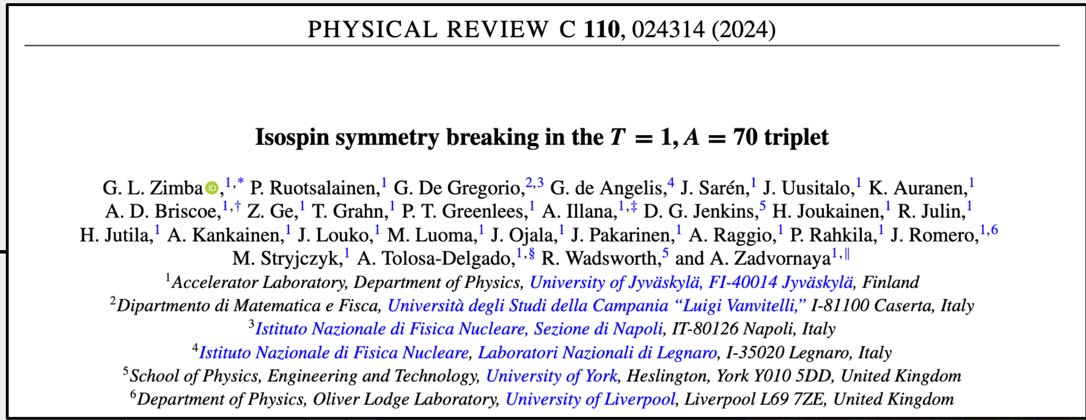
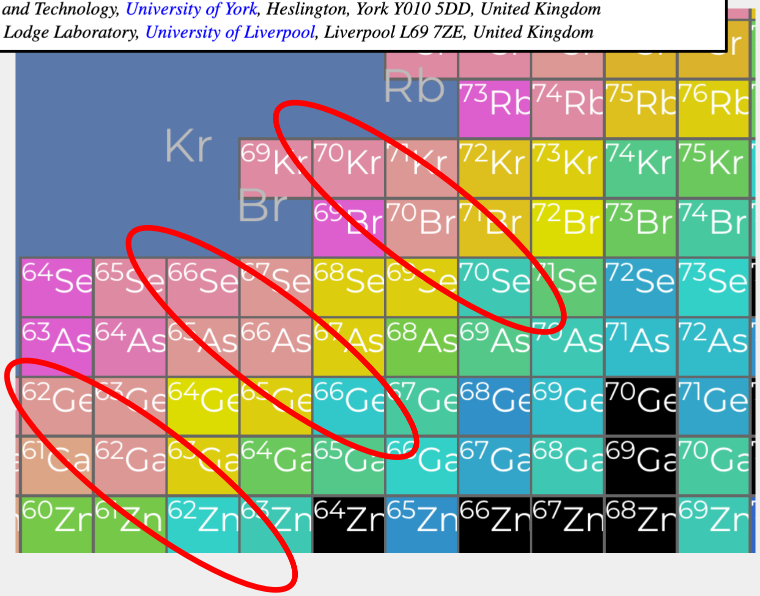



PHYSICAL REVIEW C **110**, 024314 (2024)

Isospin symmetry breaking in the $T = 1, A = 70$ triplet

G. L. Zimba,[1,*] P. Ruotsalainen,[1] G. De Gregorio,[2,3] G. de Angelis,[4] J. Sarén,[1] J. Uusitalo,[1] K. Auranen,[1] A. D. Briscoe,[1,†] Z. Ge,[1] T. Grahn,[1] P. T. Greenlees,[1] A. Illana,[1,‡] D. G. Jenkins,[5] H. Joukainen,[1] R. Julin,[1] H. Jutila,[1] A. Kankainen,[1] J. Louko,[1] M. Luoma,[1] J. Ojala,[1] J. Pakarinen,[1] A. Raggio,[1] P. Rahkila,[1] J. Romero,[1,6] M. Stryjczyk,[1] A. Tolosa-Delgado,[1,§] R. Wadsworth,[5] and A. Zadvornaya[1,‖]

[1]*Accelerator Laboratory, Department of Physics, University of Jyväskylä, FI-40014 Jyväskylä, Finland*
[2]*Dipartmento di Matematica e Fisca, Università degli Studi della Campania "Luigi Vanvitelli," I-81100 Caserta, Italy*
[3]*Istituto Nazionale di Fisica Nucleare, Sezione di Napoli, IT-80126 Napoli, Italy*
[4]*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali di Legnaro, I-35020 Legnaro, Italy*
[5]*School of Physics, Engineering and Technology, University of York, Heslington, York Y010 5DD, United Kingdom*
[6]*Department of Physics, Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, United Kingdom*



Isospin symmetry breaking - TED

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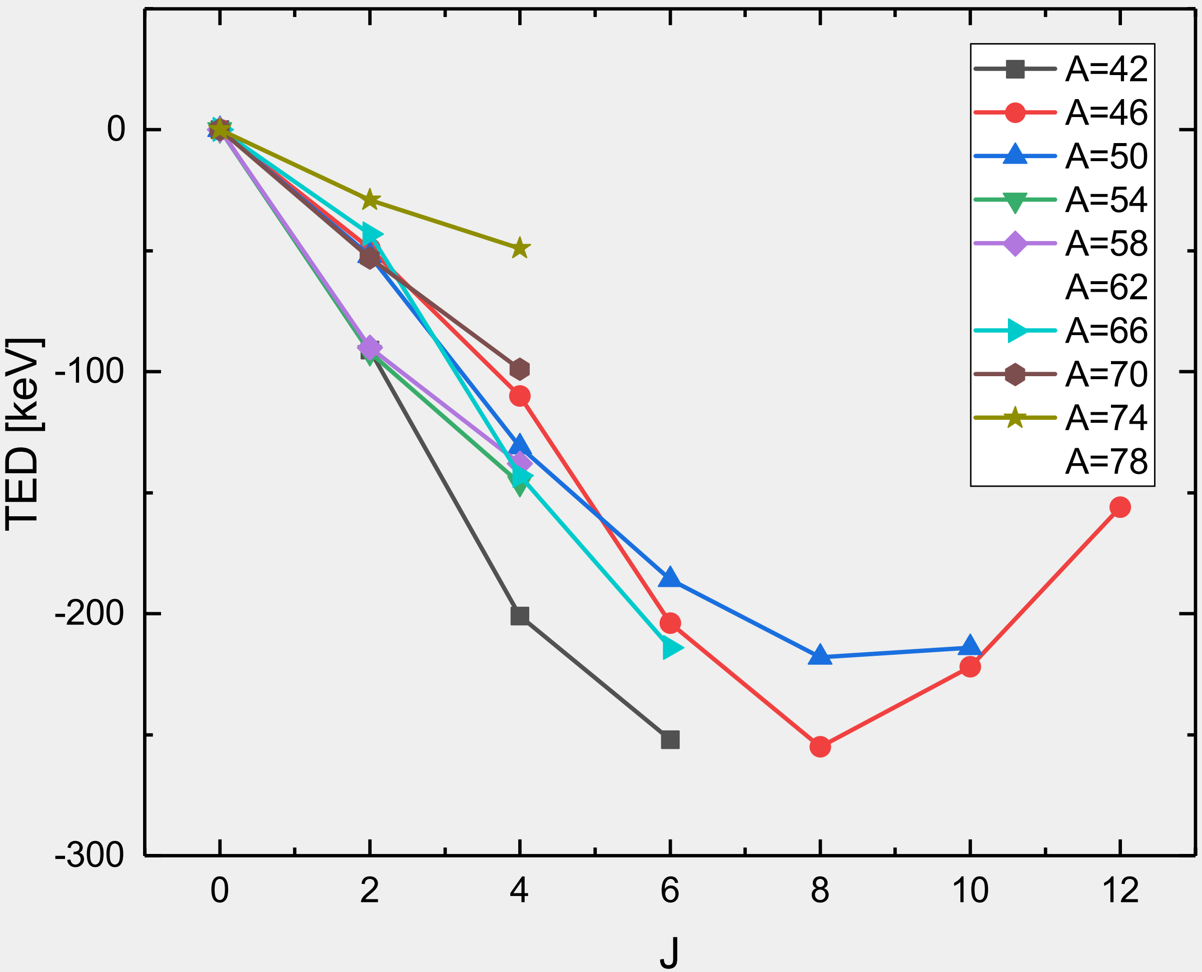
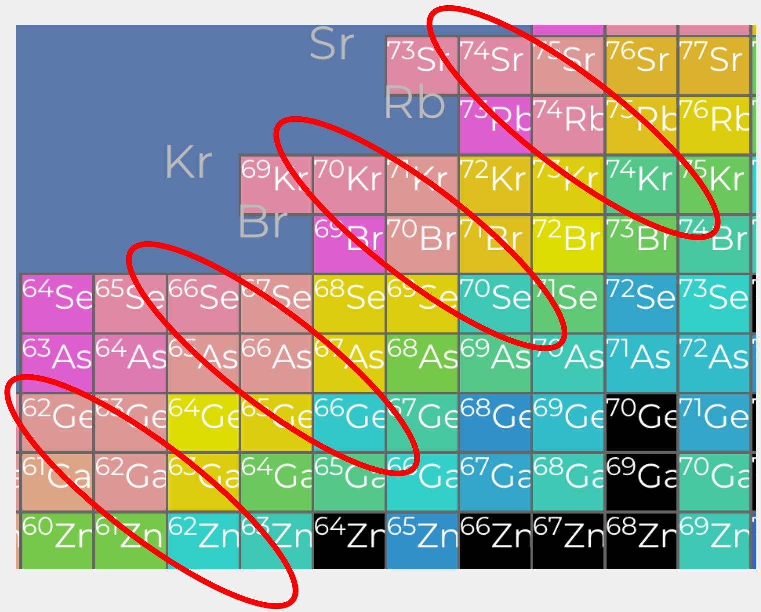
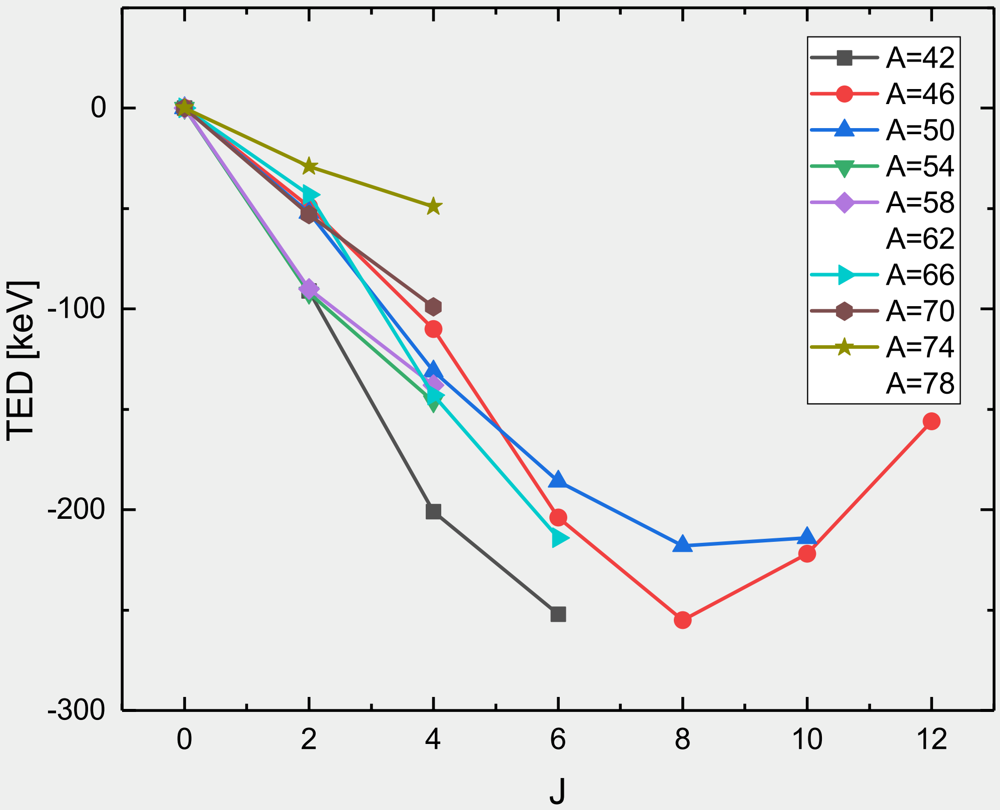
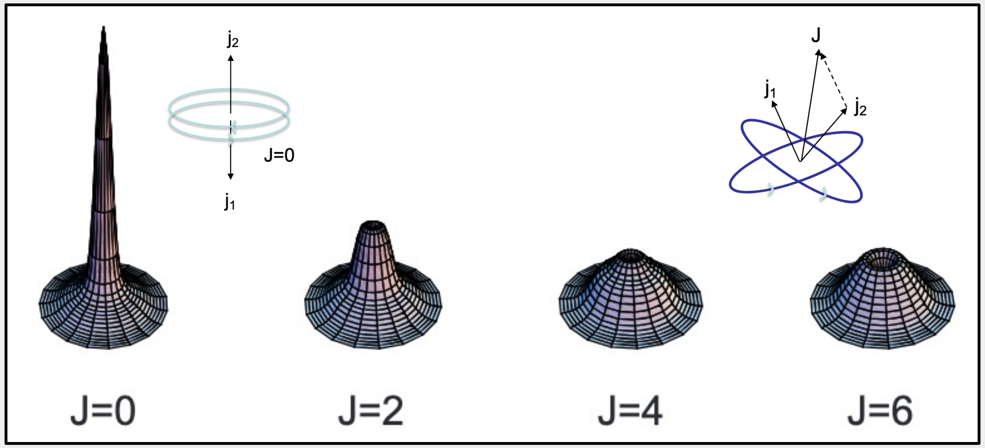


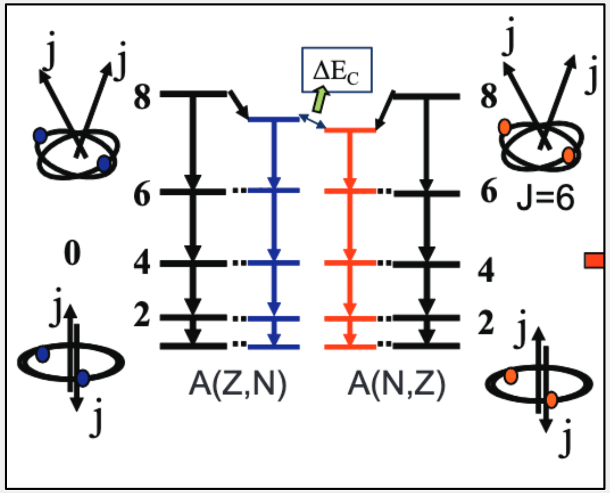


Isospin symmetry breaking - TED

- **TED** appears to be always negative with consistent magnitude, why?
- Spatial separation of pair of nucleons increase with their coupled angular momentum.
- Thus, when two protons coupled to J = 0 re-couple their angular momenta, the Coulomb energy decreases reducing the excitation energy of the nuclear state.
- This effect is the most pronounced in the proton-rich member of the triplet.



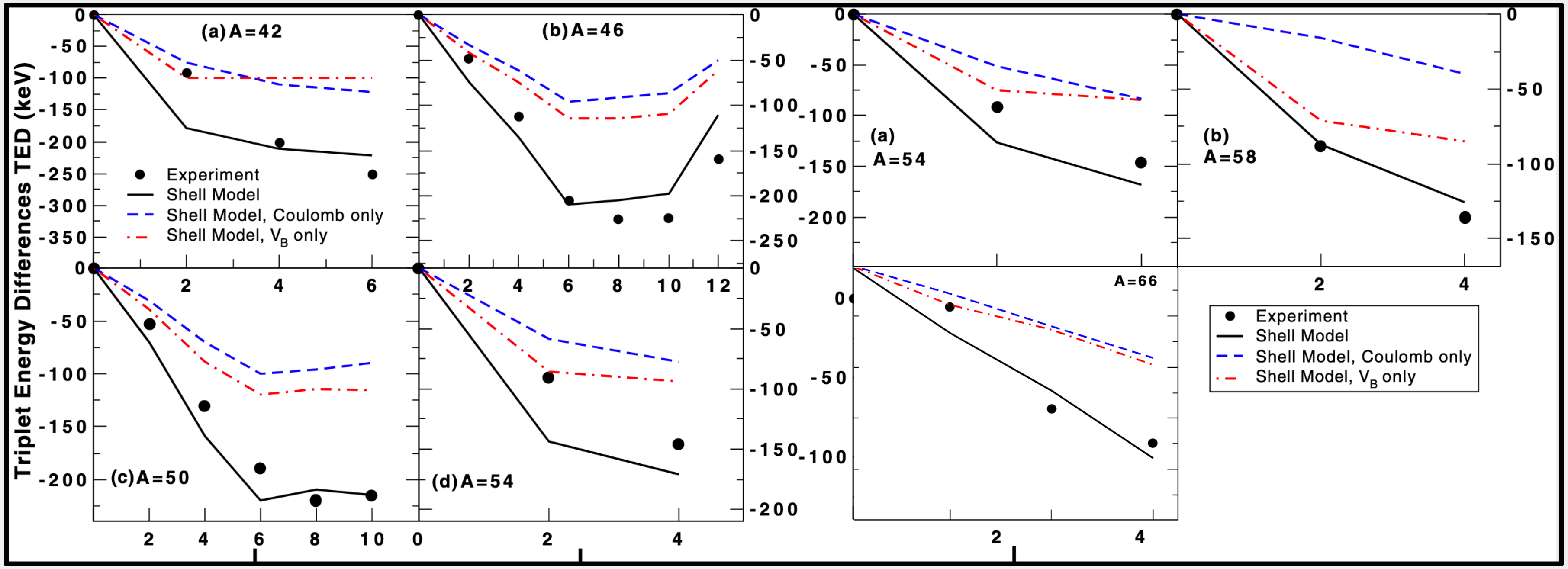




Isospin symmetry breaking - TED

- If the Coulomb effects can be theoretically estimated, isospin-breaking effects due to the nuclear interaction can be revealed.
- TED comparison to shell-model predictions → **additional isospin non-conserving interaction (V_B) required to match the experimental TED data:**

$$V_{Bi}^{(2)} = V_{Bi}^{\pi\pi,J=0} + V_{Bi}^{\nu\nu,J=0} - 2V_{Bi}^{\pi\nu,J=0} = +100\text{ keV}.$$



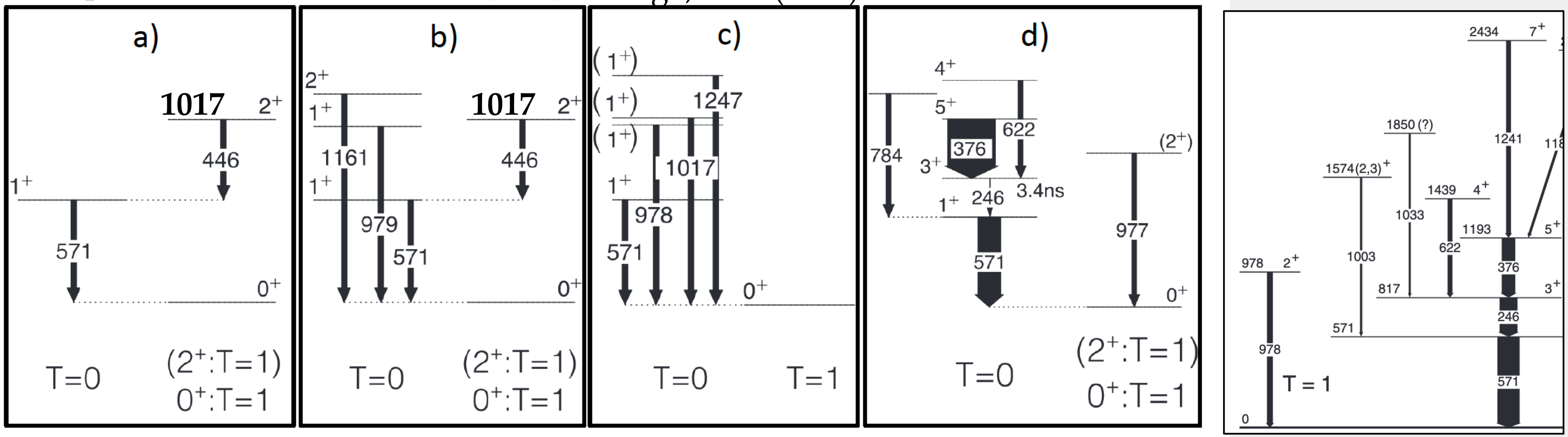
S. M. Lenzi et al. Phys. Rev. C **98**, 054322 (2018):

Conclusion: strength of the schematic isotensor INC interaction is "universal" for all studied shells, but its fundamental origin is not understood.

A=62 isobaric triplet

- TED data were not available for the A=62 isobaric triplet.
- This was because:
  - no excited states were known in the T_z = -1 nucleus ^{62}Ge
  - ambiguity for the (lowest) T=1 states in ^{62}Ga

Rudolph, PRC (2004) David, PLB (2013) Grodner, PRL (2014) Orrigo, PRC (2021) Henry, PRC (2015) Mihai, PRC (2022)



Fusion evap. Fusion evap. Beta decay of ^{62}Ge Two nucleon knockout Fusion evap.

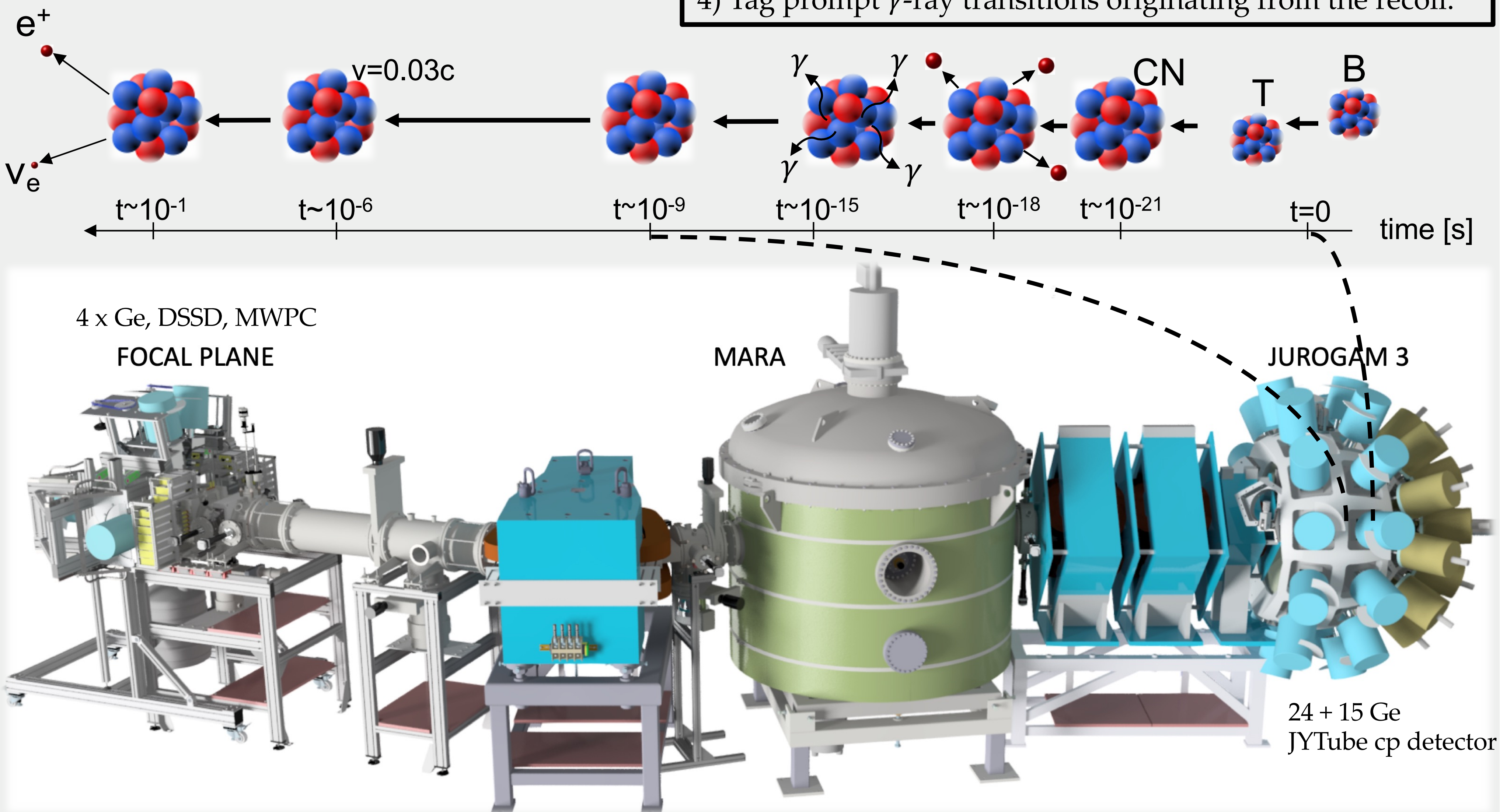
Structures of ^{62}Ge and ^{62}Ga were studied in two independent experiments employing:

1) **^{40}Ca + ^{24}Mg fusion-evaporation reaction at JYFL-ACCLAB and**
2) **inelastic scattering and neutron knockout at RIKEN**

Experimental method for *N~Z* nuclei: Recoil-beta tagging

1) Create nucleus in fusion evaporation reaction
2) Mass separate contaminant products

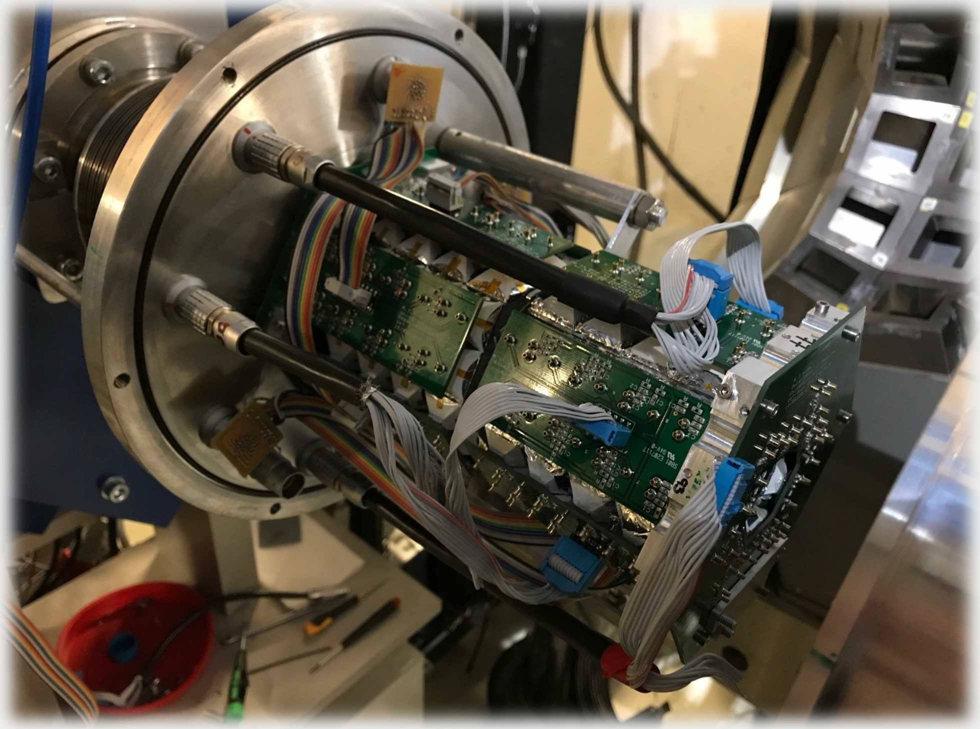
3) Identify recoil based on its <u>β decay (or chain of β decays)</u>.
4) Tag prompt γ-ray transitions originating from the recoil.

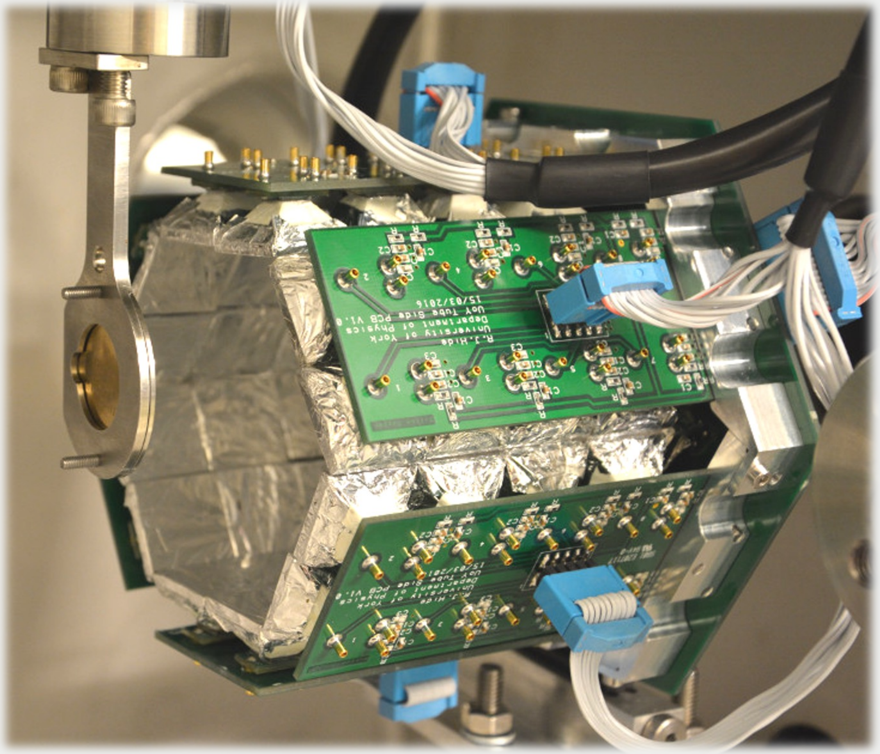


JYUTube charged particle detector

- JYUTube charged-particle veto detector is located at the target position of JUROGAM 3.
- 120 plastic scintillator elements read out by SiPMs.

Detect (and veto) evaporated charged particles:
→ <u>70%</u> proton detection efficiency
→ <u>97%</u> veto efficiency for 3*p* channel.
→ identification between *pn* (^{62}Ga) vs. 2*n* (^{62}Ge) evaporation channels.

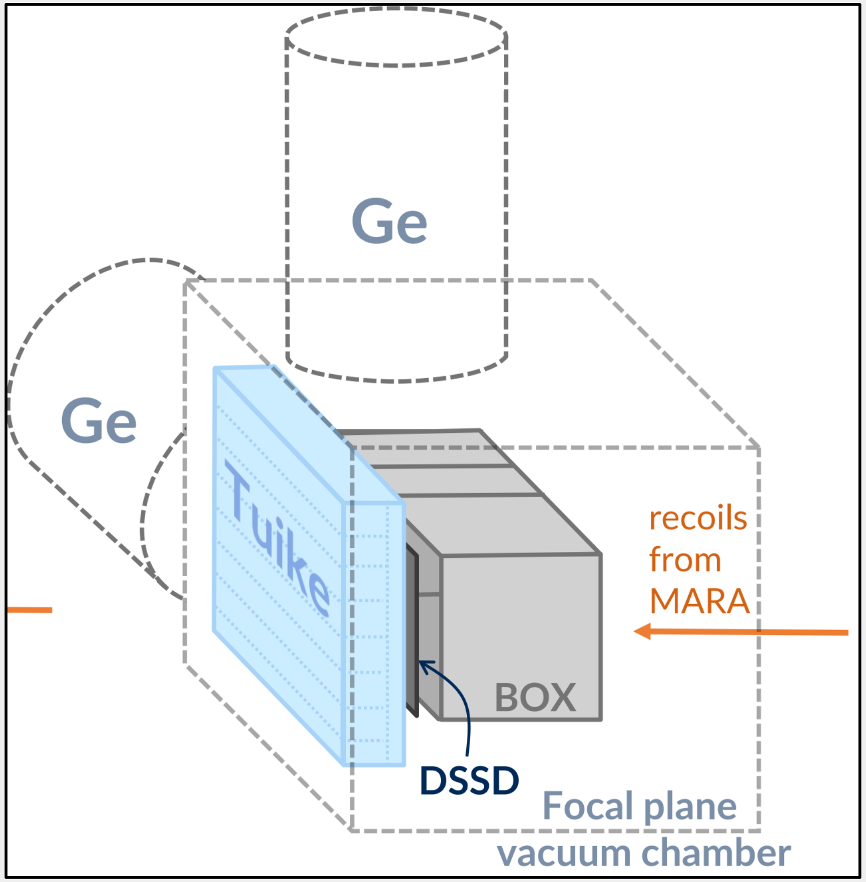


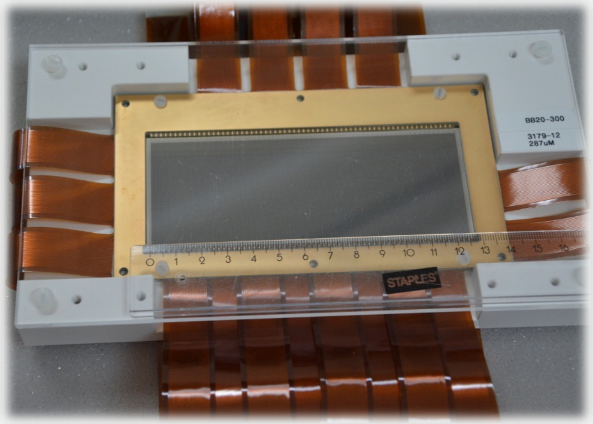


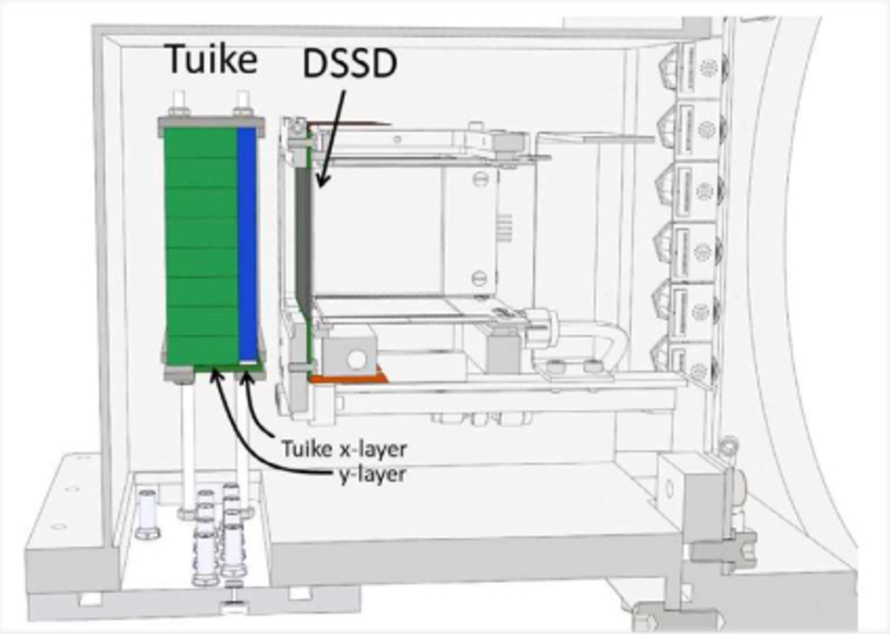
Focal plane setup

- Consists of
  1) position sensitive MWPC
  2) BB20 DSSD, silicon-strip detector
  3) "box" detector
  4) TUIKE scintillator detector
  5) 3 BEGe detectors + 1 Clover Ge detector

Micron BB20 DSSSD
Area: 128x48 mm^2
Strip pitch: 0.67 mm
Thicknesses: 150, 300, 700 um

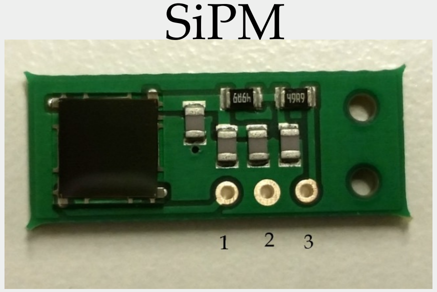


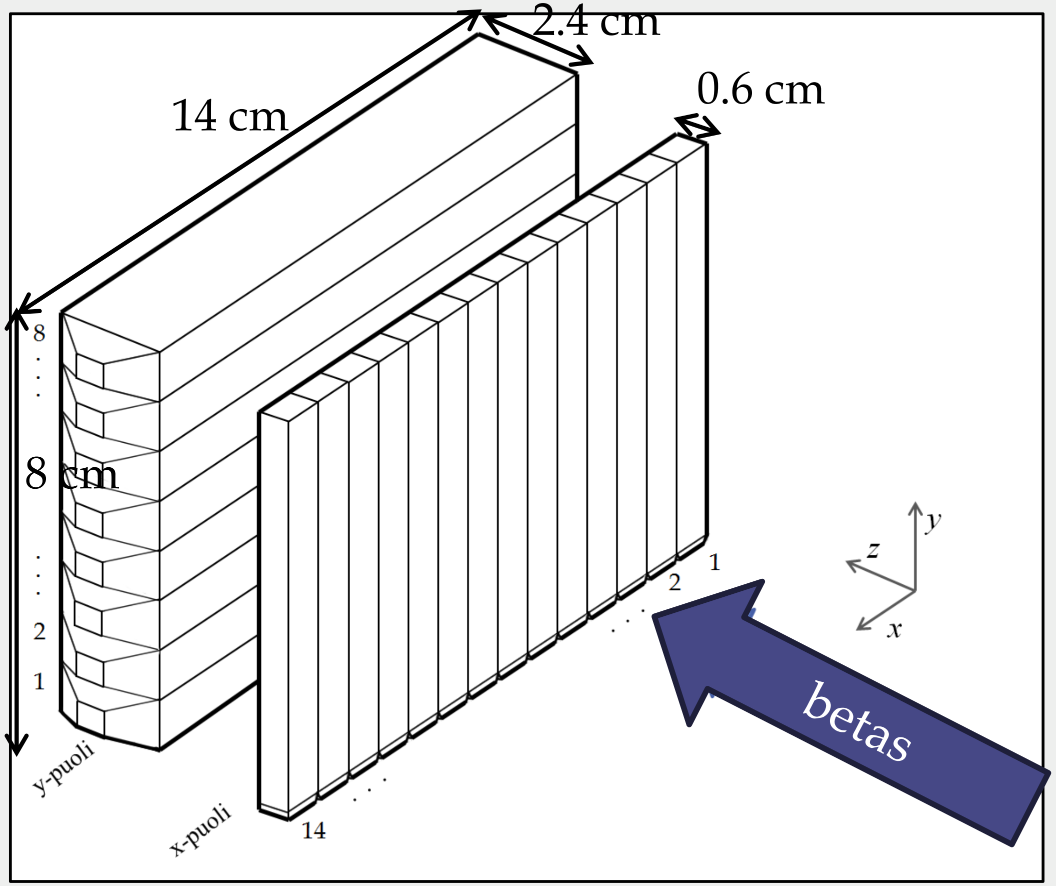


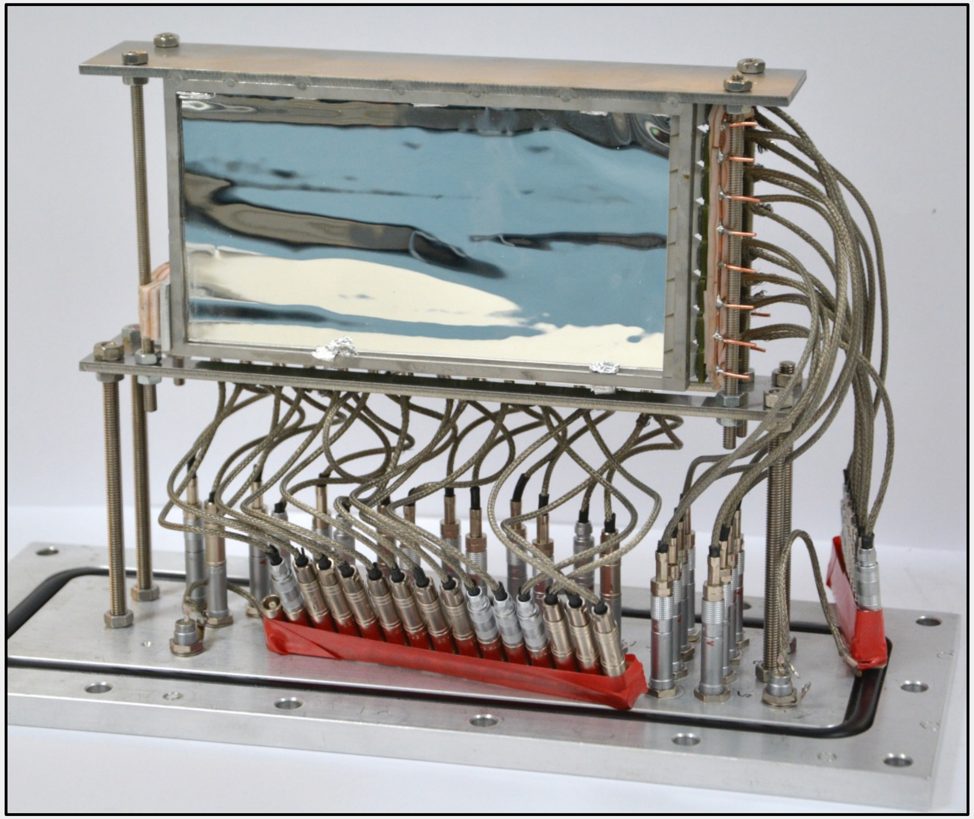


TUIKE - scintillator

- For detecting high-energy β particles.
- EJ-248 scintillator bars in two layers.
  - 14 vertical and 8 horizontal
- Light read out by SiPMs.



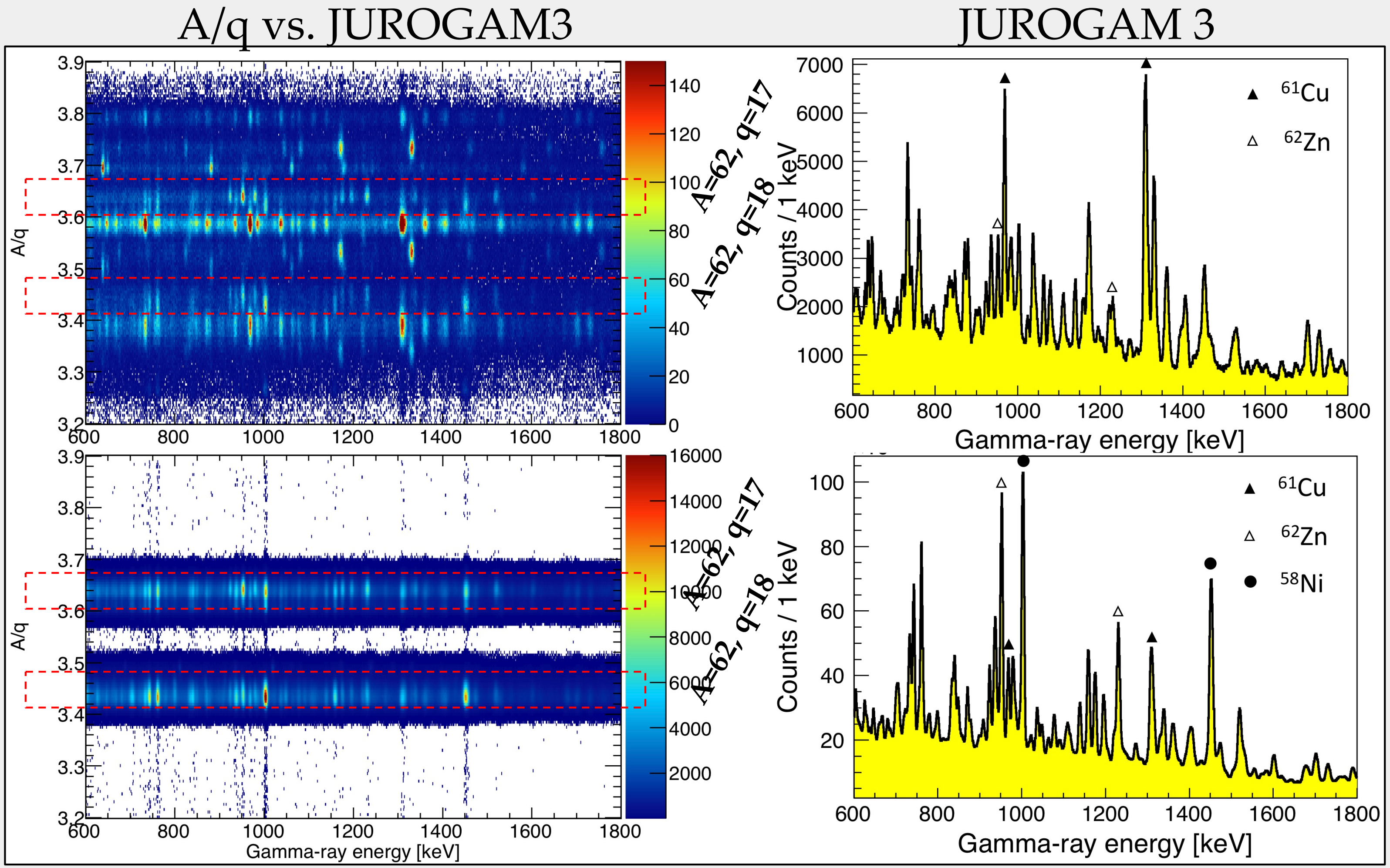




Experimental method for *N~Z* nuclei: Step 2): mass separation with MARA

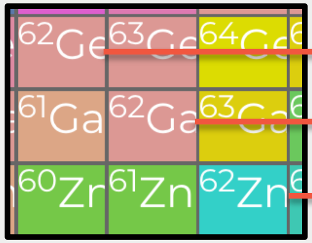
Separator tuned to pass *A*=62 residues to focal plane.
Use physical slits to "cut" neighboring masses.

Reaction: ^{40}Ca + ^{24}Mg
E_b = 106 MeV



product	[mbarn]
58Ni	142
61Cu	79.1
61Zn	37.1
55Co	28.6
59Cu	15
56Ni	12.1
58Cu	11.5
62Zn	8.73
62Ga	4.33
60Ni	4.02
57Ni	2.27
60Cu	1.71
57Co	1.4
59Zn	0.978
61Ga	0.0698
60Zn	0.0349
55Ni	0.0349
52Fe	0.0349

Experimental method for *N~Z* nuclei: Step 3): recoil-decay correlation



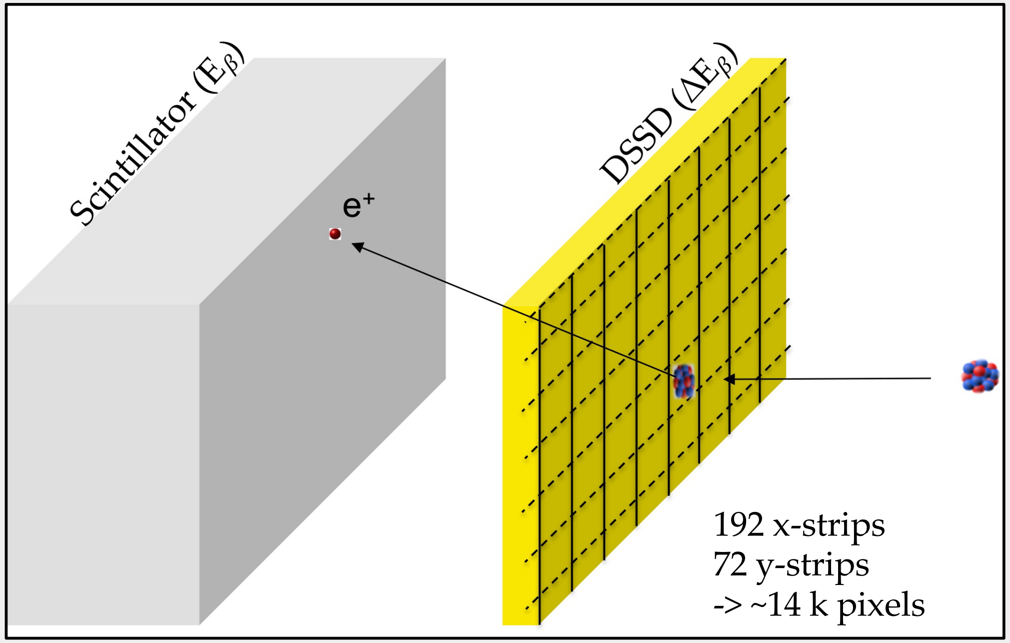
$t_{1/2}$ = 73.5 ms, Q_{EC} ~ 10 MeV

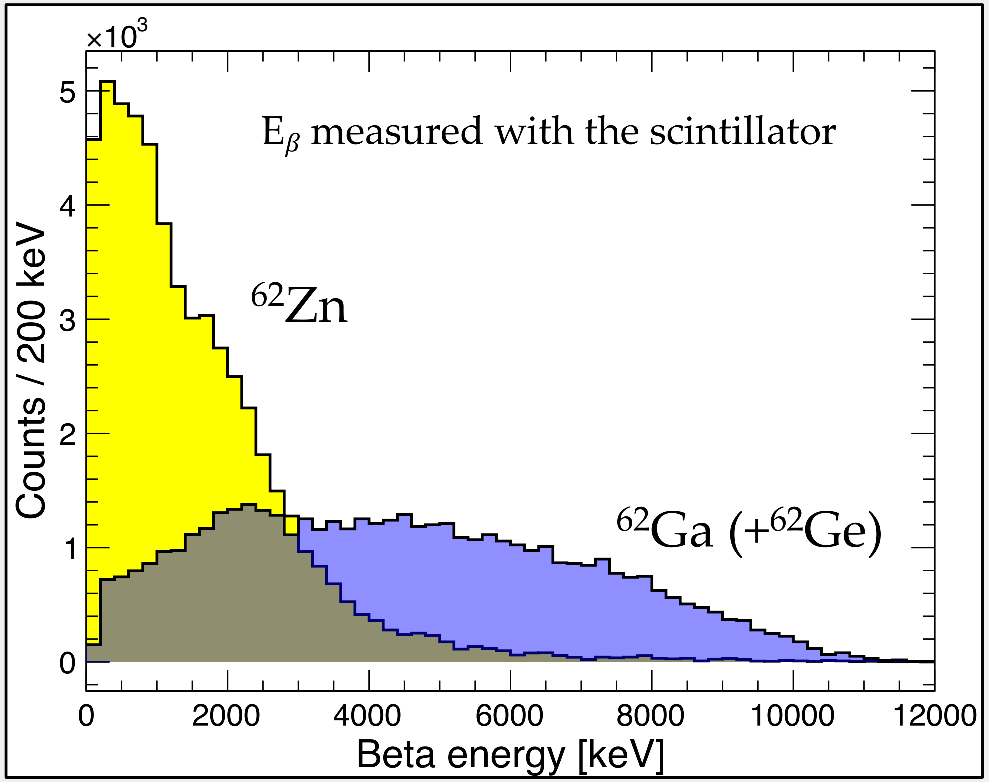
$t_{1/2}$ = 116.1 ms, Q_{EC} ~ 10 MeV

$t_{1/2}$ = 9.2 h, Q_{EC} ~ 2 MeV

1) Decay in the same pixel with the recoil implant within 3 x $t_{1/2}$
2) Register high-energy β in the scintillator.

→ Identify the nucleus of interest.

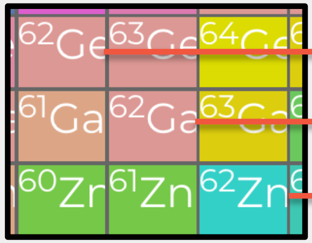




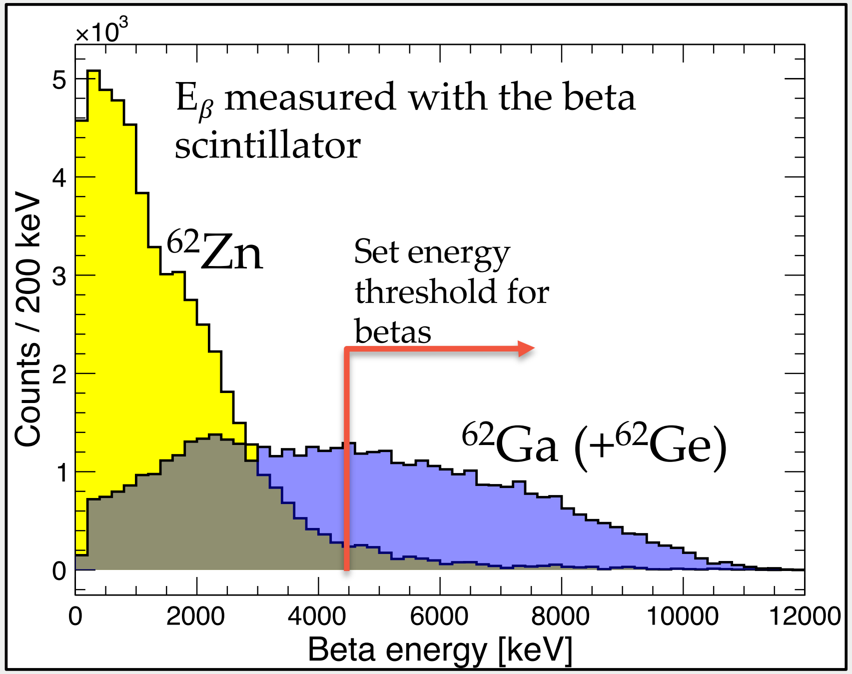
Experimental method for *N~Z* nuclei: Step 4): Recoil-β tagging

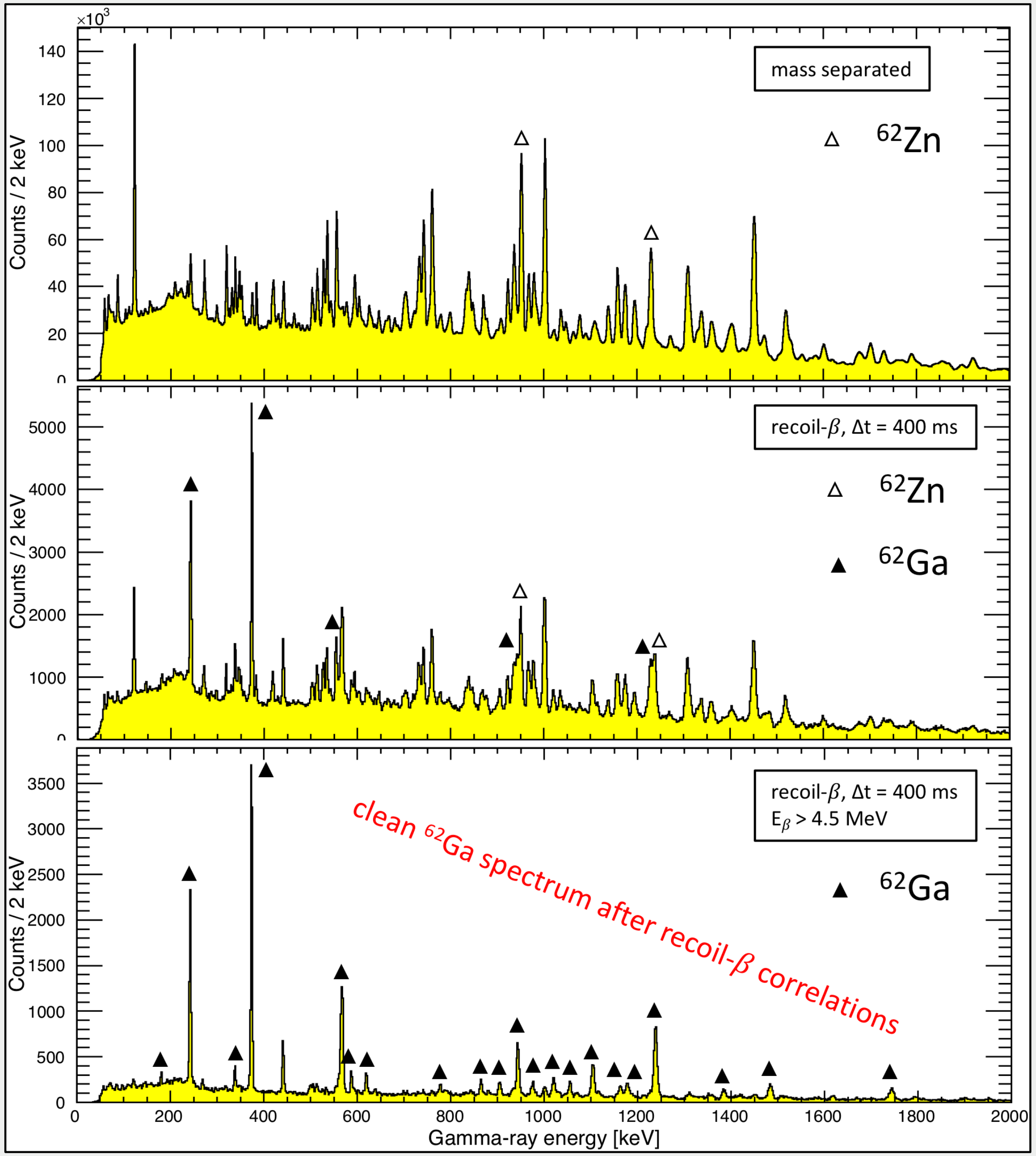
$^{40}Ca + ^{24}Mg \rightarrow ^{62}Zn + 2p, ^{62}Ga + pn, ^{62}Ge + 2n$

4) Tag prompt γ-ray transitions originating from the nucleus of interest.

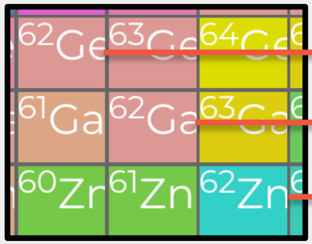


- $t_{1/2}$ = 73.5 ms, Q_{EC} ~ 10 MeV
- $t_{1/2}$ = 116.1 ms, Q_{EC} ~ 10 MeV
- $t_{1/2}$ = 9.2 h, Q_{EC} ~ 2 MeV





Experimental method for *N~Z* nuclei: recoil-beta tagging of ^{62}Ge



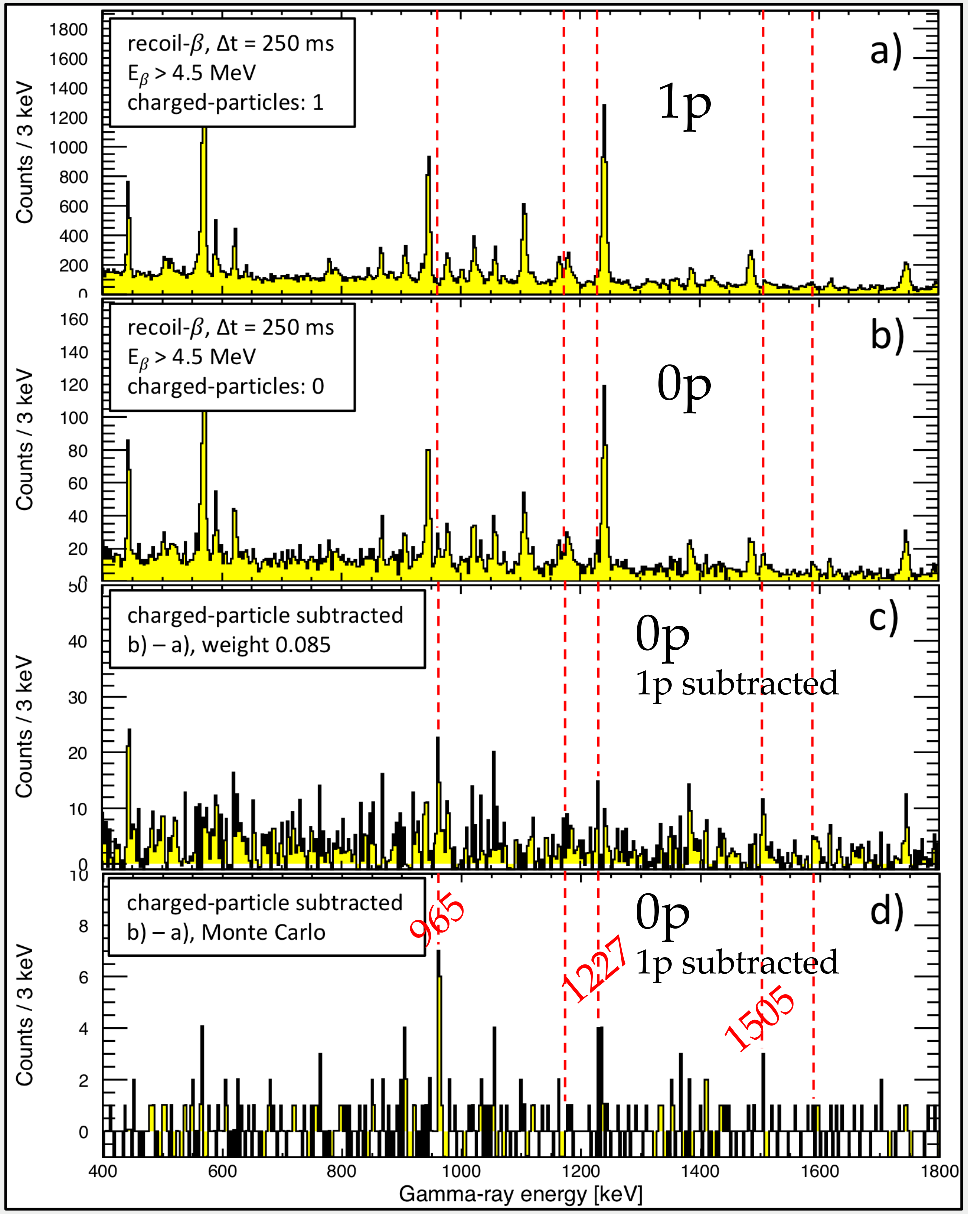
$t_{1/2}$ = 73.5 ms, Q_{EC} ~ 10 MeV

$t_{1/2}$ = 116.1 ms, Q_{EC} ~ 10 MeV

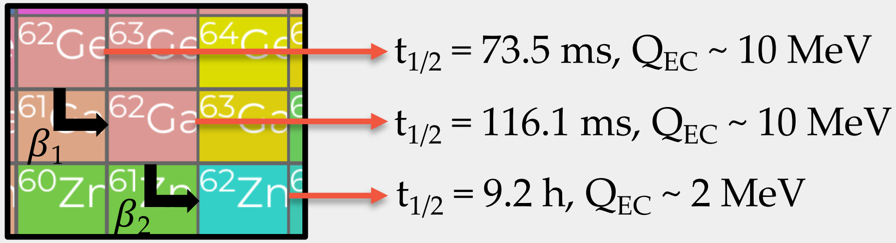
$t_{1/2}$ = 9.2 h, Q_{EC} ~ 2 MeV

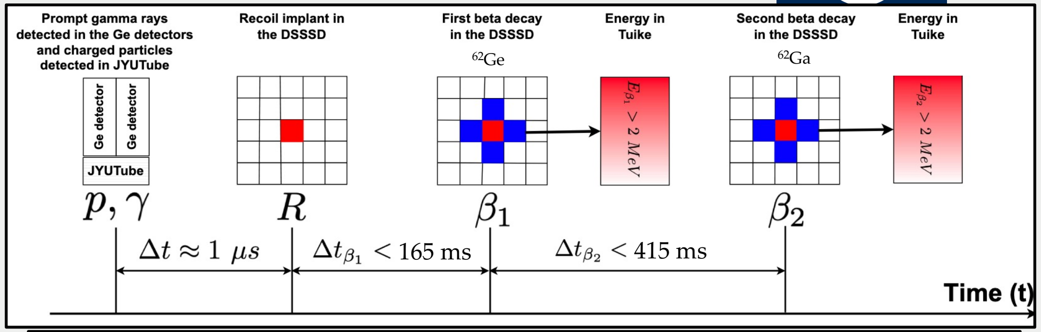
- Use JYUTube to discriminate between ^{62}Ga (*pn*) and ^{62}Ge (2*n*) gamma-ray transitions.
- Apply background subtraction -> subtract 1p spectrum from the 0p spectrum.
- Get candidates for $2^+ \rightarrow 0^+$, $4^+ \rightarrow 2^+$ and $6^+ \rightarrow 4^+$ transitions in ^{62}Ge.

^{40}Ca + ^{24}Mg → ^{62}Ga + pn, ^{62}Ge + 2n

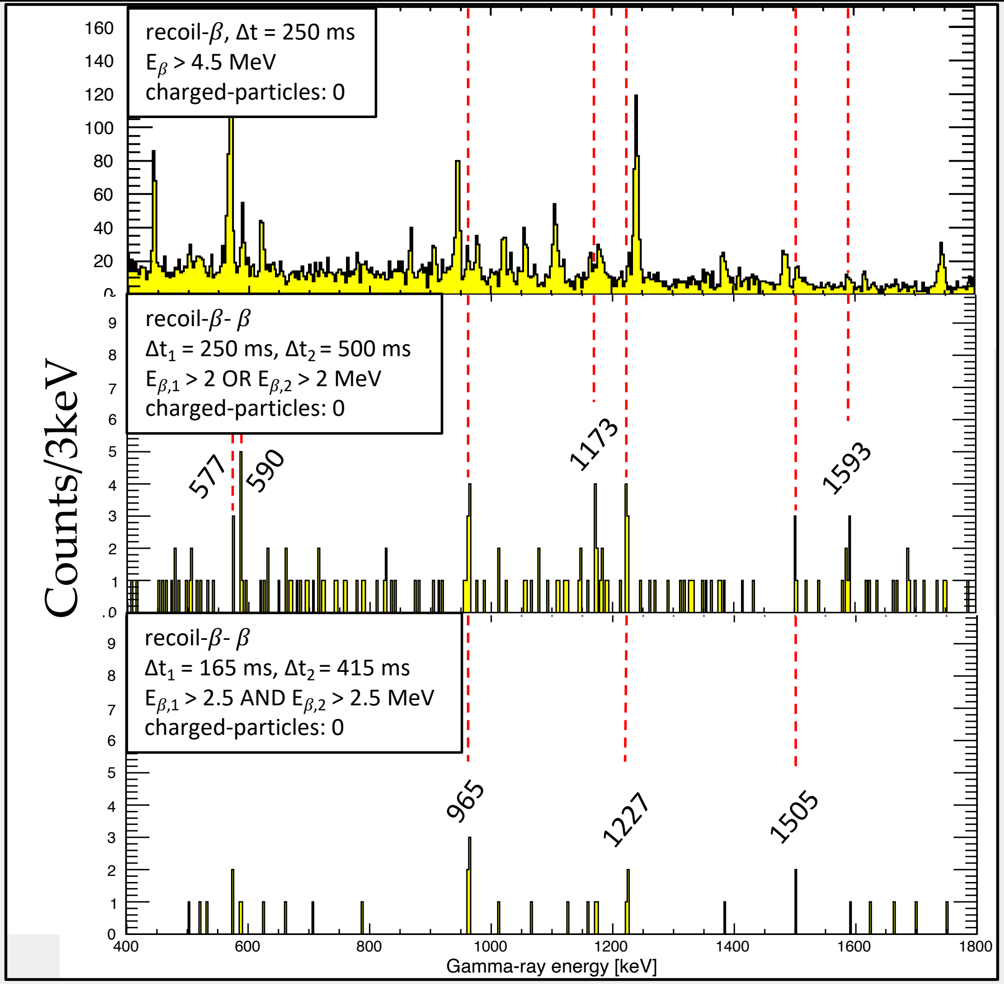


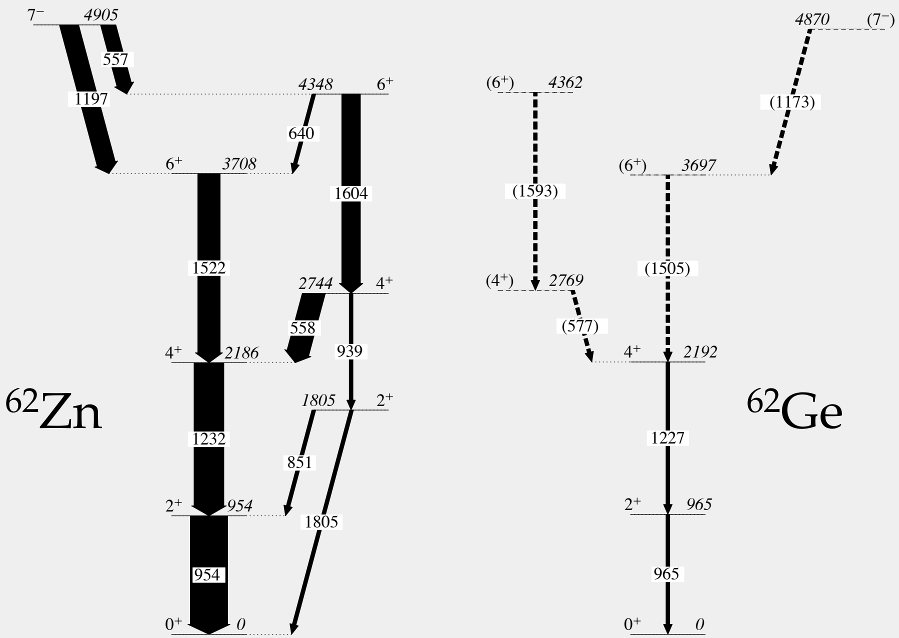
Experimental method for *N~Z* nuclei: recoil-β-β tagging of ^{62}Ge



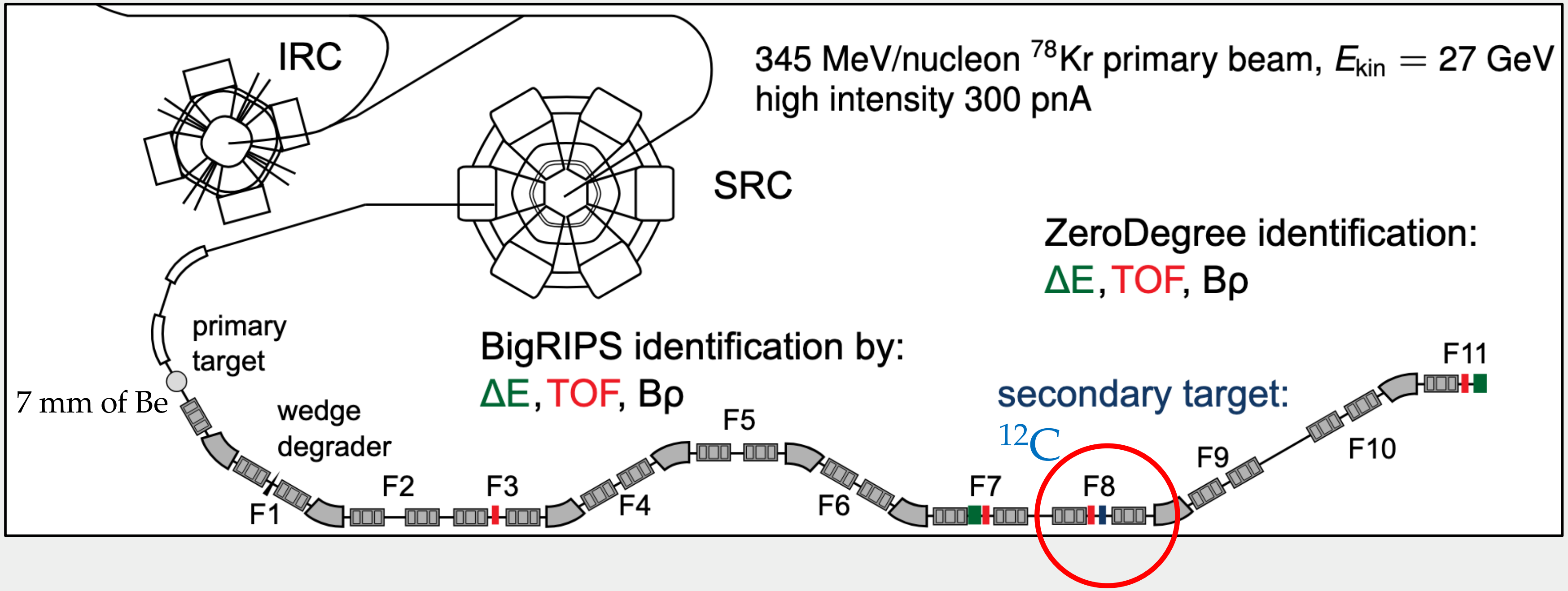


- recoil-β-β correlations pick up the same gammas as observed in the charged-particle vetoed recoil-β tagged spectrum.

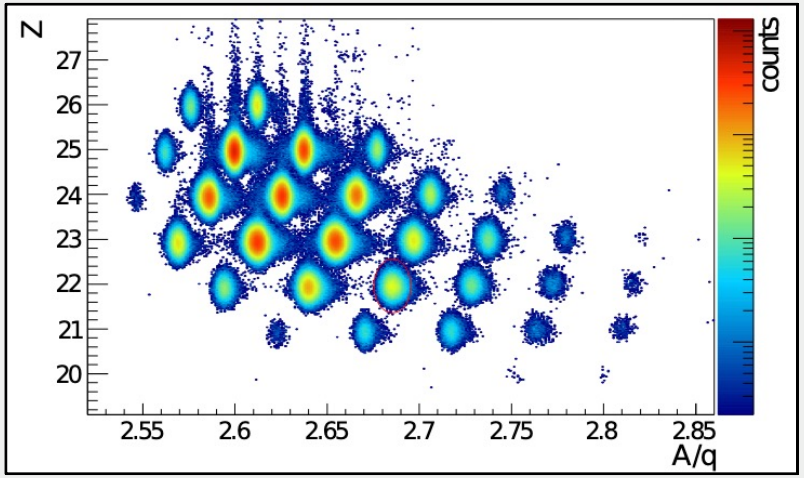




RIKEN experiment (beam production)

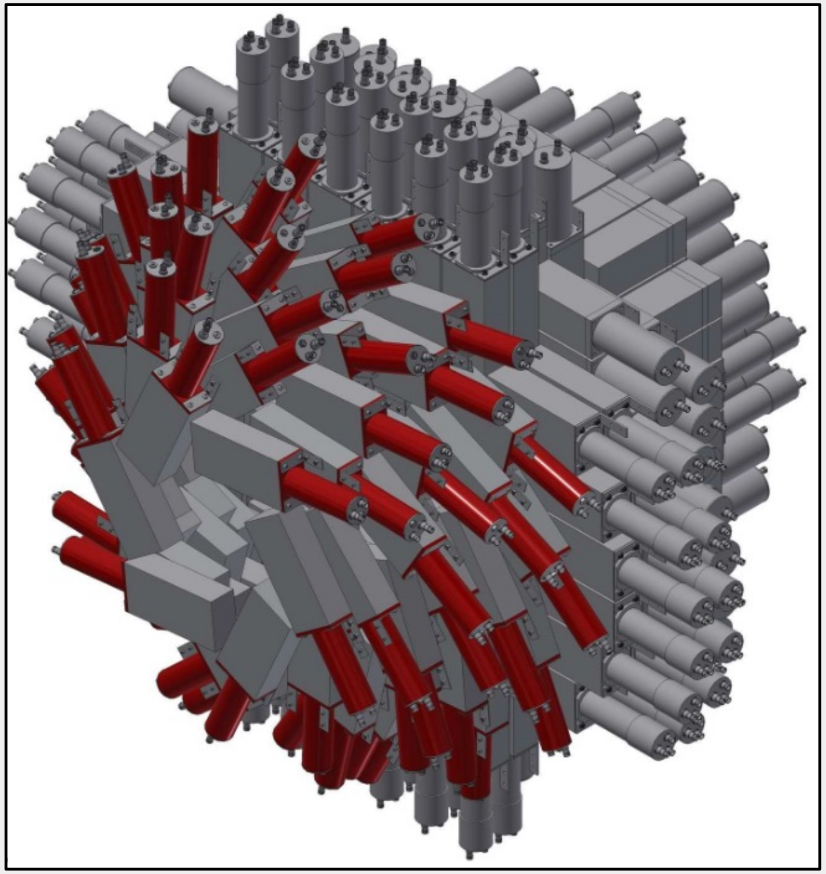


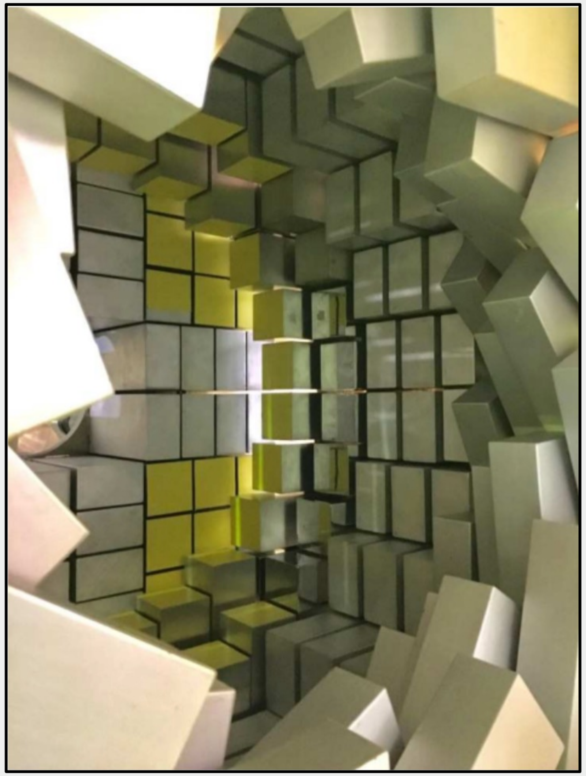
- Fragmentation (or fission) of intense primary beam
- Particle identification by Bρ - ΔE – ToF:
  - ^{62}Ge intensity ~ 290 pps, ^{62}Ga ~ 1800 pps
- Secondary reaction target at F8 surrounded by DALI2 γ-ray array.
- Particle identification after target by ZeroDegree spectrometer.



RIKEN experiment (DALI2)

DALI2:
- 226 NaI(Tl) detectors
- Intrinsic resolution 7 % at 1 MeV
- In-beam resolution ~10 % at 150 AMeV
- Efficiency ~20 % at 1 MeV (before addback)



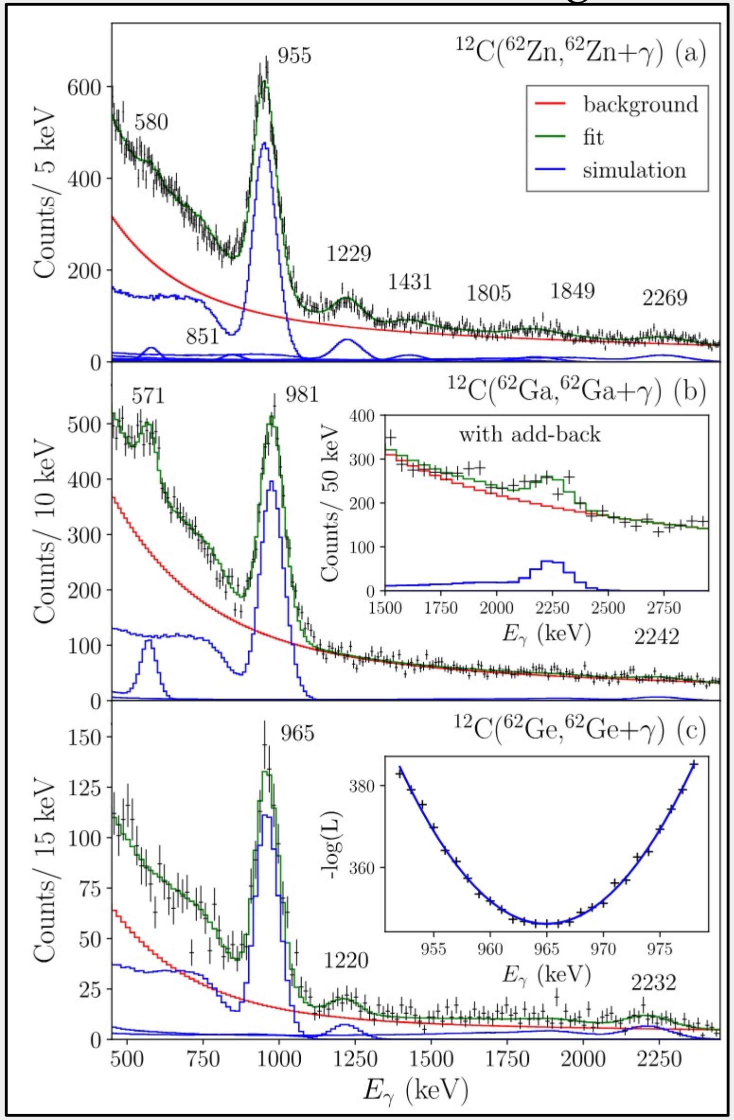


inelastic scattering:
^{62}Ge -------> |^{12}C| -------> ^{62}Ge

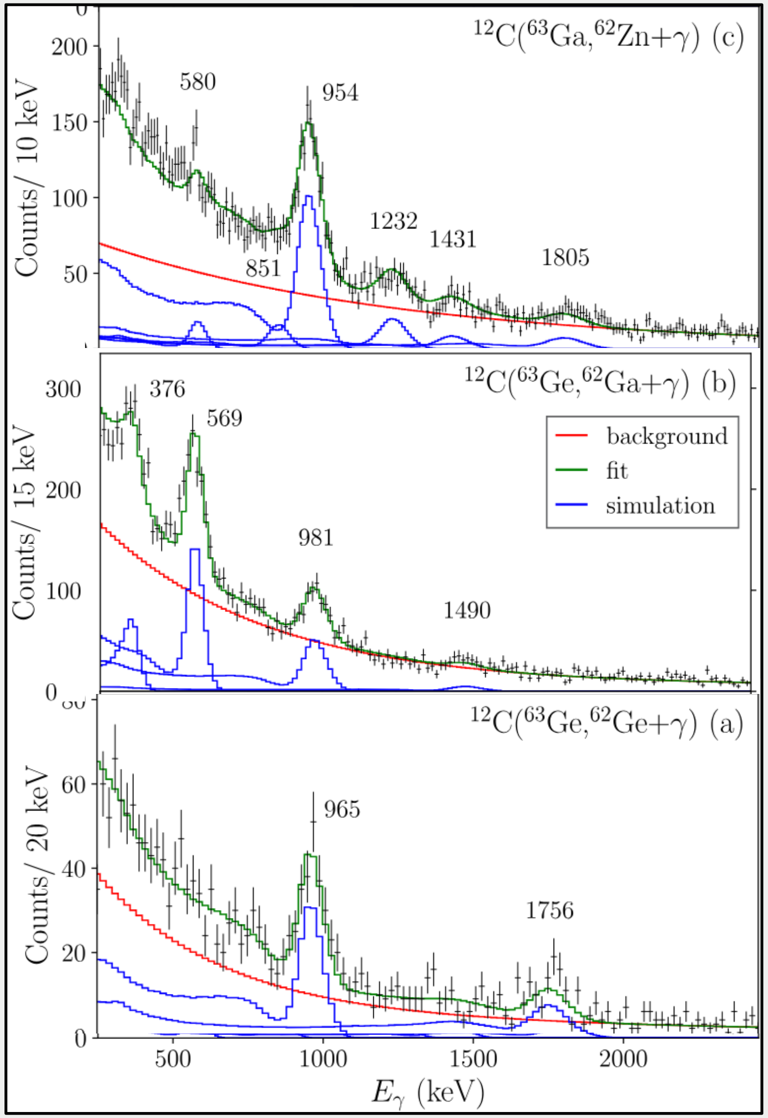
neutron (proton) knockout:
^{63}Ge -------> |^{12}C| -------> ^{62}Ge

RIKEN experiment (results)

inelastic scattering



1-nucleon removal



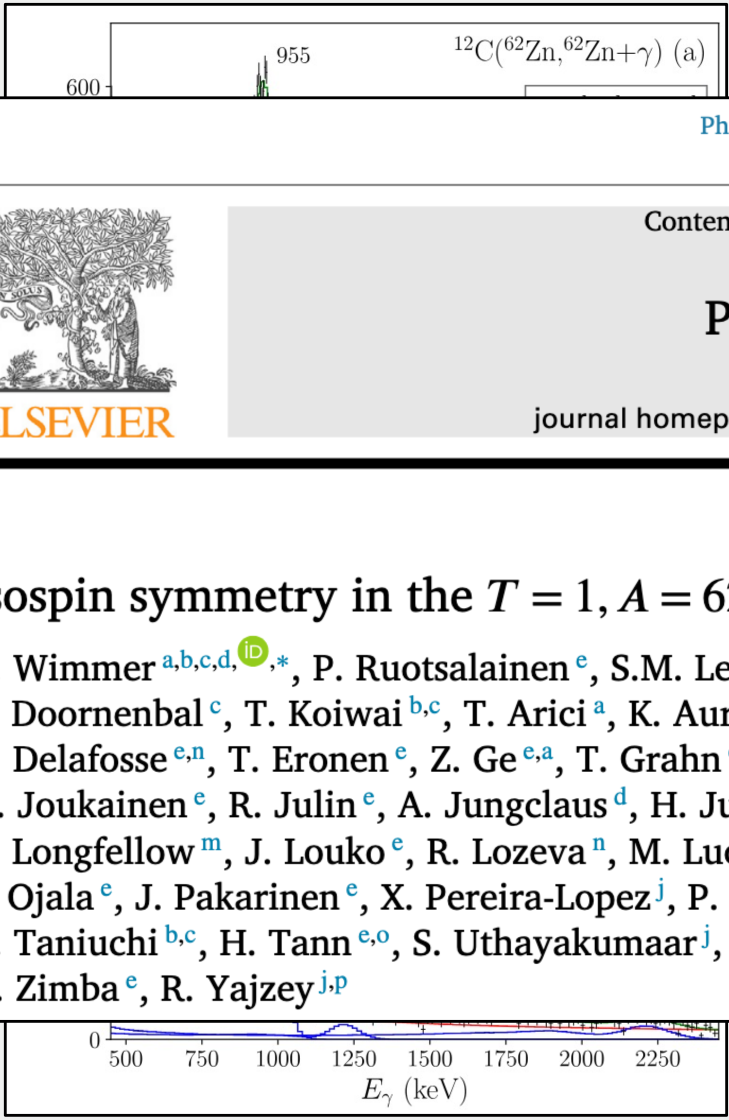
^{62}Zn

^{62}Ga

^{62}Ge

See the same gamma rays as in the JYFL experiment for the 2^+ -> 0^+ and 4^+ -> 2^+ transitions in ^{62}Ge!

RIKEN experiment (results)



Phys. Lett. B 847 (2023) 138249

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PHYSICS LETTERS B

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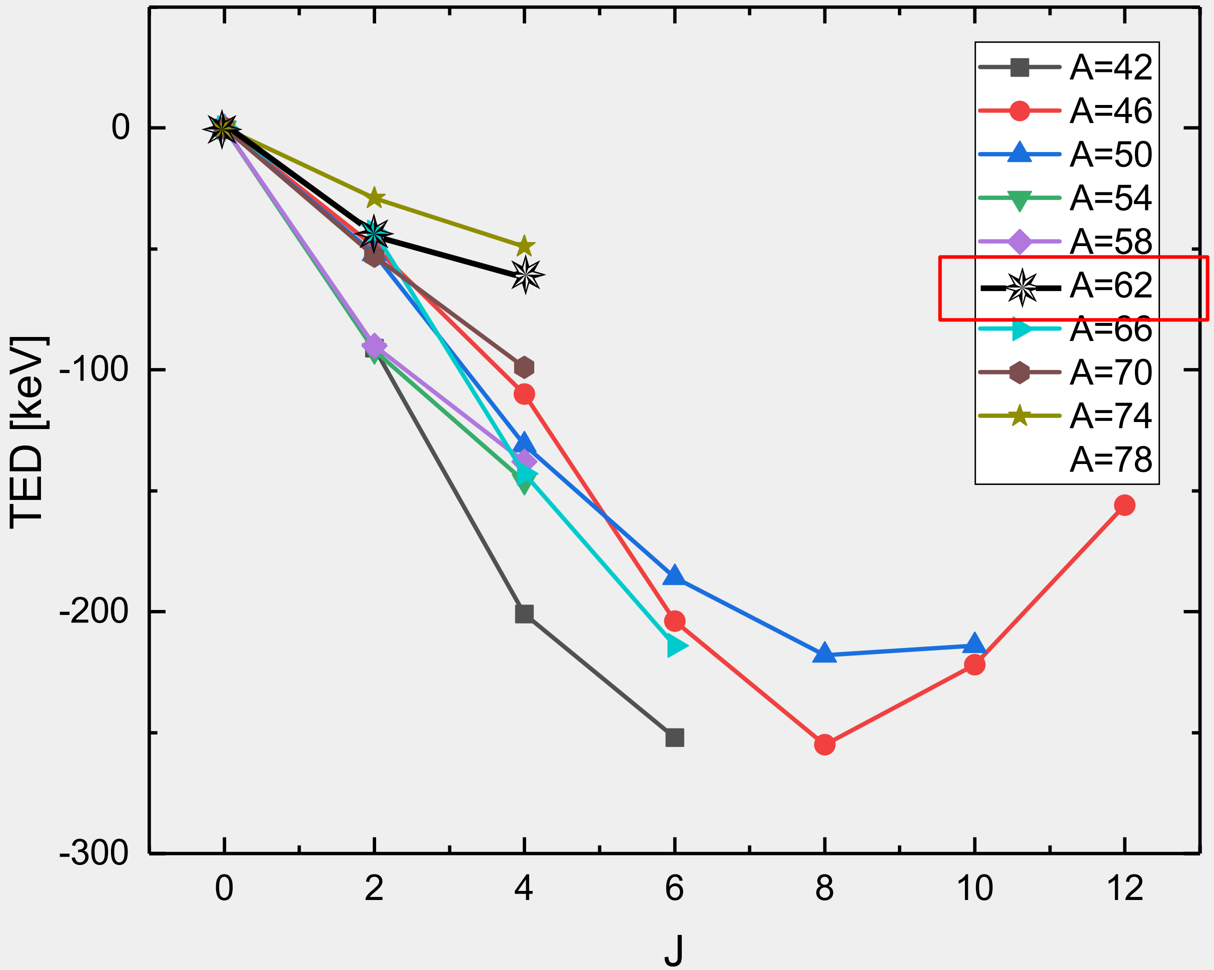
Isospin symmetry in the $T = 1, A = 62$ triplet

K. Wimmer [a,b,c,d,*], P. Ruotsalainen [e], S.M. Lenzi [f,g], A. Poves [h], T. Hüyük [i], F. Browne [c], P. Doornenbal [c], T. Koiwai [b,c], T. Arici [a], K. Auranen [e], M.A. Bentley [j], M.L. Cortés [g], C. Delafosse [e,n], T. Eronen [e], Z. Ge [e,a], T. Grahn [e], P.T. Greenlees [e], A. Illana [e], N. Imai [l], H. Joukainen [e], R. Julin [e], A. Jungclaus [d], H. Jutila [e], A. Kankainen [e], N. Kitamura [l], B. Longfellow [m], J. Louko [e], R. Lozeva [n], M. Luoma [e], B. Mauss [c], D.R. Napoli [k], M. Niikura [b], J. Ojala [e], J. Pakarinen [e], X. Pereira-Lopez [j], P. Rahkila [e], F. Recchia [f,g], M. Sandzelius [e], J. Sarén [e], R. Taniuchi [b,c], H. Tann [e,o], S. Uthayakumaar [j], J. Uusitalo [e], V. Vaquero [d], R. Wadsworth [j], G. Zimba [e], R. Yajzey [j,p]

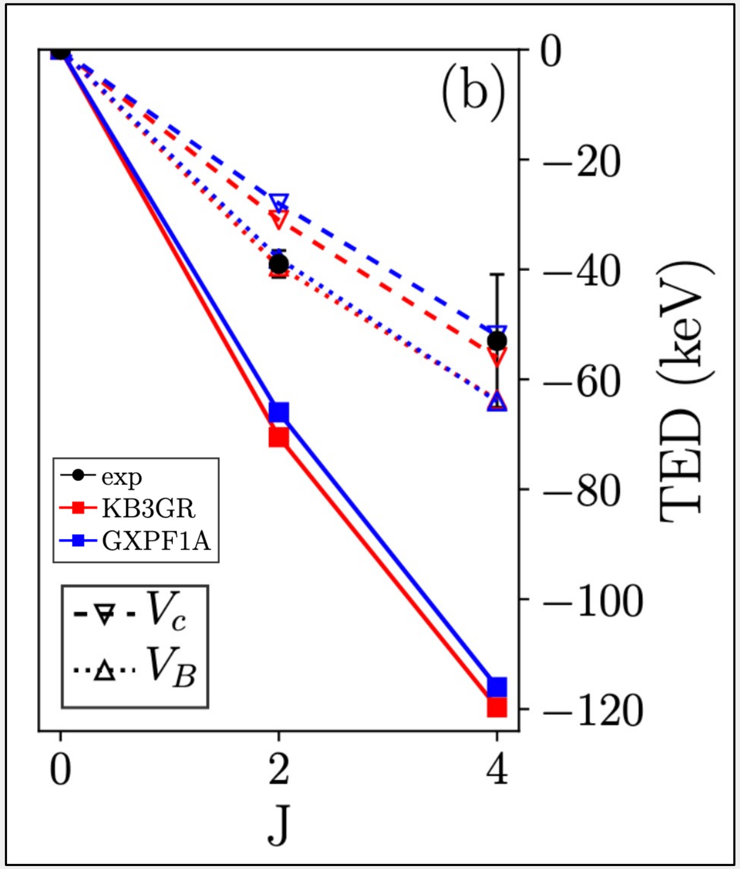
See the same gamma rays as in the JYFL experiment for the $2^+ \to 0^+$ and $4^+ \to 2^+$ transitions in ^{62}Ge!

Conclusions: new TED data at *A*=62

- $\textbf{TED}(J) = E^*(J, T_z{=}{-1}) + E^*(J, T_z = +1) - 2 \cdot E^*(J, T_z = 0)$
- Available experimental data:



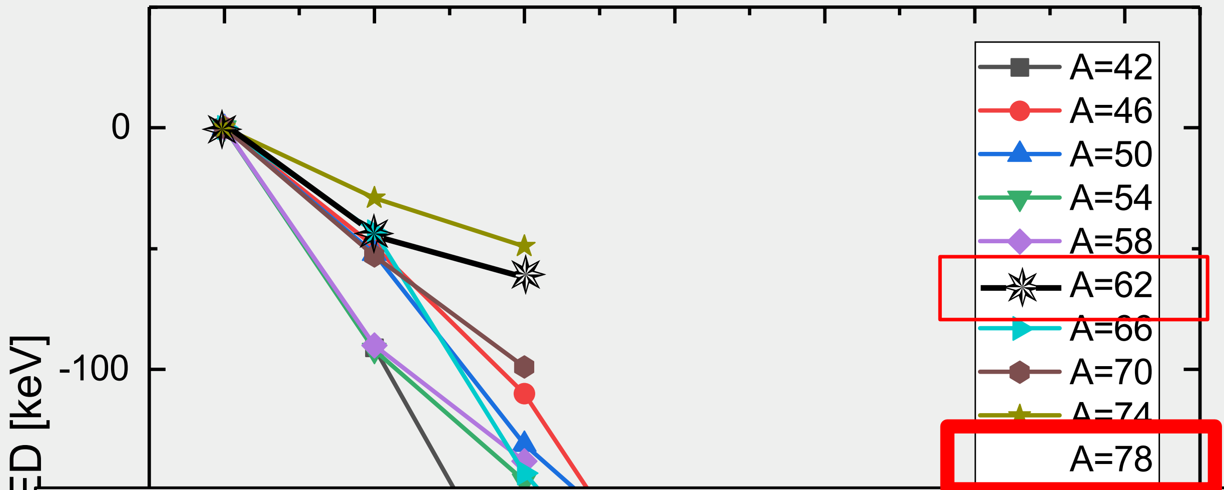
TED from SM for A=62



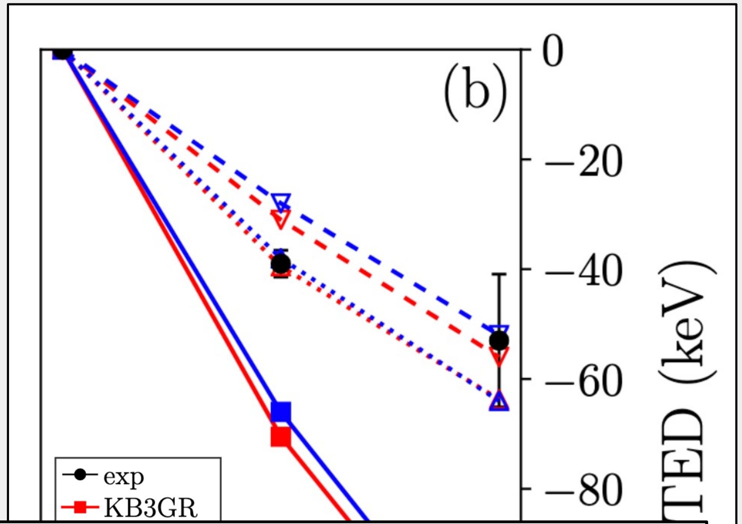
Conclusion: additional INC correction not needed for A=62 triplet! Why?

Conclusions: new TED data at *A*=62

- **TED**(J) = $E^*(J, T_z=-1) + E^*(J, T_z=+1) - 2 \cdot E^*(J, T_z=0)$
- Available experimental data:



TED from SM for A=62



PHYSICAL REVIEW LETTERS **134,** 022502 (2025)

First Identification of Excited States in ^{78}Zr and Implications for Isospin Nonconserving Forces in Nuclei

G. L. Zimba,[1,*] P. Ruotsalainen,[1] D. G. Jenkins,[2] W. Satuła,[3] J. Uusitalo,[1] R. Wadsworth,[2] X. Pereira Lopez,[4] K. Auranen,[1] A. D. Briscoe,[1,†] B. Cederwall,[5] S. Chen,[2] G. de Angelis,[6] M. Doncel,[7] A. Ertoprak,[5,‡] T. Grahn,[1] P. T. Greenlees,[1] A. Illana,[1,§] H. Joukainen,[1] R. Julin,[1] H. Jutila,[1] J. Keatings,[8] J. Louko,[1] M. Luoma,[1] A. M. Plaza,[1,9] J. Sarén,[1] B. S. Nara Singh,[8] J. Ojala,[1] J. Pakarinen,[1] P. Rahkila,[1] J. Romero,[1,9] A. Sood,[5] A. Stott,[2] C. Sullivan,[9] H. Tann,[9] and A. Tolosa Delgado[1,‖]

Summary

- A=62 triplet (^{62}Ge, ^{62}Ga and ^{62}Zn) investigated in two sperate experiments at JYFL-ACCLAB and RIKEN.
- Obtained results are in agreement for ^{62}Ge -> first confident assignment of the 2^+ and 4+ excited states in ^{62}Ge.
- RIKEN experiment confirms also the 2^+ state energy in ^{62}Ga.
- These data allowed theoretical investigations of the TED systematics for the *A*=62 isobaric triplet for the first time to study the isospin symmetry breaking effects.
- Additional isospin symmetry breaking effect appears to be weaker for A=62 than for the other studied triplets.

JYFL nuclear spectroscopy group

Thank you!