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Recoil-decay correlations with β particles at the MARA focal plane

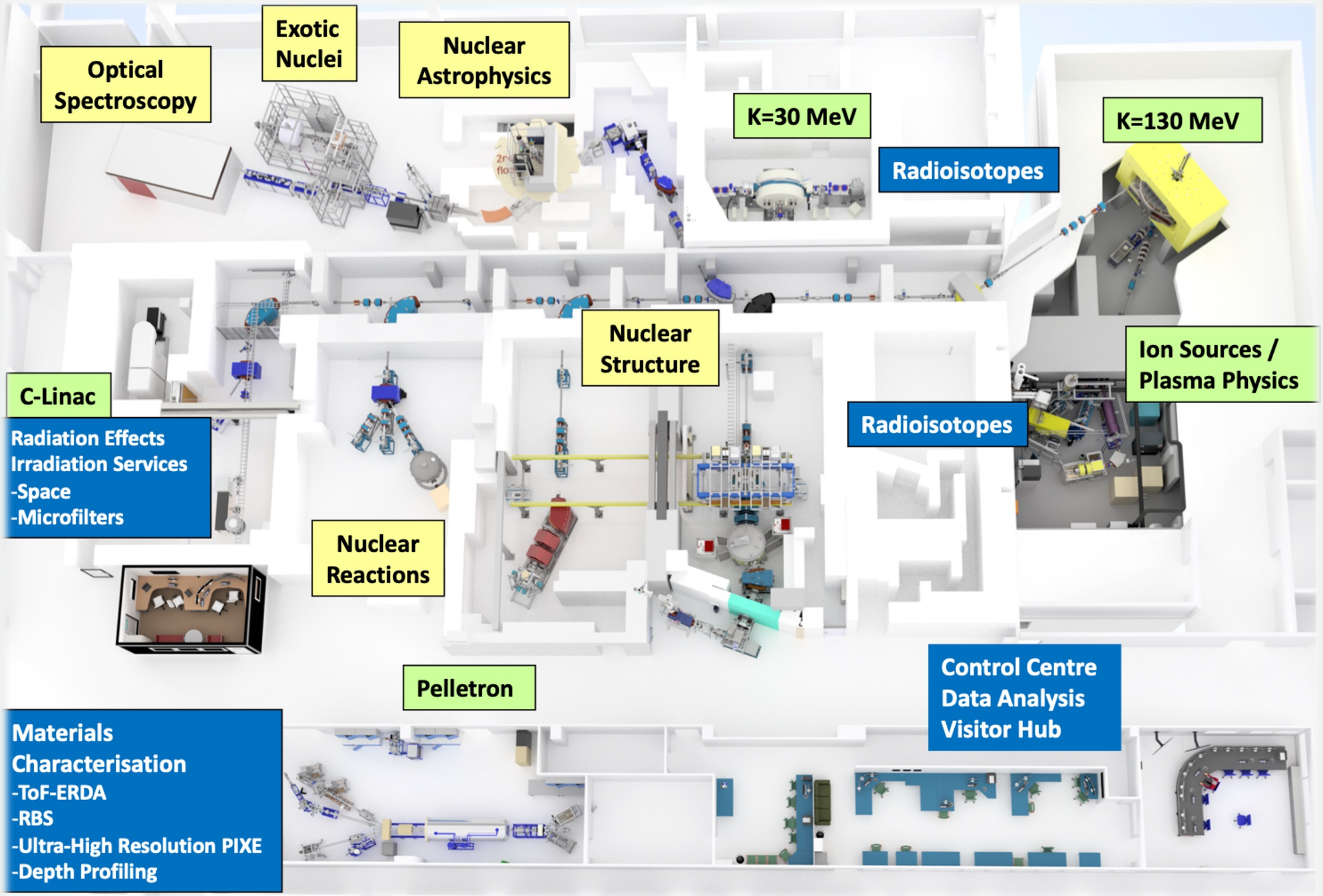
Panu Ruotsalainen

Active Stoppers for Decay Experiments, Valencia, Spain, 25.3.2025

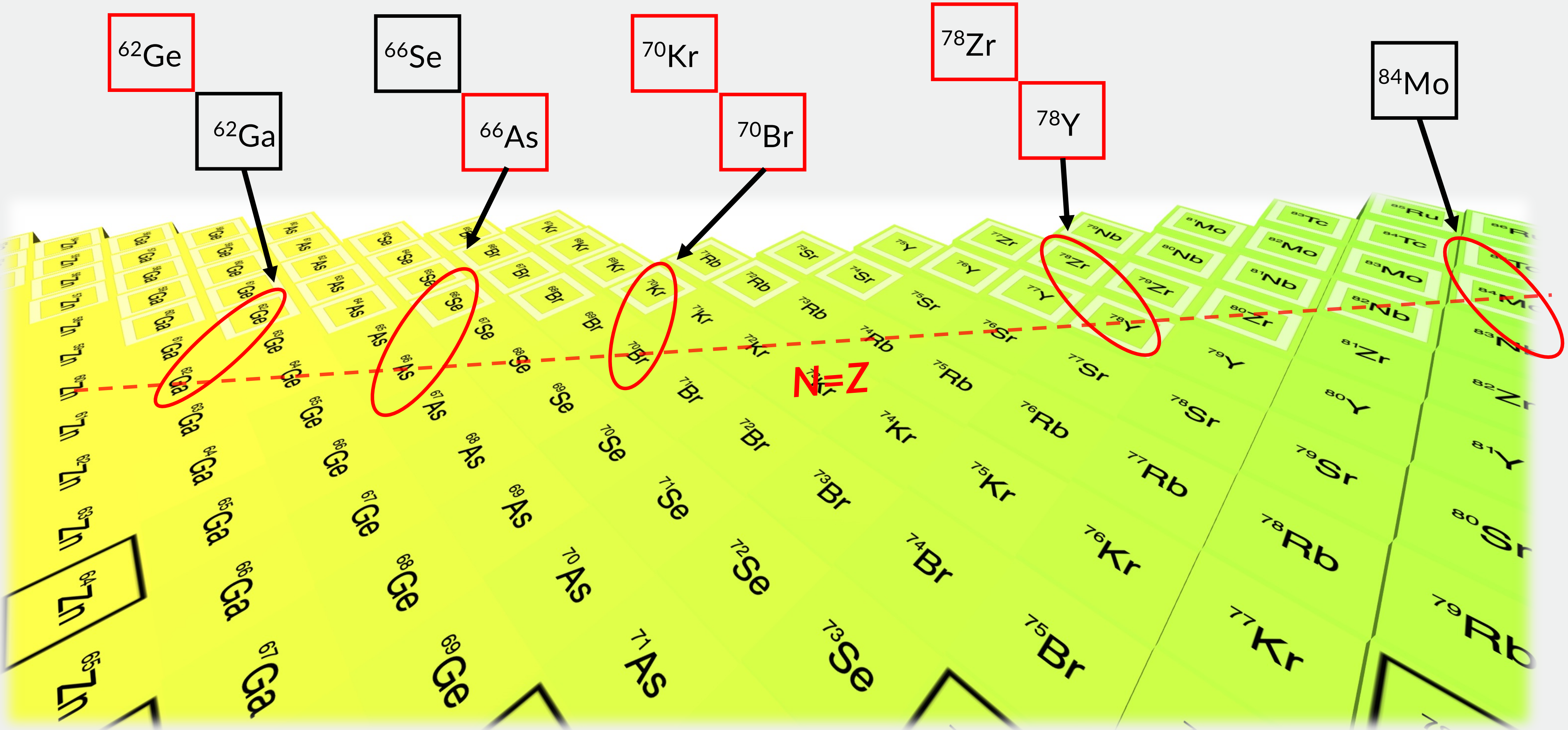
Contents

- JYFL-ACCLAB and recent research output for *N*~*Z* nuclei
- Physics motivation:
  - Isospin symmetry breaking: mirror and triplet energy differences (MED, TED)
- Recoil-β and recoil-β-β tagging methods + equipment at JYFL-ACCLAB to study *N*~*Z* nuclei:
  - ^{62}Ga, ^{62}Ge
  - ^{66}As
  - ^{70}Br, ^{70}Kr
  - ^{78}Y, ^{78}Zr
- Ongoing and future work: in-beam studies of β-delayed proton emitters in the A = 30-50 mass region
- Conclusions

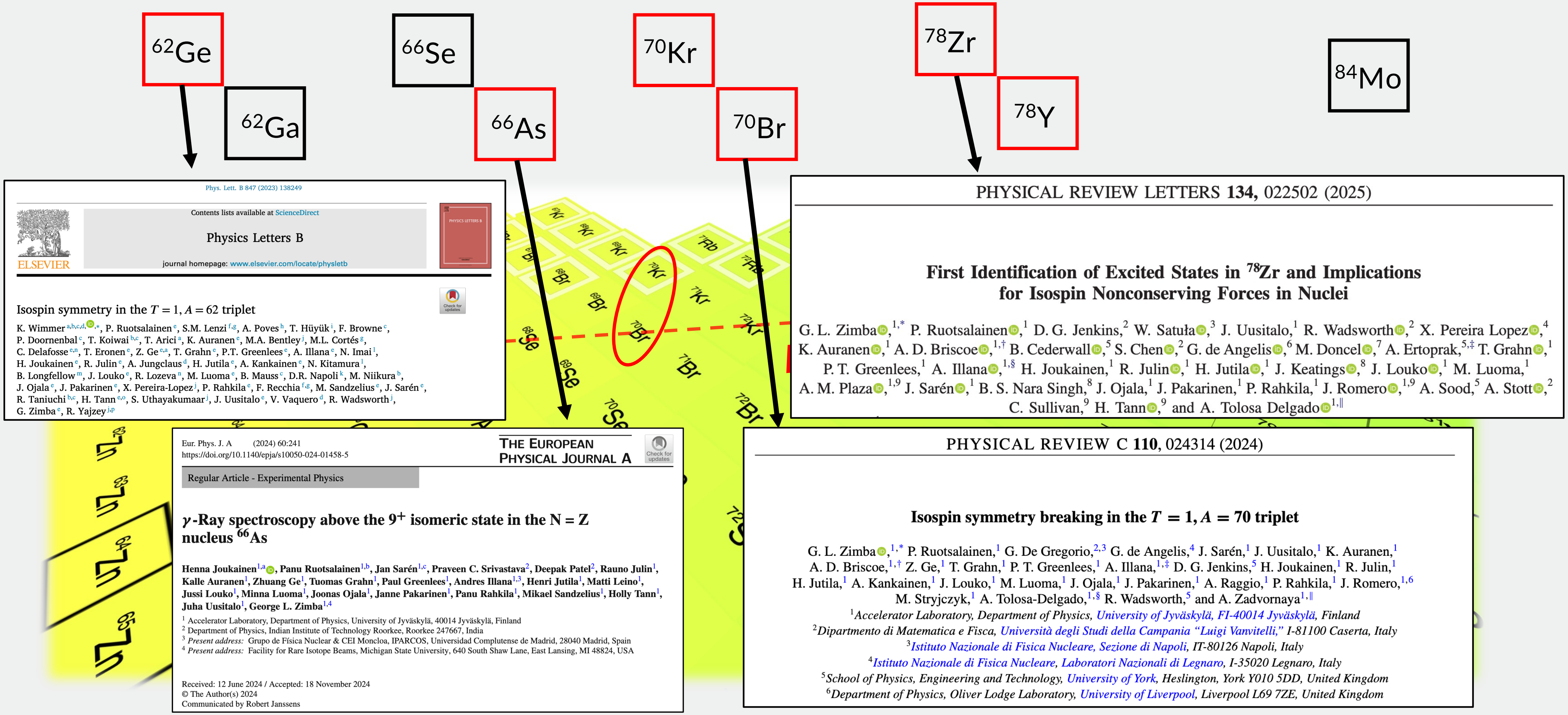
JYFL-ACCLAB @ Jyväskylä, Finland



Recent experiments around the *N*=Z line at JYFL-ACCLAB



Recent experiments around the N=Z line at JYFL-ACCLAB



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

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THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

γ-Ray spectroscopy above the 9^+ isomeric state in the N = Z nucleus ^{66}As

Henna Joukainen[1,a], Panu Ruotsalainen[1,b], Jan Sarén[1,c], Praveen C. Srivastava[2], Deepak Patel[2], Rauno Julin[1], Kalle Auranen[1], Zhuang Ge[1], Tuomas Grahn[1], Paul Greenlees[1], Andres Illana[1,3], Henri Jutila[1], Matti Leino[1], Jussi Louko[1], Minna Luoma[1], Joonas Ojala[1], Janne Pakarinen[1], Panu Rahkila[1], Mikael Sandzelius[1], Holly Tann[1], Juha Uusitalo[1], George L. Zimba[1,4]

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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,‖]

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,‖]

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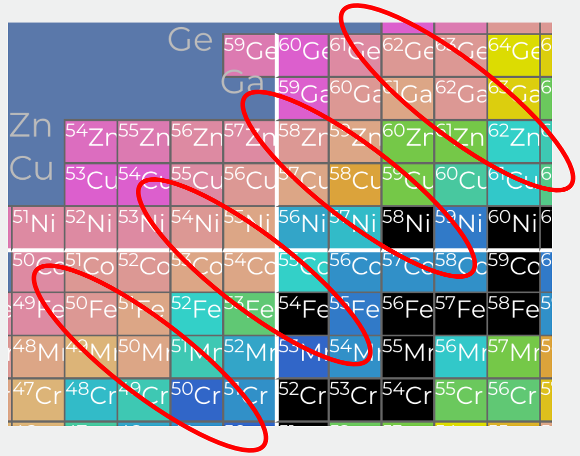
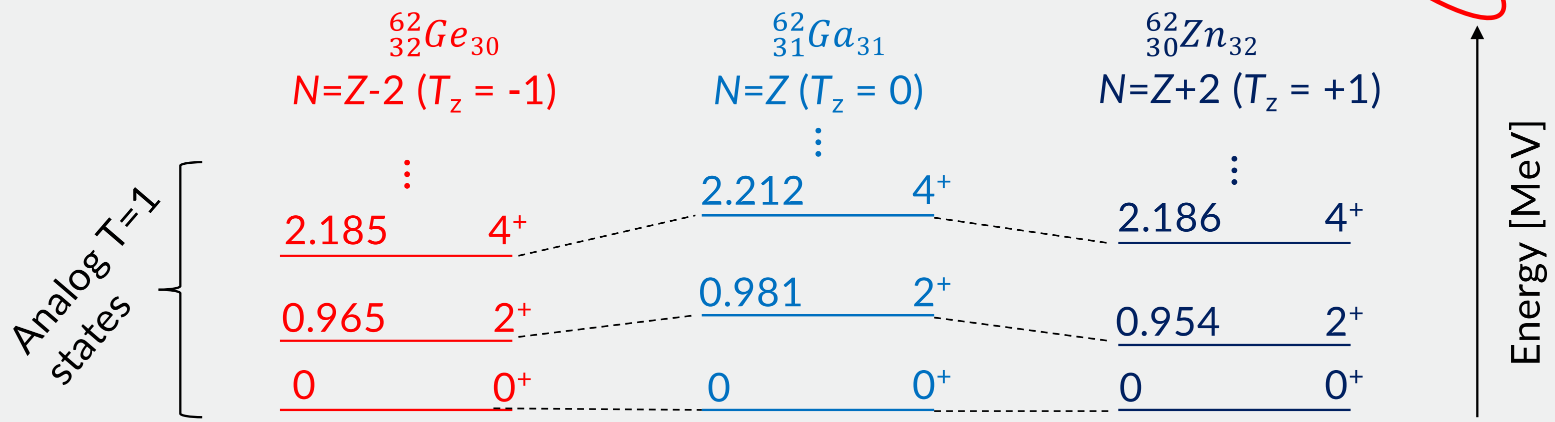
Isospin symmetry breaking

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



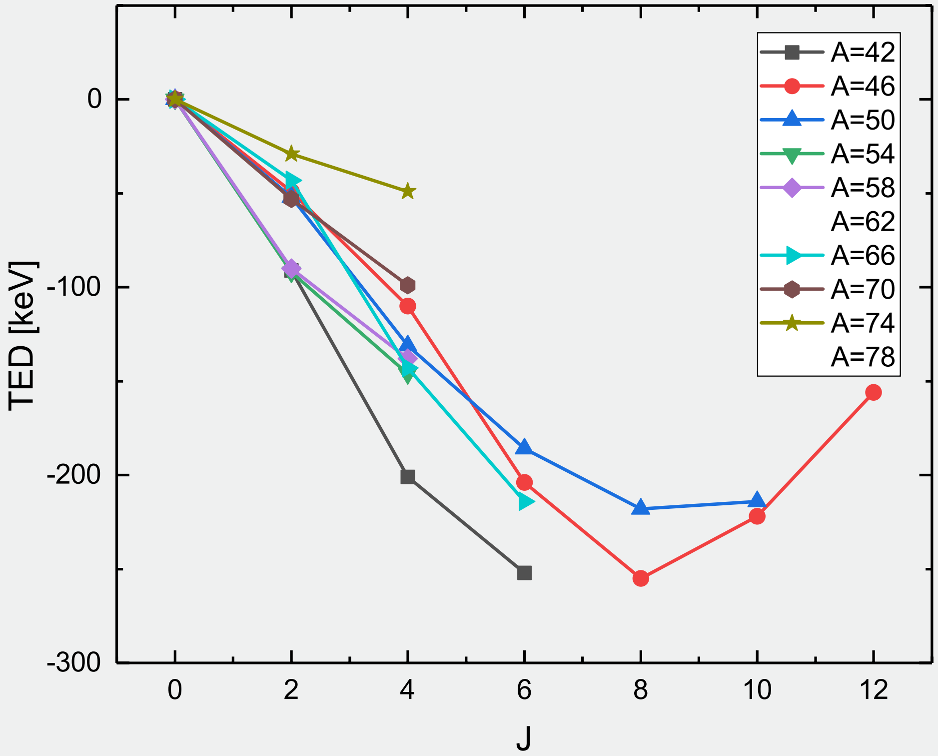


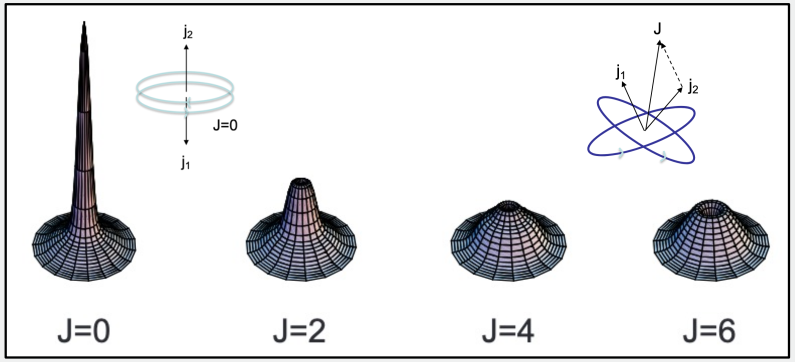
- Investigate **triplet energy differences → TED**
- **TED**(J) = $E^*(J, T_z = -1) + E^*(J, T_z = +1) - 2 \cdot E^*(J, T_z = 0)$
- **TED** tests the charge independency $(V_{pp} + V_{nn})/2 = V_{pn}$ of the nuclear interaction.

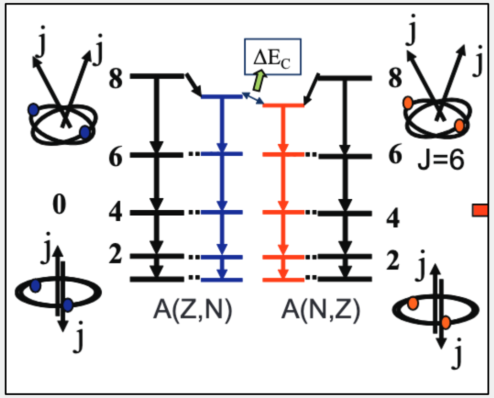
- Investigate **mirror energy differences → MED**
- **MED**(J) = $E^*(J, T_z = -1) - E^*(J, T_z = +1)$
- **MED** tests the charge symmetry $V_{pp} = V_{nn}$ of the nuclear interaction.

Isospin symmetry breaking

- **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.



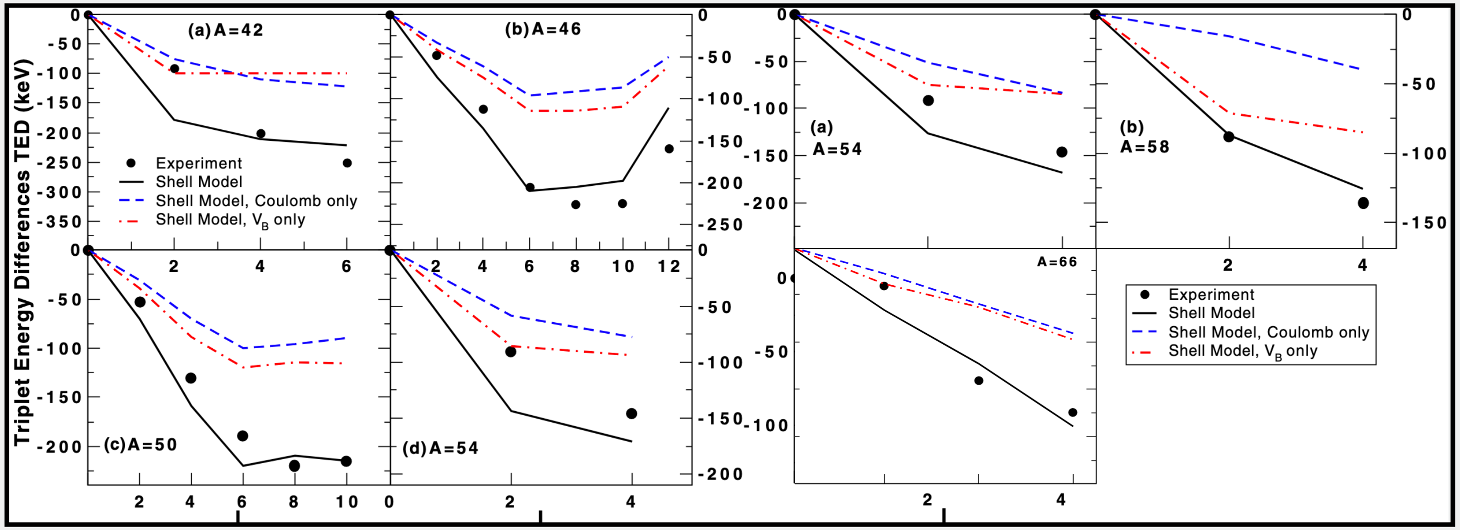




Isospin symmetry breaking - TED

- 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:**

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



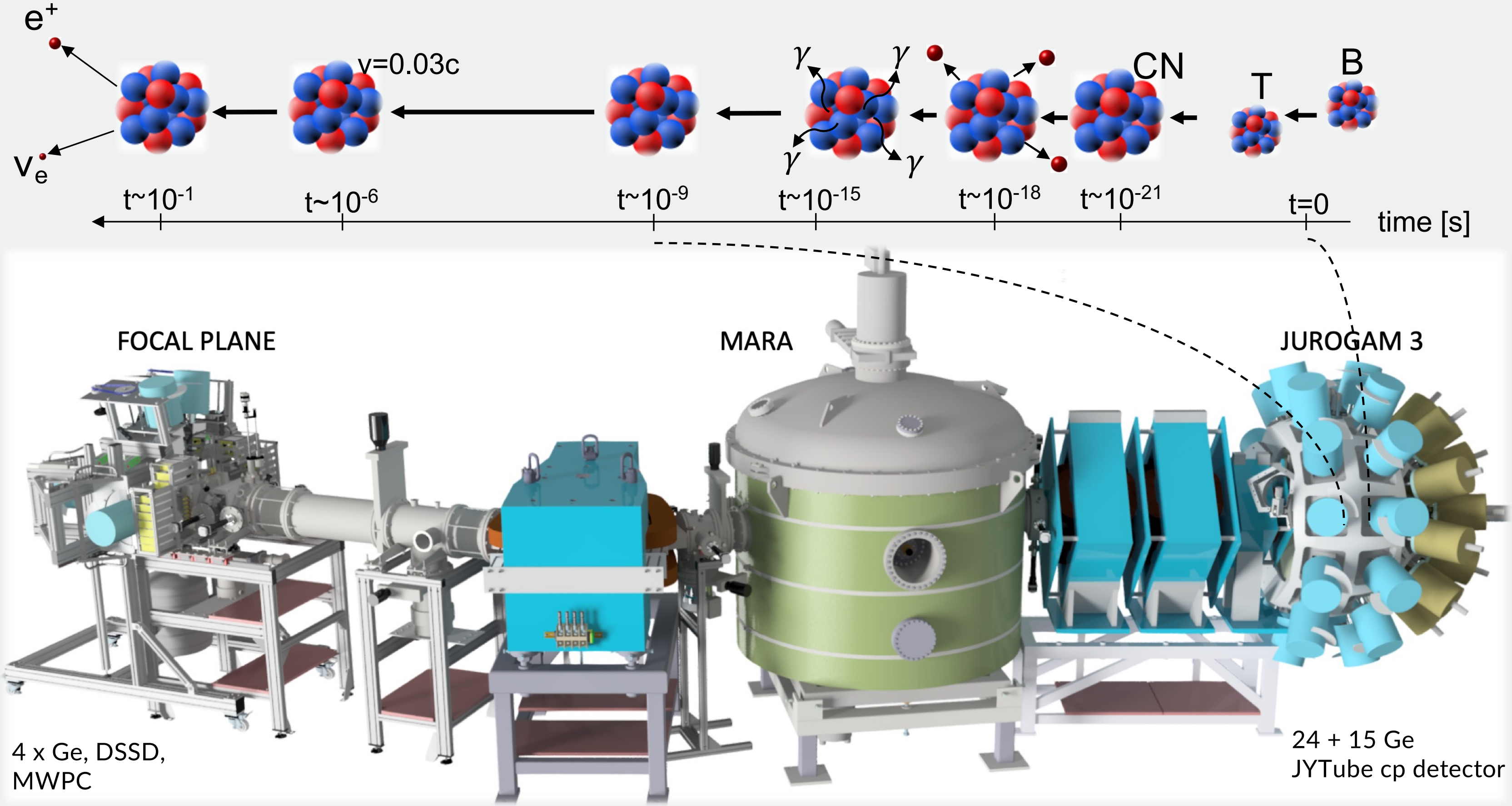
S. M. Lenzi et al. Phys. Rev. C **98**, 054322 (2018):

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

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

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

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

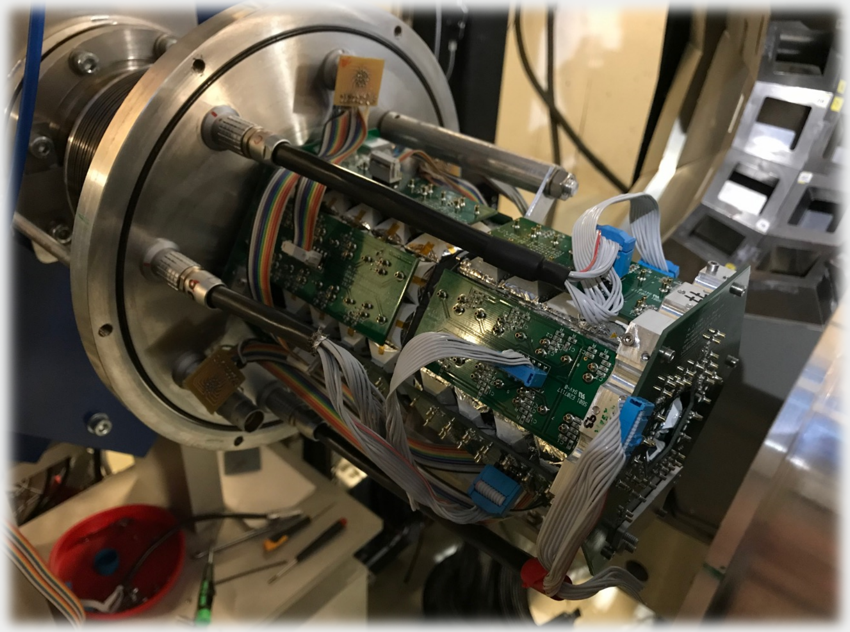


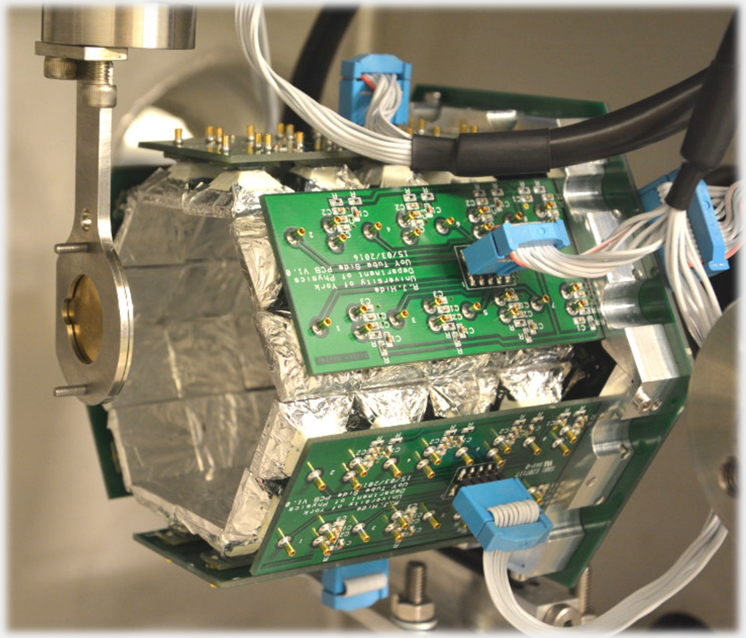
JYUTube charged particle detector

- 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:

→ 70% proton detection efficiency
→ 97% veto efficiency for 3*p* channel.
→ identification between *pn* (e.g. ^{62}Ga) vs. *2n* (e.g. ^{62}Ge) evaporation channels.

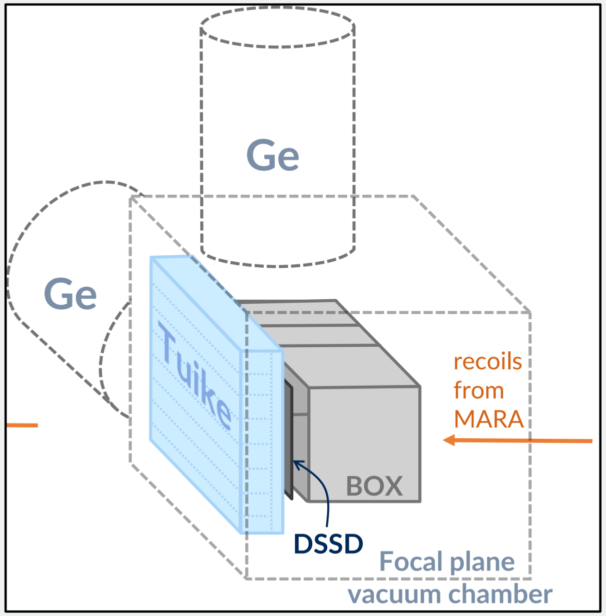


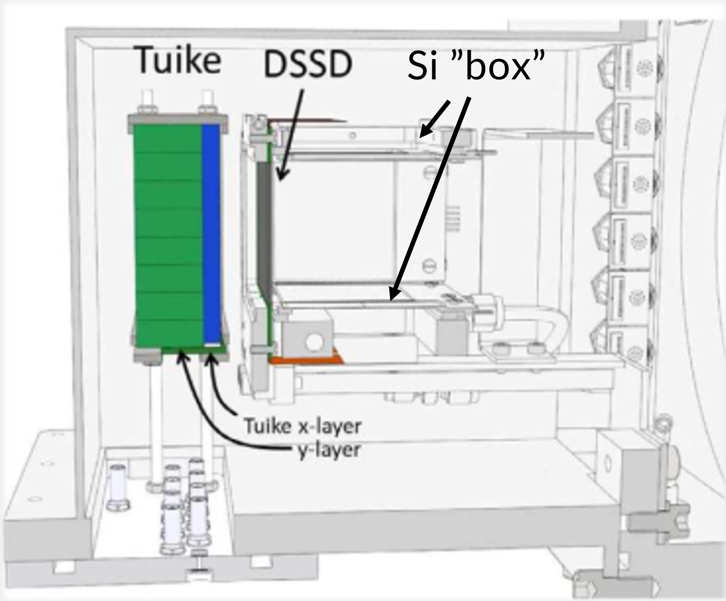


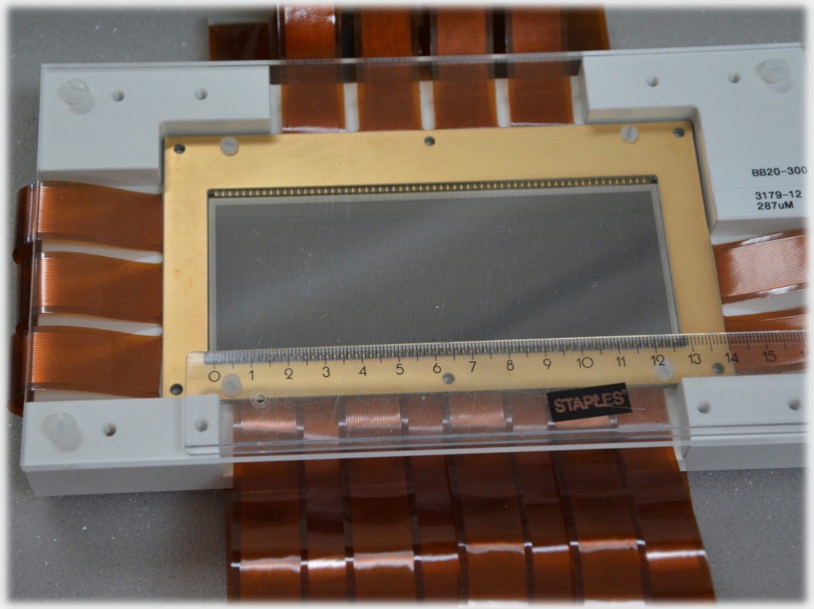
MARA focal plane setup

- Consists of
  1) position sensitive MWPC to detect incoming reaction products.
  2) BB20 DSSD, silicon-strip detector to detect recoils and their decays.
  3) “box” Si detector to detect “escaped” radioactive decay particles.
  4) TUIKE scintillator detector for high-energy beta-particle detection.
  5) 3 BEGe detectors + 1 Clover Ge detector for isomeric gamma rays.

Micron BB20 DSSSD
Area: 128x48 mm^2
Strip pitch: 0.67 mm
Strips: 192 x-strips, 72 y-strips
Thicknesses: 150, 300, 500 um

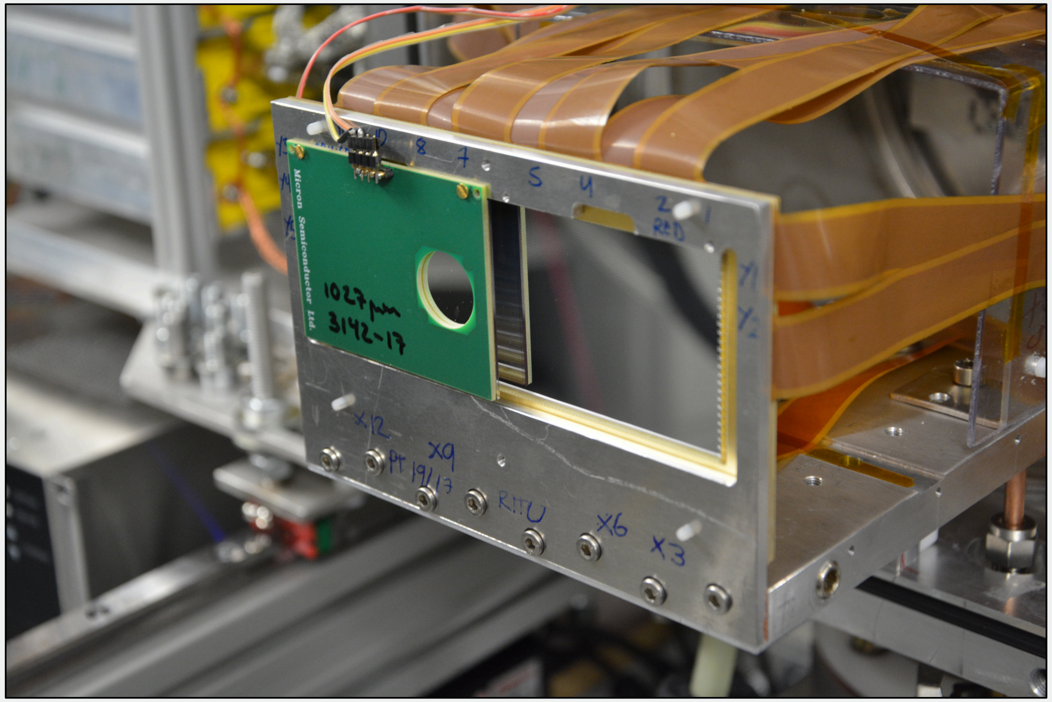


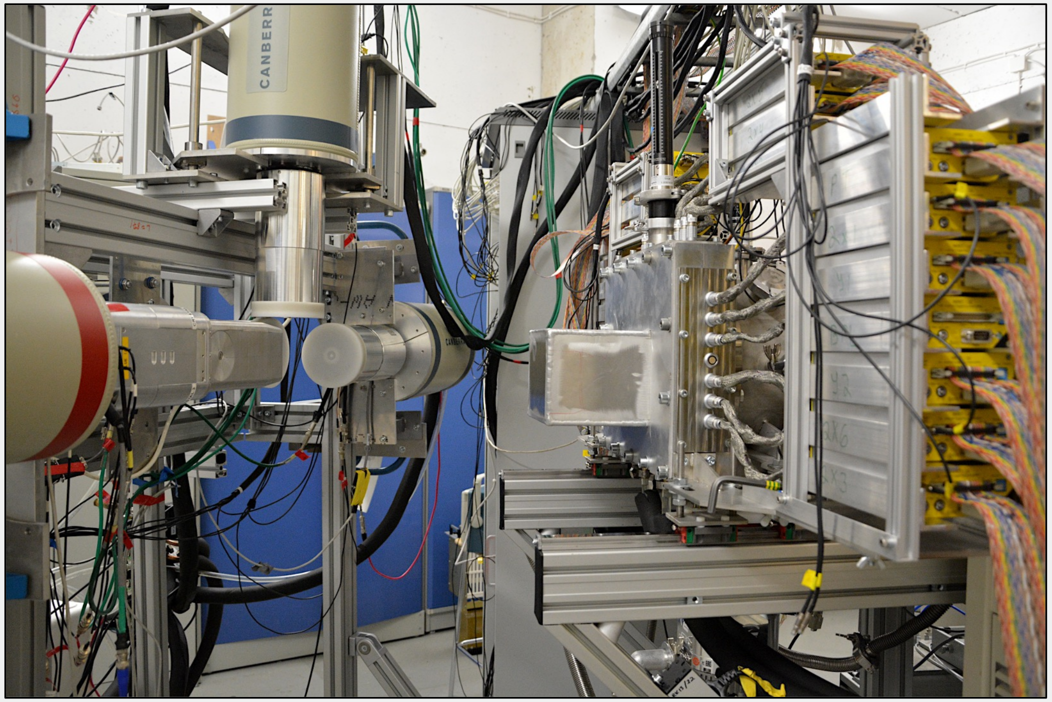




MARA focal plane setup

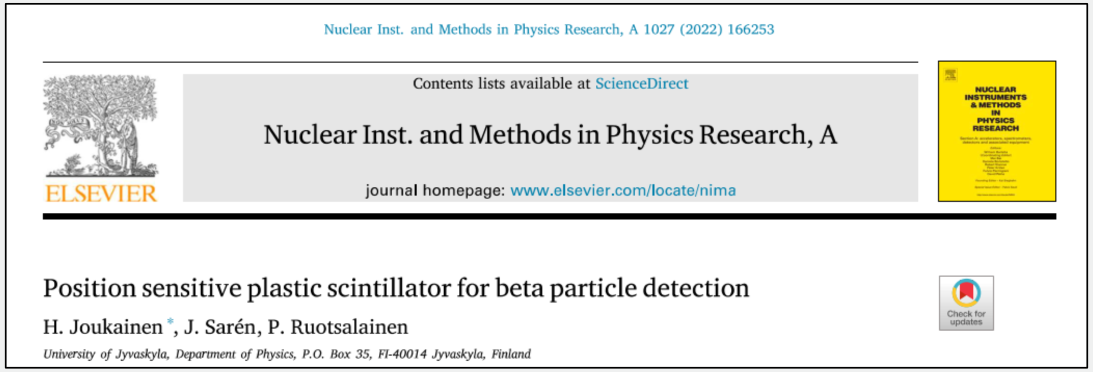
How it actually looks





Tuike scintillator

- Used for detecting the high-energy β particles.
- EJ-248 scintillator bars in two layers.
  - 14 vertical and 8 horizontal bars
- Light read out by silicon photomultipliers (SiPMs).



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Position sensitive plastic scintillator for beta particle detection

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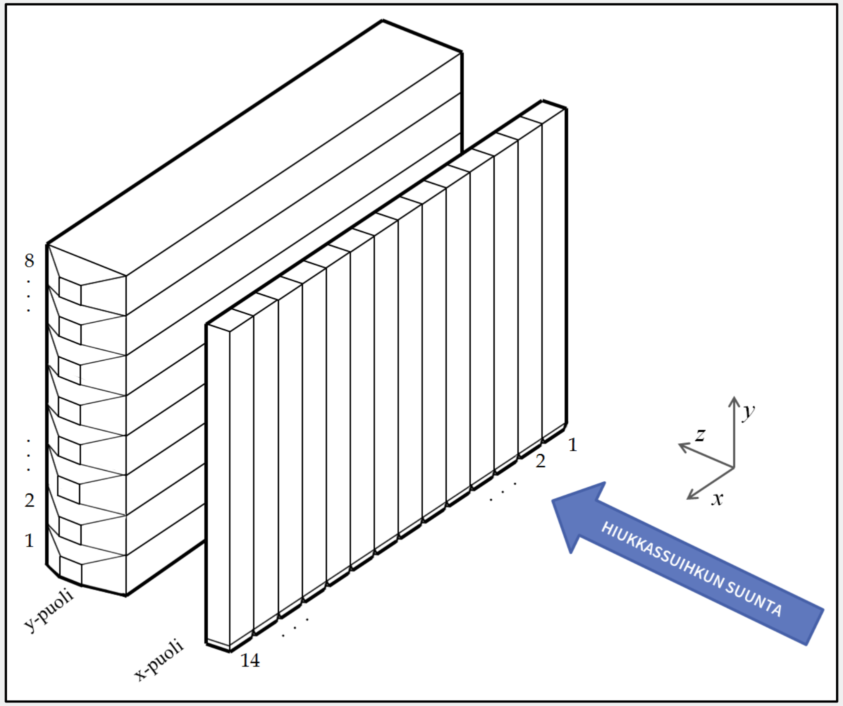
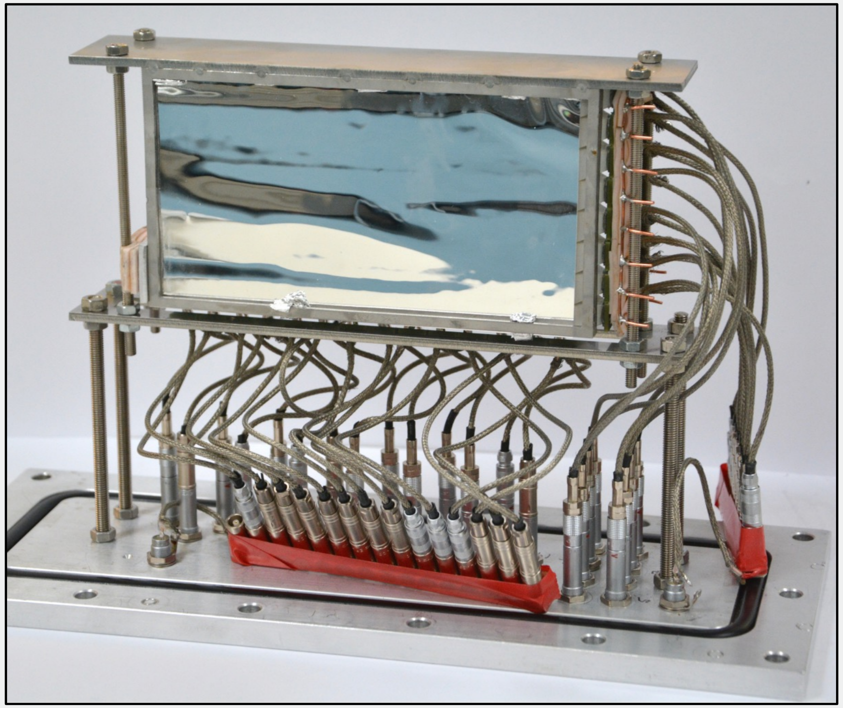
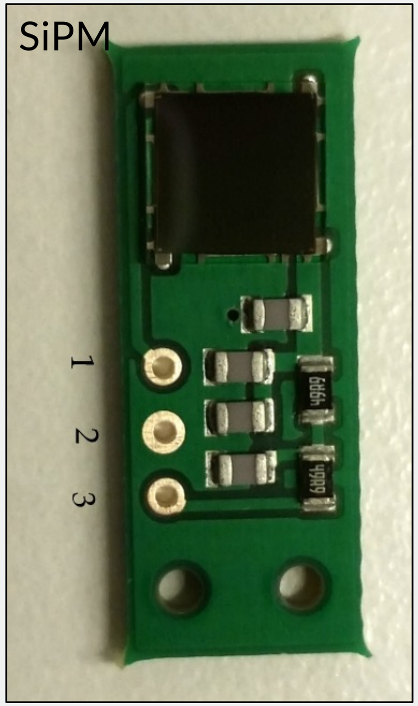
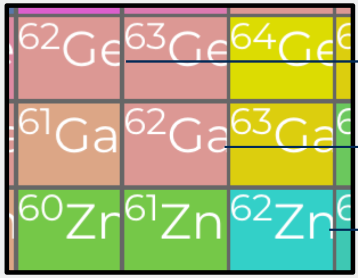






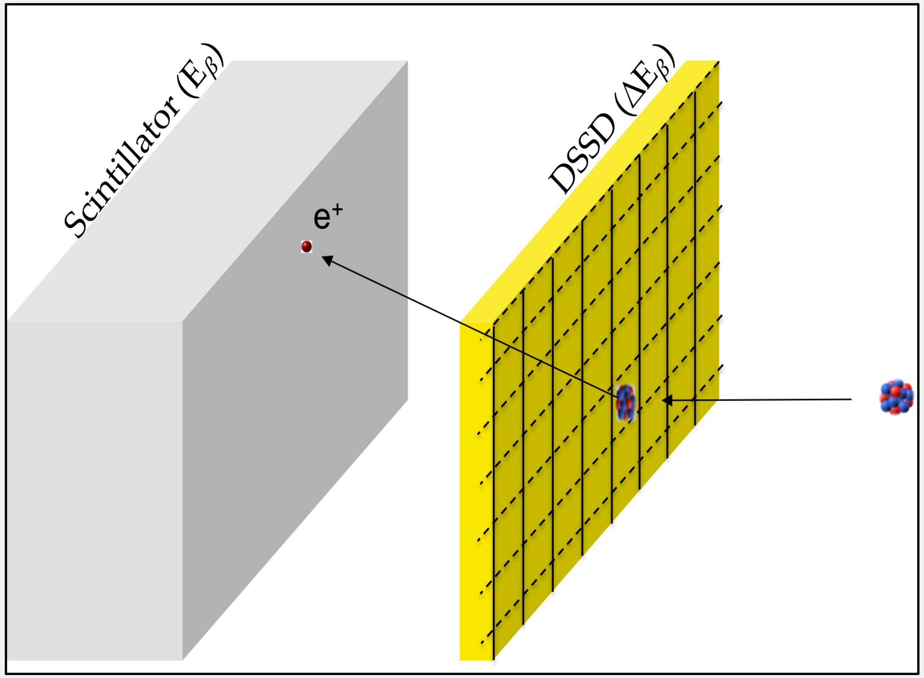
Recoil-β correlation and tagging of γ rays

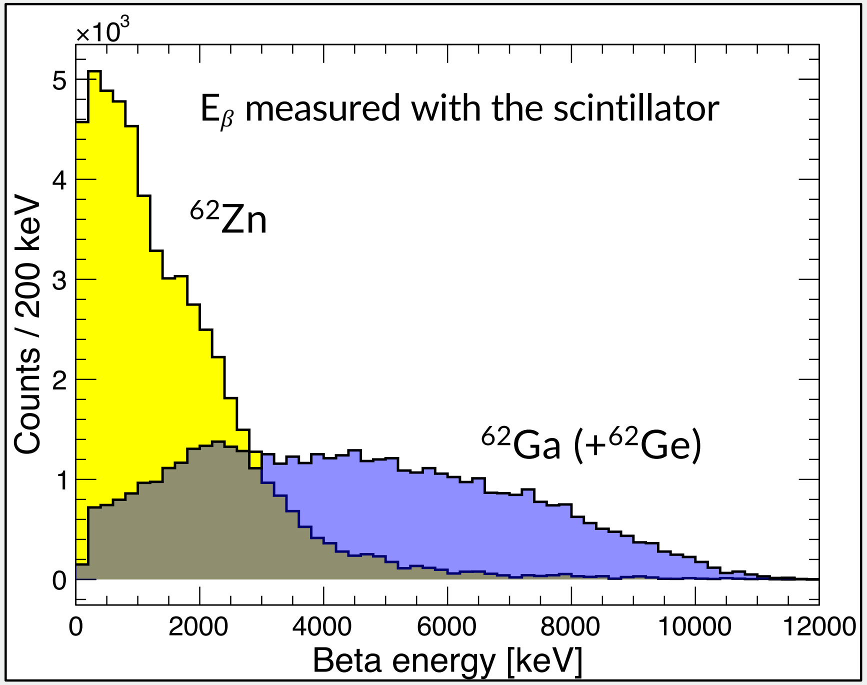


- $t_{1/2}$ = 73.5 ms, Q_{EC} ~ 10 MeV
- $t_{1/2}$ = 116.1 ms, Q_{EC} ~ 10 MeV
- $t_{1/2}$ = 9.2 h, Q_{EC} ~ 2 MeV

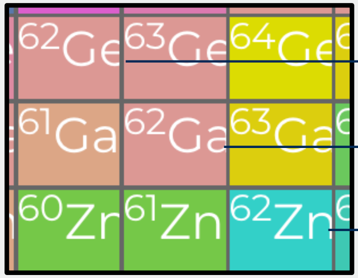
1) Decay in the same pixel with the recoil implant within 3 x $t_{1/2}$
2) Register high-energy β in the scintillator.

→ Identify the nucleus of interest.





Recoil-β correlation and tagging of γ rays



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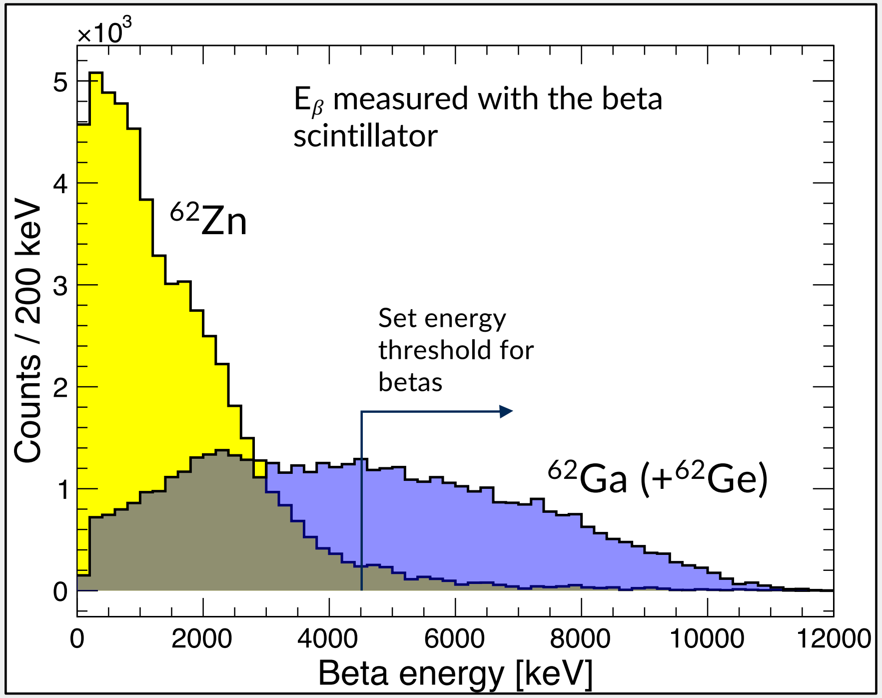
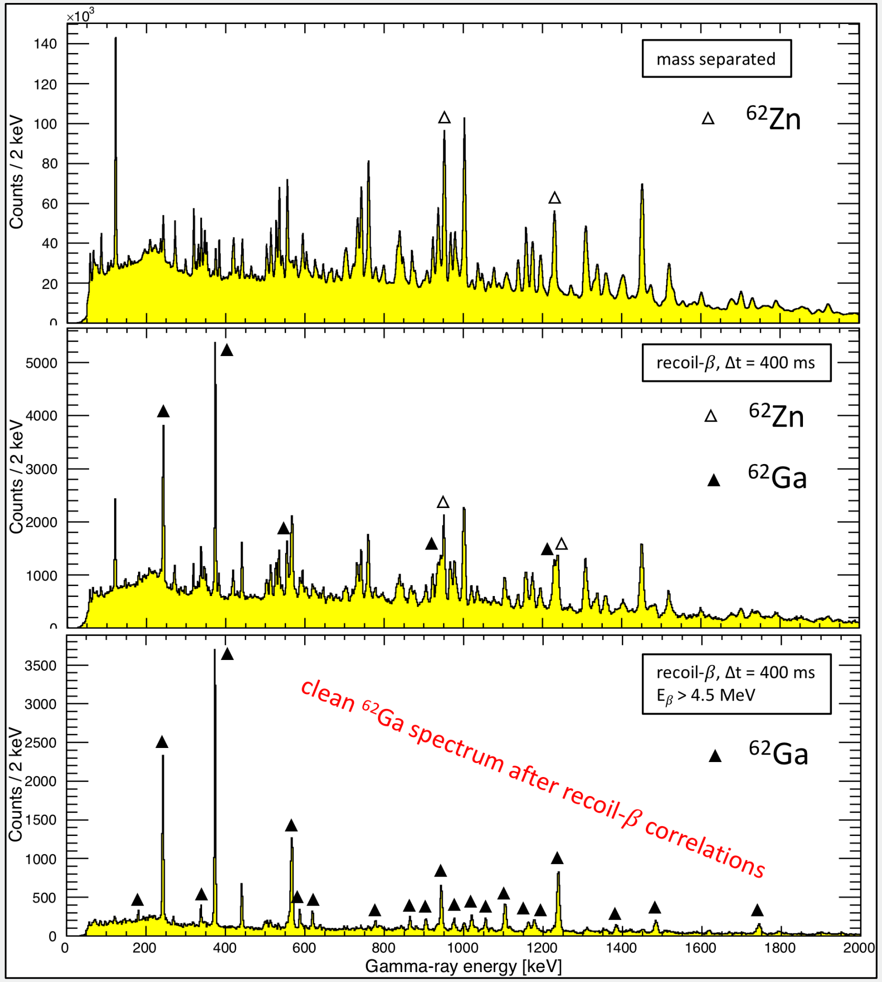


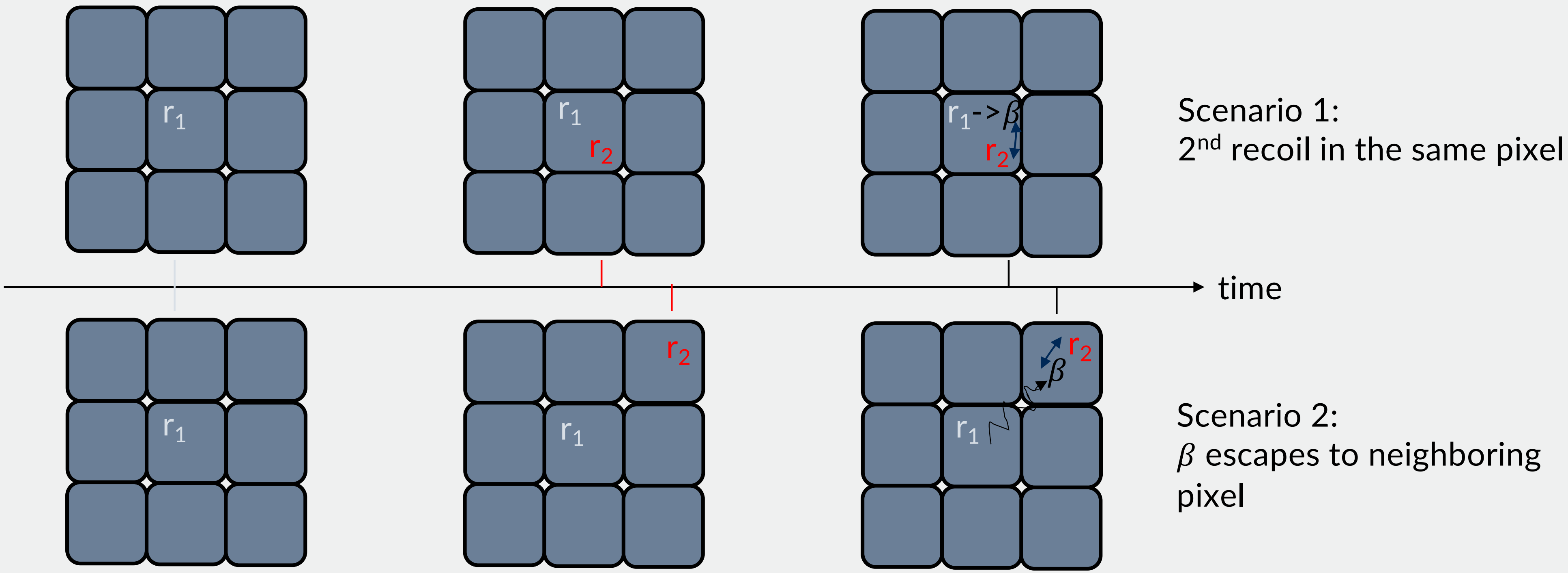
^{40}Ca + ^{24}Mg → ^{62}Zn + 2p, ^{62}Ga + pn, ^{62}Ge + 2n



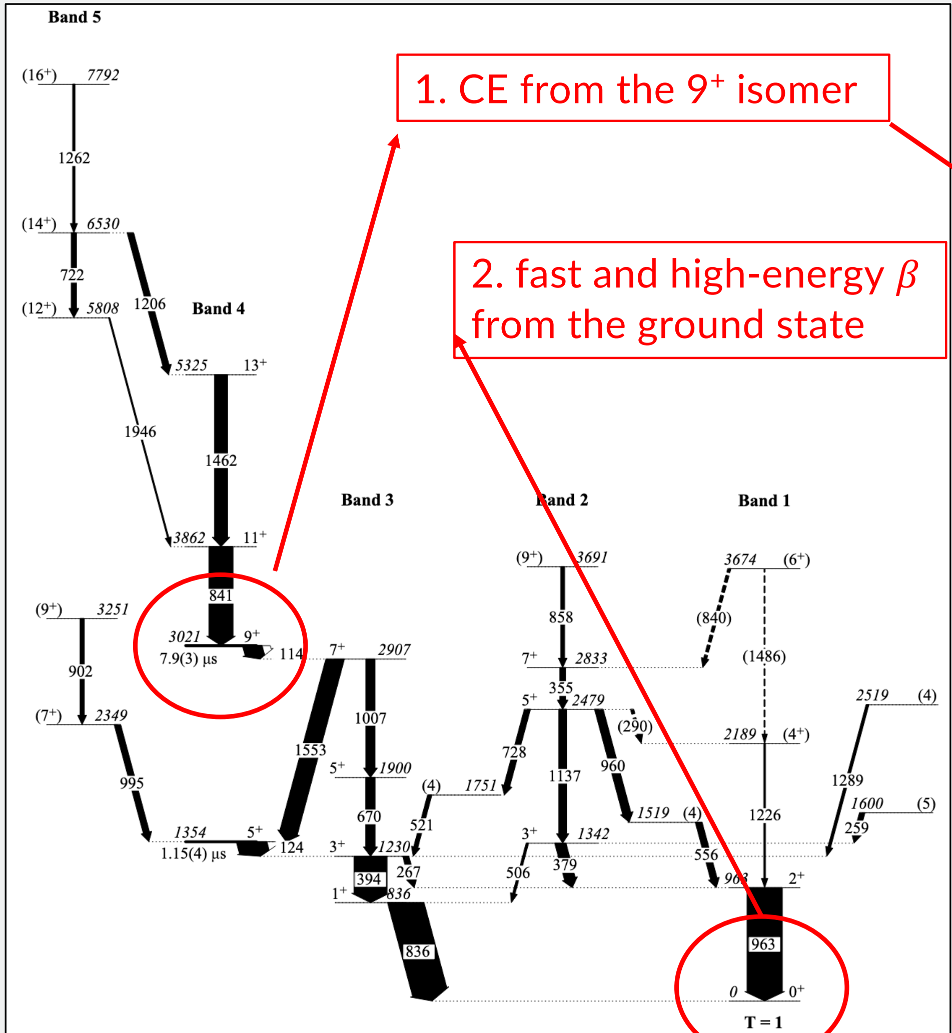
Recoil-β correlation and tagging of γ rays: challenges

There are, however, complications with correlating with beta particles:

1) No characteristic/discrete energy tag as with α or proton decays.
2) Using only the ”top end” of the β-energy distribution causes a big hit for statistics.
3) To minimize random correlations, increase the amount of pixels (i.e. reduce pixel size).
4) Range of β particles is longer than with α particles -> β decays escape to neighboring pixel.



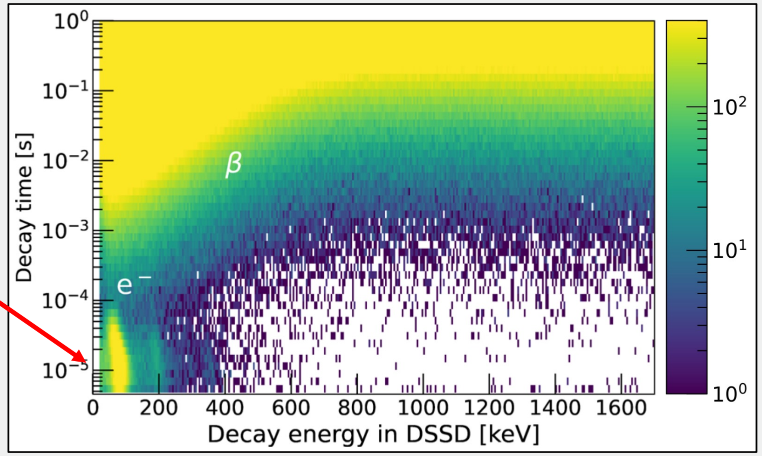
Recoil-β correlations: case of ^{66}As

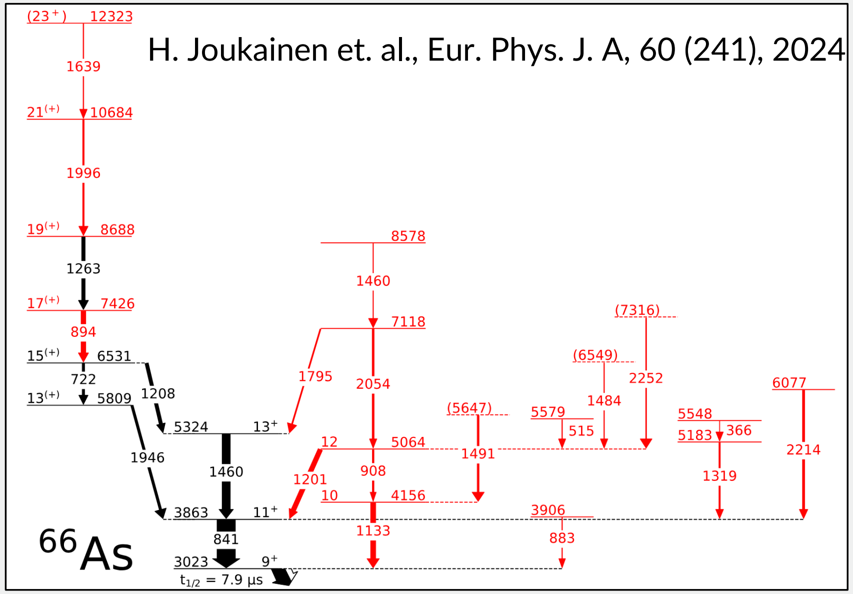


1. CE from the 9^+ isomer

2. fast and high-energy β from the ground state

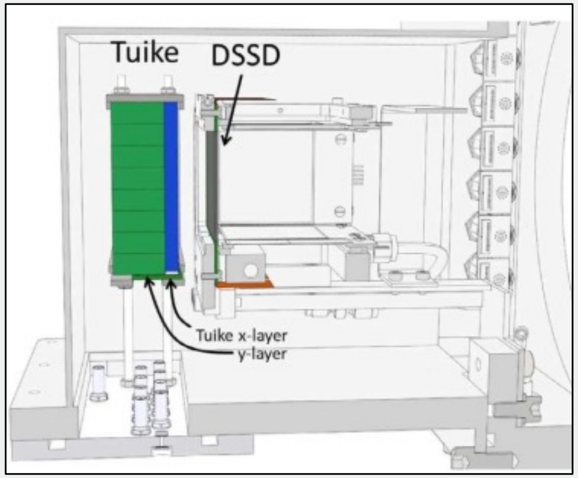
$^{28}Si + ^{40}Ca \rightarrow ^{66}As + pn$, ($^{66}Se + 2n$)





H. Joukainen et. al., Eur. Phys. J. A, 60 (241), 2024

Recoil-β correlations: case of ^{66}As

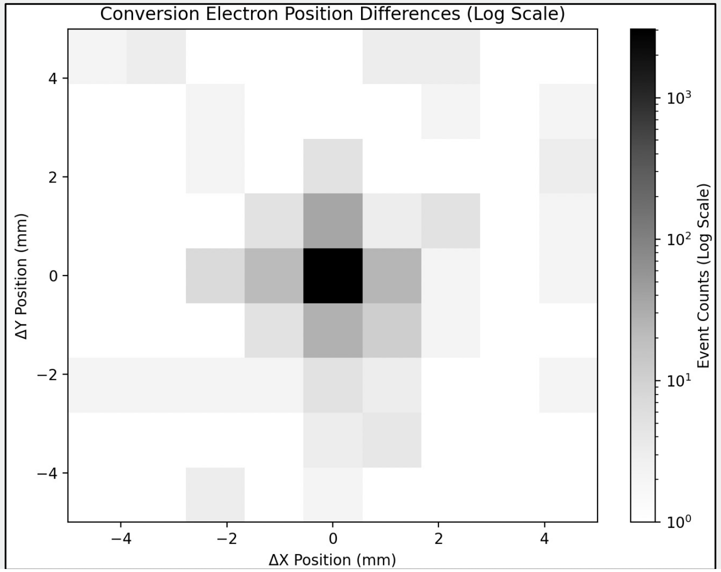


These data allowed to:

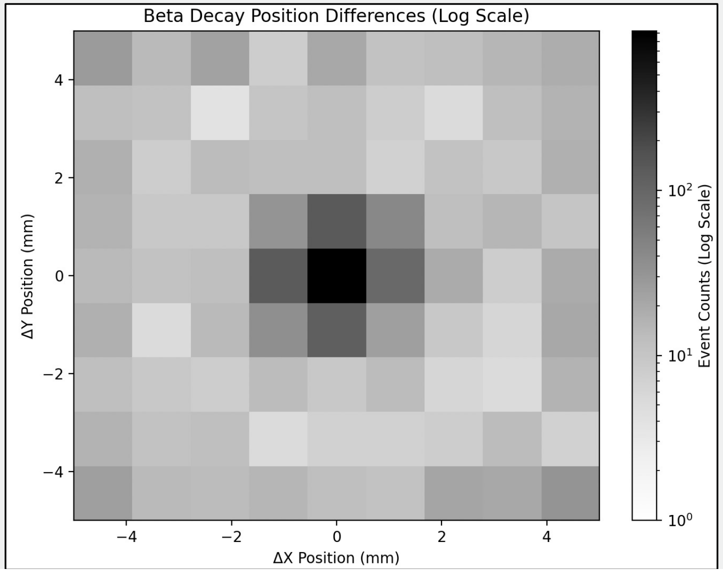
1) extract recoil-β tagging efficiencies in different scenarios:
   - fast β decay in the DSSD only -> **~20 %**
   - fast β decay in the DSSD + β seen in TUIKE -> **~13 %**
   - fast β decay in the DSSD + β seen in TUIKE with E_β > 3MeV -> **~7 %**

2) investigate β-particle distributions in DSSD.

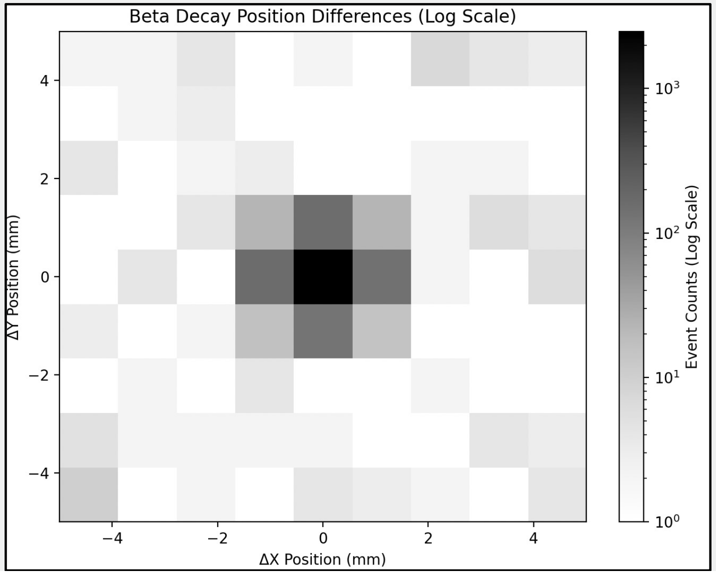
~100 keV conversion electrons



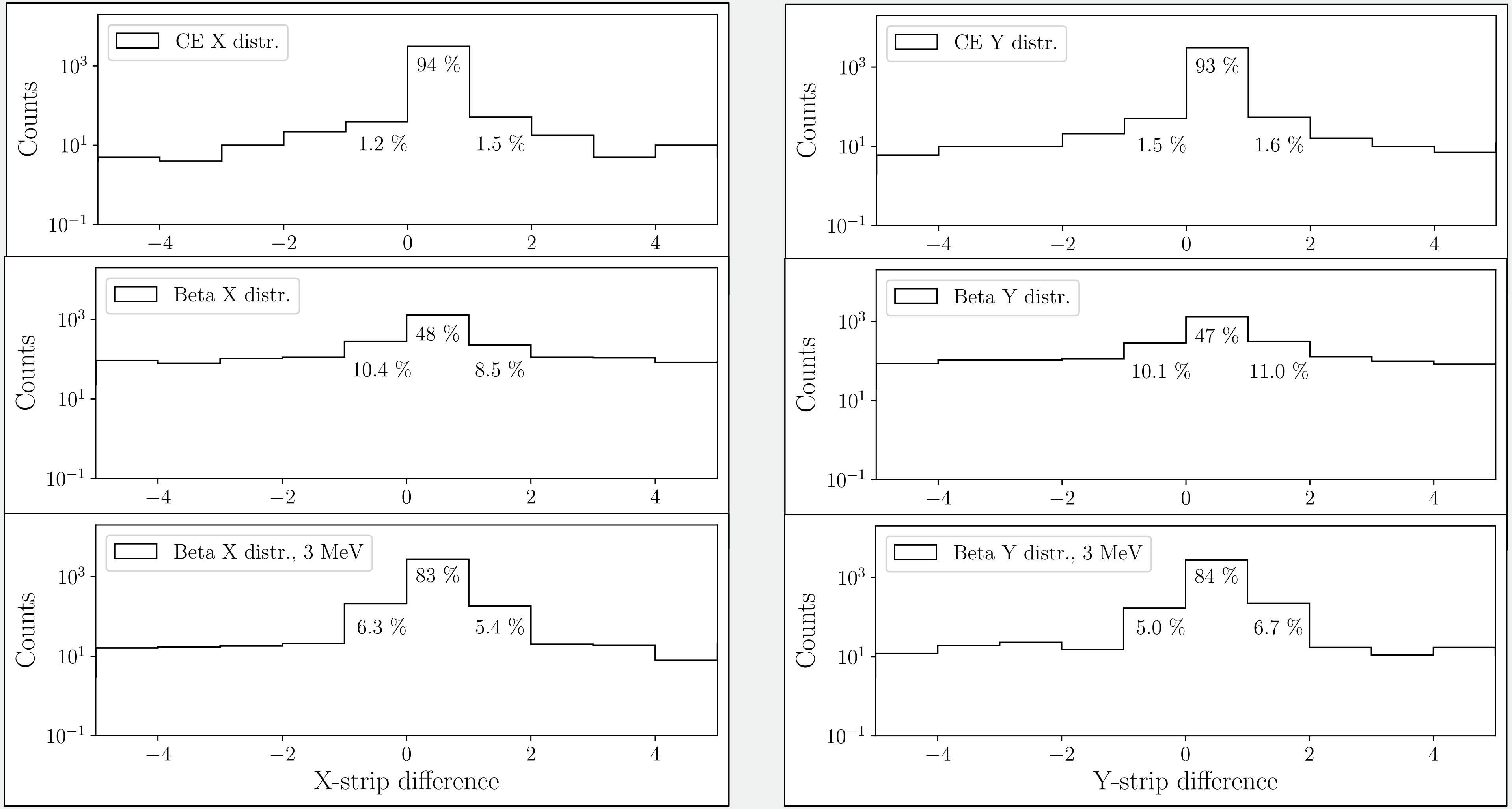
β within 300 ms



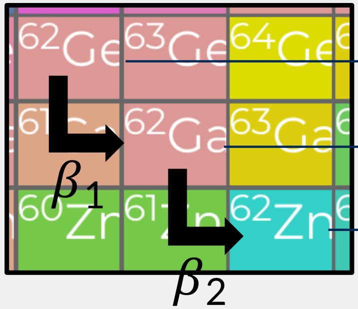
β within 300 ms + β in TUIKE > 3MeV



Recoil-β correlations: case of ^{66}As



Recoil-β-β correlations: case of ^{62}Ge



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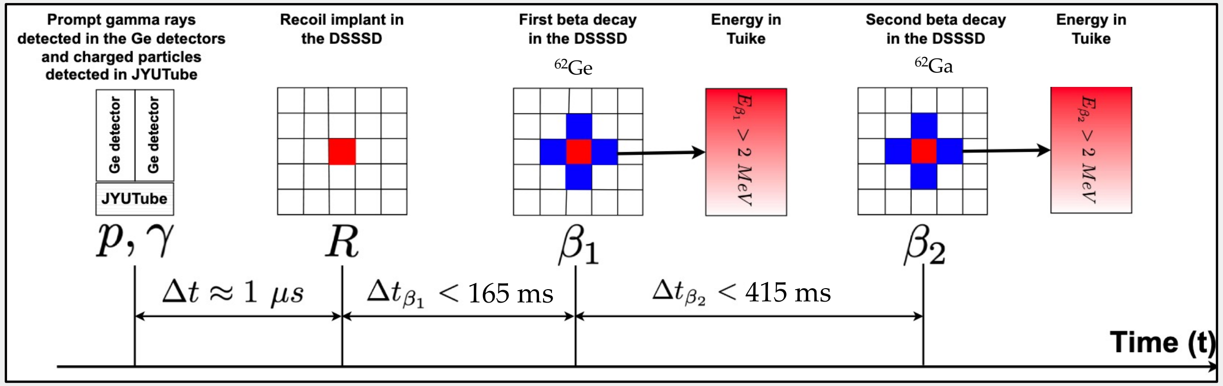
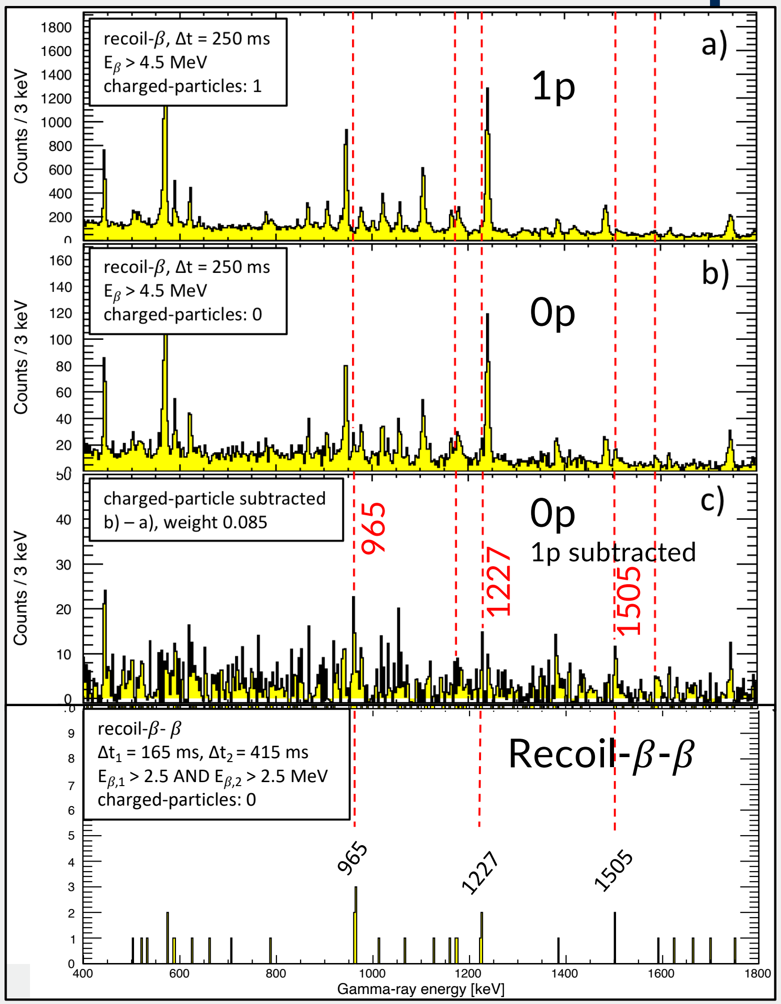


^{40}Ca + ^{24}Mg → ^{62}Ga + pn, ^{62}Ge + 2n

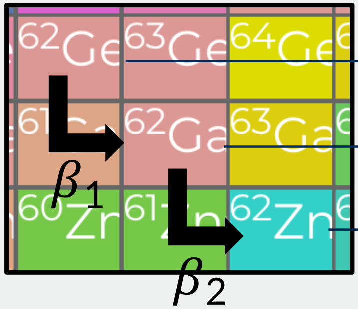


Correlation strategy:

1) Check recoil-decay correlations in <u>single pixel</u> up to 3 x $t_{1/2}$.

2) If not found, then check the adjacent pixels.

Recoil-β-β correlations: case of ^{62}Ge



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

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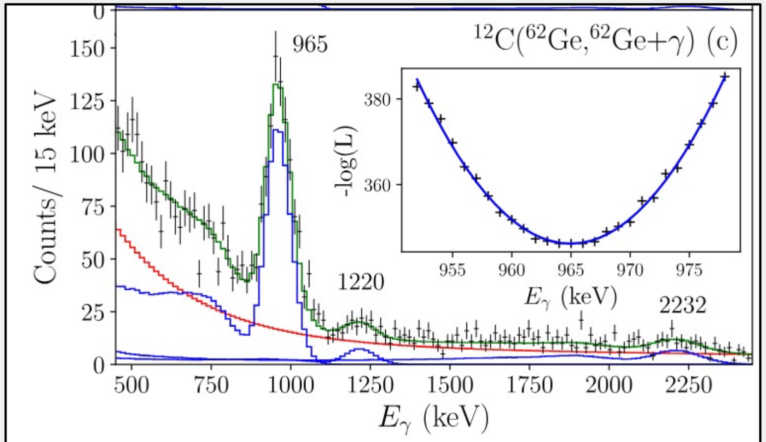
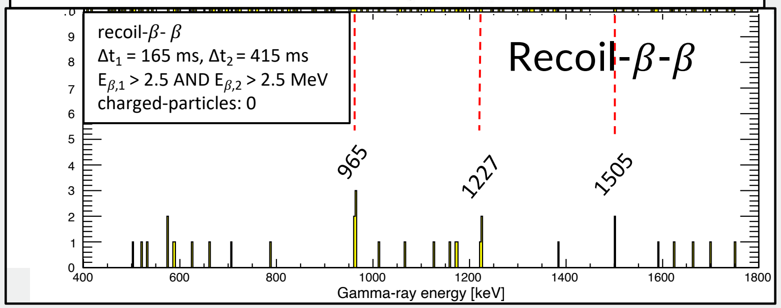
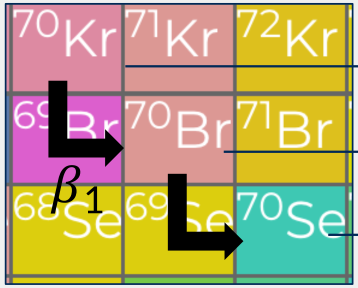
inelastic scattering (and 1-nucleon removal) @ RIKEN (K. Wimmer et al.) DALI 2 γ-ray spectrum





Recoil-β-β correlations: case of ^{70}Kr



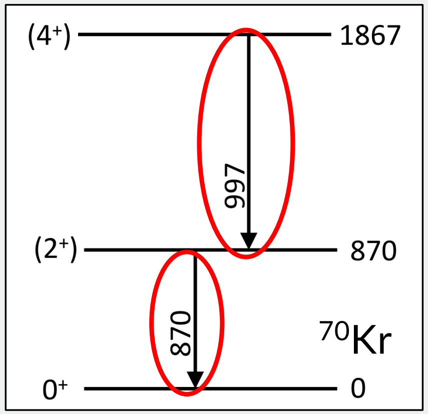
$t_{1/2}$ = 45.2 ms, Q_{EC} ~ 10 MeV

$t_{1/2}$ = 78.9 ms, Q_{EC} ~ 10 MeV

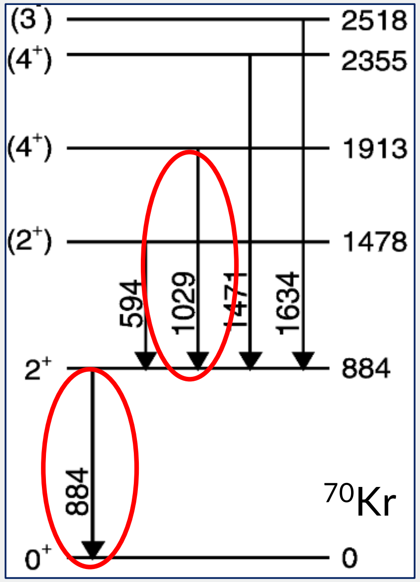
$t_{1/2}$ = 41.1 min, Q_{EC} ~ 2.4 MeV

Previous results for ^{70}Kr

D. M. Debenham et al. Phys.Rev. C 94, 054311 (2016)

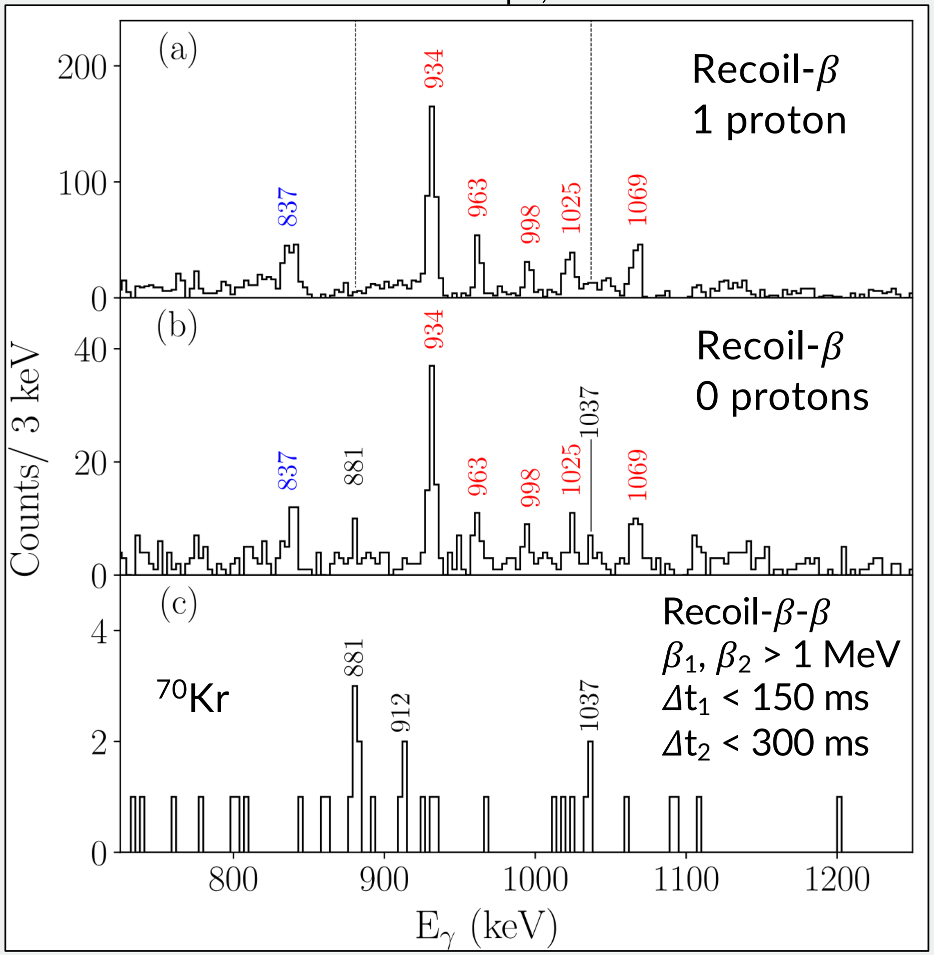


K. Wimmer et al. Phys Lett B, 786,441-446 2018



G. Zimba et al. Phys.Rev. C 110, 024314 (2024)

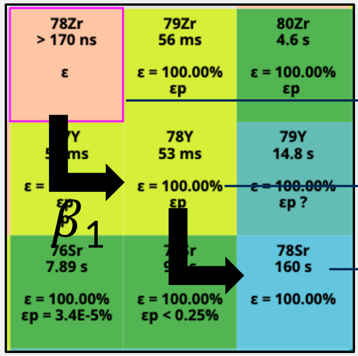
^{32}S + ^{40}Ca → ^{70}Br + pn, ^{70}Kr + 2n



Recoil-β-β correlations: case of ^{78}Zr

G. Zimba et al. Phys.Rev.Lett 134, 022502 (2025)

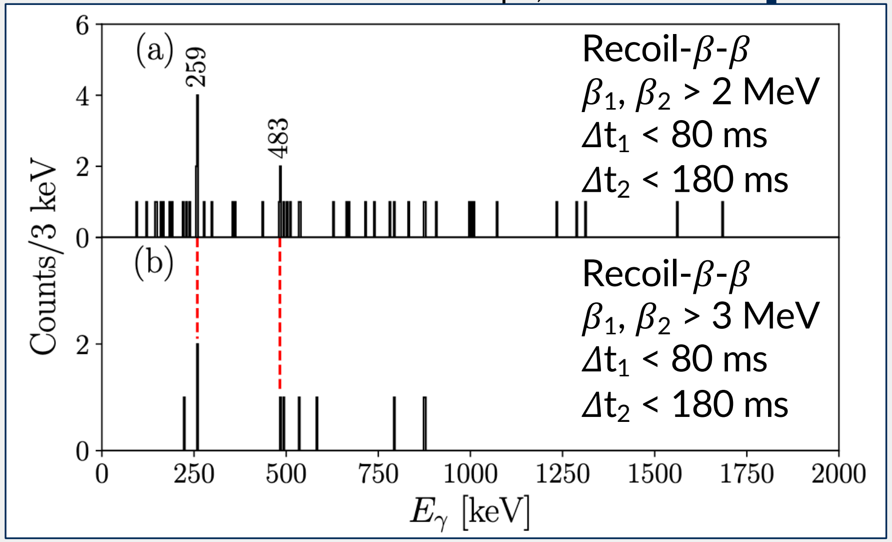
^{40}Ca + ^{40}Ca → ^{78}Y + pn, ^{78}Zr + 2n



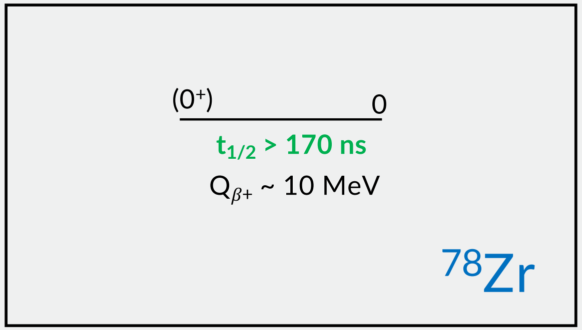
$t_{1/2}$ > 170 ns, Q_{EC} ~ 10 MeV

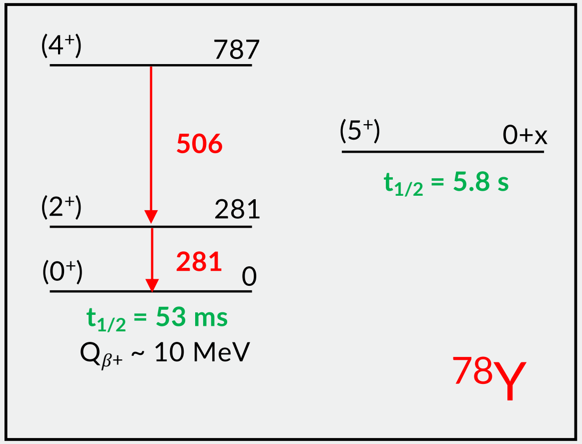
$t_{1/2}$ = 53 ms, Q_{EC} ~ 10 MeV

$t_{1/2}$ = 160 s, Q_{EC} ~ 3.8 MeV

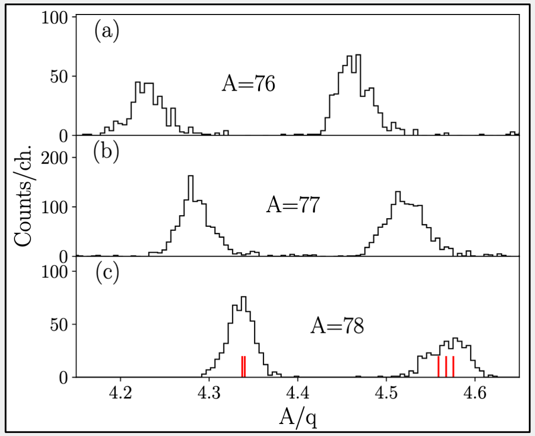


Previous information on ^{78}Zr and ^{78}Y





A/q distributions of recoils gated by prompt γ rays



^{76}Kr

^{77}Rb

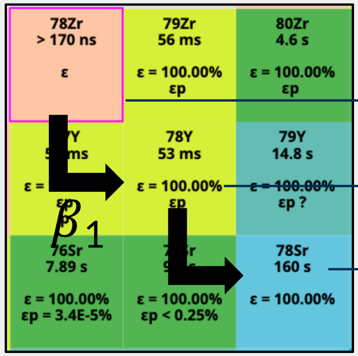
^{78}Y

“259 keV”

Recoil-β-β correlations: case of ^{78}Zr

G. Zimba et al. Phys.Rev.Lett 134, 022502 (2025)

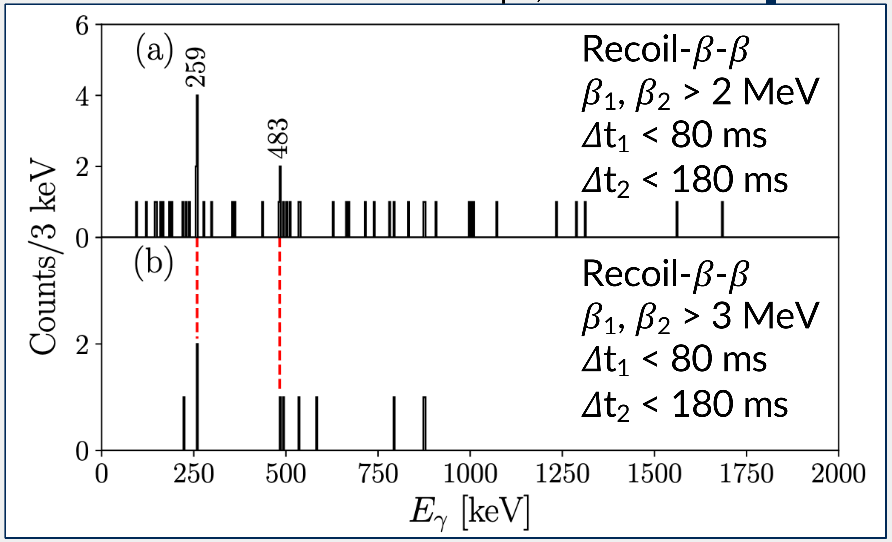
^{40}Ca + ^{40}Ca → ^{78}Y + pn, ^{78}Zr + 2n



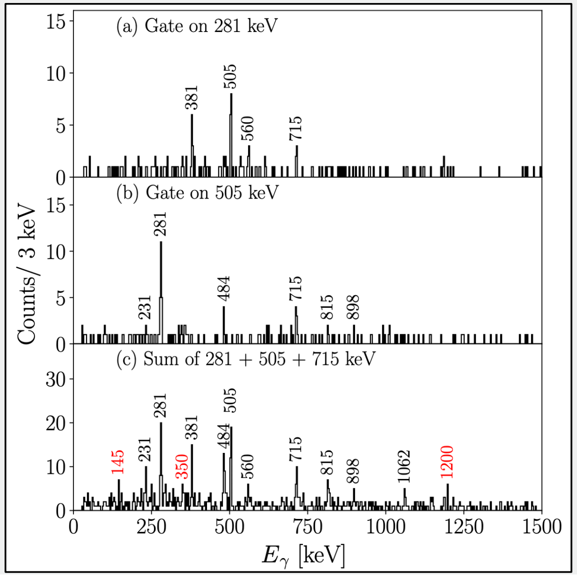
$t_{1/2}$ > 170 ns, Q_{EC} ~ 10 MeV

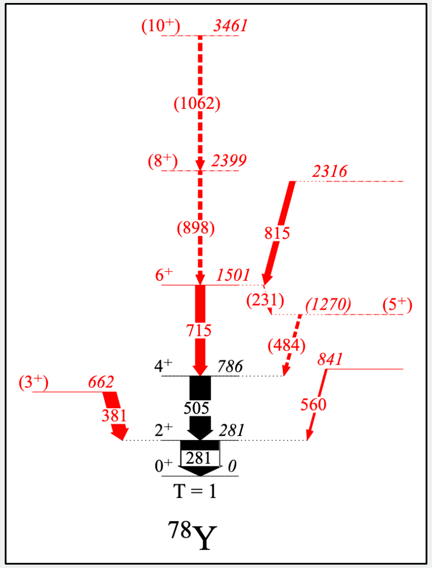
$t_{1/2}$ = 53 ms, Q_{EC} ~ 10 MeV

$t_{1/2}$ = 160 s, Q_{EC} ~ 3.8 MeV

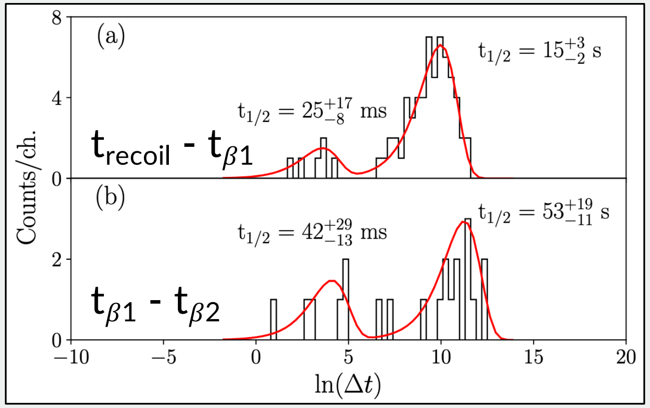


^{78}Y level scheme was also extended





Logarithmic time-difference distributions gated by the 259-keV γ rays



Recoil-β-β correlations: case of ^{78}Zr

Comparison to theory

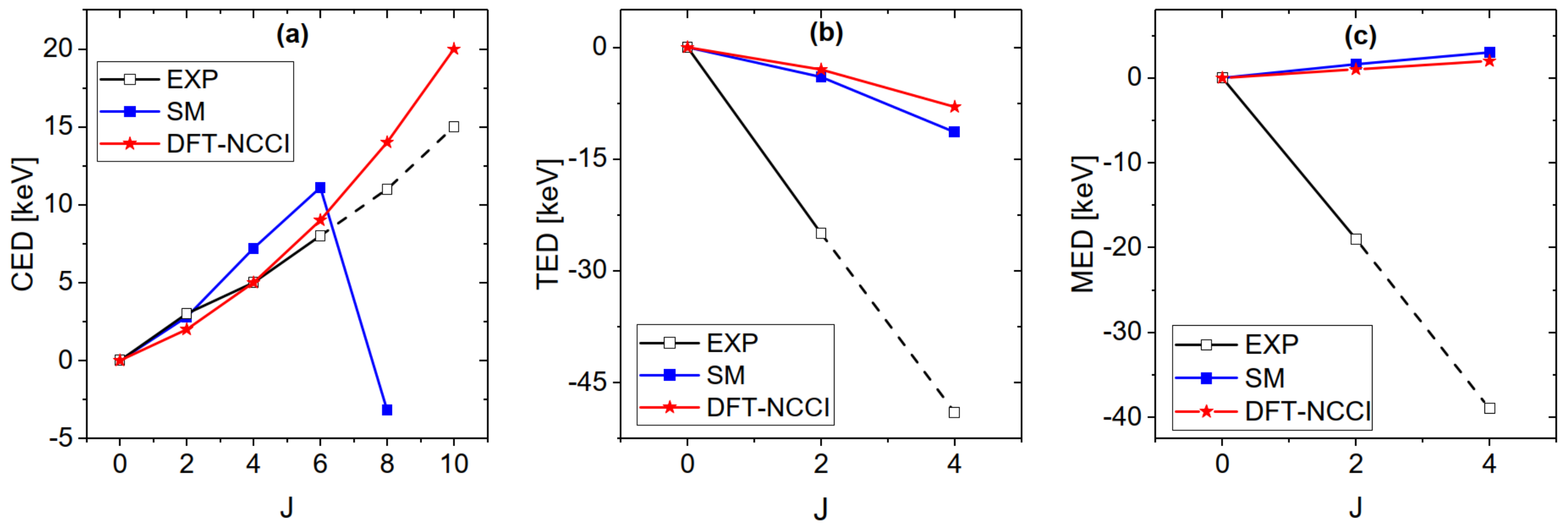
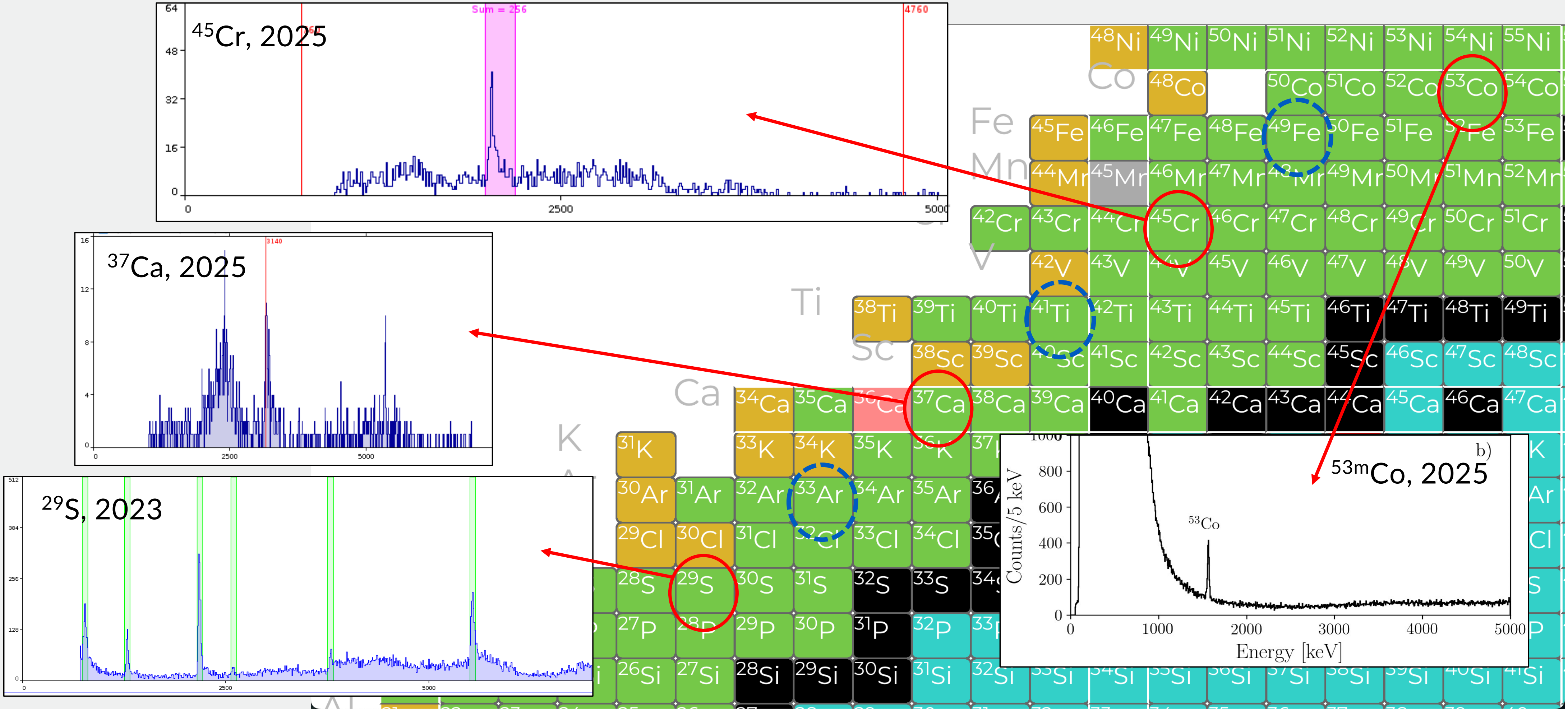


FIG. 5. Comparison of experimentally-derived CED (a), TED (b), and MED (c) as a function of spin (J) for the $A = 78$ triplet with the results of published shell model (SM) calculations [20] and DFT-NCCI calculations carried out in the present work [21]. The solid black lines connect to $T = 1$ states with confirmed spin-parities, while the dashed black lines connect to tentatively assigned $T = 1$ states.

Ongoing and future work: in-beam studies of β-delayed proton emitters in the A = 30 – 50 mass region



Conclusions

- Recoil-decay correlations with β particles have provided new spectroscopic data for the N≈Z nuclei.
- Recoil-β-β tagging method has been applied to the challenging cases of ^{62}Ge, ^{70}Kr and ^{78}Zr to identify excited states in these systems.
- These studies allow theoretical investigations of the CED, MED and TED systematics within the isobaric triplets to study the isospin symmetry breaking effects.

Thank you!

JYFL-ACCLAB Nuclear Spectroscopy group