European Nuclear Physics Conference 2022 (EuNPC 2022)

β-decay spectroscopy of neutron-deficient nuclei

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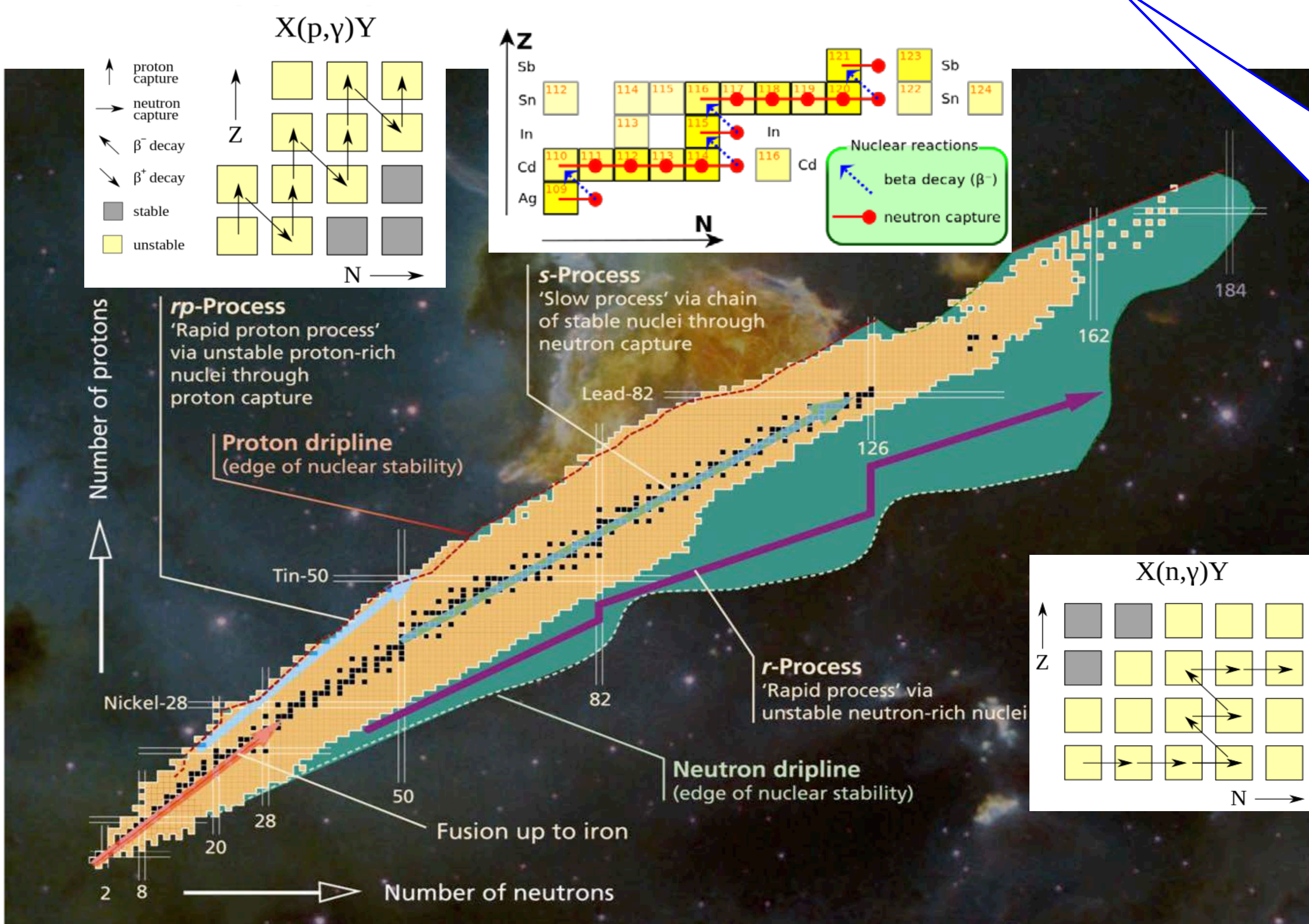
β-decay spectroscopy of exotic nuclei

- Powerful tool to study the structure of **n-deficient nuclei around the *N=Z* line**
- Information of great interest for both **Nuclear Structure** and **Nuclear Astrophysics**



Valuable information:
$T_{1/2}$, B_p, I_p, I_γ, I_β, E_X, decay schemes, B(F), B(GT), isomers, mass excesses

β-decay data are relevant for nucleosynthesis processes

β-decay transition strengths

- β-decay spectroscopy provides a direct access to the absolute values of the β-decay strengths

$$B(F) \propto \left| \left\langle \psi_f^* \middle| \tau \middle| \psi_i \right\rangle \right|^2$$

Fermi (ΔS = 0)

$$B(GT) \propto \left| \left\langle \psi_f^* \middle| \sigma\tau \middle| \psi_i \right\rangle \right|^2$$

Gamow Teller (ΔS = 1)

- **Measured in β-decay experiments**

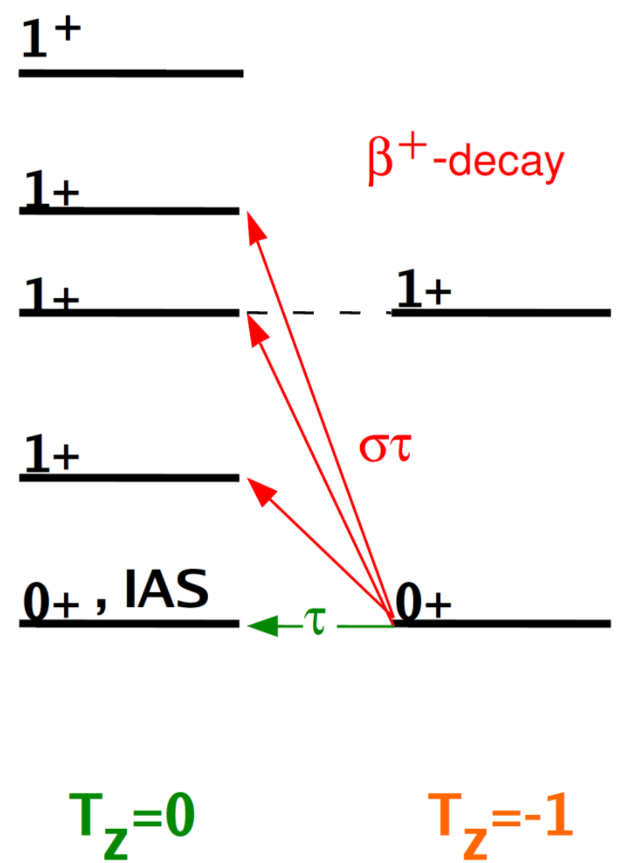
Beta feeding to states in the daughter nucleus

$$B_j(GT)^\beta = \frac{K}{\lambda^2} \frac{I_\beta^j(E_j)}{f(Q_\beta - E_j, Z) T_{1/2}}$$

$\lambda = g_A/g_V$

Parent half-life

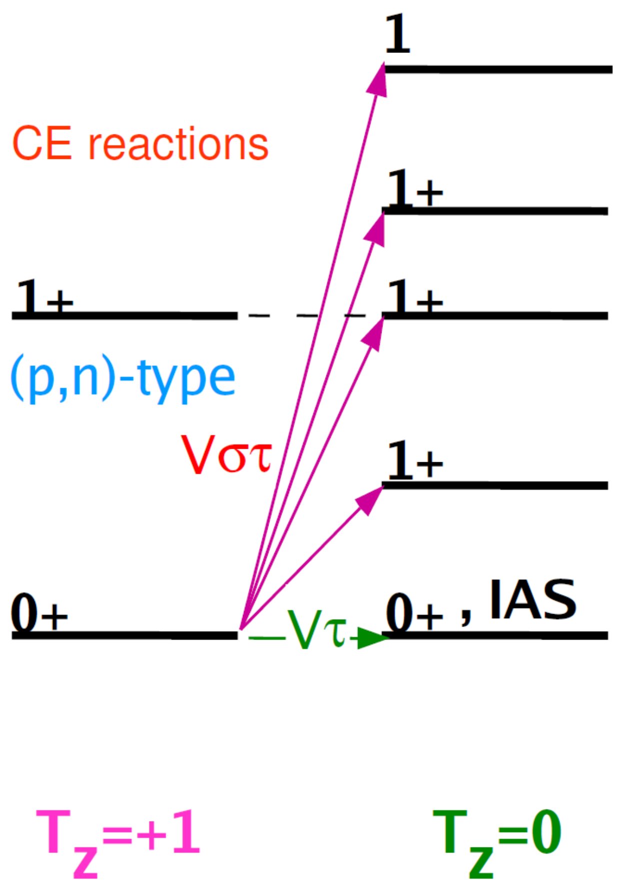
$$B(F)^\beta = K \frac{I_\beta(E)}{f(Q_\beta - E, Z) T_{1/2}}$$



- Advantage: absolute normalization of the strength

Charge Exchange (CE) reactions

Complementary **(p,n)-type CE reactions**, which are the mirror strong interaction process, also provide information on the β-decay transition strengths



- The CE cross section measured at 0° is proportional to the β-decay strengths (relative values)

$$\left.\frac{d\sigma^{CE}_{GT}}{d\Omega}(0^o)\right|_j \cong \hat{\sigma}_{GT}(0^o)B_j(GT)$$

$$\frac{d\sigma^{CE}_{F}}{d\Omega}(0^o) \cong \hat{\sigma}_{F}(0^o)B(F)$$

T.N. Taddeucci et al., NPA 469 (1987) 125-172

- Advantage: highly excited states can be accessed

Complementarity of β decay and CE reactions

- **β decay:** Weak interaction

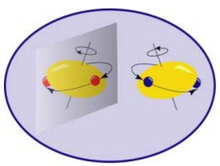
- **Charge Exchange:** Strong interaction

$$B(GT) \propto \left| \left\langle \psi_f^* \middle| \sigma\tau \middle| \psi_i \right\rangle \right|^2$$

They are ruled by the same operators

$$V_{NN}^{(\tau)} = \left(V_\tau + V_{\sigma\tau}\ \sigma_1 \cdot \sigma_2 + V_{T\tau}\ S_{12}\right) \tau_1 \cdot \tau_2$$

Mirror symmetry



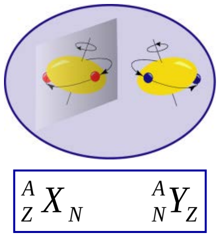
$${}^{A}_{Z}X_{N} \qquad {}^{A}_{N}Y_{Z}$$

- Mirror **Fermi** and **Gamow Teller** transitions are expected to have the same strength
- What can we learn from the comparison?
  - Investigate **isospin symmetry** in mirror nuclei
  - Improve our knowledge of **GT transitions** close to the proton drip-line and along the rp-process pathway

β decay and CE reactions

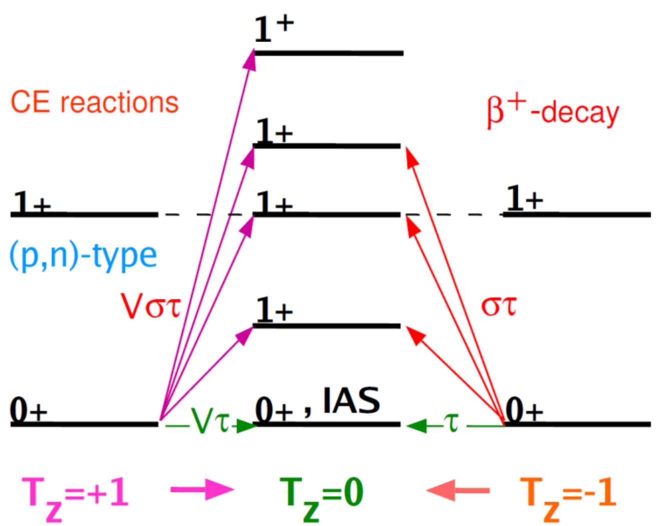
β decay and CE experiments are complementary

- Under the assumption of **isospin symmetry**, starting from **mirror nuclei**, the two processes should populate the same states in the daughter with same probability

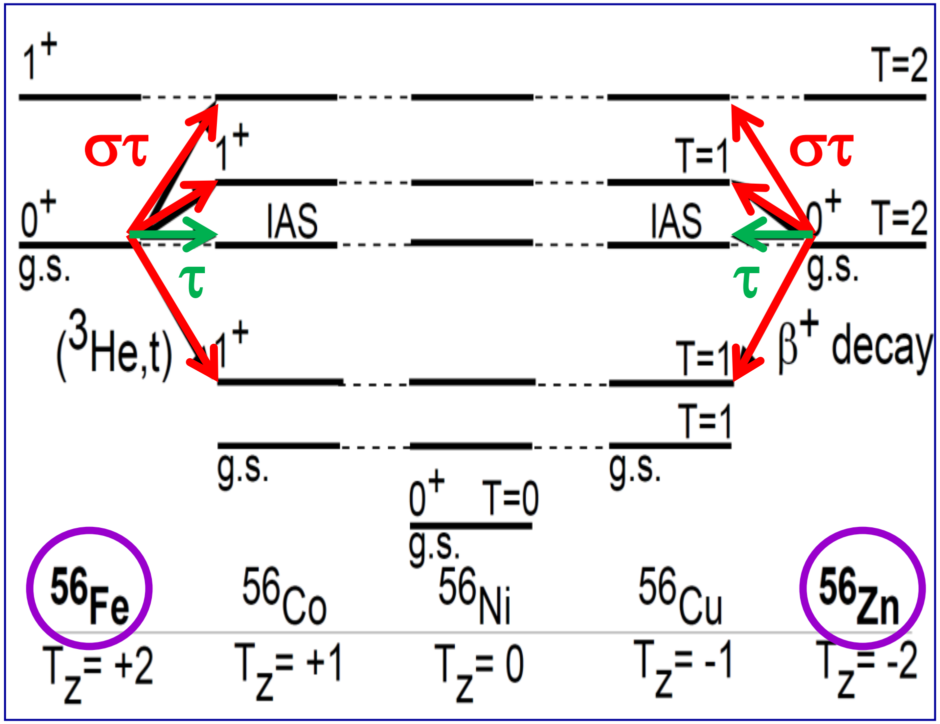


Y. Fujita, B. Rubio, W. Gelletly, PPNP 66 (2011) 549-606

The T=1 isospin multiplet:
the final state is identical



The T=2 isospin multiplet:
the final nucleus is not identical



β decay of proton-rich nuclei

Series of experiments aiming at the comparison between **β decay in proton-rich nuclei** and **Charge Exchange (CE) reactions** on the stable mirror target

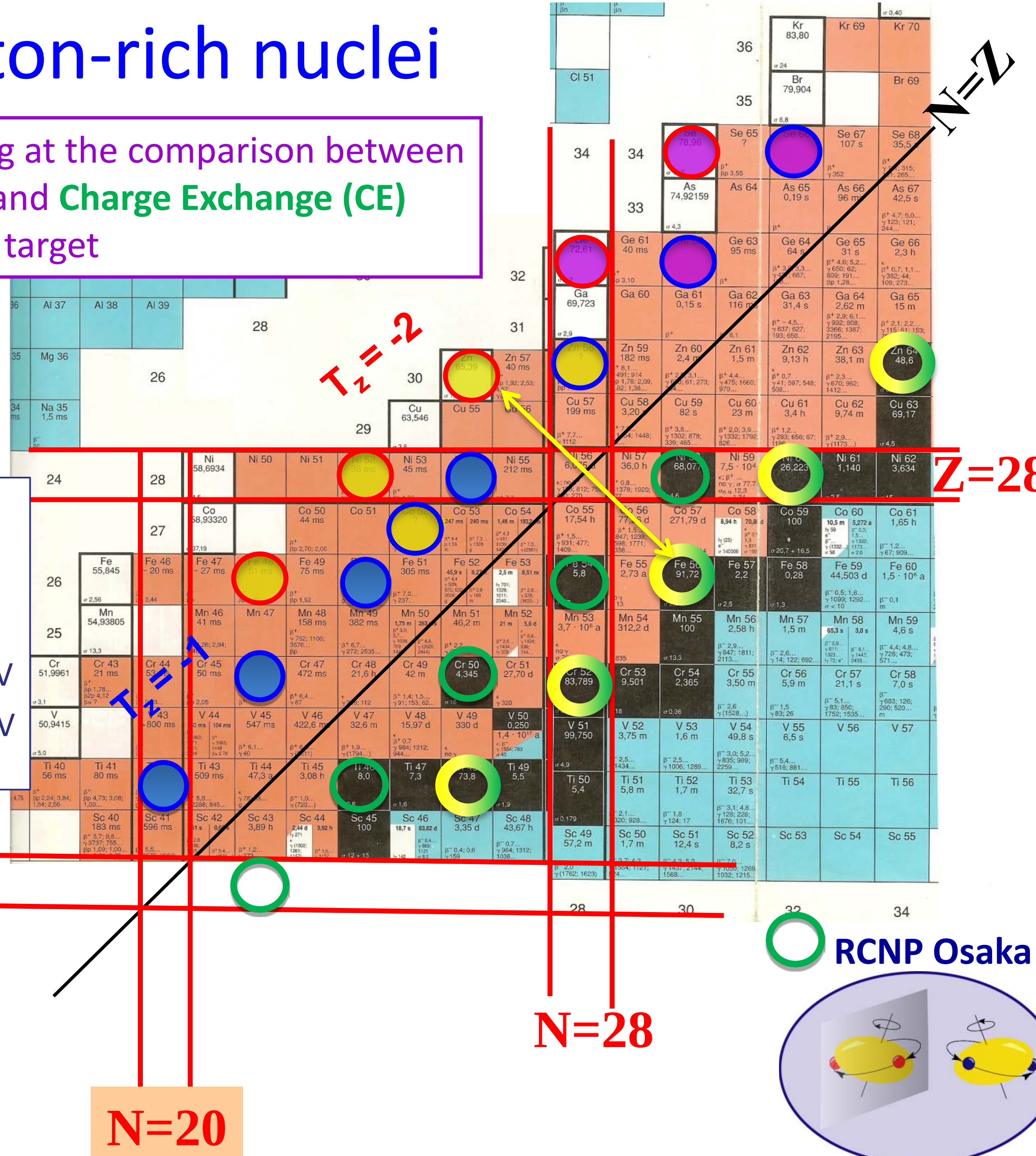
- Primary beams for RIB production

RIKEN
- ^{78}Kr @345 AMeV

GSI
- ^{58}Ni @680 AMeV

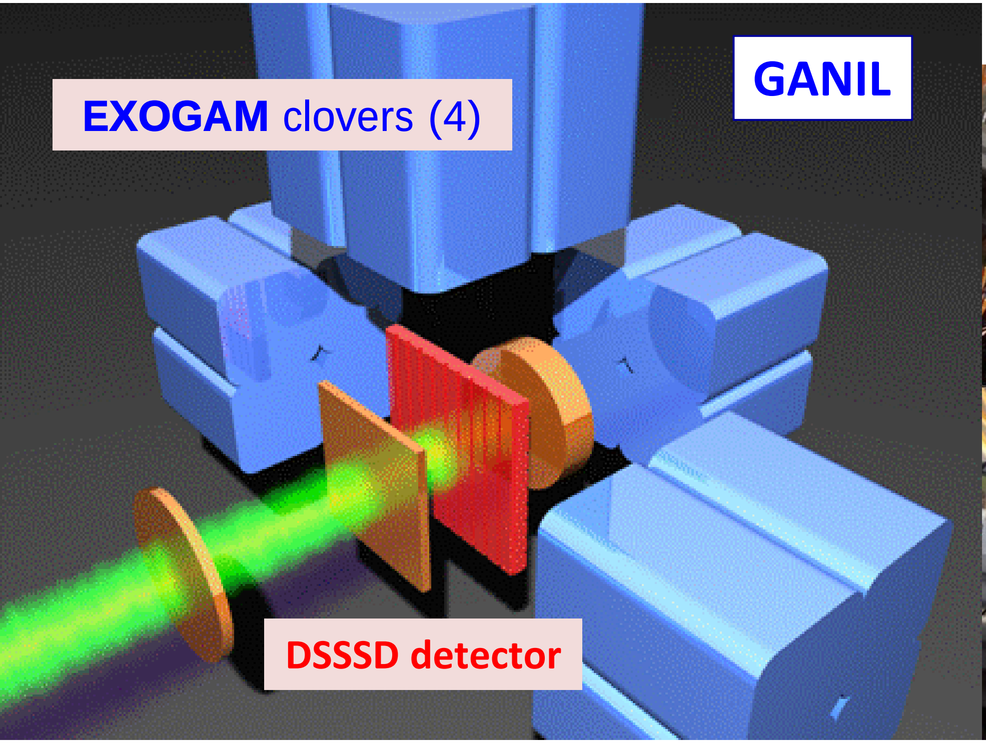
GANIL
- ^{58}Ni @75 AMeV
- ^{64}Zn @79 AMeV

RCNP Osaka



Experimental technique @ GANIL / RIKEN

- Primary beam: ^{58}Ni @75 AMeV (GANIL - LISE) / ^{78}Kr @345 AMeV (RIKEN - BigRIPS)
- Detection of implanted fragment and subsequent charged-particle (β and protons) decays: double-sided silicon strip detectors (DSSSD)
- Detection of β-delayed γ rays:
  EXOGAM Ge clovers (GANIL) / EUROBALL-RIKEN Ge Cluster Array (RIKEN)



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- **^{56}Zn**: 1st observation of β-delayed γ-proton decay

Orrigo+, PRL 112, 222501 (2014)

- β decay of **^{48}Fe** and **^{52}Ni**

Orrigo+, PRC 93, 044336 (2016)

- ^{52}Co: 1st observation of the 2^+ isomer ($T_{1/2}$ = 102_6 ms)

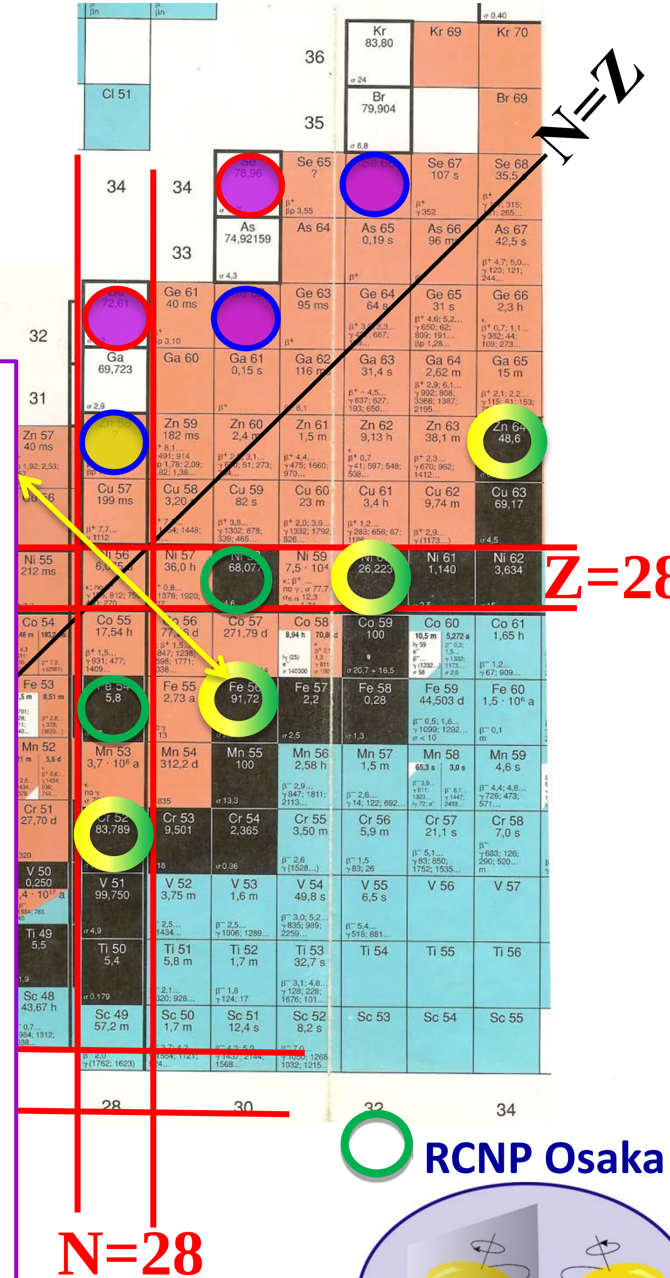
Orrigo+, PRC 94, 044315 (2016)

- **^{58}Zn** and $T_{1/2}$ of **16 nuclei** with T_z = -1, -1/2

Kucuk, Orrigo+, EPJA 53, 134 (2017)

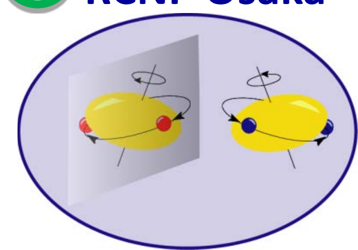
- β decay of **^{60}Ge** and **^{62}Ge**

Orrigo+, PRC 103, 014324 (2021)

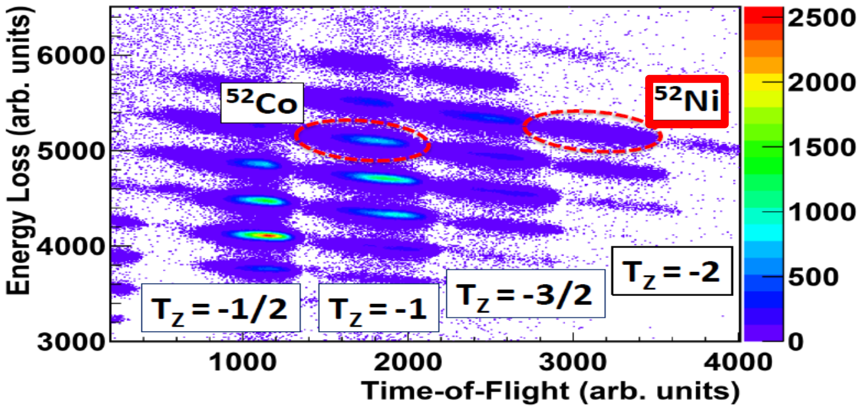


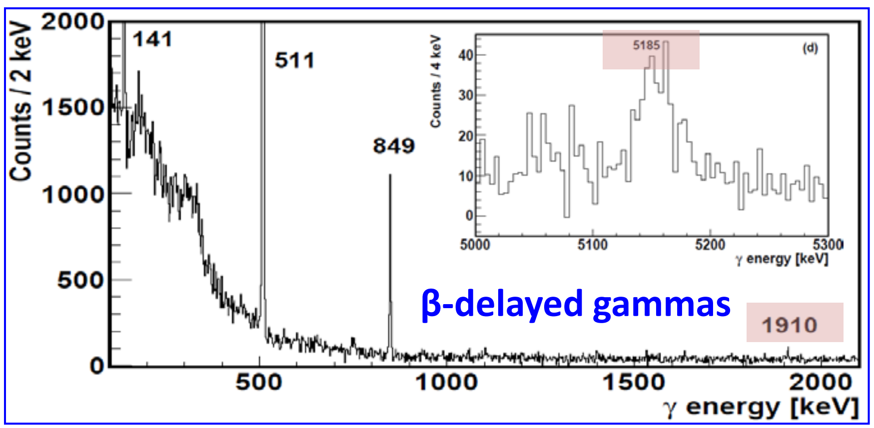
N=20

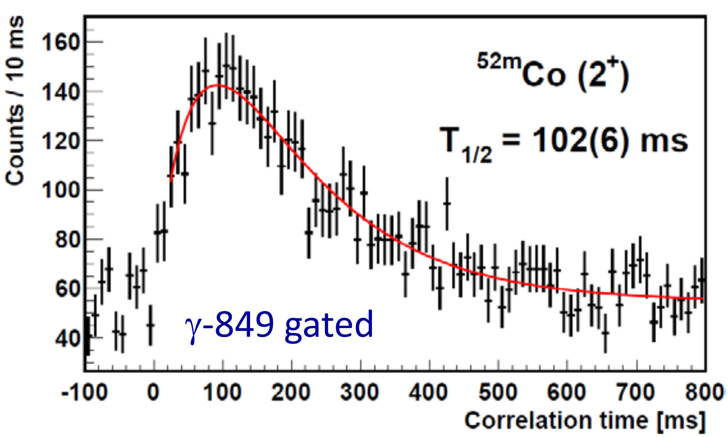
RCNP Osaka

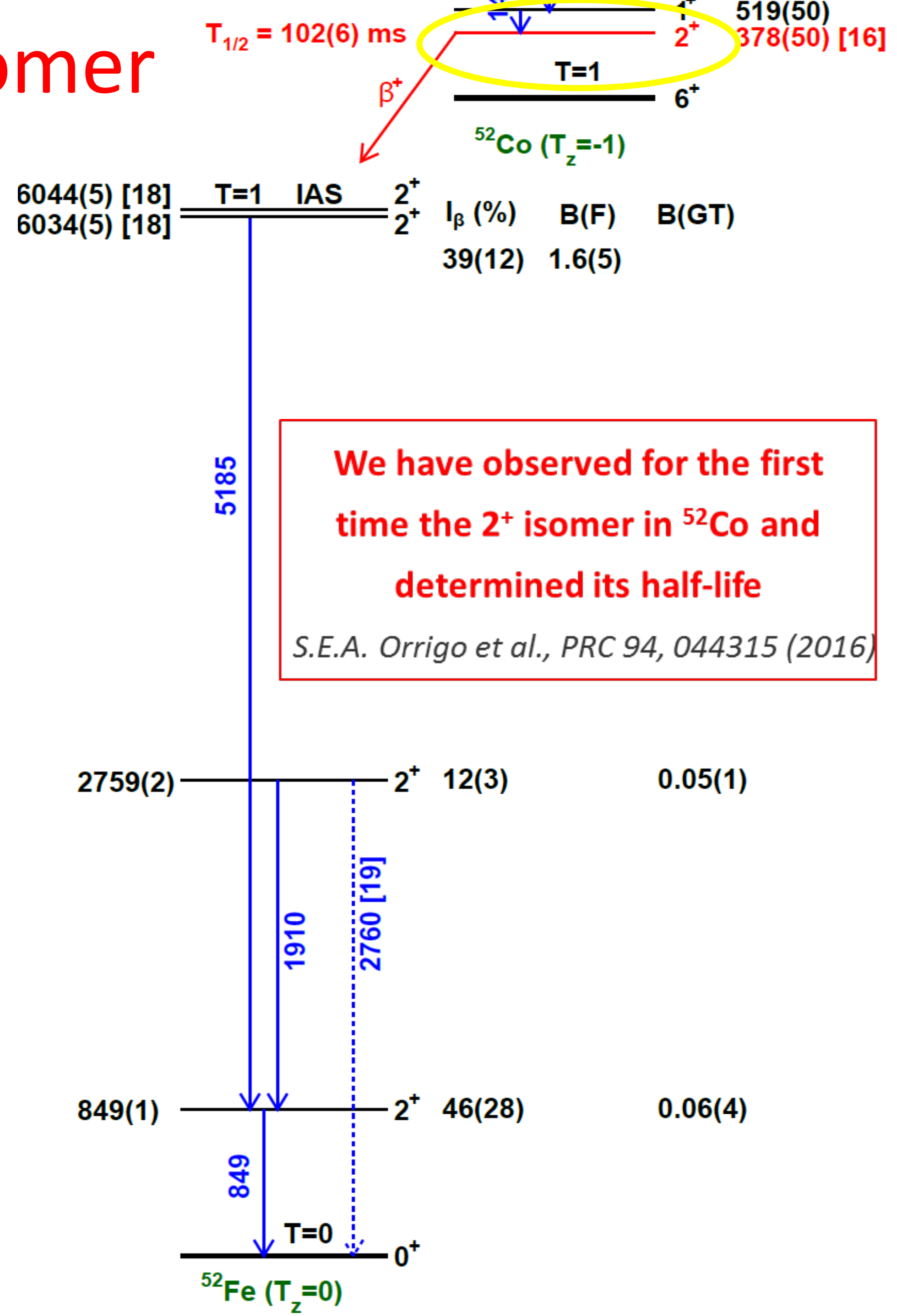


$T_{1/2}$ of the $^{52m}Co(2^+)$ isomer









We have observed for the first time the 2⁺ isomer in ^{52}Co and determined its half-life

S.E.A. Orrigo et al., PRC 94, 044315 (2016)

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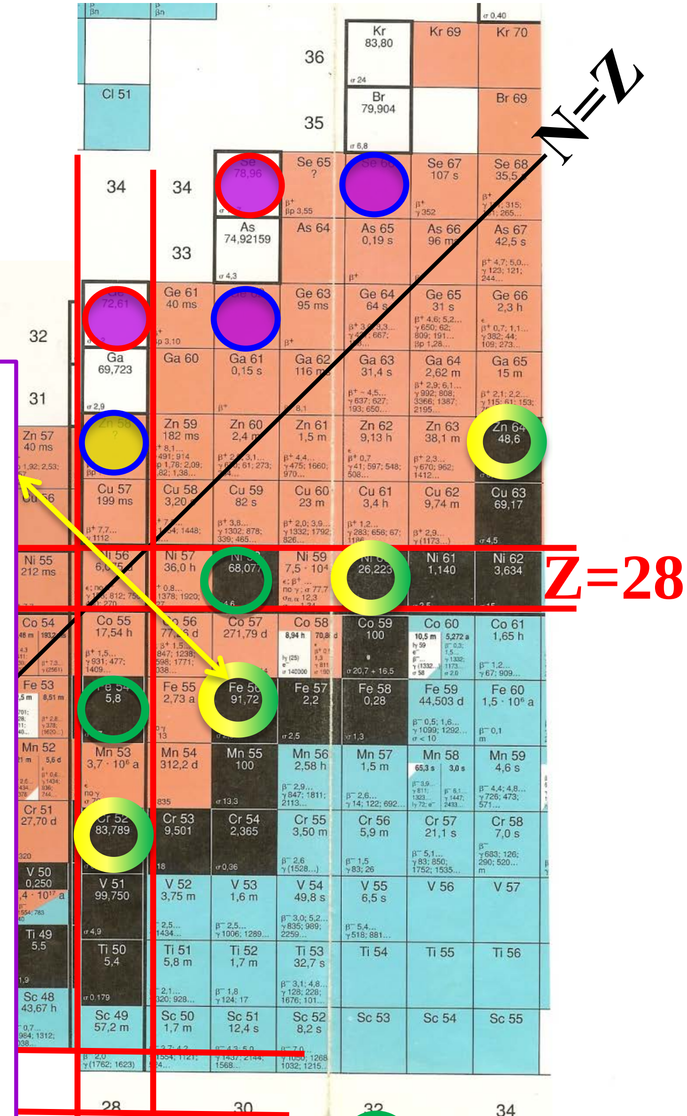
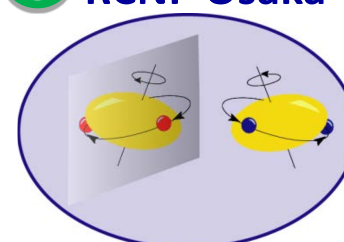
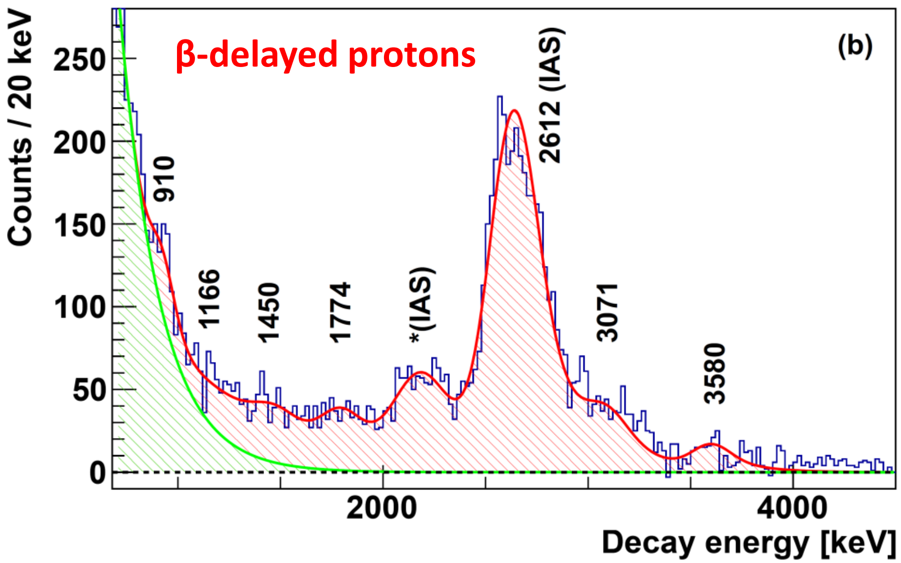
N=20

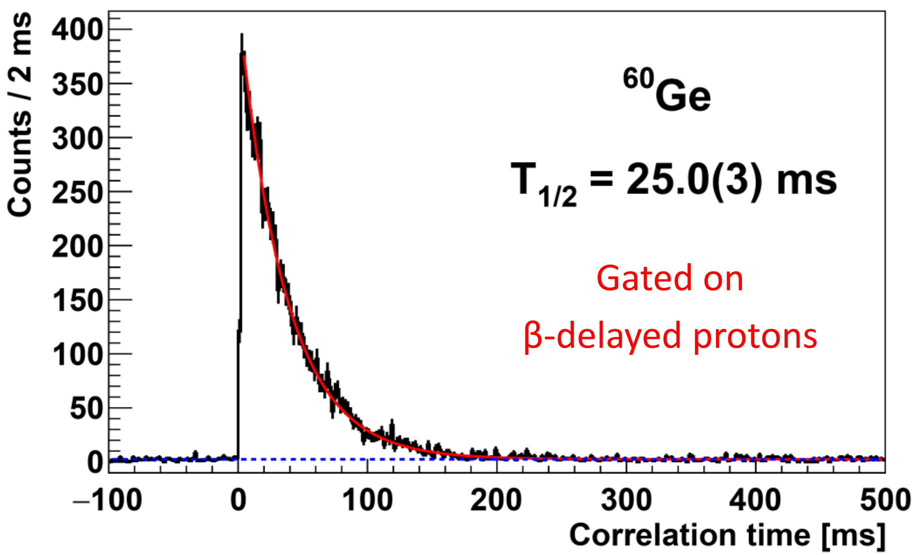


RCNP Osaka



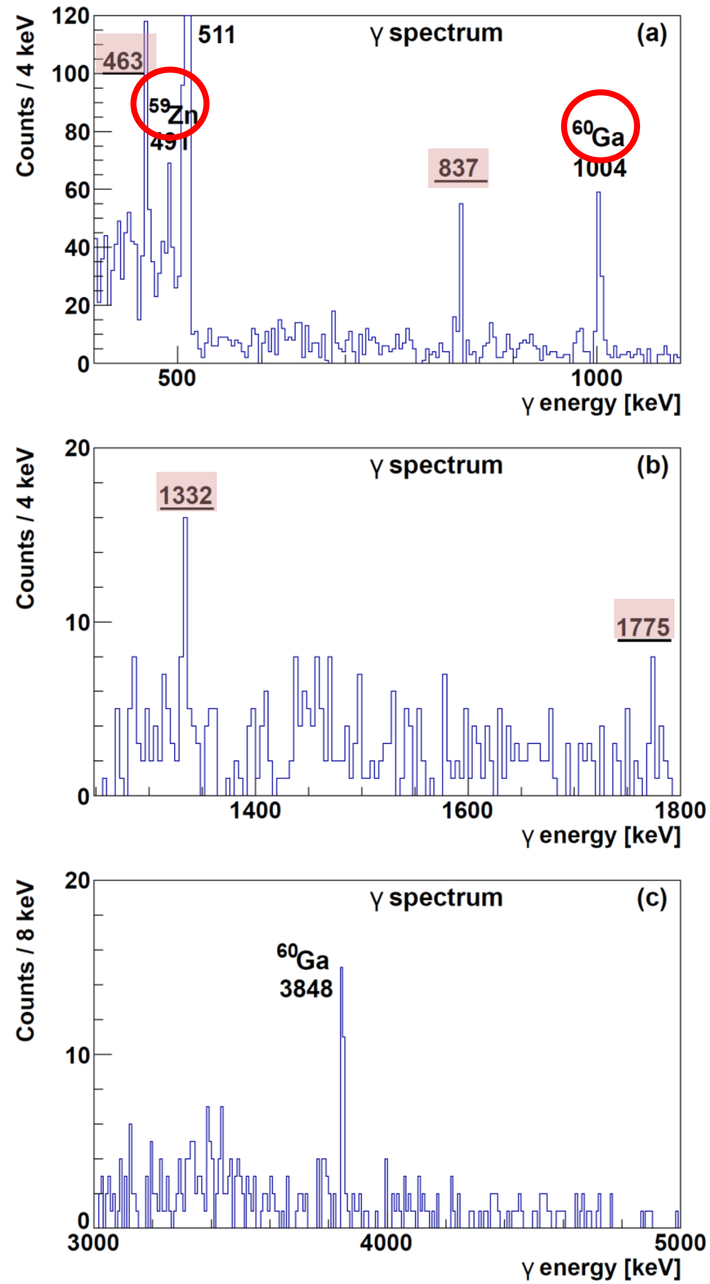
β decay of ^{60}Ge



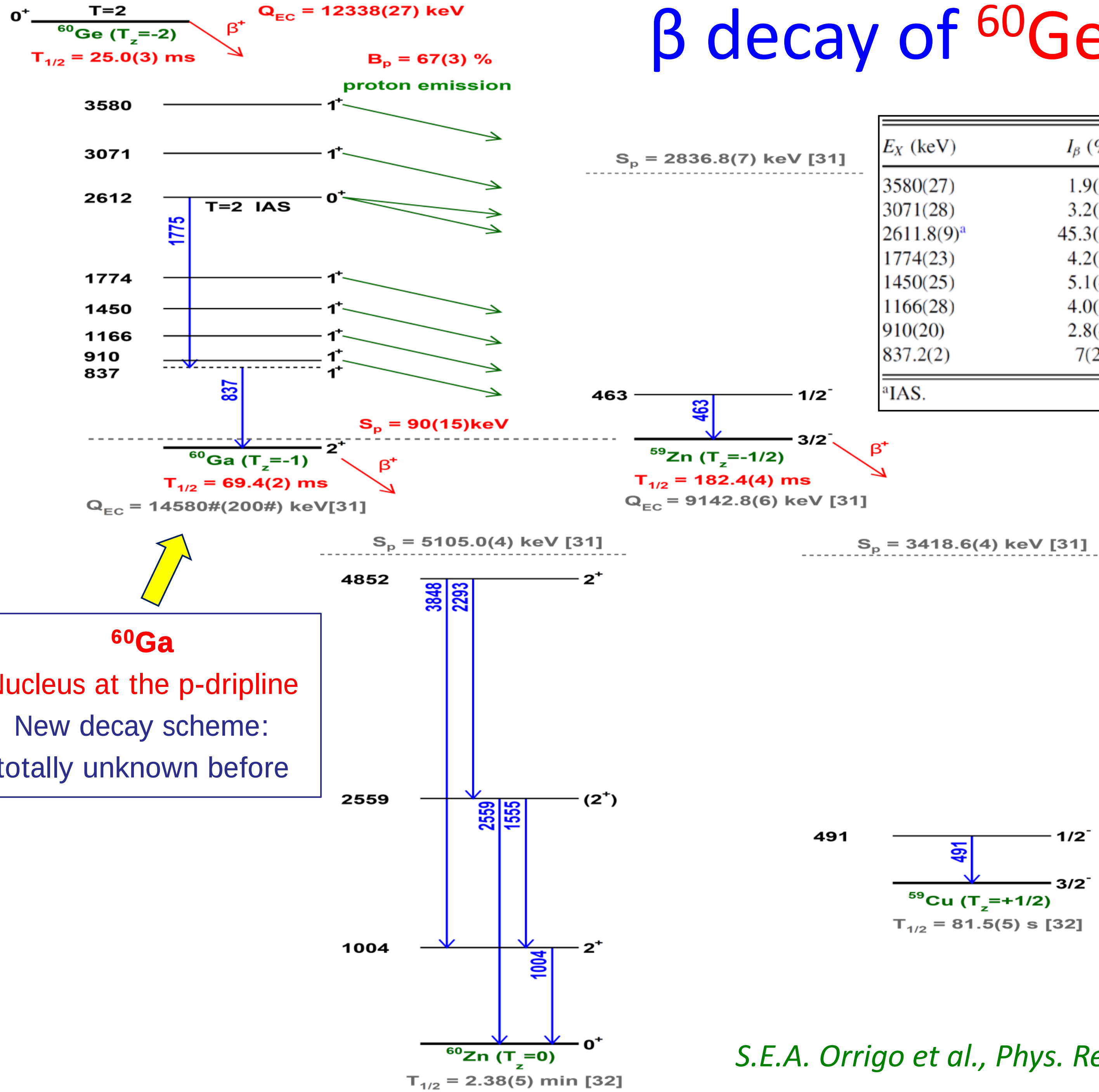


S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)

β-delayed γ rays



β decay of ^{60}Ge



E_X (keV)	I_β (%)	B(F)	B(GT)
3580(27)	1.9(2)		0.14(1)
3071(28)	3.2(3)		0.18(2)
2611.8(9)[a]	45.3(20)	3.1(1)	
1774(23)	4.2(3)		0.11(1)
1450(25)	5.1(4)		0.11(1)
1166(28)	4.0(5)		0.074(9)
910(20)	2.8(4)		0.044(6)
837.2(2)	7(2)		0.11(3)

[a]IAS.

^{60}Ga

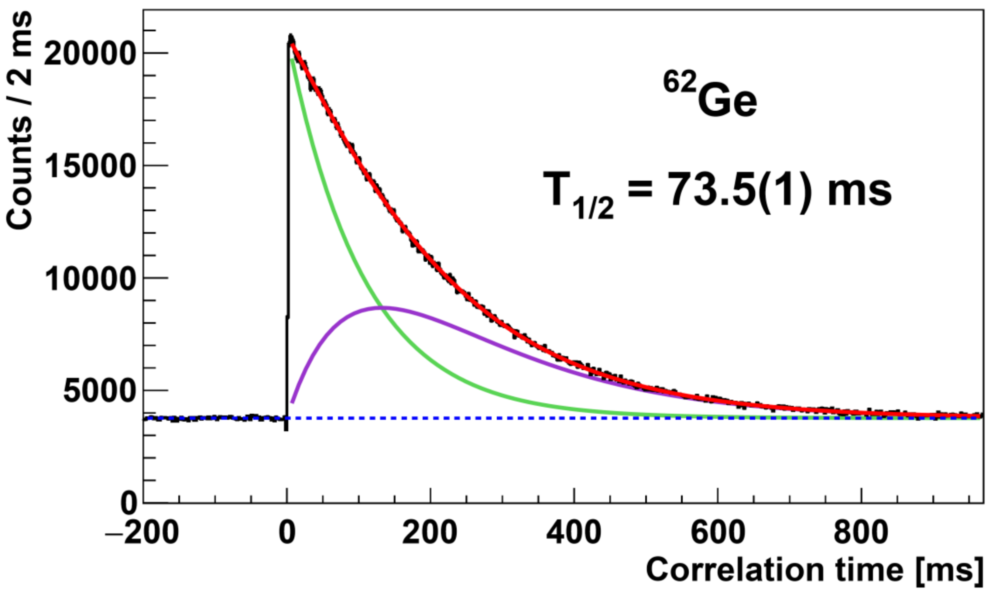
Nucleus at the p-dripline

New decay scheme:

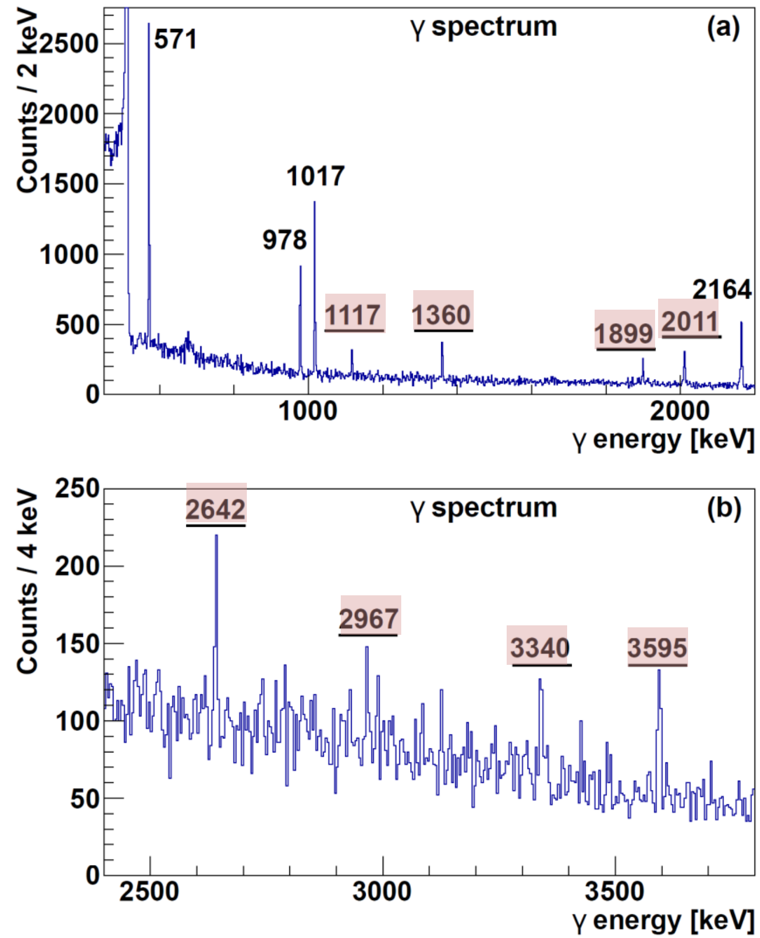
totally unknown before

S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)

β decay of ^{62}Ge



β-delayed γ rays



S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)

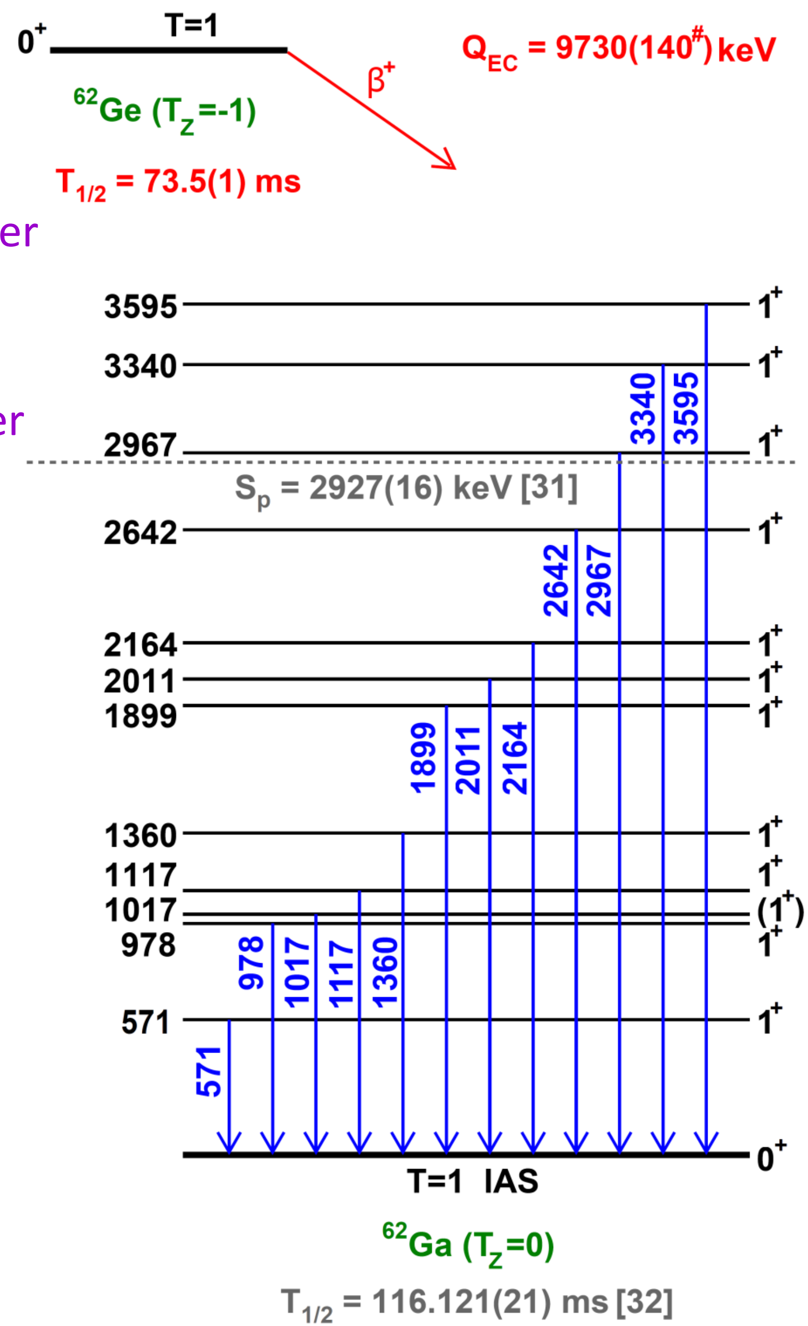
β decay of ^{62}Ge

- No $1^+ \rightarrow 1^+$ transitions ⇒ confirmed the *quasi-rule* of Warburton and Weneser (suppression of M1 isoscalar transitions between $J^\pi = 1^+$, T = 0 states)
- No evidence of enhanced low-lying Gamow-Teller strength in ^{62}Ga due to isoscalar p-n pairing [E. Grodner et al., PRL 113, 092501 (2014)]

E_γ (keV)	I_γ (%)	E_X (keV)	I_β (%)	B(F)	B(GT)
3594.7(5)	0.6(1)	3594.7(5)	0.6(1)		0.07(1)
3339.6(5)	0.30(6)	3339.6(5)	0.30(6)		0.030(7)
2966.8(5)	0.35(6)	2966.8(5)	0.35(6)		0.028(5)
2641.8(5)	0.4(1)	2641.8(5)	0.4(1)		0.029(7)
2164.1(4)	2.6(2)	2164.1(4)	2.6(2)		0.13(1)
2010.9(4)	0.96(8)	2010.9(4)	0.96(8)		0.045(5)
1899.3(4)	0.58(6)	1899.3(4)	0.58(6)		0.025(3)
1359.7(2)	0.70(5)	1359.7(2)	0.70(5)		0.022(2)
1117.4(2)	0.41(4)	1117.4(2)	0.41(4)		0.011(2)
1017.1(1)	2.6(1)	1017.1(1)	2.6(1)		0.067(6)
978.3(1)	1.8(1)	978.3(1)	1.8(1)		0.047(4)
571.3(1)	3.4(1)	571.3(1)	3.4(1)		0.068(6)
		g.s.[a]	85.3(3)[b]	2.0	

[a] IAS.
[b] The ground state–to–ground state feeding is $I_\beta^{\mathrm{IAS}} = (100 - \Sigma_i I_\gamma^i)$.

S.E.A. Orrigo et al., Phys. Rev. C 103, 014324 (2021)



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Orrigo+, PRL 112, 222501 (2014)

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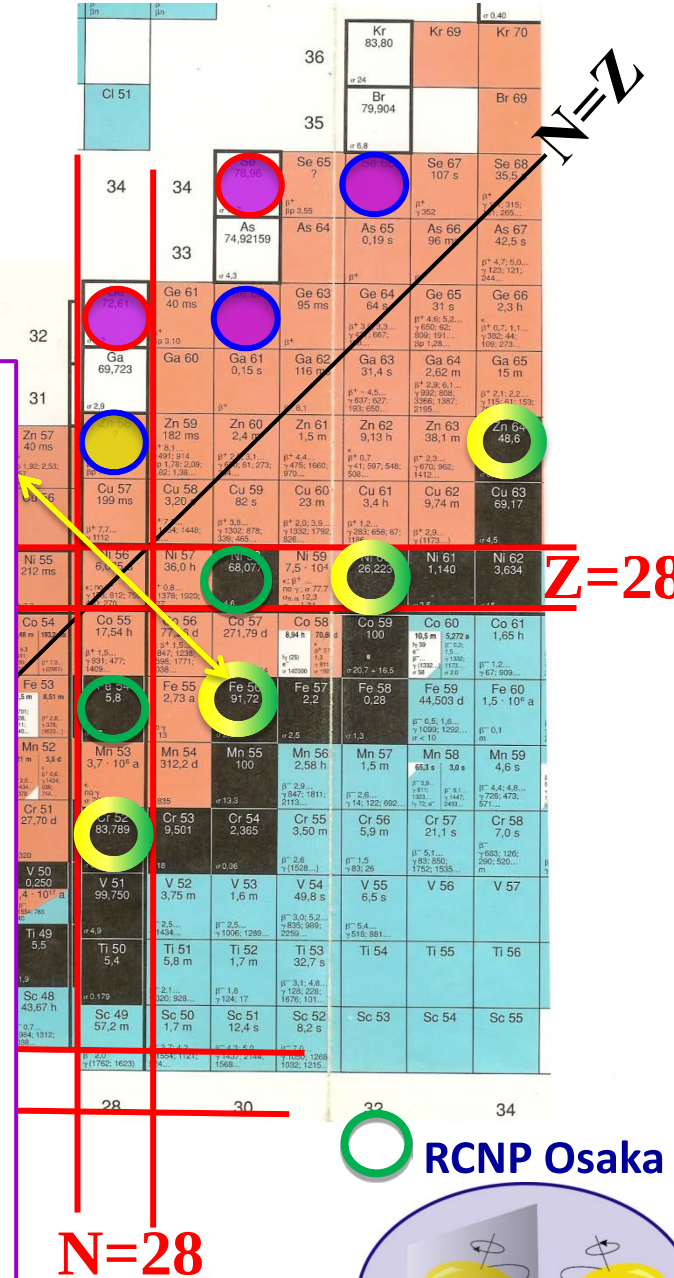

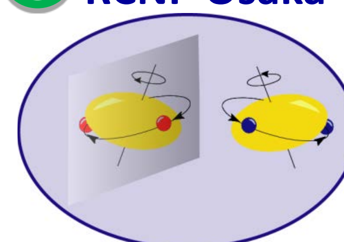

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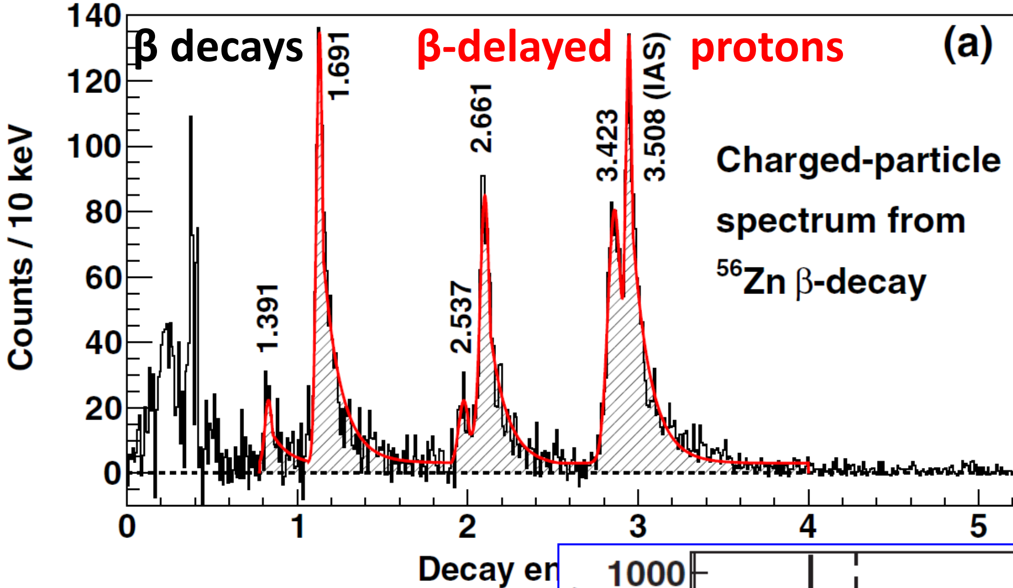
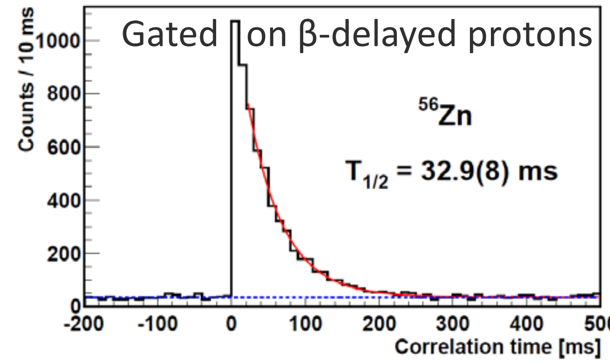
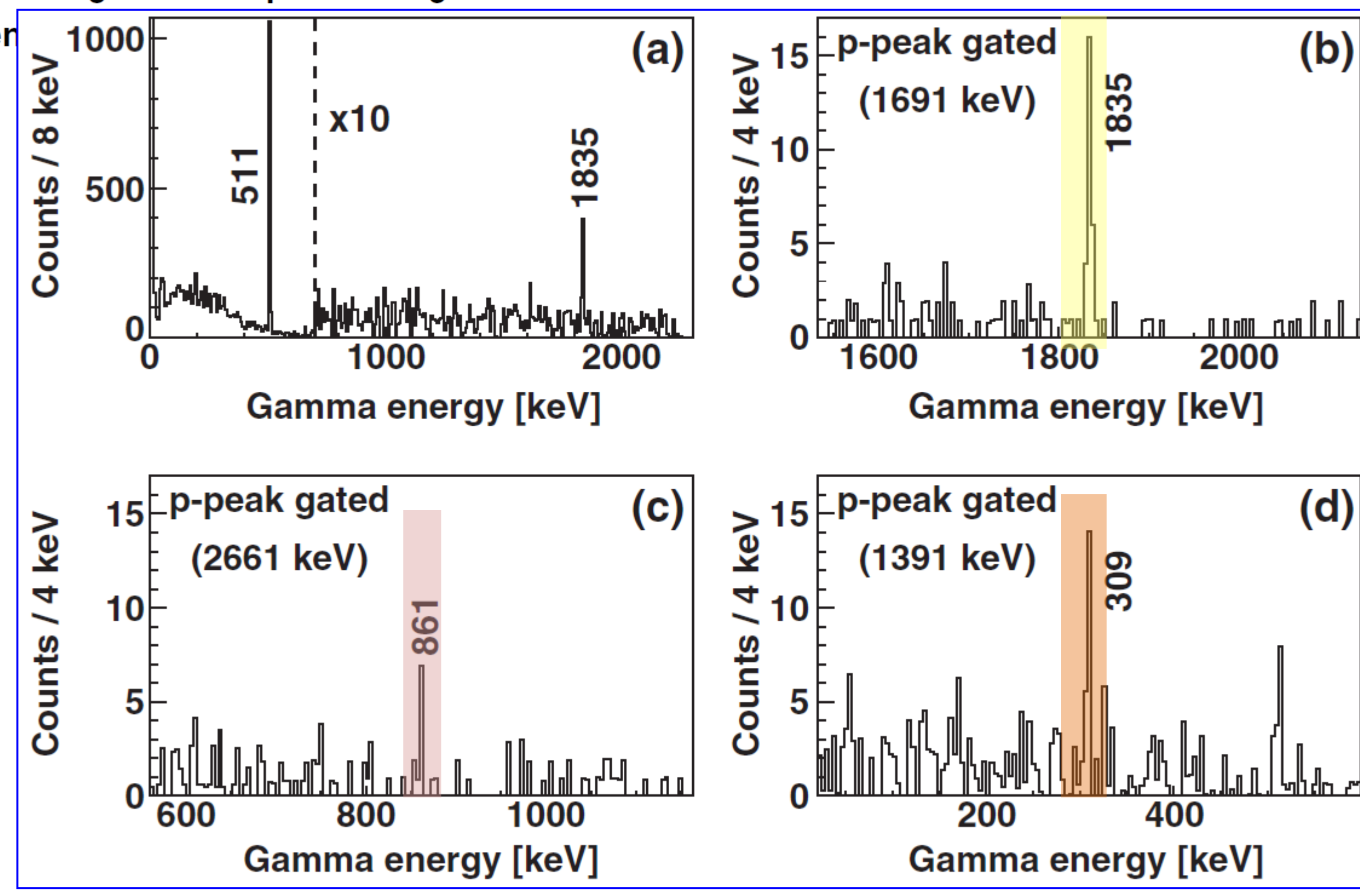


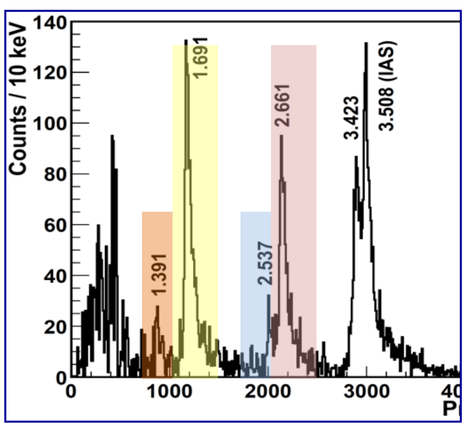


β-delayed γ rays



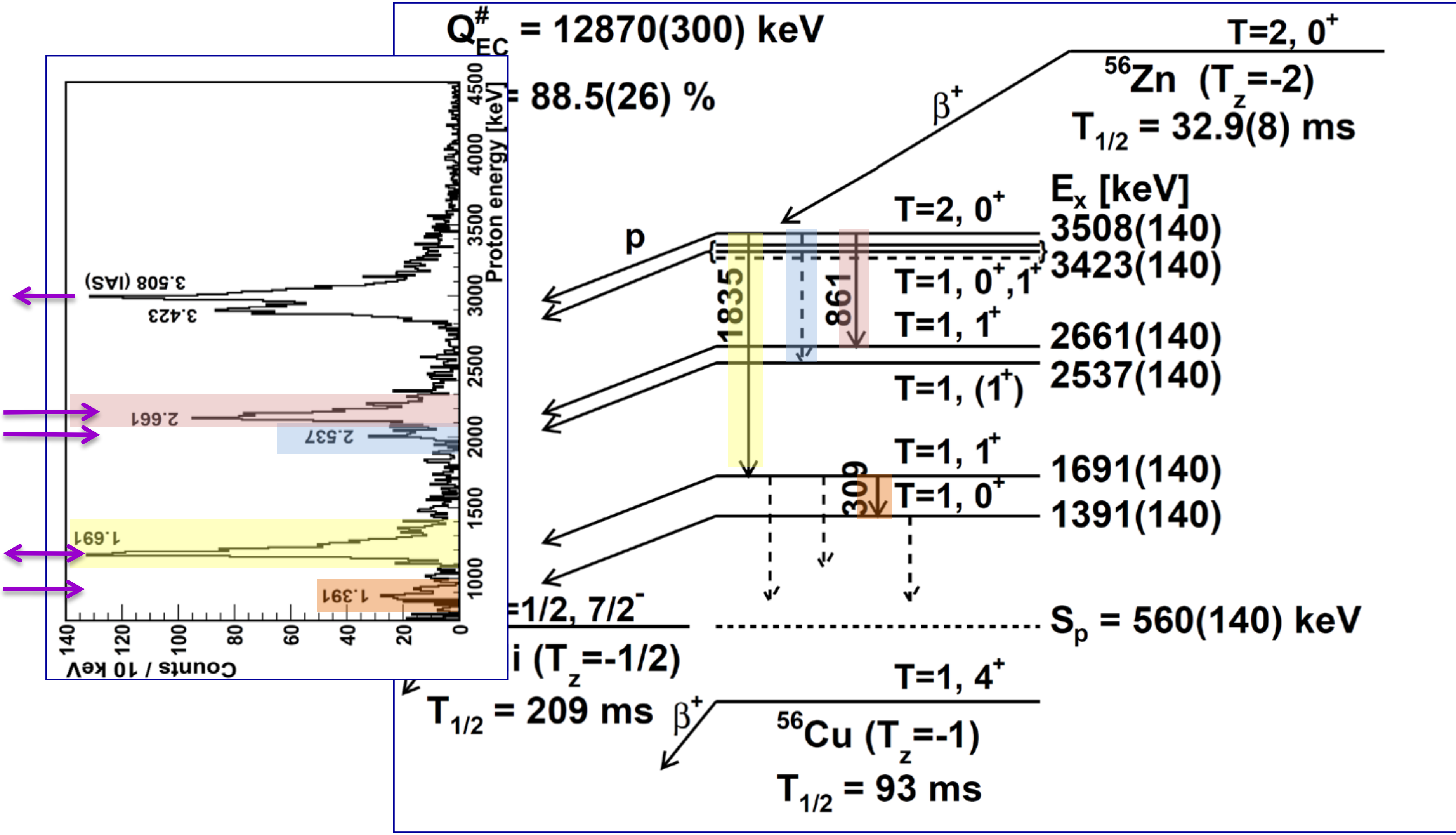
Proton-gamma coincidences

Gates on protons



S.E.A. Orrigo et al., PRL 112, 222501 (2014)

β decay of ^{56}Zn

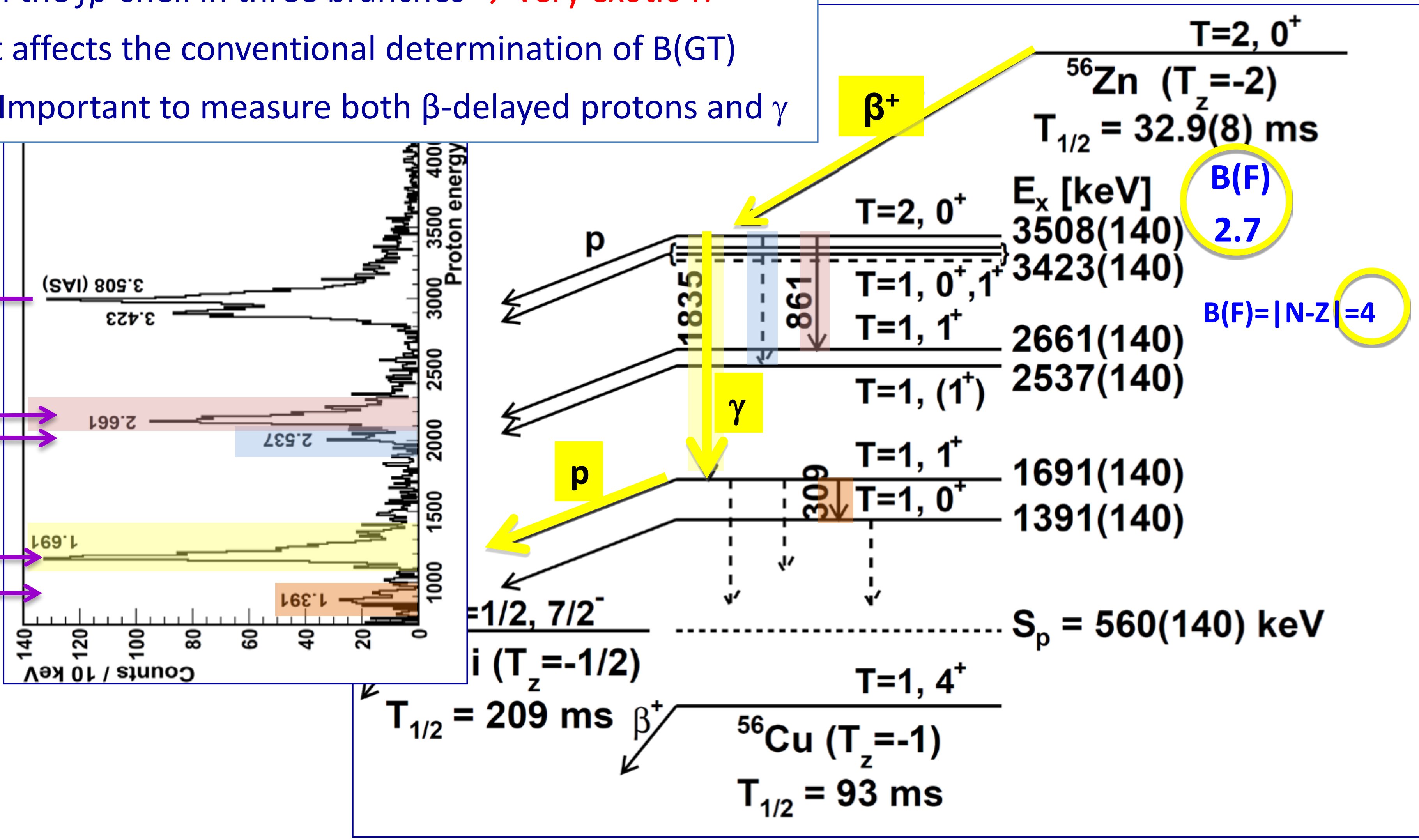


S.E.A. Orrigo et al., Phys. Rev. Lett. 112, 222501 (2014)

1st observation of β-delayed γ-proton decay

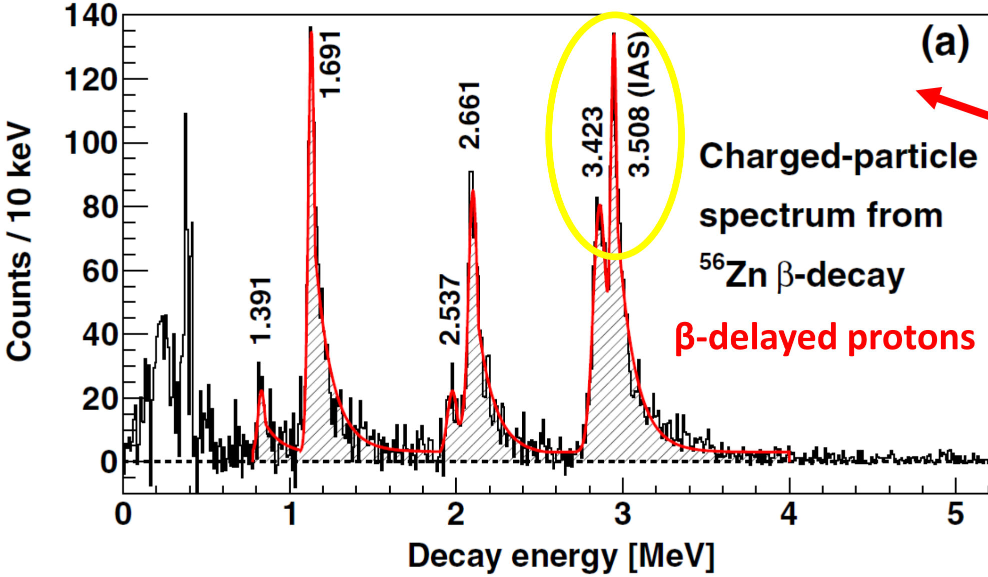
- In the *fp*-shell in three branches → very exotic !!
- It affects the conventional determination of B(GT)

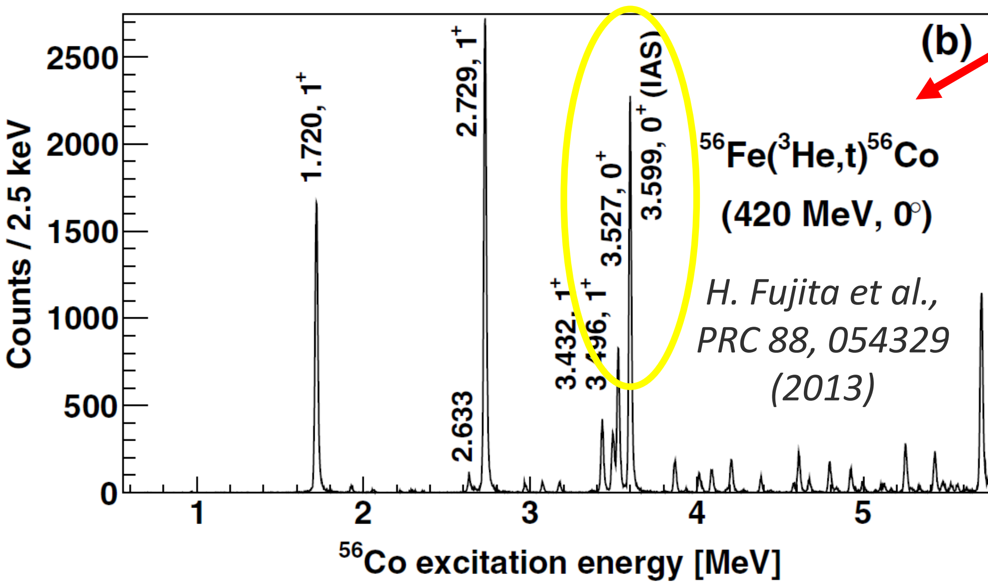
⇨ Important to measure both β-delayed protons and γ

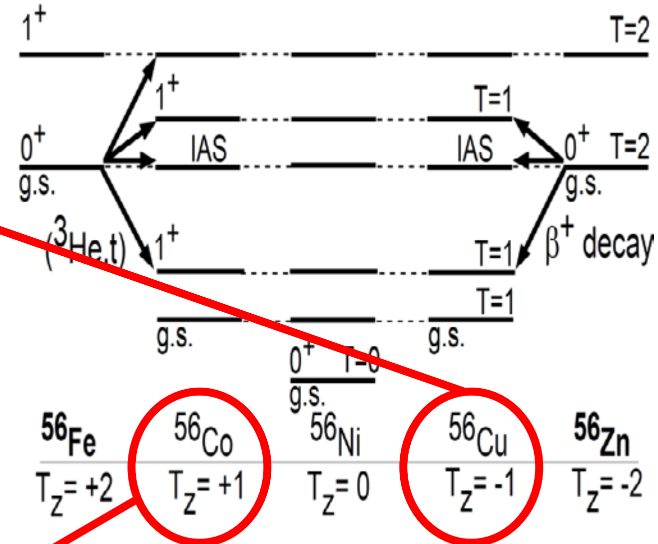


S.E.A. Orrigo et al., Phys. Rev. Lett. 112, 222501 (2014)

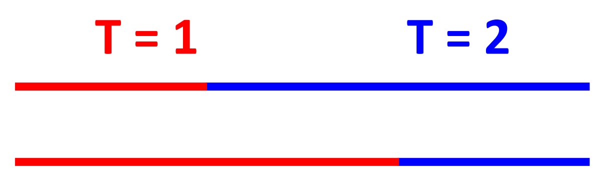
Comparison with mirror Charge Exchange







- **Isospin symmetry holds well**
  - All the dominant transitions are observed
  - We can profit from the higher energy resolution of the CE reaction

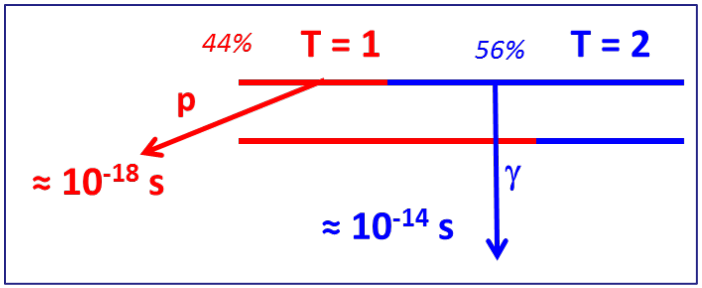


- **Isospin mixing:** the ^{56}Co IAS is fragmented

$\langle H_c \rangle$ = 32.3(5) keV $\qquad \alpha^2$ = 28(1)%

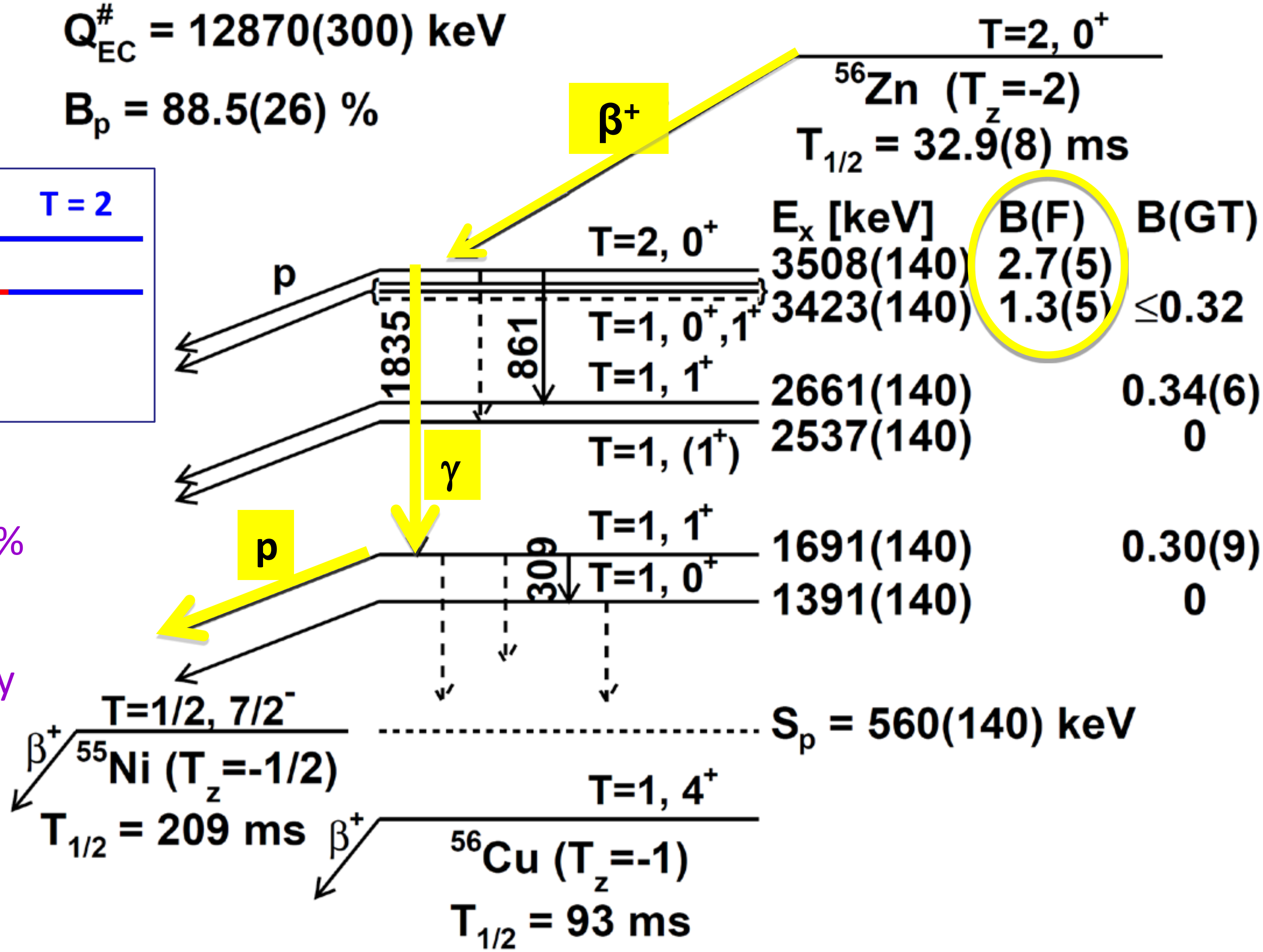
H. Fujita et al., PRC 88, 054329 (2013)

β decay of ^{56}Zn: many exotic features!



- Fragmentation of B(F)
- Isospin mixing $\alpha^2 = 33_{10}\%$
- Competition βp / βγ
- 10^3 hindrance of p-decay

S.E.A. Orrigo et al.,
PRL 112, 222501 (2014)



- 2 independent SM calculations: p-decay hindered by 10^3; isospin mixing reproduced

B. Rubio et al., Nucl. Phys. Review 33, 225 (2016) *N. Smirnova et al., Phys. Rev. C 93, 044305 (2016)*

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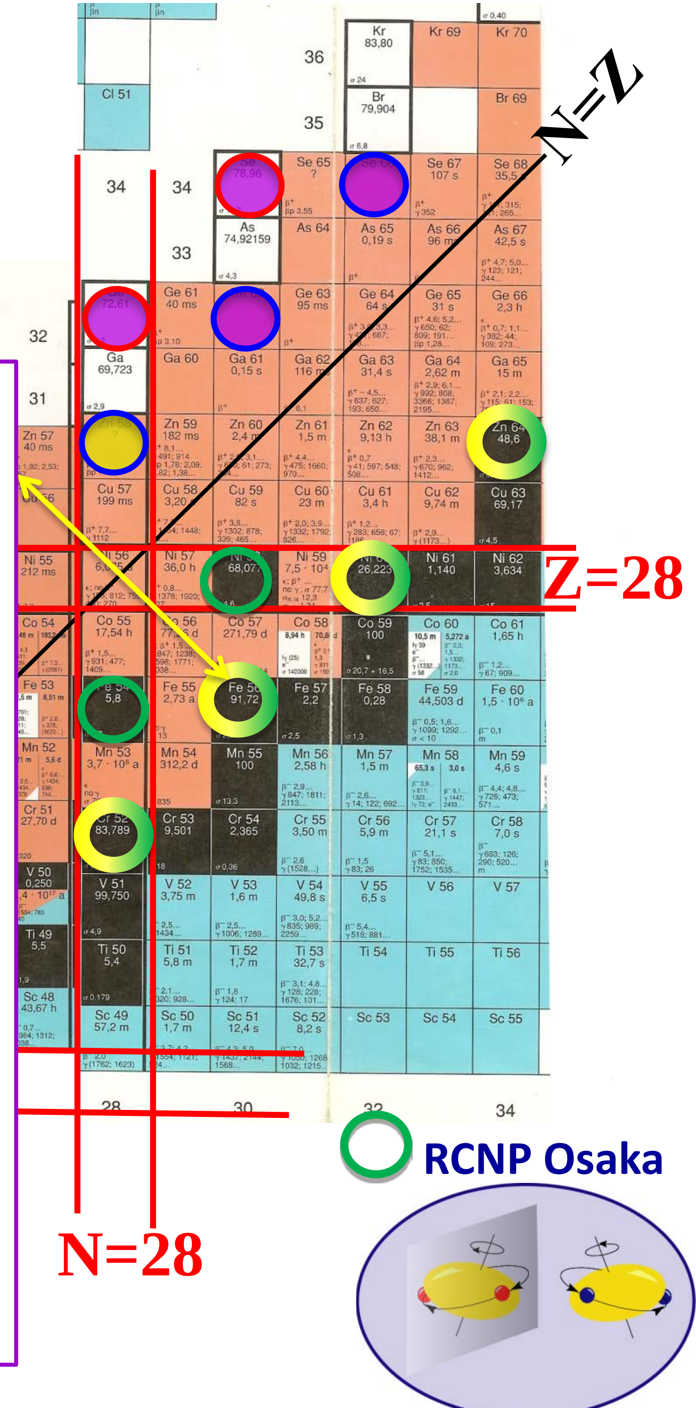
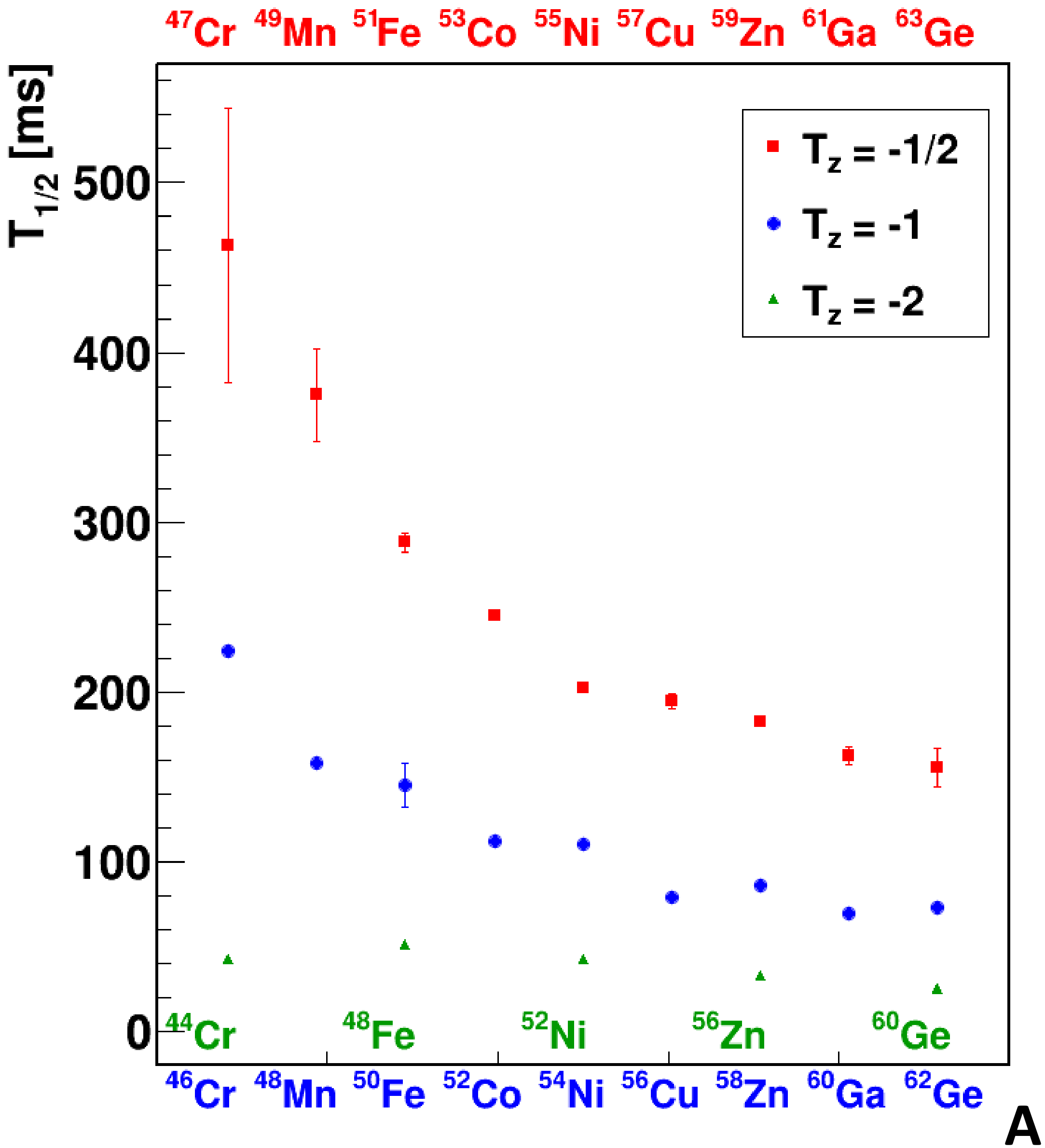
Orrigo+, PRC 103, 014324 (2021)

N=20



Half-life trends



■ $T_z = -1/2$, B(F) = 1

$T_{1/2}$ decreases as Q_β is increasing

● $T_z = -1$, B(F) = 2

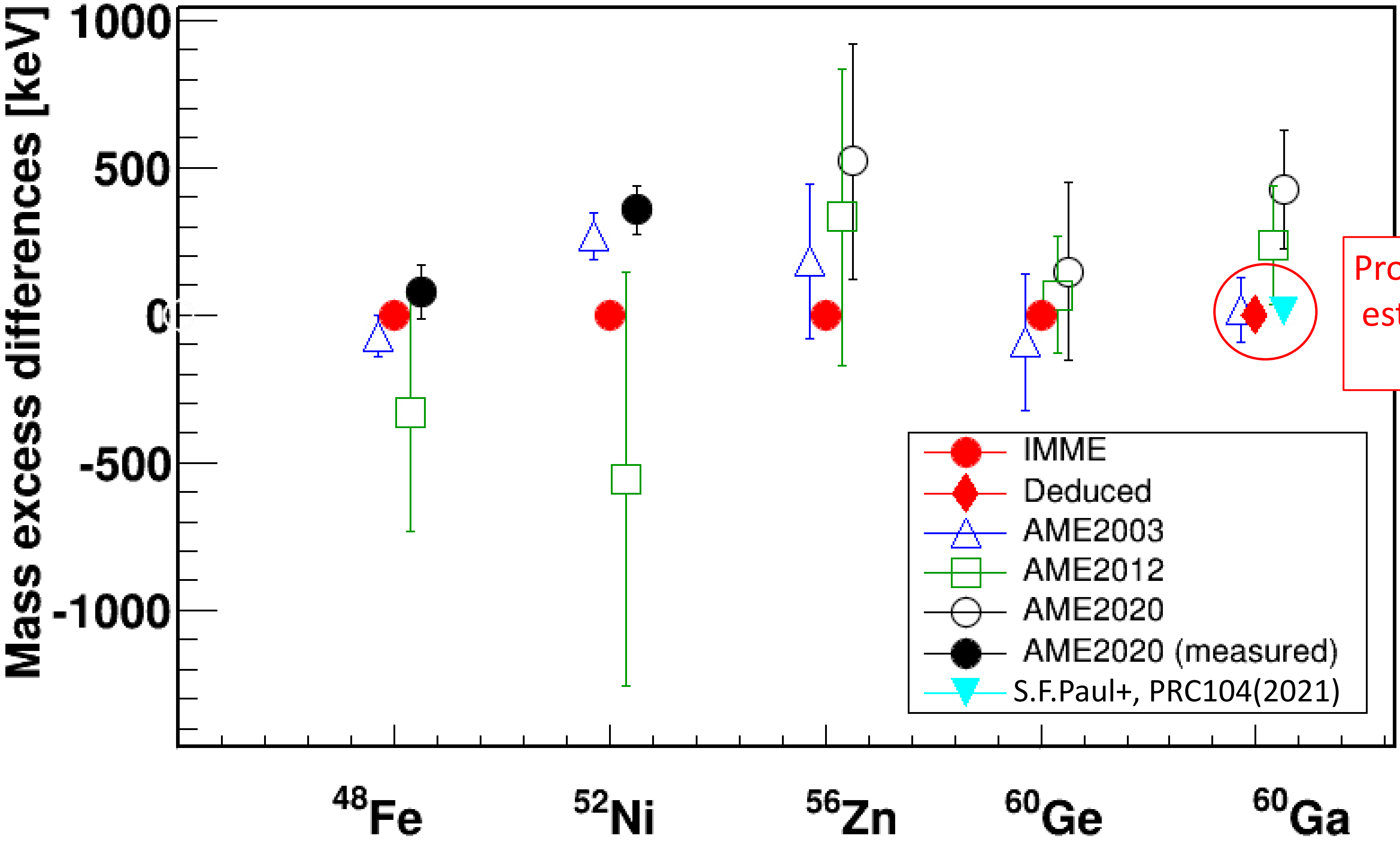
$T_{1/2}$ decreases as ($Q_\beta - E_X^{IAS}$) increases
+ even-even/odd-odd staggering
(IAS: g.s. or exc.)

▲ $T_z = -2$, B(F) = 4

$T_{1/2}$ decreases as ($Q_\beta - E_X^{IAS}$) increases

S.E.A. Orrigo et al., EPJ WOC (2022)

Mass excesses



Proton drip-line established for Z=31

S.E.A. Orrigo et al., EPJ WOC (2022)

The Collaboration

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Observation of the β-Delayed γ-Proton Decay of ^{56}Zn and its Impact on the Gamow-Teller Strength Evaluation

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Thank you

for your attention!