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Structure of proton-rich nuclei via mirror β-decay and charge exchange reactions

Sonja Orrigo

Outline

Structure of proton-rich nuclei in/beyond the *fp*-shell

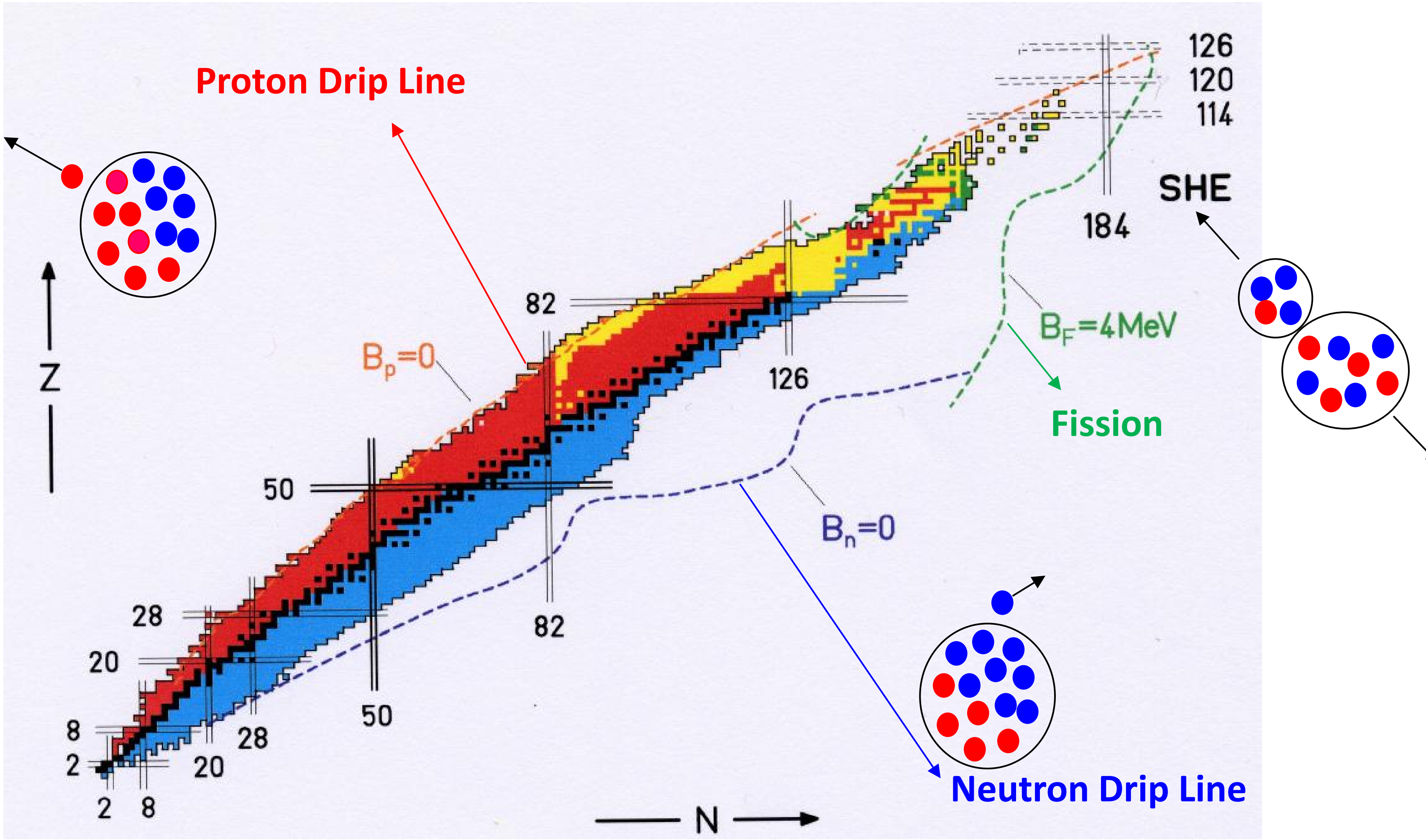
- **Introduction**
  - **Beta decay** experiments
  - Complementary process: **Charge Exchange (CE) reactions**

- **Experimental results**
  - Focus on the results from β-decay experiments done at GANIL (France)
  - Comparison with the mirror (^{3}He,t) CE experiments done at RCNP Osaka (Japan)
  - The exotic decay of **^{56}Zn**: first observation of **a new decay mode**
  - First observation of the **2^{+} isomer in ^{52}Co**

- **Summary**

β-decay spectroscopy

- Most of the nuclei we know today are beta-unstable: emission of β^+ or β^-
- The study of their β decay gives us rich spectroscopic information



β-decay spectroscopy

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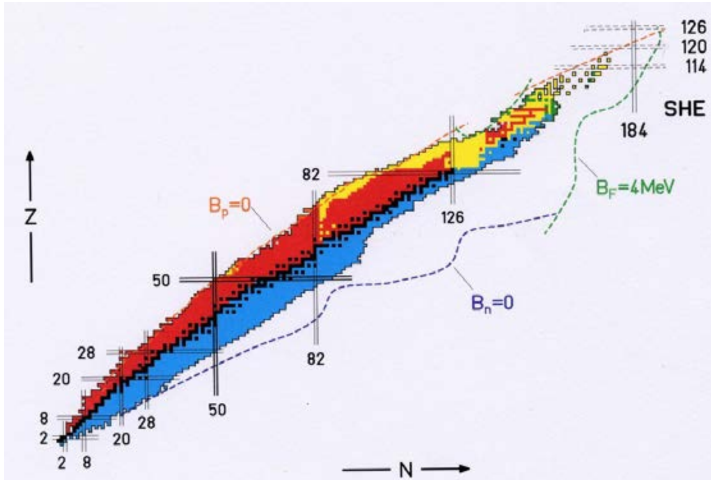
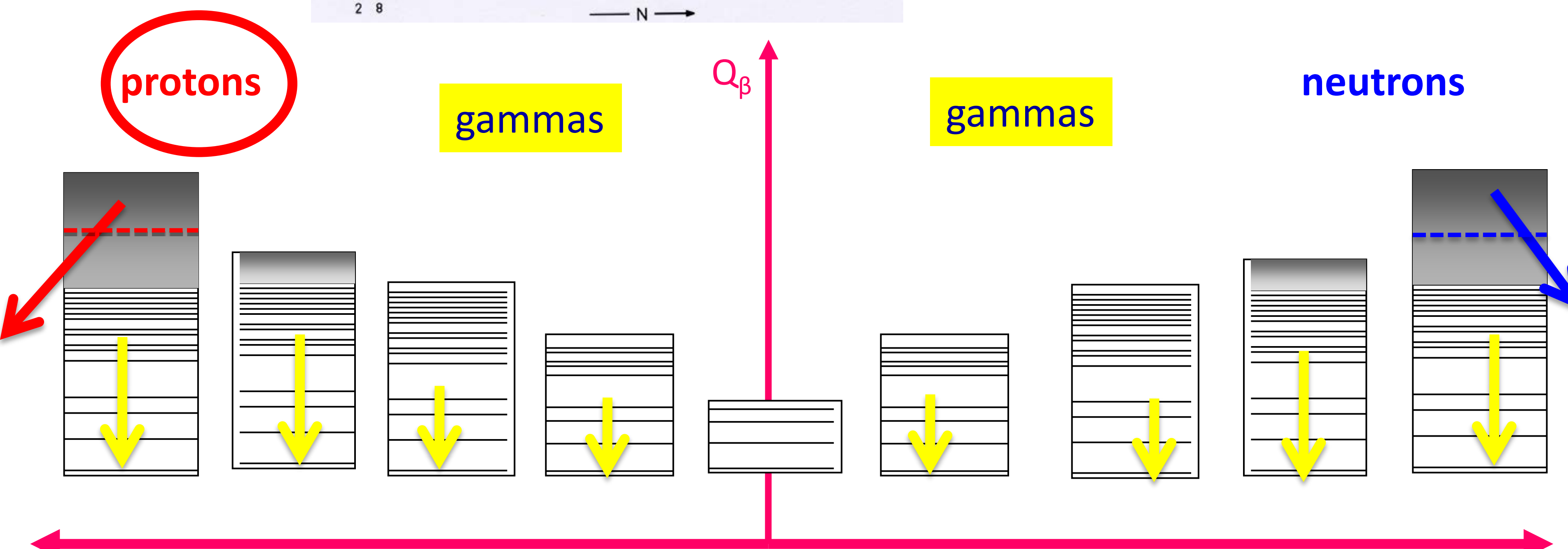


- The β decay is usually followed by emission of particles and/or gamma rays



β-decay spectroscopy

- **β-decay spectroscopy with implanted RIBs** is a powerful tool to study the structure of **proton-rich nuclei** in the *fp*-shell and above
- Information of great interest for both **nuclear structure and astrophysics**

✓ Information on **ground states and isomeric states**, masses and spins

✓ Accurate **half-life ($T_{1/2}$) values**, sometimes of β-decaying isomers

✓ By identifying individual particle groups and γ rays

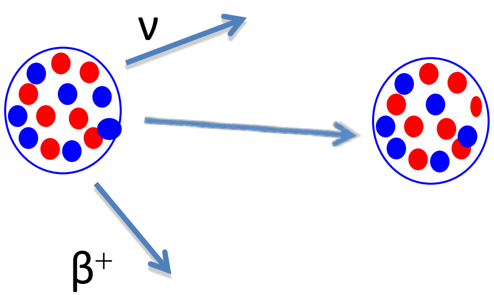
⇨ β-delayed particle-decay branching ratios, β-feedings

⇨ reconstruct the partial **decay scheme**

✓ Information on the **Isobaric Analog State (IAS)**

✓ Information on nuclei lying on the rp-process path

✓ Absolute values of the **Fermi B(F)** and **Gamow Teller B(GT)** transition strenghts



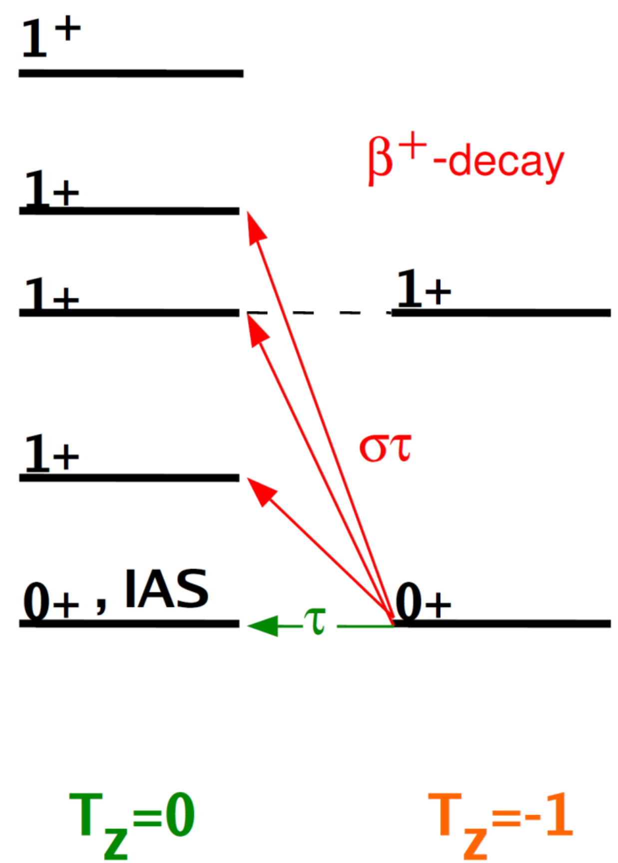
β-decay transition strengths

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

Fermi (ΔS = 0)

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

Gamow Teller (ΔS = 1)



- **Measured in β-decay experiments**

Beta feeding to states in the daughter nucleus

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

$\lambda = g_A/g_V$

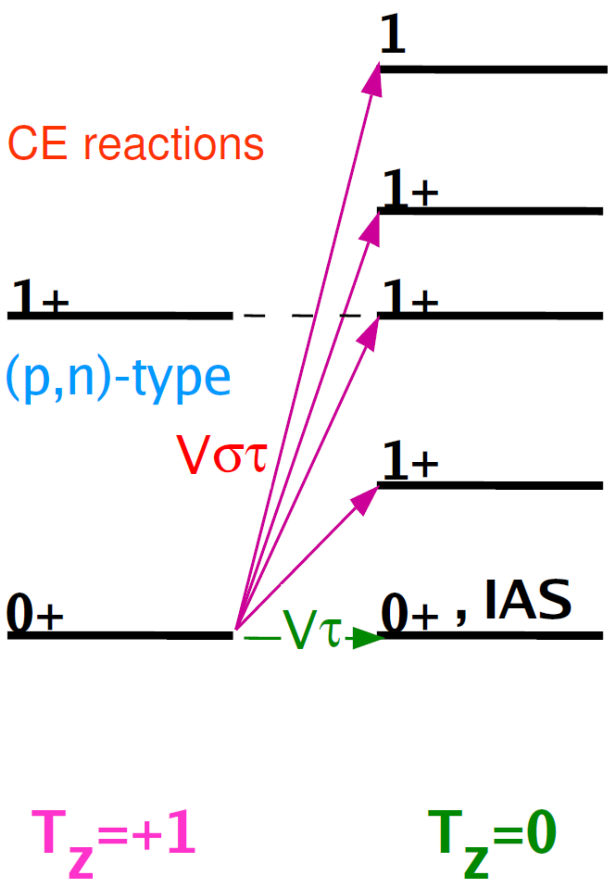
Parent half-life

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

- 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

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

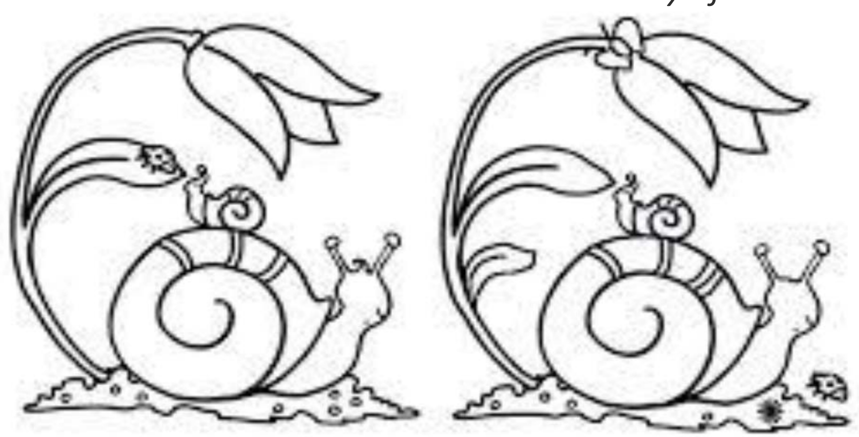
They are ruled by the same operators

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

- Mirror **Fermi** and **Gamow Teller** transitions are expected to have the same strength

- Are they really identical?

Find the difference!



Courtesy of B. Rubio

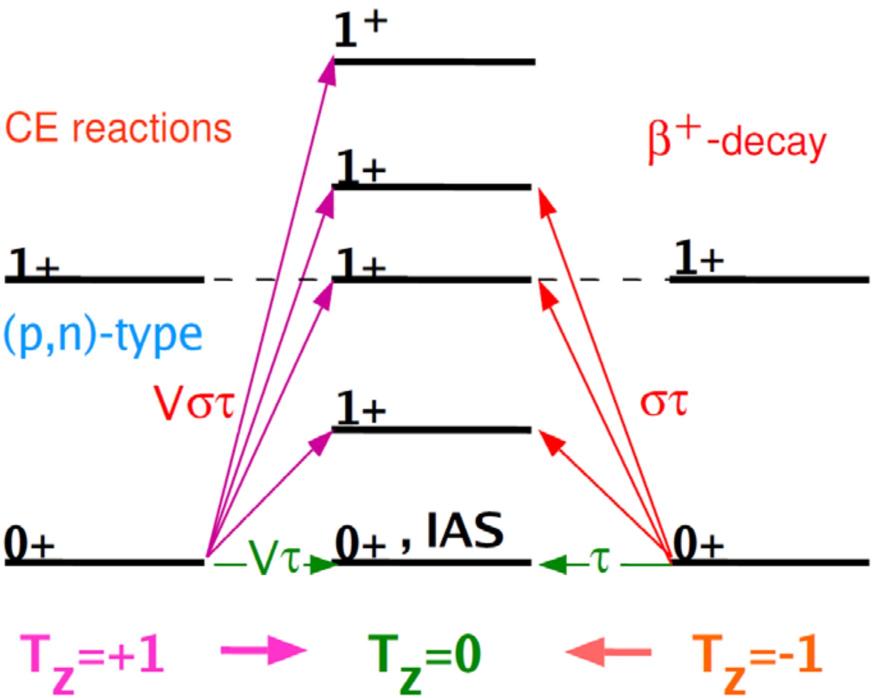
- What can we learn from the comparison?
  - Investigate **isospin symmetry** in mirror nuclei
  - Improve our knowledge of **GT transitions** close to the proton drip-line and along the rp-process pathway

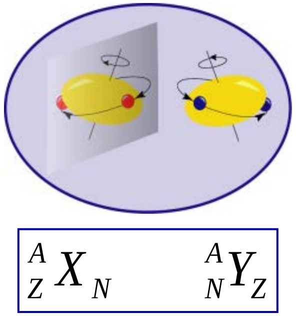
The T = 1 isospin multiplet

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 nucleus with the same probability

The final state is identical

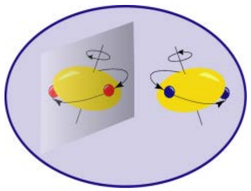




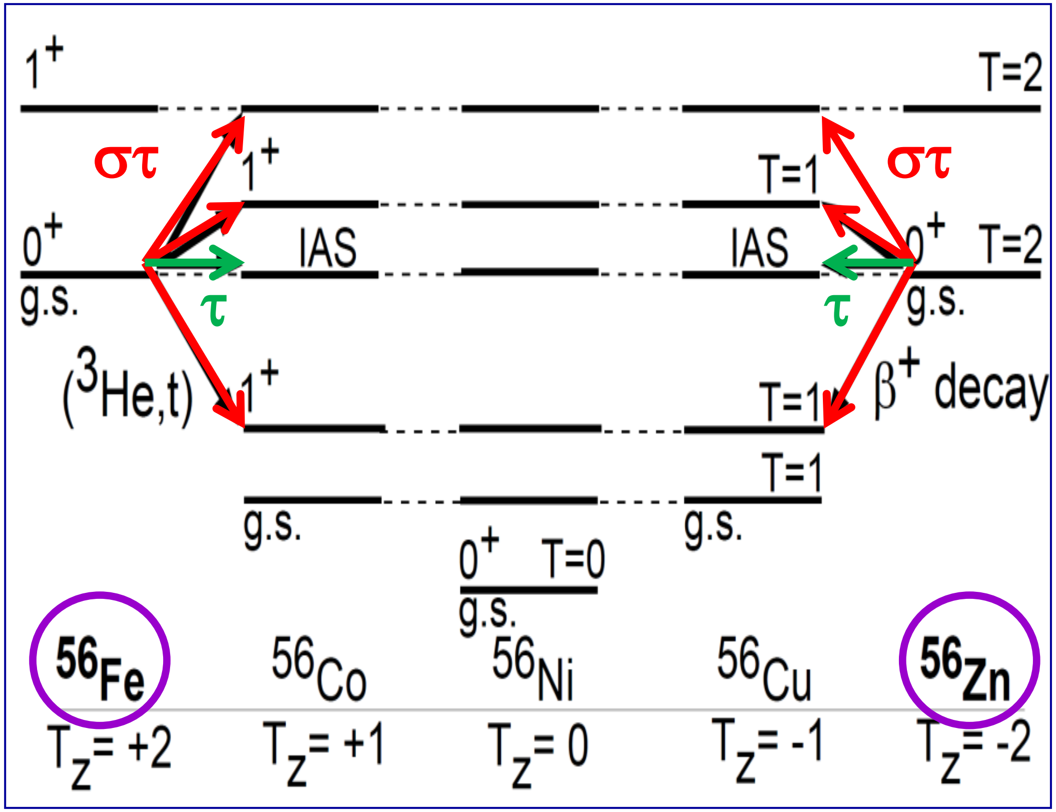
Y. Fujita, B. Rubio, W. Gelletly, PPNP 66 (2011) 549-606

F. Molina et al., PRC 91 (2015) 014301

The T = 2 isospin multiplet



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



- The final nucleus is not identical
- Excitation energy might be slightly different
- We compare transitions involving different initial and final states

- **CE experiments at RCNP Osaka**

(^{3}He,t) @ 140 AMeV and ϑ = 0°, with high energy resolution (20-30 keV)

^{56}Fe: H. Fujita et al., PRC 88, 054329 (2013)

^{52}Cr: Y. Fujita et al., PPNP 66, 549 (2011)

^{48}Ti: E. Ganioğlu et al., PRC 93, 064326 (2016)

- **β-decay experiments at GANIL**

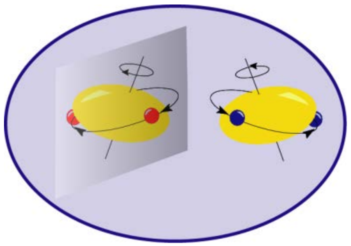
S.E.A. Orrigo, B. Rubio et al.,

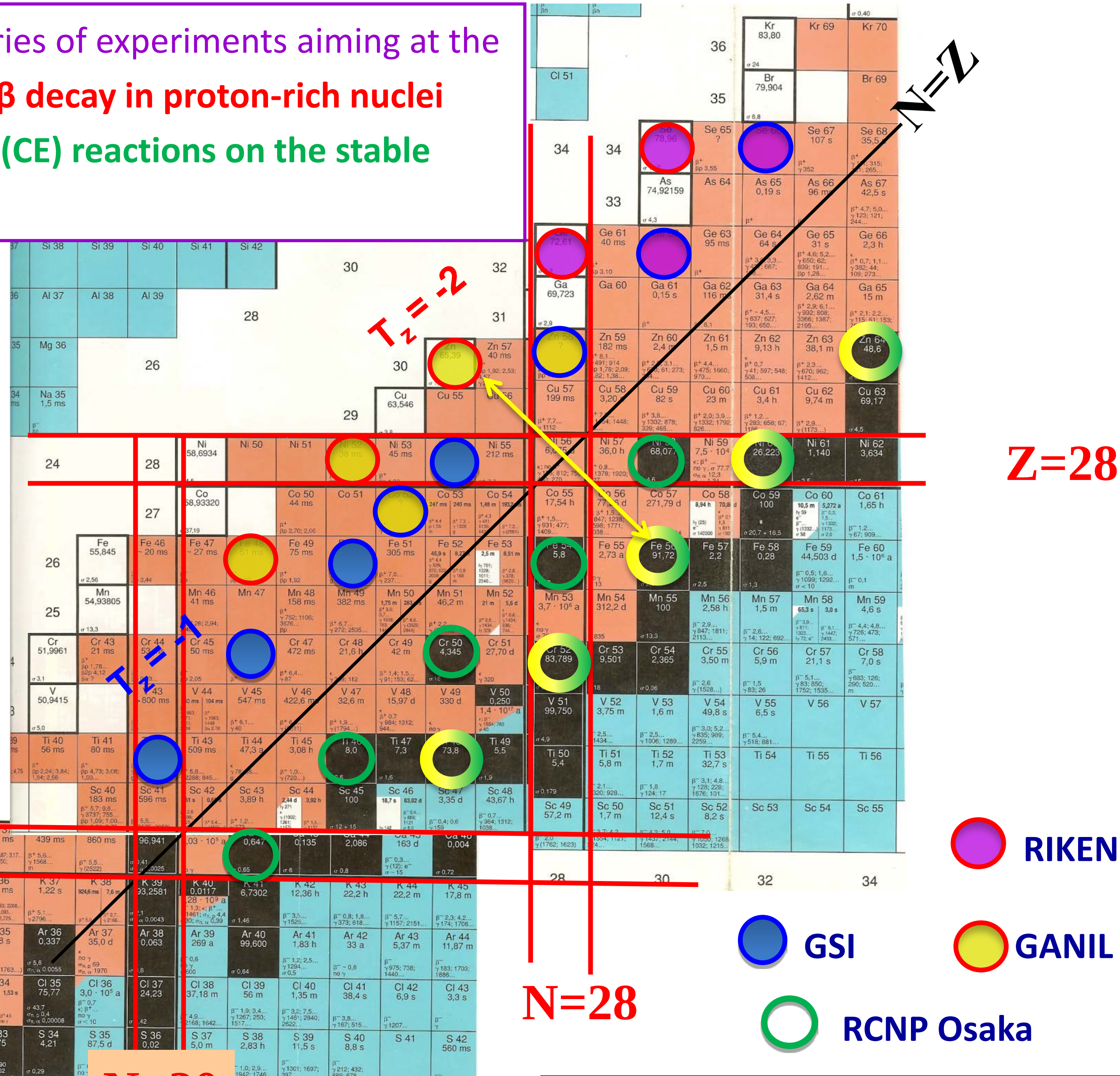
^{56}Zn: PRL 112, 222501 (2014)

^{52}Ni, ^{48}Fe: PRC 93, 044336 (2016)

^{52}Co: PRC 94, 044315 (2016)

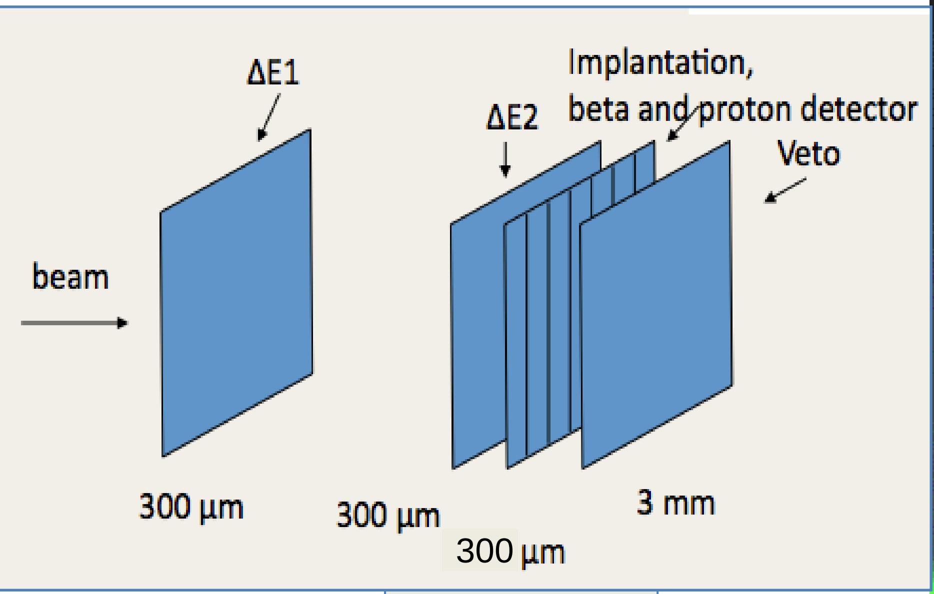
We performed a series of experiments aiming at the comparison between **β decay in proton-rich nuclei** and **Charge Exchange (CE) reactions on the stable mirror target**



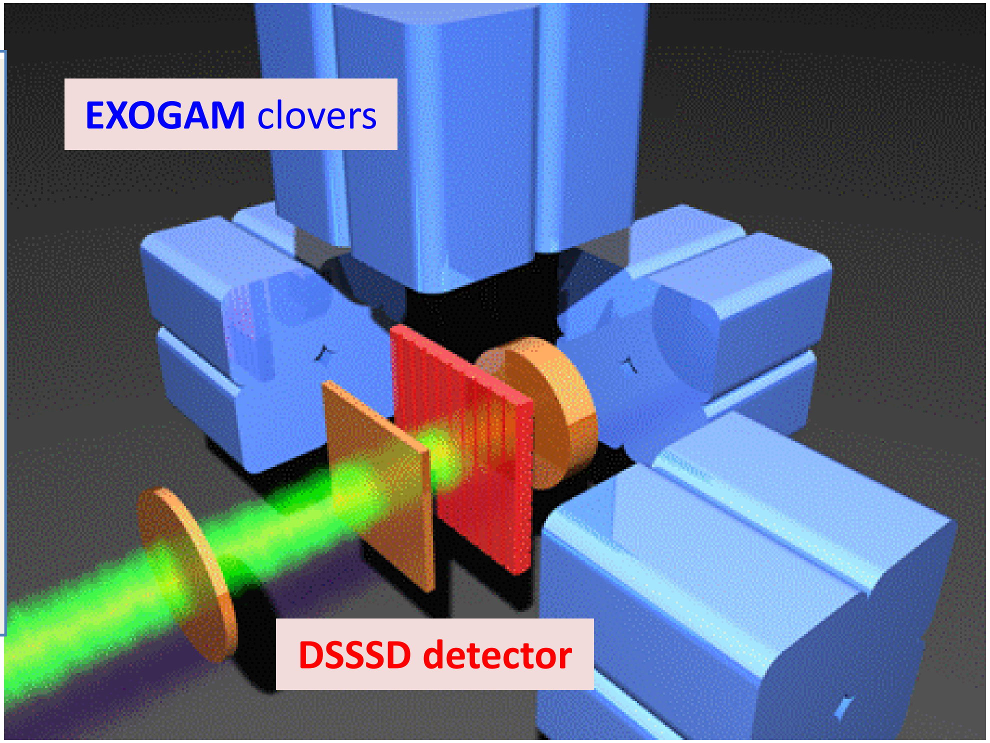


β-decay experiments @GANIL

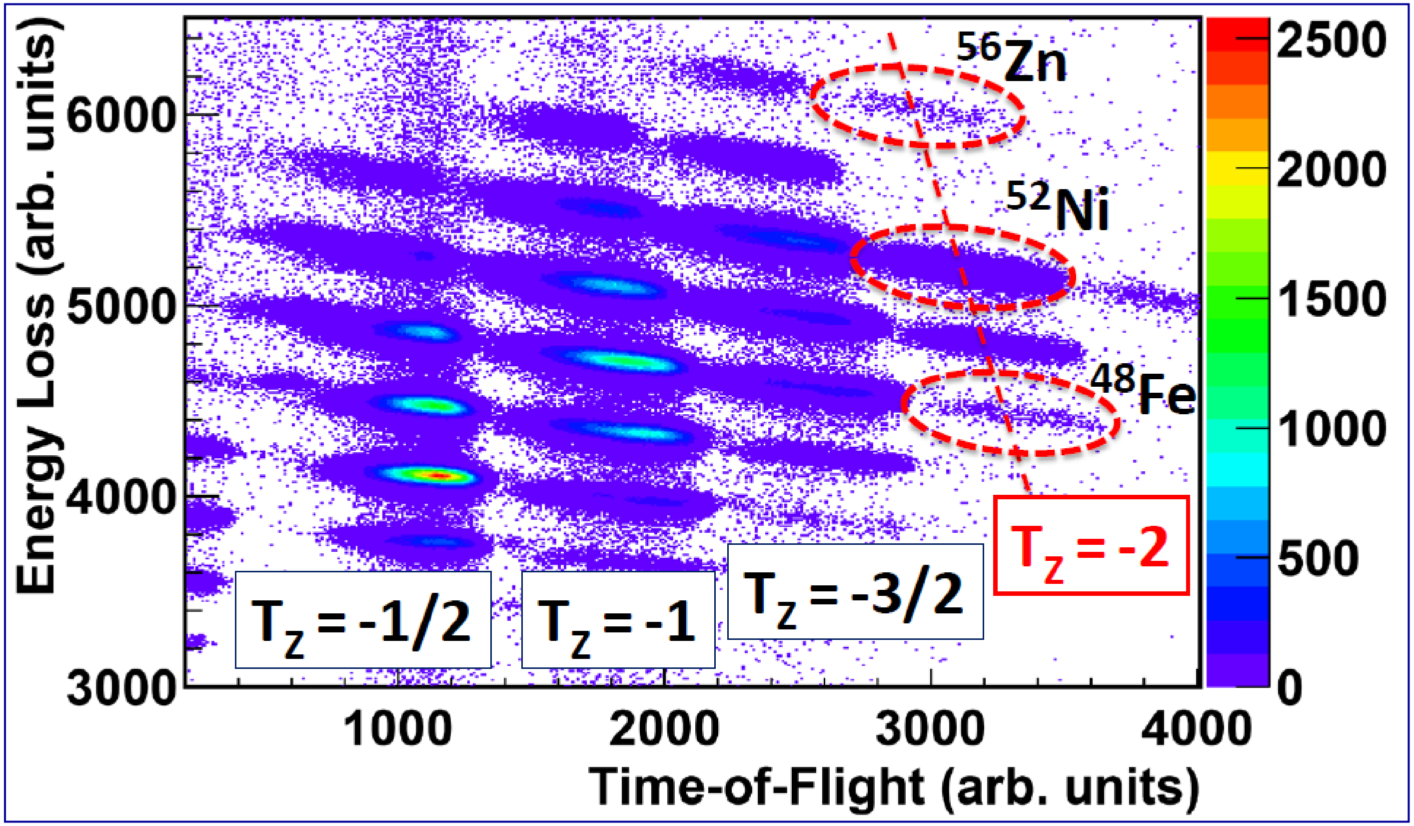
- Primary beam: **^{58}Ni @ 75 AMeV** fragmented on a ^{nat}Ni target
- Fragments selected by the LISE 3 separator
- Detection of implanted fragment and subsequent charged-particle (β and protons) decays: **double-sided silicon strip detectors (DSSSD)**
- Detection of β-delayed γ rays: **4 EXOGAM Ge clovers**



16x16 X-Y strips
3 mm pitch



New results on T_Z = -2 nuclei



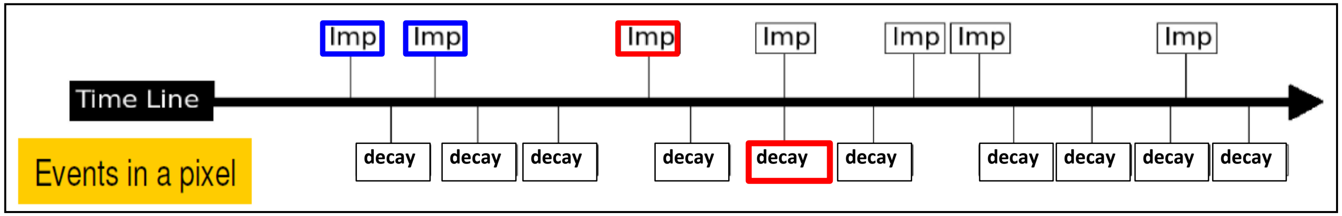
- Beyond the $f_{7/2}$-shell the production is more difficult:

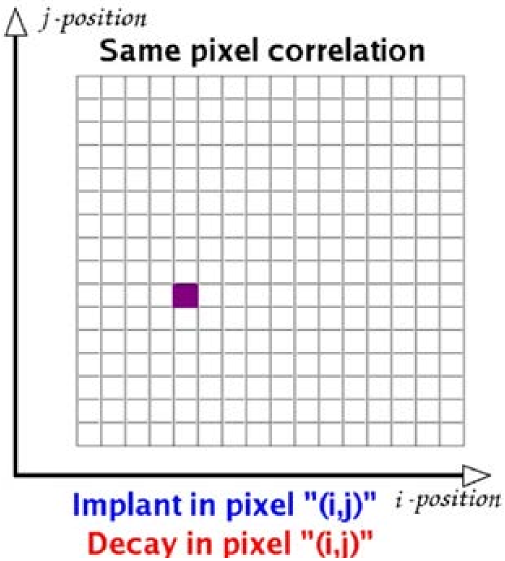
  ~ **2 imp/min** for ^{56}Zn

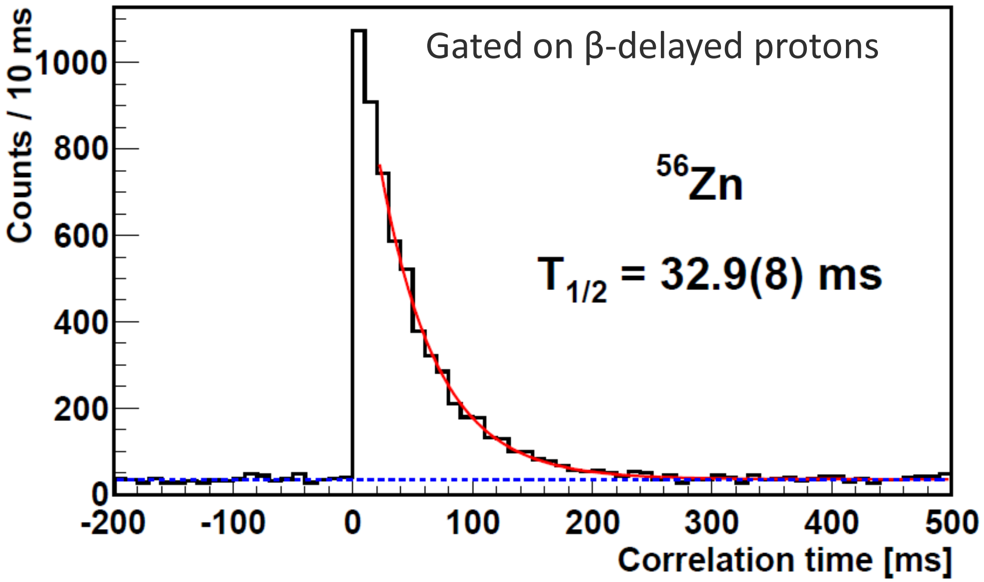
Isotope	N_{imp}	$T_{1/2}$ (ms)	B_p (%)
^{48}Fe	49 763(268)	51(3)	14.4(7)
^{52}Ni	532 054(729)	42.8(3)	31.1(5)
^{56}Zn	8861(94)	32.9(8)	88.5(26)

The exotic decay of ^{56}Zn

- The time difference between implants and β-decay events give us the **Half-life $T_{1/2}$**
- Each decay is correlated with all the implants happening in the same pixel of the DSSSD

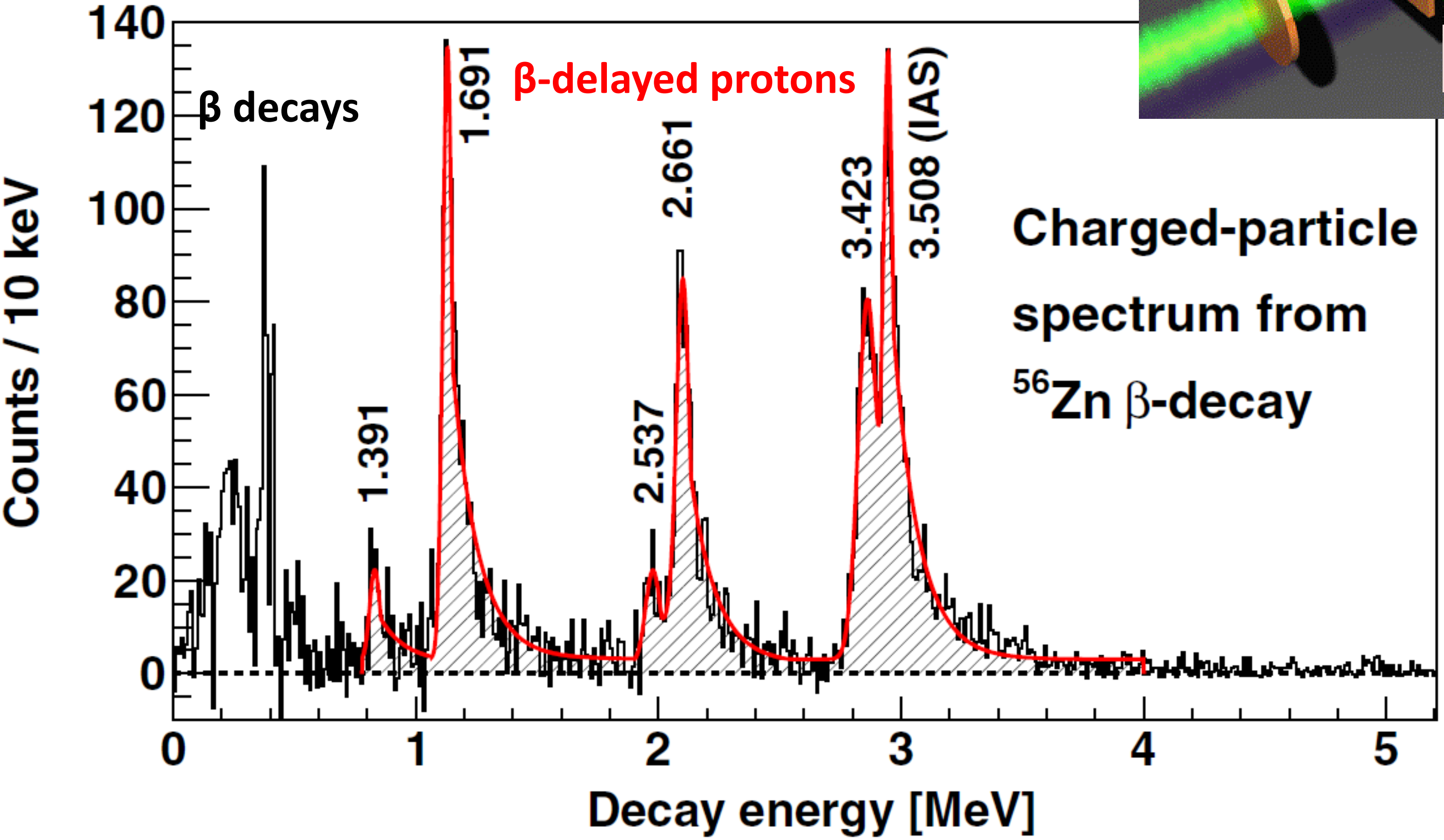


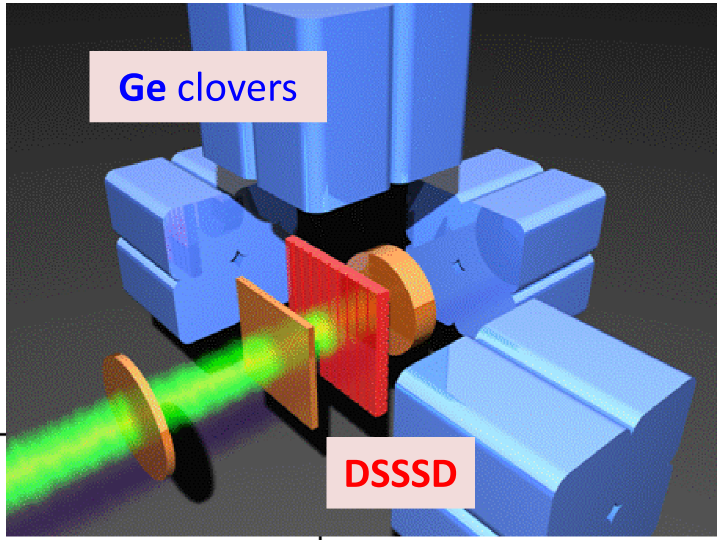




S.E.A. Orrigo et al., PRL 112, 222501 (2014)

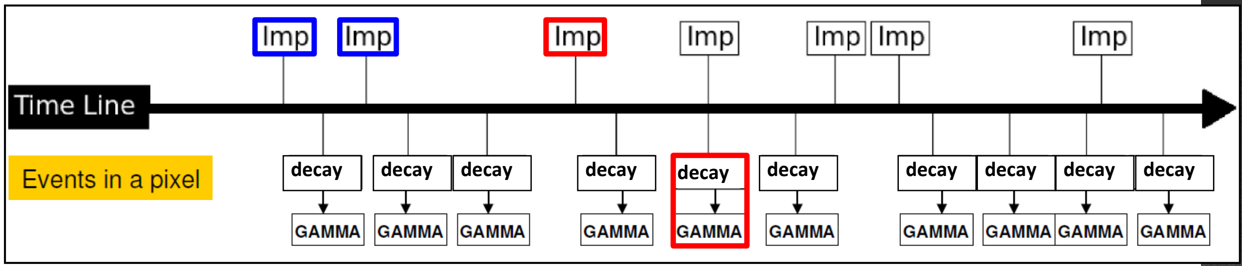
Measured DSSSD decay-energy spectrum

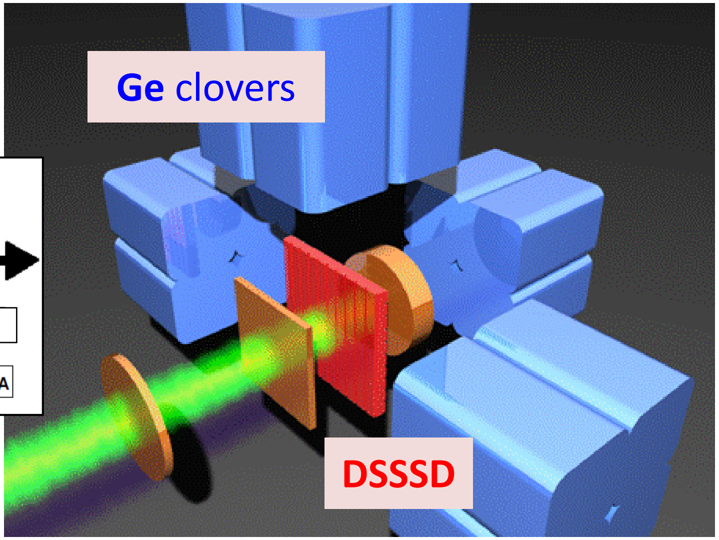




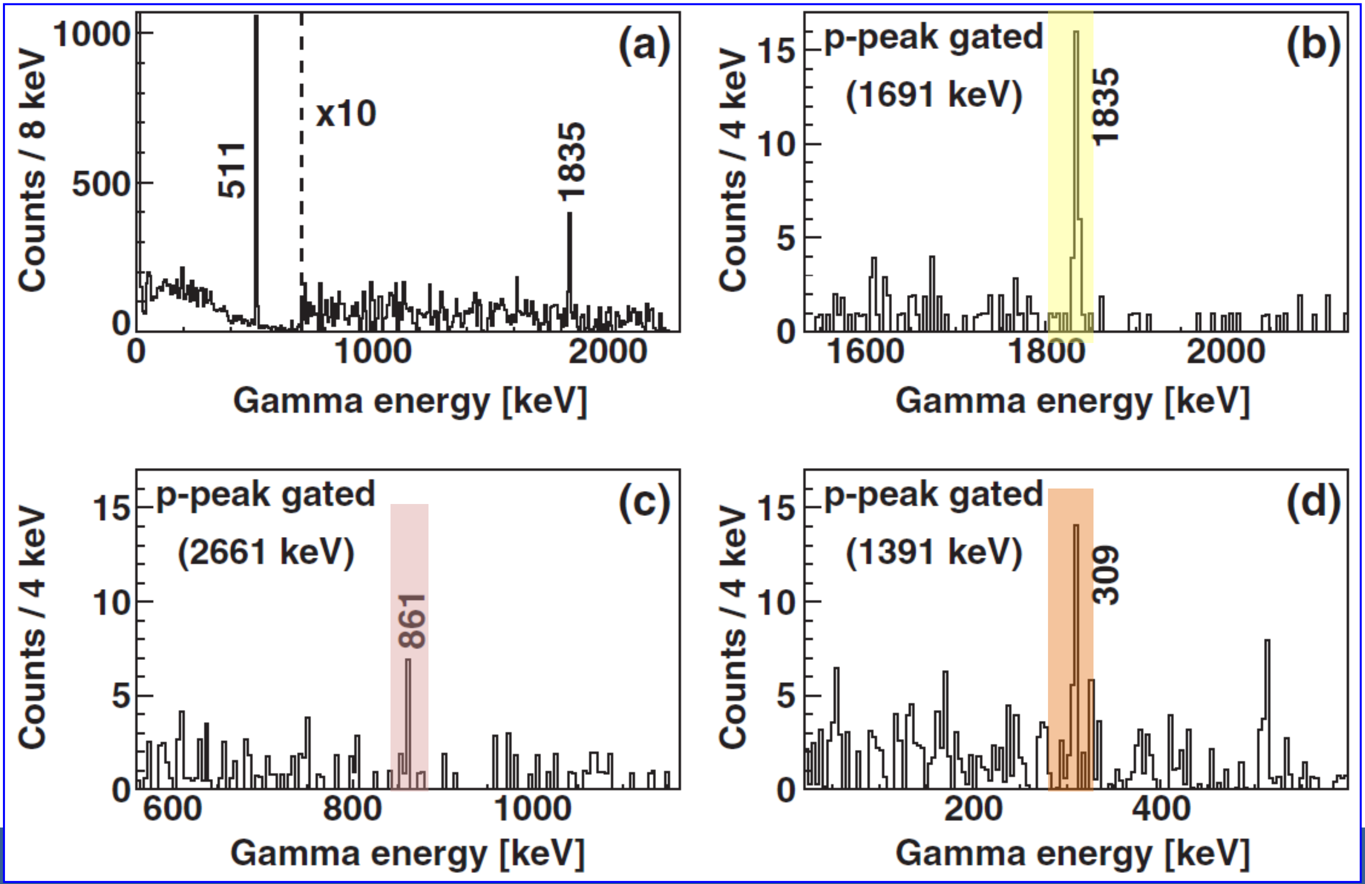
S.E.A. Orrigo et al., PRL 112, 222501 (2014)

Measured gamma spectrum



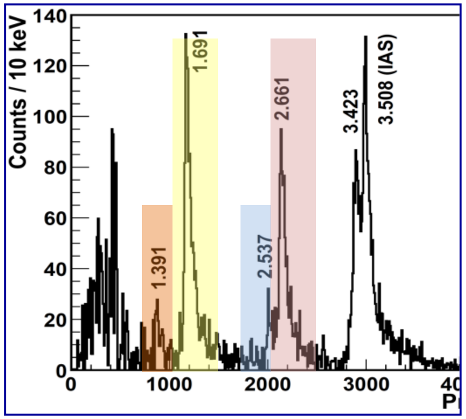


β-delayed gamma rays



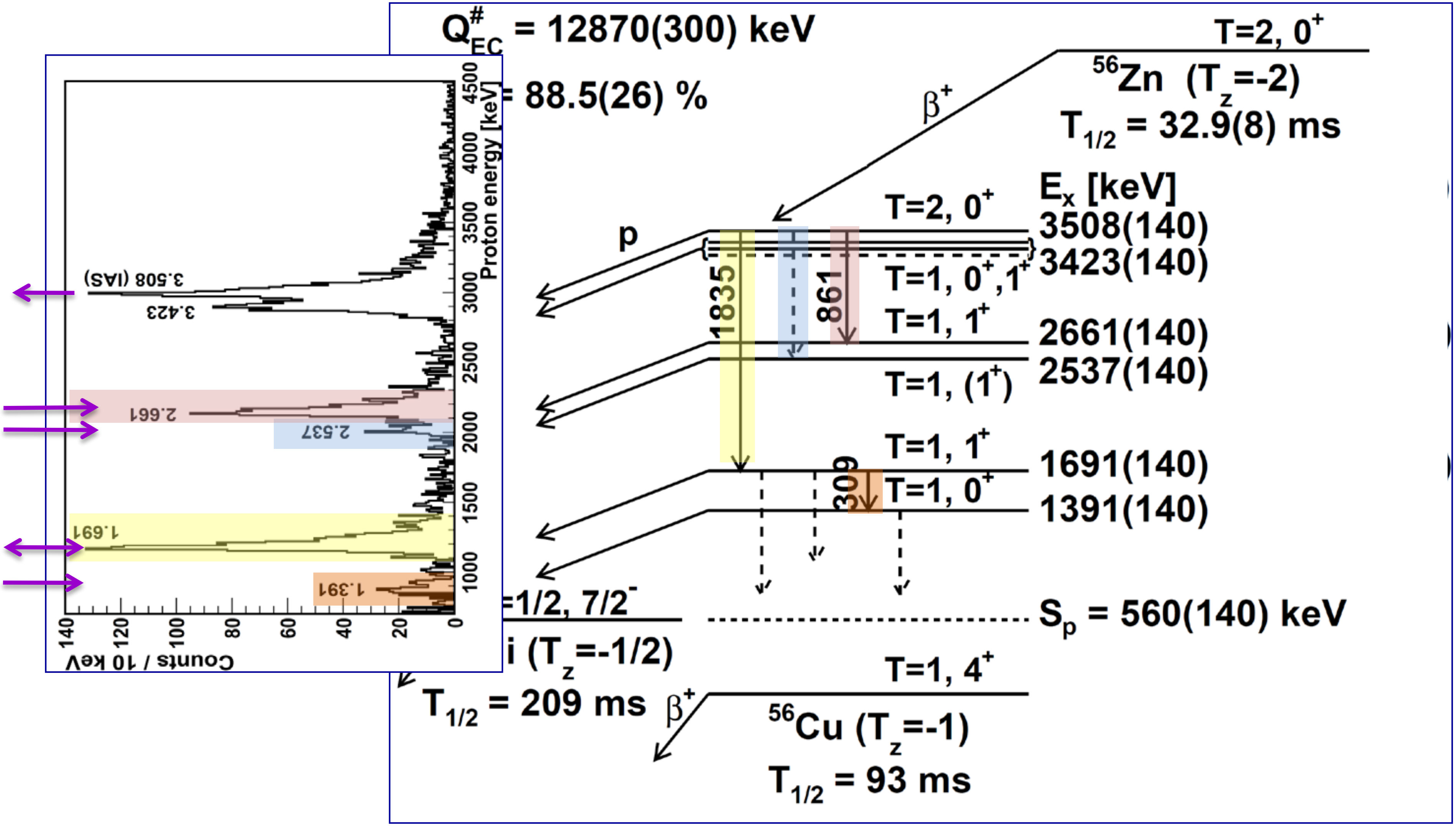
Proton-gamma coincidences

Gates on protons



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

The partial decay scheme of ^{56}Zn



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

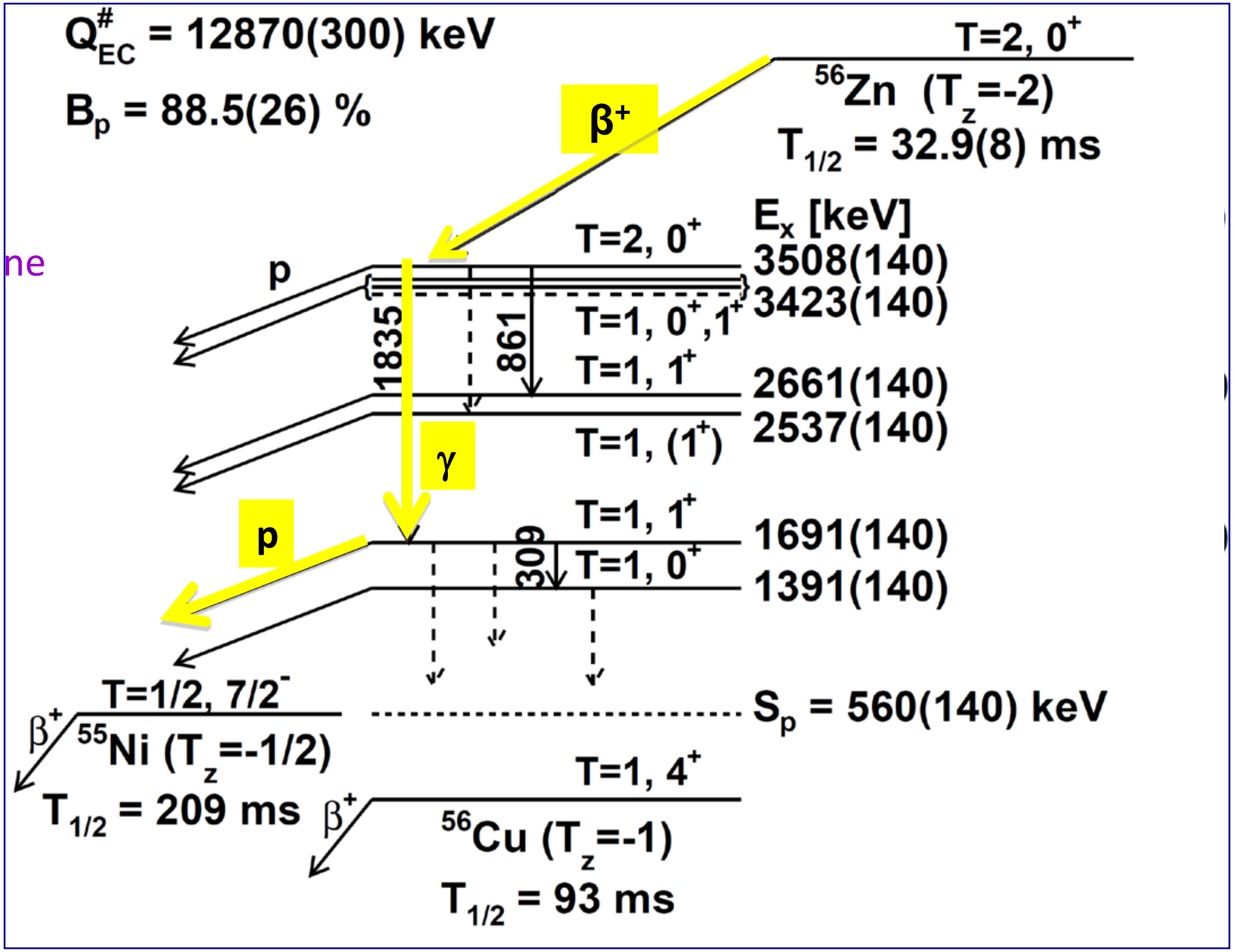
1st observation of β-delayed γ-proton decay

In the *fp*-shell in three branches → very exotic !!

- New and exotic decay mode at the proton drip-line

- It affects the conventional determination of B(GT)

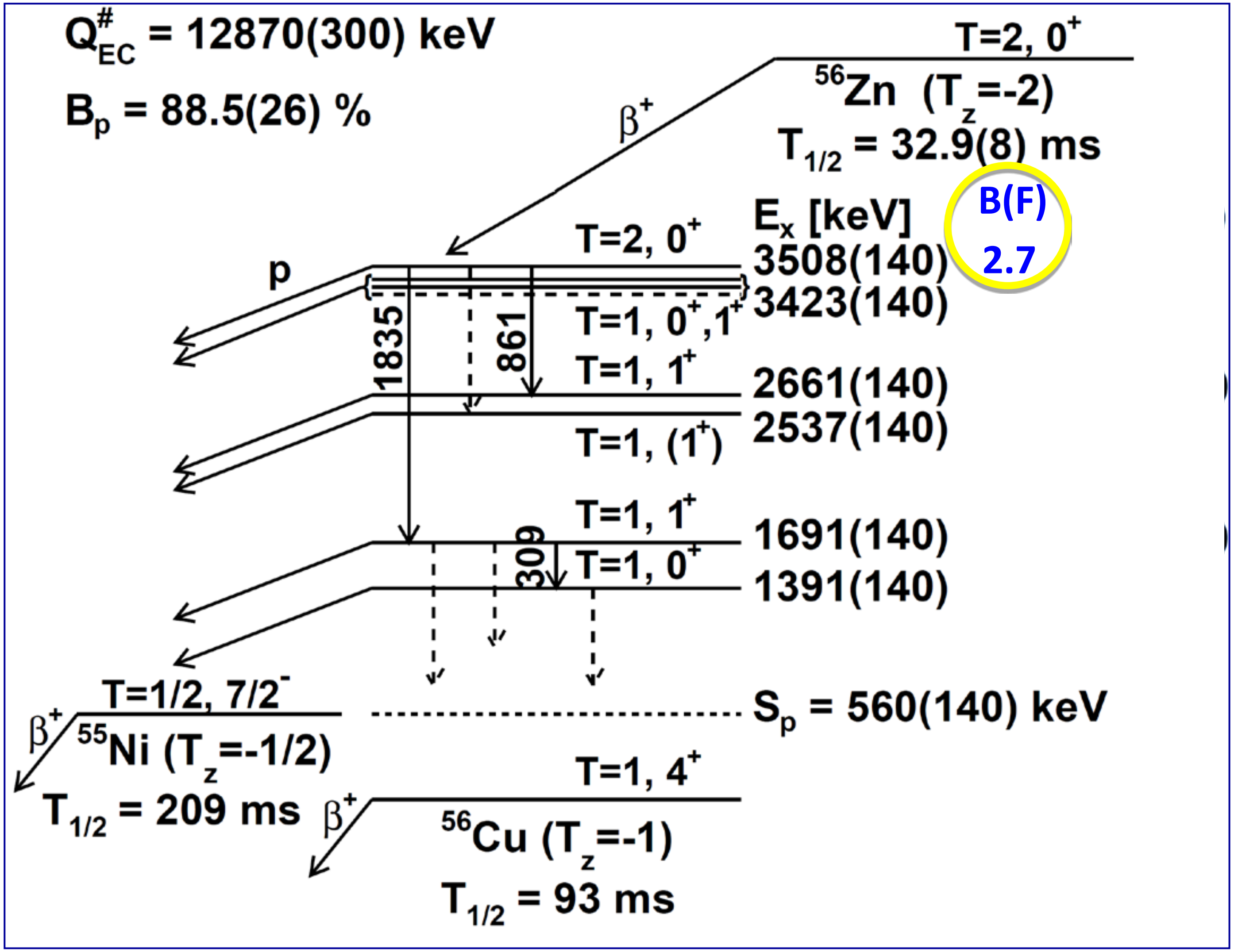
- Important to measure both β-delayed protons and γ rays



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

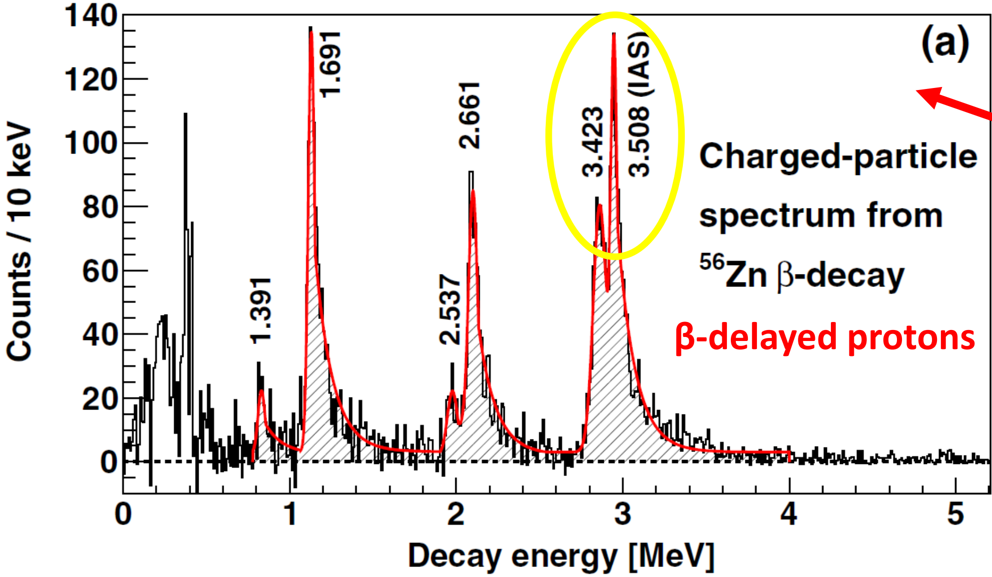
^{56}Zn: another surprise

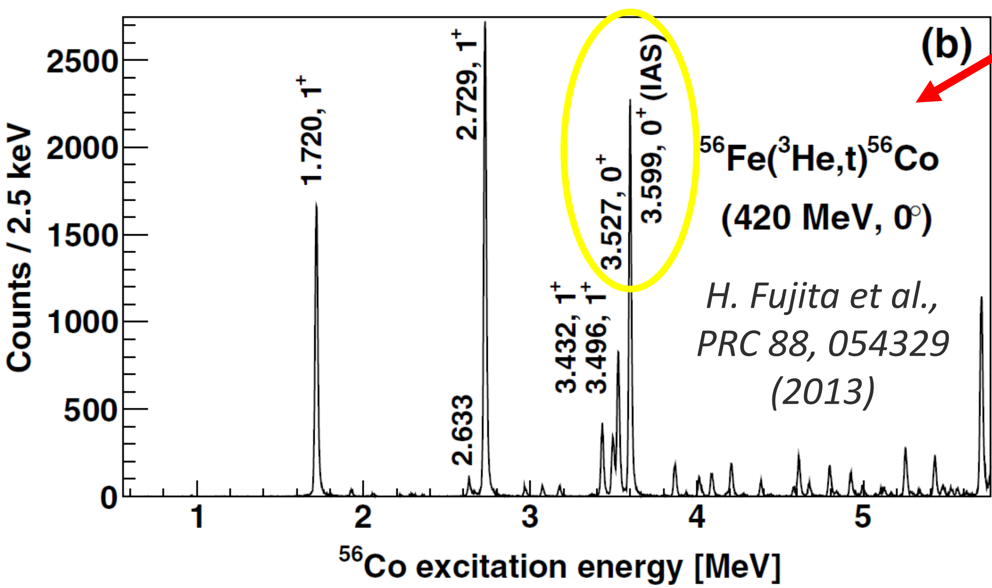
B(F) = |N – Z| = 4

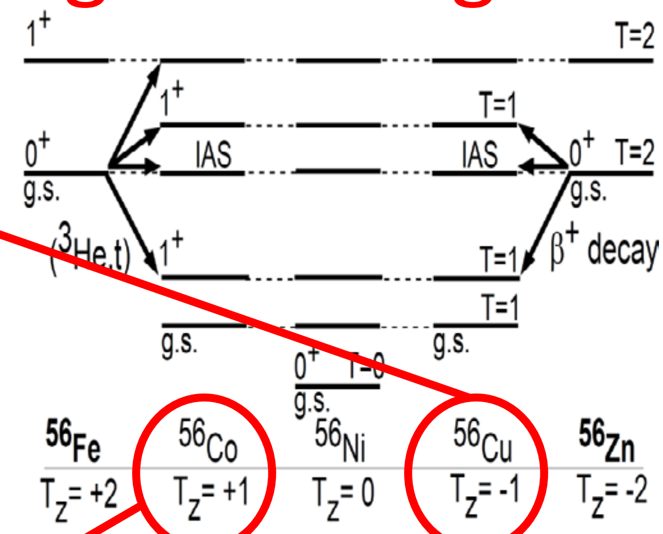


S.E.A. Orrigo et al., PRL 112, 222501 (2014)

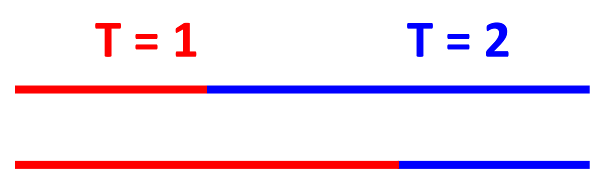
Comparison with mirror Charge Exchange







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



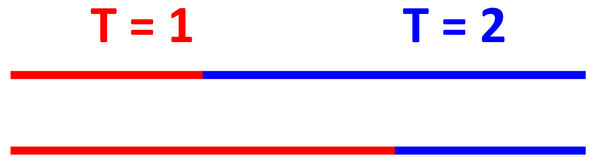
- **Isospin mixing:** the ^{56}Co IAS is fragmented

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

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

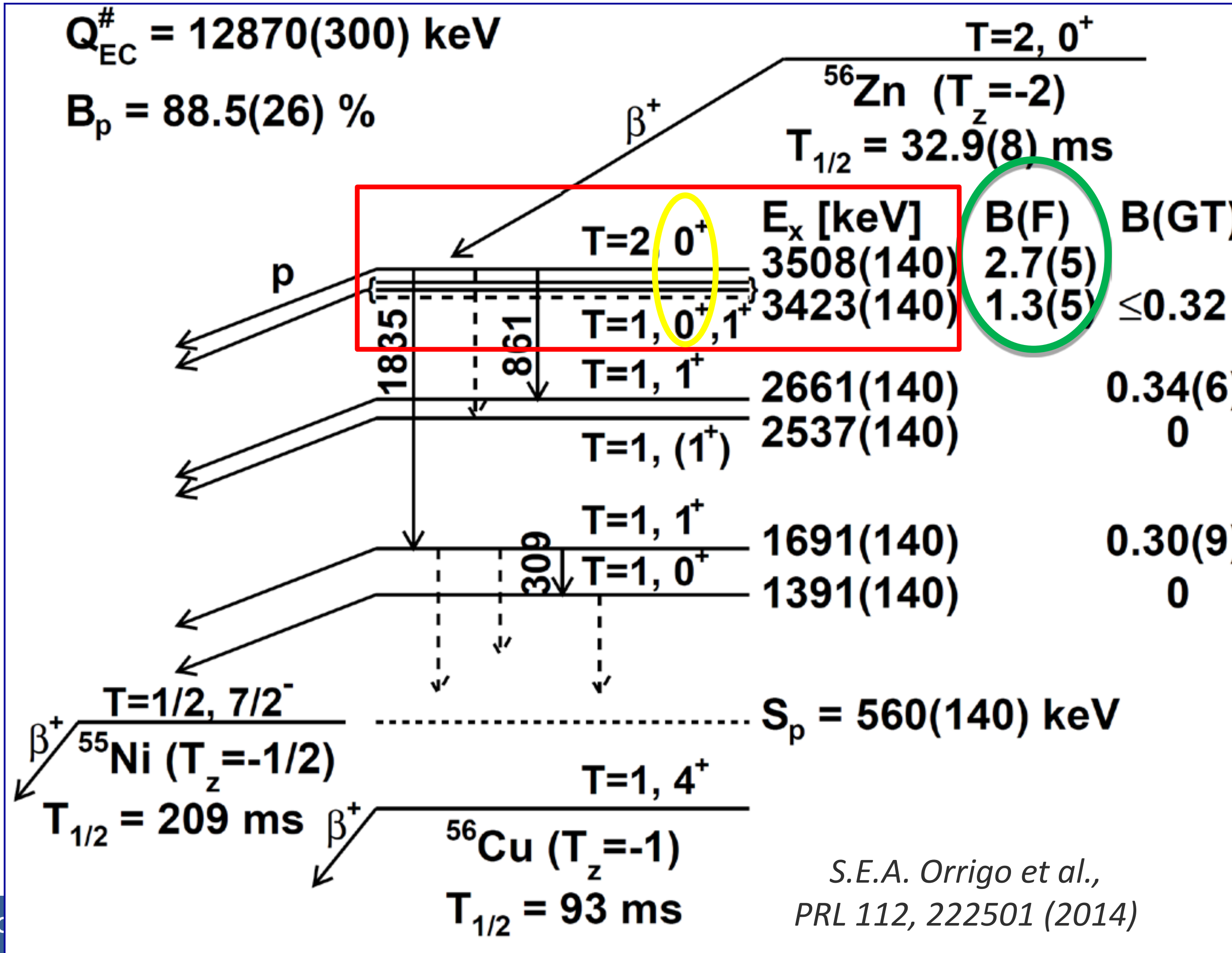
^{56}Zn: Isospin mixing

- Fragmentation of the **Fermi strength** due to a strong isospin mixing



$<H_c> = 40(23)$ keV

$\alpha^2 = 33(10)\%$



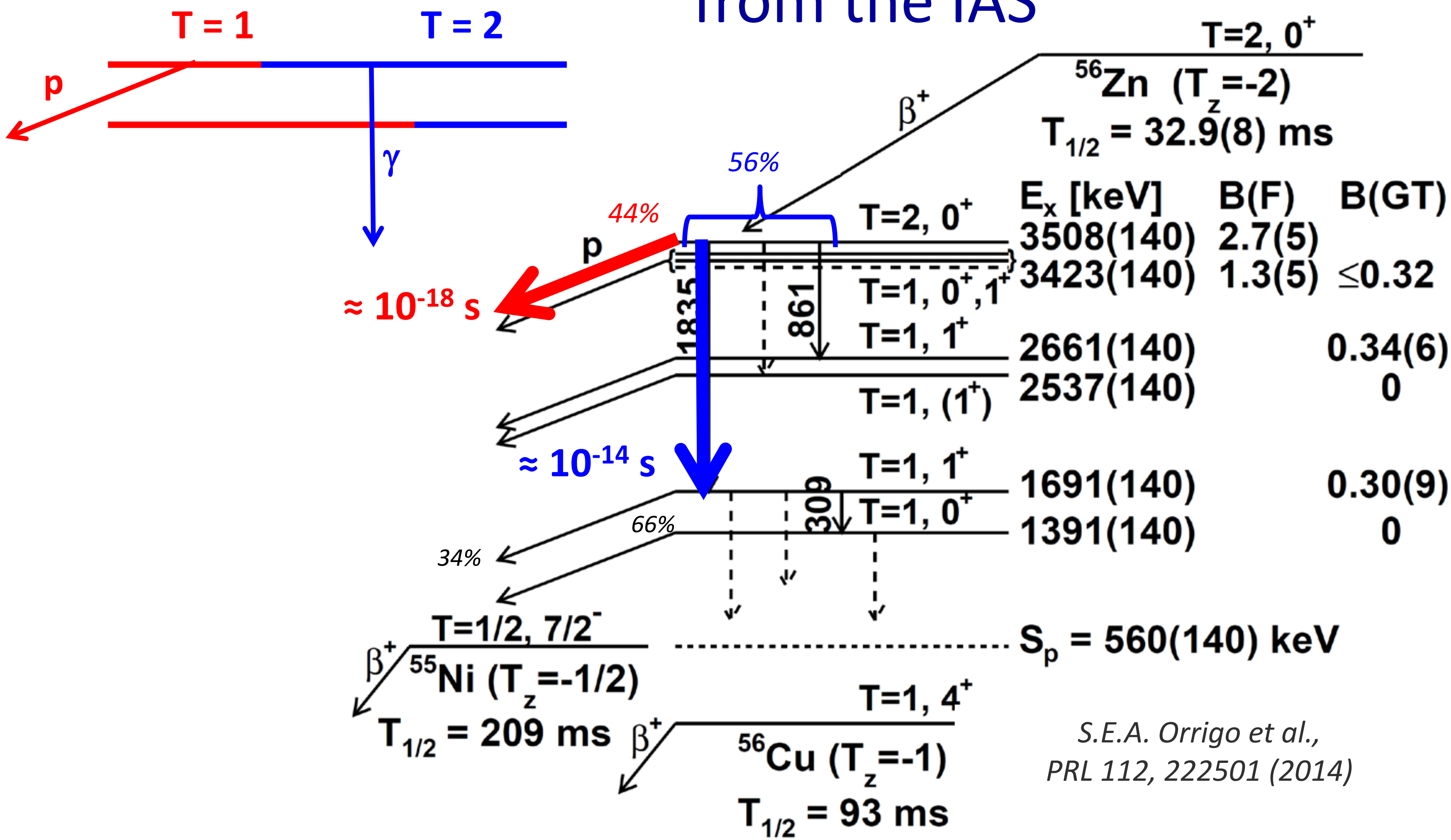
S.E.A. Orrigo et al., PRL 112, 222501 (2014)

Mirror ^{56}Co (CE)

B(F)	B(GT)
2.89(12)	
1.11(6)	0.13
	0.43
	0
	0.28
	0

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

Competition of β-delayed p and β-delayed γ decays from the IAS



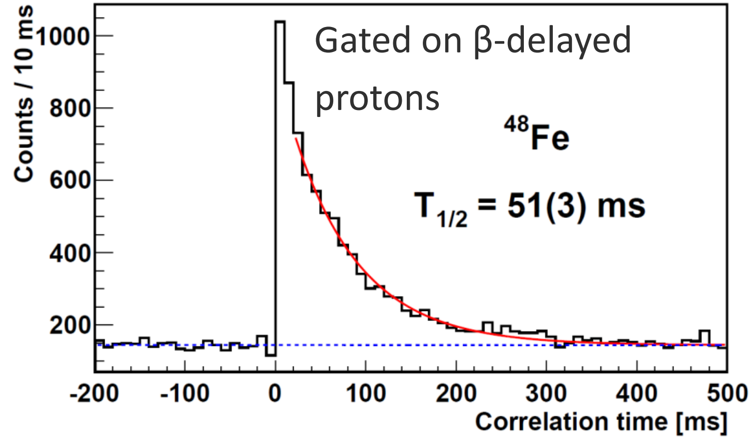
S.E.A. Orrigo et al., PRL 112, 222501 (2014)

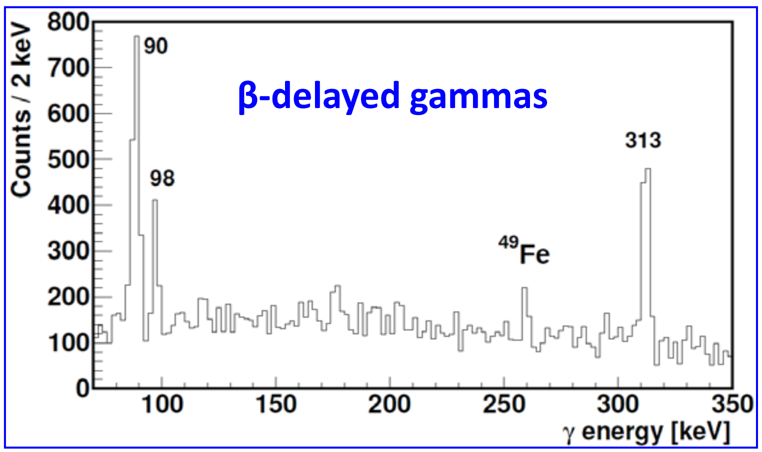
- 2 independent SM calculations: p-decay hindered by 10^3; isospin mixing reproduced

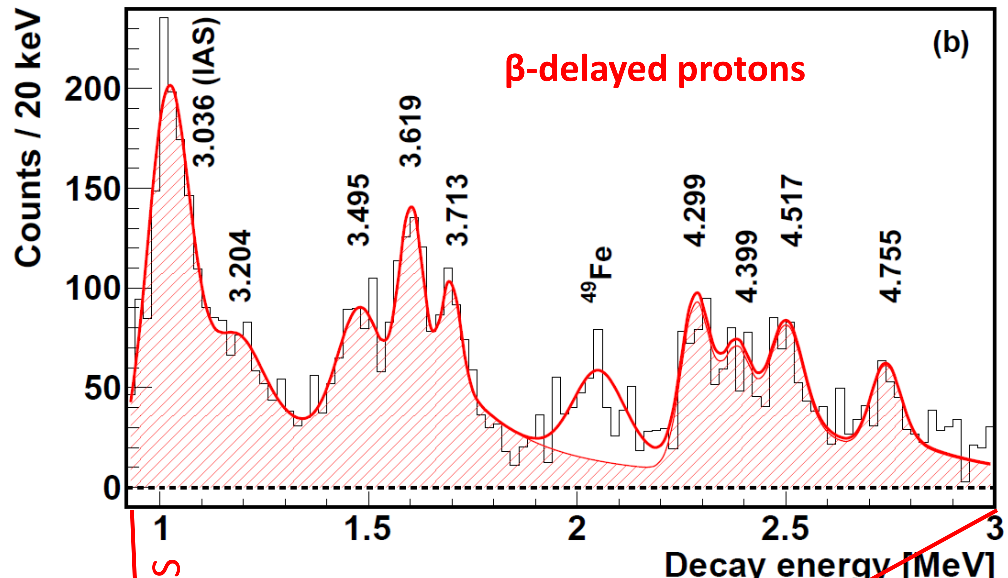
B. Rubio et al., Nucl. Phys. Review 33, 225 (2016) *N. Smirnova et al., Phys. Rev. C 93, 044305 (2016)*

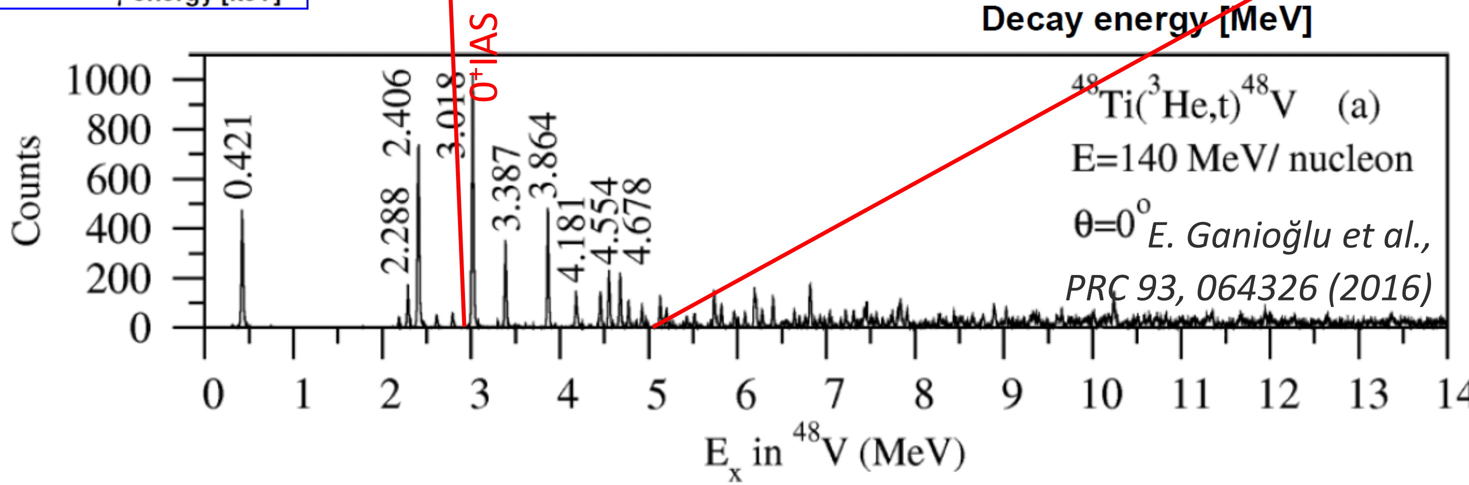
β decay of ^{48}Fe

S.E.A. Orrigo et al., PRC 93, 044336 (2016)









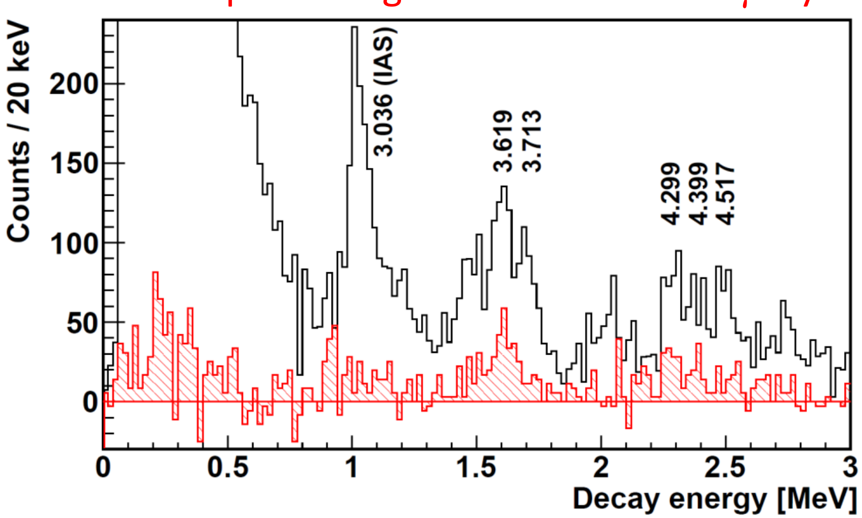
β decay of ^{48}Fe

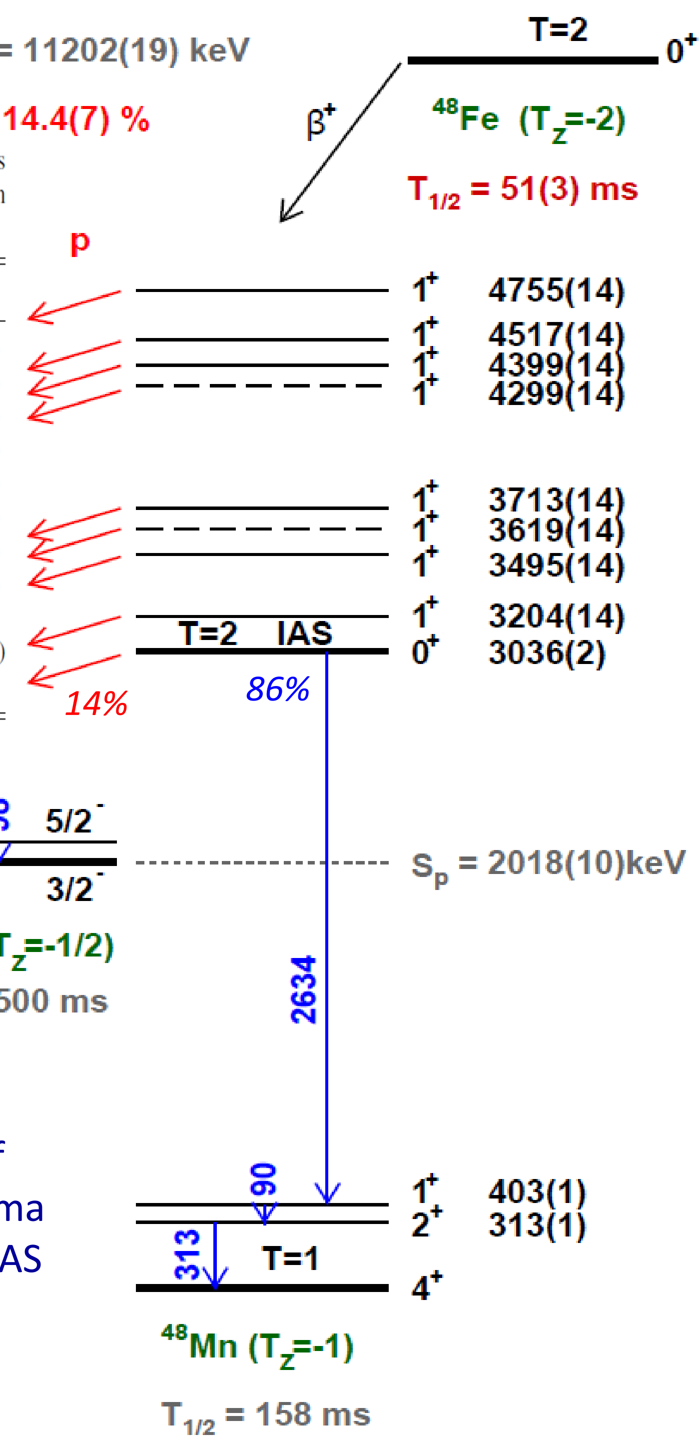
TABLE III. Summary of the results for the β^+ decay of ^{48}Fe. Center-of-mass proton energies E_p, γ-ray energies E_γ, and their intensities (normalized to 100 decays) I_p and I_γ, respectively. Excitation energies E_X, β feedings I_β, Fermi B(F), and Gamow-Teller B(GT) transition strengths to the ^{48}Mn levels. The values for the 2634-keV γ ray are taken from Ref. [8].

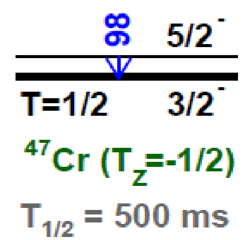
E_p(keV)	I_p (%)	E_γ(keV)	I_γ (%)	E_X (keV)	I_β (%)	B(F)	B(GT)
2737(10)	0.8(1)			4755(14)	0.8(1)		0.10(2)
2499(10)	1.3(5)			4517(14)	1.3(5)		0.16(6)
2381(10)	0.9(4)			4399(14)	0.9(4)		0.10(4)
2281(10)	1.2(3)			4299(14)	1.2(3)		0.13(3)
1695(10)	1.3(2)			3713(14)	1.3(2)		0.10(2)
1601(10)	0.9(3)			3619(14)	0.9(3)		0.06(2)
1477(10)	1.8(3)			3495(14)	1.8(3)		0.12(2)
1186(10)	1.0(3)			3204(14)	1.0(3)		0.06(2)
1018(10)	4.8(3)	2633.5(5)[a]	30(5)[a]	3036(2)[b]	34.8(50)	2.8(4)	
		90(1)	72(14)	403(1)	42(15)		0.47(17)
		313(1)	65(13)	313(1)			

[a]From Ref. [8].
[b]IAS.

DSSSD spectrum gated on the 98 keV γ ray



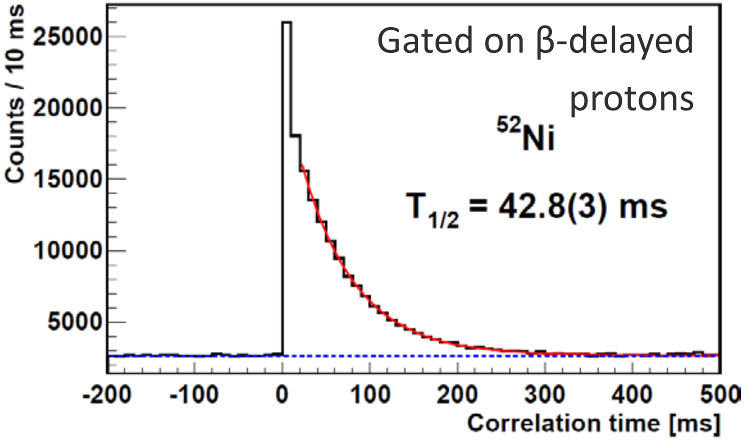


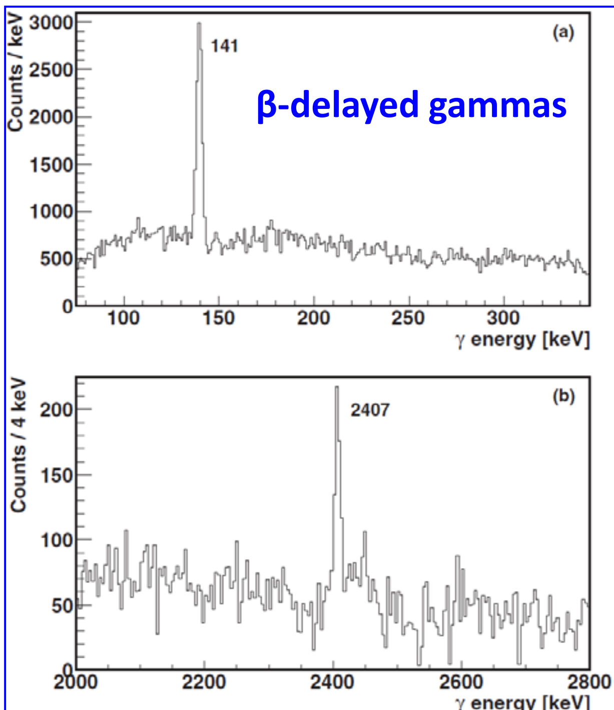


- Competition of proton and gamma emissions from IAS

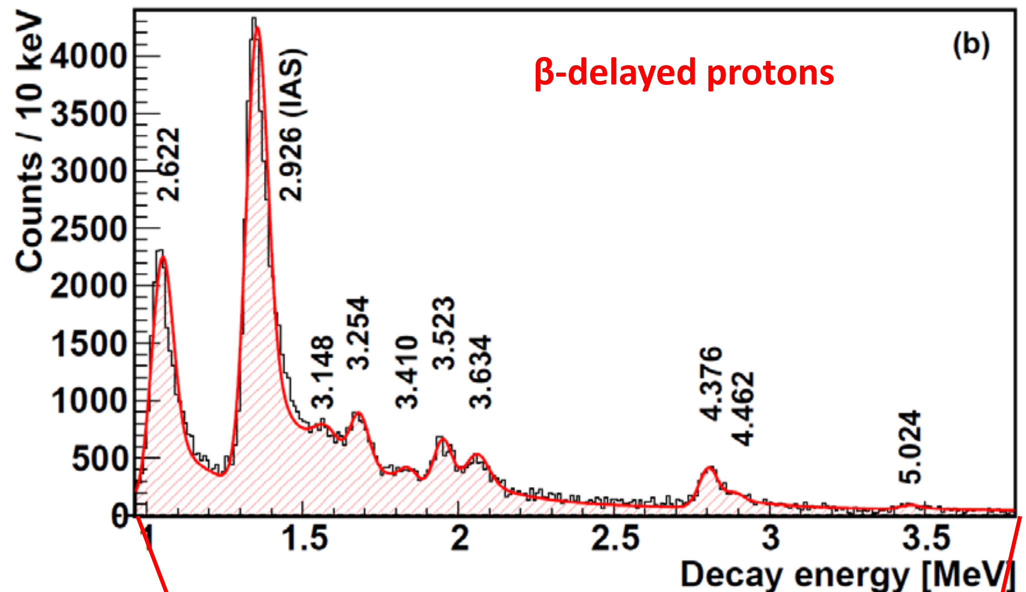
S.E.A. Orrigo et al., PRC 93, 044336 (2016)

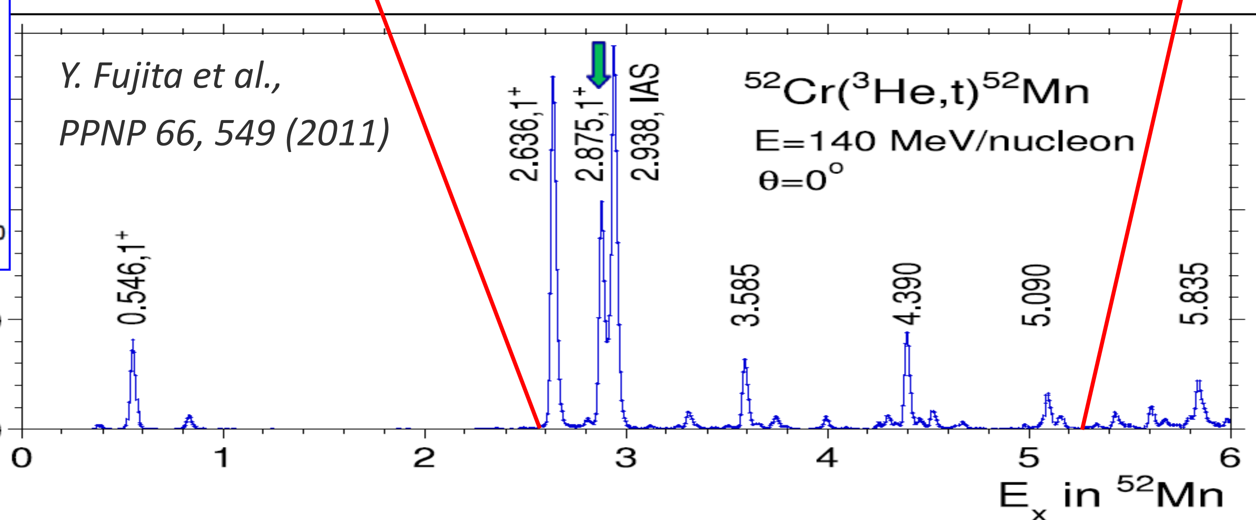
β decay of ^{52}Ni





S.E.A. Orrigo et al., PRC 93, 044336 (2016)



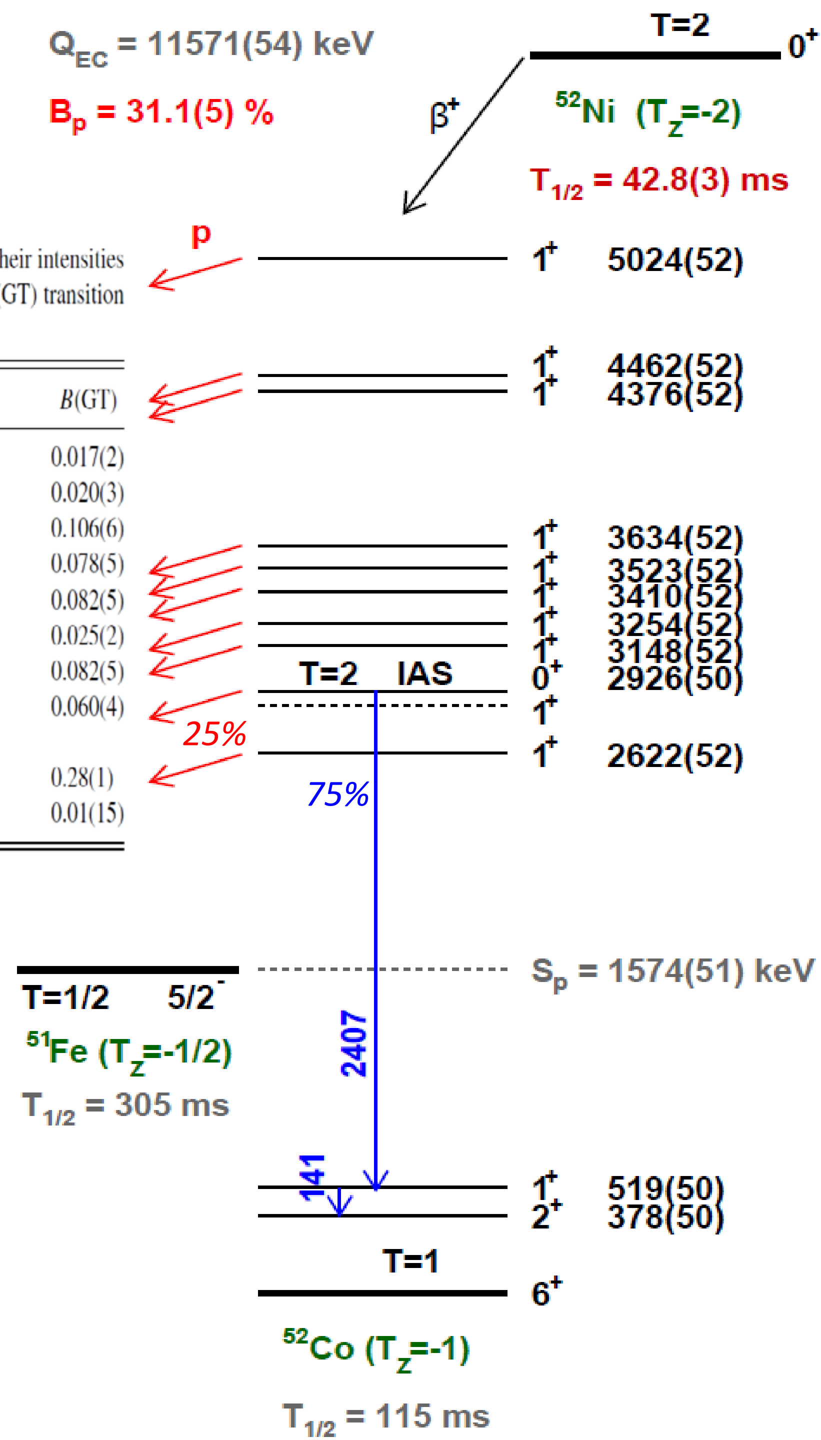


β decay of ^{52}Ni

TABLE IV. Summary of the results for the β^+ decay of ^{52}Ni. Center-of-mass proton energies E_p, γ-ray energies E_γ, and their intensities (normalized to 100 decays) I_p and I_γ, respectively. Excitation energies E_X, β feedings I_β, Fermi B(F), and Gamow-Teller B(GT) transition strengths to the ^{52}Co levels.

E_p (keV)	I_p (%)	E_γ (keV)	I_γ (%)	E_X (keV)	I_β (%)	B(F)	B(GT)
3451(10)	0.11(1)			5024(52)	0.11(1)		0.017(2)
2888(10)	0.18(2)			4462(52)	0.18(2)		0.020(3)
2802(10)	1.01(3)			4376(52)	1.01(3)		0.106(6)
2061(10)	1.14(3)			3634(52)	1.14(3)		0.078(5)
1949(10)	1.28(3)			3523(52)	1.28(3)		0.082(5)
1836(10)	0.42(3)			3410(52)	0.42(3)		0.025(2)
1681(10)	1.50(4)			3254(52)	1.50(4)		0.082(5)
1575(10)	1.17(4)			3148(52)	1.17(4)		0.060(4)
1352(10)	13.7(2)	2407(1)	42(10)	2926(50)[a]	56(10)	4.1(8)	
1048(10)	7.30(9)			2622(52)	7.30(9)		0.28(1)
		141(1)	43(8)	519(50)	1(13)		0.01(15)

[a]IAS.



- Competition of proton and gamma emissions from IAS

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β decay of ^{52}Ni

TABLE IV. Summary of the results for the β^+ decay of ^{52}Ni. Center-of-mass proton energies E_p, γ-ray energies E_γ, and their intensities (normalized to 100 decays) I_p and I_γ, respectively. Excitation energies E_X, β feedings I_β, Fermi B(F), and Gamow-Teller B(GT) transition strengths to the ^{52}Co levels.

E_p (keV)	I_p (%)	E_γ (keV)	I_γ (%)	E_X (keV)	I_β (%)	B(F)	B(GT)
3451(10)	0.11(1)			5024(52)	0.11(1)		0.017(2)
2888(10)	0.18(2)			4462(52)	0.18(2)		0.020(3)
2802(10)	1.01(3)			4376(52)	1.01(3)		0.106(6)
2061(10)	1.14(3)			3634(52)	1.14(3)		0.078(5)
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1836(10)	0.42(3)			3410(52)	0.42(3)		0.025(2)
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1352(10)	13.7(2)	2407(1)	42(10)	2926(50)[a]	56(10)	4.1(8)	
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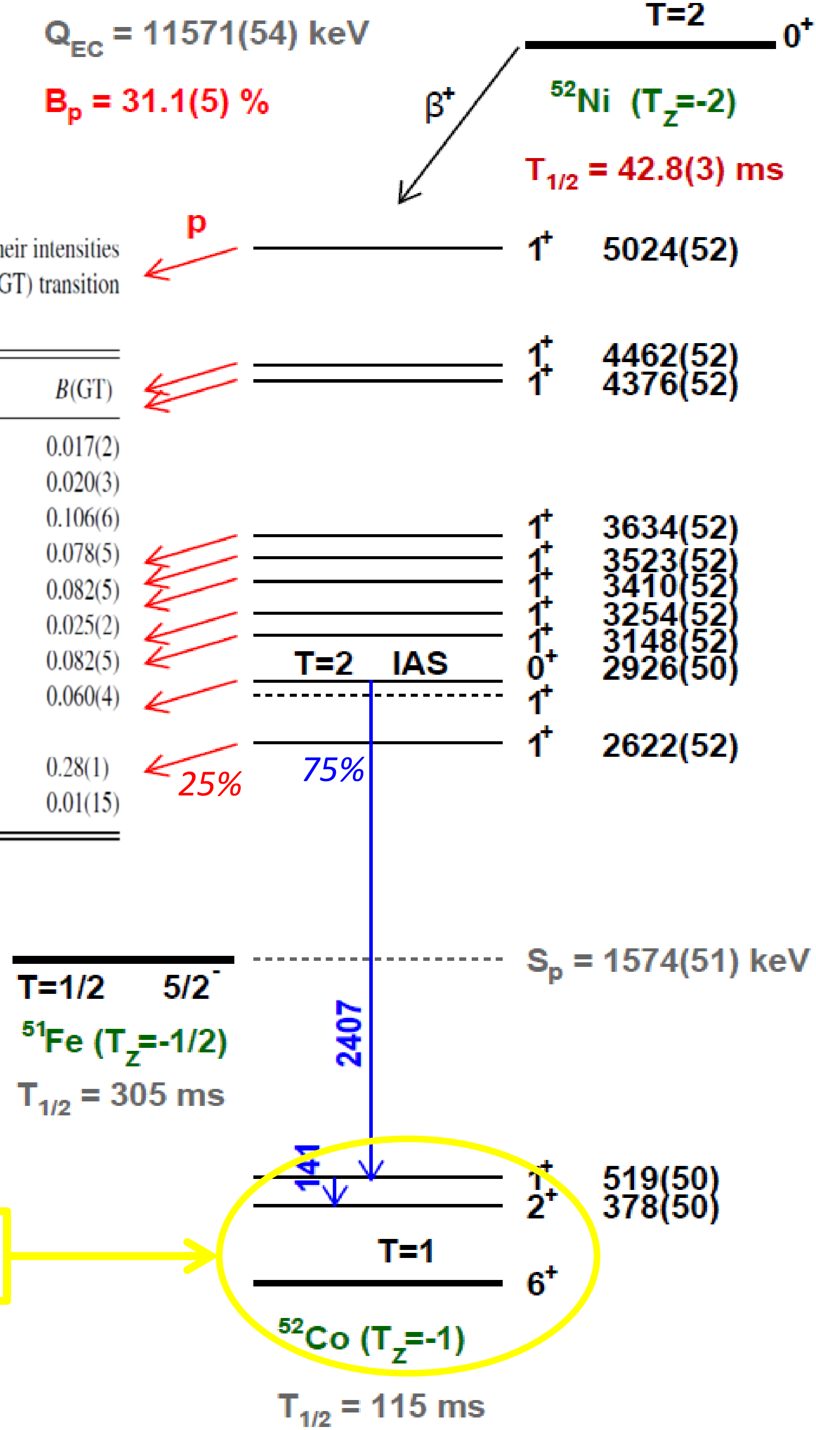
		141(1)	43(8)	519(50)	1(13)		0.01(15)

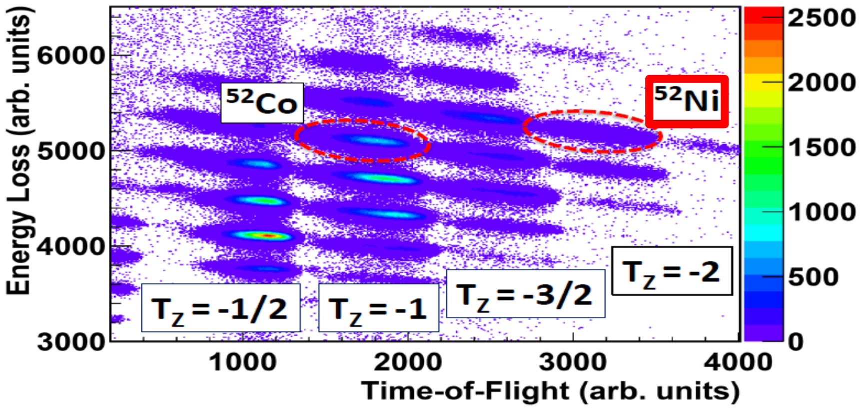
[a]IAS.

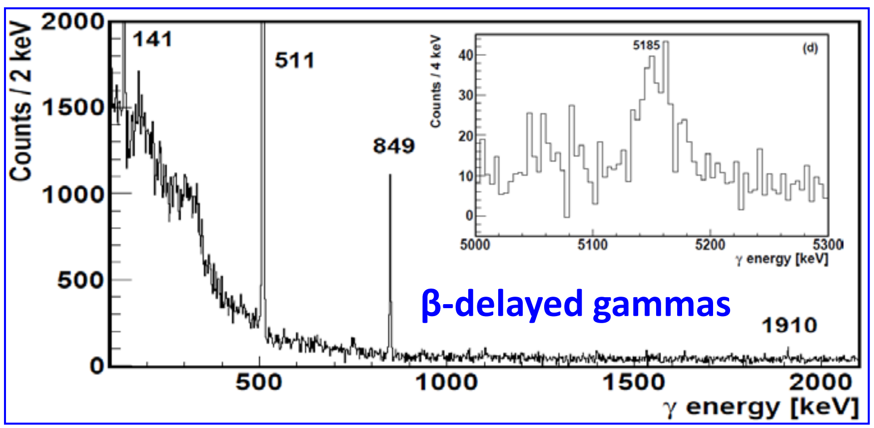


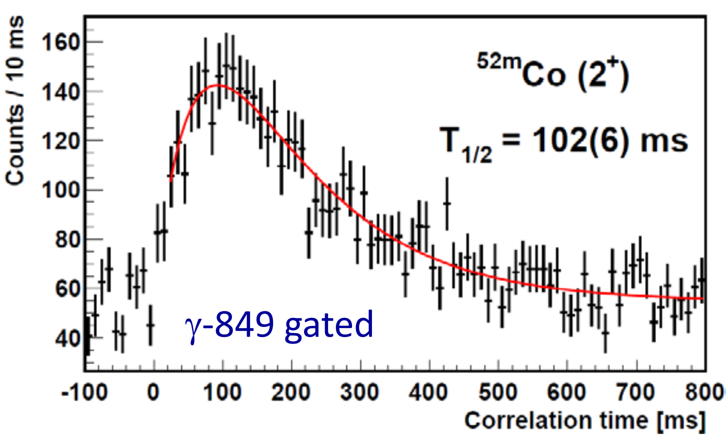
- Odd-odd nuclei (like e.g. ^{52}Co) are particularly difficult to study because there are often two long-lived states, one of which is the ground state, with similar half-lives

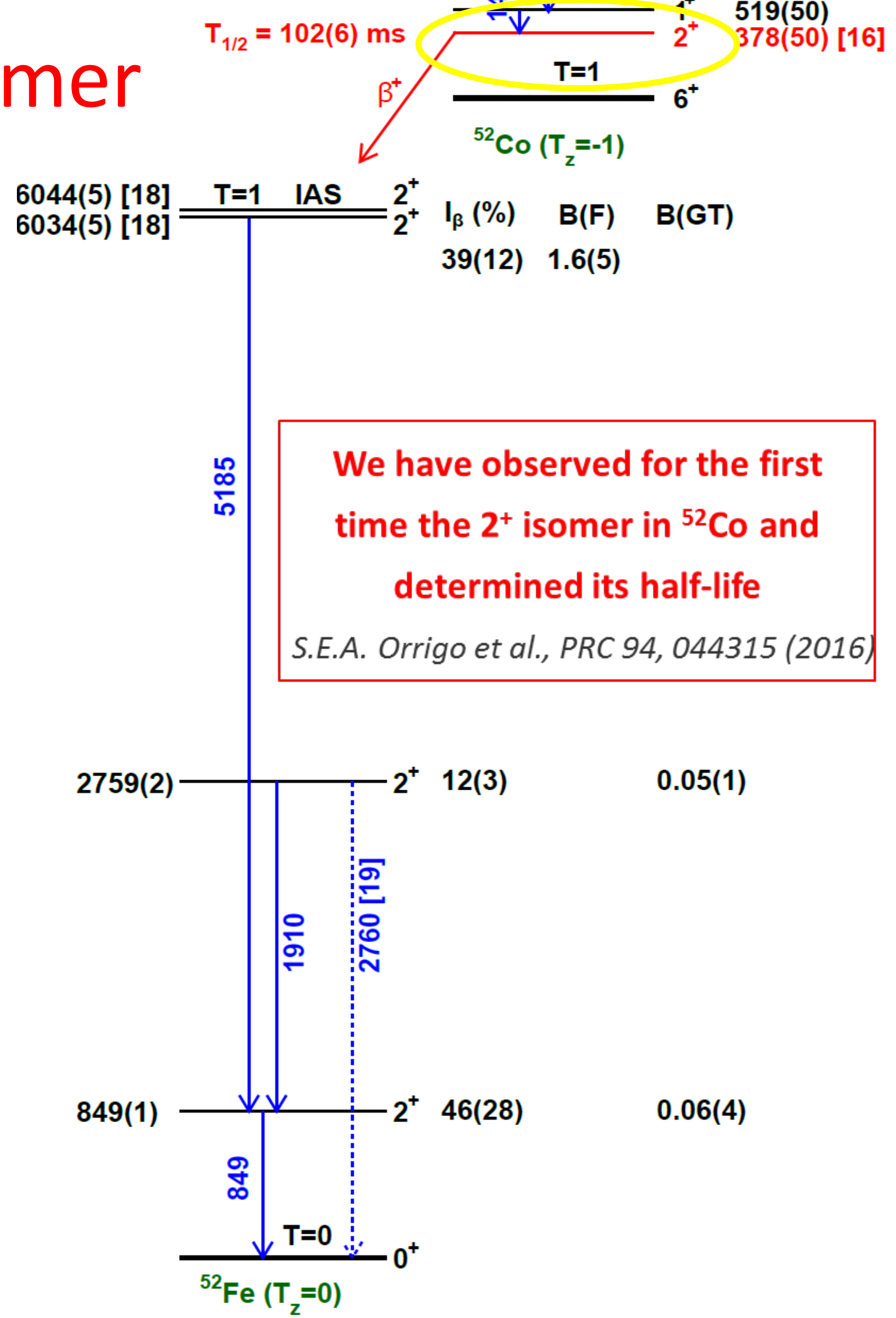
^{52}Co: 6^+ g.s. and 2^+ isomer

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









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

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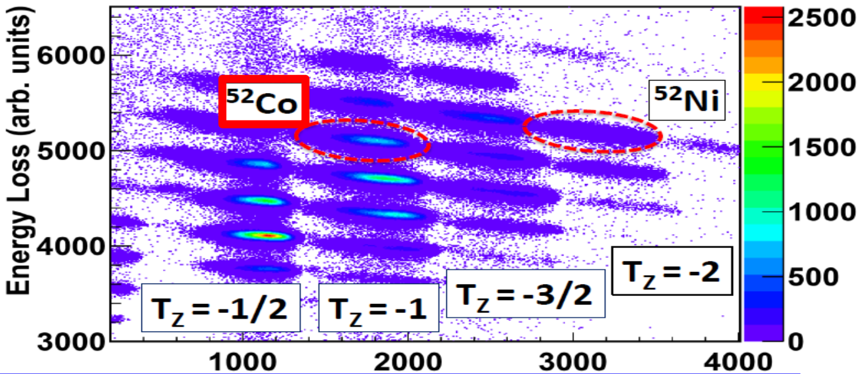
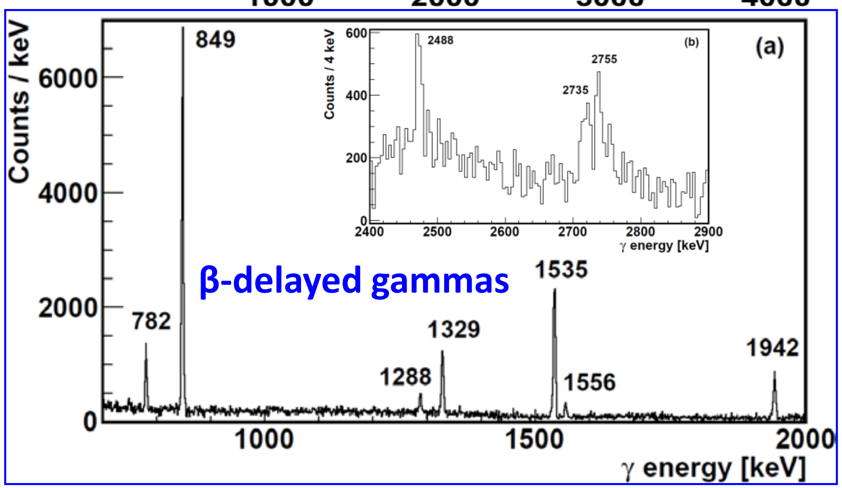
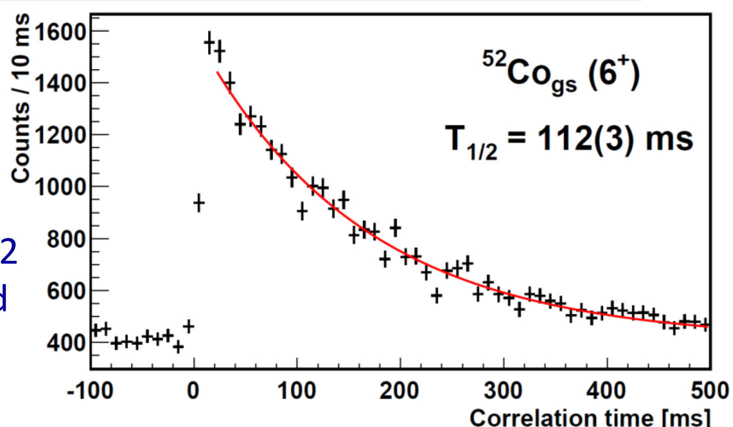
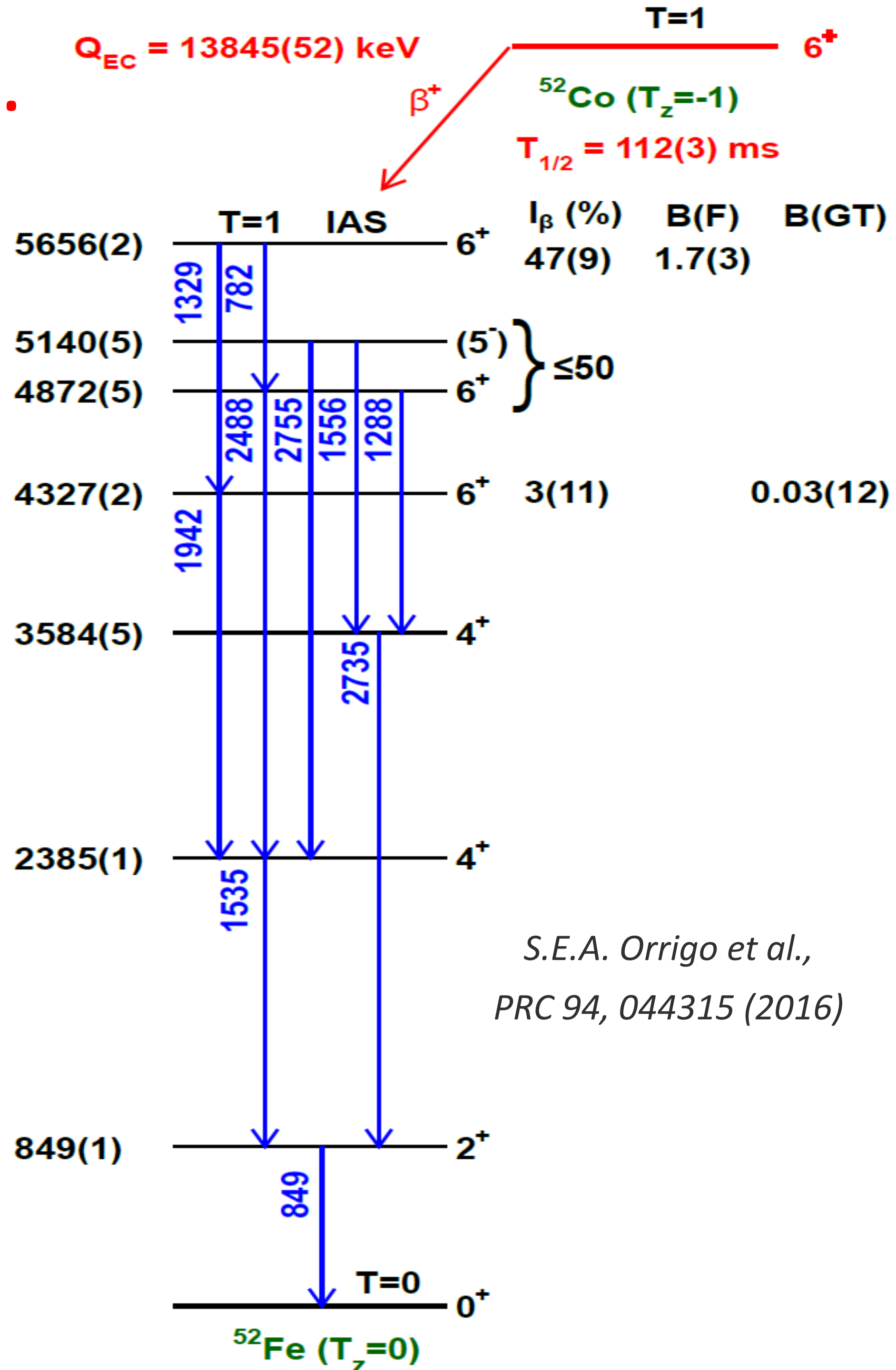
$T_{1/2}$ of the ^{52}Co(6$^+$) g.s.







γ-1329+1942
+1535 gated



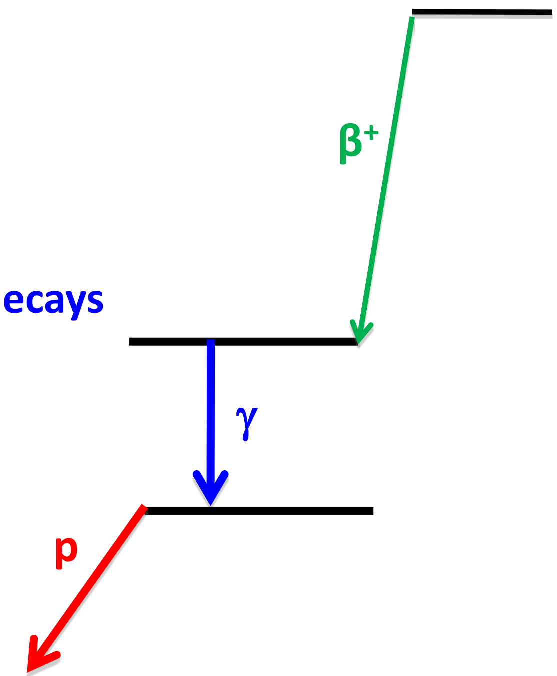
S.E.A. Orrigo et al.,
PRC 94, 044315 (2016)

Summary

- **β decay of the T_Z = -2, ^{48}Fe, ^{52}Ni and ^{56}Zn proton rich-nuclei**
  - **New decay schemes** have been determined
  - The corresponding **B(F), B(GT) values** have been determined

- **β^+ decay ⇔ (^{3}He,t) Important help in the understanding**
  - Without the CE data many interesting structural aspects would have remained unclear
  - Mirror symmetry works well in general, but some differences remain

- **Exotic decay of ^{56}Zn**
  - IAS fragmentation due to strong **isospin mixing of 33(10)%**
  - Nuclear structure is responsible for the **competition of p and γ decays**
  - First observation of **β-delayed γ-proton decay**



- **First observation of the 2$^+$ isomer in ^{52}Co: $T_{1/2}$ = 102(6) ms**
  - Improved the accuracy on the 6$^+$ g.s. **$T_{1/2}$ = 112(3) ms**

The Collaboration

PRL **112,** 222501 (2014) PHYSICAL REVIEW LETTERS week ending 6 JUNE 2014

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!