IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

CPAN ingenio 2010

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Spin-isospin excitations probed by beta decay and charge exchange reactions

Sonja Orrigo

IV Jornadas CPAN

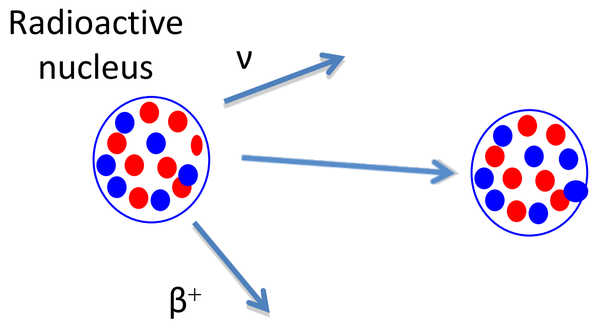
Outline

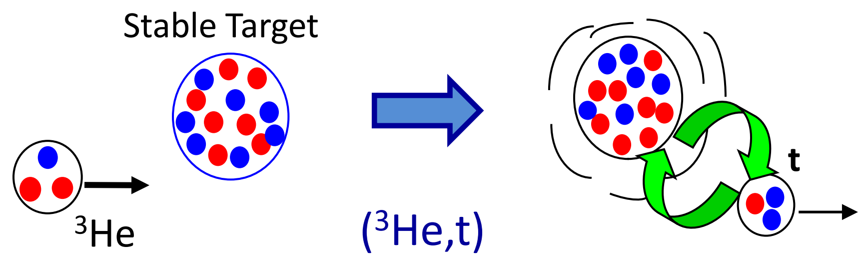
- **Analogy between Beta Decay and Charge Exchange (CE) reactions**

- **(^{7}Li,^{7}Be) CE reaction and β decay**
  - (^{7}Li,^{7}Be) CE experiments at LNS-INFN Catania using **MAGNEX**: light neutron-rich nuclei
  - Analysis in combination with β decay

- **β-decay spectroscopy and (^{3}He,t) CE reaction**
  - Beta decay at GANIL: T_z = -1 and T_z = -2 proton-rich nuclei
  - (^{3}He,t) CE experiments at RCNP Osaka
  - Combined analysis

Analogy between β decay and CE (1)





- **β decay:** Weak interaction
- **Charge Exchange:** Strong interaction

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

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

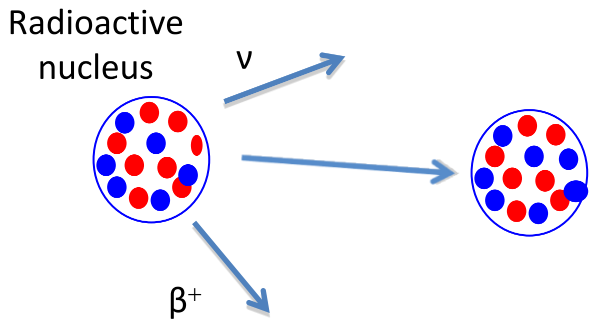
But they are ruled by the same operators

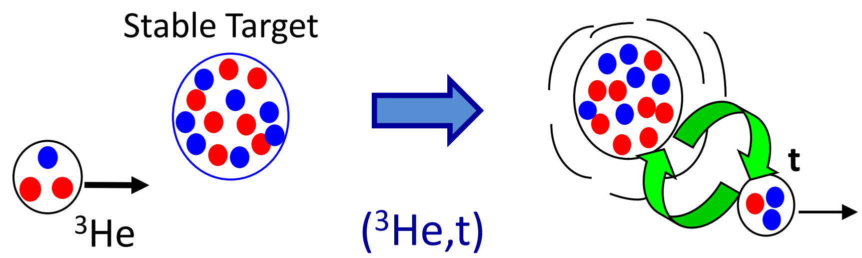
$$V_{NN}^{(\tau)} = \left(V_\tau + V_{\sigma\tau}\, \sigma_1 \cdot \sigma_2 + V_{T\tau}\, S_{12} \right) \tau_1 \cdot \tau_2$$

- **Conditions in CE for the analogy** ⟷ **Very forward angles (ϑ ~ 0°)**
  - Dominance of the one-step mechanism → $V_{NN}^{(\tau)}$
  - Low momentum transfer $q(fm^{-1}) = 0.11\, Q \left(E_{inc}/A \right)^{-1/2} \rightarrow 0$
  - Negligible contribution of the tensor component

T.N. Taddeucci et al., Nuclear Physics A 469 (1987) 125-172

Analogy between β decay and CE (2)





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- The **CE differential cross-sections** for **Fermi (ΔS = 0)** and **Gamow Teller (ΔS = 1)** transitions are approximately proportional to the β-decay strengths **B(F)** and **B(GT)**

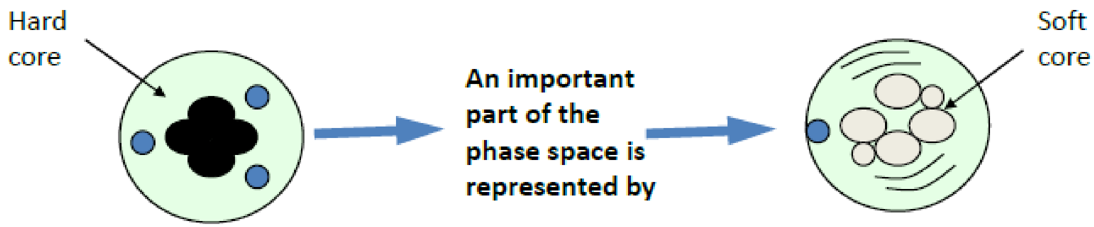
$$\frac{d\sigma_F^{CE}}{d\Omega}(0^\circ) \cong \hat{\sigma}_F(0^\circ) B(F)$$

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

✓ At intermediate beam energies (E_{inc} > 100 AMeV) and zero momentum transfer (ϑ ~ 0°)

T.N. Taddeucci et al., Nuclear Physics A 469 (1987) 125-172

Nα+3n nuclei via the (^{7}Li,^{7}Be) CE reaction



- N = 1 → ^{7}He
- N = 2 → ^{11}Be
- N = 3 → ^{15}C
- N = 4 → ^{19}O
- N = 5 → ^{23}Ne
- N = 6 → ^{27}Mg
- …

IPN-Orsay (^{7}He, ^{11}Be, ^{15}C, ^{19}O)

MAGNEX (^{19}O, ^{23}Ne, ^{27}Mg, …)

Structural properties:

- Single particle isovector excitations
- BSEC and Fano resonances in the continuum

Reaction dynamics:

- One-step / two-step contributions
- Spin transfer probabilities

References

S.E.A. Orrigo et al., Phisycs Letters B 633 (2006) 469

C. Nociforo et al., European Physical Journal A 27 (2006) 283

F.Cappuzzello, S.E.A. Orrigo et al., EuroPhysics Letters 65 (2004) 766

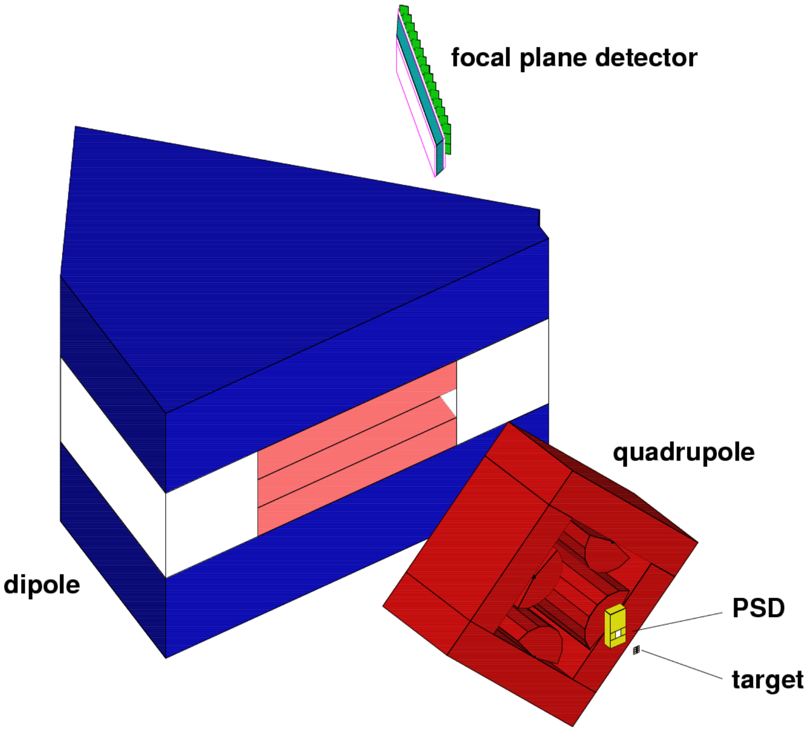
F.Cappuzzello et al., Nuclear Physics A 739 (2004) 30

S.E.A. Orrigo, PhD thesis (2004) and Proceedings of 10th Varenna Conference 122 (2003) 147

C.Nociforo et al., Acta Physica Polonica B 34 (2003) 2387

F.Cappuzzello et al., Physics Letters B 516 (2001) 21

The large-acceptance ray-tracing magnetic spectrometer MAGNEX



Upper bent limits	
E < 30 AMeV	E < 25 AMeV
2 < A < 40	40 < A < 93

Max. magnetic rigidity	1.8 T m
Solid angle	51 msr
E_{max} / E_{min}	1.7
Total energy resolution (target 1 mm^2, 90% of full acceptance)	~ 1000
Mass resolution	250

References

NIMA 621 (2010) 419
NIMA 602 (2009) 494
IEEE TNS 55 (2008) 3563
NIMA 591 (2008) 394
NIMA 585 (2008) 136
EPJ ST 150 (2007) 343
NIMA 570 (2007) 192
NIMA 495 (2002) 216
NIMA 484 (2002) 56
NIMA 481 (2002) 48

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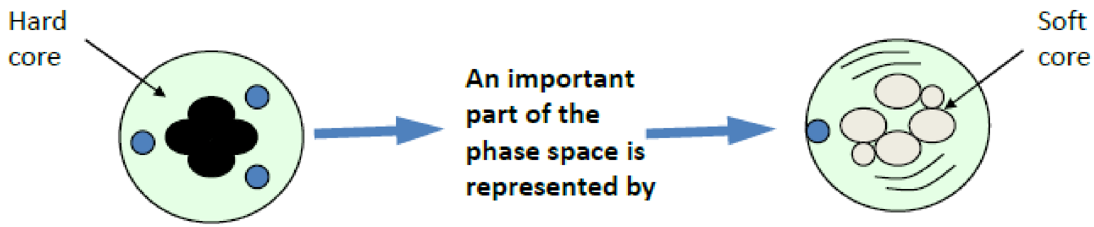

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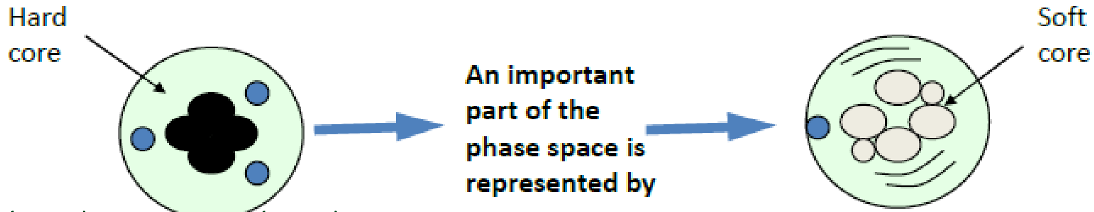
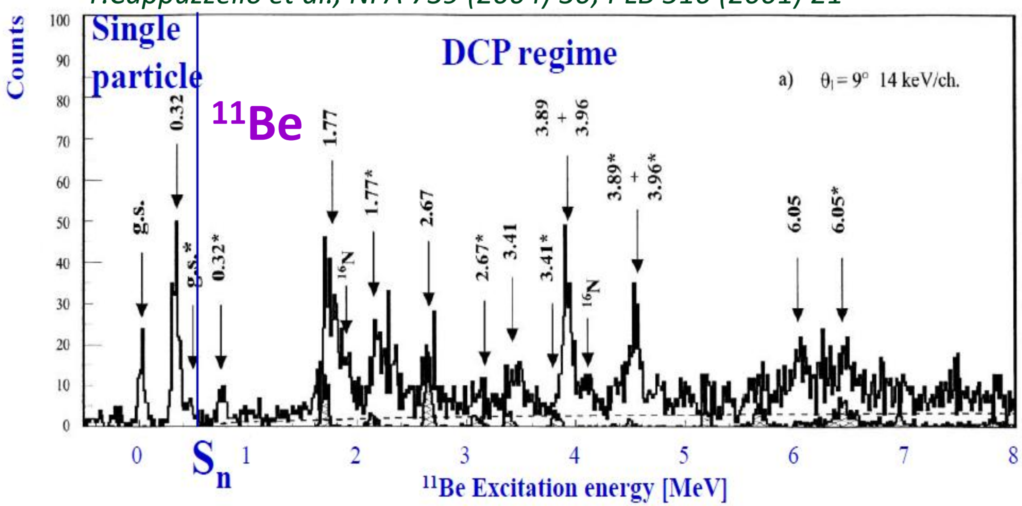
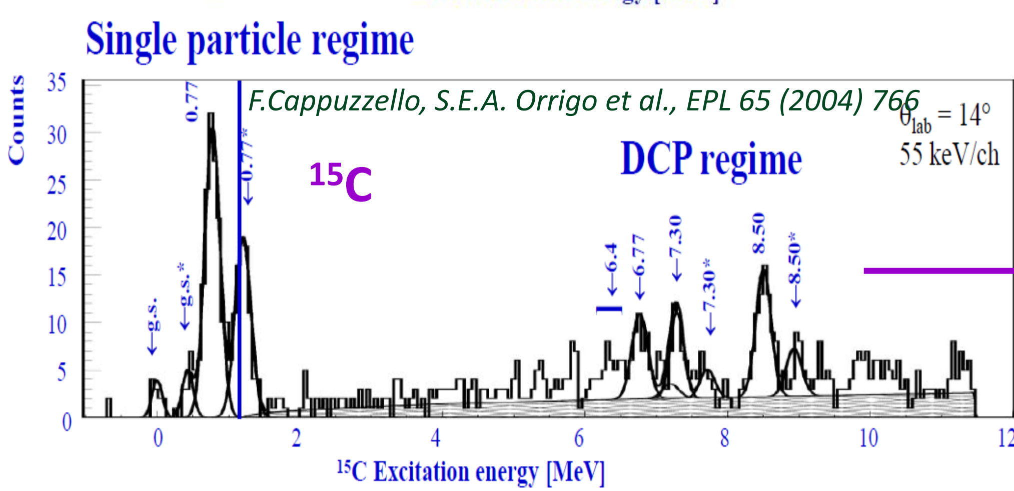


F.Cappuzzello et al., NPA 739 (2004) 30; PLB 516 (2001) 21





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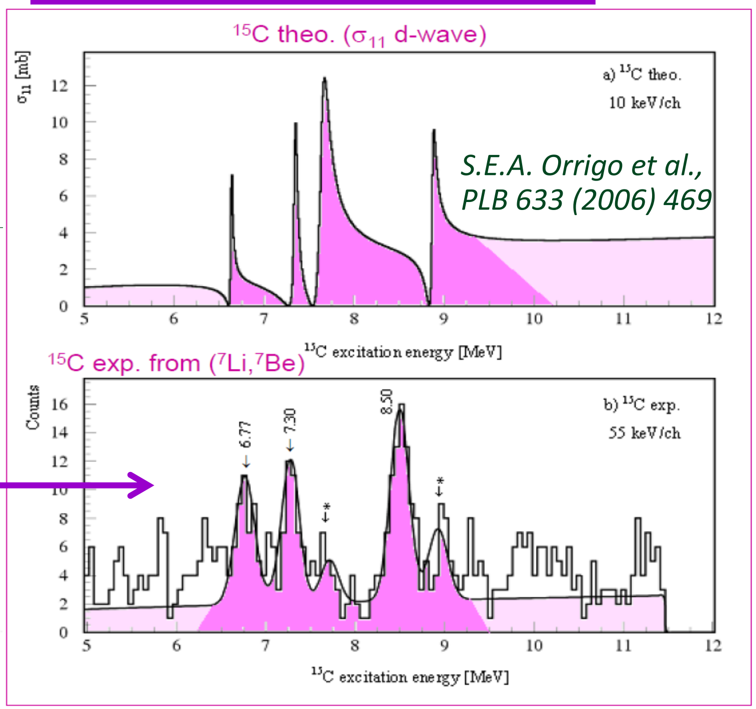
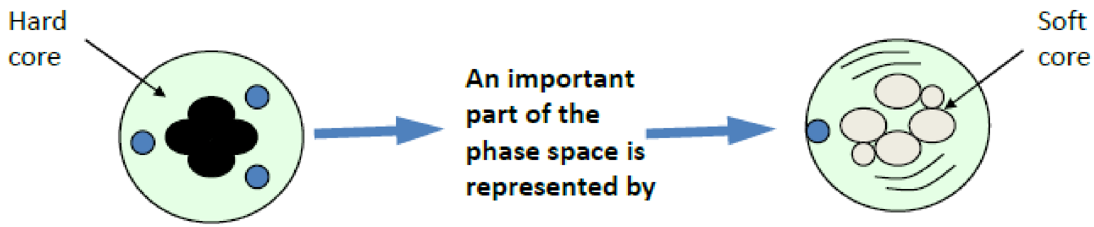


Nα+3n nuclei via the (^{7}Li,^{7}Be) CE reaction



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(^{7}Li,^{7}Be) and β decay: the G-factor

Spin-flip probability S_{NN}

$$S_{NN} \sim \frac{\sigma(\Delta s = 1)}{\sigma(\Delta s = 0) + \sigma(\Delta s = 1)}$$

$$^7\text{Li}(3/2^-) \rightarrow {}^7\text{Be}_{g.s.}(3/2^-)$$

$$^7\text{Li}(3/2^-) \rightarrow {}^7\text{Be}_{0.43}(1/2^-)$$

↔

β decay

Fermi ($\Delta\ell = 0, \Delta s = 0$)

Gamow-Teller ($\Delta\ell = 0, \Delta s = 1$)

$$\sigma({}^7\text{Be}_{g.s.}) \approx B_0(F,q)\,\sigma(\Delta s = 0) + B_0(GT,q)\,\sigma(\Delta s = 1)$$

$$\sigma({}^7\text{Be}_{0.43}) \approx B_1(GT,q)\,\sigma(\Delta s = 1)$$

S. Nakayama et al., Phys. Rev. C 60 (1991) 047303

$$G \equiv \frac{\sigma({}^7\text{Be}_{0.43})}{\sigma({}^7\text{Be}_{g.s.}) + \sigma({}^7\text{Be}_{0.43})} = \begin{cases} 0 & \text{for } \Delta s = 0 \text{ transitions} \\ 0.46 & \text{for } \Delta s = 1 \text{ transitions} \end{cases}$$

$G\ (0^o)$

J. Jänecke et al., Phys. Rev.C 54 (1996) 1070

(^{7}Li,^{7}Be) and β decay: the G-factor

	^{11}Be							^{12}B				
Ex [MeV]	g.s.	0.32	1.77	2.67	3.89	3.96	6.05	g.s.	0.95	1.67	2.62	4.50
G	0.38	0.35	0.46	0.35	0.47	0.40	0.56	0.15	0.17	0.40	0.33	0.34
ΔG	0.04	0.03	0.04	0.04	0.04	0.07	0.03	0.03	0.03	0.06	0.07	0.03

NPA 739 (2004) 30; PLB 516 (2001) 21

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G (0^o)

J. Jänecke et al., Phys. Rev.C 54 (1996) 1070

β decay and (^{3}He,t): the Collaboration

Beta Decay of Exotic fp-shell Nuclei with $T_Z = -1$ and $T_Z = -2$ at GANIL

S.E.A.Orrigo[1], L.Kucuk[2], B.Rubio[1], Y.Fujita[3], W.Gelletly[4], T.Adachi[5], J.Agramunt[1], A.Algora[1], P.Ascher[6], B.Bilgier[2], B.Blank[6], L.Cáceres[7], R.B.Cakirli[2], G.de France[7], H.Fujita[5], E.Ganioğlu[2], M.Gerbaux[6], J.Giovinazzo[6], S.Grévy[6], O.Kamalou[7], H.C.Kozer[2], T.Kurtukian-Nieto[6], M.Marqués[8], F.Molina[1], Y.Oktem[2], F.de Oliveira Santos[7], L.Perrot[9], L.Popescu[10], R.Raabe[7], A.M.Rogers[11], P.C.Srivastava[7], G.Susoy[2], C.Stodel[7], T.Suzuki[5], A.Tamii[5], and J.C.Thomas[7]

[1] *Instituto de Física Corpuscular, CSIC-Universidad de Valencia, E-46071 Valencia, Spain*

[2] *Department of Physics, Istanbul University, Istanbul, Turkey*

[3] *Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan*

[4] *Department of Physics, University of Surrey, Guilford GU2 7XH, Surrey, UK*

[5] *Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*

[6] *Centre d'Etudes Nucléaires de Bordeaux Gradignan, Université Bordeaux 1, UMR 5797 CNRS/IN2P3, BP 120, F-33175 Gradignan, France*

[7] *Grand Accélérateur National d'Ions Lourds, BP 55027, F-14076 Caen, France*

[8] *Laboratoire de Physique Corpusculaire de Caen, F-14050 Caen, France*

[9] *IPN Orsay, F-91406 Orsay, France*

[10] *Vakgroep Subatomaire en Stralingsfysica, Universiteit Gent, B-9000 Gent, Belgium*

[11] *Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*

β-decay transition strengths

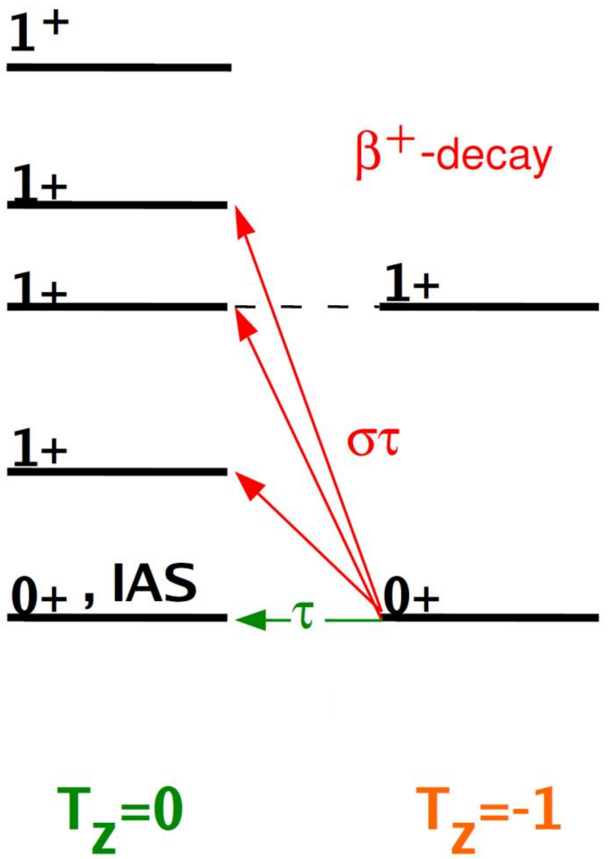
- Measured in **β-decay experiments**: half-life, β feeding, particle decay branching ratios
- The partial half-life $t_j = \frac{T_{1/2}}{I_\beta^j(E_j)}$ multiplied by the *f-factor* is related to the **Fermi** and **Gamow Teller** transition strengths

Beta feeding to states in the daughter nucleus

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

Parent half-life

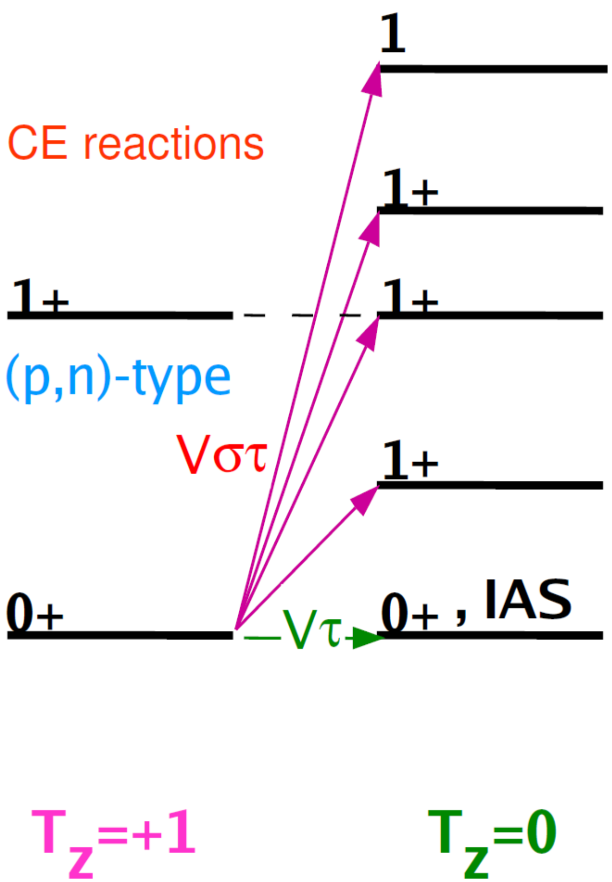
$$B(F)^\beta = K \frac{I_\beta(E)}{f(Q_\beta - E, Z)T_{1/2}}$$



- Advantage: absolute normalization of B(GT)
- Disadvantage: B(GT) only for the low-lying states (Q_β energy window)

Complementarity of β decay and CE reactions

- On the other side, **CE reactions** give also information on **B(F)** and **B(GT)**



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

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

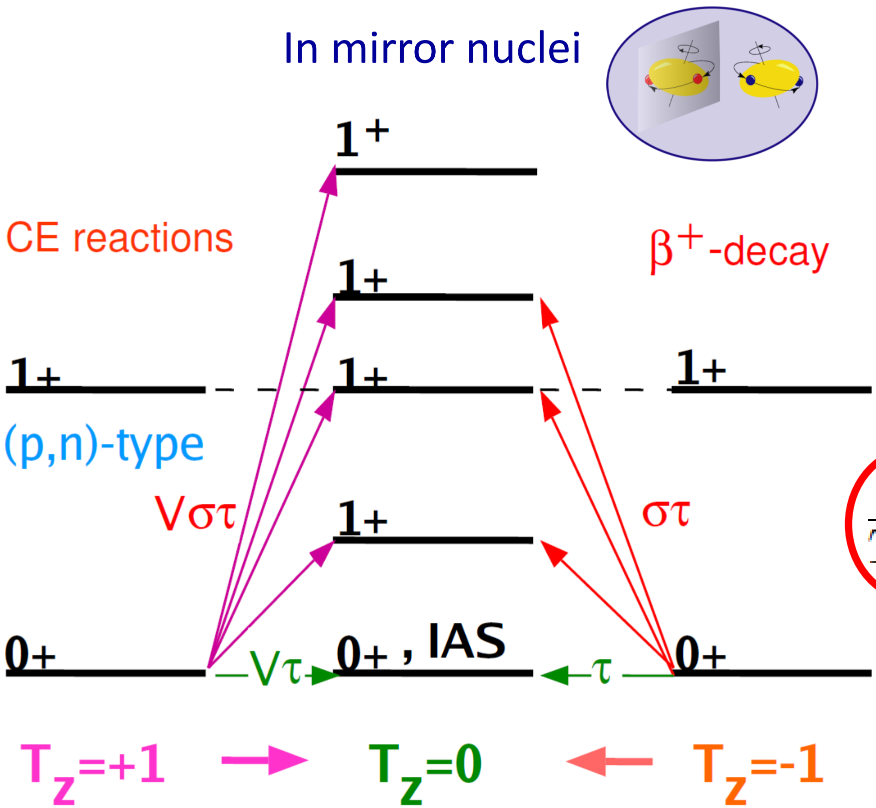
- Advantage: highly excited states can be accessed
- Disadvantage: relative B(GT) are measured

- **Therefore β decay and CE are complementary**

  ⟹ **Combined analysis of the two processes**

Combined analysis of β decay and CE

- Under the assumption of **isospin symmetry**, **mirror GT and Fermi transitions** from the **$T_z = \pm 1$** nuclei to the **$T_z = 0$** nucleus are expected to have the same transition strengths
- However, due to **Coulomb interaction**, complete symmetry is not always guaranteed



$$(1/T_{1/2}) = (1/t_{\mathrm{F}}) + \sum_{i=\mathrm{GT}} (1/t_i)$$

From β decay

B(F)=|N-Z|

From (^{3}He,t) CE

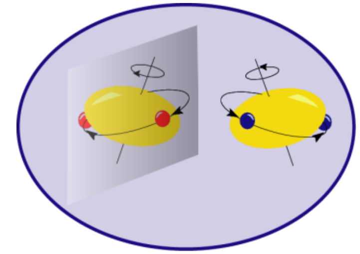
$$\frac{1}{T_{1/2}} = \frac{1}{K}\left[B(\mathrm{F})(1-\delta_c)f_{\mathrm{F}} + \sum_{j=\mathrm{GT}} \lambda^2 B_j(\mathrm{GT}) f_j\right]$$

⇨ **A precise value of the parent $T_{1/2}$ is very important**

Y. Fujita et al., Physical Review Letters 95 (2005) 212501

Y. Fujita, B. Rubio, W. Gelletly, Progress in Particle and Nuclear Physics 66 (2011) 549-606

Study of T = 1 nuclei in the fp-shell



- A series of experiments of β decay and CE reactions starting from **mirror nuclei** were carried out

✓ **CE experiments** were all performed at RCNP Osaka:

(^{3}He,t) reaction at 140 AMeV and ϑ = 0°

Y. Fujita et al., PRL 95 (2005) 21250

✓ **β-decay experiments:**

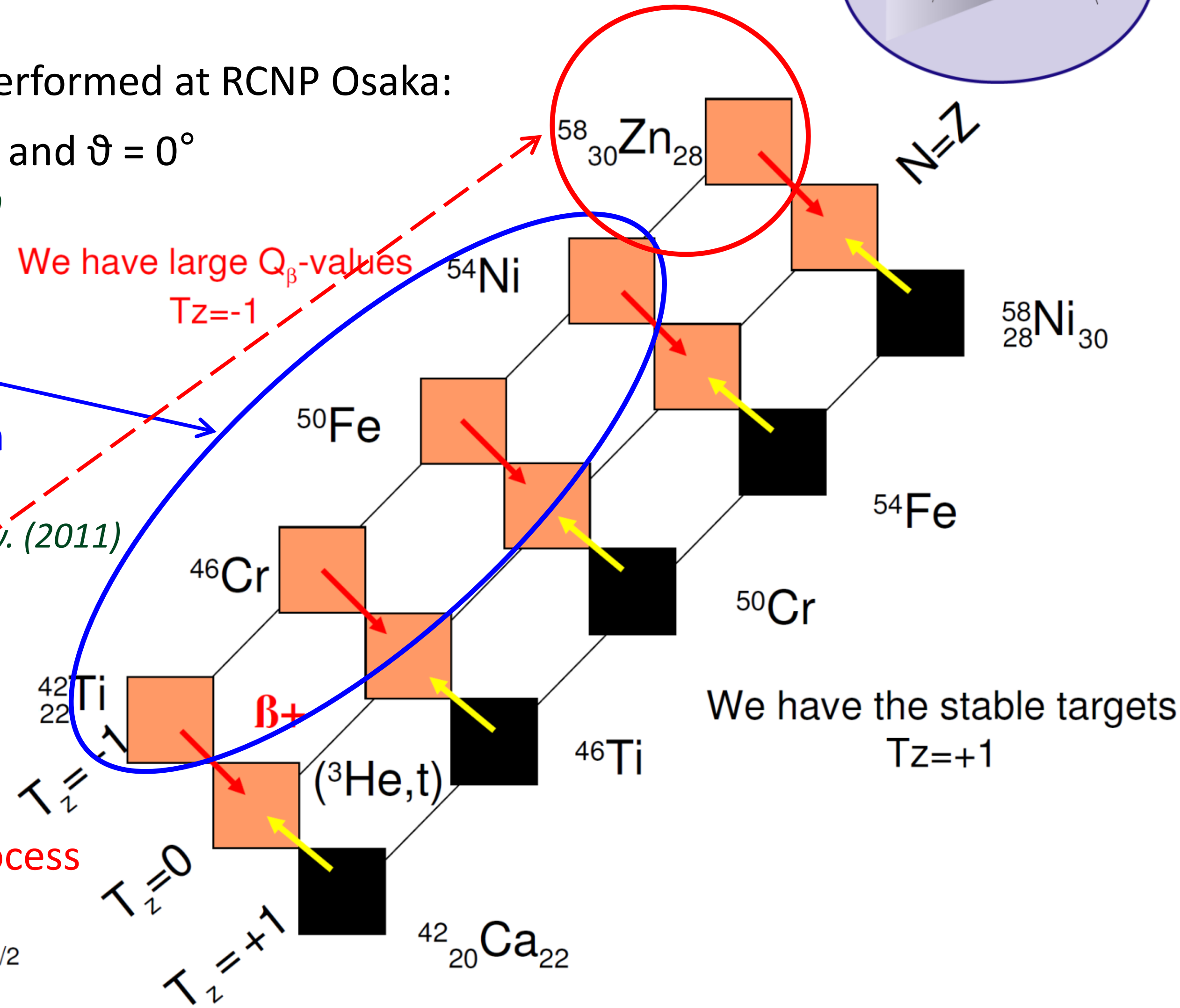
(1) 4 nuclei studied at GSI:

fragmentation of a ^{58}Ni beam

F. Molina et al., AIP 1265 (2010) 49
F. Molina, PhD thesis, Valencia Univ. (2011)

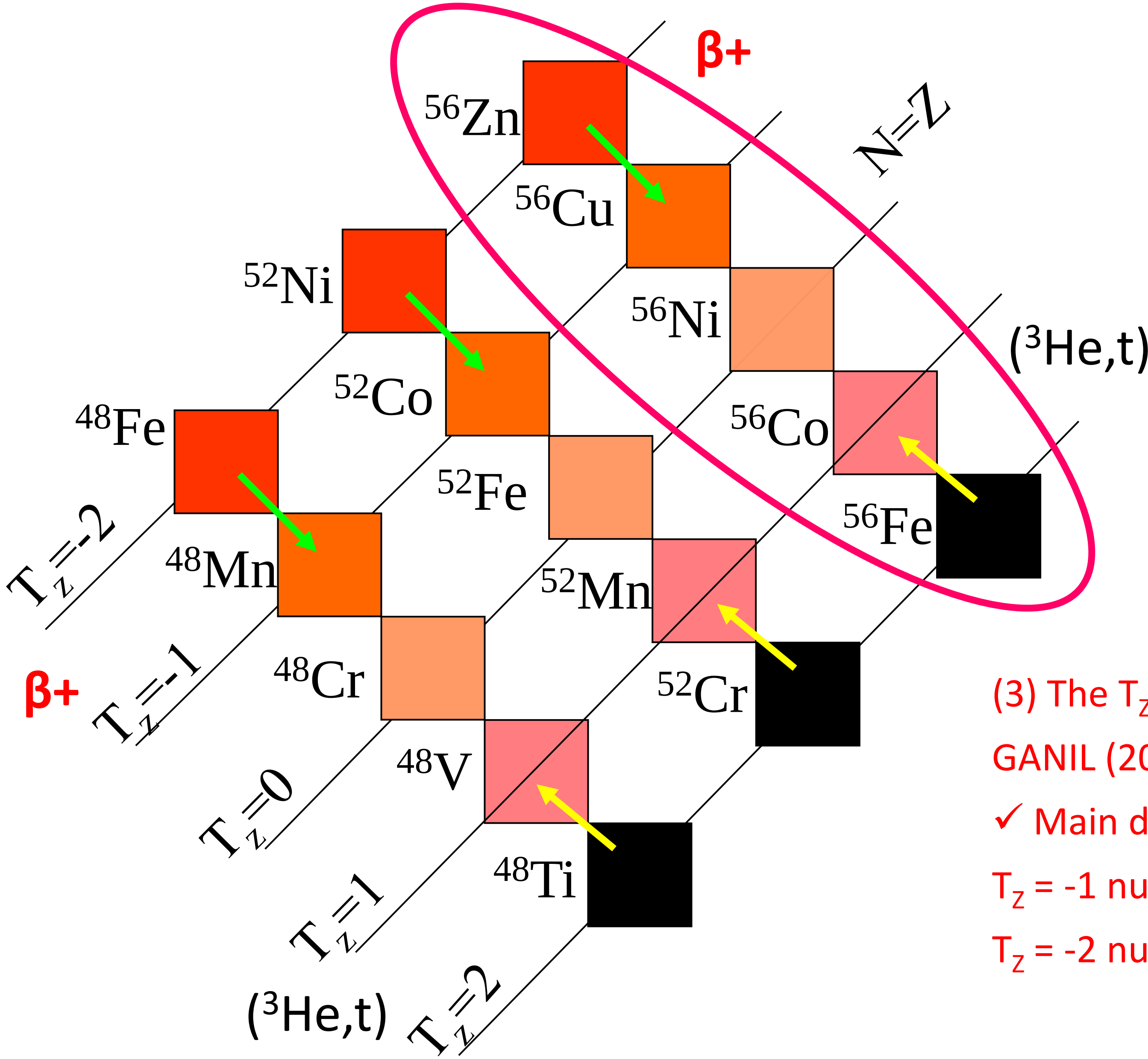
(2) The more exotic **^{58}Zn** was studied in 2 experiments at GANIL (2008, 2010)

✓ Waiting point in the rp-process

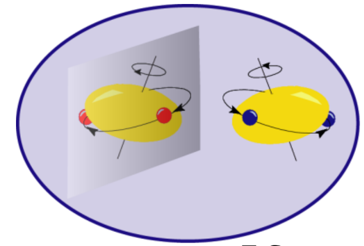


Tz=(N-Z)/2

Study of T = 2 nuclei in the fp-shell



Mirror nuclei



$^{56}_{30}Zn_{26}$ $^{56}_{26}Fe_{30}$

(3) The T_z = -2 **^{56}Zn** was studied at GANIL (2010)

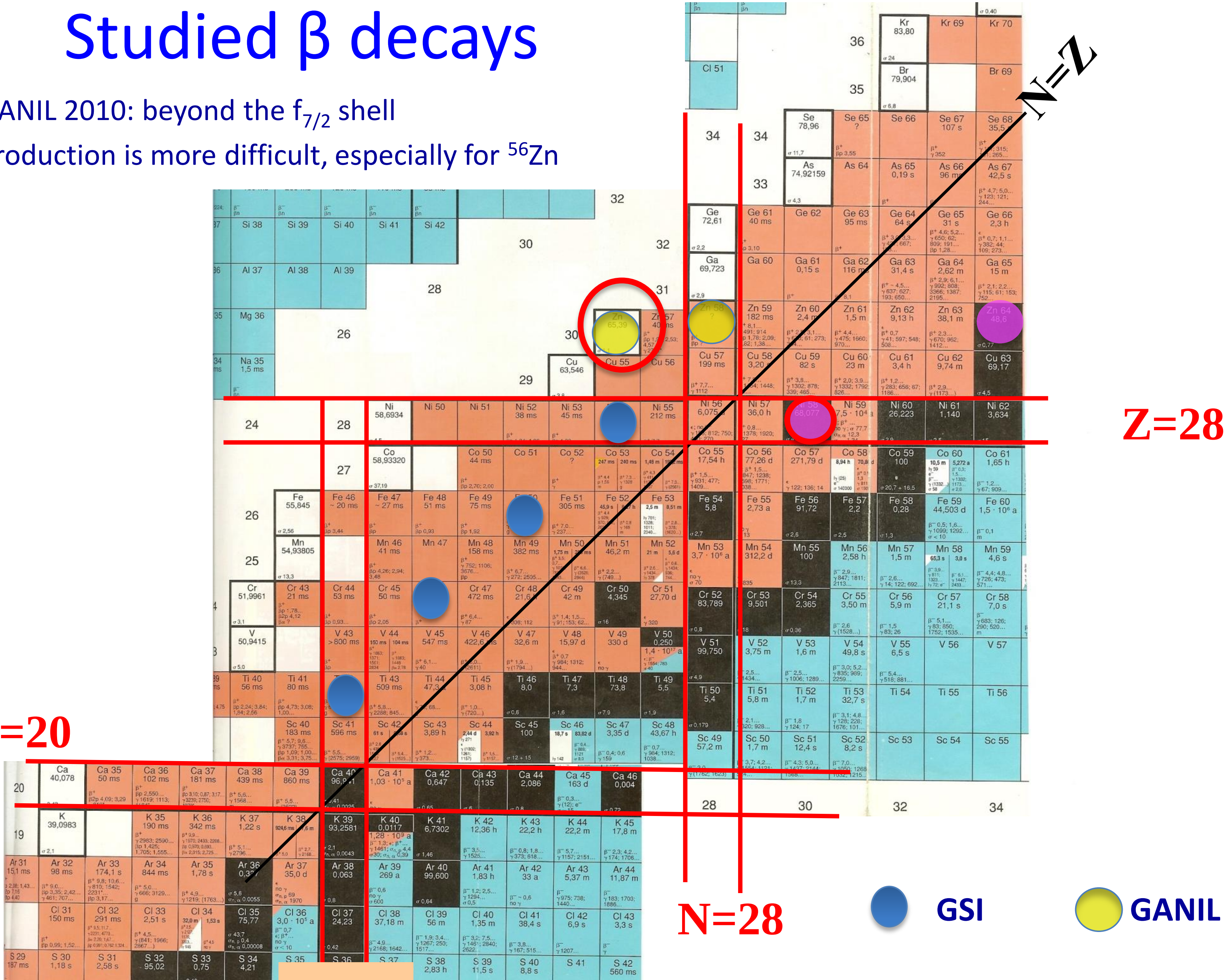
✓ Main difference (fp-shell nuclei)

T_z = -1 nuclei: β-delayed γ rays **only**

T_z = -2 nuclei: **also** β-delayed protons

Studied β decays

- GANIL 2010: beyond the $f_{7/2}$ shell
- Production is more difficult, especially for ^{56}Zn



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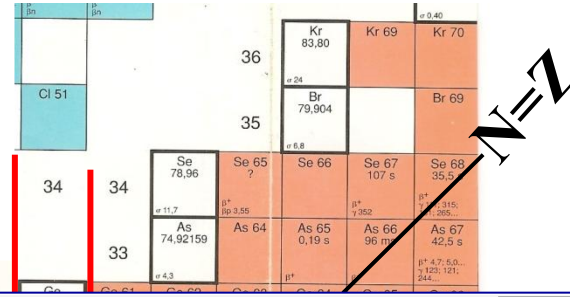
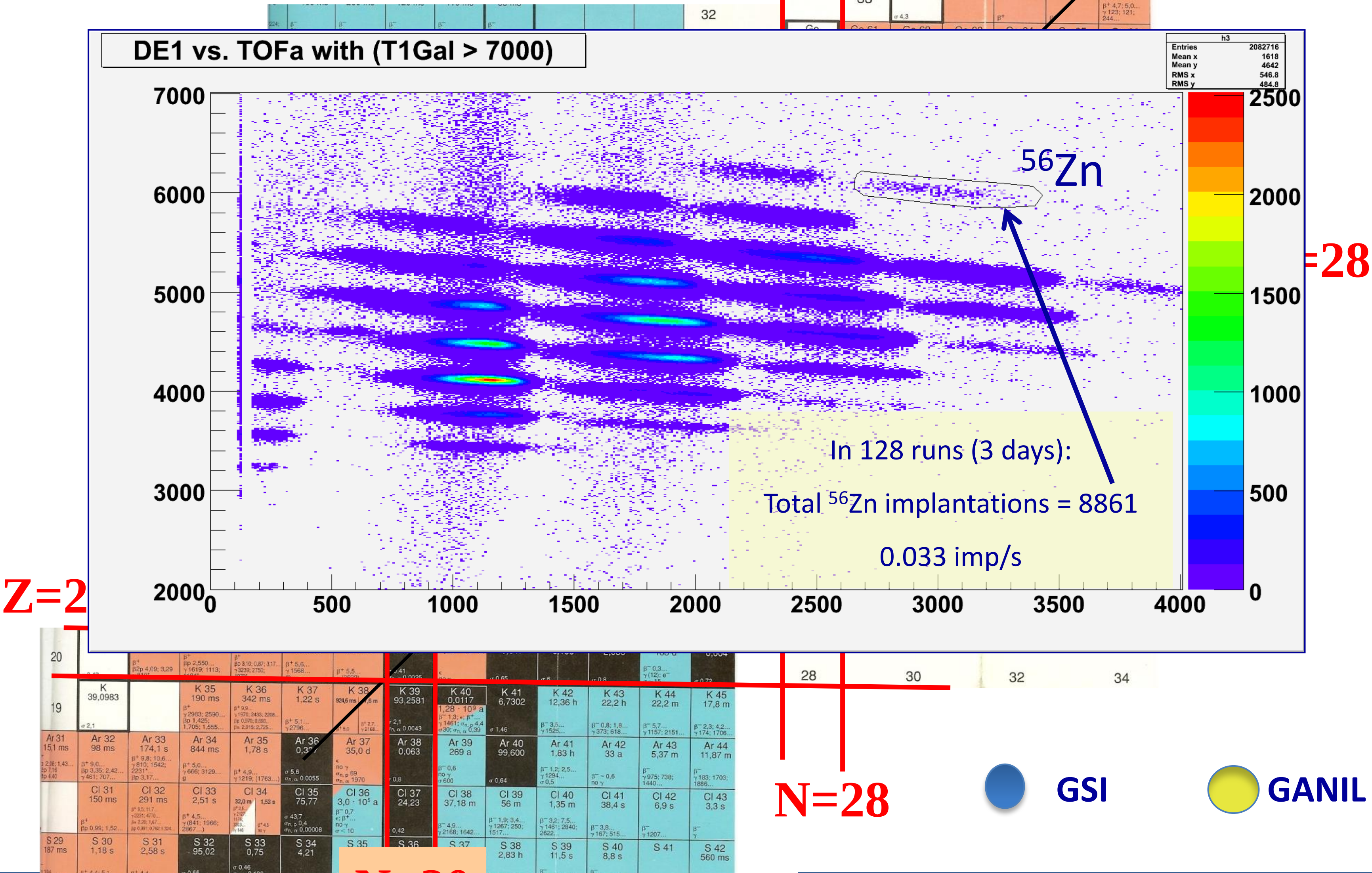
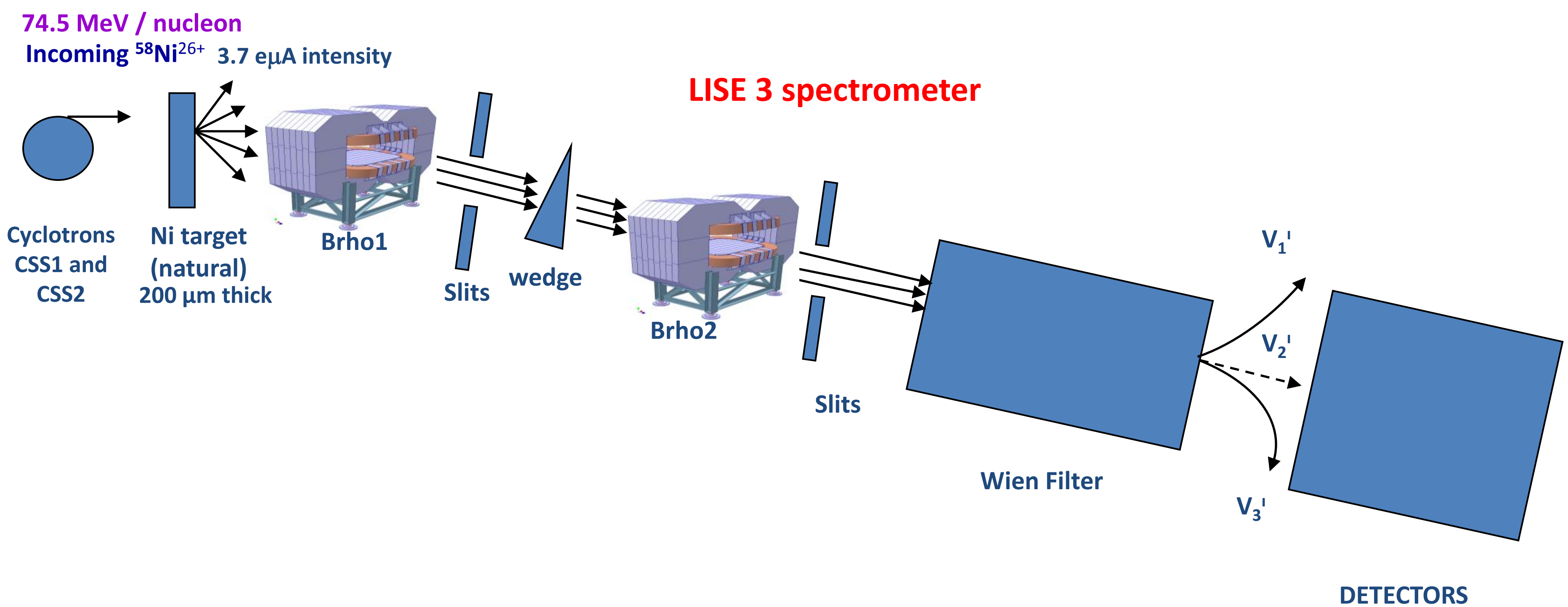




$^{58}Ni^{26+}$ (74.5 AMeV) + ^{nat}Ni @ GANIL 2010



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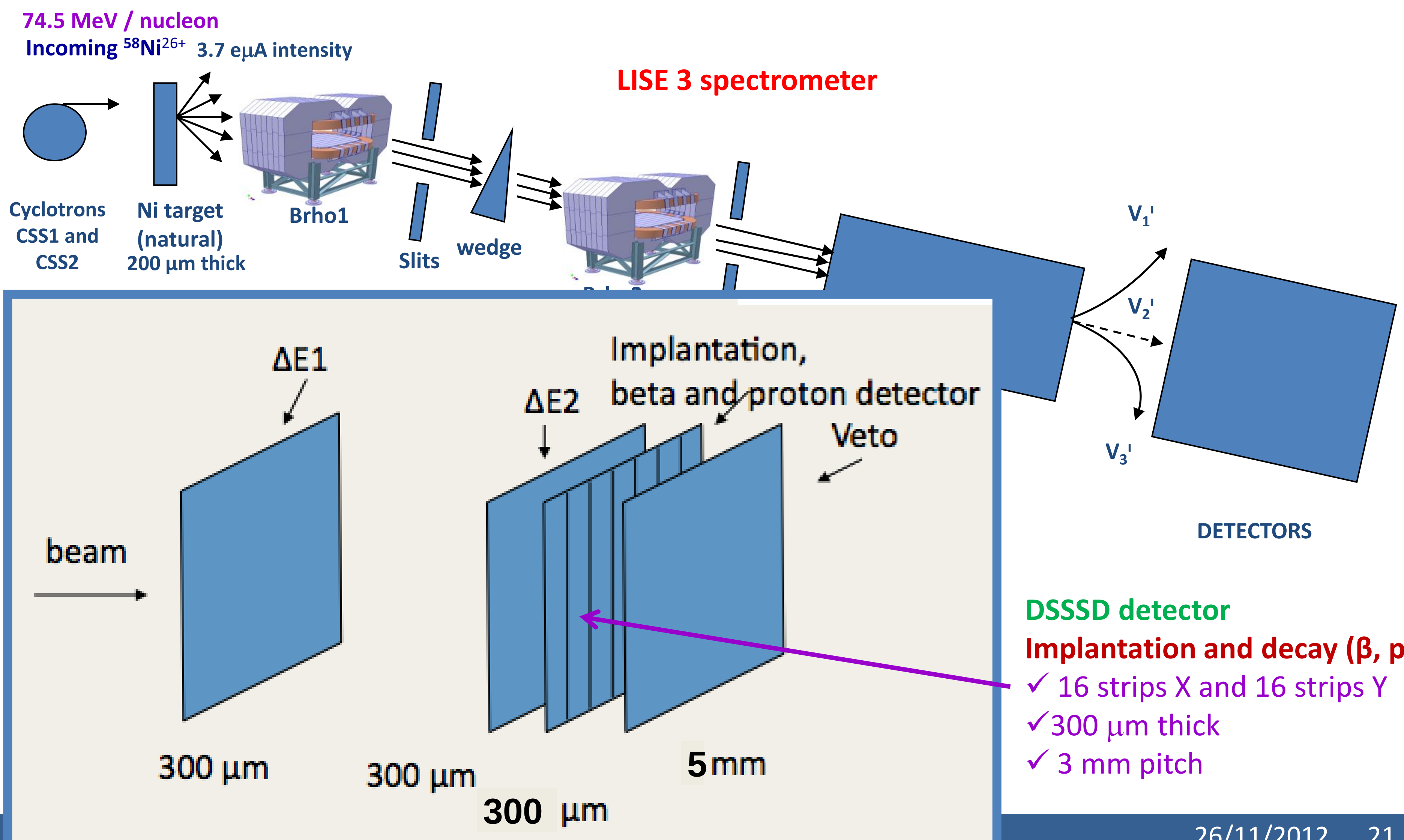

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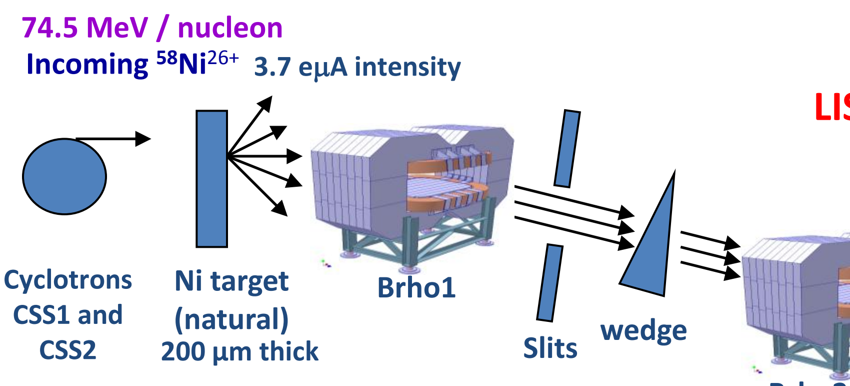
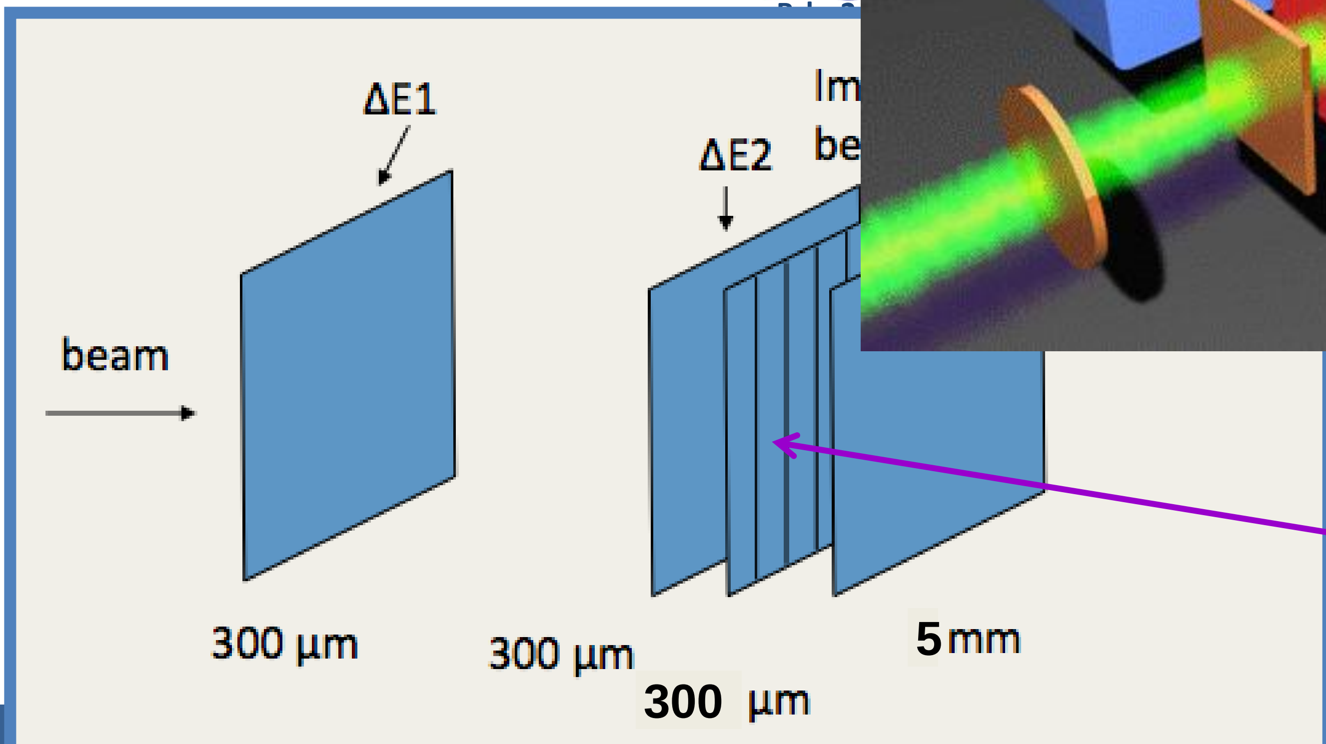
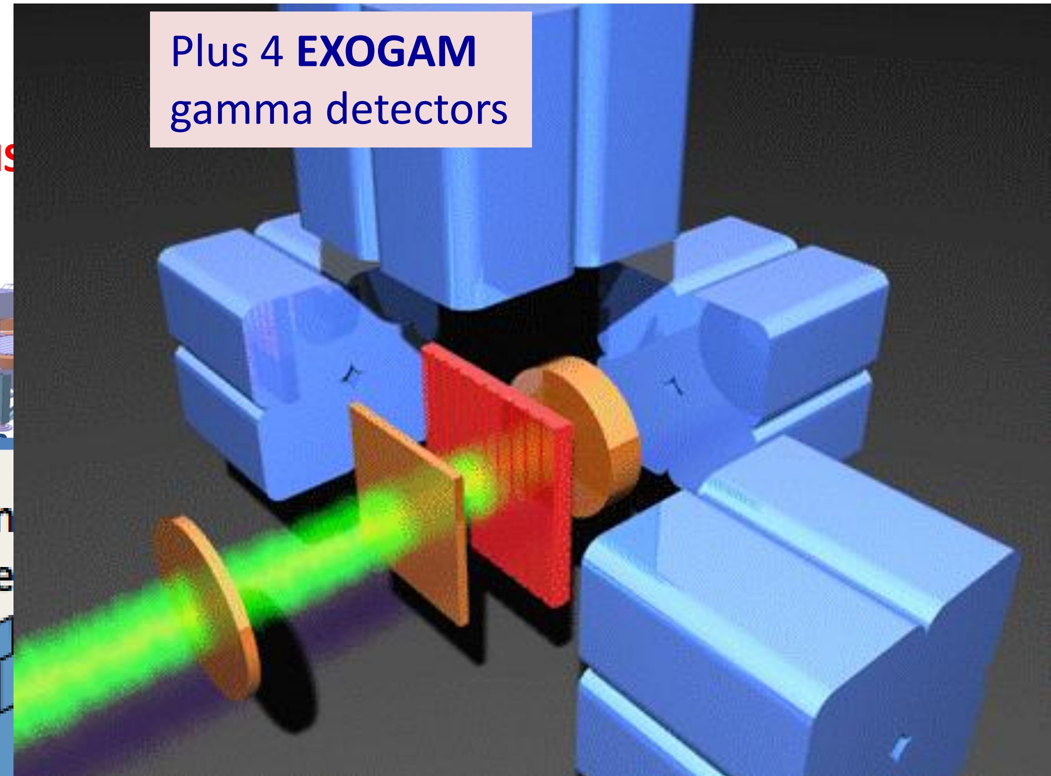






DSSSD detector

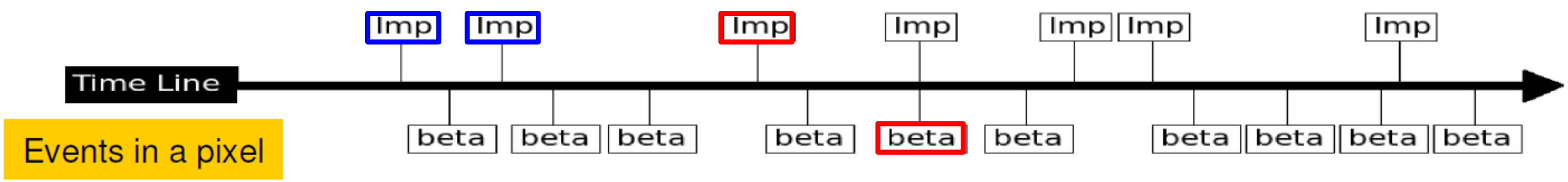
Implantation and decay (β, p)

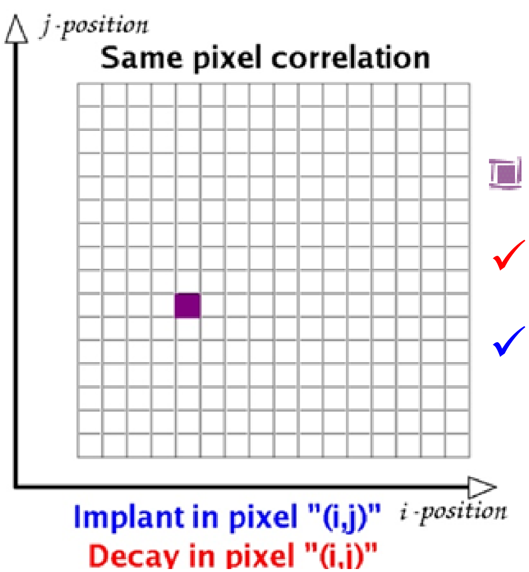
- ✓ 16 strips X and 16 strips Y
- ✓ 300 μm thick
- ✓ 3 mm pitch

Half-life analysis: β-implant correlations

- The time difference between implants and β-decay events give us the **Half-life $T_{1/2}$**
- It's **not possible** to correlate **one-by-one** a β decay with the corresponding implanted ion
- Statistical correlation:

Correlate each β decay with all the previous implantations in the same pixel of the DSSSD

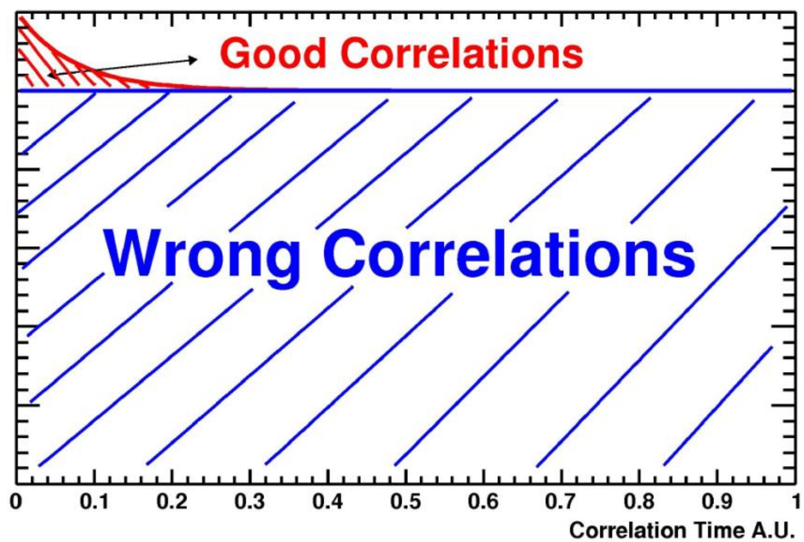




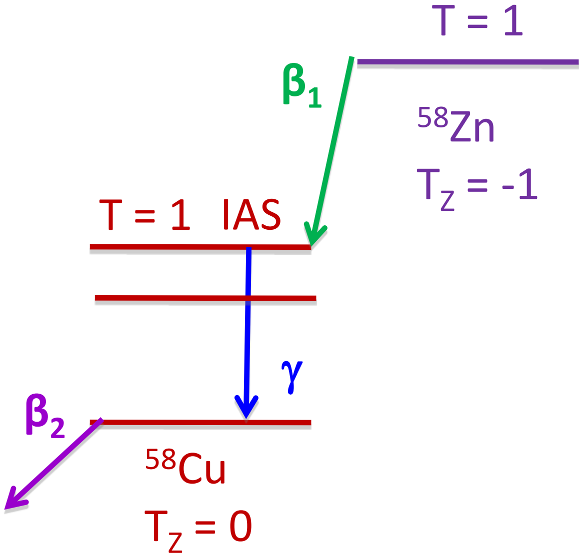
- This will result in:

✓ **Good correlations**

✓ **Random correlations**

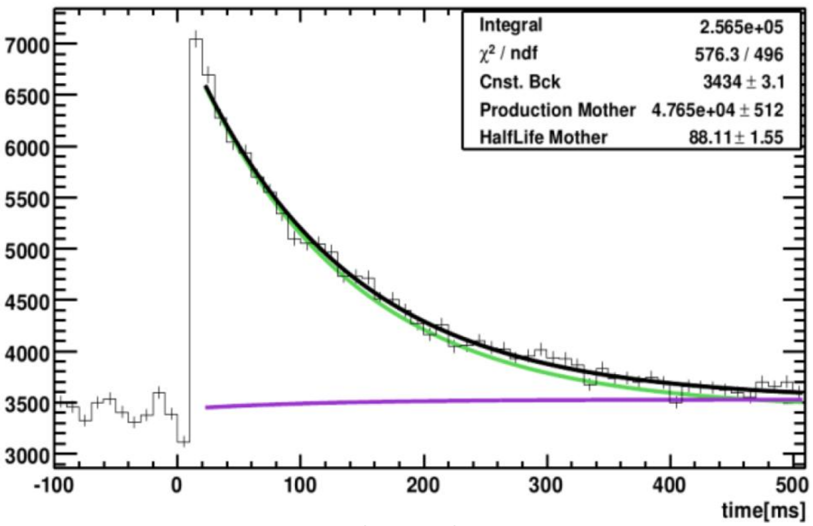


Half-life analysis for ^{58}Zn ($T_Z = -1$)



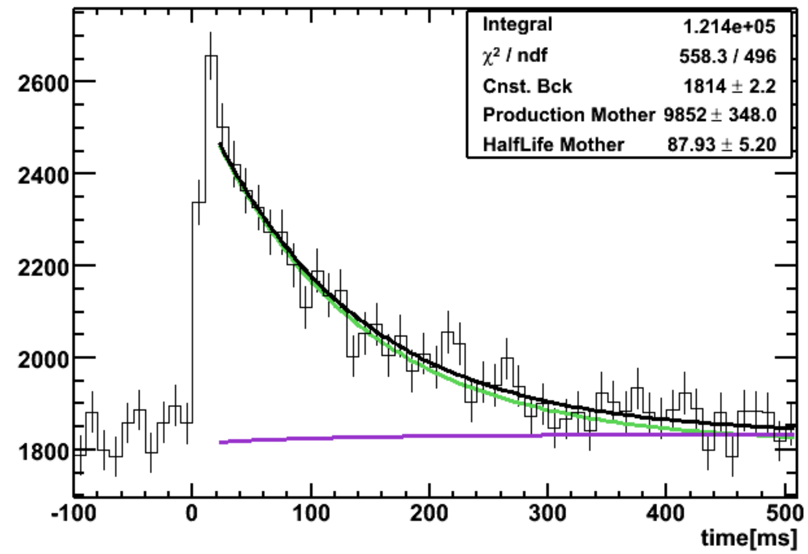
- The half-life fit includes both mother and daughter β decays: $T_{1/2\text{-}M}$ and $T_{1/2\text{-}D}$

Literature:
$T_{1/2}$ = 86 ± 18 ms (*A. Jokinen et al., EPJ A 3(2001)271*)
$T_{1/2}$ = 83 ± 10 ms (*M.J. Lopez Jimenez et al ., PRC 66(2002)025803*)
$T_{1/2}$ = 90 ± 8 ms (*Y. Fujita et al., Int J. of Phys. 18(2009)10*)



L. Kucuk et al.

GANIL 2008 experiment
✓ ^{58}Zn implants: **176960**
✓ **$T_{1/2}$ = (88 ± 1.6) ms**



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GANIL 2010 experiment
✓ ^{58}Zn implants: **82138**
✓ **$T_{1/2}$ = (88 ± 5) ms**

Half-life analysis for ^{56}Zn (T_Z = -2)

- To determinate B(GT) in T_Z = -2 nuclei is not trivial: the decay is more complex than in T_Z = -1 nuclei: **(1) β-delayed γ rays** **(2) β-delayed protons**

✓ Due to the low S_p the levels decay via proton emission

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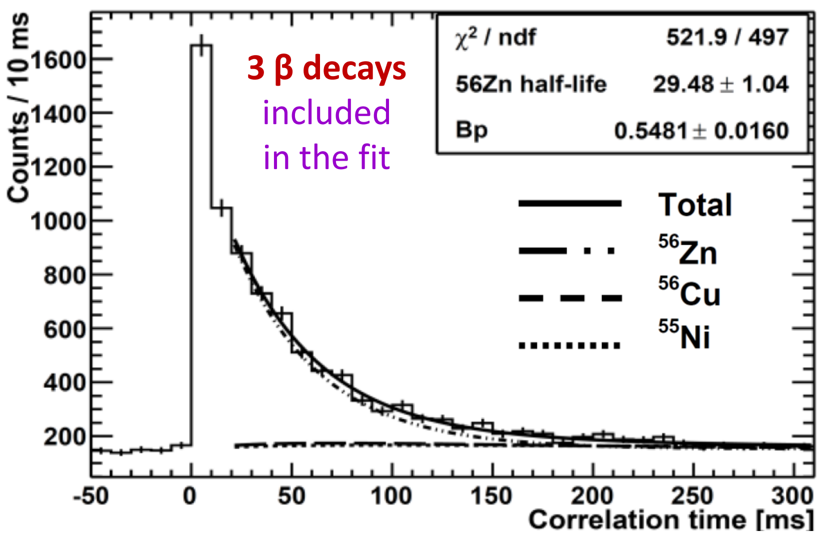
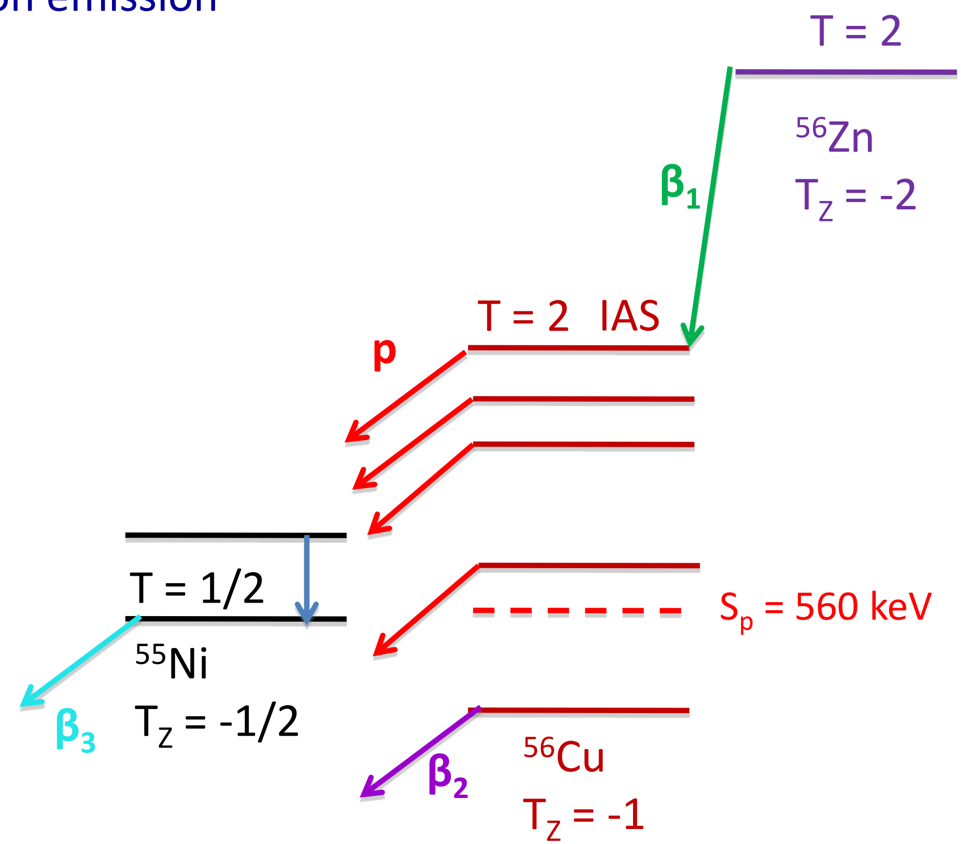


GANIL 2010 experiment

✓ ^{56}Zn implants: **8861**

✓ **$T_{1/2}$ = (29.5 ± 1.0) ms**

✓ **($T_{1/2}$ = (32.5 ± 1.0) ms using protons)**

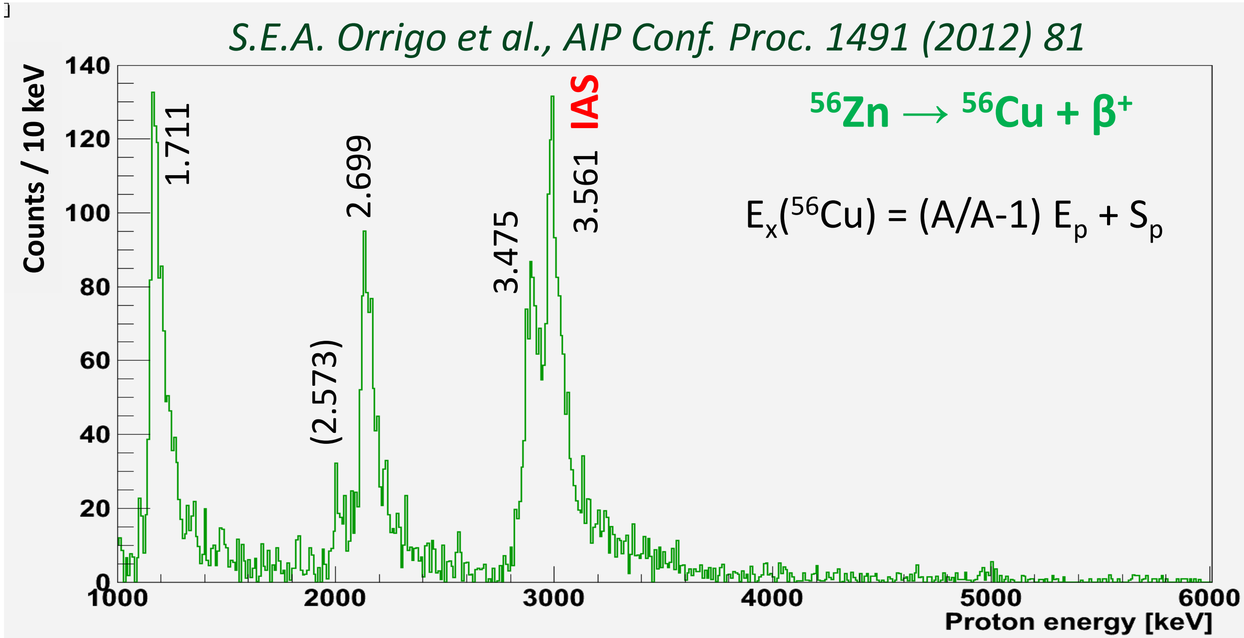


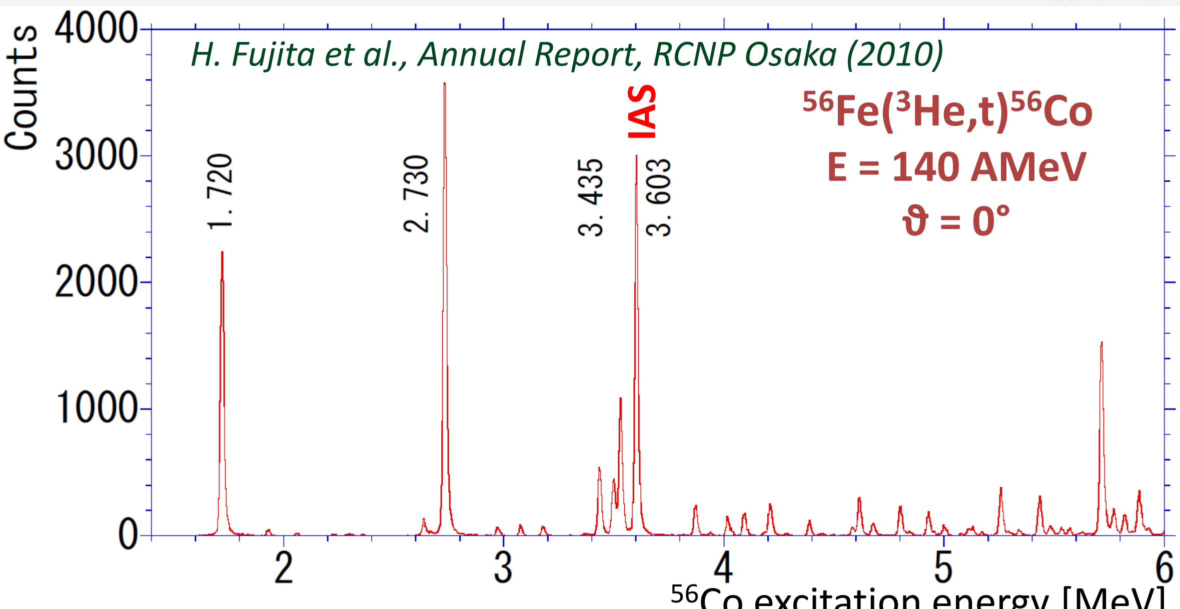
Literature:

$T_{1/2}$ = 30 ± 1.7 ms (*C. Dossat et al., NPA 792(2007)18*)

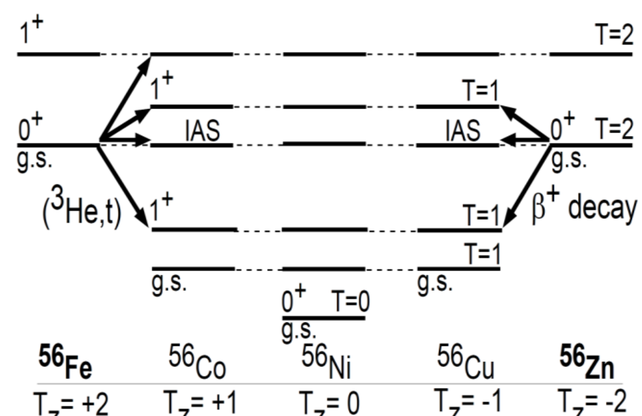
$T_{1/2}$ = 33 ms (*M. Honma et al ., PRC 69(2004)034335*)

Comparison of mirror transitions for A = 56





- The **Isobaric Analog State (IAS)** is clearly identified in both spectra
  - ✓ In agreement with previous data *(C. Dossat et al., NPA 792(2007)18)*
- **Isospin symmetry holds quite well !**
  - ✓ All the dominant transitions are observed in both β decay and CE starting from mirror nuclei



^{56}Zn decay scheme

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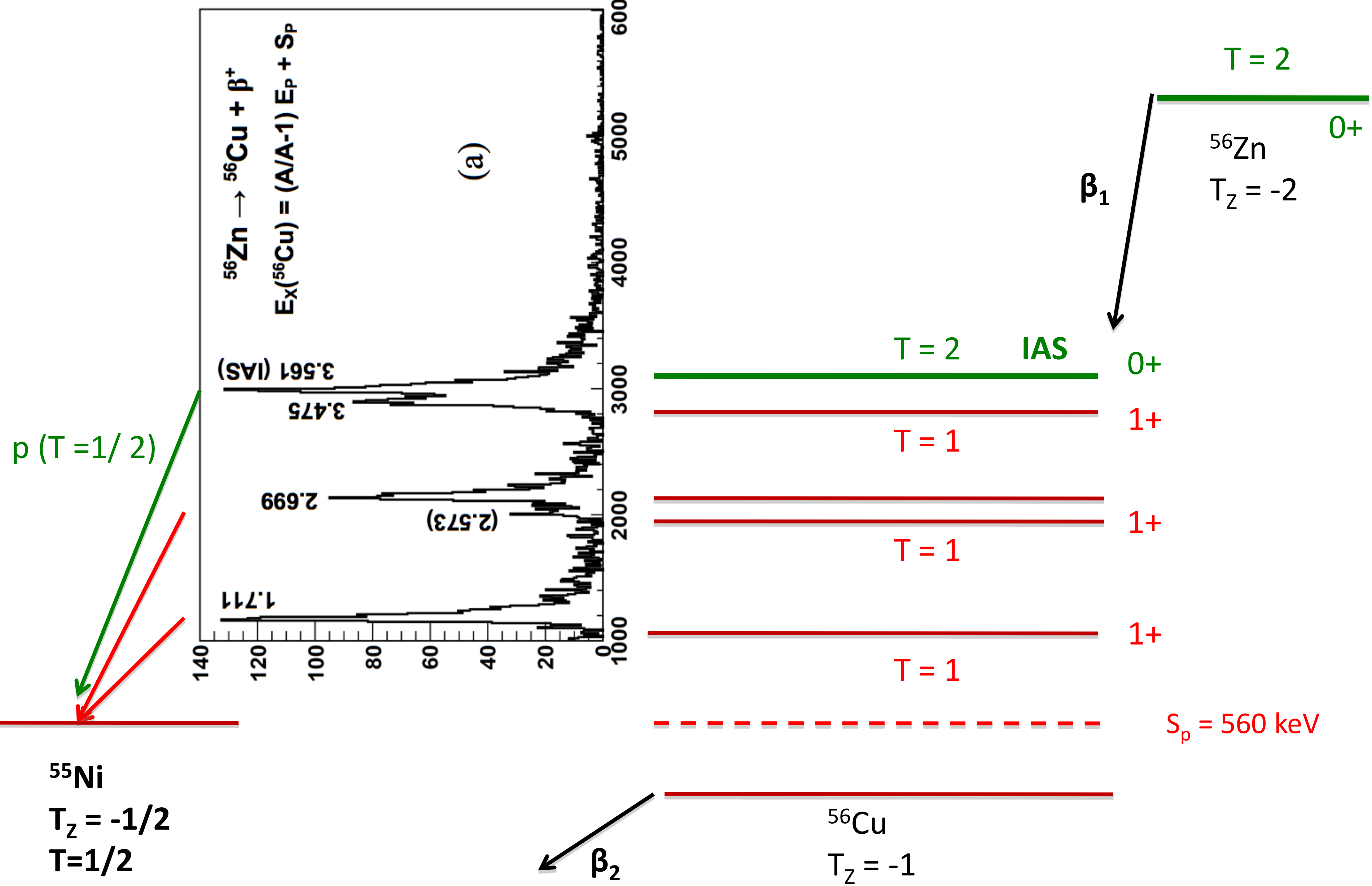

^{56}Zn decay scheme

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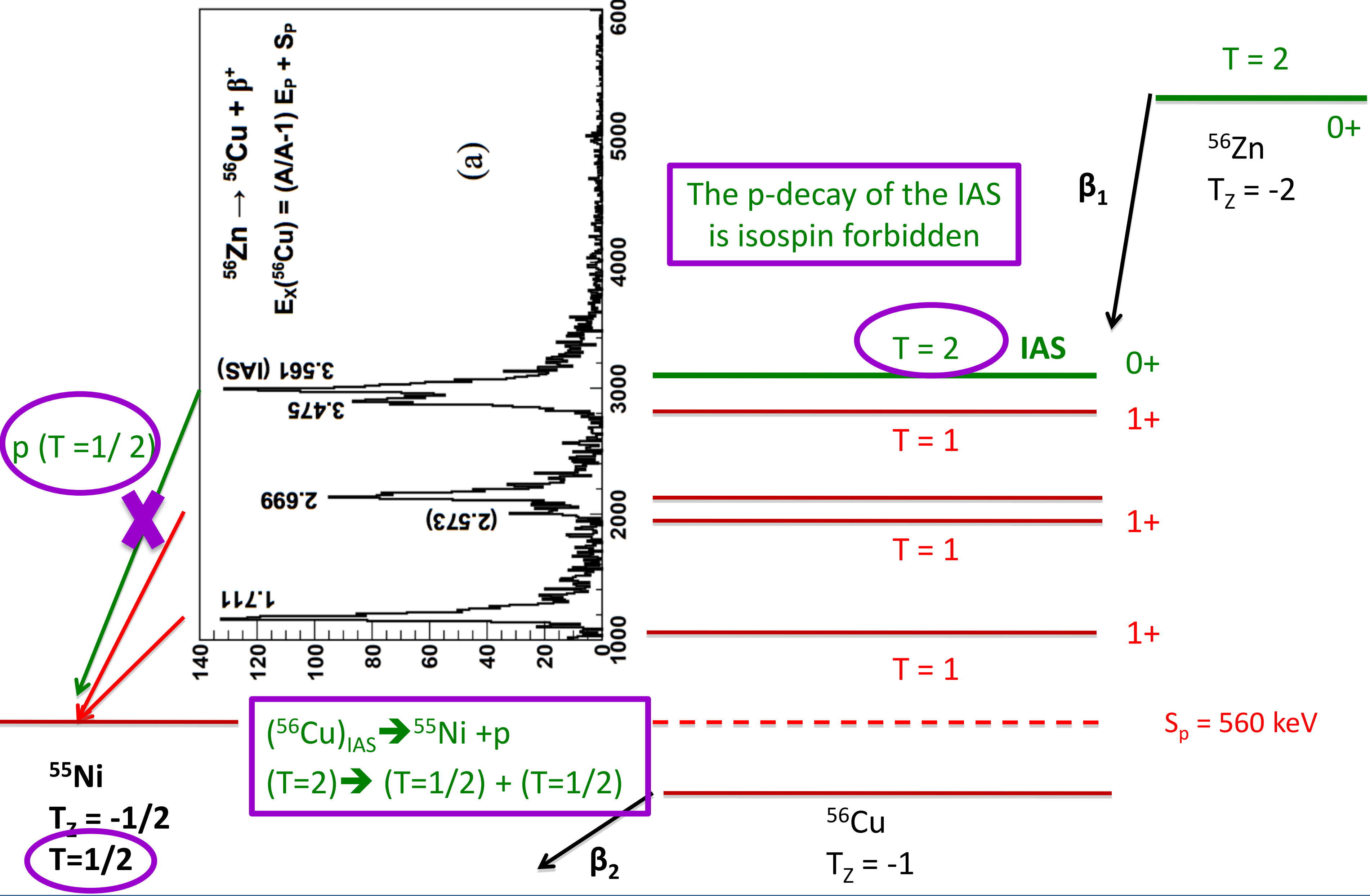

^{56}Zn decay scheme

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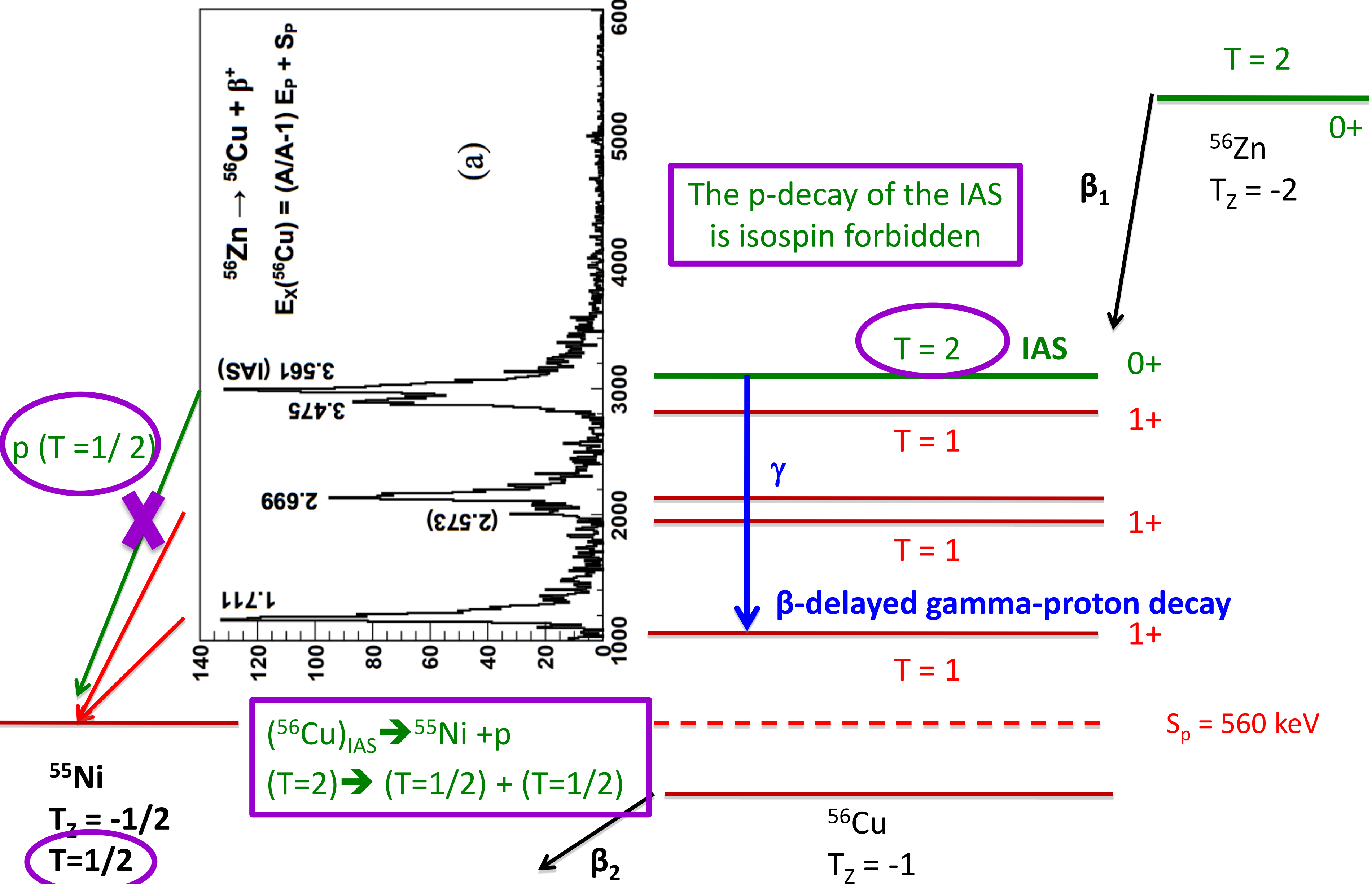
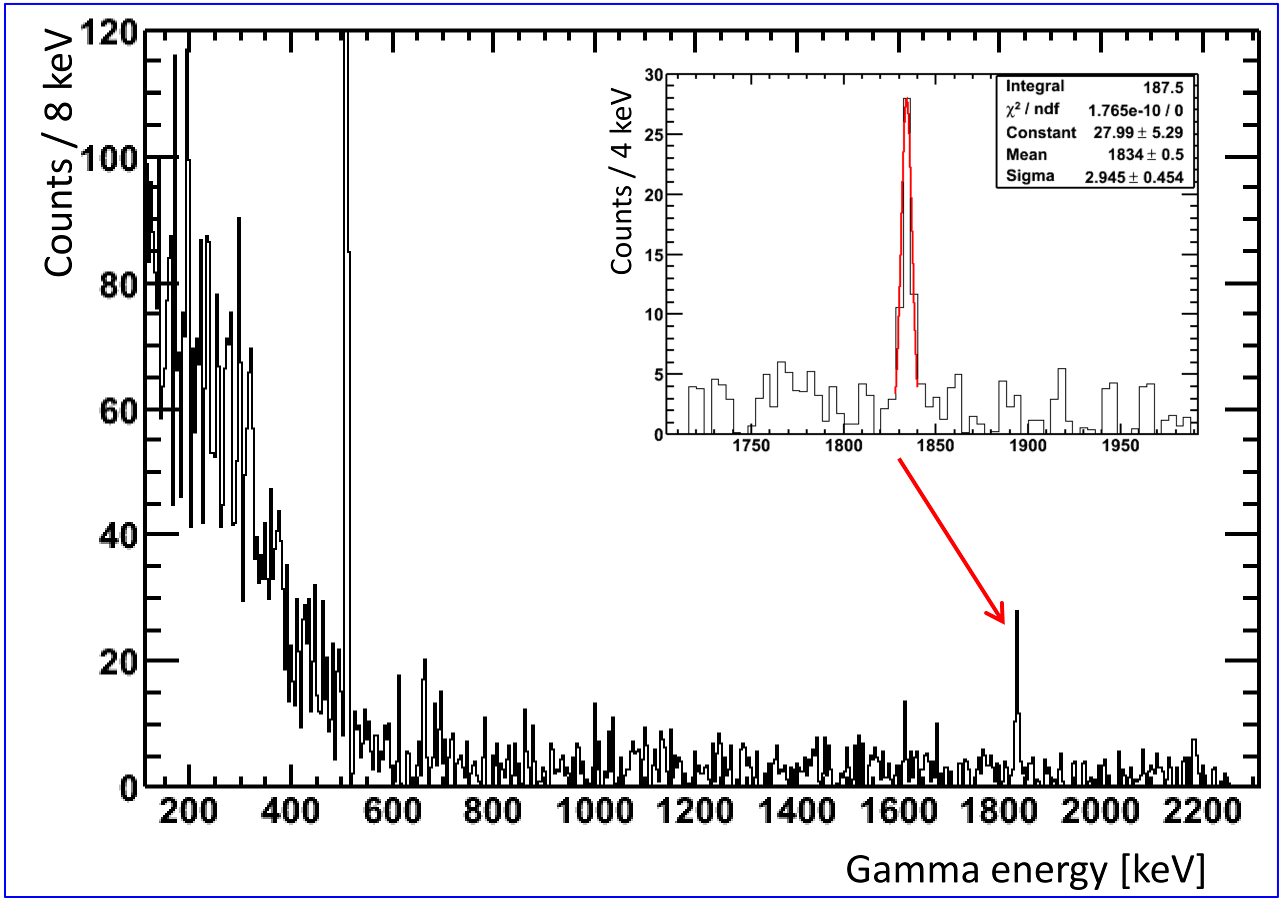


Measured gamma spectrum

- **A γ ray at 1834 keV is observed in the ^{56}Zn correlated γ spectrum corresponding to the de-excitation of the IAS**



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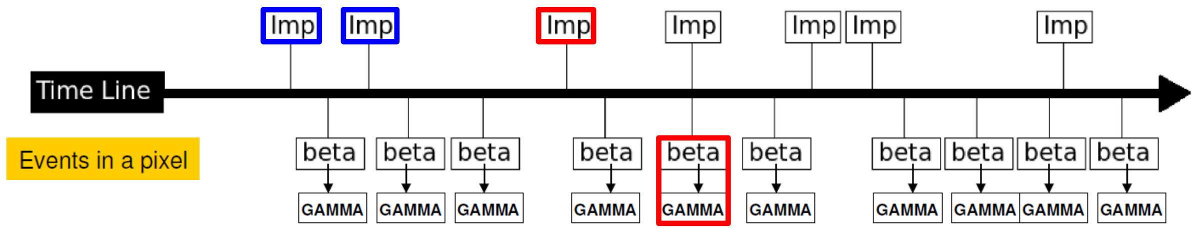
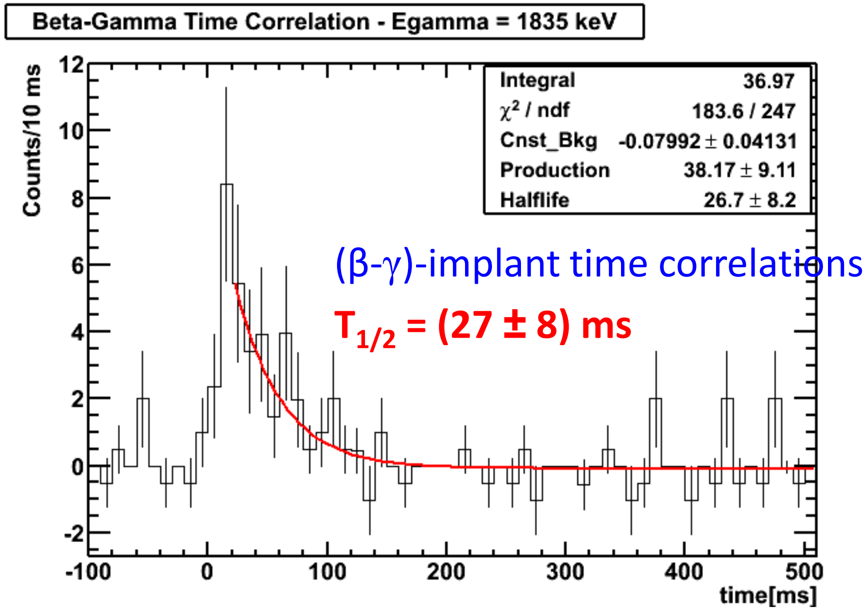
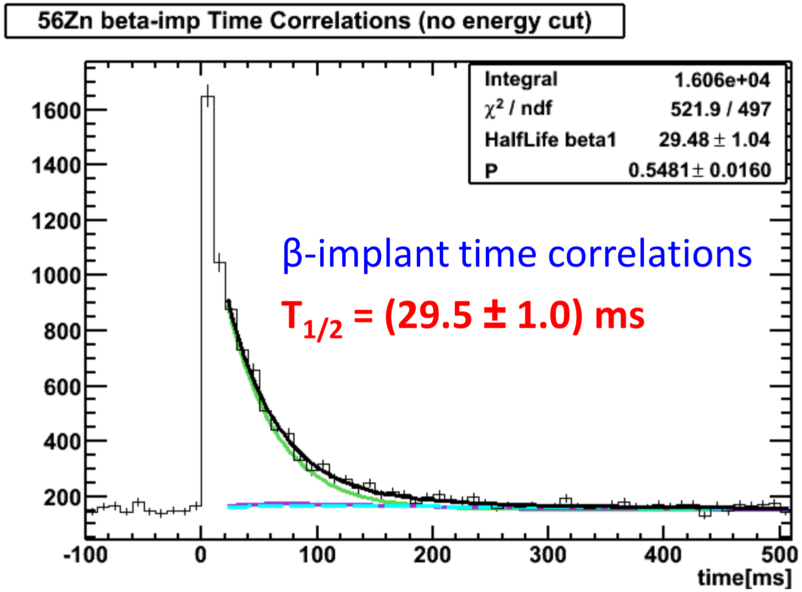
Half-life from (β-γ)-implant correlations

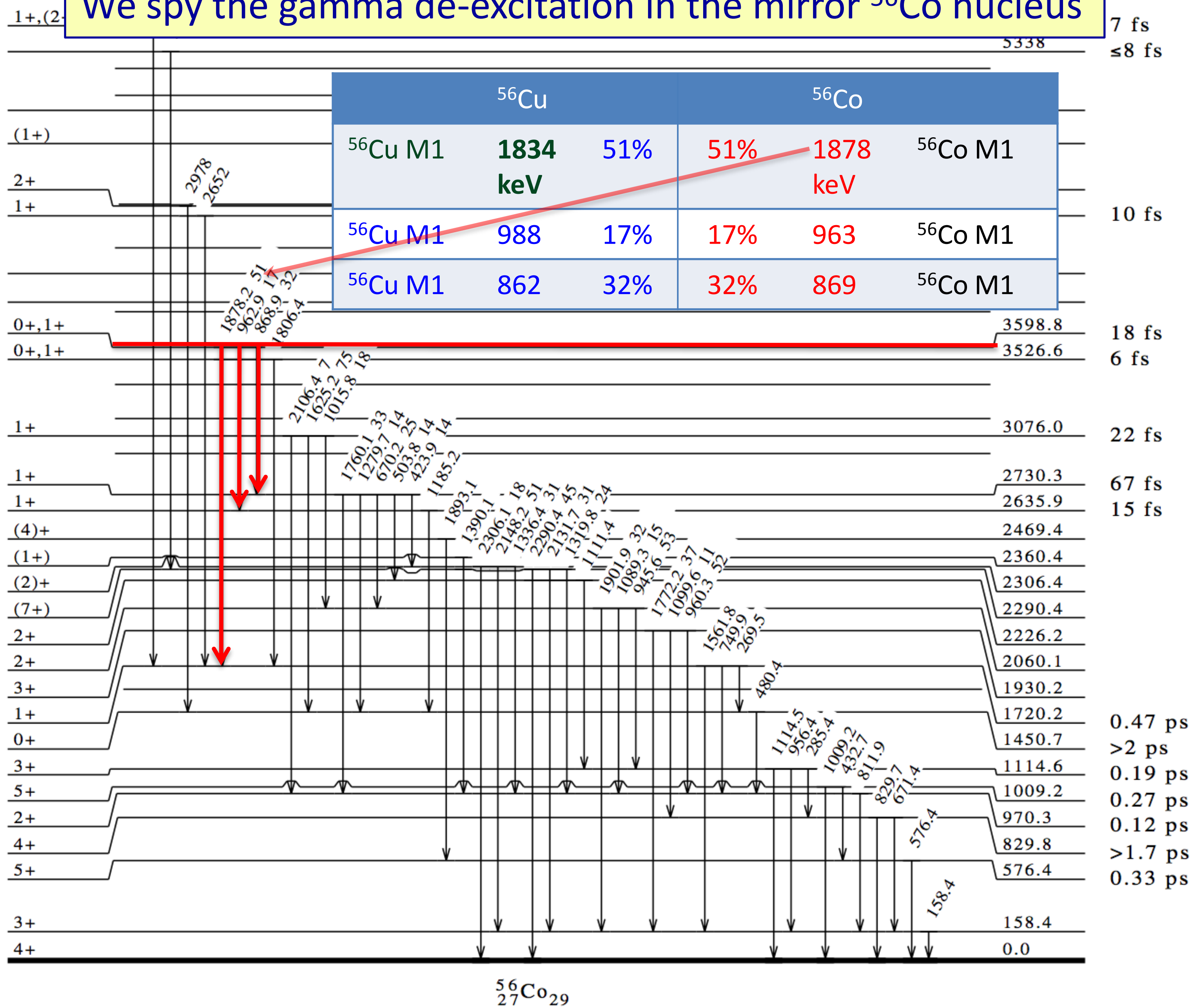
- **Correlating each β-γ event with all the previous implants** in the same pixel, and **selecting the γ peak observed at 1834 keV**, a cross-check of the ^{56}Zn half-life is obtained
- **The $T_{1/2}$ obtained by the two analysis are in good agreement**





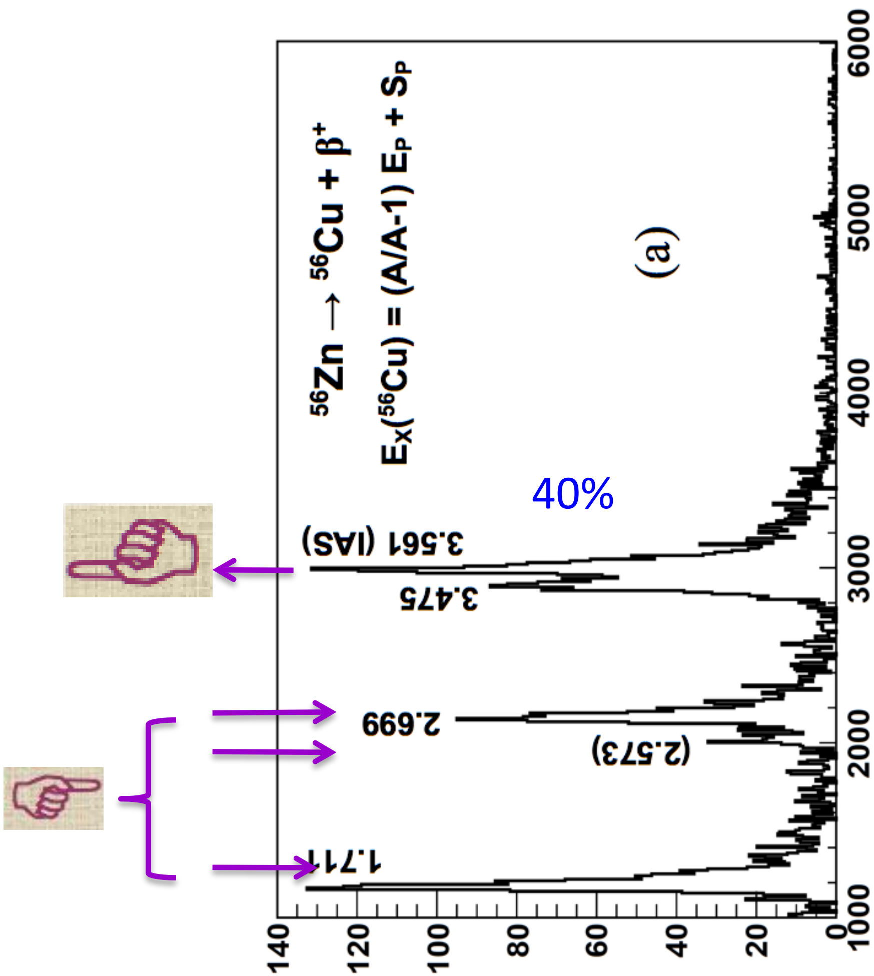


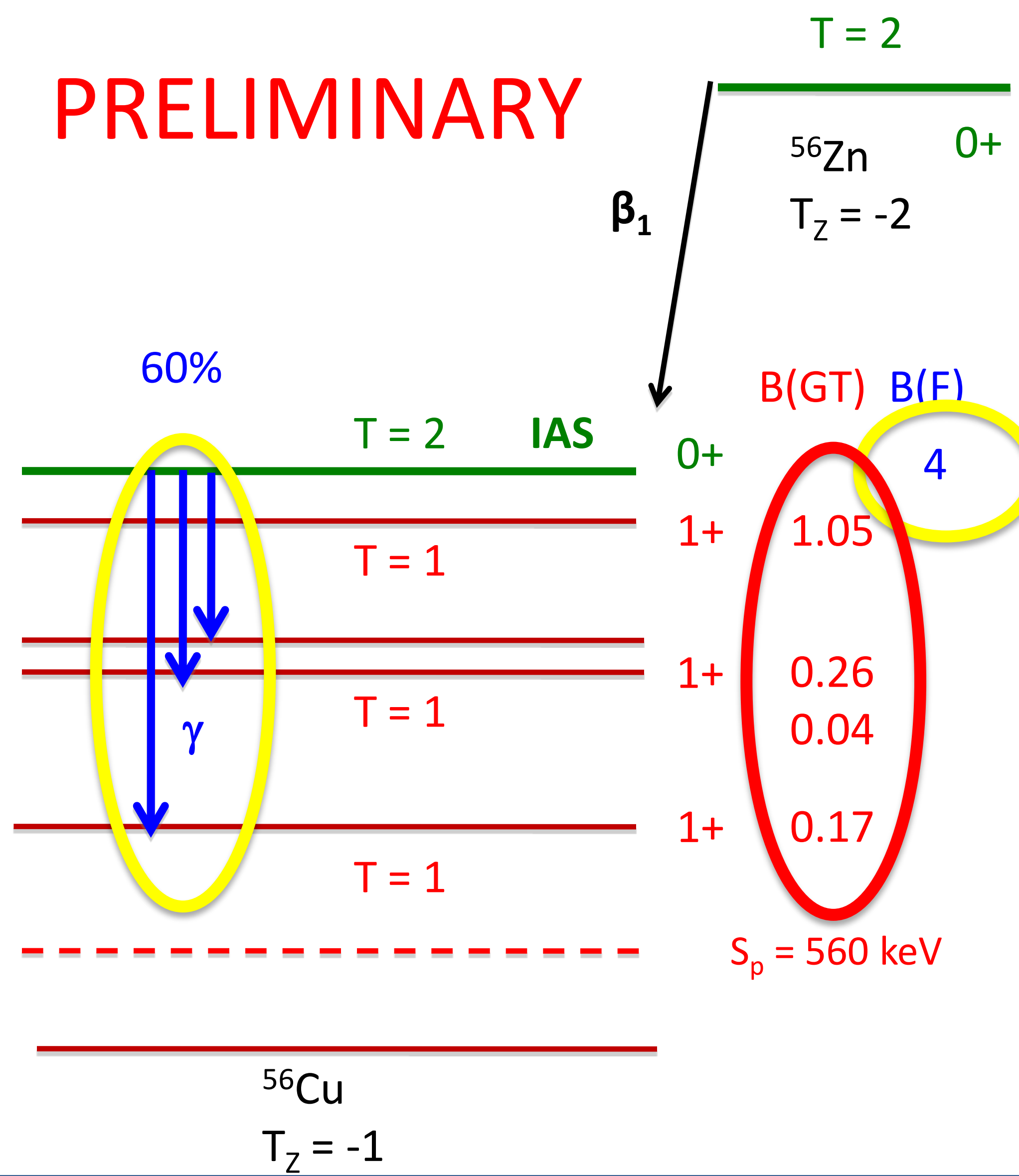
We spy the gamma de-excitation in the mirror ^{56}Co nucleus



^{56}Cu			^{56}Co		
^{56}Cu M1	**1834 keV**	51%	51%	1878 keV	^{56}Co M1
^{56}Cu M1	988	17%	17%	963	^{56}Co M1
^{56}Cu M1	862	32%	32%	869	^{56}Co M1

^{56}Zn decay scheme





- Assuming B(F)=|N – Z|= 4 and gamma de-excitation as in the mirror we can estimate the B(GT)

Summary and Outlook

- **β decay** and **CE reactions** are complementary tools, providing rich spectroscopic information
- **Light neutron-rich nuclei** by **(^{7}Li,^{7}Be)**: structure and reaction mechanism, combined with **β decay**
- **Proton rich-nuclei** by **β decay**: $T_{1/2}$, β feedings, B(GT), combined with the mirror **(^{3}He,t)** CE reaction

- GANIL β-decay experiment: T_z = -1 **^{58}Zn** and T_z = -2 **^{56}Zn** nuclei
- Comparing the **^{56}Zn β^{+} decay** and mirror **^{56}Fe(^{3}He,t)^{56}Co** reaction: **isospin symmetry works well**
- ^{56}Zn: β-delayed protons, β-delayed gammas, **β-delayed gamma-proton decay**
  (this last observation is very exotic and perhaps unique)
- Firm values for **B_j(GT)** will be soon obtained and then compared with the mirror case
- Heavier and even more exotic nuclei will be studied at RIKEN in 2013: T_z = -1 **^{62}Ge** and **^{66}Se**,
  T_z = -2 **^{60}Ge** and **^{64}Se**

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☺ Thank you for your attention! ☺