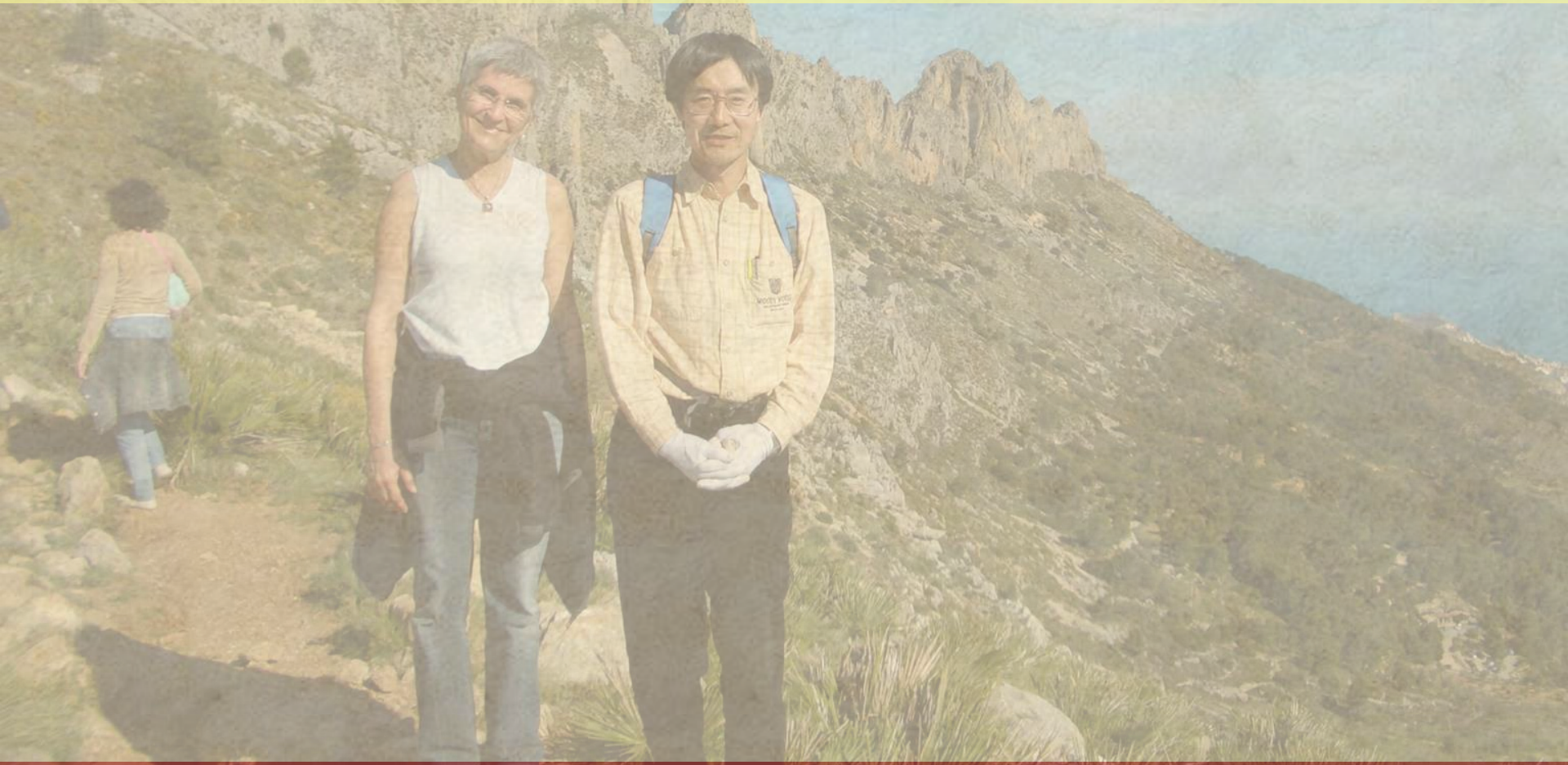
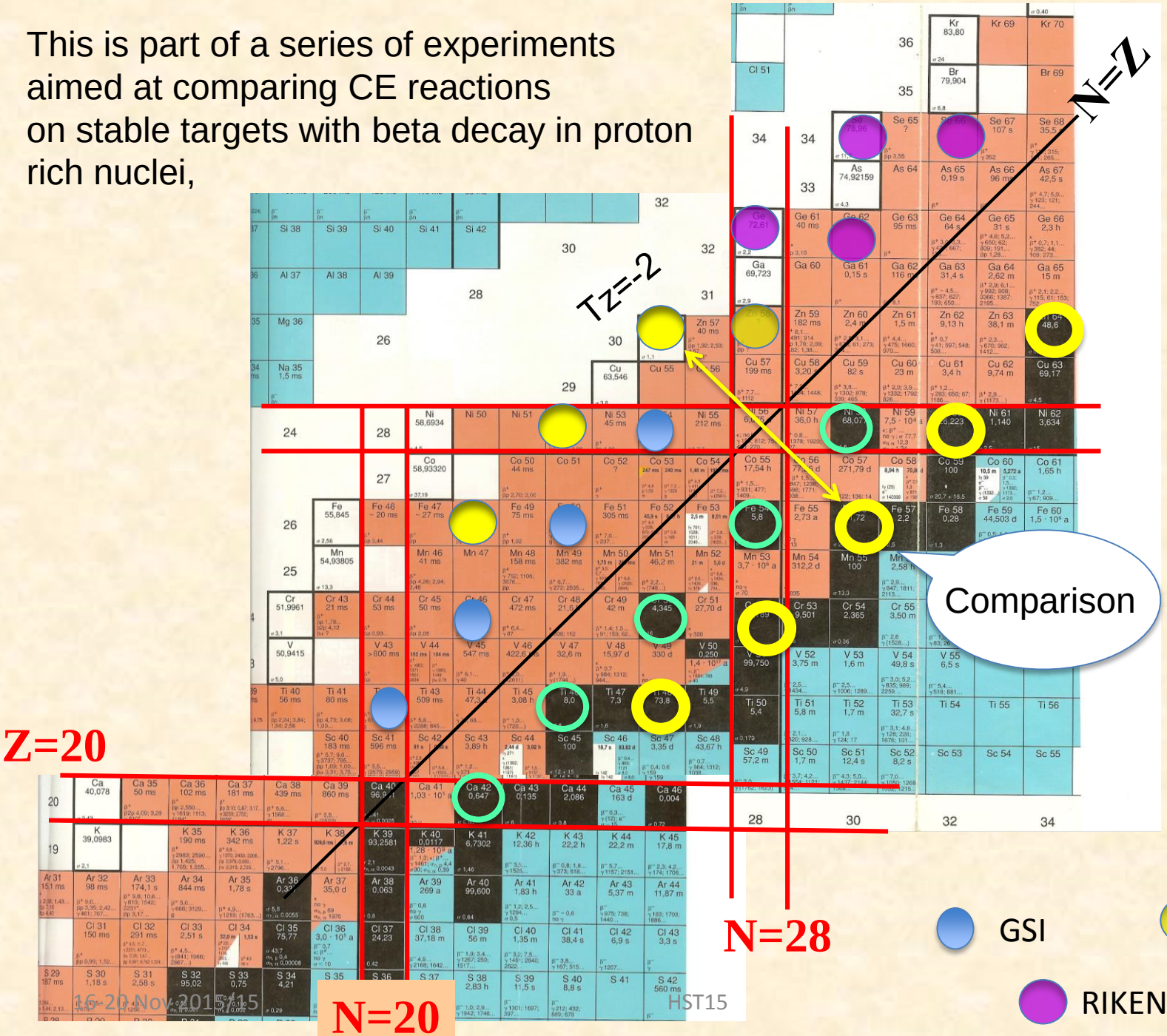
# Beta decay and Charge Exchange reactions, shedding light on mirror symmetry

B. Rubio (IFIC Valencia, Y. Fujita (RCNP-Un.Osaka) and many others



This is part of a series of experiments aimed at comparing CE reactions on stable targets with beta decay in proton rich nuclei,



AIZU2002

Some years ago……

Beta decay

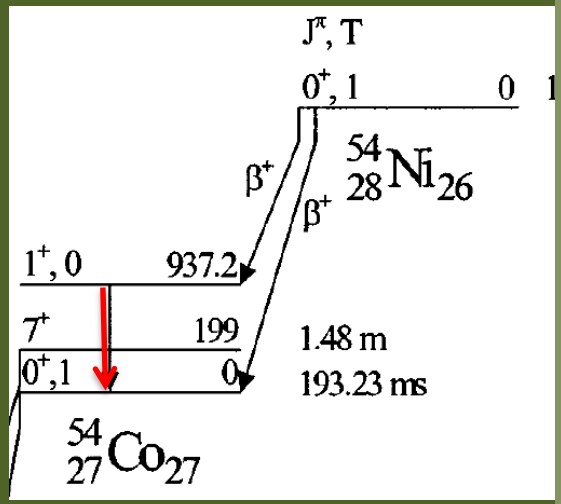
Charge Exchange Reactions

target

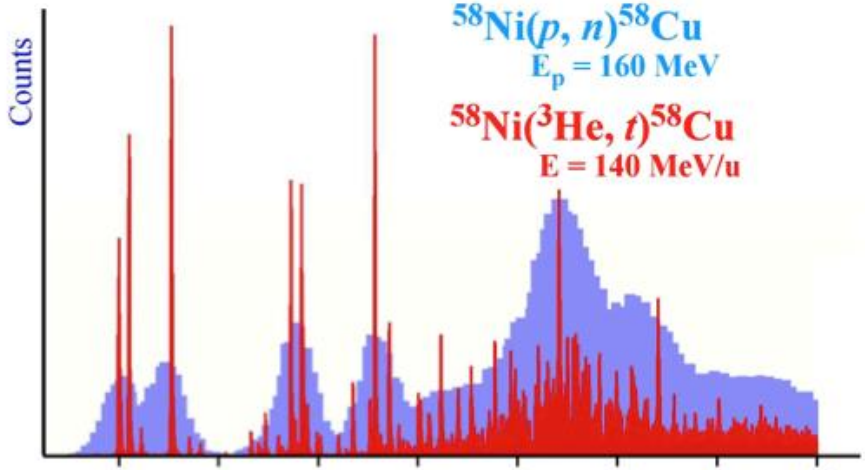
PHYSICAL REVIEW C VOLUME 59, NUMBER 5

**β-decay study of $^{54,55}$Ni produced by an element-**

I. Reusen, A. Andreyev,* J. Andrzejewski,† N. Bijnens, S. Franchoo, M
W. F. Mueller, A. Piechaczek,‡ R. Raabe, K. Rykaczewski,§,‖ J. Sze
J. Wauters,** and A. Wöhr††
*Instituut voor Kern- en Stralingsfysica, University of Leuven, Celestijne*




RCNP experiments at Osaka

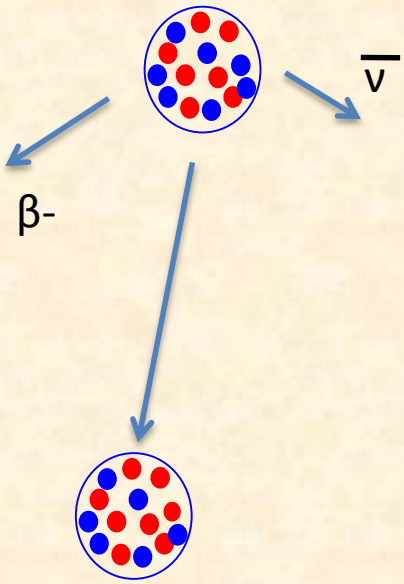


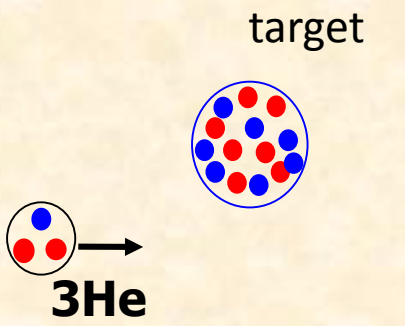
Beta decay

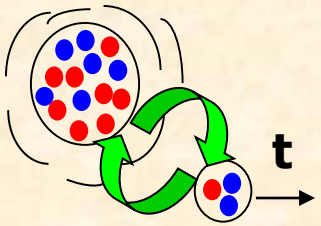
$$B(GT) = \left| \langle y_f | \sum_m \sum_k s_k^m t_k^{\pm} | y_i \rangle \right|^2$$

$$B(F) = \left| \langle y_f | t^{\pm} | y_i \rangle \right|^2$$

Charge Exchange Reactions




Beta Decay: Absolute Normalization of B(GT).

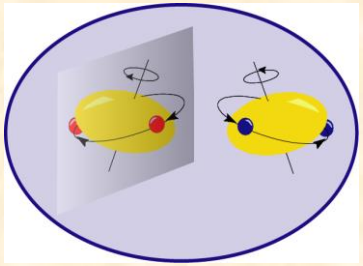
CE reactions: No restriction in excitation energy of Gamow-Teller states.

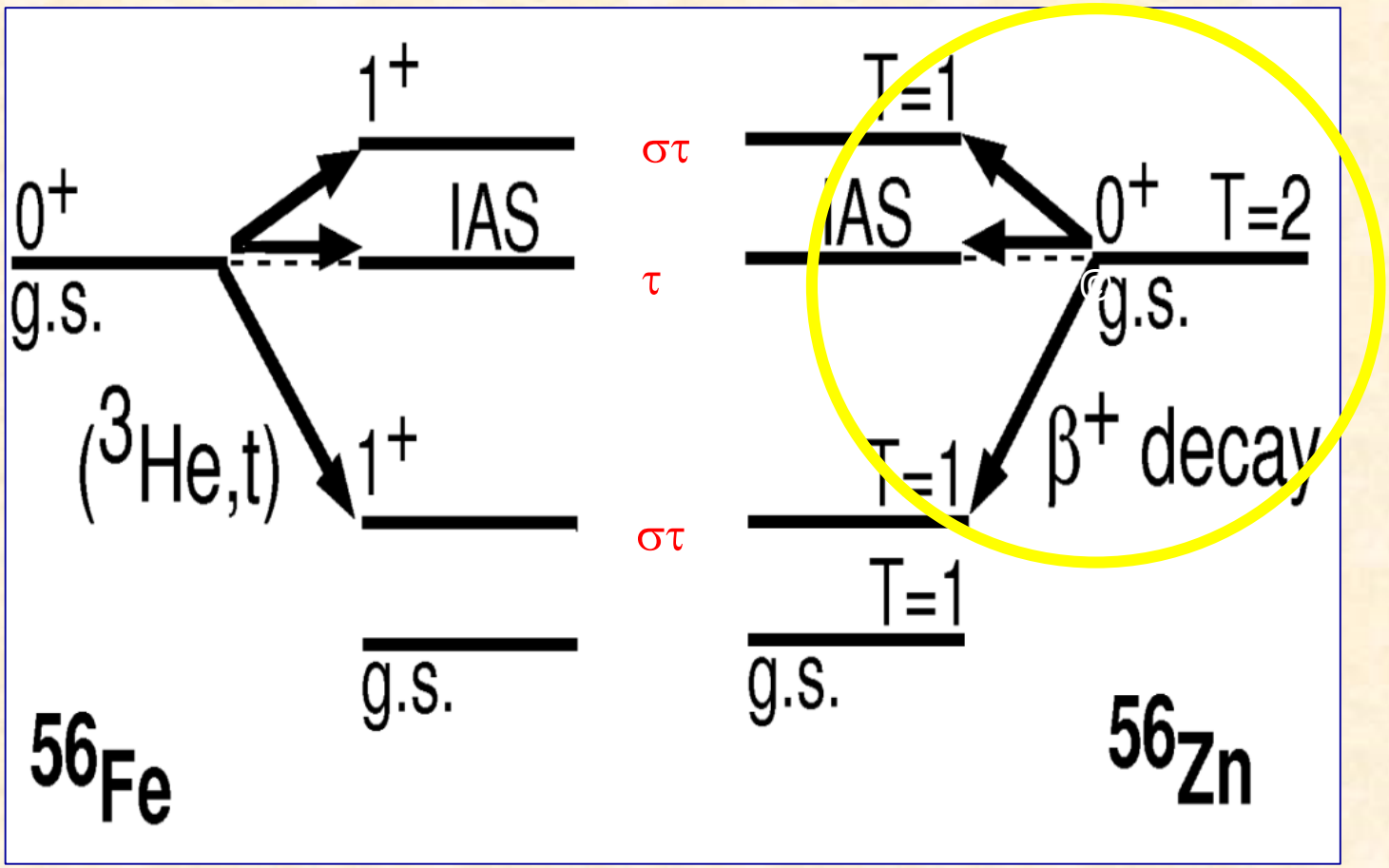
PRL 95, 212501 (2005) PHYSICAL REVIEW LETTERS week ending 18 NOVEMBER 2005

# Gamow-Teller Strengths in Proton-Rich Exotic Nuclei Deduced in the Combined Analysis of Mirror Transitions

Y. Fujita,[1,*] T. Adachi,[1] P. von Brentano,[2] G. P. A. Berg,[3,†] C. Fransen,[2] D. De Frenne,[4] H. Fujita,[1,‡] K. Fujita,[5] K. Hatanaka,[5] E. Jacobs,[4] K. Nakanishi,[5] A. Negret,[4,§] N. Pietralla,[2] L. Popescu,[4,§] B. Rubio,[6] Y. Sakemi,[5] Y. Shimbara,[1,‖] Y. Shimizu,[5] Y. Tameshige,[5] A. Tamii,[5] M. Yosoi,[5] and K. O. Zell[2]

*If isospin symmetry exists, mirror nuclei should populate the similar states in the daughter nucleus, with the same probability, in the two mirror processes*





Theoretically

$$B(GT) = \left| \langle y_f | \sum_m \sum_k s_k^m t_k^{\pm} | y_i \rangle \right|^2$$

$$B(F) = \left| \langle y_f | t^{\pm} | y_i \rangle \right|^2$$

Experimentally
Charge Exchange

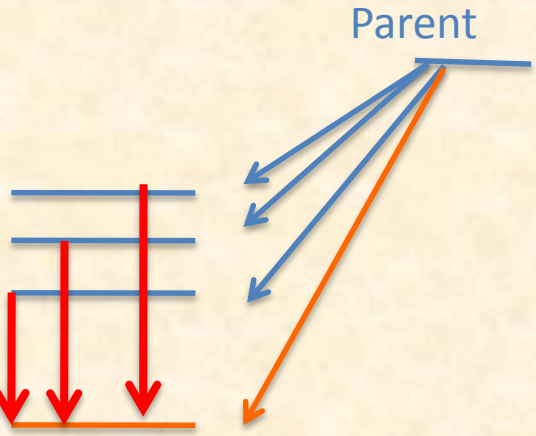
$$B(GT,F)^{CE} \propto \frac{d\sigma}{d\Omega}(0^o)$$

Experimentally
Beta-decay

Beta feeding to states
in the daughter nucleus

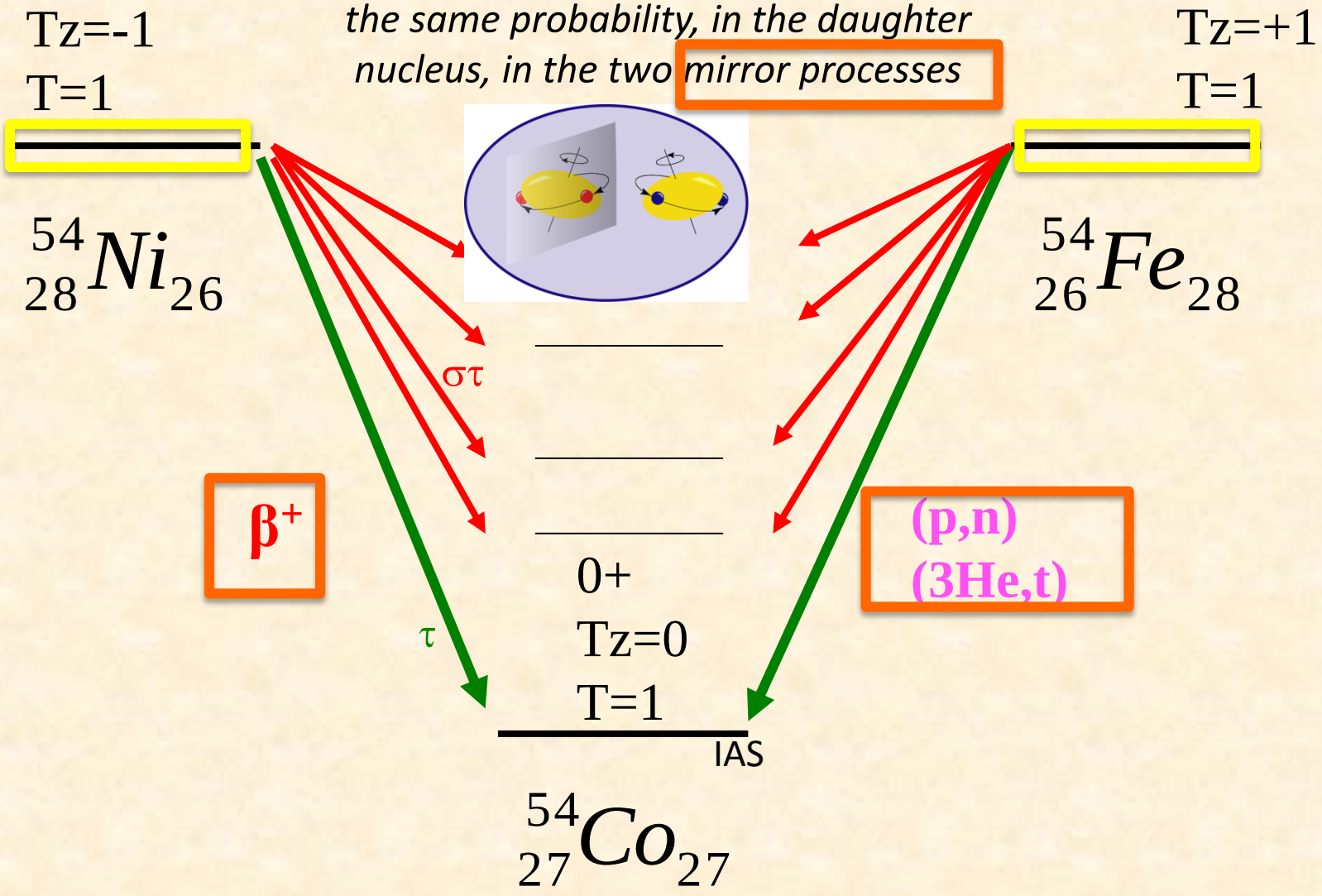
$$B(GT,F)^{\beta} \propto \frac{I_\beta(E)}{f(Q_\beta - E, Z)T_{1/2}}$$

Parent beta half life

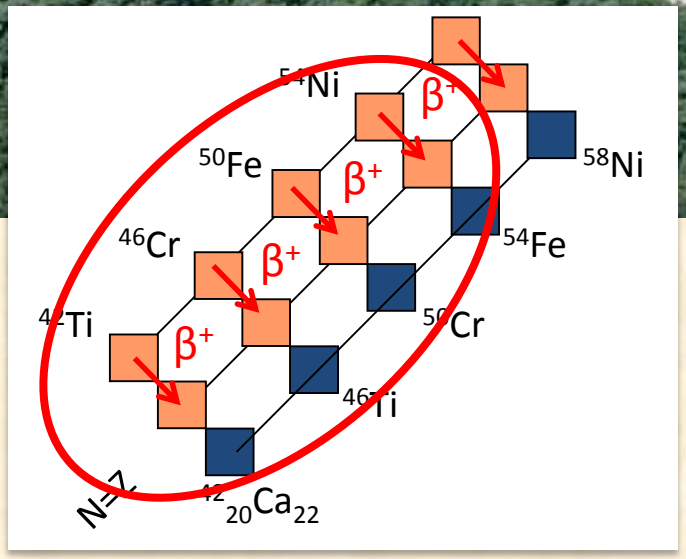


*We could compare them in mirror nuclei*

*If isospin symmetry exists, mirror nuclei should populate the same states with the same probability, in the daughter nucleus, in the two mirror processes*



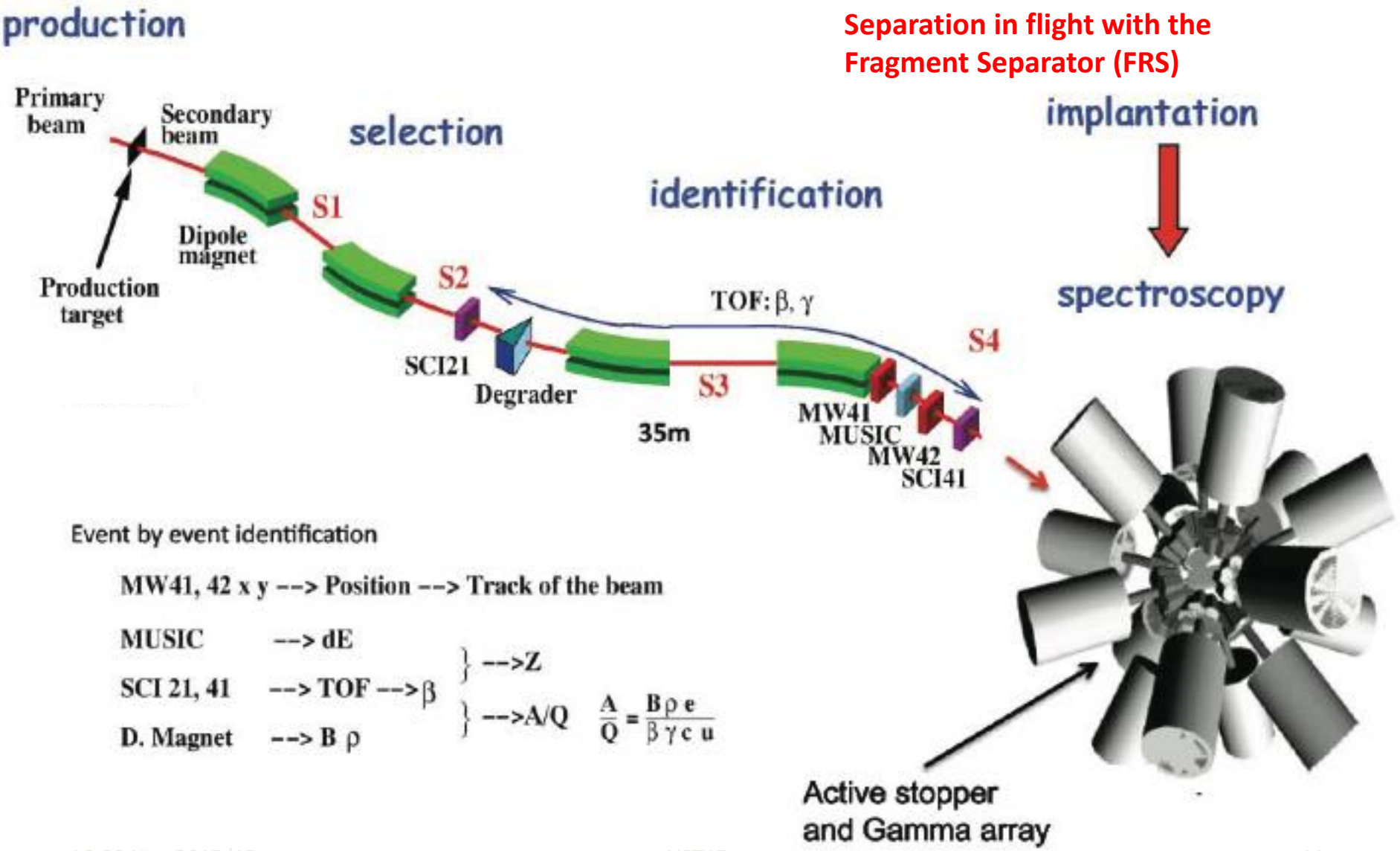
The first experiments on Tz=-1 nuclei were carried out at the GSI Large Scale Facility



# Beta Decay Experiments @ RISING

**Beam 58Ni@680 MeV/u $10^9$ pps (part per spill) Target Be 4g/cm2**

**Separation in flight with the Fragment Separator (FRS)**




Event by event identification

MW41, 42 x y --> Position --> Track of the beam

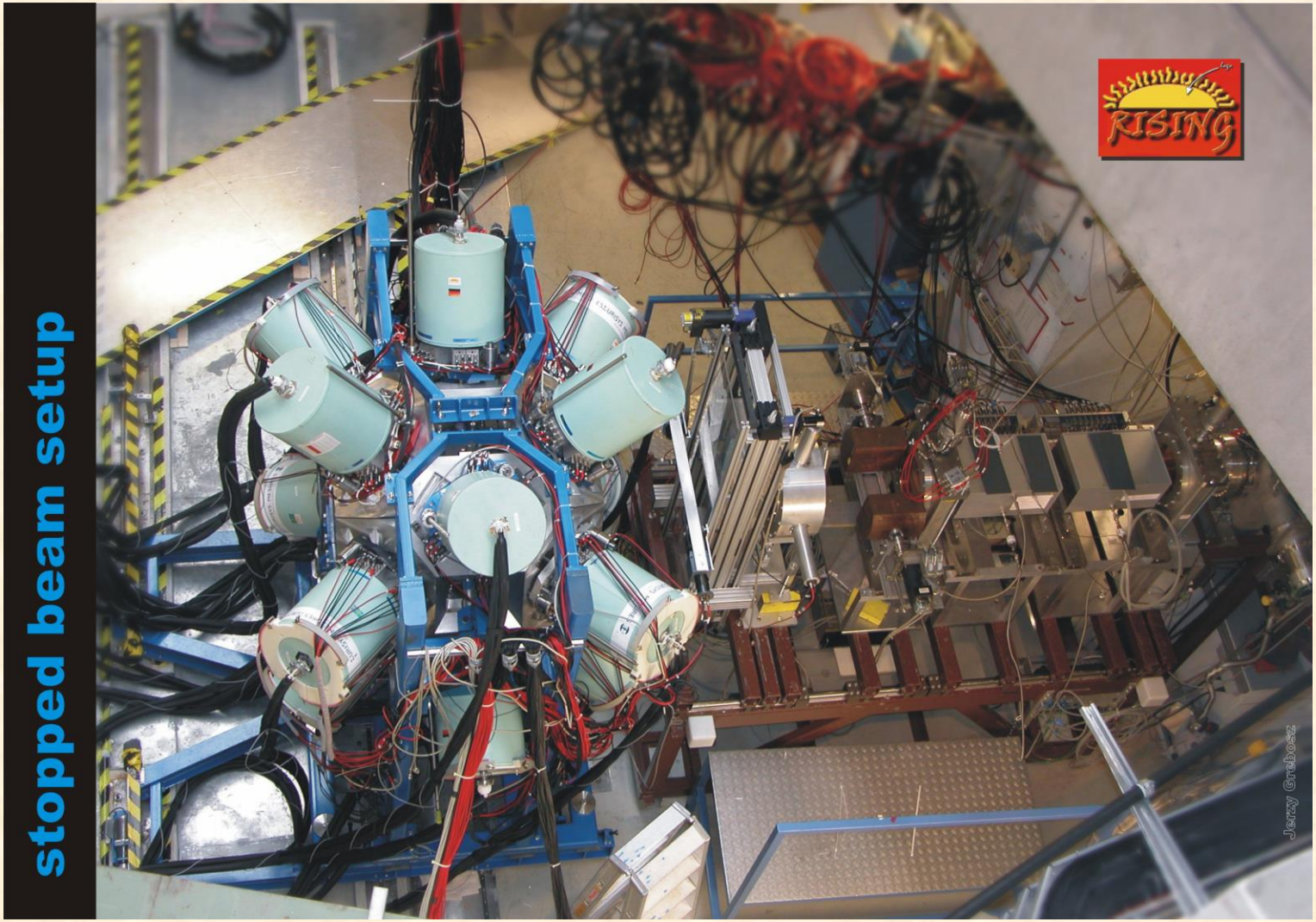
MUSIC --> dE

SCI 21, 41 --> TOF --> β } -->Z

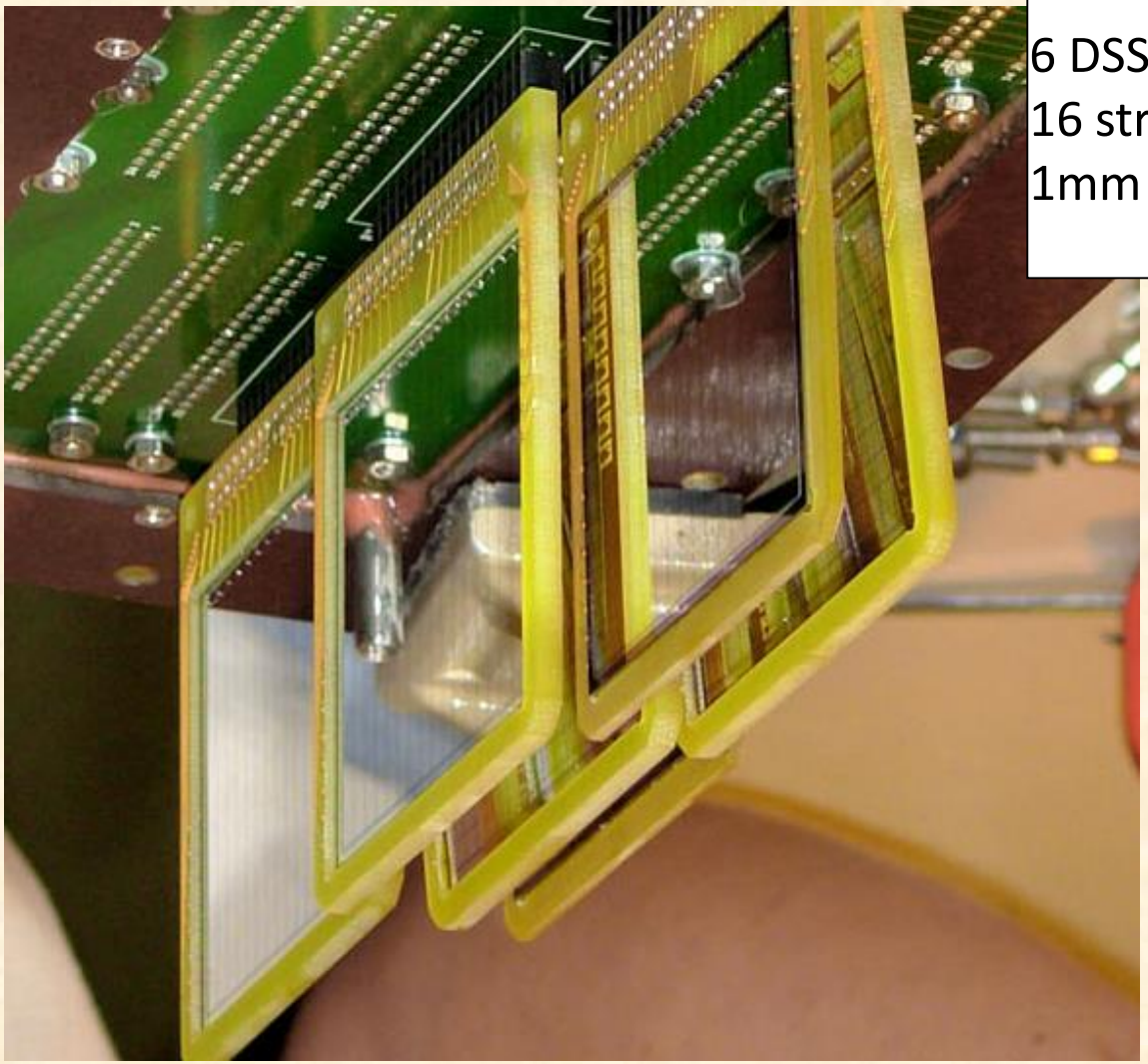
D. Magnet --> B ρ } -->A/Q

$$\frac{A}{Q} = \frac{B\rho e}{\beta \gamma c u}$$

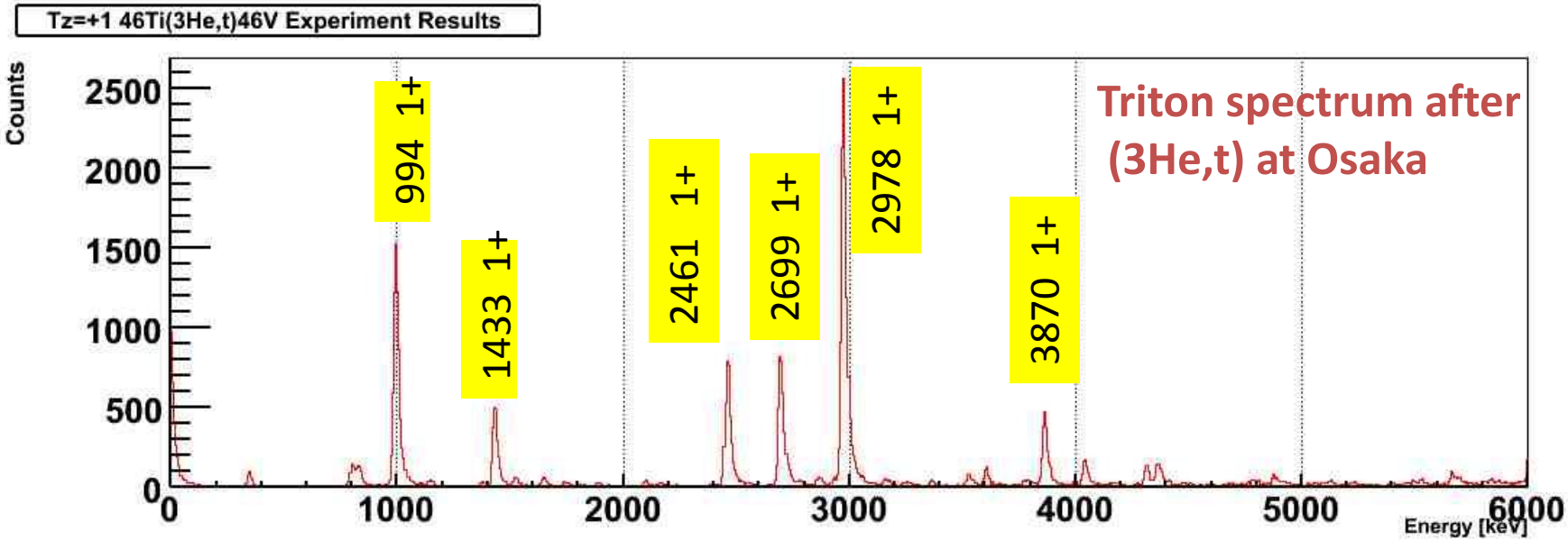
# RISING (Ge Array)

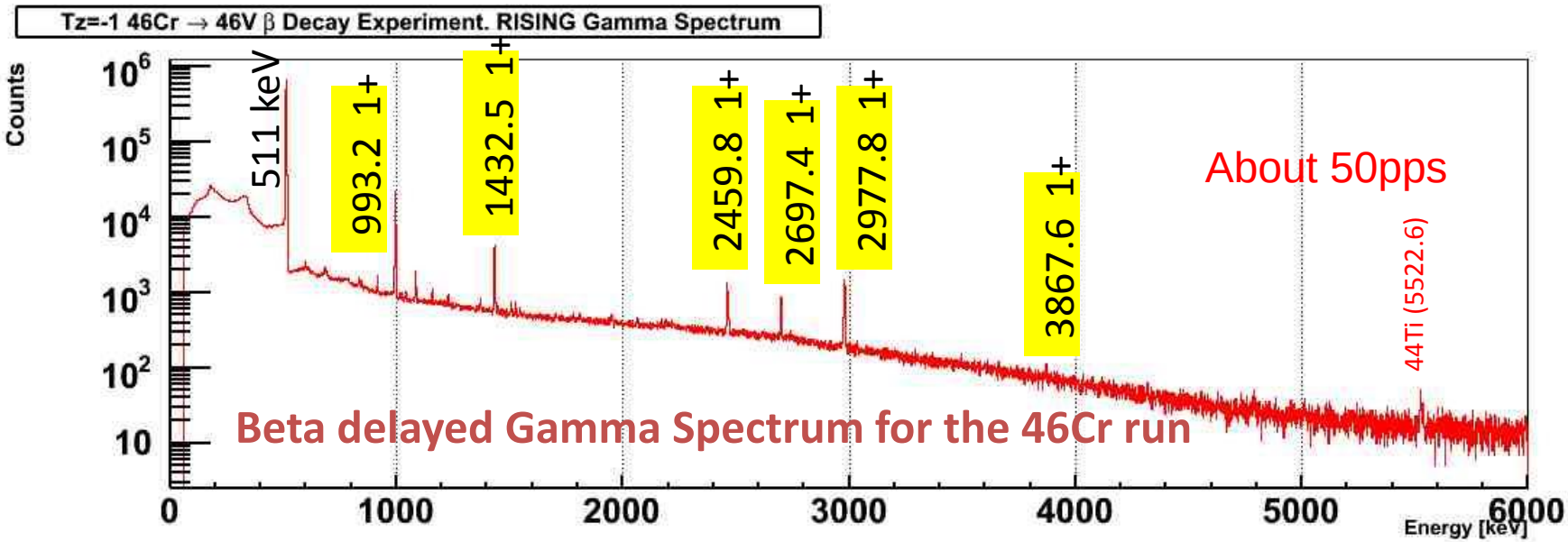


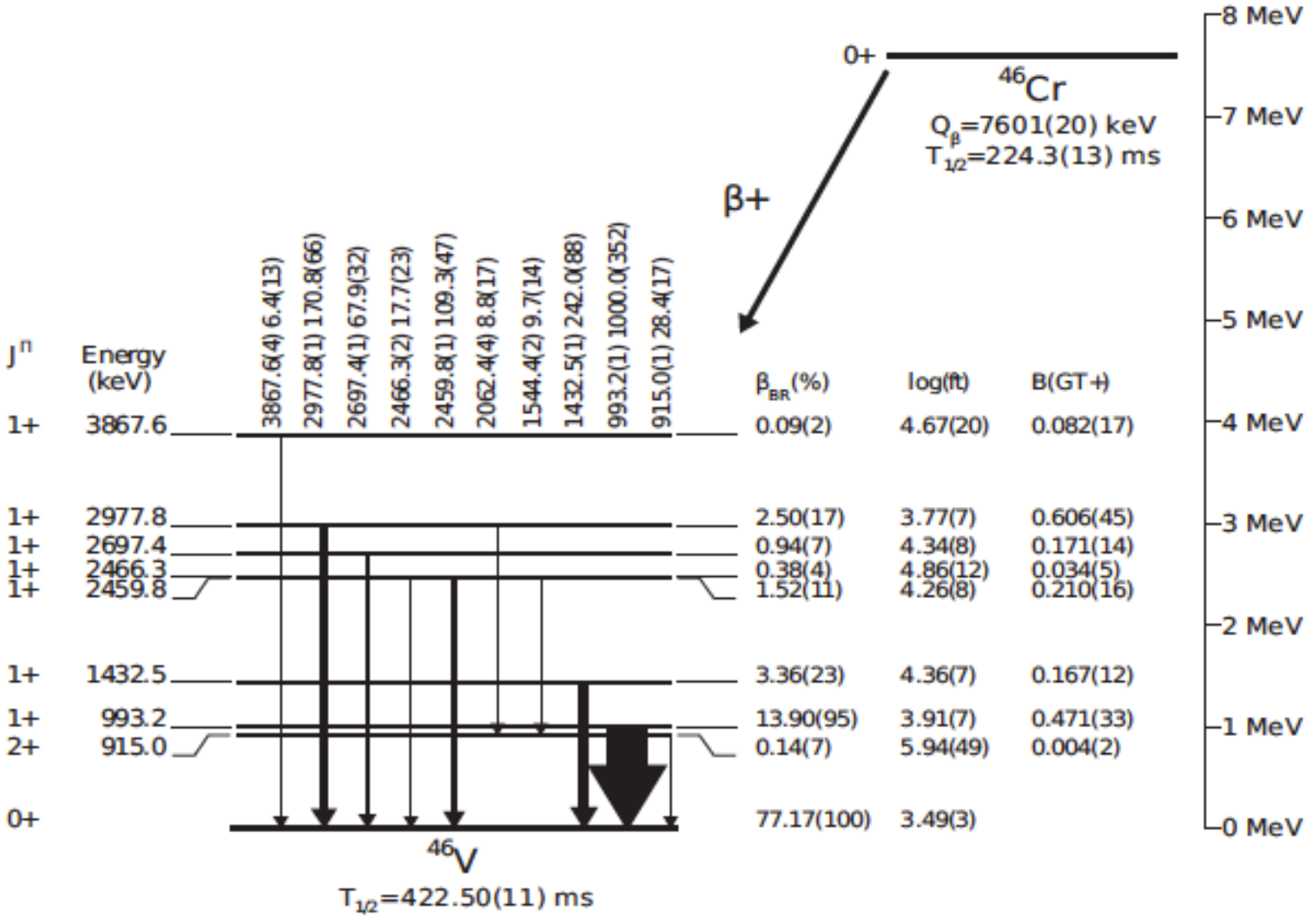
# Detector Setup (Rising and DSSSD)

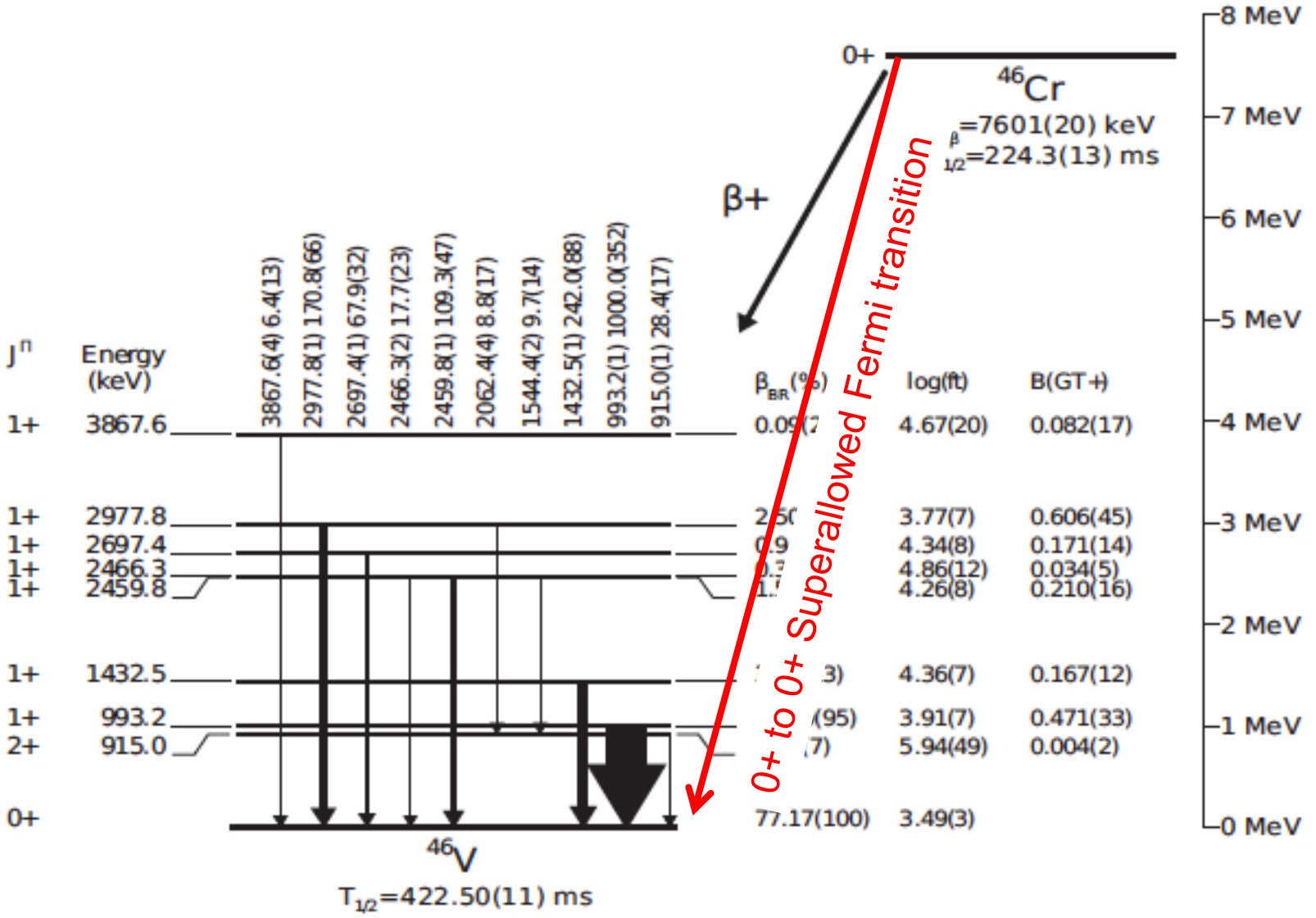


6 DSSSD detectors 1mm with 16 strips X and 16 strips Y, 1mm thick, 5 x 5 cm area


Tz=+1 46Ti(3He,t)46V Experiment Results
Counts
994 1+
1433 1+
2461 1+
2699 1+
2978 1+
3870 1+
Triton spectrum after (3He,t) at Osaka
Energy [keV]


Tz=-1 46Cr → 46V β Decay Experiment. RISING Gamma Spectrum
Counts
511 keV
993.2 1+
1432.5 1+
2459.8 1+
2697.4 1+
2977.8 1+
3867.6 1+
About 50pps
44Ti (5522.6)
Beta delayed Gamma Spectrum for the 46Cr run
Energy [keV]


0+
$^{46}$Cr
$Q_\beta$=7601(20) keV
$T_{1/2}$=224.3(13) ms
β+
8 MeV
7 MeV
6 MeV
5 MeV
4 MeV
3 MeV
2 MeV
1 MeV
0 MeV
3867.6(4) 6.4(13)
2977.8(1) 170.8(66)
2697.4(1) 67.9(32)
2466.3(2) 17.7(23)
2459.8(1) 109.3(47)
2062.4(4) 8.8(17)
1544.4(2) 9.7(14)
1432.5(1) 242.0(88)
993.2(1) 1000.0(352)
915.0(1) 28.4(17)
Jπ
Energy (keV)
$\beta_{BR}$(%)
log(ft)
B(GT+)
1+ 3867.6 0.09(2) 4.67(20) 0.082(17)
1+ 2977.8 2.50(17) 3.77(7) 0.606(45)
1+ 2697.4 0.94(7) 4.34(8) 0.171(14)
1+ 2466.3 0.38(4) 4.86(12) 0.034(5)
1+ 2459.8 1.52(11) 4.26(8) 0.210(16)
1+ 1432.5 3.36(23) 4.36(7) 0.167(12)
1+ 993.2 13.90(95) 3.91(7) 0.471(33)
2+ 915.0 0.14(7) 5.94(49) 0.004(2)
0+ 77.17(100) 3.49(3)
$^{46}$V
$T_{1/2}$=422.50(11) ms


0+
$^{46}$Cr
$Q_\beta$=7601(20) keV
$T_{1/2}$=224.3(13) ms
β+
0+ to 0+ Superallowed Fermi transition
8 MeV
7 MeV
6 MeV
5 MeV
4 MeV
3 MeV
2 MeV
1 MeV
0 MeV
Jⁿ
Energy (keV)
3867.6(4) 6.4(13)
2977.8(1) 170.8(66)
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2466.3(2) 17.7(23)
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993.2(1) 1000.0(352)
915.0(1) 28.4(17)
$\beta_{BR}$(%)
log(ft)
B(GT+)
1+ 3867.6 0.09(7) 4.67(20) 0.082(17)
1+ 2977.8 2.6( 3.77(7) 0.606(45)
1+ 2697.4 0.9 4.34(8) 0.171(14)
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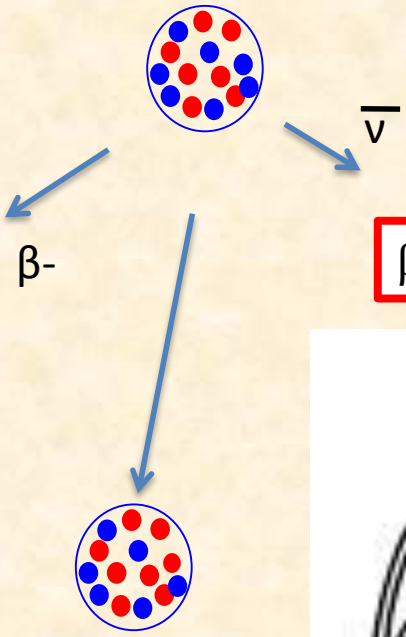
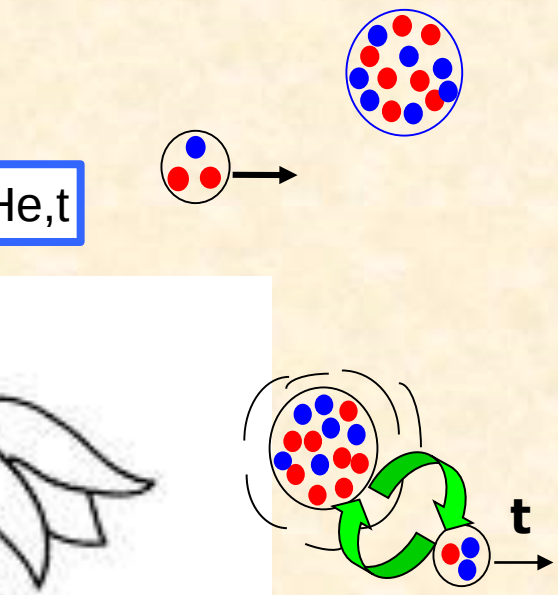
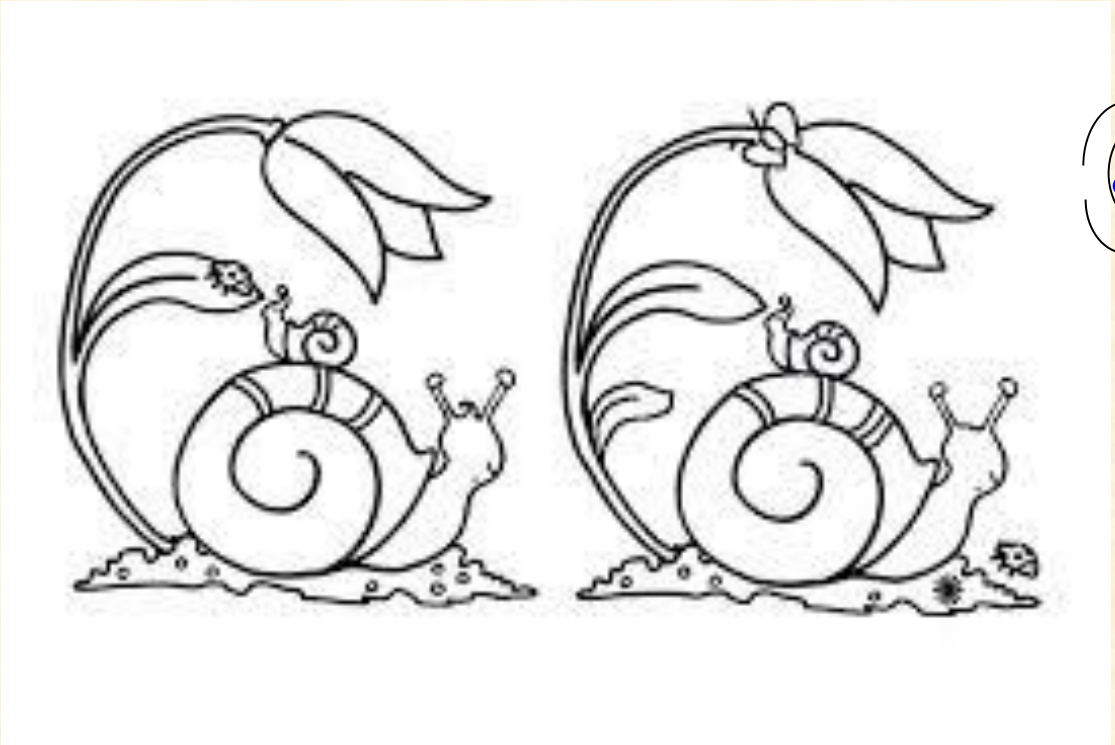
$^{46}$V
$T_{1/2}$=422.50(11) ms



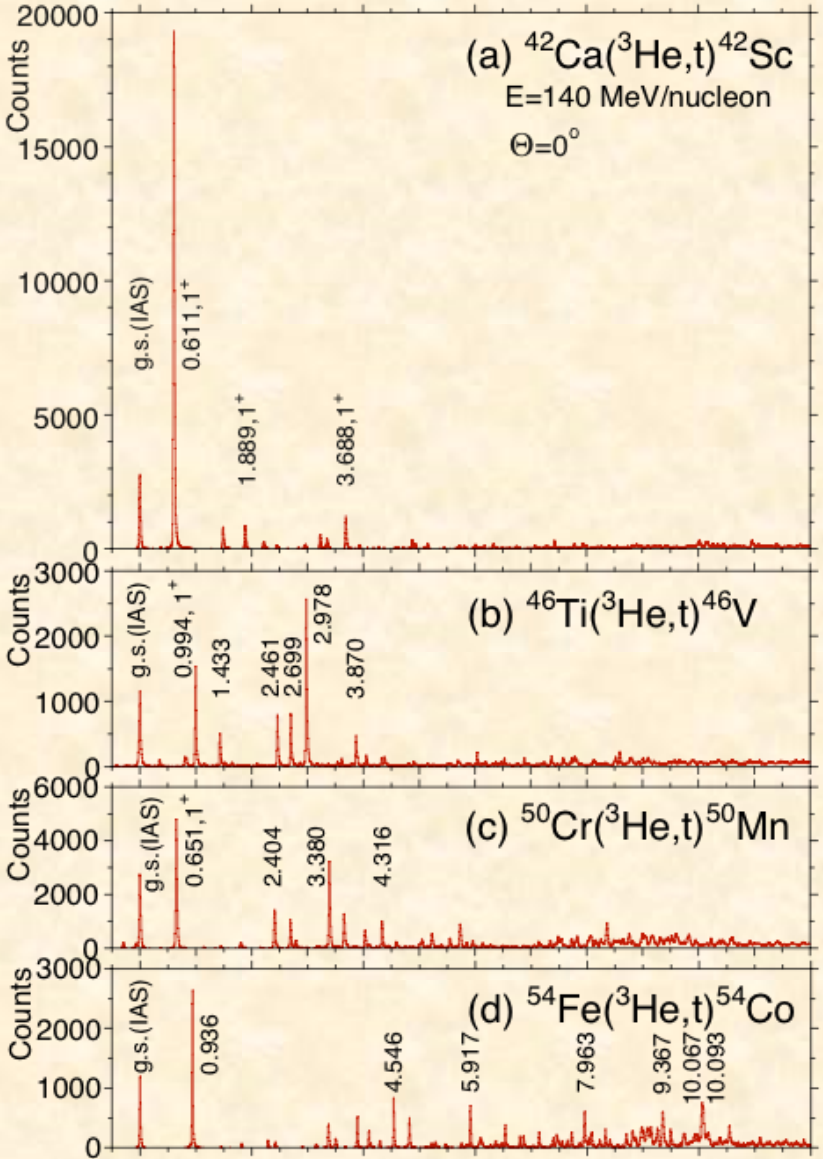

Are they really identical?

β–decay



Find the difference




PRL **112,** 112502 (2014) PHYSICAL REVIEW LETTERS week ending 21 MARCH 2014

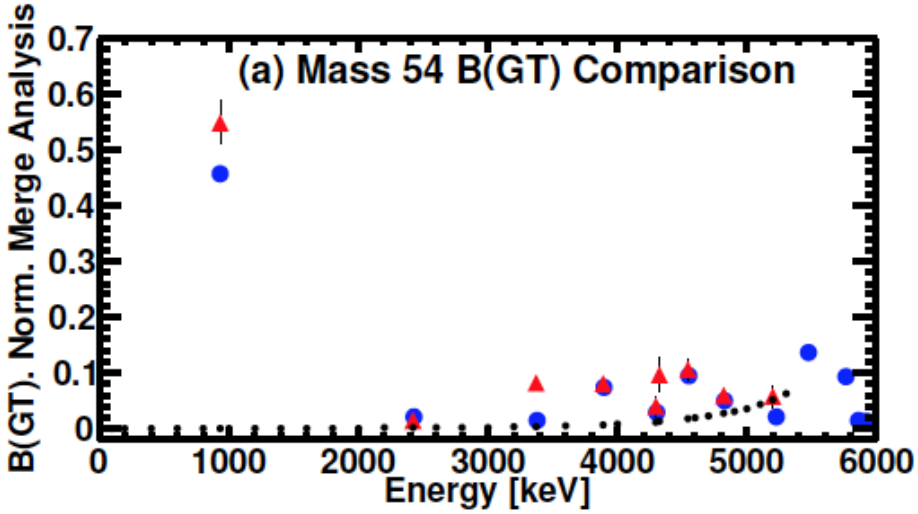
# Observation of Low- and High-Energy Gamow-Teller Phonon Excitations in Nuclei

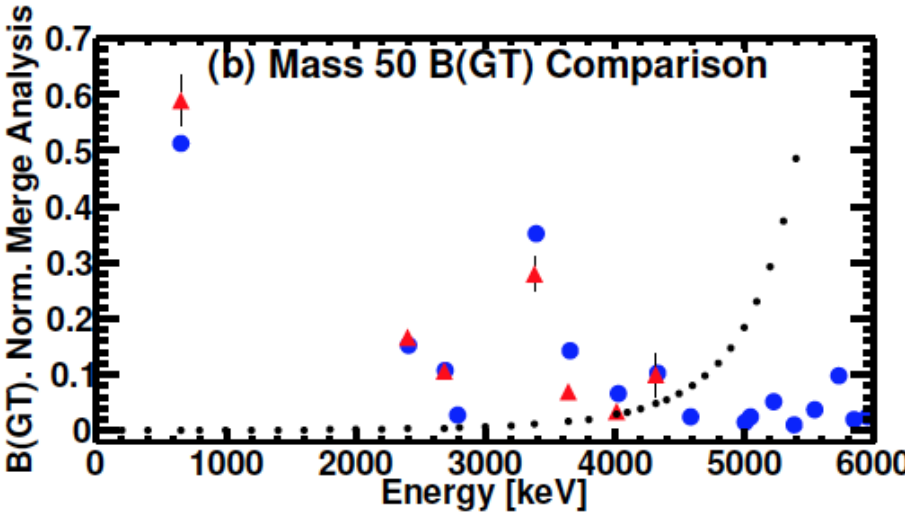
Y. Fujita,[1,2,†] H. Fujita,[1] T. Adachi,[1] C. L. Bai,[3] A. Algora,[4,5] G. P. A. Berg,[6] P. von Brentano,[7] G. Colò,[8] M. Csatlós,[5]

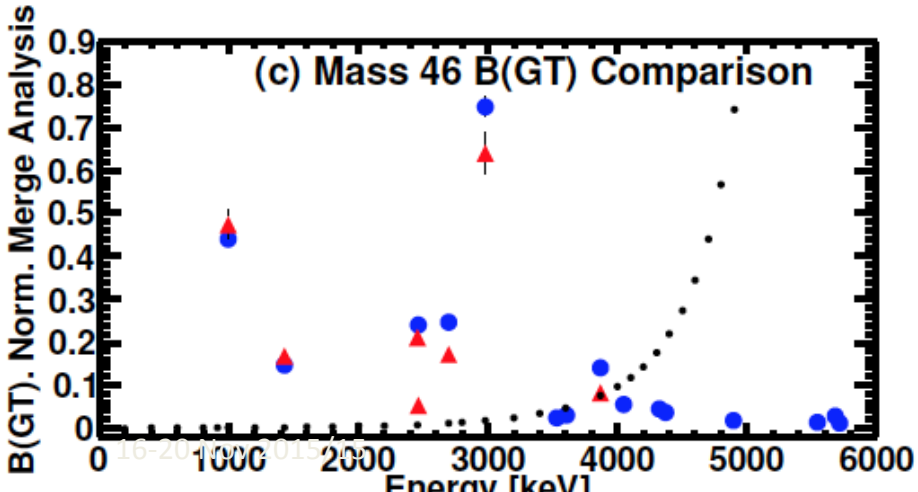
Comparison including sensitivity limit!

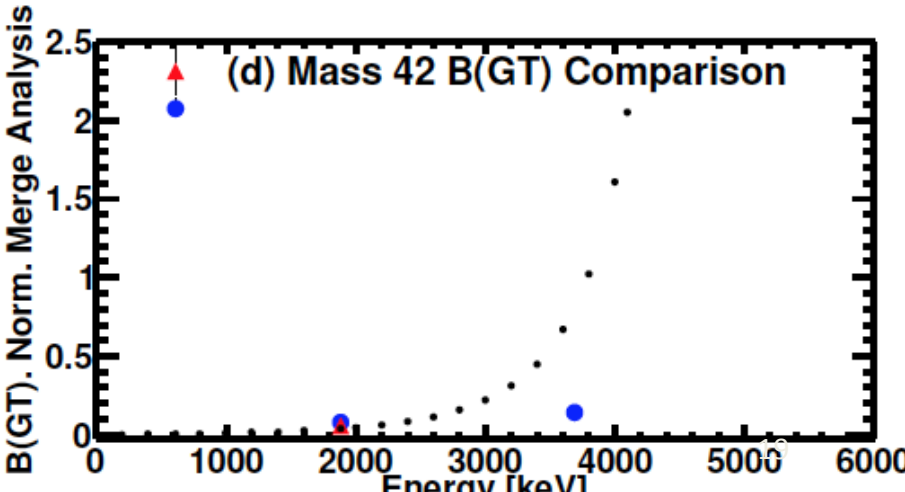
β–decay

3He,t



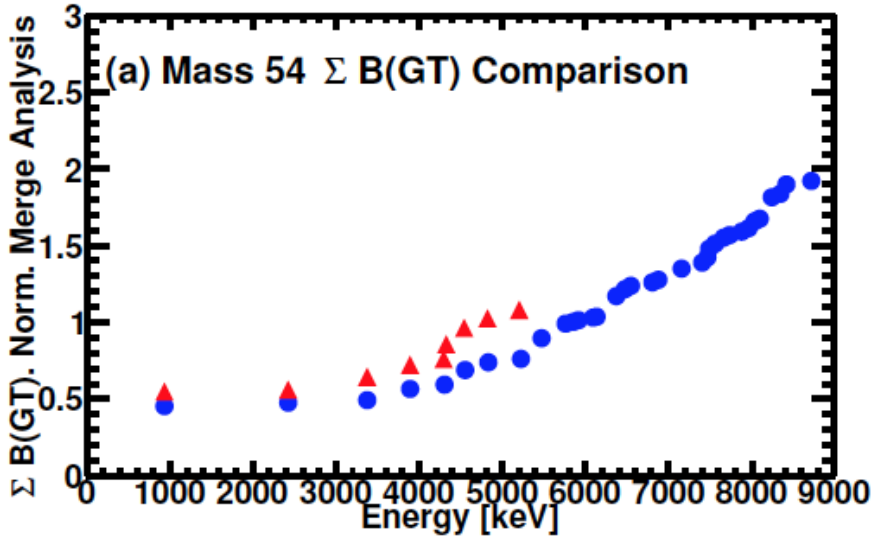



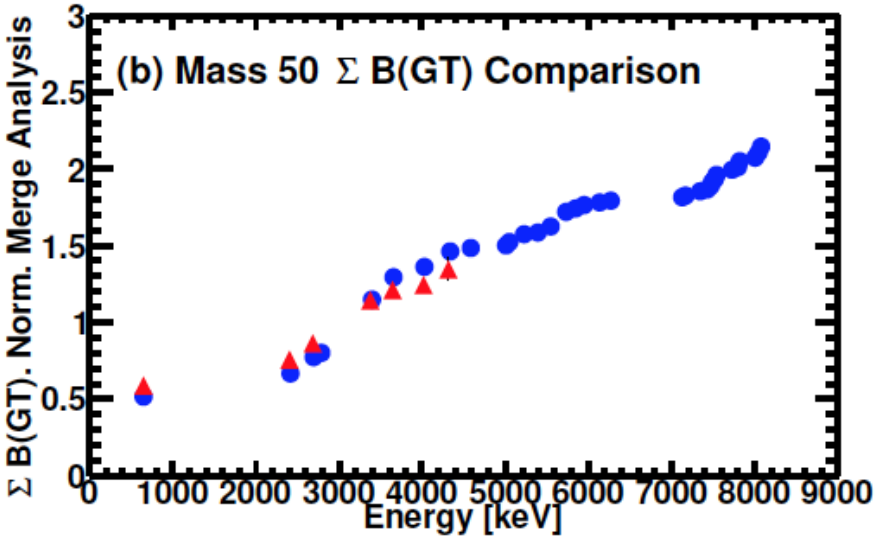
β–decay

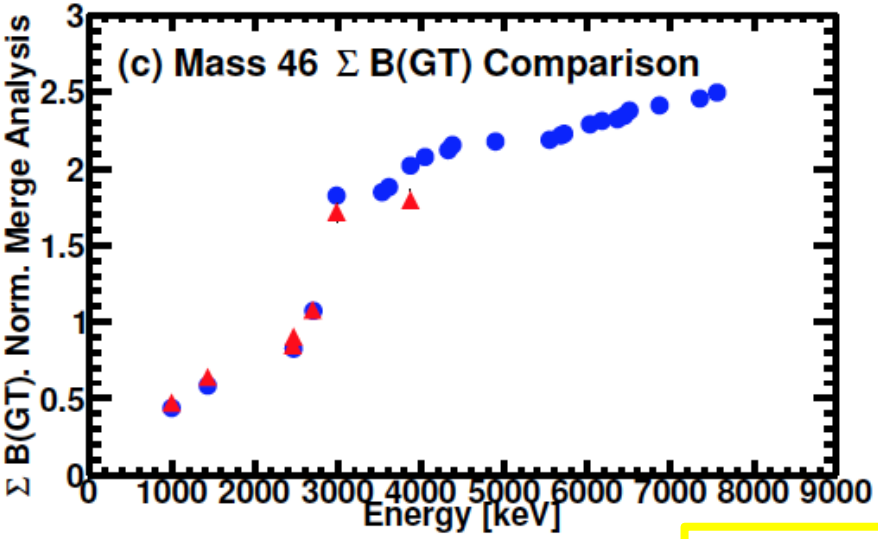
3He,t

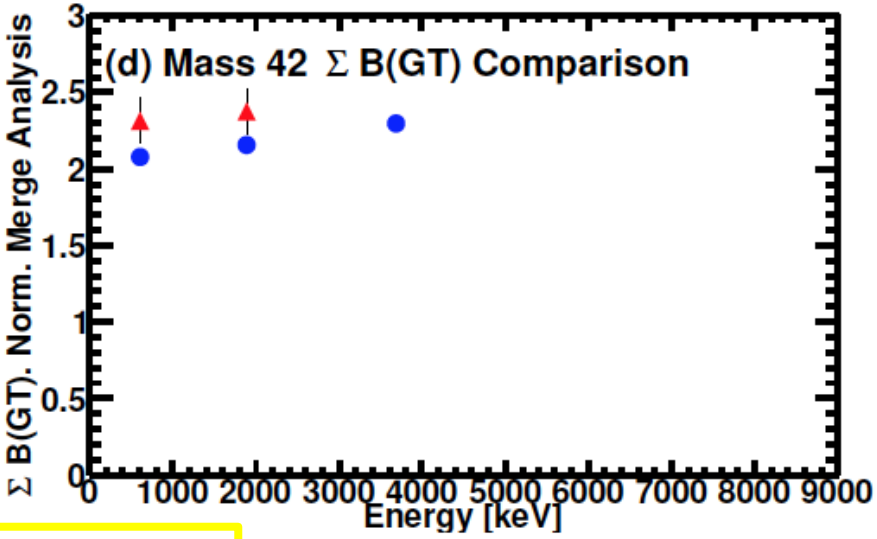
Accumulated B(GT)

Even inside the Q window, we miss some strength at high energ



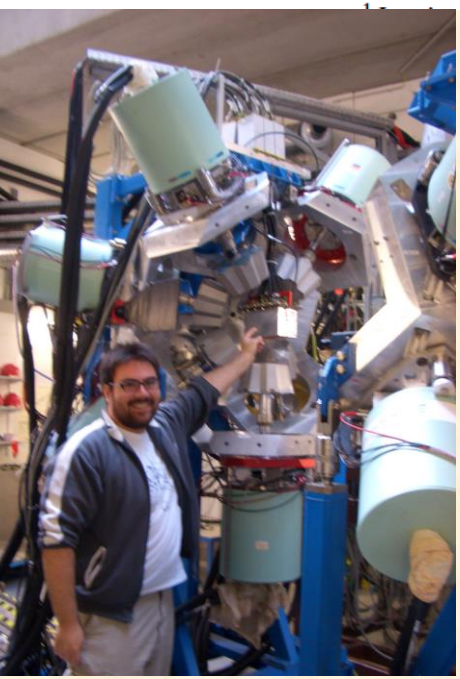



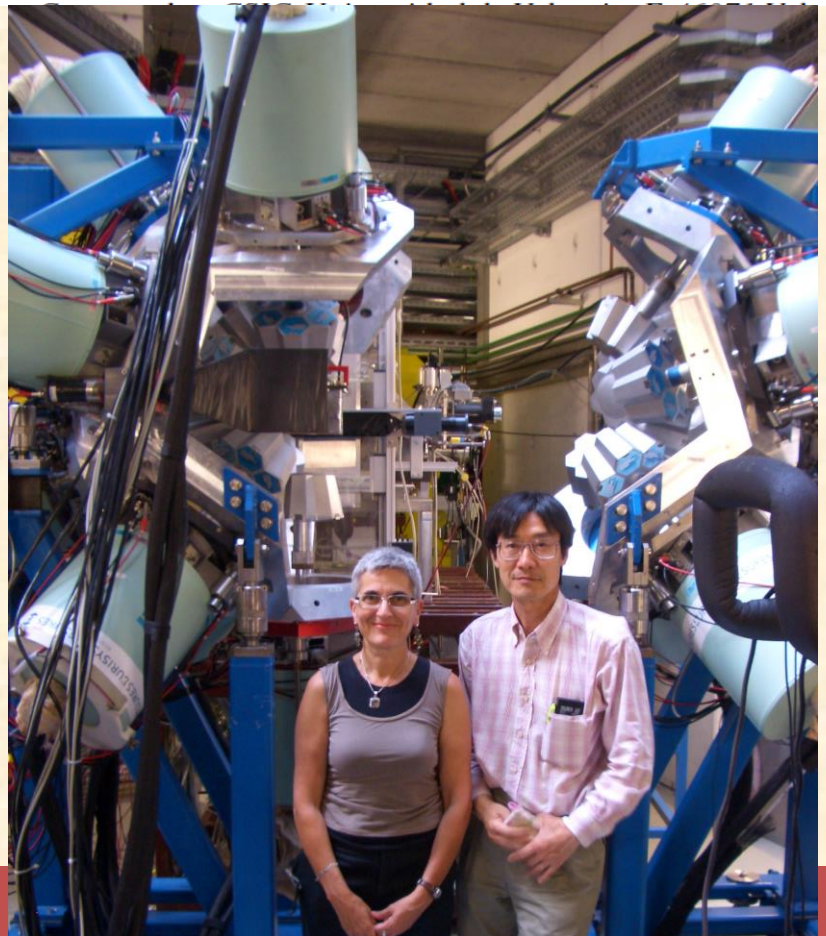

Are they really identical?

PHYSICAL REVIEW C **91**, 014301 (2015)

# $T_z = -1 \rightarrow 0$ $\beta$ decays of $^{54}$Ni, $^{50}$Fe, $^{46}$Cr, and $^{42}$Ti and comparison with mirror ($^3$He,$t$) measurements

F. Molina,[1,*] B. Rubio,[1,†] Y. Fujita,[2,3] W. Gelletly,[4] J. Agramunt,[1] A. Algora,[1,5] J. Benlliure,[6] P. Boutachkov,[7] L. Cáceres,[7,8] R. B. Cakirli,[9] E. Casarejos,[6,‡] C. Domingo-Pardo,[1,10] P. Doornenbal,[7] A. Gadea,[1,11] E. Ganioğlu,[9] M. Gascón,[6,§] H. Geissel,[7] J. Gerl,[7] M. Górska,[7] J. Gręboszc,[7,12] R. Hoischen,[7,13] R. Kumar,[14] N. Kurz,[7] I. Kojouharov,[7] L. Amon Susam,[9] H. Matsubara,[3,‖] A. I. Morales,[6] Y. Oktem,[9] D. Pauwels,[15] D. Pérez-Loureiro,[6] S. Pietri,[4] Zs. Podolyák,[4] W. Prokopowicz,[7] D. Rudolph,[13] H. Schaffner,[7] S. J. Steer,[4] J. L. Tain,[1] A. Tamii,[3] S. Tashenov,[7] J. J. Valiente-Dobón,[11] S. Verma,[6] and H-J. Wollersheim[7]

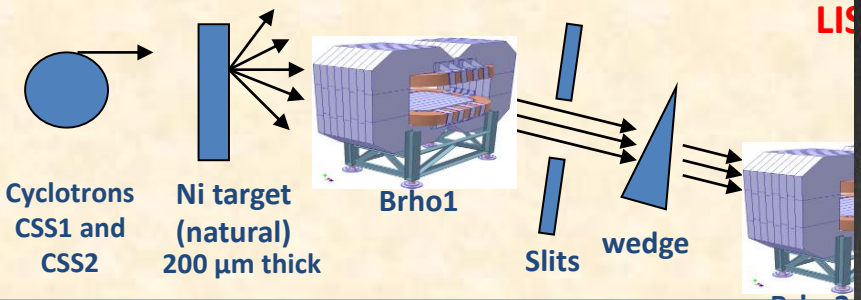


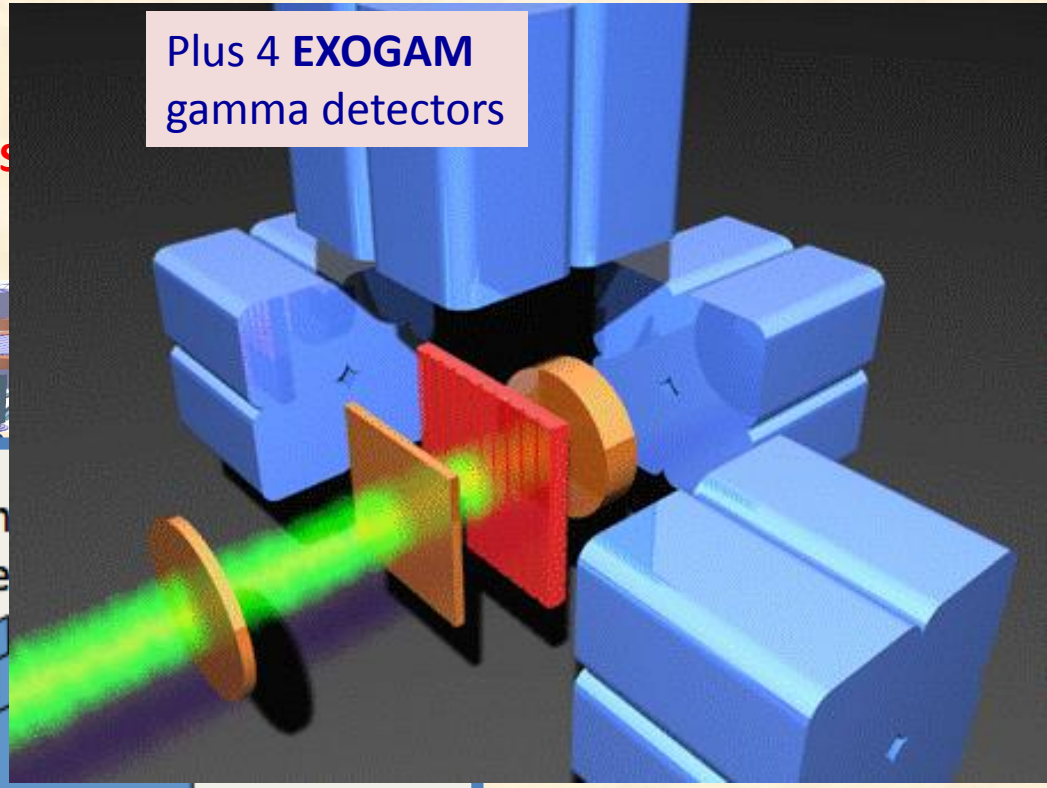


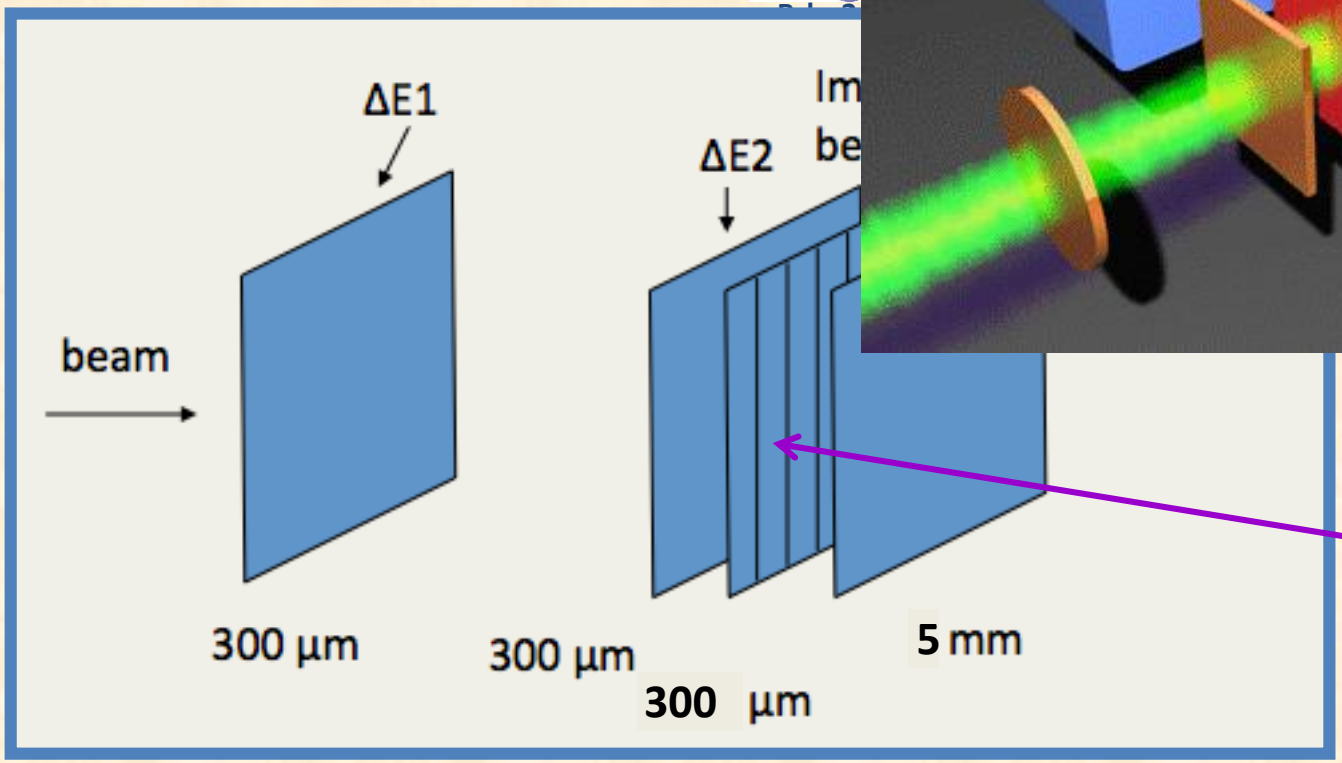
IFIC(Valencia)-Osaka-Surrey-Santiago de Compostela-Istanbul-Warsaw-Lund-Lueven Legnaro

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

74.5 MeV / nucleon
Incoming $^{58}Ni^{26+}$ 3.7 eμA intensity



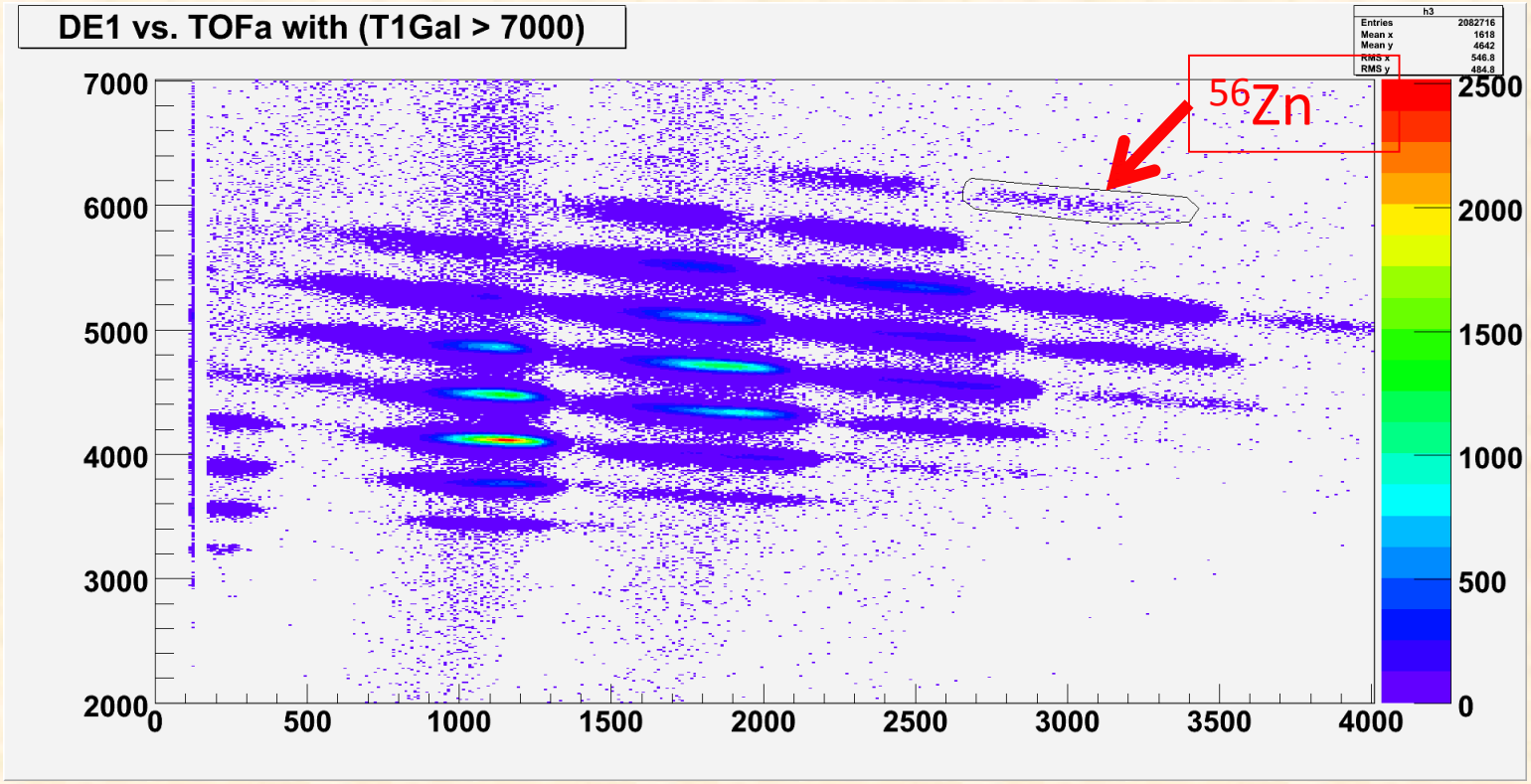

**DSSSD detector**
**Implantation and decay (β, p)**
✓ 16 strips X and 16 strips Y
✓300 μm thick
✓ 3 mm pitch

# As expected, the statistics are limited:

In 3 days:

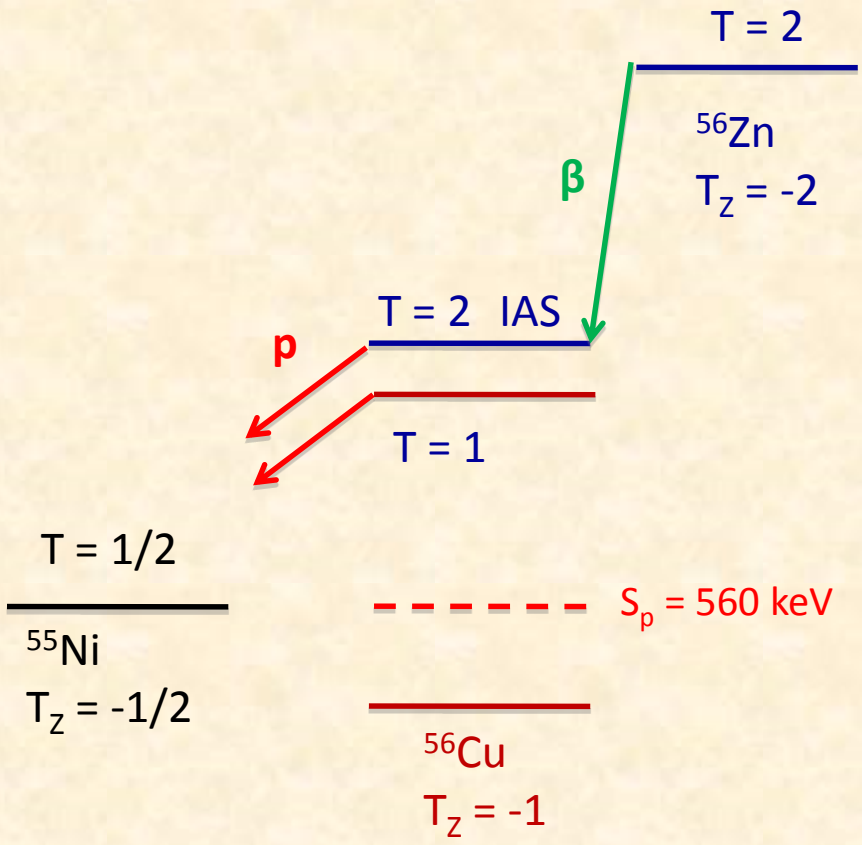
Total $^{56}$Zn implantations = 8861

0.033 pps

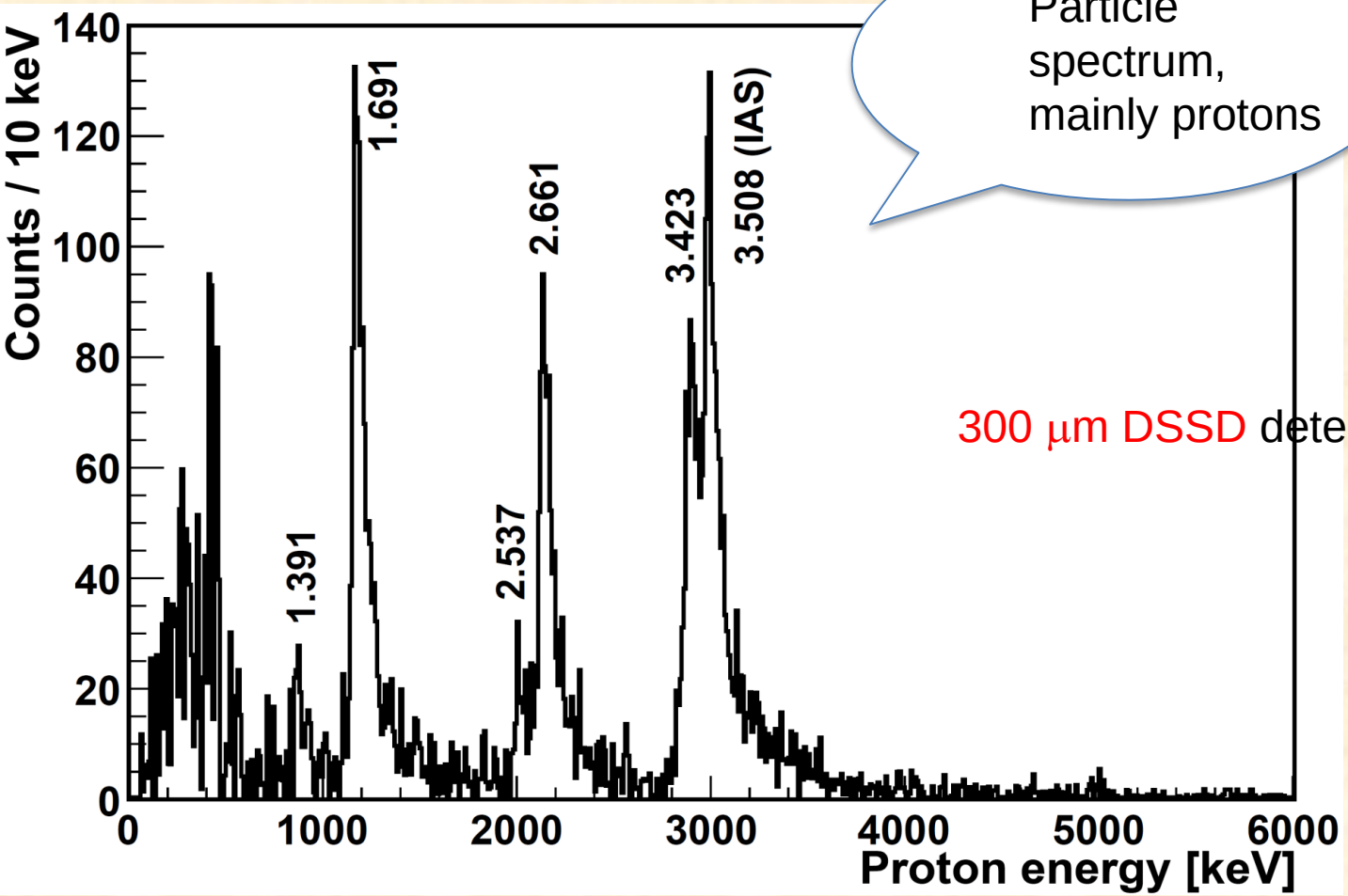


# Expectations for the beta decay of 56Zn

Because Sp is only 560 keV we expect most of the decay to proceed by proton emission



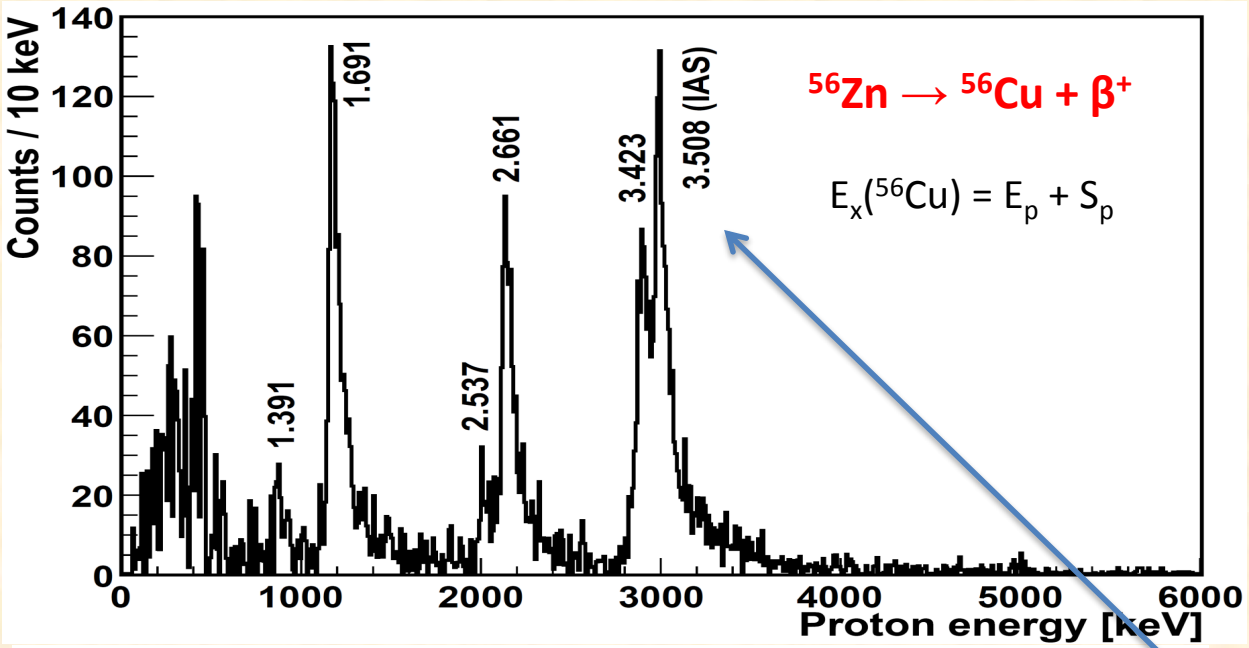
This is indeed what we saw




Particle spectrum, mainly protons

300 μm DSSD detector

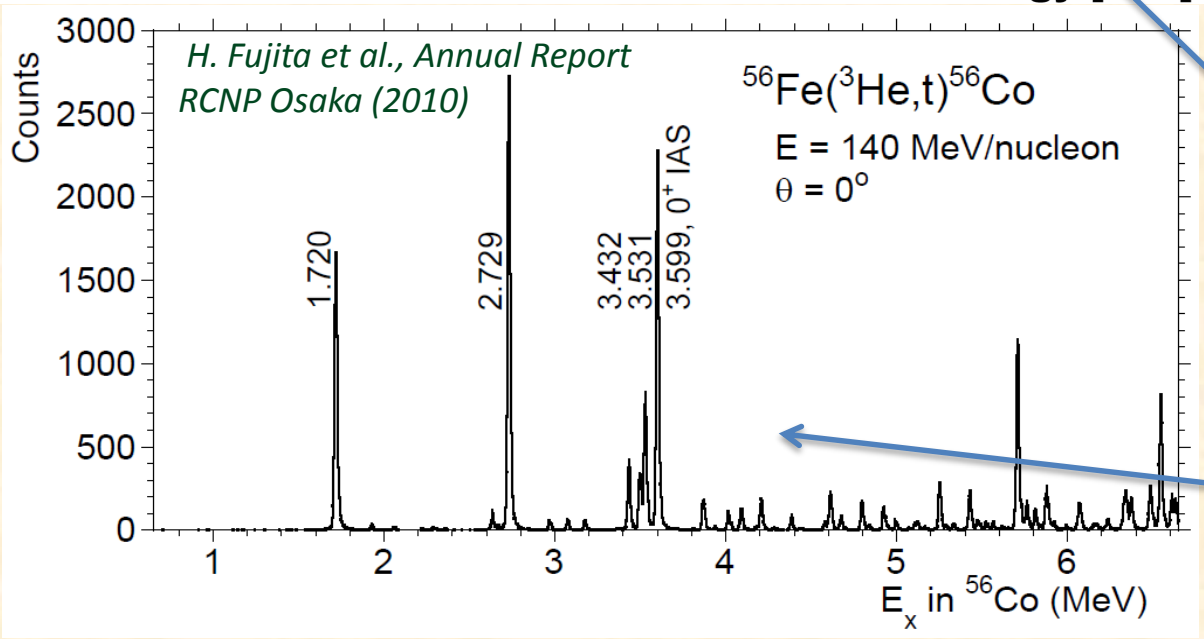
# Comparison of mirror transitions for A = 56

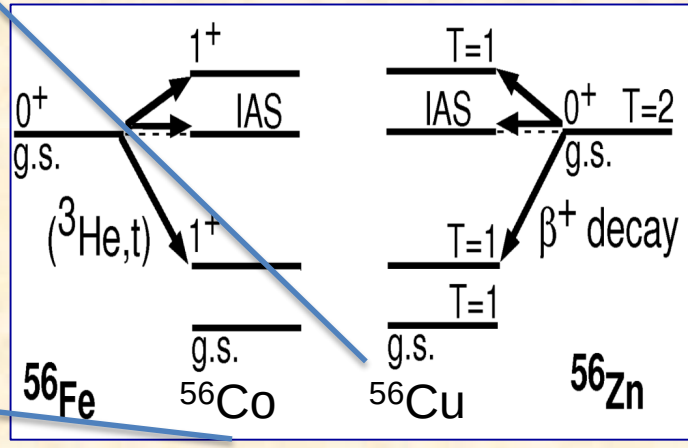



The **Isobaric Analog State (IAS)** is clearly identified in both spectra (In agreement with previous data *(C. Dossat et al., NPA 792(2007)18)*

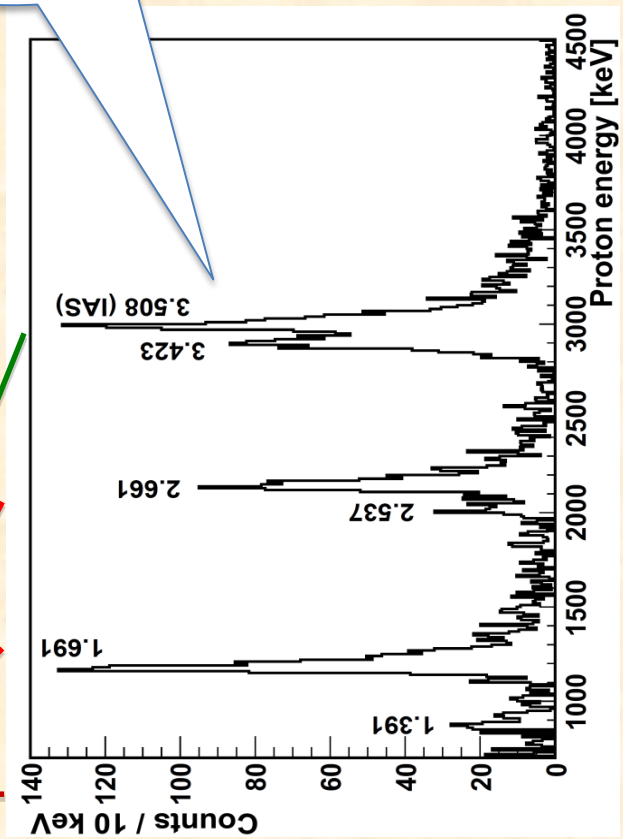
**Isospin symmetry holds well !**

All the dominant transitions are observed in both β decay and CE starting from mirror nuclei



Naively one would assume that these intensities are proportional to the beta feeding intensity




p (T =1/ 2

$^{55}$Ni

$T_z$ = -1/2

T=1/2

The p-decay of the IAS is isospin forbidden

T = 2

$^{56}$Zn

$T_z$ = -2

β

T = 2 IAS

0+

1+

T = 1

γ ??

1+

T = 1

1+

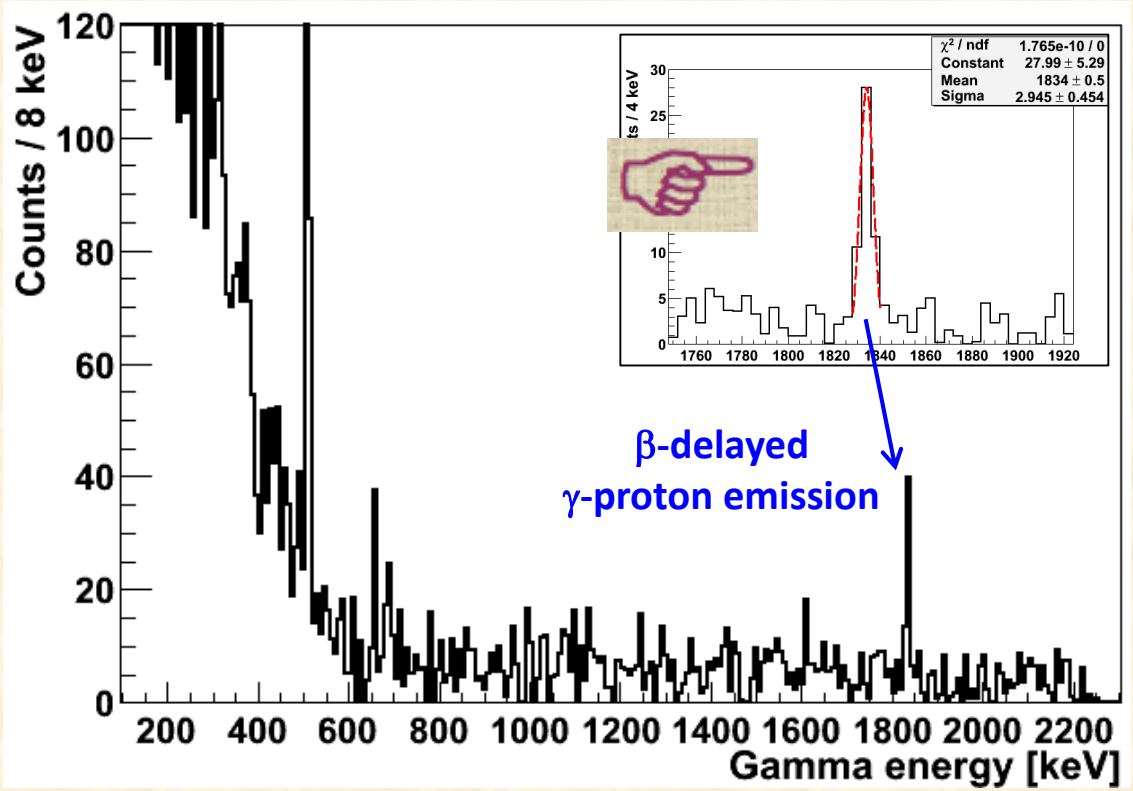
T = 1

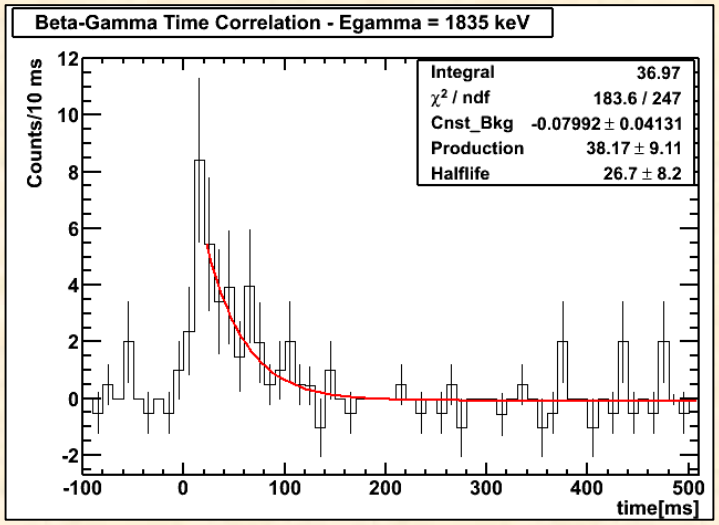
$S_p$ = 560 keV

$^{56}$Cu

$T_z$ = -1

# Indeed we observed the gamma transition deexciting the IAS



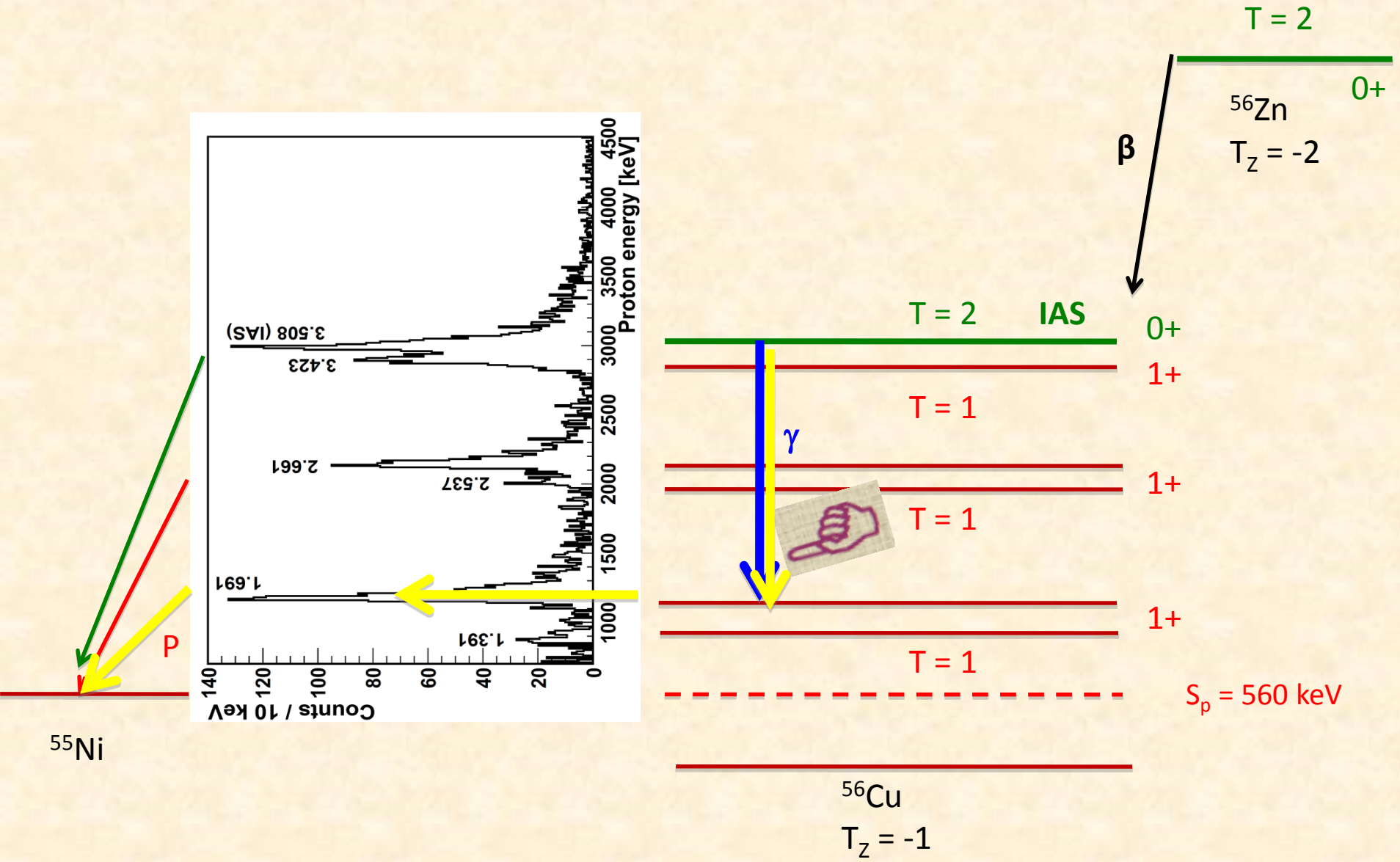




✓(β-γ)-implant time correlations

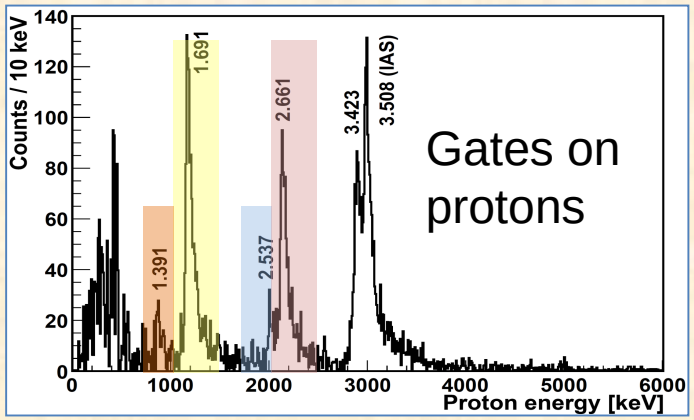
**$T_{1/2}$ = (27 ± 8) ms**

**A γ ray at 1834.5 ± 1.0 keV is observed in the $^{56}$Zn-correlated γ-spectrum corresponding to the de-excitation of the IAS**

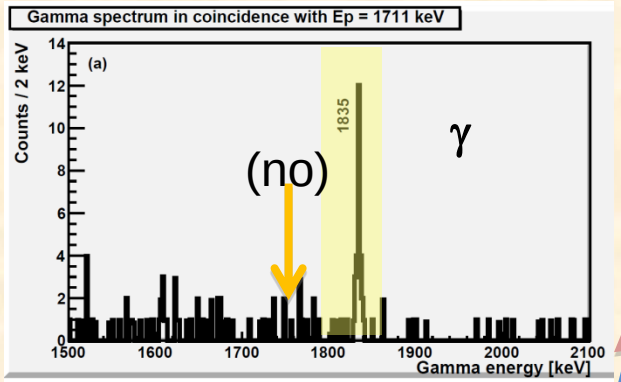
# This is the first observation of Beta-delayed gamma-proton decay in the fp shell

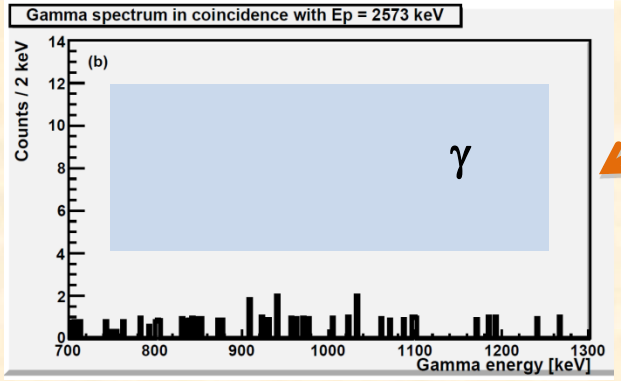


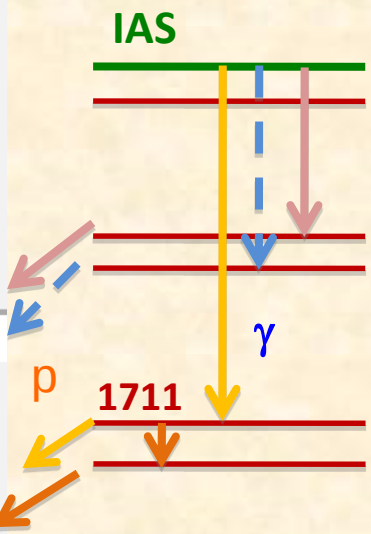
# Proton-gamma coincidences

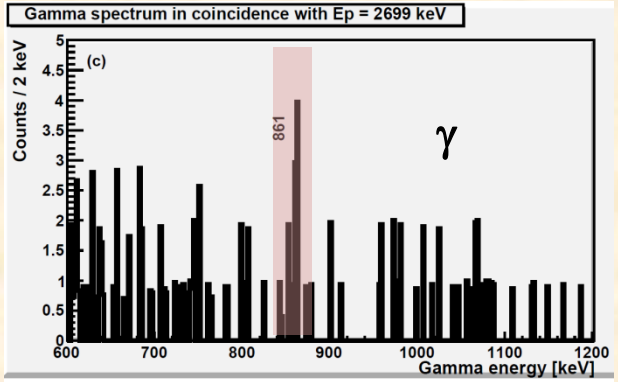


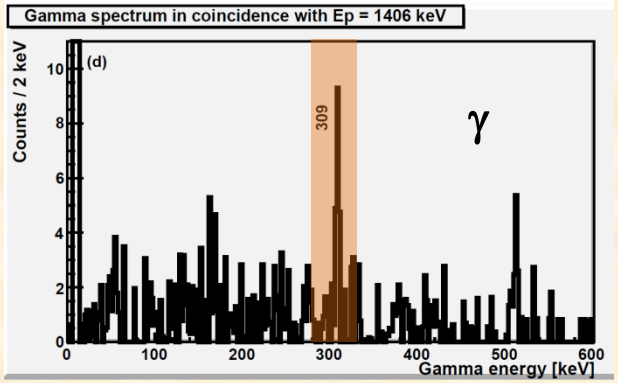

We have observed for the first time beta-delayed gamma-proton emission In three cases !!



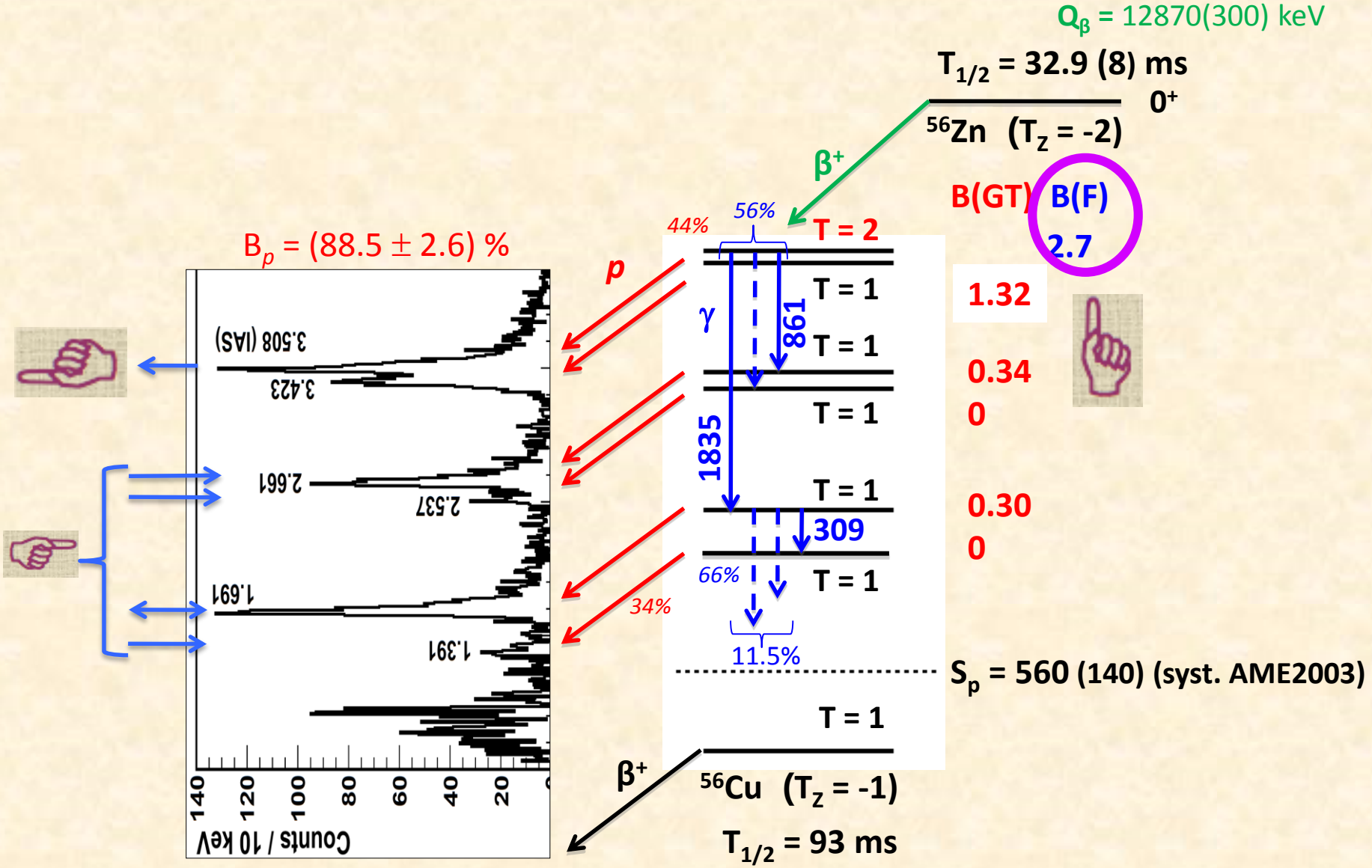



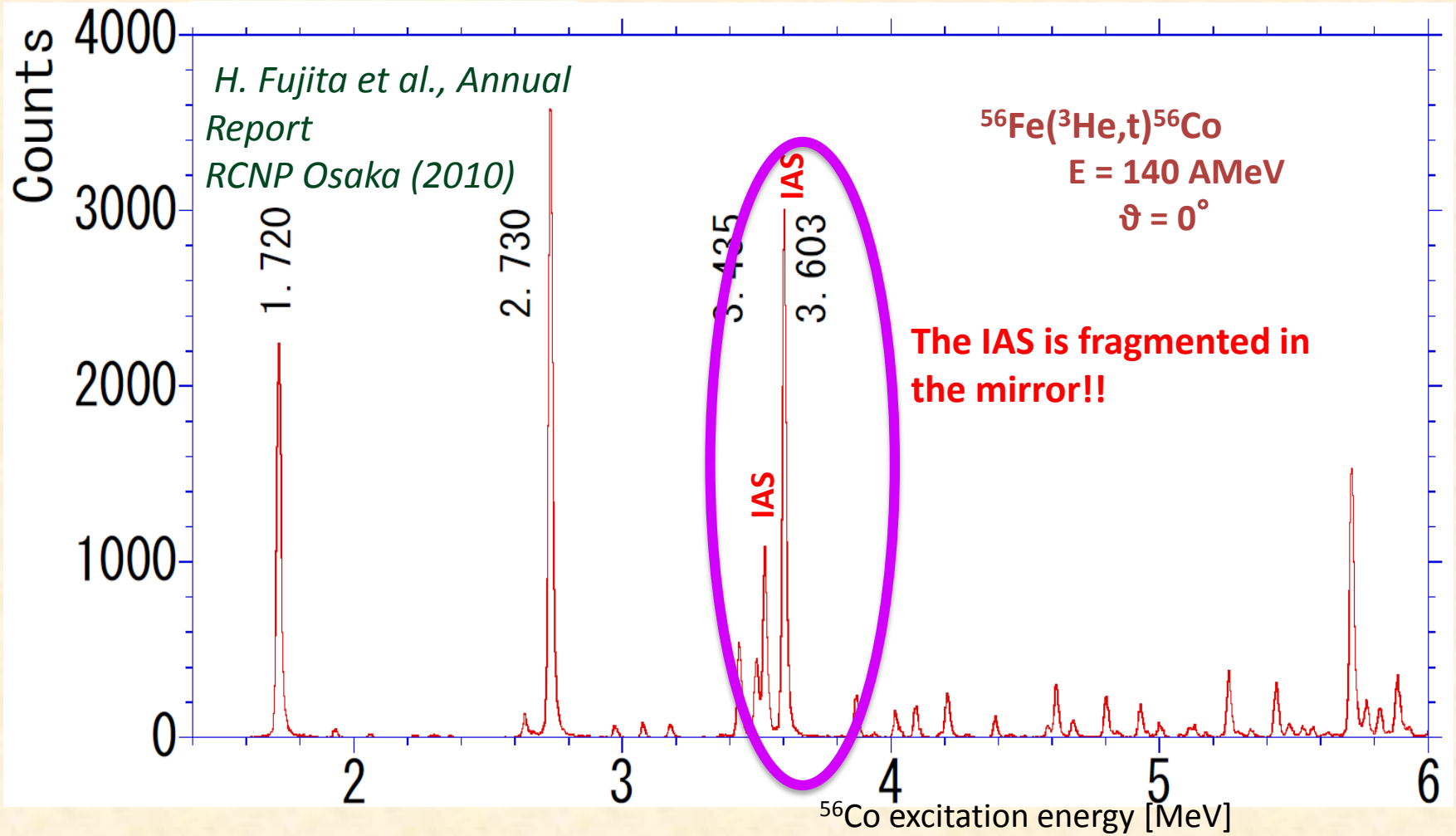



# $^{56}$Zn decay scheme, another surprise



# But this is NOT the end of the story!!!



$Q_\beta$ = 12870(300) keV

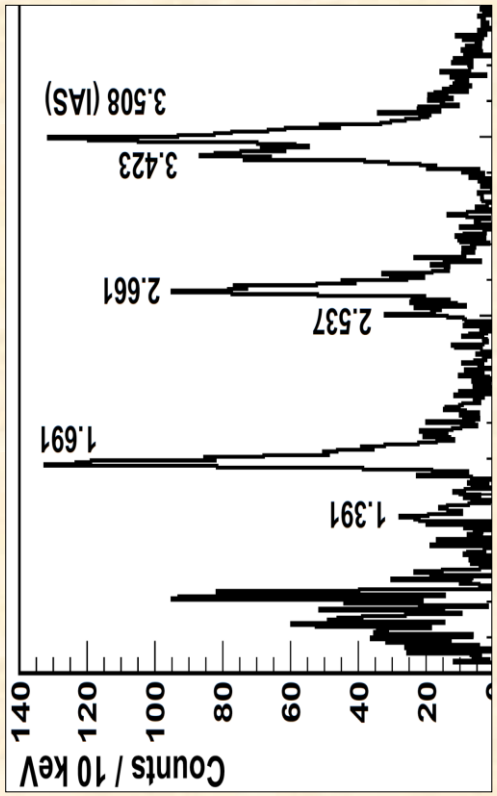
$T_{1/2}$ = 32.9 (8) ms

$^{56}$Zn ($T_z$ = -2)

T = 2, $0^+$

$\beta^+$

$B_p$ = (88.5 ± 2.6) %




p

44%

56%

T = 2

T = 1

γ

861

T = 1

T = 1

1835

T = 1

309

66%

T= 1

34%

11.5%

$S_p$ = 560 (140)

T = 1

$\beta^+$

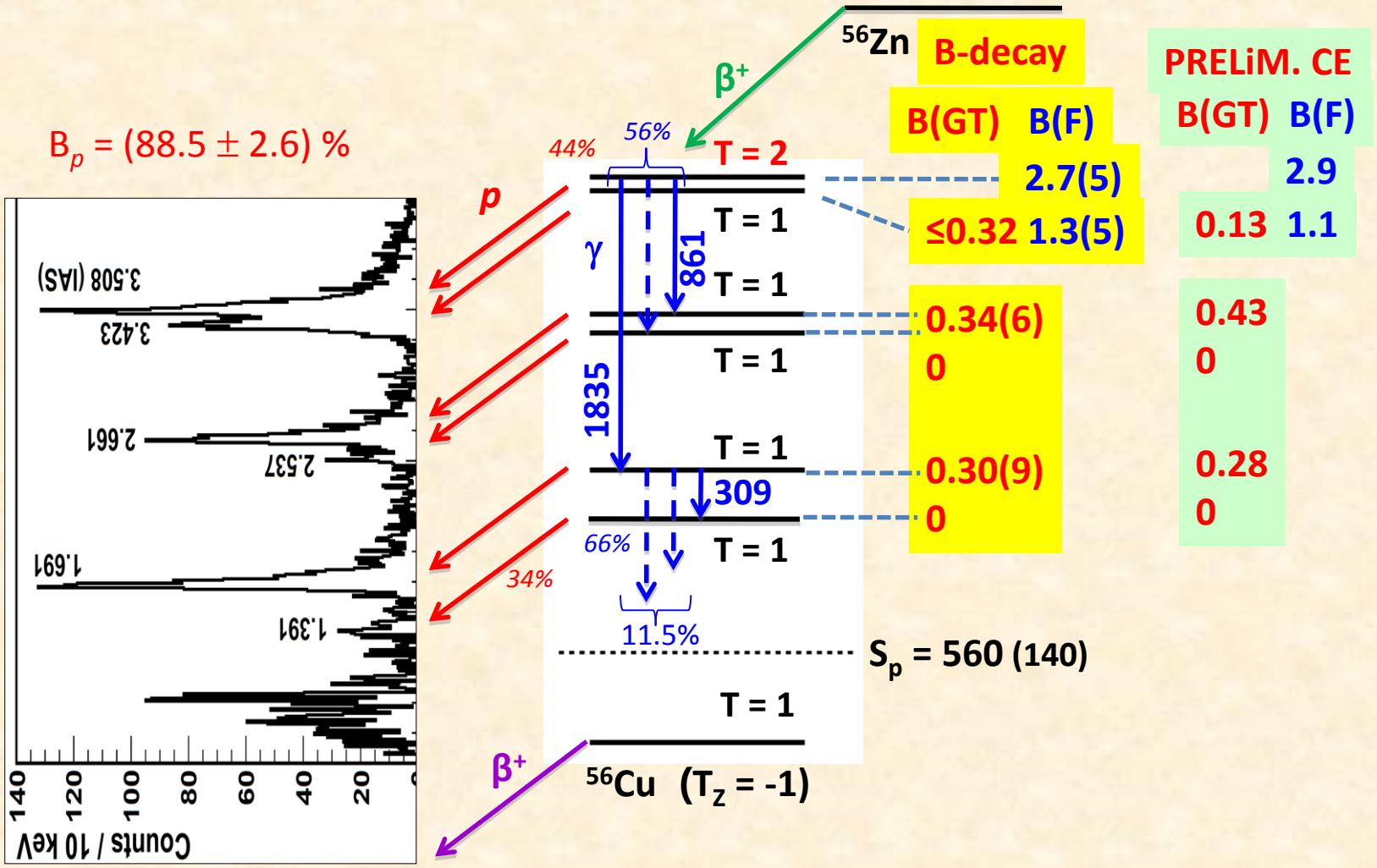
$^{56}$Cu ($T_z$ = -1)

$T_{1/2}$ = 93 ms

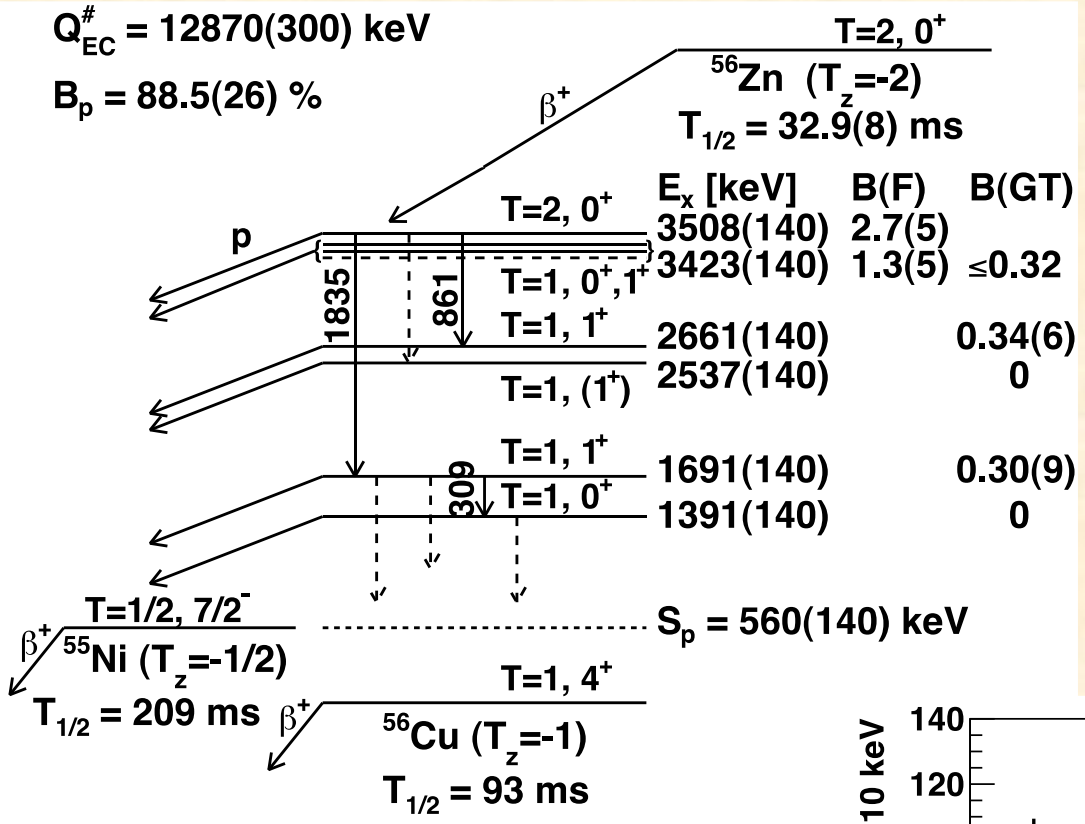
| | B(GT) | B(F) |
|---|---|---|
| | | 2.7 |
| | 0.02 | 1.3 |
| | 0.34 | |
| | 0 | |
| | 0.30 | |
| | 0 | |

the fragmentation of the IAS is important for isopin mixing and for the Mass evaluation

# And now we can compare with the Charge Exchange reaction in the mirror



# Isospin mixing




Level(3508)=77%(T=2)+33%(T=1)

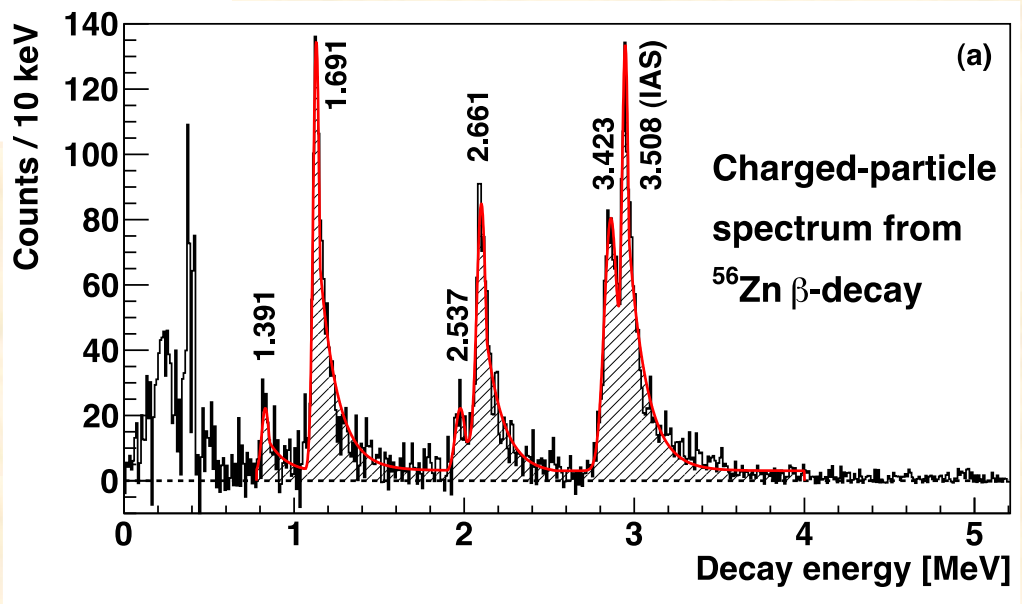
$$\left|a^2\right| = 33(10)$$

$$Hc = 40(23)keV$$

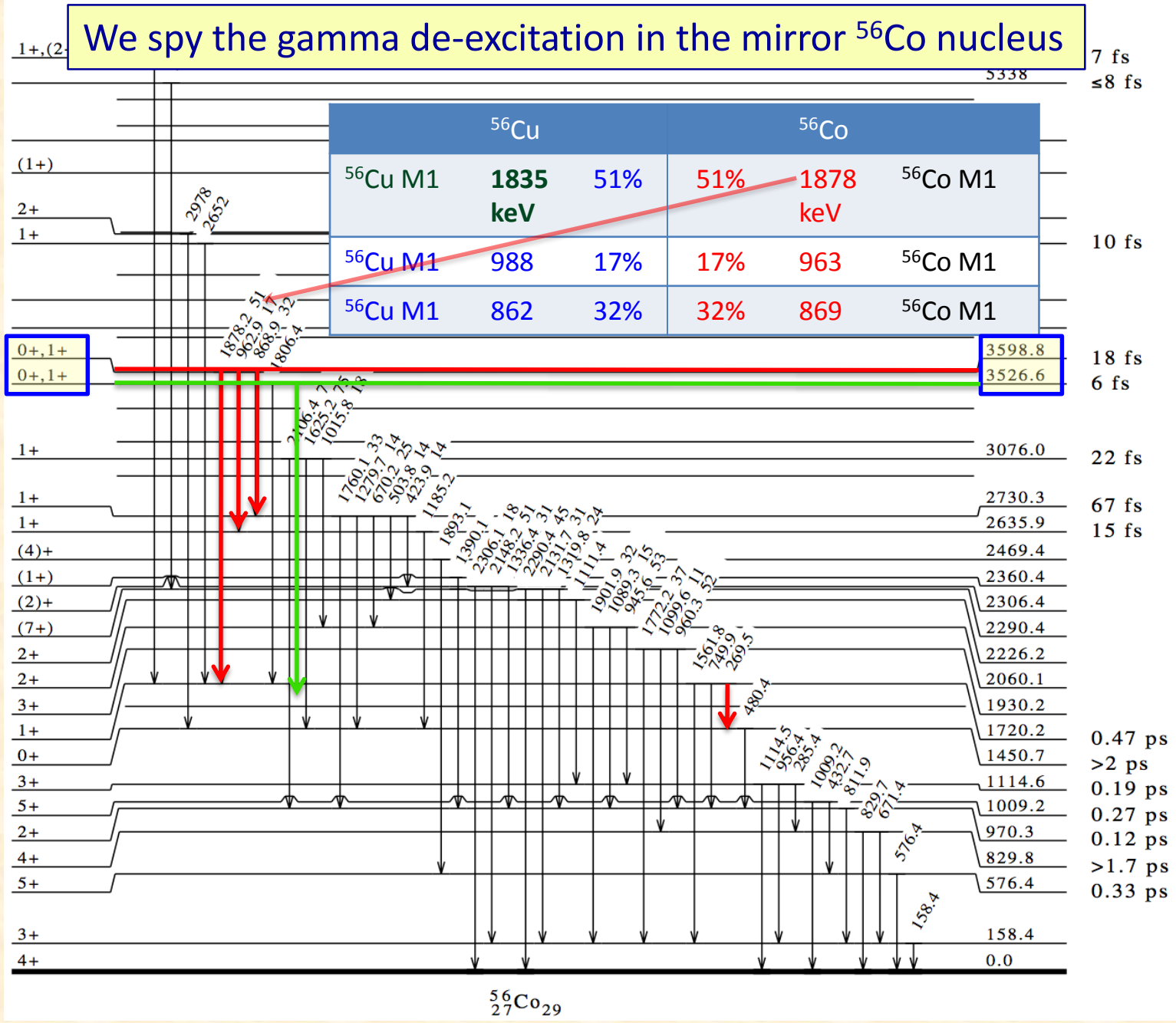
$$\left|a^2\right| = 28(1)$$

$$Hc = 32.5(5)keV$$

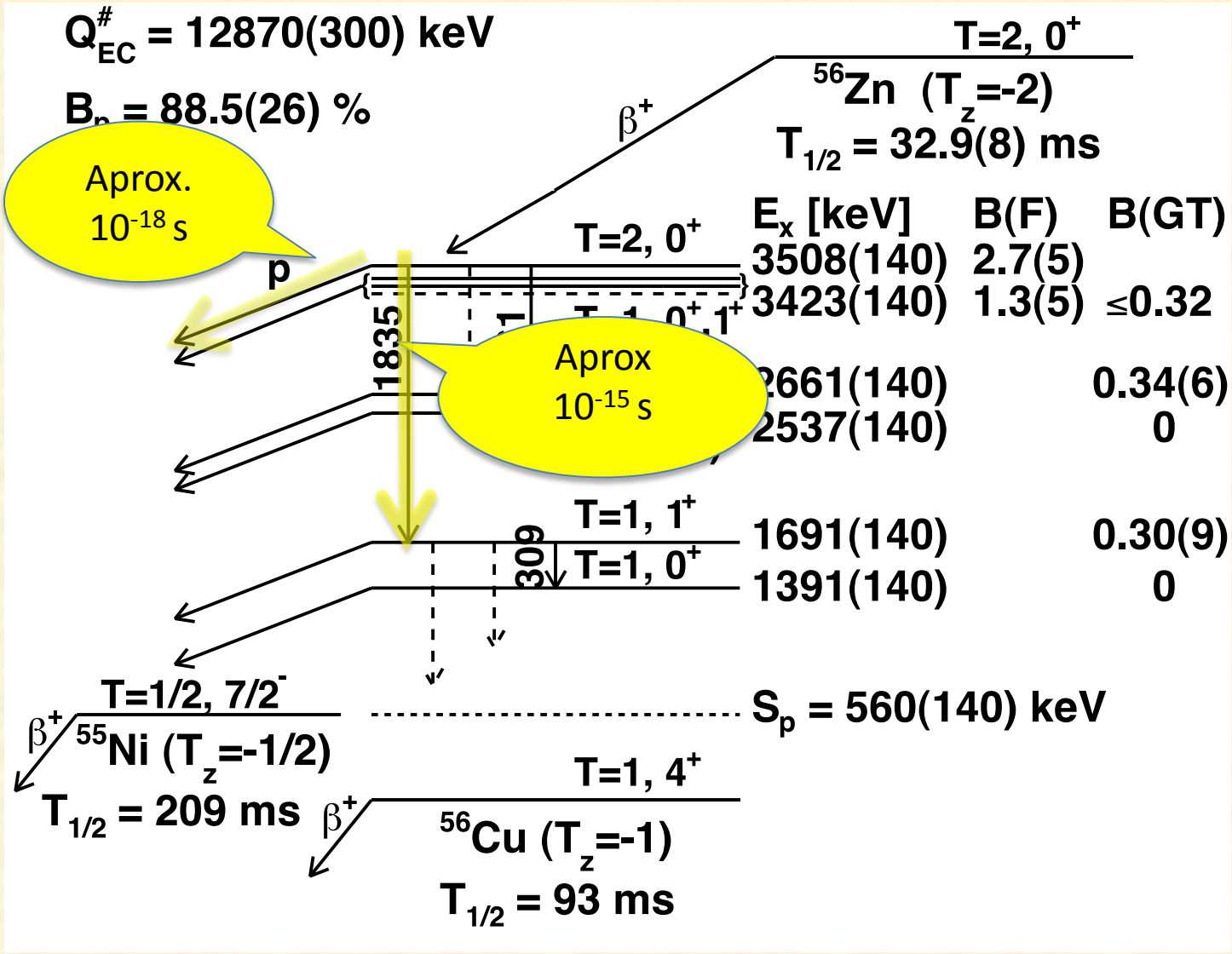
In the Mirror 56Co

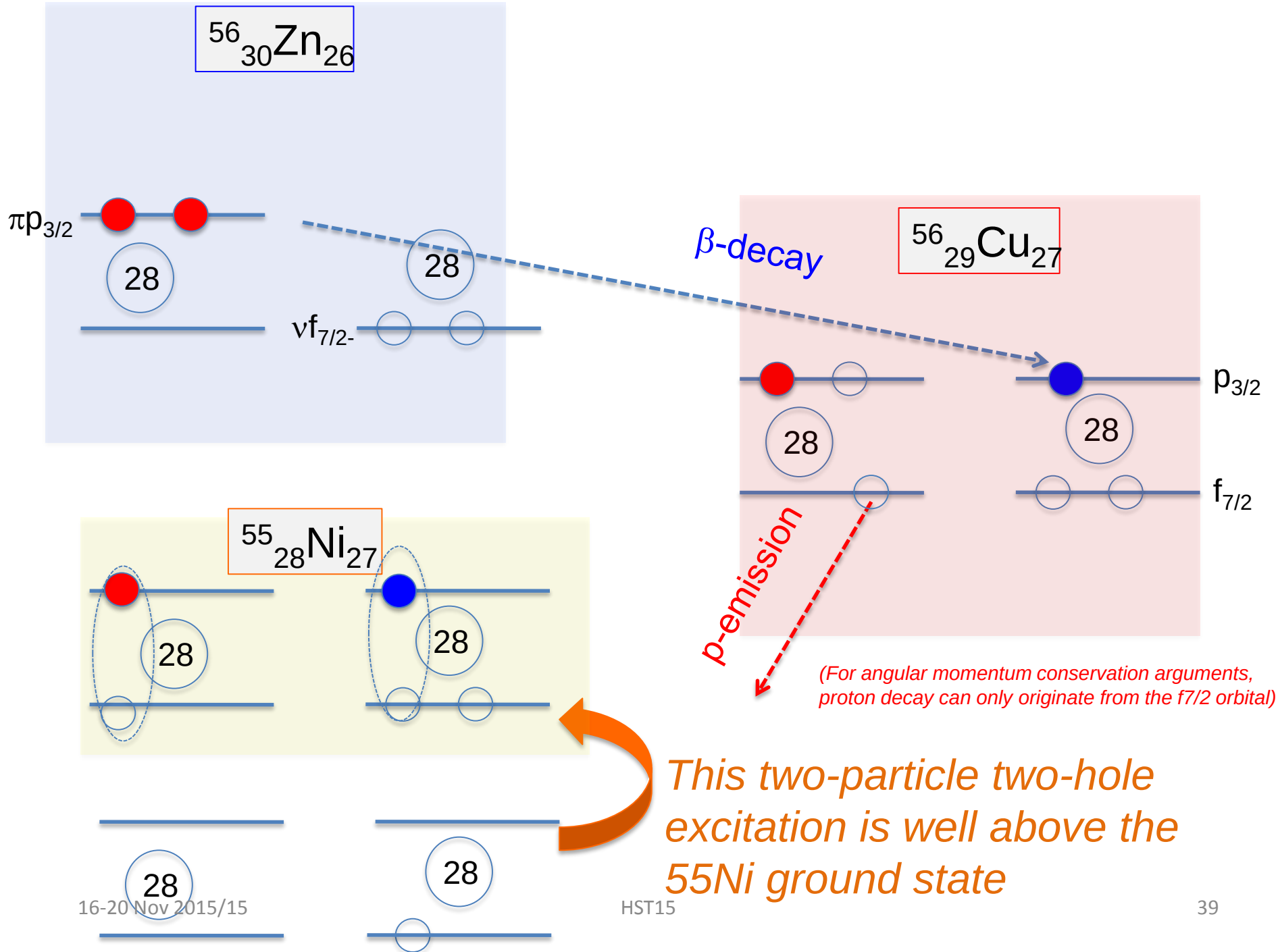


# We spy the gamma de-excitation in the mirror $^{56}$Co nucleus

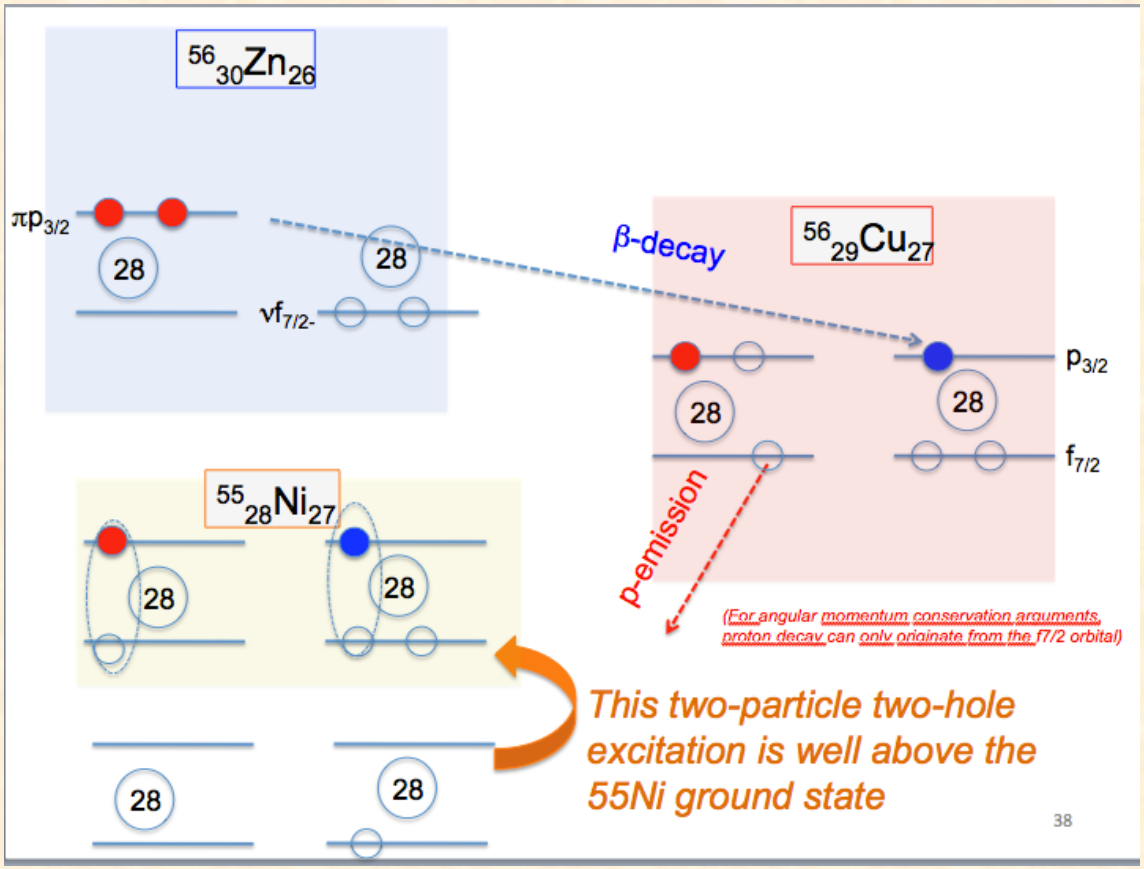


# We were puzzled for some time....




$^{56}_{30}Zn_{26}$
$\pi p_{3/2}$
28
28
$\nu f_{7/2-}$
β-decay
$^{56}_{29}Cu_{27}$
28
28
$p_{3/2}$
$f_{7/2}$
p-emission
(For angular momentum conservation arguments, proton decay can only originate from the f7/2 orbital)
$^{55}_{28}Ni_{27}$
28
28
28
28
This two-particle two-hole excitation is well above the 55Ni ground state

The spectroscopic factor for this component in the gs of 55Ni has been calculated by A. Poves using the KB3GR interaction as $10^{-3}$, he can also reproduce the mixing of the states and the
B(M1) branching.




Also calculations by Smirnova, Lam et al. in print

# The Collaboration

PRL 112, 222501 (2014) PHYSICAL REVIEW LETTERS

## Observation of the $\beta$-Delayed $\gamma$-Proton Decay of $^{56}$Zn and its Impact on the Gamow-Teller Strength Evaluation

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See talk by Sonja Orrigo of Friday on this and other Tz=-2 cases

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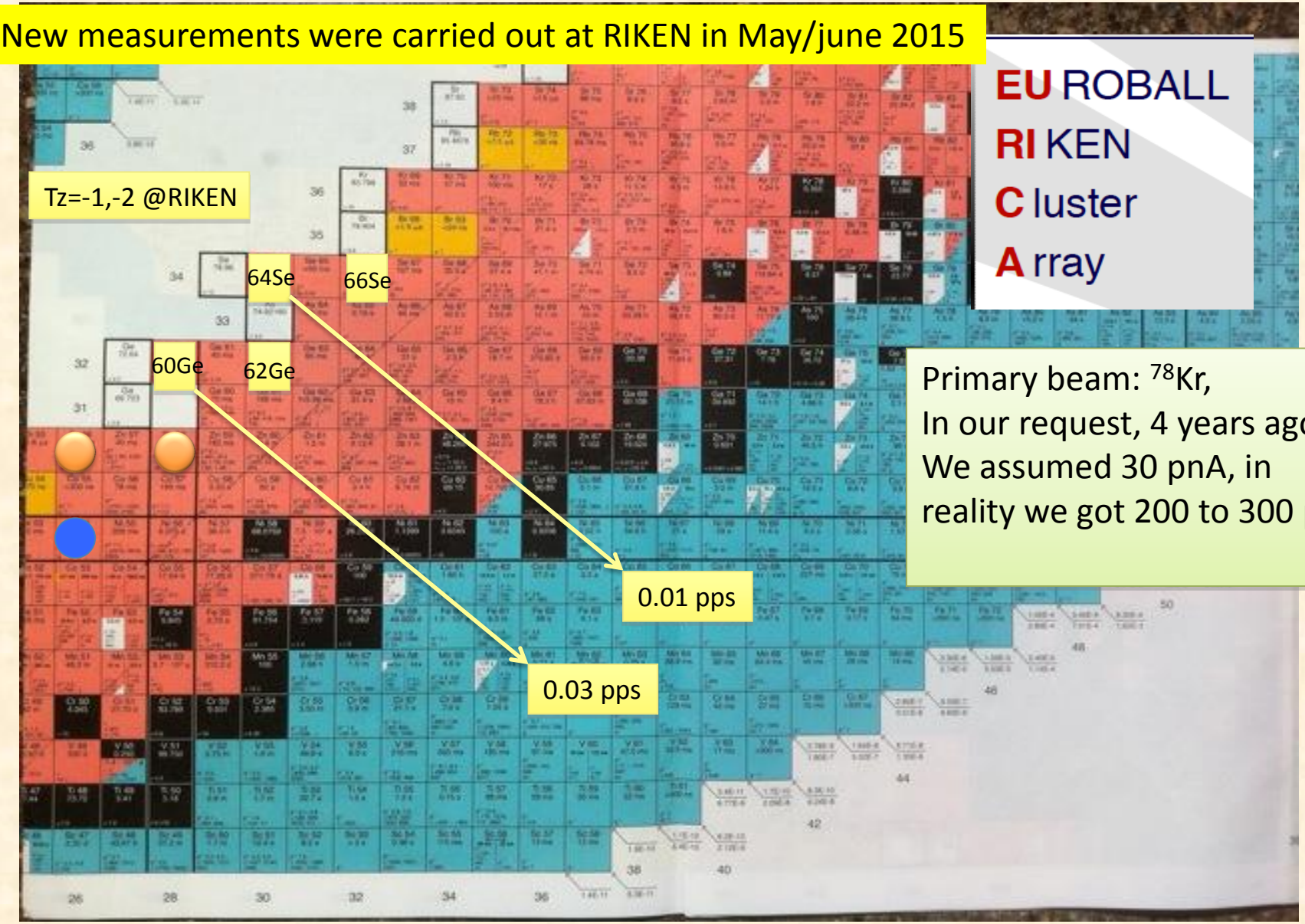
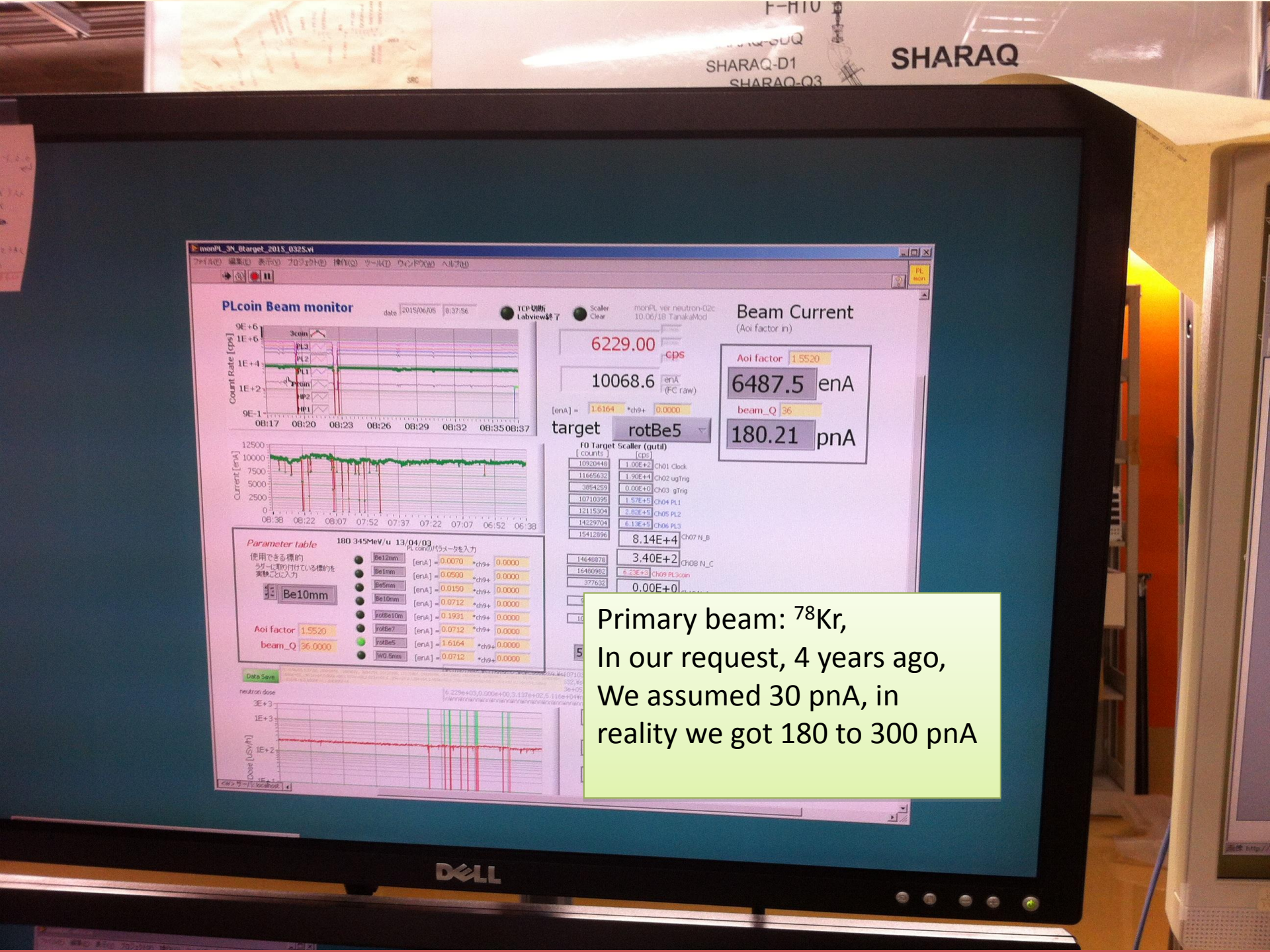
(Received 13 February 2014; published 3 June 2014)

New measurements were carried out at RIKEN in May/june 2015



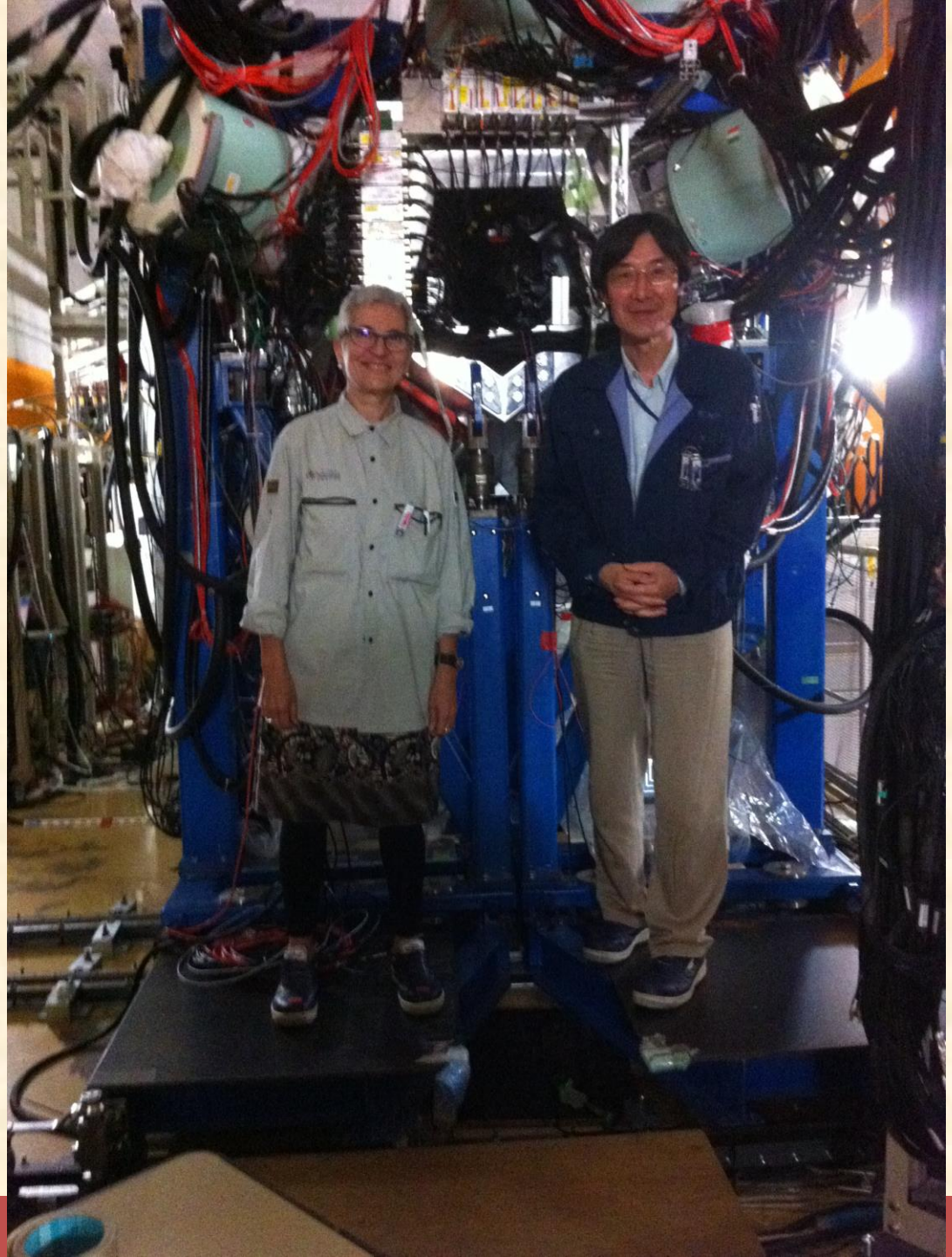

EU ROBALL
RI KEN
C luster
A rray

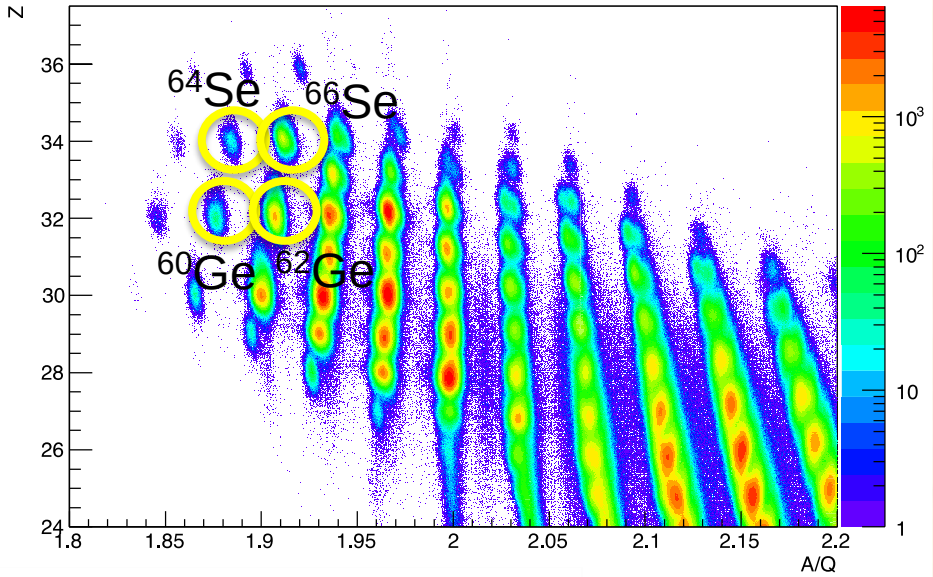
Primary beam: $^{78}$Kr,
In our request, 4 years ago,
We assumed 30 pnA, in
reality we got 200 to 300 pnA

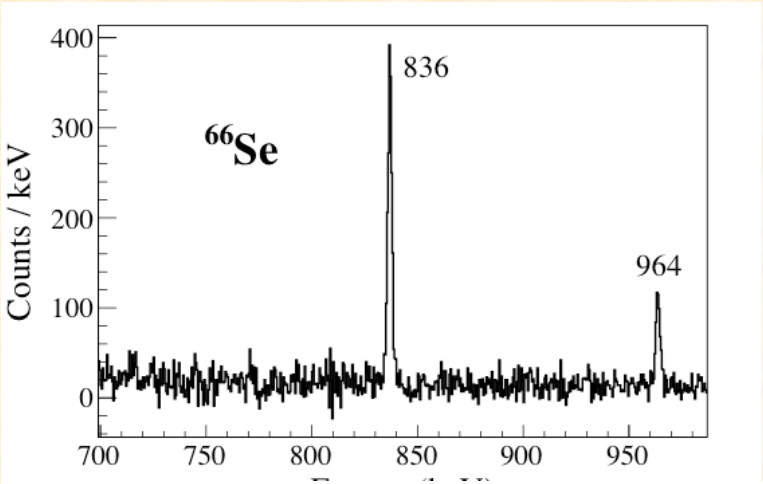


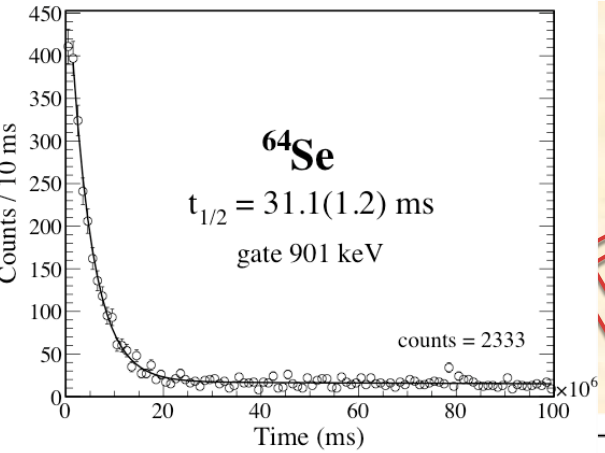

Primary beam: $^{78}$Kr,
In our request, 4 years ago,
We assumed 30 pnA, in
reality we got 180 to 300 pnA

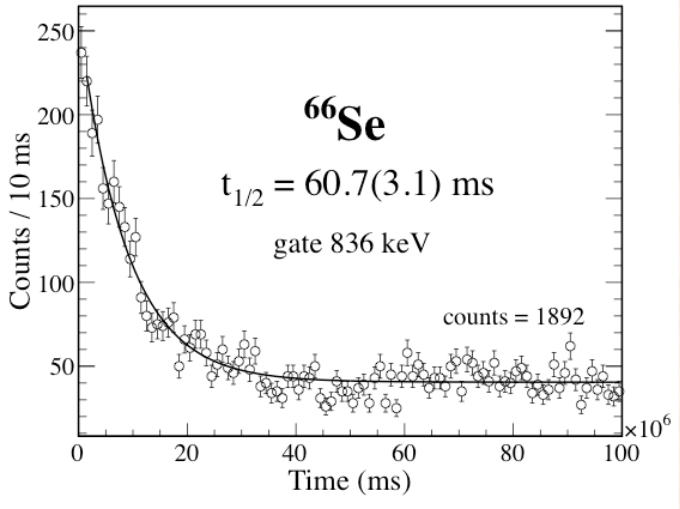
Four long intense and exhausting weeks



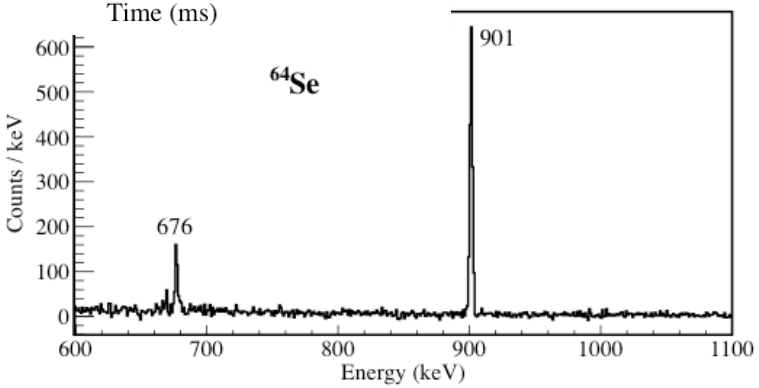


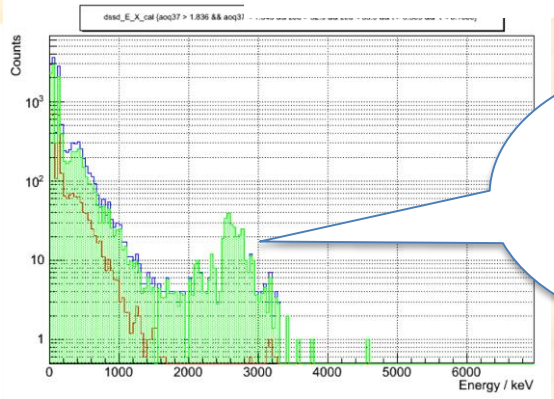




Preliminary




First observation of beta-delayed protons $^{60}$Ge decay

# Summary

We have studied the beta decay of the four Tz=-1 nuclei in the f7/2 shell and compared them with the CE reaction on the mirror Tz=+1 nuclei.
This detailed comparison was done for the first time in the f shell.
Very important: we have put a sensitivity limit to our experimental results

Mirror symmetry works well but some differences remain which can be due to mirror symmetry breaking or to extra contributions (tensor) in the hadronic (CE) probe.

I have presented the study of several Tz=-2 decays carried out at and their comparison with the mirror process Charge-Exchange reactions on the mirror stable nuclei.

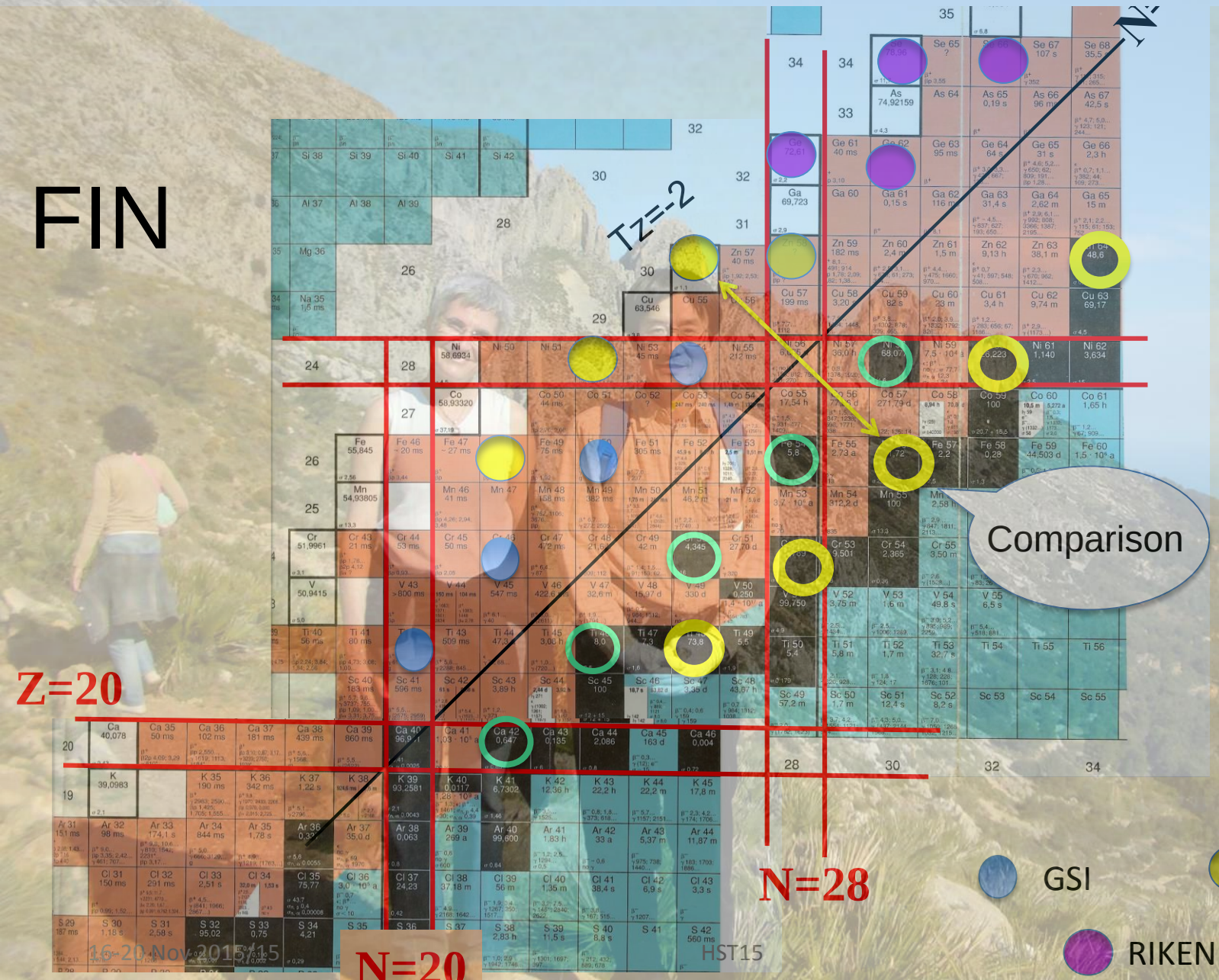
We have observed, for the first time beta-delayed gamma-proton decay in the *fp* shell in three branches. From our data we have extracted the isospin mixing.

We have observed evidence of the fragmentation of the isobaric analogue state
And obtained a value for the isospin mixing

Nuclear structure effects are responsible of the strong hindrance of the proton decay. This idea has been corroborated by Shell Model Calculations

One day, far in the future, one will be able to do high resolution experiments with radioactive beams….

# FIN



# Summary

I have presented the study of several Tz=-2 decays carried out at GANIL and their comparison with the mirror process Charge-Exchange reactions on the mirror stable nuclei.

We have measured the beta, the protons and the gammas after the decay,

The beta decay of the Tz=-2 nucleus 56Zn was studied in detail.

We have observed evidence of the fragmentation of the isobaric analogue state

We have now a good understanding of this decay which could have never been possible without the information from the mirror nucleus 56Fe, in particular the CE experiment at Osaka.

We have observed, for the first time beta-delayed gamma-proton decay in the *fp* shell in three branches. From our data we have extracted the isospin mixing.

Nuclear structure effects are responsible of the gamma de-excitation in competition with the fast proton decay of the IAS. This idea has been corroborated by Shell Model Calculations

We will have a lot of new data for the next PROCON Conference, 48Fe, 52Ni, almost ready, 60Ge, 64Se first decay studies.