Spectroscopy beyond the N=Z line

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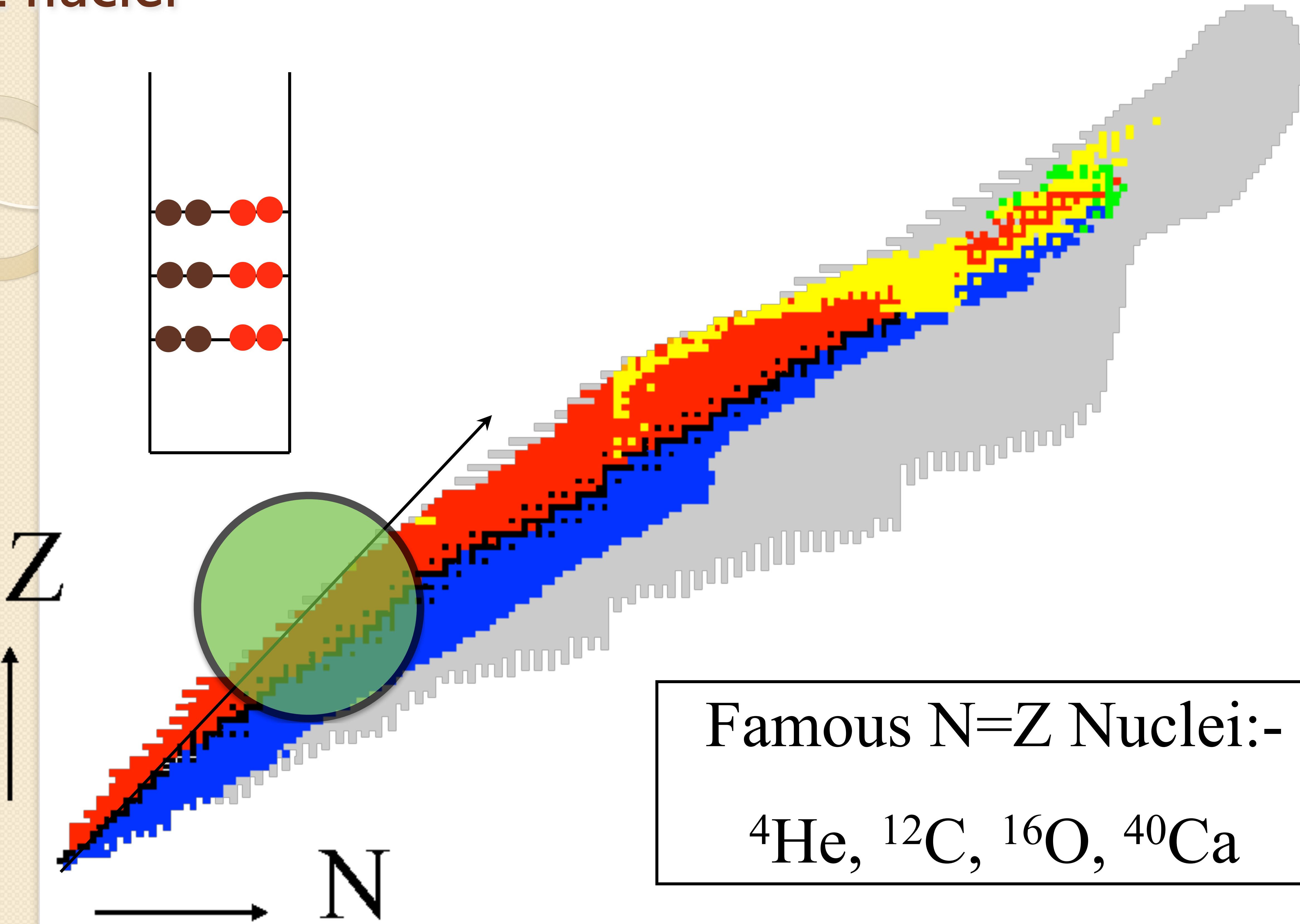
Overview

- Why study nuclei around N=Z (for A~70)?
  - Protons and neutrons in same orbitals (in N=Z)
  - Occurrence of different isospins nearby (in odd-odd N=Z)
  - Triplet and mirror energy differences
  - Region of rapidly evolving nuclear shape
- Recoil-beta tagging
  - New technique developed to tag odd-odd N=Z nuclei and other exotic nuclei
  - Sensitivity of technique being enhanced through several technical developments
- Beyond N=Z
  - First spectroscopic data on ^{66}Se and ^{74}Sr
  - Triplet energy differences appear to need an isospin-nonconserving interaction

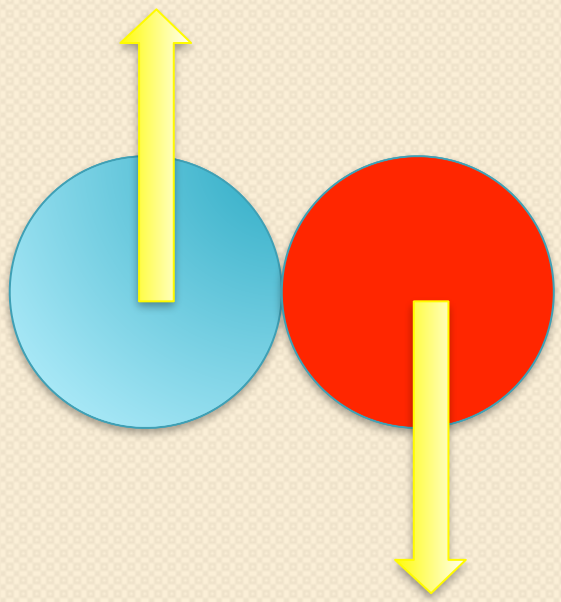
N=Z nuclei



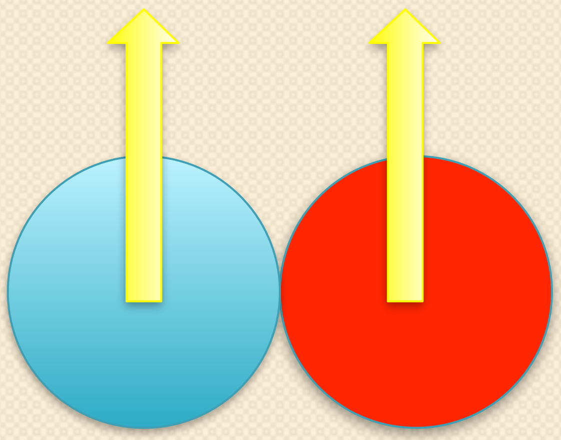
Famous N=Z Nuclei:-

^{4}He, ^{12}C, ^{16}O, ^{40}Ca

The deuteron and isospin



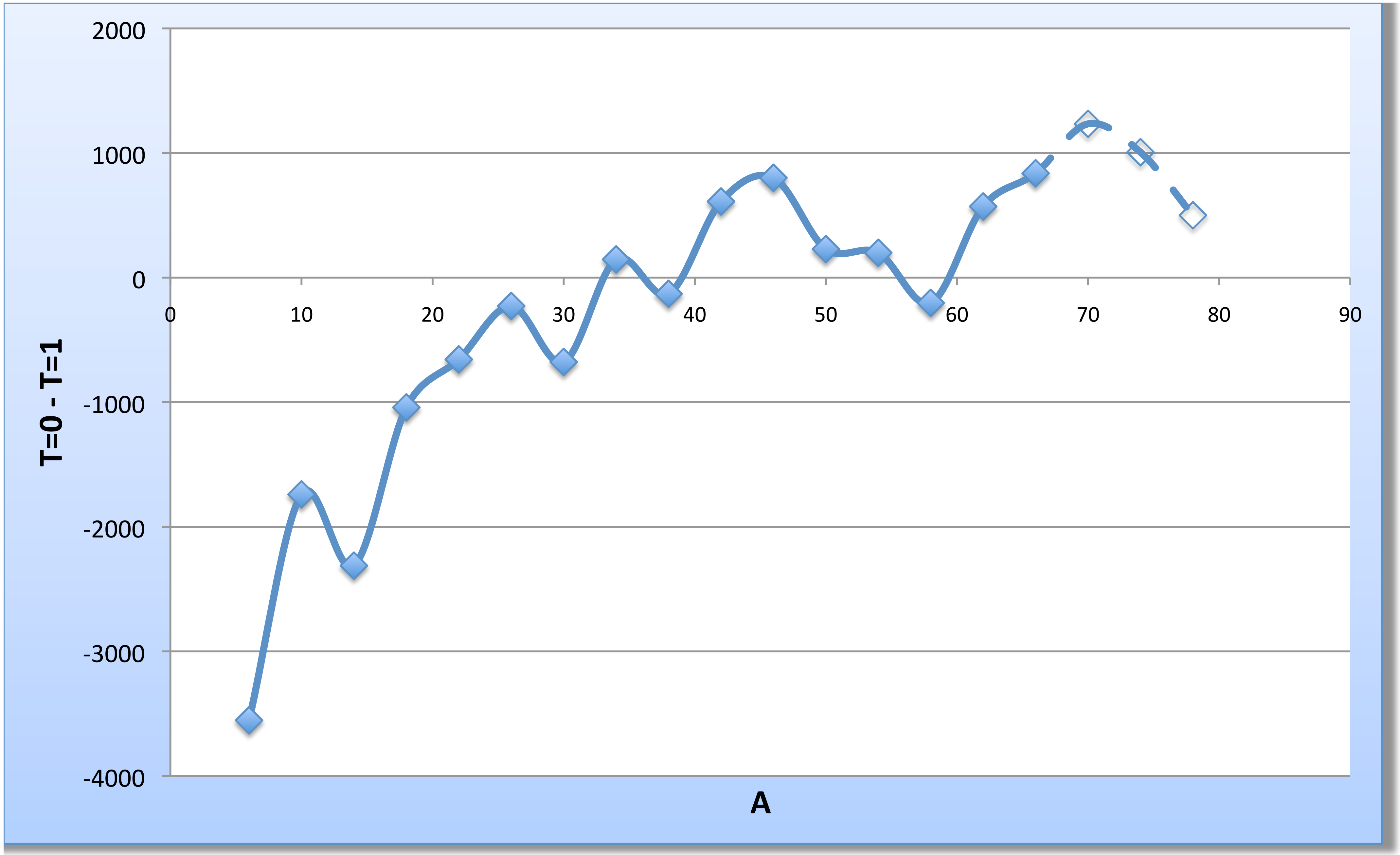
S=0, T=1



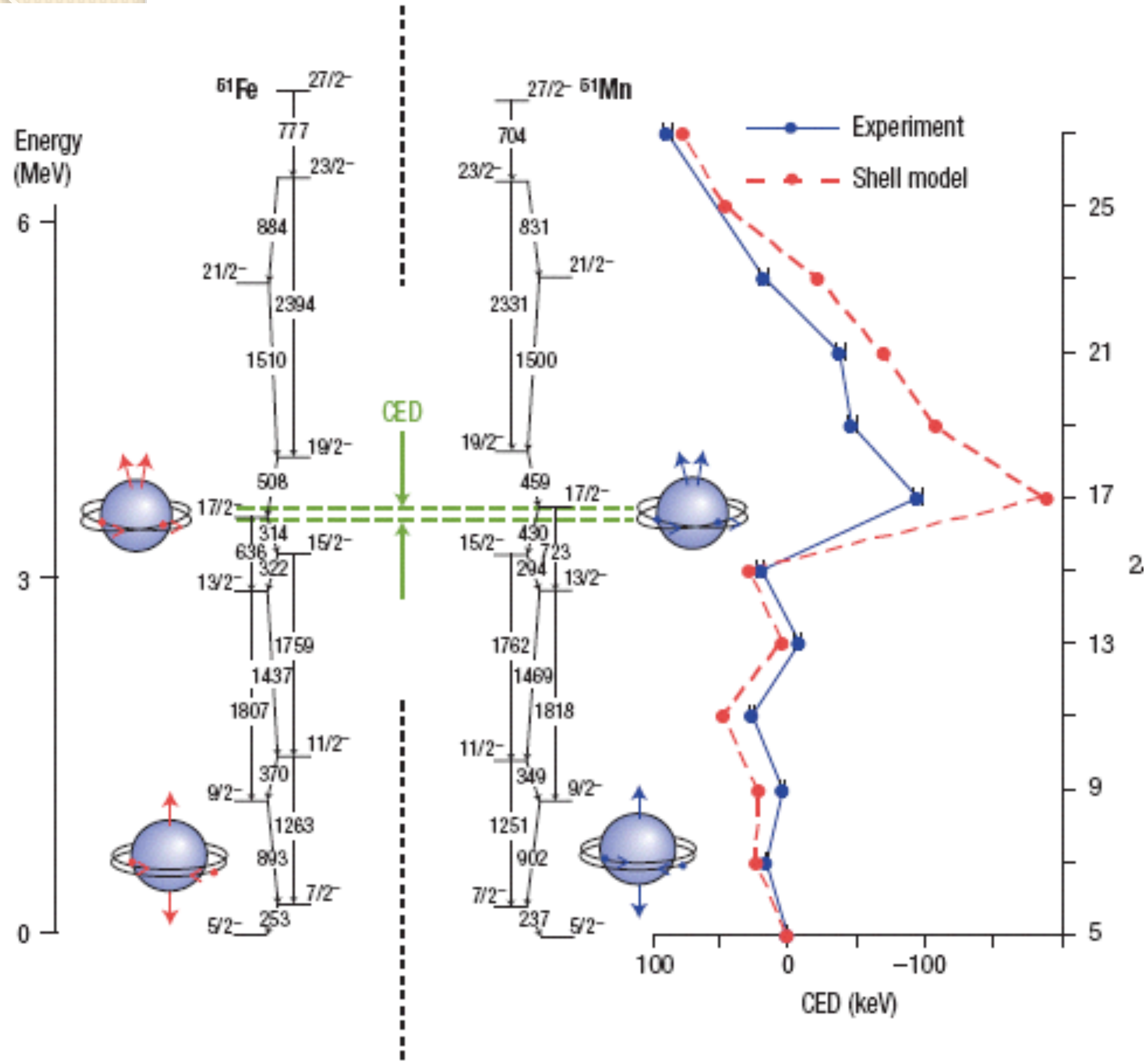
S=1, T=0

And neutron-proton pairing

Increasing dominance of T=1 in odd-odd N=Z nuclei



Coulomb Energy Differences



Extremely sensitive to nuclear structure effects:

- •Rotational alignment mechanism
- •Correlations of pairs of particles
- •Changes in deformation
- •The evolution of nuclear radii

D.D. Warner et al., Nature Physics 2, 311 (2006)

For T=1 triplets:

$$\mathrm{MED}_J = E^*_{J,T_z=-1} - E^*_{J,T_z=+1}.$$

Mirror energy differences are isovector and sensitive to:
single-particle Coulomb shifts, electromagnetic spin-orbit interaction,
changes of shape/radius of nuclei

$$\mathrm{TED}_J = E^*_{J,T_z=-1} + E^*_{J,T_z=+1} - 2E^*_{J,T_z=0}.$$

Isotensor energy differences reflecting differences between nn, pp and pn force.
Not sensitive to one-body terms but only two-body
i.e. sensitive to Coulomb multipole and isospin-nonconserving forces

Shapes of N=Z nuclei

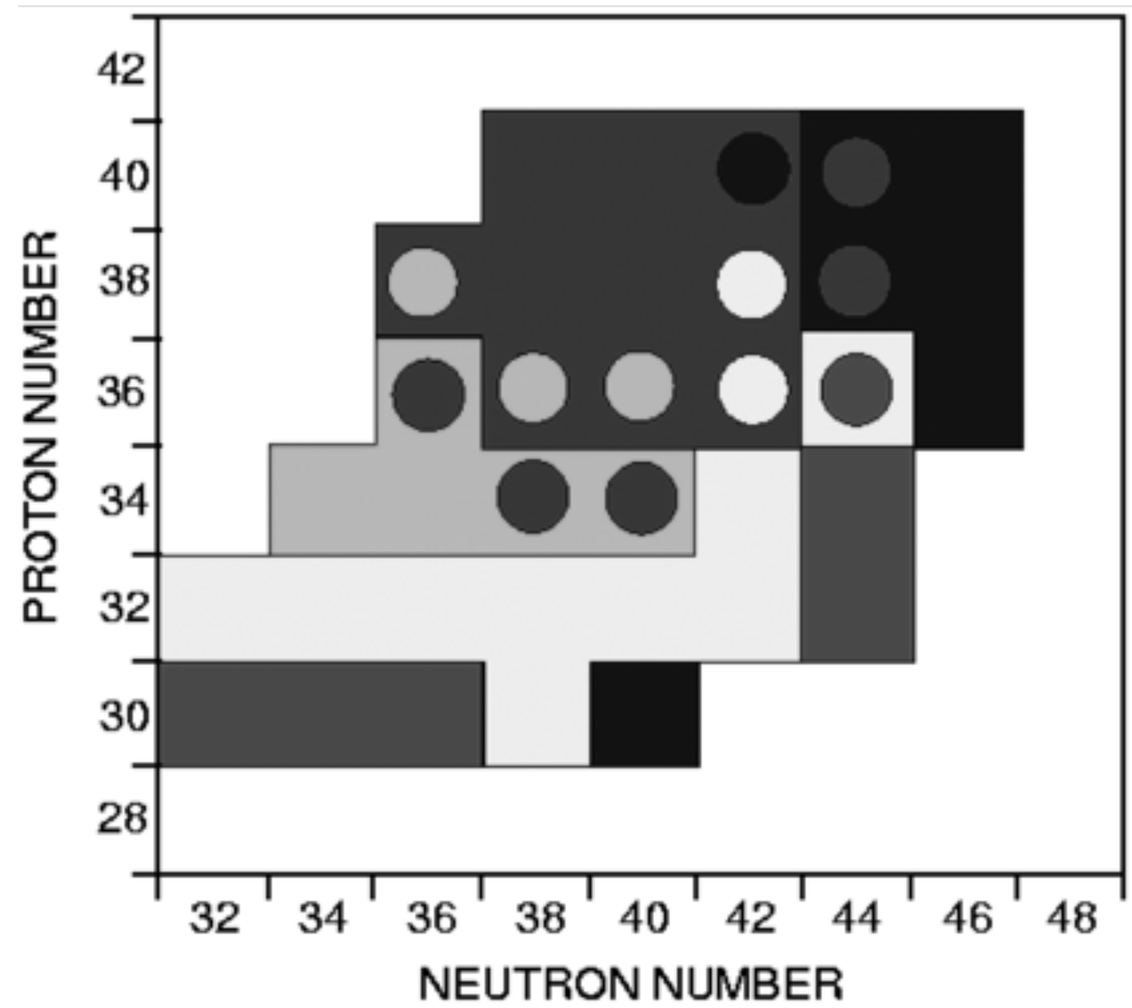
Very Prolate
Oblate
Triaxial

Very, very sensitive to underlying quantum structure…

The original phenomonological "M-M" theory, (Microscopic Macroscopic) was very sound.

P. Moller and J.R. Nix. At. Nuc. Data Tables, 26 (1981) 1965
S. Aberg. Phys Scr. 25 (1982) 23
W. Nazarewicz. Nucl. Phys A435 (1985) 397.
R. Bengtsson. Conf on the structure in the zirconium region, 1988

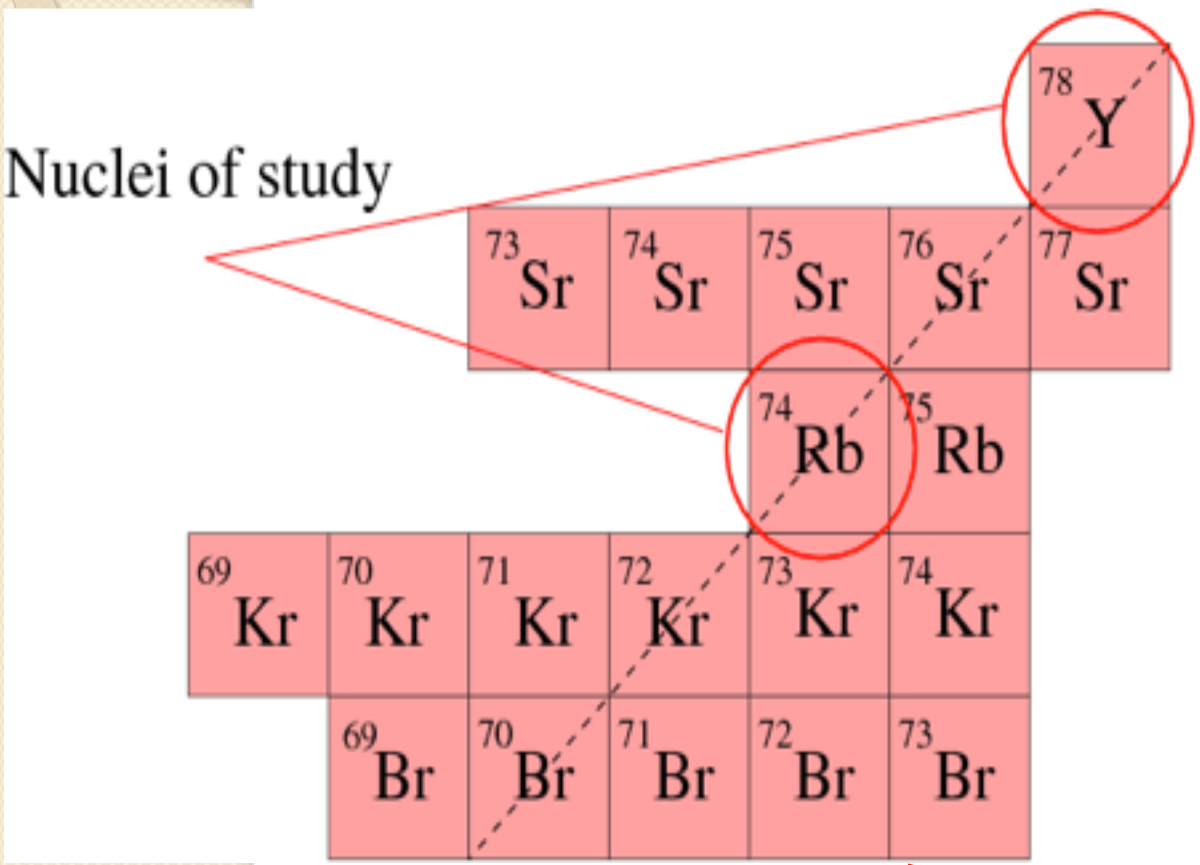
{Classic "Potential Energy Surface" calculations
…. BUT

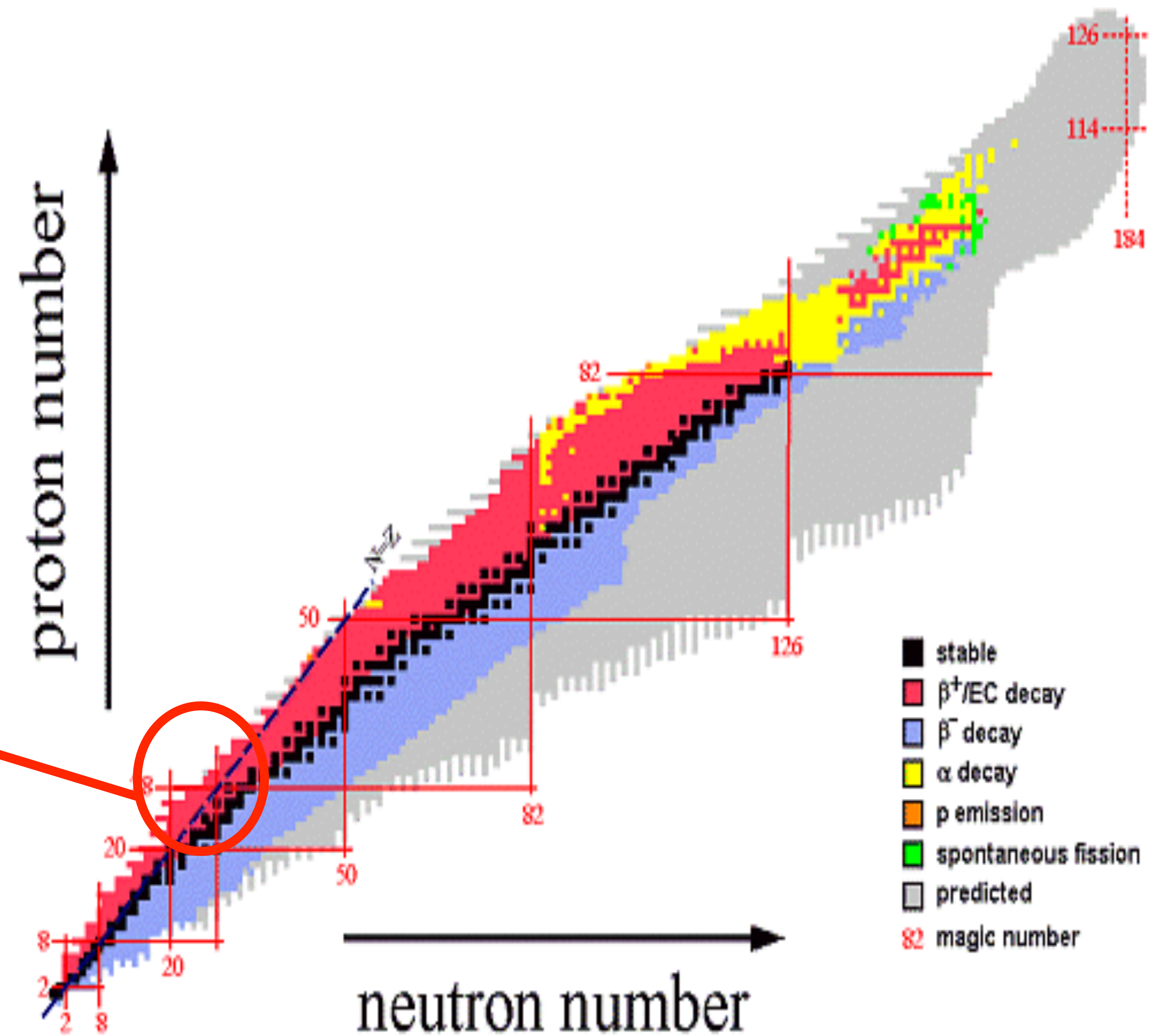


The whole concept of isolated "shapes" is naive: there are multiple shapes with lots of mixing, as the barriers between shapes are not high.

Recoil-beta tagging

The region of interest



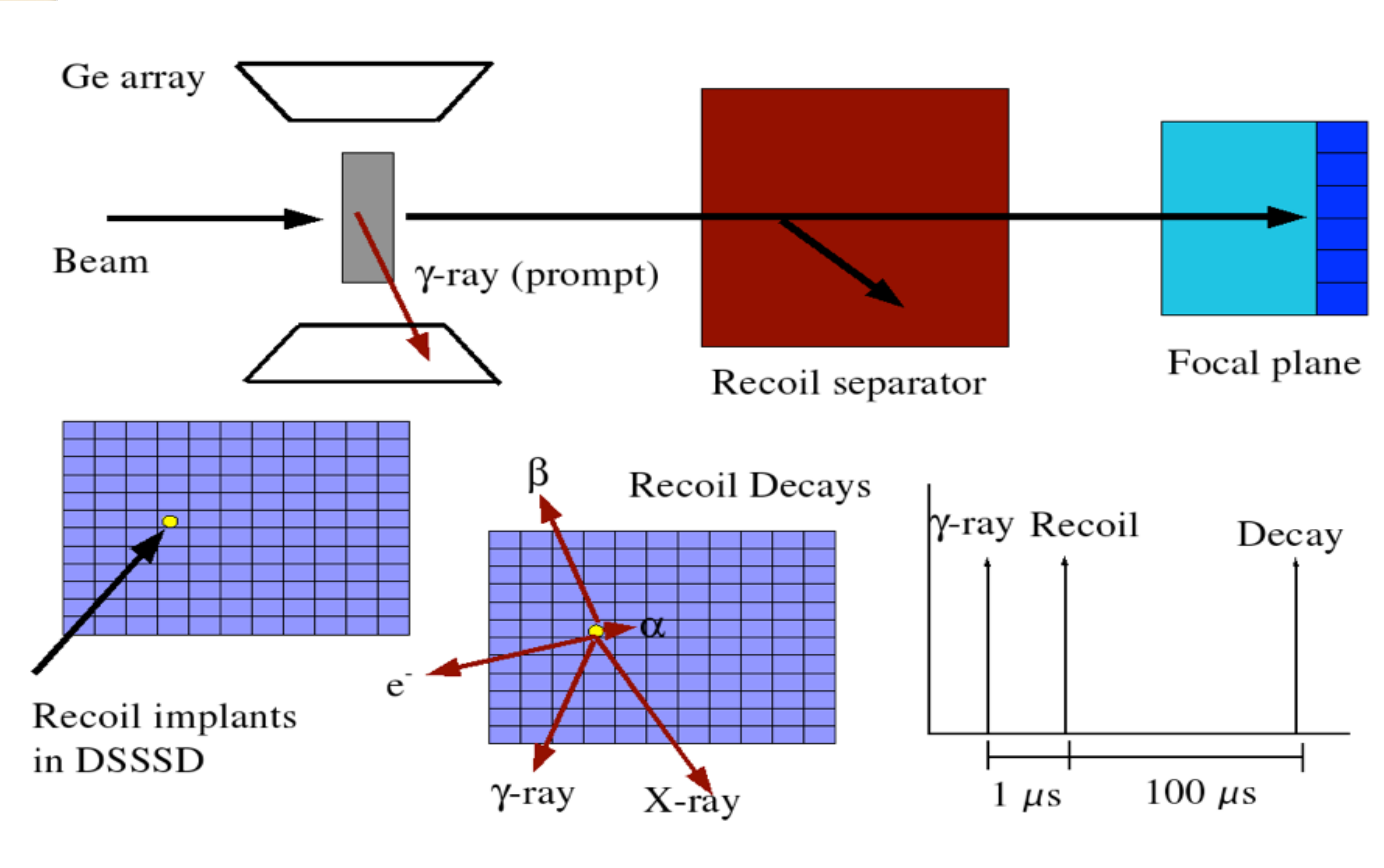


Isospin symmetry

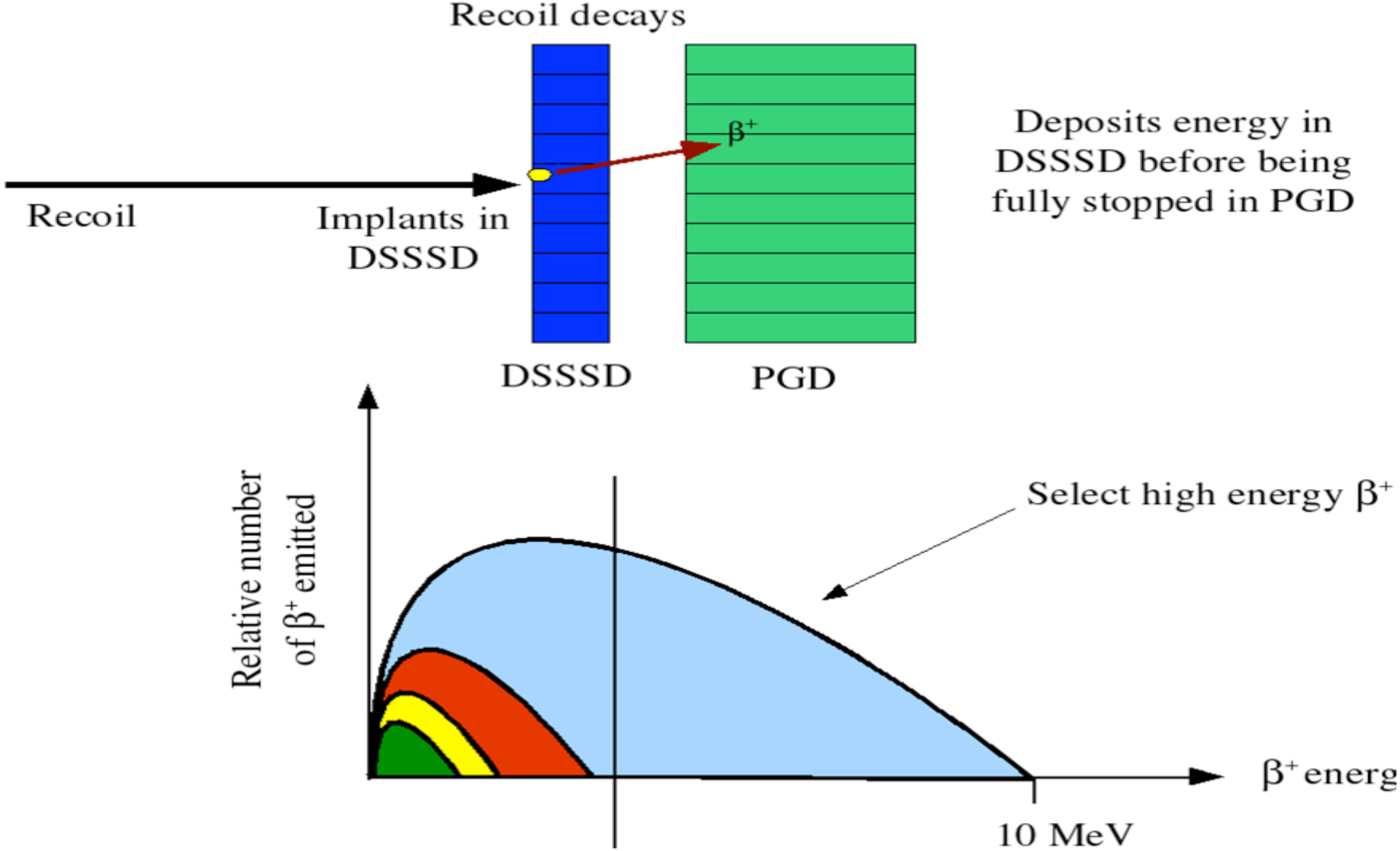
Shape-coexistence

rp-process

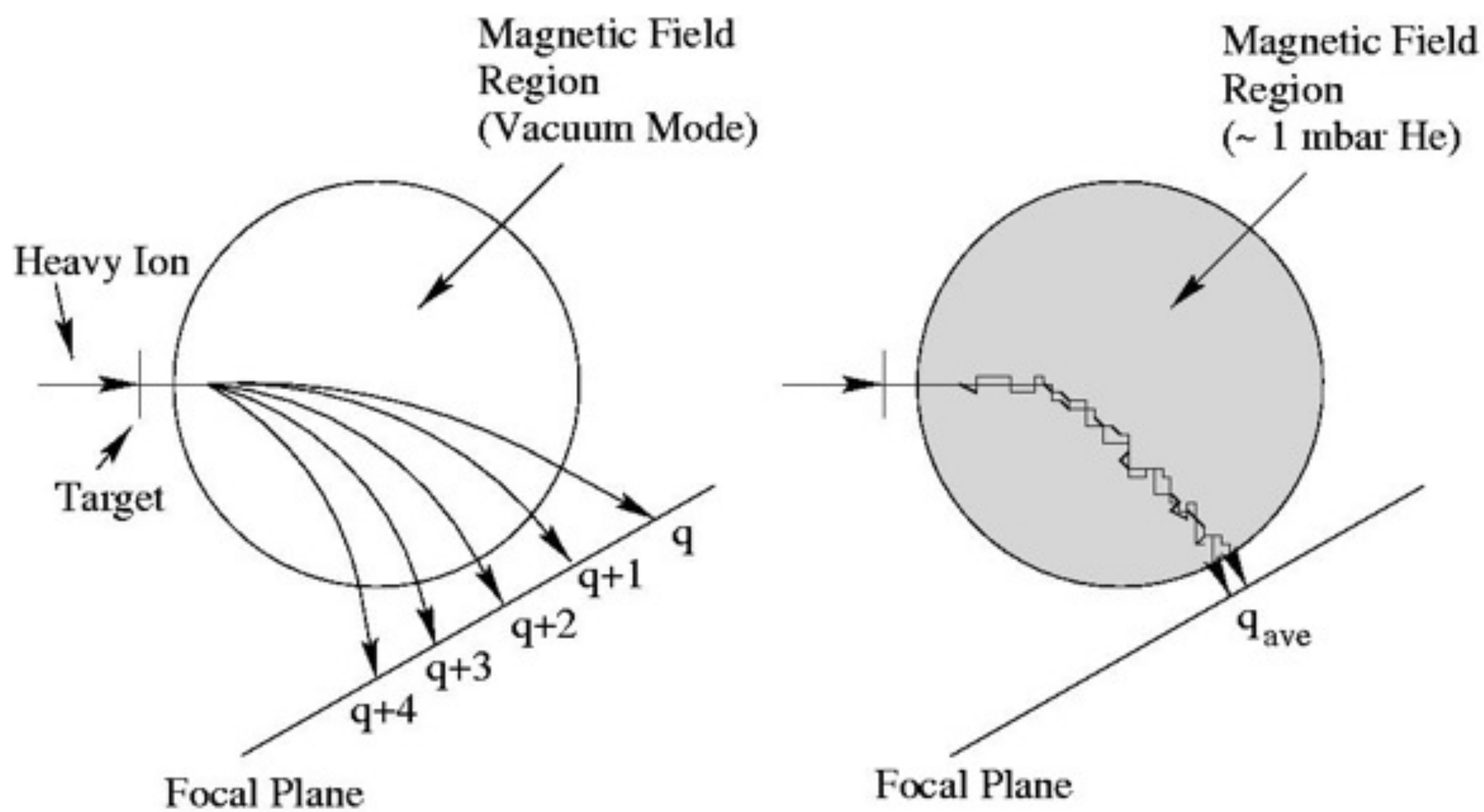
Recoil-decay tagging



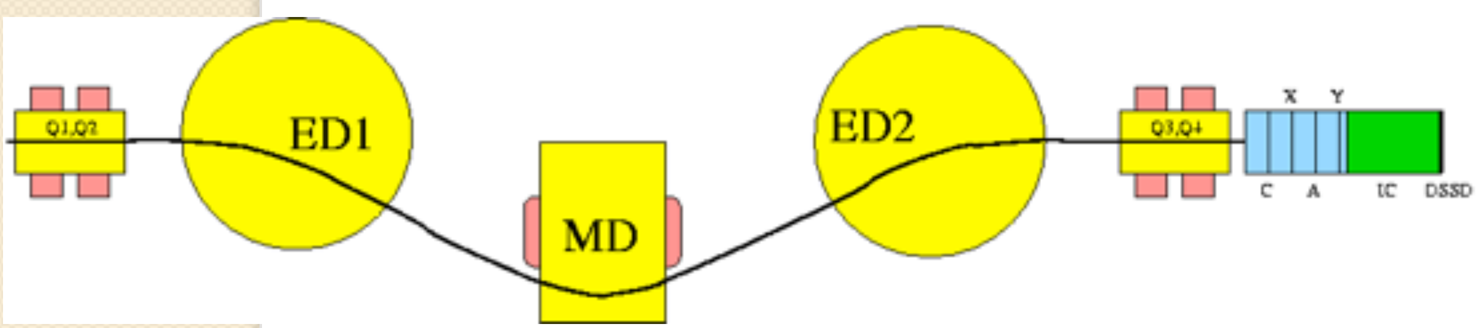
Recoil-beta tagging



Recoil separators



RITU (Jyvaskyla)

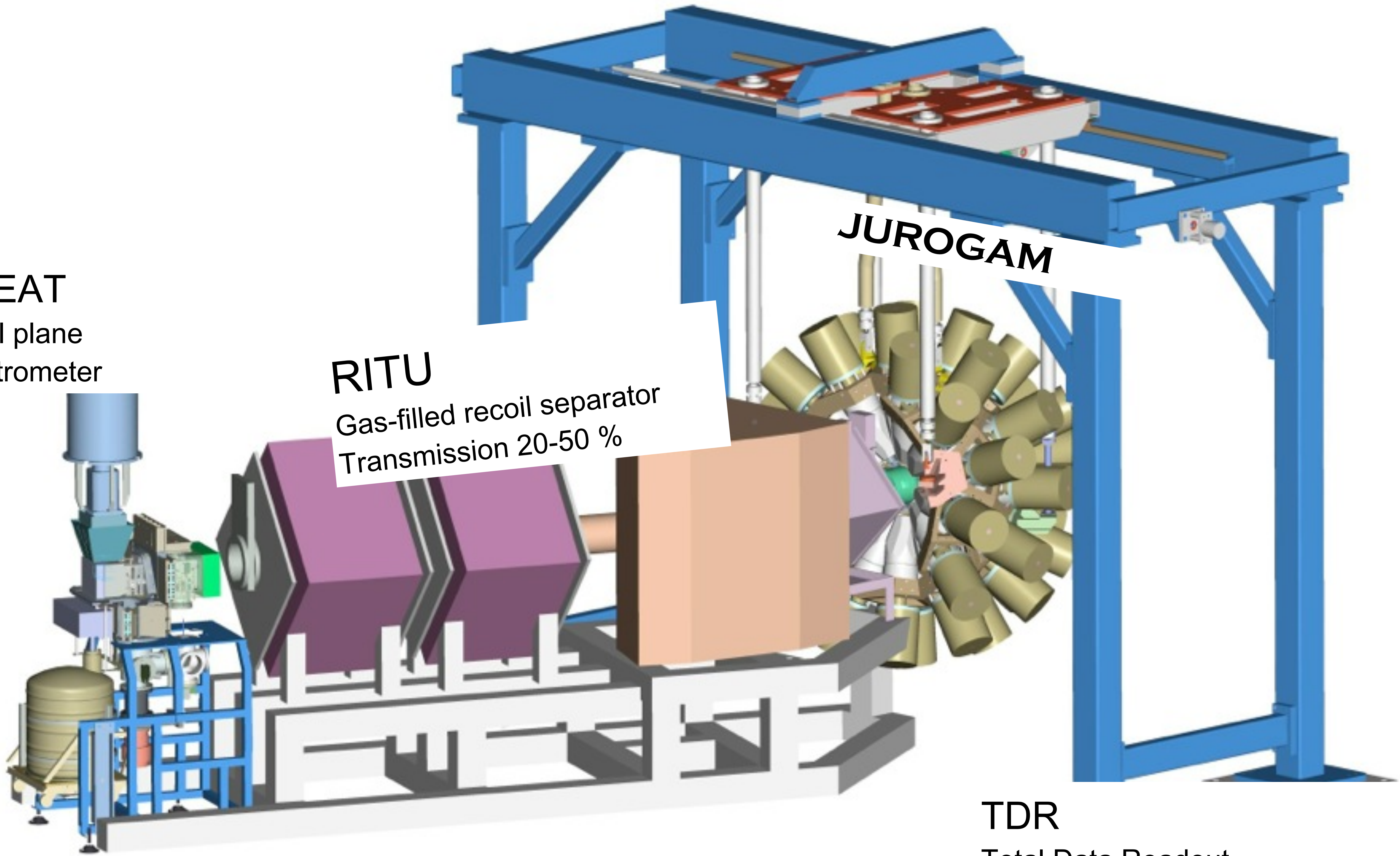


FMA (Argonne)

RDT Instrumentation at JYFL

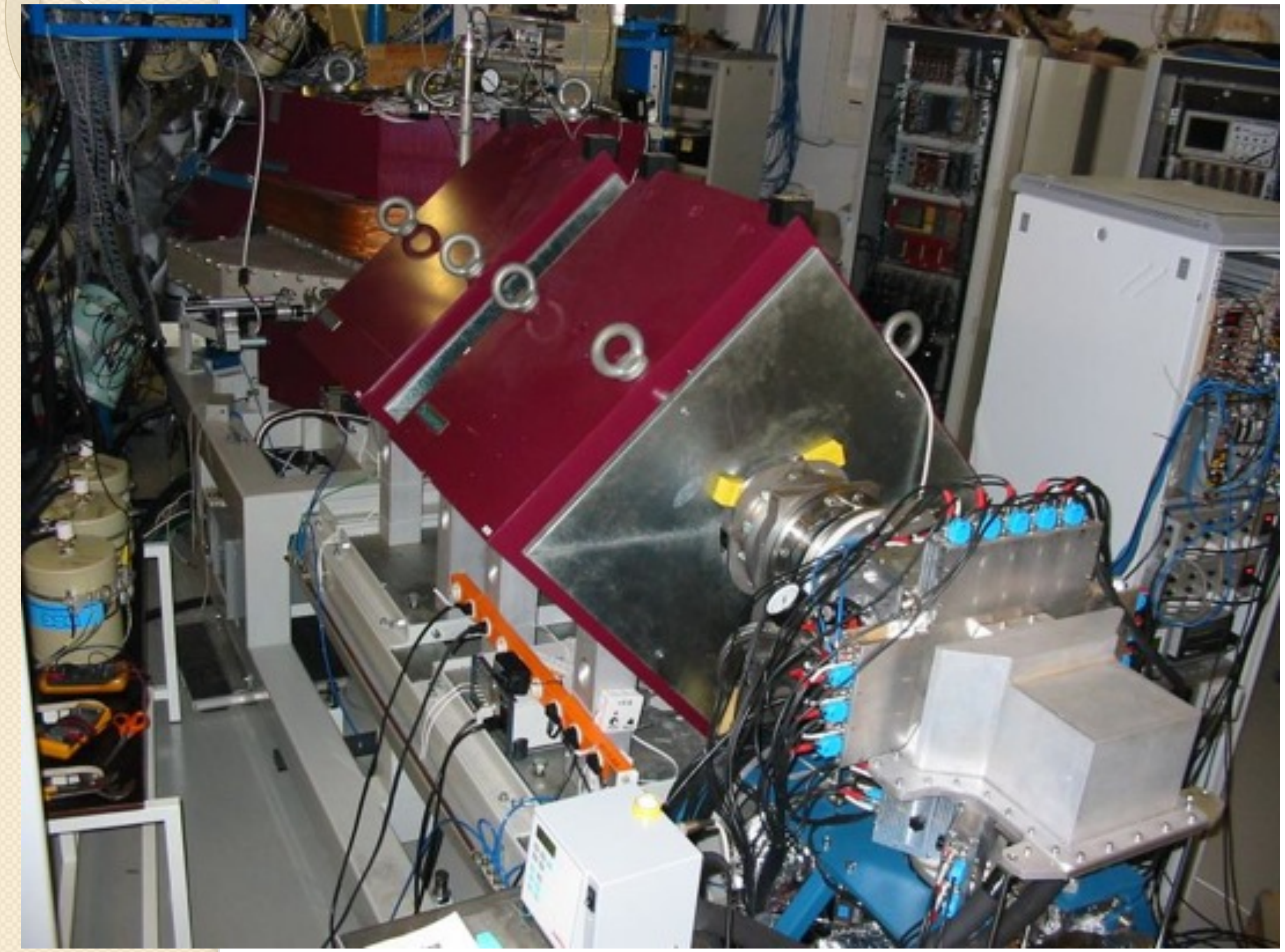
GREAT
Focal plane
spectrometer

RITU
Gas-filled recoil separator
Transmission 20-50 %

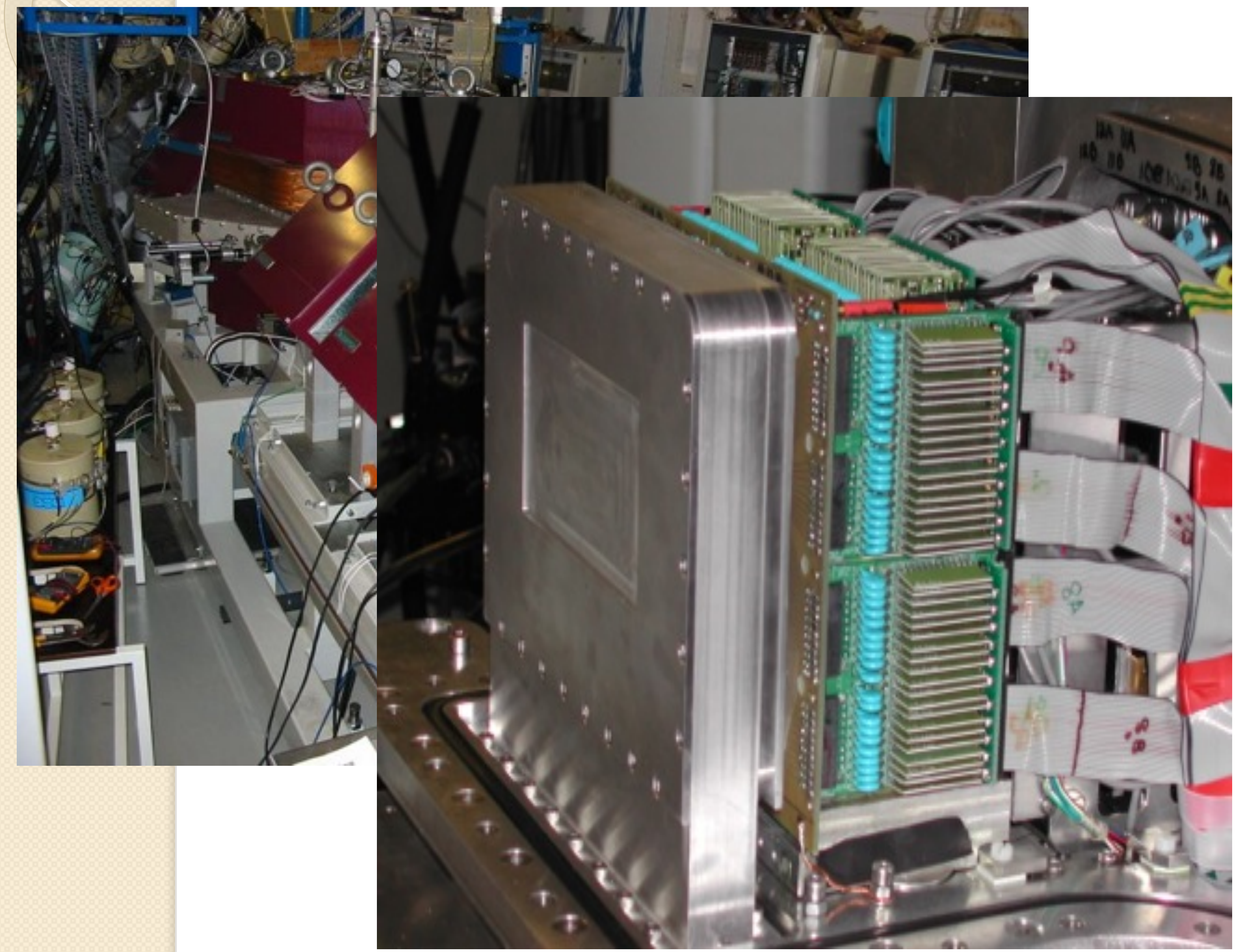


TDR
Total Data Readout
Triggerless data acquisition system
with 10 ns time stamping

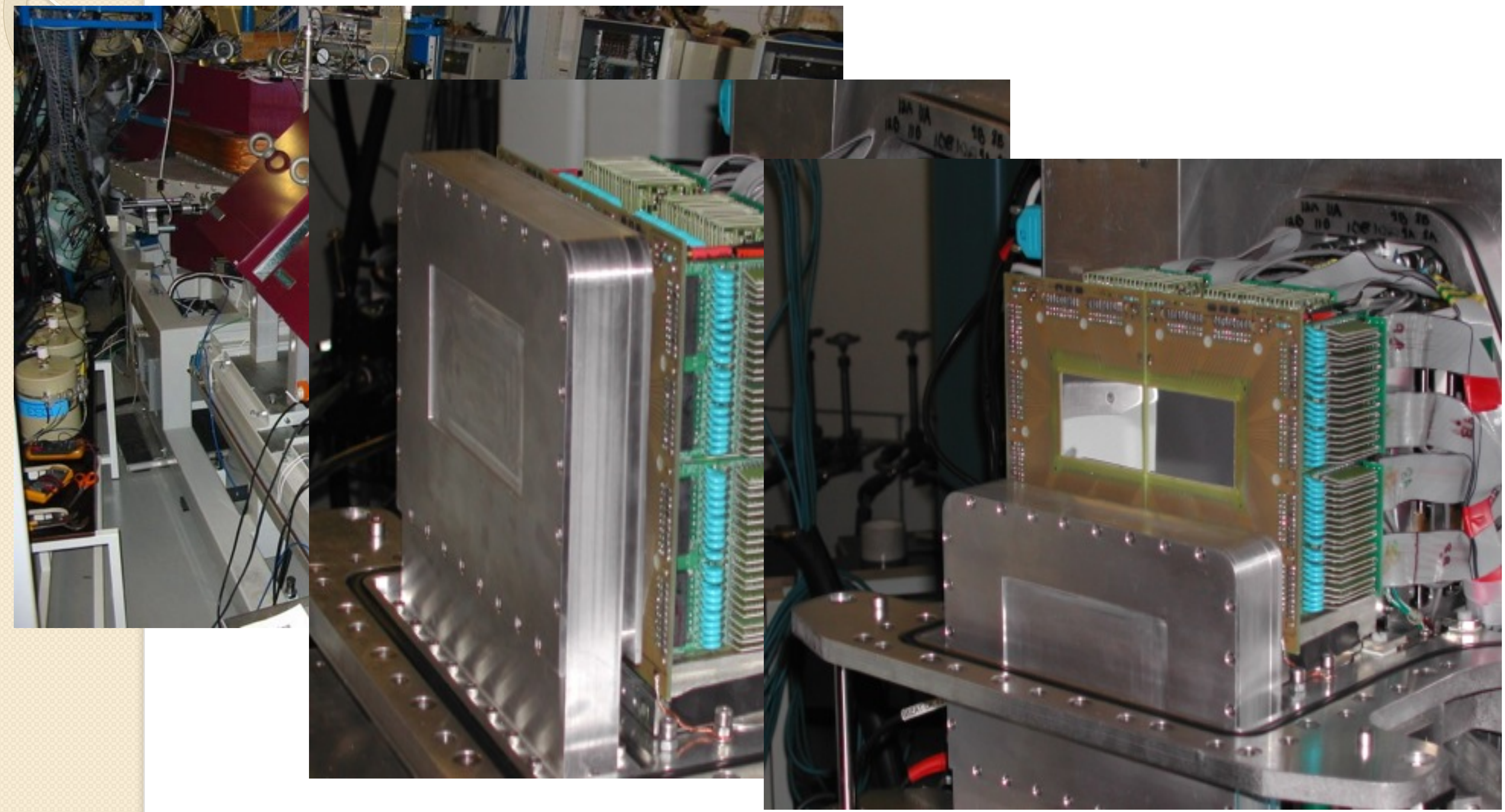
RITU+GREAT



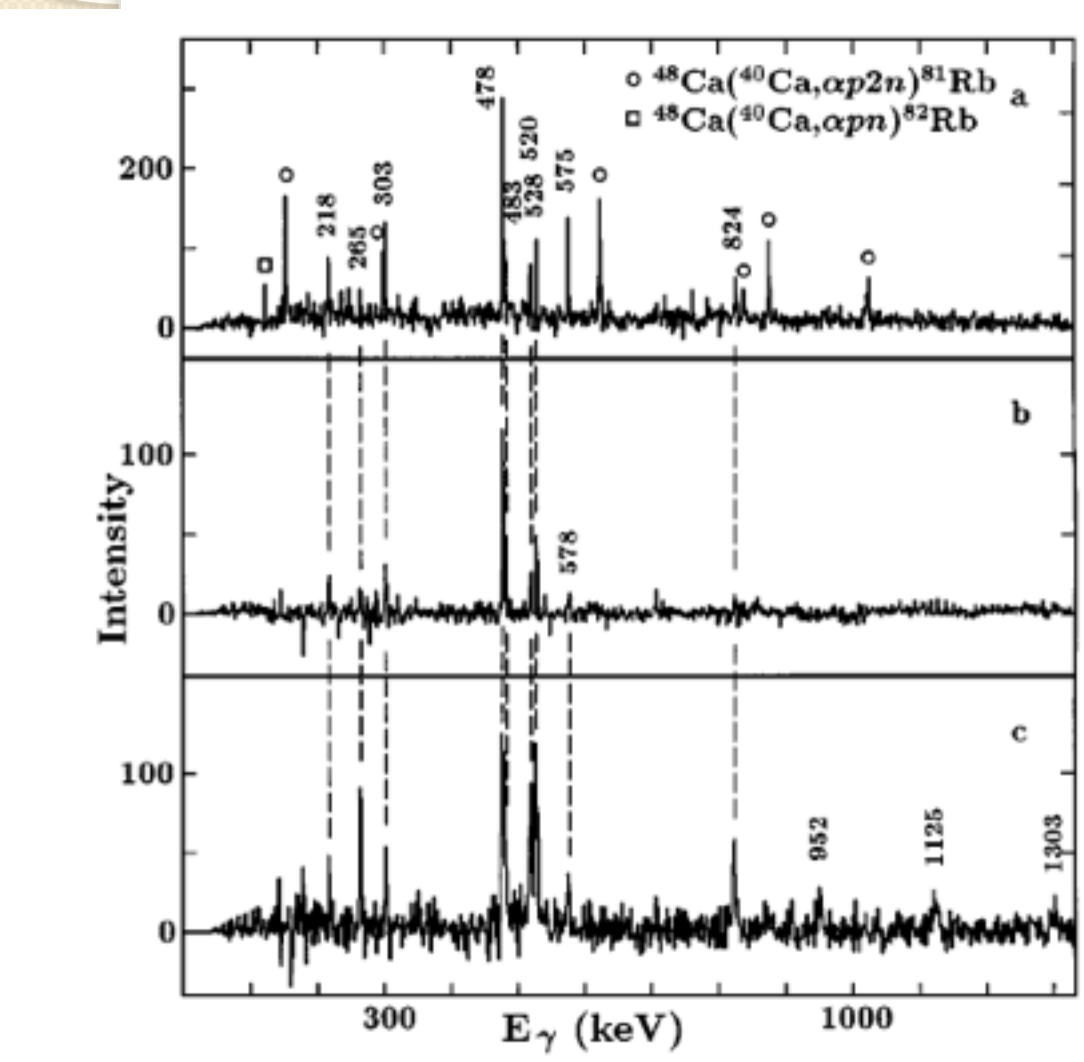
RITU+GREAT

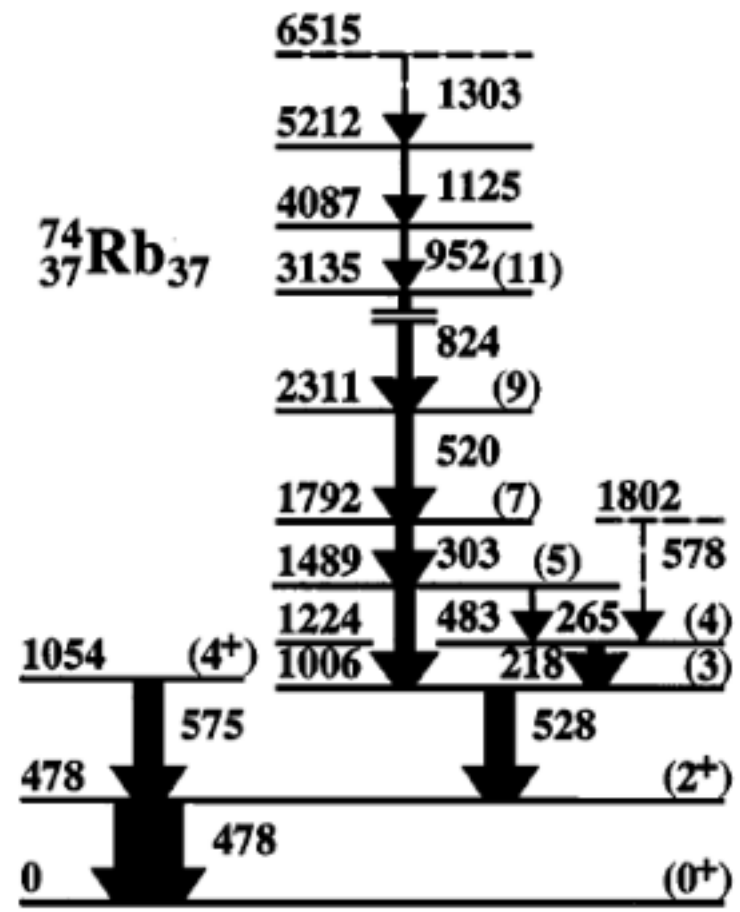


RITU+GREAT



Test case: ^{74}Rb





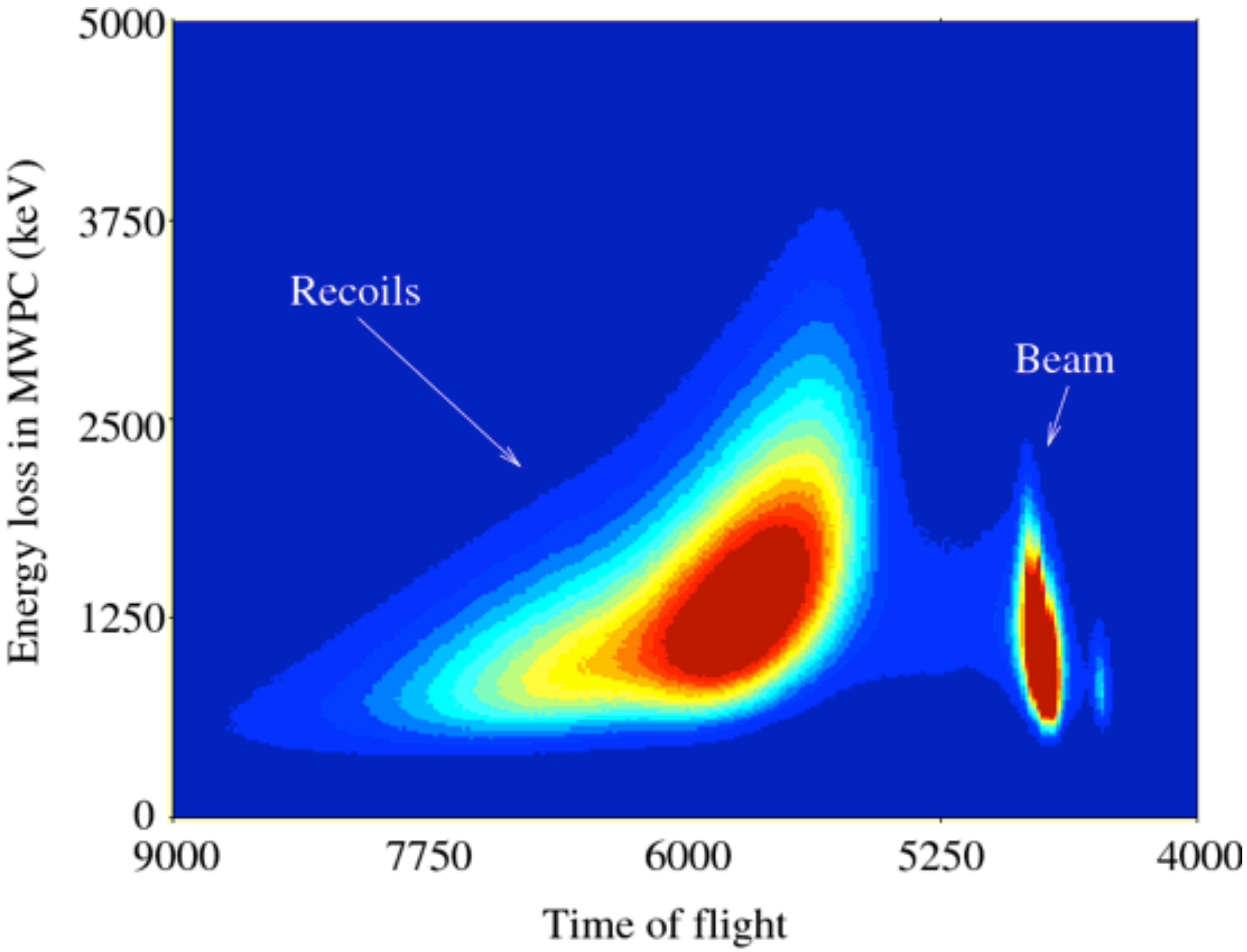
VOLUME 76, NUMBER 3 PHYSICAL REVIEW LETTERS 15 JANUARY 1996

Identification of $T = 0$ and $T = 1$ Bands in the $N = Z = 37$ Nucleus ^{74}Rb

D. Rudolph,[1,*] C. J. Gross,[2,3] J. A. Sheikh,[4] D. D. Warner,[5] I. G. Bearden,[6] R. A. Cunningham,[5] D. Foltescu,[7] W. Gelletly,[8] F. Hannachi,[5,†] A. Harder,[1] T. D. Johnson,[1,‡] A. Jungclaus,[1] M. K. Kabadiyski,[1] D. Kast,[1] K. P. Lieb,[1] H. A. Roth,[7] T. Shizuma,[6] J. Simpson,[5] Ö. Skeppstedt,[7] B. J. Varley,[9] and M. Weiszflog[1]

Proof-of-principle

- ^{nat}Ca (^{36}Ar, pn) ^{74}Rb
- E_{beam} = 103 MeV
- $\tau_{1/2}$ (^{74}Rb) = 65 ms
- $\beta^{+}_{endpoint}$ ~ 10 MeV
- σ ~ 10 μb



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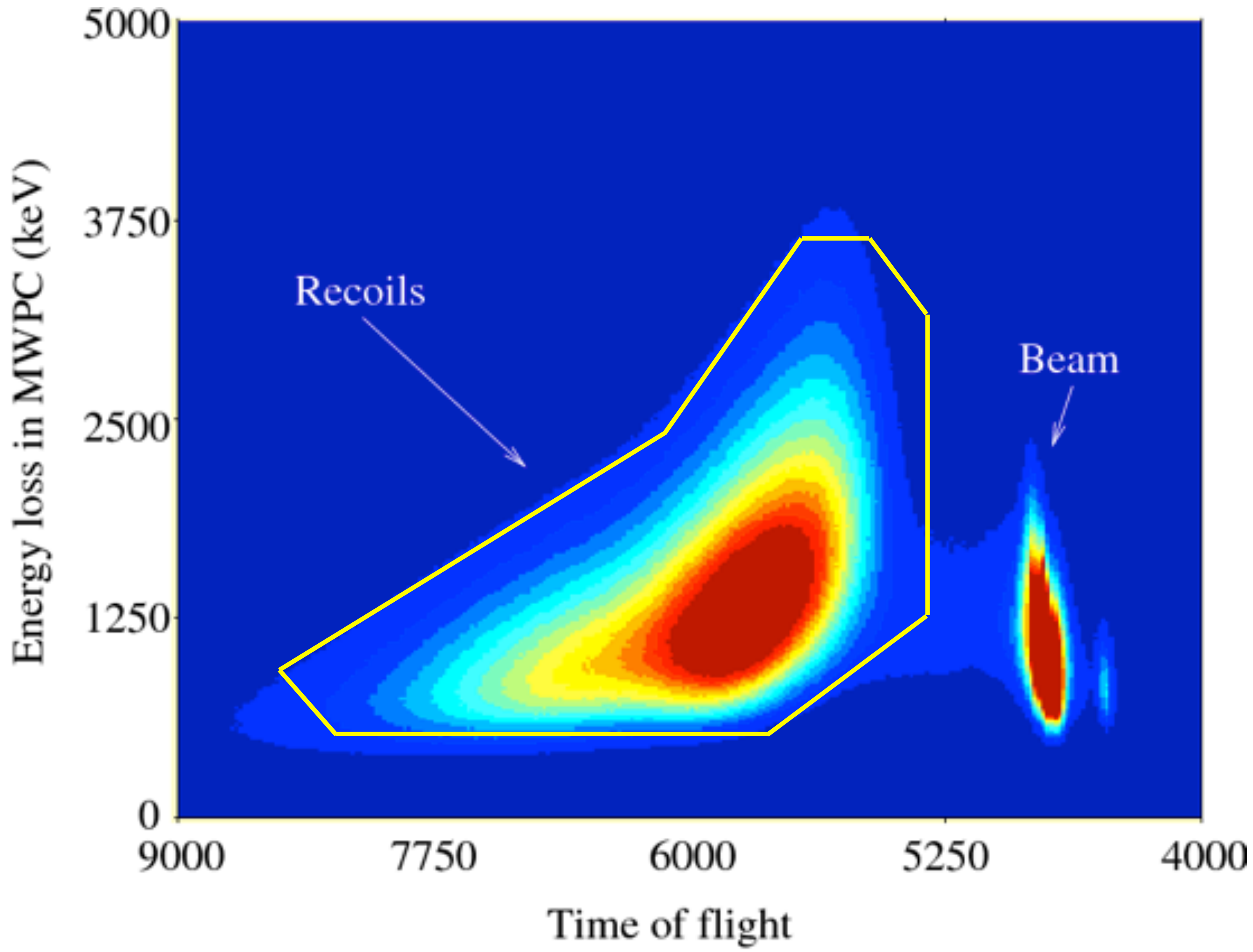
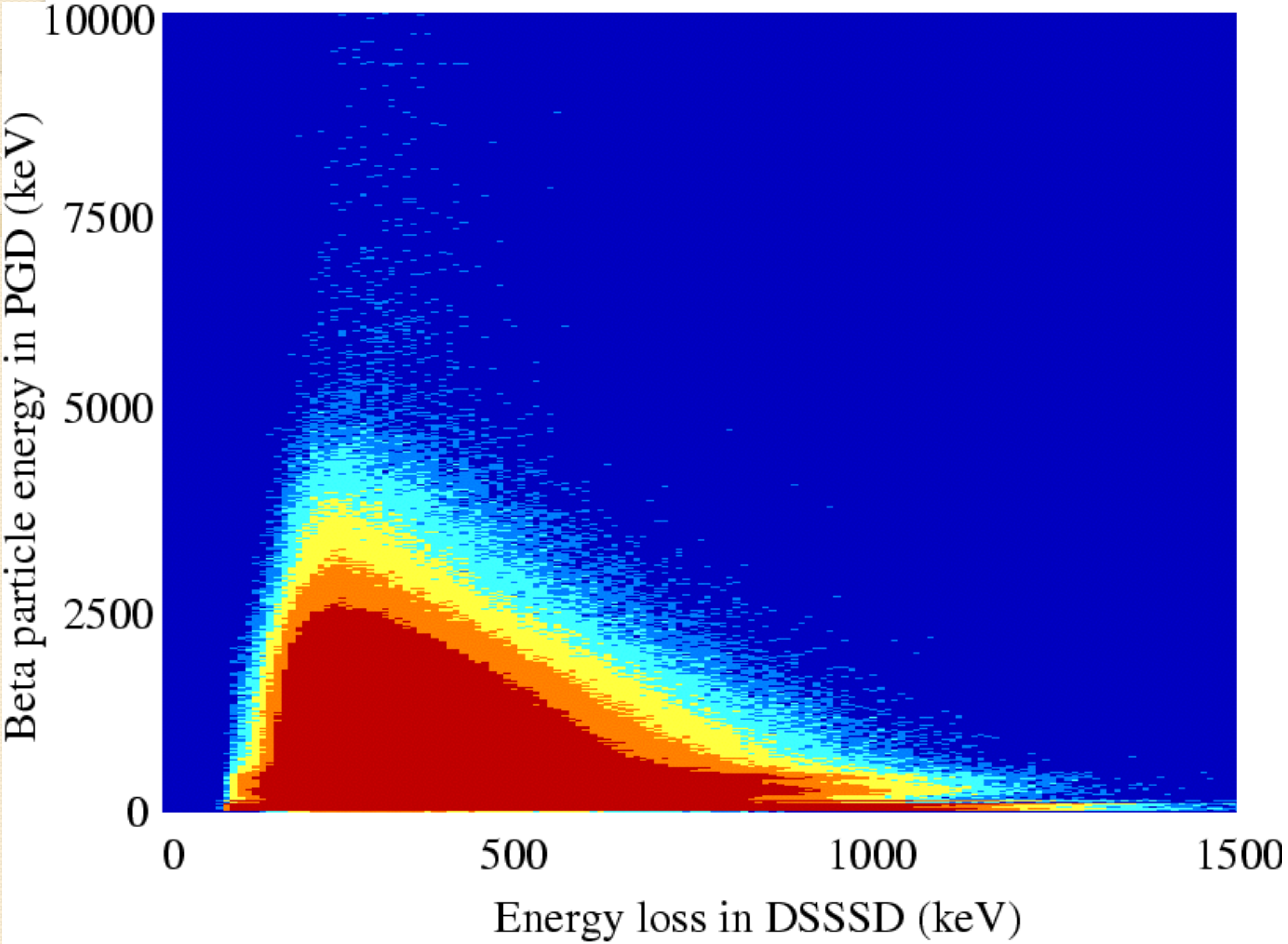
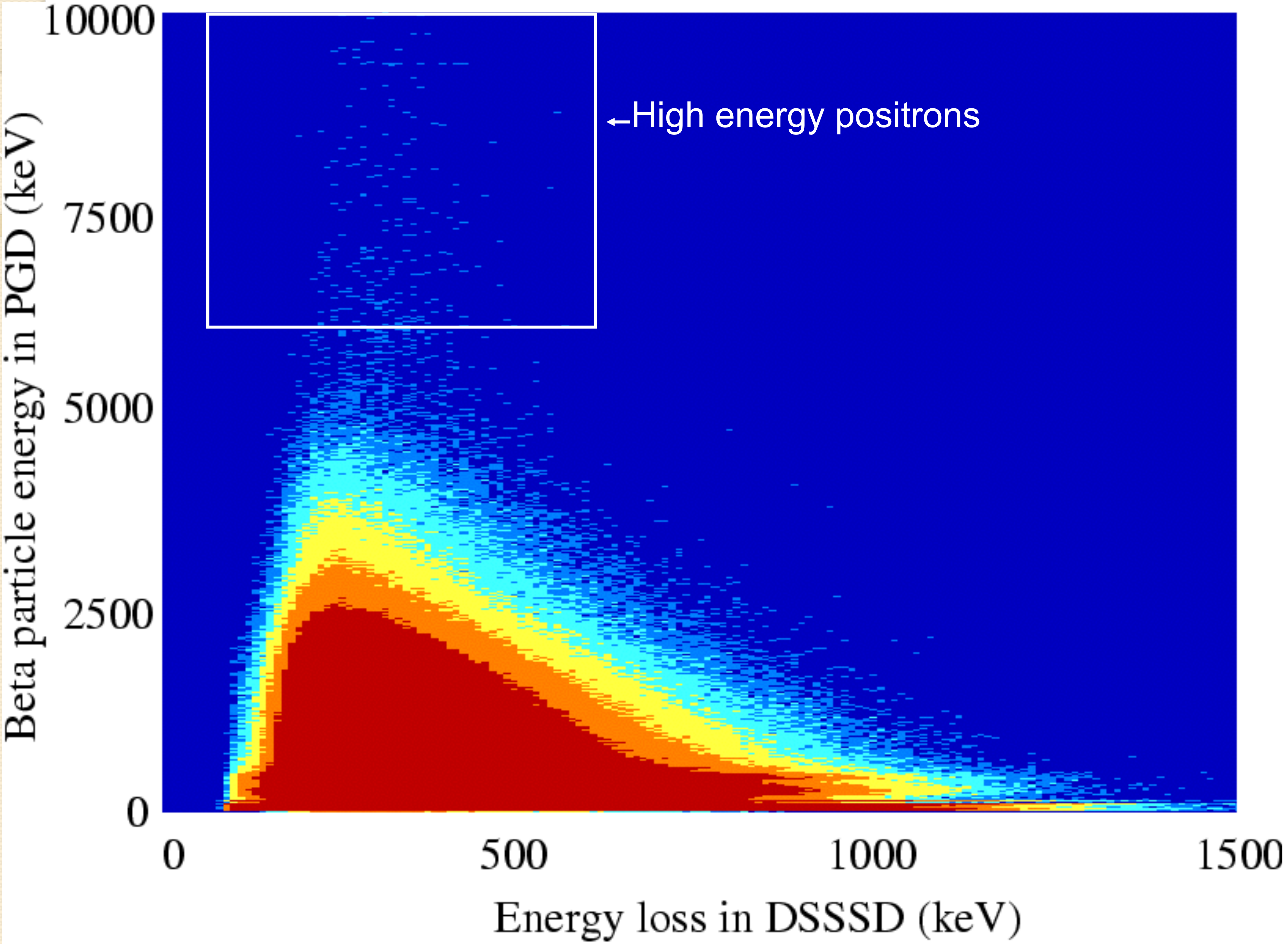
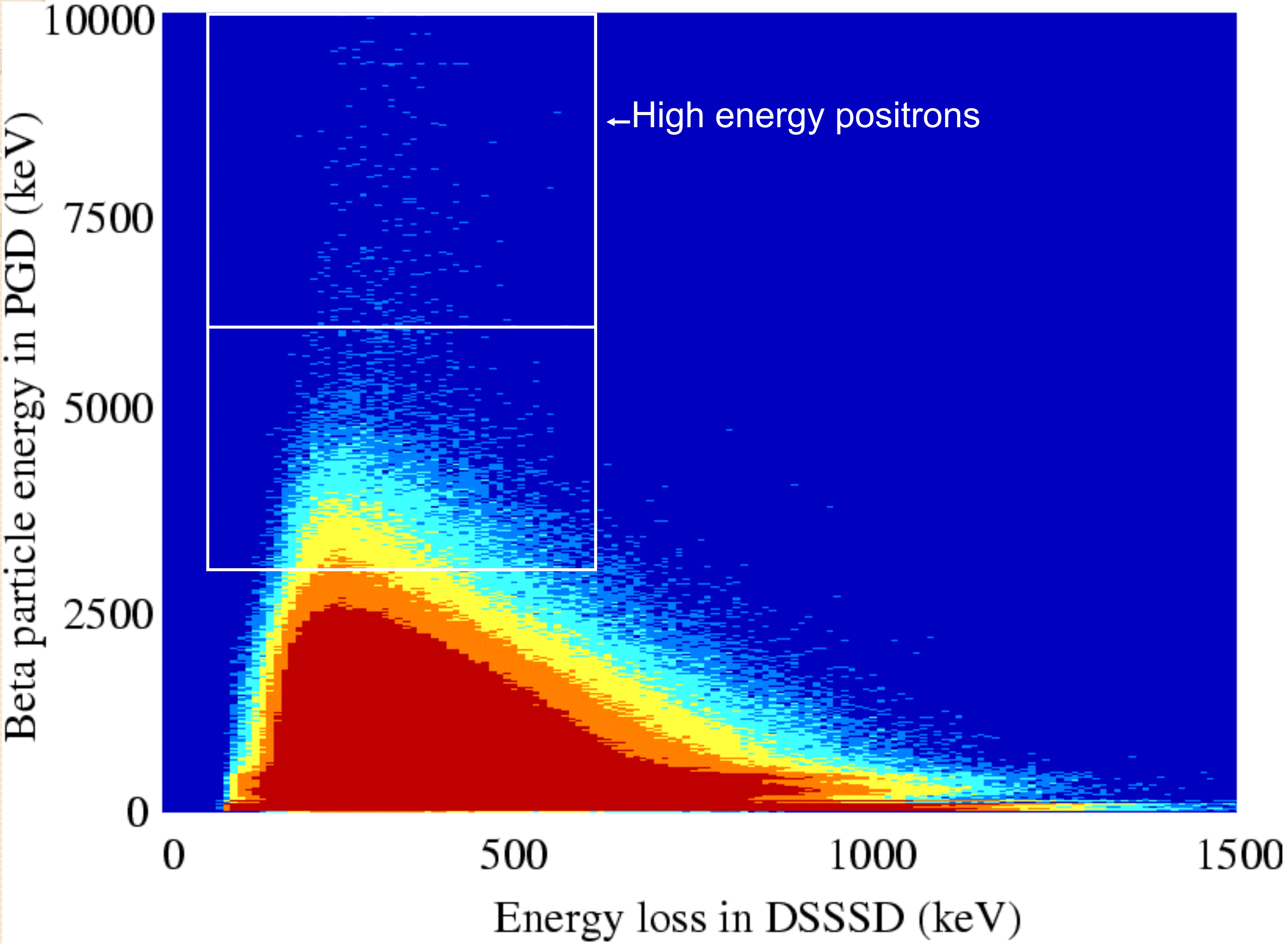


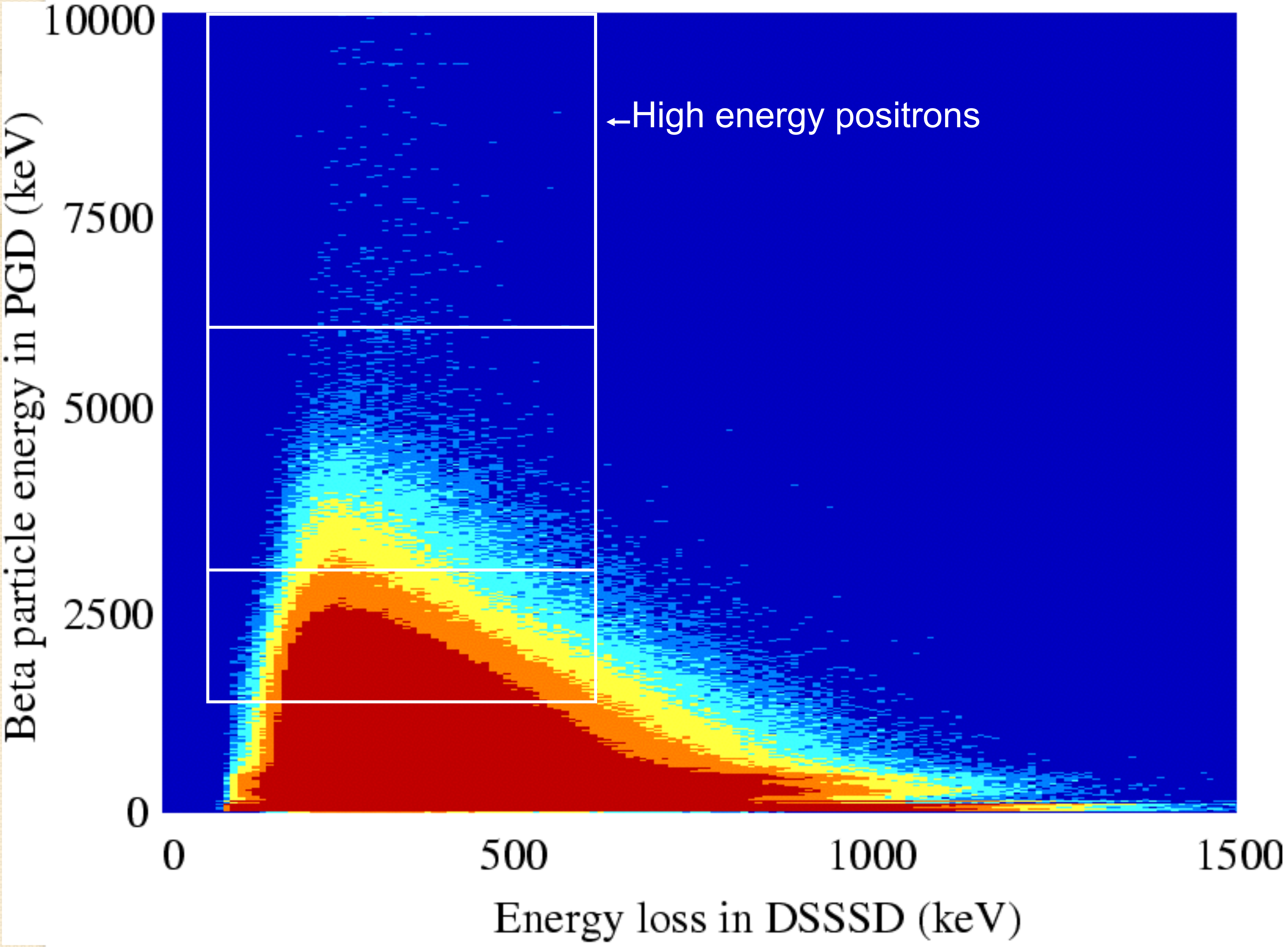


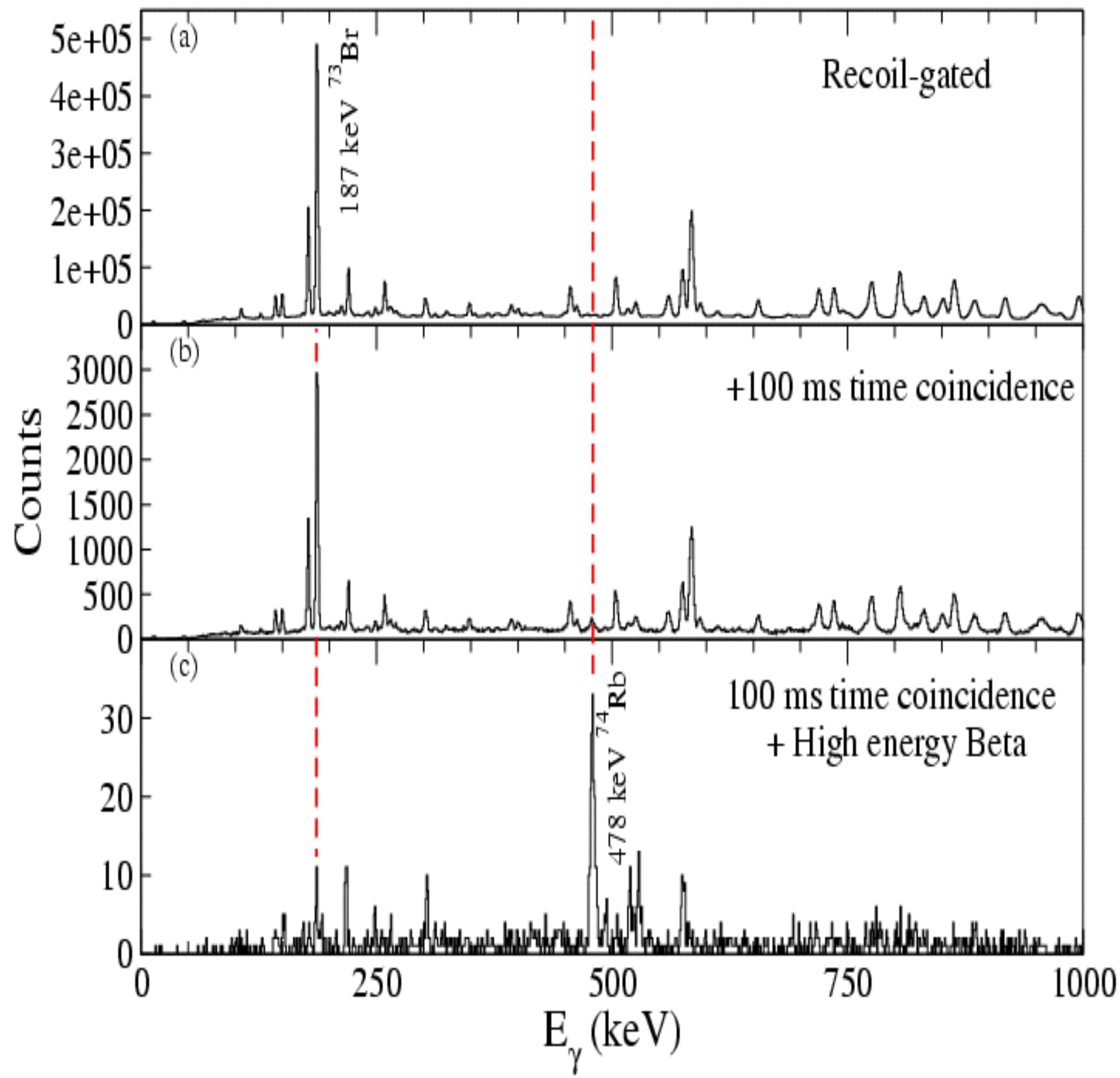
10000
7500
5000
2500
0
0
500
1000
1500
Beta particle energy in PGD (keV)
Energy loss in DSSSD (keV)



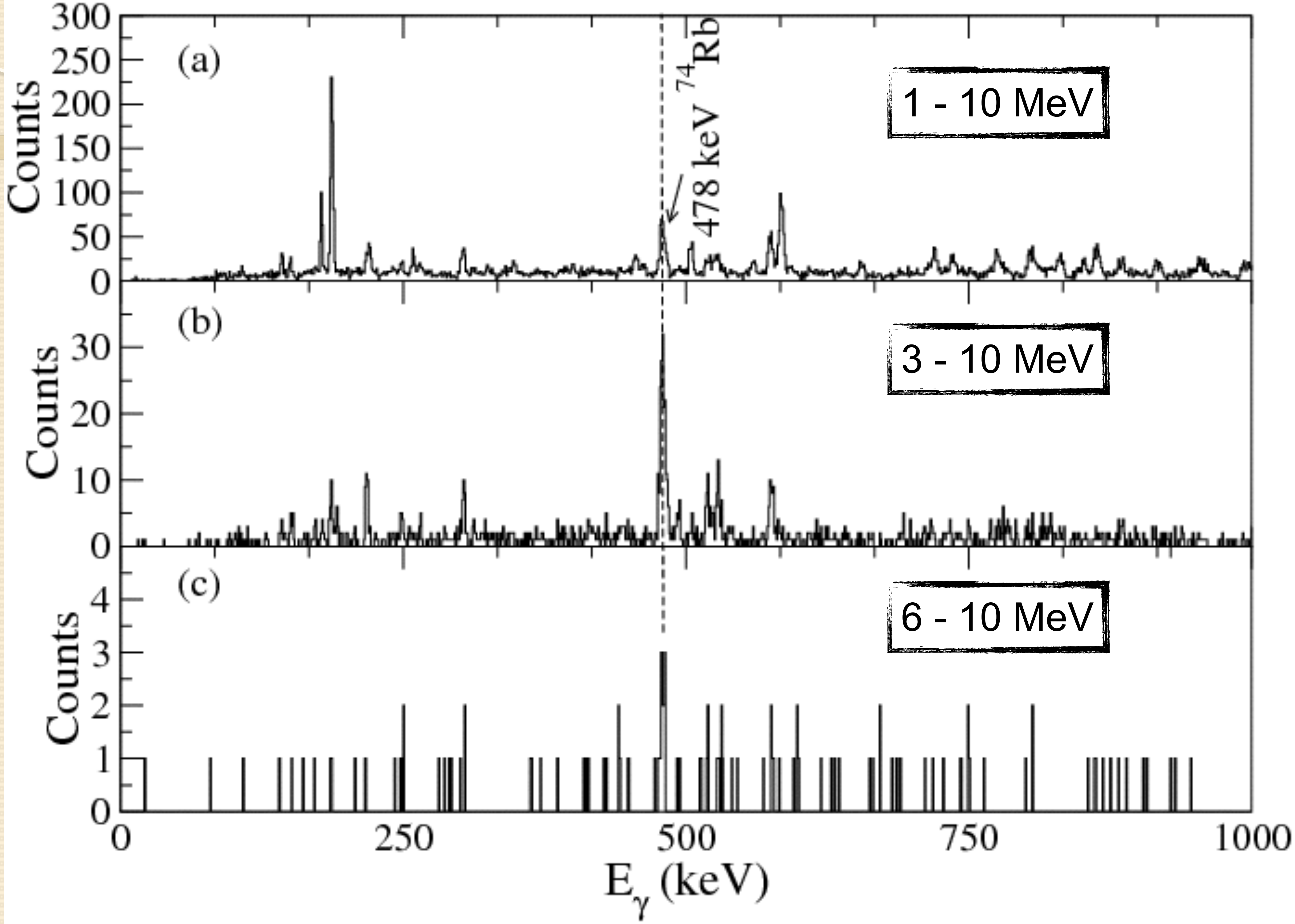
10000
7500
5000
2500
0
Beta particle energy in PGD (keV)
0
500
1000
1500
Energy loss in DSSSD (keV)
←High energy positrons


10000
7500
5000
2500
0
Beta particle energy in PGD (keV)
High energy positrons
0
500
1000
1500
Energy loss in DSSSD (keV)


10000
7500
5000
2500
0
Beta particle energy in PGD (keV)
0
500
1000
1500
Energy loss in DSSSD (keV)
←High energy positrons

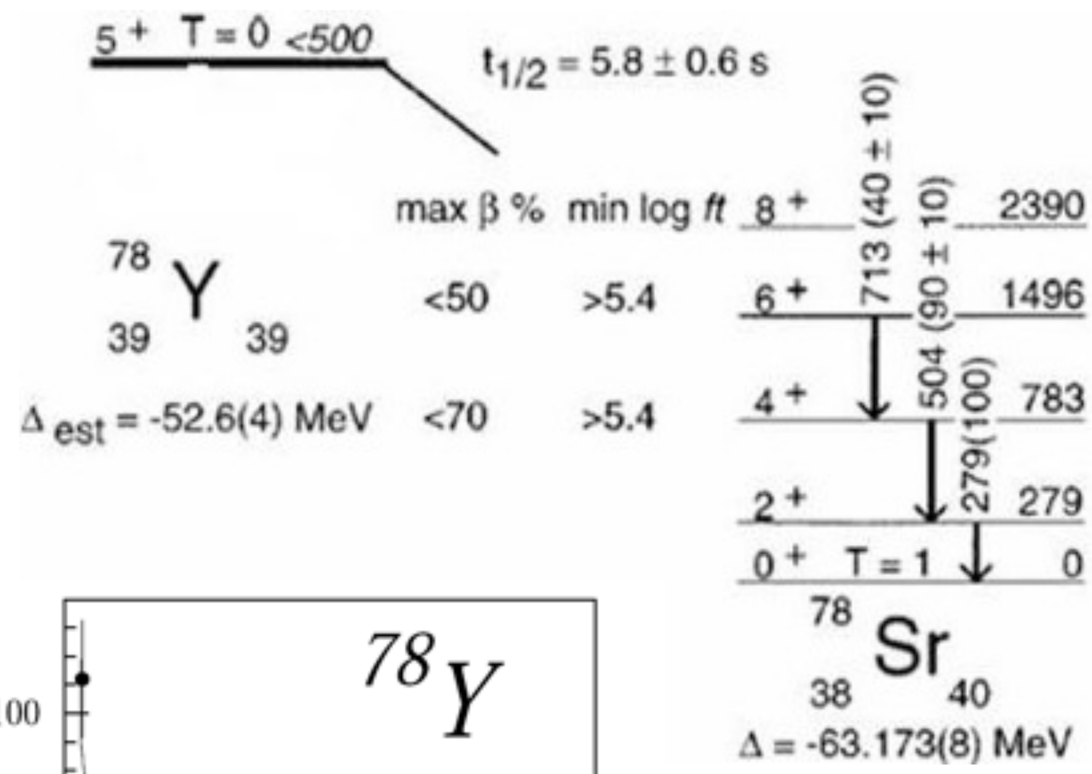

(a)
187 keV ^{73}Br
Recoil-gated
(b)
+100 ms time coincidence
(c)
478 keV ^{74}Rb
100 ms time coincidence
+ High energy Beta
Counts
E_γ (keV)
0
250
500
750
1000
5e+05
4e+05
3e+05
2e+05
1e+05
3000
2500
2000
1500
1000
500
30
20
10

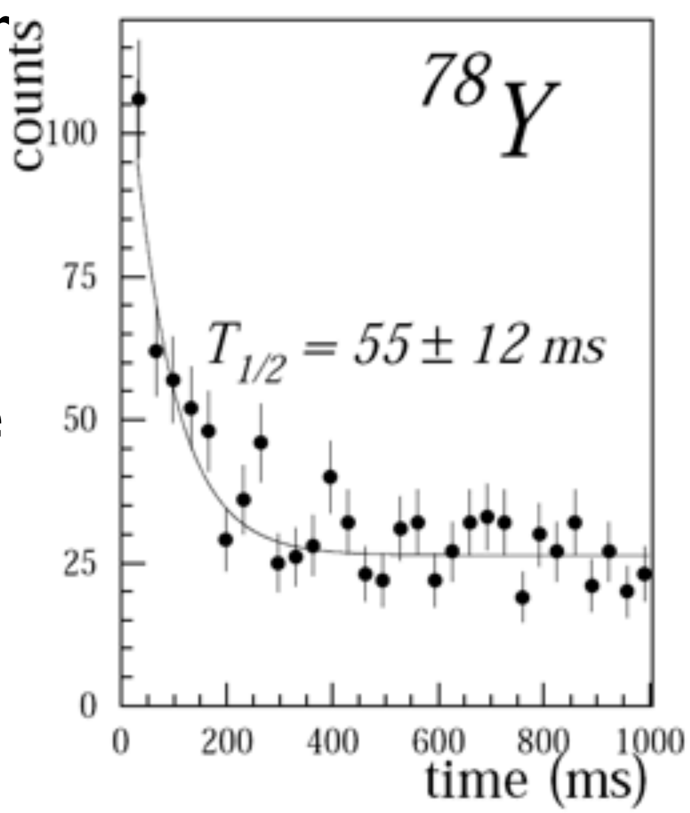
Varying the beta gate size

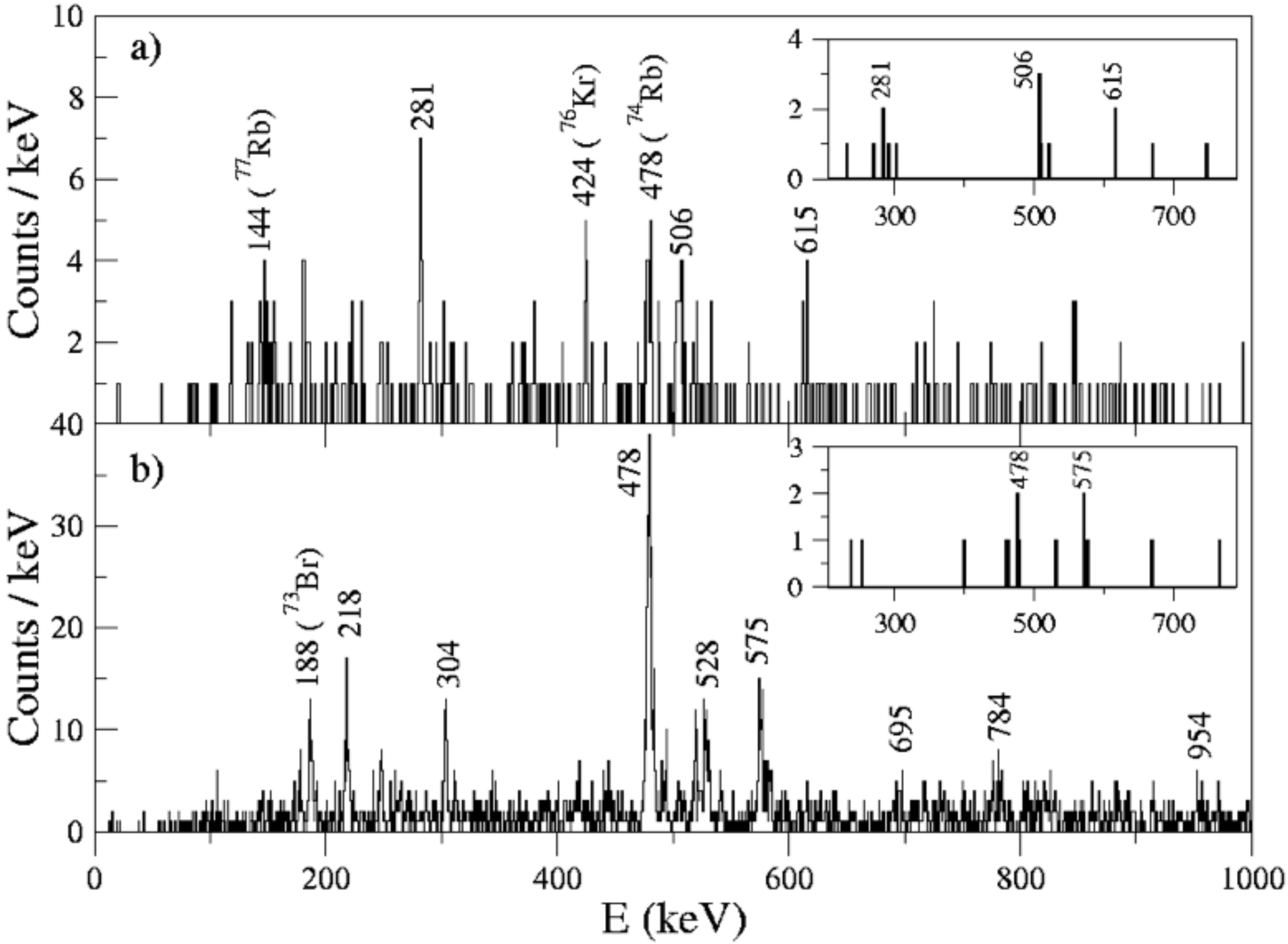


Unknown case: ^{78}Y

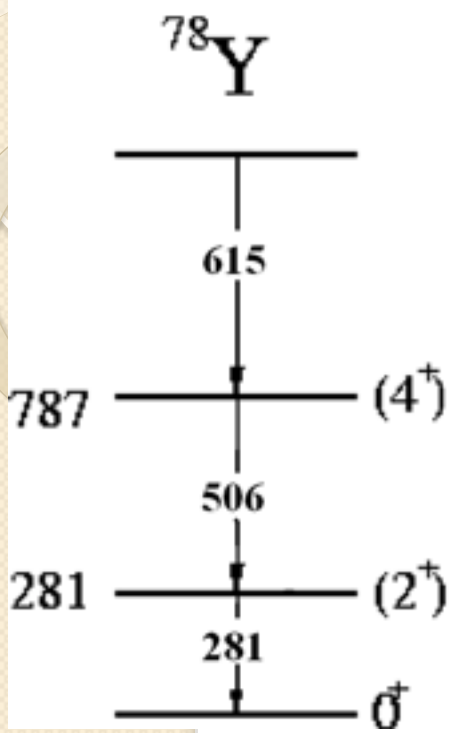
- Nothing known about ^{78}Y except 0+ superallowed decay and (5+) beta-decaying isomer
- RBT technique applied using $^{40}Ca(^{40}Ca,pn)^{78}Y$ reaction
- Cross-section should be very similar to ^{74}Rb
- 90% of flux proceeds to low-lying isomer
- Isomer is too long-lived for effective tagging

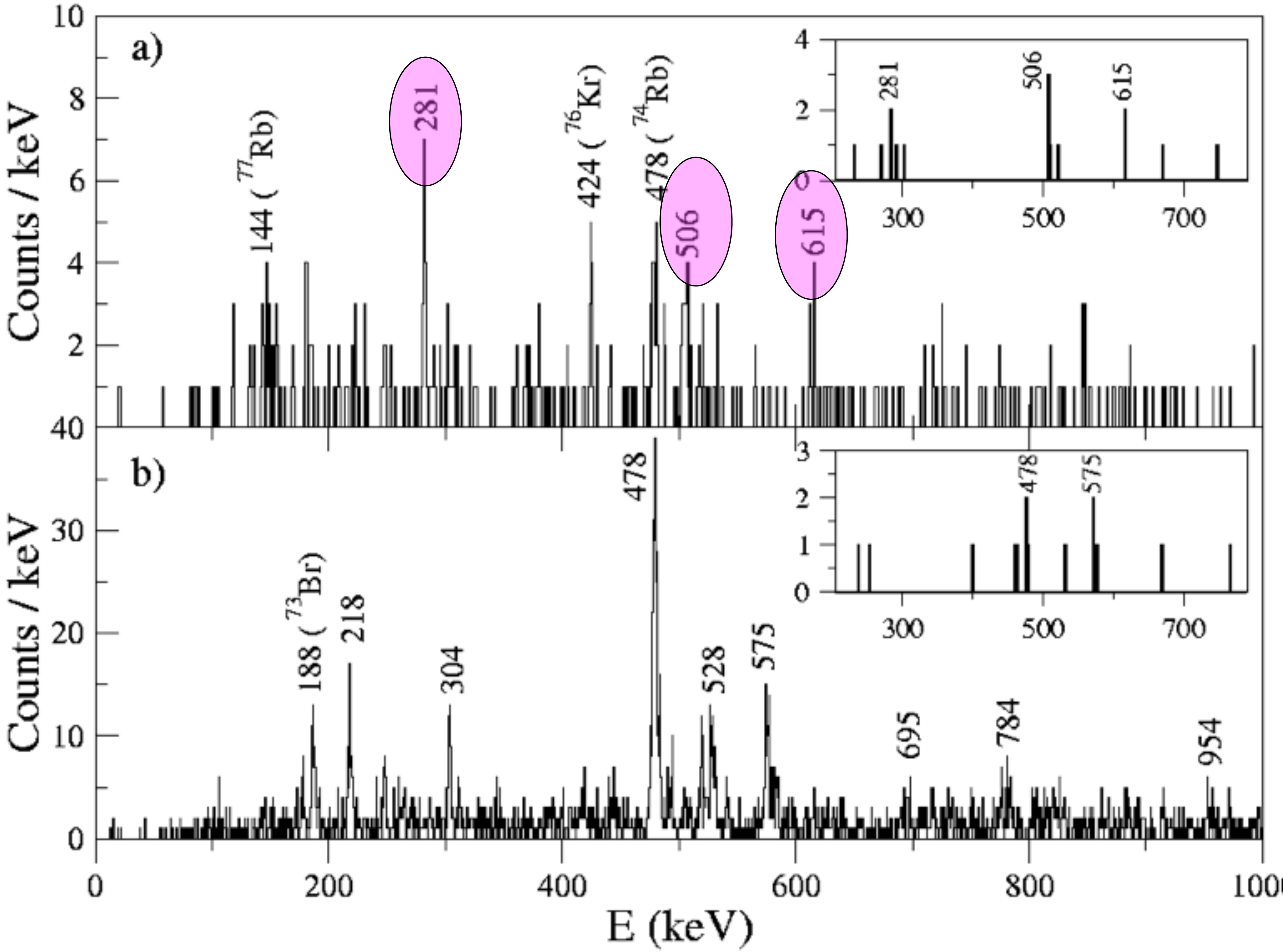






B.S. Nara Singh et al., Phys. Rev. C 75, 061301 (2007).





B.S. Nara Singh et al., Phys. Rev. C 75, 061301 (2007).

Crossing the line of N=Z

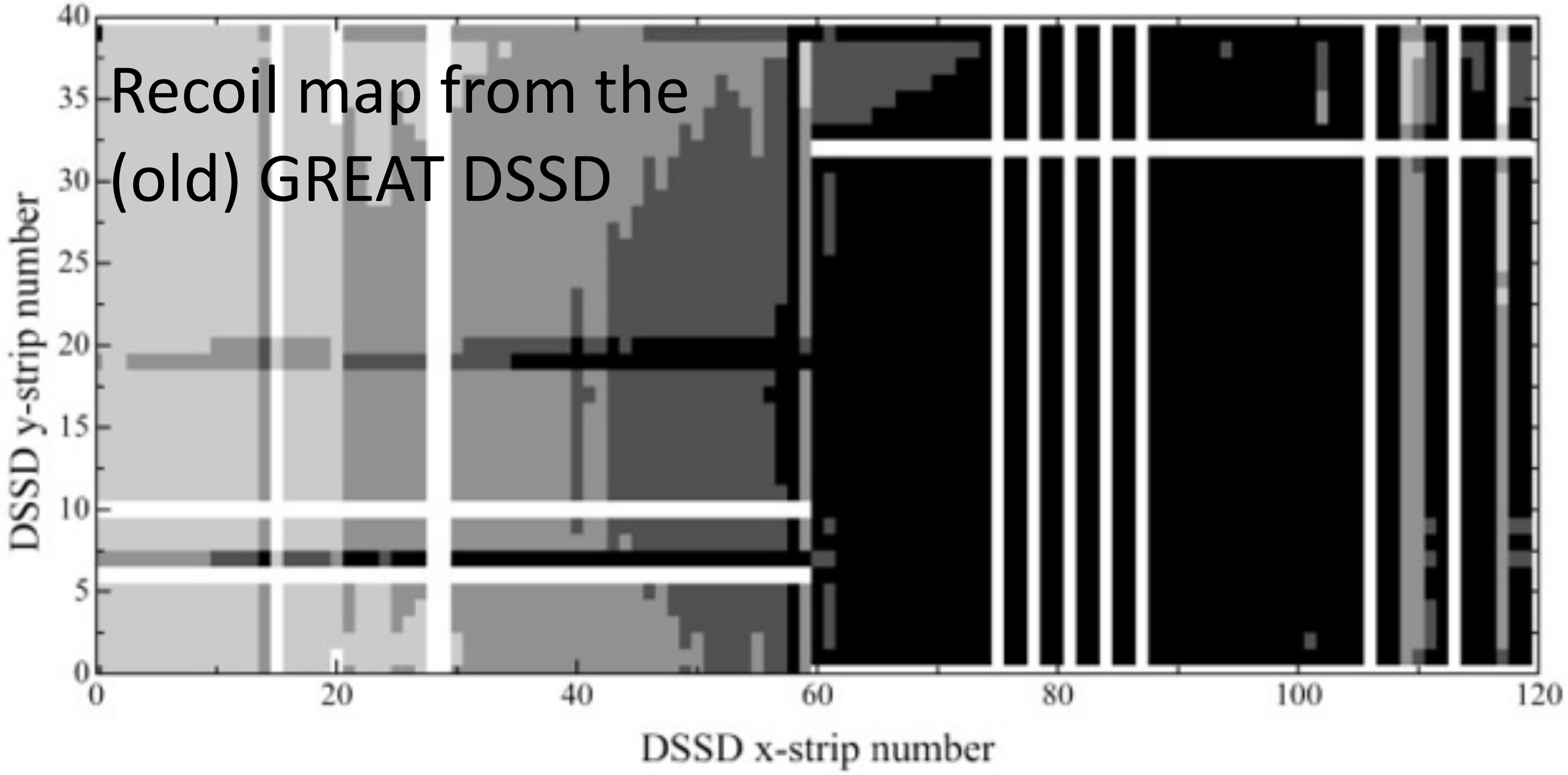
New DSSD

- As RITU is designed to operate on heavy mass regions, recoil separation is not anymore optimal in the A~70 region.

- Recoil distribution is focused on the right hand side of the DSSD (beam and scattered components follow closely the recoil distribution so it can not be centered).

- 8 kHz rate is impinged only on the half of the active area of the DSSD which in turn increases risk of random correlations!

- Device was tested with ^{28}Si + ^{40}Ca reaction at E_b=75 MeV with various different beam intensities (simultaneously with phoswich or planar ge set-up).



New DSSD design

- Only right hand side works as an active detector.

- Consists of 120 x 80 strips with strip pitch of 0.480 mm

- 500 mm thick

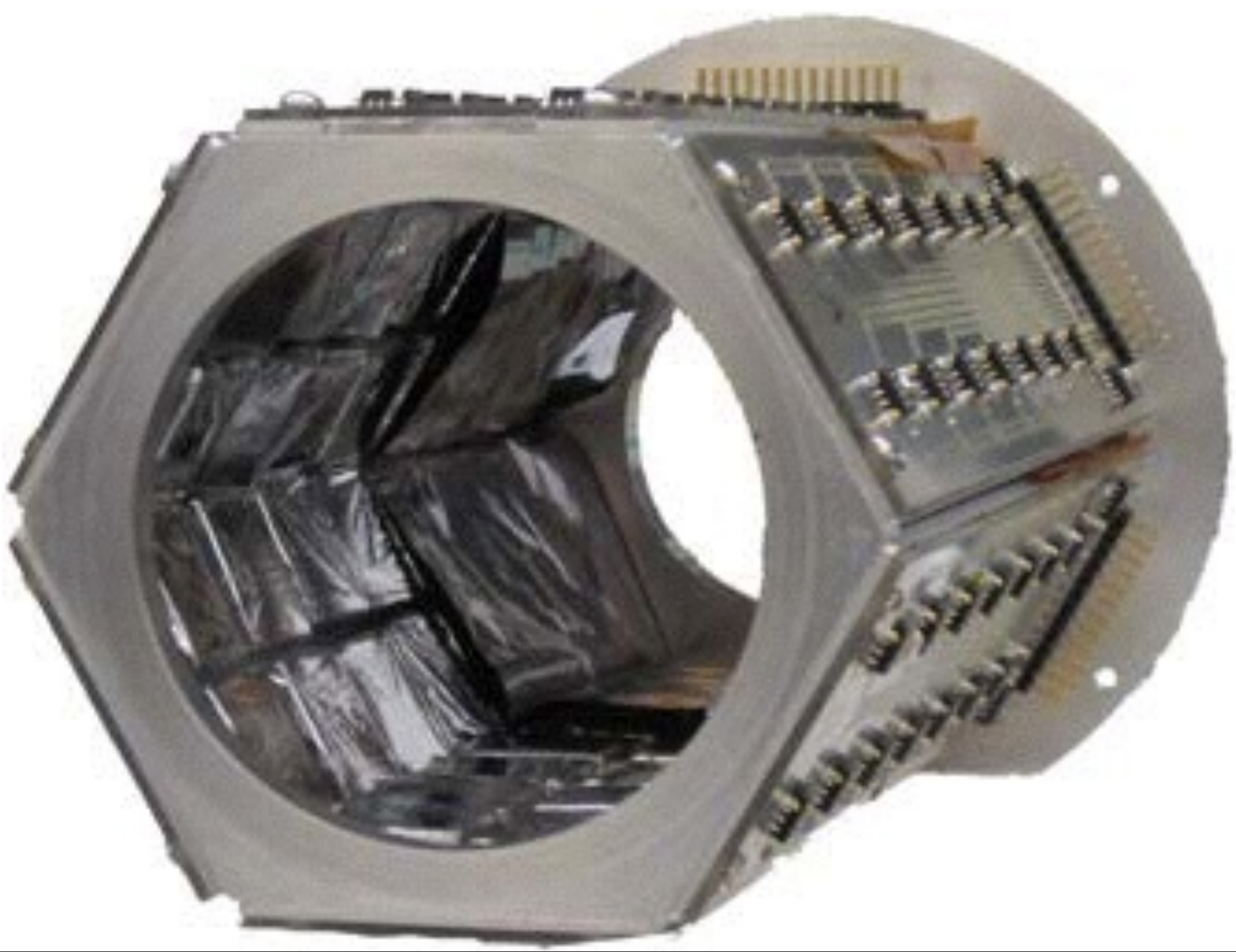
- In total ~10000 pixels!

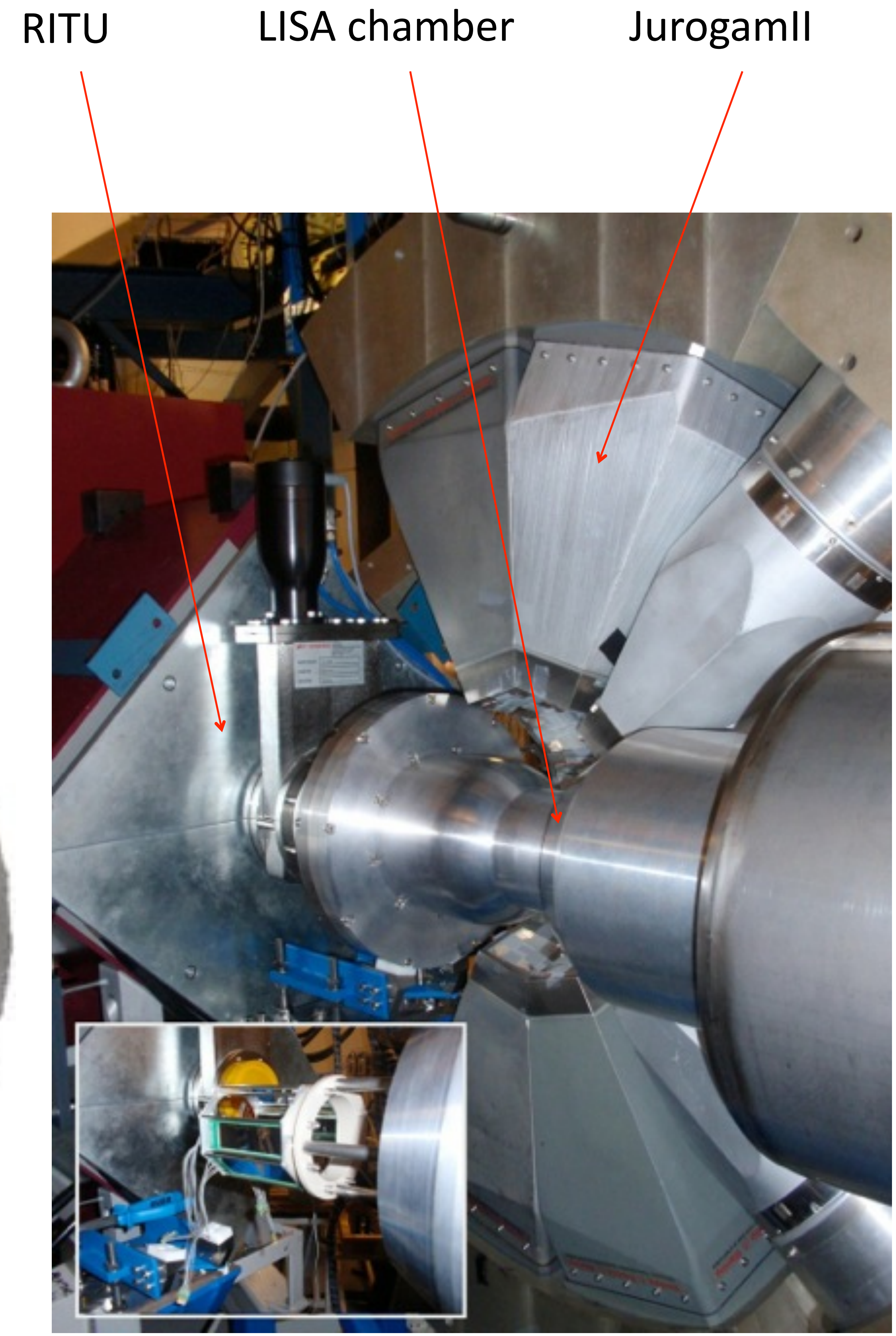
- -> 0.8 Hz recoil rate / pixel.

Slides from Panu Ruotsalainen

UoY Tube

- Designed to suppress events associated with cp evaporation channels.
- Consists of 96 20 x 20 mm CsI crystals (Hamamatsu) divided into 6 flanges (8 x 2 crystals in each flange).
- Signal chain: Mesytech preamplifiers -> ”GO-box” -> Lyrtech ADCs.
- Measured detection efficiency for 1 charged particle is 80-90 %.





Physics Letters B 701 (2011) 417–421

Contents lists available at ScienceDirect

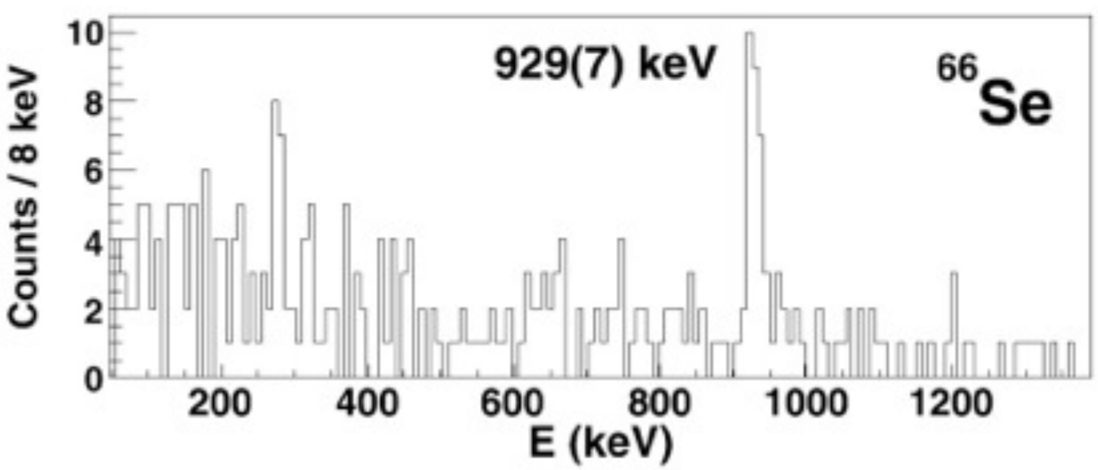
Physics Letters B

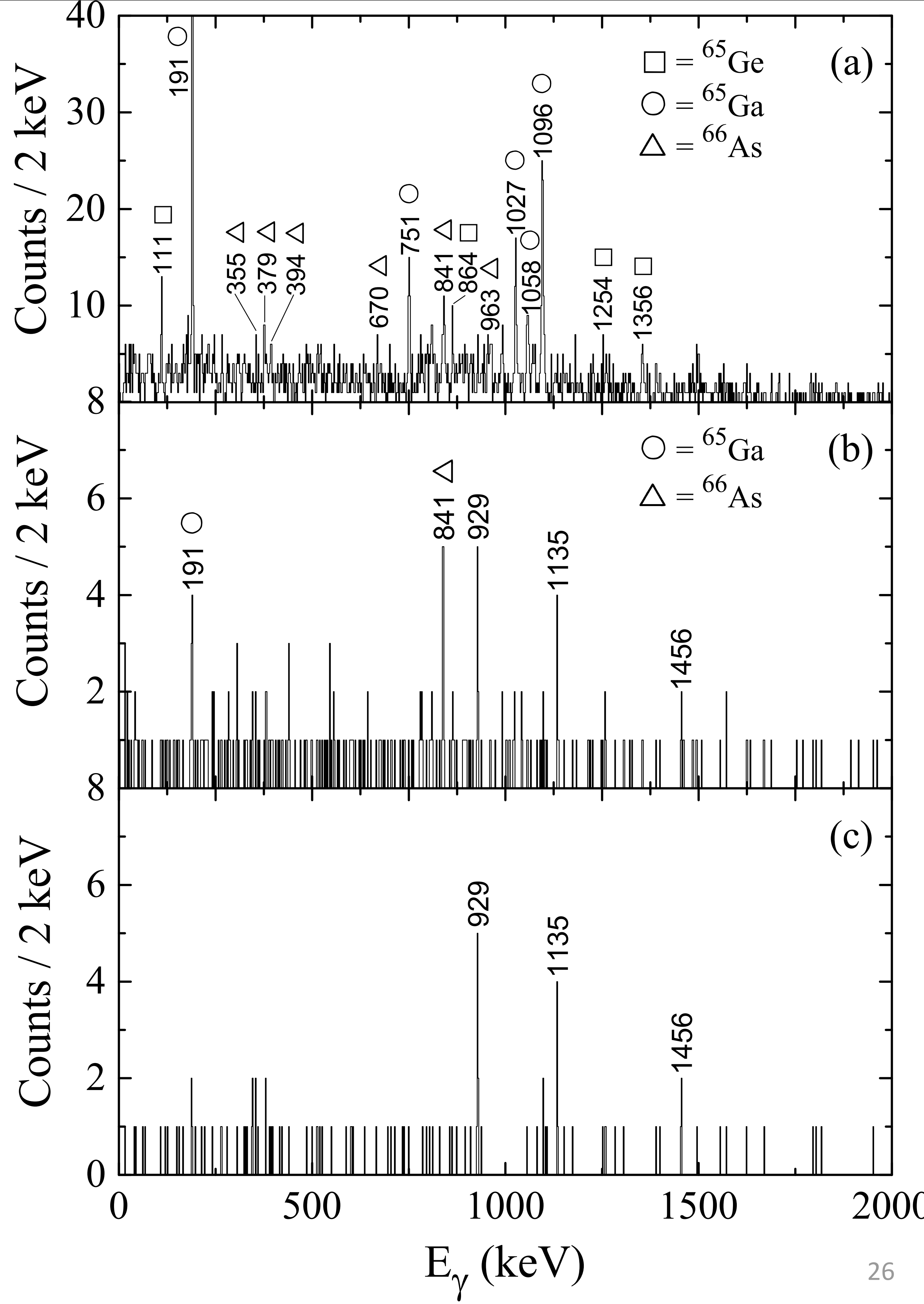
www.elsevier.com/locate/physletb

First spectroscopy of ^{66}Se and ^{65}As: Investigating shape coexistence beyond the $N = Z$ line

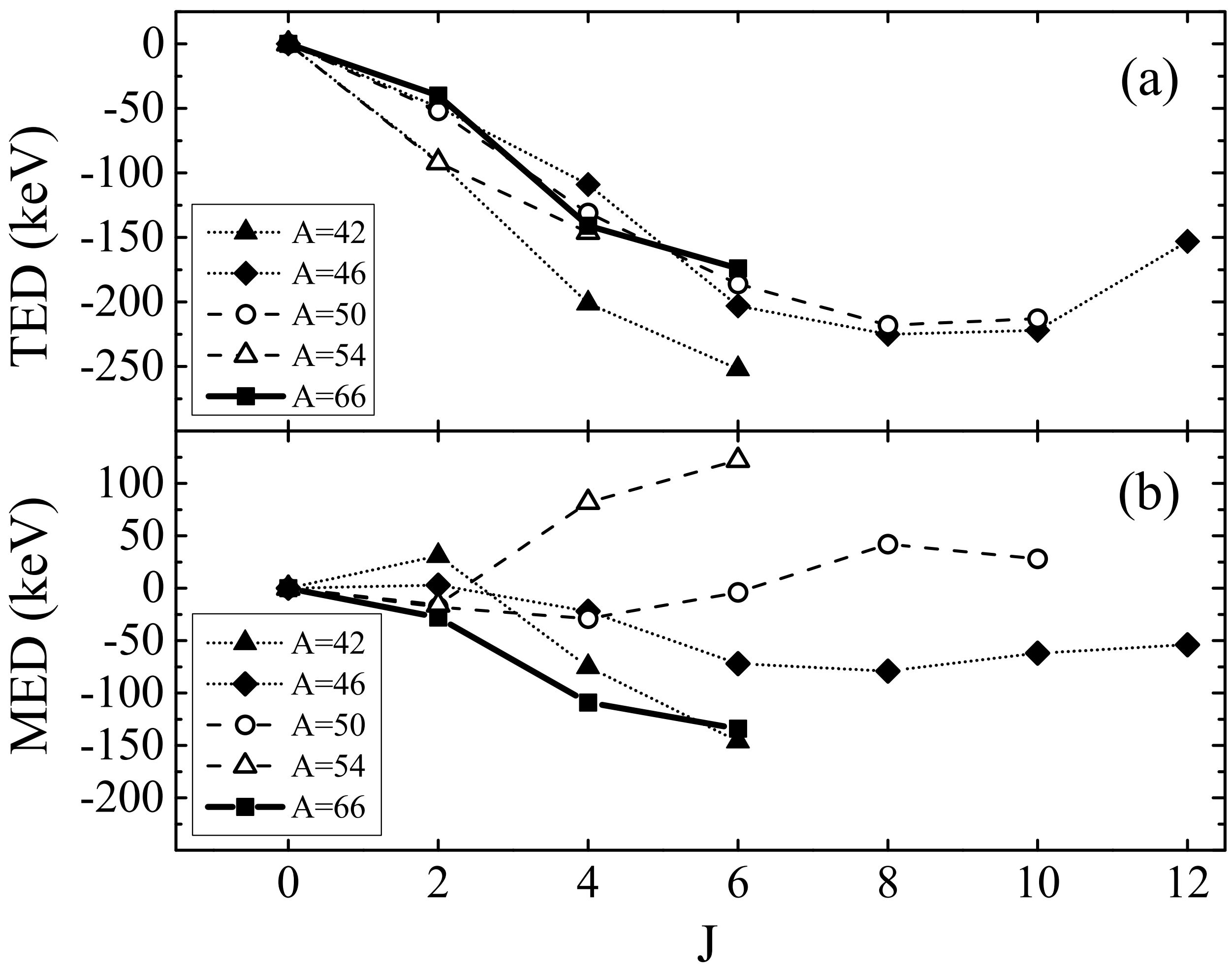
A. Obertelli[a,*], T. Baugher[b], D. Bazin[b], S. Boissinot[a], J.-P. Delaroche[d], A. Dijon[e], F. Flavigny[a], A. Gade[b,c], M. Girod[d], T. Glasmacher[b,c], G.F. Grinyer[b], W. Korten[a], J. Ljungvall[a], S. McDaniel[b,c], A. Ratkiewicz[b,c], B. Sulignano[a], P. Van Isacker[e], D. Weisshaar[b]

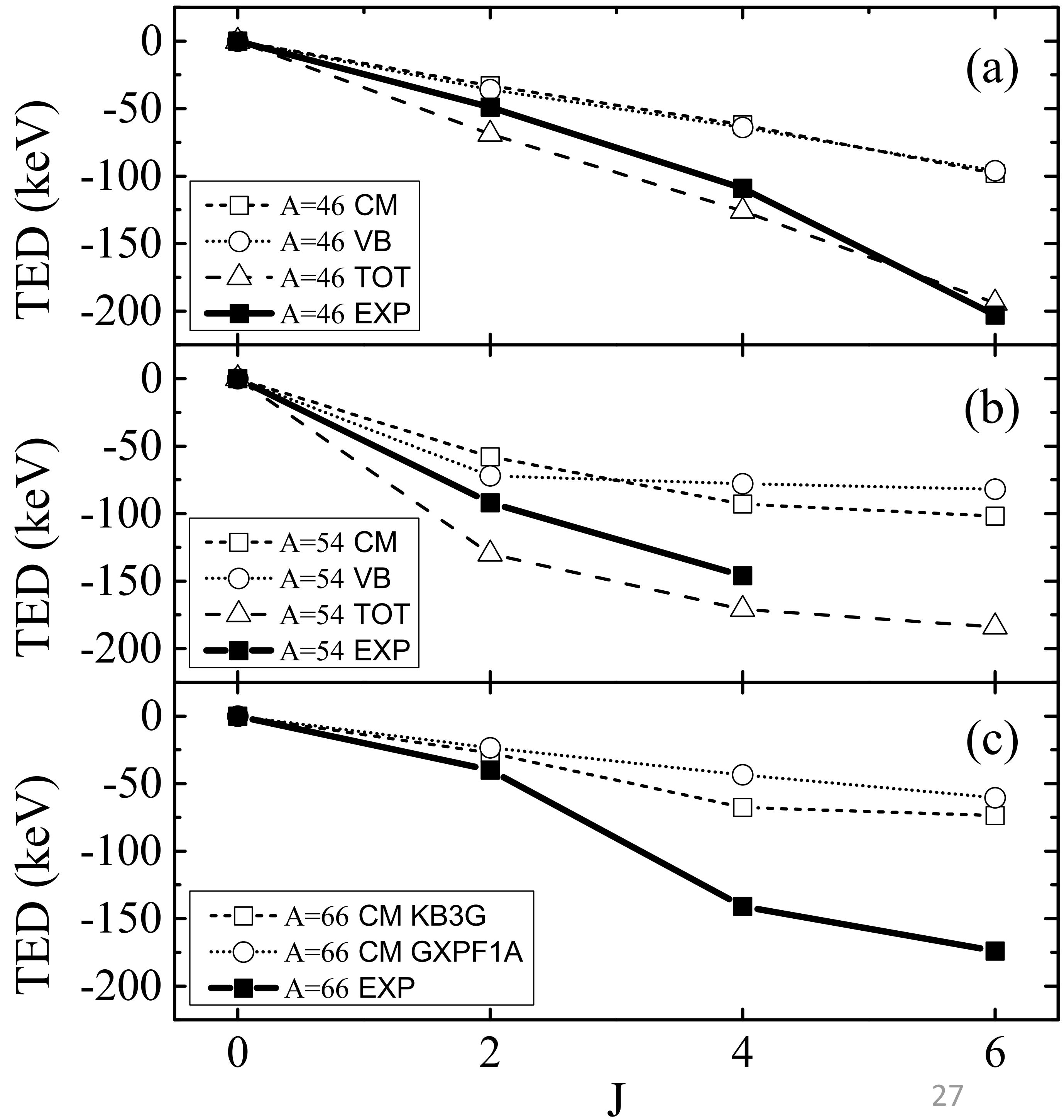
[a] CEA, Centre de Saclay, IRFU/Service de Physique Nucléaire, F-91191 Gif-sur-Yvette, France
[b] National Superconducting Cyclotron Laboratory, East Lansing, MI, USA
[c] Michigan State University, East Lansing, MI, USA
[d] CEA, DAM, DIF, F-91297 Arpajon, France
[e] Grand Accélérateur National d'Ions Lourds, CEA/DSM–CNRS/IN2P3, BP 55027, F-14076 Caen Cedex 5, France





Now published:
P. Ruotsalainen et al., Phys. Rev. C 83, 037303 (2013)

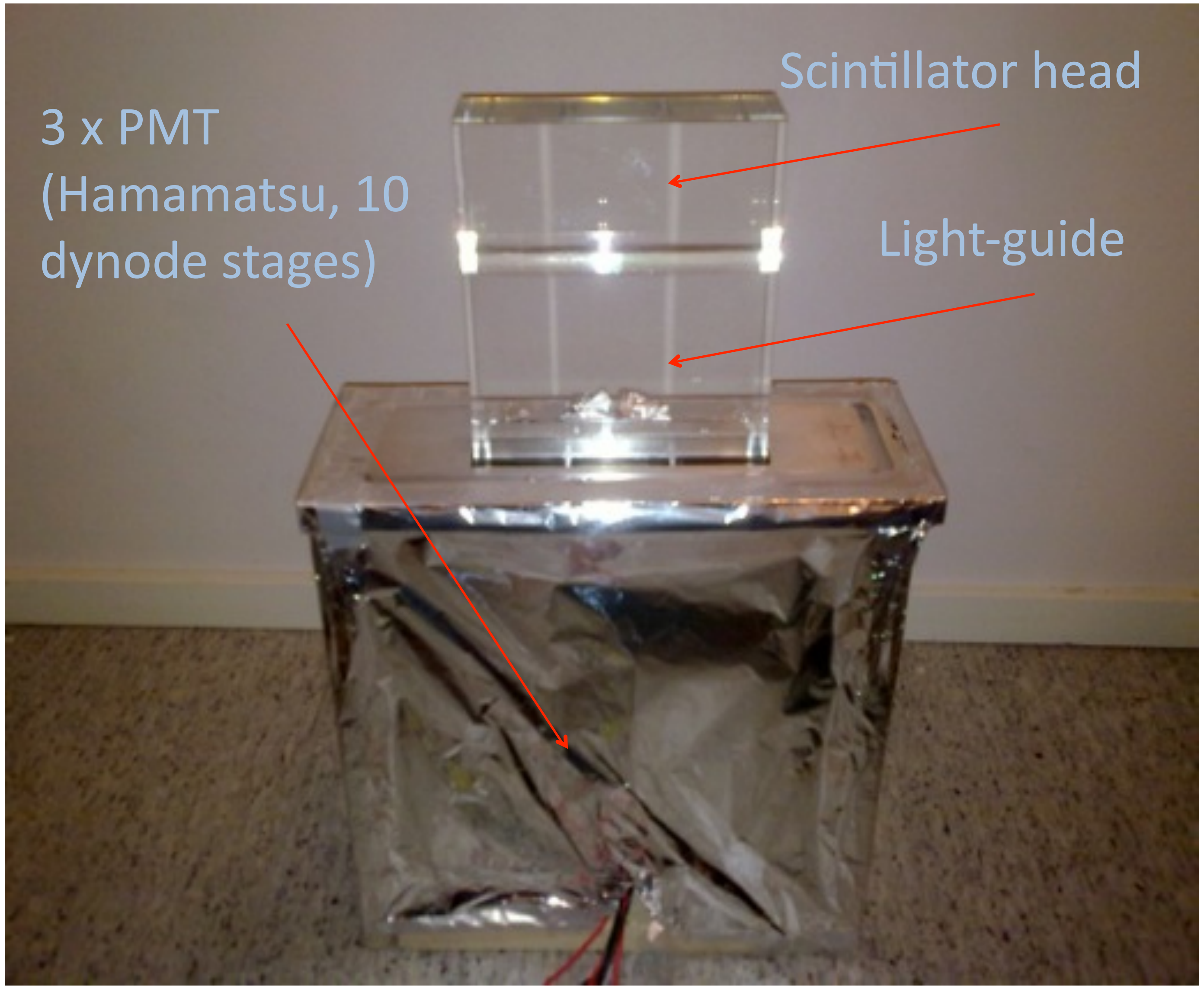


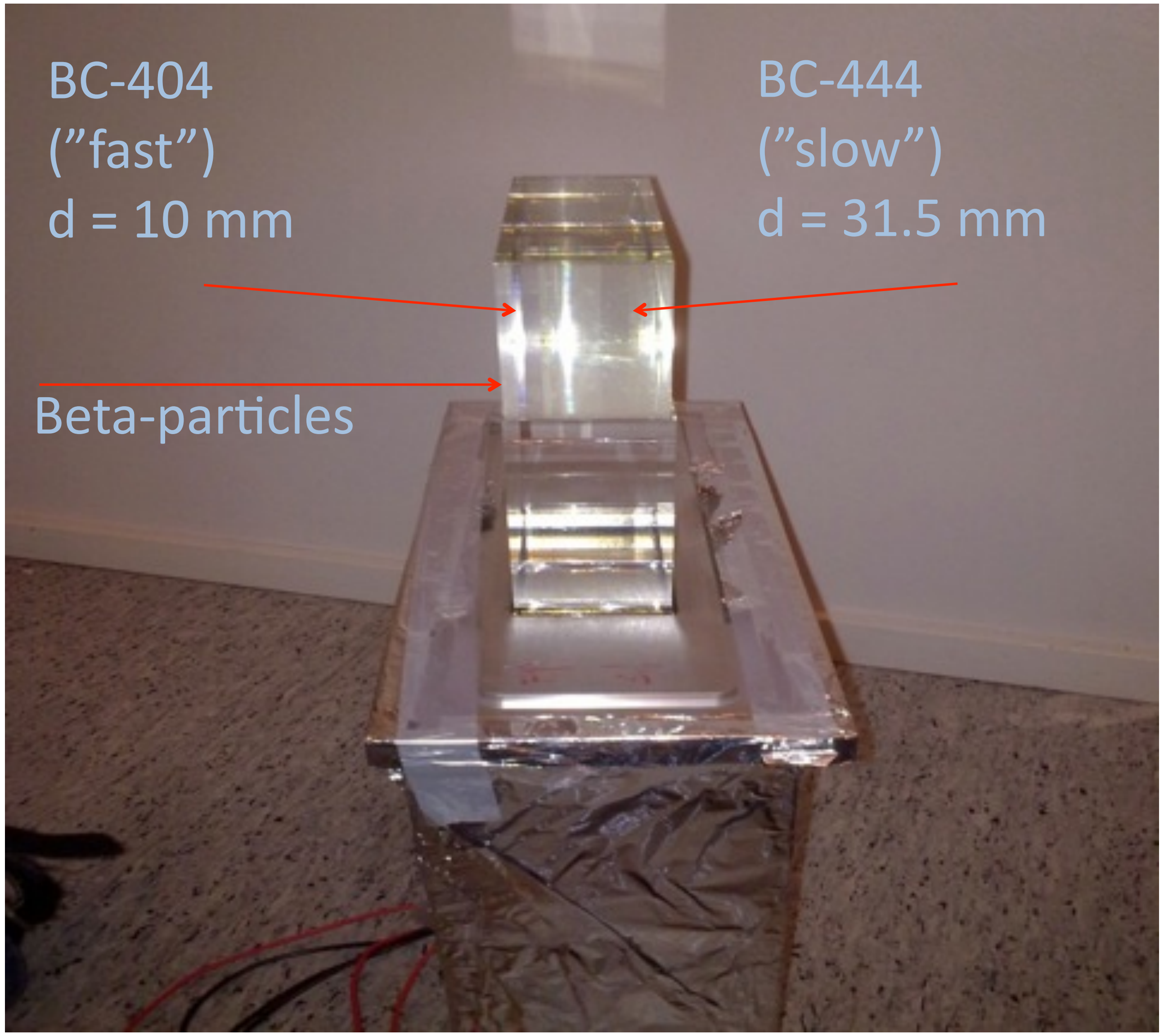


TEDs for A=66 cannot be reproduced
with only Coulomb terms -
clear need for isospin non-conserving term

Phoswich scintillator

- High/low energy beta-particle detection and discrimination: Direct energy & full pile-up discrimination
- Beta/gamma discrimination
- Discriminations can be done on the basis of pulse shape analysis.

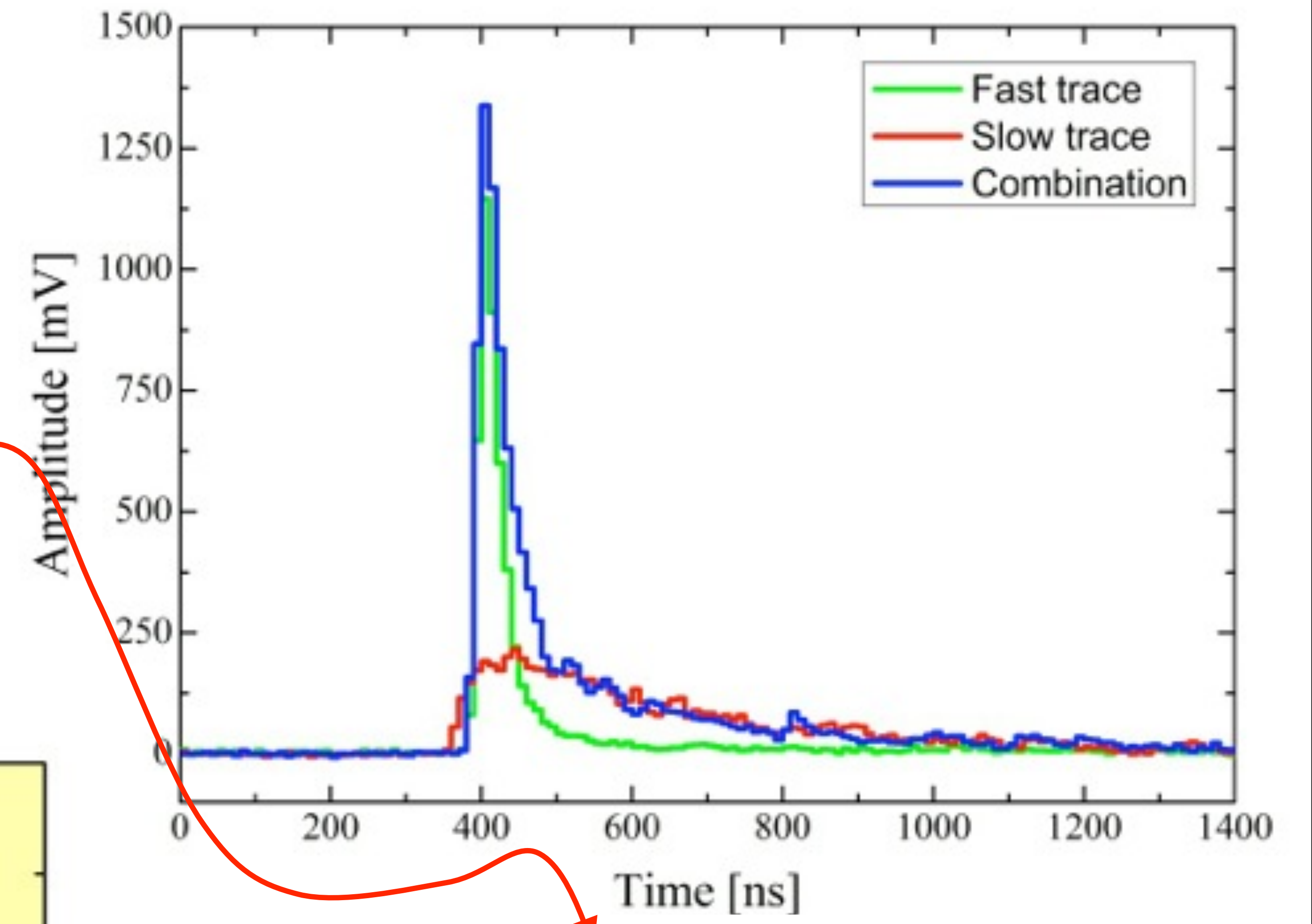


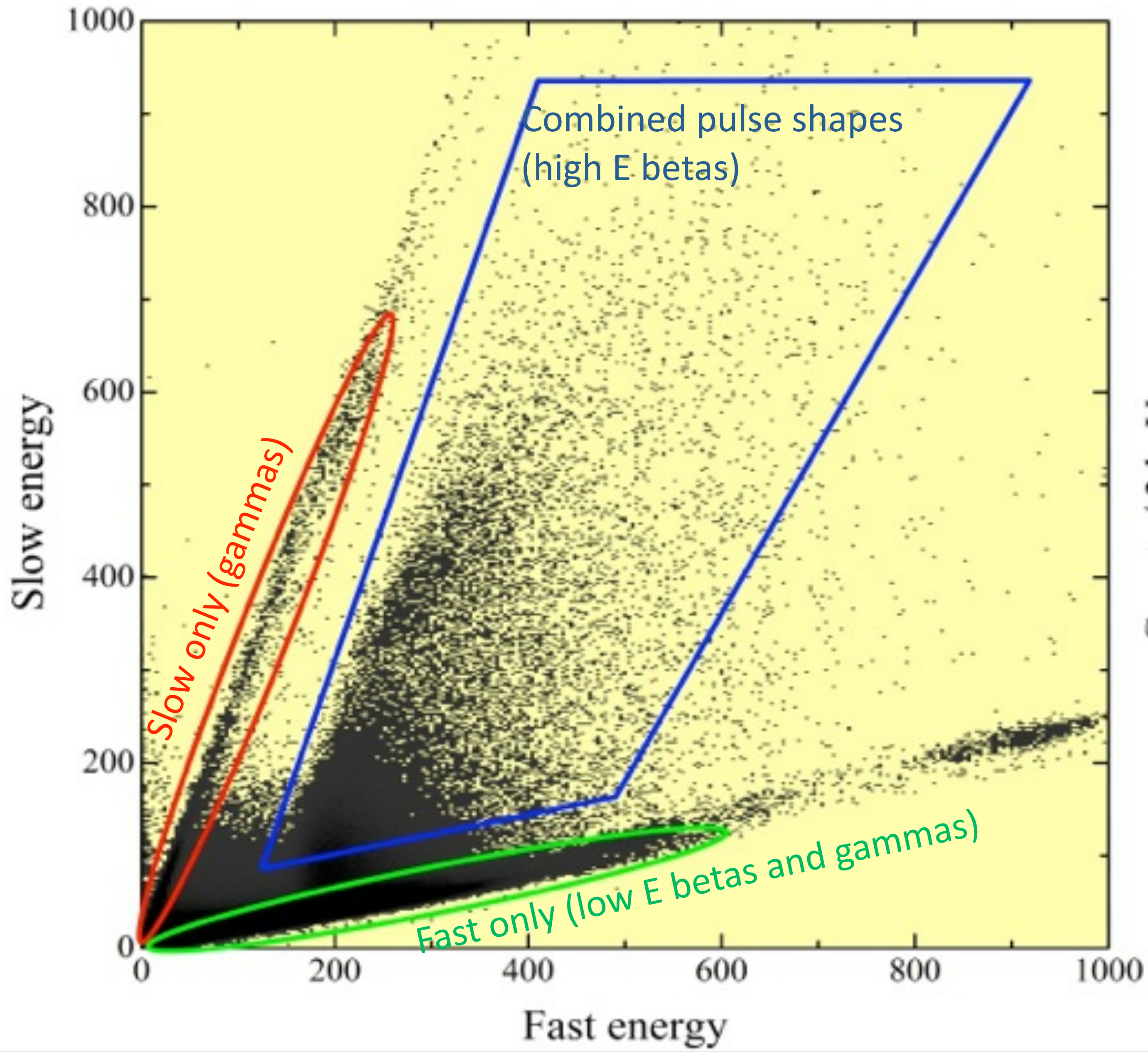


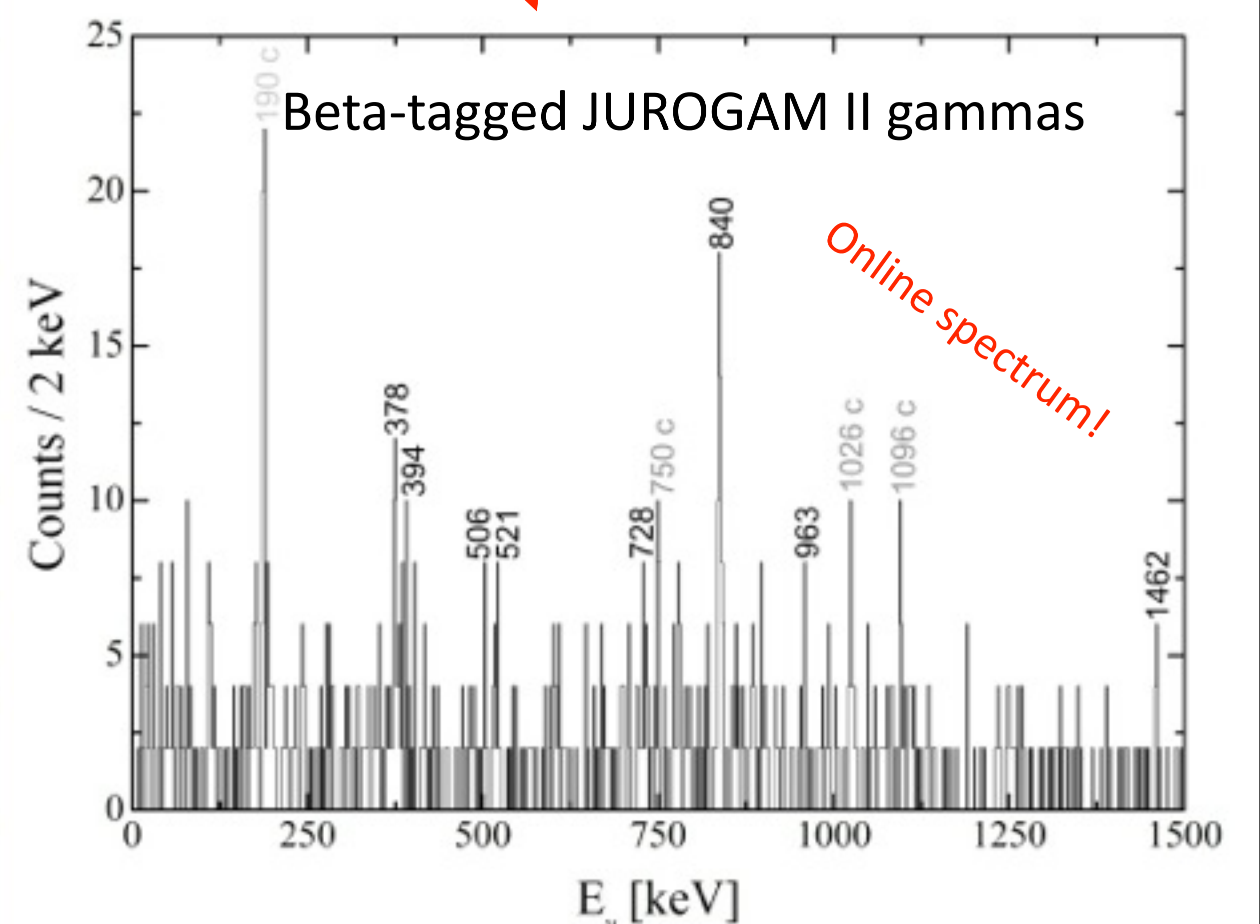
- BC-404: rise time ~ 0.7 ns, decay time ~ 1.8 ns, light output 68 % of anthracene
- BC-444: rise time ~ 19.5 ns, decay time ~ 285 ns, light output 41 % of anthracene

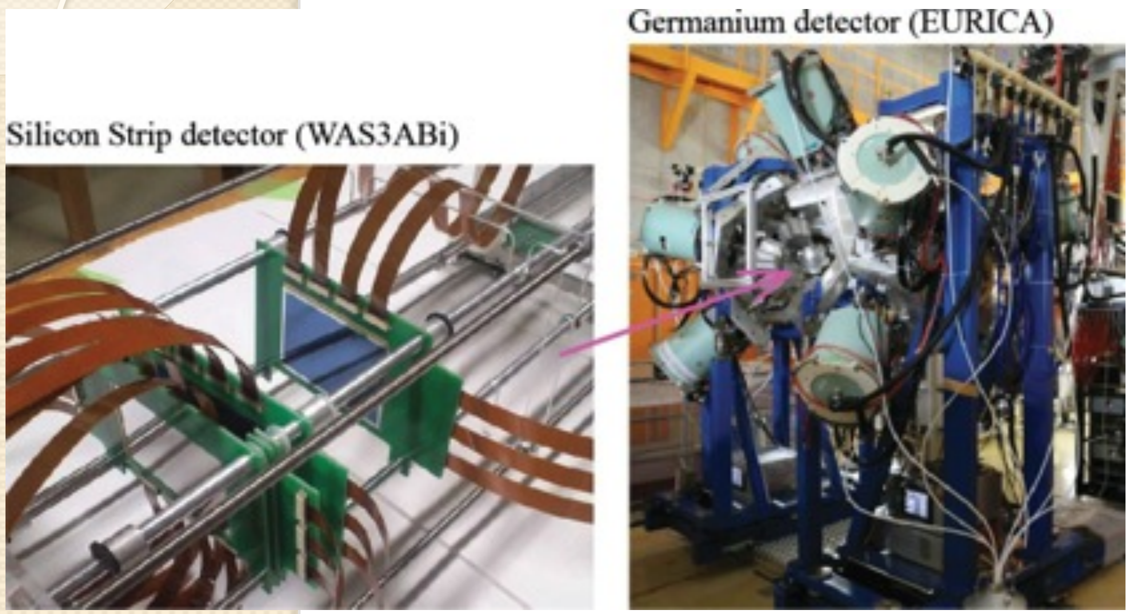
Phoswich scintillator

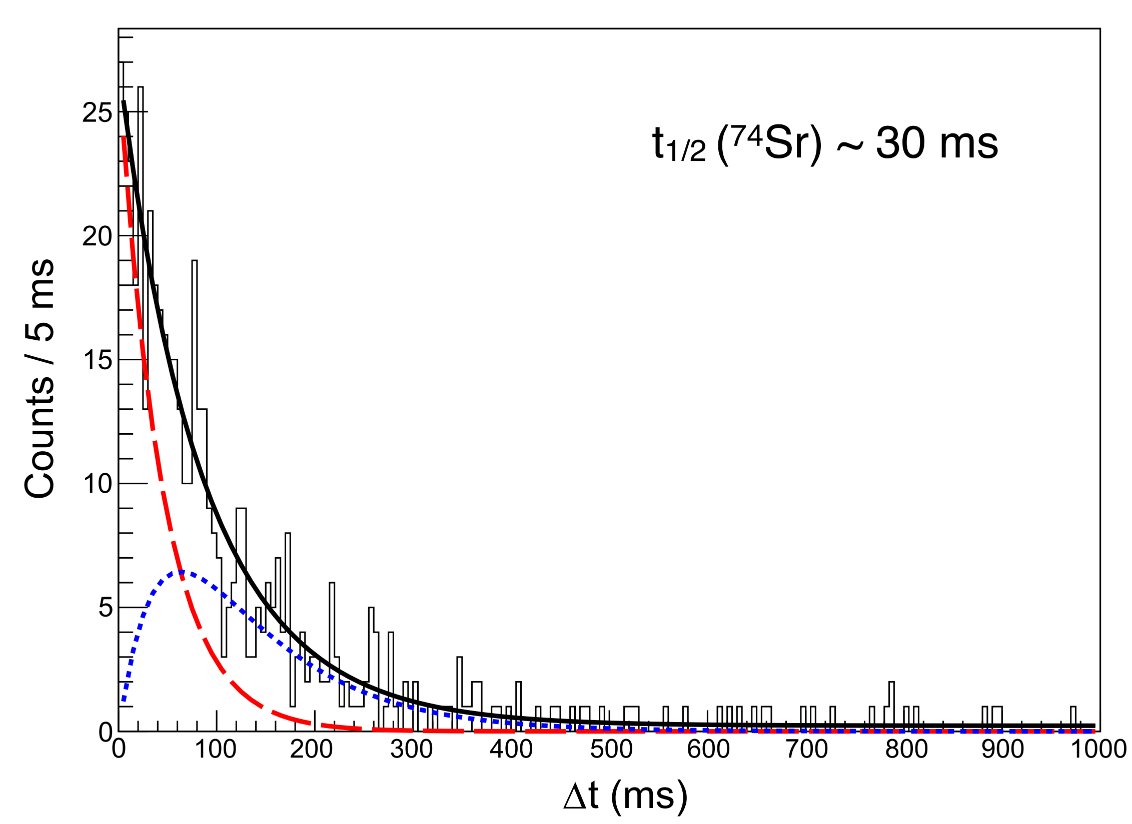
- Traces were recorded from Lyrtech ADCs.
- Pulse shapes were categorized online by rudimentary algorithm.
- On the basis of online analysis, device works and can be utilized for tagging purposes!
- We still need to resolve the possible gain in data quality…

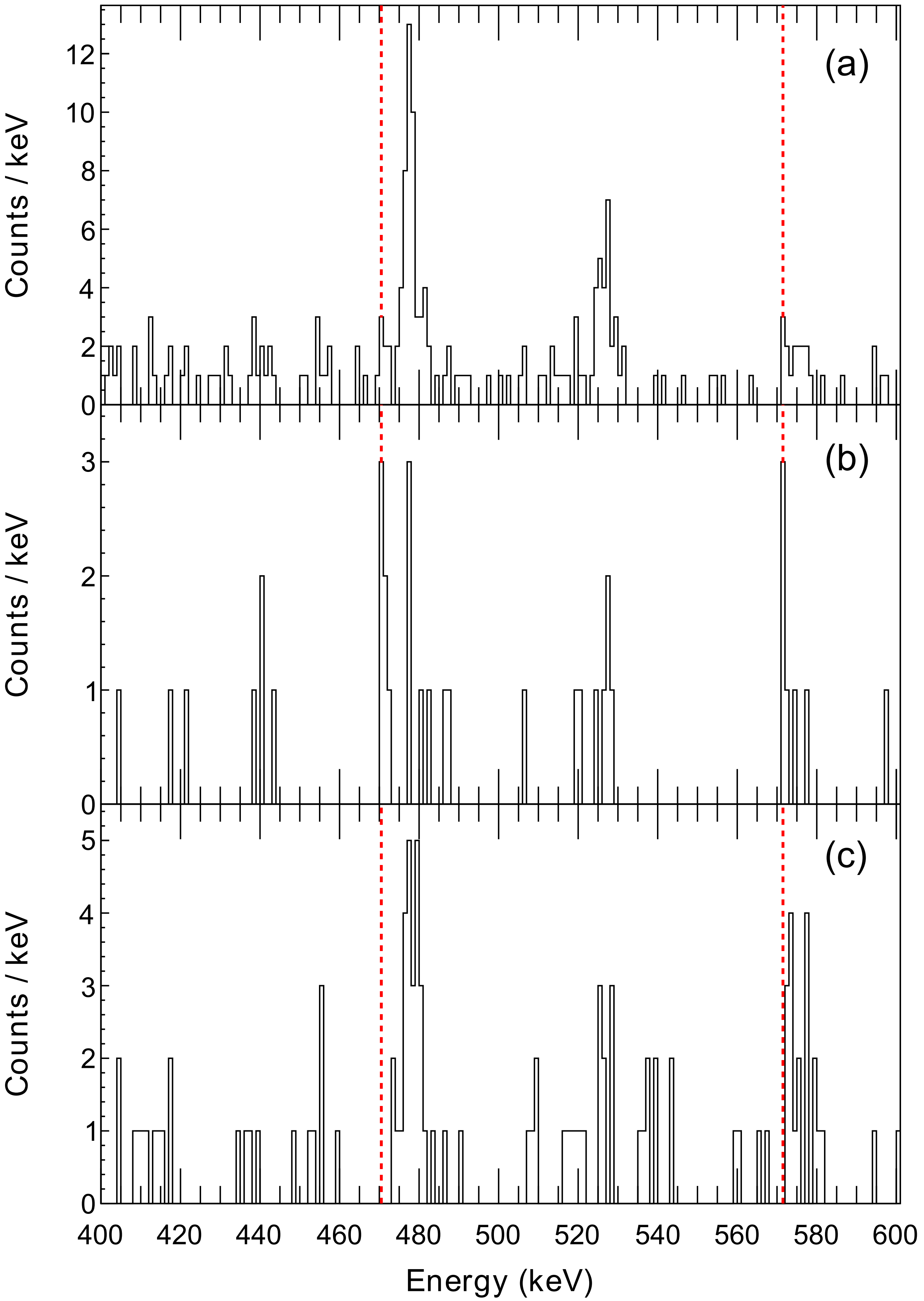


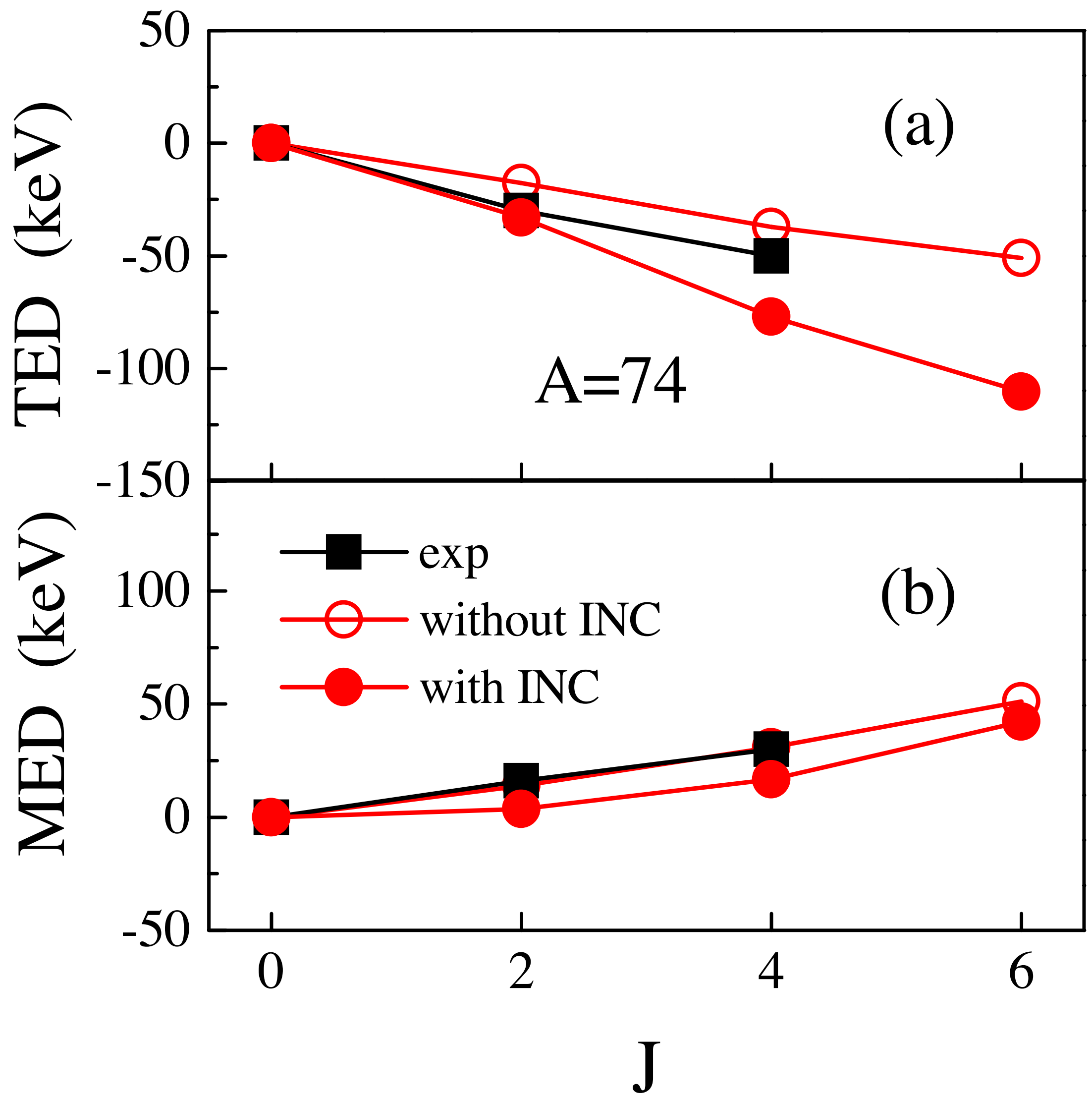





Silicon Strip detector (WAS3ABi)
Germanium detector (EURICA)

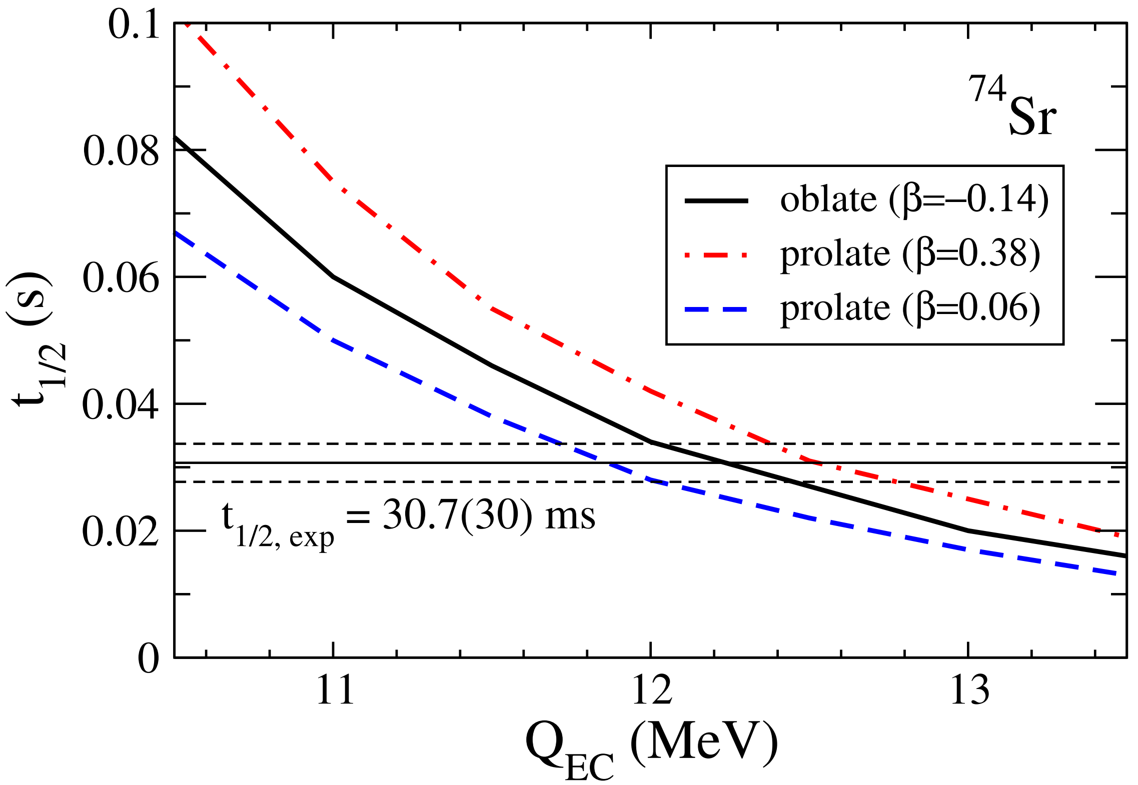

$t_{1/2}$ (^{74}Sr) ~ 30 ms
Counts / 5 ms
Δt (ms)


(a)
(b)
(c)
Counts / keV
Energy (keV)



INC component needed to explain J=2 but discrepancy for J=4

Half-life for ^{74}Sr is much shorter than QRPA calculations. Adjusting to reproduce half-life gives S_{2p} ~ 0.5 MeV. This means that 4^+ state is two-proton unbound.



Collaboration

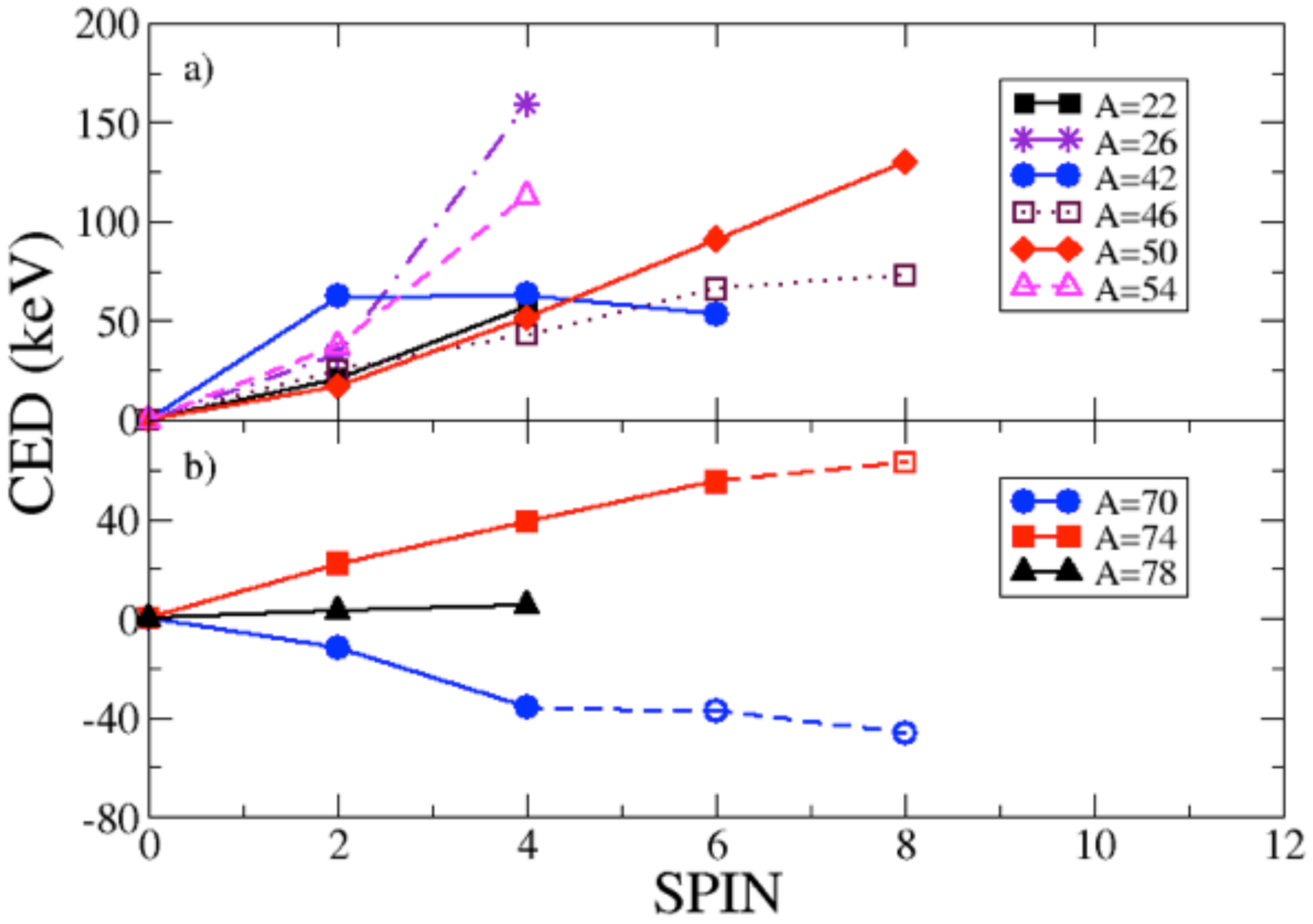
York, RITU-GAMMA group at JYFL, WA3SABI-EURICA collaboration at RIKEN

Theory: K. Kaneko and P. Sarriguren

Spare slides

CEDs for A~70

$CED(J)=E_x(J,T=1,T_{z<})-E_x(J,T=1,T_{z>})$



Difference in np and NN pairs gives CED rise of ~12 keV/J

Uniform upward trend for deformed nuclei except:

A=78 - flat

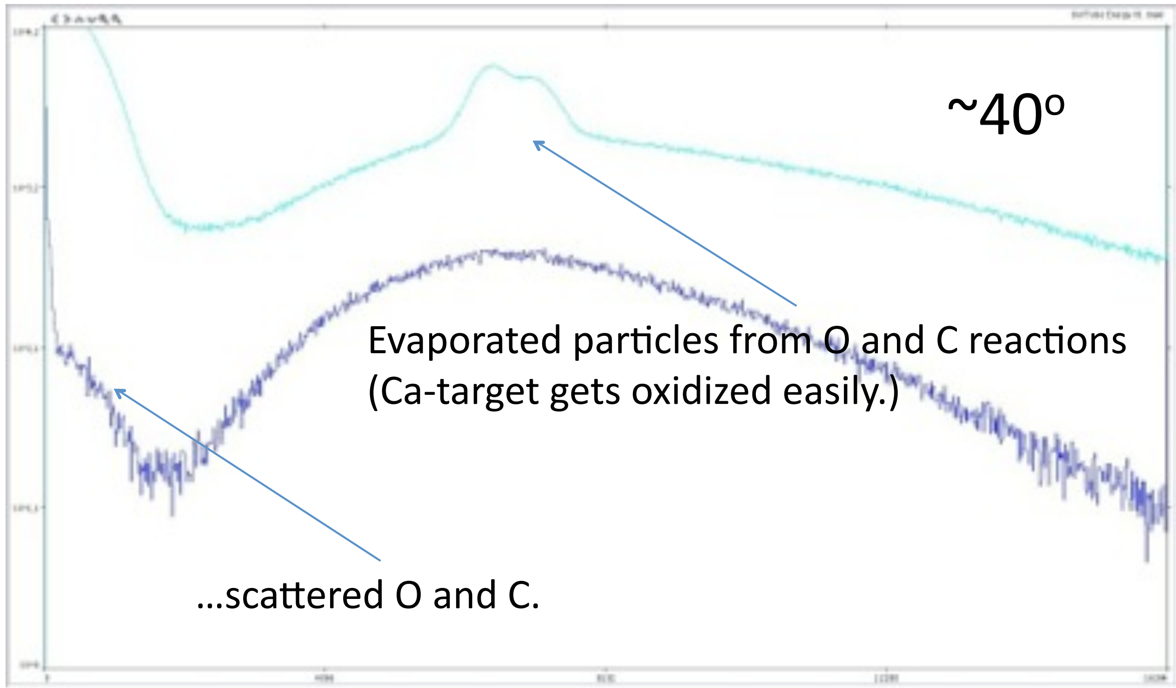
A=70 - strongly down

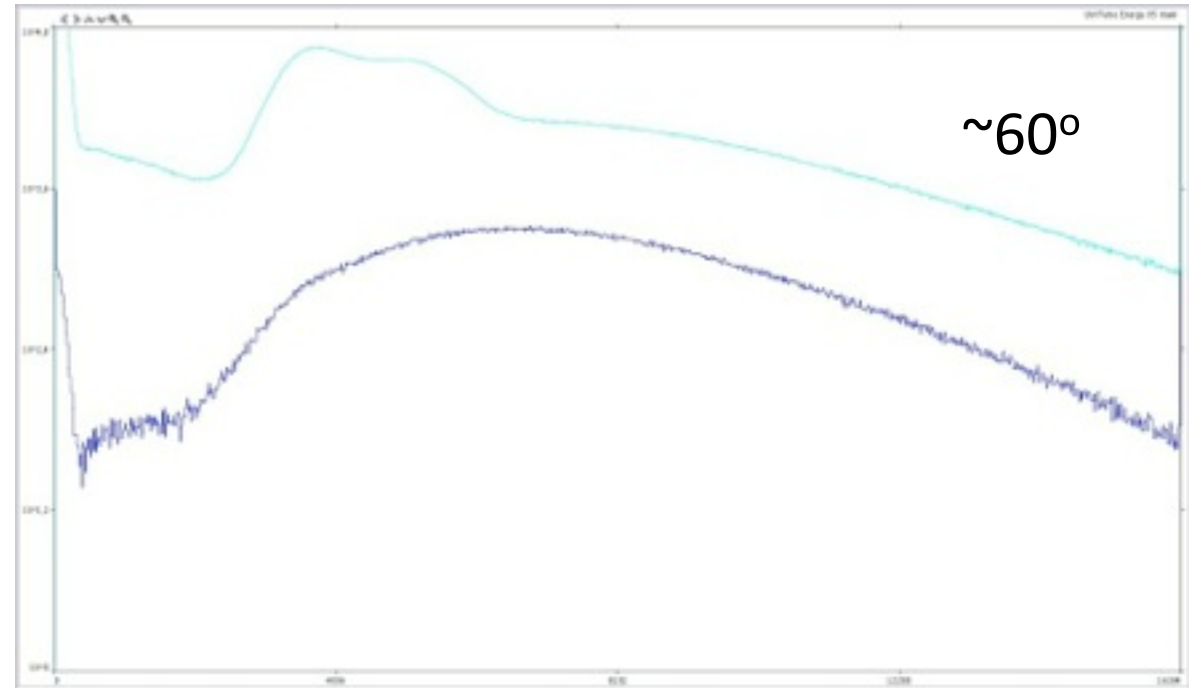
A=70 data from G. de Angelis, EPJ A12, 51 (2001) and

D.G. Jenkins et al., PRC 65, 064307 (2002)

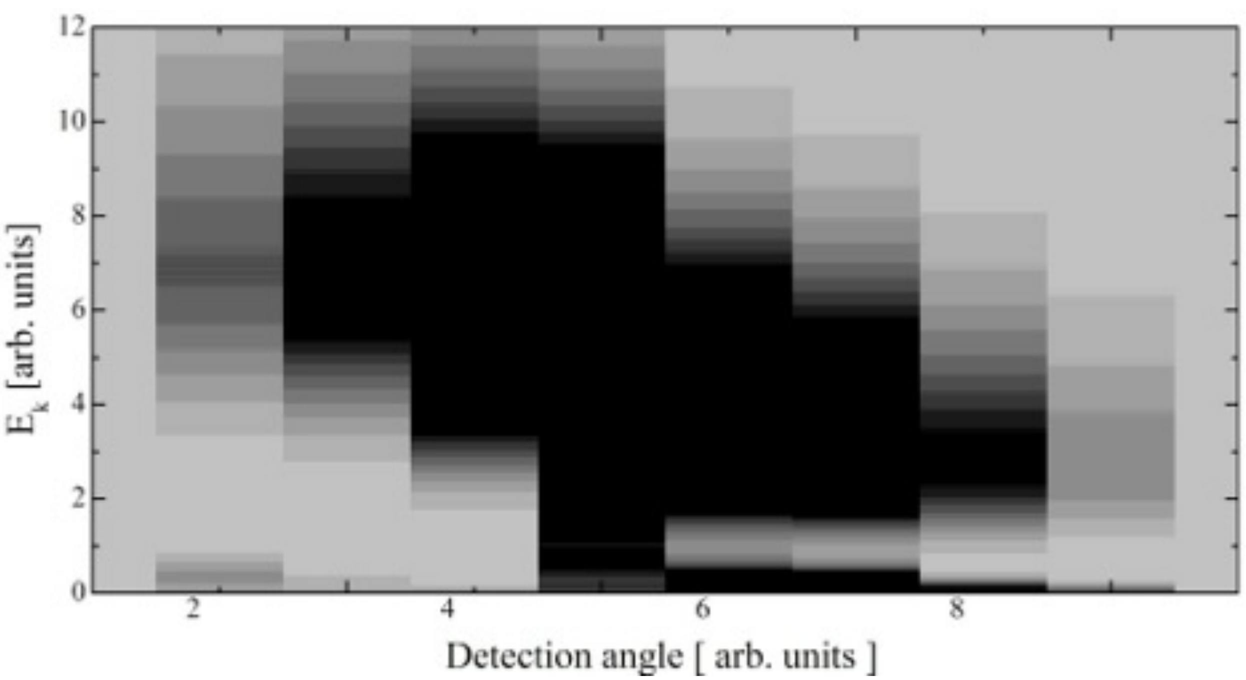
UoY Tube

Comparison of recoil gated (blue curve) and raw UoYTube (light blue) spectra from ^{28}Si + ^{40}Ca reaction.

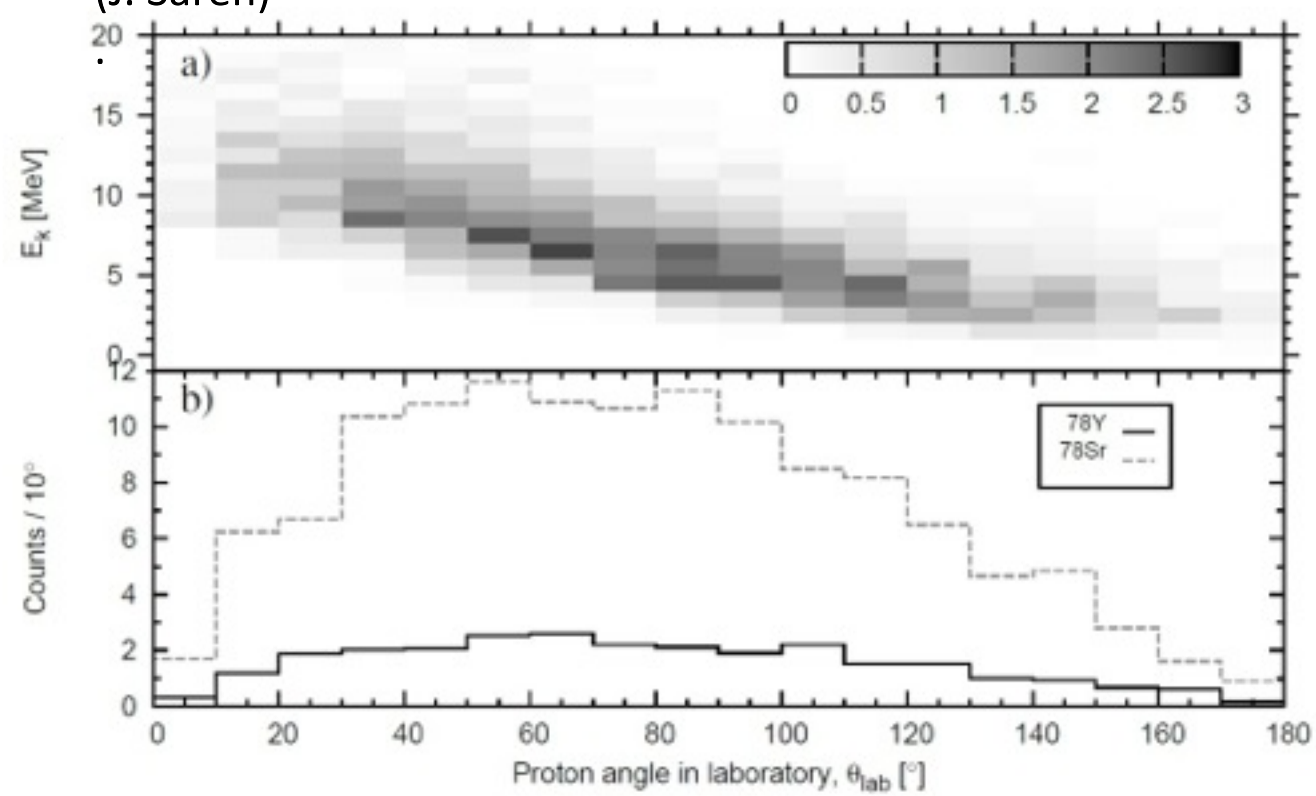




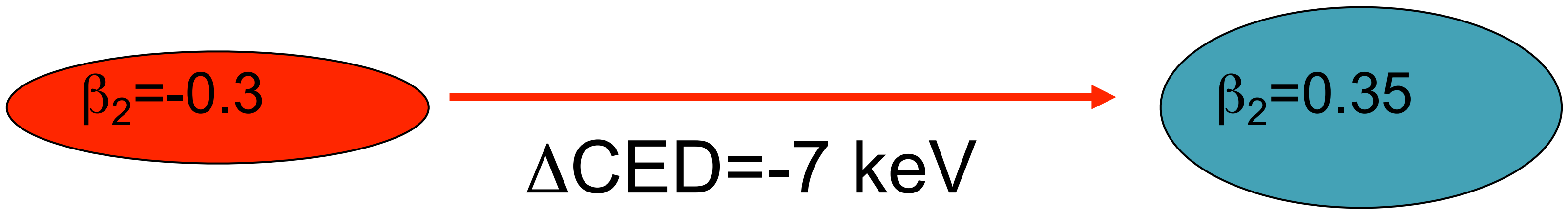
Measured distribution of evaporated particles in ^{28}Si + ^{40}Ca reaction.



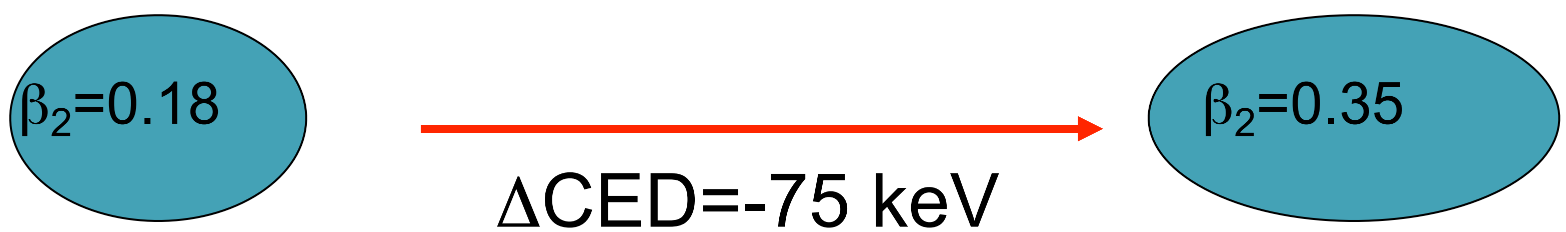
Simulated distribution of evaporated particles in ^{40}Ca + ^{40}Ca reactio
(J. Saren)



Effect of shape change



TRS calculations: T. Mylaeus et al., J. Phys. G 15, L135 (1989)

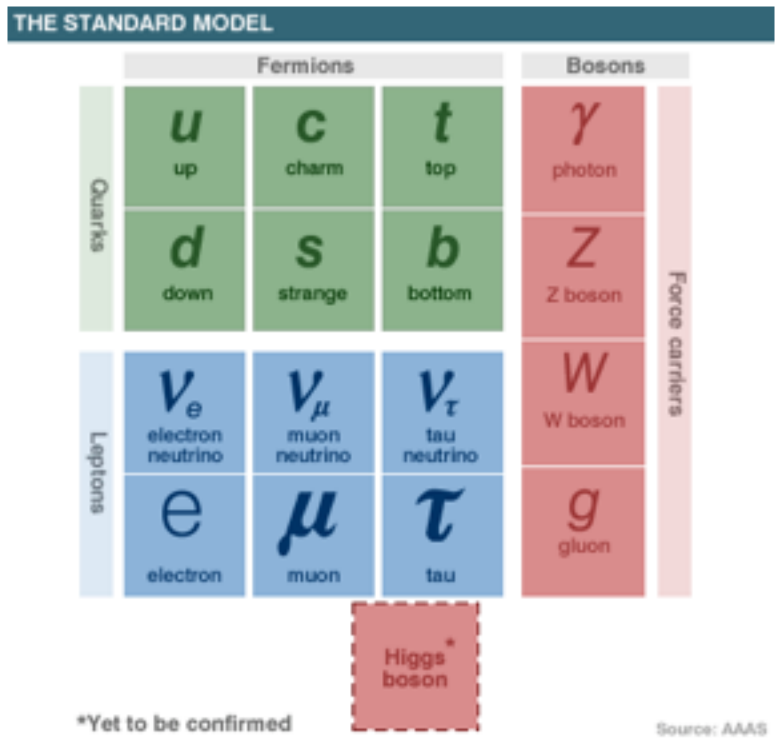


R. Sahu et al., J. Phys. G 13, 603 (1987)

Coulomb energies calculated after S. Larsson, Phys. Scri 8, 17 (1973).

$$E_C = \frac{3e^2 Z(Z-1)}{5R_C}$$

Testing unitarity of the CKM matrix



For beta decays between T=1 analogue states, the CVC hypothesis demands that:

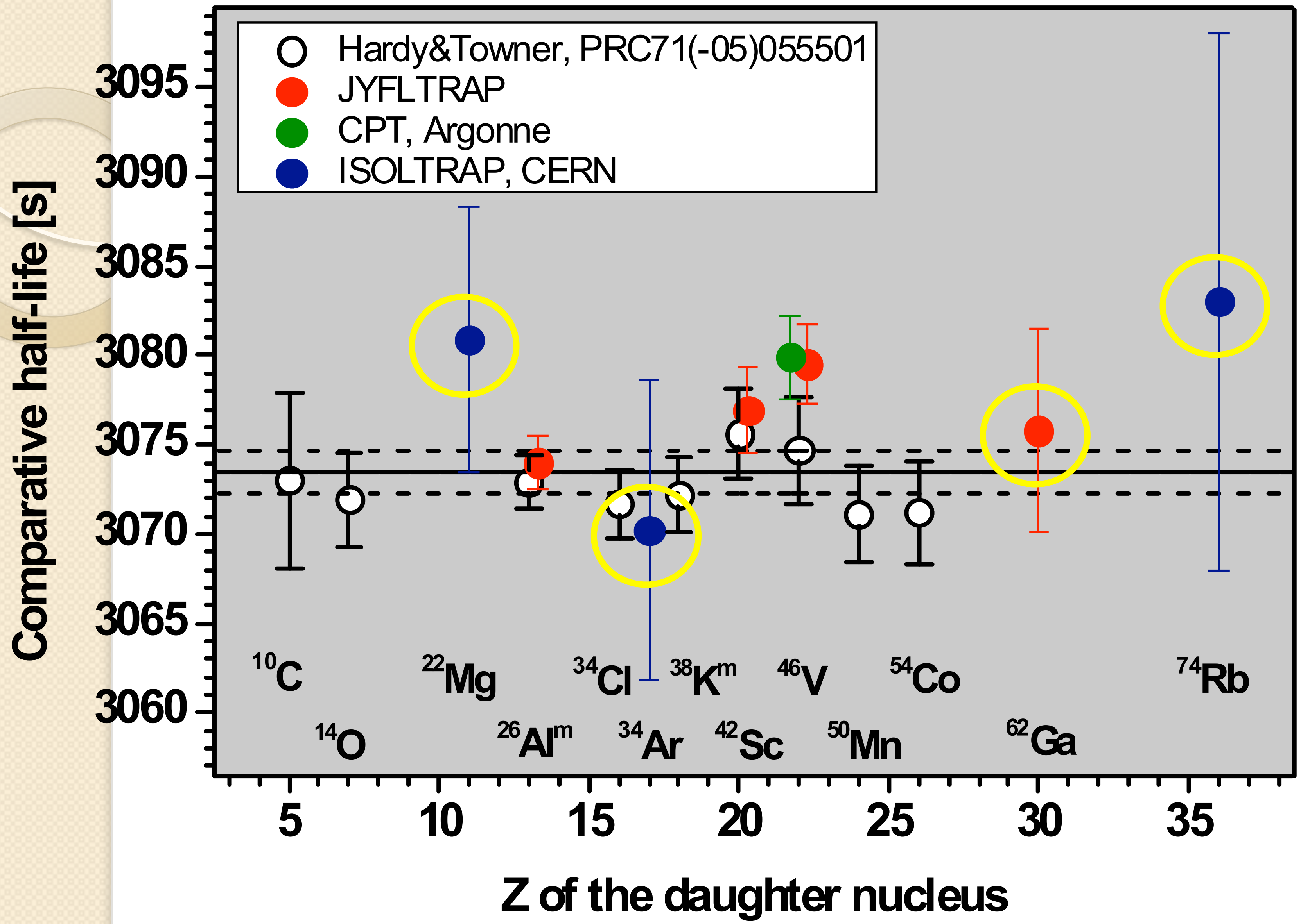
$$ft = \frac{K}{G_V^2 |M_F|^2} = \text{const},$$

Tests of this can therefore be performed for N=Z nuclei with T=1 ground states or for T_z=-1 nuclei (harder)

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

The CKM matrix

Ft-values



^{22}Mg, ^{34}Ar, ^{62}Ga and ^{74}Rb: Error bars in Ft dos not reflect the accuracy of Q_{EC}-determination

Q_{EC}-values of ^{26}Si and ^{42}Ti in progress

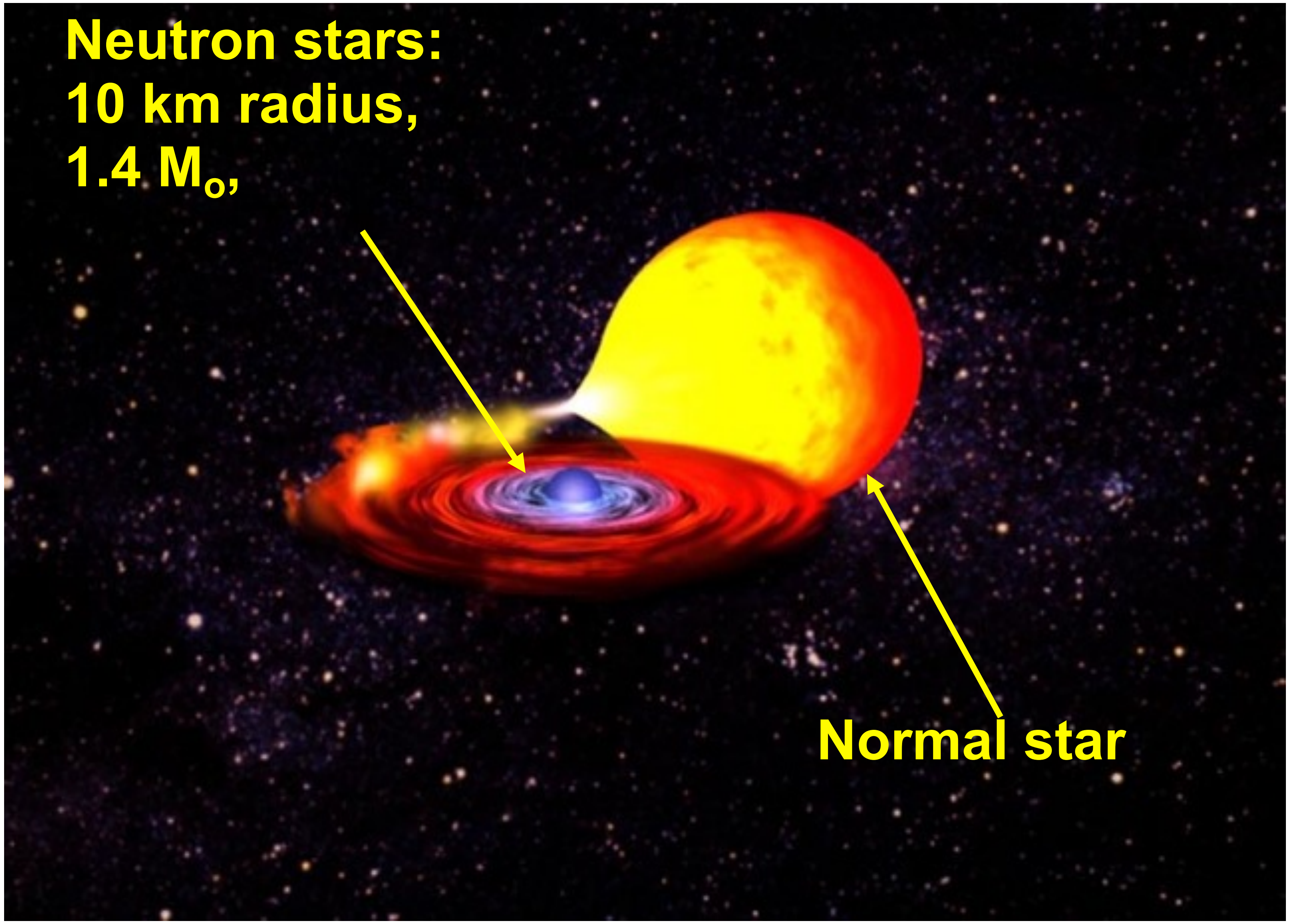
V_{ud} = 0.97408(26)

$V_{ud}^2 + V_{us}^2 + V_{ub}^2$ = 0.9998(10)

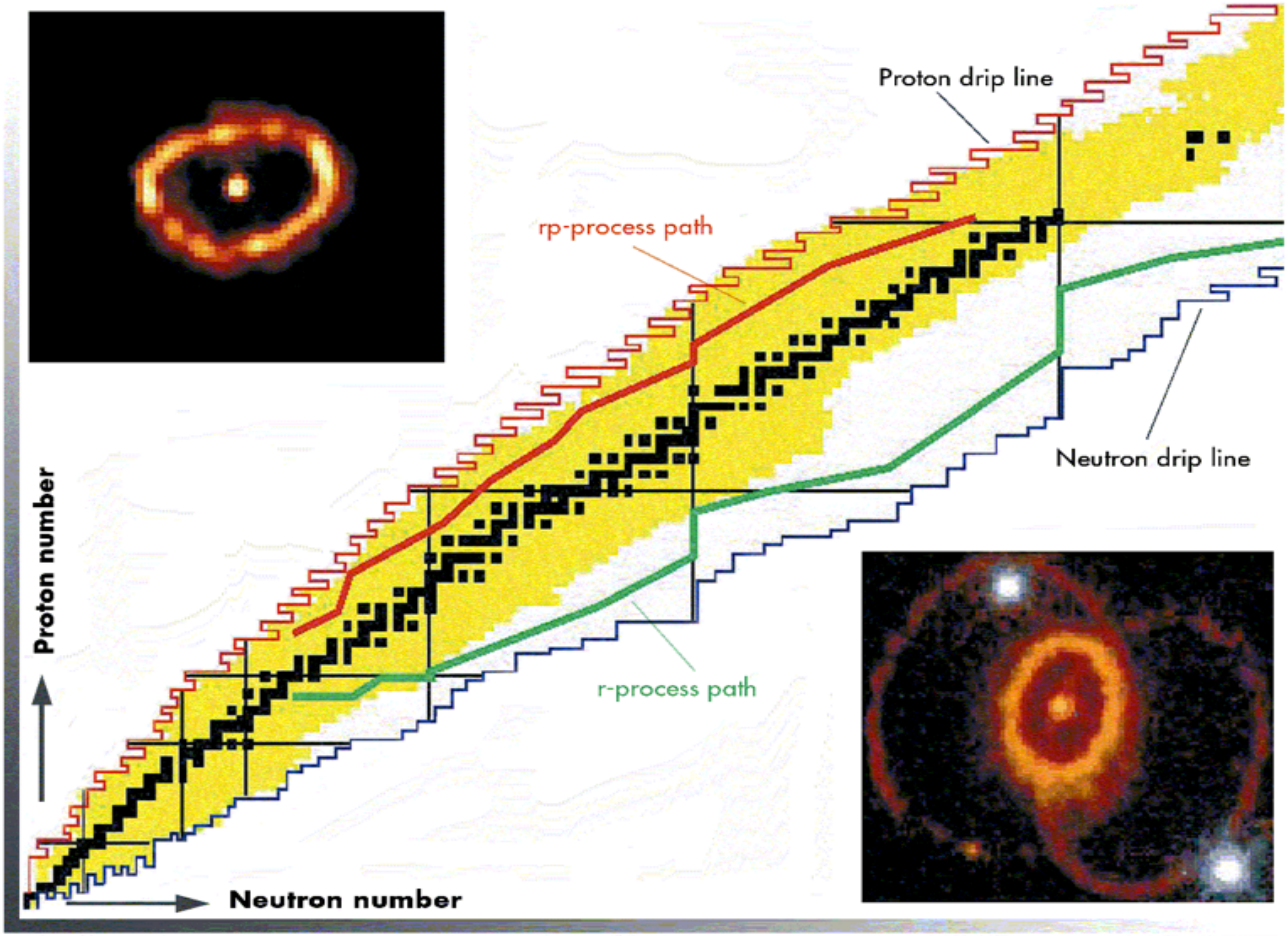
New Q_{EC}-value determinations (Penning Trap):

^{22}Mg	M. Mukherjee *et al.*, Phys. Rev. Lett. 93 (2004) 150801
$^{26}Al^m$, ^{42}Sc, ^{46}V	T. Eronen *et al.*, Phys. Rev. Lett. 97 (2006) 232501
^{34}Ar	F. Herfurth *et al.*, Eur. Phys. J. A 15 (2002) 17
^{38}Ca	G. Bollen *et al.*, Phys. Rev. Lett. 96 (2006) 152501
	S. George *et al.*, Phys. Rev. Lett. 98 (2007) 162501
^{46}V	G. Savard *et al,*, Phys. Rev. Lett. 95 (2005) 102501
^{62}Ga	T. Eronen *et al.*, Phys. Lett. B 636 (2006) 191
^{74}Rb	A. Kellerbauer *et al.*, Phys. Rev. Lett. 93 (2004) 072502
^{50}Mn and ^{54}Co	T. Eronen et al., Phys. Rev. Lett. 100 (2008) 132502

X-ray burst scenario



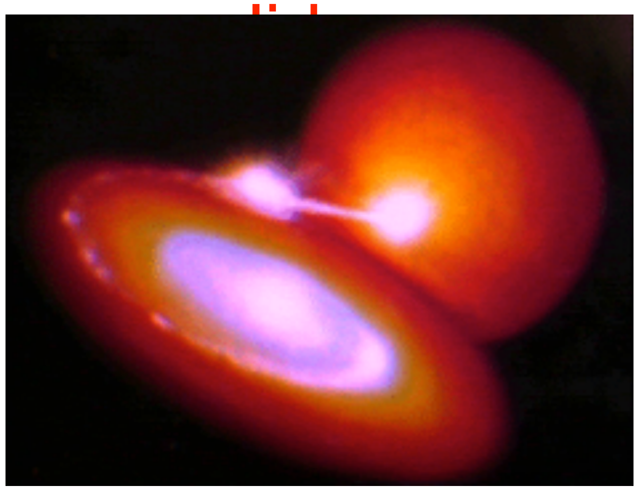
Nuclear Astrophysics and N=Z



Astrophysical rp-process

From: www.nscl.msu.edu/research/ria/whitepaper.pdf

Possible waiting-point



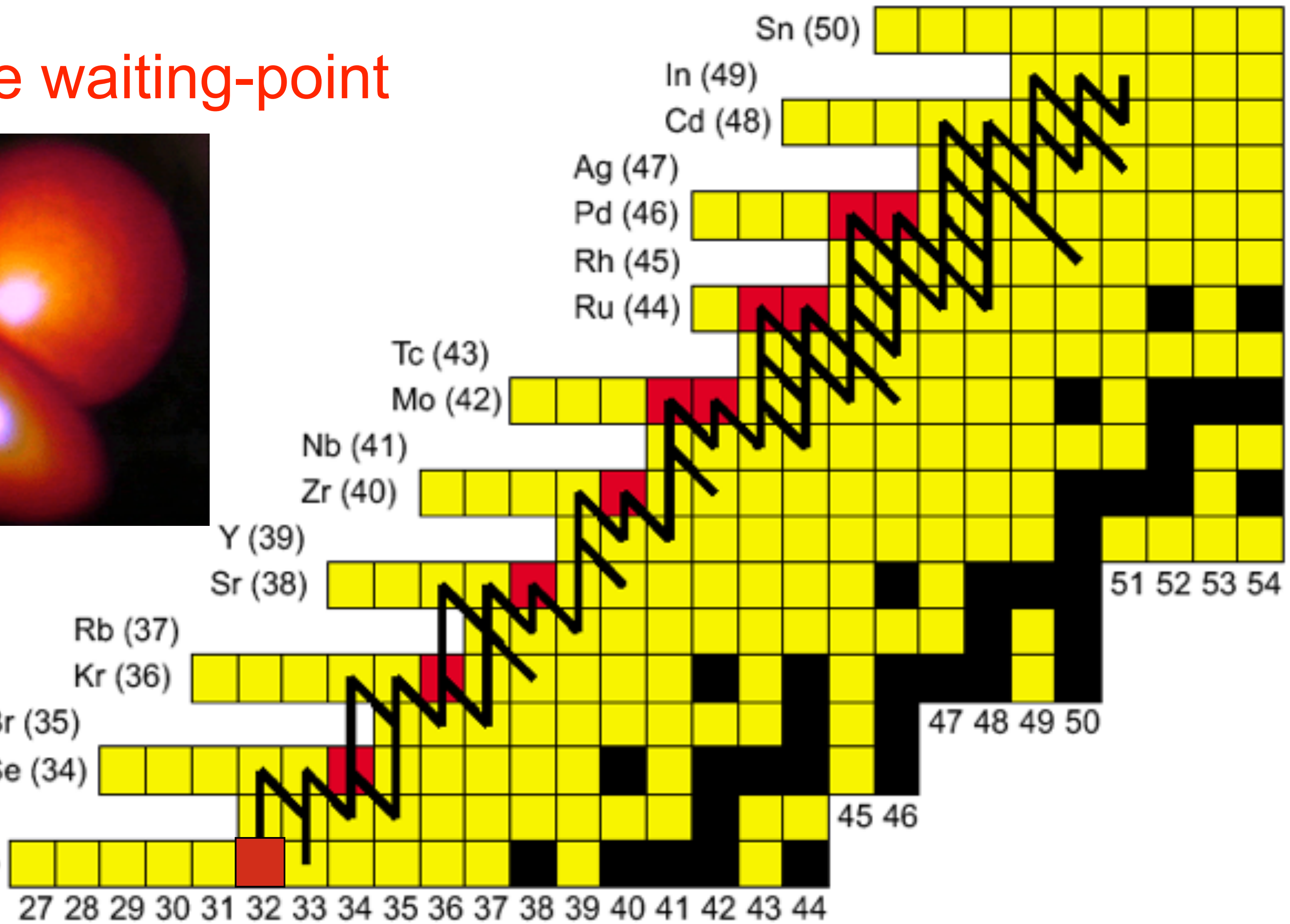
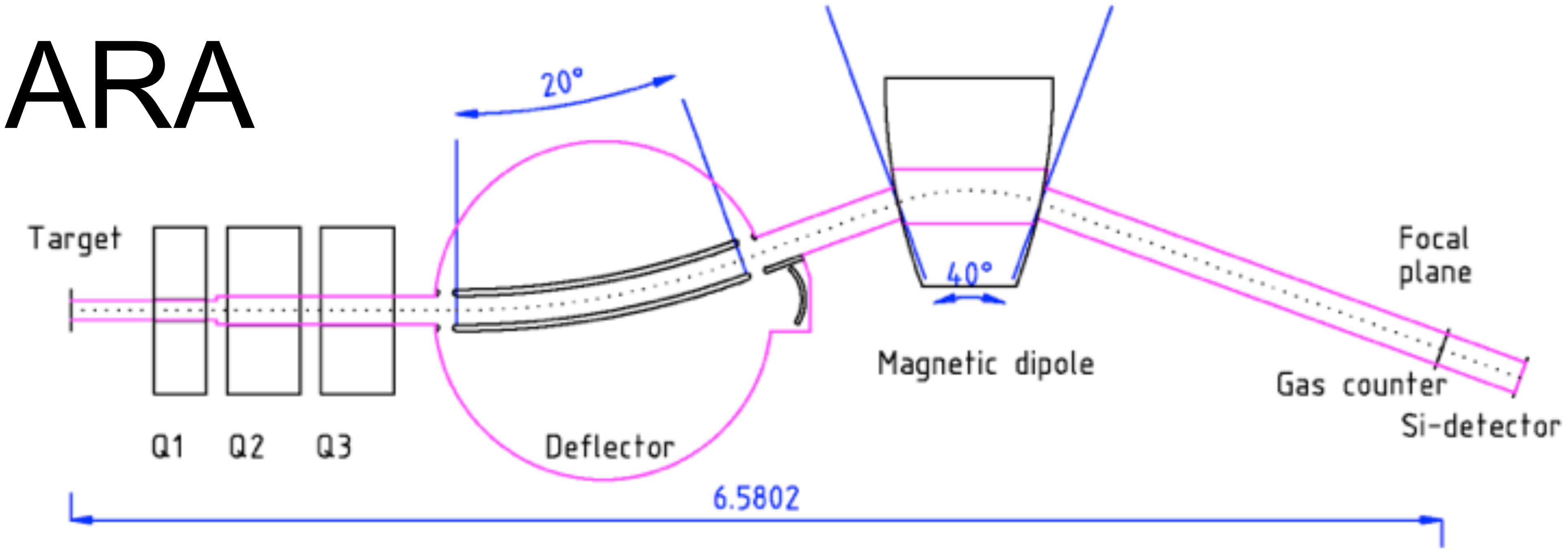
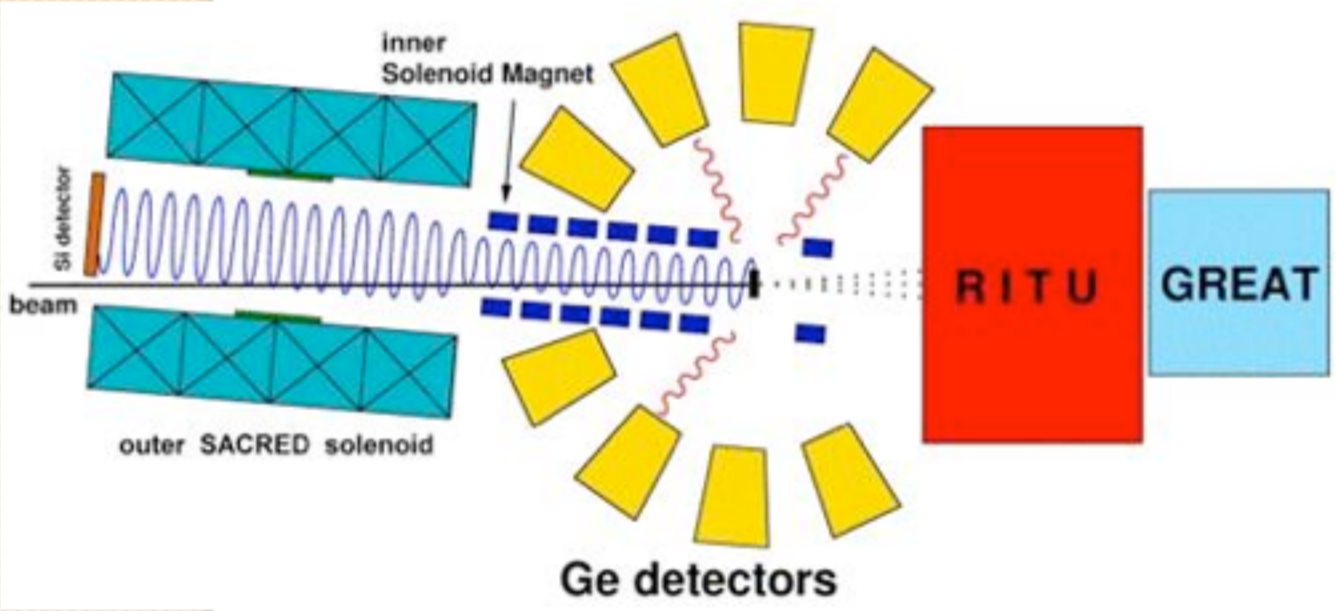


Figure 7: rp-process path predicted by network calculations. The waiting points are indicated in red, other proton-bound nuclei in yellow. Adapted from [sch98a].

Future plans at Jyvaskyla

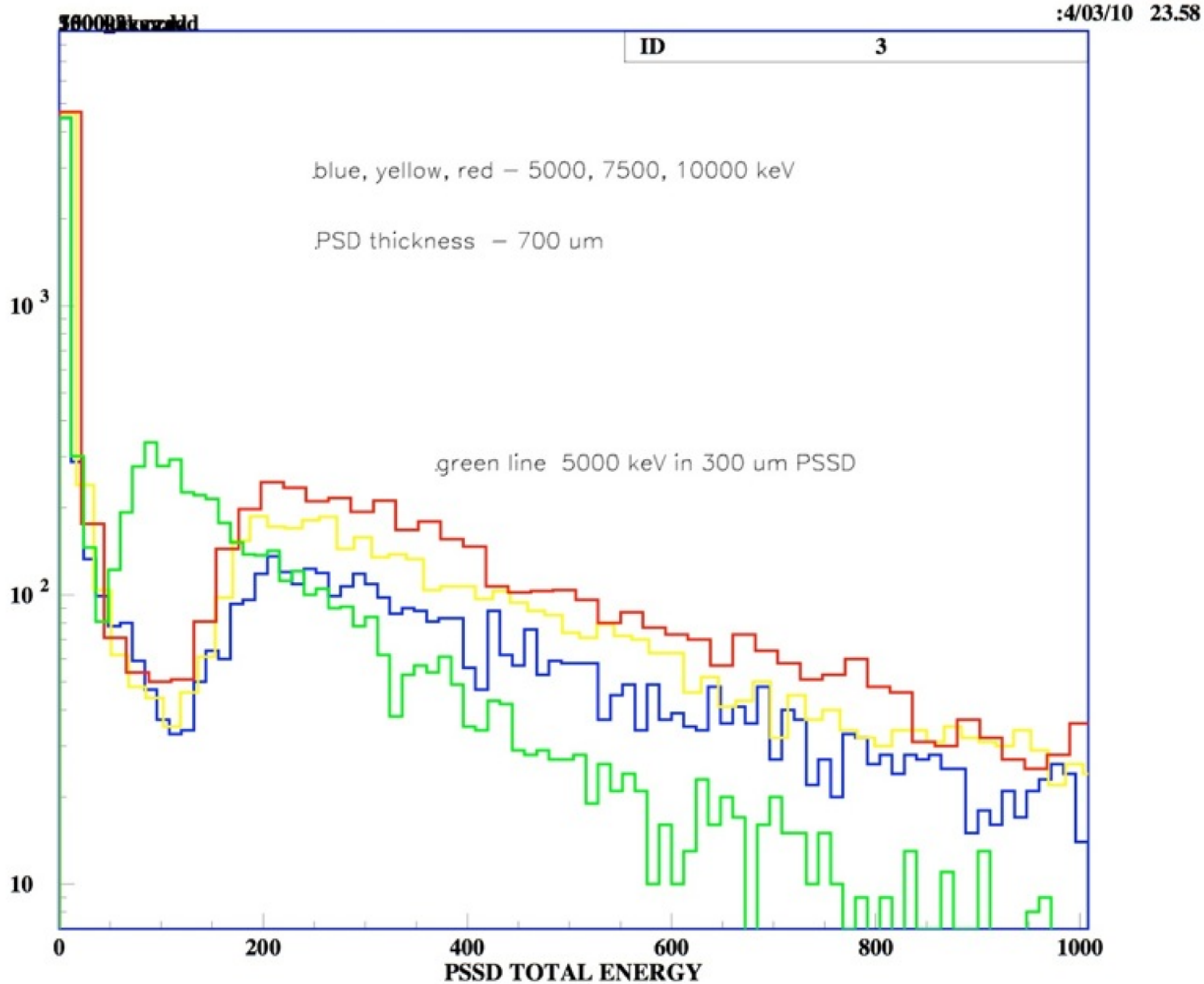
MARA





LISA

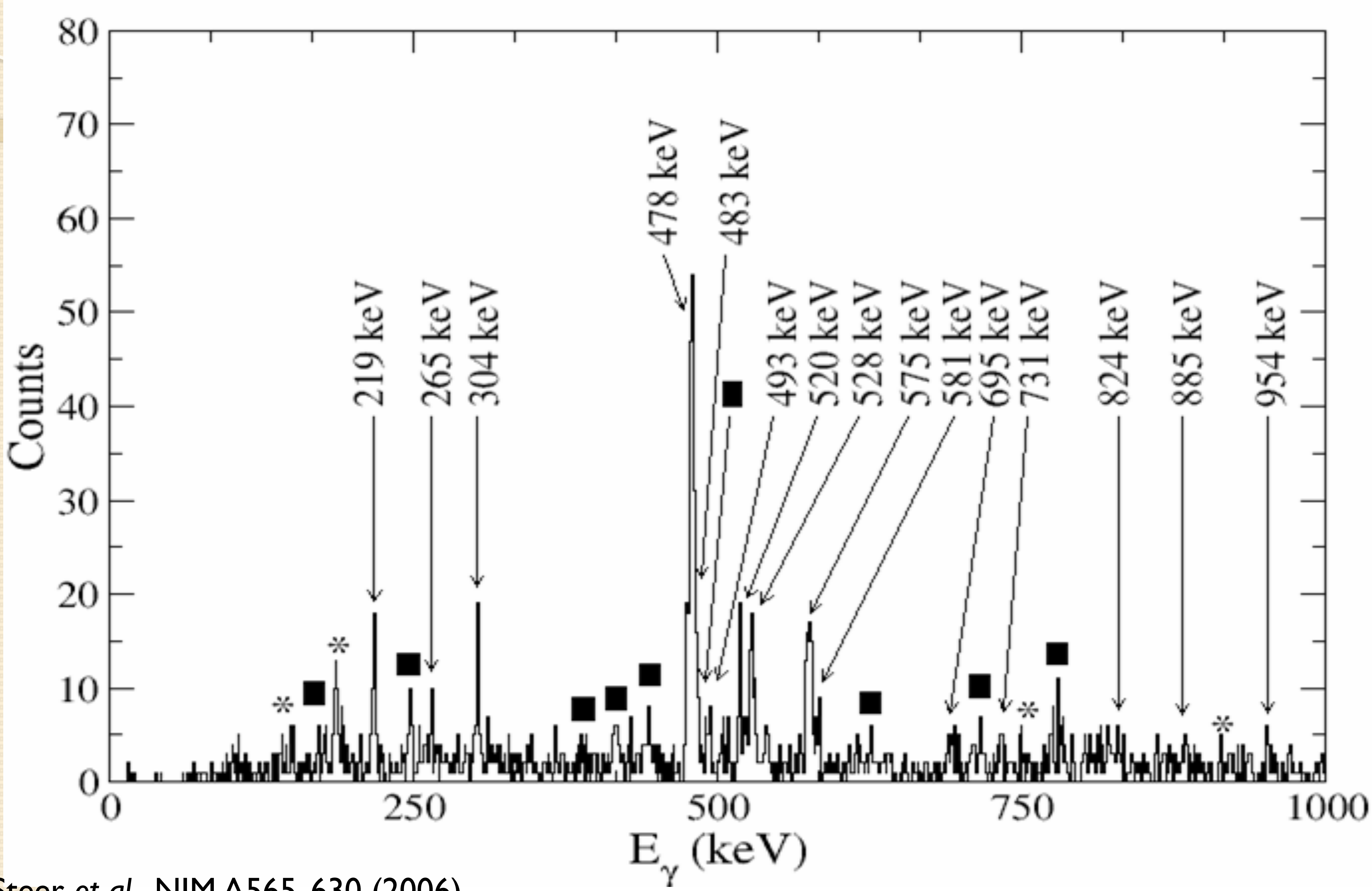
Target silicon array for prompt protons and alphas


:4/03/10 23.58
ID 3
blue, yellow, red – 5000, 7500, 10000 keV
PSD thickness – 700 um
green line 5000 keV in 300 um PSSD
10 3
10 2
10
0
200
400
600
800
1000
PSSD TOTAL ENERGY

TDR : Total Data Readout

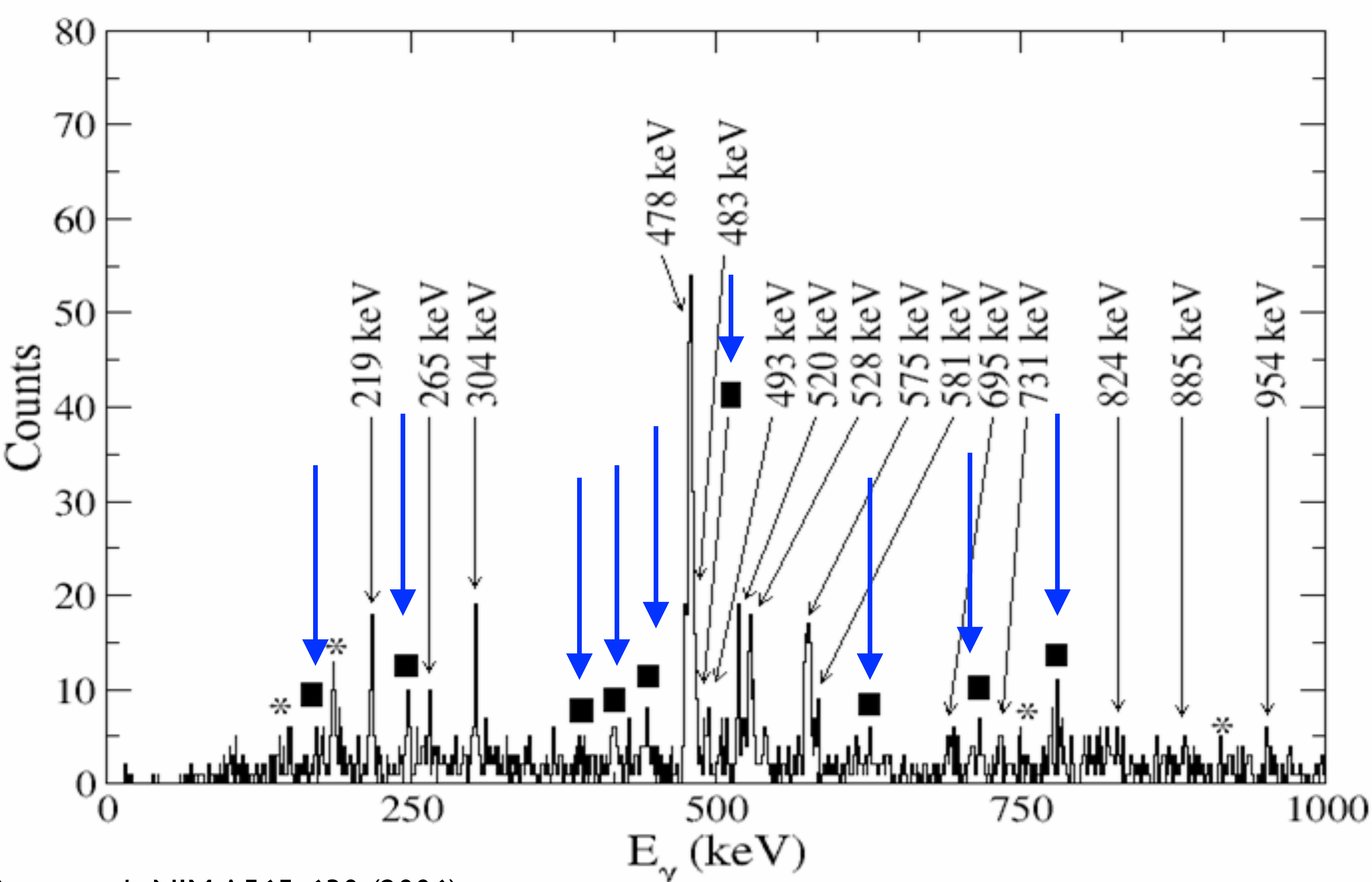
- Triggerless Data Acquisition System
- Rates up to 850 kHz without deadtime
- 380 channels timestamped data
- 10 ns resolution
- Time-of-Day clock with 32 day rollover
- Flexible + Easily Scalable

Identification of ^{74}Rb



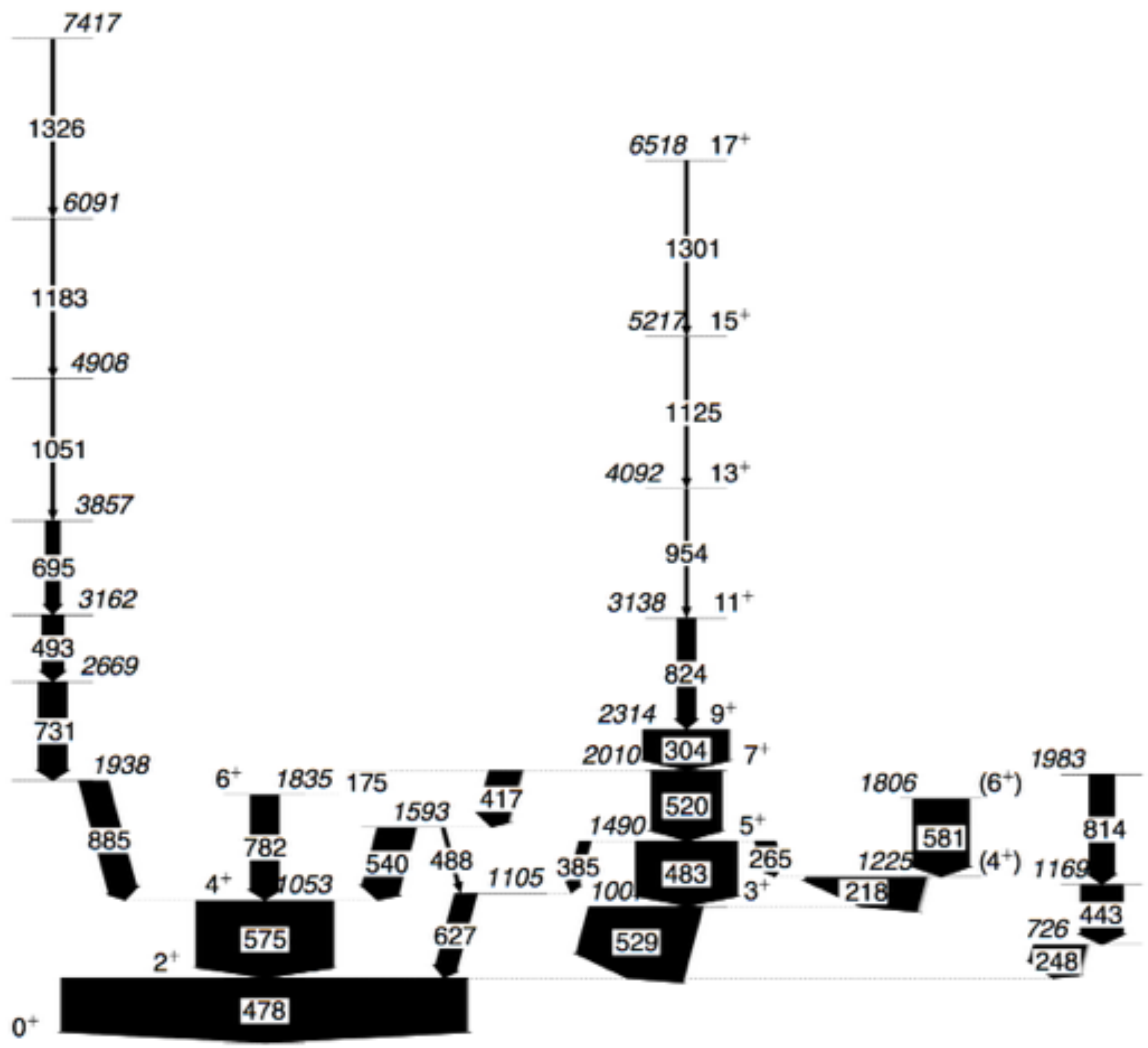
A.N. Steer, *et al.,* NIM A565, 630 (2006)

Identification of ^{74}Rb

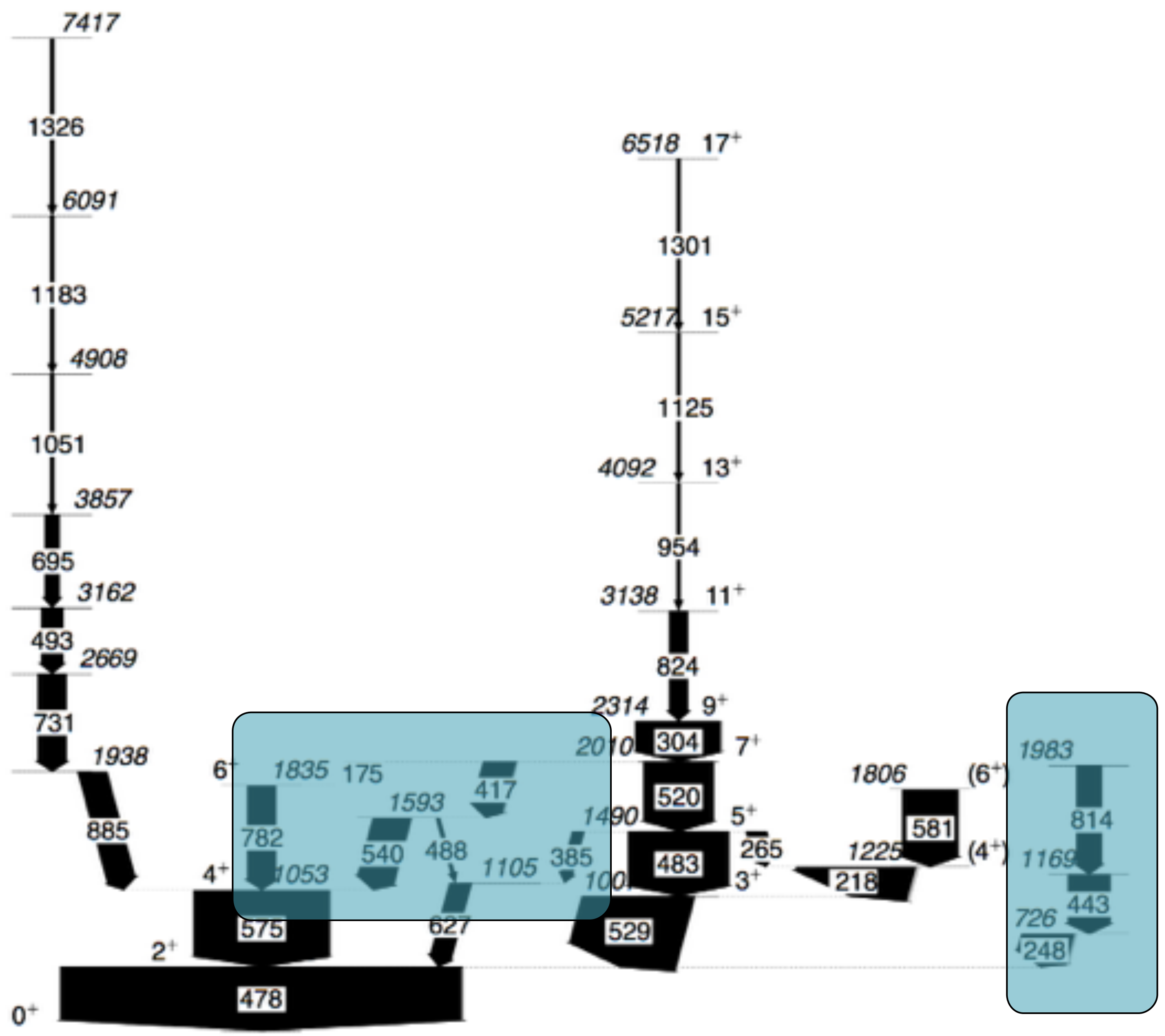


A.N. Steer, *et al.,* NIM A565, 630 (2006)

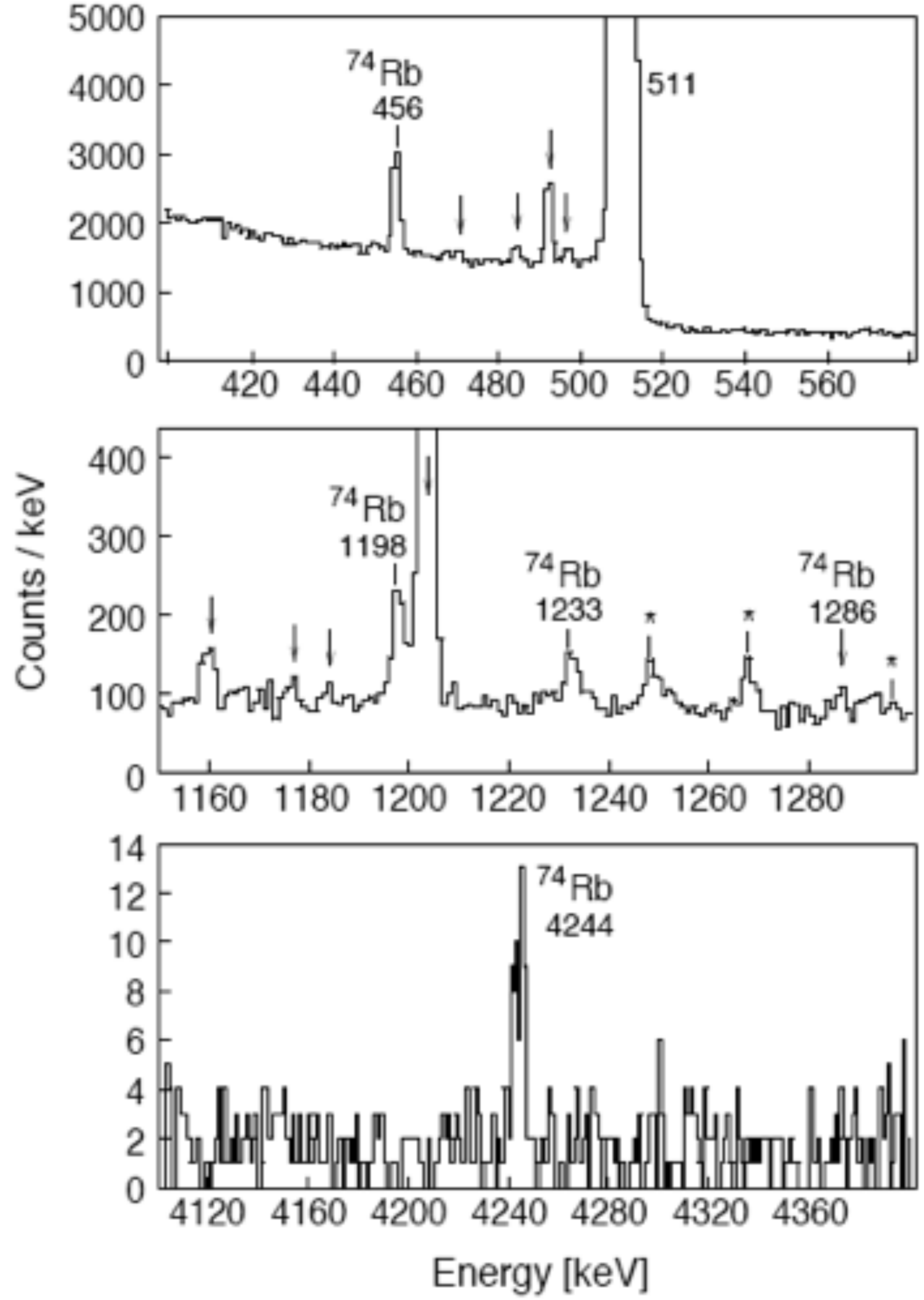
^{74}Rb level scheme from RBT

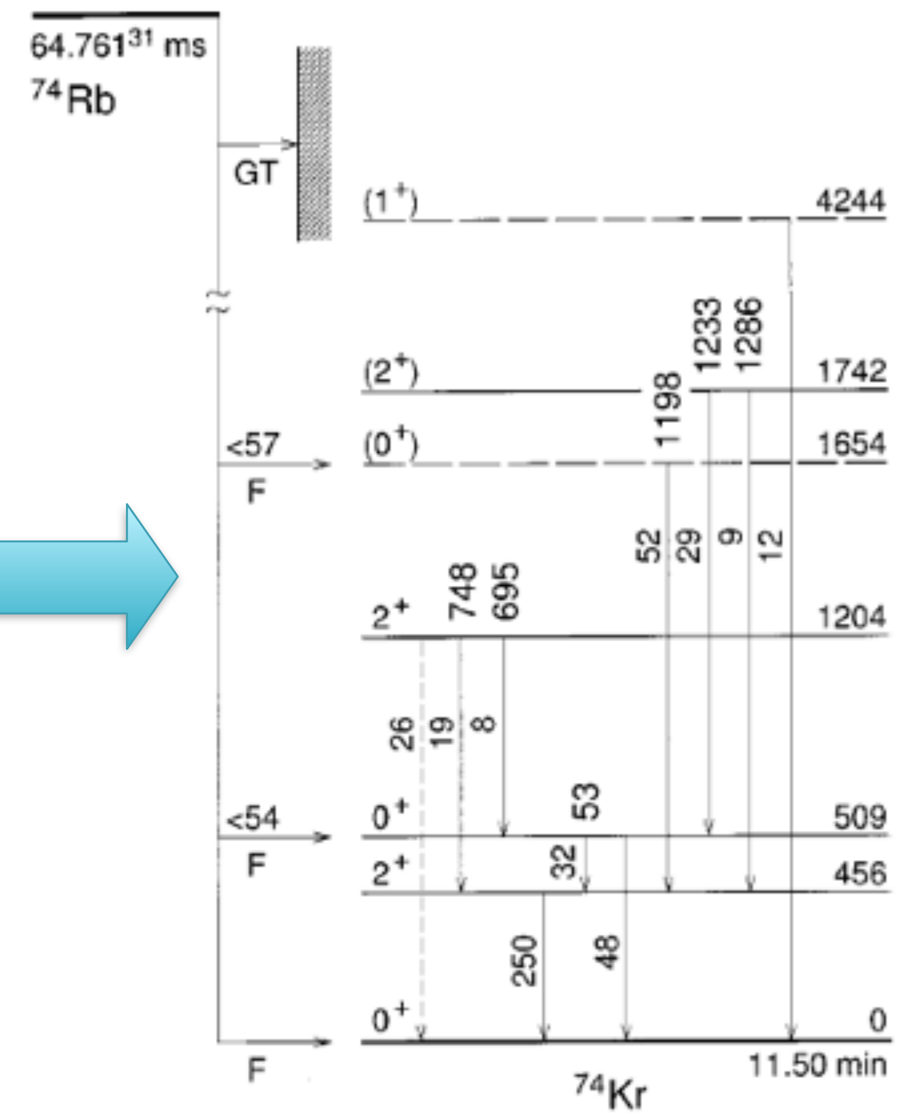


^{74}Rb level scheme from RBT



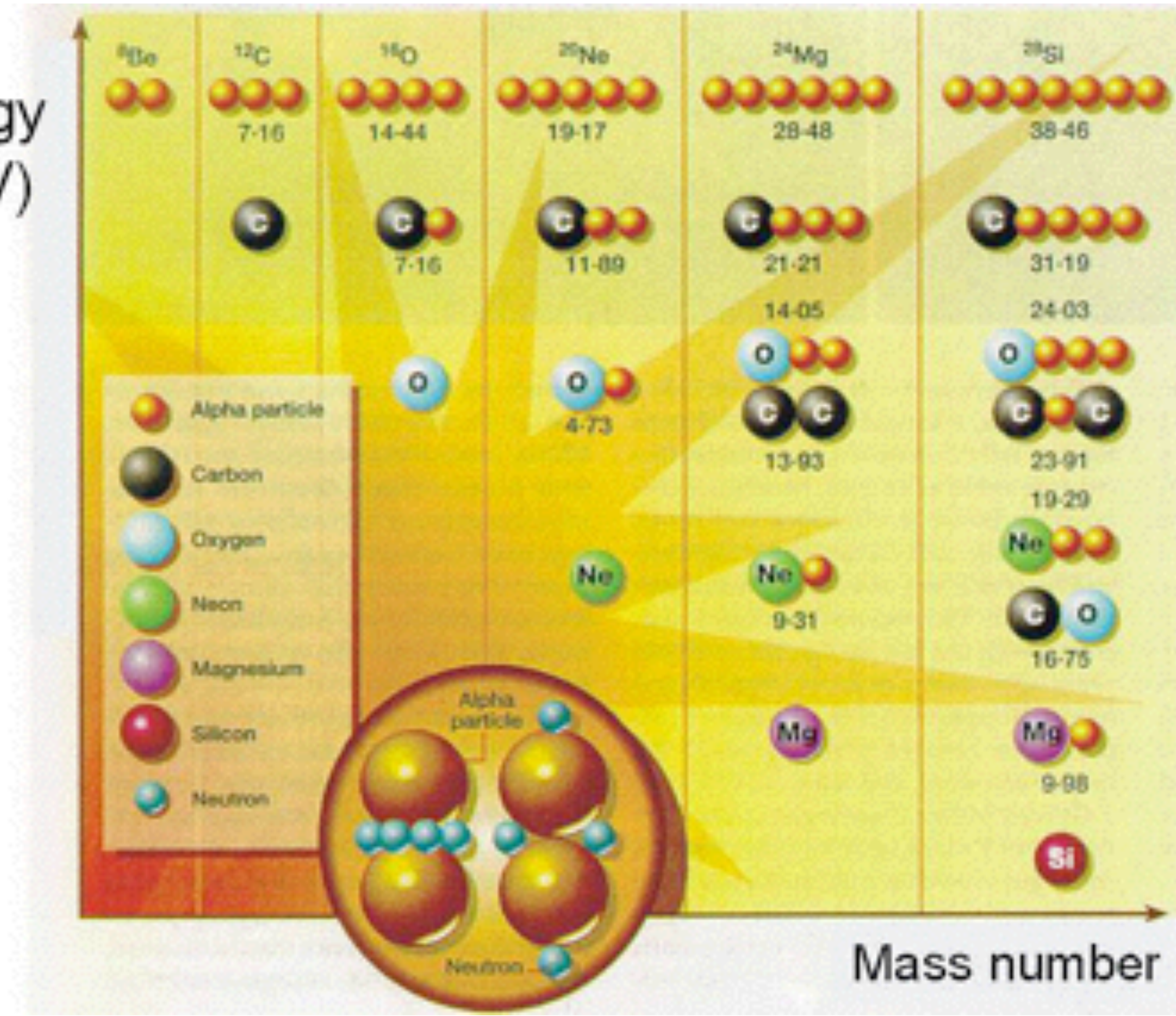
Precision branching ratio measurement for decay of ^{74}Rb



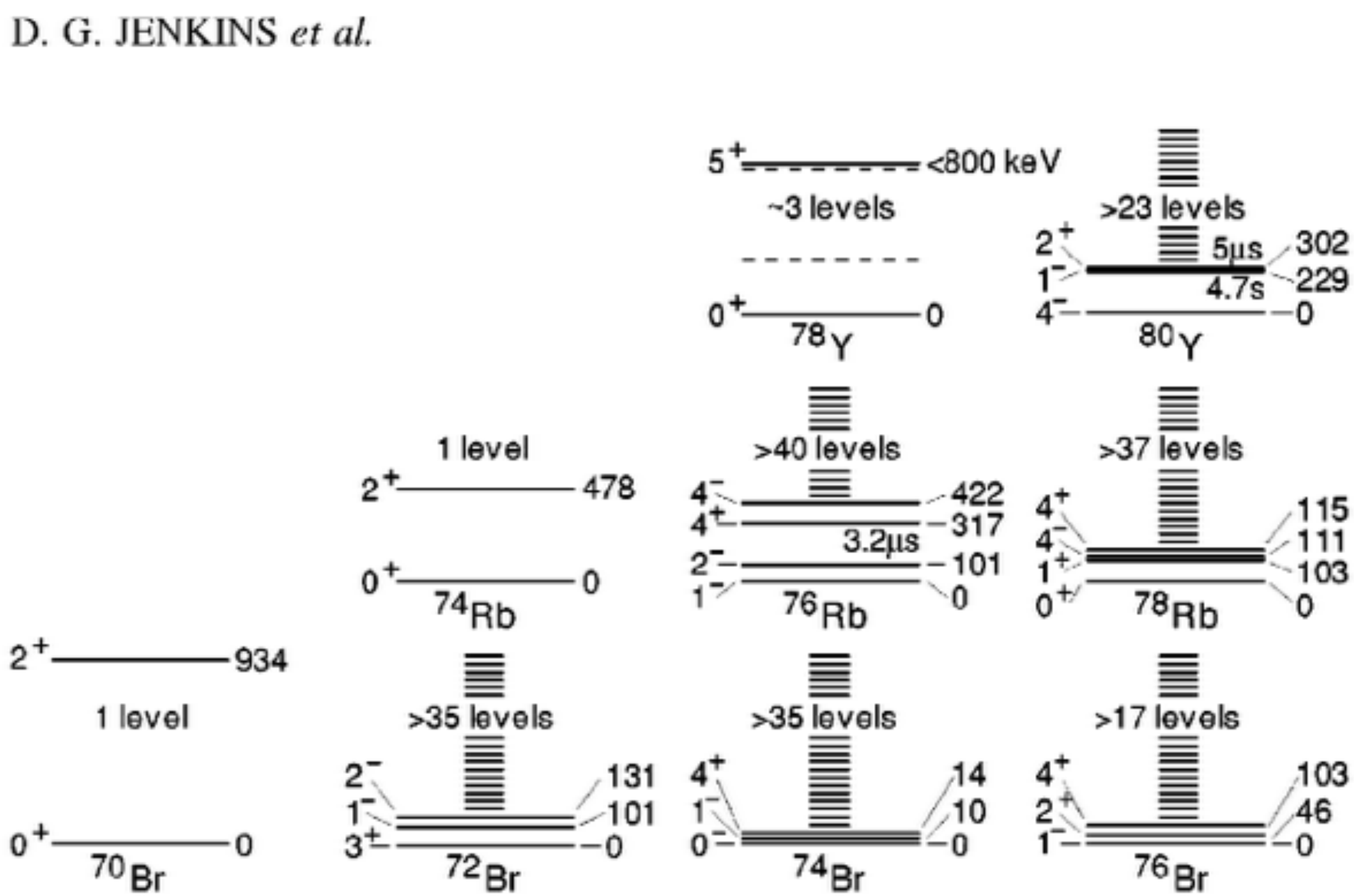


A. Piechaczek et al., Phys. Rev. C 67, 051305 (2003)

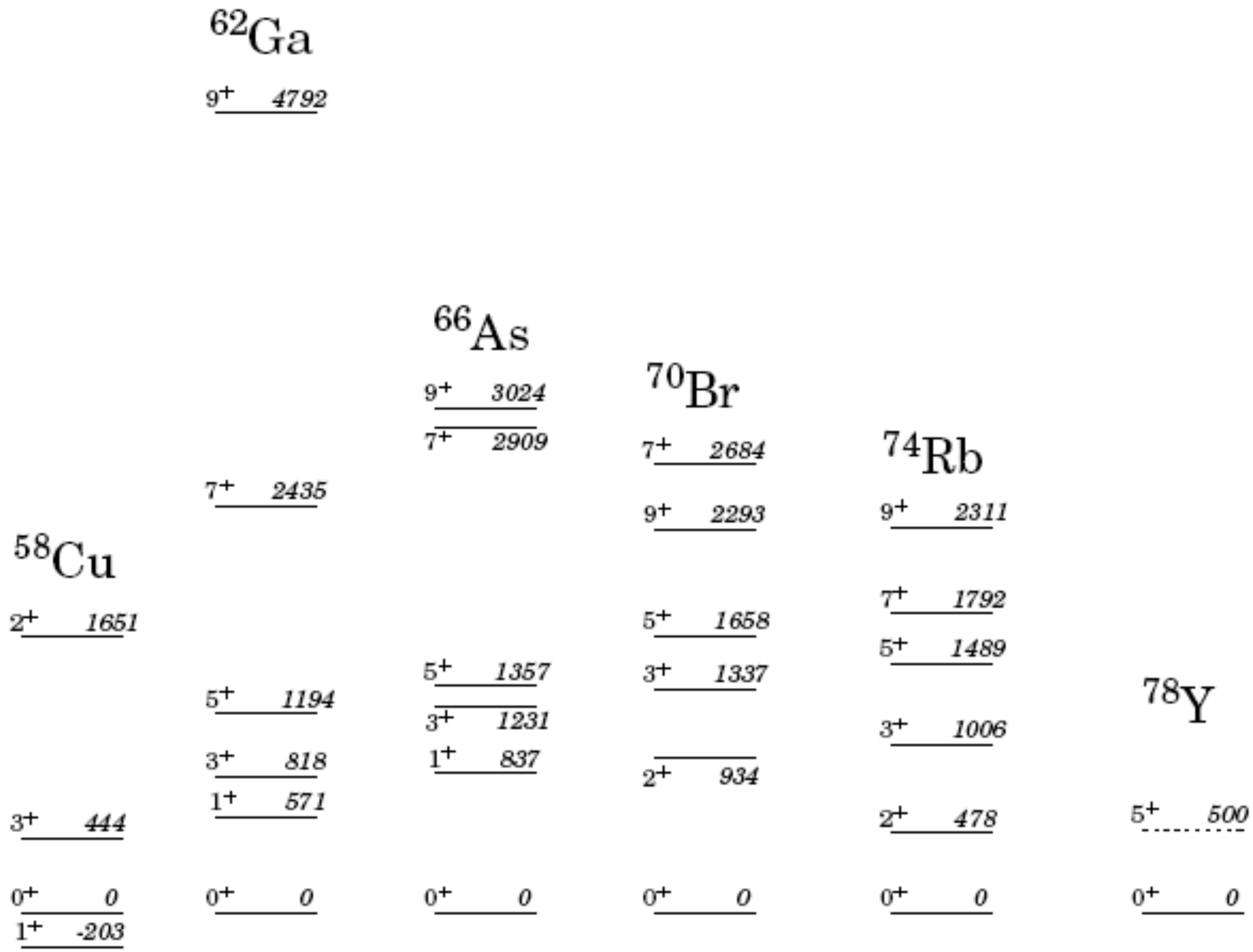
Alpha clustering in light nuclei



Empirical observations



Odd-odd N=Z



62Ga
9+ 4792
7+ 2435
5+ 1194
3+ 818
1+ 571
0+ 0
66As
9+ 3024
7+ 2909
5+ 1357
3+ 1231
1+ 837
0+ 0
70Br
7+ 2684
9+ 2293
5+ 1658
3+ 1337
2+ 934
0+ 0
74Rb
9+ 2311
7+ 1792
5+ 1489
3+ 1006
2+ 478
0+ 0
58Cu
2+ 1651
3+ 444
0+ 0
1+ -203
78Y
5+ 500
0+ 0