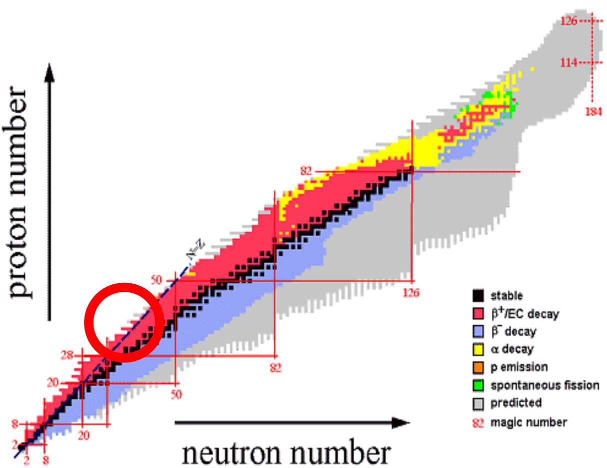
Recoil beta tagging study of near proton drip-line nuclei in the A~70 region

- Motivation
- Recoil beta tagging technique
- Results
- Future plans

B.S. Nara Singh

The region of interest



				76Y >200 NS ε P	77Y 57 MS ε: 100.00% P	78Y 50 MS ε: 100.00%	79Y 14.8 S ε: 100.00% εp	80Y 30.1 S ε: 100.00% εp
		73Sr >25 MS ε: 100.00% εp > 0.00%	74Sr >1.2 μS ε	75Sr 88 MS ε: 100.00% εp: 5.20%	76Sr 7.89 S ε: 100.00% εp: 0.34%	77Sr 9.0 S ε: 100.00% εp < 0.25%	78Sr 2.5 M ε: 100.00%	79Sr 2.25 M ε: 100.00%
	71Rb P	72Rb <1.2 μS P	73Rb >30 NS P > 0.00% ε	74Rb 64.9 MS ε: 100.00%	75Rb 19.0 S ε: 100.00%	76Rb 36.5 S ε: 100.00% εα: 3.8E-7%	77Rb 3.77 M ε: 100.00%	78Rb 17.66 M ε: 100.00%
69Kr 32 MS ε: 100.00%	70Kr 52 MS ε: 100.00% εp ≤ 1.30%	71Kr 100 MS ε: 100.00% εp: 5.20%	72Kr 17.1 S ε: 100.00%	73Kr 27.3 S ε: 100.00% εp: 0.25%	74Kr 11.50 M ε: 100.00%	75Kr 4.29 M ε: 100.00%	76Kr 14.8 H ε: 100.00%	77Kr 74.4 M ε: 100.00%
68Br <1.2 μS P	69Br <24 NS P	70Br 79.1 MS ε: 100.00%	71Br 21.4 S ε: 100.00%	72Br 78.6 S ε: 100.00%	73Br 3.4 M ε: 100.00%	74Br 25.4 M ε: 100.00%	75Br 96.7 M ε: 100.00%	76Br 16.2 H ε: 100.00%

Astrophysical relevance

Influences rp-process nuclear abundances beyond Fe.

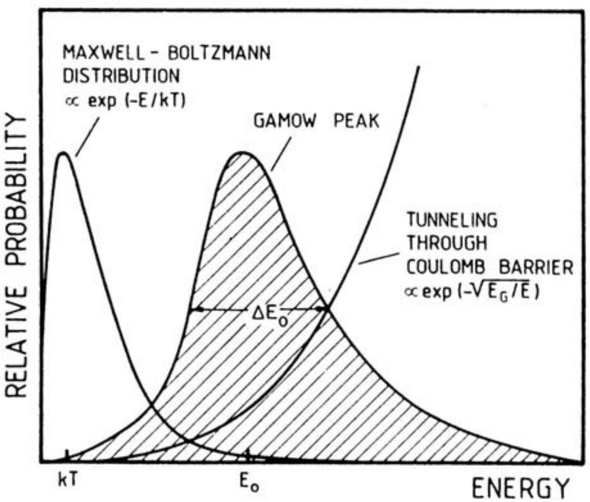
H. Schatz et al, EPJ A11, 257 (2001)

^{68}Se→ ^{69}Br→ ^{70}Kr, 2p capture

Q-value 1.33 MeV

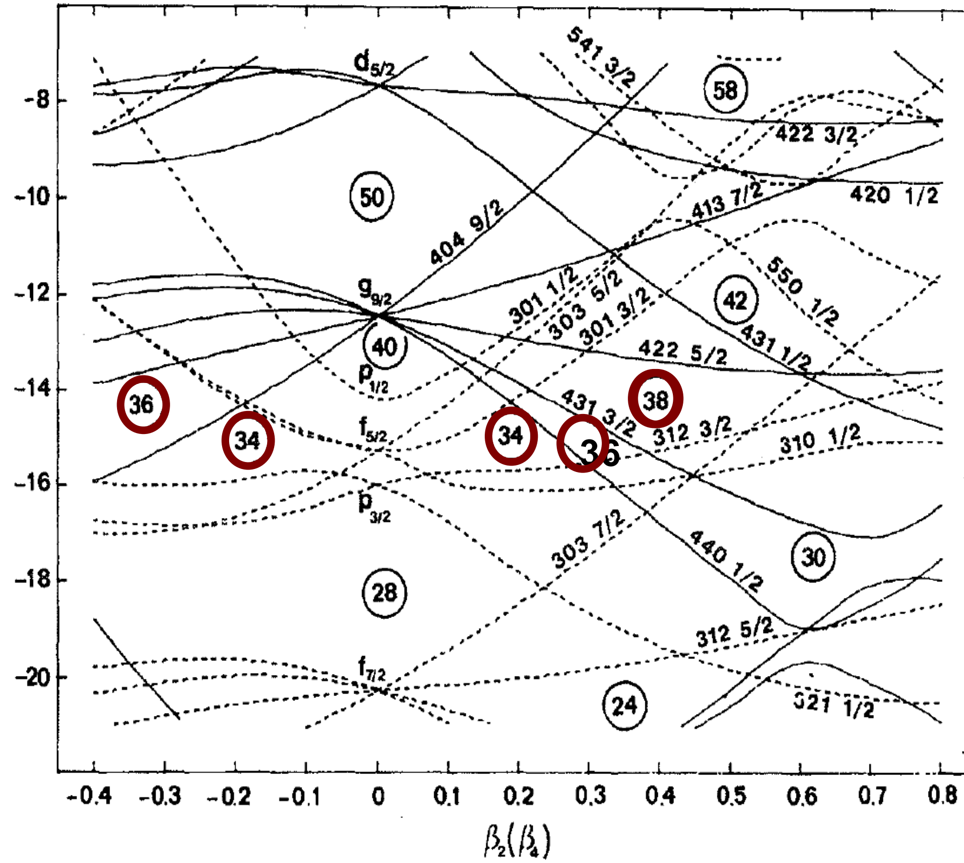
Gamow peak 2.2 (1.1) MeV

Low density of levels below 1 MeV



Shape co-existence in A=70 region

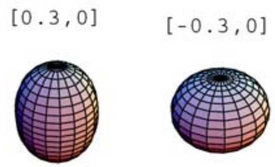
W. Nazarewicz et al., NPA 435 (1985) 397



Se and Kr isotopes are expected to show co-existing oblate and prolate structures

Shape co-existence & CED

Coulomb excitation
Life time measurements
Electro-magnetic moments
Isomers, excited 0^+ states etc.



For the exotic nuclei, CED can be used to probe the mirror symmetry and the shape co-existence

Coulomb energy differences of isobaric analogue states probe various macroscopic and microscopic nuclear phenomena

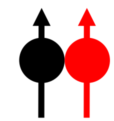
D.D. Warner et al, nature physics 2, 311 (2006),
S.M. Lenzi and M. A. Bentley, Prog. Part. Nucl. Phys. (2006)

Neutron-proton pairing

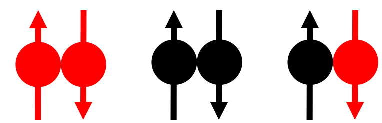
Best candidates to study neutron-proton coupling from the relative location of T=0 and T=1 states in odd-odd nuclei,

A.L. Goodman et al., PRC 60, 014311 (1999), 63, 044325(2001), Adv. Nucl. Phys. 11 (1979), p. 263

J=1 T=0



J=0 T=1



Binding Energies, Pair transfer,
Delays in Back Bending,
Low lying level Structure
Iso-spin mixing

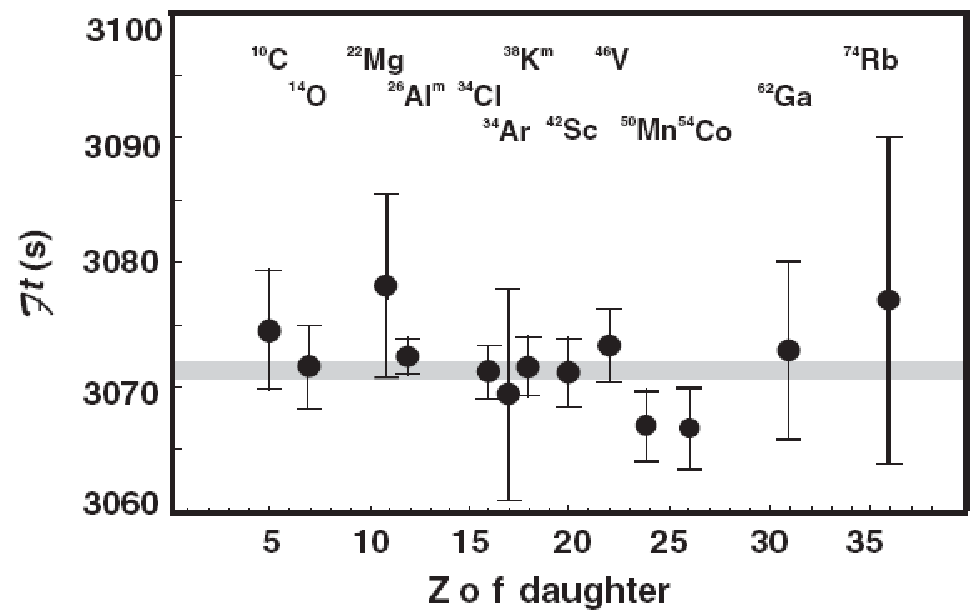
Standard Model

β decay strengths and the nuclear structure information (e.g., Iso-spin mixing) can be used to check unitarity of the CKM matrix and Conserved Vector Current hypothesis in the Standard model.

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9966 \pm 0.0014,$$

$$\mathcal{F}t \equiv ft(1+\delta_R')(1+\delta_{NS}-\delta_C) = \frac{K}{2G_V^2(1+\Delta_R^V)}$$

G_v independent of nuclear medium



J.C. Hardy et al., PRL 94, 092502 (2005), PRC 77, 025501(2008)

Need high selectivity…

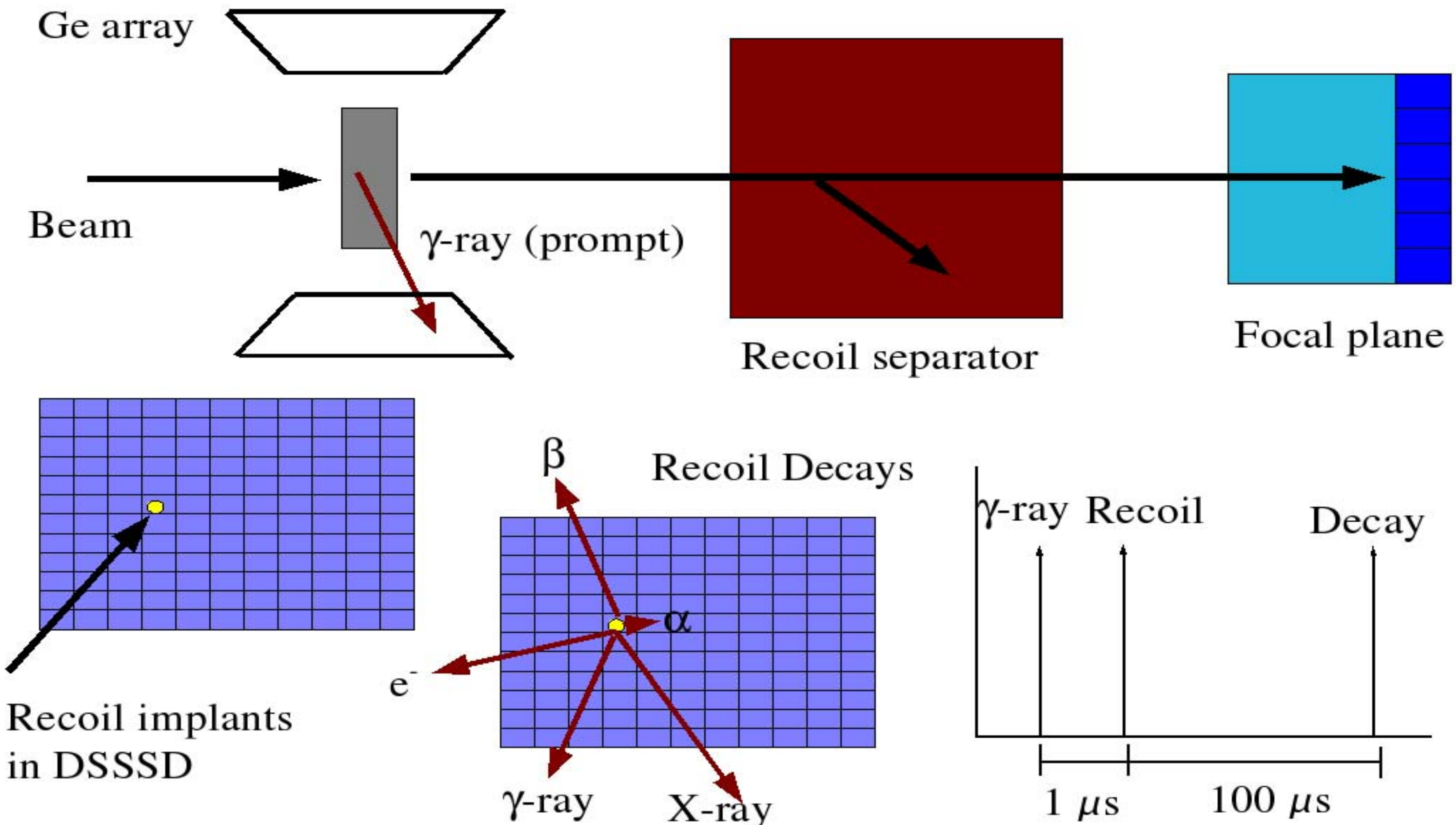
Conventional fusion evaporation studies become increasingly difficult as we go towards N=Z line for medium mass nuclei:

- **Low proton separation energies**
- **Around the barrier, slow recoils**
- **Limited choice of reactions**
- **Low production cross sections**

A clean identification becomes an absolute requirement to study these exotic nuclei

Recoil decay tagging

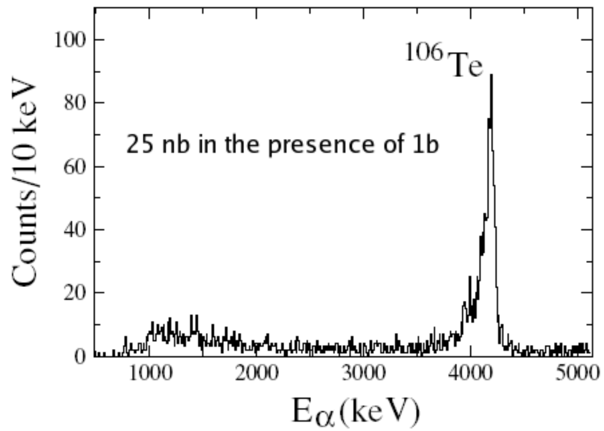
Sensitive tool for exotic nuclear studies with characteristic decays



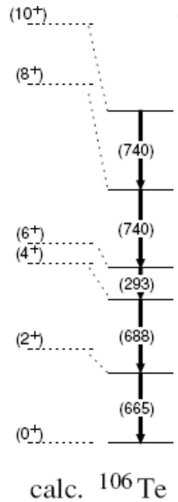
Hadinia et al, 72, 041303, PRC (2005), Sandzelius et al, PRL 99, 022501 (2007) (R. Julin, P. Jones)

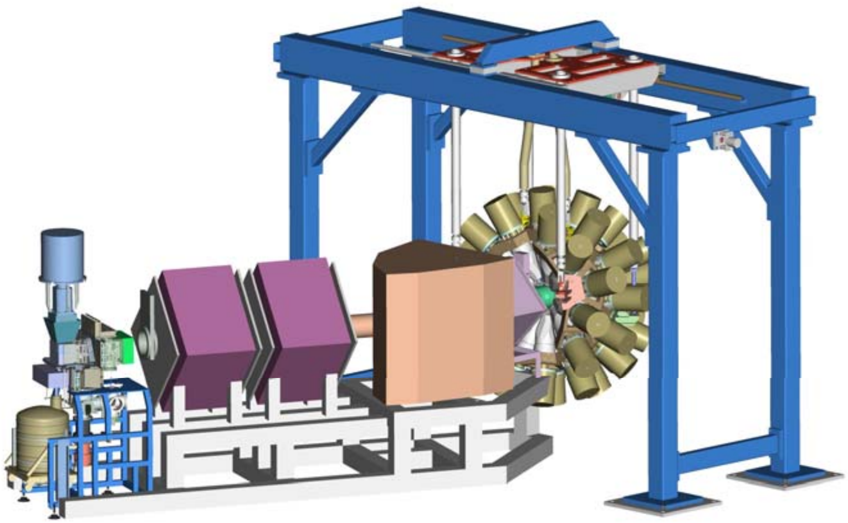
Recoil decay tagging

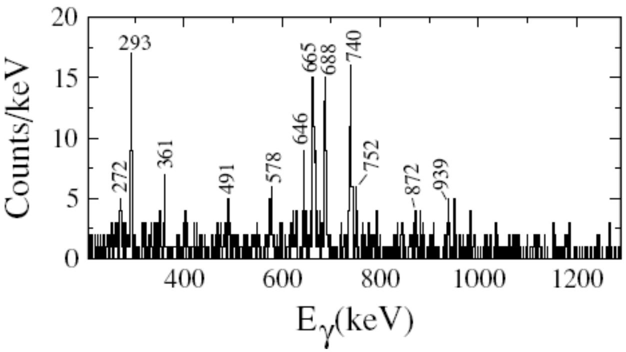
Hadinia et al PHYSICAL REVIEW C **72**, 041303(R) (2005)



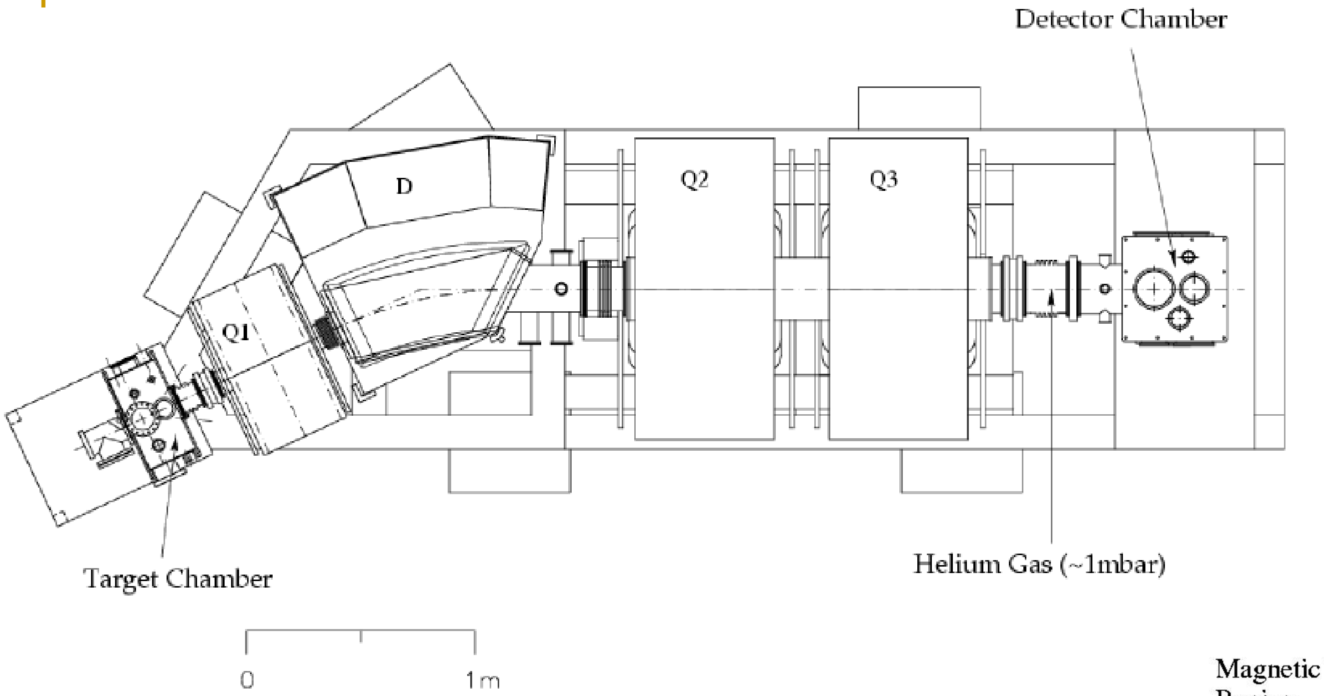
Alpha Tagging



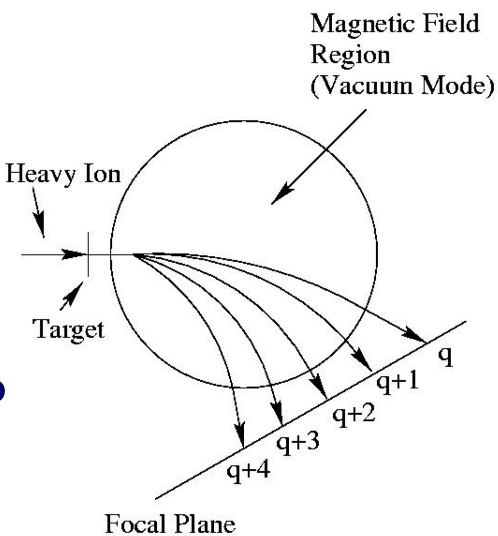


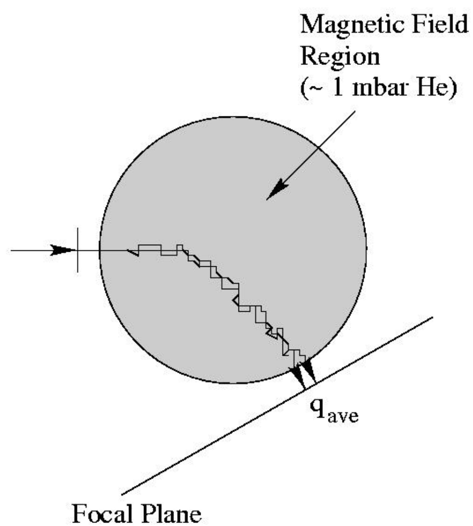


^{106}Te is studied that was produced with 25nb in the presence of 1 barn total cross section



>30%



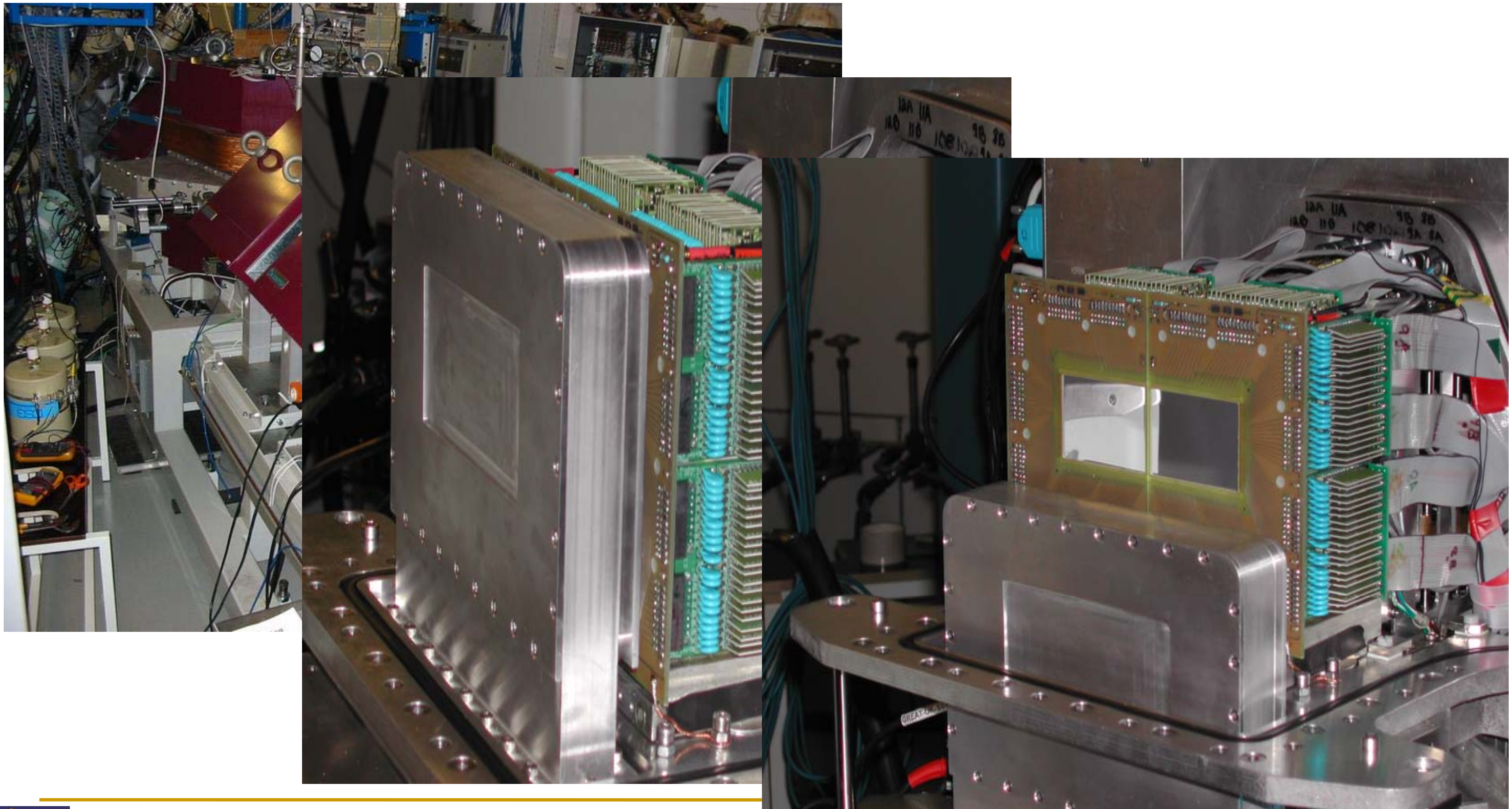


10-20%

RITU higher efficiency

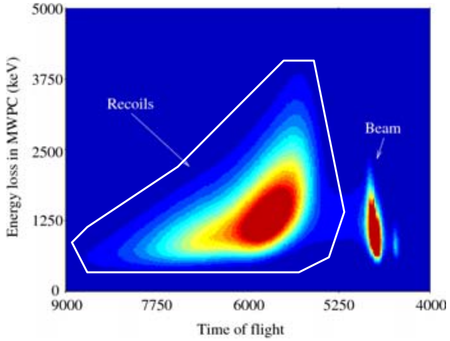
JUROGAM & RITU @ Jyväskylä

GREAT

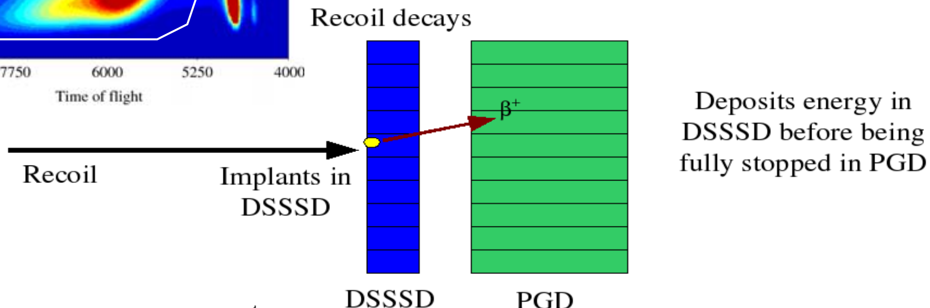


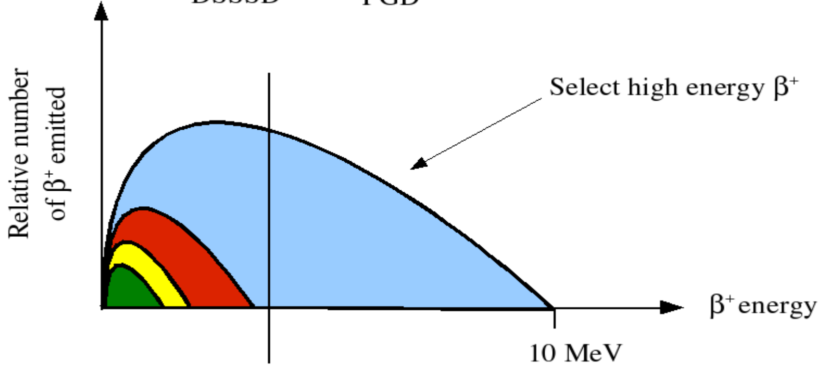
Recoil-β-tagging using GREAT

We successfully pursued for the first time, A.N. Steer et al, NIM A 565, 630(2006).



Relatively longer half lives





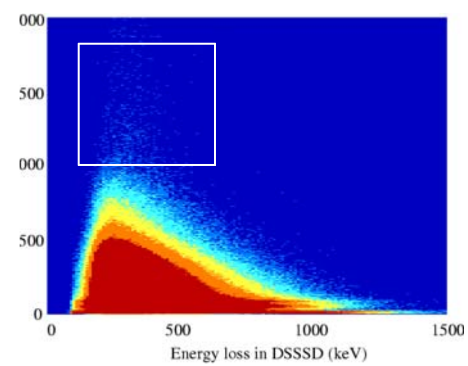
No characteristic energy

N=Z nuclei in A~70 region are ideal for trial.

Fermi super allowed β decays,

~10's of ms half lives
~10 MeV end point energies

Established the technique with a known case of ^{74}Rb

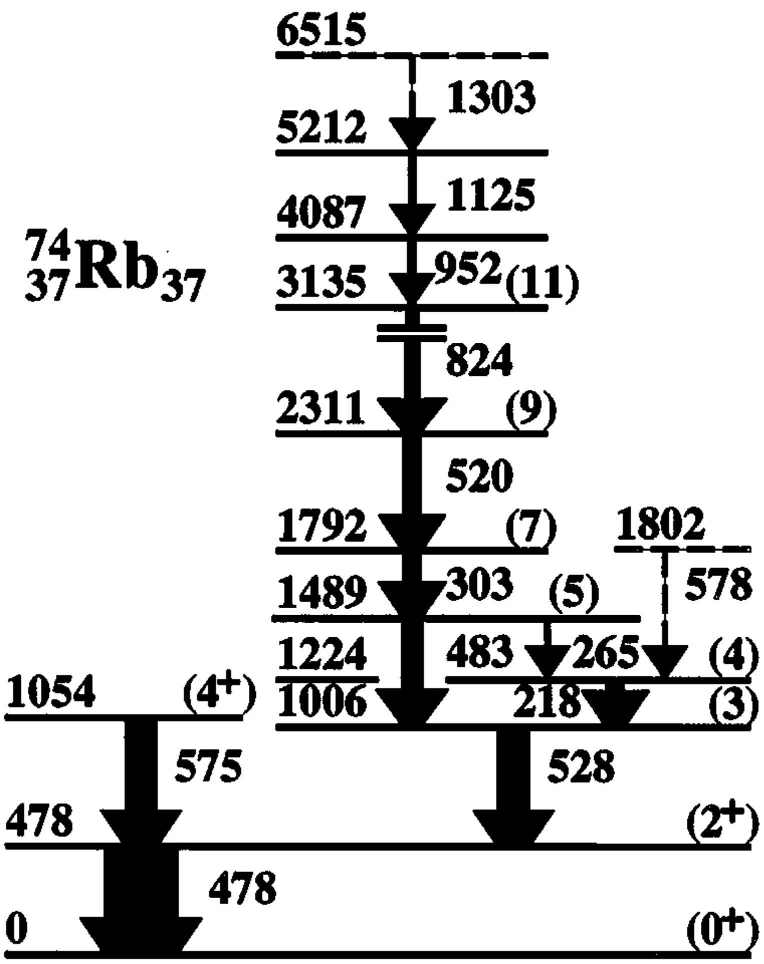


Proof-of-principle experiment

- ^{40}Ca (^{36}Ar, pn) ^{74}Rb
- E_{beam} = 103 MeV
- $\tau_{1/2}$ (^{74}Rb) = 65 ms
- $\beta^{+}_{endpoint}$ ~ 10 MeV
- σ ~ 0.15 mb

D. Rudolph, *et al.*, PRL 76, 376 (1996)

C. D. O'Leary, *et al.*, PRC 67, 021301(R) (2003)

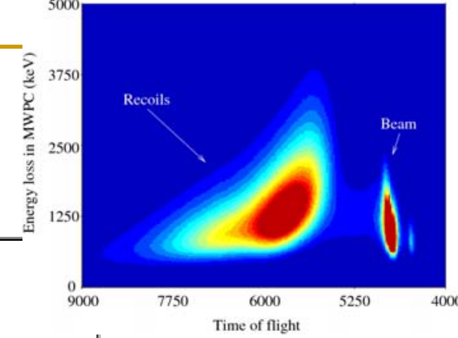


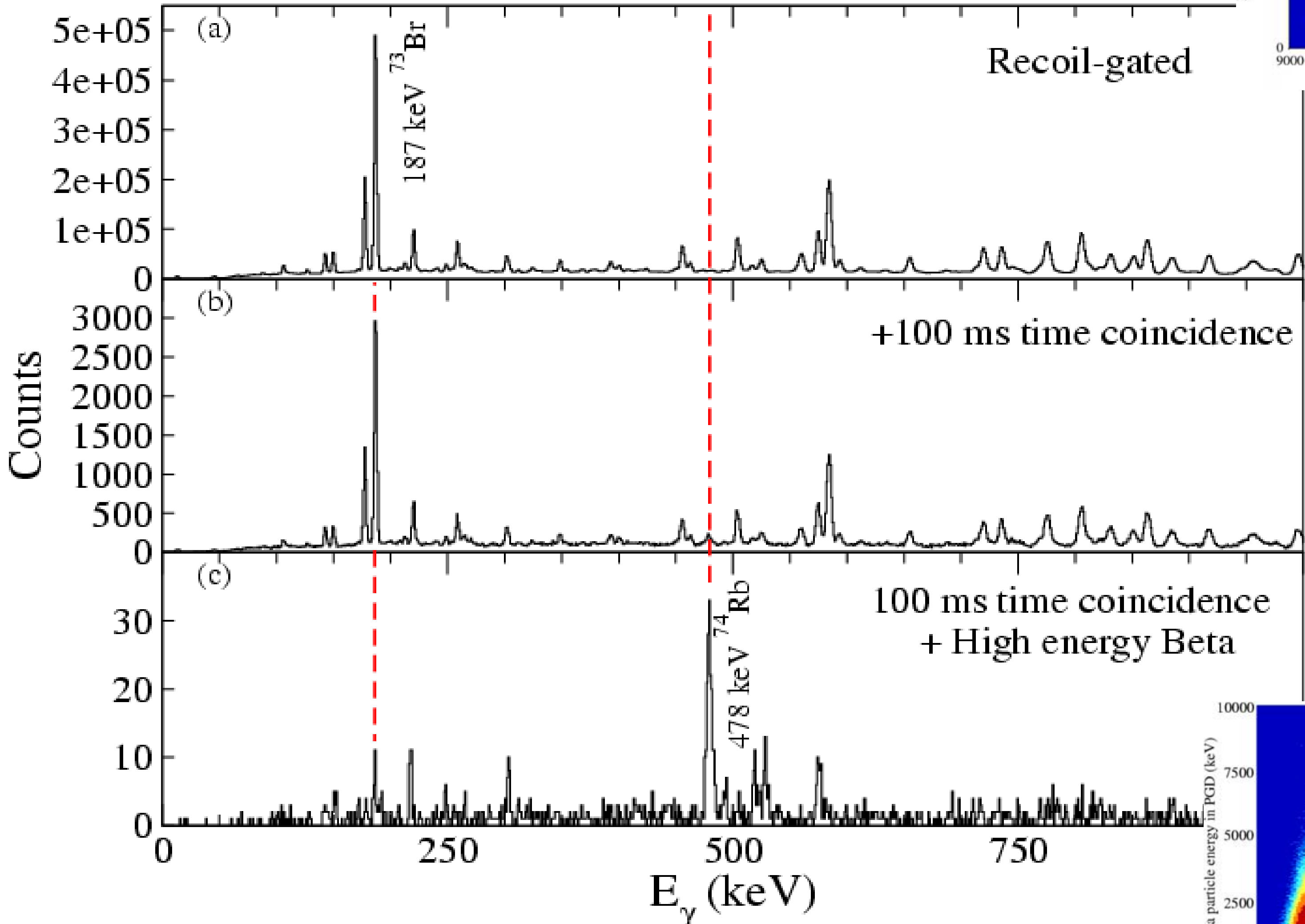
Reaction channels

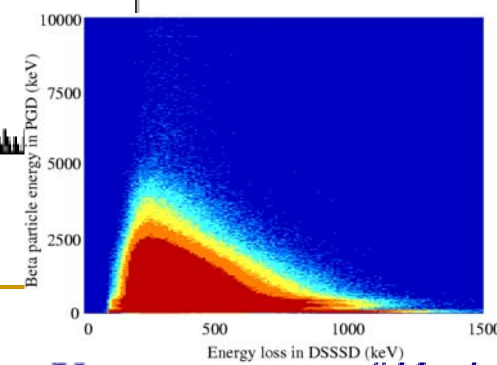
The perfect test case

Nucleus	Channel	Half-life	Q (EC) (MeV)	σ (mb)
^{74}Rb	pn	65 ms	10.4	0.26
^{74}Kr	2p	11 min	3.14	3.01
^{74}Sr	2n	> 1.2 μs	-	0.014
^{73}Kr	2pn	12 s	6.67	5.62
^{73}Br	3p	3.4 min	4.66	41.8
^{72}Kr	α	17.2 s	5.04	0.044
^{72}Br	3pn	78.6 s	8.7	0.439
^{72}Se	4p	8.4 d	0.355	6.28
^{71}Br	αp	21.4 s	6.5	2.20

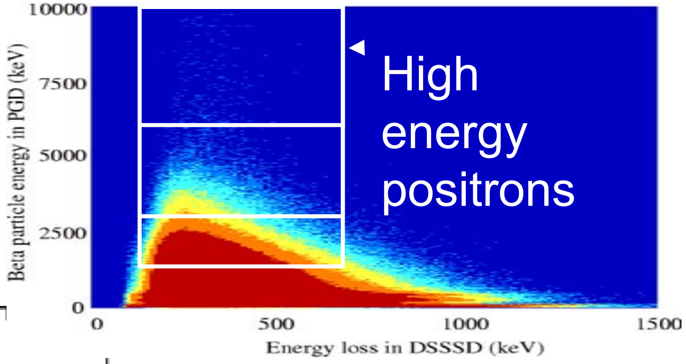
Gated spectra

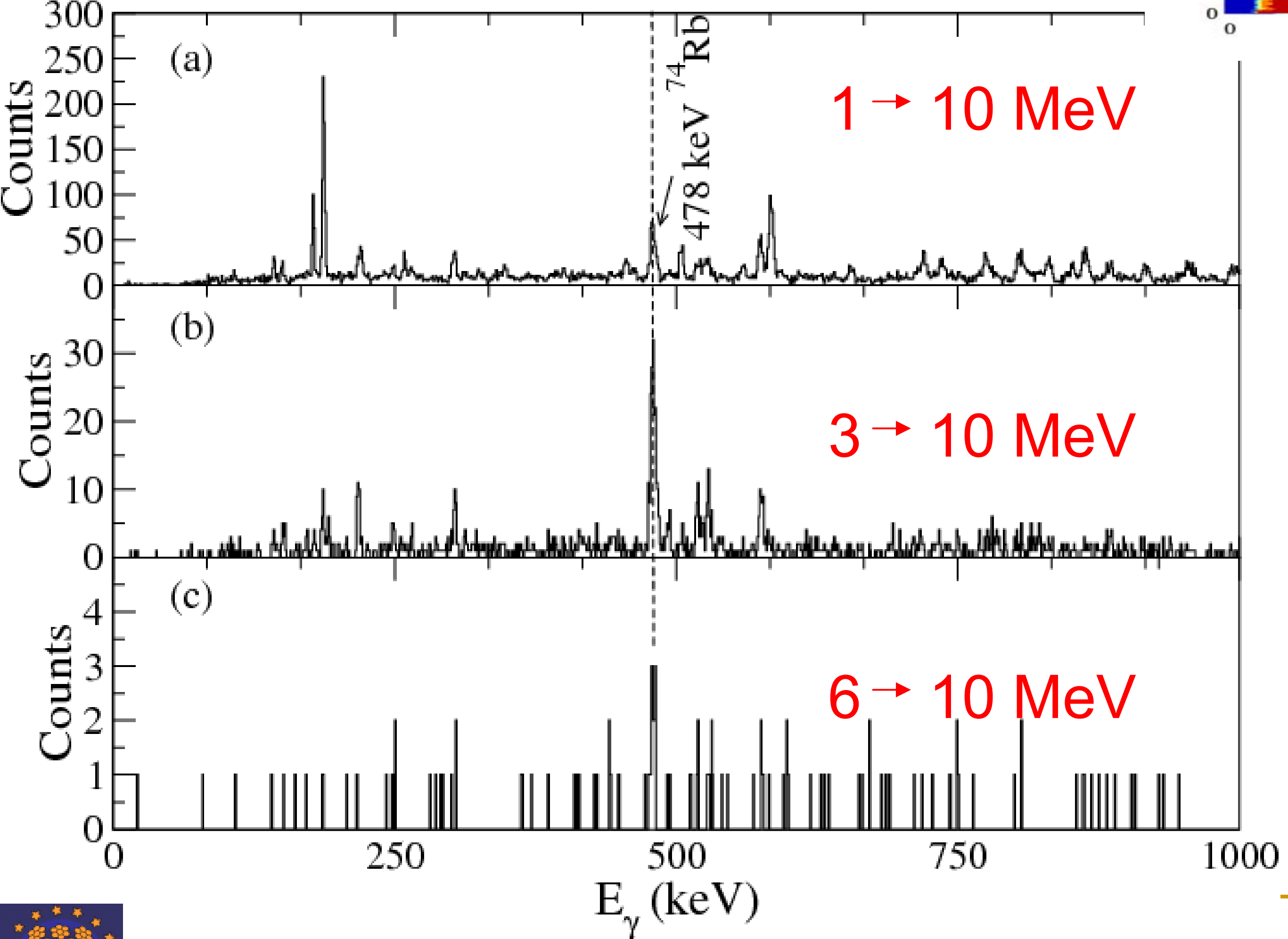




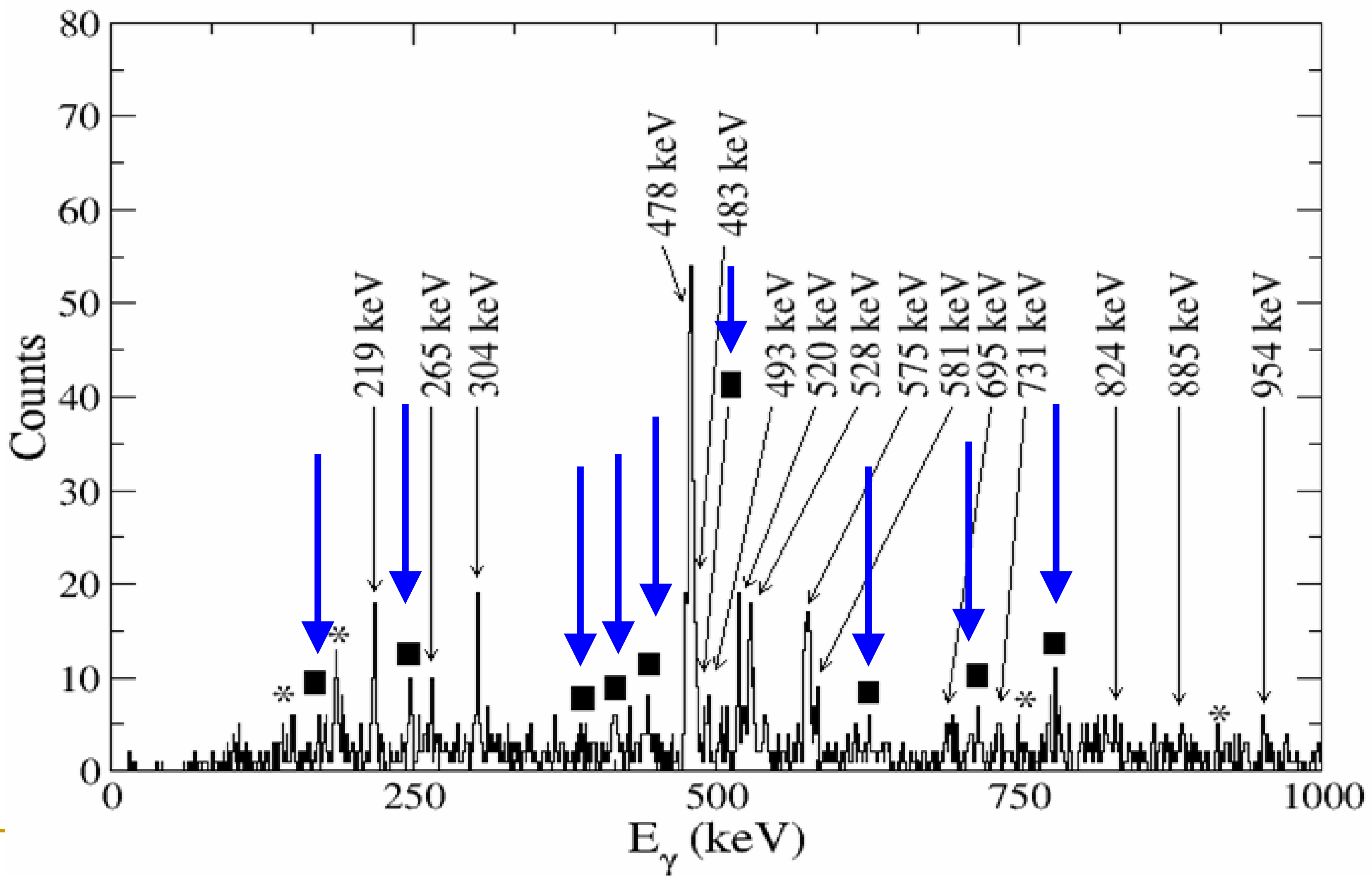


Varying β gates



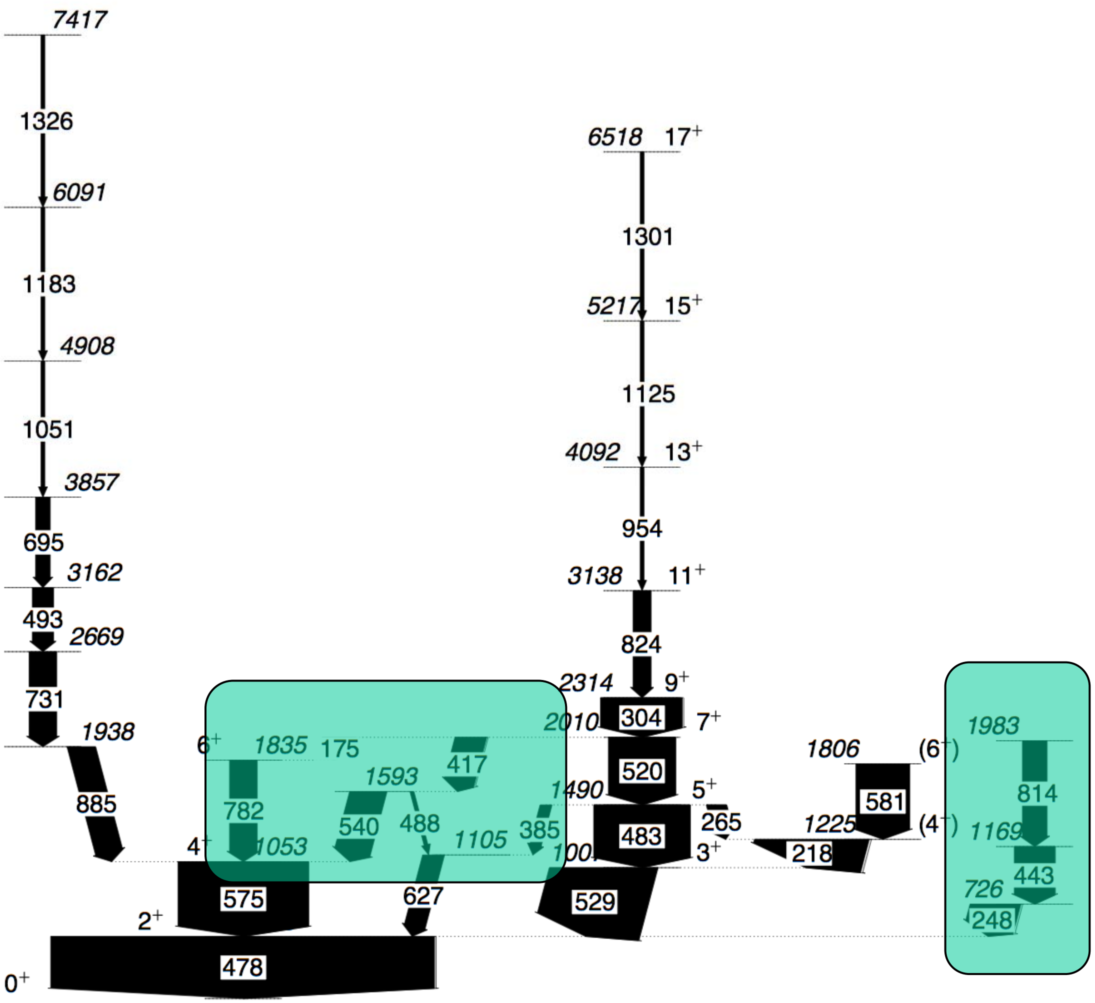


Identification of ^{74}Rb

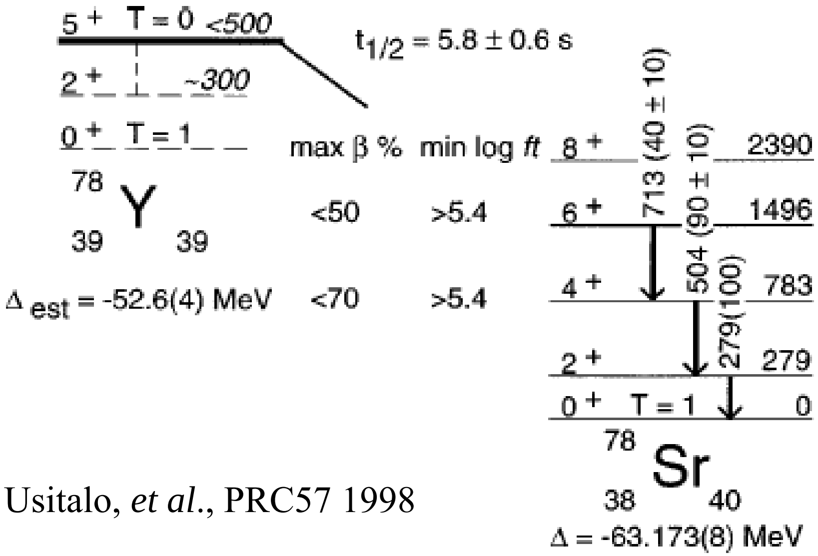


^{74}Rb level scheme from RBT

A.N. Steer, Thesis, Univ of York, 2007

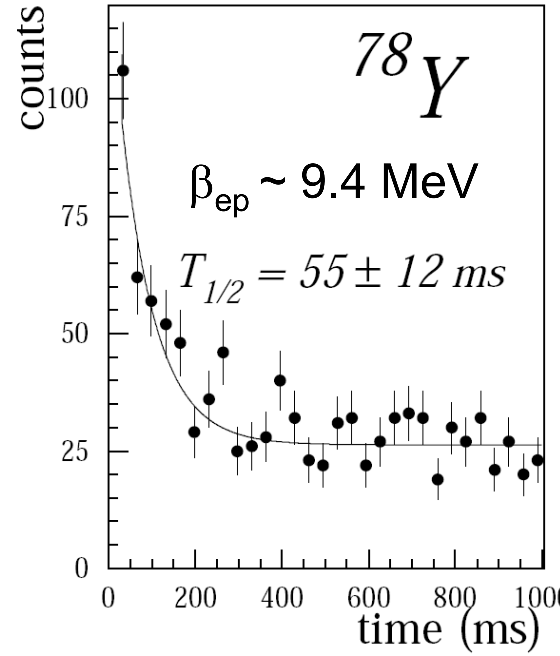


Only T=1, 0^+ ground state and a T=0, 5^+ state were known



J. Usitalo, *et al.*, PRC57 1998

C. Longour, *et al.*, PRL81 1998



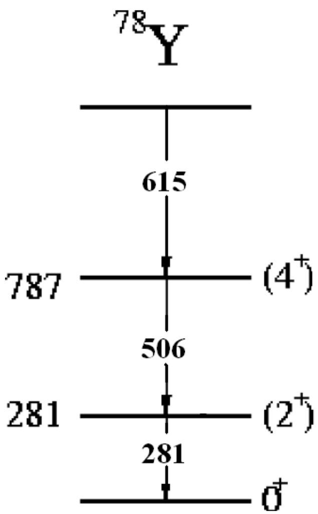
^{40}Ca (^{40}Ca, pn) ^{78}Y, E_b = 118, 121 MeV, σ_T ~ 55 mb,

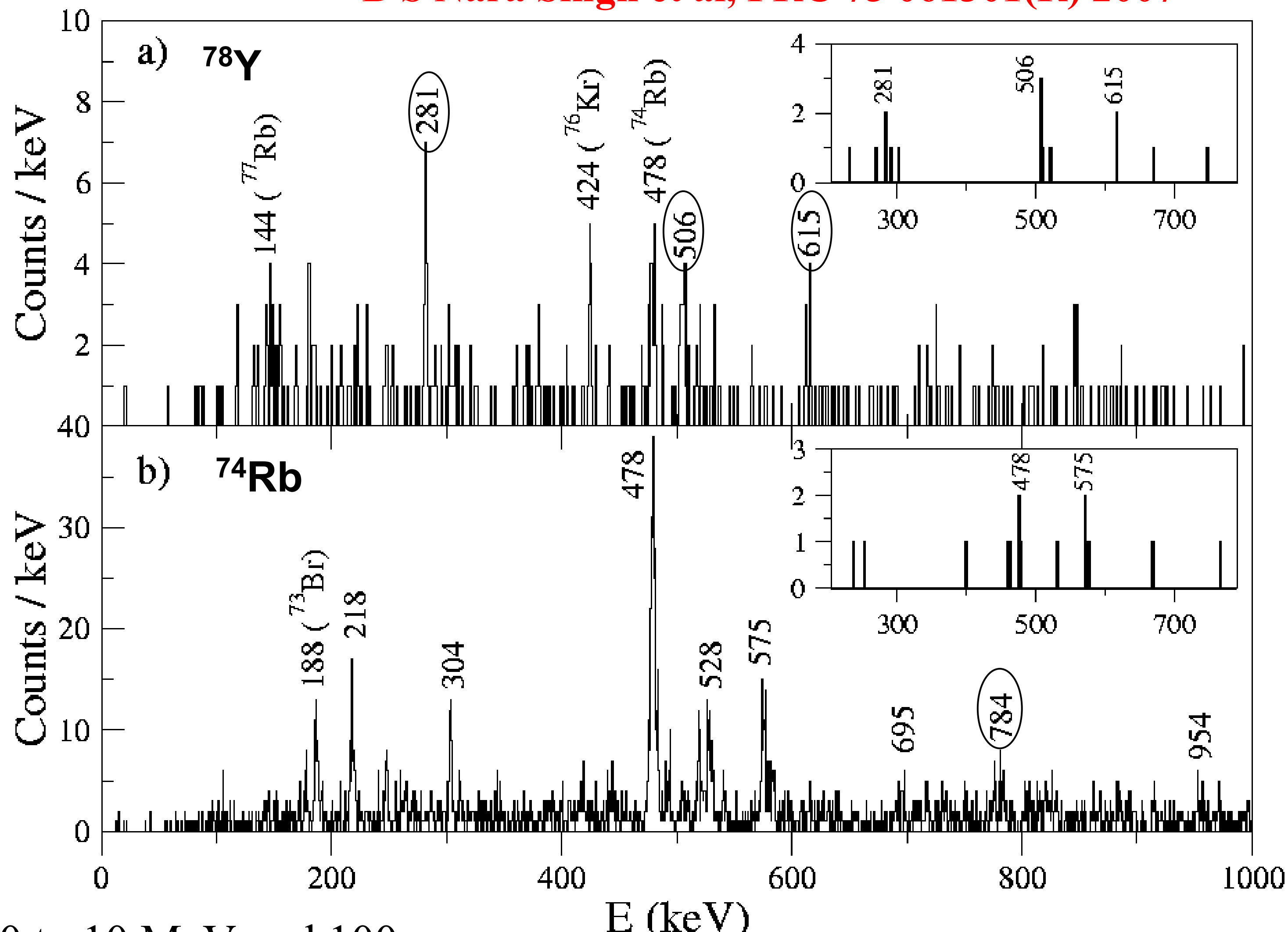
$\sigma(^{78}$Y)~ 5 μb ~90% to T=0 5^+ isomer, ~ 10 % to the rest

→A large population trapped in the isomer makes the study of the ground state band difficult.

4.5 to 10 MeV and 150 ms

B S Nara Singh et al, PRC 75 061301(R) 2007

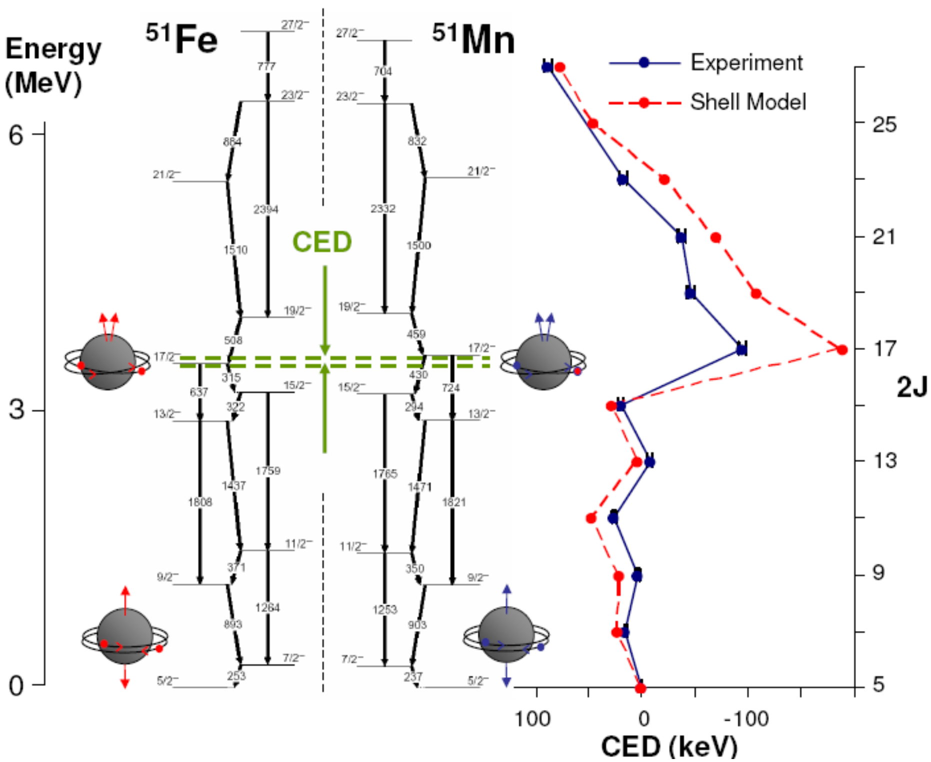




3.0 to 10 MeV and 100 ms

Coulomb Energy Differences

$E_x(J, Z>) - E_x(J, Z<)$ is non-zero for isobaric analogue states of nuclei with same mass due to the effects coming from Coulomb force.



T=1/2,

$T_z=(N-Z)/2$ -1/2 1/2

Extremely sensitive to nuclear structure effects:

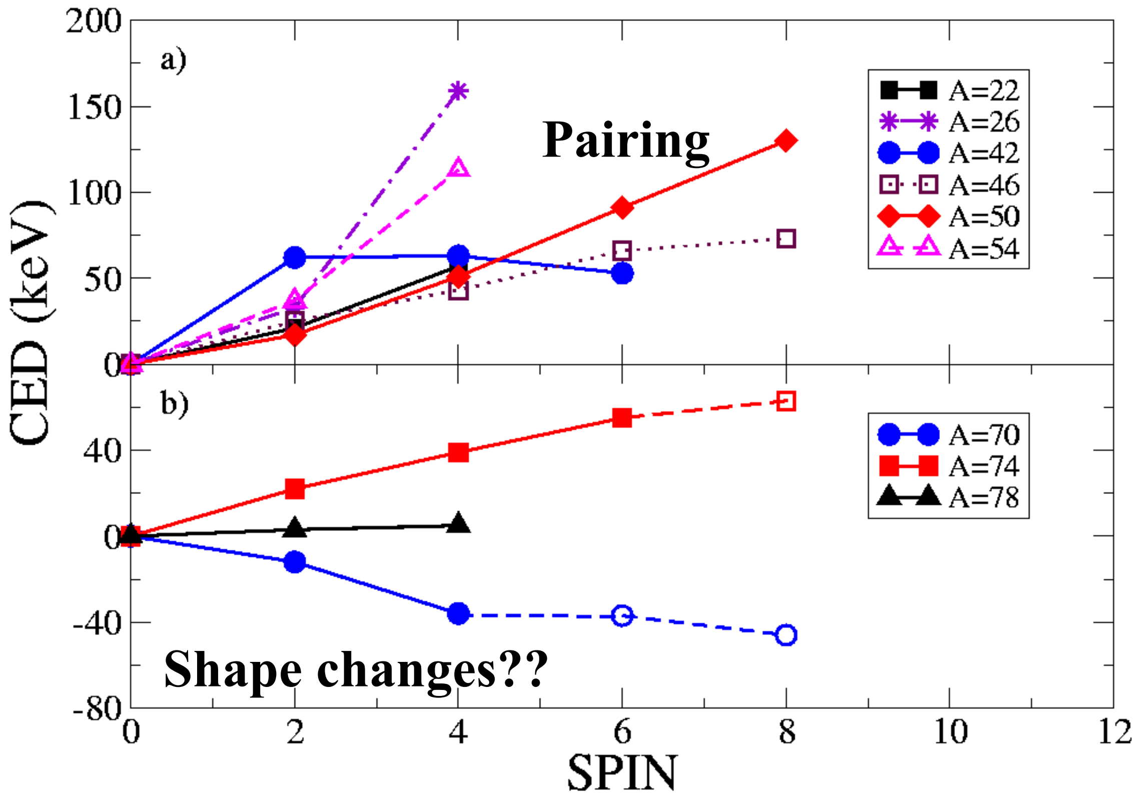
- **Rotational alignment mechanism**
- **Correlations of pairs of particles**
- **Changes in deformation**
- **The evolution of nuclear raddii:**

D.D. Warner et al. , nature physics 2, 311 (2006)
S.M. Lenzi and M. A. Bentley, Prog. Part. Nucl. Phys. (2006)

CED can be used to probe shape changes

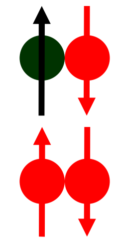
B S Nara Singh et al, PRC 75 061301(R) 2007

$E_x(J, T=1, Z>)-E_x(J, T=1, Z<)$



A=70 data from G. de Angelis, EPJ A12, 51 (2001) and
D.G. Jenkins et al., PRC 65, 064307 (2002) + present work

Lighter mass region:
T=1 Pairing,
np, Z=N, T_z=0 vs
pp, Z=N-2, T_z=1



74:T=1 pairing

78: Stable Prolate Shape and Reduced Pairing,
D. Rudolph et al, PRL 76, 376 (1996), Janecke et al PLB 605, 87 (2005)

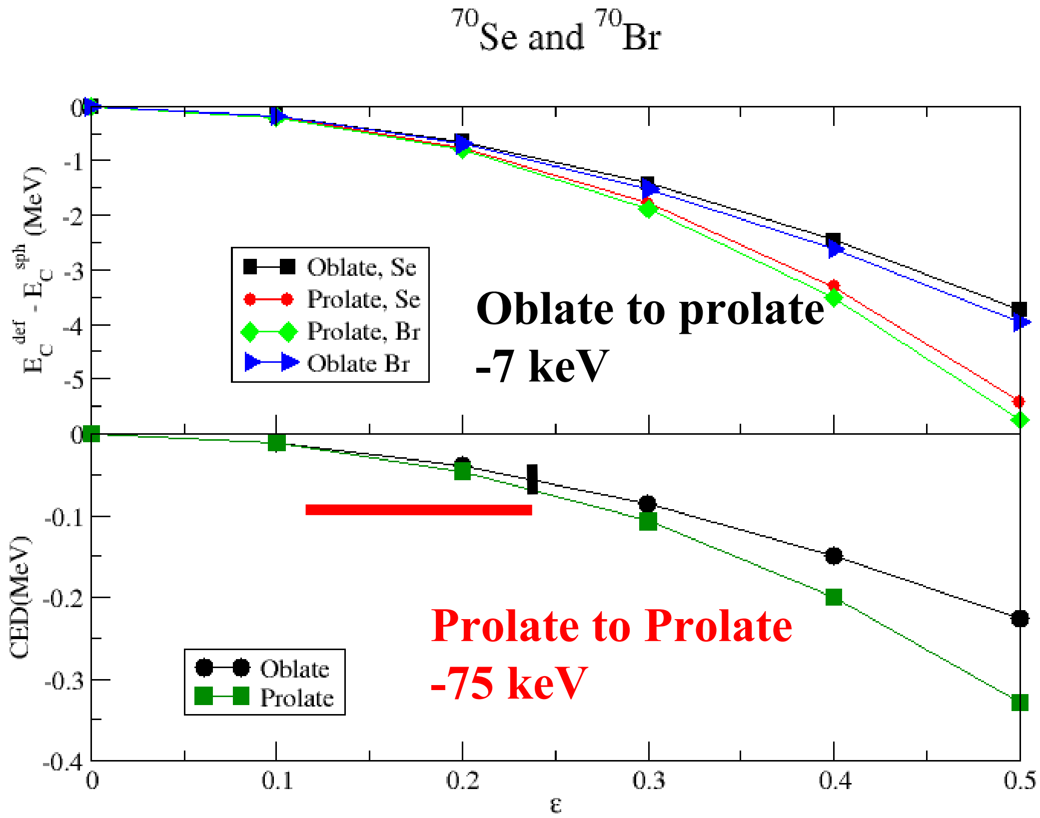
70: Prolate Stretch (0.18 to 0.33) R. Sahu et al, JPG13, 603 (1987)

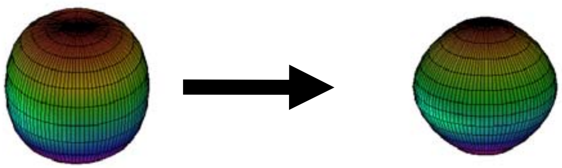
Coulomb Energy Differences

Deformed liquid drop model :

Larsson et al, Phys. Scri. 8, 17 (1973)

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

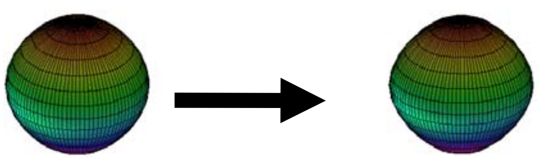




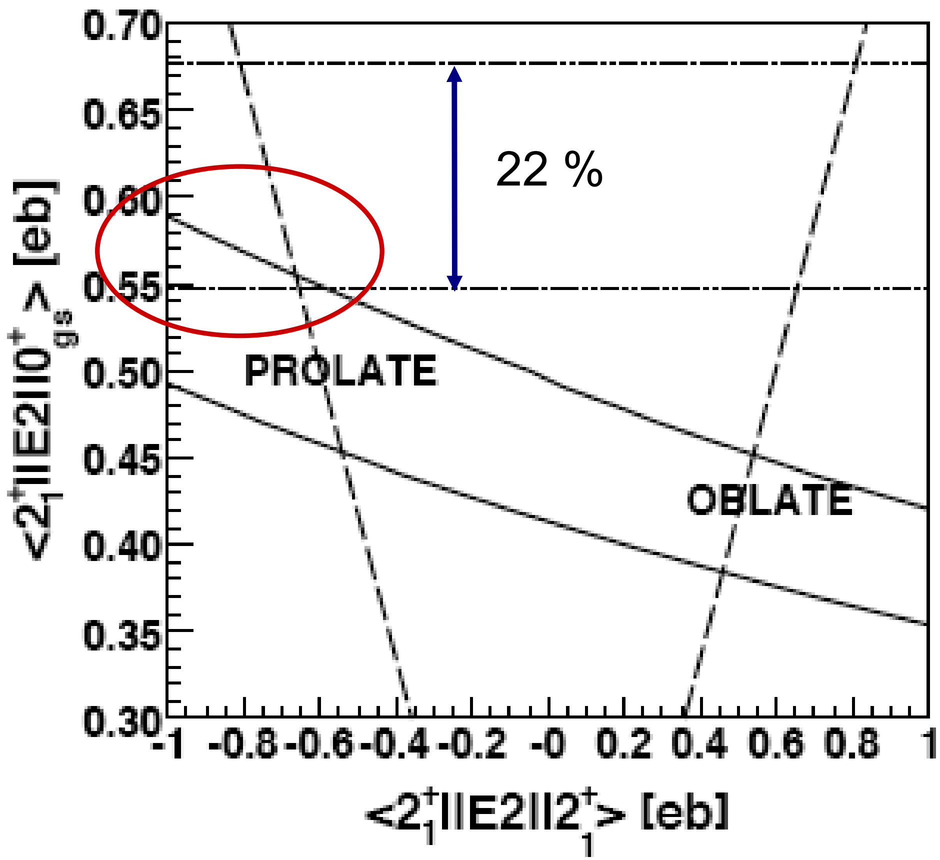
β_2 from -0.3 to 0.35
does not account for the effect.

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

Stretch in β_2 from 0.18 to 0.33
accounts for the effect.

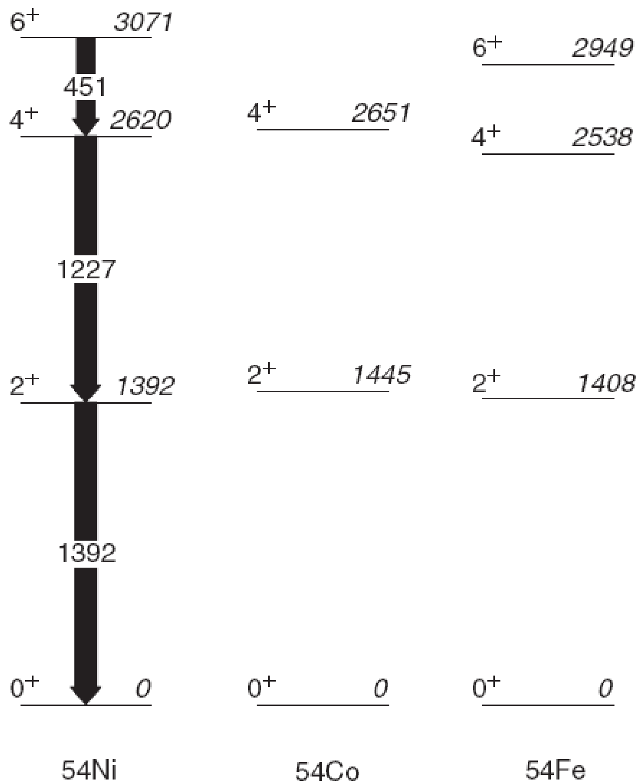


A.M. Hurst et al PRL 98, 072501 (2007)



Proton rich → More number of protons → Further reduction in CED

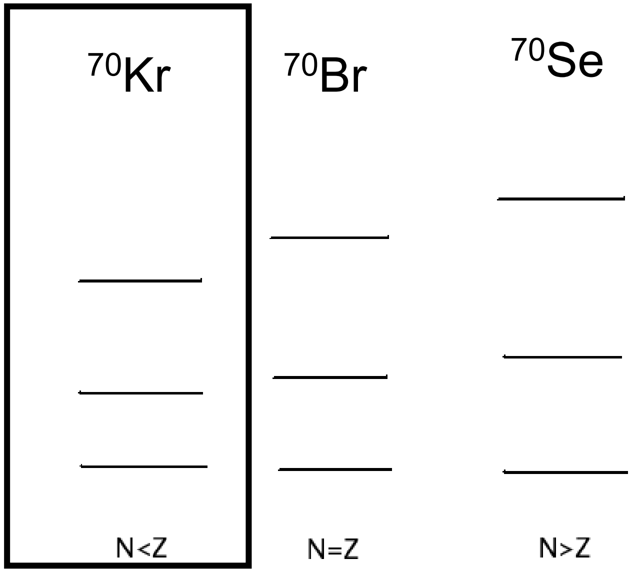
S.M. Lenzi and M. A. Bentley, Prog. Part. Nucl. Phys. 59 497 (2007)



A. Gadea et al., PRL97 (2006) 152501

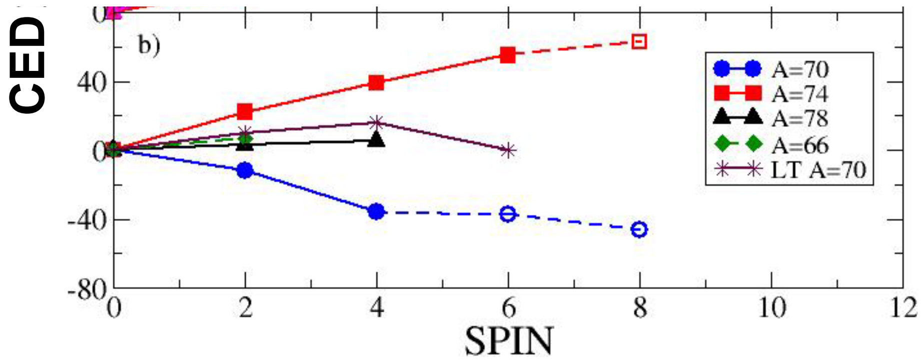
Pairing Scenario

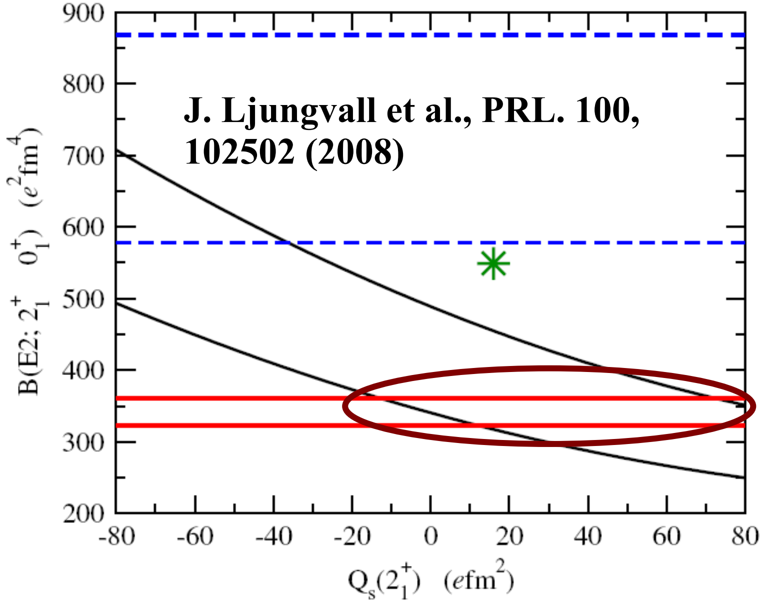
Prediction from deformed liquid drop model



Shape changing Scenario

Recent work does not support such a shape change and reports a strongly prolate 6^+ to weakly oblate 4^+ and 2^+ states.

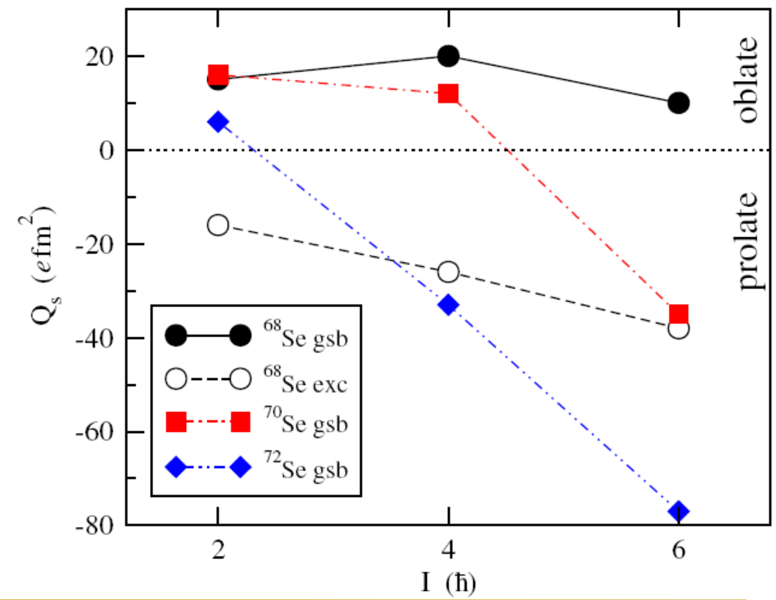




Different shapes for analogue nuclei??
Are they T=1 analogue states??
Need more refinement of Coulomb excitation results??

No excited 0^+ states found in ^{68,70}Se

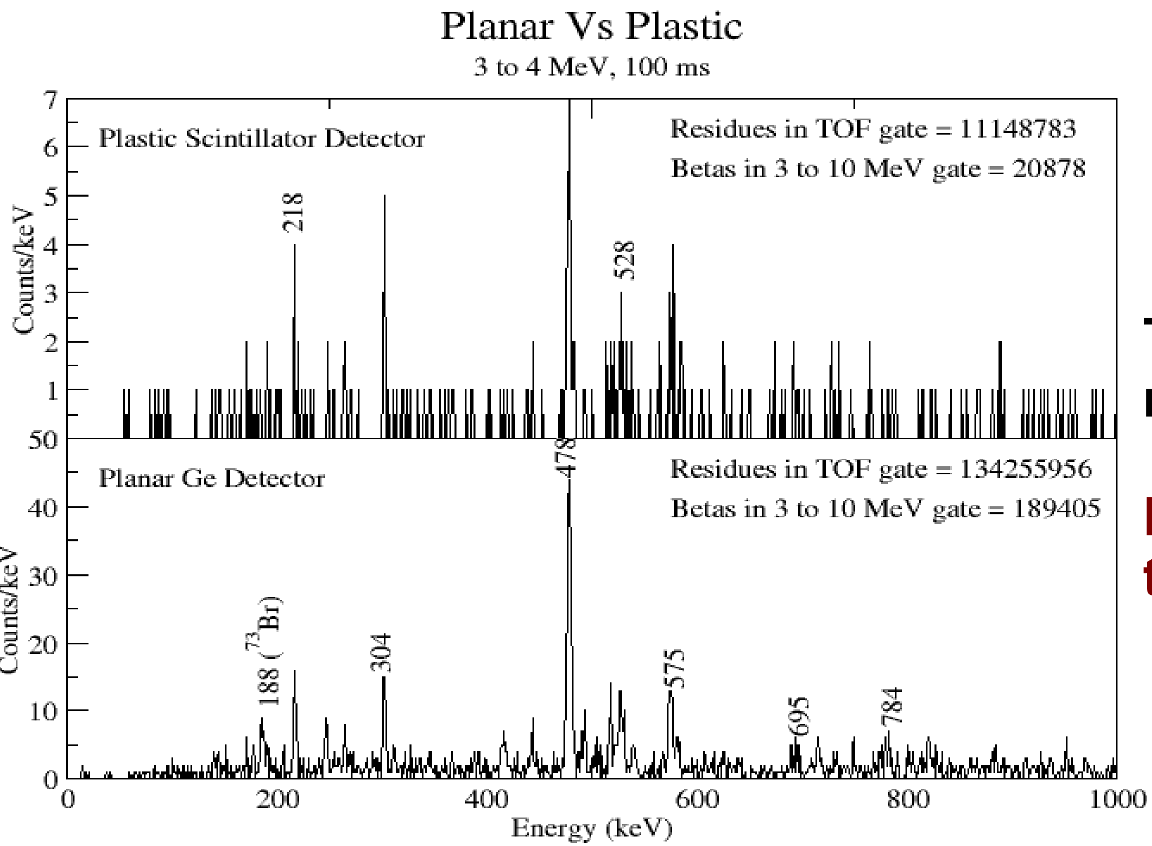
Further work needs to be done.



Scintillator Test

Calibration:
0.6 mg/cm^2 Ti + ^{36}Ar at E_{lab} = 103 MeV
^{81}Sr, 2.73 MeV, 22m, ~ 77 mb,
^{82}Zr, 4.7 MeV, ~ 0.13 mb

0.7 mg/cm^2 ^{40}Ca + ^{36}Ar, ^{74}Rb

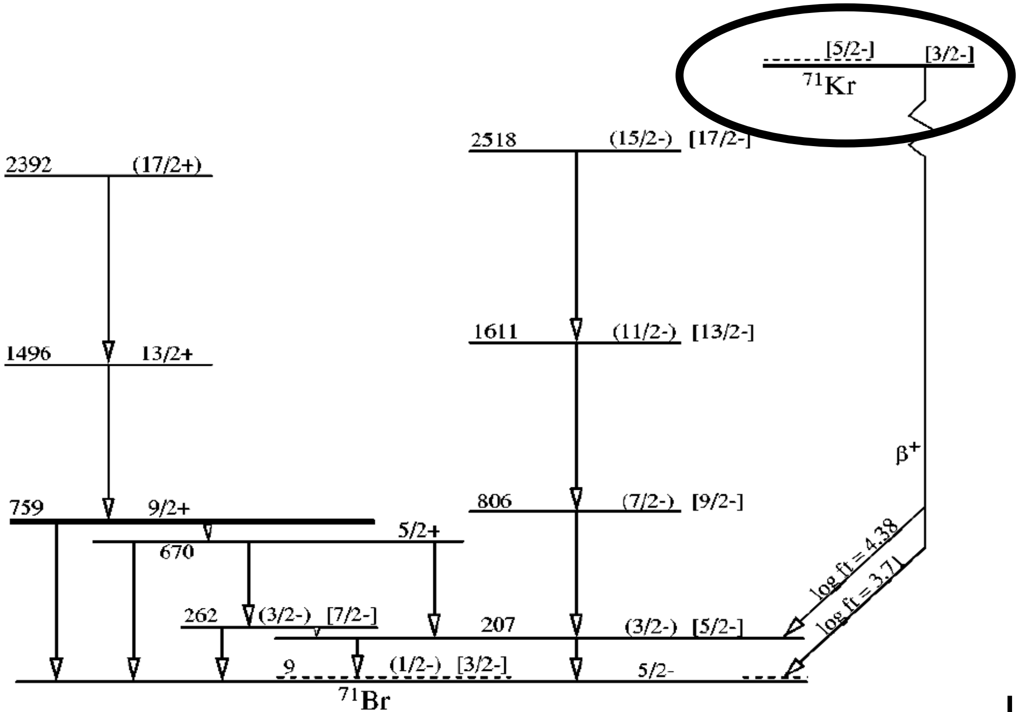


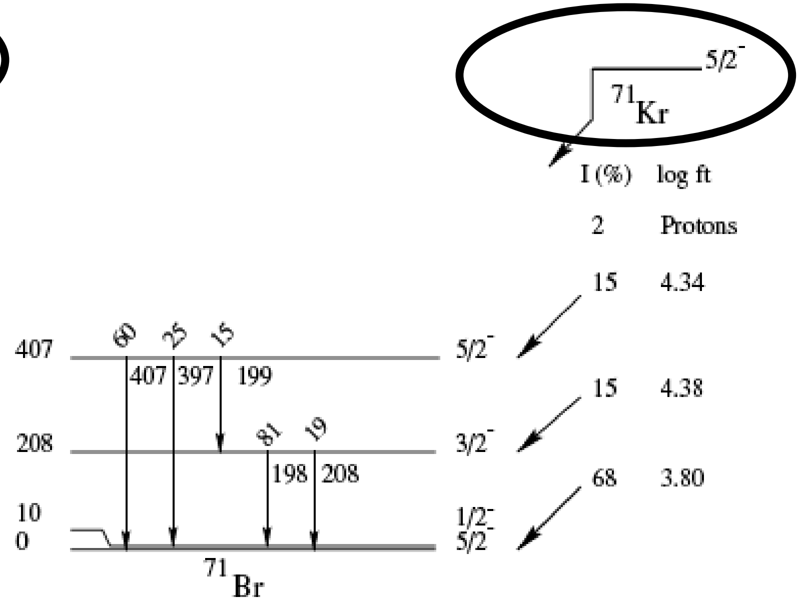
Test showed 1.25 times more β detection efficiency

Efforts are ongoing further to increase the efficiency

Search for breakdown of T=1/2 mirror symmetry: Recoil-β tagging and decay spectroscopy of ^{71}Kr

S.M. Fischer *et al.*, PRC72, (2005) 024321.





Delicate interplay of nuclear forces may lead to Different ground states spin-parities.

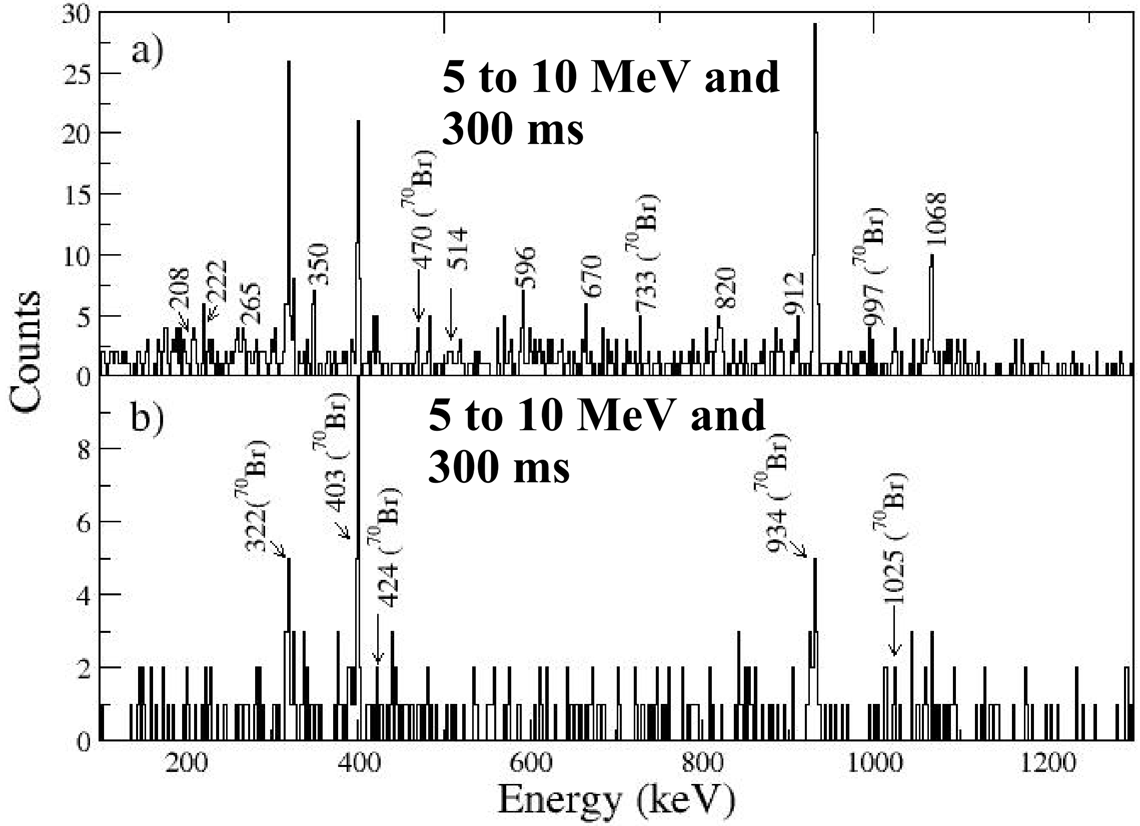
P. Urkedal and I. Hamamoto, Phys. Rev. C58, (1998) R1889.

Unusually large β decay population of 30% to excited staes

J.W. Arrison *et al.*, Phys. Lett. B248, (1990) 39
M. Oinonen *et al.*, Phys. Rev. C56, (1997) 745

$^{nat}Ca\ (^{33}S, 2n)\ ^{71}Kr$, $E_{beam} = 89$ MeV, , target ~ 1 mg/cm2 $\sigma(^{71}Kr) \sim 300$nb, σ_T ~ 64 mb,

$\tau½\ (^{71}Kr) = 100$ ms, $\beta^+_{endpoint}$ = 8.9 MeV, , $\sigma(^{70}Br) \sim 1\ \mu$ b beam ~ 7 days



Very Preliminary!!

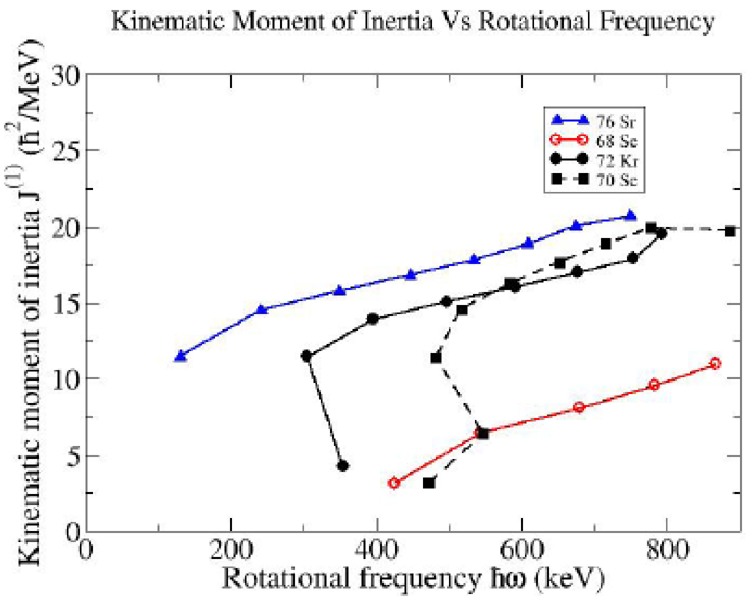
^{70}Br channel elimination from comparison with

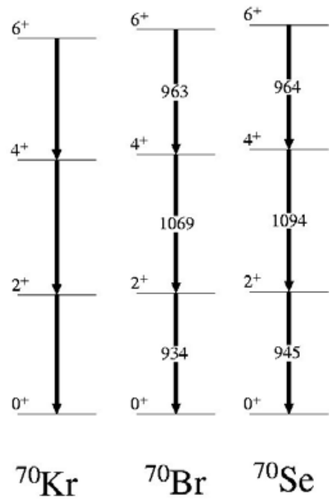
$^{nat}Ca\ (^{32}S, pn)\ ^{70}Br$, $E_{beam} = 89$ MeV, $\sigma(^{70}Br) \sim 4\mu$ b,

$\tau½\ (^{70}Br) = 78$ ms, $\beta^+_{endpoint}$ = 9.1 MeV, beam ~ 1 day

^{70}Kr (52 ms, 9.7 MeV) and the bonus ^{70}Br (79.1 ms, 10.6 MeV) , Just done (May 16th to 26th 2008)

- ^{68}Se→ ^{69}Br→ ^{70}Kr, 2p capture Q-value 1.33 MeV, Gamow peak 2.2(1.1) MeV
- Moment of Inertia, Shape Co-existence and effect on IAS in ^{70}Se
- Proton drip-line effects and further negative trend in CED
- Exploration of Recoil beta beta tagging as ^{70}Kr has a grand daughter ^{70}Se

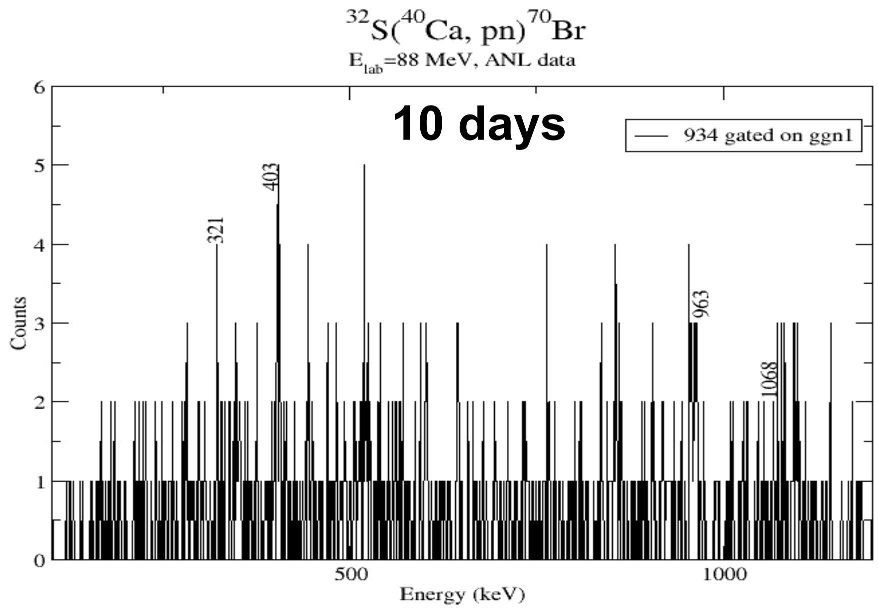




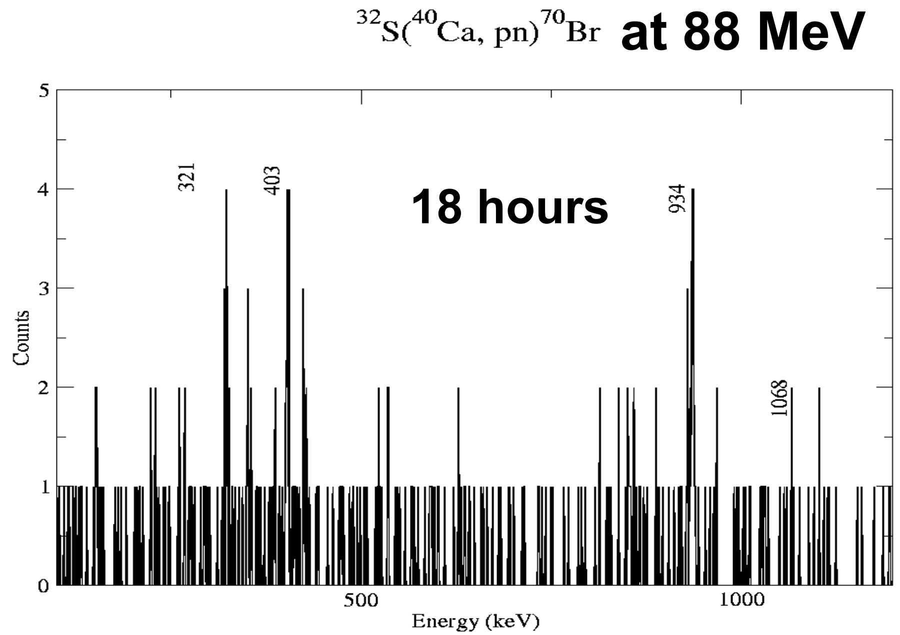
Summary

- **Recoil beta tagging was successfully pursued**
- **Very clean correlations identified levels in ^{78}Y**
- **Prolate stretch accounts for A ~ 70 CED**
- **In view of recent life-time measurements further work is suggested.**
- **Scintillator test with ^{74}Rb**
- **To place the γ rays in a proposed level scheme for ^{71}Kr, further supporting data from the ^{nat}Ca (^{32}S, pn) ^{70}Br reaction will be required, which we just carried out during May08.**

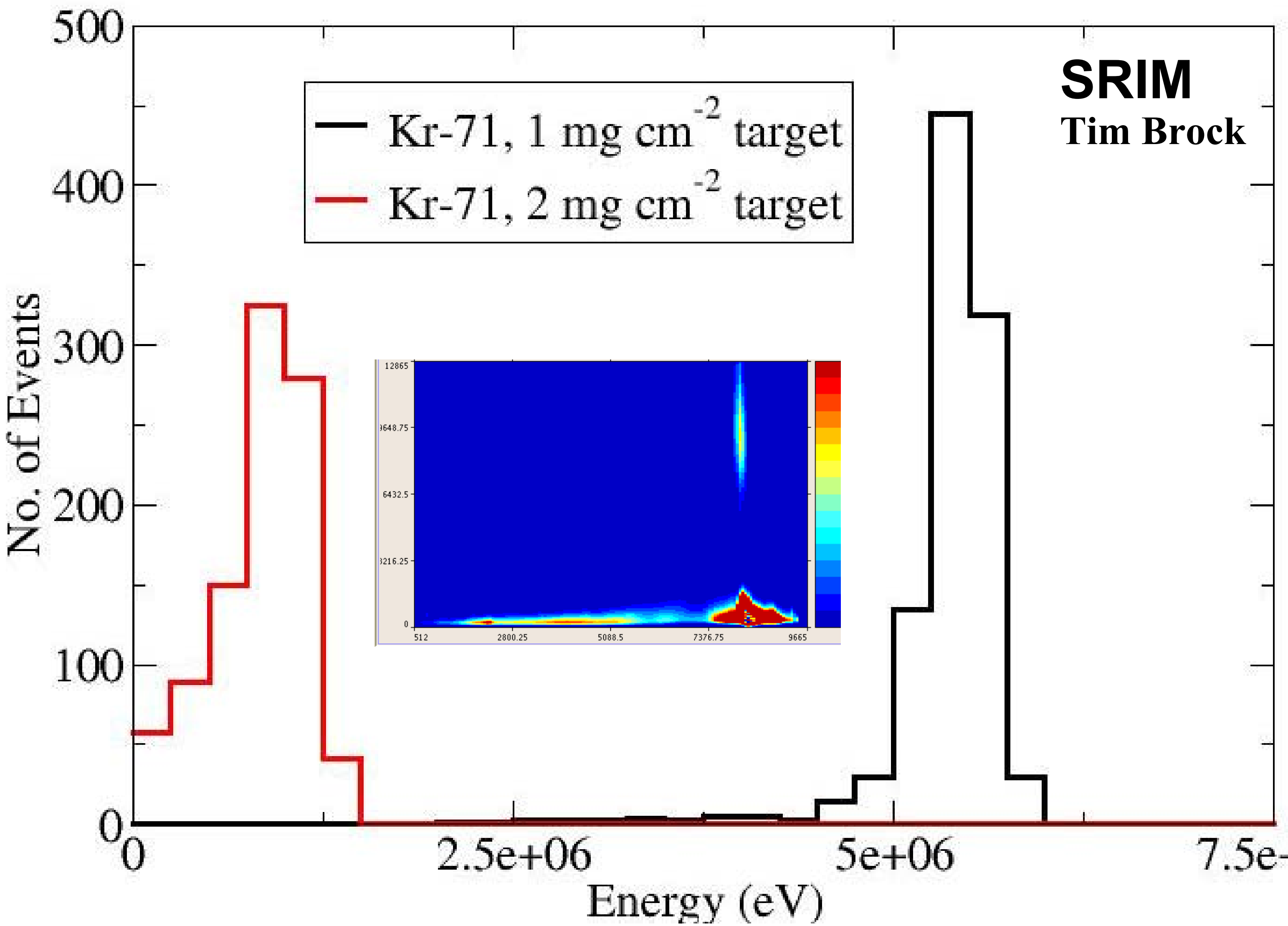
Conventional vs. RBT



Very Preliminary!!



Recoil energy losses



Future and developments

^{66}As, 95.8 ms, 9.6 MeV

T_z=-1

- ^{74}Sr,>1 μs,
- ^{78}Zr,>200ns,

Mass separators

Recoil beta and other particle combinations

Improve beta detection efficiency

Reduce recoil energy losses in the separator

Collaborators

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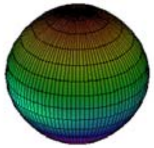
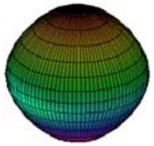
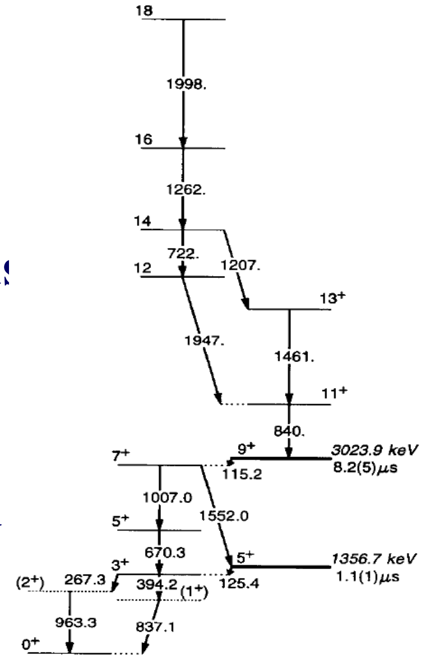


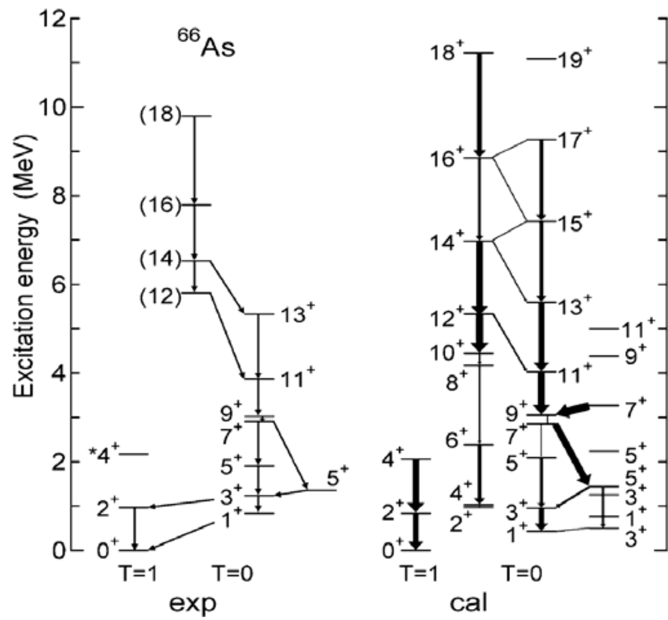
Thanks



^{66}As (95.8 ms 9.6 MeV) and the bonus ^{66}Se (30 ms ~ 10 MeV) from ^{28}Si on ^{40} Ca,

- Only 2^+ state is know with tentative assignment.
- Near zero trend ??, then needs a different explanation to ^{78}Y case
- A predicted 3^+ micro-second shape isomer around 900 keV
- ^{66}Se from 2n channel with 50 times lower cross section, heaviest Tz=-1 nucleus and ^{66}Se/ ^{66}As/ ^{66}Ge isobaric triplet on which info will be known

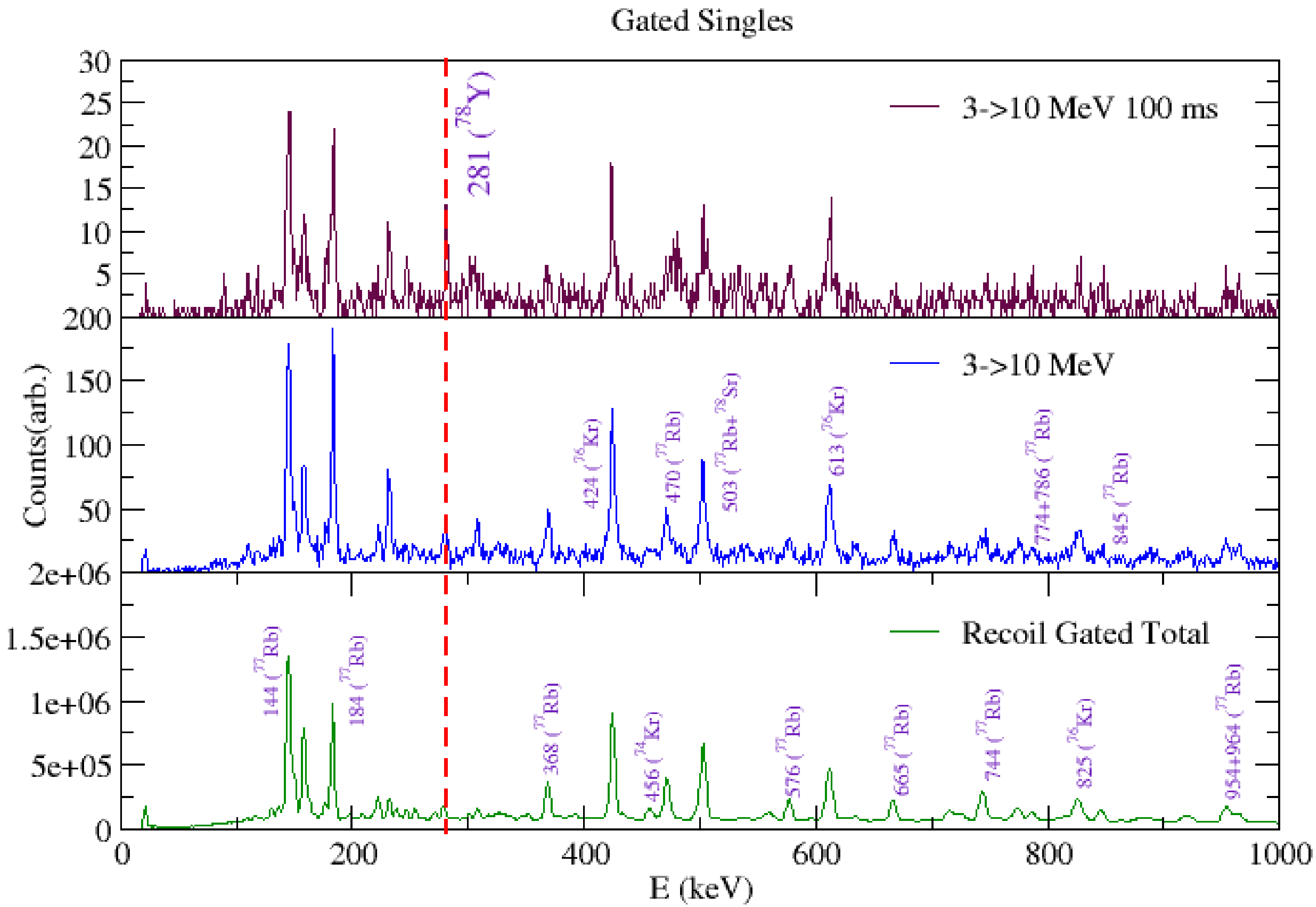




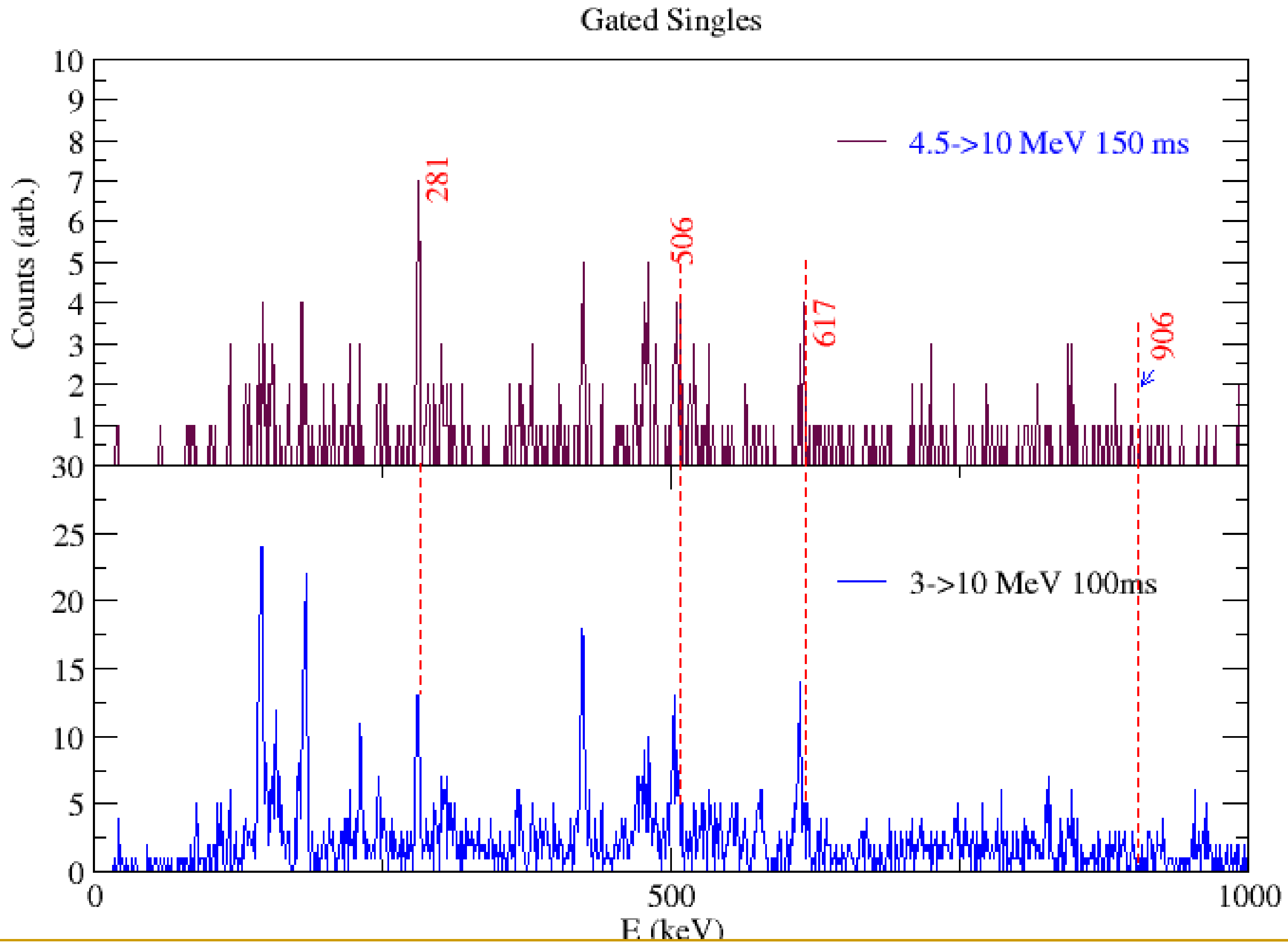
Approved proposal

R. Grzywacz *et al*, Phys. Lett. B 429, 247 (1998), Nucl. Phys. A 682 41 (2001).
M. Hasegawa *et al.*, Phys. Lett. B 617, 150 (2005).

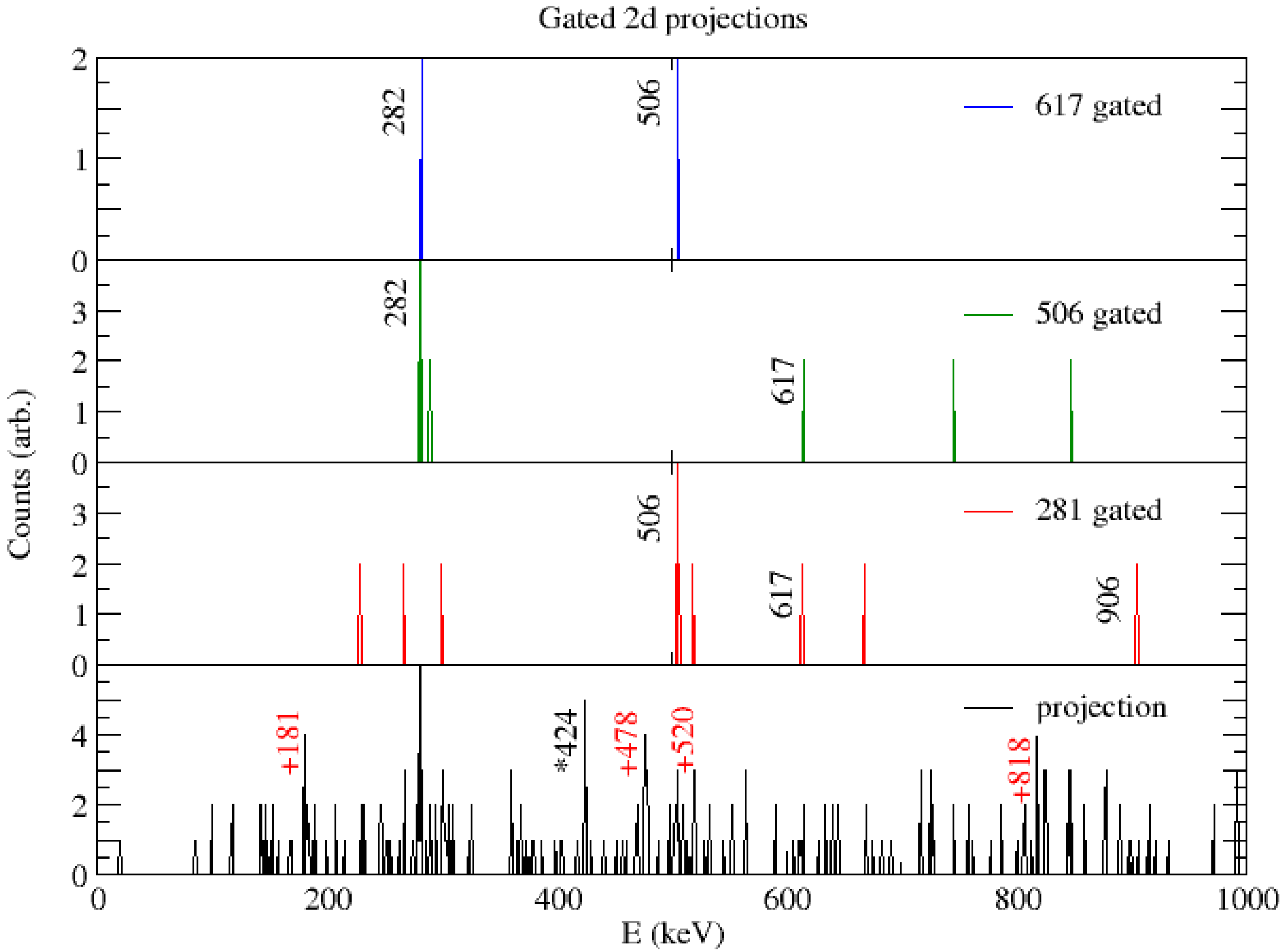
$^{40}Ca(^{40}Ca, pn)^{78}Y$



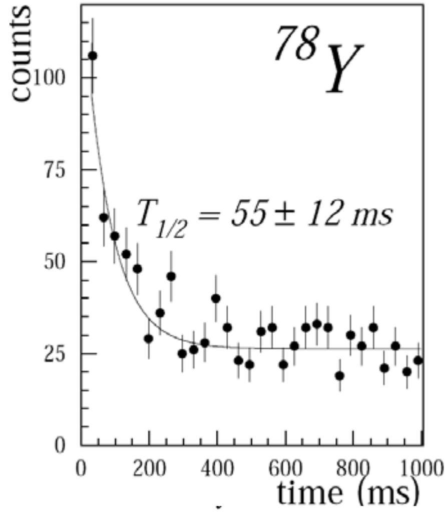
$^{40}Ca(^{40}Ca,pn)^{78}Y$

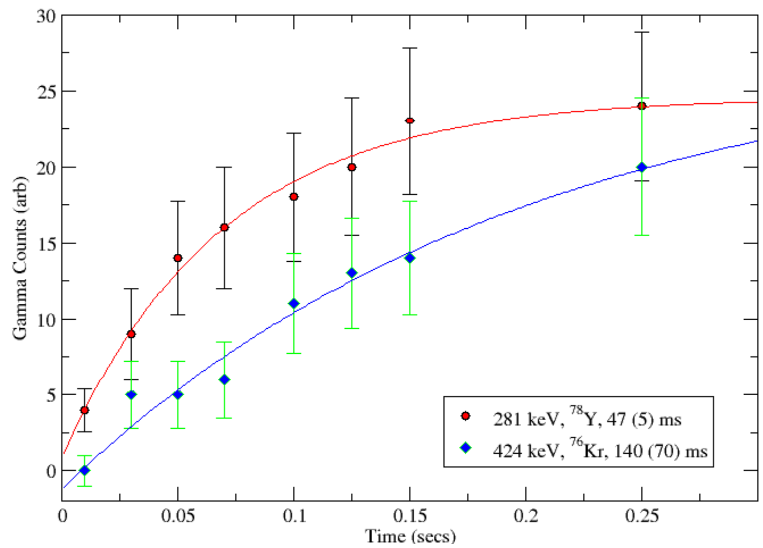


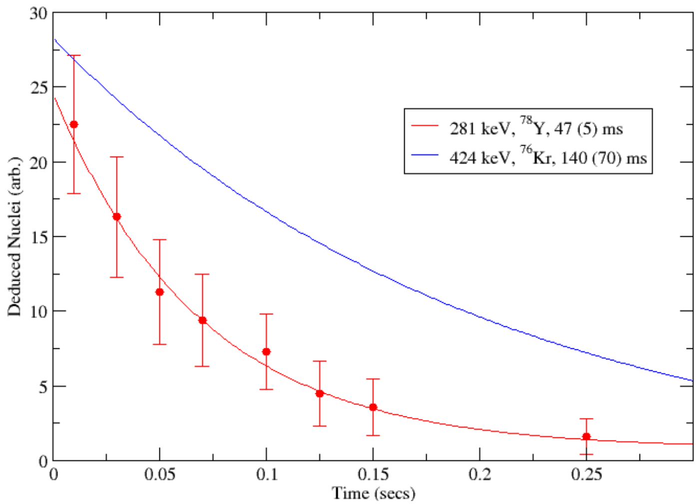
$^{40}Ca(^{40}Ca, pn)^{78}Y$

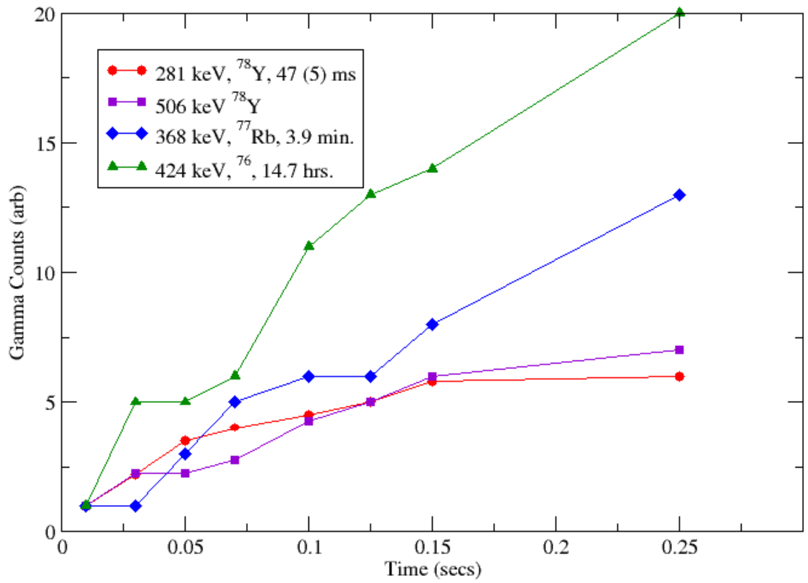


β decay life times









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

$$Z_> = Z_< + n, Z = Z_>$$

$$\begin{aligned} \Delta E_C &= E_C(Z_>) - E_C(Z_<) \\ &\simeq \frac{3}{5}\frac{n(2Z-n)e^2}{R_C} - \frac{3}{5}(Z-n)^2 e^2 \frac{\Delta R_C}{R_C^2} \end{aligned}$$

$$\boxed{\Delta E_C(J) - \Delta E_C(0) = -\frac{3}{5}n(2Z-n)e^2\frac{\Delta R(J)}{R_C^2}}$$

S.M. Lenzi and M. A. Bentley, Prog. Part. Nucl. Phys. (2006)