The Potential for Deep-Inelastic Spectroscopy with RIBs

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CENTRE FOR
NUCLEAR & RADIATION PHYSICS

Problems with neutron-rich spectroscopy ?

- Production (RIBs, fission, binary reactions).
  - Small cross-sections, need high efficiencies.
- Identification (N,Z)
  - lots of products, need clean id or ‘tags’ (e.g. isomers)
- Population in (Ex,I) plane (reaction selection)
  - need to know spin/excitation energy range of products

Some Issues With DICs for RIBS ?

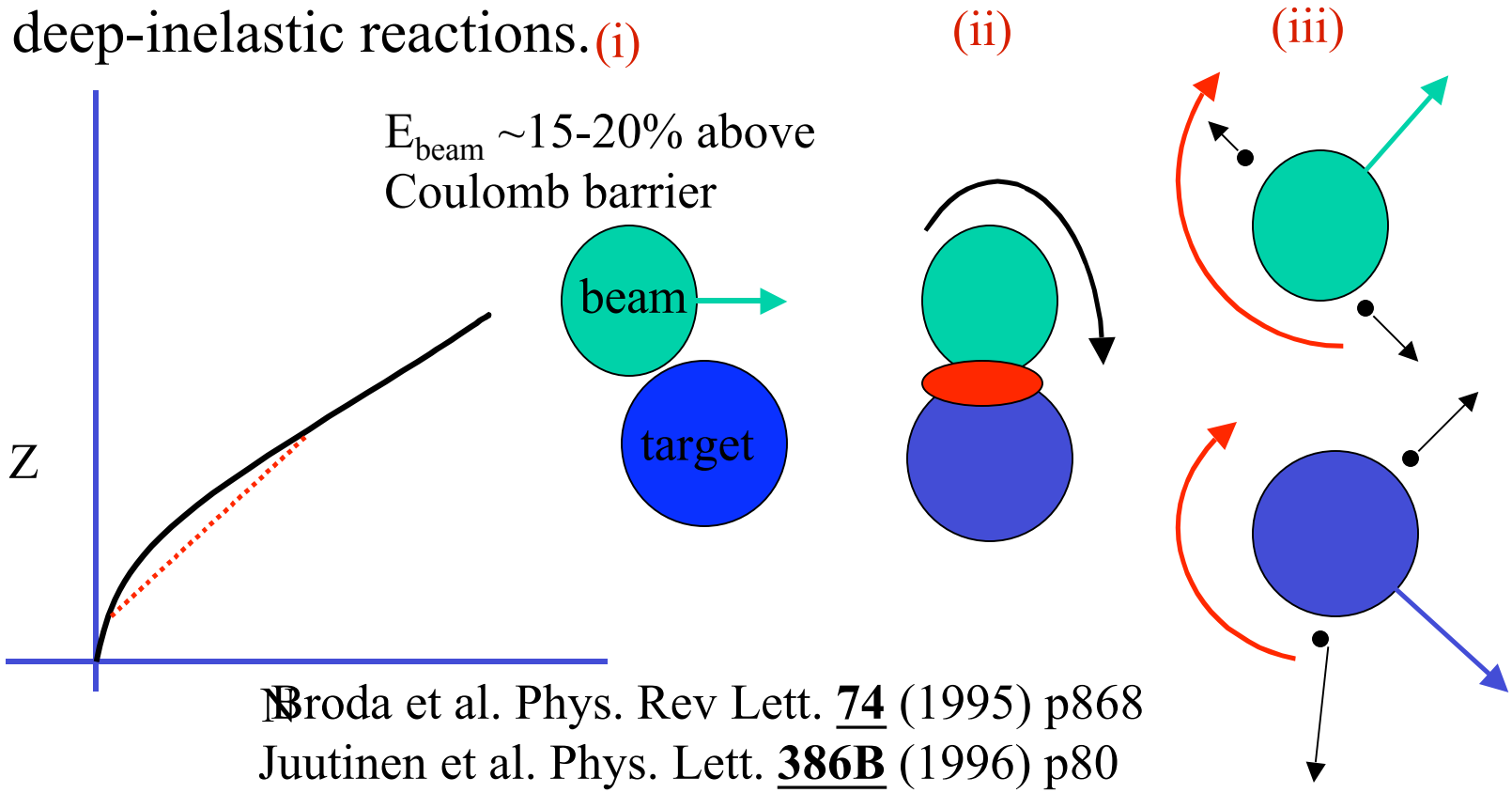
- Small beams, $10^{7\text{-}8}$ pps max. + high background ~$10^{5\text{-}8}$ γrays/s
  - need high quality 'trigger' or clean-up mechanisms
  - May want to stop the beam in the target chamber.

- Experimental Considerations ?
  - Spectrometer (prisma?)…not enough yield.
  - Thick target/inner detector (CHICO)…stop beam in target
    - big background, need pulsed beam and/or high-fold (multiplicity) trigger for DICs

- RIBS to make neutron-rich decay products/β-decay….put on MTC (a la WNSL Yale?)
    - use plug to block beam on to tape, use tape cycle to reduce beam-related decay background.

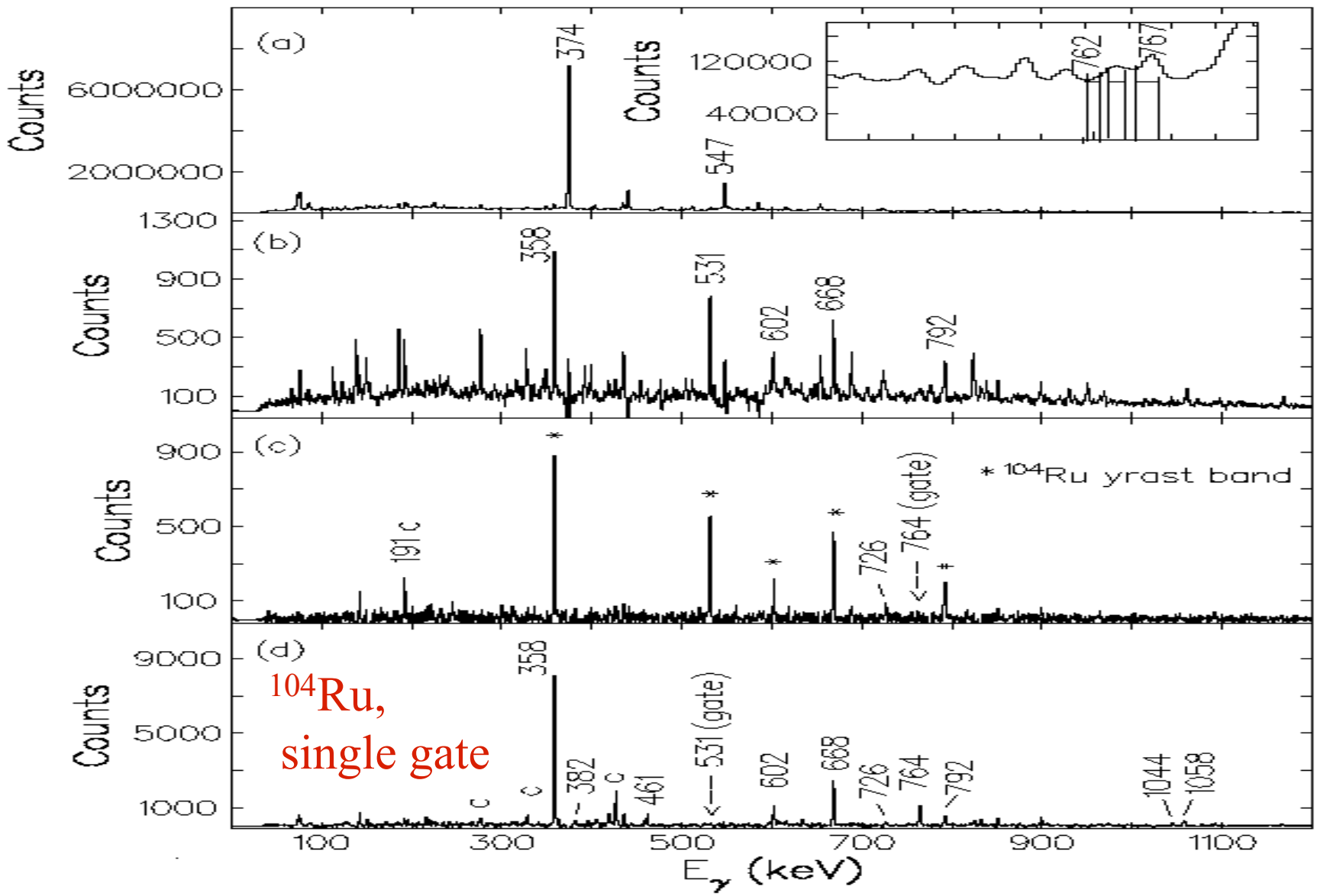
Can not use fusion-evaporation reactions to study high-spin states in beta-stable and neutron-rich systems.

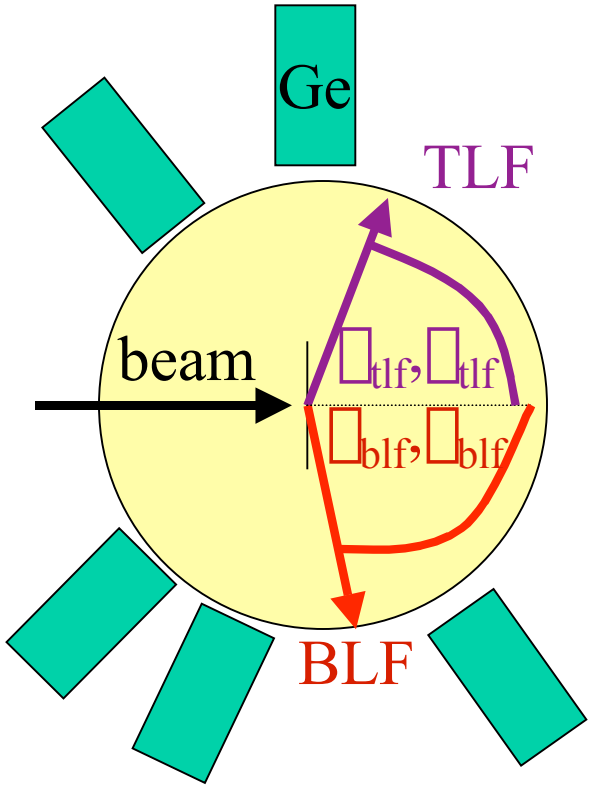
Use deep-inelastic reactions.



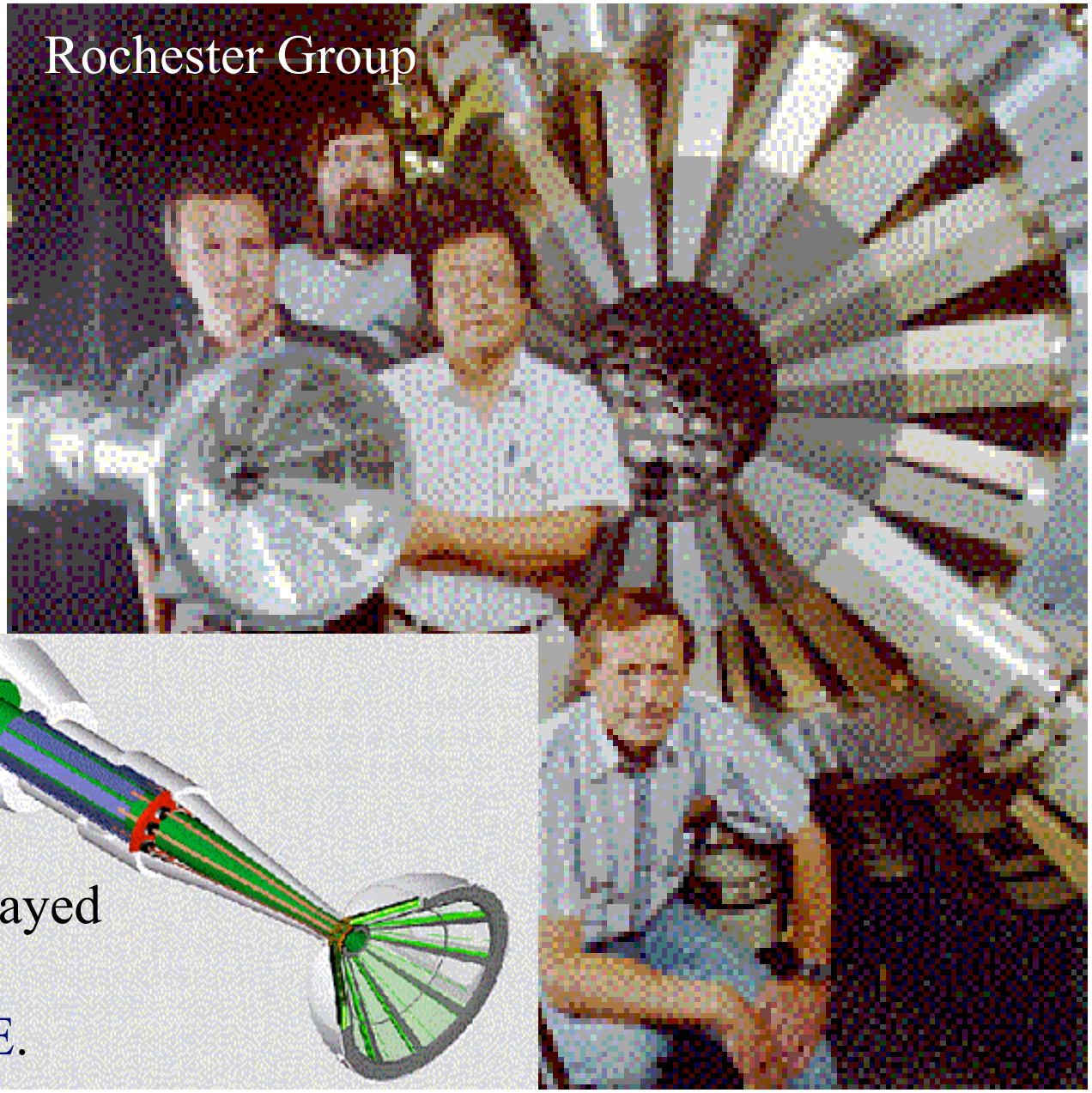
Broda et al. Phys. Rev Lett. **74** (1995) p868
Juutinen et al. Phys. Lett. **386B** (1996) p80
PHR et al., Phys. Rev. **C55** (1997) no 5.
Wheldon et al. Phys. Lett. **425B** (1998) p239
Cocks et al. J. Phys. **G26** (2000) p23
Krolas et al. Acta. Phys. Pol. **B27** (1996) p493
Asztalos et al. Phys. Rev. **C60** (1999) 044307

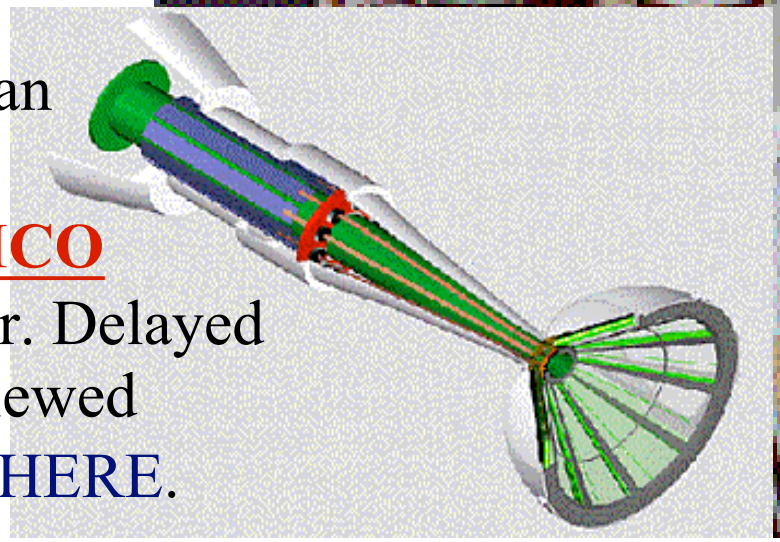
PHR et al., PR**C55** (1997), $^{86}Kr+^{110}Pd$ at Jyvaskyla,
0.5% array 'DORIS', 4 days with 10^{10}pps, □□□only





Simon et al., Nucl. Inst. Meth. **A452**, 205 (2000)





TOF ~5-10 ns.
ns-μs isomers can de-excite in be stopped by **CHICO** position detector. Delayed γs can still be viewed by GAMMASPHERE.

For Cartesian unit vectors i, j and k,

$$x = r\sin(\theta)\cos(\phi)\,\bar{\mathrm{i}},\quad y = r\sin(\theta)\sin(\phi)\,\bar{\mathrm{j}},\ z = r\cos(\theta)\,\bar{\mathrm{k}}$$

the fragment/γ- ray angle is given by

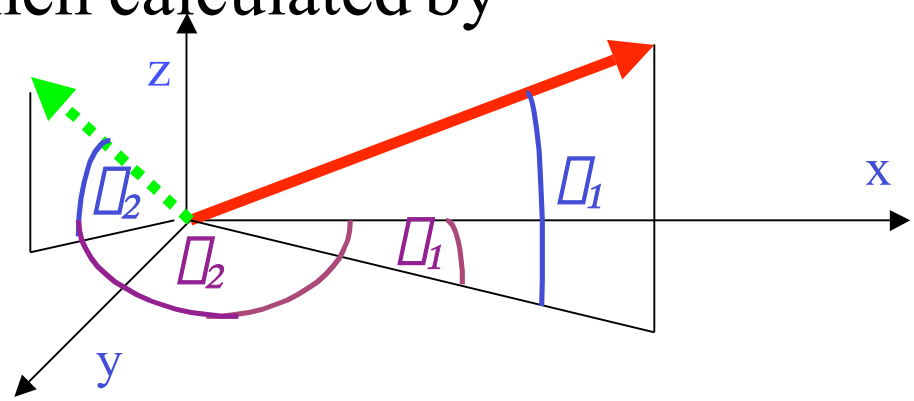
$$\bar{\mathrm{r}}_1.\bar{\mathrm{r}}_2 = r_1 r_2 \cos(\theta_{12})$$

where

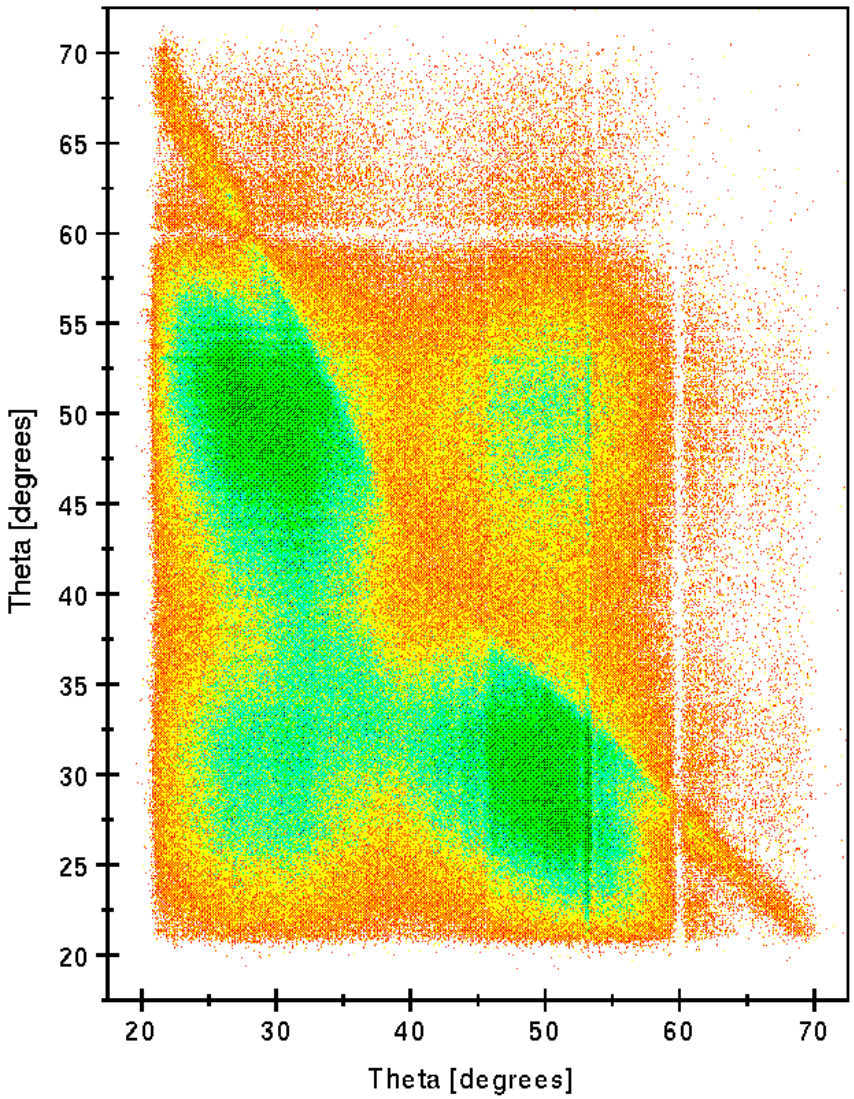
$$\cos(\theta_{12}) = \sin\theta_1\sin\theta_2\left(\sin\theta_1\sin\theta_2 + \cos\theta_1\cos\theta_2\right) + \cos\theta_1\cos\theta_2$$

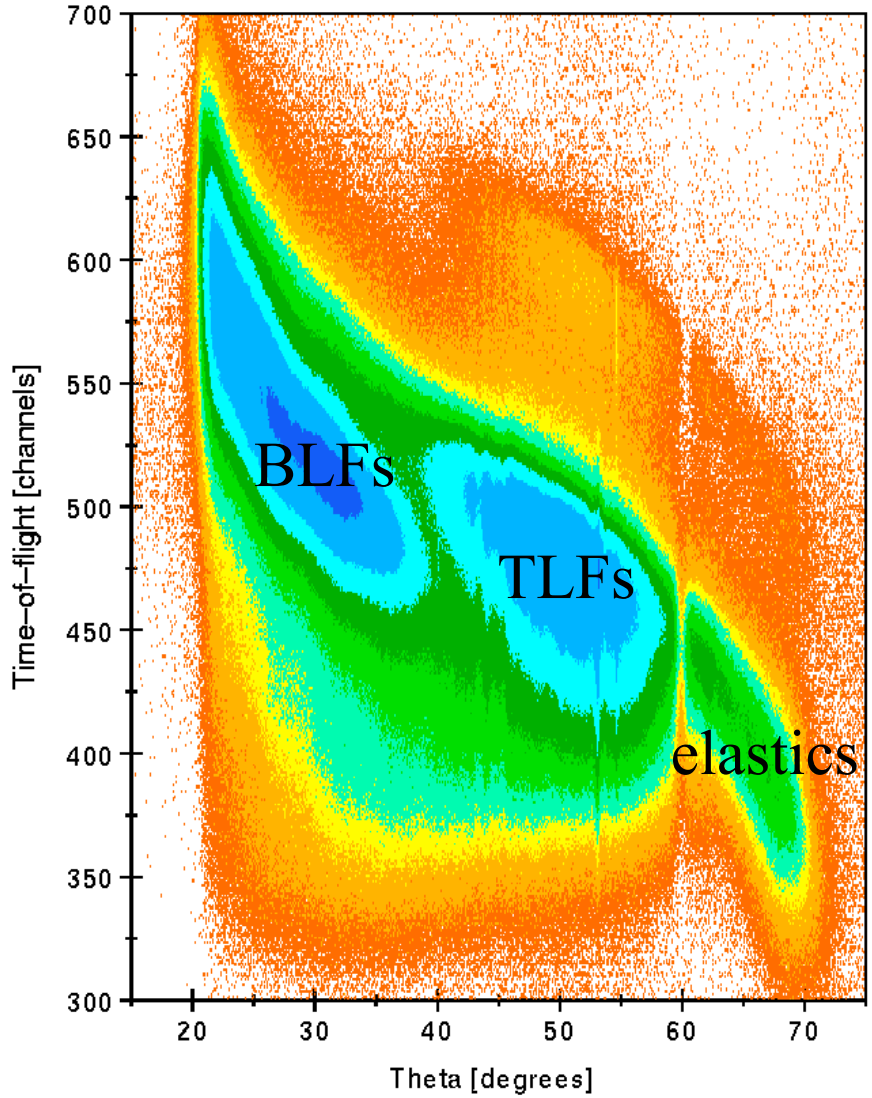
The Doppler correction is then calculated by

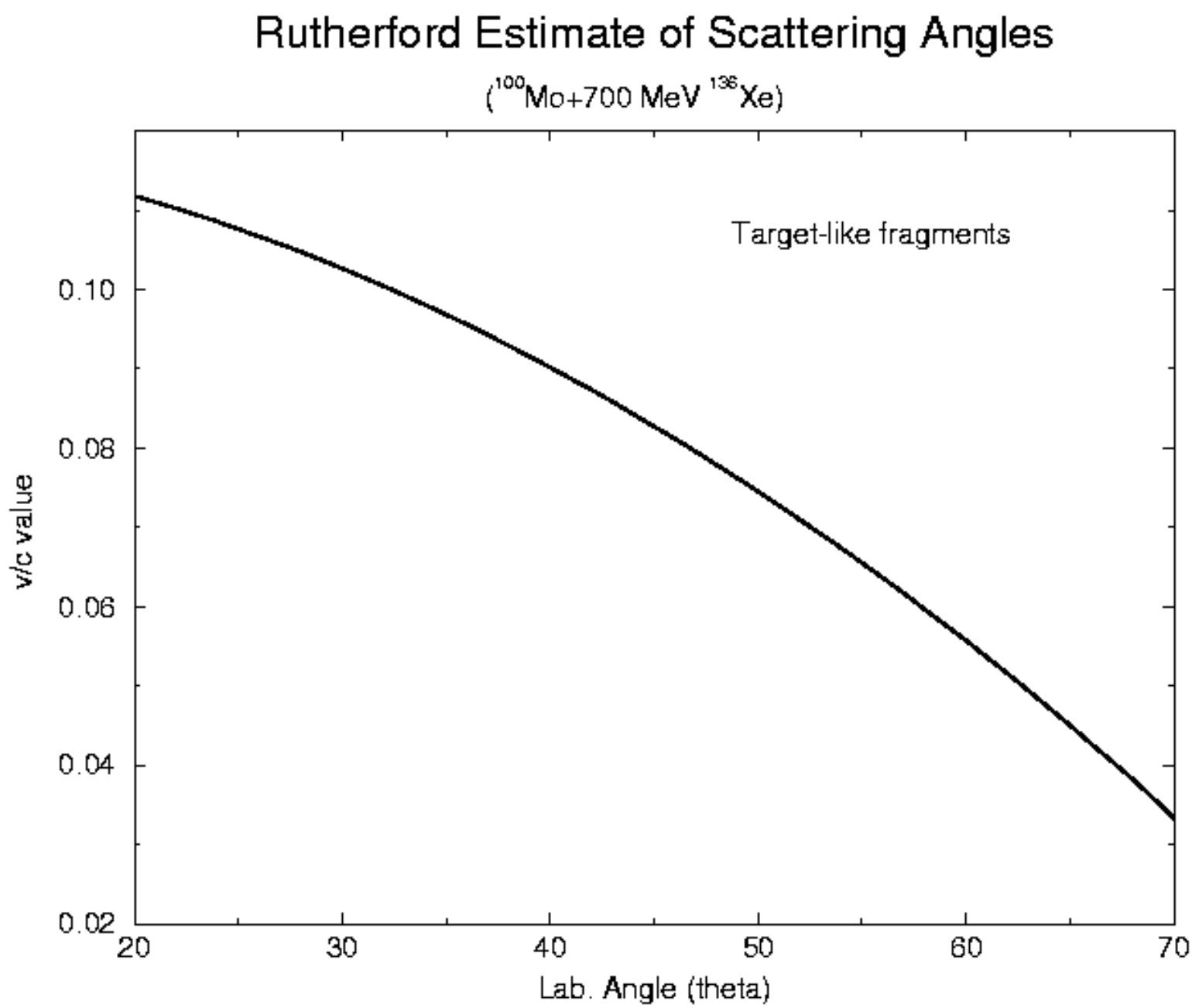
$$E_\gamma = E_\gamma^{'}\frac{1-\beta\cos\theta_{1,2}}{\sqrt{\left(1-\beta_{1,2}^2\right)}}$$



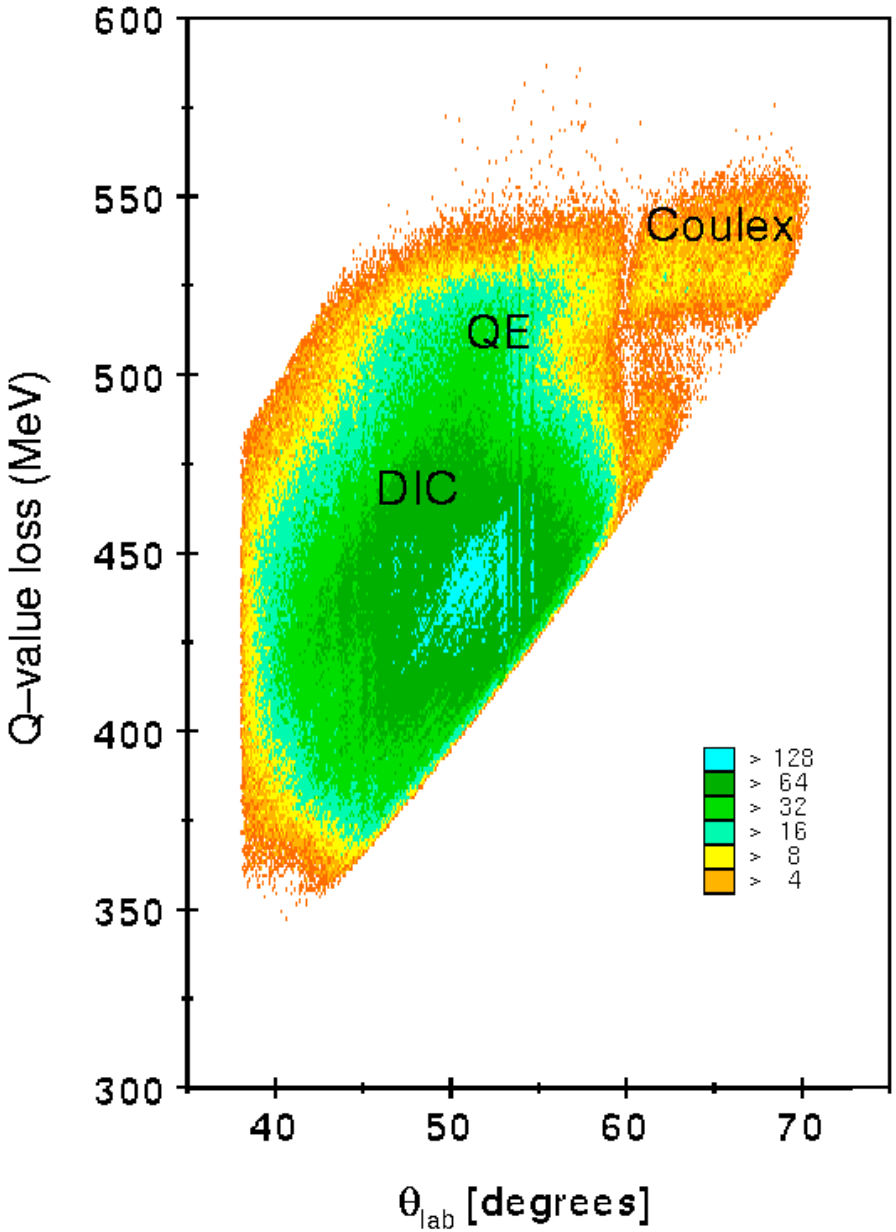
$^{100}Mo + ^{136}Xe$ @ 750 MeV
GAMMASPHERE + CHICO

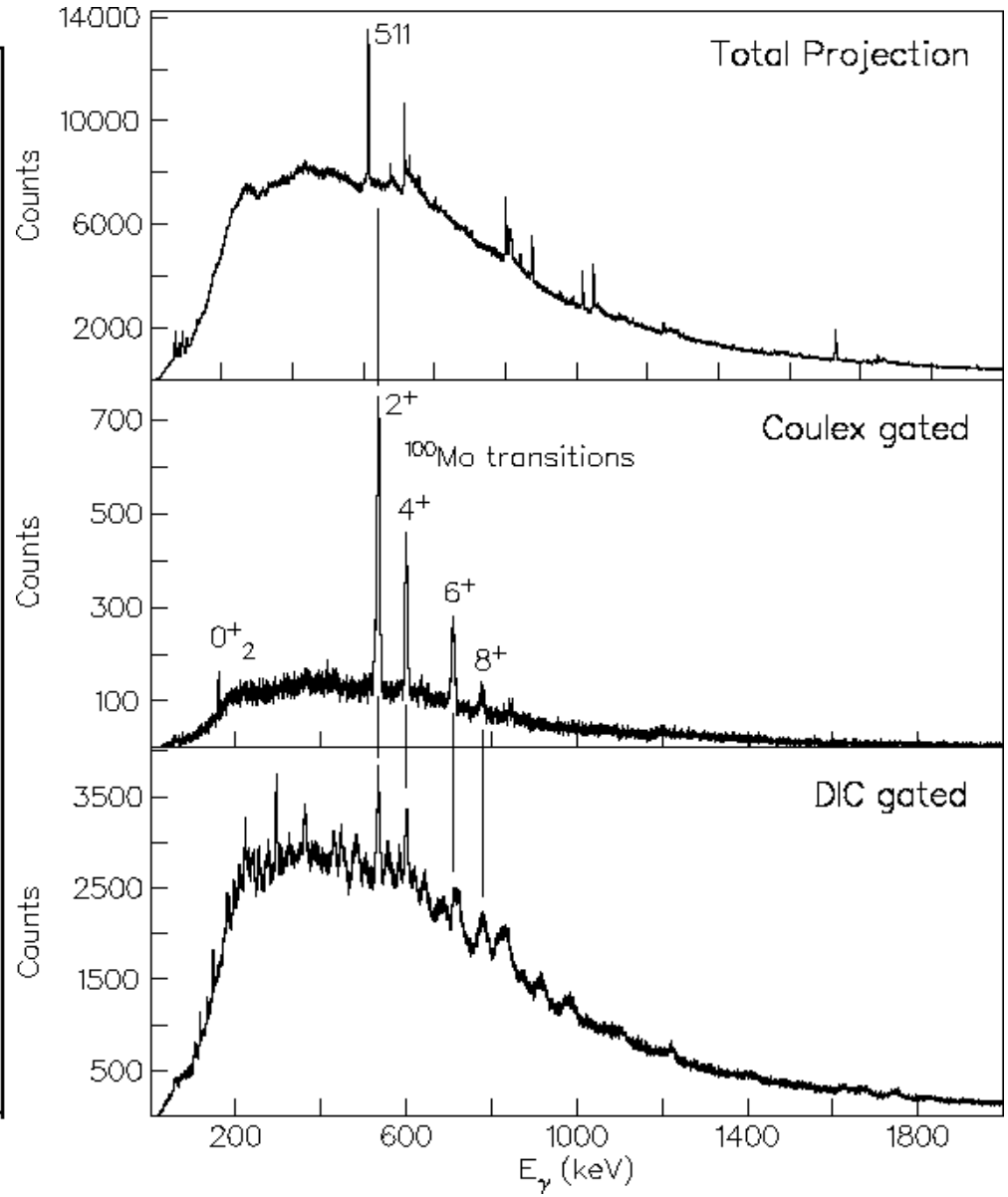




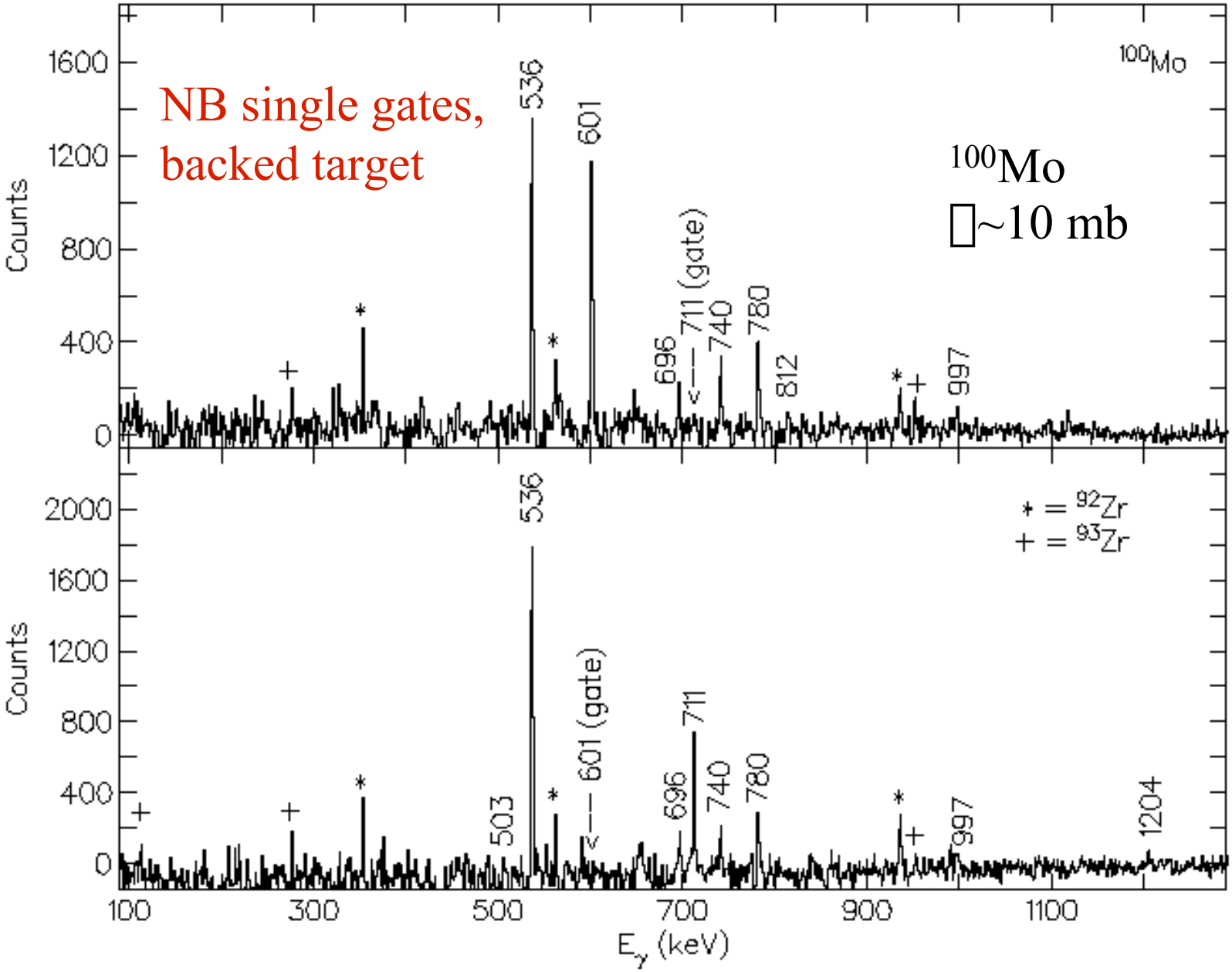

Rutherford Estimate of Scattering Angles
(^{100}Mo+700 MeV ^{136}Xe)
Target-like fragments
v/c value
0.10
0.08
0.06
0.04
0.02
20
30
40
50
60
70
Lab. Angle (theta)

Wilczynski Plot

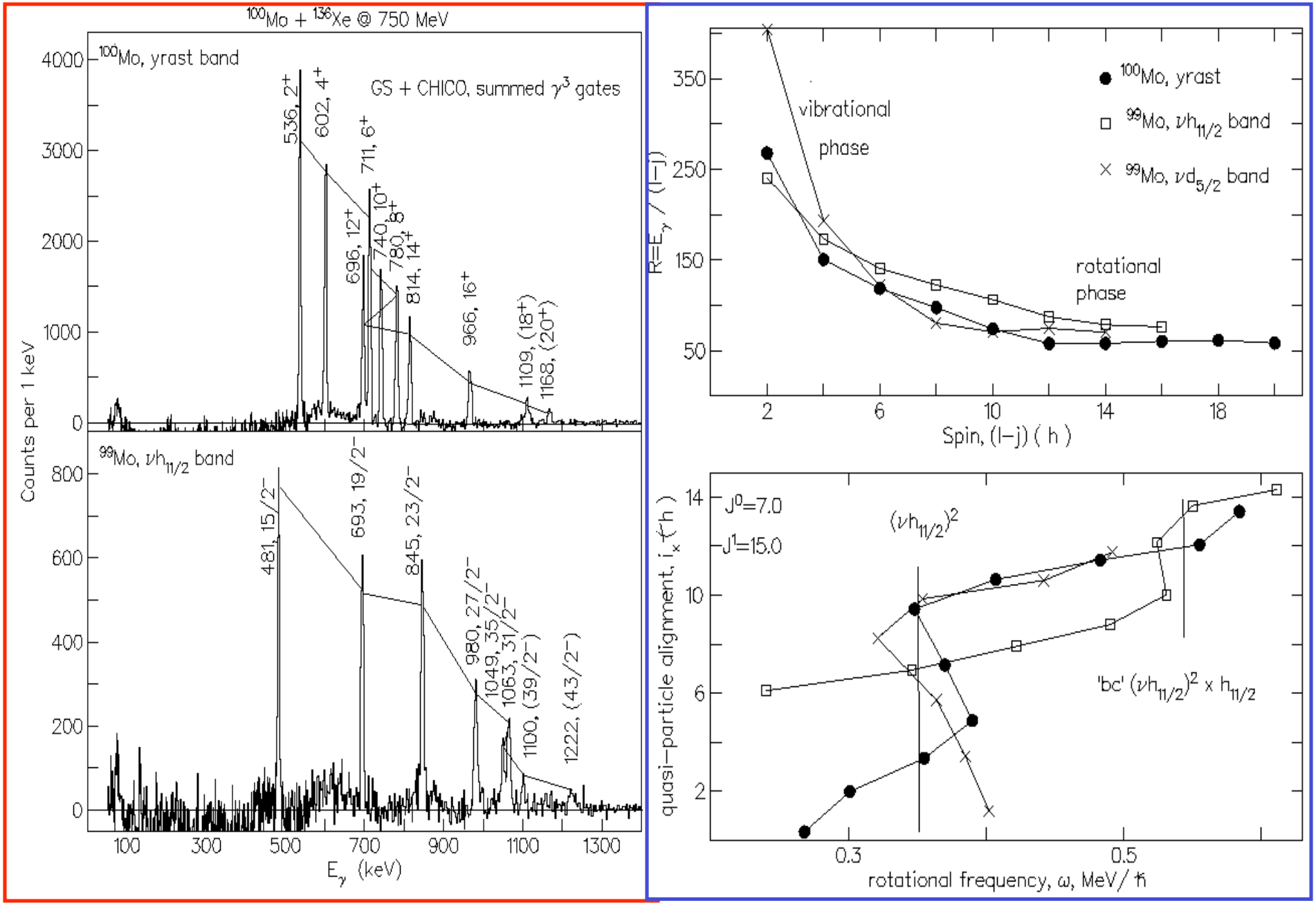




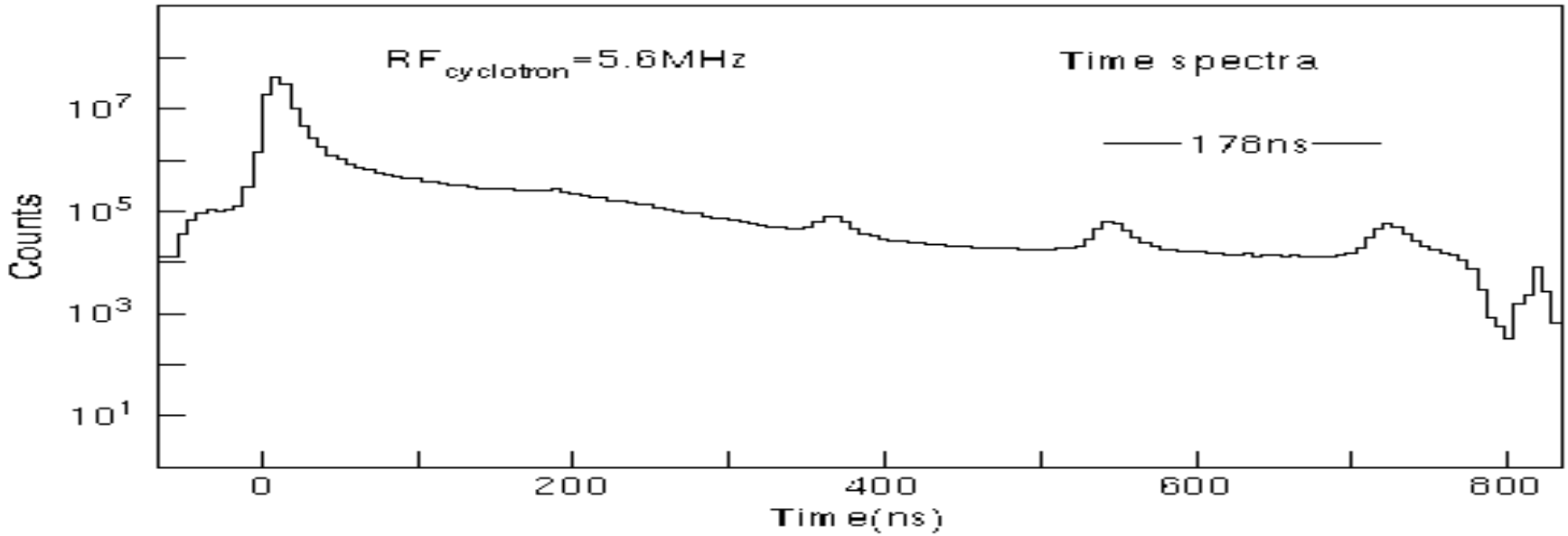
0.5% array with ~10^{10}pps beam for 4 days (c 1997), γ-γ trigger

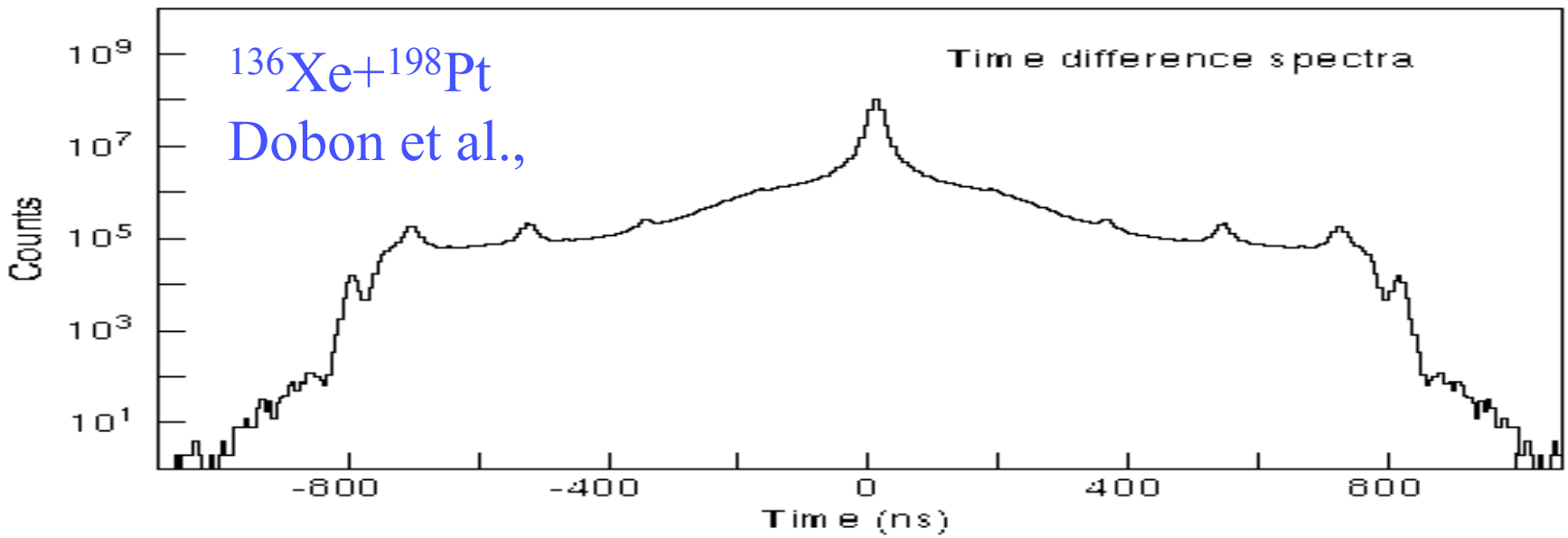


PHR et al., submitted to Phys. Rev. C, Surrey/Rochester/ LBNL/Manchester collab

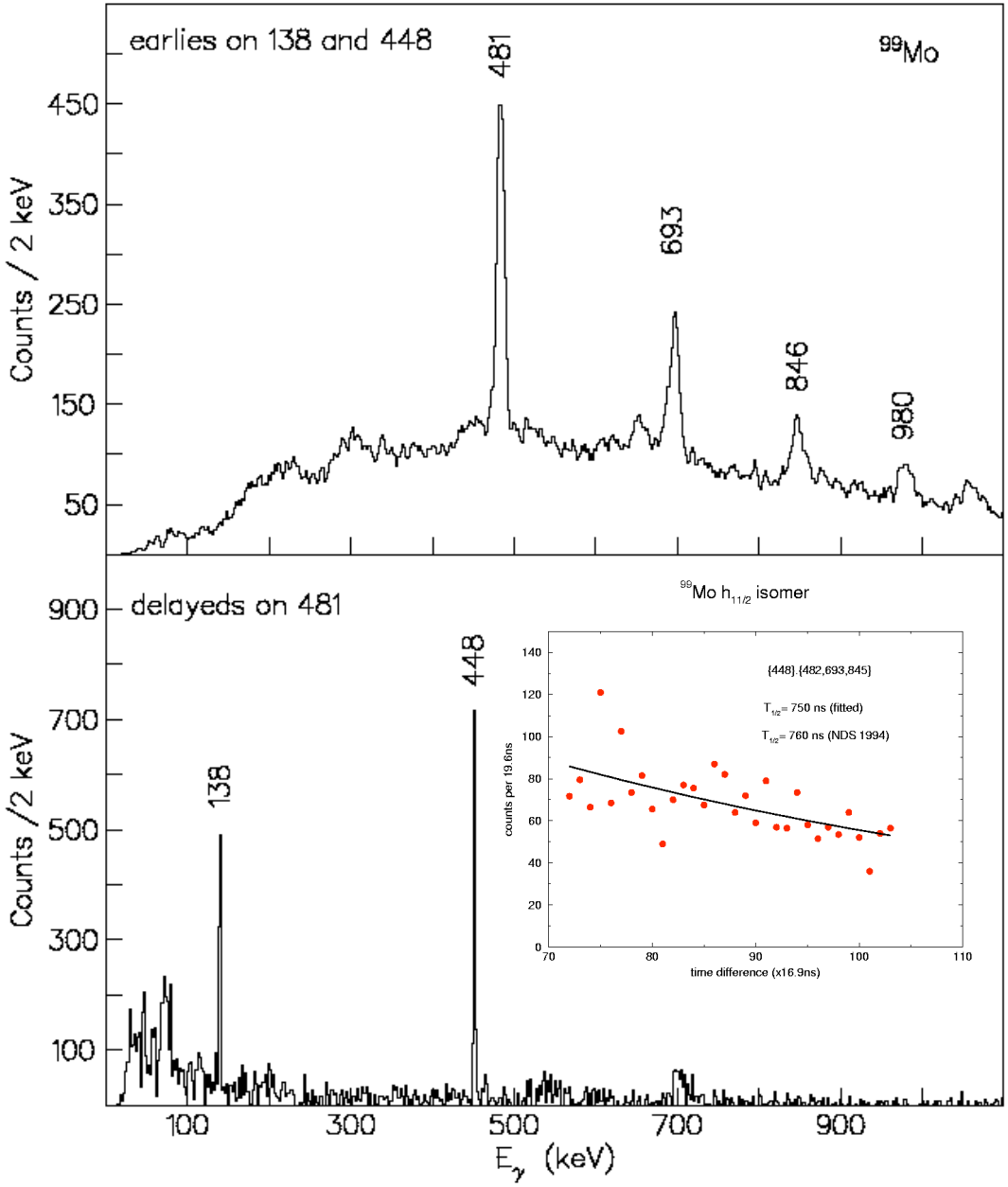


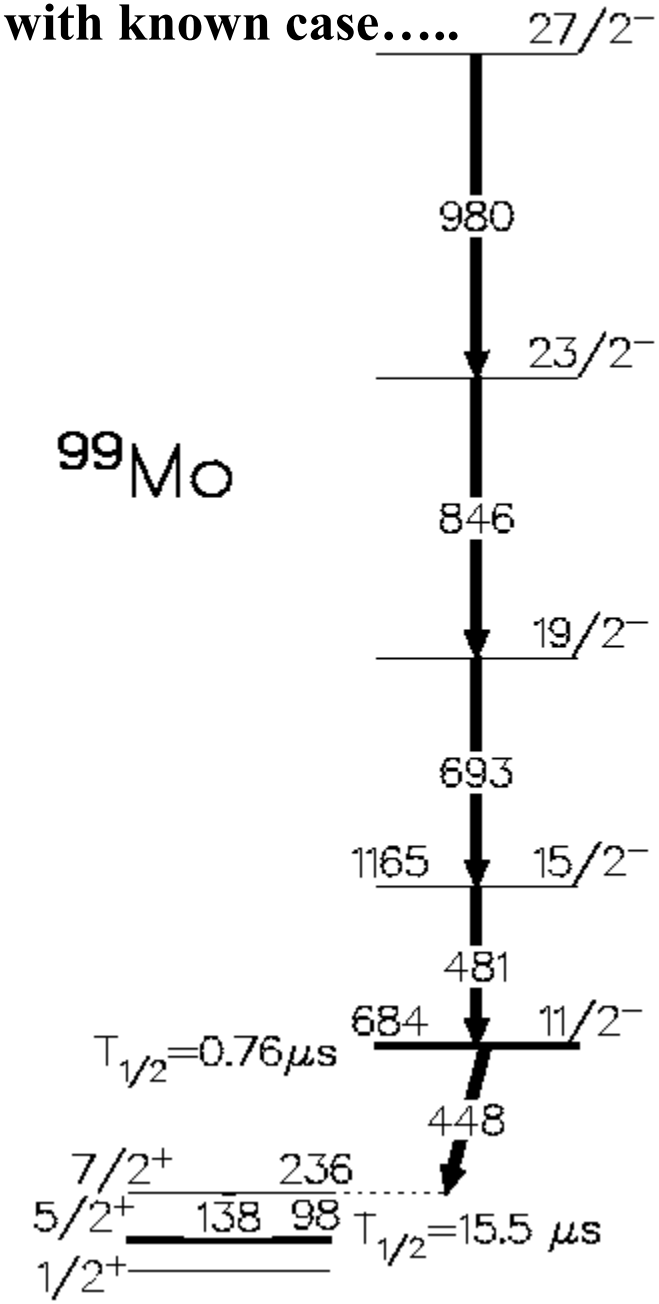
nano to microsecond isomer tagging ?





Isomer gating very useful in DIC experiments. Test with known case…..





What about the spin input ?

Semi-classically the max. peripheral ang. mom. is

$$l_{\max} = 0.219 R \sqrt{\mu (E_{CM} - V_{CM})} \quad \text{and} \quad \mu = \frac{A_B . A_T}{A_B + A_T}$$

The *grazing* angle where the DIC cross-section is max. is given by the distance of closest approach, d, where

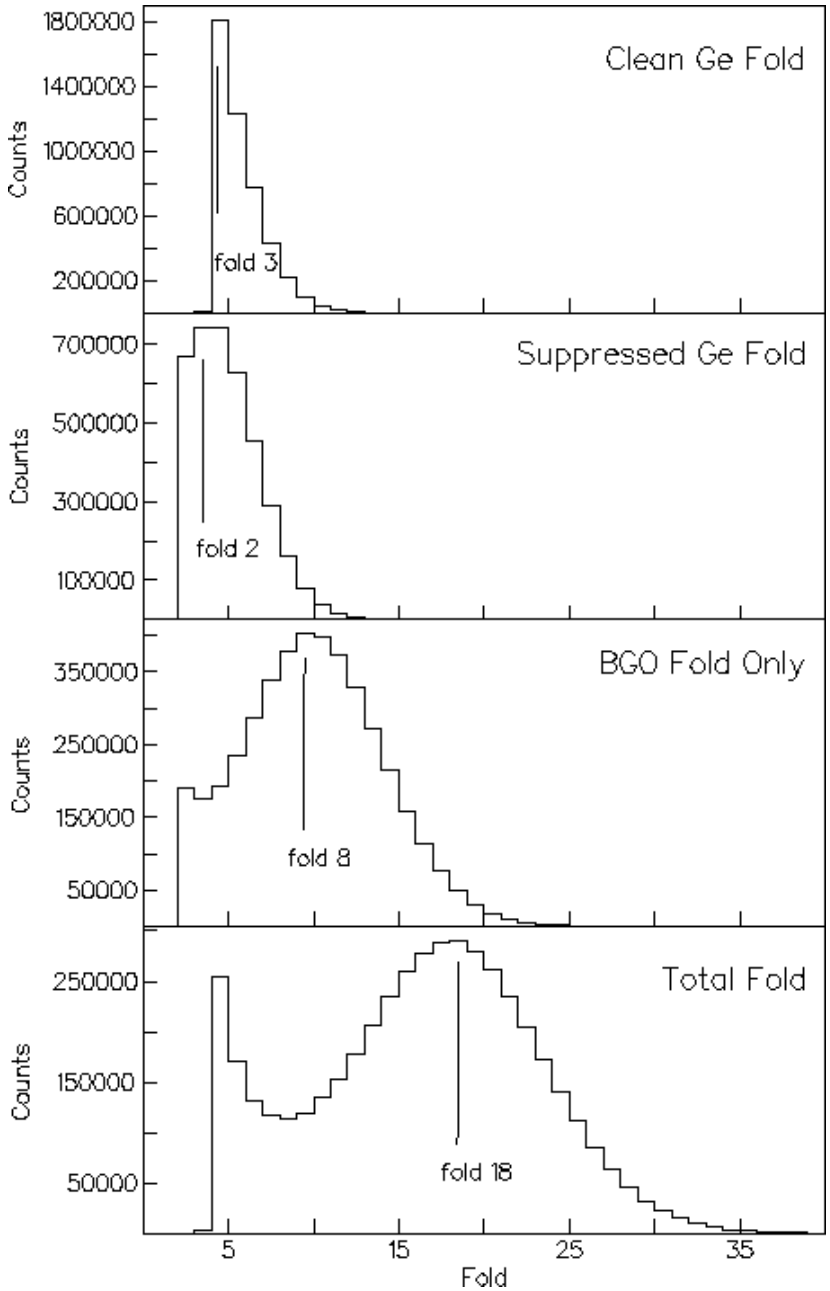
$$d = \left(\frac{Z_1 Z_2 e^2}{4\pi\varepsilon_0 E_k} \right) \cdot \left(1 + \operatorname{cosec} \left(\frac{\theta_{graz}}{2} \right) \right) = 1.25 \left(A_B^{1/3} + A_T^{1/3} \right) fm$$

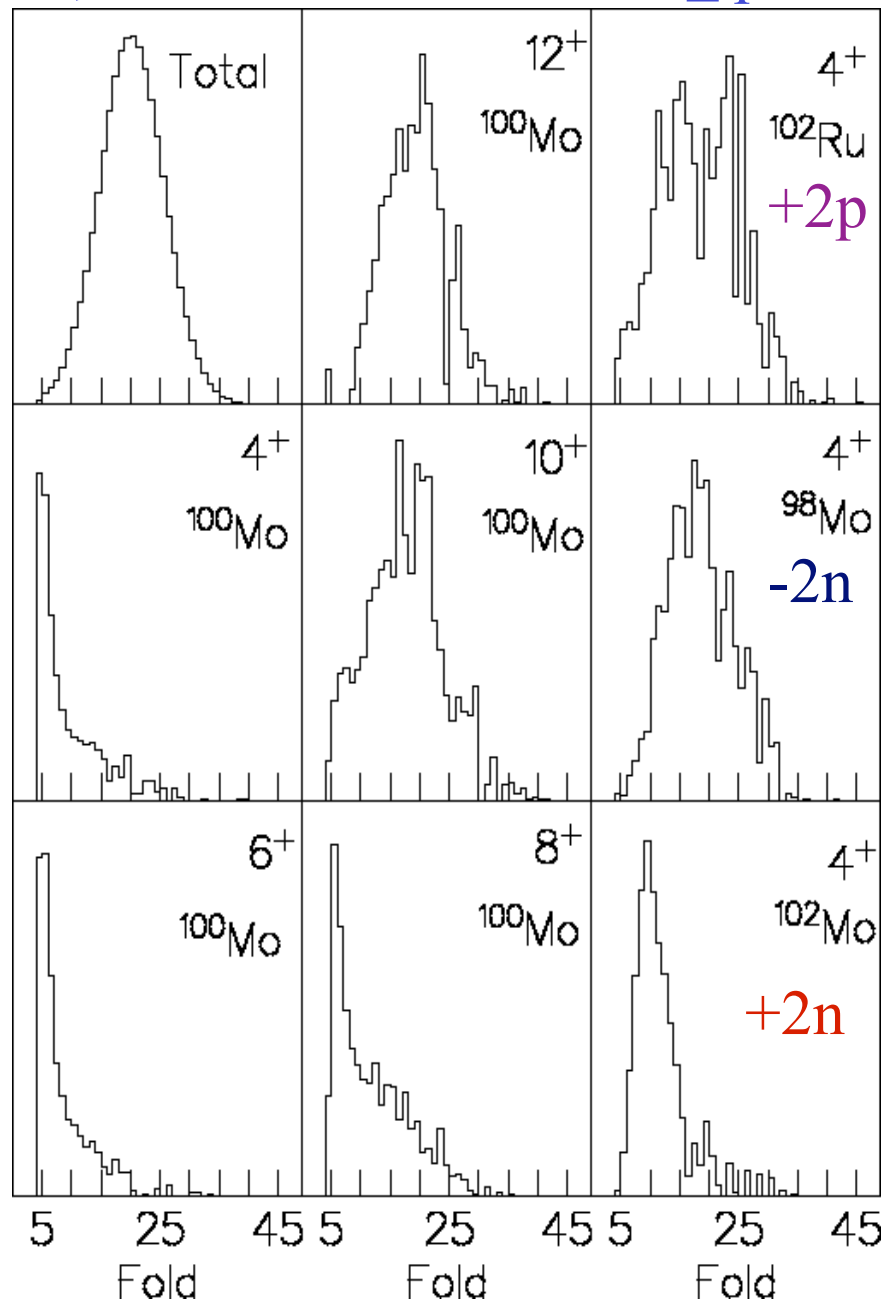
In the rolling mode limit, $l_{\max}$ is split into l_{tlf}, l_{blf} and the relative ang. mom. between the two fragments.

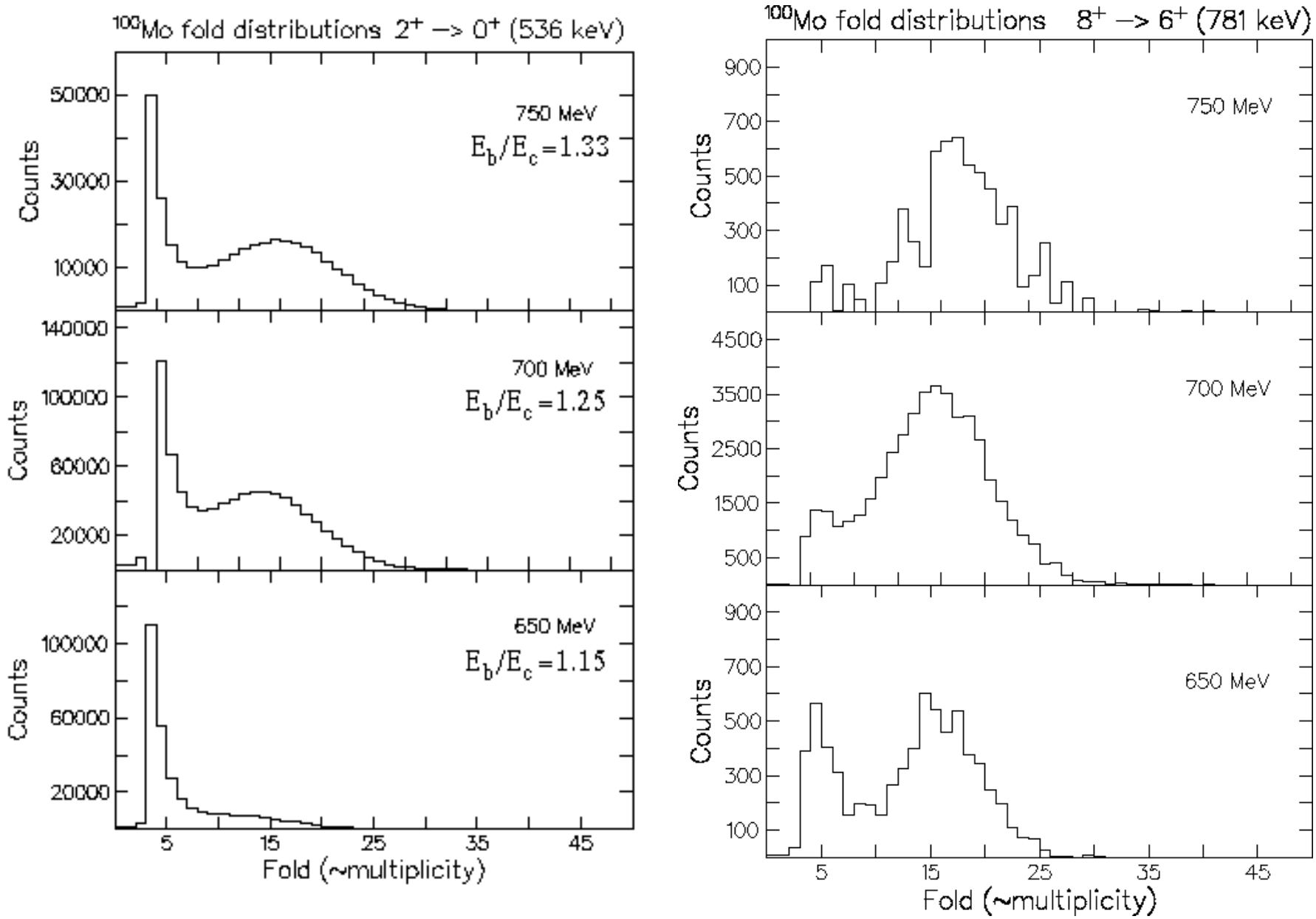
$$l_{\text{tlf}} = \frac{2}{7} \left(\frac{1}{1 + \left(\frac{A_B}{A_T} \right)^{\frac{1}{3}}} \right) l_{\max} \qquad l_{\text{blf}} = \frac{2}{7} \left(\frac{1}{1 + \left(\frac{A_T}{A_B} \right)^{\frac{1}{3}}} \right) l_{\max}$$

Bock et al., Nukleonika **22** (1977) 529

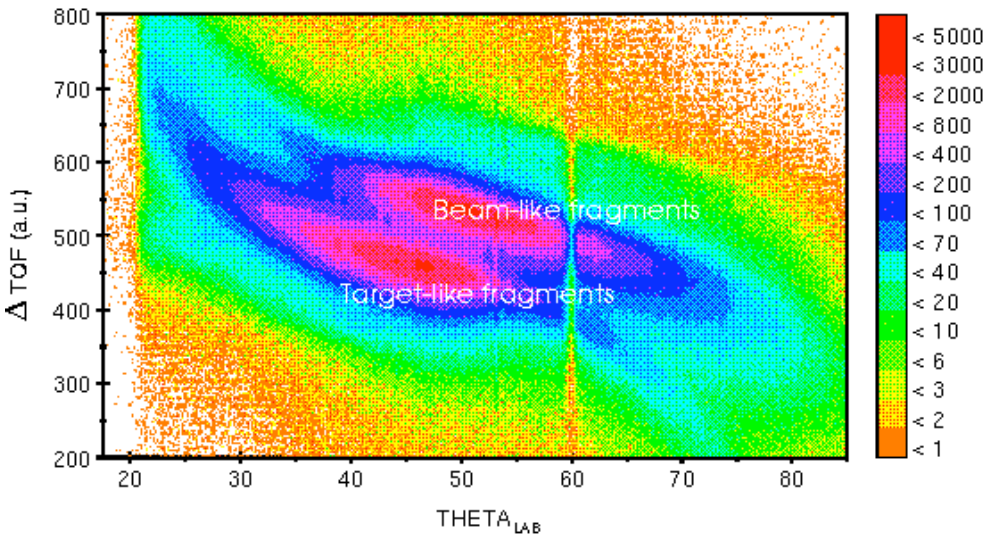
PHR et al., submitted to Phys. Rev. C, $^{136}Xe+^{100}Mo$ CHICO+γsphere.

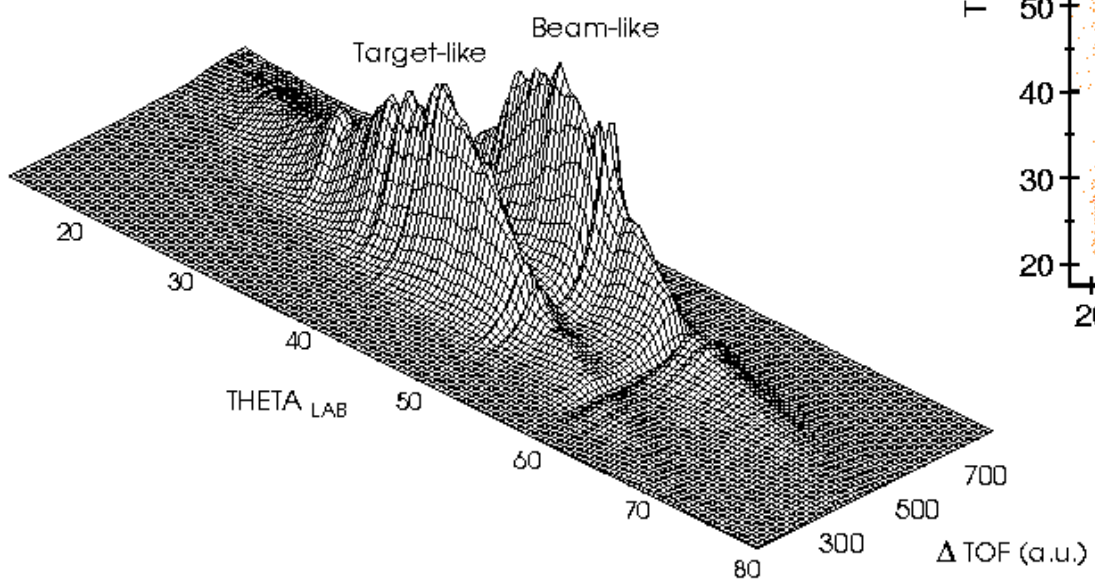


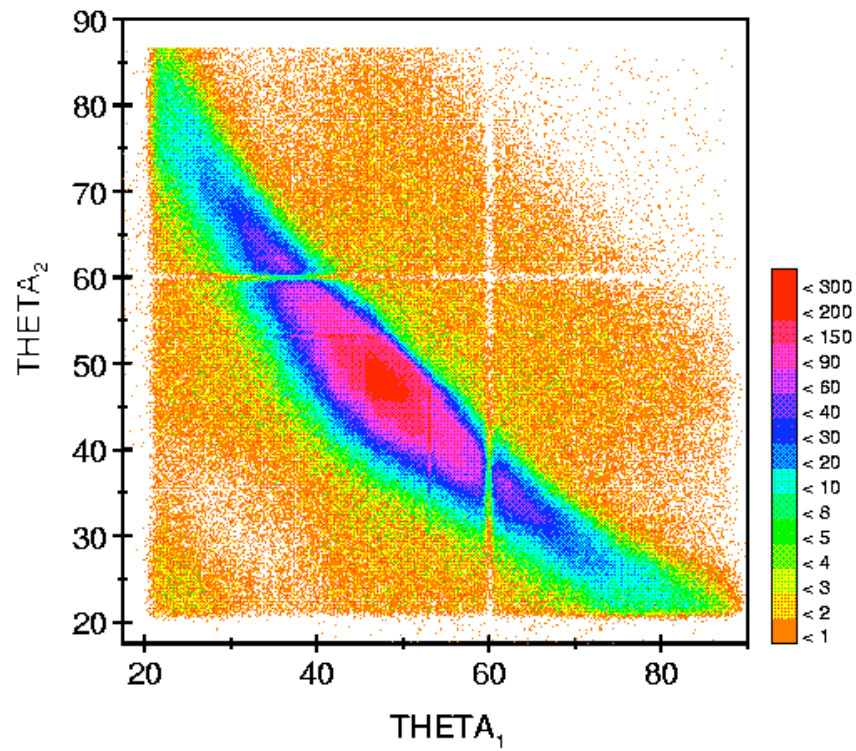


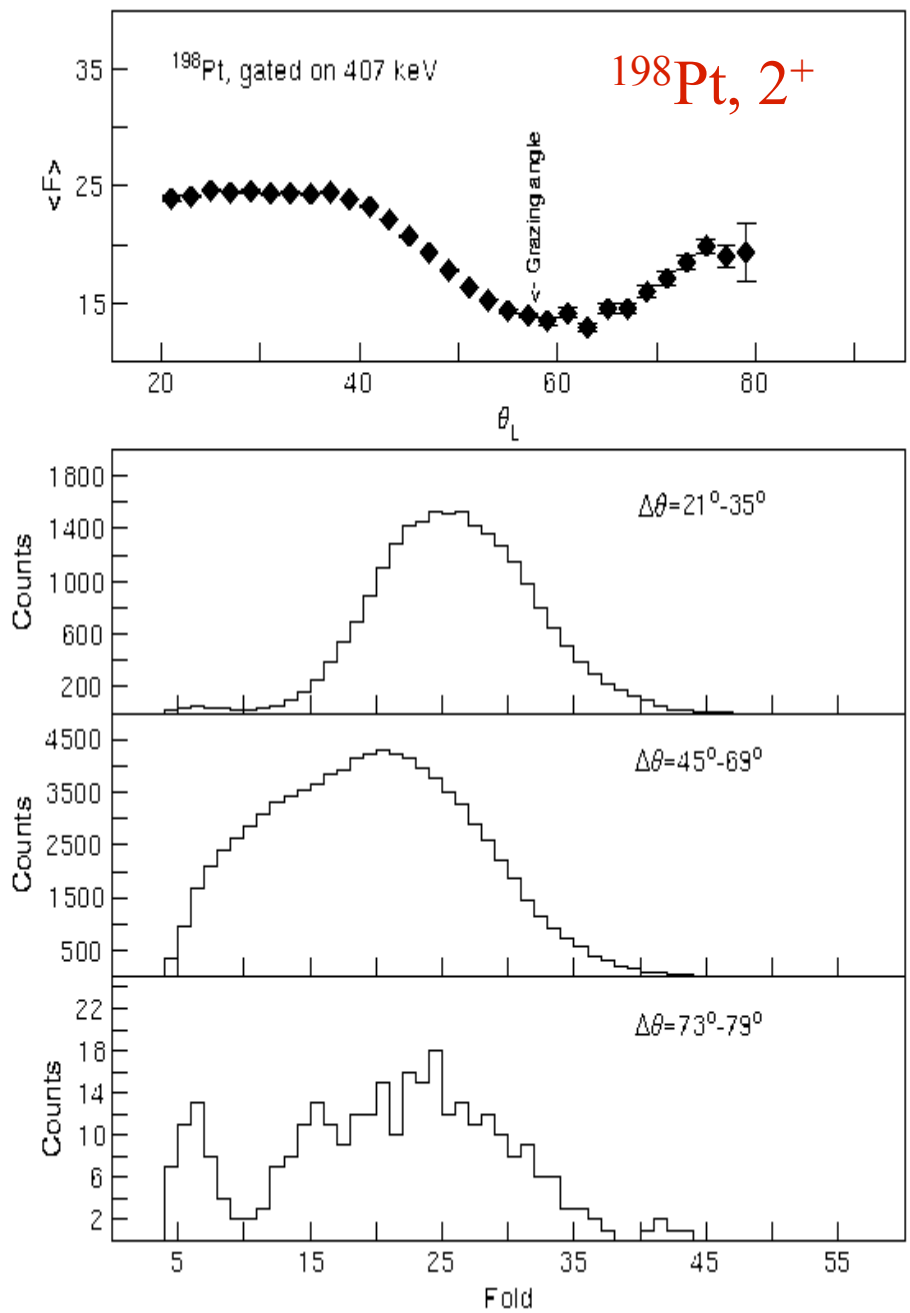

^{100}Mo fold distributions 2$^+$ –> 0$^+$ (536 keV)
750 MeV
E_b/E_c=1.33
700 MeV
E_b/E_c=1.25
650 MeV
E_b/E_c=1.15
Counts
Fold (~multiplicity)
^{100}Mo fold distributions 8$^+$ –> 6$^+$ (781 keV)
750 MeV
700 MeV
650 MeV
Counts
Fold (~multiplicity)

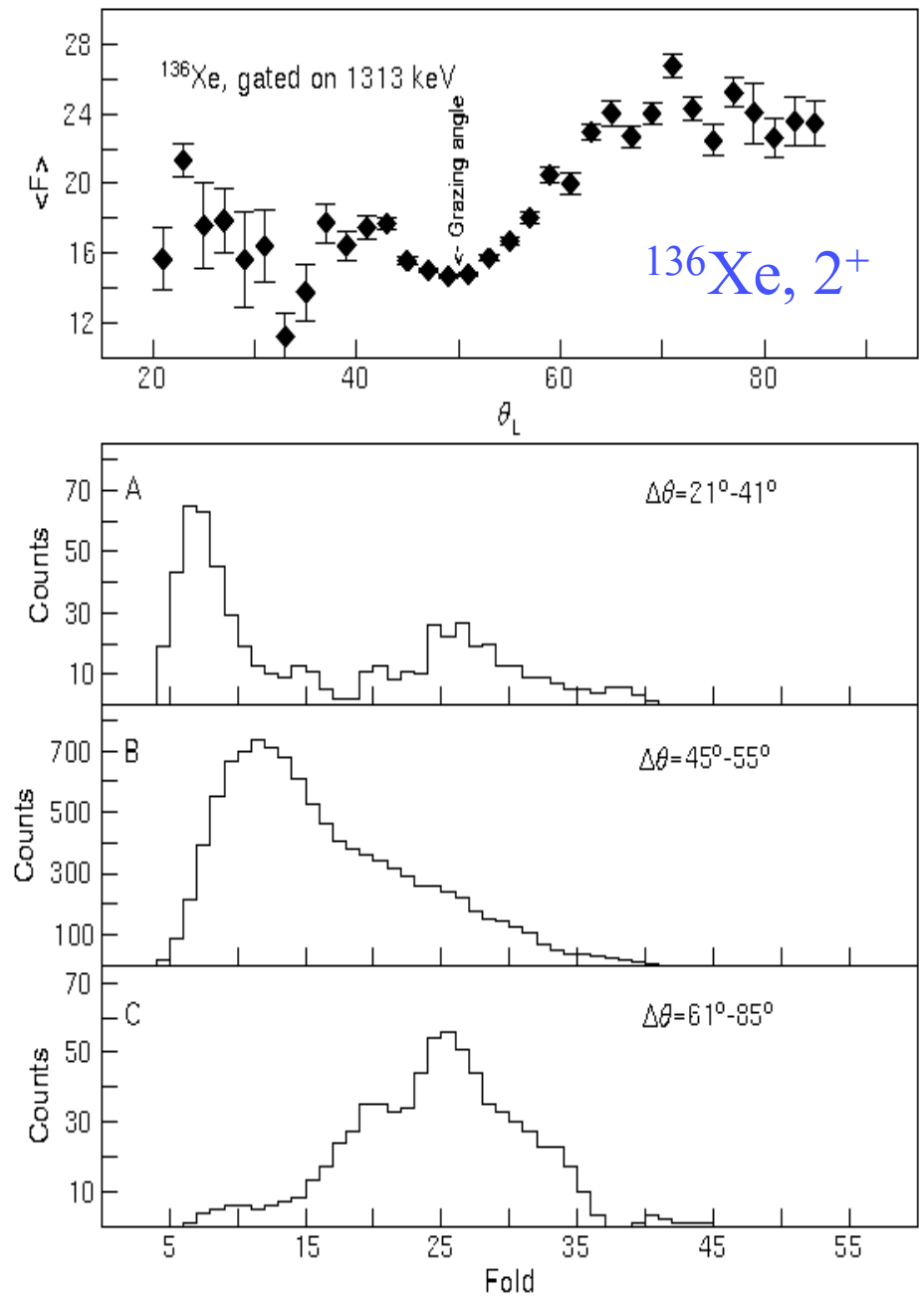
$^{198}Pt + ^{136}Xe$, 850 MeV

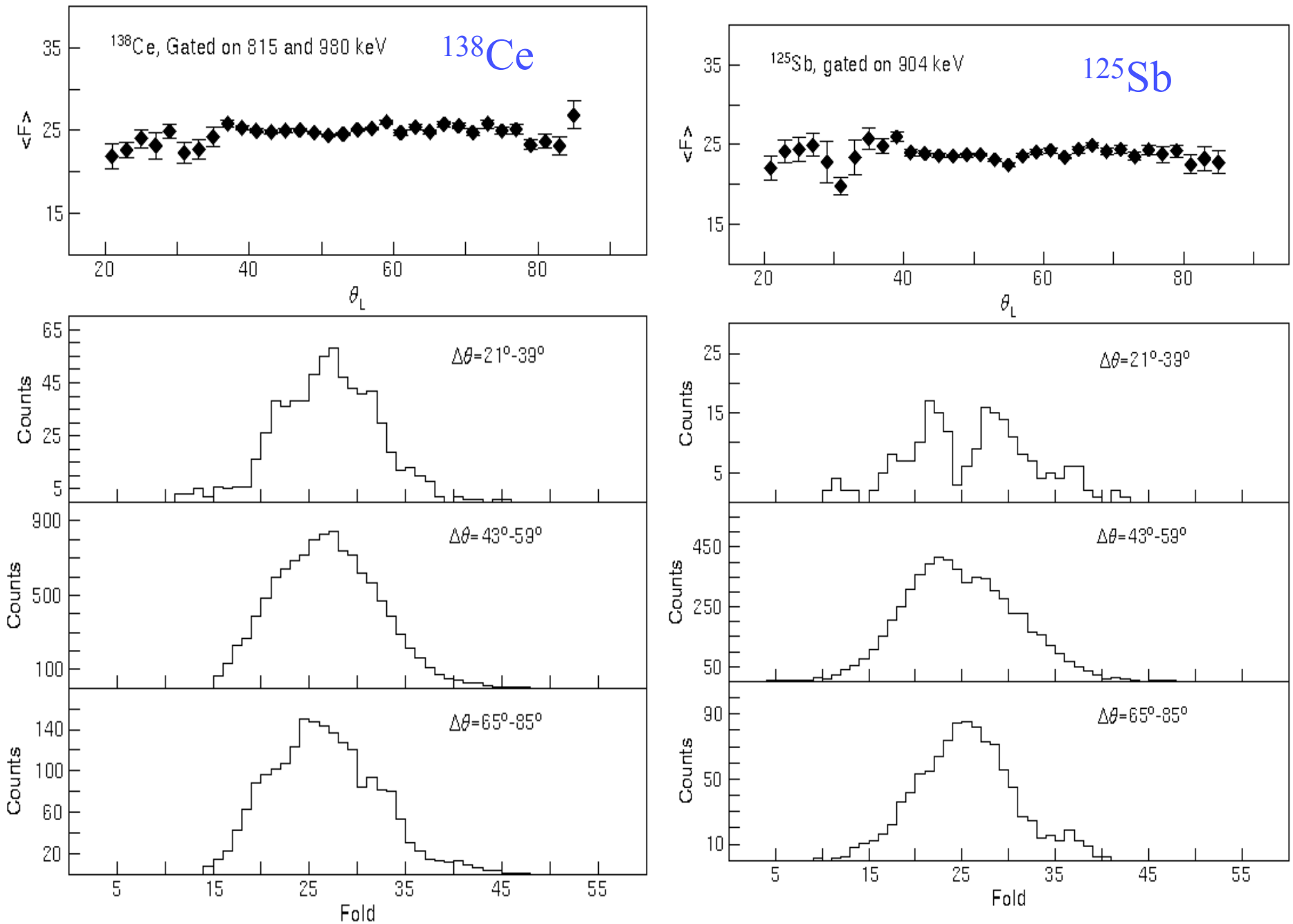







198Pt, gated on 407 keV
198Pt, 2+
<F>
<- Grazing angle
θL
Counts
Δθ=21°-35°
Δθ=45°-69°
Δθ=73°-79°
Fold


136Xe, gated on 1313 keV
136Xe, 2+
<F>
<- Grazing angle
θL
Counts
A
Δθ=21°-41°
B
Δθ=45°-55°
C
Δθ=61°-85°
Fold

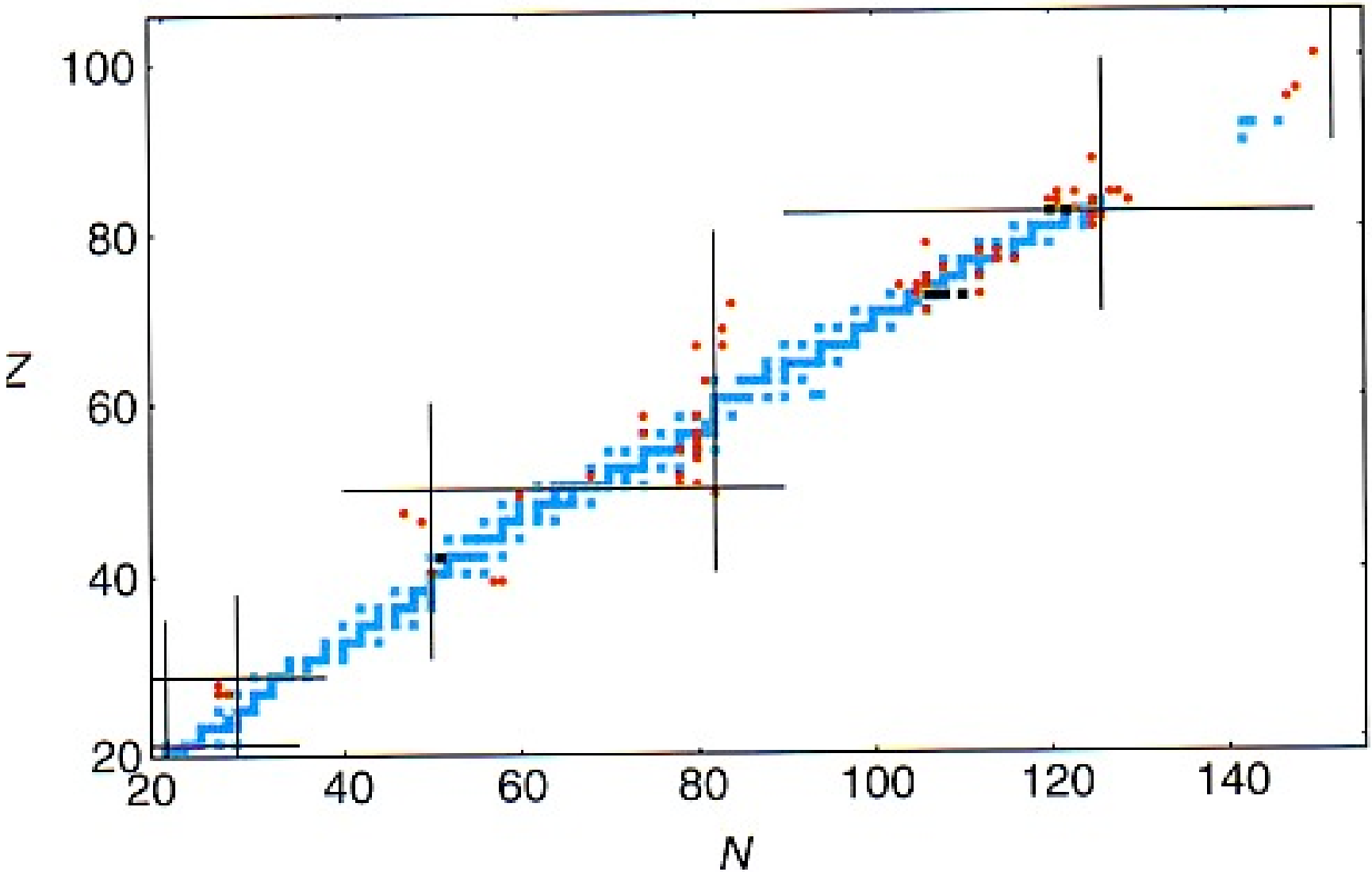

^{138}Ce, Gated on 815 and 980 keV
^{138}Ce
<F>
θ_L
^{125}Sb, gated on 904 keV
^{125}Sb
$\Delta\theta$=21°-39°
$\Delta\theta$=43°-59°
$\Delta\theta$=65°-85°
Counts
Fold

Physics areas to attack with DIC!!!!

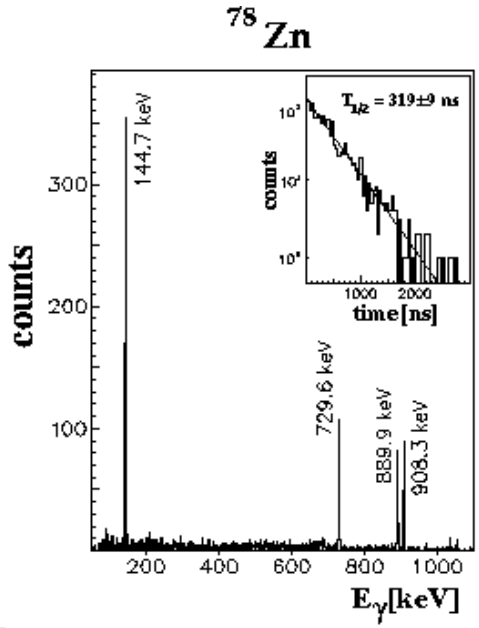
- ~^{78}Ni, doubly magic, effect on r-process path.
  - (e.g., ^{78}Zn beam on heavy target)
- ^{170}Dy mid-shell, best SU(3) case, best K-isomer
  - ^{132}Sn beams on ^{170}Er, ^{174,6}Yb targets
- A~190,
  - Limits of K-isomerism, pairing, sub-shell closures
  - odd-odd isomers effect on r-process path ?
- Neutron-rich NE of ^{208}Pb
  - new α, β-decaying isomers (e.g., ^{212}Bi, ^{212}Po)

All of these complement fragmentation studies

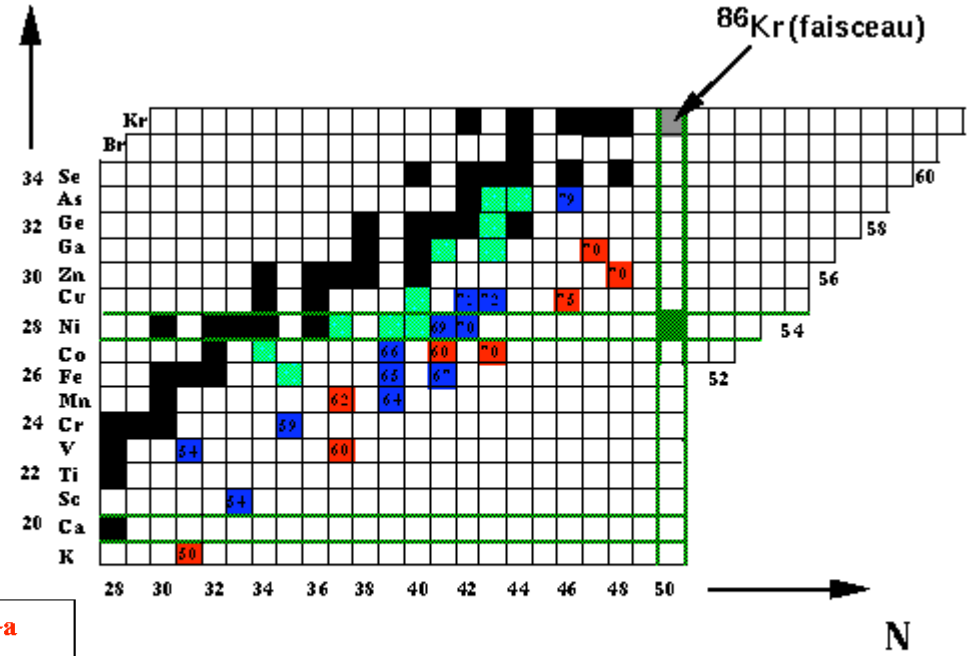
Where are the long-lived, high-spin isomers ?
From Walker and Dracoulis, Nature **399**, p35 (1999)

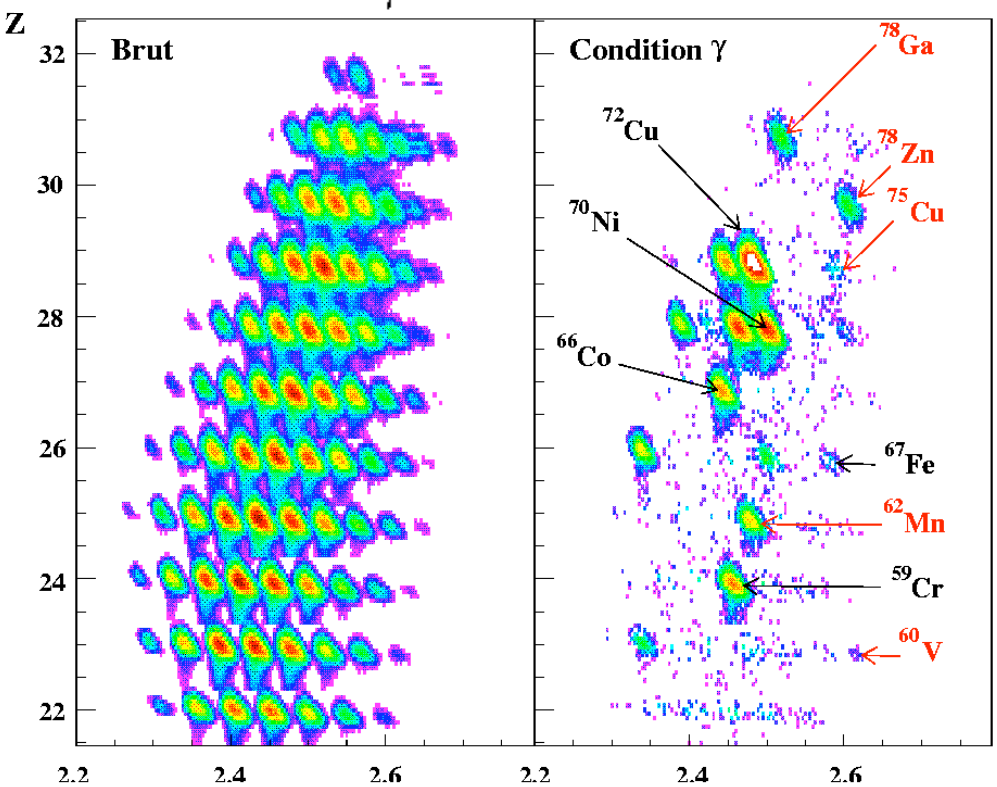


$E_x > 1$ MeV, $T_{1/2} > 1$ ms (red), $T_{1/2} > 1$ hour (black)

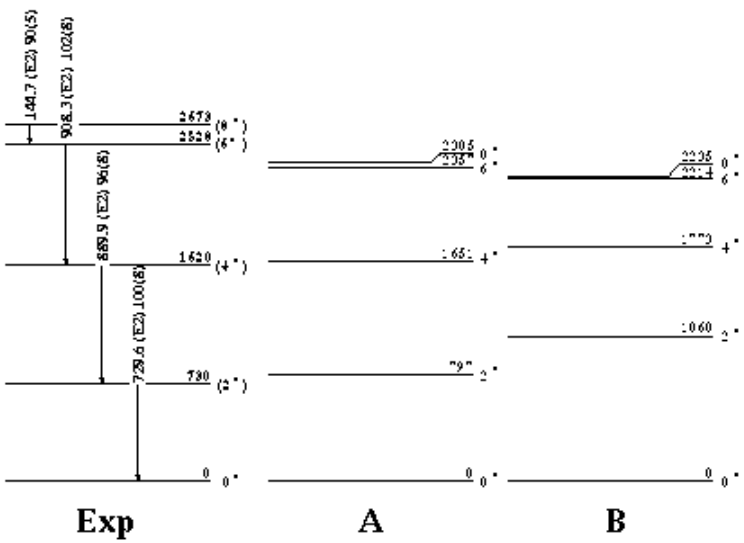


8^+ isomer in ^{78}Zn, real evidence of ^{78}Ni shell closure. J.M.Daugas et al. Phys. Lett. **B476** (2000) p213

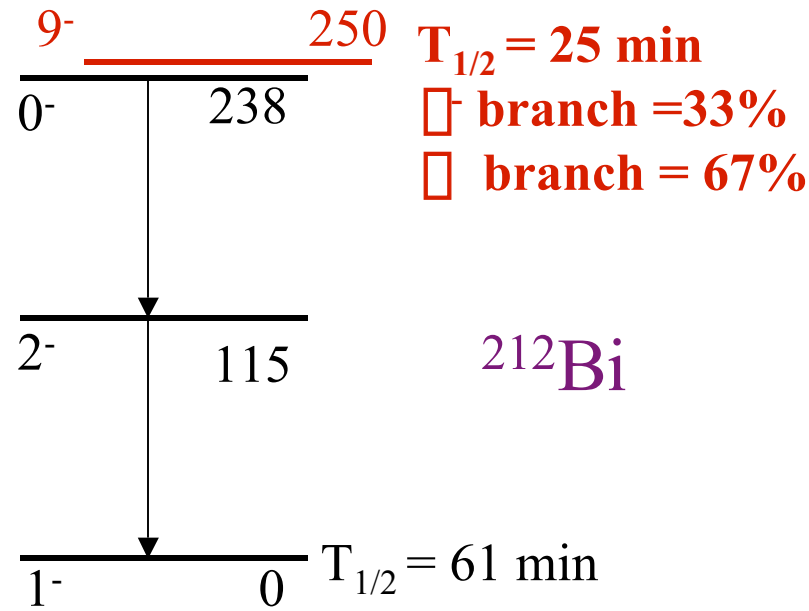


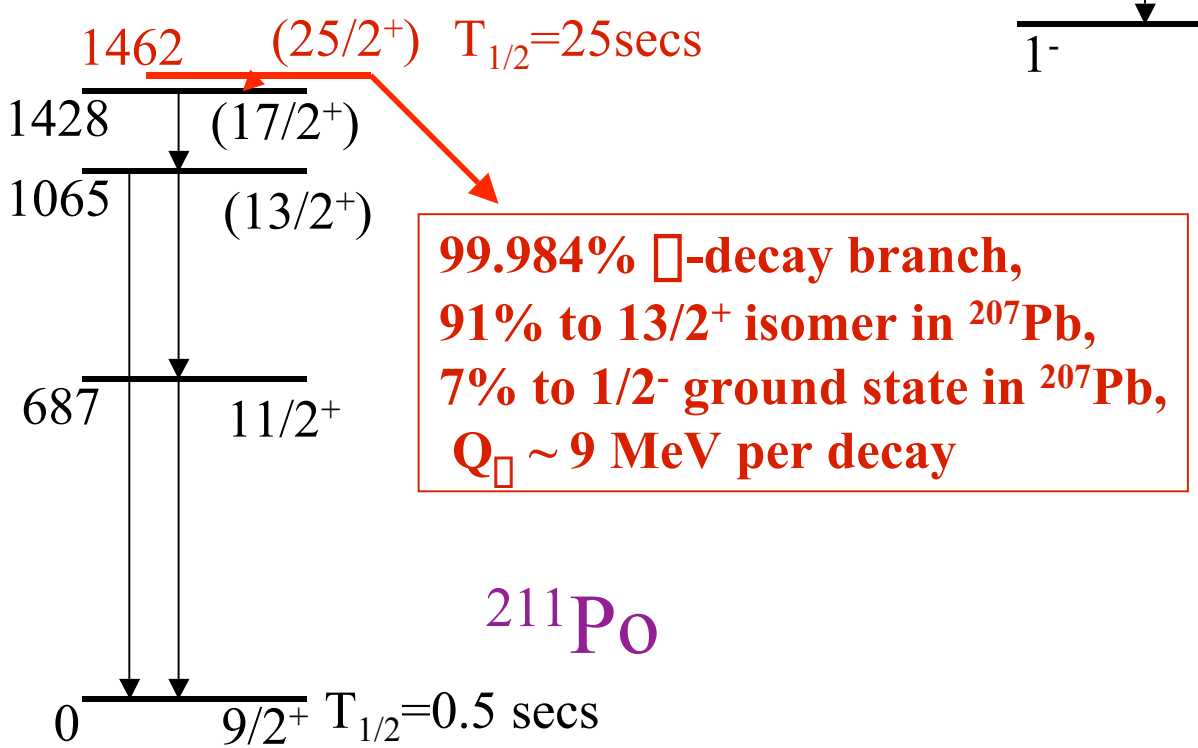


Isomères déjà connus
Nouveaux Isomères - Expérience 1996
Nouveaux Isomères - Expérience 1998

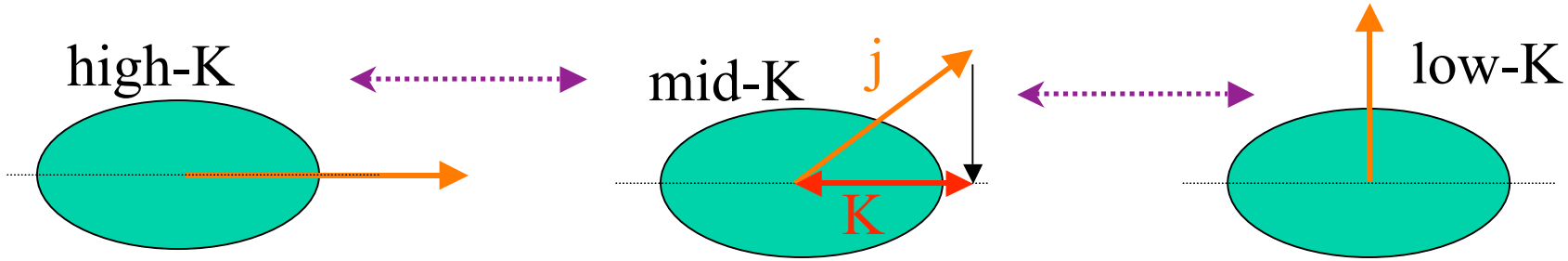


‘High-spin’ □ and □-decaying isomers just above ^{208}Pb, basically as a result of ‘yrast’ (spin) traps..





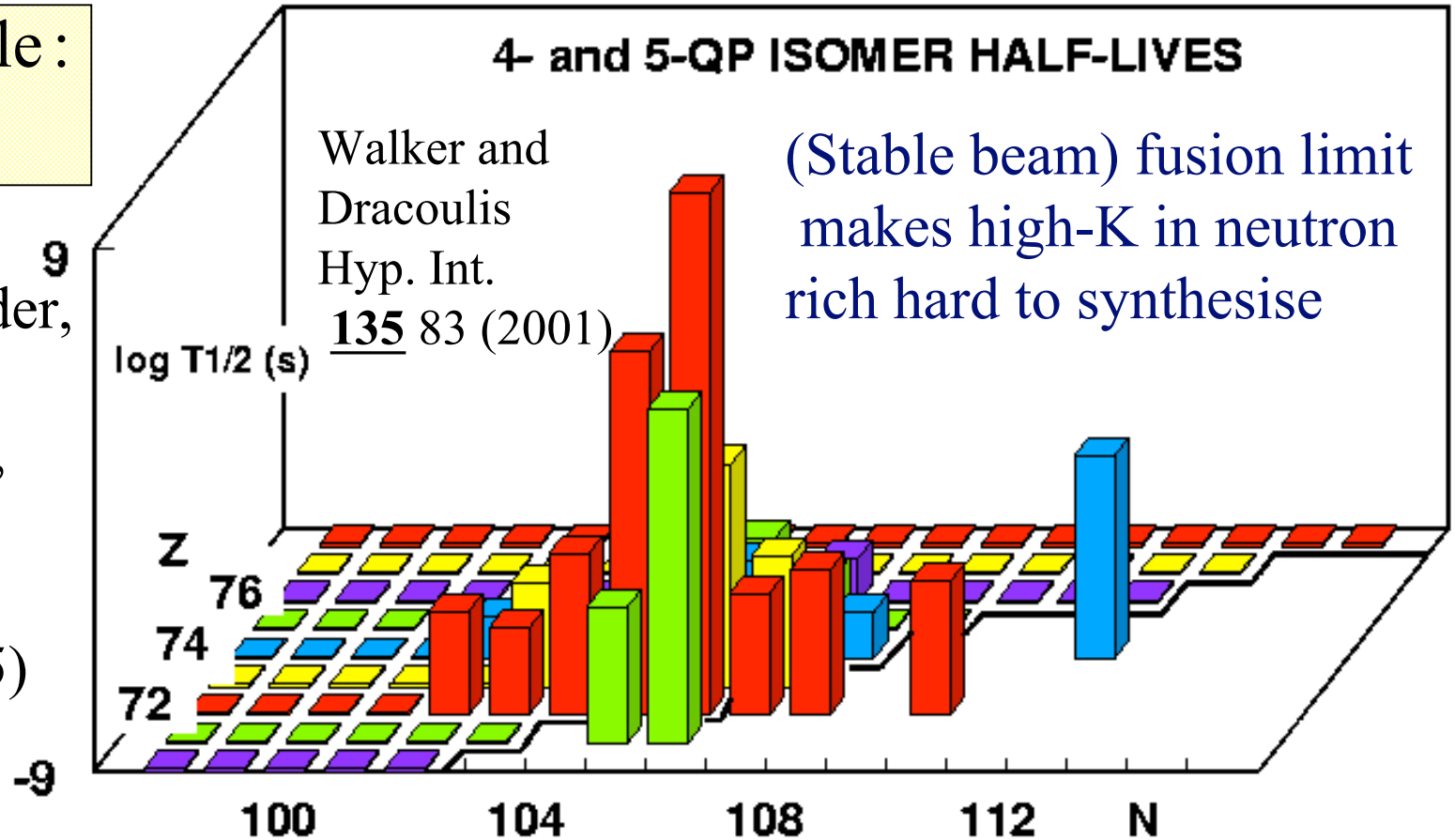
Search for long (>100ms) K-isomers in neutron-rich(ish) A~180 nuclei.



K - sel. rule :

□/□ ≥ □□

Alaga, Alder, Bohr and Mottelson, Mat. Fys. Medd. **29** no 9 (1955)



Walker and Dracoulis Hyp. Int. **135** 83 (2001)

(Stable beam) fusion limit makes high-K in neutron rich hard to synthesise

Ex~1 MeV β-decaying K-'driven' isomer in ^{177}Lu.

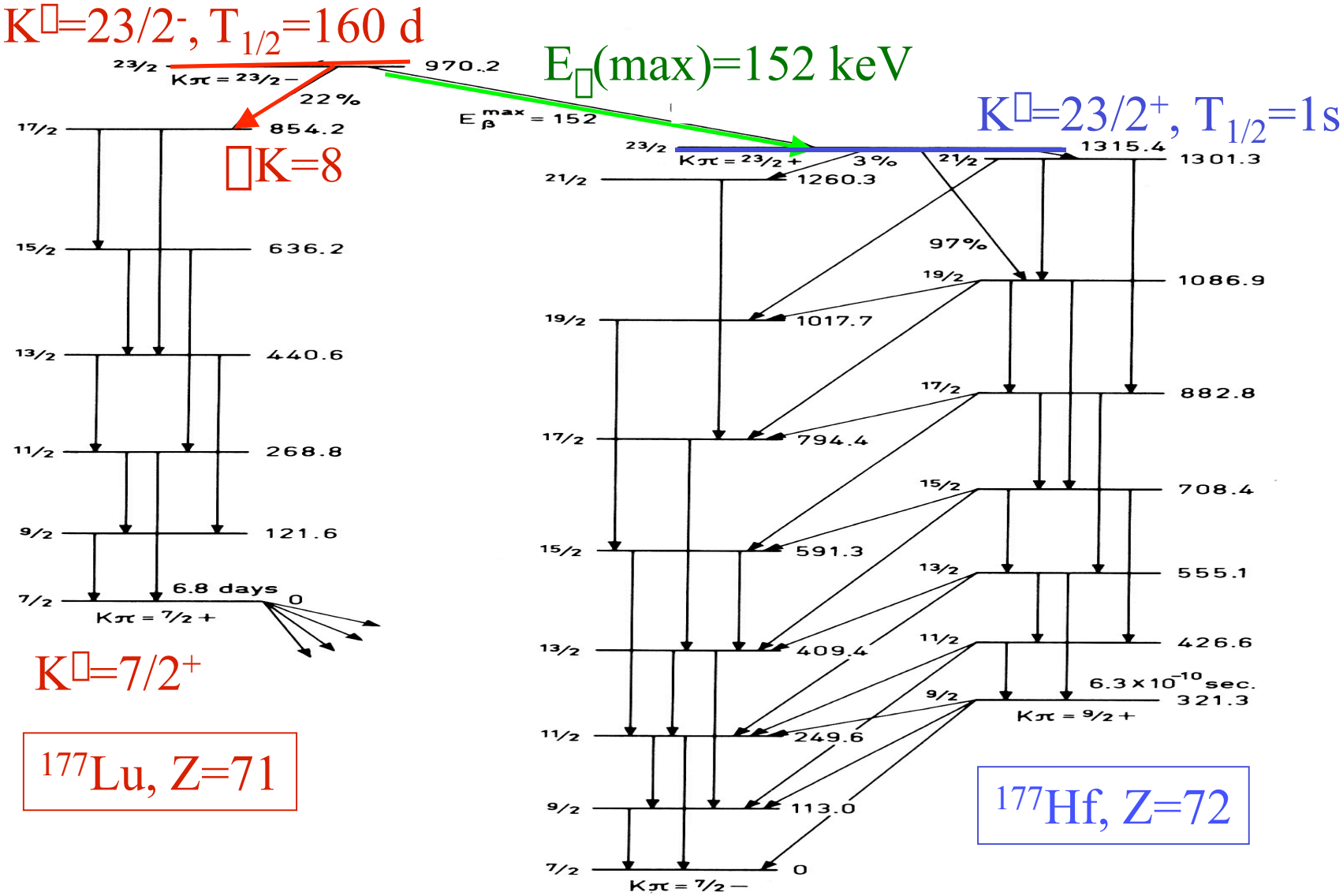
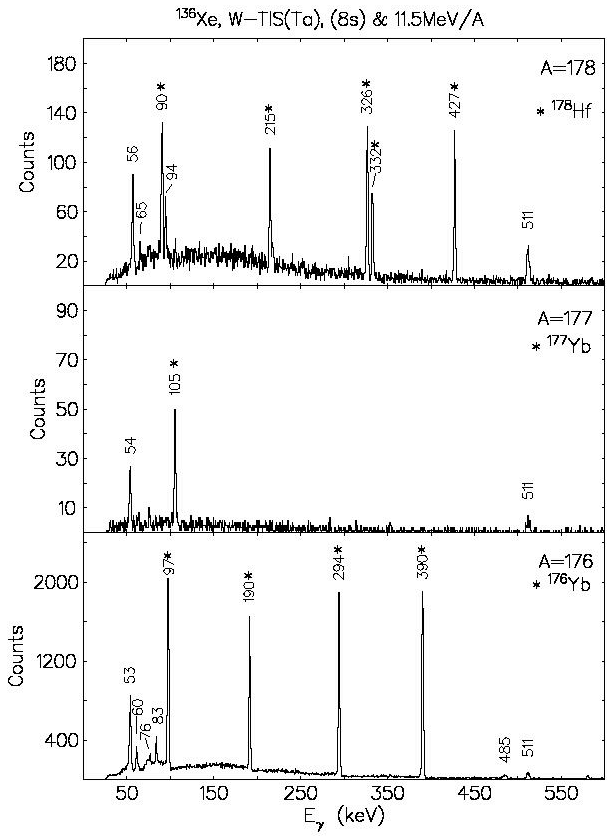


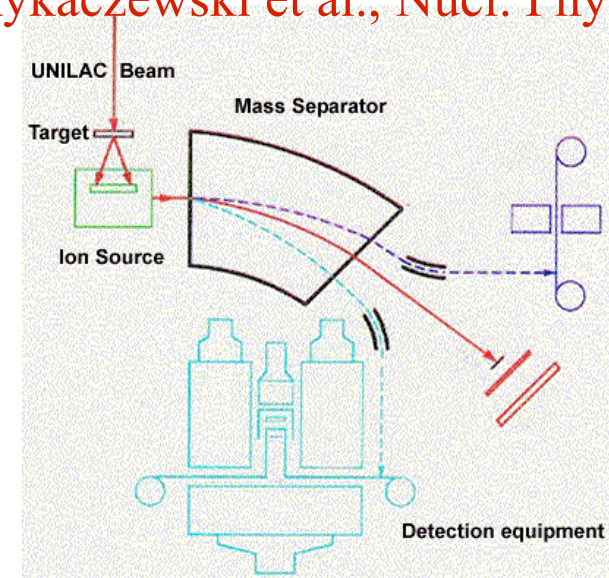
Figure 4-16 Decay scheme for ^{177}Lu^{m}. The data are taken from A. J. Haverfield, F. M. Bernthal, and J. M. Hollander, *Nuclear Phys.* **A94**, 337 (1967), which also includes results of previous investigations. Additional transitions reported by F. Bernthal (private communication) have also been included. The energies in the figure are in keV, and the decay times represent half lives.

Online-Mass Separation Technique

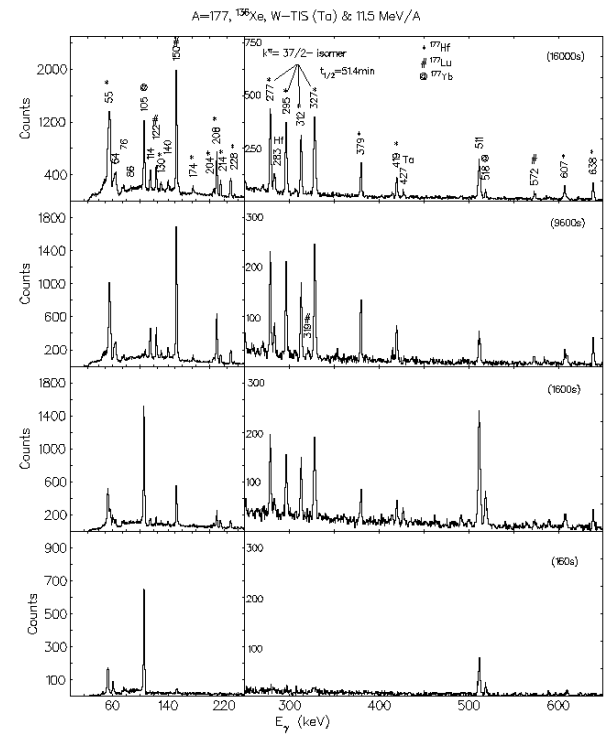
See eg., K. Rykaczewski et al., Nucl. Phys. **A499** (1989) p529

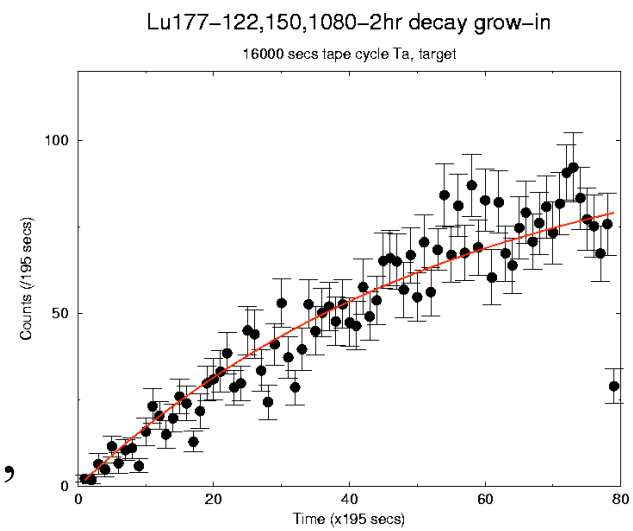
Select by mass





Select by decay times

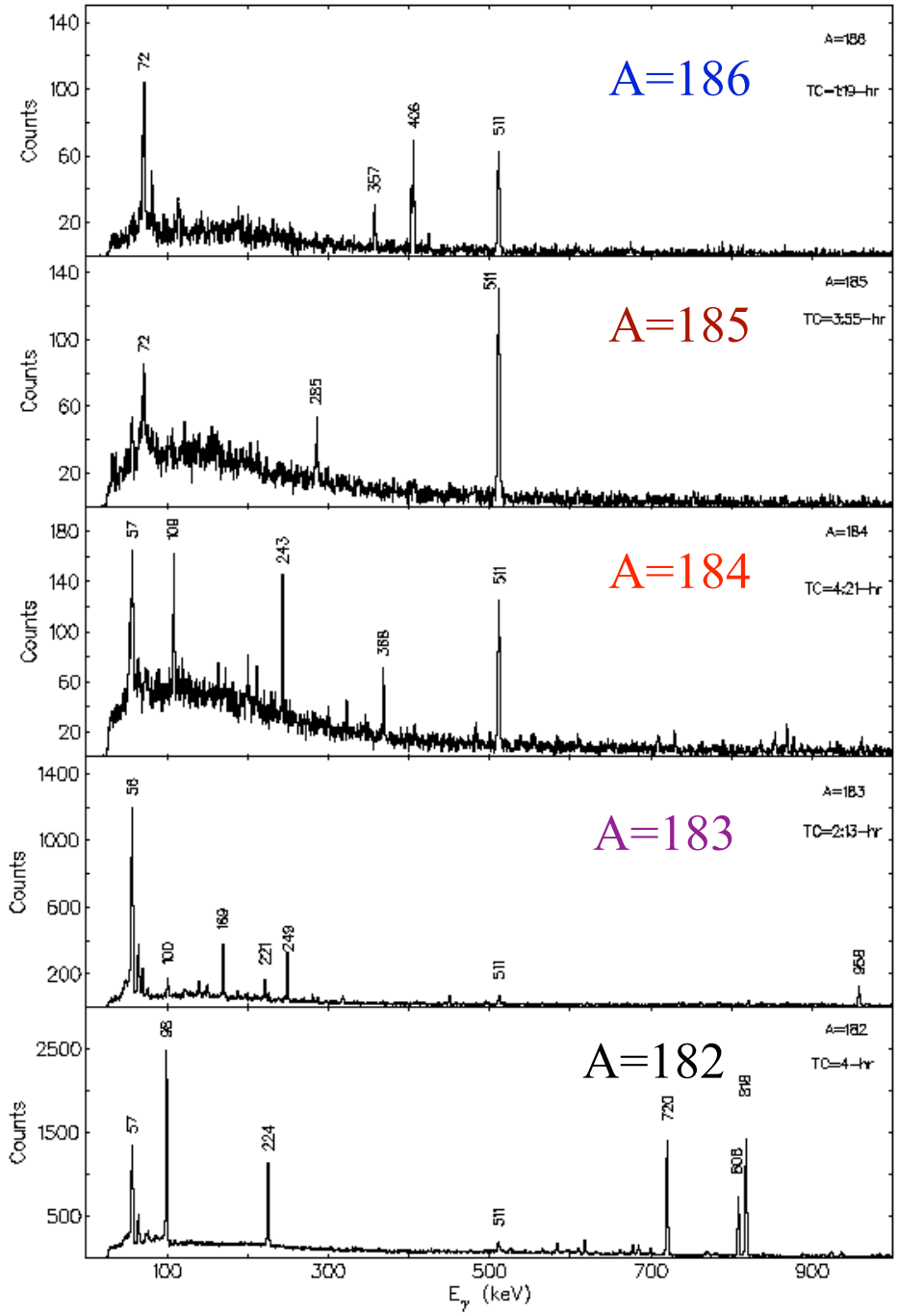




Surrey/GSI/Liverpool,

$^{136}Xe+Ta^{nat}$

Lifetimes from grow-in curve



S. Al Garni submitted to Phys. Rev. C
Surrey/GSI/Liv./Goettingen/Milano

^{136}Xe @11.4 MeV/u on to ^{186}W target in thermal ion source (TIS), tape speed 160 s.

Mass selection achieved using dipole magnet in GSI Online mass separator (ASEP).

$$B\rho = \frac{Au.v}{Qe} = \frac{\sqrt{2EAu}}{Qe}$$

$$Q = 1, E = 60\ keV$$

See Bruske et al. NIM **186** (1981) p61

Z selection by tape speed to remove activity.

^{176}Lu survival depends on ***not*** exciting β-decaying isomer. Note ^{176}Lu shielded from r-process by stable ^{176}Yb.

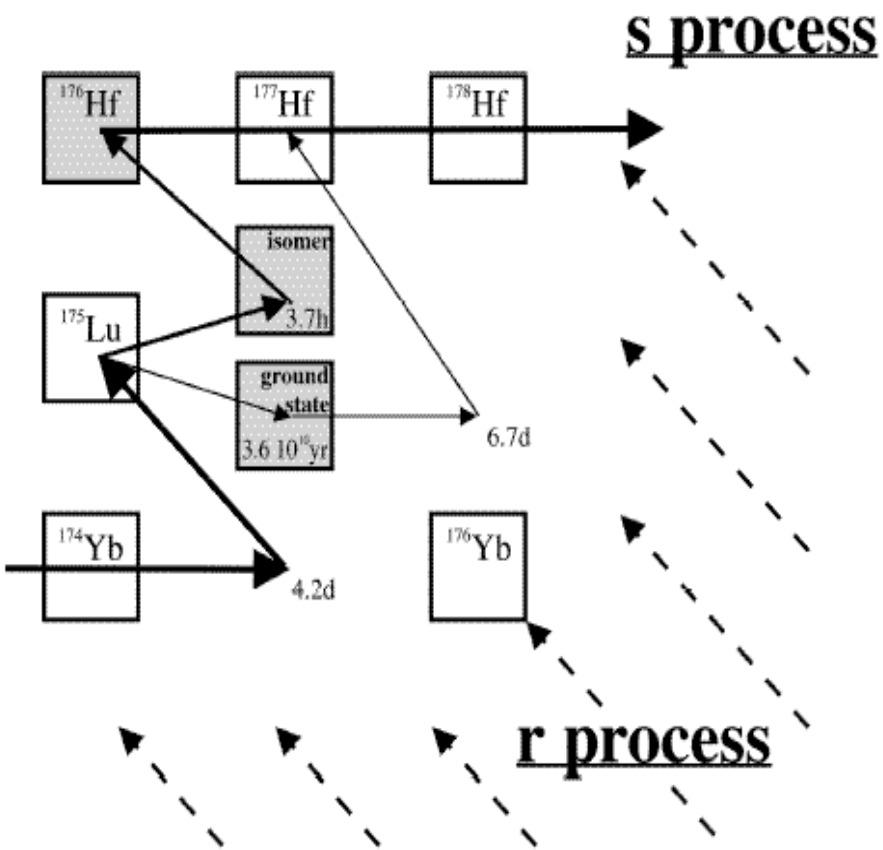


FIG. 1. The *s*-process neutron capture chain in the Yb-Lu-Hf region (solid lines). For ^{176}Lu, the ground state and isomer are shown separately. Note that ^{176}Lu and ^{176}Hf are shielded against *r*-process β decays.

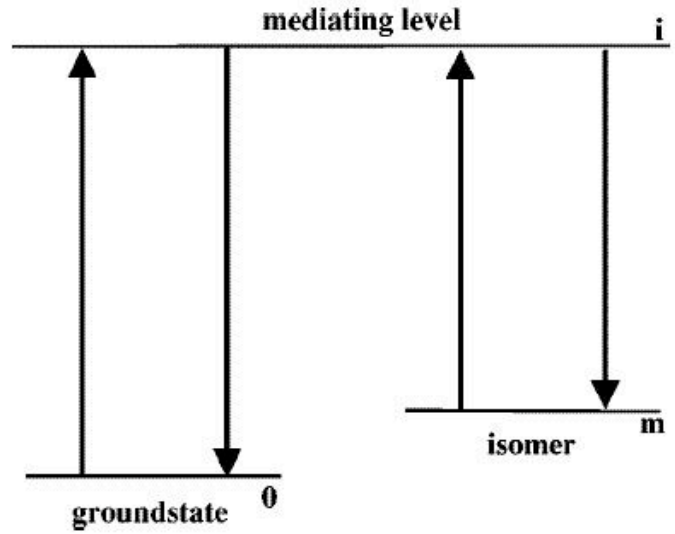
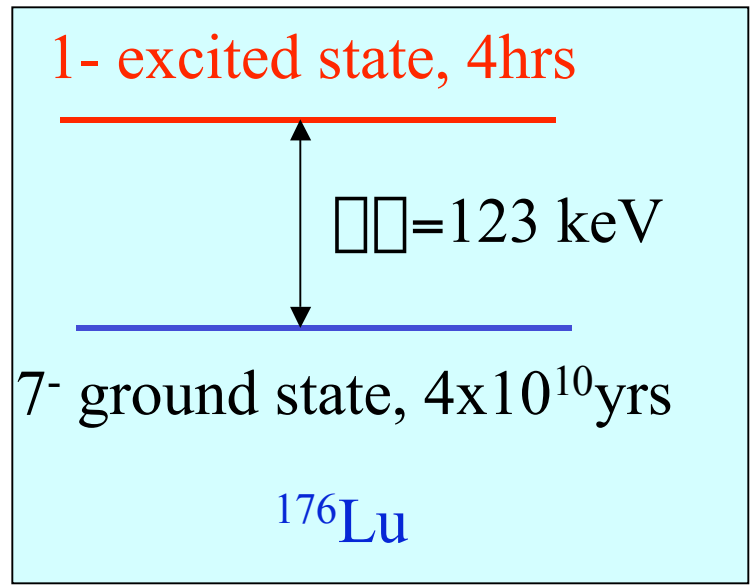
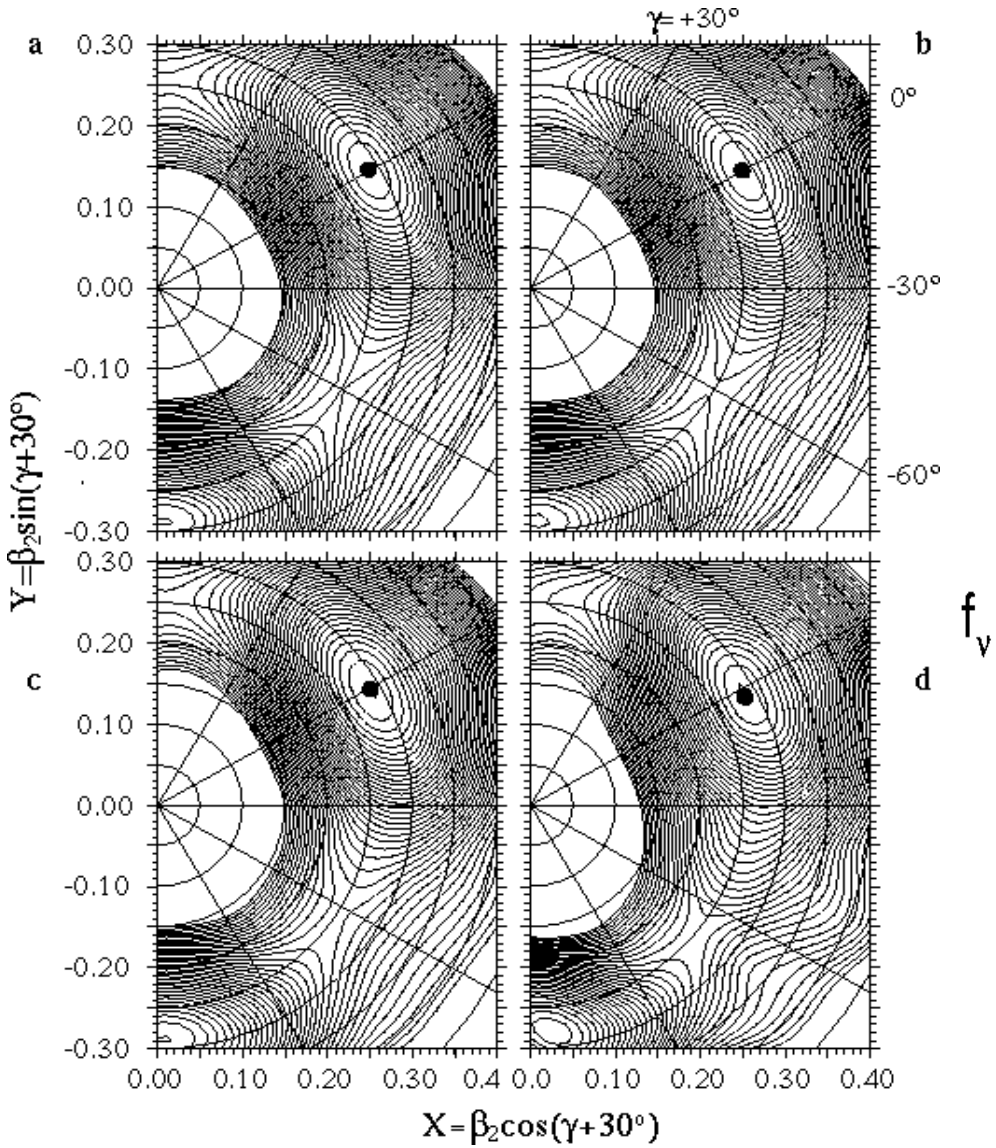


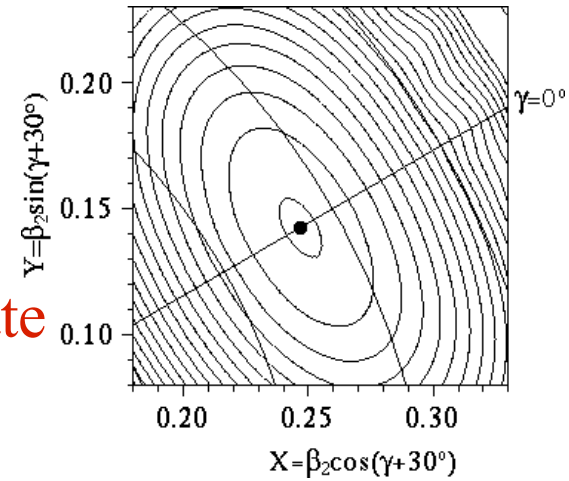
FIG. 2. The thermal coupling scheme of isomer and ground state in ^{176}Lu via thermally induced transitions to the mediating state at 38 keV.



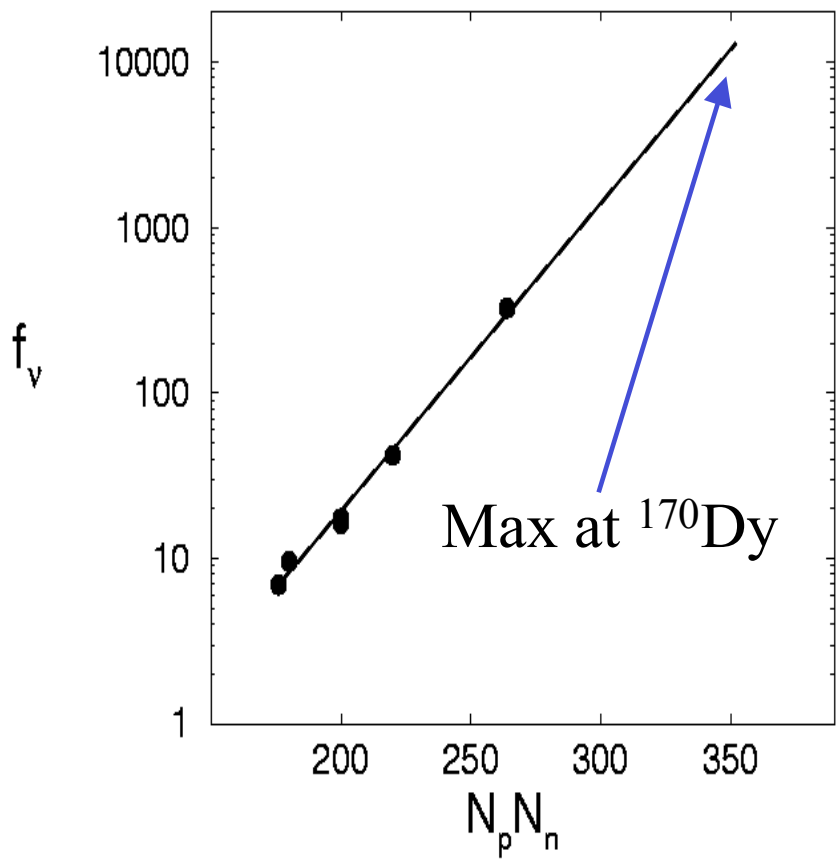
^{170}Dy, double mid-shell, 'purest' K-isomer ?

(see PHR, Oi, Walker, Stevenson and Rath, Phys. Rev. **C65** (2002) 037302)

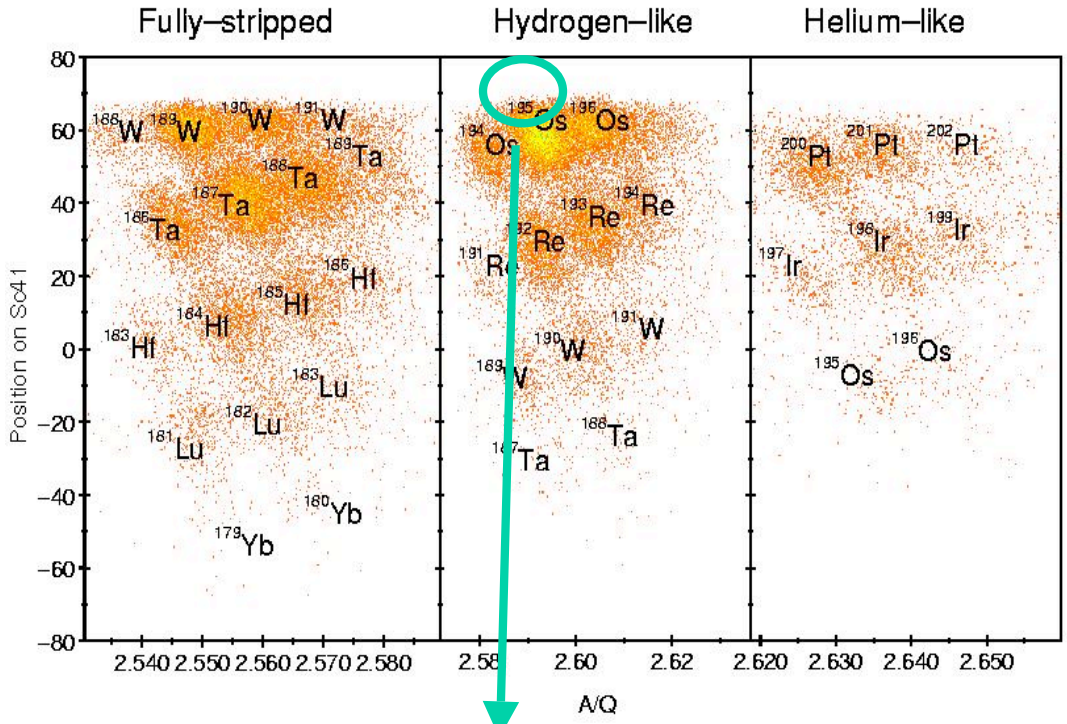


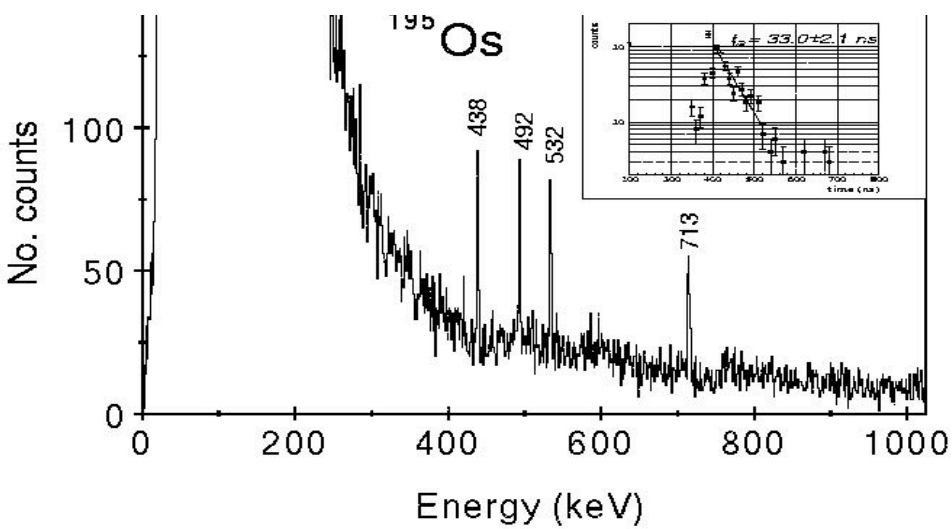


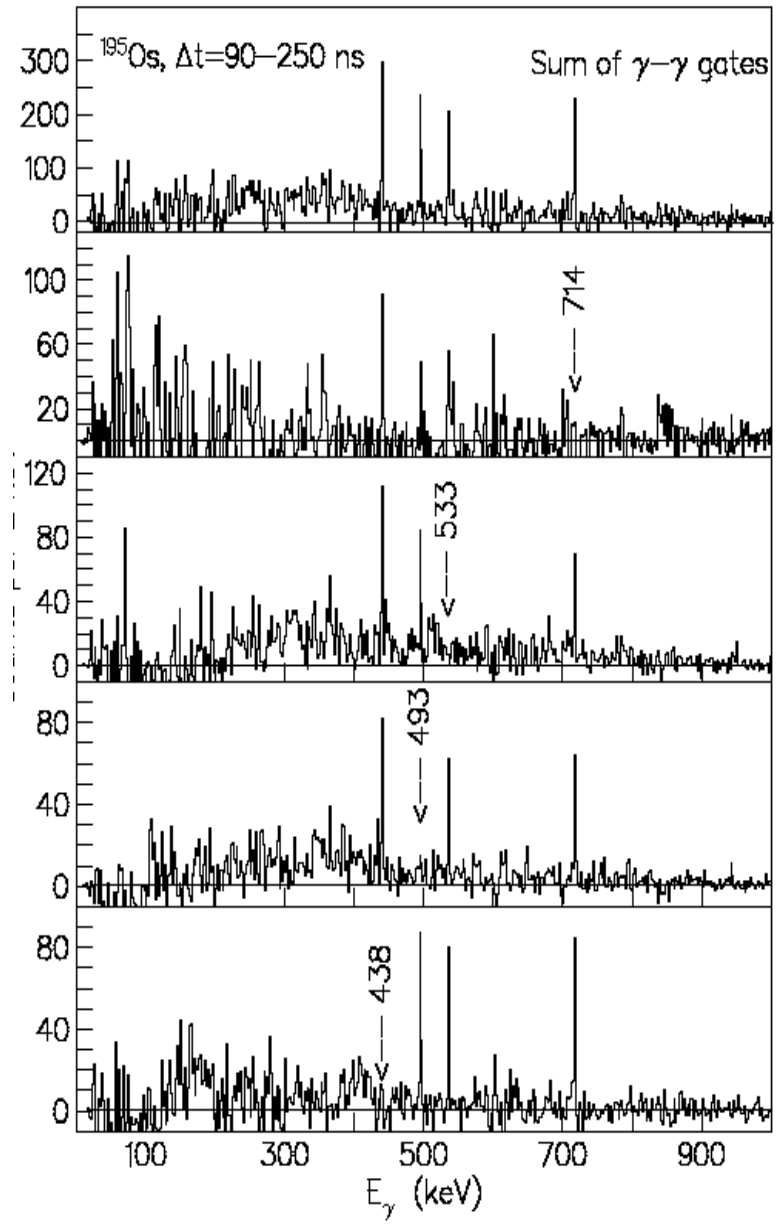
K=6$^+$state favoured



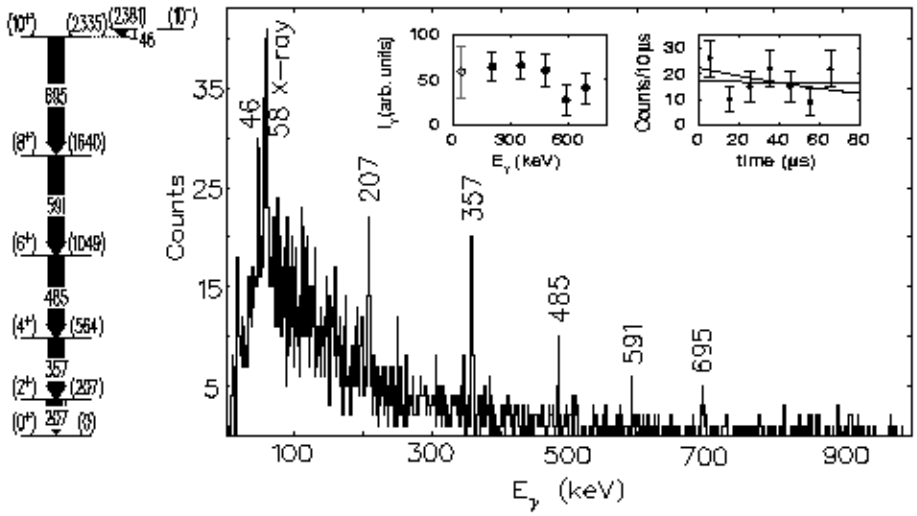
New isomer in ^{195}Os confirmed 'in-beam' CHICO+GAMMASPHERE



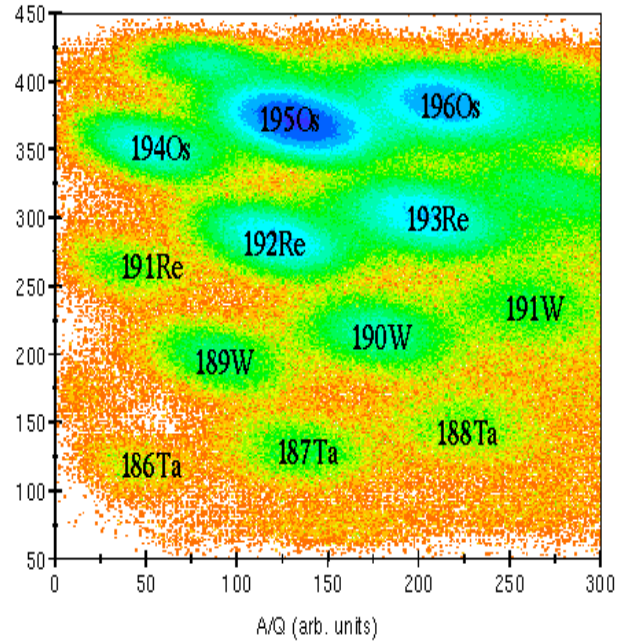


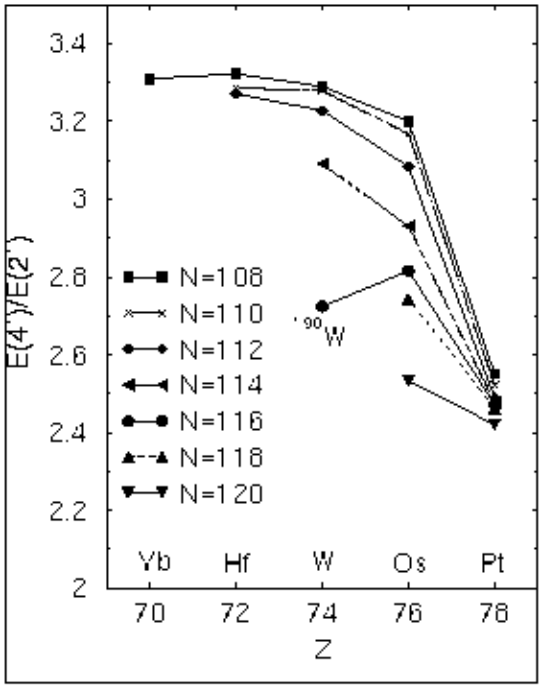


'New Physics' Around 190W



Z. Podolyak et al. Phys. Lett. B491 (2000) p225

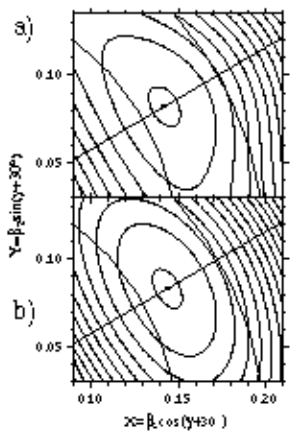


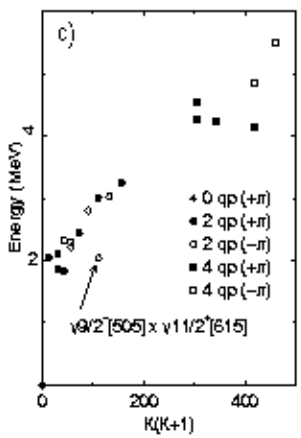


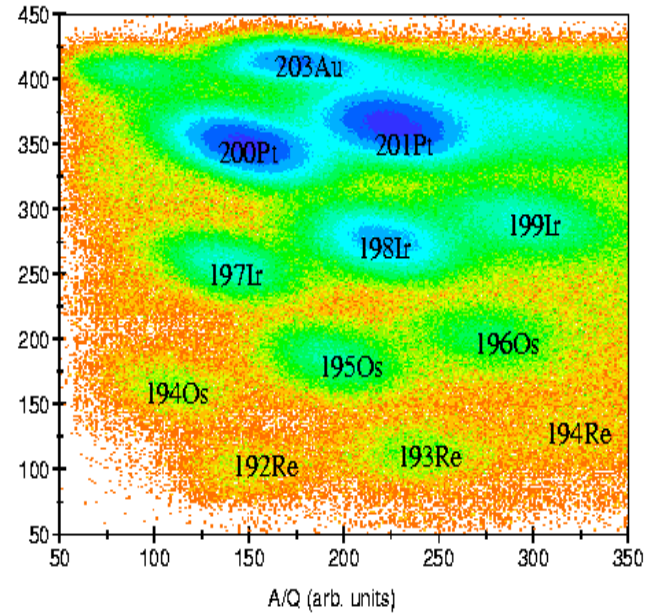
Possible sub-shell effect from E(4:2)

Triaxial softness at high spins ?

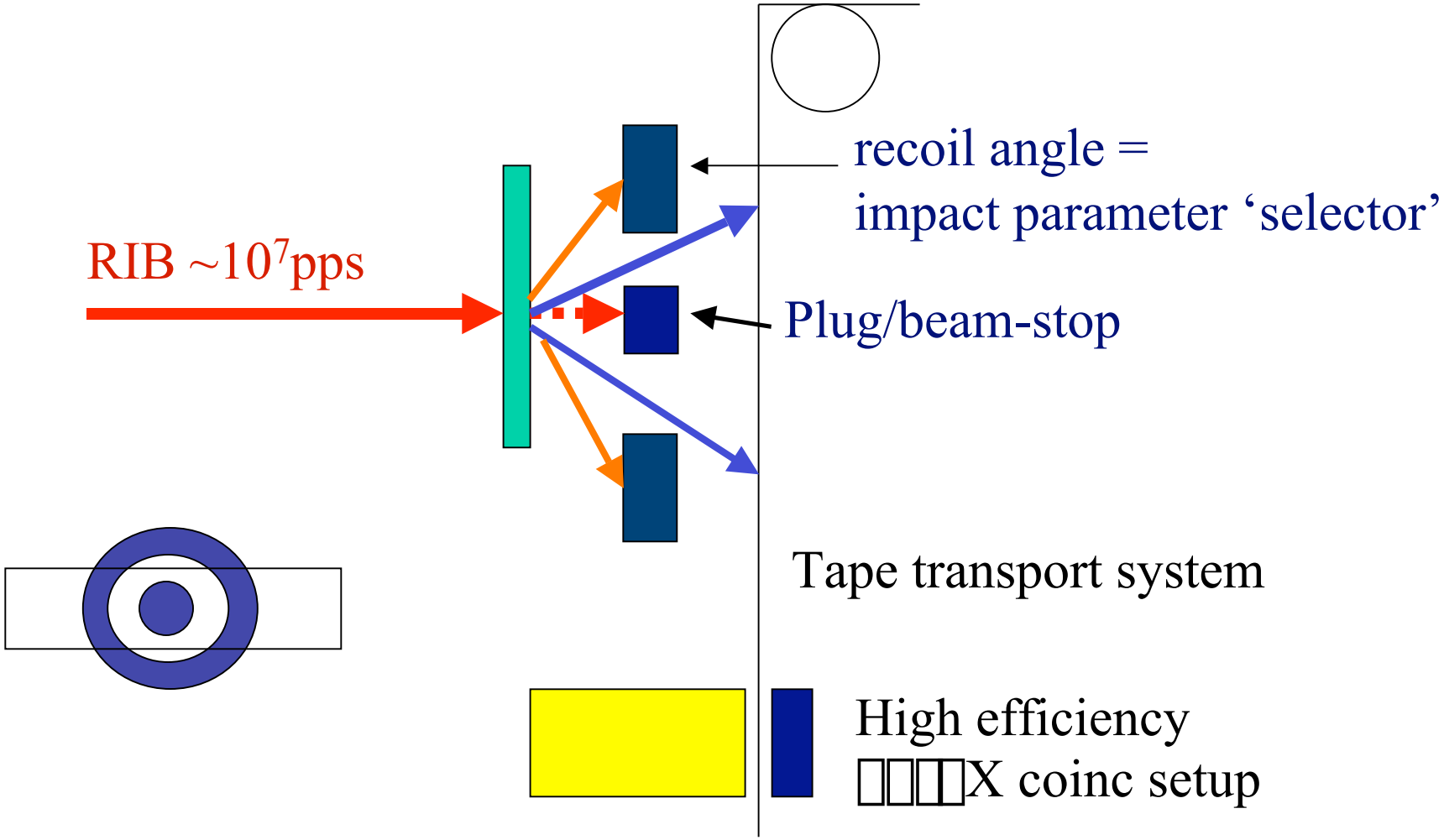
First band-crossing ?







Poor-man's Separator



see e.g., Caprio, Zamfir et al., Eur. Phys. Jour. **A16** (2003) p177

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- CHICO + GAMMASPHERE Experiments
  - Rochester (**Chin-Yen Wu**, Doug Cline, Adam Hayes, Hui Hua, Ray Teng et al.,)
  - LBNL (**Augusto Macchiavelli**, Paul Fallon, I-Yang Lee, Mario Cromaz)
  - Manchester. (**John Smith**, Sean Freeman, Ravi Chakrawarthy)
  - Daresbury (Dave Warner),
  - Paisley (Bob Chapman, Xiaoying Liang)
- Vibrator-Rotator (E-GOS) plots, **Con Beausang, Rick Casten, Victor Zamfir, Jing-Ye Zhang.**

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