Coulomb Excitation and RDDS measurement of a Triaxial Superdeformed "β-band" in ^{162}Yb

R.A. Bark[1], C. Fransen[2], A.N. Andreyev[3], N. Bernier[4], M.G. Borge[5], D. Bucher[6], J.C. Cubiss[3], F. Dunkel[2], L. Gaffney[7], J. Gerl[8], K. Hadyńska-Klęk[9], H. Hess[2], R. Hirsch[2], E. Ince[9], M. Jafta[4], J. Jolie[2], P. Jones1, T. Kröll[11], C.-D. Lakenbrink[2], E. Lawrie[1], J.J. Lawrie[1], Z. P. Li[12], S. Majola[13], B.O. Mampaso[5], C. Mehl[4], S.M. Mullins[14], C. Müller-Gatermann[15], P.J. Napiorkowski[9], C. Ngwetsheni[4], S. Ntshangase[16], G. O'Neill, N. Orce[4], C. Page[3], J. Pakarinen[17], N. Pietralla[11], L. Pellegri[1], P. Reiter[2], A. Ilana[18] J. Srebrny[9], M. Stryjczyk[17], J.F.Sharpey-Schafer[16], F. von Spee[2], N. Warr[2], K. Wrzosek-Lipska[9], M. Wiedeking[1], Z. Yue[3] and S.Q. Zhang[19]

INTC-P-708

Studying the origin of 0_2^+ bands in mass 160 region

β vibrations?
shape coexistence?
"pairing isomers" – "second vacuum"?
X(5)....?

Experiments in mass 160 region using AFRODITE array of 8 or 9 clover detectors + LEP detectors

e.g.

$^{152}Sm(\alpha,2n)^{154}Gd$

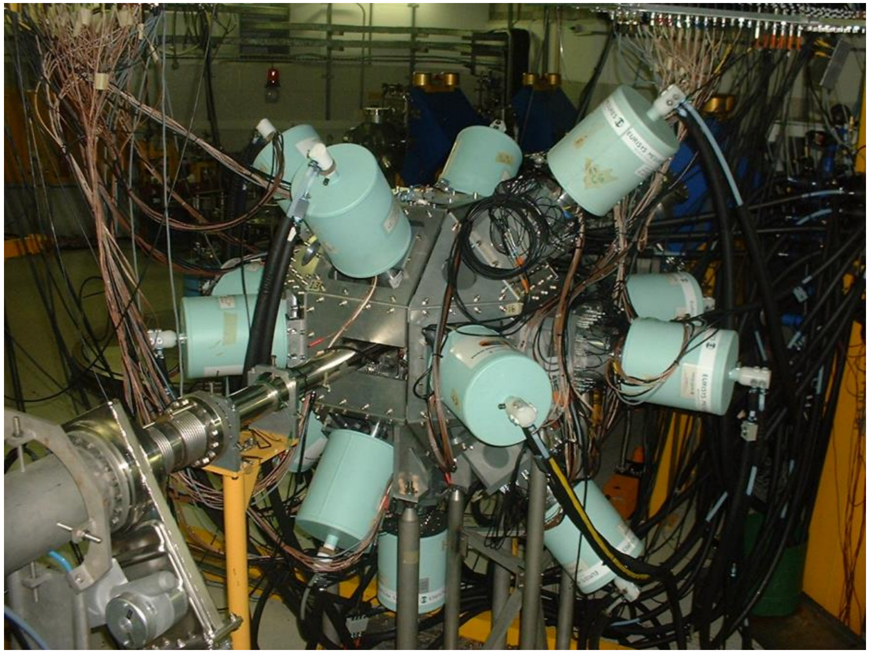
$^{152}Sm(\alpha,4n)^{152}Gd$

$^{147}Sm(^{16}O,4n)^{160}Yb$

$^{144}Sm(^{17}O,3n)^{158}Yb$

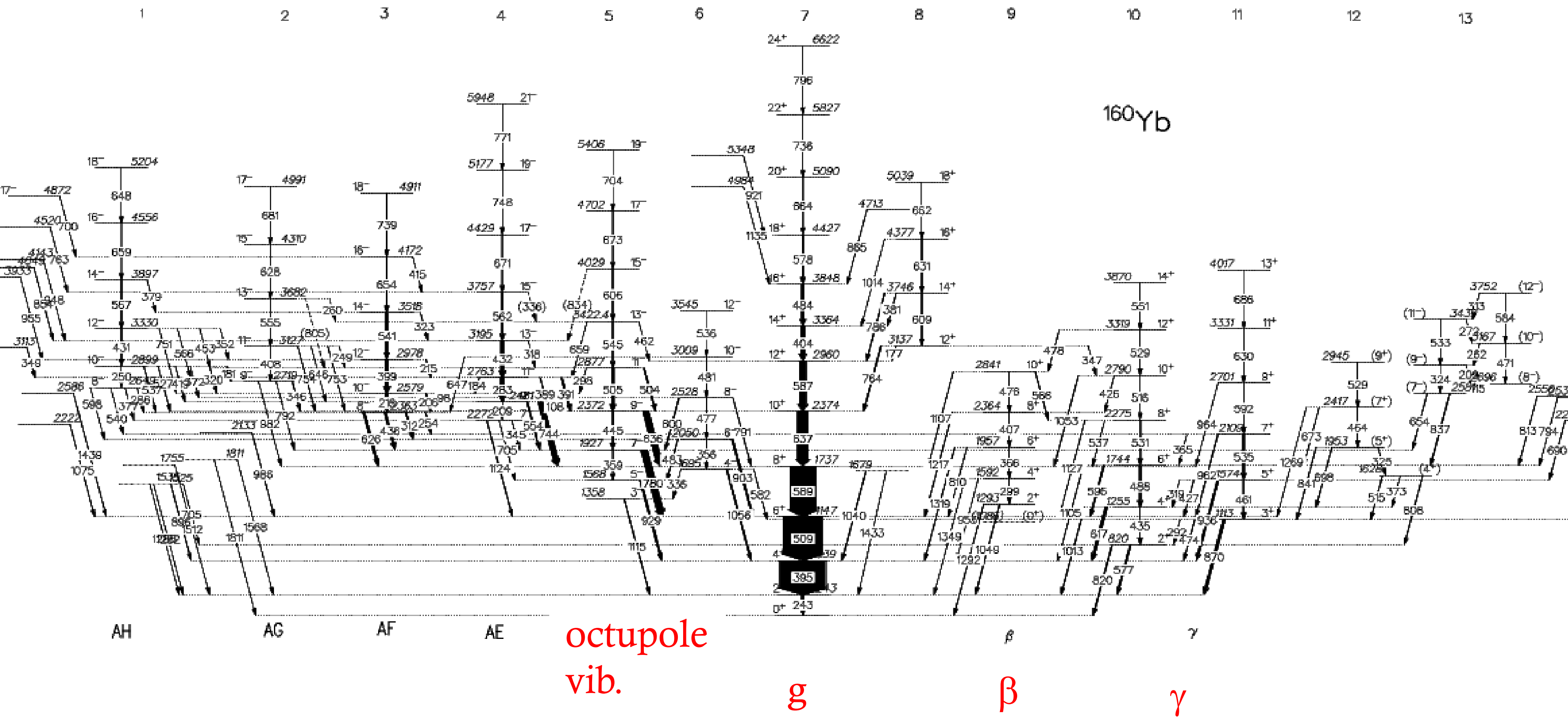
$^{152}Sm(^{12}C,4n)^{160}Er$

$^{148}Sm(^{12}C,4n)^{156}Er$



Experiments optimized to study LOW-SPIN states
Light, low-energy beams – low recoil velocities

$^{147}Sm(^{16}O,3n)^{160}Yb$

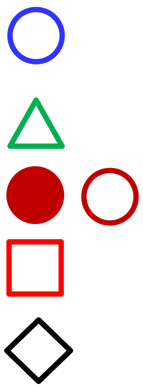


Energy Systematics

PHYSICAL REVIEW C **100**, 044324 (2019)

β and γ bands in $N = 88$, 90, and 92 isotones investigated with a five-dimensional collective Hamiltonian based on covariant density functional theory: Vibrations, shape coexistence, and superdeformation

S. N. T. Majola,[1,2,3,4] Z. Shi,[5] B. Y. Song,[6] Z. P. Li,[6] S. Q. Zhang,[7] R. A. Bark,[2] J. F. Sharpey-Schafer,[8] D. G. Aschman,[4]



ground band

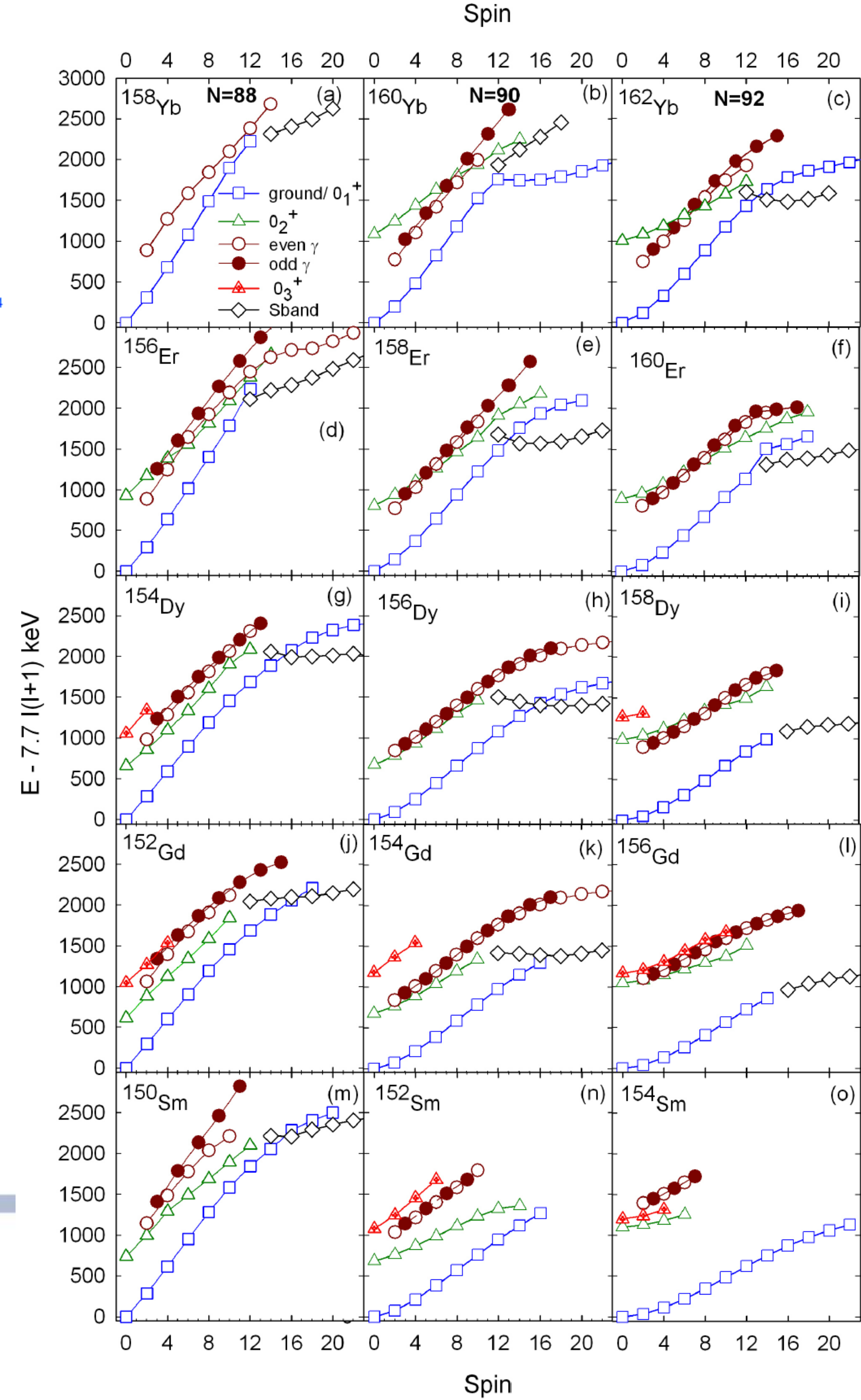
β band

γ band

0_3^+ band

S-band

- γ-band almost always parallel to ground band
- β-band not always parallel, especially in Er and Yb nuclei



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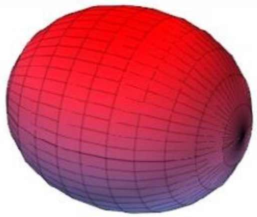
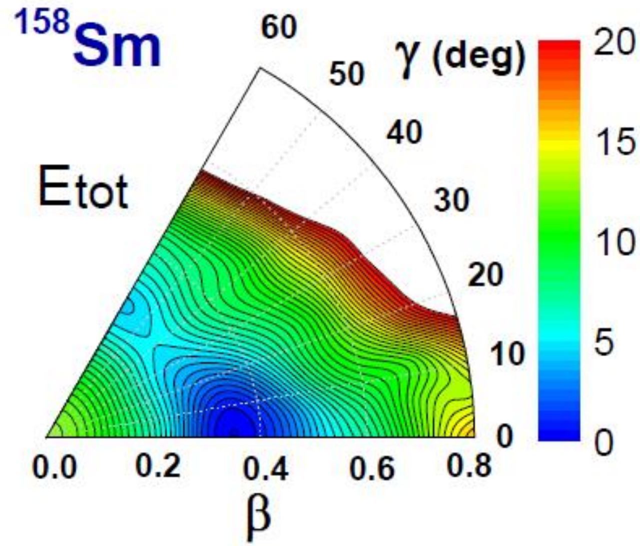
The vibrating nucleus





Vibrating Liquid drop

The Bohr Hamiltonian

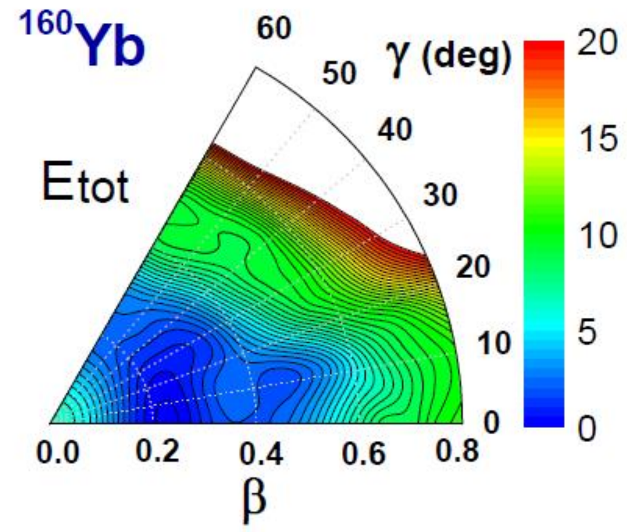
The differential Bohr equation with

$$H = -\frac{\hbar^2}{2B}\left[\frac{1}{\beta^4}\frac{\partial}{\partial\beta}\beta^4\frac{\partial}{\partial\beta} + \frac{1}{\beta^2\sin 3\gamma}\frac{\partial}{\partial\gamma}\sin 3\gamma\frac{\partial}{\partial\gamma} - \frac{1}{4\beta^2}\sum_\kappa \frac{Q_\kappa^2}{\sin^2(\gamma - \frac{2}{3}\pi\kappa)}\right] + V(\beta,\gamma)$$

T_{vib}

T_{rot}

In reality:
Complicated Potential Energy Surfaces



The Bohr Hamiltonian

The differential Bohr equation with

$$H = -\frac{\hbar^2}{2B}\left[\frac{1}{\beta^4}\frac{\partial}{\partial\beta}\beta^4\frac{\partial}{\partial\beta} + \frac{1}{\beta^2\sin 3\gamma}\frac{\partial}{\partial\gamma}\sin 3\gamma\frac{\partial}{\partial\gamma} - \frac{1}{4\beta^2}\sum_{\kappa}\frac{Q_\kappa^2}{\sin^2(\gamma - \frac{2}{3}\pi\kappa)}\right] + V(\beta,\gamma)$$

T_{vib}

T_{rot}

Re-cast Bohr Hamiltonian: 5 Dimensional Collective Hamiltonian

$$\hat{H} = \hat{T}_{\mathrm{vib}} + \hat{T}_{\mathrm{rot}} + V_{\mathrm{coll}}$$

$$\hat{T}_{\mathrm{vib}} = -\frac{\hbar^2}{2\sqrt{wr}}\left\{\frac{1}{\beta^4}\left[\frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^4 B_{\gamma\gamma}\frac{\partial}{\partial\beta} - \frac{\partial}{\partial\beta}\sqrt{\frac{r}{w}}\beta^3 B_{\beta\gamma}\frac{\partial}{\partial\gamma}\right] + \frac{1}{\beta\sin 3\gamma}\left[-\frac{\partial}{\partial\gamma}\times\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\gamma}\frac{\partial}{\partial\beta} + \frac{1}{\beta}\frac{\partial}{\partial\gamma}\sqrt{\frac{r}{w}}\sin 3\gamma B_{\beta\beta}\frac{\partial}{\partial\gamma}\right]\right\}$$

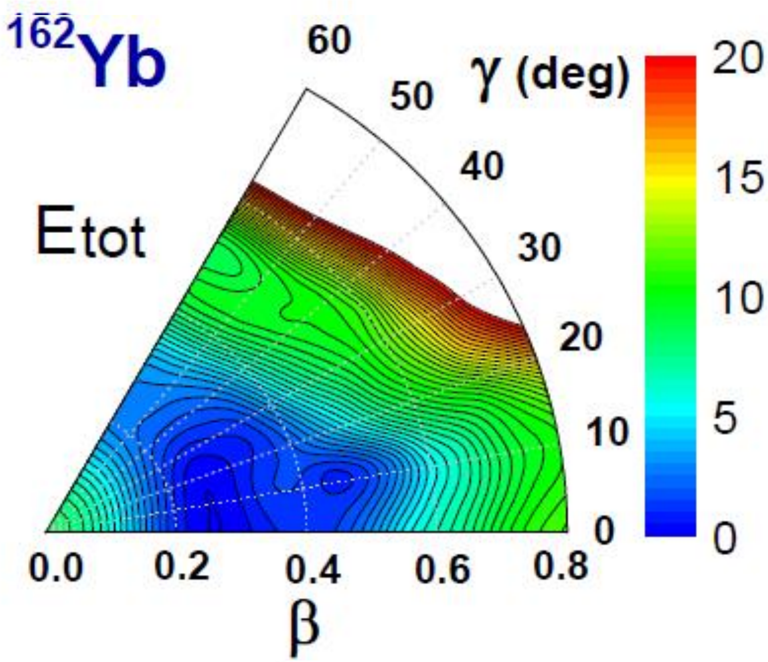
$$\hat{T}_{\mathrm{rot}} = \frac{1}{2}\sum_{k=1}^{3}\frac{\hat{J}_k^2}{\mathcal{I}_k}$$

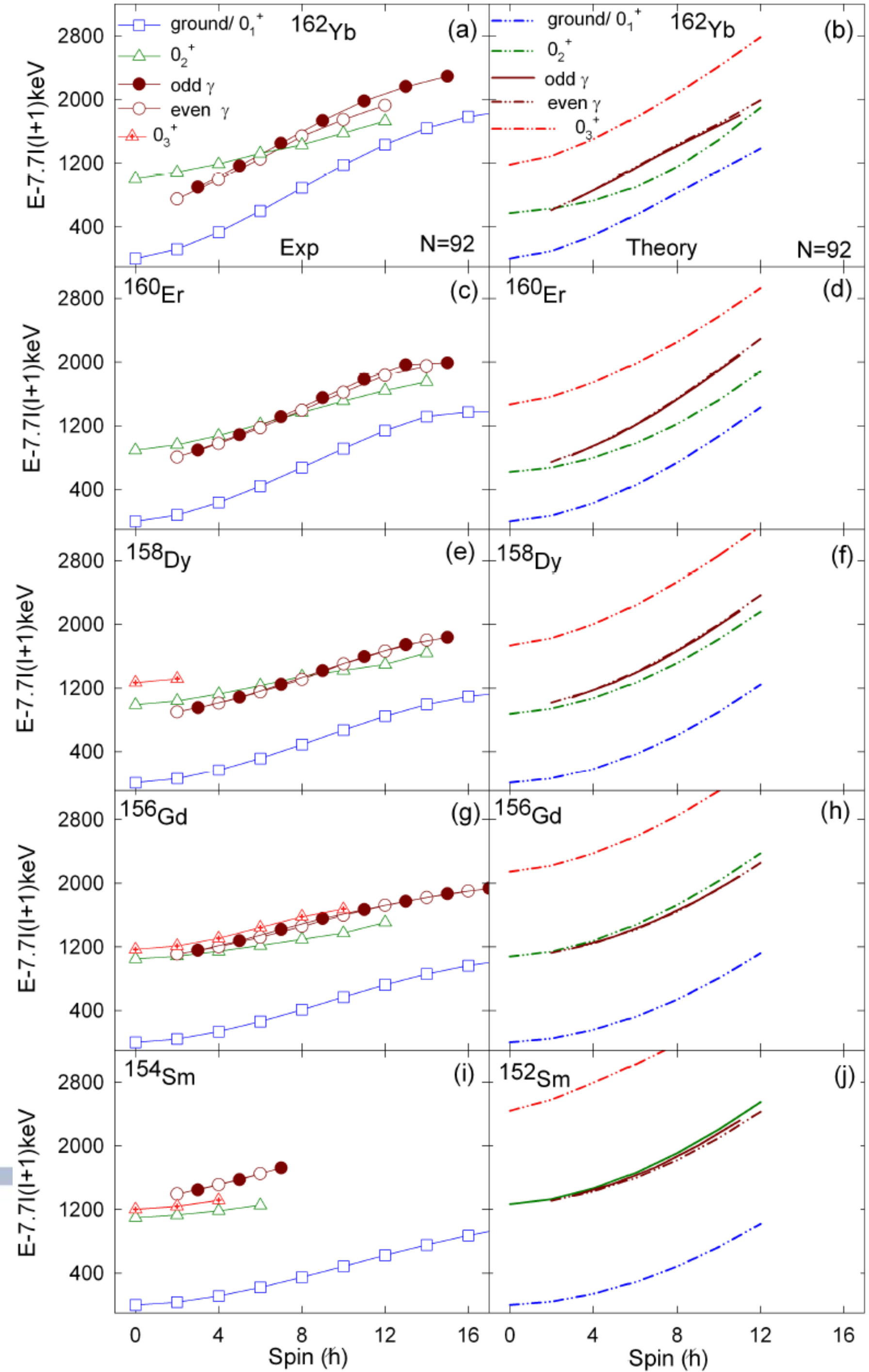
Need to determine *I*’s, *B*’s

T. Niksic et al PRC 79, 034303 (2009)
Z.P. Li et al., PRC 79, 054301 (2009)

N=92

Calculated Energies (lines) compared to experiment (points)





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Superdeformed triaxial bands in ^{163,165}Lu

H. Schnack-Petersen[a], R. Bengtsson[b], R.A. Bark[a,c], P. Bosetti[a,1], A. Brockstedt[c], H. Carlsson[c], L.P. Ekström[c], G.B. Hagemann[a], B. Herskind[a], F. Ingebretsen[d], H.J. Jensen[a], S. Leoni[a], A. Nordlund[c], H. Ryde[c], P.O. Tjøm[d], C.X. Yang[c,2]

Nuclear Physics A 594 (1995) 175–202

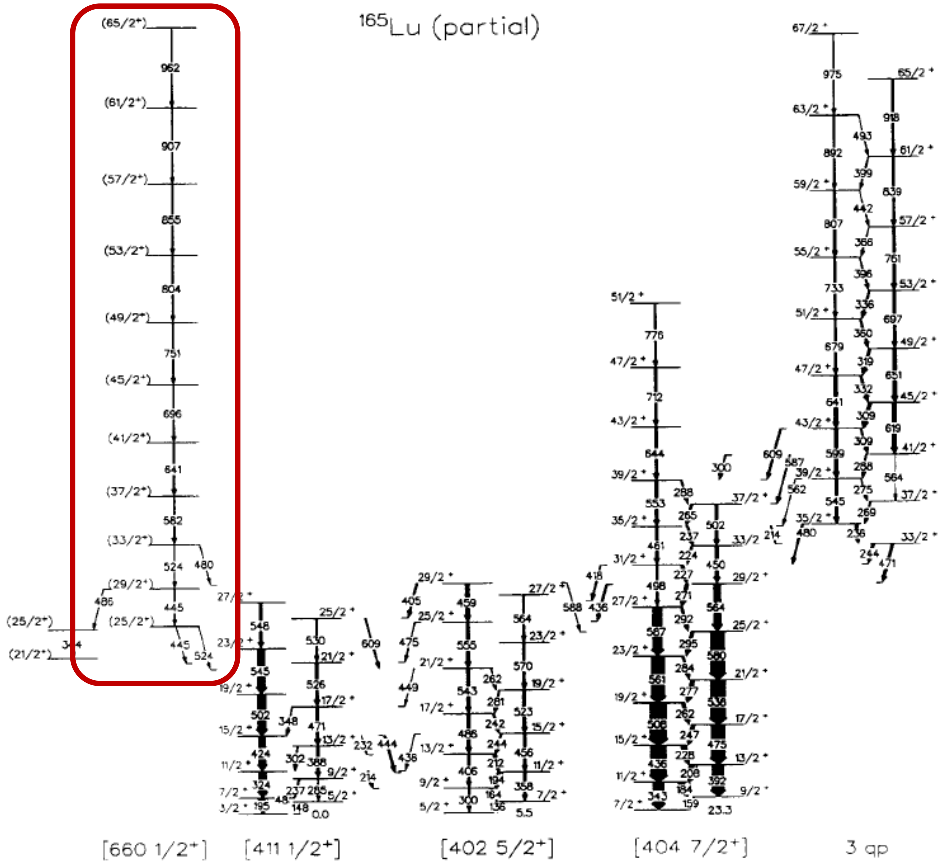
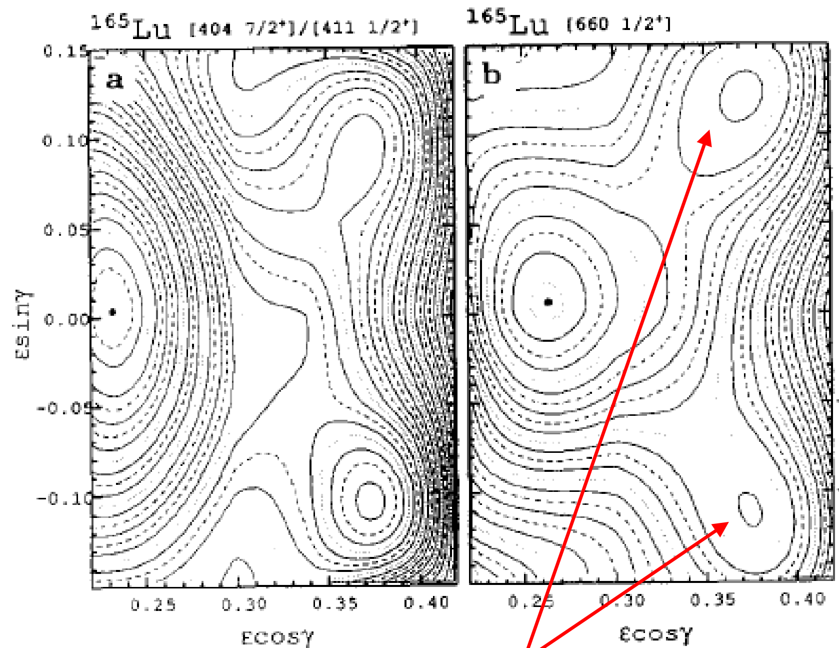


Fig. 1. Partial level scheme of the selected positive parity bands related to the $i_{13/2}$[660 1/2+] band.

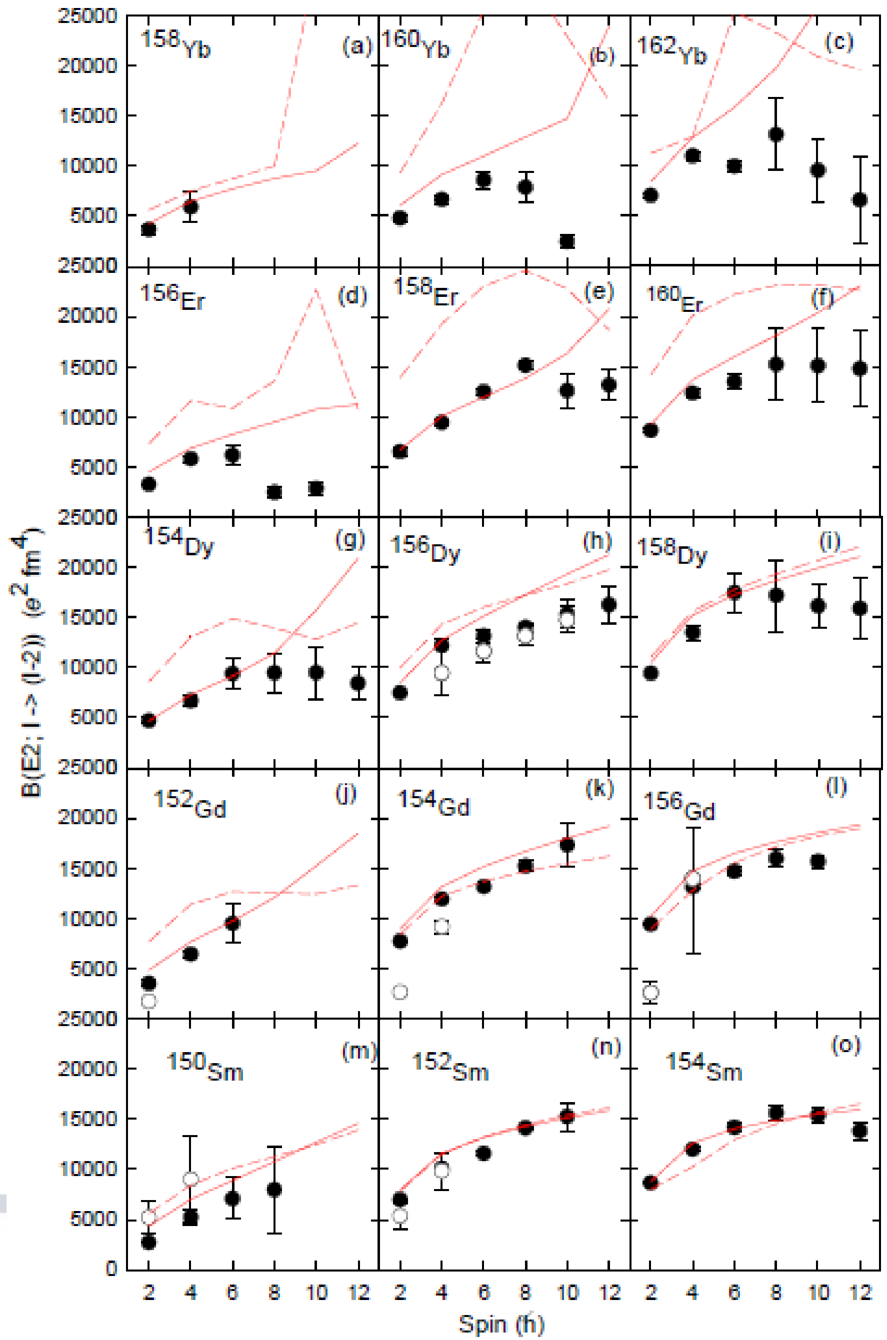


$(\varepsilon_2 = 0.389,\ \gamma = |18°|)$

In-band B(E2)s

—— ground band (theory)

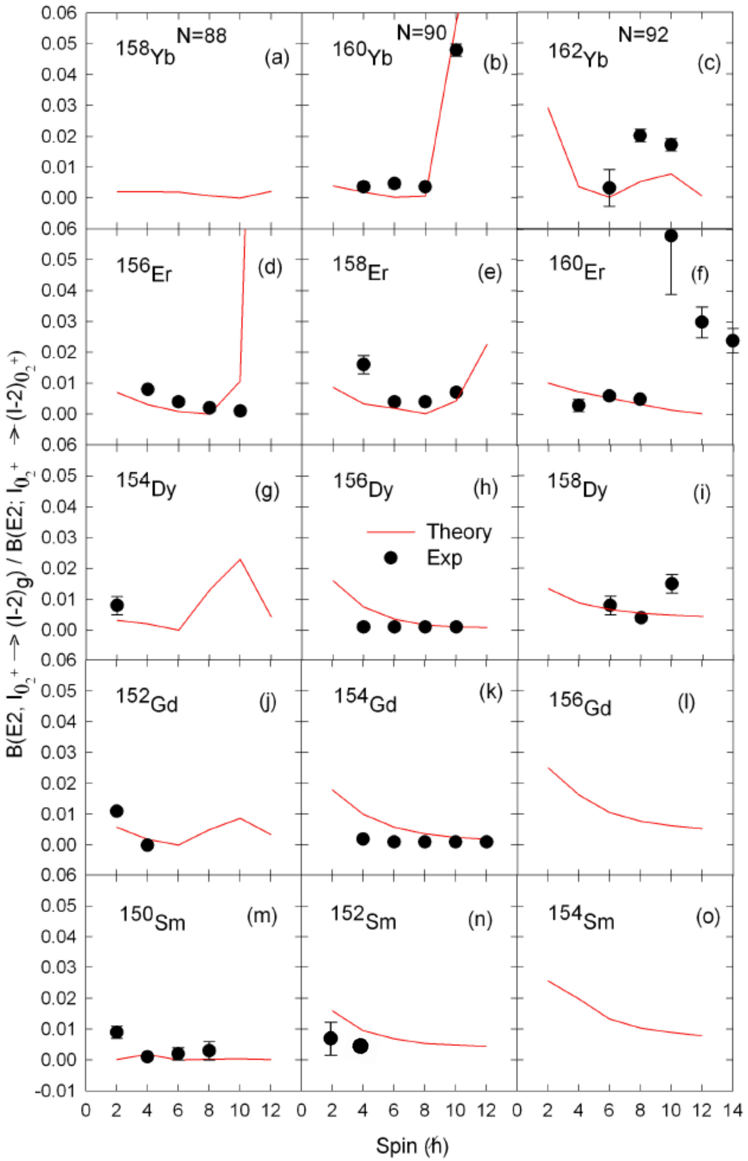
- - - - 0_2^+ band (theory)



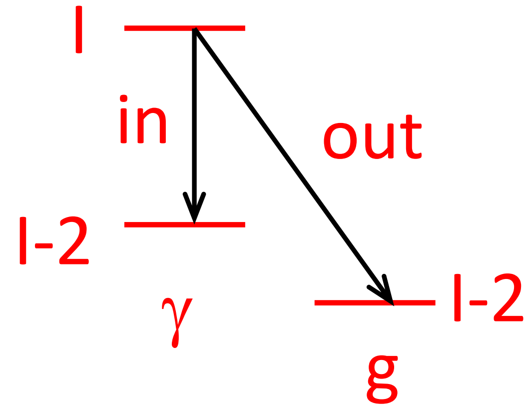
● ground band (exp)

○ 0_2^+ band (exp)

Branching Ratios β-band



β-band B(E2) branching ratios: out/in

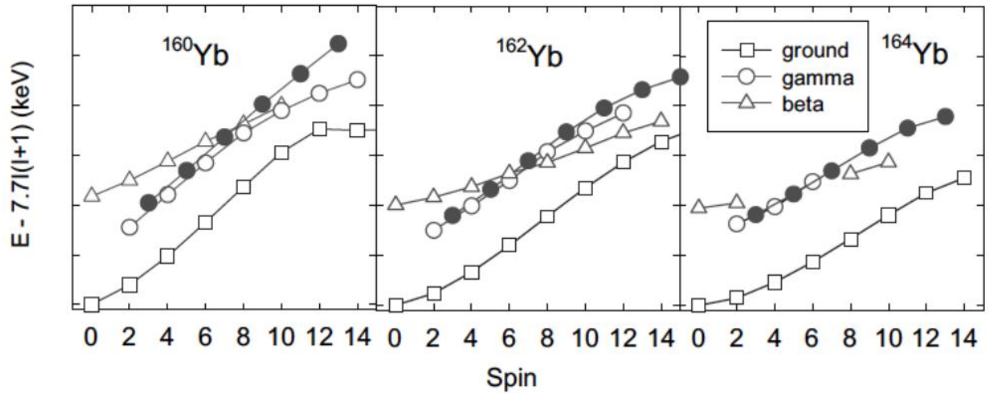


Aim: measure transition rates to test the Superdeformed Triaxial Shape of the “β -bands”

But which nucleus to study?

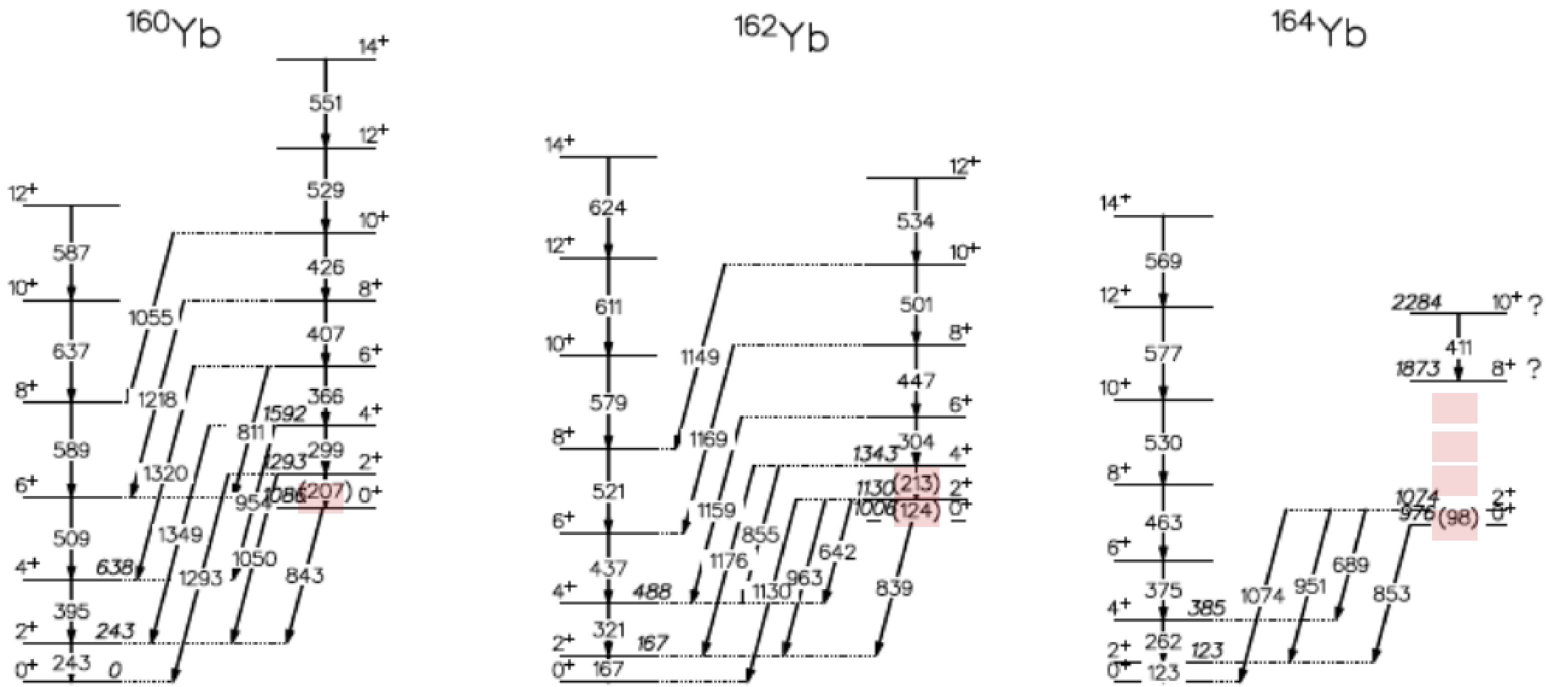
LoI 226: ^{160,162,164}Yb Yields measured:

A	With LIST on: (pps/μC)	Impurities with LIST off	*Yield with LIST off:* (pps/μC)
160	7×10^{6}	50%	3.5×10^{8}
162	2×10^{7}	6.5%	10^{9}
164	3×10^{7}	4%	1.5×10^{9}



Unknown transitions

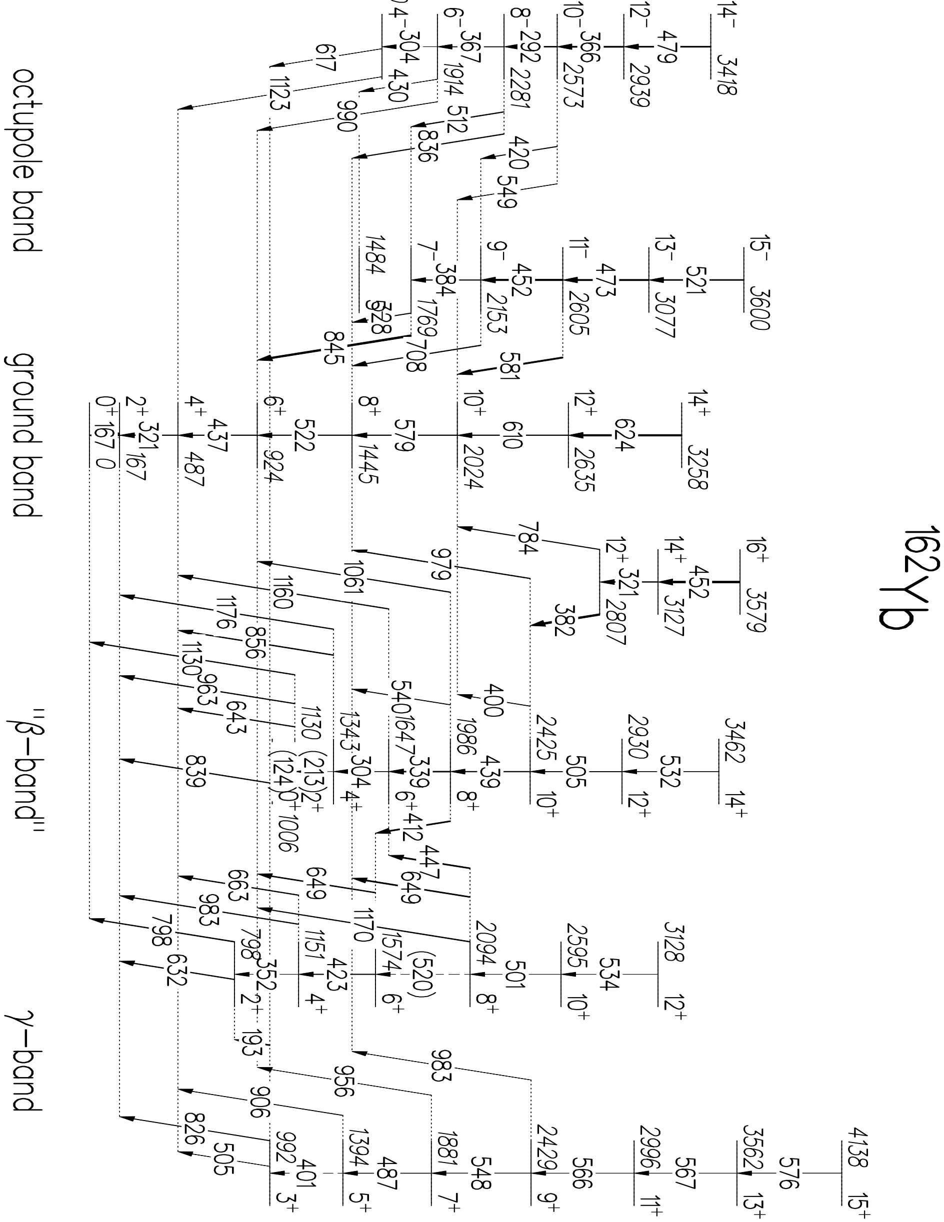
Known Least



No E0’s

One E0

No E0’s



162Yb
octupole band
ground band
"β–band"
γ–band

Aim: measure transition rates to test the Superdeformed Triaxial Shape of the “β -bands”

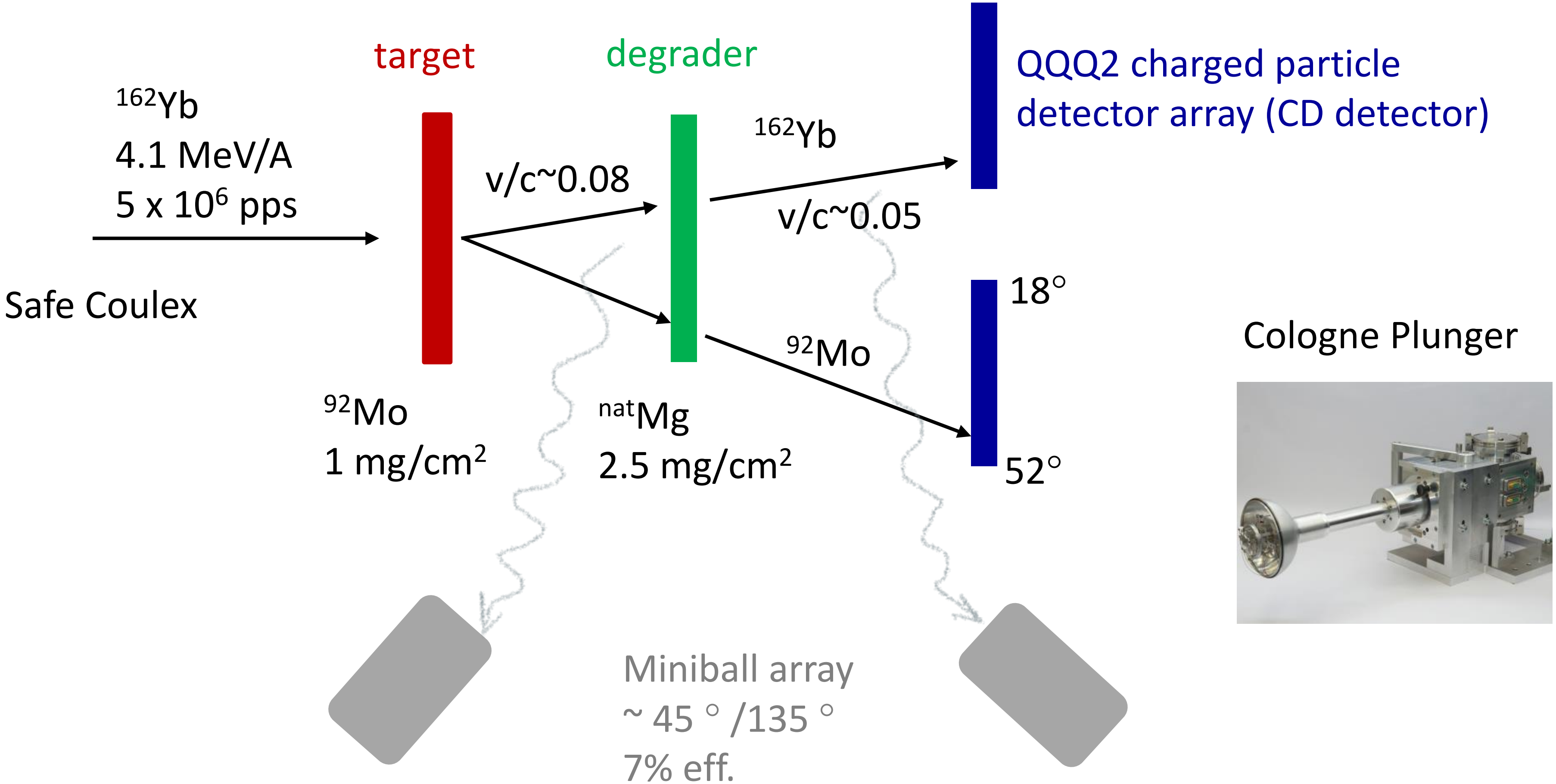
Methods to measure transitions rates:

Recoil Distance Doppler Shift

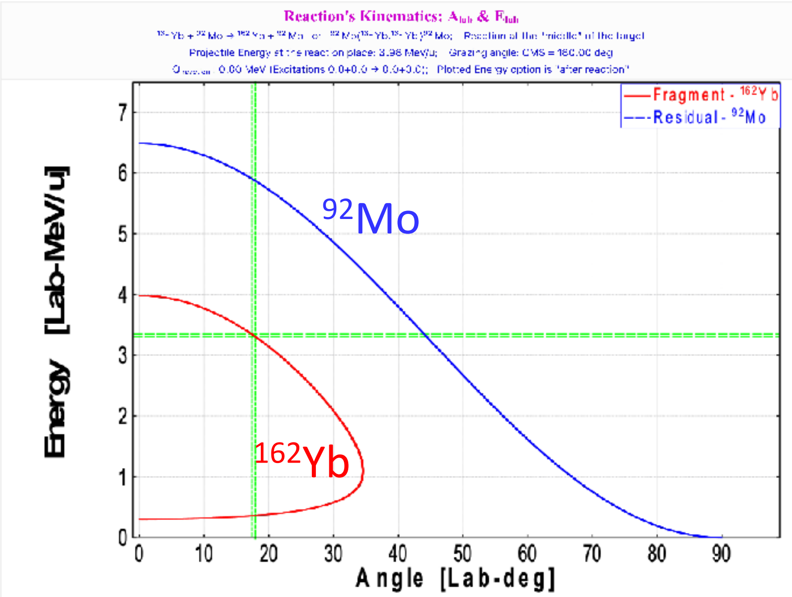
+

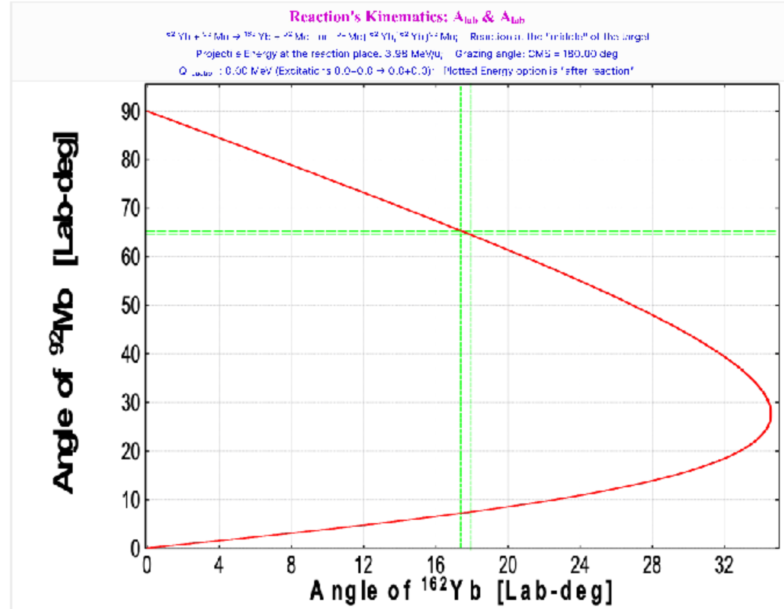
Coulomb Excitation Sum Rules

Setup: Coulomb Excitation/RDDS Setup

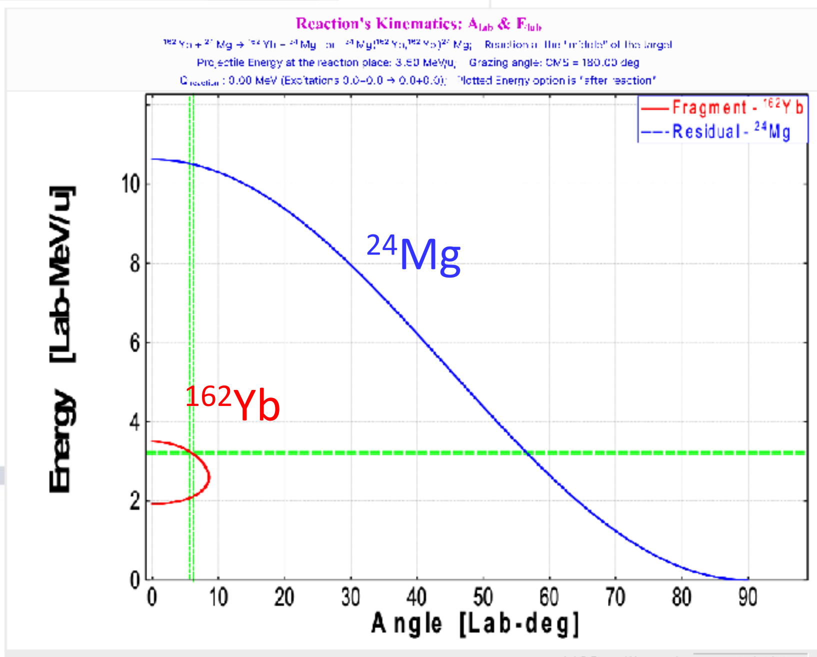


Kinematics





^{162}Yb distinguished from ^{92}Mo and Mg in angle-energy



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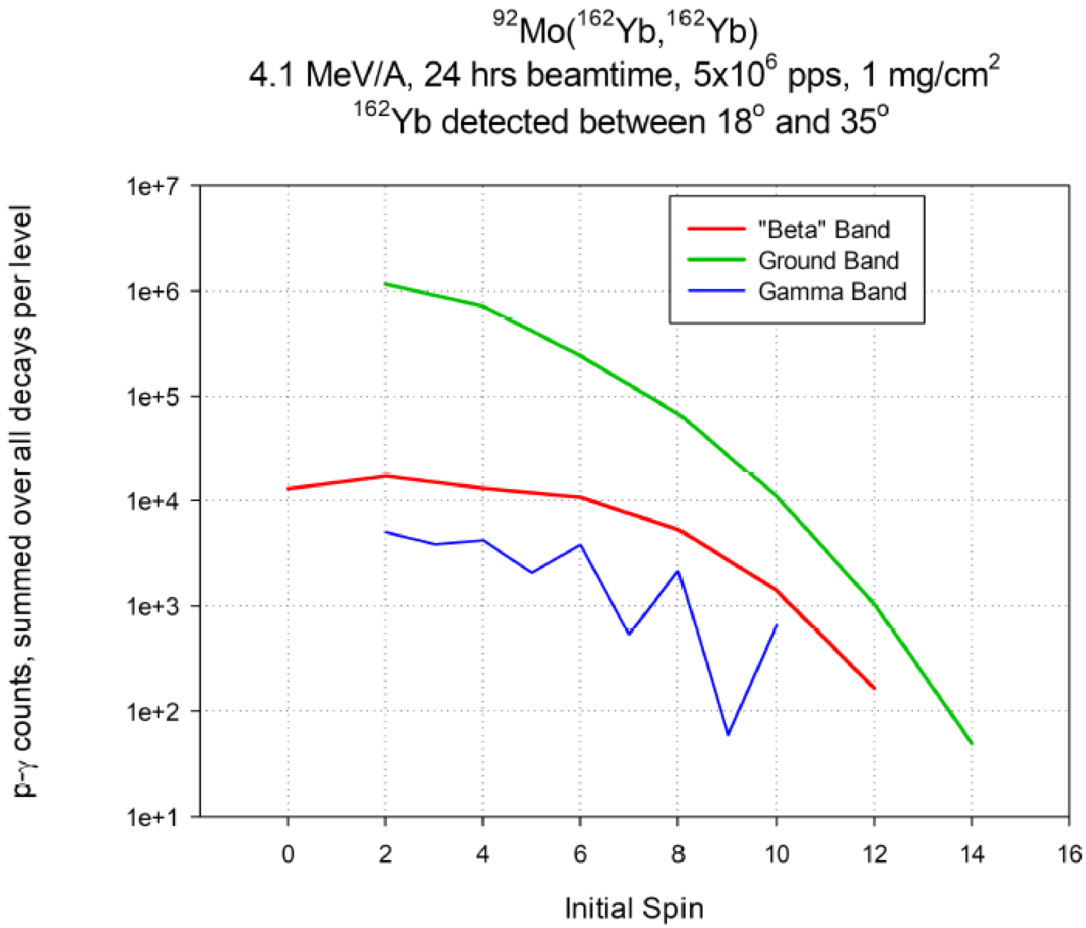
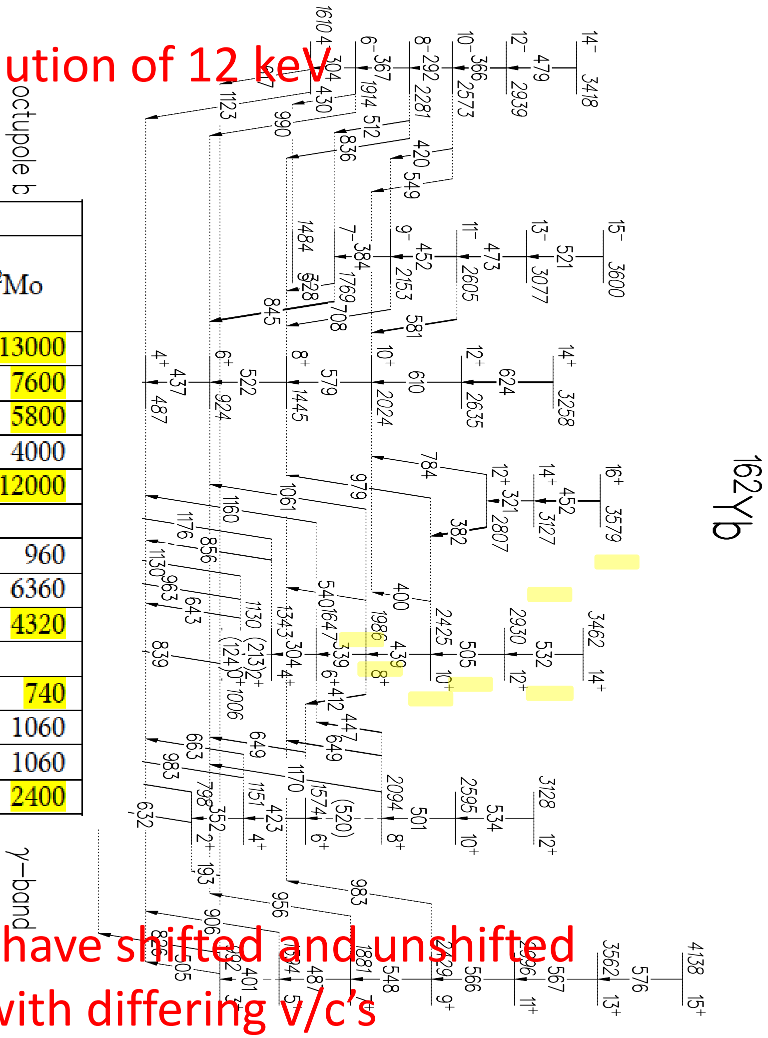
GOSIA Calculation: Coulomb Excitation of ^{162}Yb



“Clean lines” of ^{162}Yb “β -band”

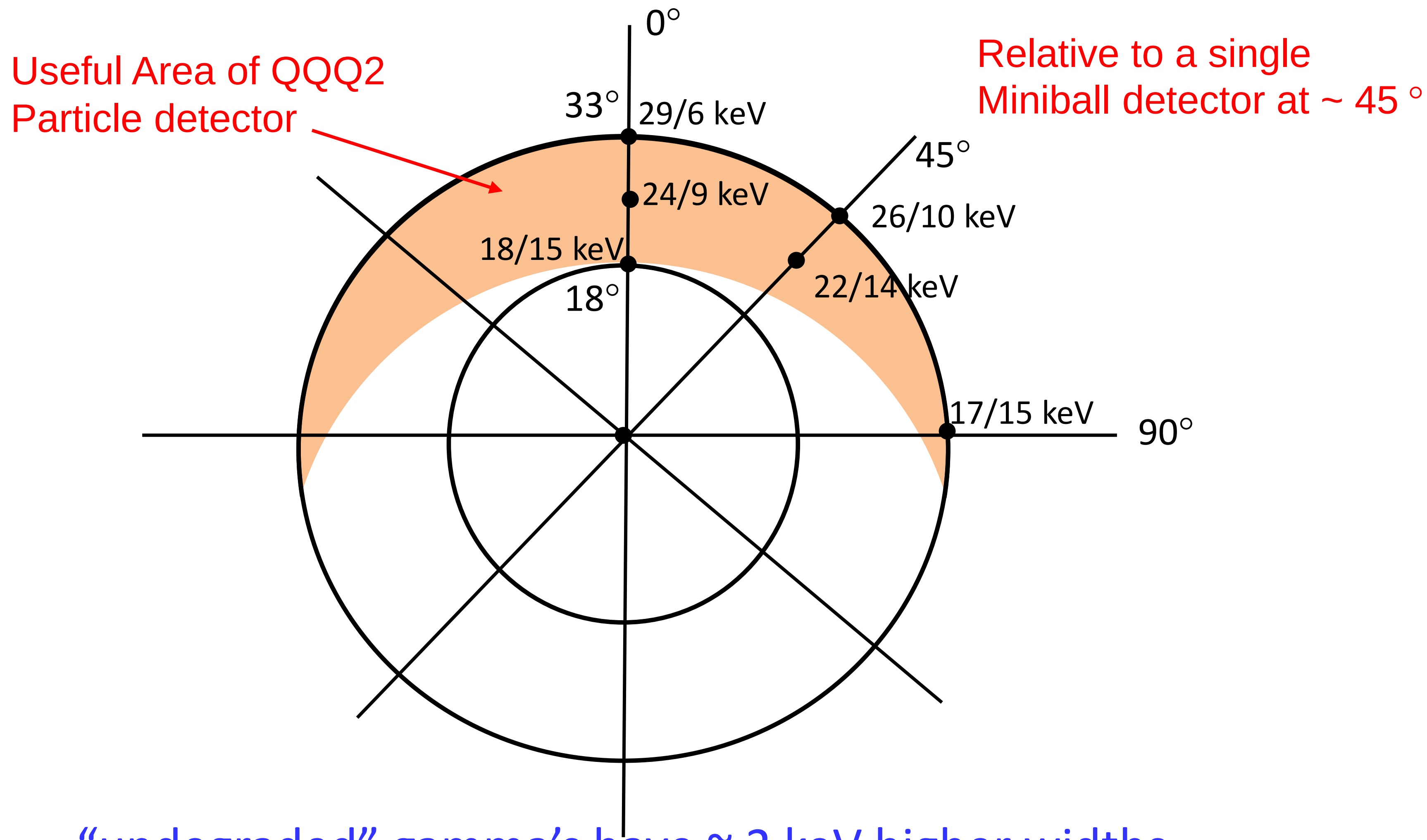
Typical resolution of 12 keV

		^{162}Yb		
Level	Transition	Eγ (keV)	Experimental γ-branching	p-γ yield 1 mg/cm^2 ^{92}Mo 5 ×10^6 pps
0_β	$0_\beta \to 2_1$	839	100	13000
2_β	$2_\beta \to 0_1$	1130	100	7600
	$2_\beta \to 2_1$	963	74	5800
	$2_\beta \to 4_1$	643	50	4000
4_β	$4_\beta \to 2_1$	1176	100	12000
	$4_\beta \to 2_\beta$			
	$4_\beta \to 4_1$	856	8	960
6_β	$6_\beta \to 4_1$	1160	100	6360
	$6_\beta \to 4_\beta$	304	68	4320
	$6_\beta \to 6_1$			
8_β	$8_\beta \to 6_1$	1061	31	740
	$8_\beta \to 6_\beta$	339	44	1060
	$8_\beta \to 8_1$	540	44	1060
	$8_\beta \to 6_\gamma$	412	100	2400



But RDDS will have shifted and unshifted components with differing v/c’s

Doppler Shift/Width Map 1 MeV "degraded" gamma



"undegraded" gamma's have ~ 2 keV higher widths

Coulomb Excitation without degrader

- Degrader removed – only “undegraded” lines
- Necessary to aid interpretation of RDDS spectra
- If only one of the degraded/undegraded lines are clean in RDDS, will be provide the total strength of the line
- Allows analysis of triaxiality using sum rules

Sum Rules determine shape

J. Srebrny et al. / Nuclear Physics A 766 (2006) 25–51

Quadrupole tensor

$$[\mathcal{M}(\mathrm{E2}) \times \mathcal{M}(\mathrm{E2})]_0 = \frac{1}{\sqrt{5}} Q^2,$$

Quadrupole moment

$$\langle S|[\mathcal{M}(\mathrm{E2}) \times \mathcal{M}(\mathrm{E2})]_0|S\rangle = \frac{(-1)^{2S}}{\sqrt{2S+1}} \sum_R \langle S\|\mathrm{E2}\|R\rangle\langle R\|\mathrm{E2}\|S\rangle \begin{Bmatrix} 2 & 2 & 0 \\ S & S & R \end{Bmatrix}$$

$$[[\mathcal{M}(\mathrm{E2}) \times \mathcal{M}(E2)]_2 \times \mathcal{M}(\mathrm{E2})]_0 = -\sqrt{\frac{2}{35}} Q^3 \cos 3\delta,$$

triaxiality

$$\langle S|[[\mathcal{M}(\mathrm{E2}) \times \mathcal{M}(\mathrm{E2})]_2 \times \mathcal{M}(\mathrm{E2})]_0|S\rangle$$
$$= \sqrt{\frac{5}{2S+1}} \sum_{RT} \langle S\|\mathrm{E2}\|R\rangle\langle R\|\mathrm{E2}\|T\rangle\langle T\|\mathrm{E2}\|S\rangle \begin{Bmatrix} 2 & 2 & 0 \\ S & S & T \end{Bmatrix} \begin{Bmatrix} 2 & 2 & 2 \\ T & S & R \end{Bmatrix} (-1)^{3S+T},$$

In-band matrix elements most important, e.g.

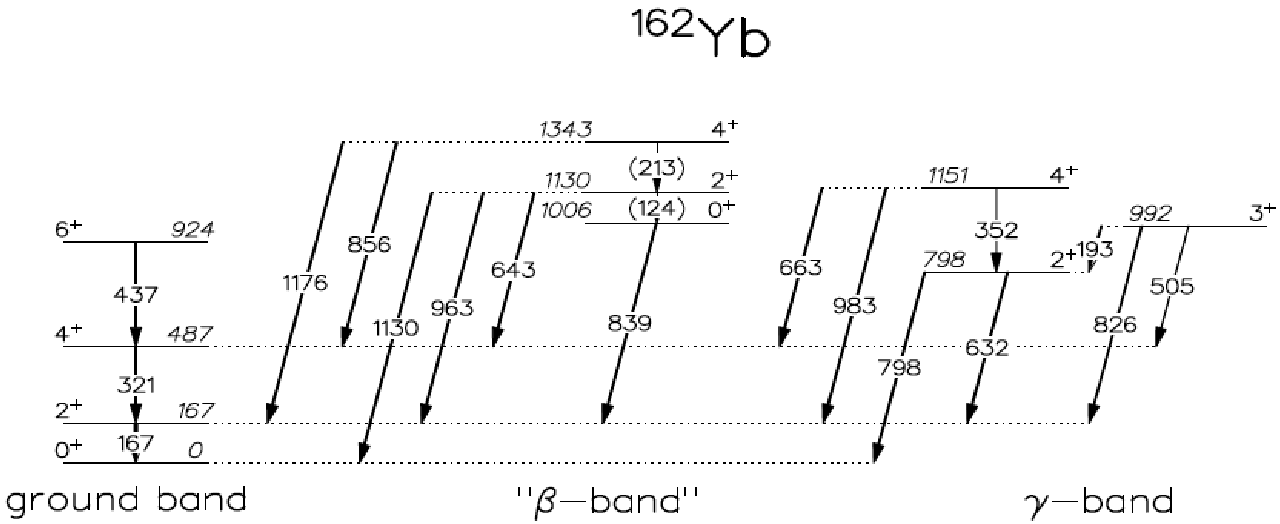
$$\langle 2_2\|E2\|4_2\rangle\langle 4_2\|E2\|4_2\rangle\langle 4_2\|E2\|2_2\rangle$$

β - decay of ^{162}Lu

Determine branching ratios at 4_2^+ and 2_2^+ levels

To get in-band B(E2)'s of 213 and 124 keV transitions

Q_t



LoI 268 approved to determine yields of ^{162}Lu

Estimate need about 3 x 10^{12} decays

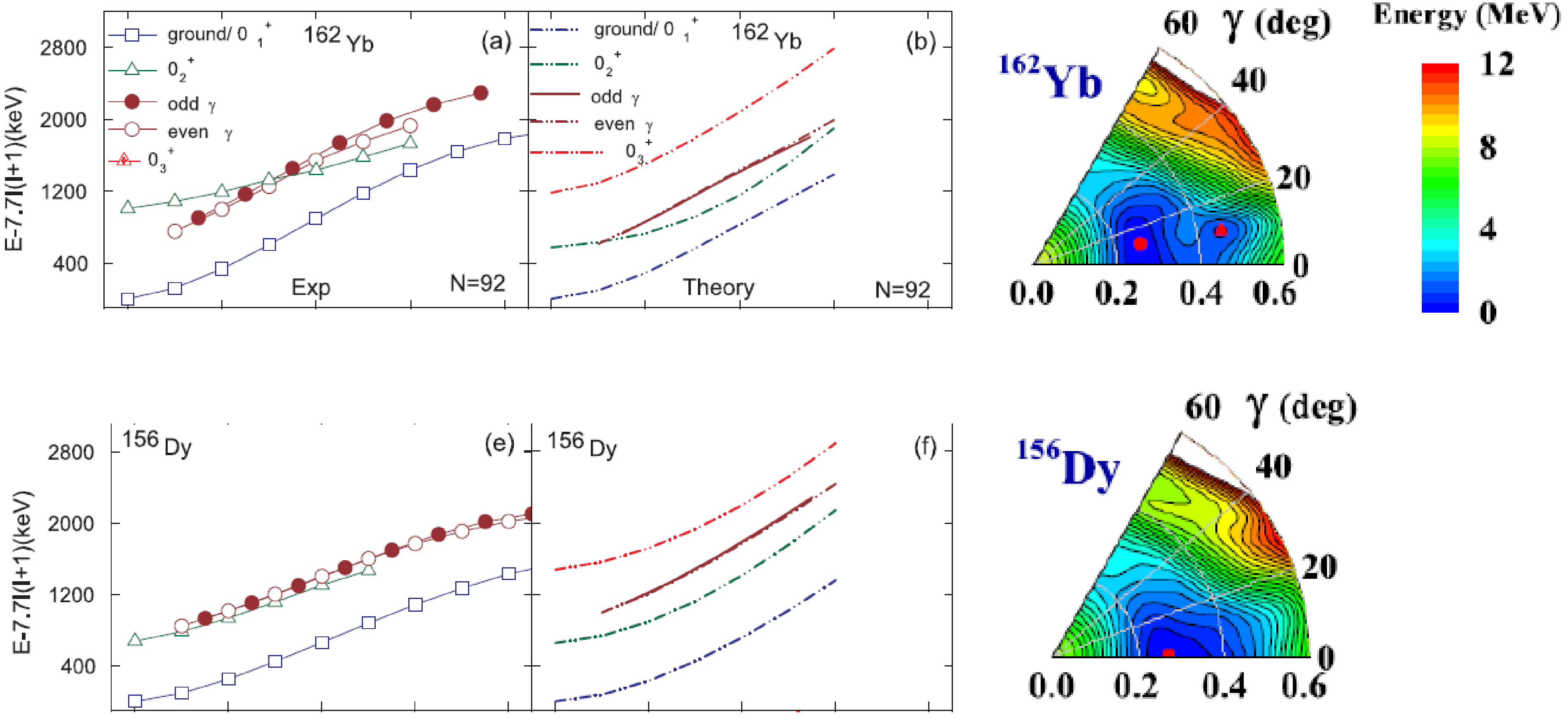
Summary of beamtime request ^{162}Yb

- 4 days for RDDS
- 1 day pure Coulomb Excitation
- 5 days - 15 shifts total

Summary of beamtime request ^{162}Lu decay

- None – await results of LoI 268

Thank You



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