Search for rare shape-phase transitions in hot rotating heavy nuclei

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Tata Institute of Fundamental Research, Mumbai

Collective Motion in Nuclei Under Extreme Conditions
September 14 – 18, 2015 krakow, Poland

Plan of the talk

- **Introduction**:

  Motivation for this programme

- The experimental facilities

  simple tools for a very complex problem

- GDR decay from hot and rotating A~190 nuclei
  - *Statistical model analysis*
  - *Finite temperature microscopic-macroscopic analysis*

- Summary & Conclusion

- Future Scope: *what lies ahead*

Giant Resonances:

Based on Ground states : *inelastic scattering, charge exchange reactions, photo-nuclear reactions*

Based on excited states : *Heavy-ion induced fusion-evaporation reactions*

D. Brink (55)
J.O Newton et al (1981)

Studies in hot GDR

- **Variation of E_{GDR} & Γ_{GDR} with T & J**
- **Saturation of Γ_{GDR} with temperature?**

- Nuclear shape-phase evolution
- Dissipative effects: Fission hindrance

- Internal Pair decay

- Entrance Channel effect in HI reactions
- Isospin mixing at finite temperature

References:

Reviews:
- *Snover, 1986*
- *.Gaardhoje, 1992*
- *Paul & Thoennessen, 1994,*

It is now a matured subject and so the richness of our understanding has revealed the richness of complexity and challenges

Monographs:
- Giant Resonances; *Harakeh & van der Woude*
- Oscillations in finite quantum systems: *Bertsch & Broglia*
- Giant Resonances at Finite Temperature; *Bortignon, Bracco, Broglia*

Populating hot GDR states through heavy-ion induced fusion-evaporation reaction:

need for decoupling the effects of temperature and angular momentum on the GDR observables and nuclear structural evolution

- *Γ_{GDR} in ^{208}Pb & ^{120}Sn by α scattering (increase from 5 MeV to 12 MeV)*
E. Ramakrishnan et al. Phys. Lett B 383 (1996); PRL 76 (1996)

- *Γ_{GDR} increases almost linearly with T~ 4 MeV in ^{132}Ce; O. Wieland et. al. PRL 97, (2006)*
(γ-rays in coincidence with ER & LCP)

- *A possible onset of saturation of width around T = 3 MeV in ^{88}Mo; Ciemala et al. PRC (2015)*

to grow or not to grow; the saga of GDR width continues

- *Isospin mixing in ^{80}Zr, ^{81}Rb, A Corsi et. al. (Phys. Rev. C 84 (2011)*
(ER & LCP gated GDR spectra)

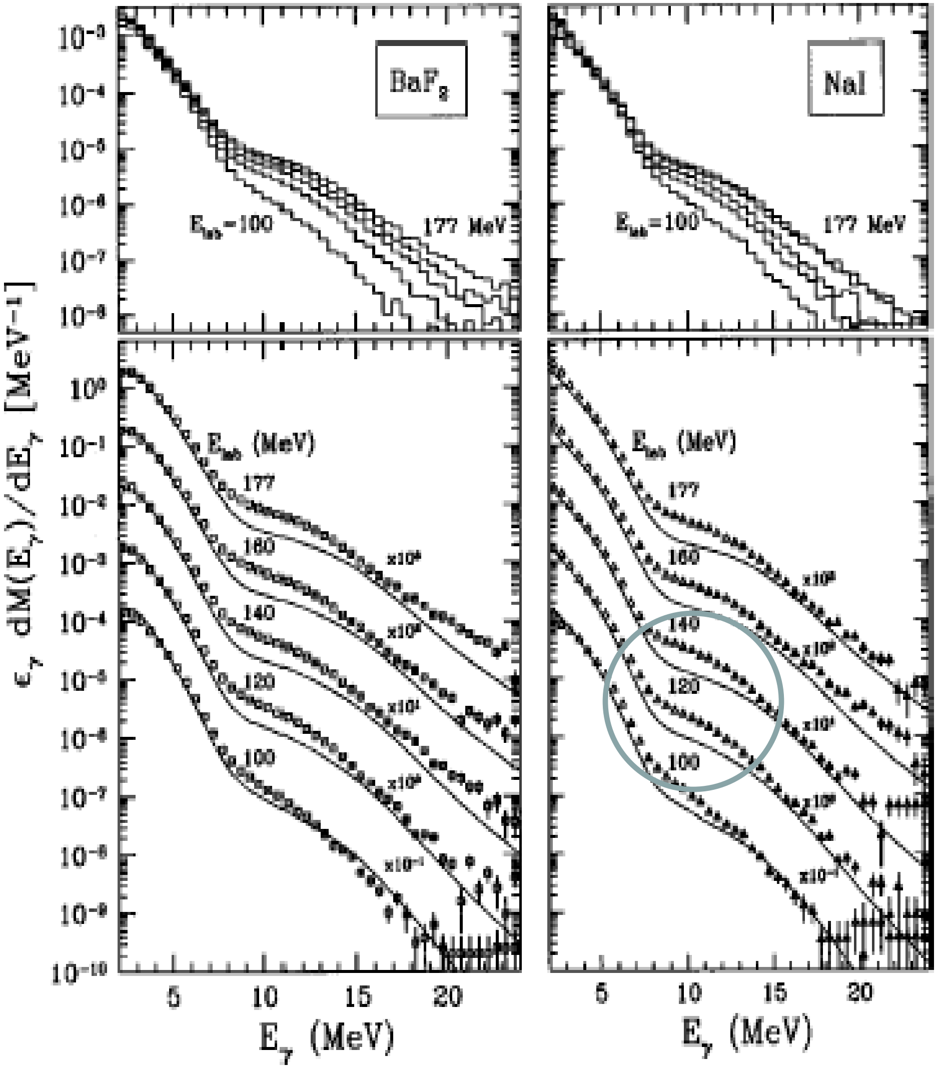
Harakeh et al PLB176 (1986)
Behr et al. PRL 70 (1993)
early pioneers

- *The pygmy dipole resonance:* *O. Wieland & A. Bracco, - Prog. Part. Nucl. Phys. 66 (2011)*

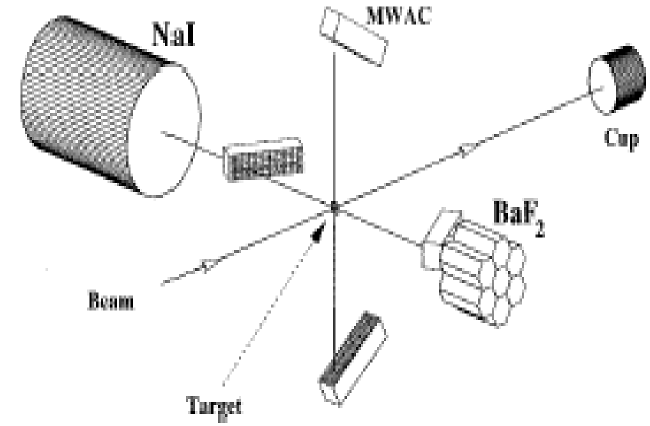
- *Giant Resonance studies with RIB:* *M. Thoennessen, Nucl. Phys. A, 788 (2007)*

- ***Hot GDR , Nuclear Fission & Quantum Dissipative processes***

GDR and nuclear viscosity:
The Phenomenon of Fission Hindrance



Fission fragments gated GDR γ-ray spectra from ^{224}Th



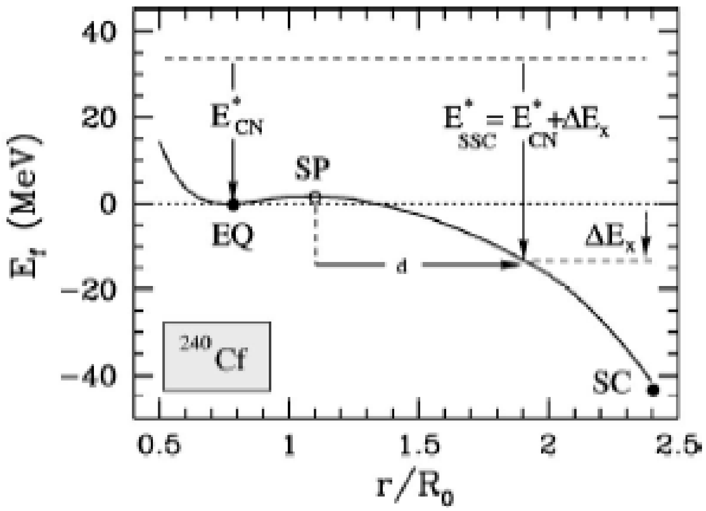
Gamma rays measured in coincidence with fission fragments:

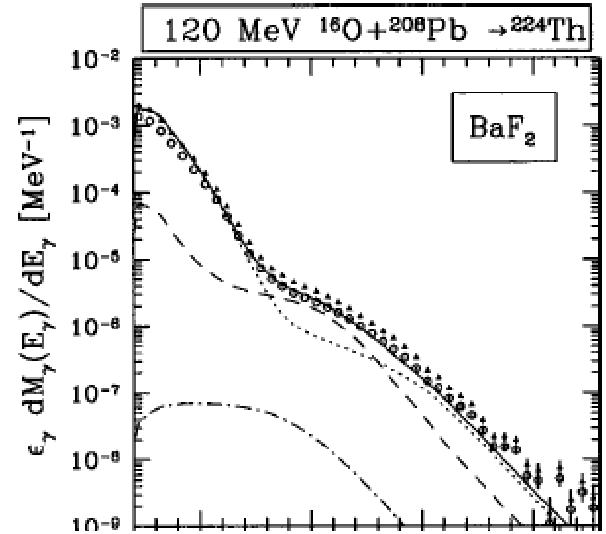
The Stony Brook Setup

The problem of dissipative mechanism in classical and quantum systems:

flow of glass to fission hindrance to QGP to string theory

Excess high energy γ–rays in the compound nuclear region





Saddle point transition state model: Bohr & Wheeler, Phys. Rev. 56 426 (1939)

Y_{total} = Pre-Saddle + Post-Saddle + Fission Fragments

$$\Gamma^{BW}_{fiss} = \frac{1}{2\pi\rho_1(E_i, J_i)} \int_0^{E_i - E_b} \rho_2(E_i - E_b - E, J_i)\, dE,$$

$$\gamma = \beta/2\omega_0$$
$$\omega_0 = 10^{21}\ s^{-1}$$

H.A. Kramers, Physica, 4 284 (1940)

$$\Gamma_f^{Kramers} = \Gamma_f^{BW}[(1+\gamma^2)^{1/2} - \gamma]$$

$$\tau_{ssc} = \tau^0_{ssc}[(1+\gamma^2)^{1/2} + \gamma].$$

$$\tau^0_{ssc} = \frac{2}{\omega_0} R[(\Delta V/T)^{1/2}]$$

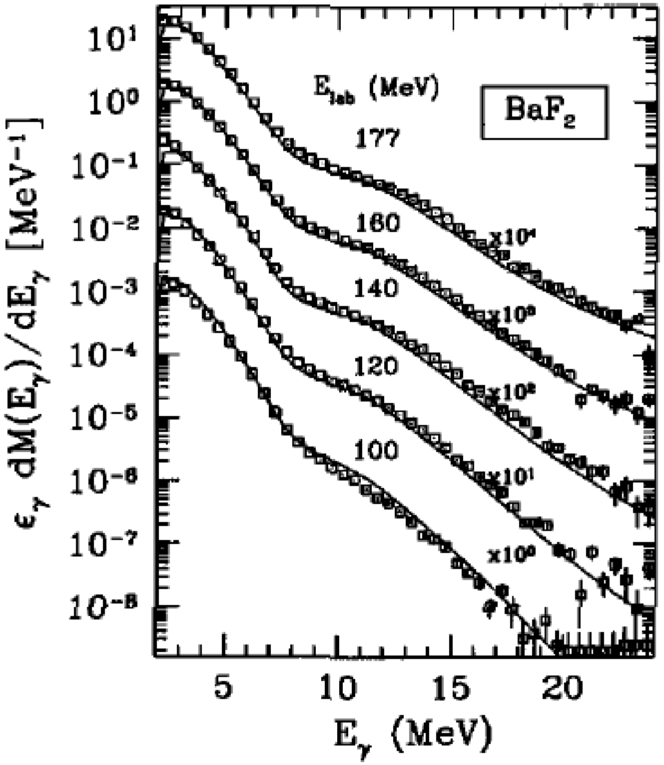
$$R(z) = \int_0^z \exp(y^2)\,dy \int_y^\infty \exp(-x^2)\,dx.$$

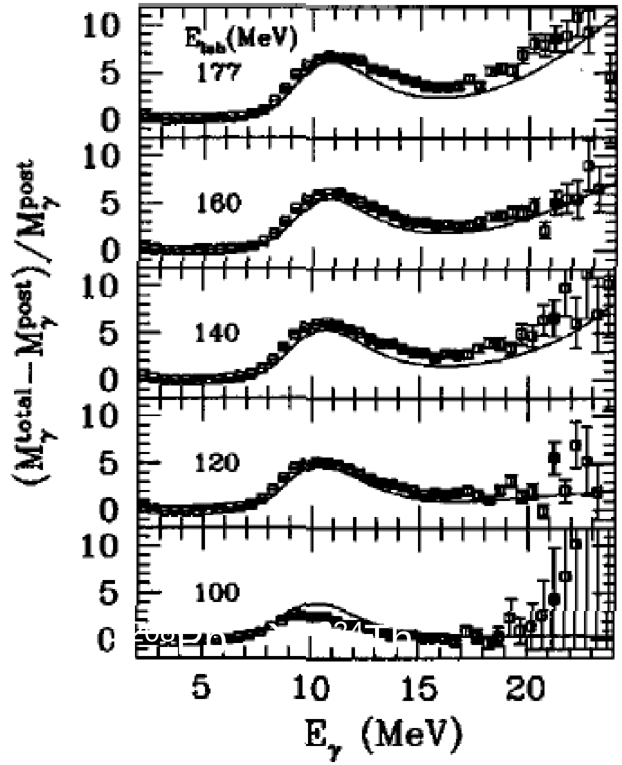
Additional buildup time

Grange, Jun-Qing, Weidenmuller (1983)

$$\tau_f = \beta/2\omega_1^2[\ln(10B_f / T)]$$

^{16}O +^{208}Pb → ^{224}Th

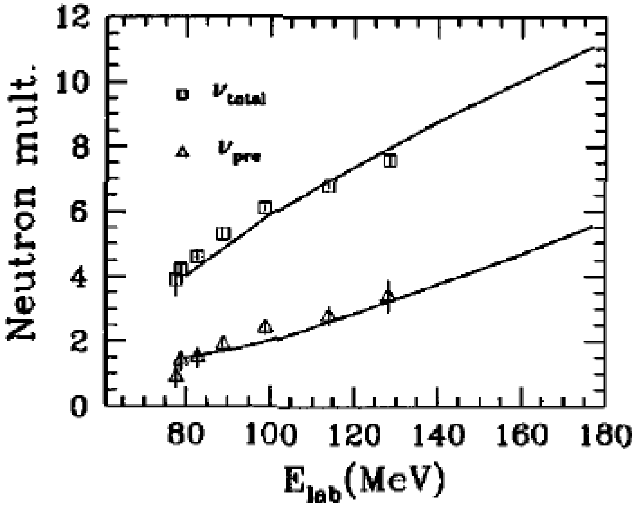


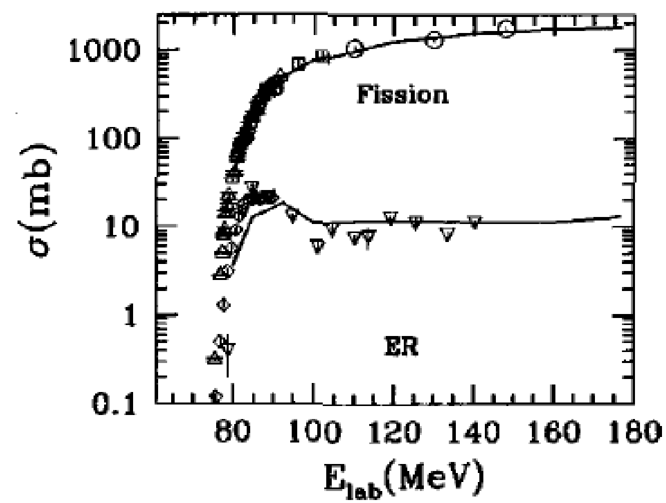


Stronger temperature dependence of a

and

$\gamma = 0.2 + 1.7T^2$





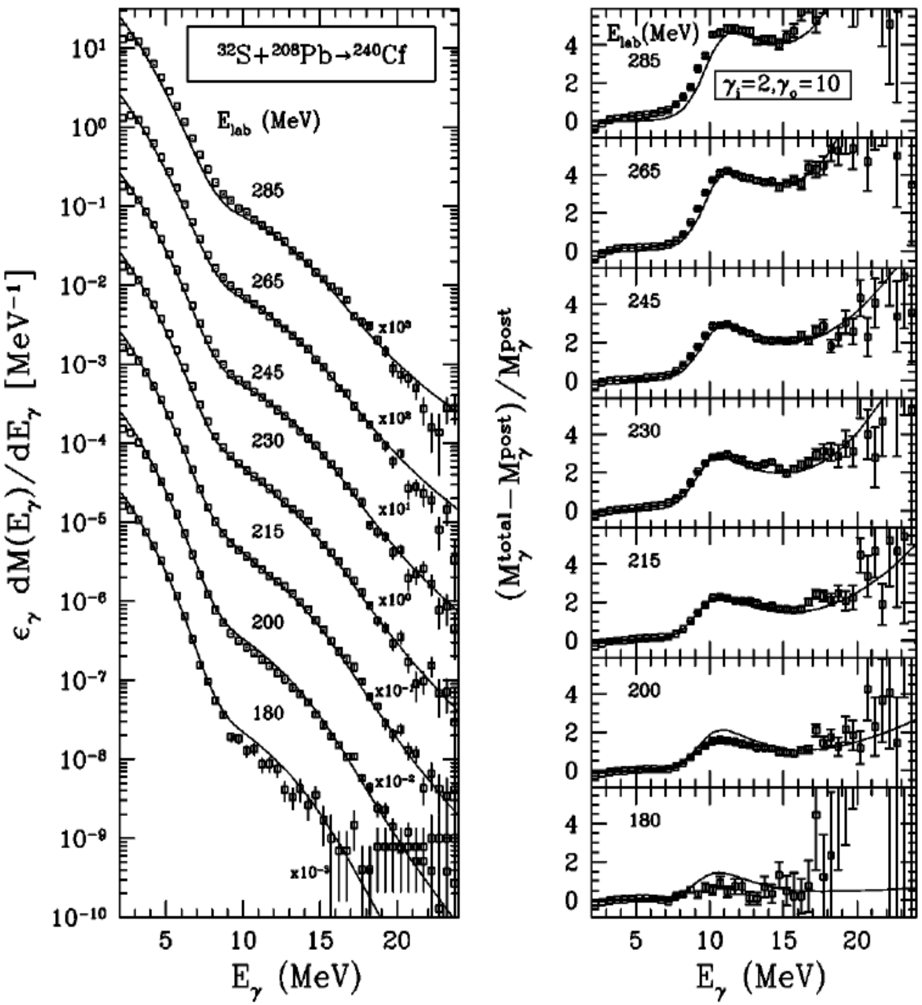
Excellet fits to γ, n, ER

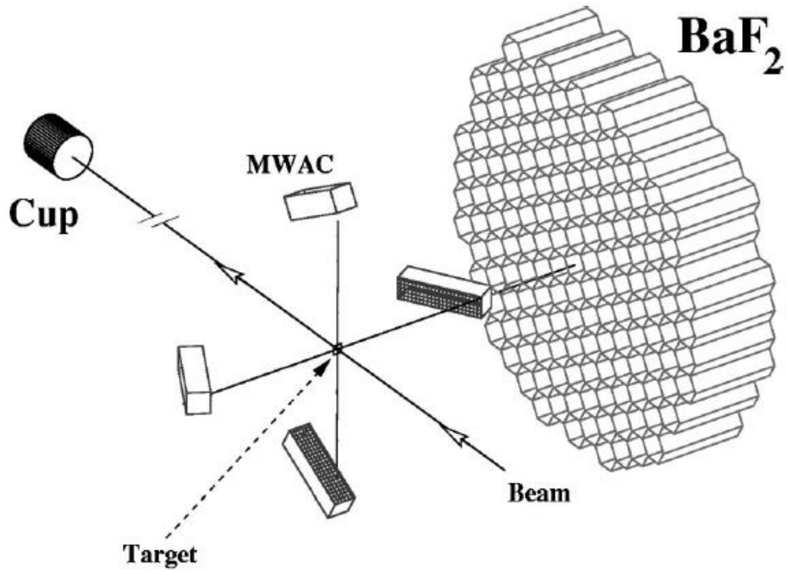
but

is T^2 dependence correct?

Contributions are from both pre-saddle and ssc region..
γ may be different in these two Regions.

Fission Delay in ^{240}Cf: $^{32}S + ^{208}Pb$





Phys. Rev C61, 044612
Phys. Rev. C61, 024613
Phys. Rev. C63, 047601
Phys. Rev. C63, 014611
Pramana 85, No.2 (2015)

$\gamma_i = 2$; $\gamma_o = 10$ fit all the spectra

No apparent temperature dependence of γ
It may be spin(deformation) dependent

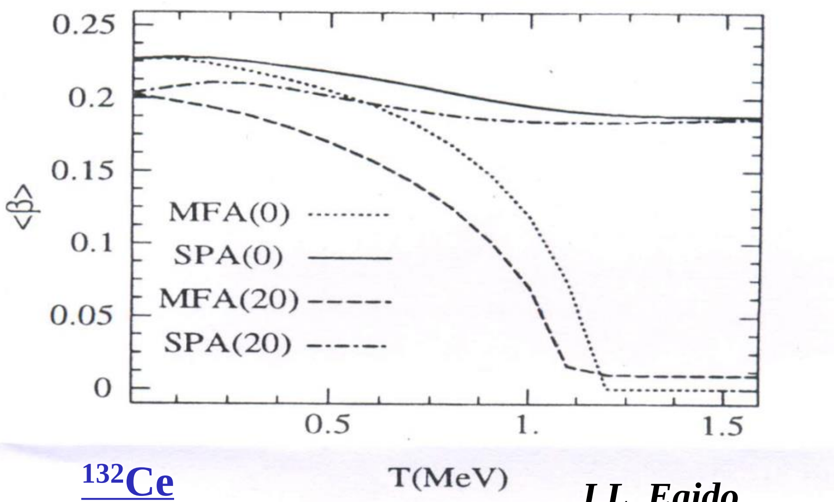
With increasing T γ-yield is almost entirely from Saddle to scission

η/s Ratio in Finite Nuclei at low temperature

- *Auerbach & Shlomo PRL 103, 172501 (2009)*
- *N. Dinh Dang, PRC 85, 064323 (2012)*
- *Hung & Dang PRC86, 024302 (2012)*

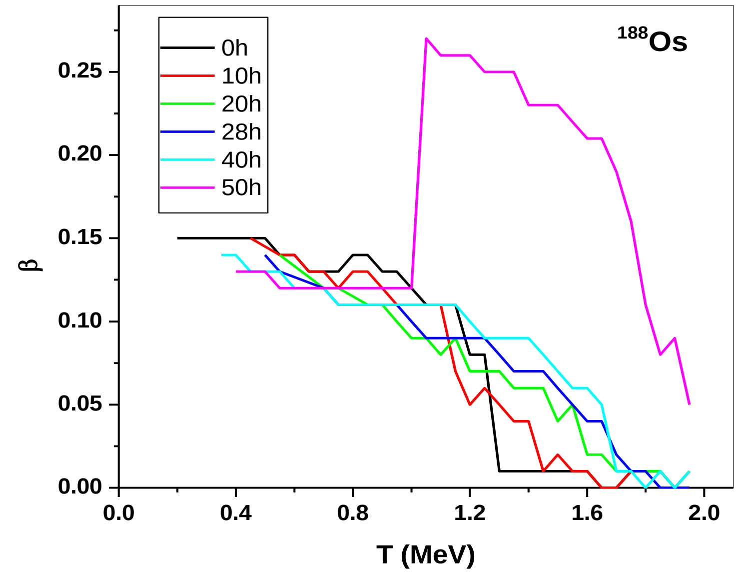
Extracted from GR widths

GDR and Structural Evolution in Hot and Rotating Nuclei

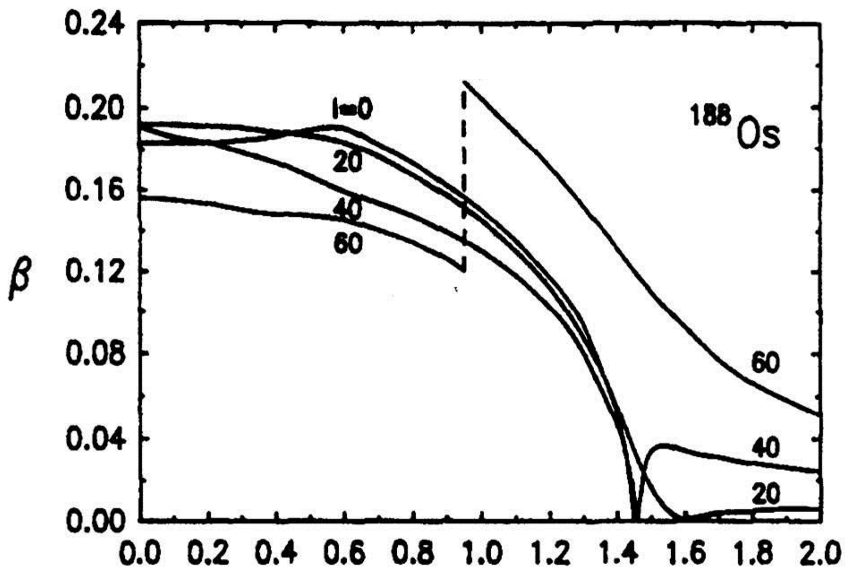


^{132}Ce

J.L. Egido,
Private communication



Aggarwal & Mazumdar



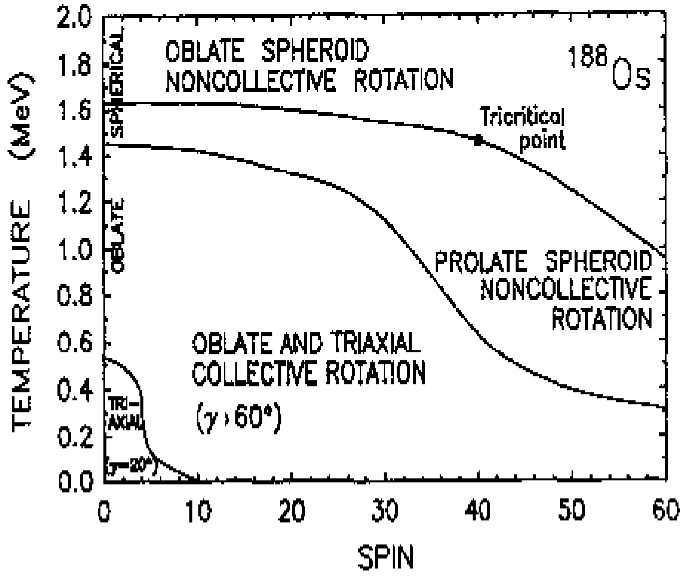
T (MeV)

A.L. Goodman, NPA (95)

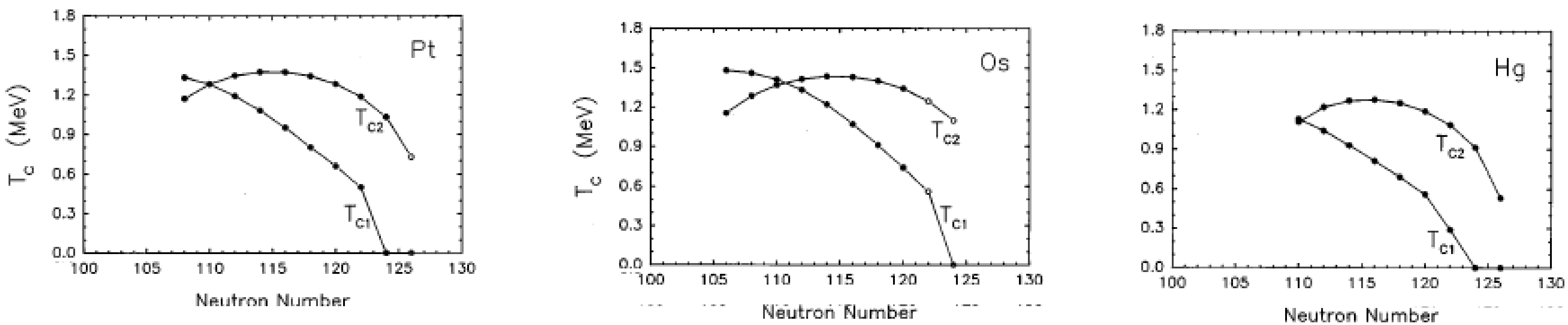
A variety of shape transitions are possible as the nucleus traverses from one point to another in the phase-space

M.K-Habior et al (93)
A. Maj et al. (01, 04)
M. Brekiesz et .al (07)
D. Pandit et al. (10)

Pomorski, Dudek (2003)
Dinh Dang et al (2013)
Mazurek, Dudek, Maj, Rouvel (2015)



- *A.L. Goodman, PRL 73, 416 (1994)*
- *A.L. Goodman, Nucl. Phys. A 592, 151 (1995)*
- *A.L. Goodman, Nucl. Phys. A 591, 182 (1995)*



31 even-even isotopes (Z=72-80 and N = 110-126) have two shape transition temperatures, where $T_{c2} > T_{c1}$

Goodman & Jin PRC 54, (1996)

The Programme in a nutshell

To search for (rare) shape-phase transitions in heavy nuclei at high excitation energy

The nuclei chosen for **exclusive** measurements of high energy gamma rays:

^{194}Au ^{188}Os ^{192}Pt ^{196}Hg

Modus Operandi:

1) *To measure GDR γ-ray spectra from different non-overlapping regions in phase-space (key word: as small domains as possible with the detection systems)*

Spin window:	*better spin-spectrometer*
Temperature window:	*differential technique*
Residue gated GDR γ-rays:	*use of gas filled magnetic separator*

2) *Measure the angular distribution of the GDR γ-rays with respect to the beam direction*

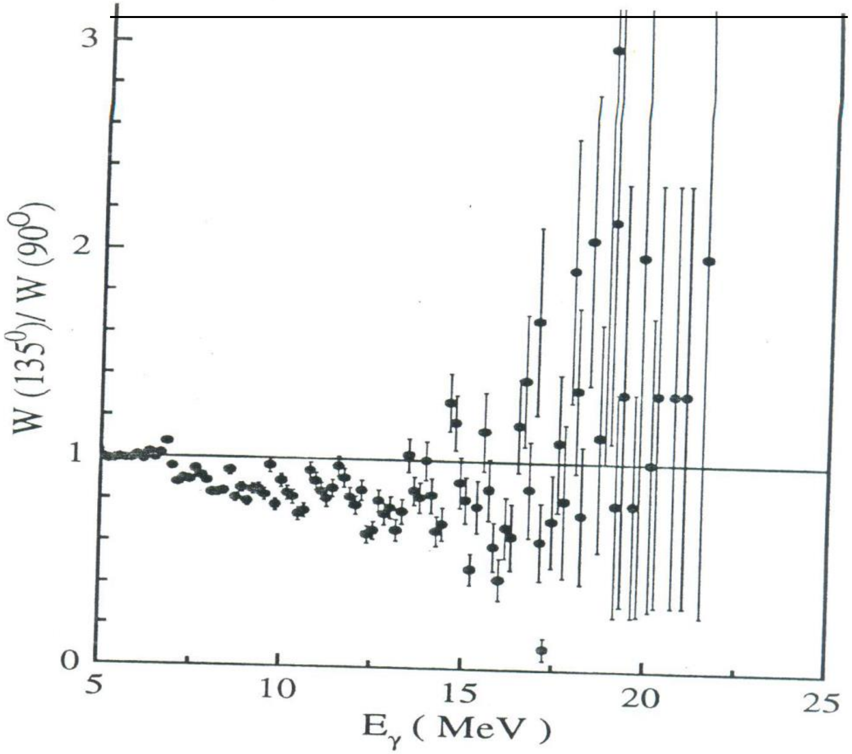
3) *Keep the system simple: (no fission, charged particle emission, moderate temperature)*

4) *Special care about background subtraction and estimation*

Thermal fluctuation is less,
Average and most probable shapes
are not too different

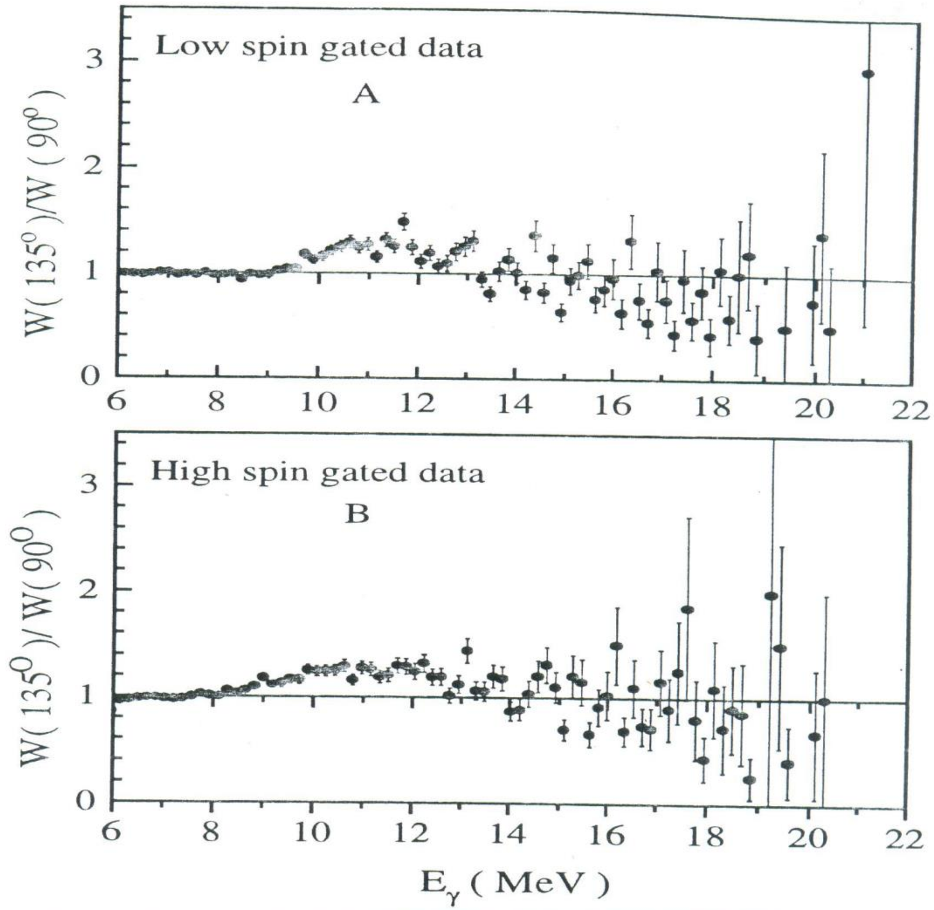
Choice of nuclei is governed by:

- ***theoretical predictions of rare shape-phase transition***
- ***Need for exclusive measurement using differential technique***
- ***Some past observations***



CN IS ^{133}Nd

Reaction : ^{28}Si + ^{105}Pd

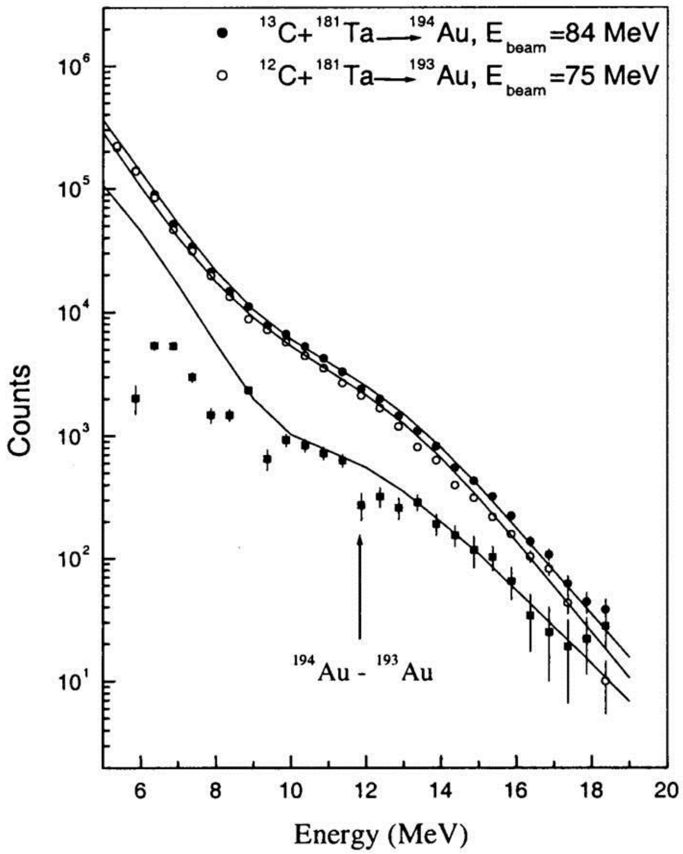


E_{bem} = 123 MeV

Mazumdar et al.

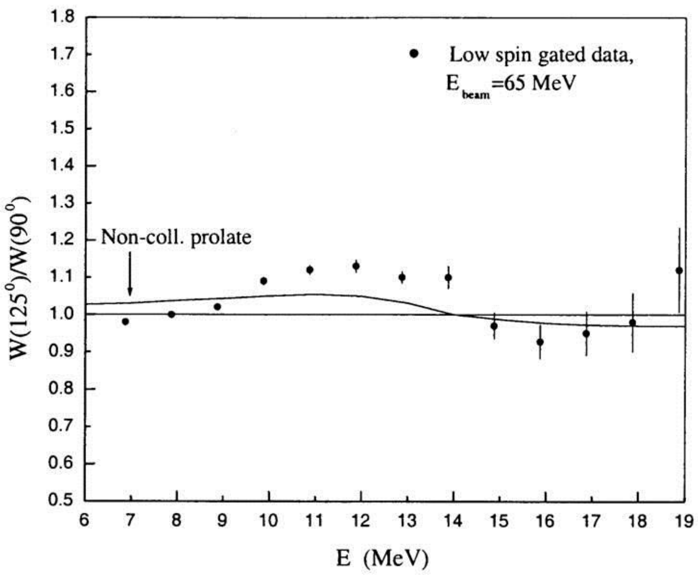
E_{beam} = 140 MeV

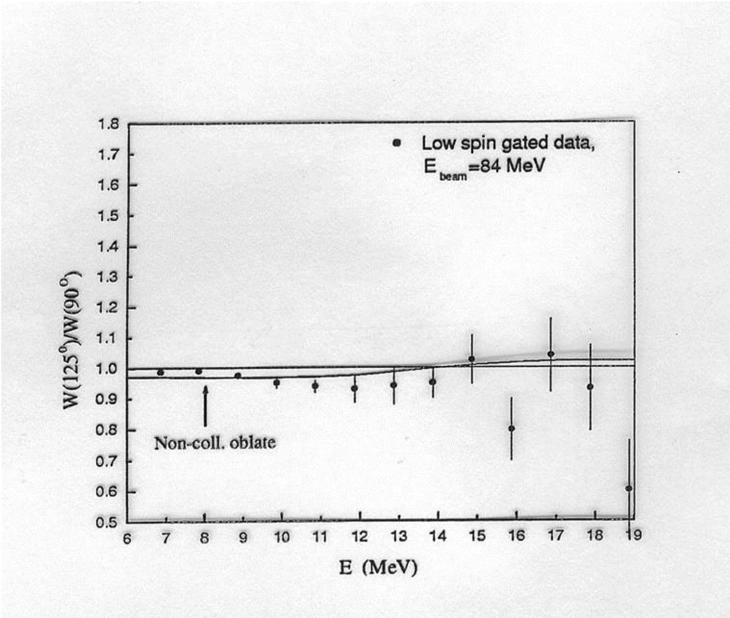
GDR decay from ^{194}Au



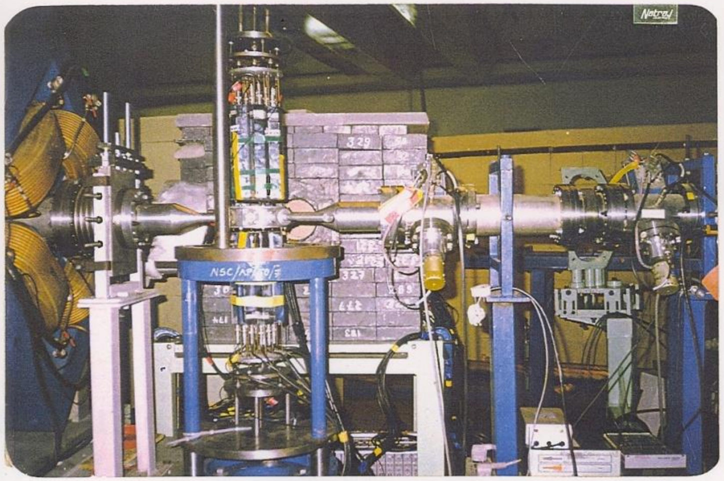
Mazumdar et al., Nucl. Phys. A 731, 146 (2004)

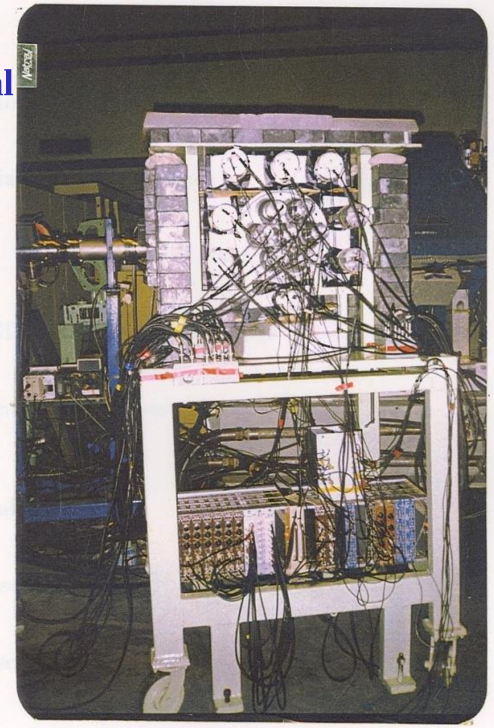
A. Maj et. al. Nucl. Phys. A. (1995) Angular distribution Of GDR photons from ^{162}Yb (^{162}Yb-^{161}Yb)



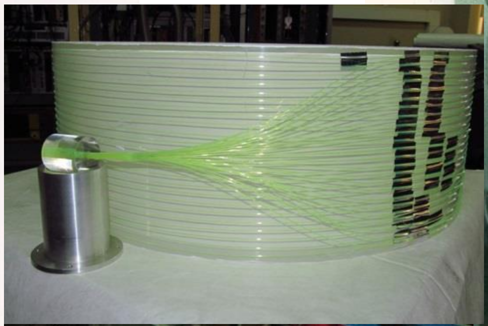


Angular anisotropy of GDR γ-rays from CN ^{194}Au



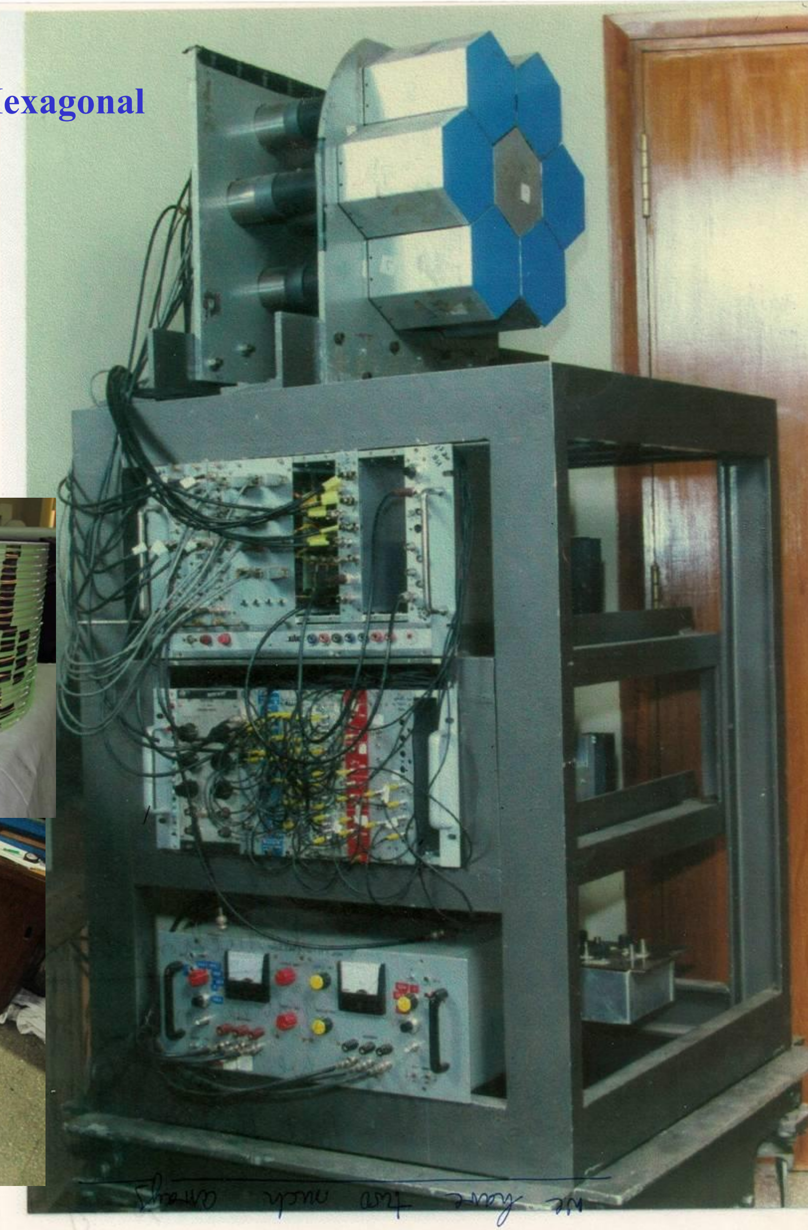


10”X12” Cylindrical NaI(Tl)



Annular anti-cosmic shield

6” Long Hexagonal NaI(Tl)

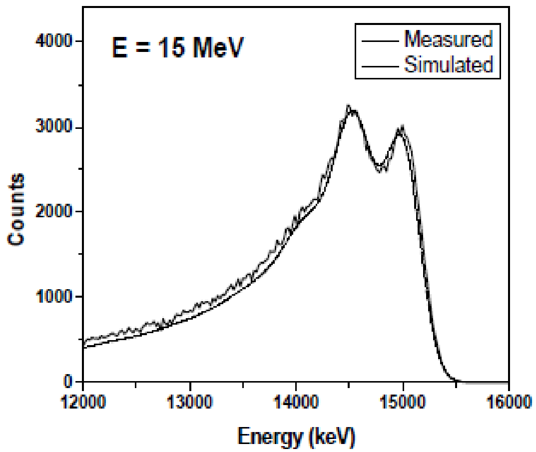


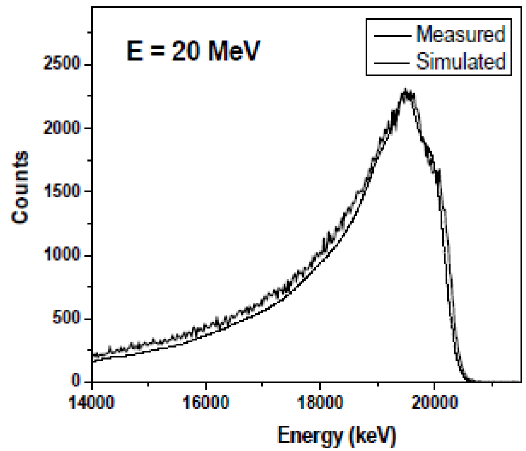
7 Elements NaI array, TIFR, Mumbai

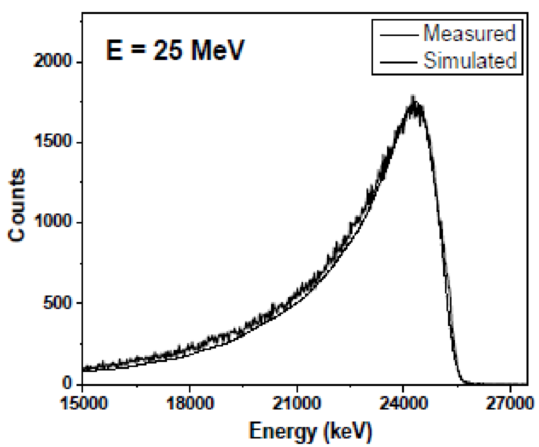
HIGRASP at IUAC, Delhi

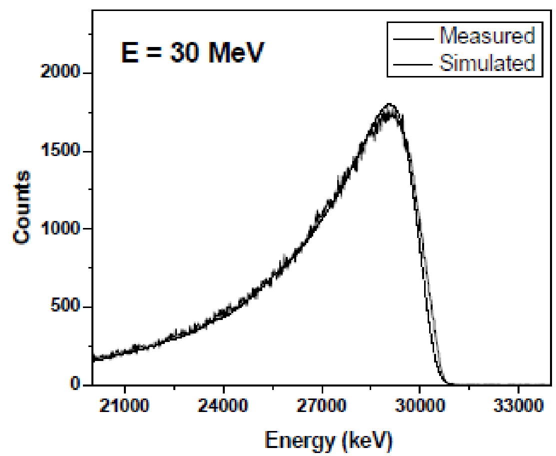
I.Mazumdar et al.
NIM A417

Mazumdar et al (under preparation)









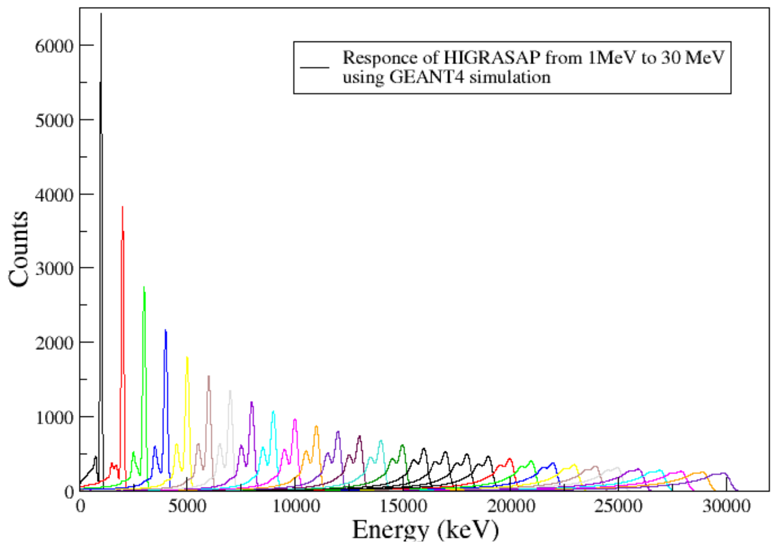
Results of GEANT Simulations

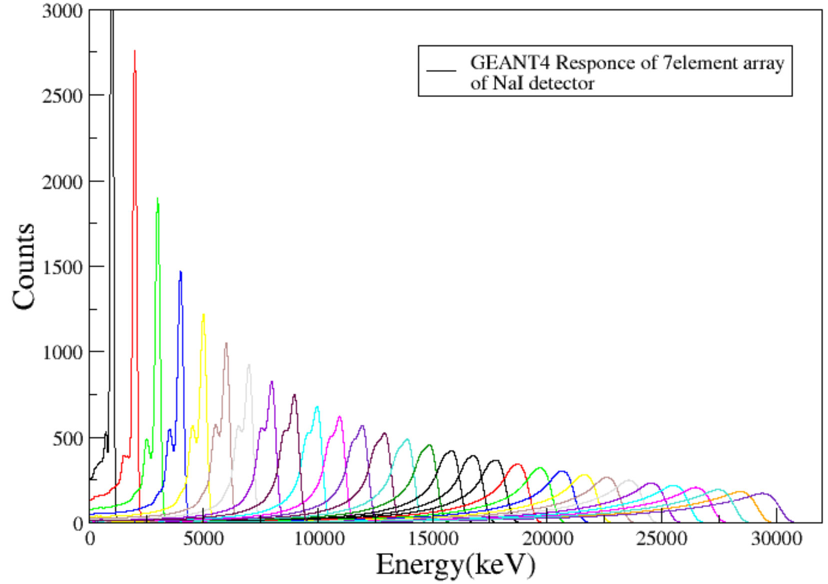
E(MeV)	ε_{PP}	ε_{D}
5.5	37.57	92.55
6.5	34.56	92.82
7.5	32.04	93.13
8.5	29.84	93.24
9.9	26.55	93.73
15	17.46	95.07
20	11.12	96.04
25	6.7	96.77
30	3.95	97.05

Measurement of absolute photo-peak and total detection efficiencies of a large cylindrical $LaBr_3$:Ce crystal using monochromatic γ-rays from HIγS facility.

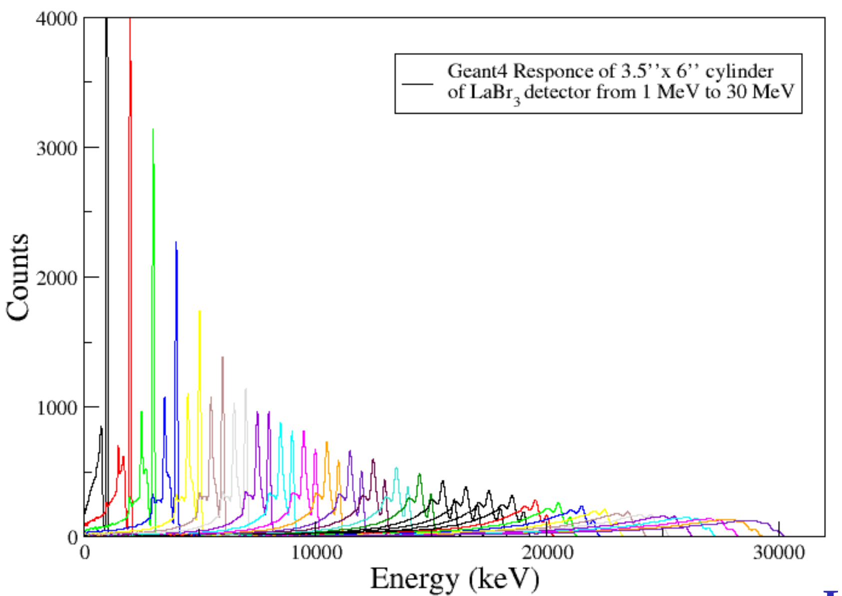
Mazumdar et al

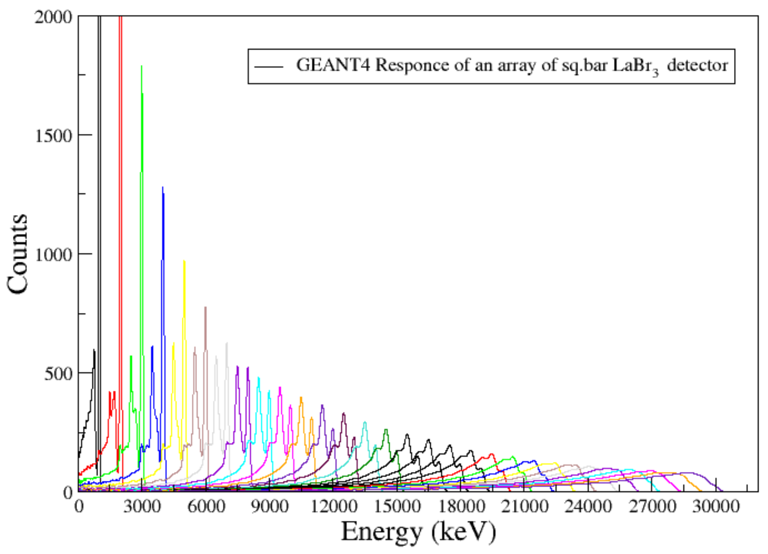
GEANT4 Simulations



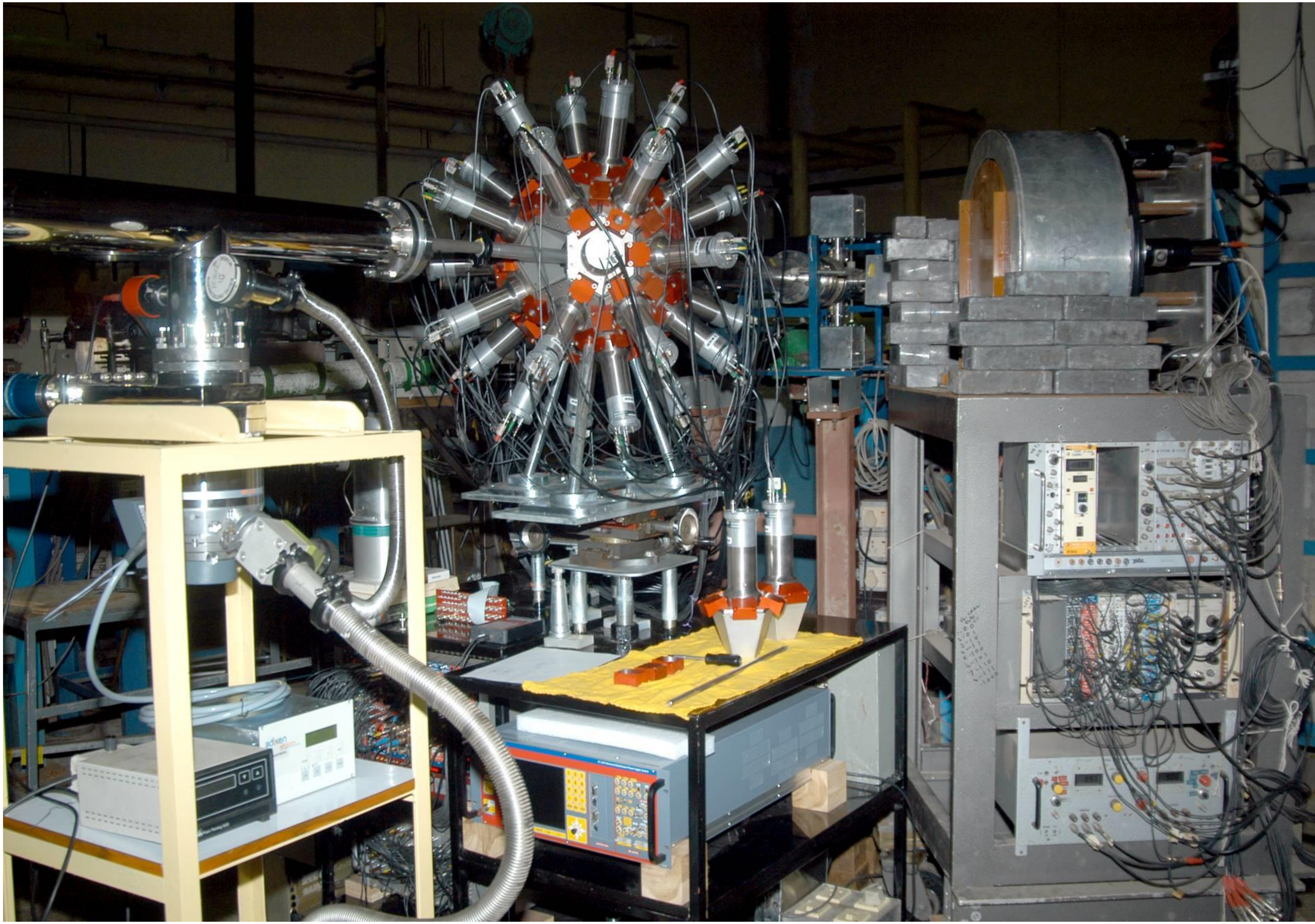


NaI(Tl)





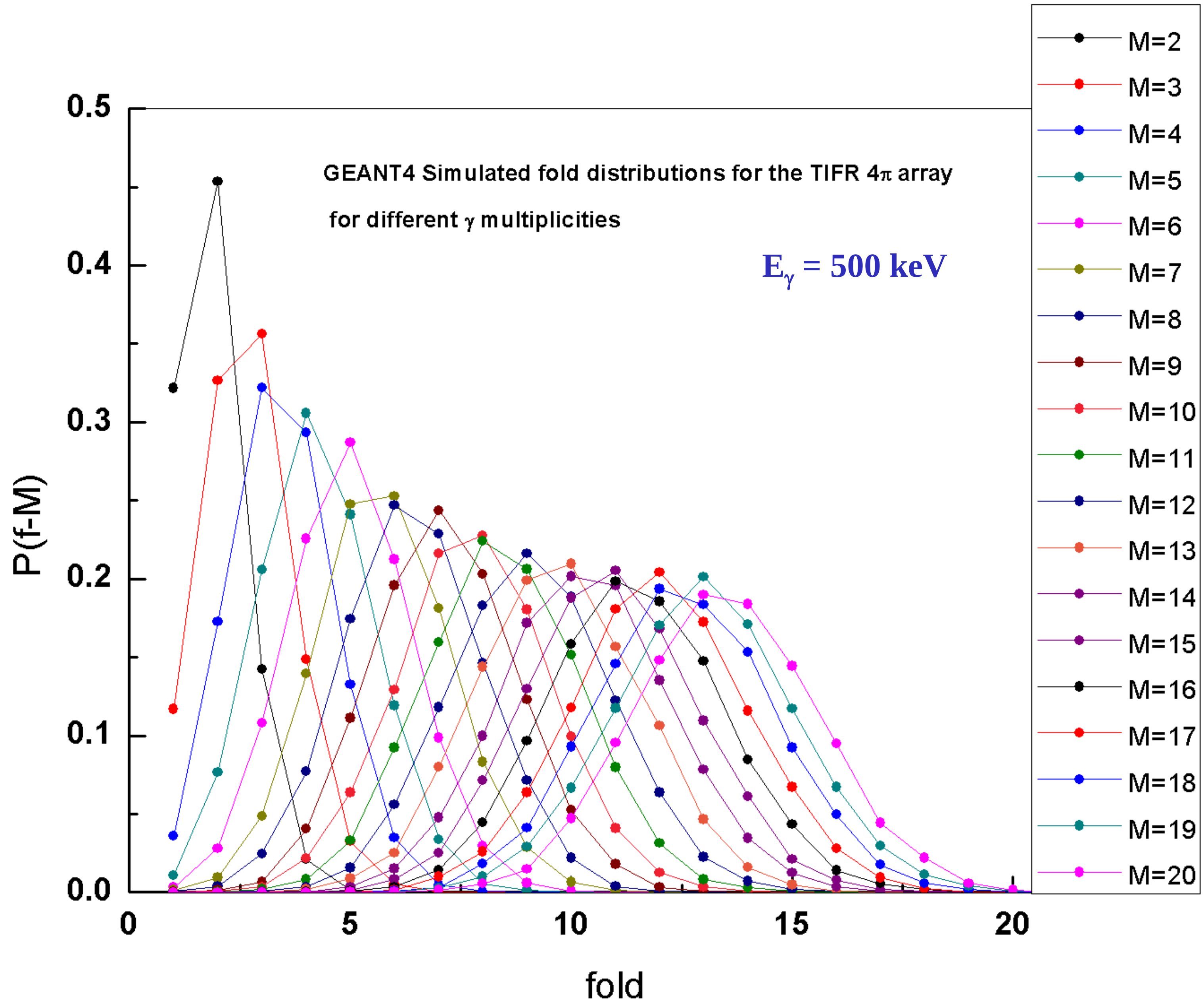
$LaBr_3$:Ce



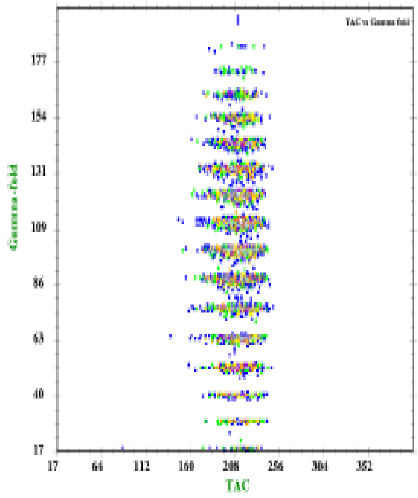
The 4π Sum-Spin Spectrometer at TIFR

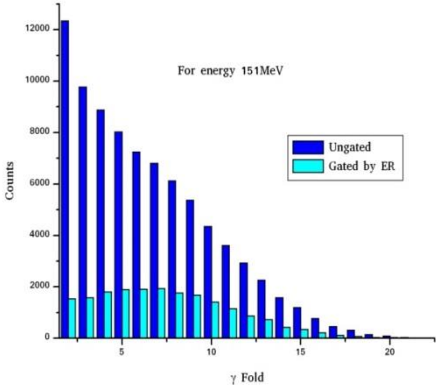
Kumar, Mazumdar, Gothe, NIM-A 611 (76) (2009);

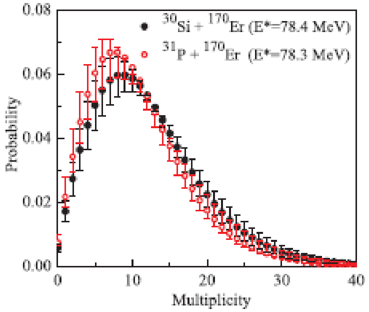
32 Conical NaI(Tl) detectors.
12 Pentagonal & 20 Hexagonal.


GEANT4 Simulated fold distributions for the TIFR 4π array
for different γ multiplicities
E_γ = 500 keV
P(f-M)
fold
0.0
0.1
0.2
0.3
0.4
0.5
0
5
10
15
20
M=2
M=3
M=4
M=5
M=6
M=7
M=8
M=9
M=10
M=11
M=12
M=13
M=14
M=15
M=16
M=17
M=18
M=19
M=20

Hybrid Recoil Analyzer (HYRA) at Inter University Accelerator Centre, Delhi Coupled with the TIFR 4π Sum-Spin Spectrometer







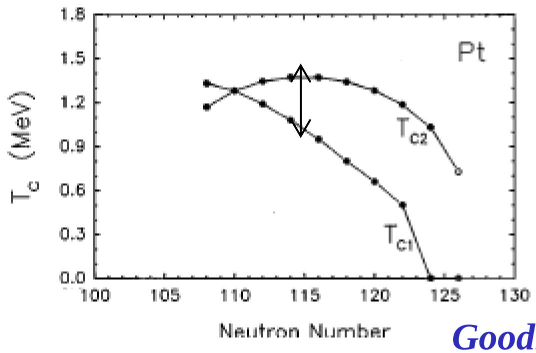
- *GDR decay from ^{192}Pt, ^{196}Hg, ^{144}Sm*
- *ER cross section, spin distribution for*

(^{31}P+^{170}Er), (^{30}Si, ^{31}P+ ^{170}Er), (^{28}Si + ^{176} Yb) (^{48}Ti+^{150}Nd), (^{19}F,^{16}O + ^{197}Au)

- *Phys Rev. C 88 024312 (2013)*
- *Phys Rev C 88 034606 (2013)*
- *Nucl. Phys. A 890, 62 (2012)*
- *Jour. Phys. G 41 (2014)*
- *EPJ Web of Sc.(2011,2013)*

High energy γ-rays in coincidence with residual nuclei, Camera et al. (99); CN is ^{194}Hg

GDR Decay from excited ^{192}Pt



Goodman & Jin, PRC (96)

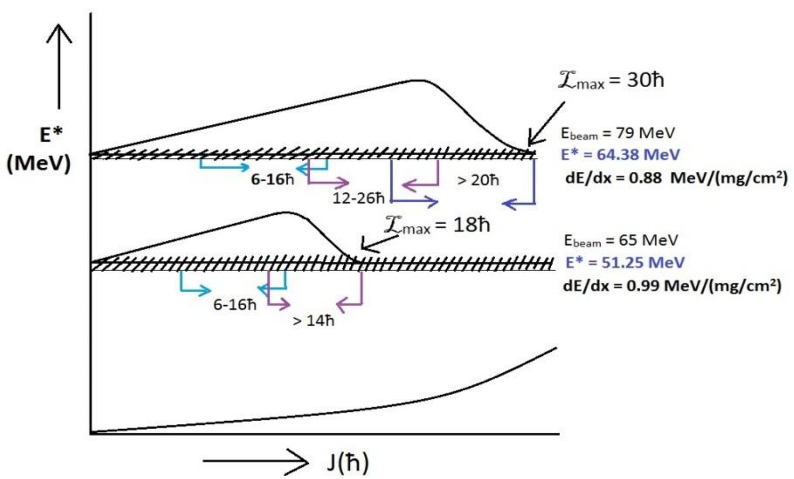
Reaction

$^{12}C + {}^{180}Hf \longrightarrow {}^{192}Pt^*$

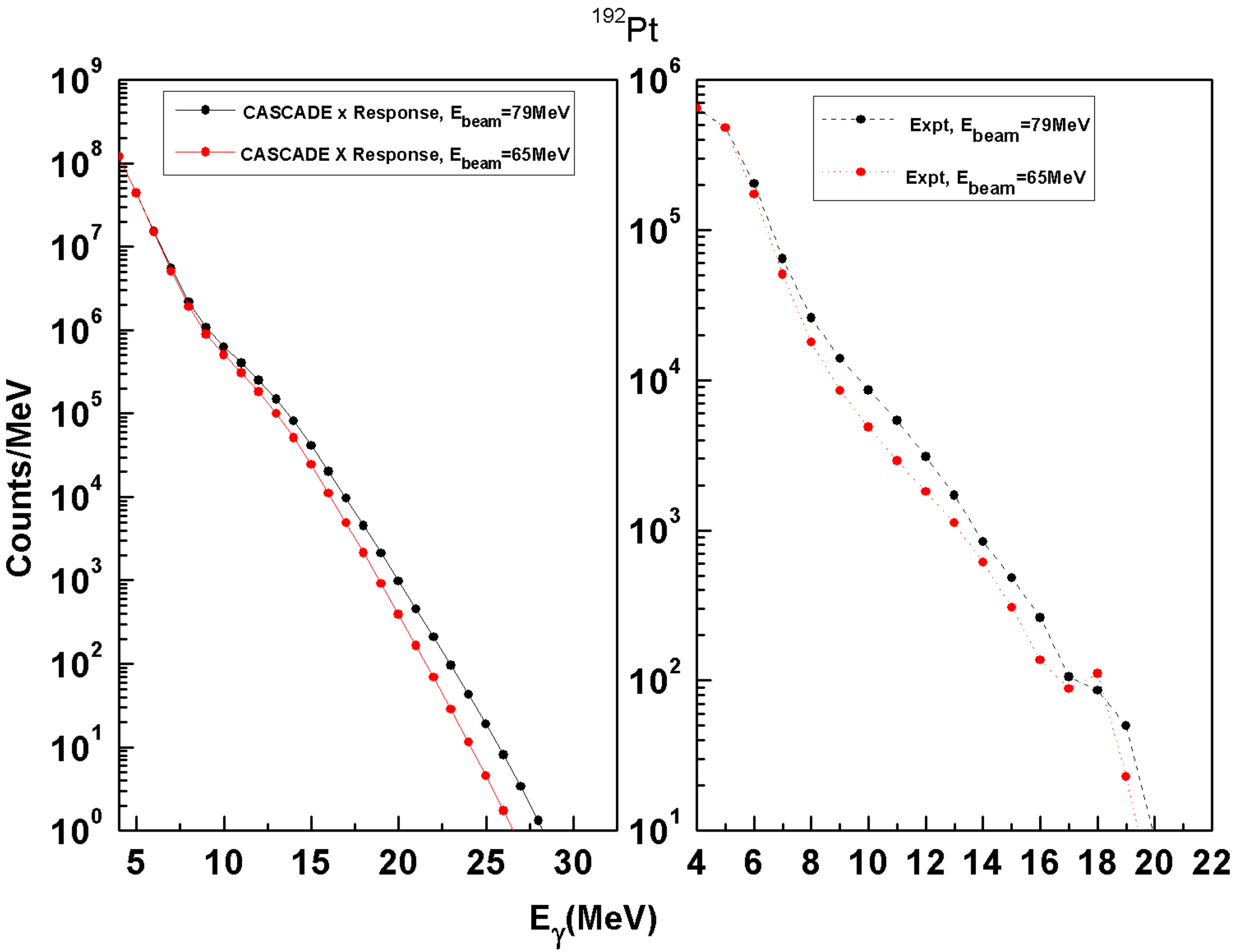
Measurements carried out at TIFR, Mumbai

7 Element NaI(Tl) + 4π spin spectrometer

E_{beam} (MeV)	E* (MeV)	E_{rot} (MeV)	T (MeV)
79	64.38	2.83 (22ħ)	1.6
65	51.25	0.87 (12ħ)	1.4

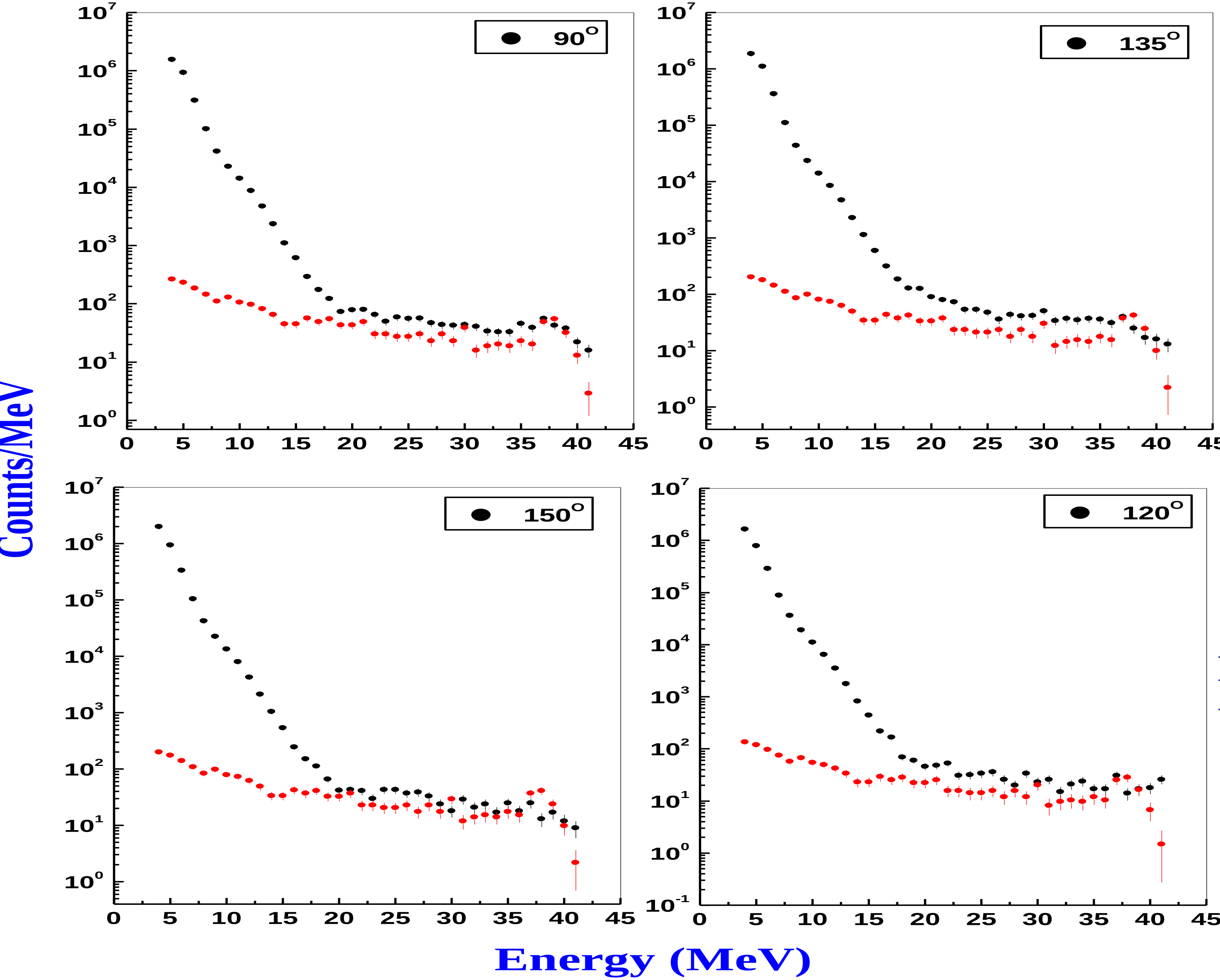


E_{beam} (MeV)	<J>		
65	10ħ	16ħ	
79	10ħ	20ħ	26ħ



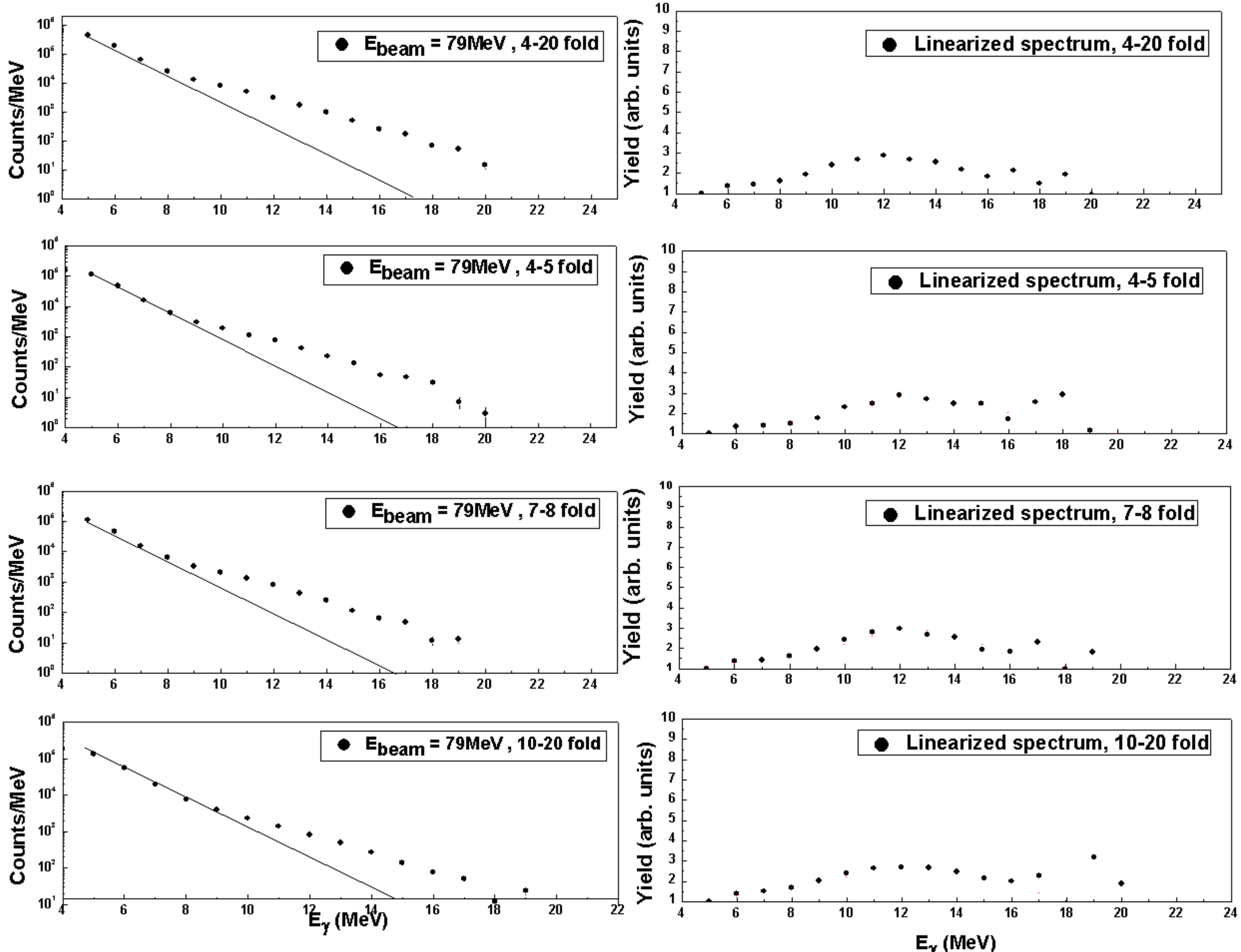
^{192}Pt
CASCADE x Response, E_{beam}=79MeV
CASCADE X Response, E_{beam}=65MeV
Expt, E_{beam}=79MeV
Expt, E_{beam}=65MeV
Counts/MeV
E_{γ}(MeV)

65 MeV



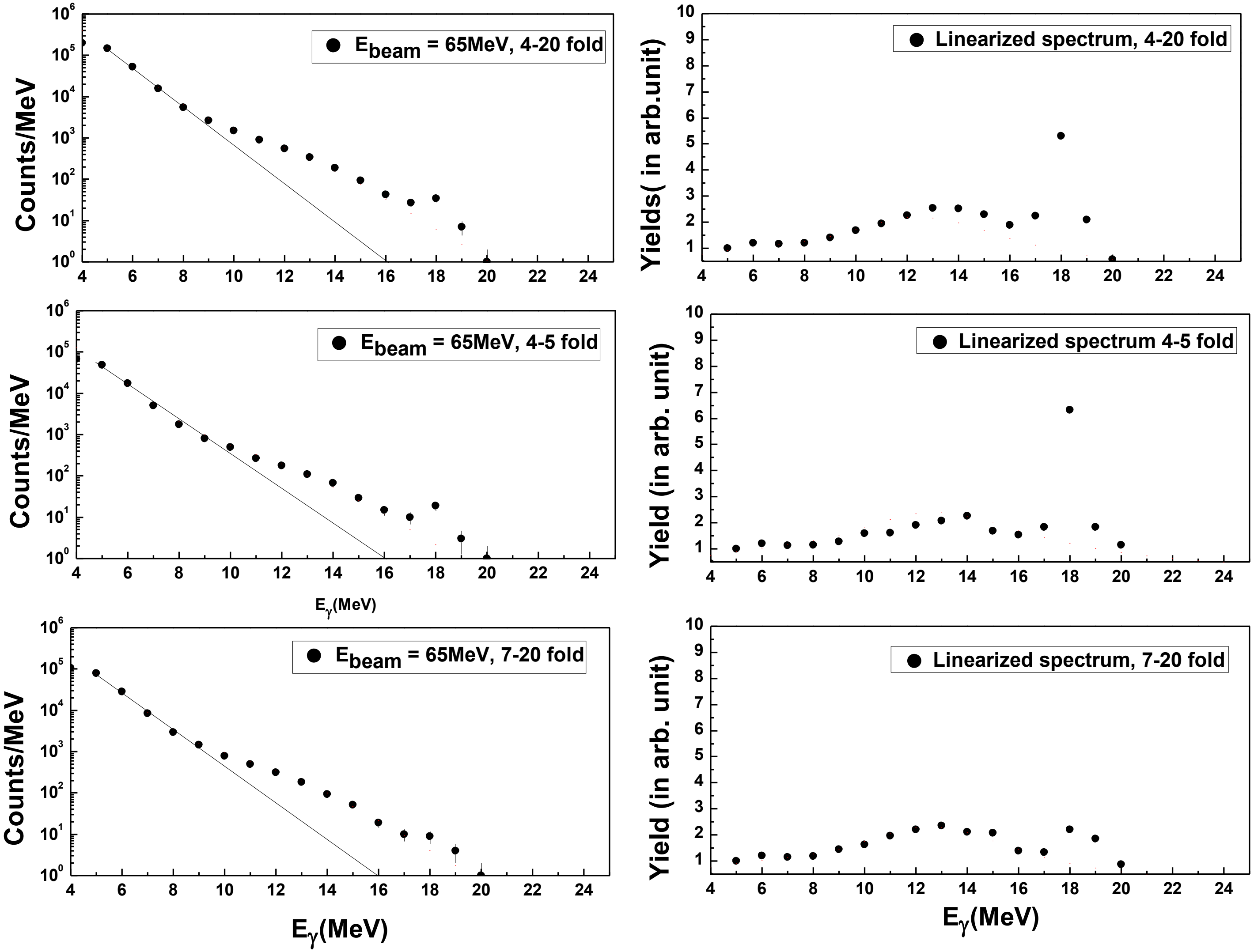
Dynamical range up to 41MeV

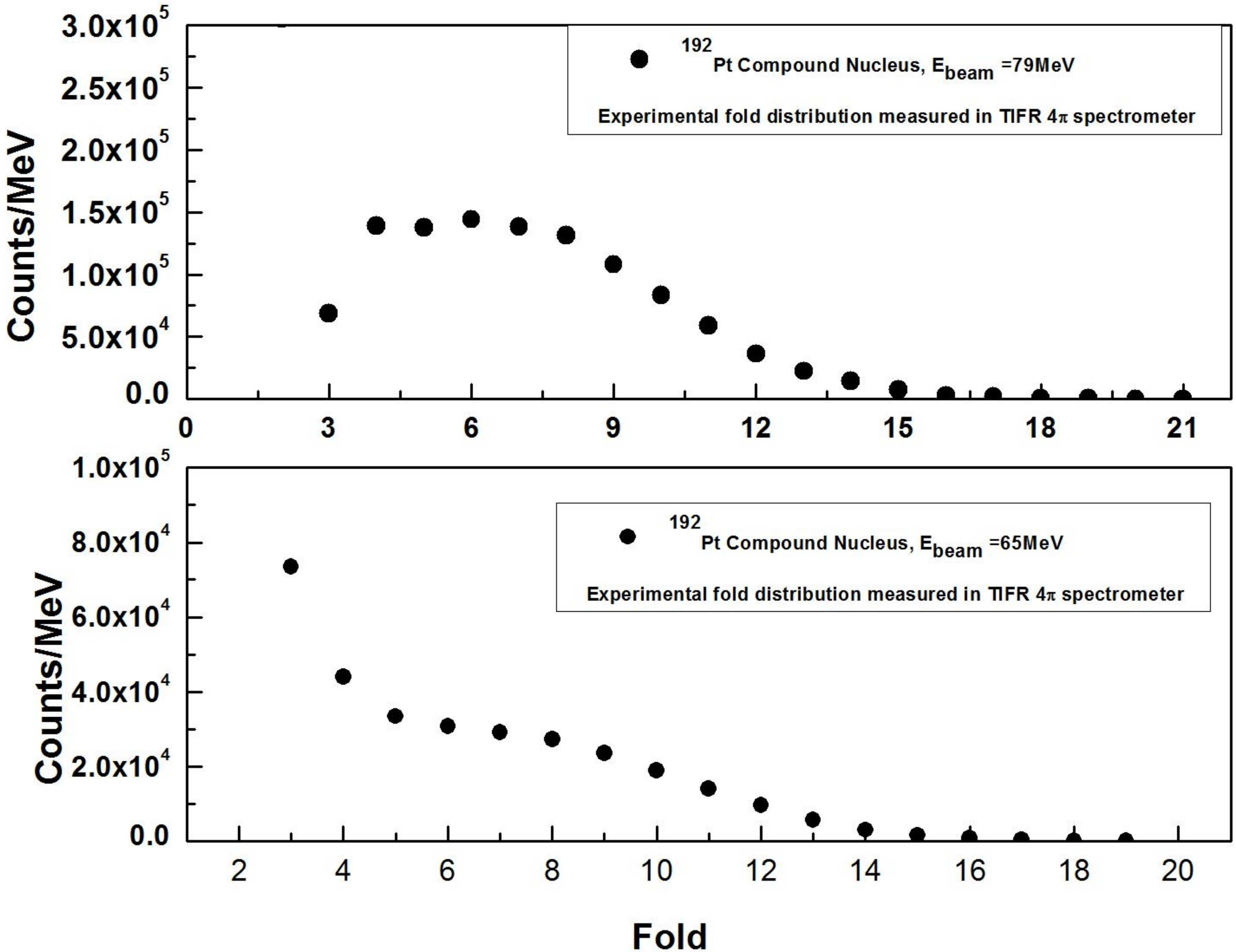
^{192}Pt, 79 MeV data



^{192}Pt

^{192}Pt, 65 MeV data





3.0x10^5
2.5x10^5
2.0x10^5
1.5x10^5
1.0x10^5
5.0x10^4
0.0
Counts/MeV
192Pt Compound Nucleus, E beam =79MeV
Experimental fold distribution measured in TIFR 4π spectrometer
0
3
6
9
12
15
18
21
1.0x10^5
8.0x10^4
6.0x10^4
4.0x10^4
2.0x10^4
0.0
Counts/MeV
192Pt Compound Nucleus, E beam =65MeV
Experimental fold distribution measured in TIFR 4π spectrometer
2
4
6
8
10
12
14
16
18
20
Fold

1. **Statistical model analysis of spin-gated GDR spectra**

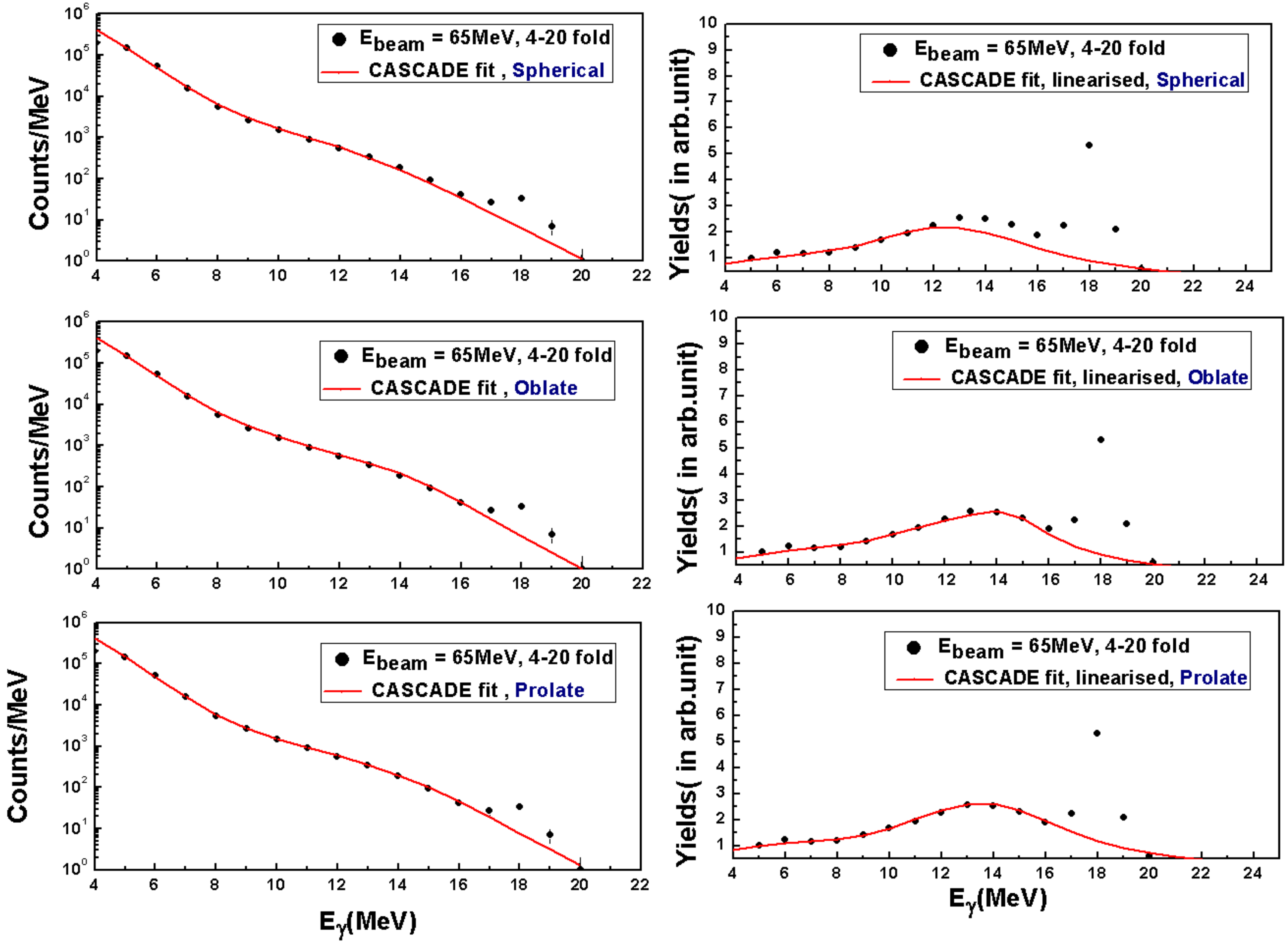
Cascade fits

- ***Ignatyuk-Reisdorf formalism for NLD.***
- ***GDR width varied in successive steps.***
- ***Constrained realistic fits not allowing the centroid to vary more than 500KeV from known systematics.***
- ***Convoluted with response matrix of the array and normalized at 5 MeV.***
- ***Fit parameters chosen after χ^2 minimisation and visual inspection.***
- ***Total strength kept fixed at 100% of TRK sum-rule*** $(S = S_1 + S_1 = 1.0)$

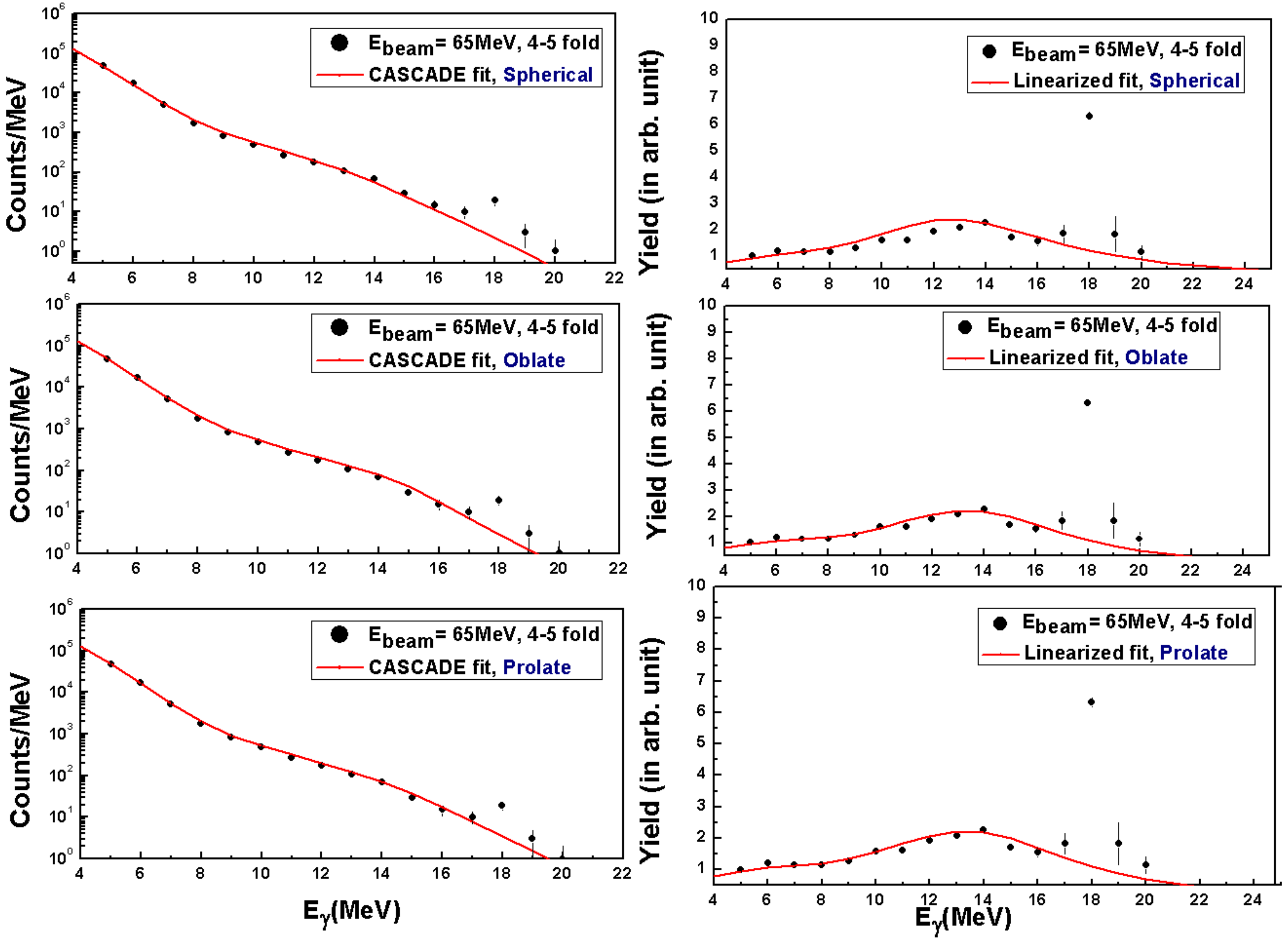
2. **Analysis of angular anisotropy**

3. **Finite temperature PES calculations and analysis including fluctuation effect**

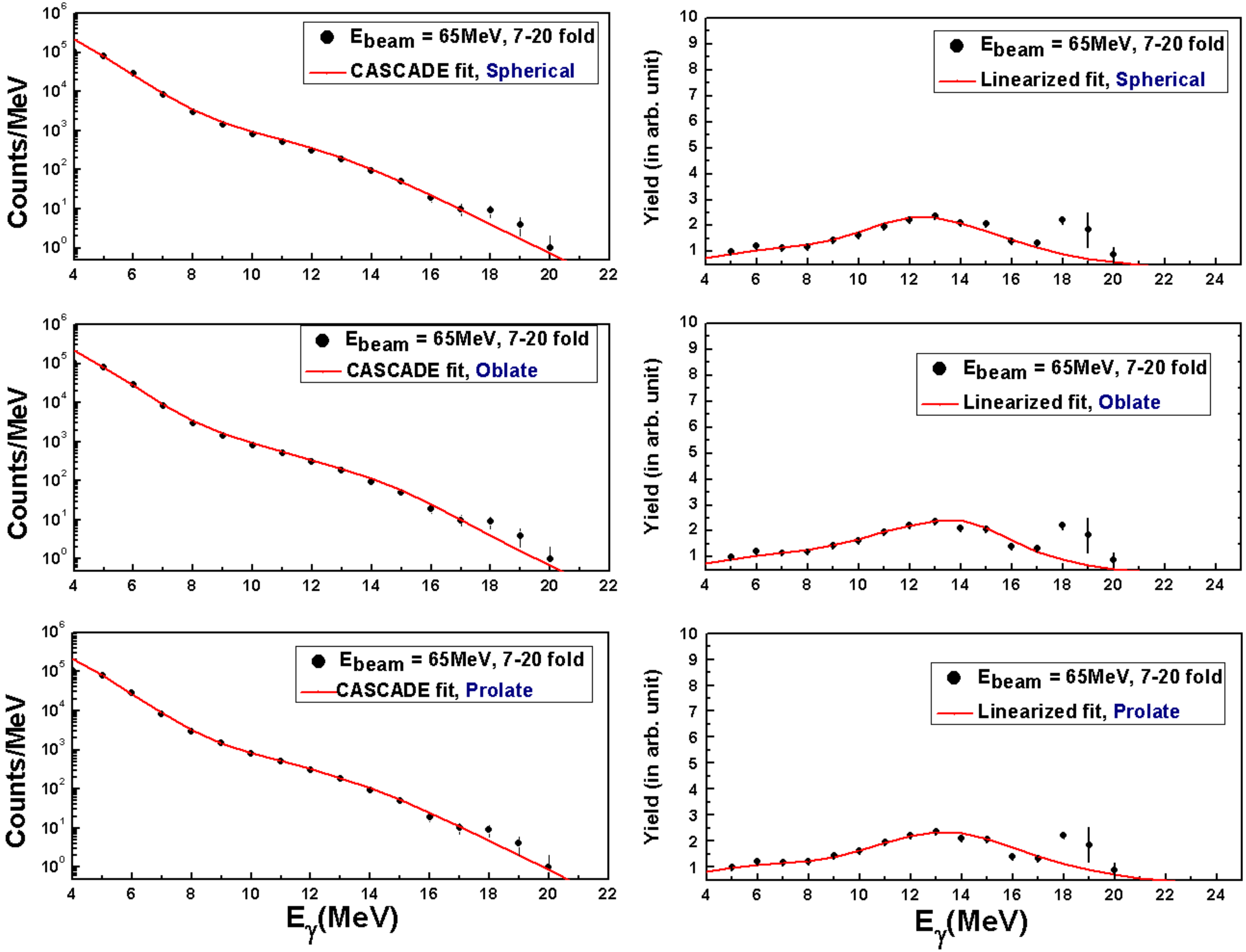
^{192}Pt



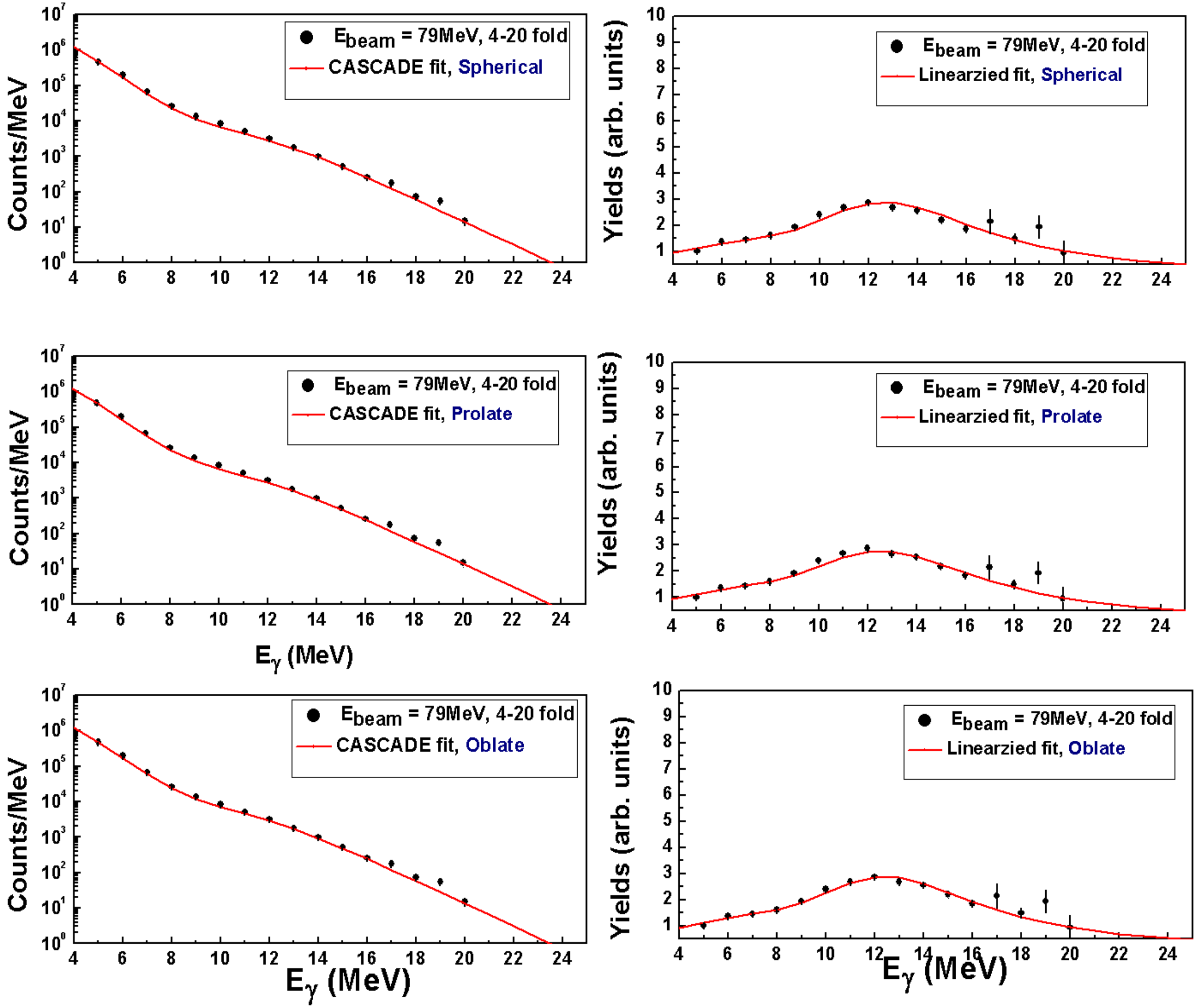
Inclusive spectrum for 65 MeV beam energy



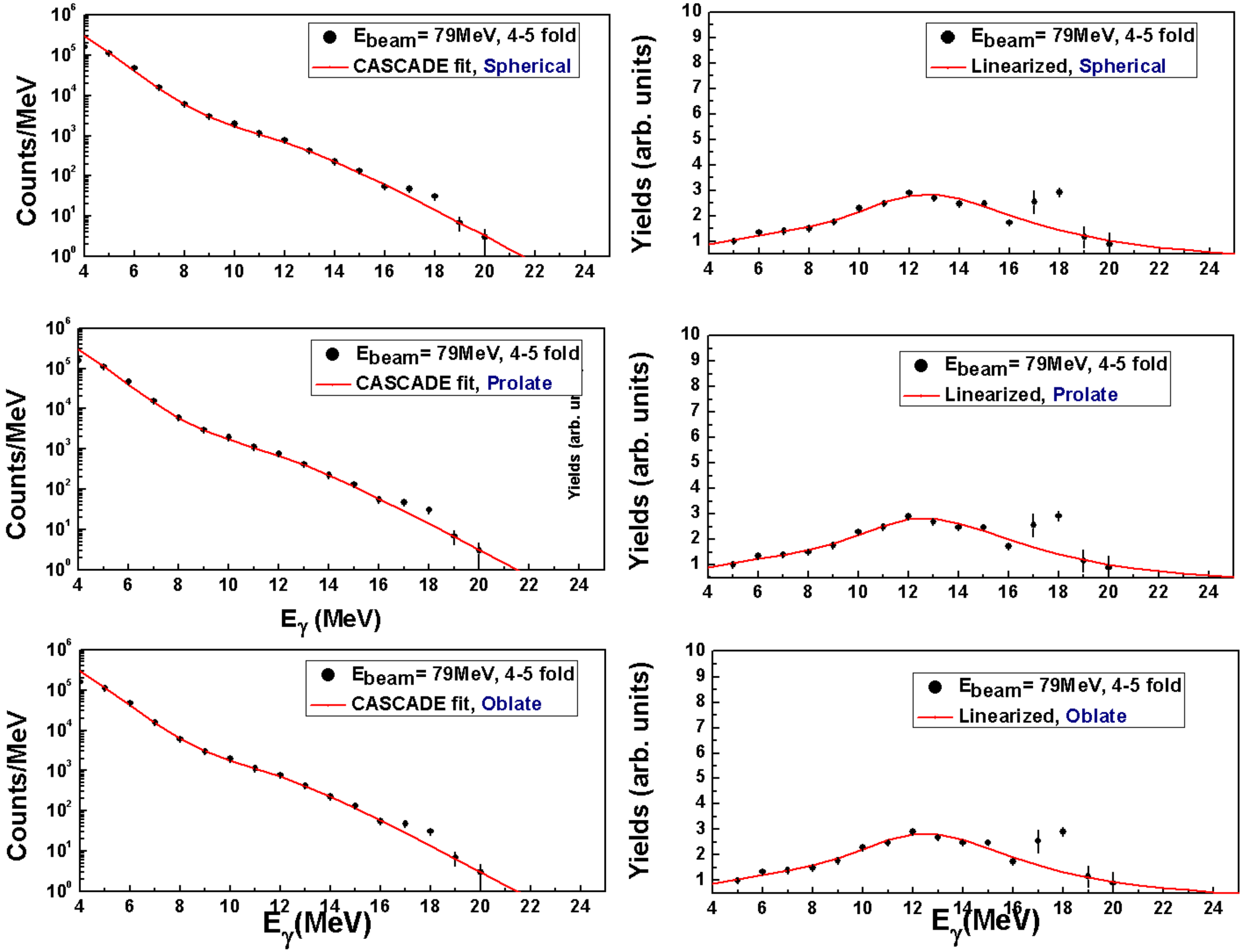
Low spin gated spectrum for 65 MeV beam energy



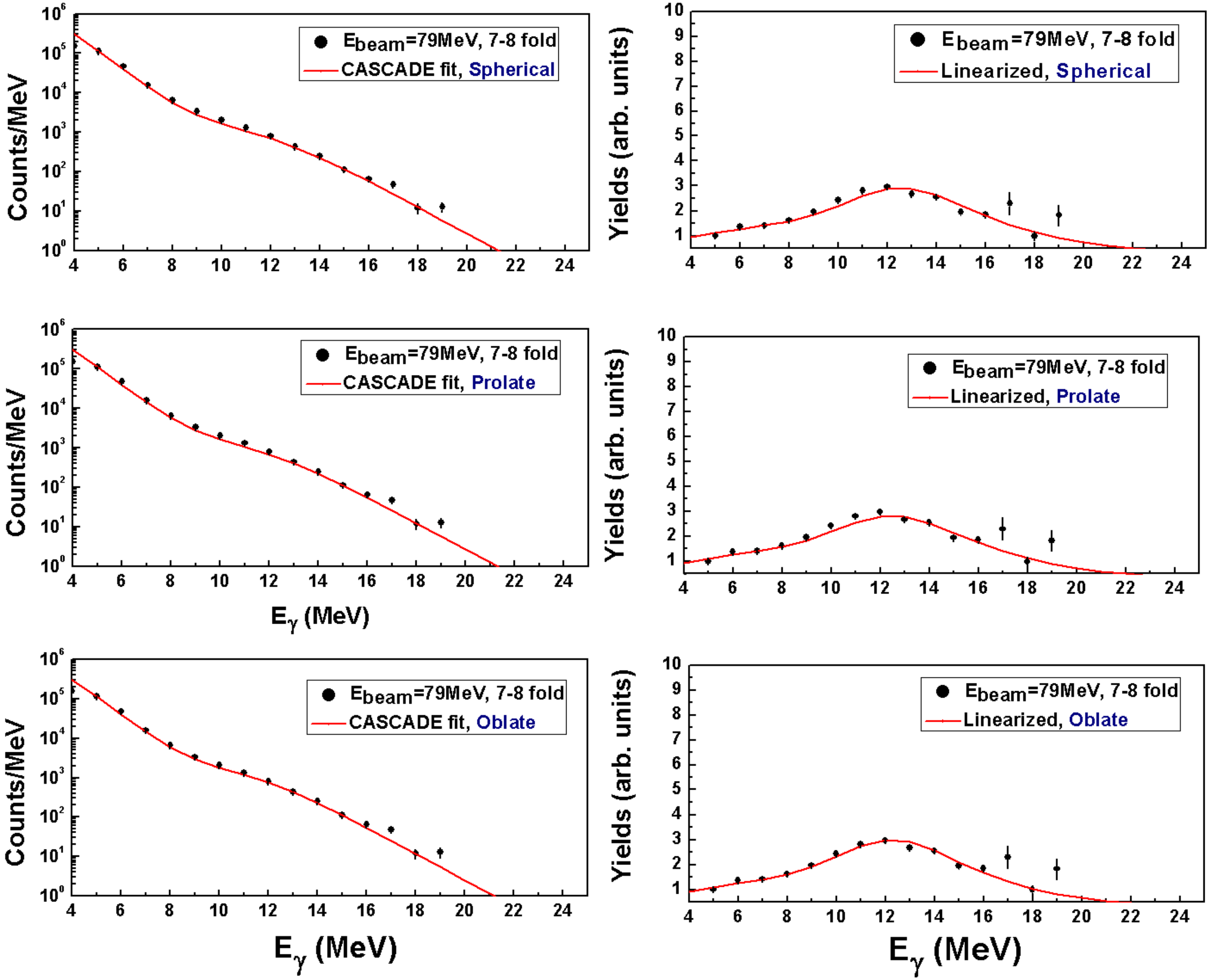
High spin gated spectrum for 65 MeV beam energy



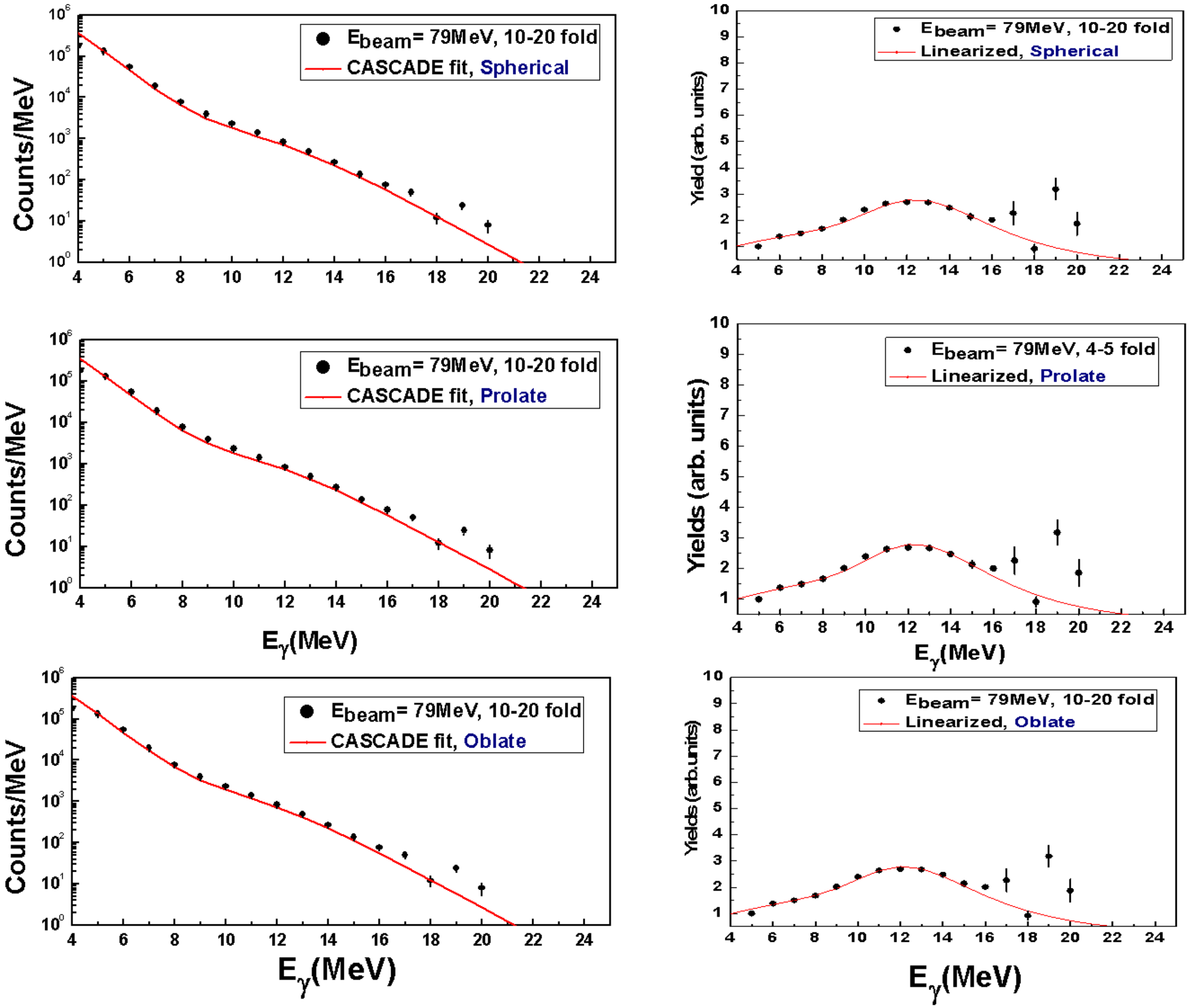
Inclusive spectrum for 79 MeV beam energy



Low spin gated spectrum for 79 MeV beam energy



High spin gated spectrum for 79 MeV beam energy



High spin gated spectrum for 79 MeV beam energy

^{192}Pt , 79MeV

4-20 fold

Shape	E1	Γ1	E2	Γ2
Spherical	13.3	10.0	-	-
Prolate	12.8	9.0	13.5	11.0
Oblate	12.8	9.0	13.8	11.5

4-5 fold <J>=10h

Shape	E1	Γ1	E2	Γ2
Spherical	13.3	10.0	-	-
Prolate	12.8	9.0	13.5	10.5
Oblate	12.8	9.0	13.8	11.5

7-8 fold <J>=20h

Shape	E1	Γ1	E2	Γ2
Spherical	13.3	9.0	-	-
Prolate	12.8	8.5	13.5	9.5
Oblate	12.8	7.9	13.5	9.9

10-20 fold <J>=26h

Shape	E1	Γ1	E2	Γ2
Spherical	13.3	9.8	-	-
Prolate	12.8	8.5	13.5	10.4
Oblate	12.8	9.0	13.8	10.8

65MeV

Shape	E1	Γ1	E2	Γ2
Spherical	13.3	9.5	-	-
Prolate	12.5	9.5	14.5	7.5
Oblate	12.5	9.5	14.5	4.5

4-20 fold

Shape	E1	Γ1	E2	Γ2
Spherical	13.3	9.5	-	-
Prolate	12.5	10.5	14.5	8.5
Oblate	12.5	10.5	14.5	4.5

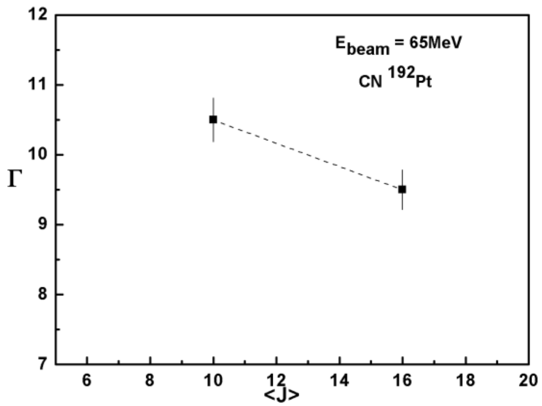
4-5 fold <J>=10h

Shape	E1	Γ1	E2	Γ2
Spheical	13.3	9.0	-	-
Prolate	12.5	9.5	14.5	8.5
Oblate	12.5	9.5	14.5	5.0

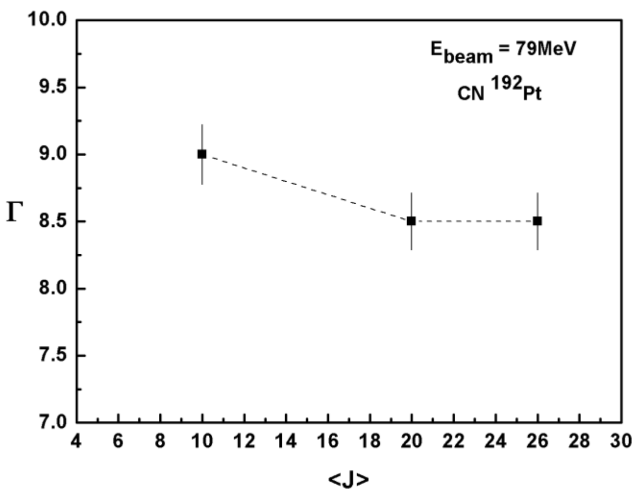
7-20 fold <J>=16h

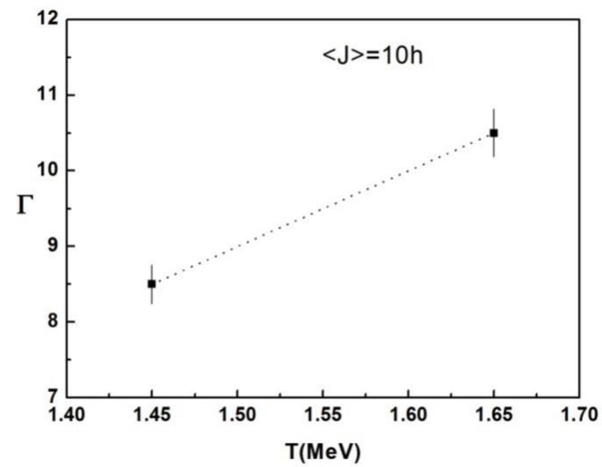
Salient observations from Statistical model analysis

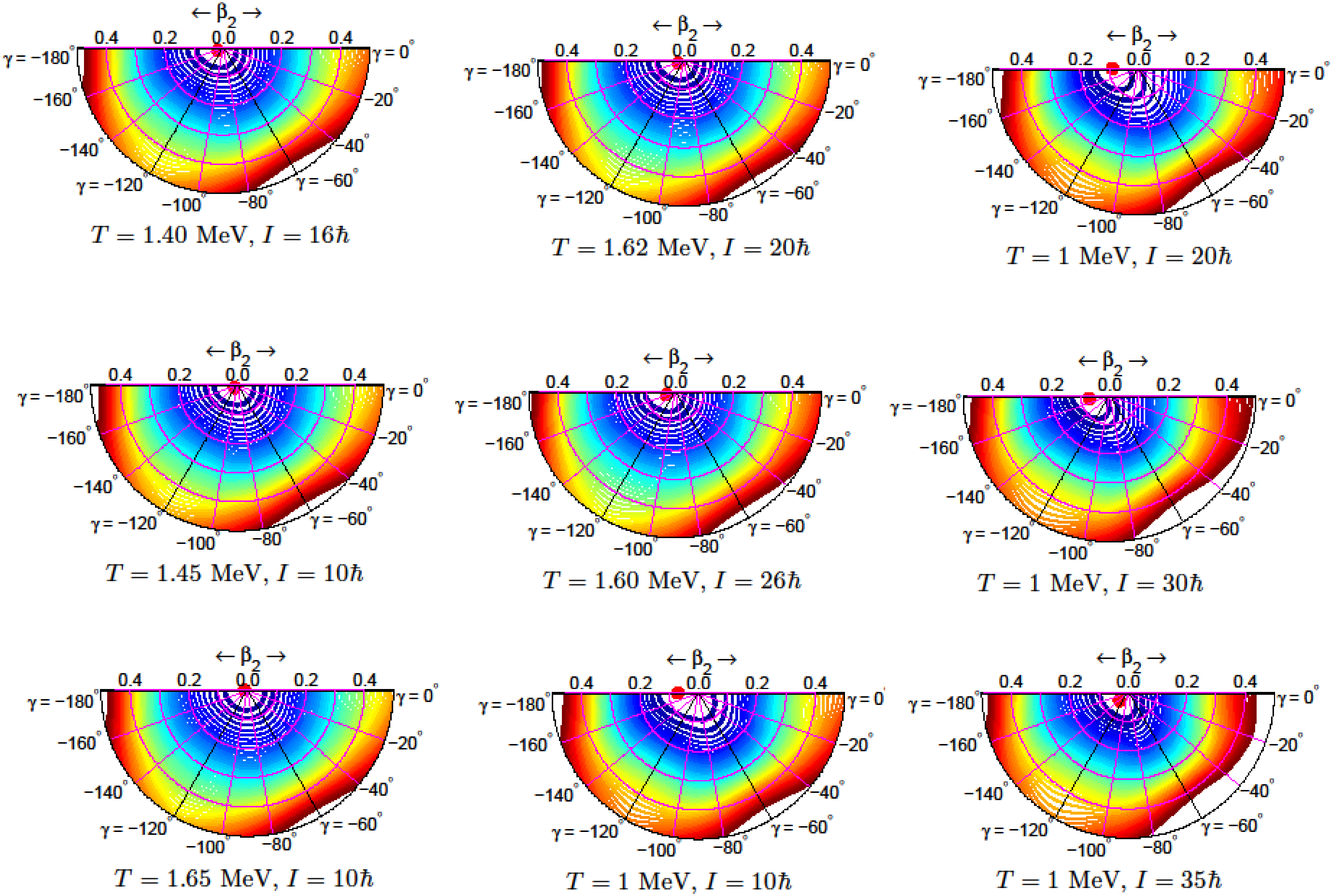
E_{beam} (MeV)	<J>		
65	10ħ	16ħ	
79	10ħ	20ħ	26ħ



- *The best fit (effective) widths seem to decrease with spin for given E_{beam}*
- *The best fit (effective) widths increase with temperature for given <J>*
- *The extracted deformation decreases with temperature for given <J> (~ .17 to ~ .08)*
- *The spectra for 65 MeV cannot be fitted with spherical shape*
- *Average Shape cannot be ascertained for 79 MeV data*

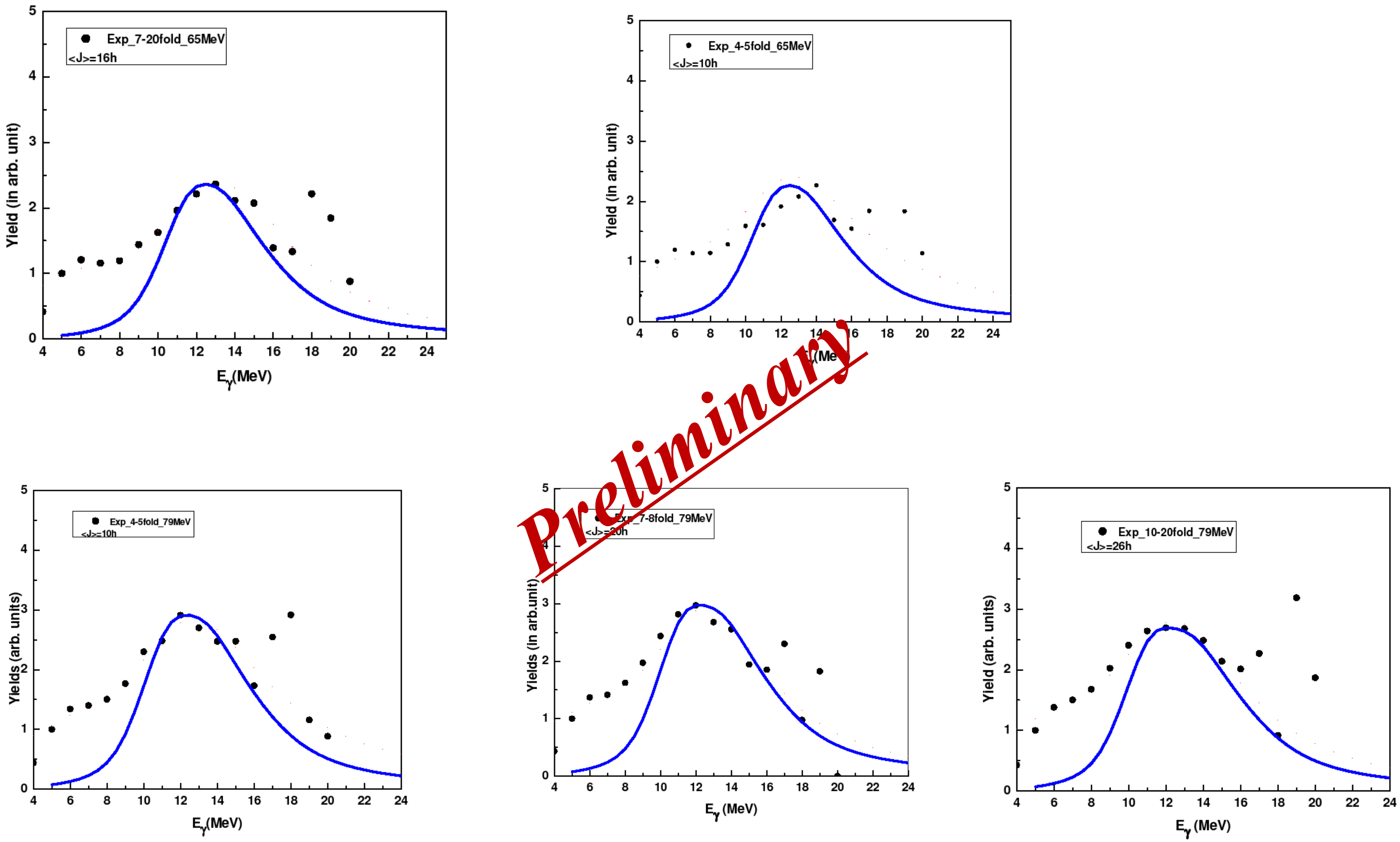






Finite temperature TSF calculations

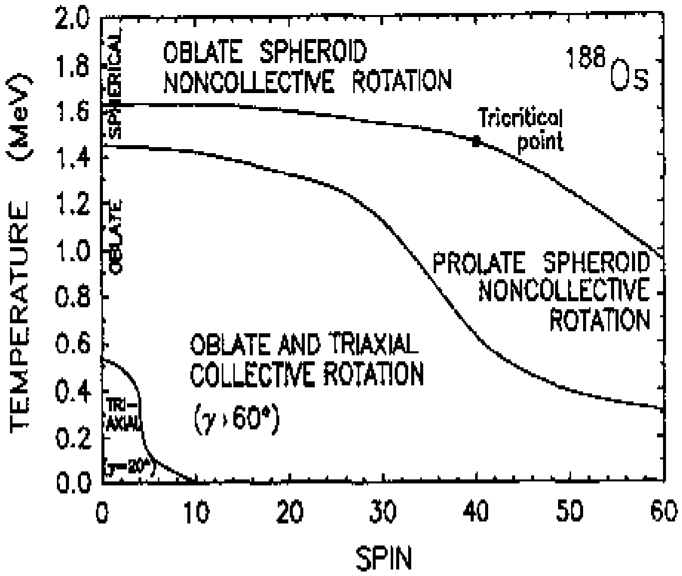
P. Arumugam et al., (2005)

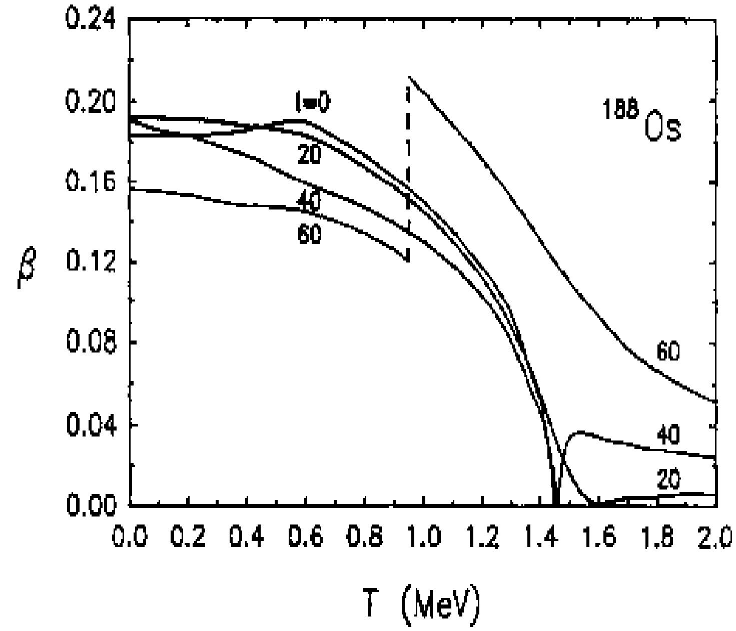


Calculated photo-absorption cross sections for the two beam energies and spin gates

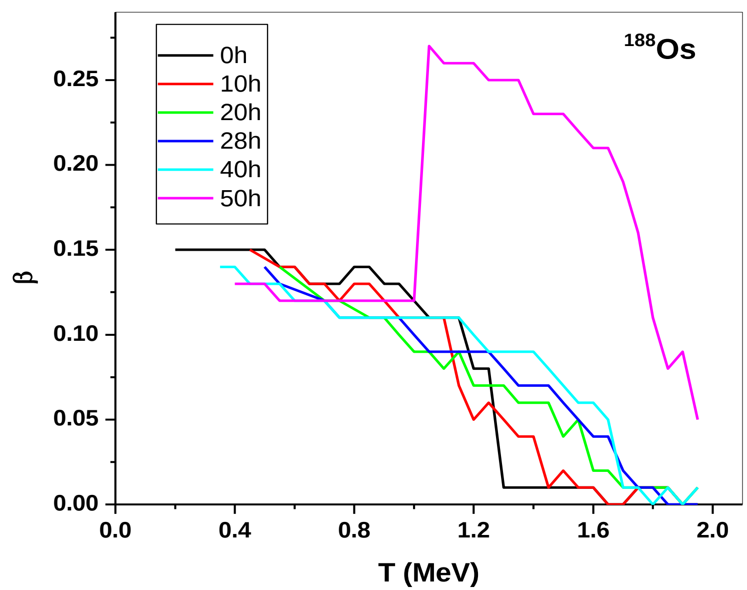
GDR Decay from ^{188}Os

A.L. Goodman, Nucl. Phys. A611, (1996)





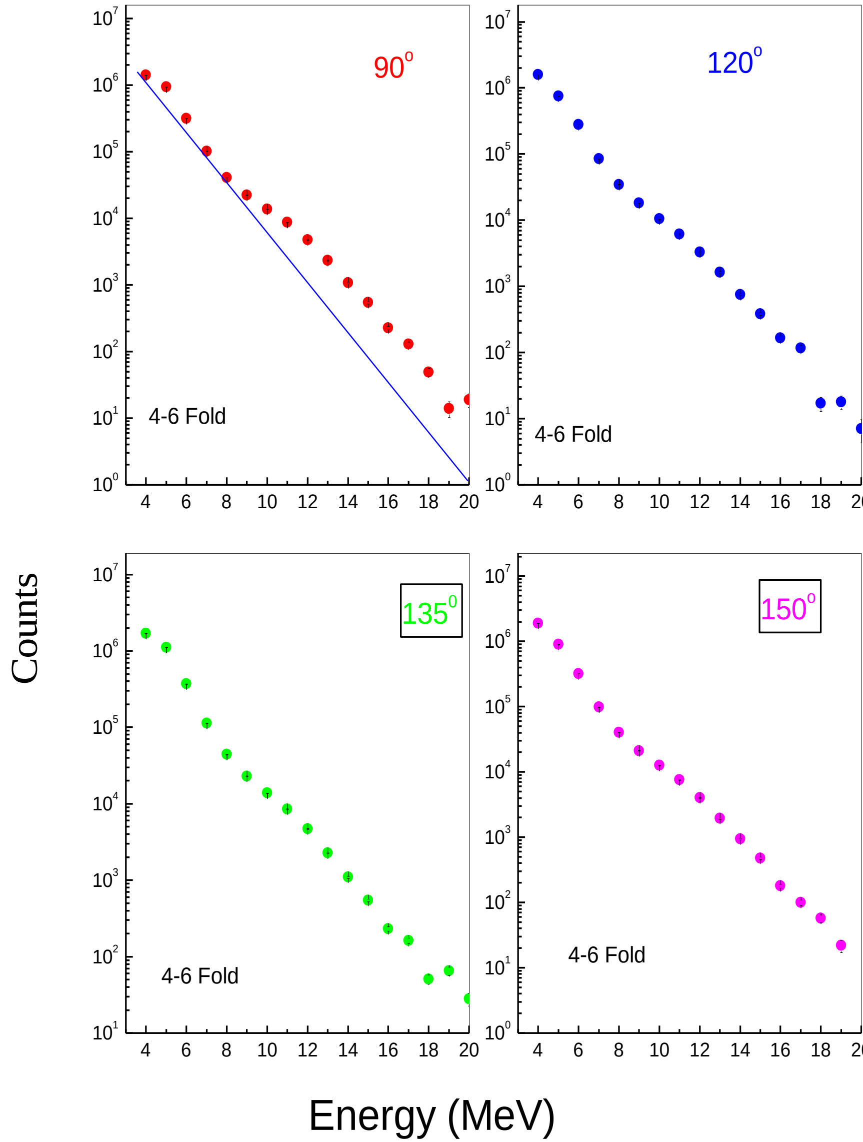
E_{beam} (MeV)	σ_{fusion} (mb)	E^* (MeV)	L_{max} (h)	<Erot> (MeV)	T_{eff} (MeV)
65	624	53	20	1.2	1.5
84	1326	71	37	3.8	1.8
73	718	57.5	30	2.45	1.6



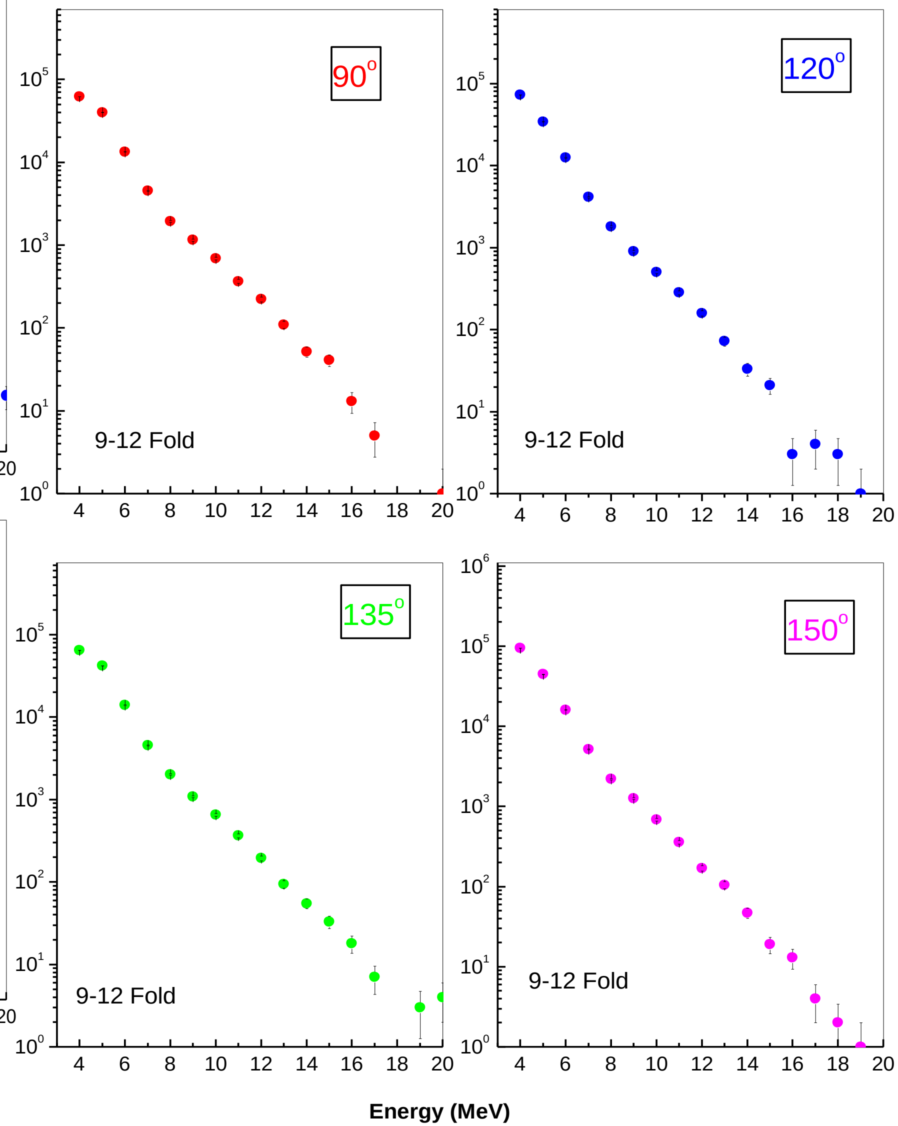
Aggarwal & Mazumdar

Spectra measured at 4 different angles

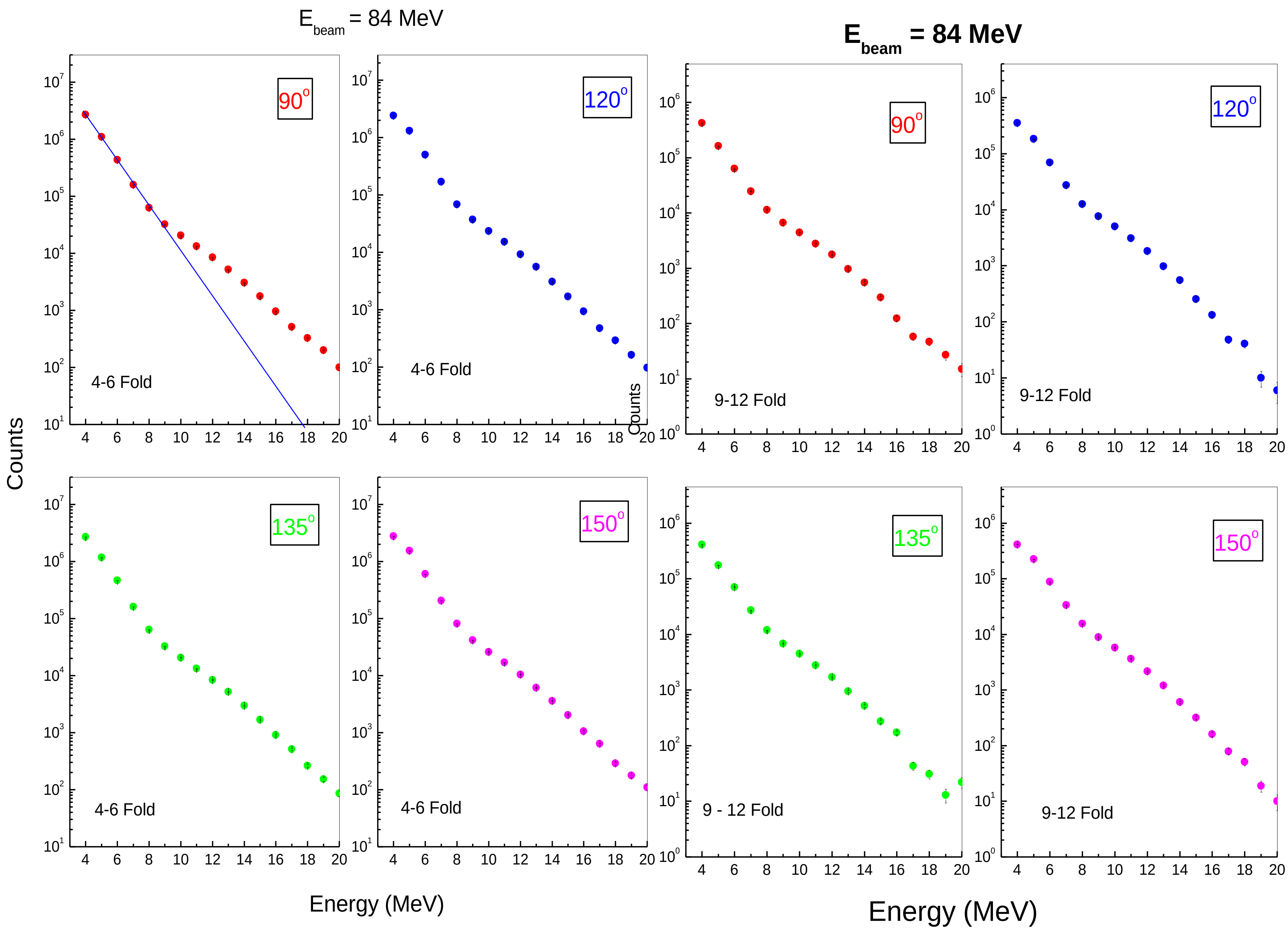
E_{beam} = 65 MeV



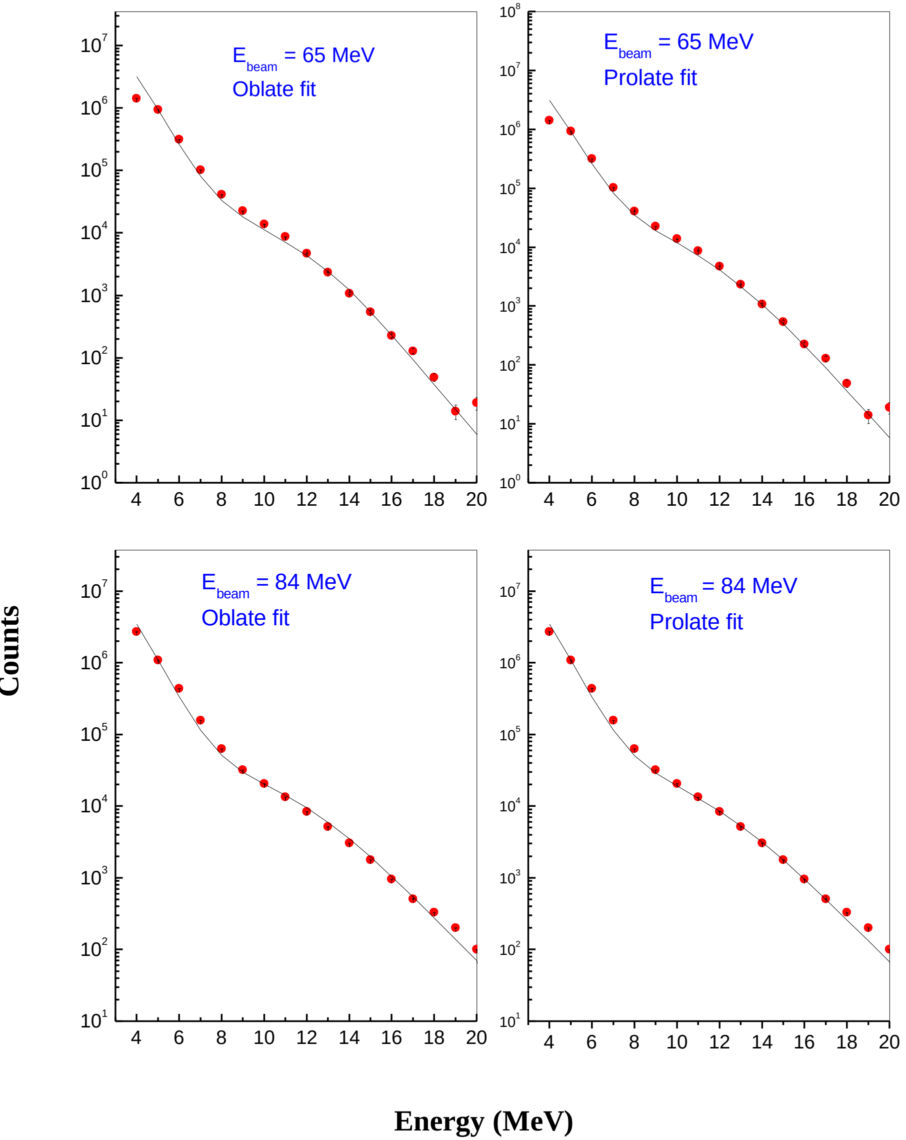
E_{beam} = 65 MeV

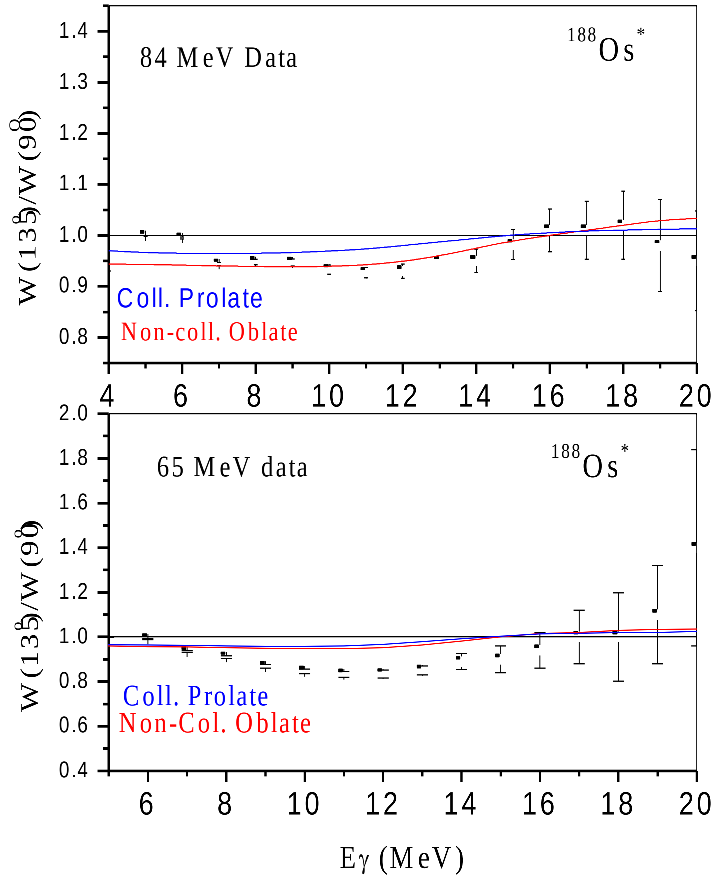


Spectra measured at 4 different angles



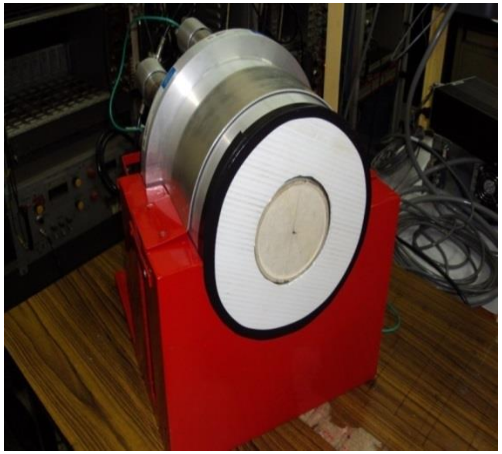
GDR Decay from ^{188}Os

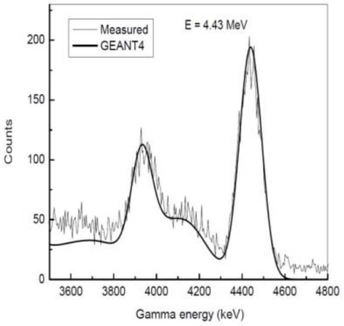




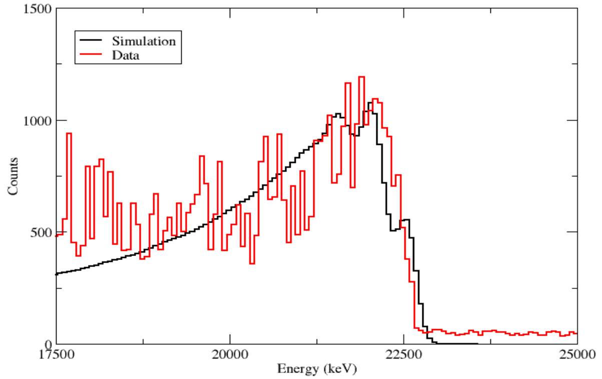
No apparent flip in the angular anisotropy pattern

GDR Decay from hot-rotating 196Hg



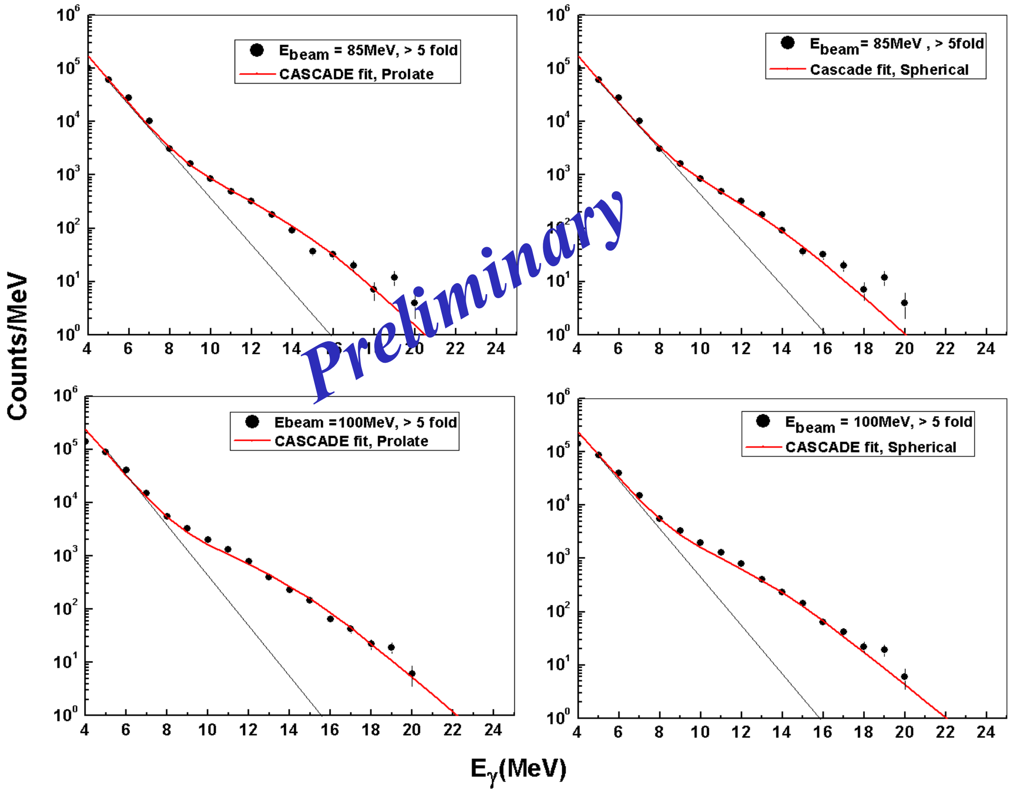


4.4 MeV spectrum



22.5 MeV spectrum

- **Measurements carried out at IUAC,New Delhi**
- **Reaction: $^{16}O + ^{180}Hf \quad ^{196}Hg^*$**
- **E_{beam} = 85 MeV & 100 MeV**
- **γ-rays measured in LaBr+NaI(Tl) assembly & 4π spin-spectrometer**



Summary

- Exclusive measurements of GDR spectra carried out for mass A~ 190 nuclei, namely, ^{194}Au, ^{188}Os, ^{192}Pt and ^{196}Hg
- Difference technique has been applied for ^{194}Au and ^{188}Os.
- GDR γ ray spectrum from ^{196}Hg measured with a combined assembly of $LaBr_3$:Ce+ NaI(Tl)
- Spin gated GDR γ-ray spectra measured with 4π spin-spectrometer for ^{192}Pt, ^{196}Hg and ^{144}Sm
- Angular distribution of GDR gamma rays shows complete reversal of pattern for ^{194}Au and ^{194}Pt indicating a clear signature of shape-phase transition .
  Similar shape transition not seen in case of ^{188}Os.
  (In case this phase exists in ^{188}Os, we might have missed the (T,J) window)

Future plans:

- To measure GDR spectra and angular distribution for ^{195}Hg and ^{191}Pt
- Further improvements in the Statistical model calculations

collaborators:

M.Dhibar, D.A. Gothe, P.B. Chavan
G.Anil. Kumar, A.K. Rine Kumar, P. Arumugam

As you set out for Ithaka
hope the voyage is a long one,
full of adventure, full of discovery. *C.P. Kavafy*

Acknowledgements

Y.K. Agarwal, C.V.K.Baba, C.S.Warke
P.F. Bortignon, A. Bracco, F. Camera, A.L. Goodman, M.K-Habior, M.N. Harakeh, A. Maj ,
P. Paul, H.R. Weller

Collective efforts of kindred spirits can not be measured by sum-rules.


Thank You