

NUCLEAR PHYSICS OVER THE YEARS: FROM THE HIGH SPIN ERA TO RARE ISOTOPES



SUPERDEFORMATION AT ATLAS: FROM THE ARGONNE-NOTRE DAME BGO ARRAY TO GRETINA



Argonne

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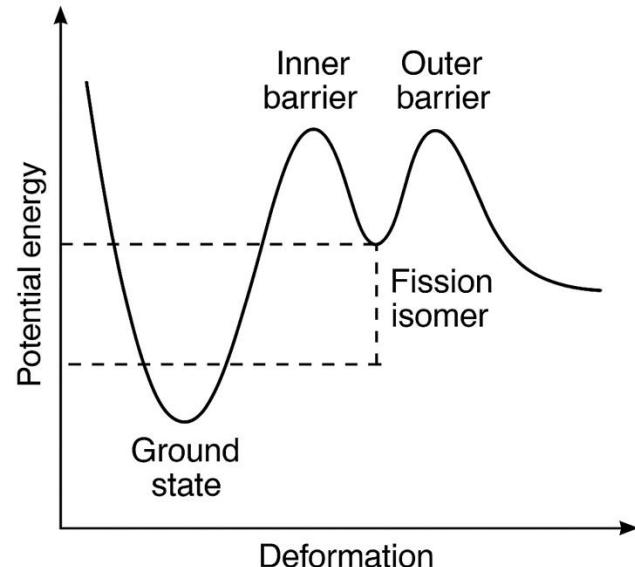
FISSION ISOMERS IN ACTINIDE NUCLEI

Experimental Discoveries

- First observed in early 1960s in neutron-induced fission of ^{236}U and other actinides
- Key signature: delayed fission events with μs – ms half-lives
- Detection: fast timing and fragment–fission coincidence techniques
- Excitation energies $\approx 2\text{--}3$ MeV above ground state, confirmed in ^{238}U , ^{240}Pu , ^{242}Cm
- Evidence for metastable, superdeformed states at large quadrupole deformation

Theoretical Interpretation

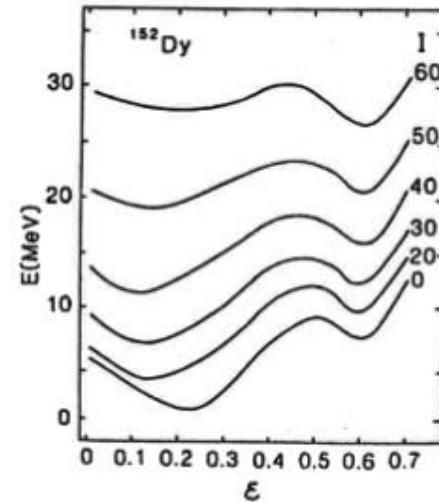
- Macroscopic–microscopic framework using Strutinsky shell-correction method
- Prediction of a second minimum at $\beta_2 \approx 0.6\text{--}0.8$ (superdeformed well)
- Double-humped fission barrier: inner and outer saddle points
- Shell effects add extra binding, stabilizing isomeric state
- Explains lifetimes and energies; motivated studies of super/hyperdeformation



THEORETICAL PREDICTIONS LEADING UP TO 1986

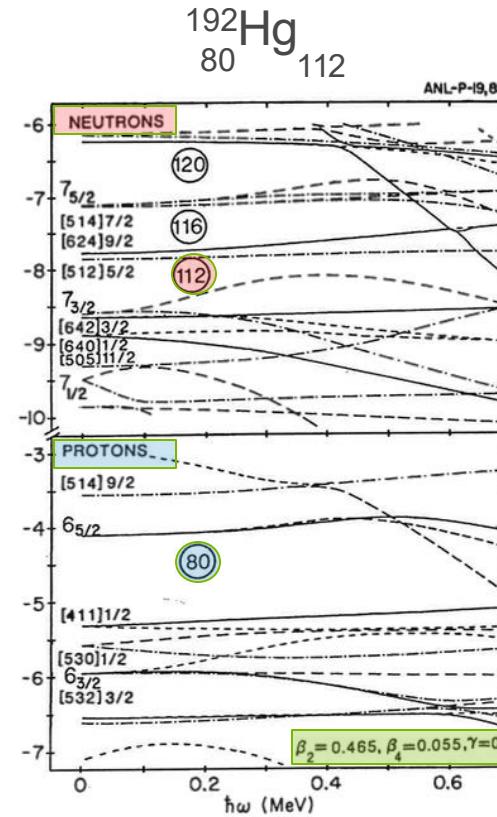
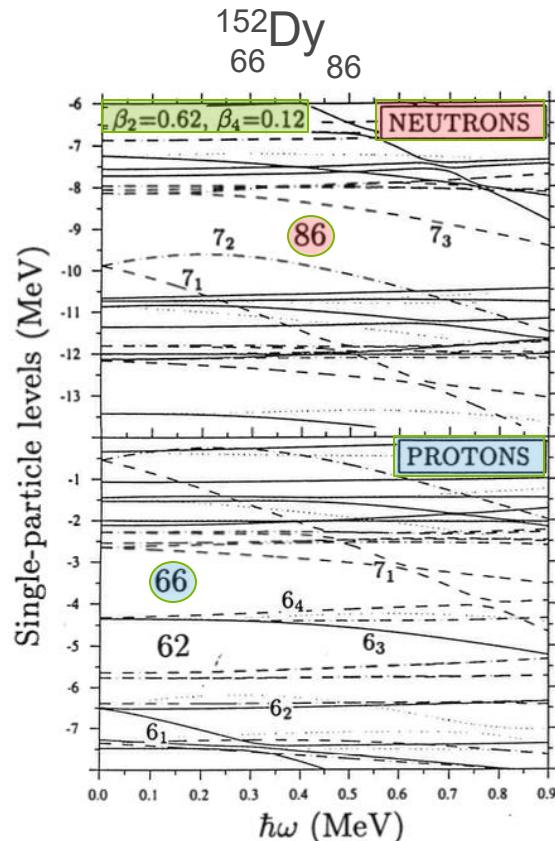
- 1970s: Strutinsky macroscopic–microscopic calculations revealed large shell gaps at $\beta_2 \approx 0.6$ (superdeformation).
- Late 1970s–Early 1980s: Cranked Nilsson–Strutinsky (CNS) model predicted superdeformed minima could support rotational bands.
- Predicted properties: constant γ -ray spacings, large transition quadrupole moments (≈ 17 – 20 b), and high spins ($I \approx 20$ – $60\hbar$).
- Global surveys identified $A \approx 150$ region (Dy, Gd) as promising for superdeformed band observation.
- These predictions motivated gamma-ray spectroscopy experiments with heavy-ion fusion reactions, using the newly developed gamma-ray spectrometers (TESSA, HERA, SPIN SPECTROMETER and ARGONNE-NOTRE DAME BGO FACILITY) to search for evidence of superdeformation.

Cranked Nilsson Strutinsky



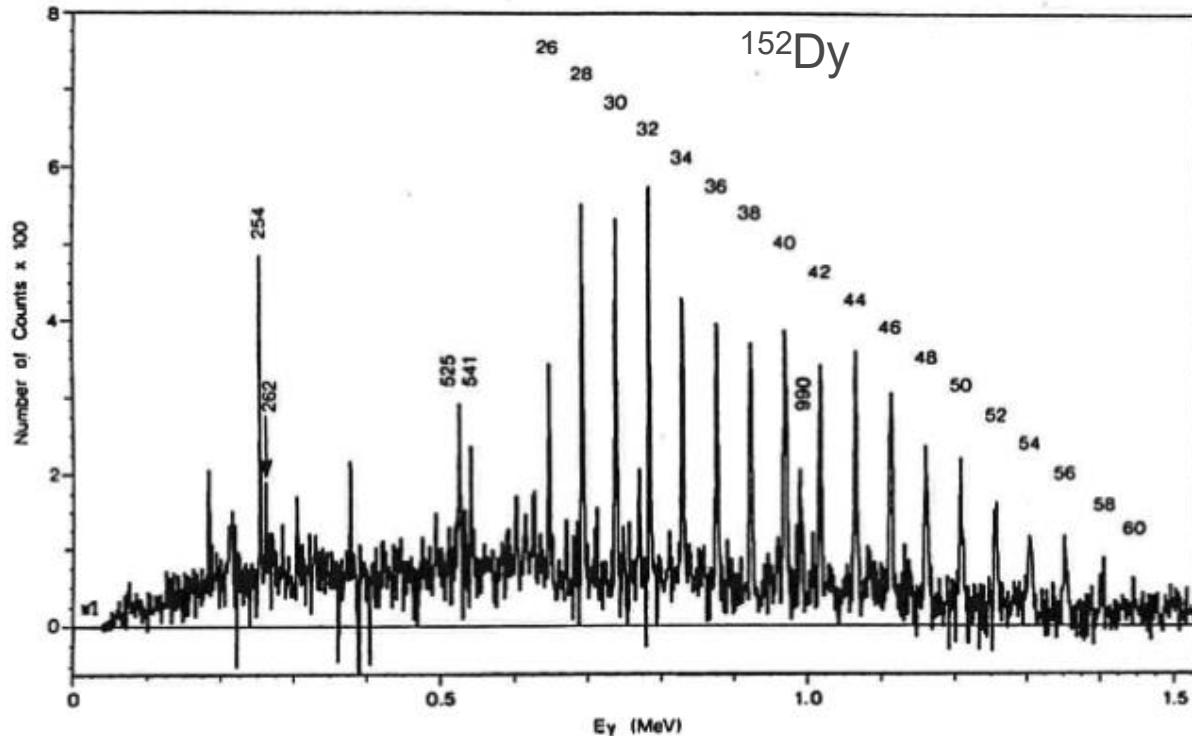
I. Ragnarson *et al.*, Nucl. Phys. **A 347**, 387 (1980)

SUPERDEFORMED SHAPE STABILIZED BY GAPS IN SP LEVELS



THE FIRST CASE OF SD ROTATIONAL BAND

P.J. Twin *et al.*, Phys. Rev. Lett **57**, 811 (1986)

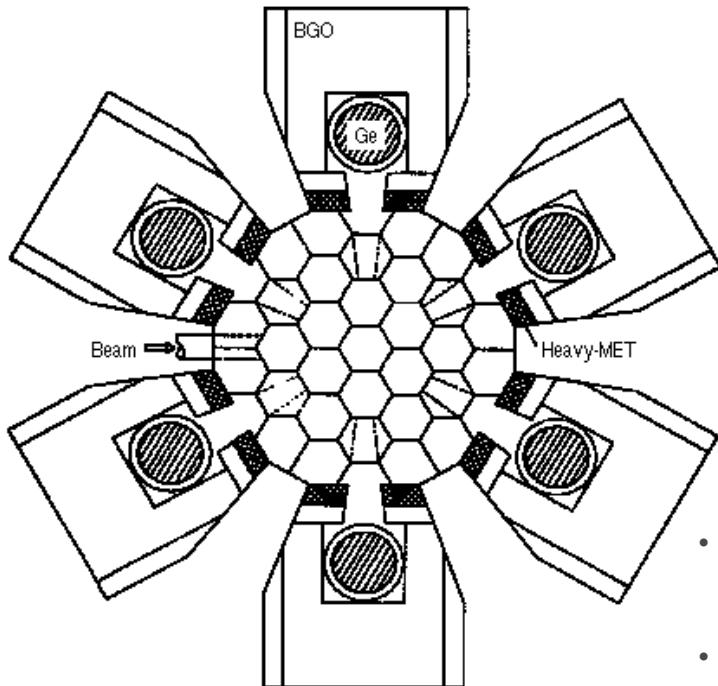


- 12 Compton Suppressed Ge Detectors (TESSA3) – Daresbury
- $\Delta E_\gamma \sim 47 \text{ keV}$
- $Q_t = 19 \pm 3 \text{ e}\text{b}$ $\beta_2 = 0.6$ (2:1 axis ratio)

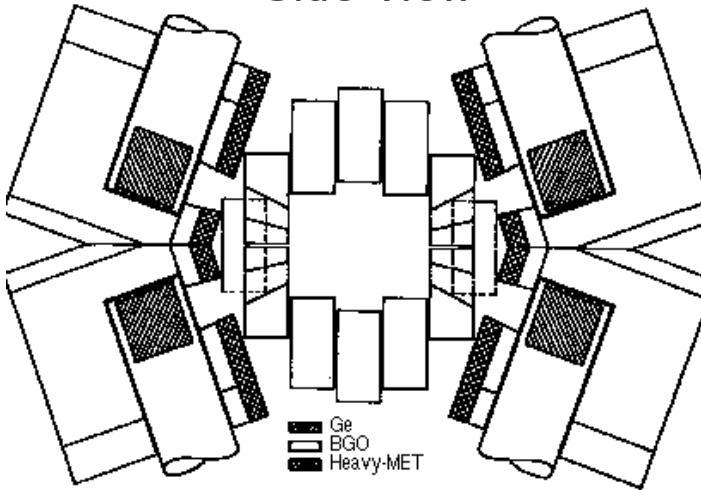
ARGONNE-NOTRE DAME GAMMA-RAY FACILITY

R. V. F. Janssens (ANL), T. L. Khoo (ANL), U. Garg (Notre Dame)

Top View



Side View

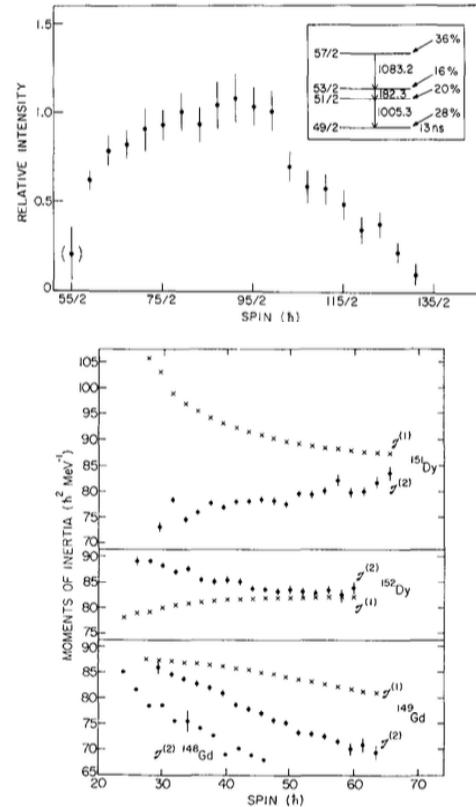
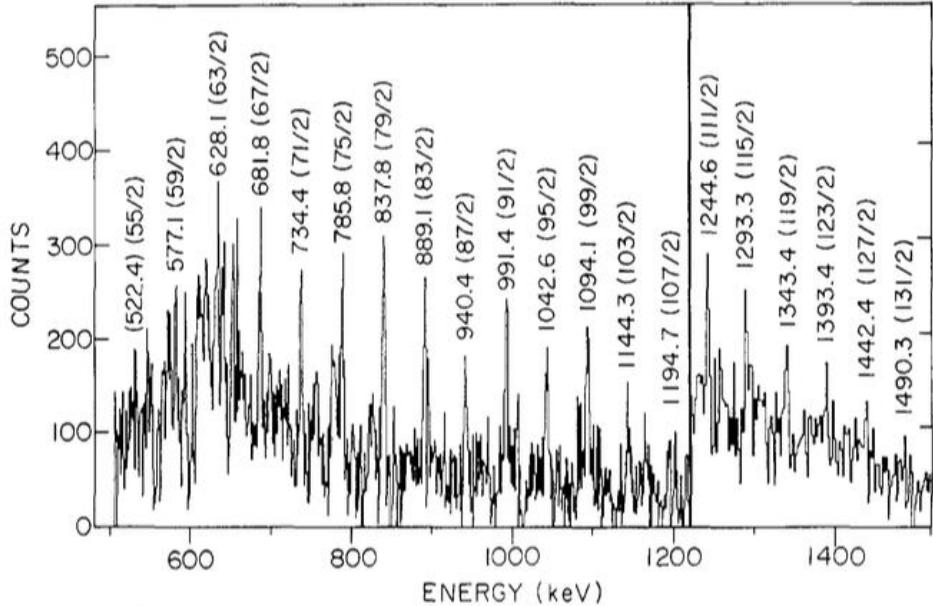


- Inner array of 50 hexagonal BGO detectors.
- 12 Compton suppressed HPGe detectors $\sim 20\%$ efficiency.



FIRST SD BAND FOUND AT ATLAS – ^{151}Dy

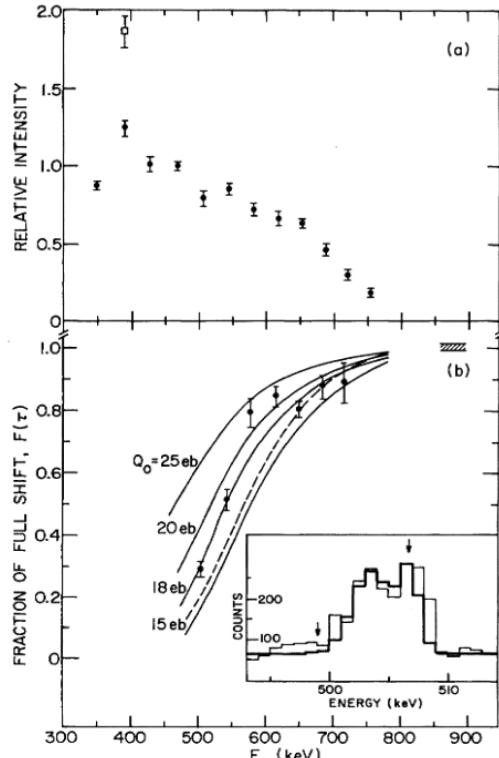
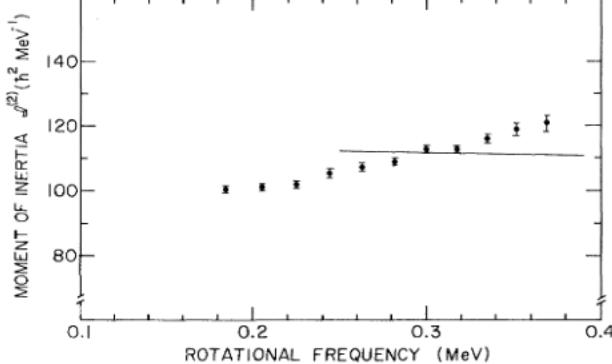
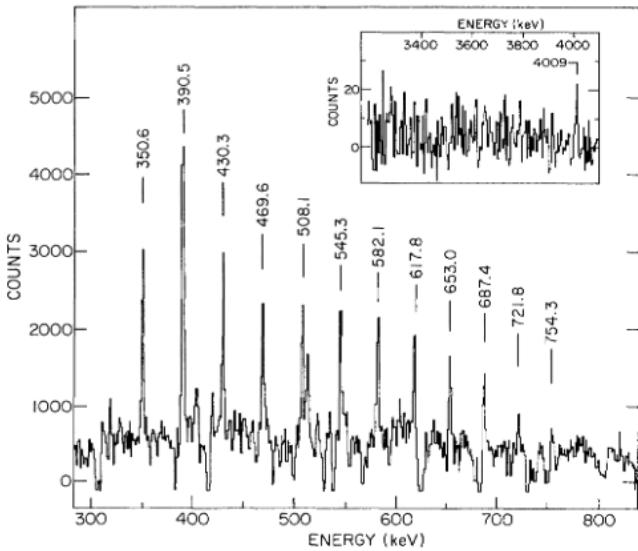
G.-E. Rathke, R.V.F. Janssens, et al., Phys. Lett. B 209, 177 (1988)



- $^{122}\text{Sn}(^{34}\text{S},5n)$ reaction at 174.5 MeV bombarding energy from ATLAS
- Argonne-Notre Dame BGO Facility gamma-ray facility (12 Compton Suppressed Ge detectors)

FIRST CASE IN THE A~190 REGION: ^{191}Hg

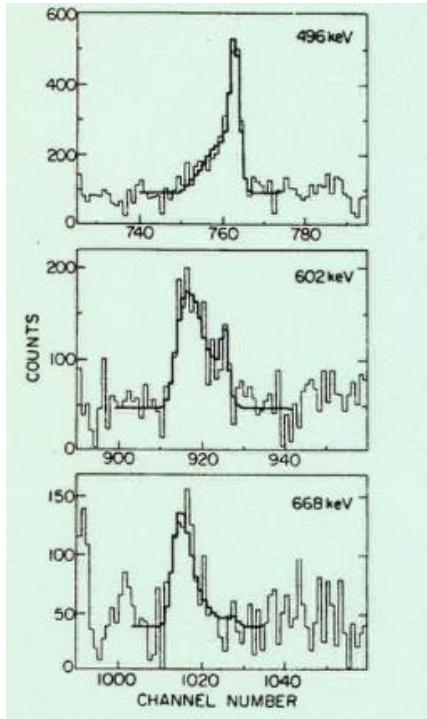
E.F. Moore *et al.*, Phys. Rev. Lett. **63**, 360 (1989)



- $^{160}\text{Gd}(^{36}\text{S},5n)$ reaction at 172 MeV from ATLAS
- Argonne-Notre Dame BGO Facility gamma-ray facility (12 Compton Suppressed Ge detectors)
- R. R. Chasman *et al.*, Phys. Lett. B **219**, 227 (1989)

LIFETIME MEASUREMENTS IN THE SUPERDEFORMED BAND OF ^{192}Hg

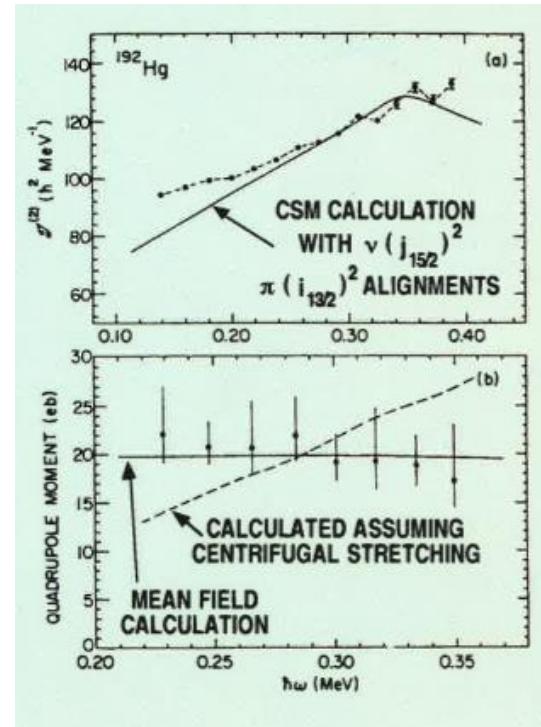
E.F. Moore, R.V.F. Janssens, *et al.*, Phys. Rev. Lett. 64, 3127 (1990)



- Target: $990 \mu\text{g}/\text{cm}^2$ ^{160}Gd backed by $14 \text{ mg}/\text{cm}^2$ Au
- Reaction: $^{36}\text{S}(\text{ }^{160}\text{Gd}, 4\text{n})\text{ }^{192}\text{Hg}$
- Spectrometer: ANL-Notre Dame γ -ray facility.

TABLE I. Summary of lifetime, $B(E2)$, and transition quadrupole moment information for the SD band in ^{192}Hg .

E_γ (keV)	τ (ps)	$B(E2)$ (W.u.) ^a	Q_t (e b)	$(Q_t)_{\text{SF}}$ (e b) ^b
458.4	0.234(75)	$2700(\pm 120)$	$22.0(\pm 2)$	$26(\pm 3)$
495.9	0.184(40)	$2310(\pm 44)$	$20.6(\pm 2)$	> 24
532.0	0.129(45)	$2310(\pm 120)$	$20.6(\pm 2)$	$17(\pm 1)$
567.5	0.083(24)	$2590(\pm 100)$	$21.8(\pm 2)$	$16(\pm 3)$
602.0	0.080(20)	$2000(\pm 40)$	$19.1(\pm 2)$	$14(\pm 3)$
634.9	0.060(24) ^c	$2040(\pm 120)$	$19.3(\pm 2)$	> 8
668.2	0.049(13)	$1930(\pm 70)$	$18.7(\pm 2)$	$15(\pm 3)$
700.0	0.046(20)	$1630(\pm 120)$	$17.2(\pm 2)$	$9(\pm 3)$
730.4				
761.8	$< 0.04^d$	> 1500	> 6	...
791.9				

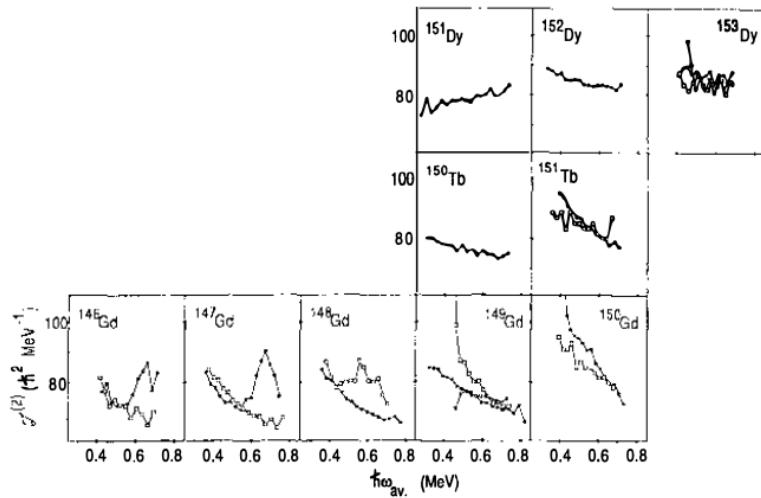


D. Ye *et al.*, PRC 41 (1990) R13 (^{192}Hg)
M. A. Riley *et al.*, NPA 512 (1990) 178 (^{194}Hg)

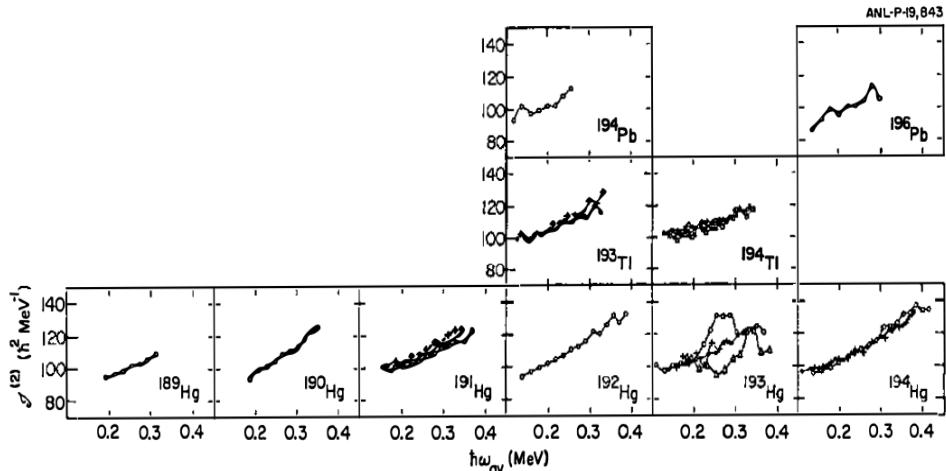
SUPERDEFORMED BANDS IN A~150 AND A~190 REGION CIRA 1993

R.V.F. Janssens and T.L. Khoo, Annu. Rev. Nucl. Part. Sci. 41, 321 (1990)

A~150 SD BANDS



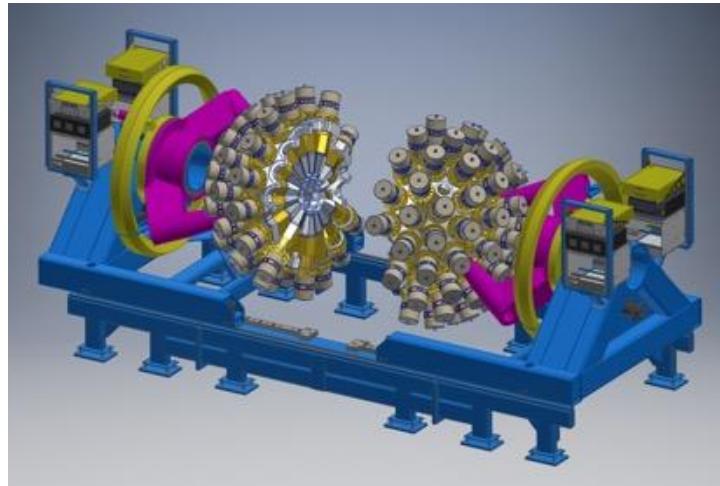
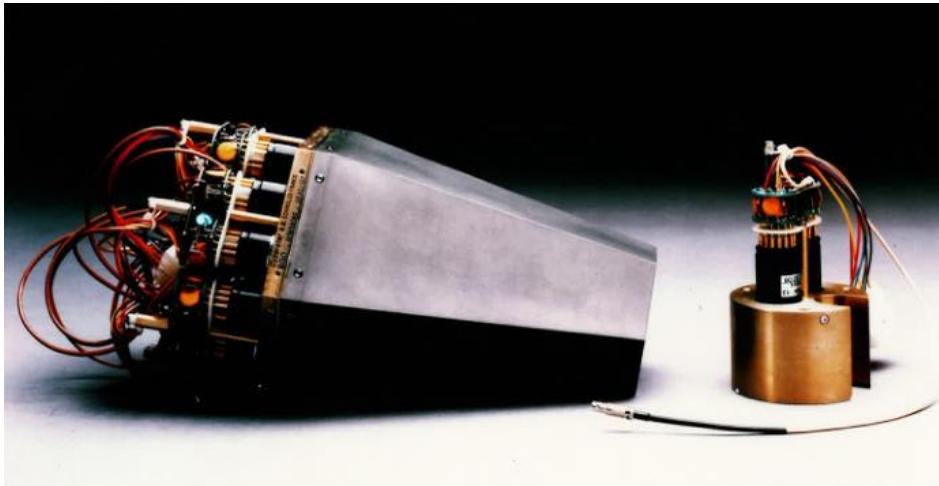
A~190 SD BANDS



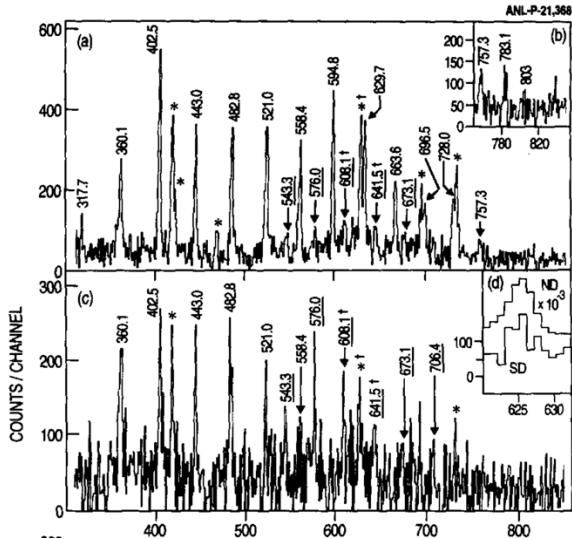
Can the behavior of these bands be understood without knowing excitation energies, spins and parities?

THEN CAME GAMMASPHERE

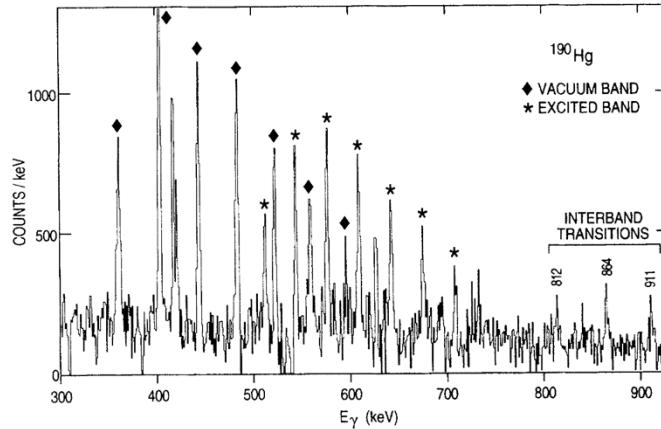
- ANL procured and tested the BGO Compton Suppressors for the project
- The construction of GS was led by LBNL and GS initially operated at the 88-inch cyclotron – Nominally 110 CS Ge detectors (~10% eff. @ 1 MeV)
- ANL currently hosts the device at ATLAS
- Gammasphere operates with digital electronics (GRETINA hardware) – all of which sit on the support structure (no longer tethered to data shack)



OPPORTUNITY TO LOOK AT THE SD WELL WITH A BETTER MICROSCOPE: GAMMASPHERE AND EUROGAM



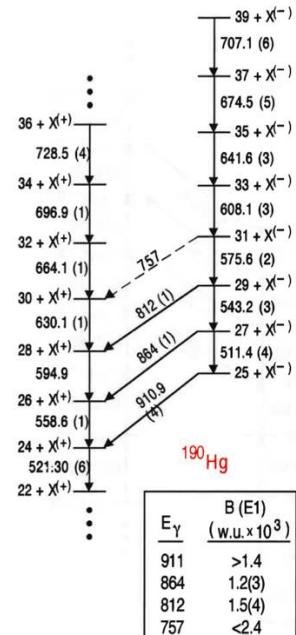
- Gammasphere Early Implementation
32 HPGe detectors
- B. Crowell *et al.*, PLB 333 (1994) 320.



- Eurogam Phase II
54 HPGe detectors

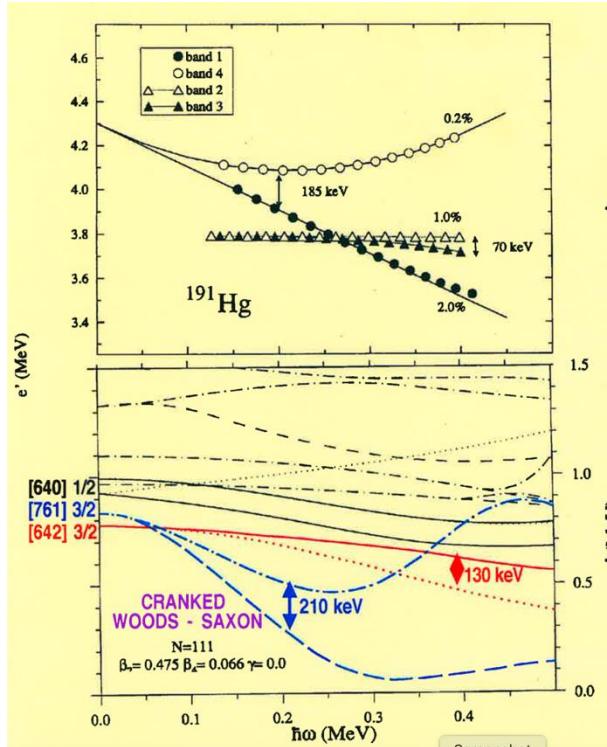
B. Crowell *et al.*, PRC 51 (1995) R1599

190Hg



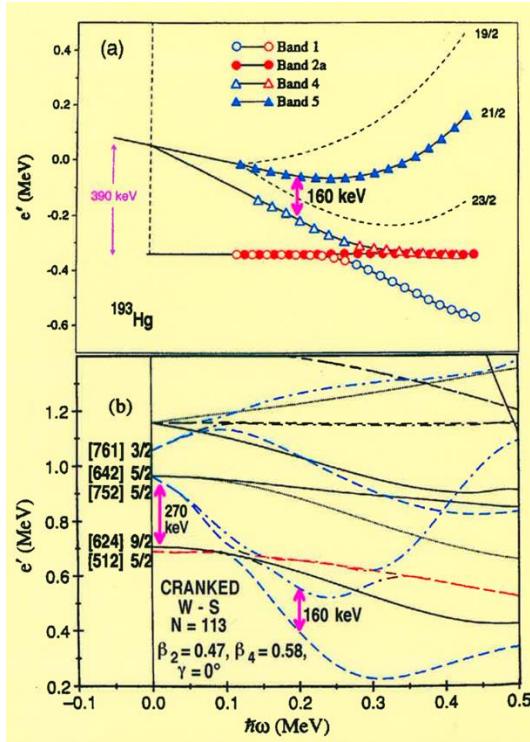
NEW ARRAYS ALLOWED FOR MORE DETAILED SPECTROSCOPY

M.P. Carpenter et al, Phys. Rev. C 51 (1995) 2400



Gammasphere

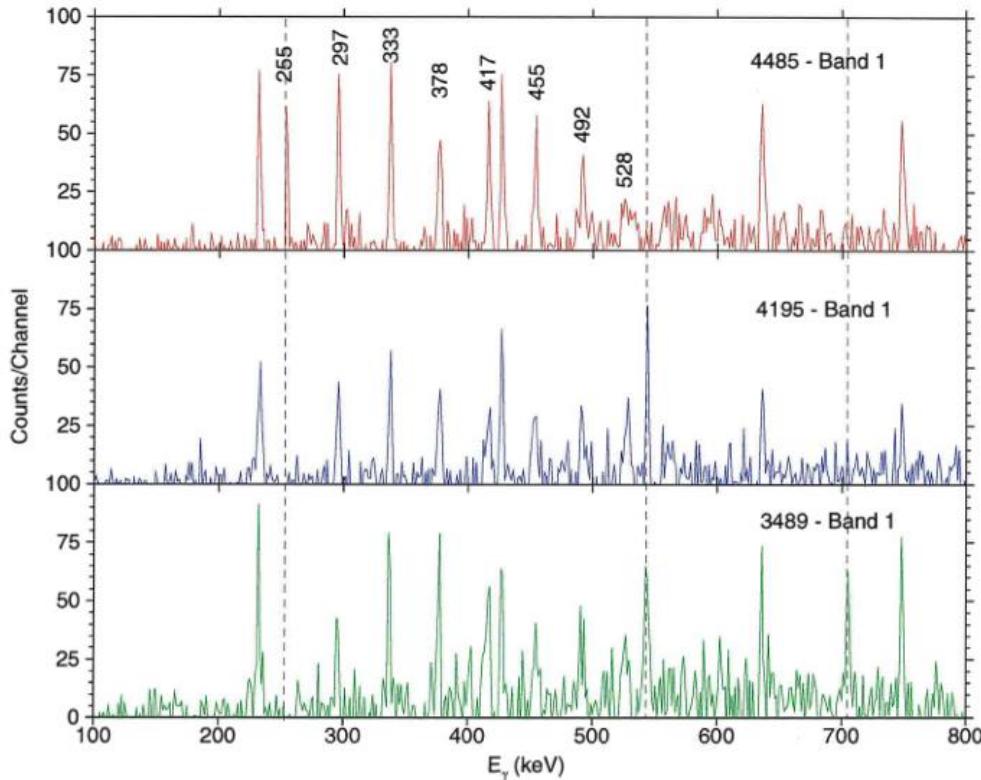
M.P. Joyce et al, Phys. Rev. C 51 (1995) 2400



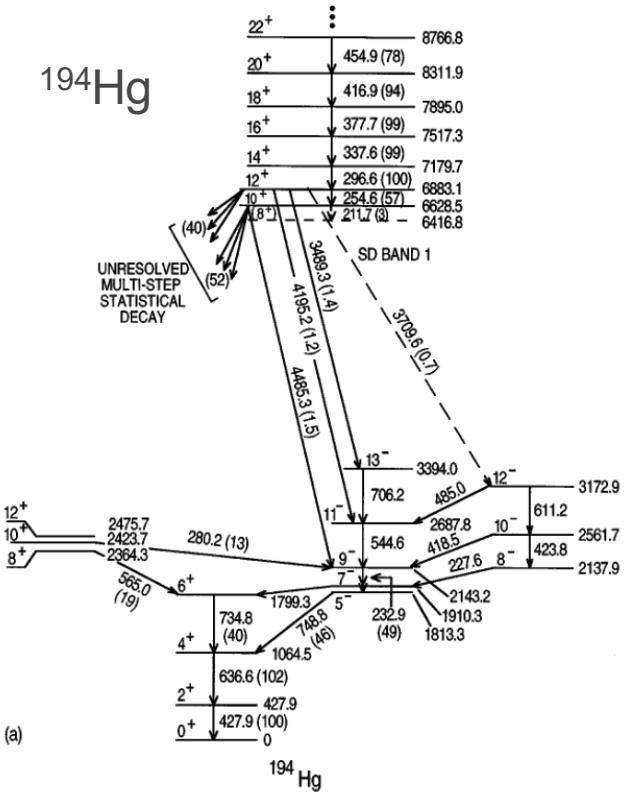
EUROGAM

FINDING THE LINKS FROM SD TO ND BANDS

T.L. Khoo, M.P. Carpenter *et al.*, Phys. Rev. Lett. **76** (1996) 1583

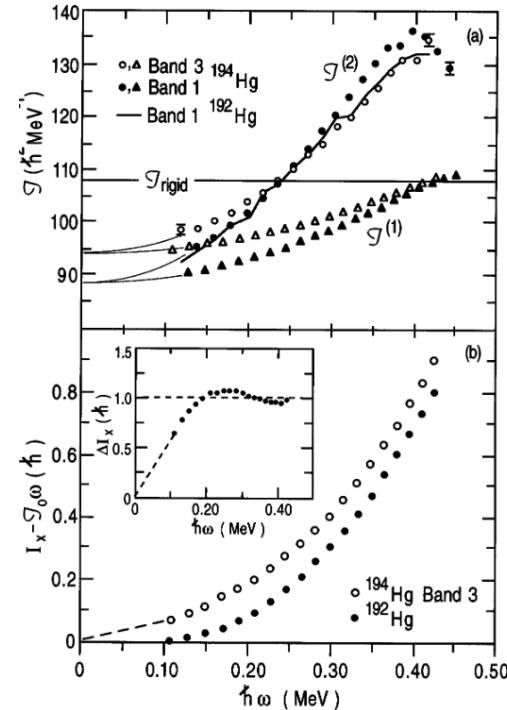
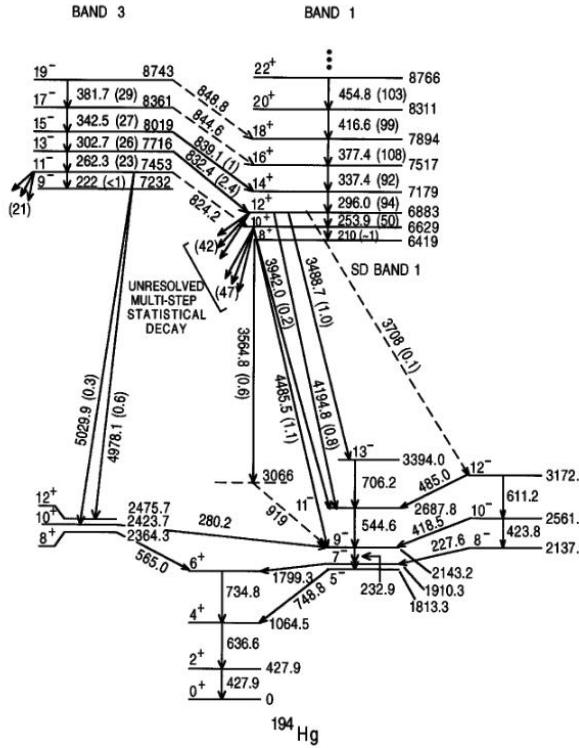
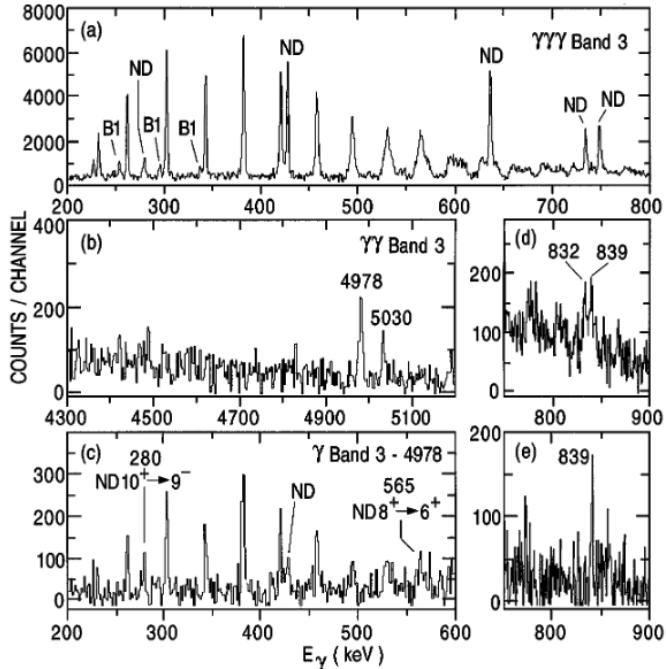


(a)



^{194}Hg Excited Bands

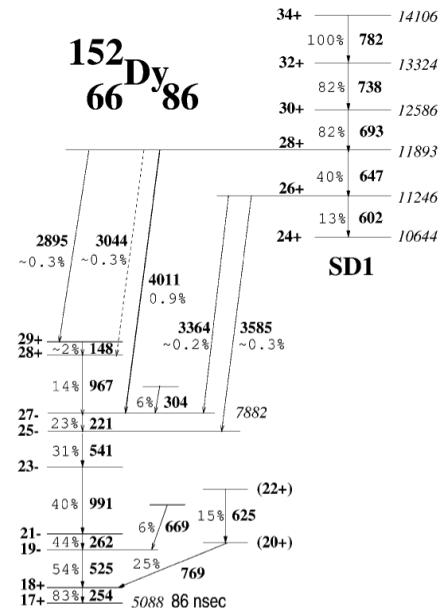
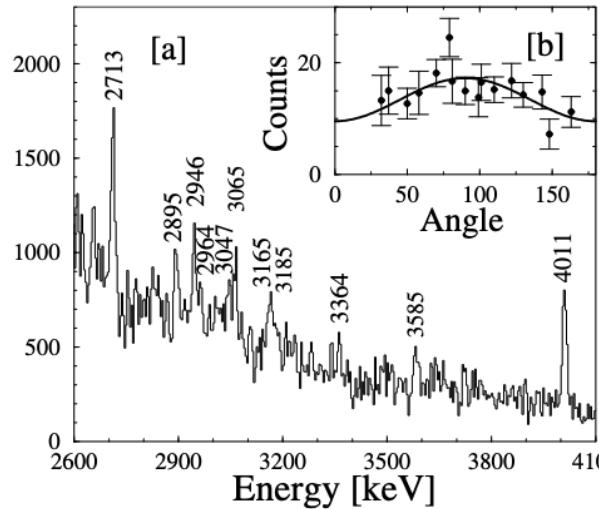
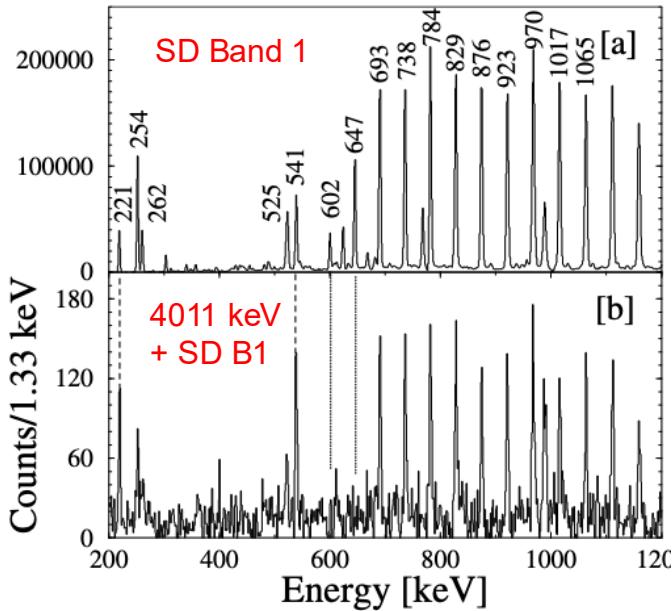
G. Hackman, T.L. Khoo, M.P. Carpenter *et al.*, Phys. Rev. Lett. **79**, 4100 (1997)



- Band 3 decays to Band 1 via E1 – consistent band built on octupole phonon state

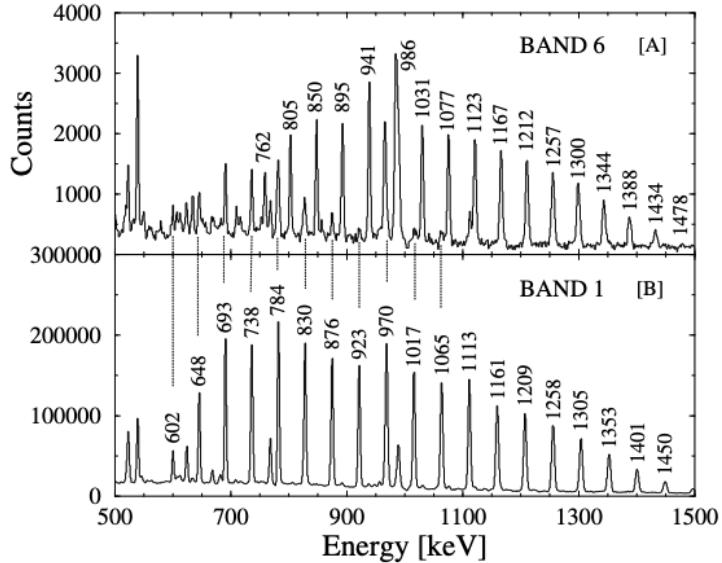
DECAY OUT OF ^{152}Dy SD BAND 1

T. Lauritsen et al., Phys. Rev. Lett., 042501 (2002)

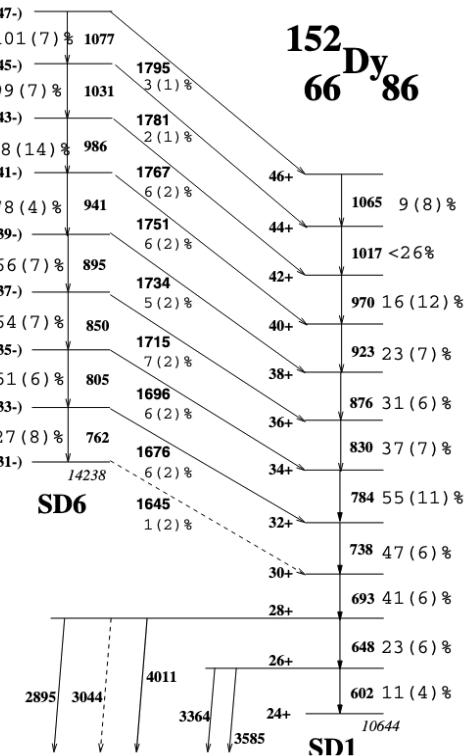
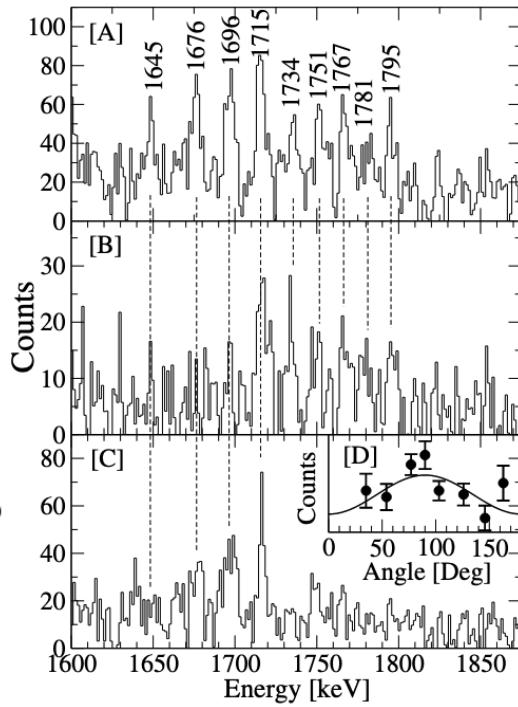


^{152}Dy – DECAY OF SD BAND 6 TO SB BAND 1

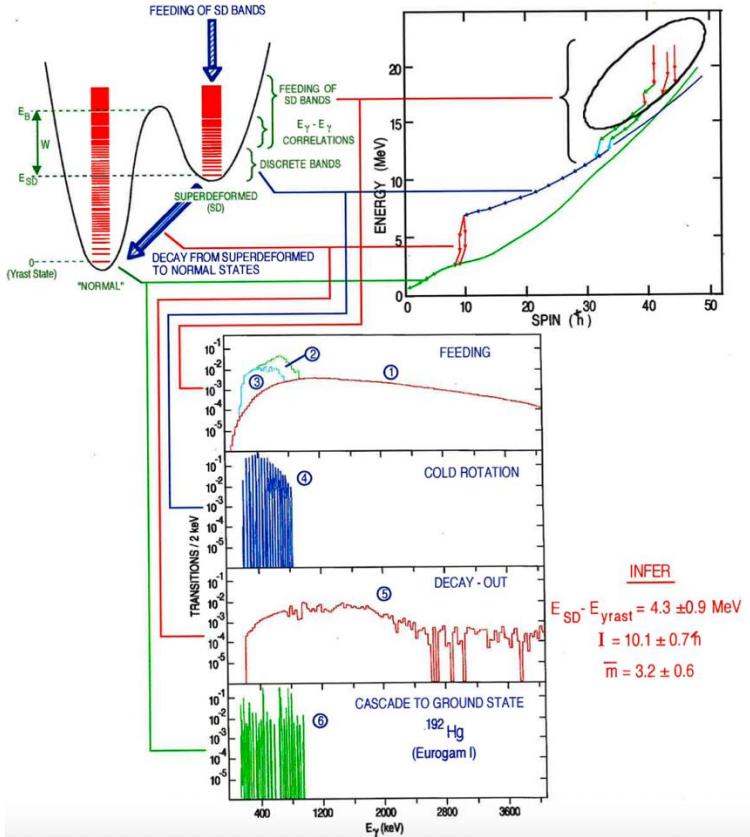
T. Lauritsen *et al.*, Phys. Rev. Lett. **28**, 282501 (2002)



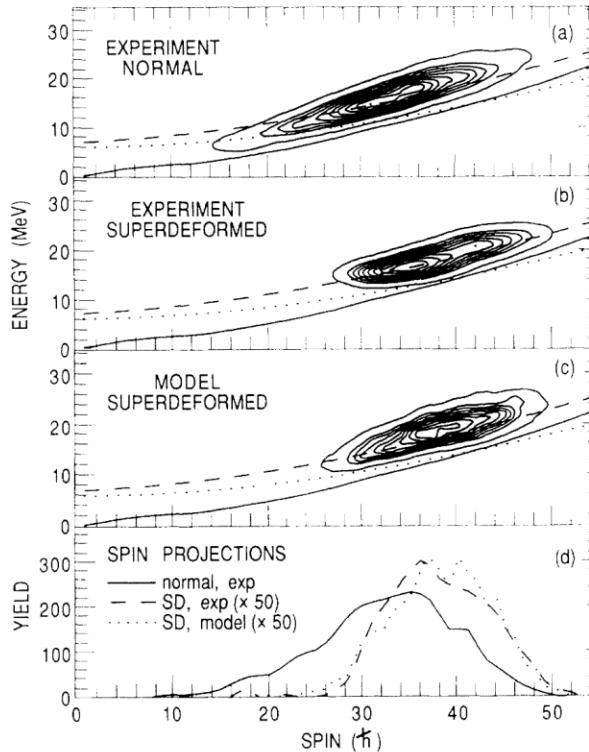
E_γ (keV)	Branching ratio	Partial half-life (fs)	$B(E1)$ (W.u. 10^{-4})	$B(M1)$ (W.u. 10^{-2})
1751	0.08(3)	130	4.9	4.6
1734	0.08(3)	169	3.9	3.7
1715	0.11(3)	152	4.5	4.2
1696	0.12(4)	185	3.8	3.6
1676	0.22(10)	331	2.2	2.1



FEEDING AND DECAY OF SD BANDS (^{192}Hg)



R. G. Henry *et al.*, PRL 73 (1994) 777 (Eurogam)



T. Lauritsen *et al.*, PRL 69 (1992) 2479
(Argonne-Notre Dame gamma-ray facility)

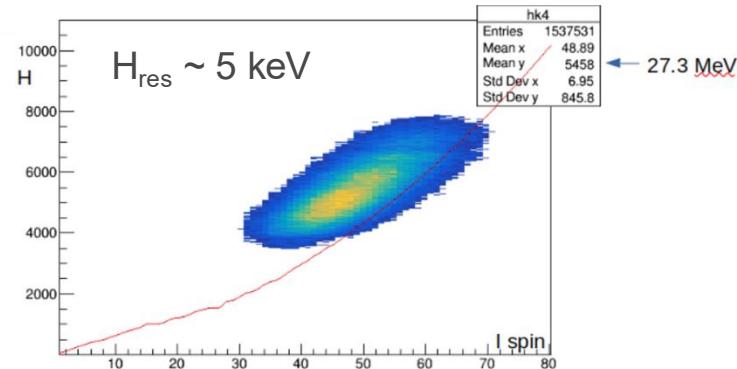
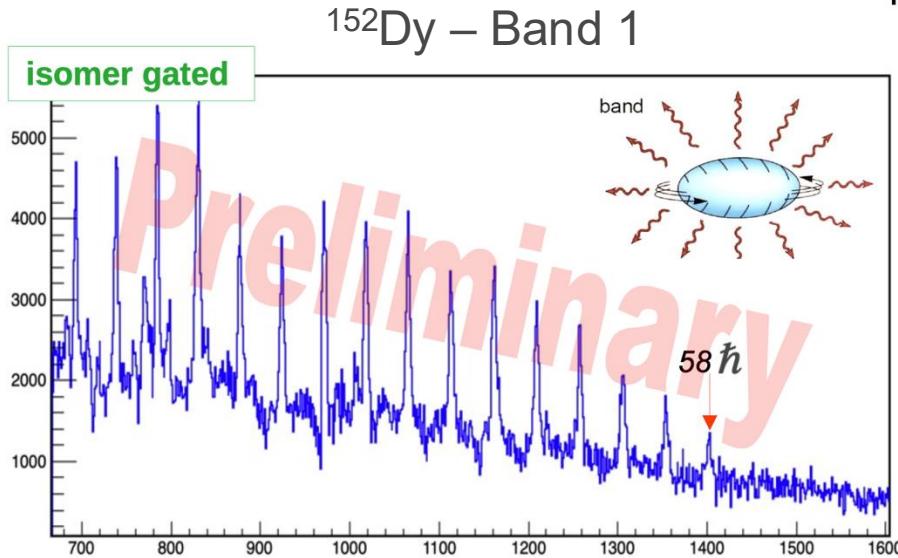
Entry-distribution measurements and quasi-continuum extraction with GRETINA: a proof of concept for new physics opportunities

Spokespersons: T. Lauritsen, A. Korichi

$^{108}\text{Pb}(^{48}\text{Ca},4\text{n})^{152}\text{Dy}$, 196 MeV, 4 pnA

Response function measurement (18 sources)

Measurement of the entry distribution, i.e. the locations in the spin-excitation energy plane that a nucleus occupies after the last particle has been emitted following a fusion-evaporation reaction.



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+ Cast of Many



Thank You Robert!