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IBA FOR NOVICE EXPERIMENTALISTS.

I. INTRODUCTION TO IBA:

Mostly Symmetries

II. TESTS IN EVEN-EVEN NUCLEI:

Mostly Transitional Systems

III. SUPERSYMMETRIES:

Theory and Experiment

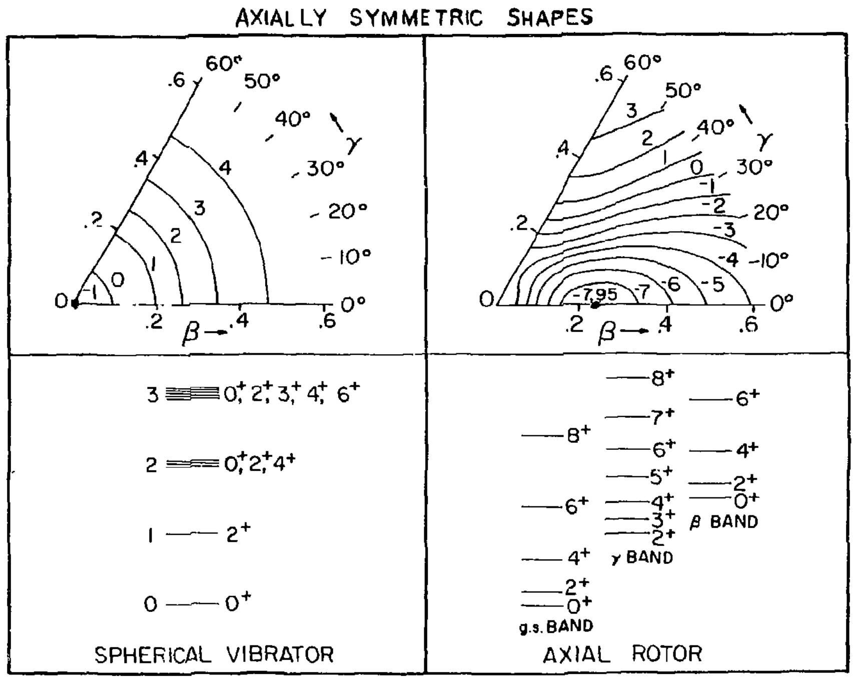
THE IBA FOR NOVICE EXPERIMENTALISTS

The following report contains the notes from a series of lectures on the Interacting Boson Approximation (IBA) model. The lectures were presented at Lawrence Livermore National Laboratory on July 28, 30 and August 1, 1982 by Jolie A. Cizewski from Yale University.

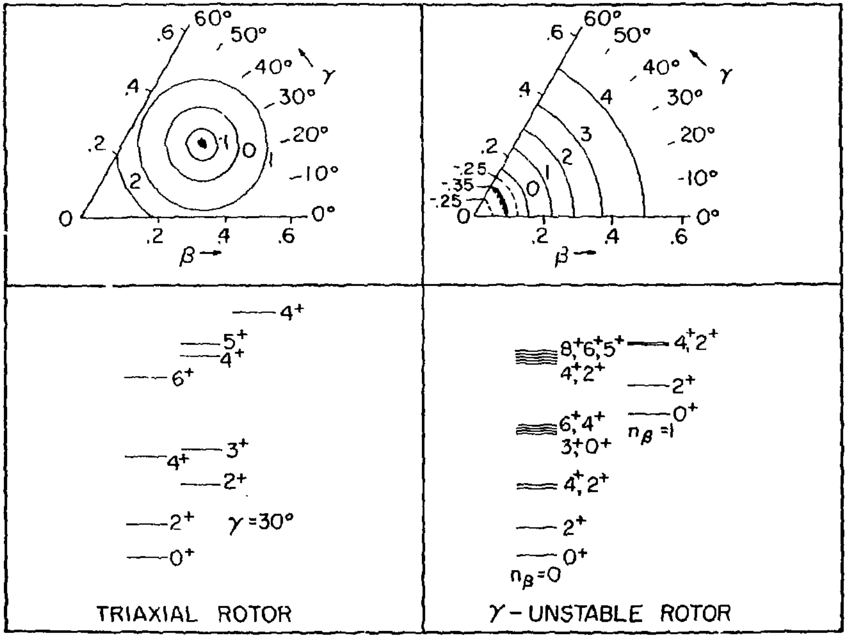
The IBA was developed by F. Iachello and A. Arima starting about seven years ago to understand collective quadrupole excitations in medium and heavy mass nuclei away from closed shells. Since then the formalism has been extended to odd-mass nuclei and considerable work has gone into understanding the microscopic construction of the bosons in this model. The IBA has been applied to nuclei as light as Zn and Ge and as heavy as U and Pu; to nuclei near closed shells, such as Mo and Hg; to stable nuclei and nuclei far from stability.

The present lectures were designed to give the experimentalist an introduction to the IBA and to give specific examples of how it could be applied to understand the structure of heavy even and odd mass nuclei. Much of the emphasis was on the symmetries (and supersymmetries) of the model and how the use of symmetries enabled the relatively straightforward understanding of empirical systems as deviations from these symmetries.

The richness of possible applications of the IBA to understanding collective phenomena in nuclei was not fully explored, but rather a few illustrative examples were selected and described in detail. The references, accumulated at the end of this report, provide a more comprehensive, although not complete, list of tests of the IBA in even mass nuclei and the new symmetries in odd mass nuclei. The references also list the main theoretical papers which provide the details of the IBA formalism.


AXIALLY SYMMETRIC SHAPES
60°
50°
40°
30°
20°
10°
0°
γ
β
.2
.4
.6
3
0⁺, 2⁺, 3⁺, 4⁺, 6⁺
2
0⁺, 2⁺, 4⁺
1
2⁺
0
0⁺
SPHERICAL VIBRATOR
-7.95
g.s. BAND
γ BAND
β BAND
AXIAL ROTOR

NON-AXIAL SHAPES

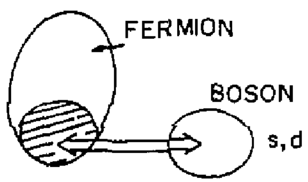


INTERACTING BOSON APPROXIMATION (IBA) MODEL

DEVELOPED BY: F. IACHELLO (Yale & Groningen)
A. ARIMA (Tokyo)

~ 1975 – PRESENT

MODEL TO EXPLAIN ALL COLLECTIVE QUADRUPOLE EXCITATIONS IN EVEN-EVEN NUCLEI WITH $A \geq 100$



ASSUMES DOMINANT COMPONENTS OF COLLECTIVE EXCITATIONS ARE DUE TO PAIRS OF PARTICLES, NEUTRONS OR PROTONS, COUPLED TO ANGULAR MOMENTUM 0 or 2

CALLS THESE PAIRS BOSONS

s-BOSONS d-BOSONS

IBA - 1

TOTAL NUMBER OF BOSONS N

$$N = n_d + n_s = \frac{|\mathcal{Z} - \mathcal{Z}_{c.s.}| + |\mathcal{N} - \mathcal{N}_{c.s.}|}{2}$$

WITHOUT REGARD TO PARTICLE OR HOLE CHARACTER OF NEUTRONS OR PROTONS

Examples: ${}^{148}_{62}Sm_{86}$ $\quad N = \left|\frac{62-50}{2}\right| + \left|\frac{86-82}{2}\right| = 8$

${}^{162}_{68}Er_{94}$ $\quad N = \left|\frac{68-82}{2}\right| + \left|\frac{94-82}{2}\right| = 13$

${}^{196}_{78}Pt_{118}$ $\quad N = \left|\frac{78-82}{2}\right| + \left|\frac{118-126}{2}\right| = 6$

$$H = \epsilon_s \cdot s^{+} s + \epsilon_d \cdot \sum_m d_m^{+} d_m + V$$

where V includes all pairwise interactions between bosons

H has group structure SU (6)

a) Redefine E_0 by introducing $\epsilon = \epsilon_d - \epsilon_s$

b) For certain forms of V can solve H analytically — SUBGROUPS OF SU(6)

IBA LIMITING SYMMETRIES

$$H = \epsilon \sum_m d_m^{\dagger} d_m + V$$

I. $\epsilon \gg V$ VIBRATIONAL LIMIT SU (5)

II. $V \gg \epsilon$ SYMMETRIC ROTOR LIMIT SU (3)

$V = Q \cdot Q + L^2$

quadrupole interaction

III. $V \gg \epsilon$ γ-UNSTABLE ROTOR LIMIT O (6)

$V = P + T_3 + L^2$

repulsive pairing and octupole

IBA SU(6) HAMILTONIAN

$$H = \varepsilon_s s^+ s + \varepsilon_d \sum_m d^+_m d_m$$

$$+ \sum_{J=0,2,4} \tfrac{1}{2}(2J+1)^{1/2} c_J \left[(d^+ d^+)^{(J)} (d d)^{(J)} \right]^{(0)}$$

$$+ \tfrac{1}{\sqrt{2}} v_2 \left[(d^+ d^+)^{(2)} (d s)^{(2)} + (s^+ d^+)^{(2)} (d d)^{(2)} \right]^{(0)}$$

$$+ \tfrac{1}{2} v_0 \left[(d^+ d^+)^0 (s s)^0 + (s^+ s^+)^0 (d d)^0 \right]^0$$

$$+ u_2 \left[(d^+ s^+)^2 (d s)^2 \right]^0 + \tfrac{1}{2} u_0 \left[(s^+ s^+)^0 (s s)^0 \right]^0$$

all boson – boson interactions to
<u>second order</u>

ELECTROMAGNETIC TRANSITIONS

E2

$$T_m(E2) = (d^\dagger s + s^\dagger d)^{(2)}_m + \chi\,(d^\dagger d)^{(2)}_m$$

value of χ depends on limit

$\chi = 0$ SU(5), O(6)

$\chi = -2.958$ SU(3)

SELECTION RULES

FIRST TERM $\Delta n_d = \pm 1$

SECOND TERM $\Delta n_d = 0$

M1 – No first order M1 : $T(M1) \sim d^\dagger d$

SU(5) LIMIT

$$H = \varepsilon \sum_m d_m^\dagger d_m + \sum_{J=0,2,4} \tfrac{1}{2}(2J+1)^{1/2}\, C_J \left[(d^\dagger d^\dagger)^J (\tilde{d}\tilde{d})^J \right]^{(0)}$$

ANHARMONIC VIBRATOR

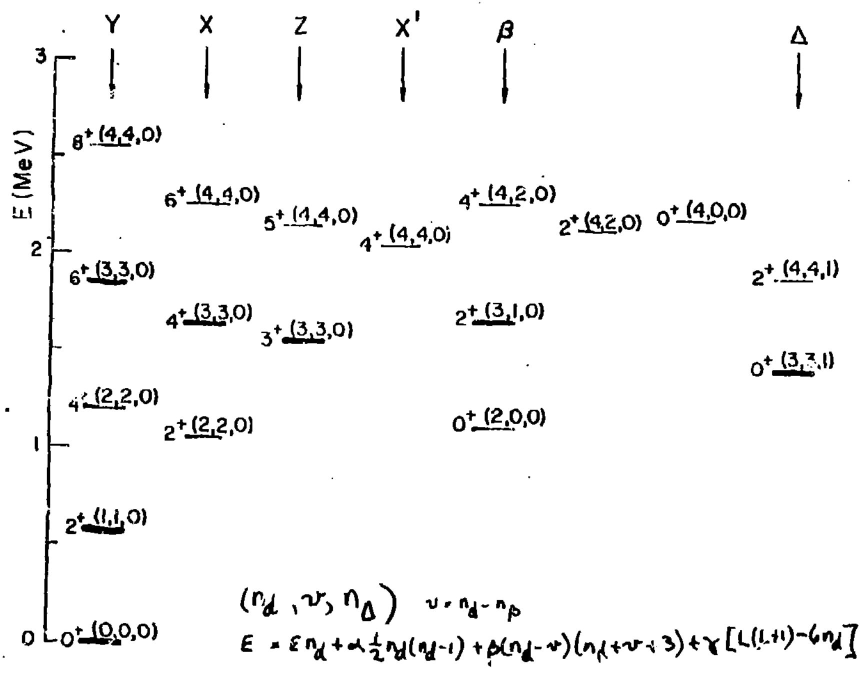
$$E(N\, n_d\, v\, n_\Delta\, JM) = \varepsilon n_d + \alpha \tfrac{1}{2} n_d(n_d-1) + \beta (n_d - v)(n_d + v + 3) + \gamma [J(J+1) - 6 n_d]$$

QUANTUM NUMBERS

$n_d \quad v \quad n_\Delta \quad J$

$v = n_d - 2n_\beta \qquad n_d = 2n_\beta + 3n_\Delta + \lambda$

$J = 2\lambda, 2\lambda - 2, 2\lambda - 3, \ldots \lambda + 1, \lambda$



(n_d, v, n_Δ) $\quad v = n_d - n_\beta$

$E = \varepsilon n_d + \alpha \frac{1}{2} n_d(n_d-1) + \beta(n_d - v)(n_d + v + 3) + \gamma\,[L(L+1) - 6n_d]$

ALTERNATE HAMILTONIAN

MULTIPOLE EXPANSION

$$H = \varepsilon \Sigma_m d^\dagger_m d_m + \kappa \Sigma \vec{Q} \cdot \vec{Q}$$

$$+ \kappa' \Sigma L \cdot L + \kappa'' \Sigma P \cdot P + \cdots$$

QQ quadrupole interaction

$(d^\dagger s + s^\dagger d)^2$ $\Delta n_d = 1$

$+ \chi (d^\dagger d)^2$

LL angular momentum

$(d^\dagger d^\dagger)^L (d d)^L$ $\Delta n_d = 0$

PP repulsive pairing

$(d^\dagger d^\dagger)^0 (s s)^0$ $\Delta n_d = 2$

T_3 octupole

$(d^\dagger d)^3 (d^\dagger d)^3$

SU(3) LIMIT

$$H = \kappa \sum \vec{Q}\cdot\vec{Q} - \kappa' \sum \vec{L}\cdot\vec{L}$$

SPECIAL SYMMETRIC ROTOR

$$E(N(\lambda\mu)KJM) = (\kappa' - \tfrac{3}{4}\kappa)J(J+1) + \kappa\, C(\lambda\mu)$$

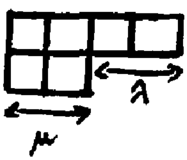
where

$$C(\lambda\mu) = \lambda^2 + \lambda\mu + \mu^2 + 3(\lambda + \mu)$$

BOSONS – SYMMETRIC COUPLINGS

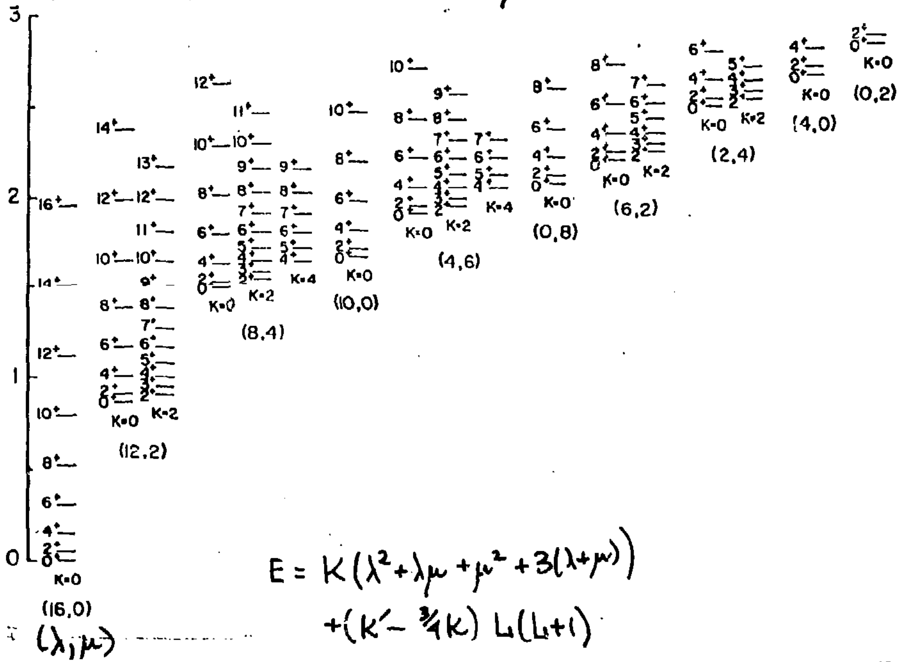
N = 3 LOWEST CONFIG.

(6,0)

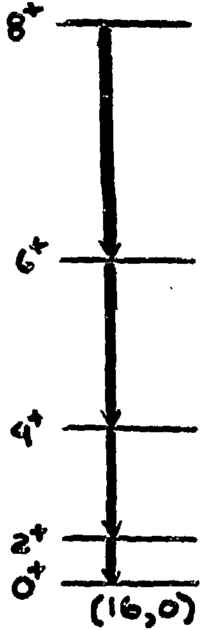


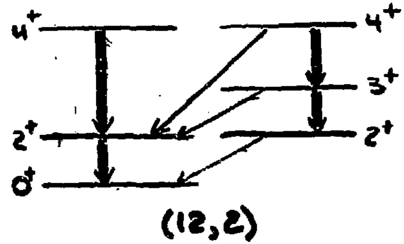
(2,2)

E2 SELECTION $\Delta(\lambda\mu) = 0$



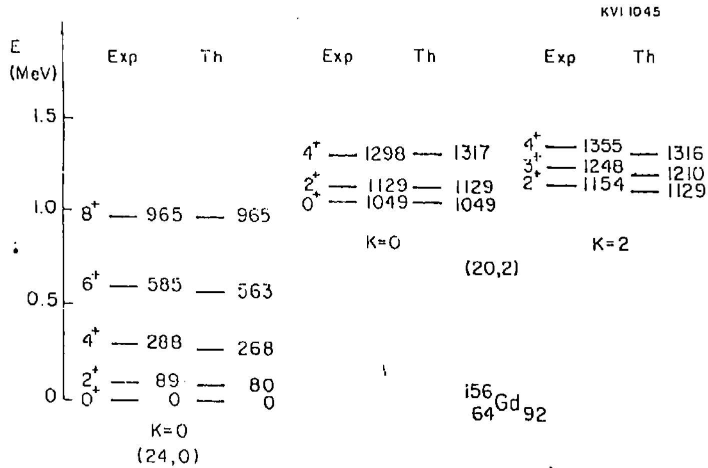
$$E = K\left(\lambda^2 + \lambda\mu + \mu^2 + 3(\lambda+\mu)\right) + \left(K' - \tfrac{3}{4}K\right) L(L+1)$$





$\Delta(\lambda\mu) = 0$

$N = 8$


KVI 1045
E
(MeV)
1.5
1.0
0.5
0
Exp
Th
8+ 965 965
6+ 585 563
4+ 288 268
2+ 89 80
0+ 0 0
K=0
(24,0)
Exp
Th
4+ 1298 1317
2+ 1129 1129
0+ 1049 1049
K=0
Exp
Th
4+ 1355 1316
3+ 1248 1210
2+ 1154 1129
K=2
(20,2)
156 64 Gd 92

O(6) LIMIT

$$H = A\,P_6 + B\,C_5 + C\,C_3$$

$$P_6 \sim (d^+d^+)^0(dd)^0 + (d^+d^+)^0(ss)^0 + (s^+s^+)^0(ss)^0$$

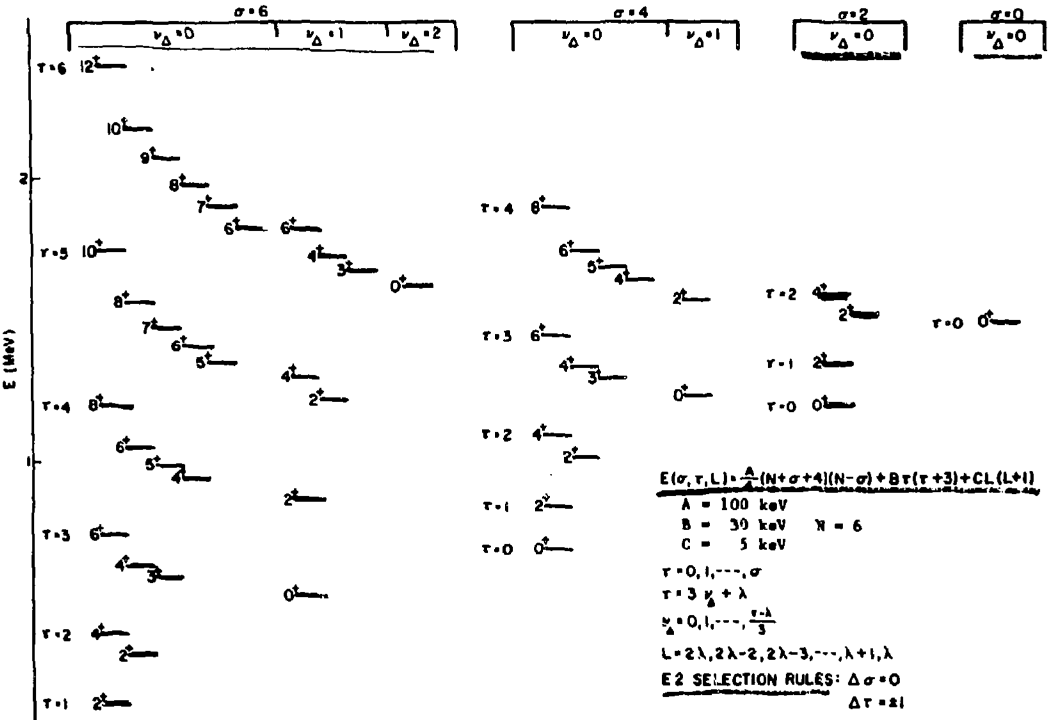
$$C_5 \sim (d^+d)^3(d^+d)^3 + (d^+d)^1(d^+d)^1$$

$$C_3 \sim (d^+d)^1(d^+d)^1$$

$$E(N, \sigma\,\tau\,\nu_\Delta\,J\,M) = \frac{A}{4}(N-\sigma)(N+\sigma+4) + \frac{B}{6}\tau(\tau+3) + C\,J(J+1)$$

QUANTUM NUMBERS

σ τ ν_Δ

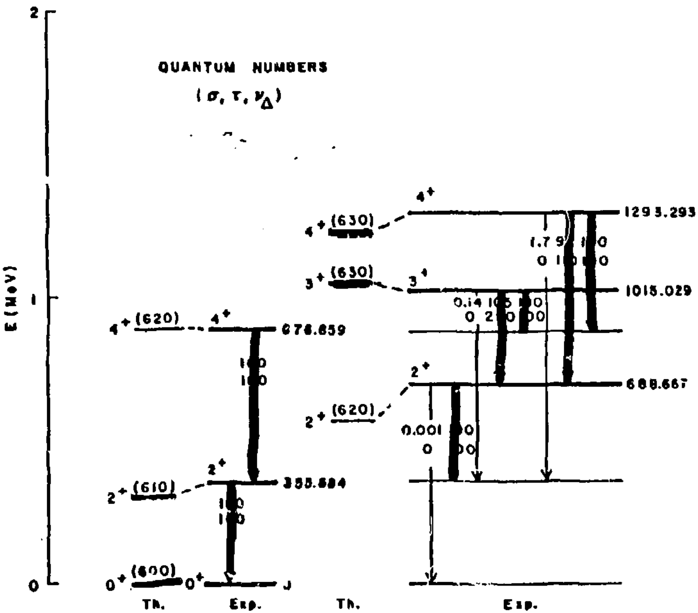


σ = 6
σ = 4
σ = 2
σ = 0
ν_Δ = 0
ν_Δ = 1
ν_Δ = 2
E (MeV)
τ = 6
τ = 5
τ = 4
τ = 3
τ = 2
τ = 1
τ = 0
E(σ, τ, L) = A/4 (N + σ + 4)(N − σ) + B τ(τ + 3) + C L(L + 1)
A = 100 keV
B = 30 keV   N = 6
C = 5 keV
τ = 0, 1, ---, σ
τ = 3 ν_Δ + λ
ν_Δ = 0, 1, ---, (τ−λ)/3
L = 2λ, 2λ−2, 2λ−3, ---, λ+1, λ
E2 SELECTION RULES: Δσ = 0
Δτ = ±1

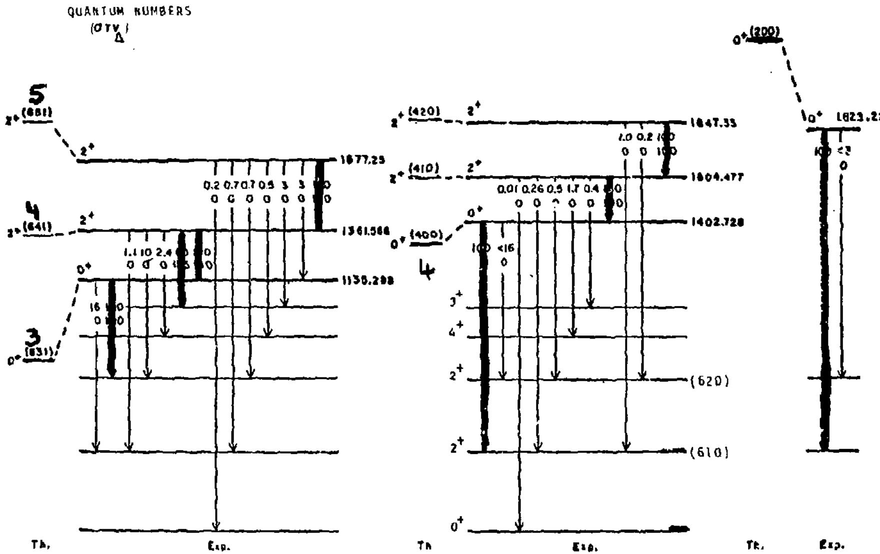
O (6) LIMIT

τ= 0
τ= 1

τ= 3

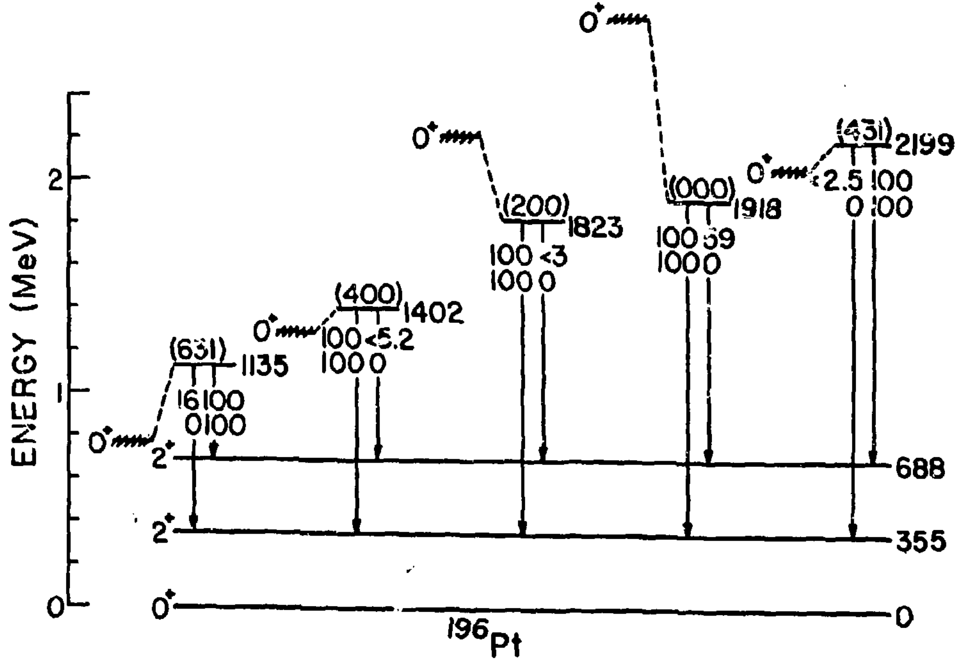


CIZEWSKI, ET AL., P.R.L. 40 167 (1978)



E2 SELECTION RULE: $\Delta\sigma=0$ $\Delta\tau=\pm1$

CIZEWSKI ET AL., P.R.L. 40 167 (1978)


ENERGY (MeV)
0
1
2
0⁺
2⁺
2⁺
0⁺
(631)
1135
16 100
0 100
(400)
1402
100 <5.2
100 0
(200)
1823
100 <3
100 0
(000)
1918
100 59
100 0
(431)
2199
<2.5 100
0 100
688
355
0
196Pt

TWO-NUCLEON TRANSFER REACTIONS

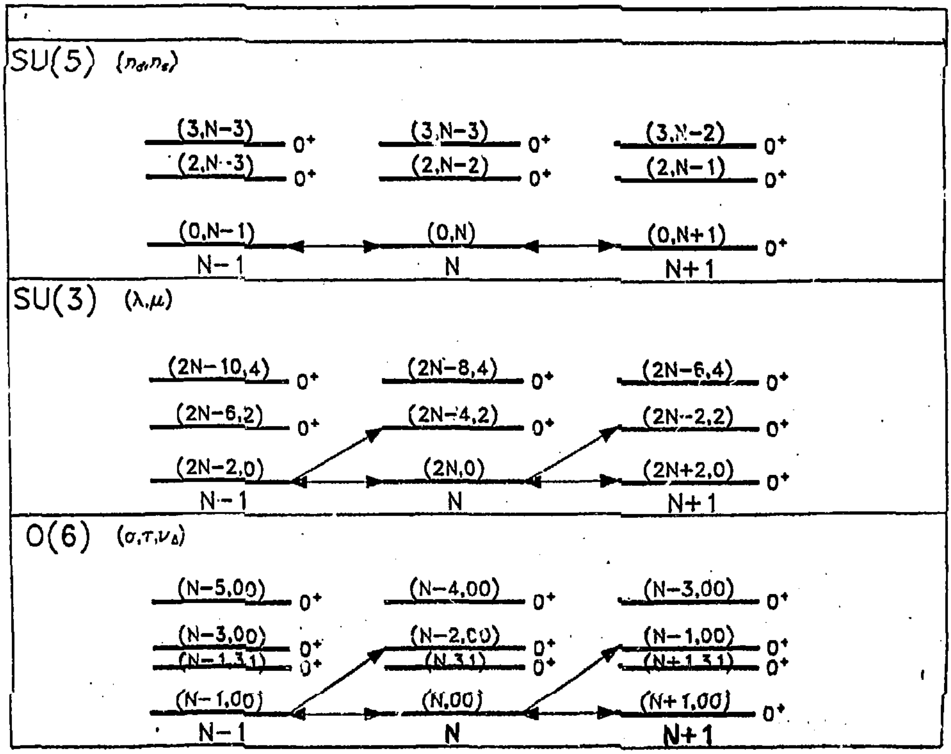
START WITH A TARGET A WITH
N BOSONS

BY ADDING TWO PROTONS OR TWO
NEUTRONS GO TO NUCLEUS WITH
A+2 OR N+1 BOSONS

OR COULD SUBTRACT TWO PARTICLES
A−2 OR N−1 BOSONS

EXAMPLES OF THESE REACTIONS:

(t,p)	(^{3}He,n)
(p,t)	(n,^{3}He)
TWO-NEUTRON	TWO-PROTON



SU(5) (nd,ns)
(3,N−3) 0+
(2,N−3) 0+
(0,N−1)
N−1
(3,N−3) 0+
(2,N−2) 0+
(0,N)
N
(3,N−2) 0+
(2,N−1) 0+
(0,N+1) 0+
N+1
SU(3) (λ,μ)
(2N−10,4) 0+
(2N−6,2) 0+
(2N−2,0)
N−1
(2N−8,4) 0+
(2N−4,2) 0+
(2N,0)
N
(2N−6,4) 0+
(2N−2,2) 0+
(2N+2,0) 0+
N+1
O(6) (σ,τ,νΔ)
(N−5,00) 0+
(N−3,00) 0+
(N−1,31) 0+
(N−1,00)
N−1
(N−4,00) 0+
(N−2,00) 0+
(N,31) 0+
(N,00)
N
(N−3,00) 0+
(N−1,00) 0+
(N+1,31) 0+
(N+1,00) 0+
N+1

INTERACTING BOSON APPROXIMATION MODEL
TWO-NEUTRON TRANSFER RELATIONS

SU(5) LIMIT (VIBRATIONAL)

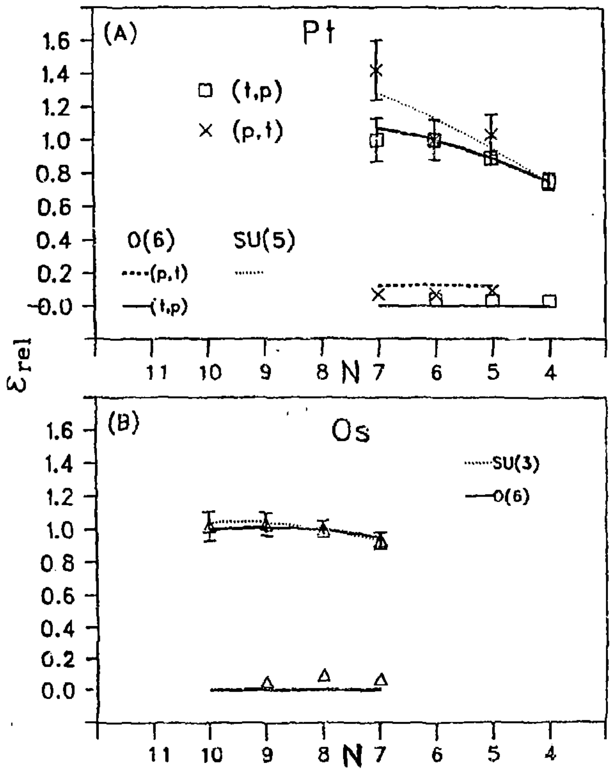
$$I^{VIB}(N_v \rightarrow N_v+1) = \alpha_v^2 (N_v+1)\ (\Omega_v - N_v)$$

SU(3) LIMIT (ROTATIONAL)

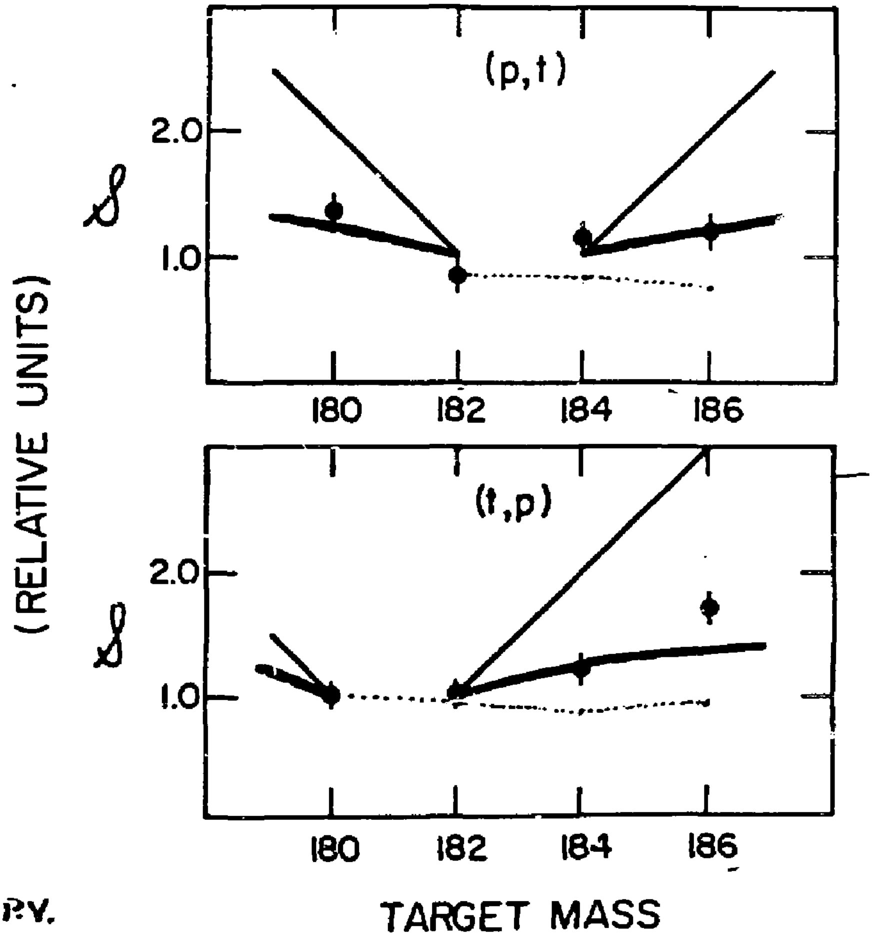
$$I^{ROT}\ (N_v \rightarrow N_v+1) = \alpha_v^2 (N_v+1)\ \left(\frac{2N+3}{3(2N+1}\right)\ \left(\Omega_v - N_v - \frac{4(N-1)}{3(2N-1)} N_v\right)$$

O(6) LIMIT (γ-UNSTABLE)

$$I^{O(6)}(N_v \rightarrow N_v+1) = \alpha_v^2\ \frac{(N+4)\ (N_v+1)}{2(N+2)}\ \left(\Omega_v - N_v - \frac{(N-1)\ N_v}{2(N+1)}\right)$$



(A)
Pt
□ (t,p)
× (p,t)
O(6)
SU(5)
(p,t)
(t,p)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
11 10 9 8 N 7 6 5 4
ε_{rel}
(B)
Os
SU(3)
O(6)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
11 10 9 8 N 7 6 5 4



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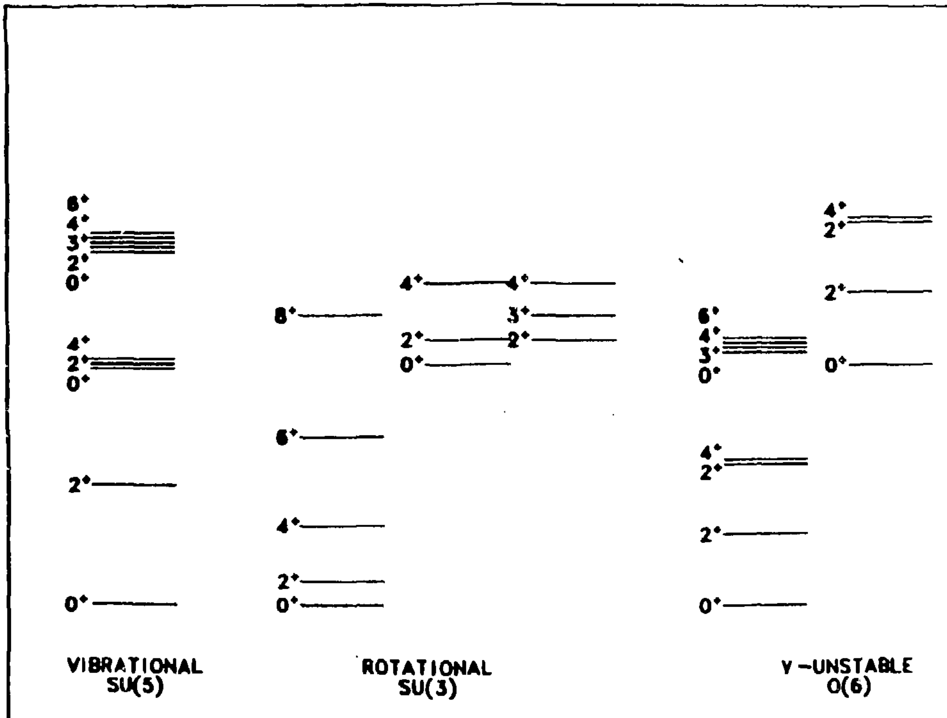
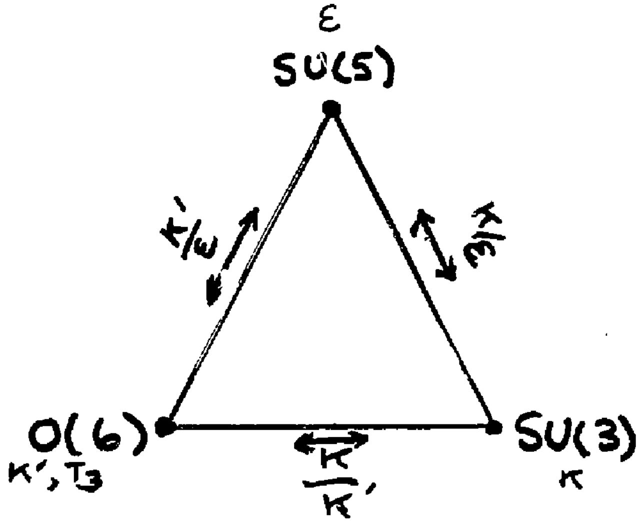
Betts & Mortensen P.R.L. 43, 616 (79)

— IBA-1

···· IBA-2 DUVAL + BARRETT

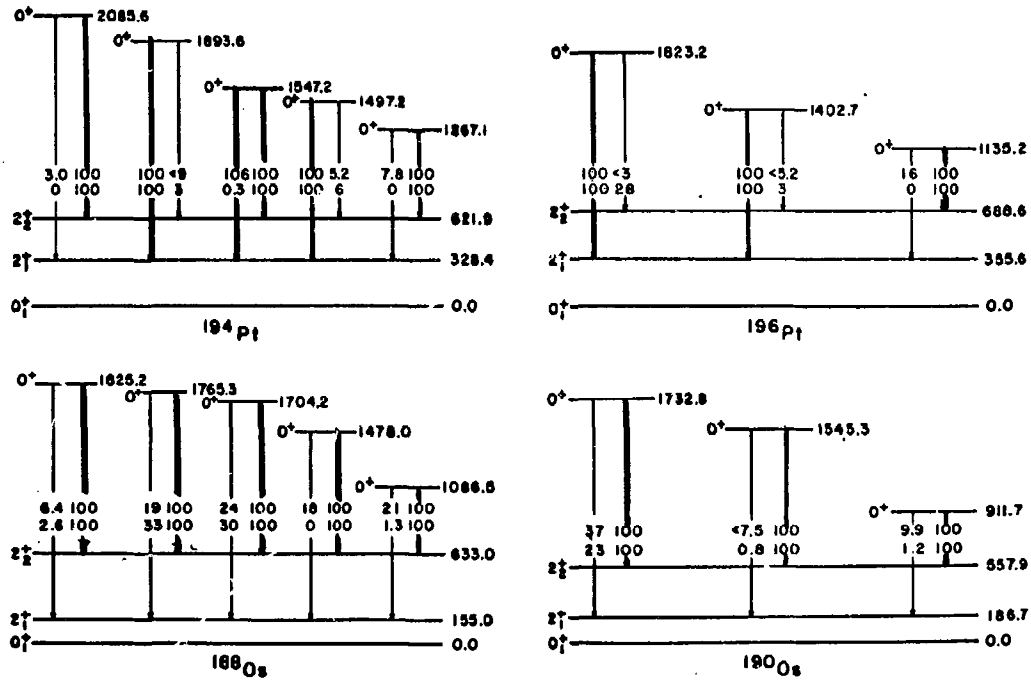

6+
4+
3+
2+
0+
4+
2+
0+
2+
0+
8+
6+
4+
2+
0+
4+
2+
0+
4+
3+
2+
6+
4+
3+
0+
4+
2+
2+
0+
4+
2+
2+
0+
VIBRATIONAL
SU(5)
ROTATIONAL
SU(3)
γ-UNSTABLE
O(6)



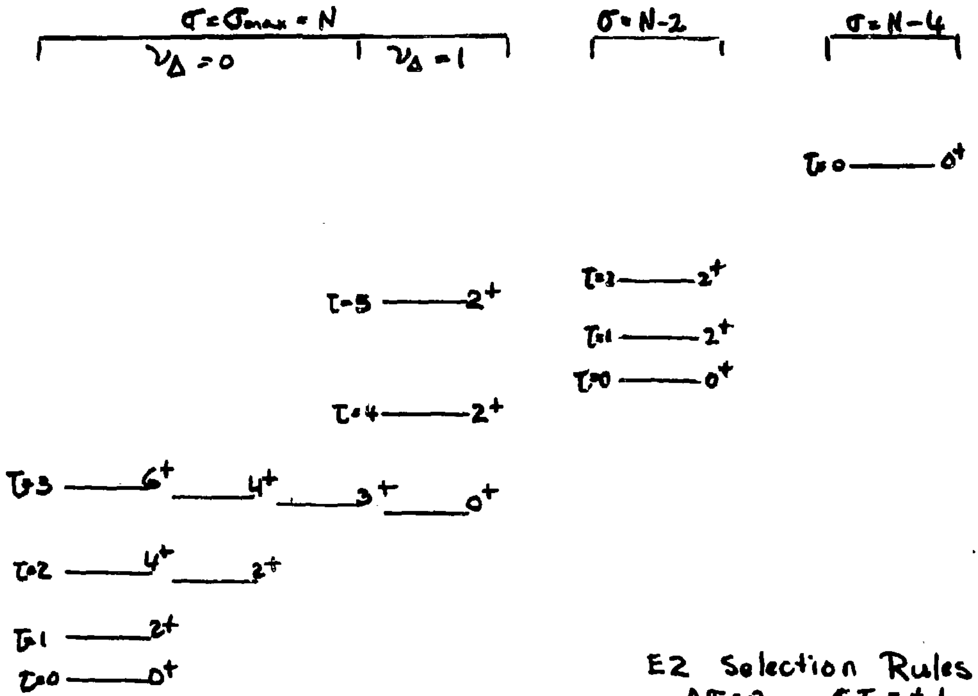
SU(5) $\quad H \sim \varepsilon\, n_d$

SU(3) $\quad H \sim \kappa\, Q \cdot Q$

O(6) $\quad H \sim \kappa' P \cdot P + T_3 (d^\dagger d)^3 (d^\dagger d)^3$



0+ 2085.6
0+ 1893.6
0+ 1547.2
0+ 1497.2
0+ 1267.1
3.0 100 100 <9 106 100 100 5.2 7.8 100
0 100 100 3 0.3 100 100 6 0 100
2+2 621.9
2+1 328.4
0+1 0.0
194Pt
0+ 1823.2
0+ 1402.7
0+ 1135.2
100 <3 100 <5.2 16 100
100 28 100 3 0 100
2+2 688.6
2+1 355.6
0+1 0.0
196Pt
0+ 1825.2
0+ 1765.3
0+ 1704.2
0+ 1478.0
0+ 1086.5
6.4 100 19 100 24 100 18 100 21 100
2.6 100 33 100 30 100 0 100 1.3 100
2+2 633.0
2+1 155.0
0+1 0.0
188Os
0+ 1732.8
0+ 1545.3
0+ 911.7
37 100 <7.5 100 9.9 100
23 100 0.8 100 1.2 100
2+2 557.9
2+1 186.7
0+1 0.0
190Os



E2 Selection Rules

$\Delta\sigma = 0 \qquad \Delta\tau = \pm 1$

O(6) WAVE FUNCTIONS

BASIS STATES - SU(5) LIMIT

$$J^{\pi}(n_d\, n_\beta\, n_\Delta)$$

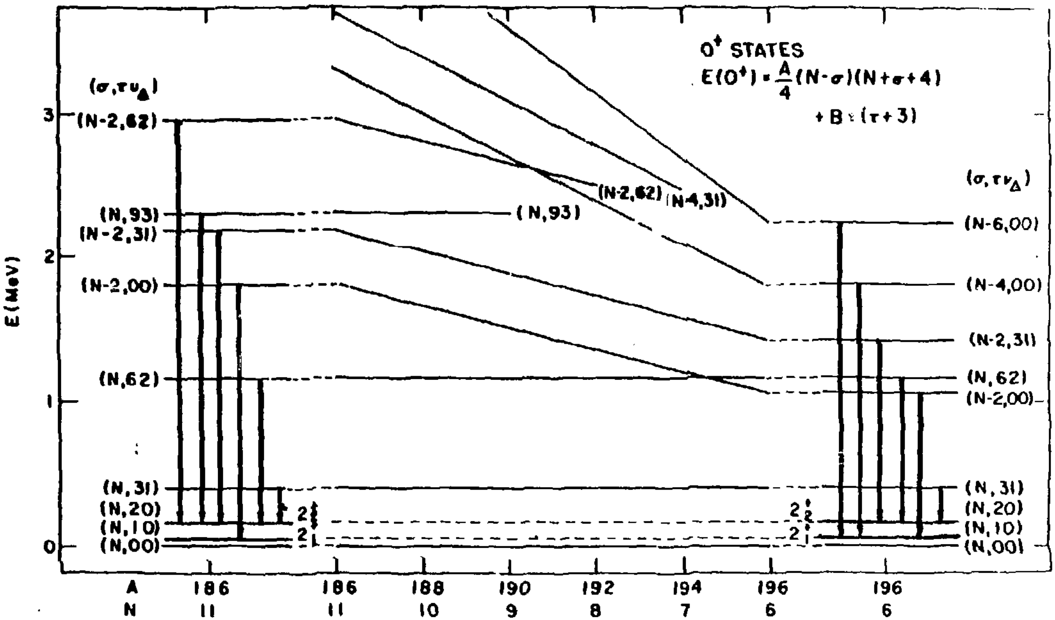
$^{196}Pt \qquad N = 6$

$$0_1^+ = .4330\; 0^+(000) + .7500\; 0^+(210) + .4910\; 0^+(420) + .0945\; 0^+(630)$$

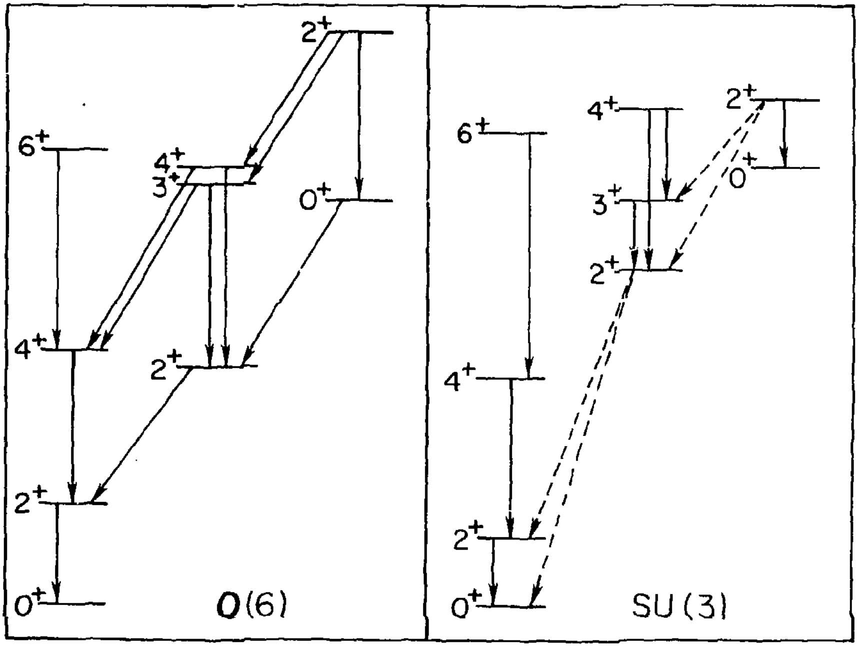
$$0_3^+ = -.6847\; 0^+(000) - .0791\; 0^+(210) + .6728\; 0^+(420) + .2689\; 0^+(630)$$

$$2_1^+ = +.6124\; 2^+(100) + .7319\; 2^+(310) + .2988\; 2^+(520)$$

$$T(E2) = \alpha(d^\dagger s + s^\dagger d) \Rightarrow \Delta n_d = \pm 1$$



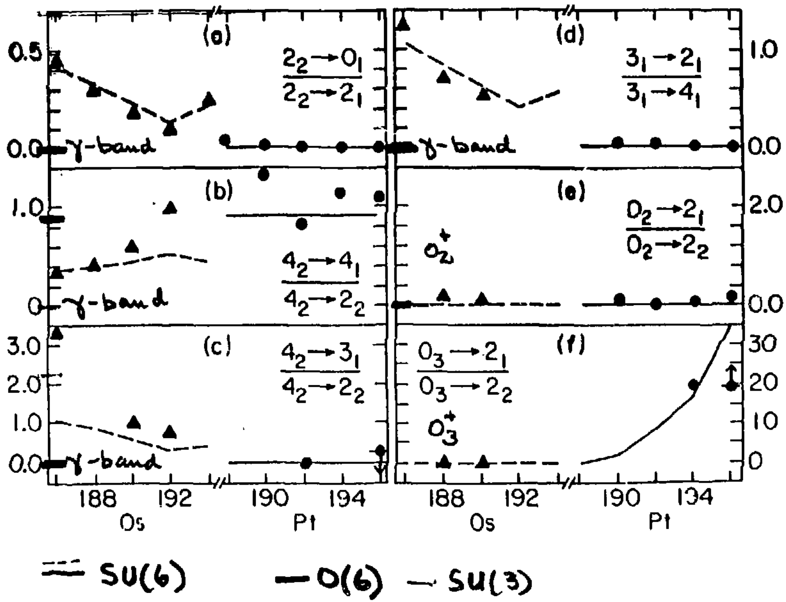
0+ STATES
E(0+) = A/4 (N-σ)(N+σ+4) + B τ(τ+3)
(σ,τν_Δ)
E (MeV)
(N-2,62)
(N,93)
(N-2,31)
(N-2,00)
(N,62)
(N,31)
(N,20)
(N,10)
(N,00)
(N-2,62)
(N-4,31)
(N,93)
(N-6,00)
(N-4,00)
(N-2,31)
(N,62)
(N-2,00)
(N,31)
(N,20)
(N,10)
(N,00)
A 186 186 188 190 192 194 196 196
N 11 11 10 9 8 7 6 6



2+
6+
4+
3+
0+
4+
2+
2+
0+
O(6)
6+
4+
2+
0+
3+
2+
4+
2+
0+
2+
0+
SU(3)

RELATIVE E2 TRANSITION PROBABILITIES

	O(6)	^{196}Pt	^{192}Os	^{186}Os	SU(3)
$\frac{2_2 \rightarrow 0_1}{2_2 \rightarrow 2_1}$	0	7×10^{-6}	0.105	0.30	0.70
$\frac{3_1 \rightarrow 2_1}{3_1 \rightarrow 4_1}$	0	0.0014		0.72	2.50
$\frac{4_2 \rightarrow 4_1}{4_2 \rightarrow 3_1}$	∞	>3.5	1.2		SMALL (~0.02)
$\frac{4_2 \rightarrow 3_1}{4_2 \rightarrow 2_2}$	0	<0.31	0.81		2.23
$\frac{2_3 \rightarrow 3_1}{2_3 \rightarrow 0_2}$	1.25	0.60		0.20	SMALL (~0.02)


(a)
2₂→0₁ / 2₂→2₁
γ-band
(b)
4₂→4₁ / 4₂→2₂
γ-band
(c)
4₂→3₁ / 4₂→2₂
γ-band
(d)
3₁→2₁ / 3₁→4₁
γ-band
(e)
0₂→2₁ / 0₂→2₂
0₂⁺
(f)
0₃→2₁ / 0₃→2₂
0₃⁺
188 192 190 194
Os Pt
188 192 190 194
Os Pt
0.5 0.0 1.0 0 3.0 2.0 1.0 0.0
1.0 0.0 2.0 0.0 30 20 10 0
SU(6)
O(6)
SU(3)

Pt - Os NUCLEI

REGION O(6) → SU(3)

0^+ STATES PARAMETER FREE

OTHER PROPERTIES –

ESSENTIALLY ONE PARAMETER

~ QQ/PAIR

DEFORMED NUCLEI

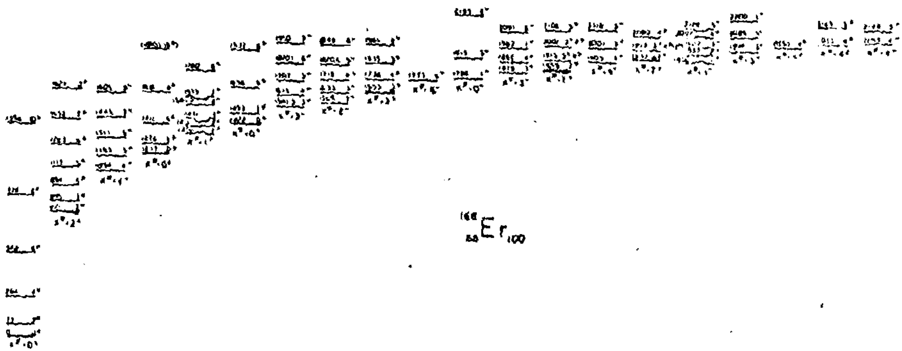
SU(3) β γ bands
degenerate.

MOST DEFORMED NUCLEI
β band above γ band

INTRODUCE PAIR TO IBA SU(3)
H TO PUSH UP β band

^{168}Er $N=16$

W.F. DAVIDSON, et al. J. Phys. G7,
455, 843(1981)



W.F. DAVIDSON, ET AL., J.PHYS. G7, 455 AND 843 (1981)

^{168}Er WARNER et al.

$$H = -\kappa \vec{Q}\cdot\vec{Q} - \kappa' \vec{L}\cdot\vec{L} + \kappa'' \vec{P}\cdot\vec{P}$$

κ κ' FIXED FROM 2_1^+ 2_2^+

κ'' VARIED TO CALCULATE REST OF LEVEL SCHEME

$$T(E2) = \alpha\,(d^\dagger s + s^\dagger d)^{(2)} + \frac{\beta}{\sqrt{5}}\,(d^\dagger d)^{(2)}$$

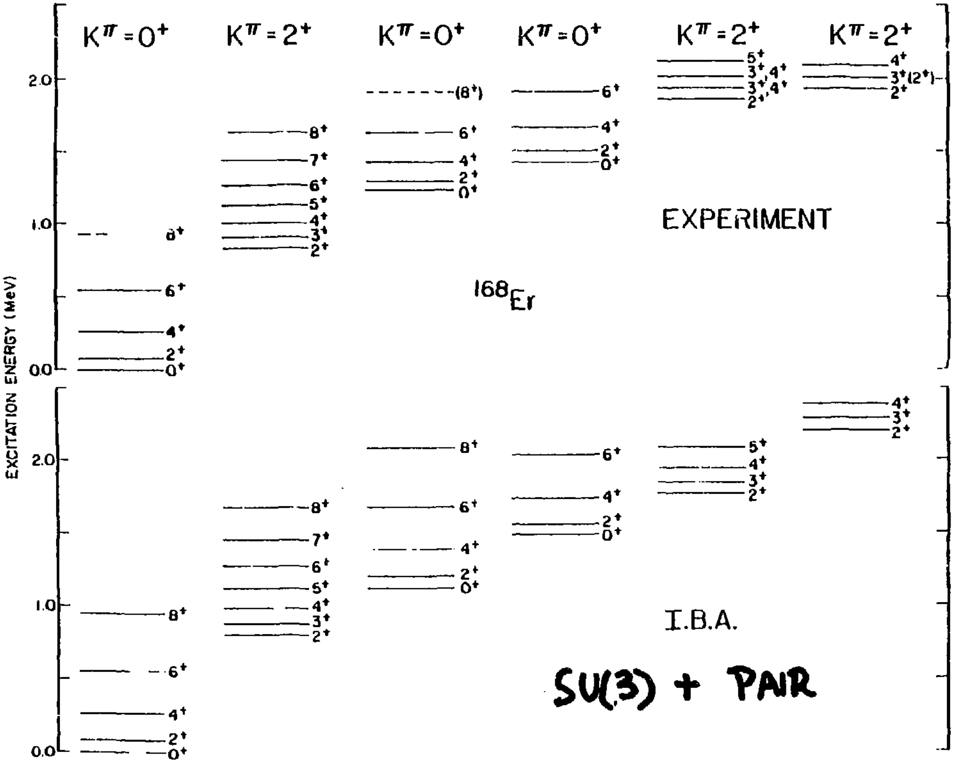
$$\beta/\alpha = -2.958 \quad SU(3)$$

$$0 \quad O(6)$$

$$\frac{B(E2: 0_1 \to 2_2)}{B(E2: 0_1 \to 2_1)} \Longrightarrow \beta/\alpha = -0.68$$

$$(-0.85)$$

WARNER, et al P.R.L. 45



$\gamma \rightarrow \gamma$

$\gamma \rightarrow g$

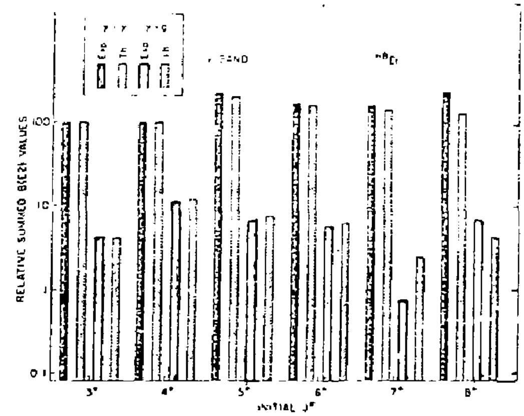


FIG. 4. Comparison of the calculated and experimental summed $B(E2)$ strengths from states in the γ band. For each initial state, the bars represent the sum of all observed or calculated transitions to either the γ band or ground band.

$0_2 \rightarrow 0_2$ | $0_3 \rightarrow 0_3$

$0_2 \rightarrow \gamma$ | $0_3 \rightarrow \gamma$

$0_2 \rightarrow g$ | $0_3 \rightarrow g$

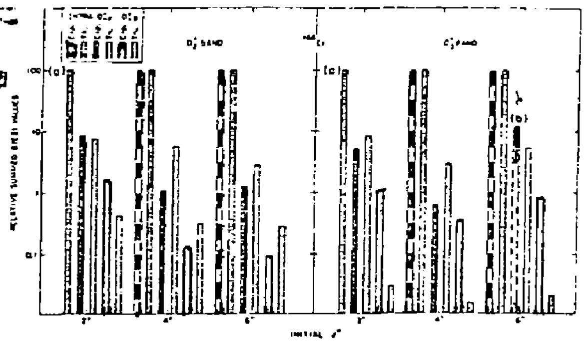
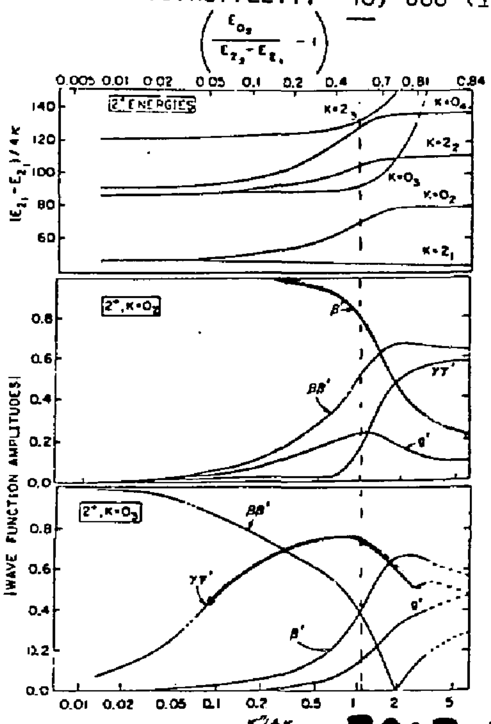


FIG. 5. Comparison of the calculated and experimental summed $B(E2)$ strengths from states in the 0_2^+ and 0_3^+ bands. For each initial state, the bars represent the sum of all observed or calculated transitions to a given final band. The normalization for each case is defined in Tables II and III. The symbol (a) denotes that no experimental information was available for the strength of the intraband transition in these cases. The symbol (b) denotes that the experimental upper limit for this transition has been plotted.

SUMMED B(E2) STRENGTHS
$J^{\pi}_{i} \rightarrow$ FINAL BAND

R.F.CASTEN AND D.D.WARNER PHYS.REV.LETT. 48, 666 (1982)



PAIR / QQ

FIG. 1. Energies and major SU(3) wave function amplitudes (absolute values) for 2^+ states in the lowest band vs *magnitude of SU(3) symmetry breaking*. $N = 16$. Note that $\kappa''/4\kappa$ is used as the symmetry-breaking parameter because of its close relation to PAIR/QQ as is evident from the definitions below Eq. (1).

0_2^+

0_3^+

2^+ STATES

168 Er PAIR/QQ ~ 1.0

ALOT OF $\Delta K = 0$ MIXING

LITTLE $\Delta K = 2$ MIXING

E2 TRANSITIONS IN ^{168}Er

MIXING BETWEEN "FUNDAMENTAL" CONFIGURATIONS

DIRECT $\beta \rightarrow \gamma$ TRANSITION IN SU(3)

GEOMETRY REDEFINES β-VIBE IN EACH NUCLEUS

F-BOSONS   π⁻ BANDS

$E(3^-)$ $(d+f)^{1^-,2^-,3^-,4^-,5^-}$

6 parameters

APPROXIMATE H:

$$H \sim H_c + \varepsilon_f n_f + \Gamma\left[Q^{(2)}(f^+f)^{(2)}\right]^{(0)} + \Lambda\left[(d^+f)^{(3)}(f^+d)^{(3)}\right]^{(0)}$$

$$Q^{(2)} = (d^+s + s^+d)^{(2)} + \chi\,(d^+d)^{(2)}$$

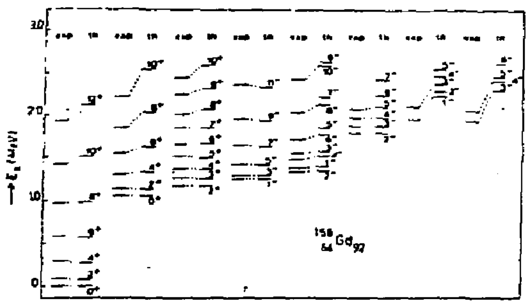


Fig. 1 Comparison of the energy levels as calculated in the IBA model with the experimental energy levels. The three high-lying NPB's are from ref. *).

J. KONIJN, ET AL., NUCL. PHYS. A352, 191 (1981)

OTHER PHENOMENOLOGICAL IBA

IBA-2

distinguishes between π, ν

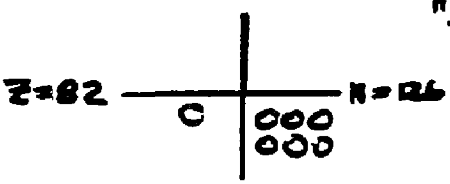
N_π N_ν $d_{\pi,\nu}$ $s_{\pi,\nu}$

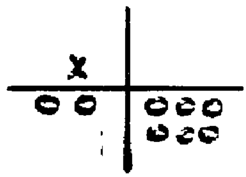
microscopic predictions of trends in parameters

IBA-2 + Coexistence

Near closed shells or subshells

Hg





$N_\pi = 1$ N_ν $N_\pi = 3$ N_ν

also Mo, Cd, Te

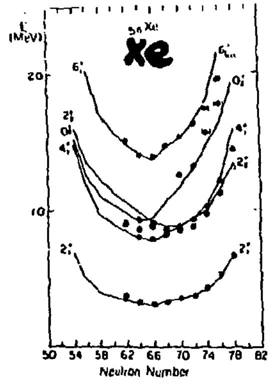


Figure 15. Calculated energy spectra in $_{54}$Xe. The circles, squares, and triangles denote the experimental values.

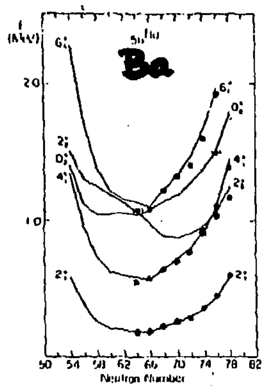


Figure 16. Calculated energy spectra in $_{56}$Ba. The circles, squares, and triangles denote the experimental values.

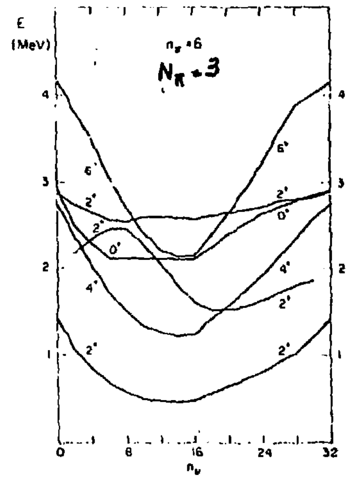


Figure 20. Energy spectra of even-even nuclei, for fixed proton number, $n_\pi = 2N_\pi = 6$, and varying neutron number, $0 \leq n_\nu \leq 32$, in the single-[illegible] orbit approximation.

MICROSCOPIC

BALANTEKIN, BARS, IACHELLO, NP A370, 284 (1981)

SUPER - SYMMETRY

ALL EARLIER SYMMETRIES APPLIED EITHER TO BOSE OR TO FERMI SYSTEMS

ie BOSONS ⟷ BOSONS

OR

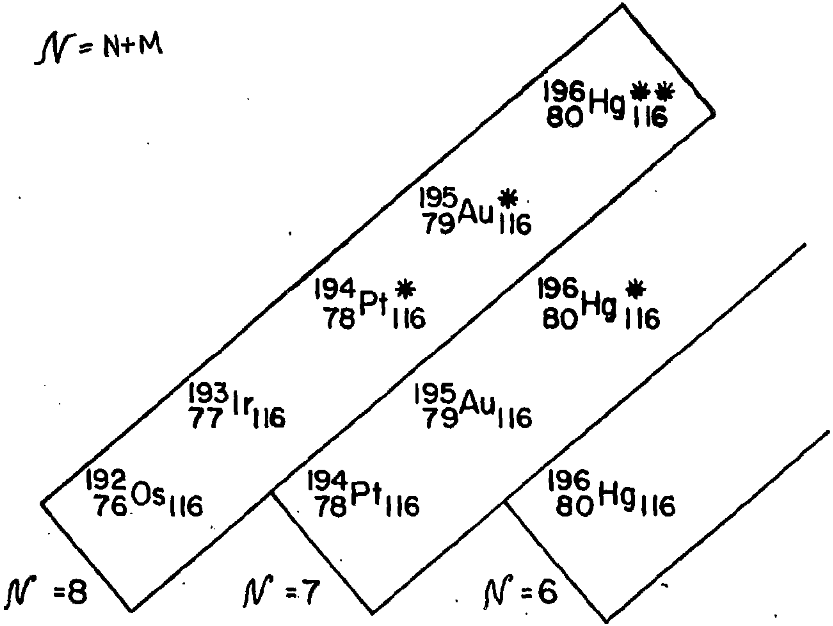
FERMIONS ⟷ FERMIONS

MORE COMPLEX SYMMETRY WOULD PLACE BOSONS AND FERMIONS IN SAME MULTIPLET

ie COULD HAVE OPERATIONS THAT

BOSONS ⇄ FERMIONS

SAME EIGENVALUE EQUATION FOR FERMI AND BOSE SYSTEM


$\mathcal{N} = N+M$
$^{196}_{80}Hg^{**}_{116}$
$^{195}_{79}Au^{*}_{116}$
$^{194}_{78}Pt^{*}_{116}$
$^{196}_{80}Hg^{*}_{116}$
$^{193}_{77}Ir_{116}$
$^{195}_{79}Au_{116}$
$^{192}_{76}Os_{116}$
$^{194}_{78}Pt_{116}$
$^{196}_{80}Hg_{116}$
$\mathcal{N} = 8$
$\mathcal{N} = 7$
$\mathcal{N} = 6$

F. IACHELLO RECENTLY PREDICTED SUPERSYMMETRY STRUCTURE IN Pt-Ir-Os

COUPLE $j = 3/2$ fermion (g.s. Ir)

to O(6) boson (Pt cores)
Os

IF ONE LOOKS AT ONLY ONE NUCLEUS

SPIN (6)

IF ONE LOOKS AT TRANSITIONS BETWEEN OR SUM-RULES

U(6/4)

QUANTUM NUMBERS

N-# of BOSONS M-# of FERMIONS

$$(\sigma_1\ \sigma_2\ \sigma_3)\ (\tau_1\ \tau_2)\qquad \nu_\Delta$$

$$O(6):\quad \sigma\qquad \tau\qquad \nu_\Delta$$

Spin(6) / Supersymmetry
E_x Energies:

$$E(N, M, (\sigma_1 \sigma_2 \sigma_3), (\tau_1 \tau_2), \nu_\Delta, J, M_J) =$$
$$-\frac{A}{4}\left[\sigma_1(\sigma_1+4) + \sigma_2(\sigma_2+2) + \sigma_3^2\right]$$
$$+\frac{B}{6}\left[\tau_1(\tau_1+3) + \tau_2(\tau_2+1)\right] + C\,J(J+1)$$

even-A $\quad \sigma_2 = \sigma_3 = 0 \qquad \tau_2 = 0$

$$E_x = -\frac{A}{4}\sigma(\sigma+4) + \frac{B}{6}\tau(\tau+3) + C\,J(J+1)$$

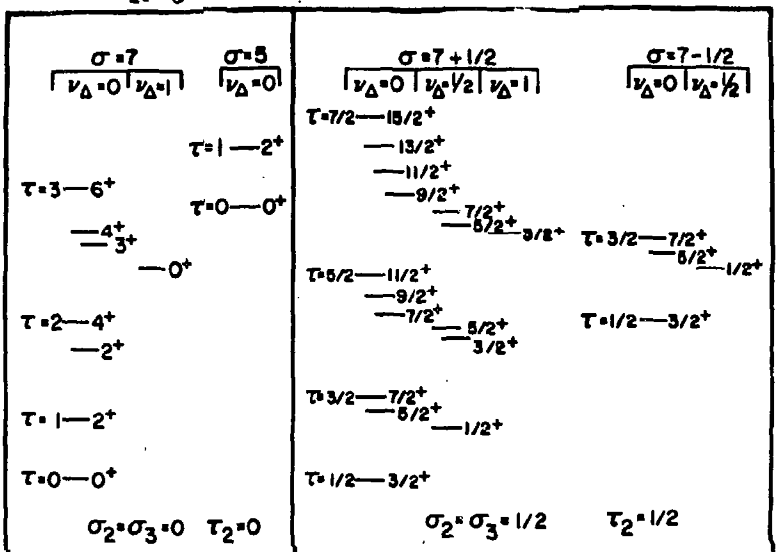
odd-A $\quad \sigma_3 = |\sigma_3| = \frac{1}{2} \qquad \tau_2 = \frac{1}{2}$

$$E_x = -\frac{A}{4}\left[\sigma(\sigma+4) + \frac{3}{2}\right] + \frac{B}{6}\left[\tau(\tau+3) + \frac{3}{4}\right]$$
$$+ C\,J(J+1)$$

even A: $\sigma = N, N-2, \cdots 0$ or 1 ; odd A $\sigma = N+\frac{1}{2}, N-\frac{1}{2}, \cdots \frac{1}{2}$

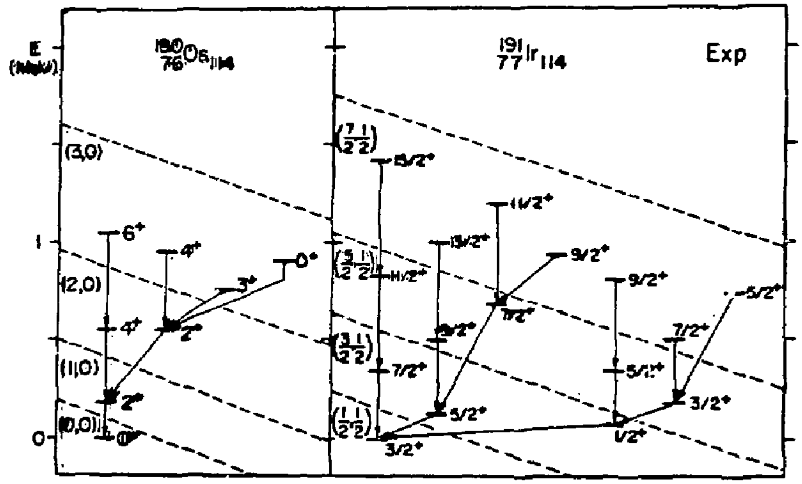
E2 Selection: $\Delta\tau = \pm 1$, $\Delta\sigma = 0$

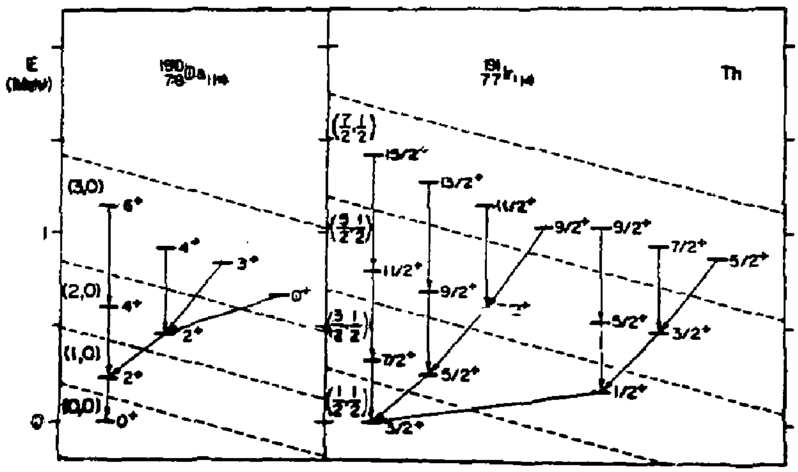
E2 : $\Delta\tau = 0, \pm 1$, $\Delta\sigma = 0$



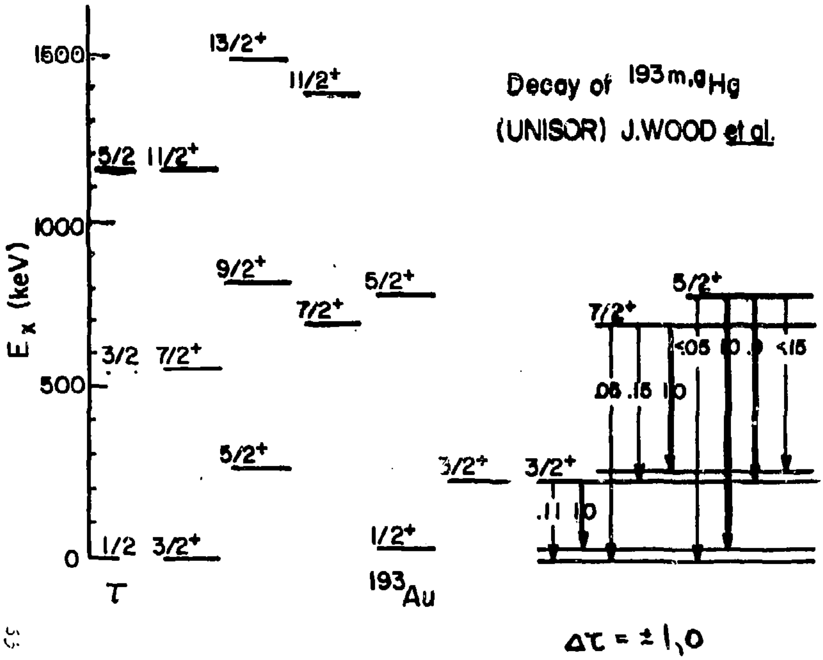
$\mathcal{N}=7$
$N=7$ $M=0$

$\mathcal{N}=8$
$N=7$ $M=1$


E
(MeV)
$^{190}_{76}Os_{114}$
$^{191}_{77}Ir_{114}$
Exp
(3,0)
(2,0)
(1,0)
(0,0)
1
0
6+
4+
4+
3+
0+
2+
2+
0+
15/2+
13/2+
11/2+
9/2+
11/2+
7/2+
9/2+
7/2+
5/2+
3/2+
9/2+
5/2+
1/2+
7/2+
3/2+
5/2+


E
(MeV)
$^{190}_{76}Os_{114}$
$^{191}_{77}Ir_{114}$
Th
(3,0)
(2,0)
(1,0)
(0,0)
1
0
6+
4+
3+
0+
4+
2+
2+
0+
15/2+
13/2+
11/2+
9/2+
9/2+
11/2+
9/2+
7/2+
5/2+
3/2+
5/2+
1/2+
7/2+
5/2+
3/2+

52


Decay of $^{193m,g}Hg$
(UNISOR) J.WOOD et al.
1500
1000
500
0
E_x (keV)
13/2+
11/2+
5/2
11/2+
9/2+
5/2+
7/2+
3/2
7/2+
5/2+
3/2+
3/2+
1/2
3/2+
1/2+
τ
^{193}Au
5/2+
7/2+
.05
.15
1.0
<.05
1.0
<.15
.11
1.0
Δτ = ±1,0

odd Au

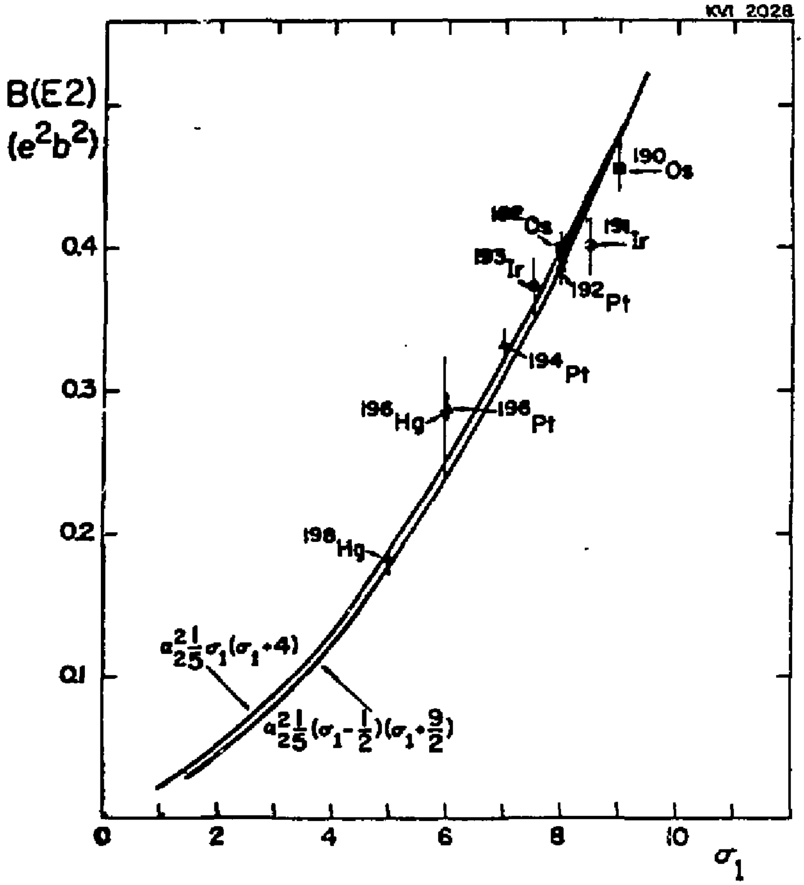
$$\frac{B(E2: 3/2^+_2 \rightarrow 3/2^+_1)}{B(E2: 3/2^+_2 \rightarrow 1/2^+_1)} = 0$$

SPIN(6) / SUPERSYMMETRY

^{193}Au	:	0.11
^{195}Au	:	0.29
^{197}Au	:	0.70

J. WOOD, priv. comm.
Phys. Rev. C24 1788 (1981)

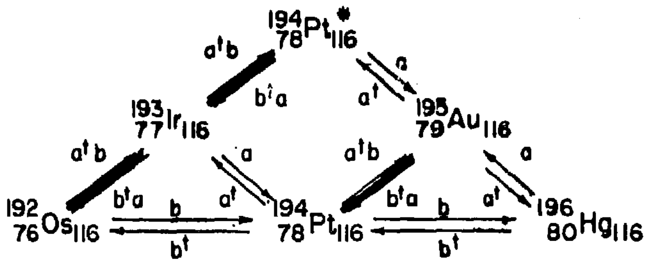
BALANTEKIN, et al. NP A370, 284 (1981)

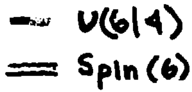


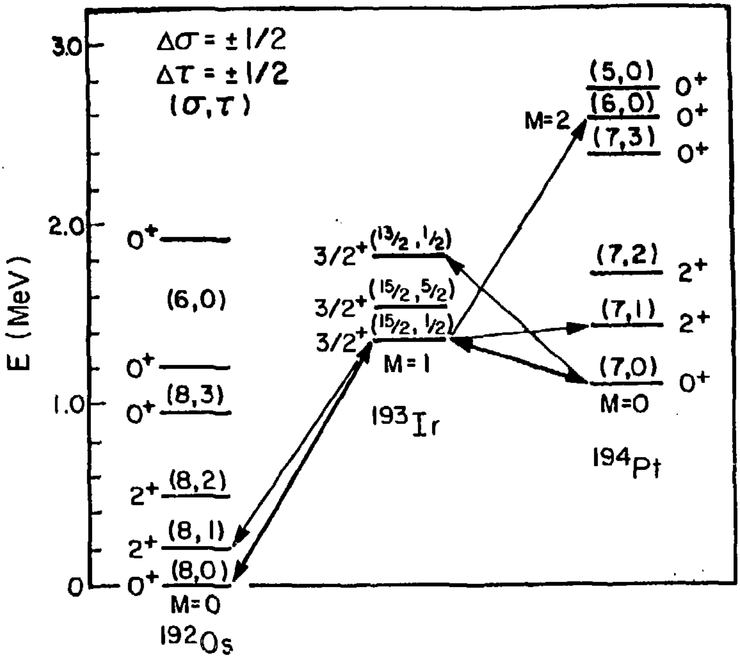
even-A: $B(E2: 2^+ \to 0^+)$

odd-A: $\frac{1}{3}[B(E2: \frac{7}{2} \to \frac{3}{2}) + B(E2: \frac{5}{2} \to \frac{3}{2}) + B(E2: \frac{1}{2} \to \frac{3}{2})]$

PARTICLE TRANSFER

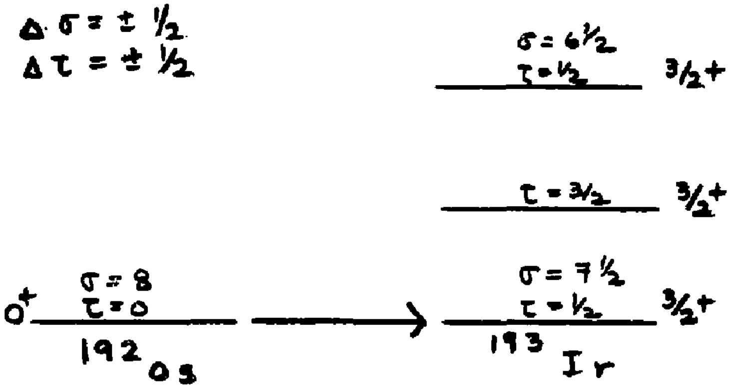






Δσ = ± 1/2
Δτ = ± 1/2
(σ,τ)
E (MeV)
3.0
2.0
1.0
0
0+
(6,0)
0+
0+ (8,3)
2+ (8,2)
2+ (8,1)
0+ (8,0)
M=0
192Os
3/2+ (13/2, 1/2)
3/2+ (15/2, 5/2)
3/2+ (15/2, 1/2)
M=1
193Ir
M=2
(5,0) 0+
(6,0) 0+
(7,3) 0+
(7,2) 2+
(7,1) 2+
(7,0) 0+
M=0
194Pt

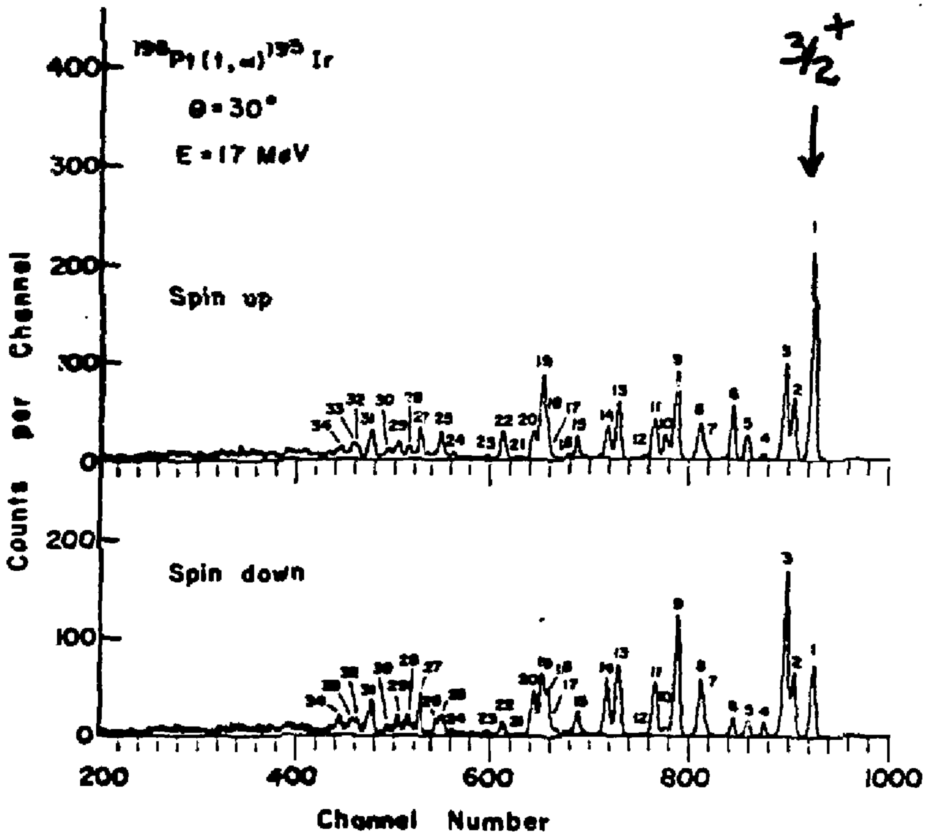
$\Delta\sigma = \pm 1/2$
$\Delta\tau = \pm 1/2$

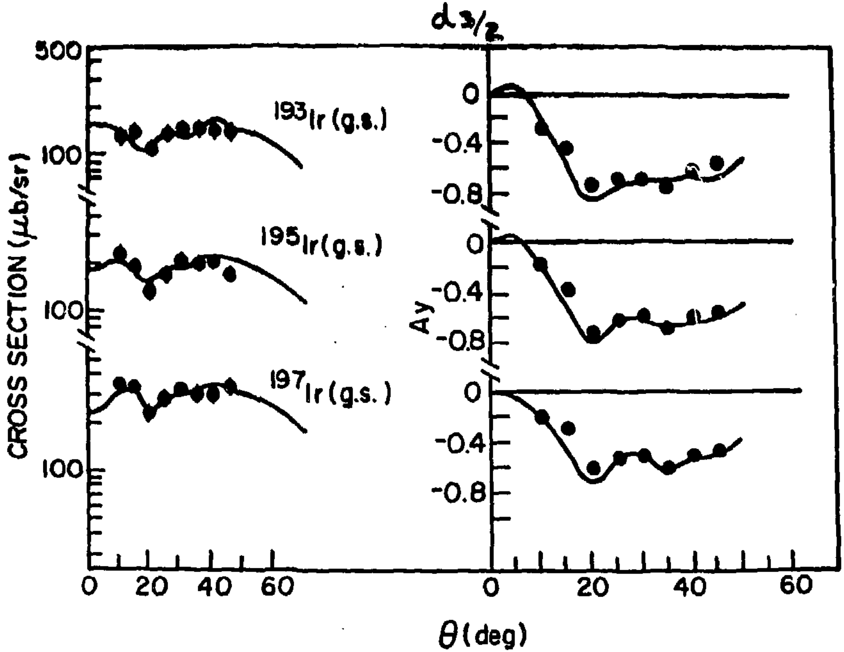


Os(^{3}He, d) Ir

	E_x	J^π	S (Exp)	S_{rel} (Exp)	Thy
^{193}Ir	0	3/2+	0.67	≡ 1.00	1.00
	180	3/2+	0.04	0.06	0
	460	3/2+	N.O.	—	0
^{191}Ir	0	3/2+	0.70	≡ 1.00	1.00
	179	3/2+	0.06	0.09	0

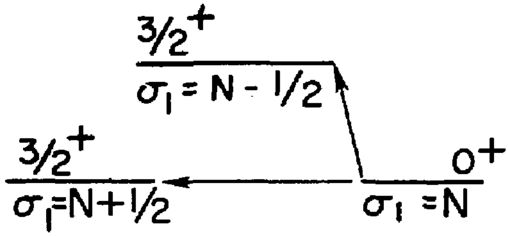
R.H. Price, et al. N.P. A176, 338 (1971)


^{198}Pt (t, α)^{193} Ir
θ = 30°
E = 17 MeV
3/2$^+$
Spin up
Spin down
Counts per Channel
Channel Number
400
300
200
100
0
200
100
0
200
400
600
800
1000



d 3/2
500
100
100
100
CROSS SECTION (μb/sr)
^{193}Ir (g.s.)
^{195}Ir (g.s.)
^{197}Ir (g.s.)
0
-0.4
-0.8
Ay
0 20 40 60
0 20 40 60
θ (deg)

$Pt(\vec{t},\alpha)\,Ir$



RATIO OF STRENGTHS, S, FOR STATES $(\sigma_1\ \tau_1)$

$$\frac{S(N-\frac{1}{2},\frac{1}{2})}{S(N+\frac{1}{2},\frac{1}{2})} \approx \frac{N}{N+4} \sim 0.70$$

ONLY <u>TWO</u> STATES, BOTH J= 3/2, WILL BE SEEN

	E_x	J^π	S_{exp}	S_{rel}	S_{thy}
^{193}Ir	0	$3/2^+$	1.6	≡1.00	≡1.00
N= 7	180	$3/2^+$	0.11	0.07	0
	460	$3/2^+$	1.1	0.69	0.64
	73	$1/2^+$	$\lesssim$0.5		

D.G. BURKE, E.R.FLYNN, R.E. BROWN, J.W. SUNIER, J.A.C

P.R.L. <u>46</u>, 1264 (1981)

Pt($\vec{t}$,α)

	E_x	J^π	S_{exp}	S_{rel}	S_{thy}
^{193}Ir	0	$3/2^+$	1.6	≡1.00	≡1.00
N=7	180	$3/2^+$	0.11	0.07	0
	460	$3/2^+$	1.1	0.69	0.64
	73	$1/2^+$	≲0.5		
^{195}Ir	0	$3/2^+$	2.1	≡1.00	≡1.00
N=6	234	$(3/2^+)$	0.33	0.16	0
	287	$3/2^+$	0.49	0.23	0.60
	70	$1/2^+$	0.75		
^{197}Ir	0	$3/2^+$	3.5		
N=5	52	$1/2^+$	1.2		

(α, t) or $(^3He, d)$ Reactions

TARGET $\quad$ Ir $\quad$ N BOSONS + 1 FERMION

FINAL $\quad$ Pt $\quad$ N BOSONS

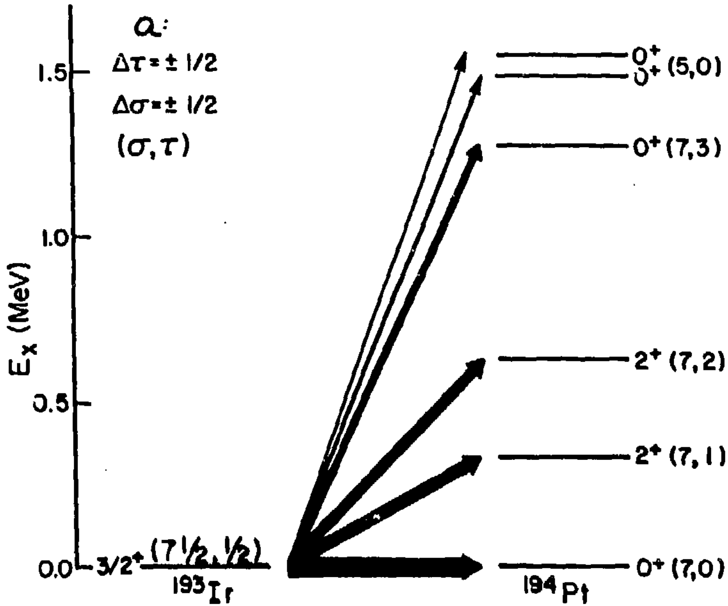
OPERATOR $\quad$ a $\quad$ DESTROYS ONE FERMION

MEASURED Spectra

Vergnes, et al. P.R.L. 46, 584 (1981)

{ no ang. dist. / no A_y } NEW RESULTS - Blasi, et al.

→ no clear knowledge of ℓ or j transfer



VERGNES, BURKE, et al. P.R.L. 46, 584 (1981)

N. Blasi, et al.

KNOW MANY SINGLE PARTICLE ORBITALS

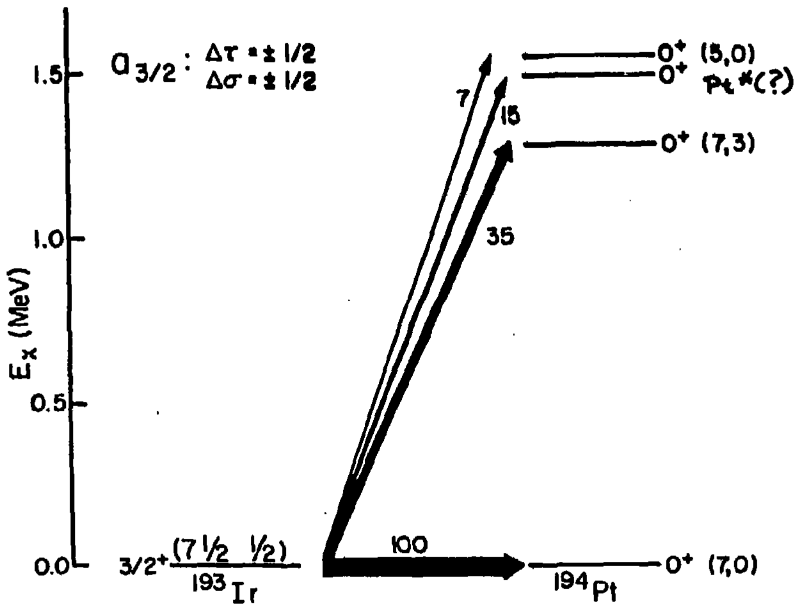
g.s. $d_{3/2}$

~500 – 1000 keV $s_{1/2}$ $d_{5/2}$ $g_{7/2}$

CAN BE PART OF BOSONS

ONLY $d_{3/2}$ transfer

$\Longrightarrow$ ONLY 0^+ STATES IN Pt



VERGNES, BURKE, et al. P.R.L. 46, 584 (1981)
N. Blasi, et al.

SUPERSYMMETRY / SPIN(6)

REQUIRES

1) GOOD O(6) BOSON CORE

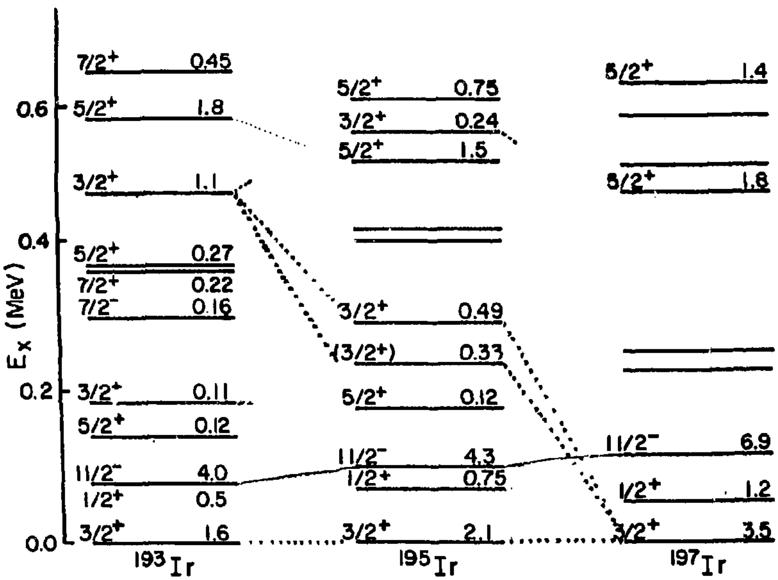
2) SINGLE $d_{3/2}$ odd particle

3) PARTICULAR FORM OF V_{BF}

$\left\{ \begin{array}{l} {}^{190}Os \quad {}^{191}Ir \qquad {}^{192}Os \quad {}^{193}Ir \\ \qquad {}^{192}Pt \quad {}^{193}Au \end{array} \right.$

${}^{195,197}Ir$ ${}^{195}Au$ (?) ${}^{197}Au \rightarrow {}^{203}Au$

NO Why?



E_x (MeV)
0.0
0.2
0.4
0.6
7/2+ 0.45
5/2+ 1.8
3/2+ 1.1
5/2+ 0.27
7/2+ 0.22
7/2− 0.16
3/2+ 0.11
5/2+ 0.12
11/2− 4.0
1/2+ 0.5
3/2+ 1.6
5/2+ 0.75
3/2+ 0.24
5/2+ 1.5
3/2+ 0.49
(3/2+) 0.33
5/2+ 0.12
11/2− 4.3
1/2+ 0.75
3/2+ 2.1
5/2+ 1.4
5/2+ 1.8
11/2− 6.9
1/2+ 1.2
3/2+ 3.5
193Ir
195Ir
197Ir

PERTURBED SPIN(6)

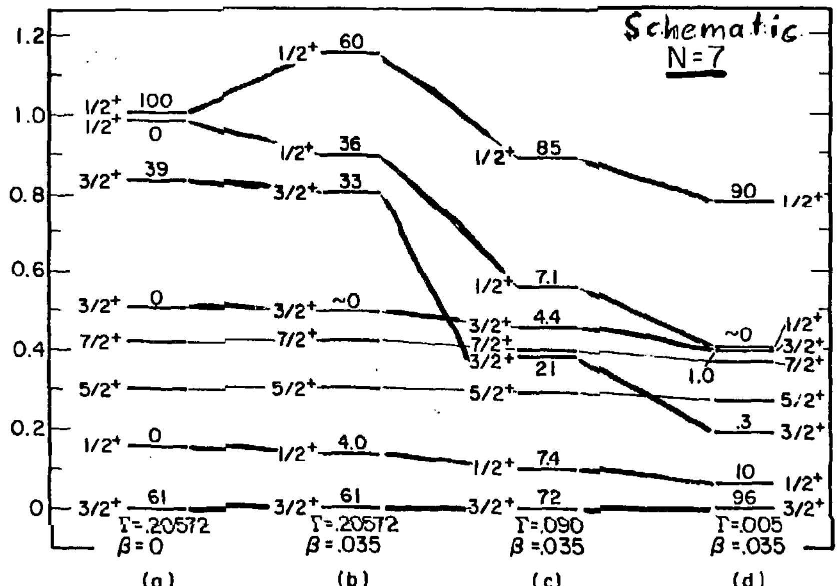
CHANGE V_{BF}:

$$V_{BF} = -\Lambda_1 \left[(d^+\tilde{d})^1 (a^+\tilde{a})^1\right]^0$$
$$- \Lambda_3 \left[(d^+\tilde{d})^3 (a^+\tilde{a})^3\right]^0$$
$$- \Gamma \left[\left[(d^+s)^{(2)} (a^+a)^2\right]^0 + \left[(s^+d)^2 (a^+\tilde{a})^2\right]^0\right]$$

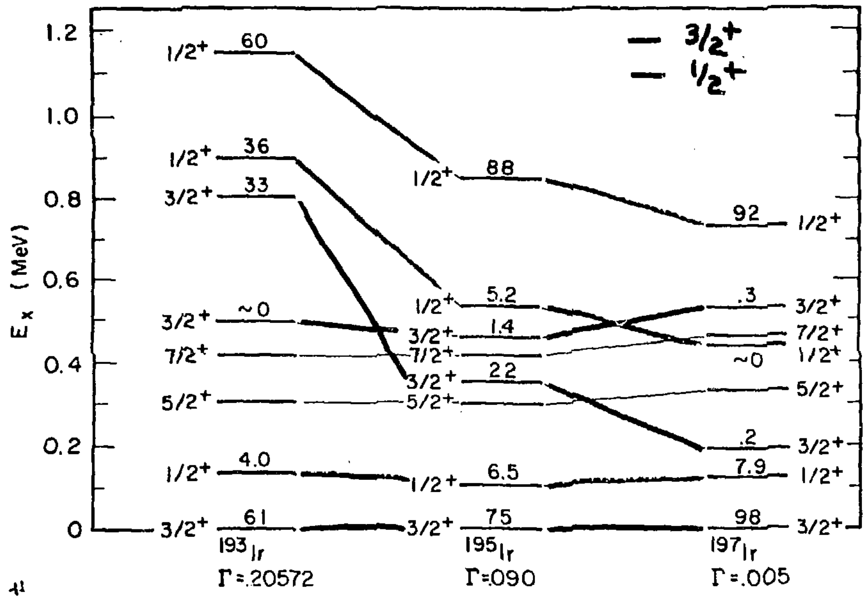
Γ term is significant —
determines much of Spin(6)
wavefunctions $J^\pi(\sigma, \tau, \nu_\Delta)$

$$|3/2_1^+\rangle = -.78\left[3/2 \bullet 0^+(700)\right] + .62\left[3/2 \bullet 2^+(710)\right]$$

$$|3/2_3^+\rangle = .62\left[3/2 \bullet 0^+(700)\right] + .78\left[3/2 \bullet 2^+(710)\right]$$



$$H_c = \beta\left[(d^\dagger s + s^\dagger \tilde{d})^{(2)}(a^\dagger_{1/2}\tilde{a}_{3/2} - a^\dagger_{3/2}\tilde{a}_{1/2})^{(2)}\right]$$



3/2+
1/2+
1.2
1.0
0.8
0.6
0.4
0.2
0
Ex (MeV)
1/2+ 60
1/2+ 36
3/2+ 33
3/2+ ~0
7/2+
5/2+
1/2+ 4.0
3/2+ 61
193Ir
Γ=.20572
1/2+ 88
1/2+ 5.2
3/2+ 1.4
7/2+
3/2+ 22
5/2+
1/2+ 6.5
3/2+ 75
195Ir
Γ=.090
92 1/2+
.3 3/2+
7/2+
~0 1/2+
5/2+
.2 3/2+
7.9 1/2+
98 3/2+
197Ir
Γ=.005

OTHER SUPERSYMMETRIES

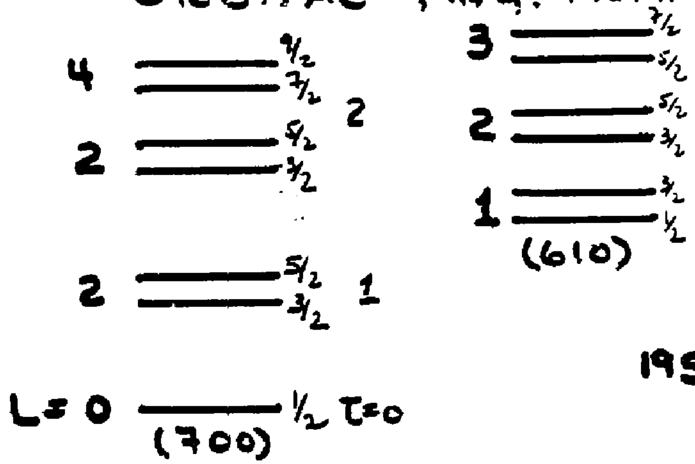
$U(5/2)$ . . . . .

$\frac{1}{2} \otimes SU(5)$ or $SU(3)$ . . . . .

NEW CLASS

$U(6/12)$: $\underbrace{\tfrac{1}{2}}_{L=0}, \underbrace{\tfrac{3}{2}, \tfrac{5}{2}}_{L=2} \otimes O(6)$

"ORBITAL ANG. MOM." L



^{195}Pt ?

SUPERSYMMETRIES IN NUCLEI ?

APPROXIMATE:

$^{191,193}Ir$ $\quad$ ^{193}Au $\quad$ (^{195}Au, ^{197}Au?)

Os - Pt cores

PERTURBED

$^{193-197}Ir$ $\quad$ $^{193-201}Au$?

SIMPLER APPROACH TO COMPLEX ODD-A NUCLEI

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