SHAPE COEXISTENCE AND PHASE TRANSITIONS N ATOMIC NUCLEI

Int'l workshop on Physics with AGATA

March 22 ·24 Orsay

K. Heyde

AIM OF THIS TALK

EXPLORE CONDITIONS NEEDED TO FIND SHAPE COEXISTENCE STARTING FROM ESSENTIAL INGREDIENTS OF THE N-N FORCE

EXPLORE POWER AND LIMITATIONS OF THE NUCLEAR SHELL MODEL

POSSIBILITIES USING SYMMETRY IDEAS- SAMPLE COLLECTIVE MODES

EXPLORE MEAN-FIELD METHODS

STUDY QUADRUPOLE SHAPE VARIABLES FOR SHAPE TRANSITIONS

OUTLOOK

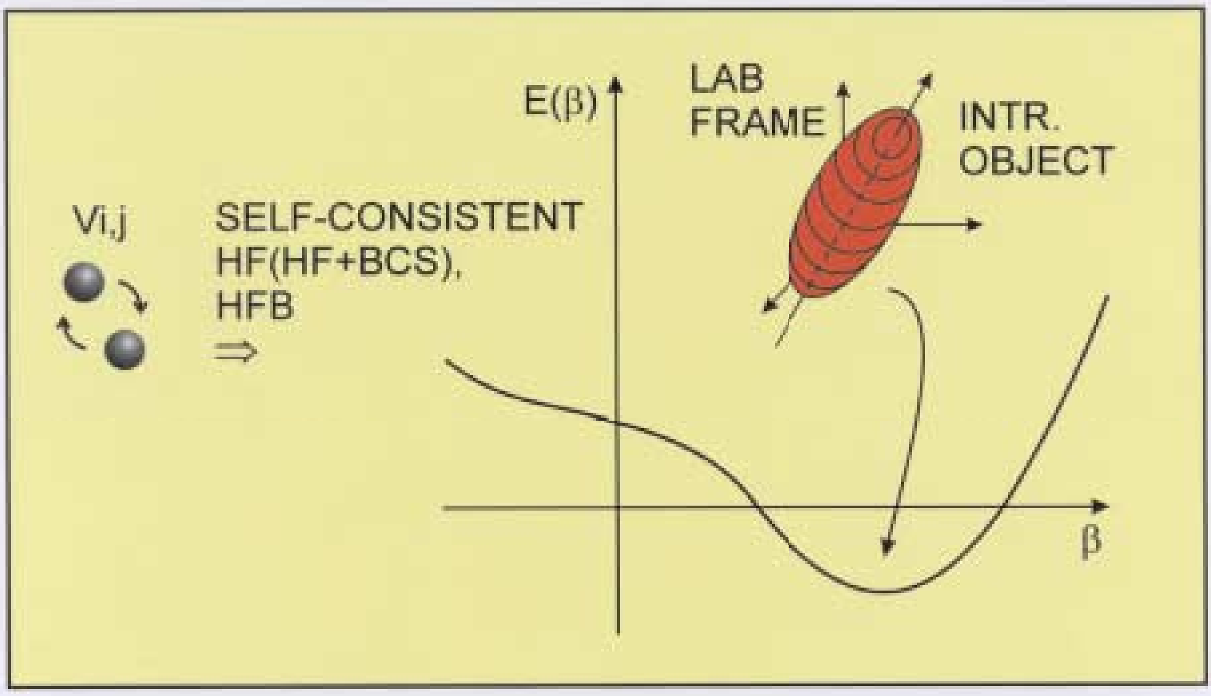
- NUCLEONS INTERACTING THROUGH V(i,j) GENERATE MEAN-FIELDS WITH SHELL STRUCTURE

  HF, HF + pairing (BCS), HFB

- SELF - CONSISTENT CALCULATIONS IMPLY THAT ENERGY MINIMA CORRESPOND WITH DEFORMED MEAN - FIELDS MAINLY

→ DISADVANTAGE : NOT IN LAB FRAME (no good J^{π}, T, N, Z,.)

→ ADVANTAGE : GIVES "INTRINSIC" STRUCTURES → INT. FOR MODELS WITH SHAPE VARIABLES



* VERY - LIGHT NUCLEI ($A \lesssim 10$). AB - INITIO CALCULATIONS

* SHELL - MODEL

1p shell : Cohen, Kurath,...
2s, 1d shell : Brown, Wildenthal,...
2p, 1f shell : Madrid - Strasbourg, (restricted)
: GXPF1 : Honma, Otsuka, Brown, Mizusaki
Heavier ?

MAIN CONCEPT

BUILDING UP OF A (VERY) LARGE MODEL SPACE dim (N) + METHODS TO DETERMINE THE LOWEST ENERGY EIGENVALUES + WAVE FUNCTIONS

OXBASH code

ANTOINE code :~ 10^9 states in fp shell

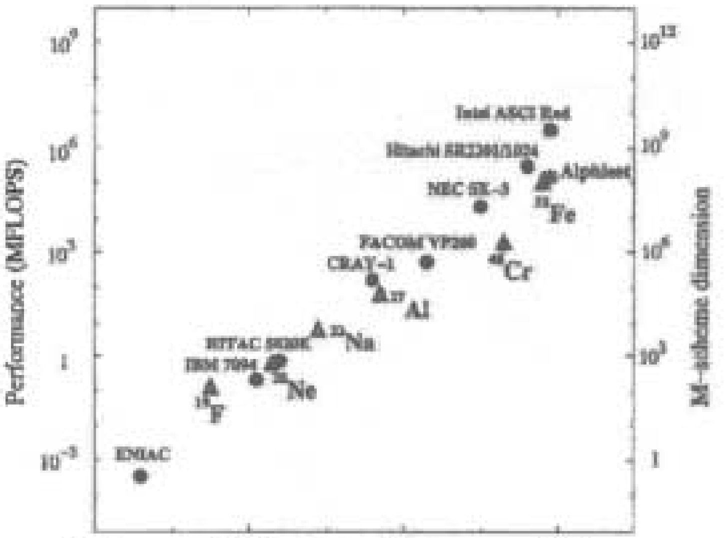
RESTRICTIONS

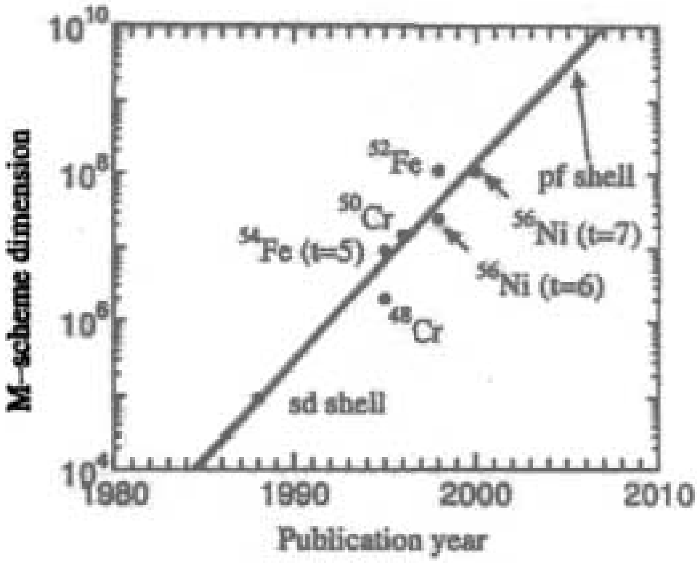
$C^{n}_{N_s}$ ex. $n \cong 100$ nucleons
$N_s = 200$ basis states, dim $\simeq 10^{60}$!

NUCLEAR SHELL-MODEL

- LIMITED NUMBER OF S.P. ORBITALS
  (p-shell, sd-shell, fp(g)-shell)

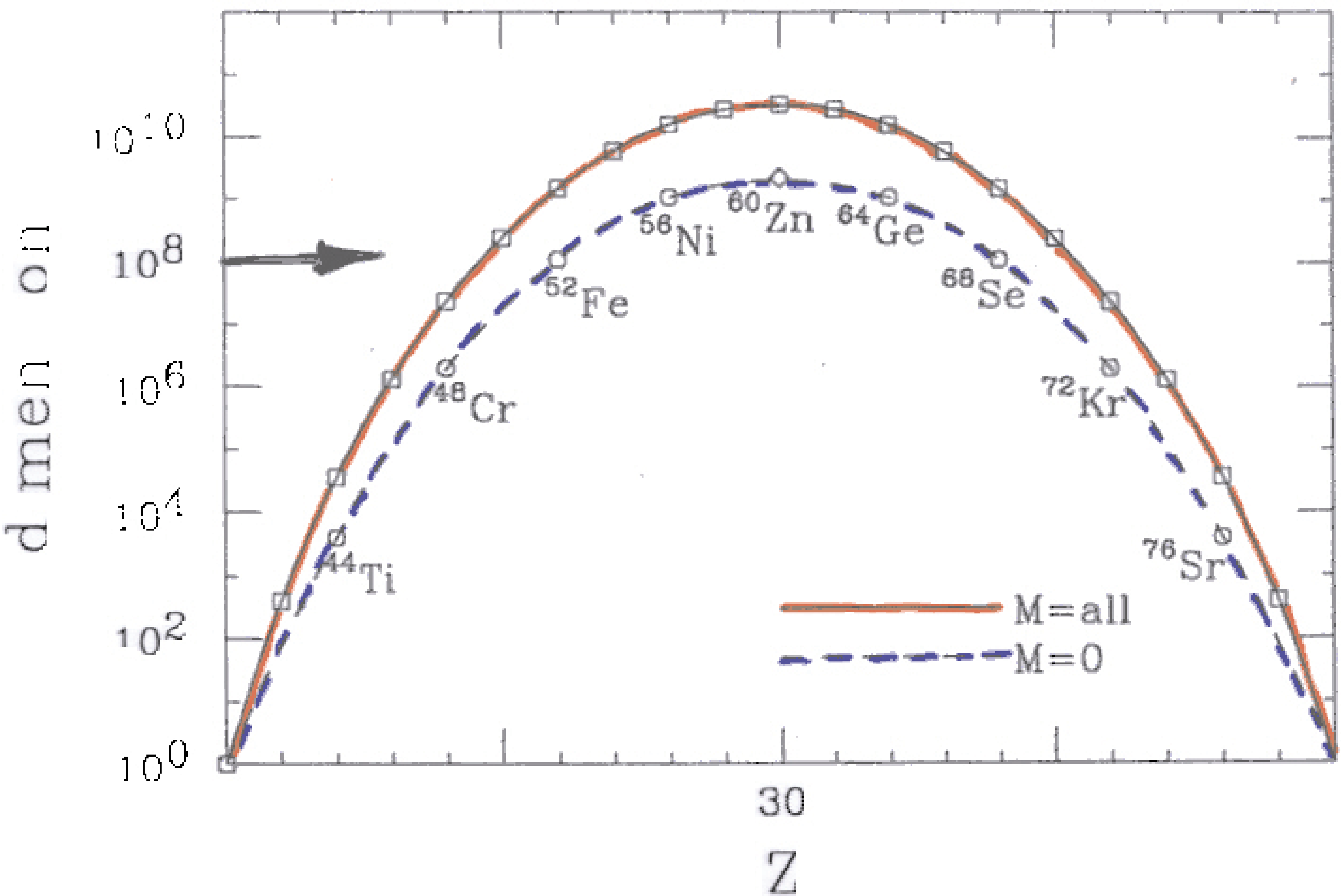
- LIMITED NUMBER OF VALENCE PARTICLES
  (12-middle sd shell (16-40))
  (20-middle fp shell (40-80))



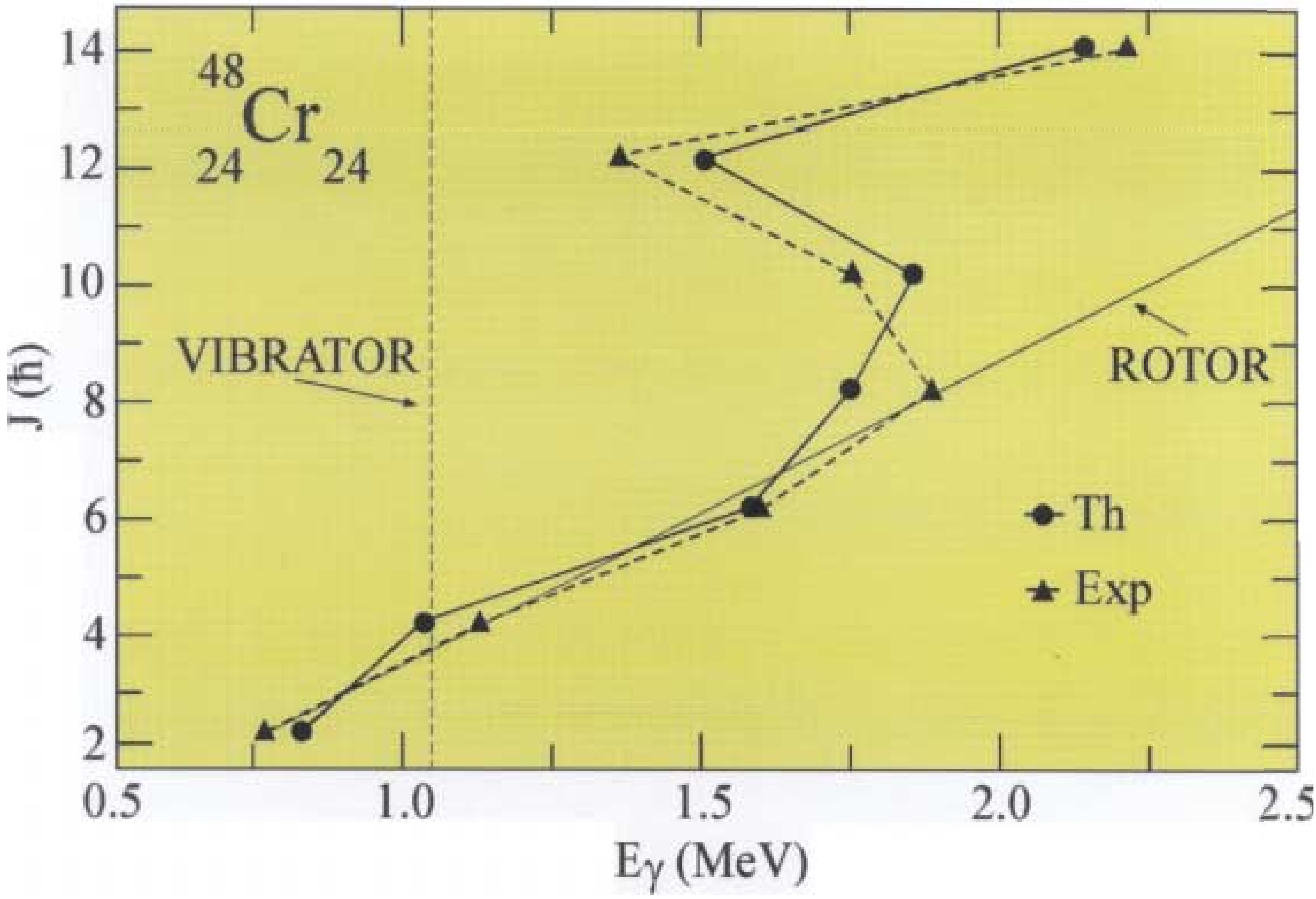


CODES: ANTOINE, NATHAN (Strasbourg, Madrid)
VECSSE, MSHELL (Tokyo)
OXBASH (Oxford, Buenos-Aires)

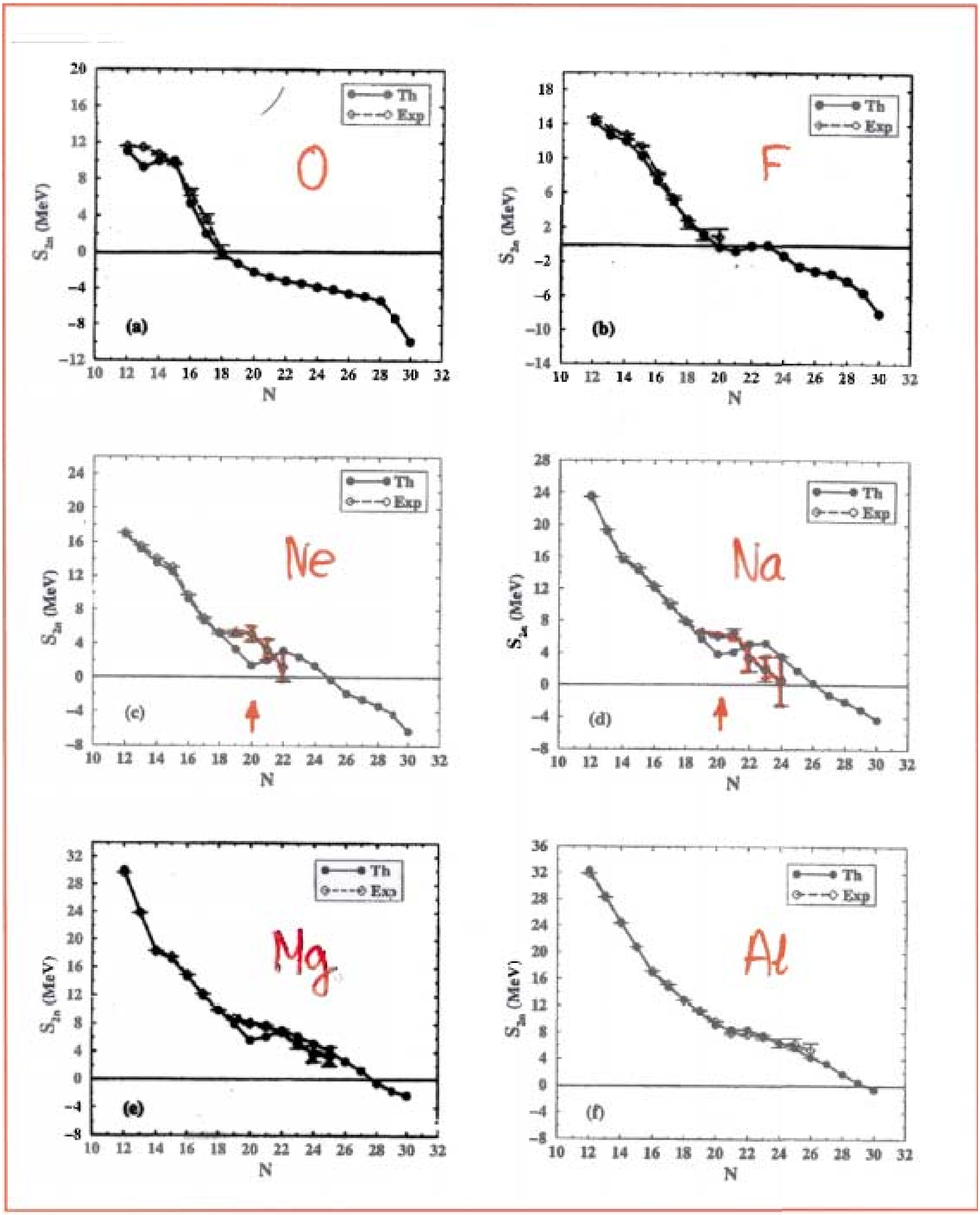
N -Z nuclei in pf shell



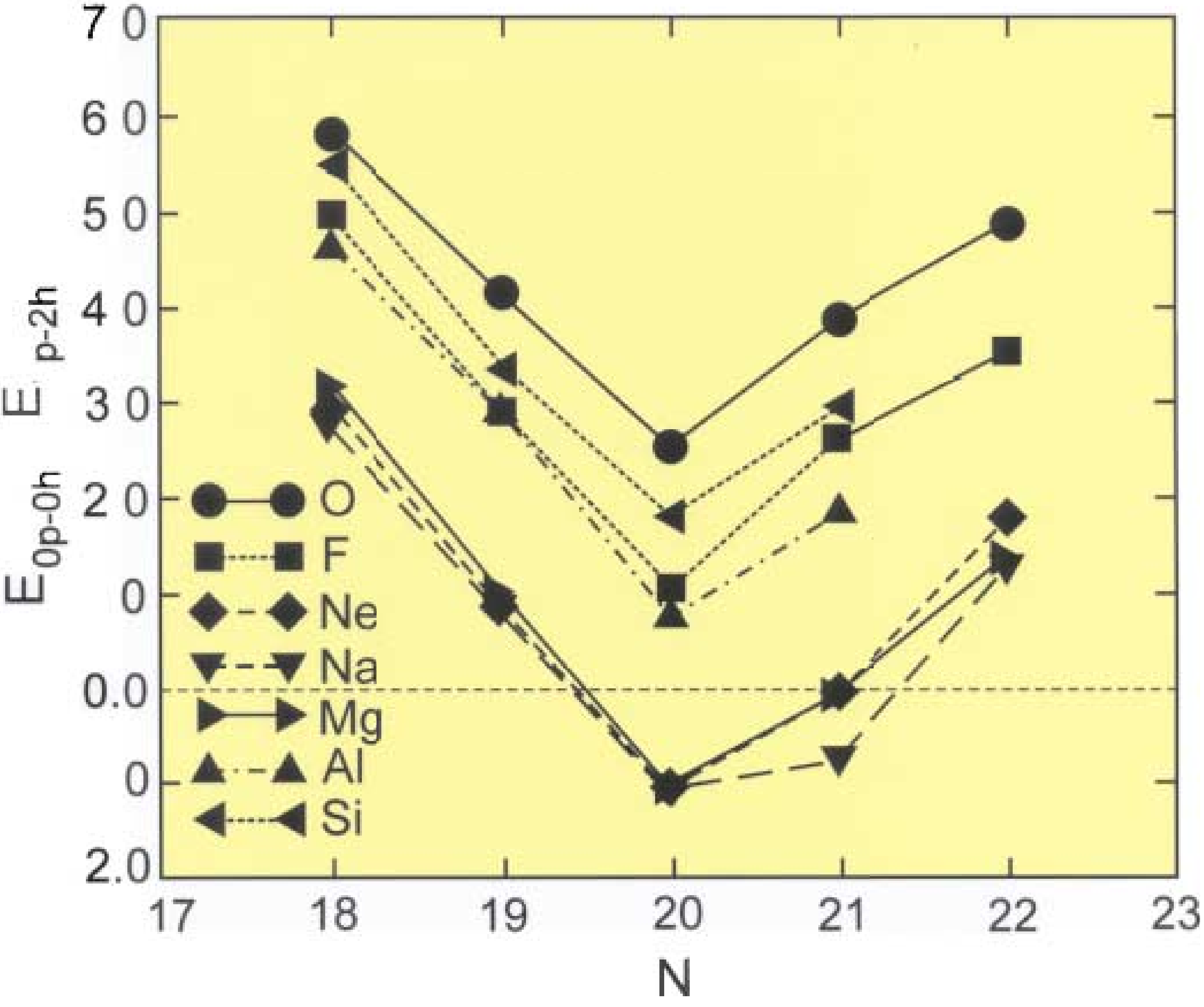
STATE-OF-THE ART SHELL-MODEL CALCULATION IN fp SHELL



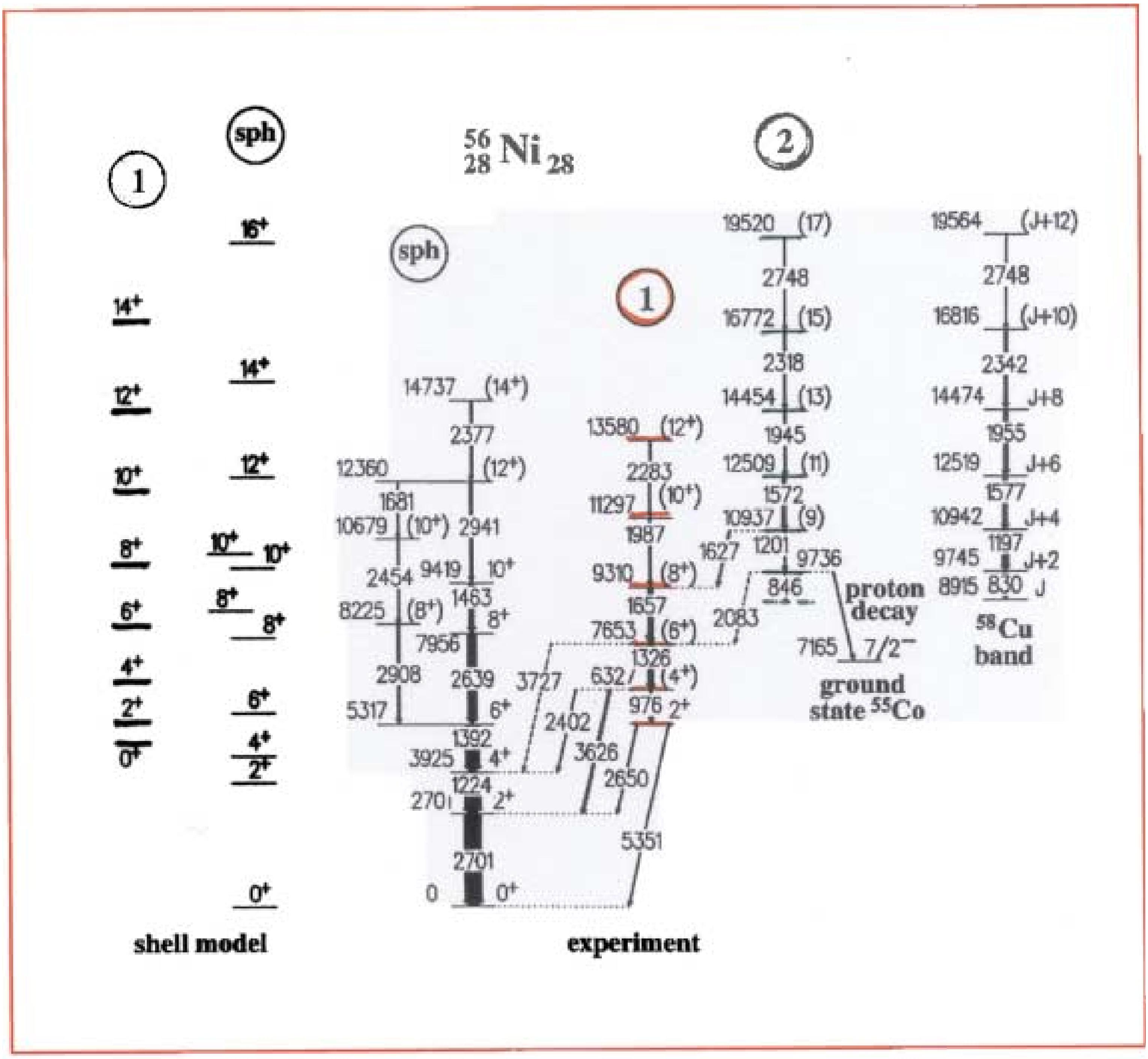
Strasbourg-Madrid
(CAURIER, NOWACKI, ZUKER, POVES et al.)



Theoretical and experimental S_{2n} values
E Caurier et al, PRC58 (1998) 2033



E Caurier et al., PRC58 (1998), 2033



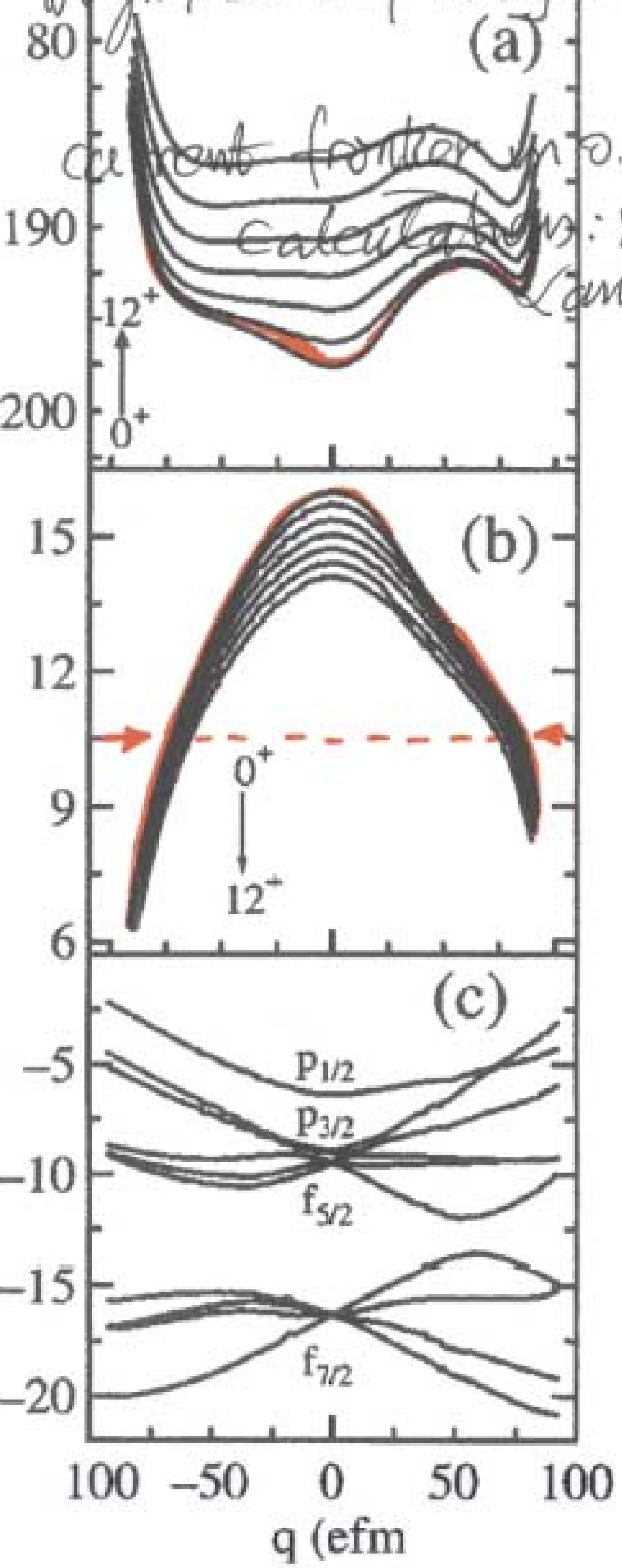
D. Rudolph et al., PRL 82 (1999), 3763

Band 1 Main components 4p-4h
Calculation in 6p-6h basis
: 25x10^6 states

will be more det disc N~Z nucl

to m Yrugo, Lenzi, Marginean

fp shell current frontier info. m calculations: standard Lanczos methods



Mizusaki et al PRC59 (1999) R1846

Constrained Hartree Fock "CHF"

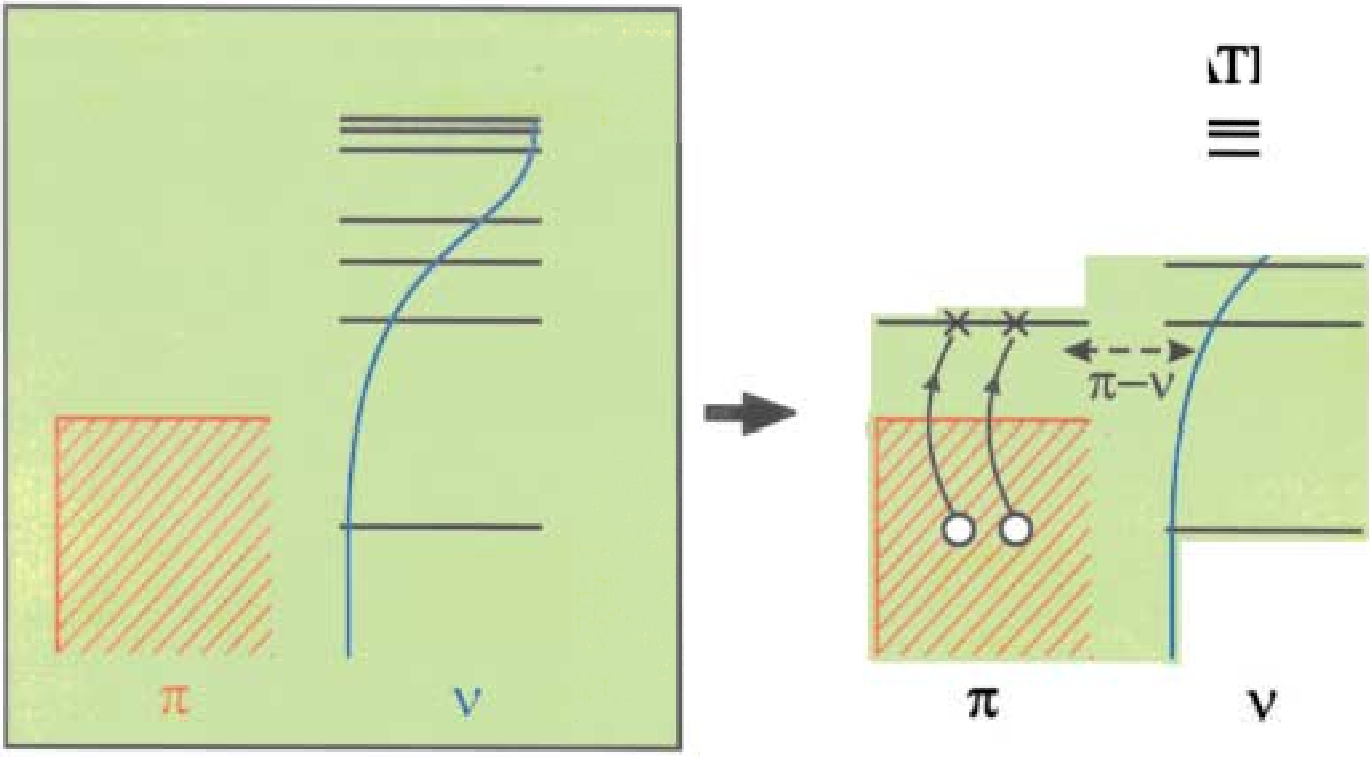
FIND PRECISE BALANCE BETWEEN
VALENCE PROTONS - "CLOSED" NEUTRON SHELL
OR SUBSHELL

IN ORDER TO MEET CONDITIONS APPROPRIATE FOR HAVING SHAPE COEXISTENCE DEVELOP

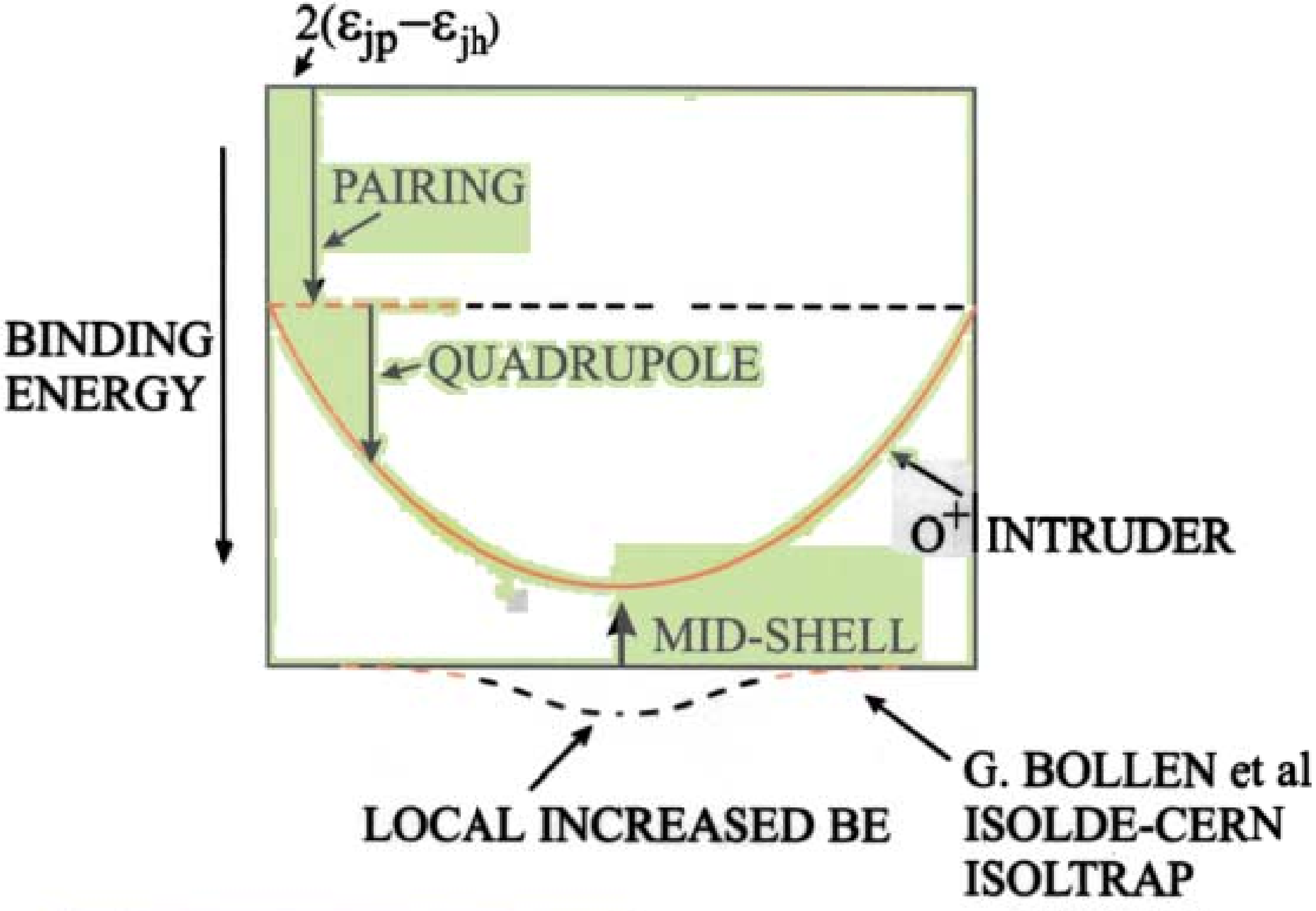
NUCLEI WITH N=Z AT CLOSED SHELLS OR SUB SHELLS

e.g.
- Ne, Na, Mg N= 20
- region near ^{56}Ni

NEED FOR " IMPORTANCE" SAMPLING OF BOTH THE N -N INTERACTION AND MODEL SPACE

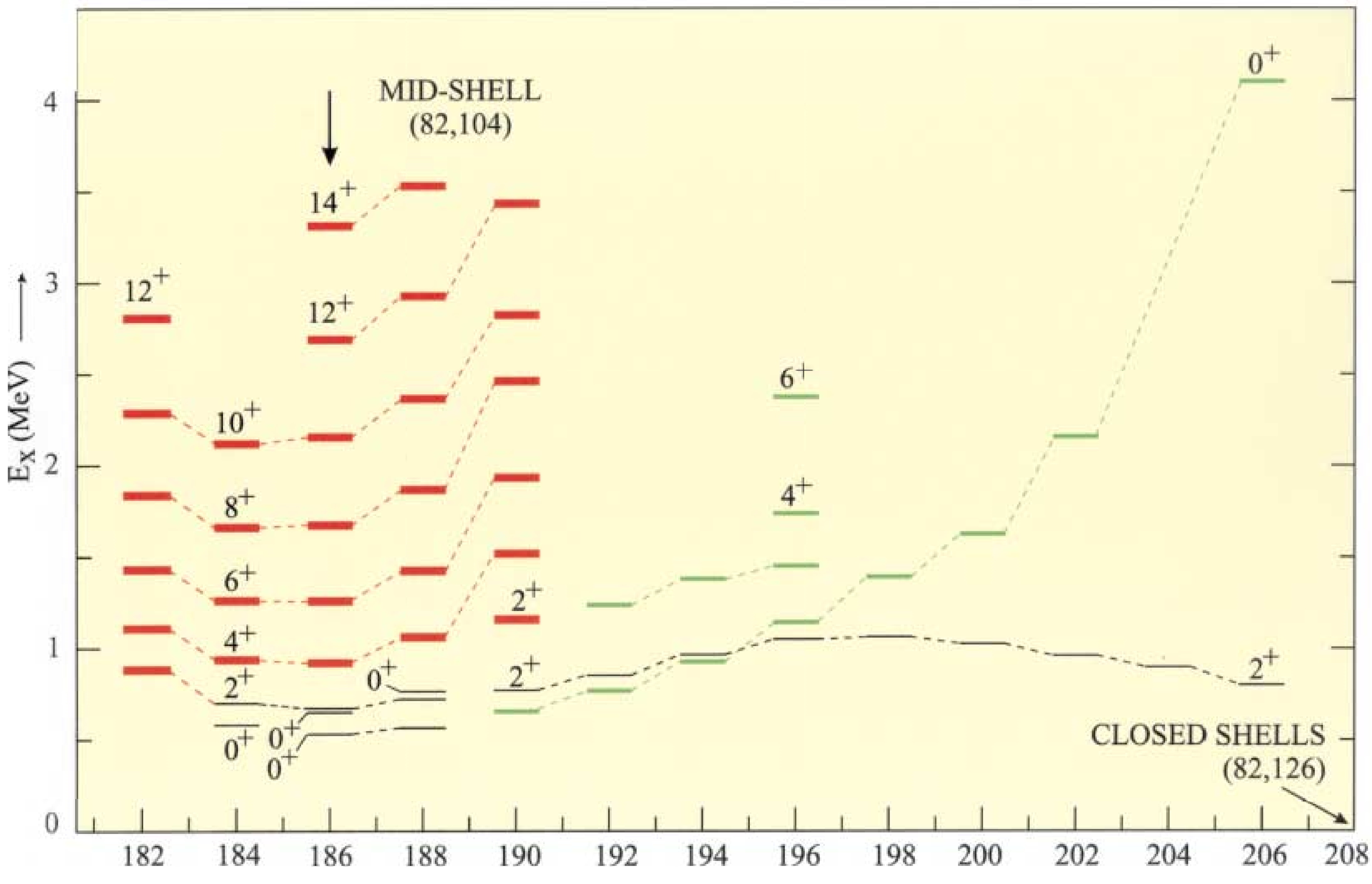


$$\Delta E = \langle 0^+_I | \hat{H} | 0^+_I \rangle - \langle 0^+_{GS} | \hat{H} | 0^+_{GS} \rangle$$

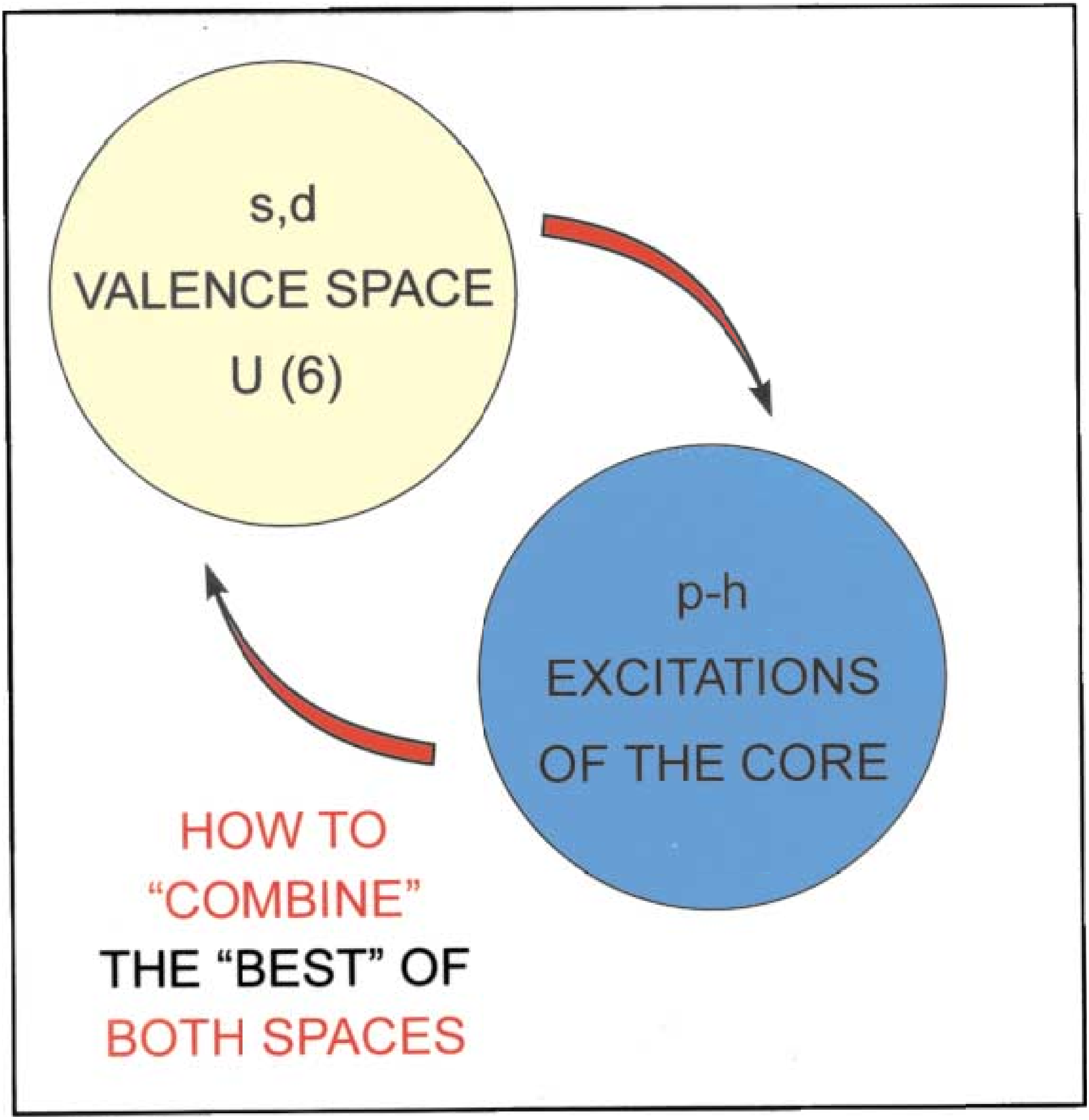


$$\Delta E_{QUAD.} \simeq 2\kappa N_\nu . \Delta N_\pi$$

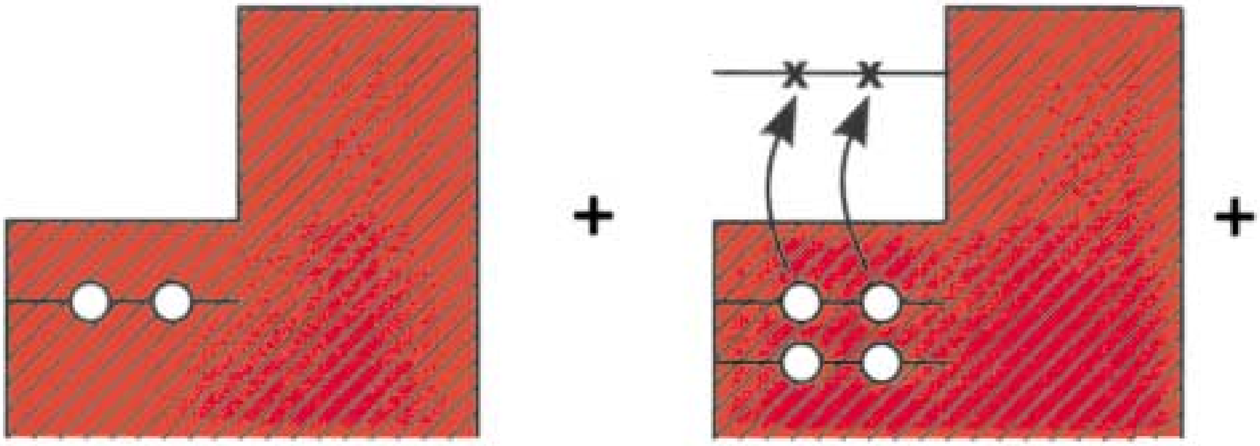
Pb NUCLEI



MID-SHELL
(82,104)
CLOSED SHELLS
(82,126)
E_X (MeV)
0
1
2
3
4
182
184
186
188
190
192
194
196
198
200
202
204
206
208
12^+
10^+
8^+
6^+
4^+
2^+
0^+
14^+
2^+
6^+
4^+
0^+


s,d
VALENCE SPACE
U (6)
p-h
EXCITATIONS
OF THE CORE
HOW TO
"COMBINE"
THE "BEST" OF
BOTH SPACES

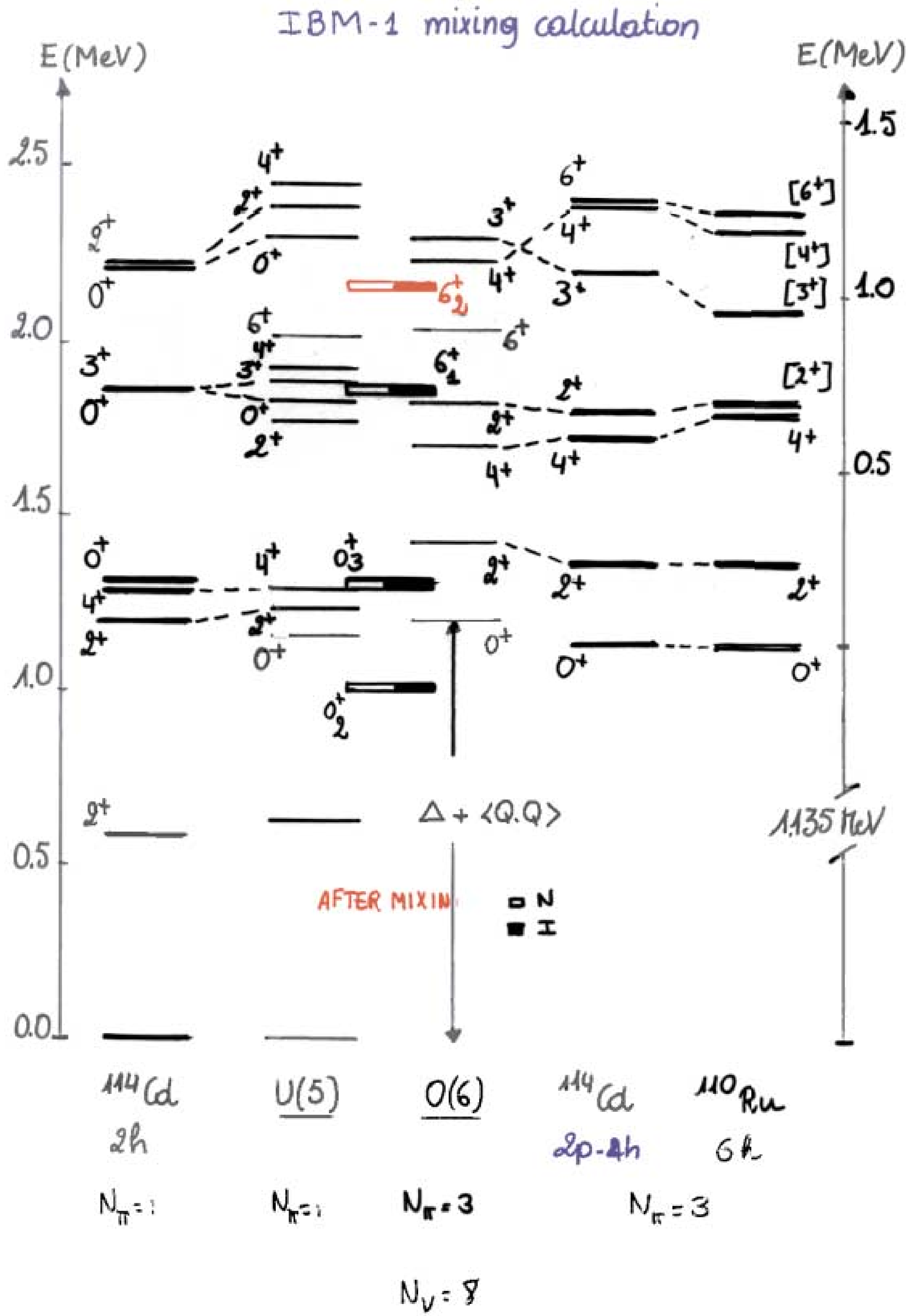
CONSIDER 2p-2h, 4p-4h,.. EXCITATIONS AS SEPARATE MODEL SPACE WITH N, N+2, N+4 BOSONS.



$$\begin{bmatrix} E_i(N) & \langle V\rangle & 0 \\ \langle V\rangle & E_i(N+2)+\Delta & \langle V\rangle \\ 0 & \langle V\rangle & E_i(N+4)+\Delta' \end{bmatrix}$$

$$H_{mix} = \alpha(s_p^+ s_h^+ + h.c.)^{(o)} + \beta\,(d_p^+ d_h^+ + h.c.)^{(o)}$$

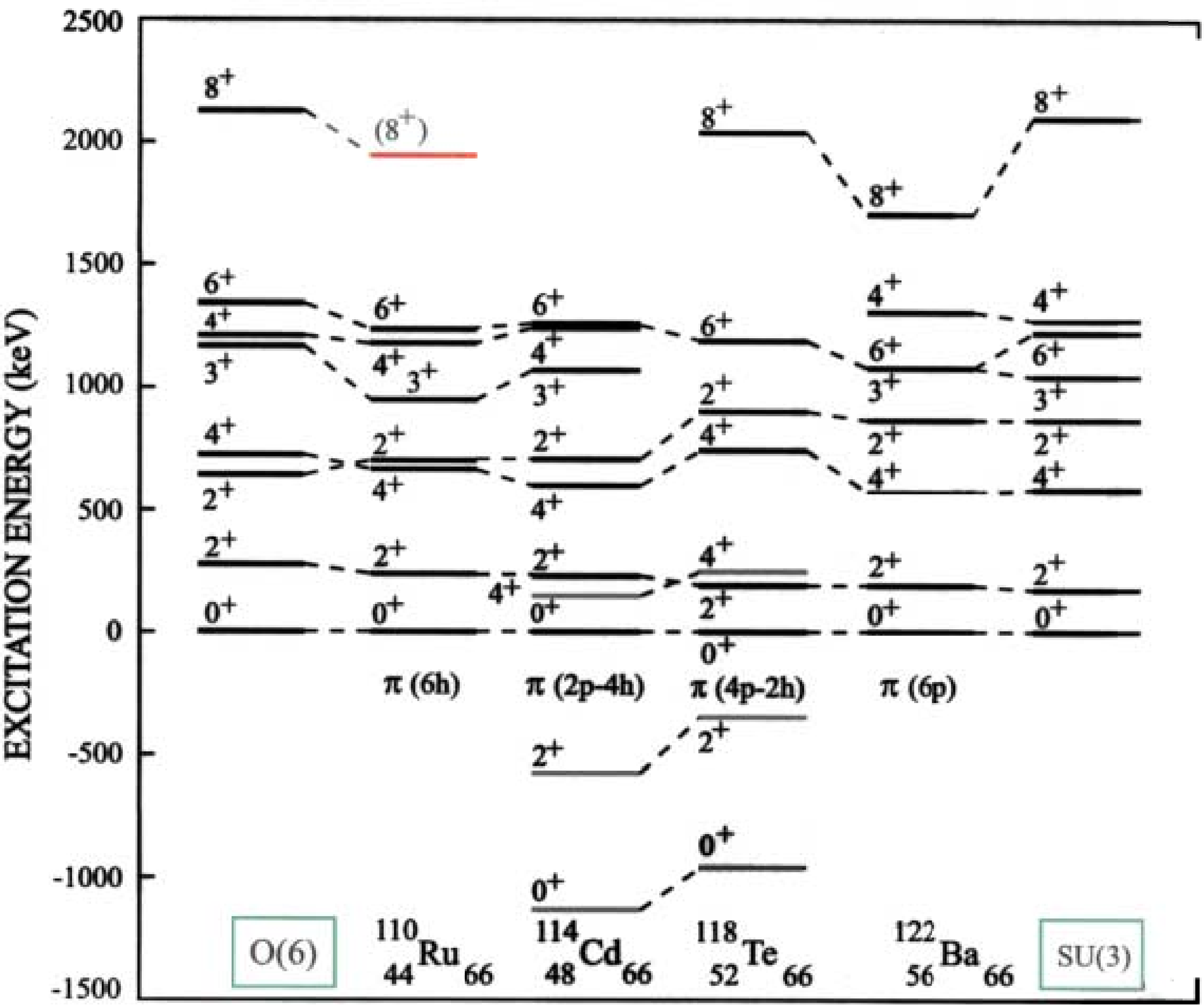
Duval, Barret, NPA 376(1982), 213
Applications in Z=50, Z=82 regions



IBM-1 mixing calculation
E(MeV)
E(MeV)
AFTER MIXIN
N
I
Δ + ⟨Q.Q⟩
1.135 MeV
114Cd 2h
U(5)
O(6)
114Cd 2p-4h
110Ru 6h
Nπ = 1
Nπ = 1
Nπ = 3
Nπ = 3
Nν = 8

FULL I = 3/2 MULTIPLET

I_Z = -3/2 -1/2 +1/2 +3/2



B(E2 Values in 3/2 MULT PLET

Neutron Number	Cd Intruder $B(E2;2_3^+ \rightarrow 0_A^+)$	Ru $B(E2;2_1^+ \rightarrow 0_1^+)$	Ba $B(E2;2_1^+ \rightarrow 0_1^+)$
62	23^{+27}_{-18}	– –	– –
64	56 ± 17	58 ± 5	– –
66	61 ± 8	70 ± 5	154 ± 14
68	86^{+24}_{-30}	74 ± 7	116 ± 6
70	– –	– –	98 ± 16

nature letters to nature

A. Andreyev et al.

May, 25

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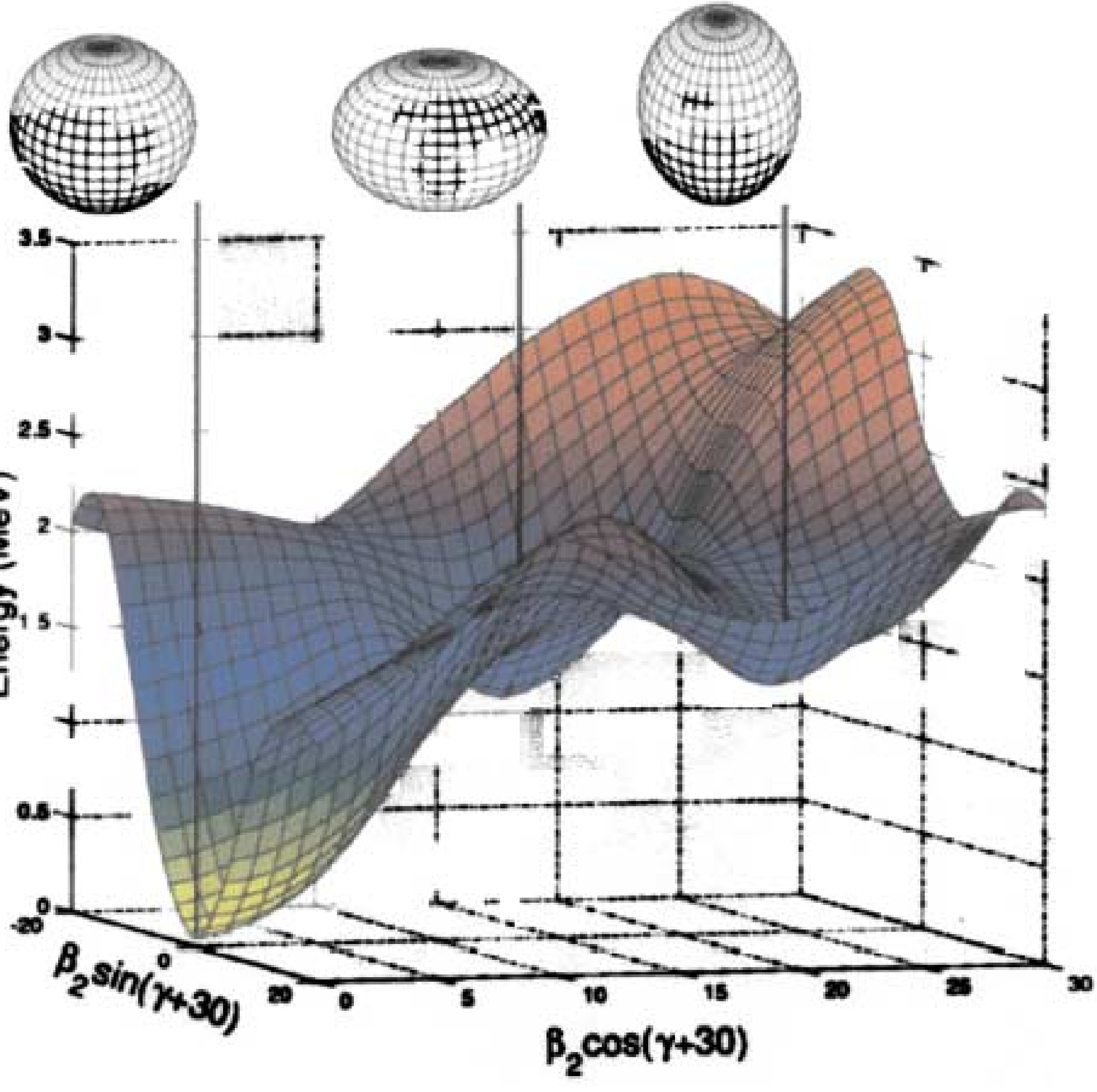


Figure 1 Calculated potential energy surface of ^{186}Pb. Spherical, oblate and prolate minima are indicated by thick vertical black lines. Calculations are performed on the cartesian mesh. The β_2 parameter expresses the elongation of the nucleus along the symmetry axis, while the γ parameter relates to the degree of triaxiality in the deformation (that is, the relative lengths of the three principal axes of the spheroidal nucleus). The γ parameter is defined such that $\gamma = 0$ corresponds to a prolate (cigar-like) shape and $\gamma = 60$ to an oblate (disk-like) shape.

← item →

Note: Figures may be difficult to render in a web browser. In such cases, we recommend

HF + BCS method

STATE $|\psi(q)>$ GENERATED BY A SELF-CONSISTENT MEAN- FIELD CALCULATION, USING A CONSTRAINT ON A COLLECTIVE COORDINATE q, STARTING FROM V (i,j)

↓

INTRINSIC STATE

↓

BREAKS A NUMBER OF SYMMETRIES OF "EXACT" MANY-BODY STATES → NEED TO GO TO LAB FRAME

↓

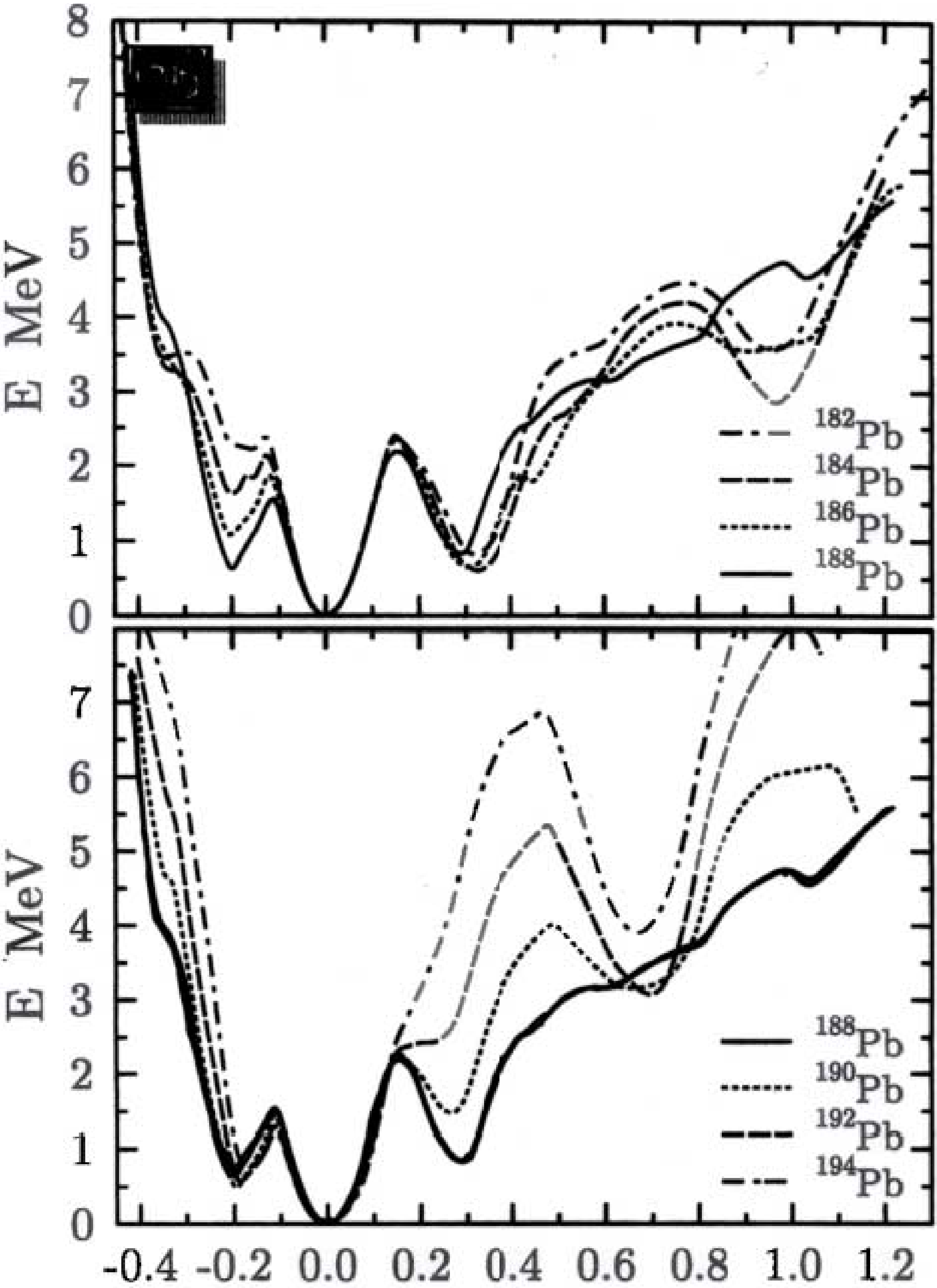
PROJECT ON J^{π}, N, Z, T,.. → $|J, M, q>$

↓

VARIATIONAL CONFIGURATION MIXING IN THE COLLECTIVE COORDINATE q, FOR EACH J^{π}

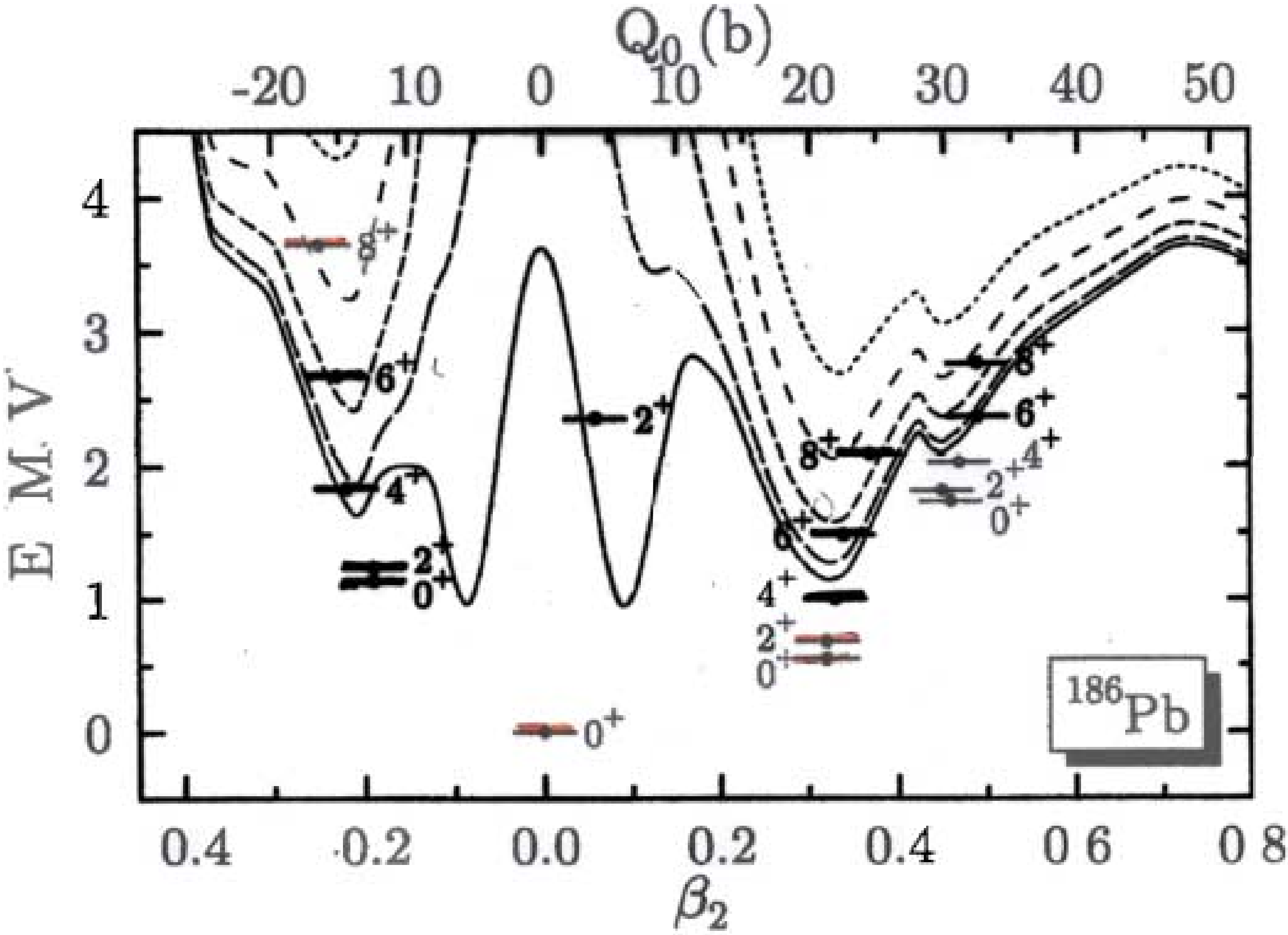
$$|JM, k> = \sum_q f_{J,k}(q)\,|JM,q>$$

$$E_{J,k} = \frac{<JM, k|\hat{H}|JM,k>}{<JM, k|JM,k>}$$



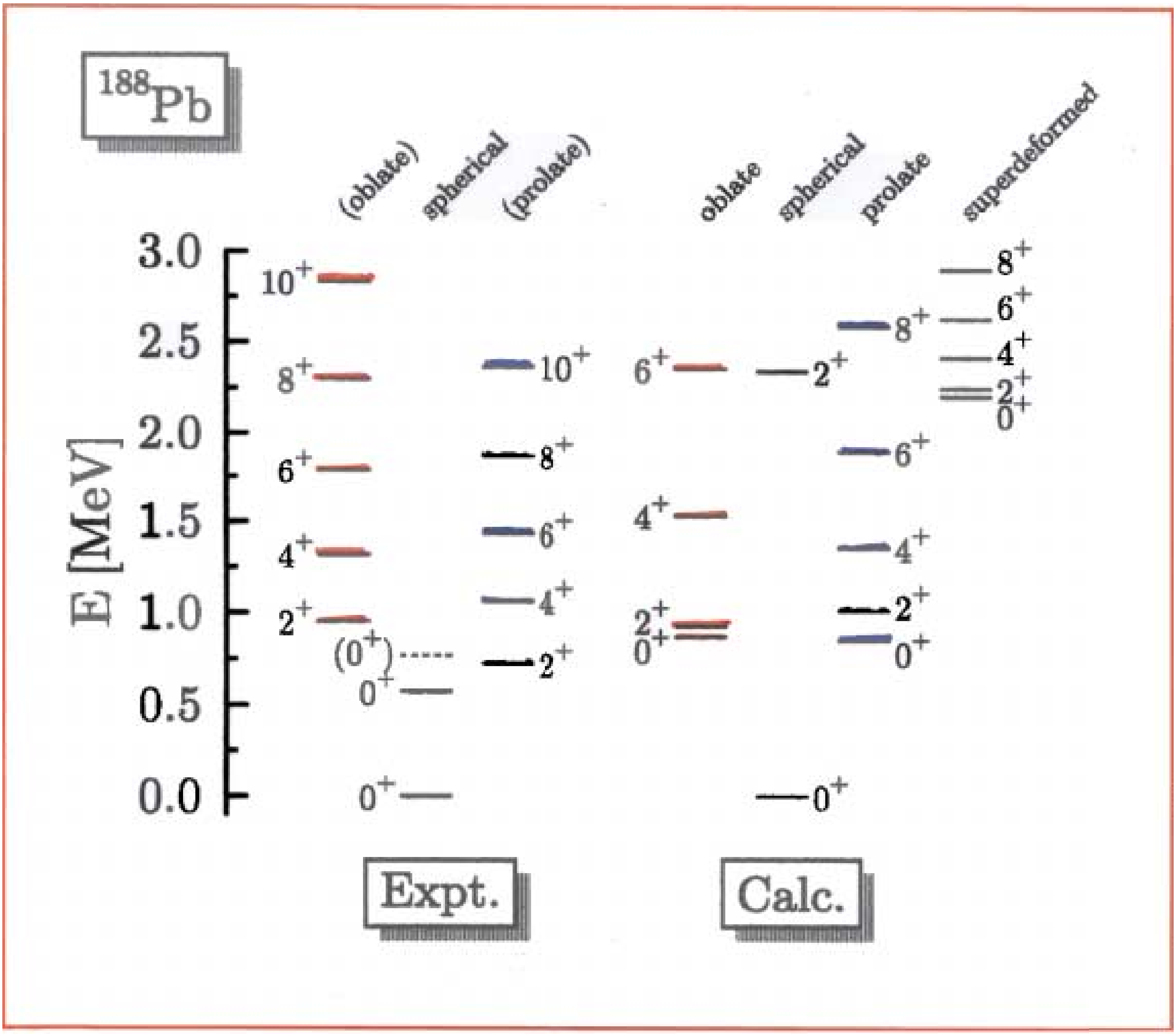
Particle number projected deformation energy curves for $^{182-194}$Pb

M Bender et al , t b.p



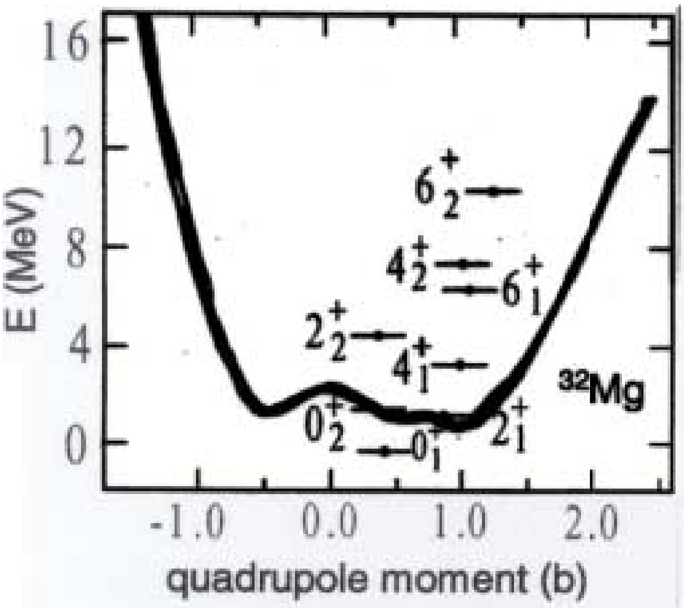
pectrum of the lowest pos tive parity bands with even and K=0
The ang lar momentum projected energy curves are also given

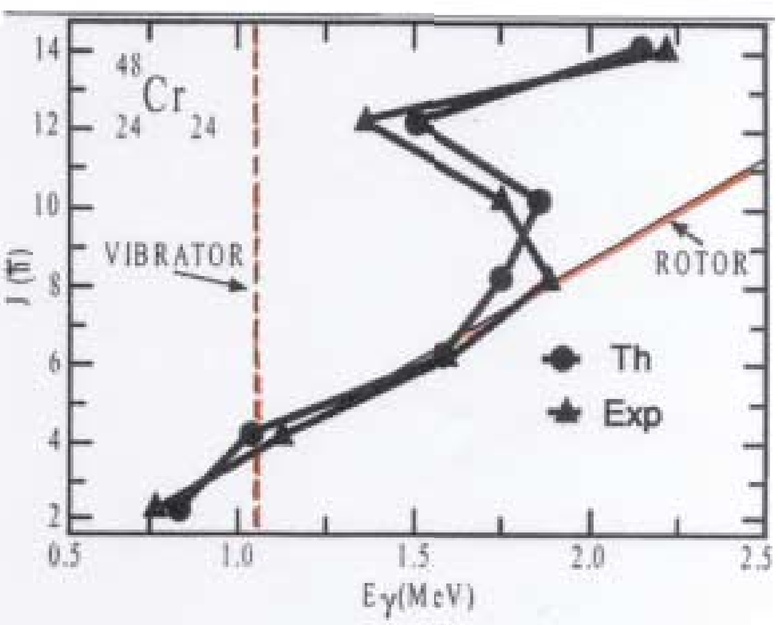
Duguet et al PLB 559 2003), 20



Bender et al . b p

MERGING MEAN-FIELD AND SHELL-MODEL APPROACHES

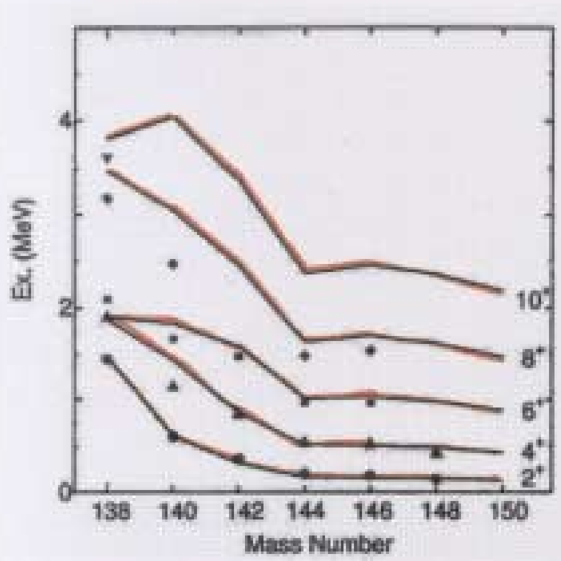


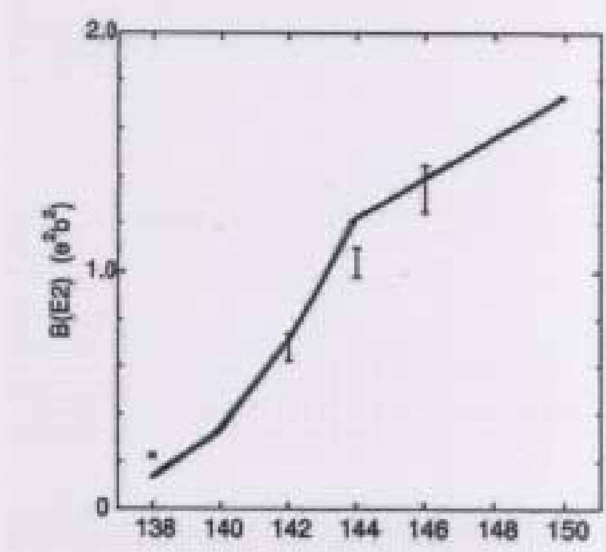


METHOD FOR DIAGONALIZING HAMILTONIANS FOR NUCLEAR MANY-BODY SYSTEMS USING QUANTUM MONTE CARLO METHODS (SMMC / Otsuka et al.) : CALL IT AN "IMPORTANCE TRUNCATION SCHEME" (SIMILARITIES WITH SELF- CONSISTENT MEAN-FIELD METHODS + CONFIG. MIXING CALC.)

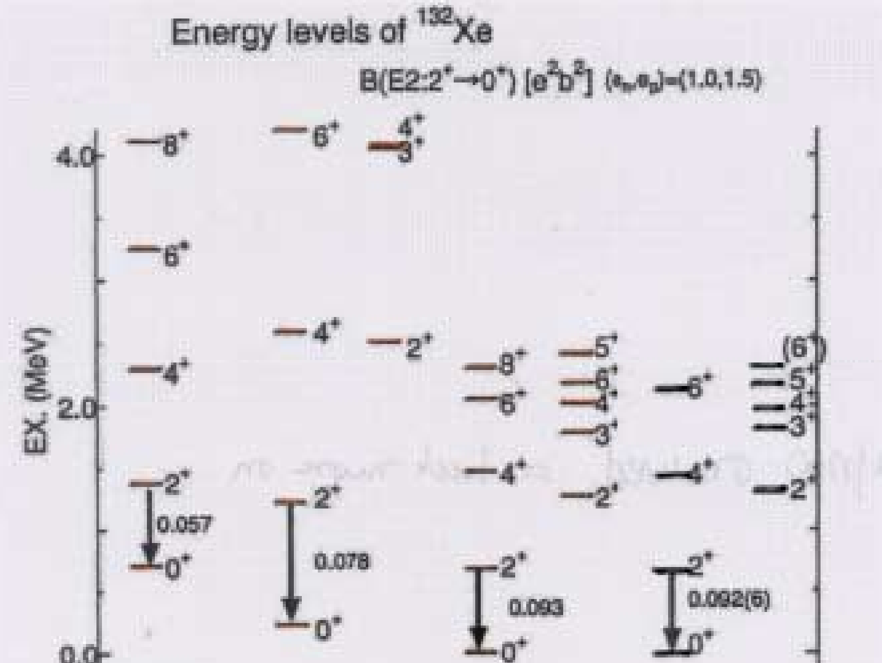
RECENT DEVELOPMENT : OTSUKA et al.
MONTE-CARLO SELECTION OF BASIS STATES
REDUCTION OF BASIS TO 30~50 STATES

MONTE-CARLO SHELL-MODEL (MCSM)





BA NUCLEI



GENERAL SOLUTION TO COLLECTIVE QUADRUPOLE MOTION - BOHR HAMILTONIAN SOLUTIONS

$$\hat{H}\psi = E\psi$$

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

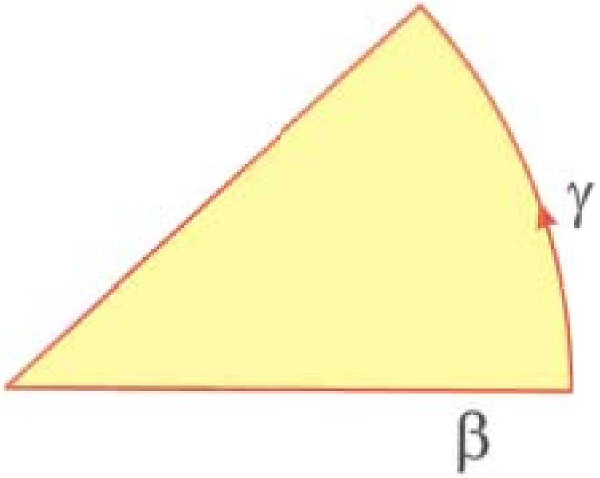
$\psi(\beta,\gamma,\theta_i) \Rightarrow$

RECENT STUDIES

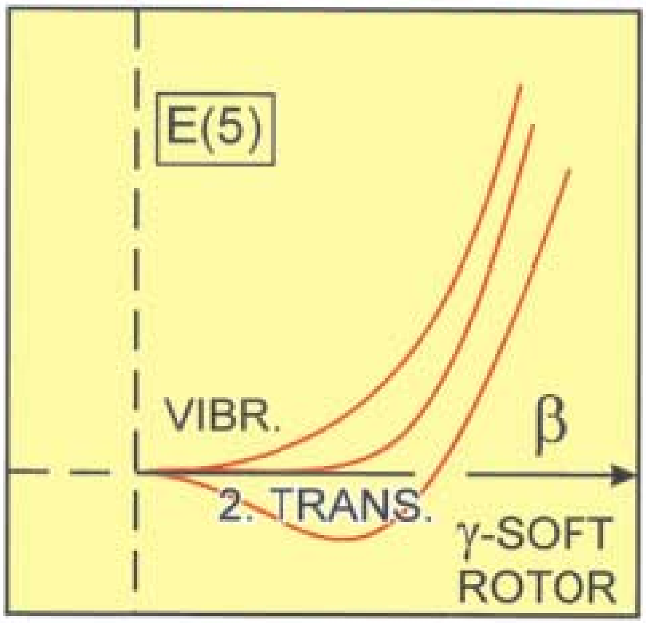
F. Iachello, PRL 85 (2000), 3580; PRL 87 (2001) 052502; PRL 91 (2003), 132502

DISCUSS 3 NTEREST NG EXACT SOLUTIONS FOR APPROXIMATE POTENTIALS TO V(β,γ)

CRITICAL POINTS

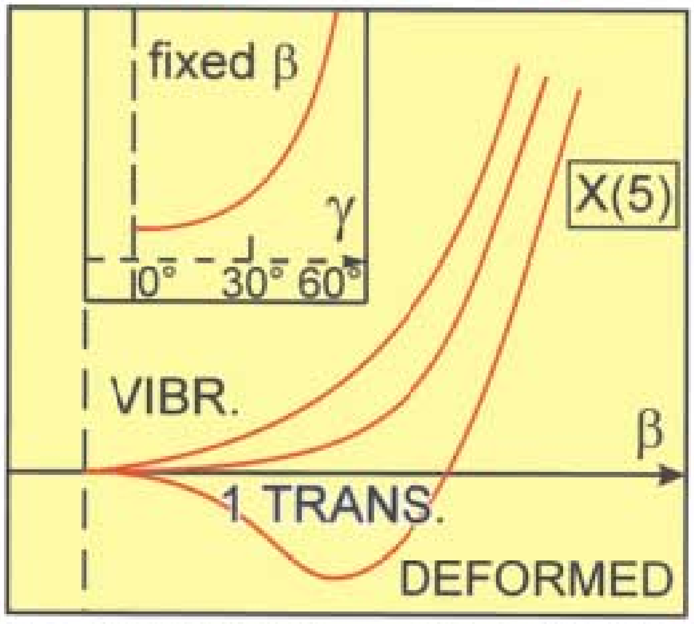


$V(\beta,\gamma)$: γ INDEPENDENT

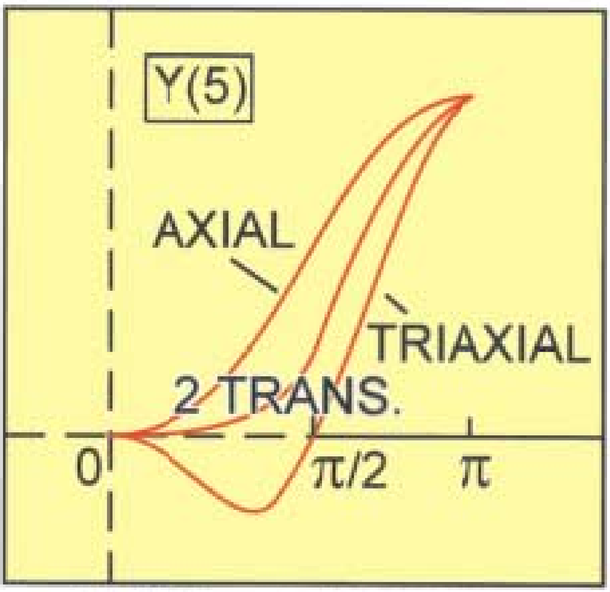


VIBRATIONAL → γ - SOFT ROTOR

$V(\beta,\gamma) = V'(\beta) + V''(\gamma)$



VIBRATIONAL → DEFORMED

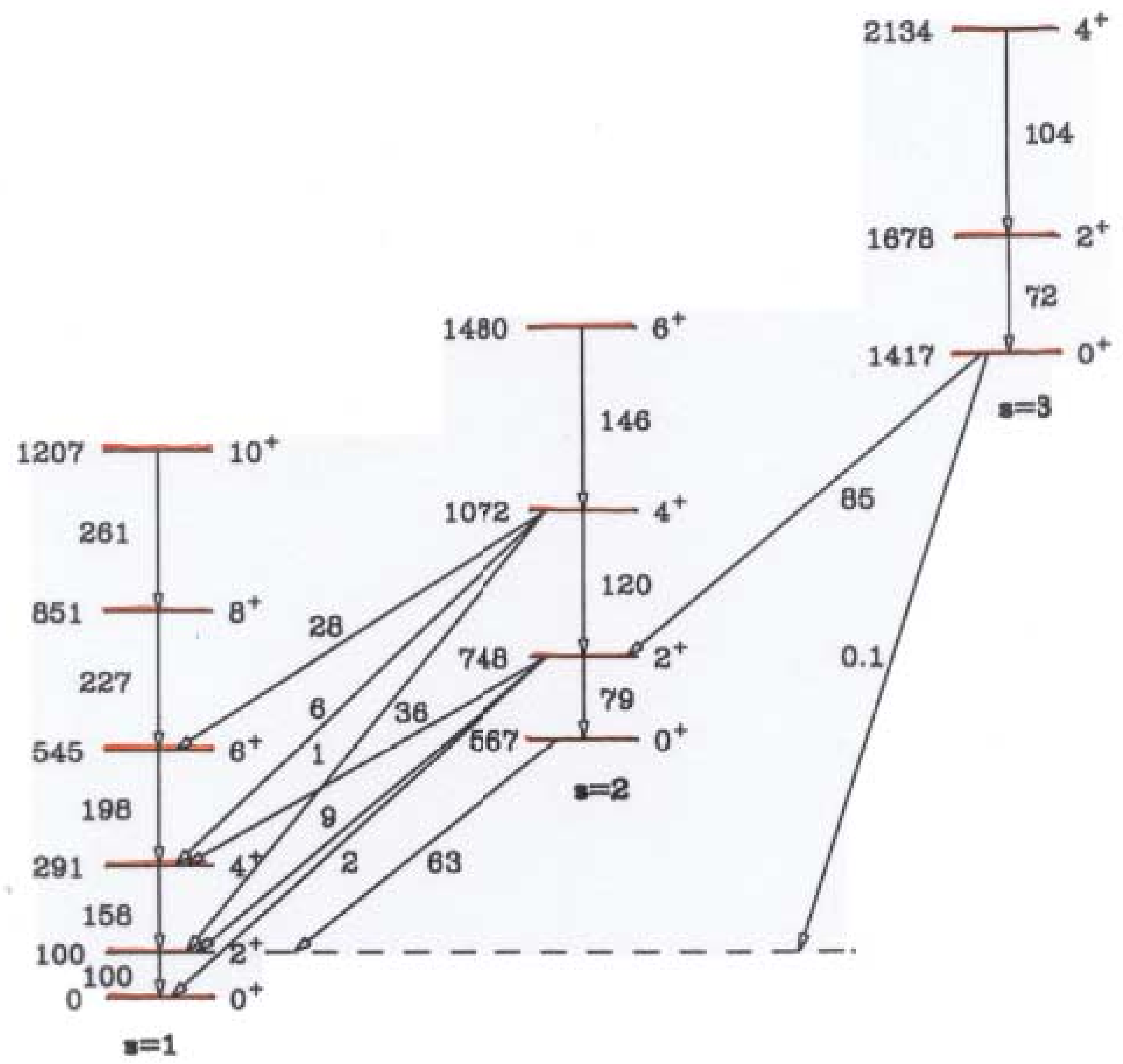


$V(\beta,\gamma) = V'(\beta)+V''(\gamma)$

$\frac{u_o}{2}(\beta-\beta_o)^2$

AXIAL → TRIAXIAL

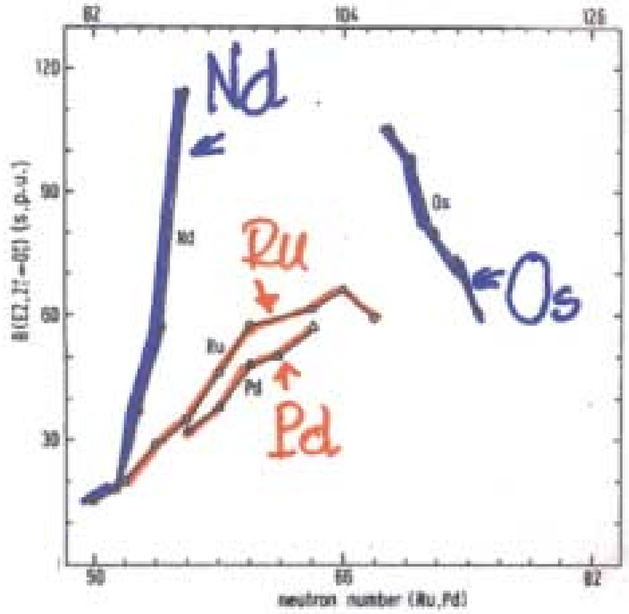
$$\boxed{E(s, L, n_\gamma, K, M) = E_0 + A\, x^2_{s,L} + C n_\gamma + D K^2}$$



Only states with n_γ 0

POSSIBLE EXPERIMENTAL TEST

(a) Ru, Pd REGION : transitional region from
vibrational to γ-soft
energy spectra



A. Frank et al, PRC 65 (2001), 014301
V.M Zamfir et al., PRC 65 (2002), 044325

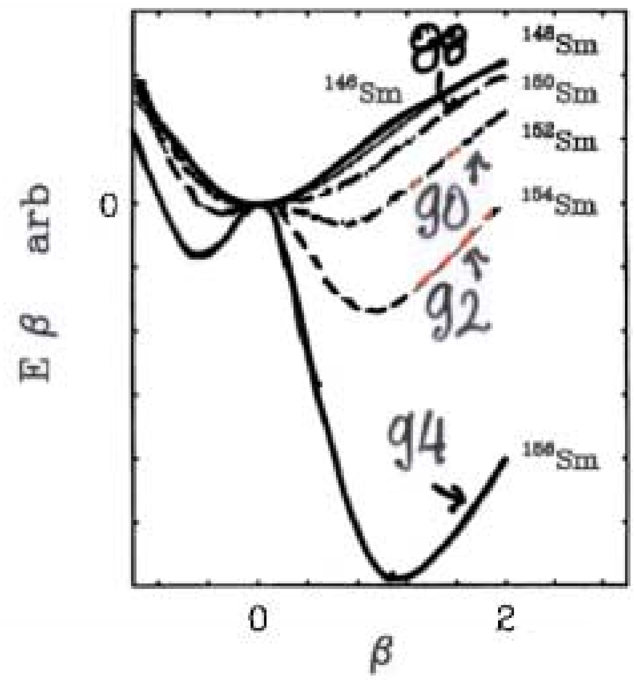
Ba, Xe REGION

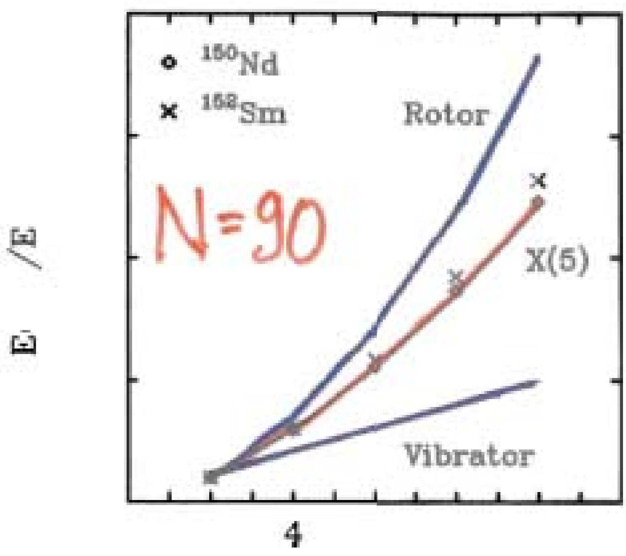
R.F. Casten, V.M. Zamfir, PRL 85 (2001), 3584 : ^{134}Ba

(b) Nd, Sm, Gd REGION NEAR N 90

possible transition region from vibrational

towards axial deformed rotor



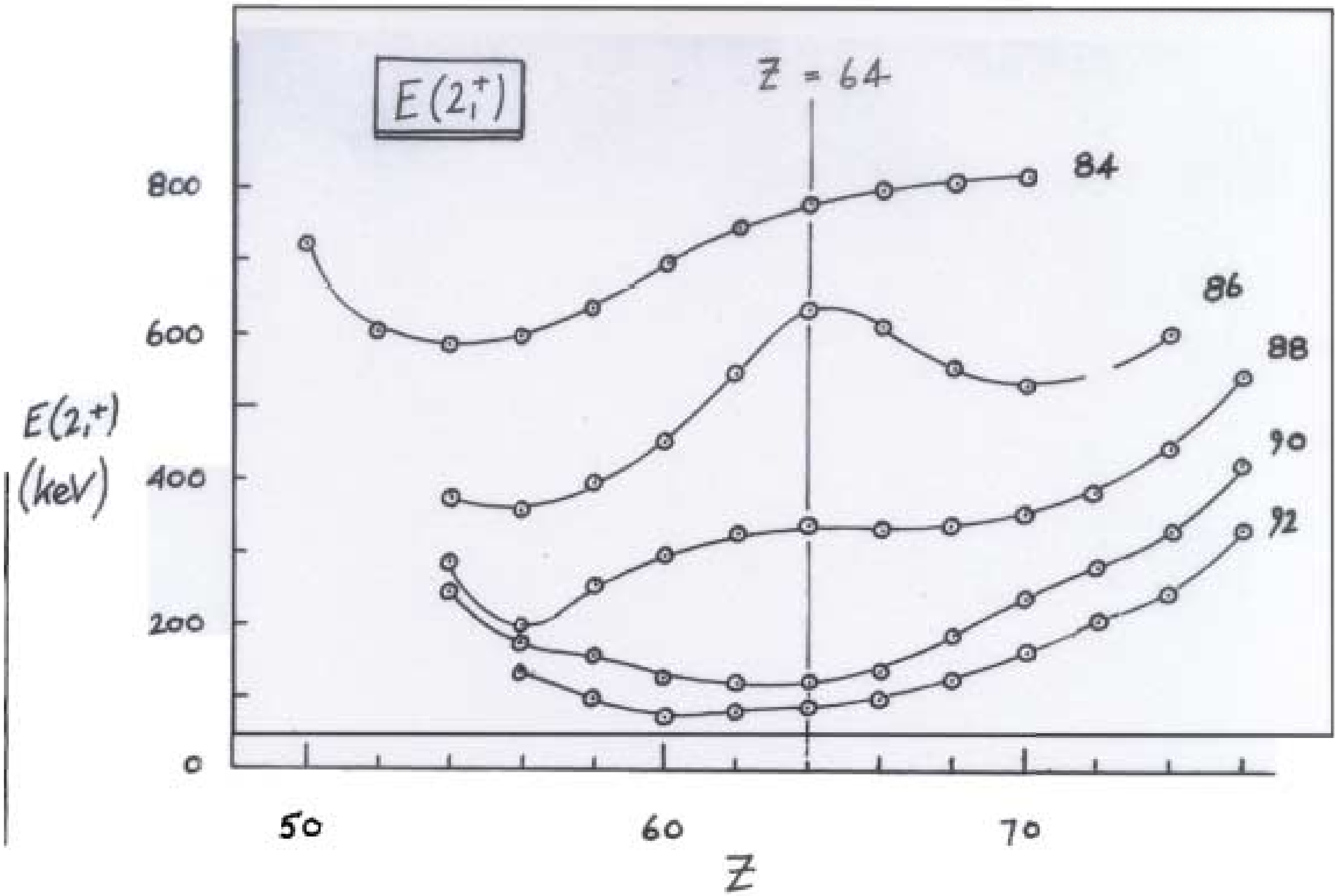


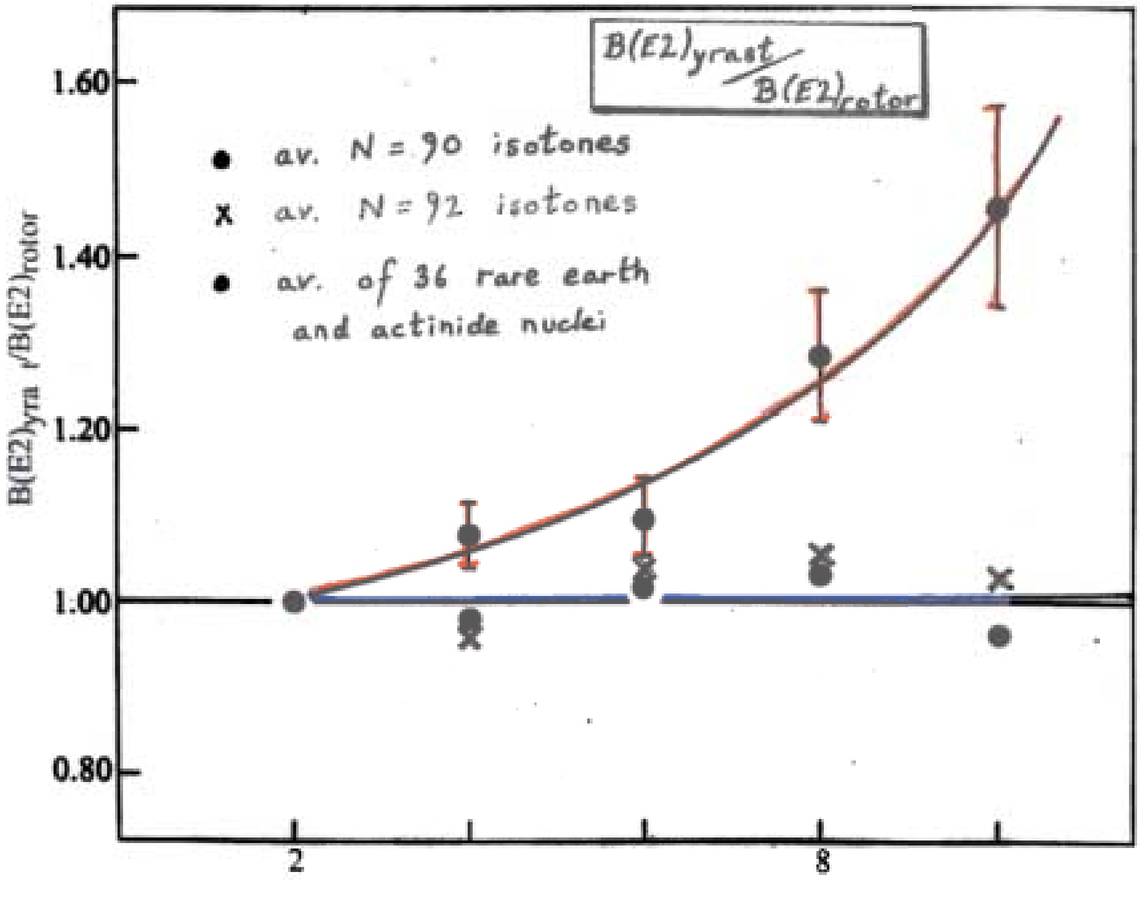
R Krucken et al PRL 88 (2002), 23250 ^{50}Nd

R Casten V M Zamfir PRL 87 (200 052503 ^{52}Sm

W D Kulp J L Wood et al PRL 91 (2003 0250 ^{154}Gd

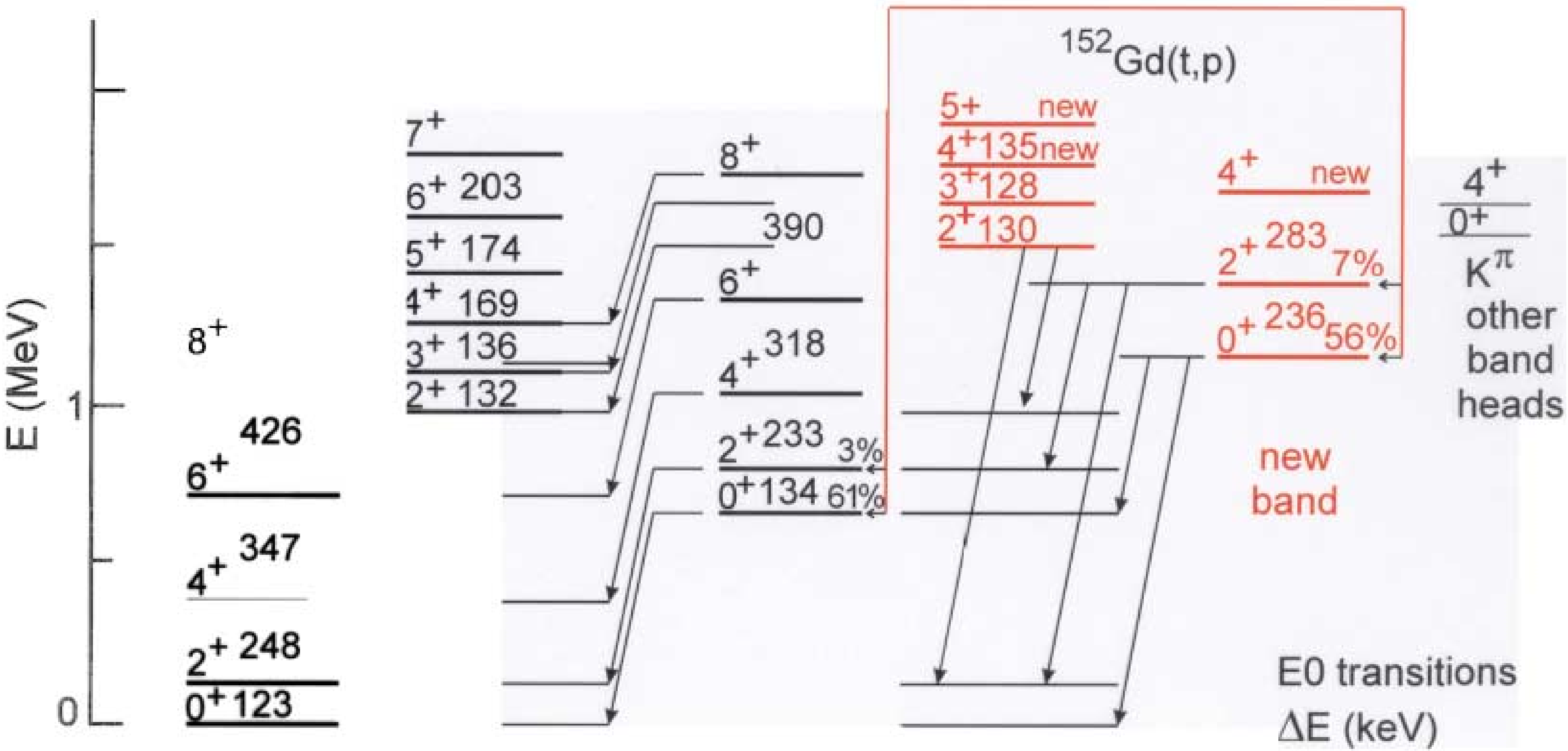
Evidence for the Z 64 subshell gap from $E(2_1^+)$ vs Z and



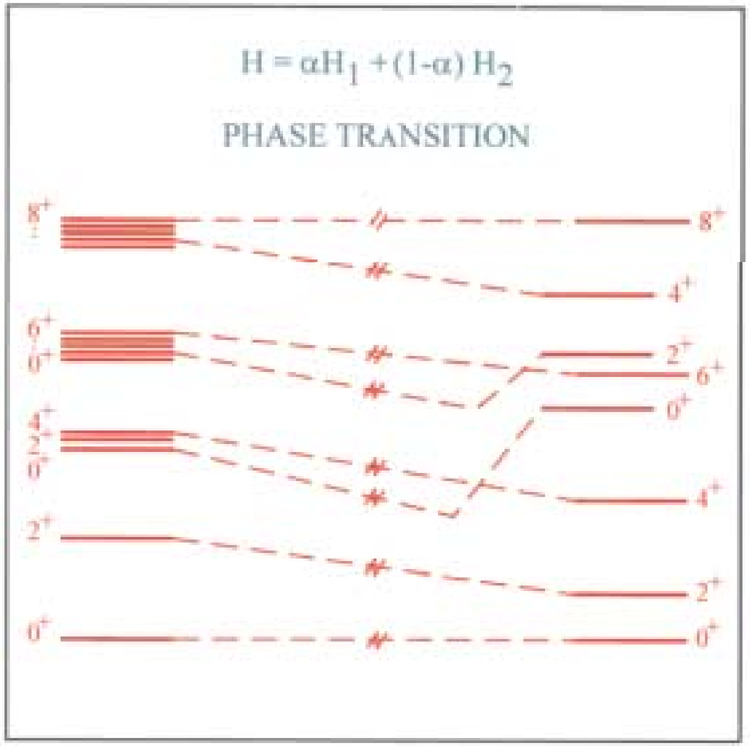


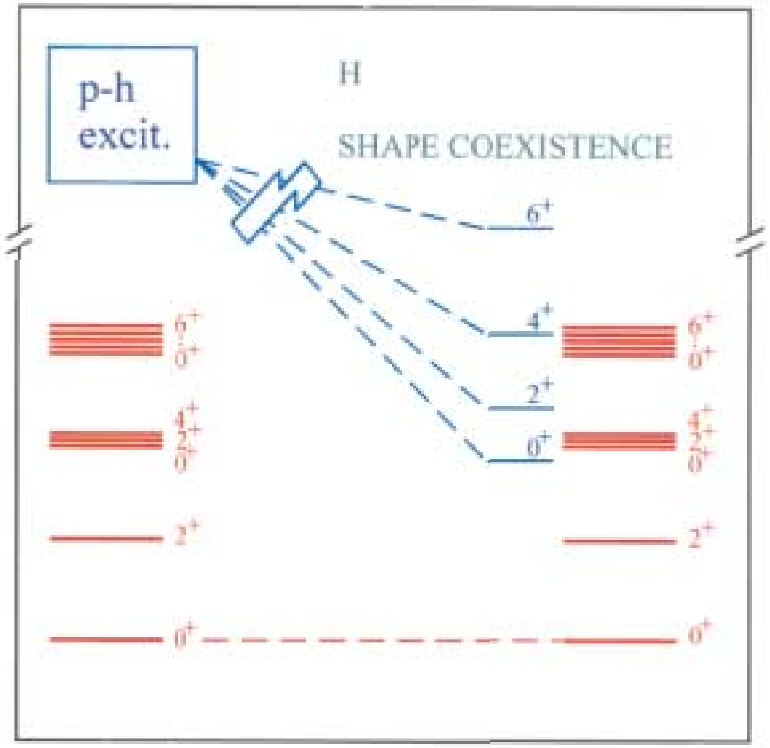
L Wood priv com

^{154}Gd



J. L. Wood, priv. com.

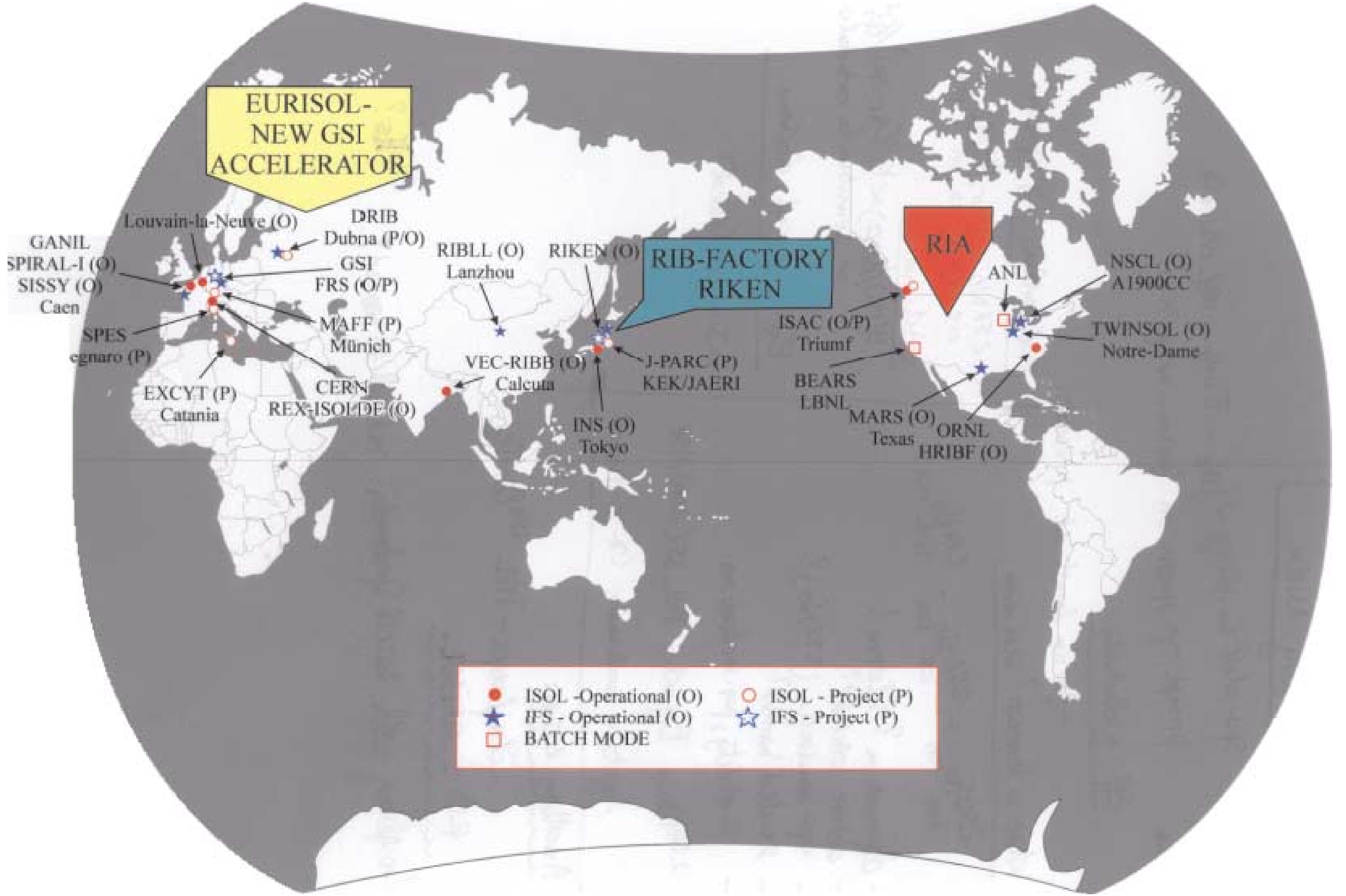




- TRANSITION THROUGH LONG SERIES OF ISOTOPES (ISOTONES)
- TRANSITION POINTS LOCALIZED

- LIGHT N = Z NUCLEI AT SUBSHELL AND SHELL CLOSURE
- CLOSED PROTON SHELL - LARGE OPEN NEUTRON SHELL

np - mh excitations


EURISOL-
NEW GSI
ACCELERATOR
RIB-FACTORY
RIKEN
RIA
GANIL
SPIRAL-I (O)
SISSY (O)
Caen
Louvain-la-Neuve (O)
DRIB
Dubna (P/O)
GSI
FRS (O/P)
MAFF (P)
Münich
SPES
egnaro (P)
EXCYT (P)
Catania
CERN
REX-ISOLDE (O)
RIBLL (O)
Lanzhou
VEC-RIBB (O)
Calcuta
RIKEN (O)
J-PARC (P)
KEK/JAERI
INS (O)
Tokyo
ISAC (O/P)
Triumf
BEARS
LBNL
MARS (O)
Texas
ORNL
HRIBF (O)
ANL
NSCL (O)
A1900CC
TWINSOL (O)
Notre-Dame
ISOL -Operational (O)
IFS - Operational (O)
BATCH MODE
ISOL - Project (P)
IFS - Project (P)

COLLABORATORS (over the years)

B. DECROIX	Gent *
J. DE BEULE	Gent *
C. DE COSTER	Gent *
R FOSSION	Gent
N. SMIRNOVA	Gent
K. HEYDE	Gent
JOLIE	Köln
H. LEHMANN	Grenoble
P. VAN ISACKER	Ganil
J. WOOD	Georgia Tech., Atlanta

MUCH INPUT FROM EXPERIMENTAL GROUPS

IKS Leuven, Jyväskylä, ISOLDE-CERN, ANU-Canberra, Oak-Ridge, GSI, Mainz, Ganil, ANL, Liverpool,...