核子多体系の基本的性質と原子核集団運動

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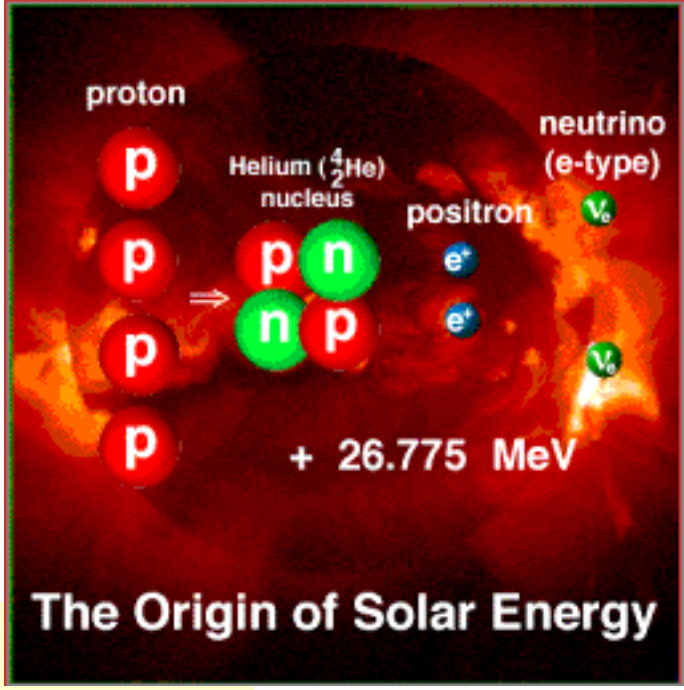
2013.12.25　中性子星核物質ウィンタースクール　講義

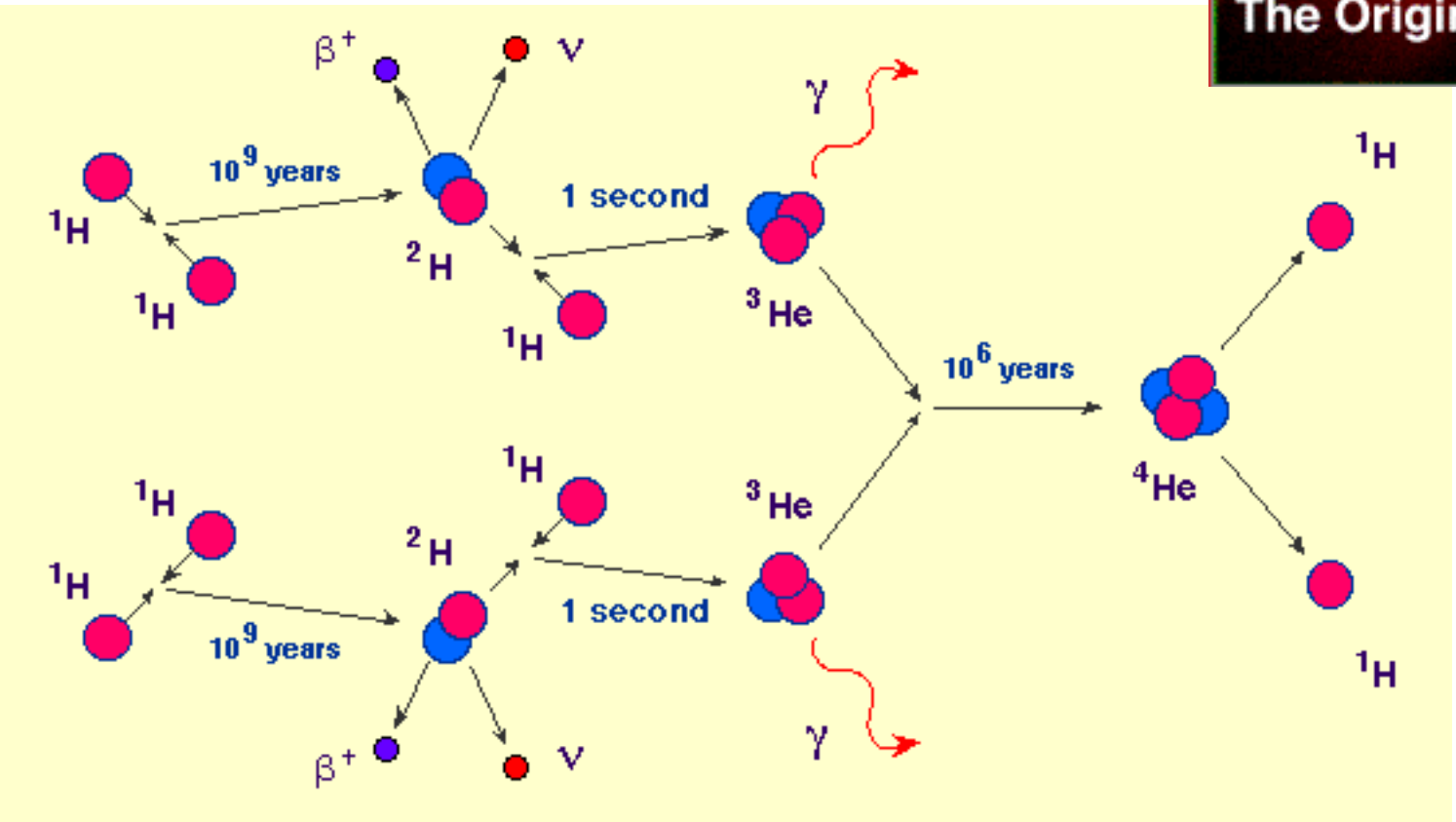
Contents

- Basic properties of nuclear systems
- Different aspects in different time scales
- Symmetry breaking in finite time scale
- Rapidly rotating nuclei
- Superdeformation and new type of symmetry breaking

ppチェイン

- $p(p,e^+\nu)d$ reaction determines the lifetime of the sun

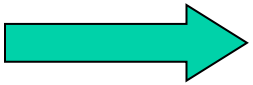




核物理に関わる異なる反応率

- 移行反応 (強い相互作用)
  - $^{15}N(p,\alpha)^{12}C$
  - $\sigma \sim 0.5$ b (E=2 MeV)
- 捕獲反応 (電磁気相互作用)
  - $^{3}He(\alpha,\gamma)^{7}Be$
  - $\sigma \sim 10^{-6}$ b (E=2 MeV)
- 弱過程 (弱い相互作用)
  - $p(p,e^{+}\nu)d$
  - $\sigma \sim 10^{-20}$ b (E=2 MeV)

1 b = 100 fm^2



異なる時間スケール

液滴模型

束縛エネルギー

B/A ≈ 8 MeV

密度分布

$\rho \approx 0.16\ \mathrm{fm}^{-3}$　　$d \approx 2$ fm

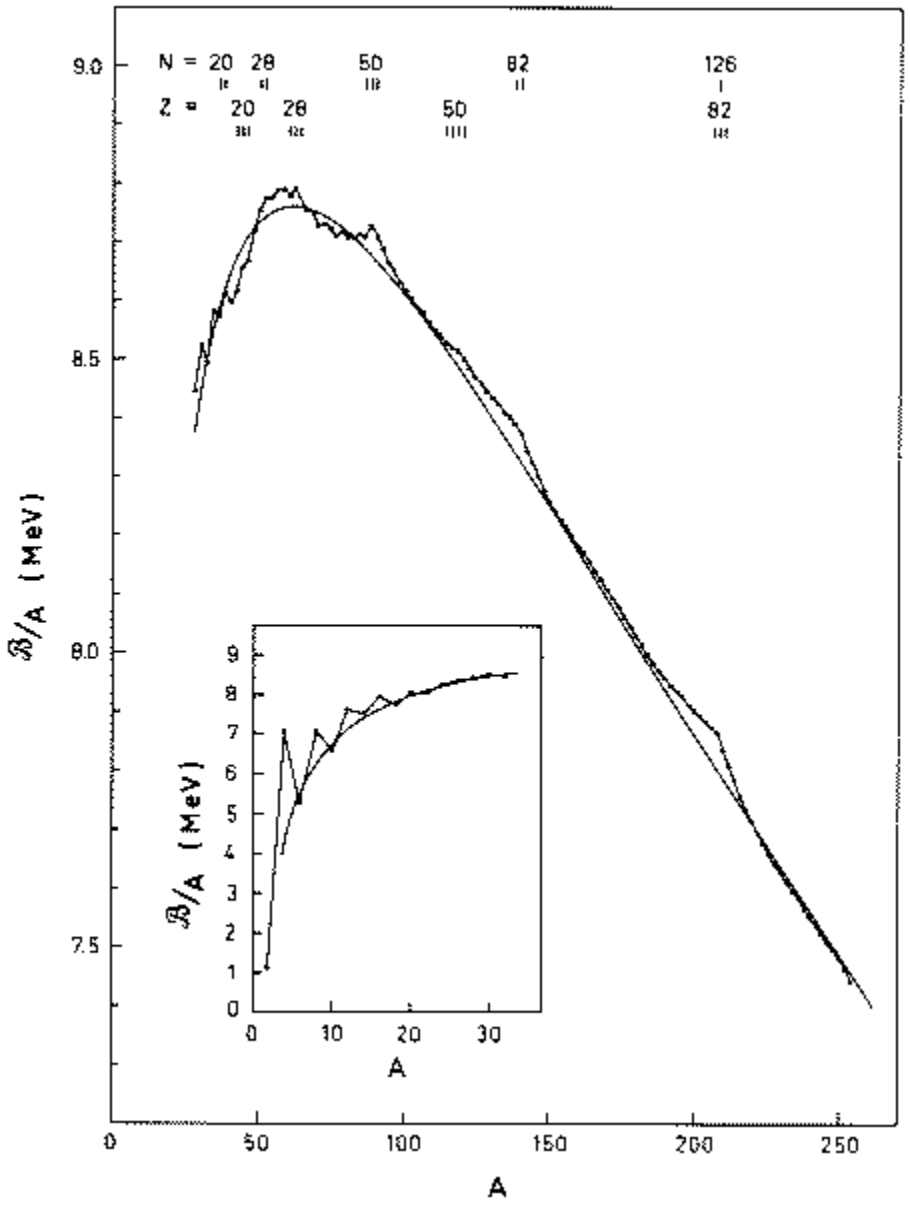
飽和性　(Saturation)

Bethe-Weizsäcker 質量公式

$$B(N,Z) = a_V A - a_S A^{2/3} - a_{sym}\frac{(N-Z)^2}{A} - a_C \frac{Z^2}{A^{1/3}} + \delta(A)$$

Bohr & Mottelson

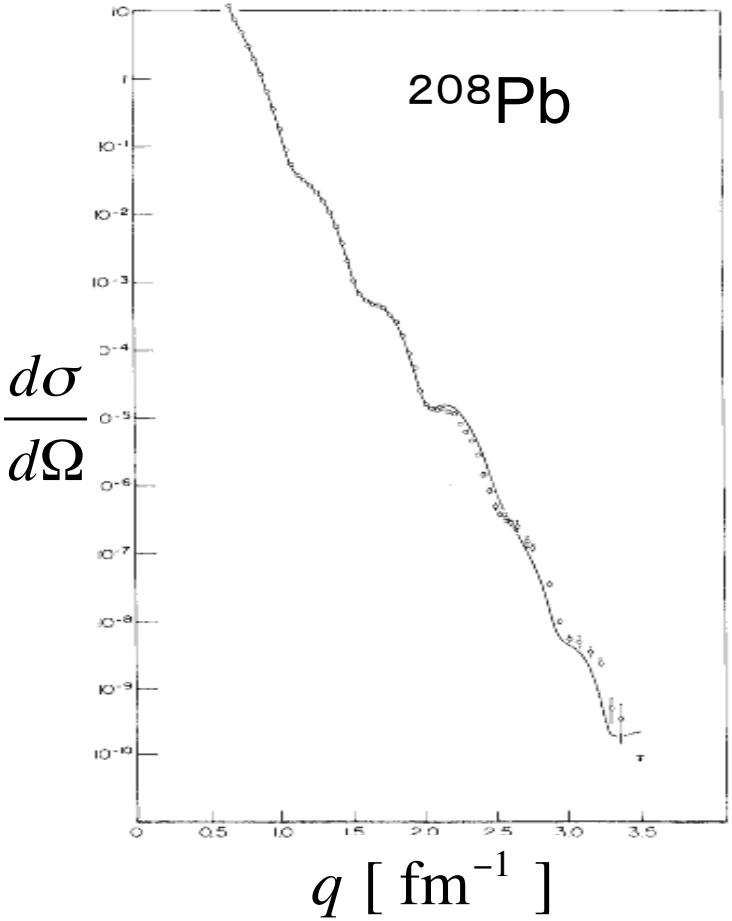
Nuclear Structure Vol.1

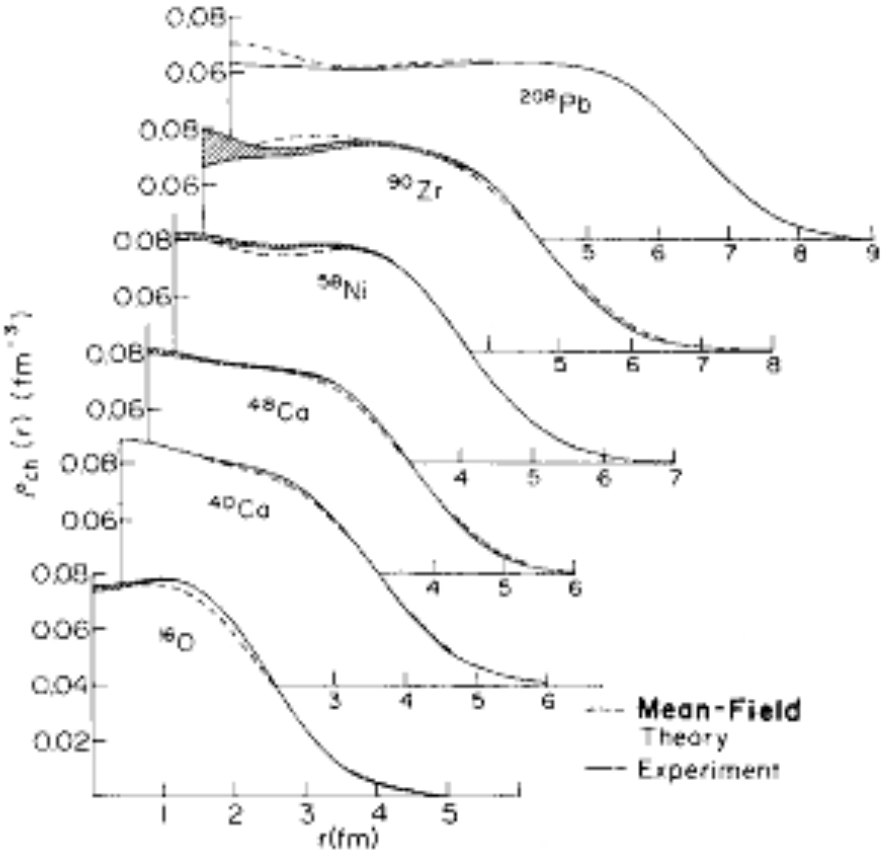


原子核の電子散乱

- 原子核の電子散乱

$$\rho(\vec{r}) = \frac{1}{(2\pi)^3}\int G_E(q^2)e^{-i\vec{q}\cdot\vec{r}}\,d\vec{q}$$

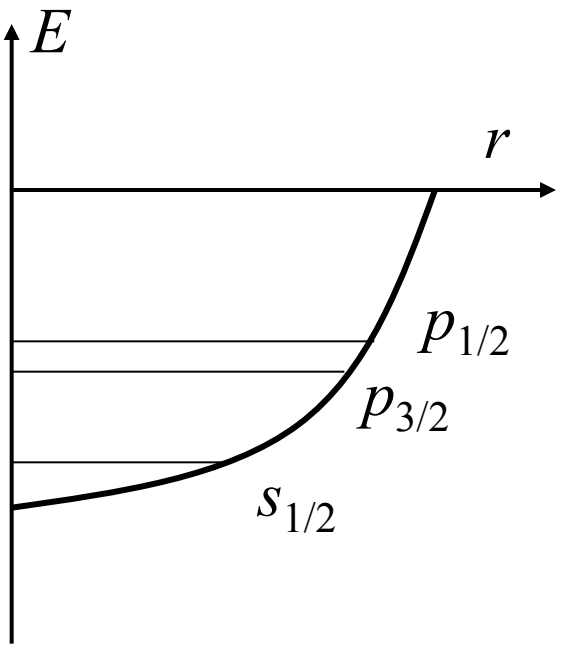




Mayer-Jensen's Shell Model

調和振動子ポテンシャル + スピン・軌道ポテンシャル

$$V(r) = \frac{1}{2} M\omega^2 r^2 + v_{ll}\ell^2 + v_{ls}\vec{\ell}\cdot\vec{s}$$



→ 魔法数（magic numbers）:

(N,Z)=2, 8, 20, 28, 50, 82, 126

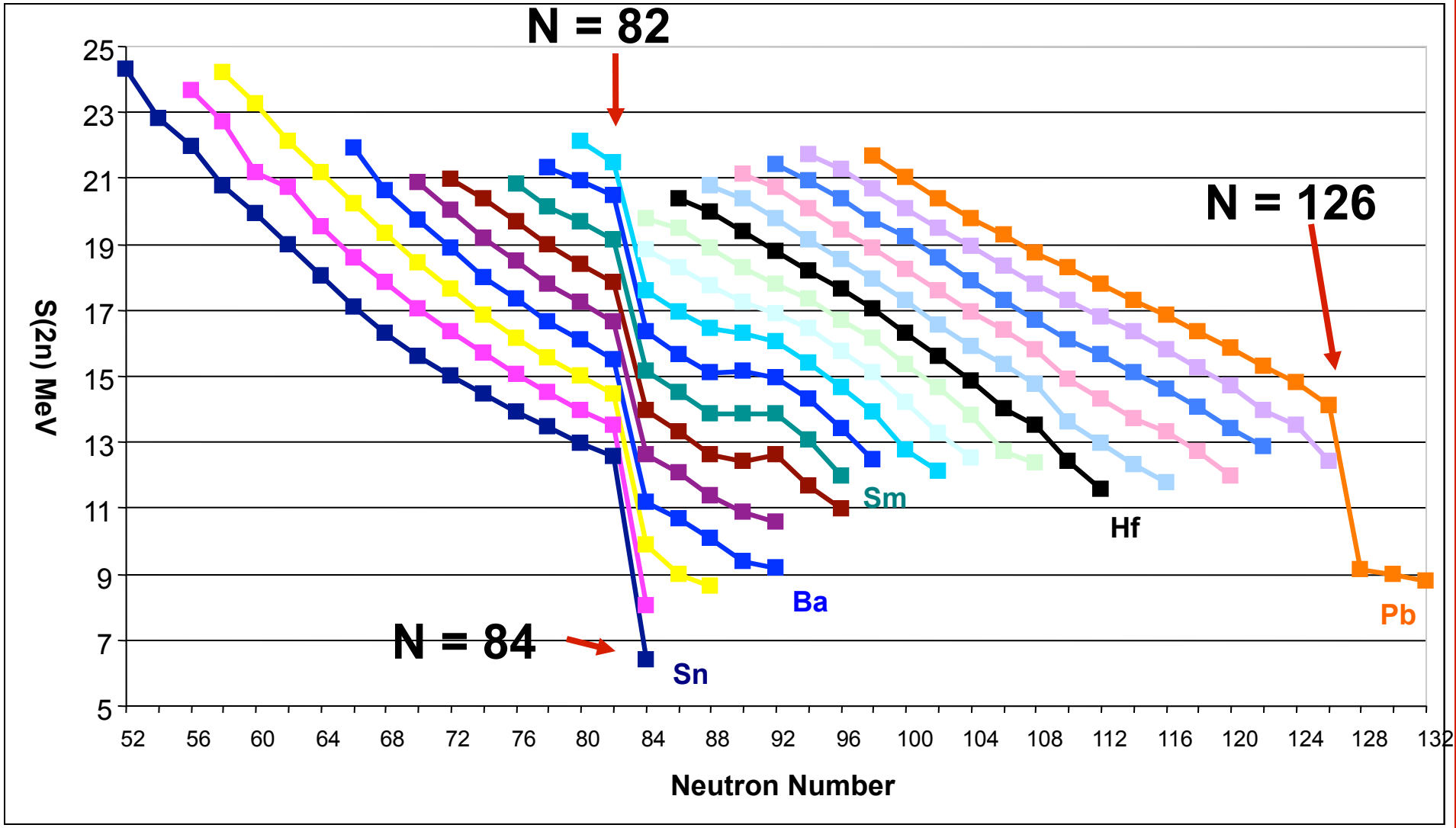
“気体”的な性質

$$\lambda >> R$$

平均自由行程は原子核の大きさよりもはるかに大きい

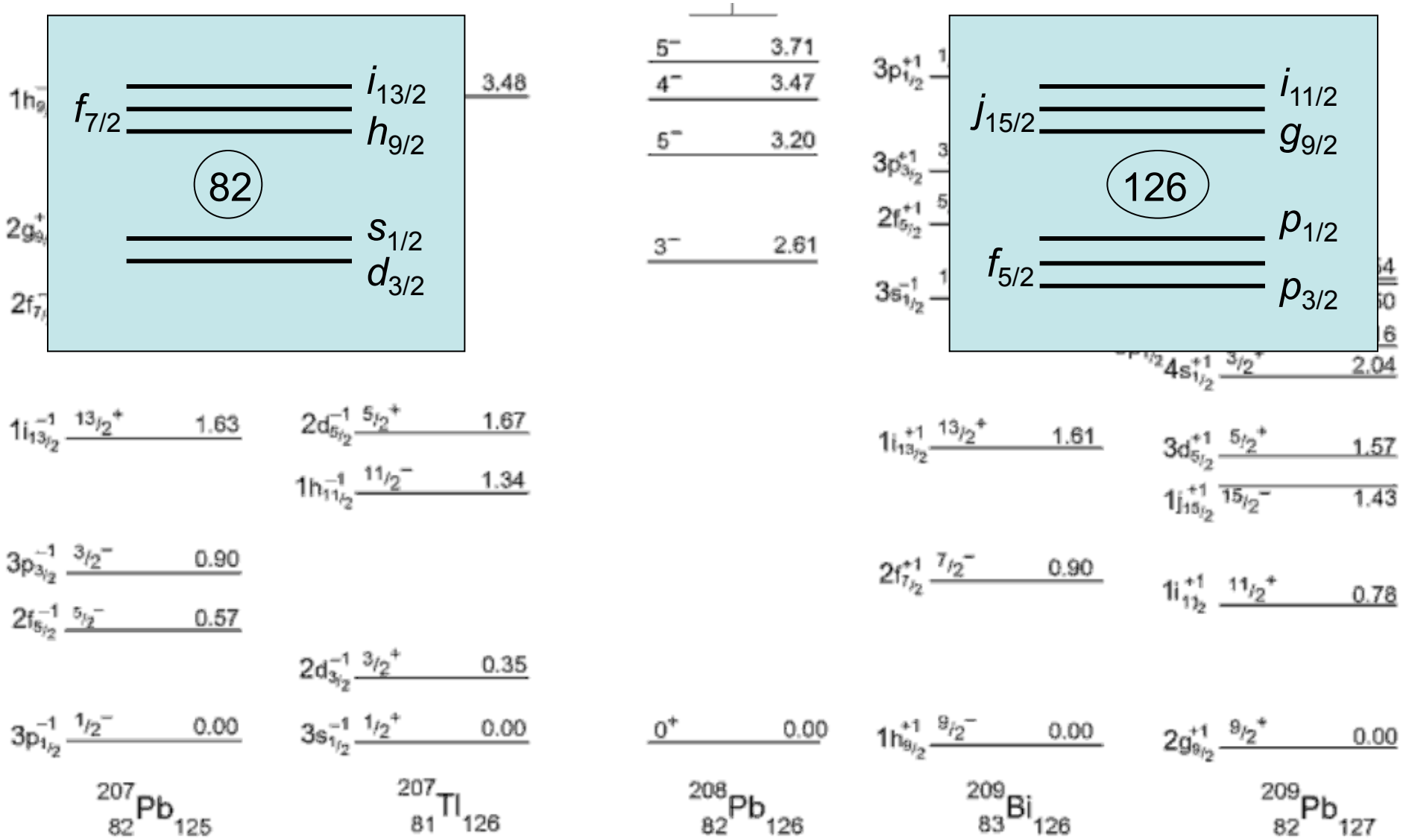
２中性子分離エネルギー

(＝２中性子束縛エネルギー)

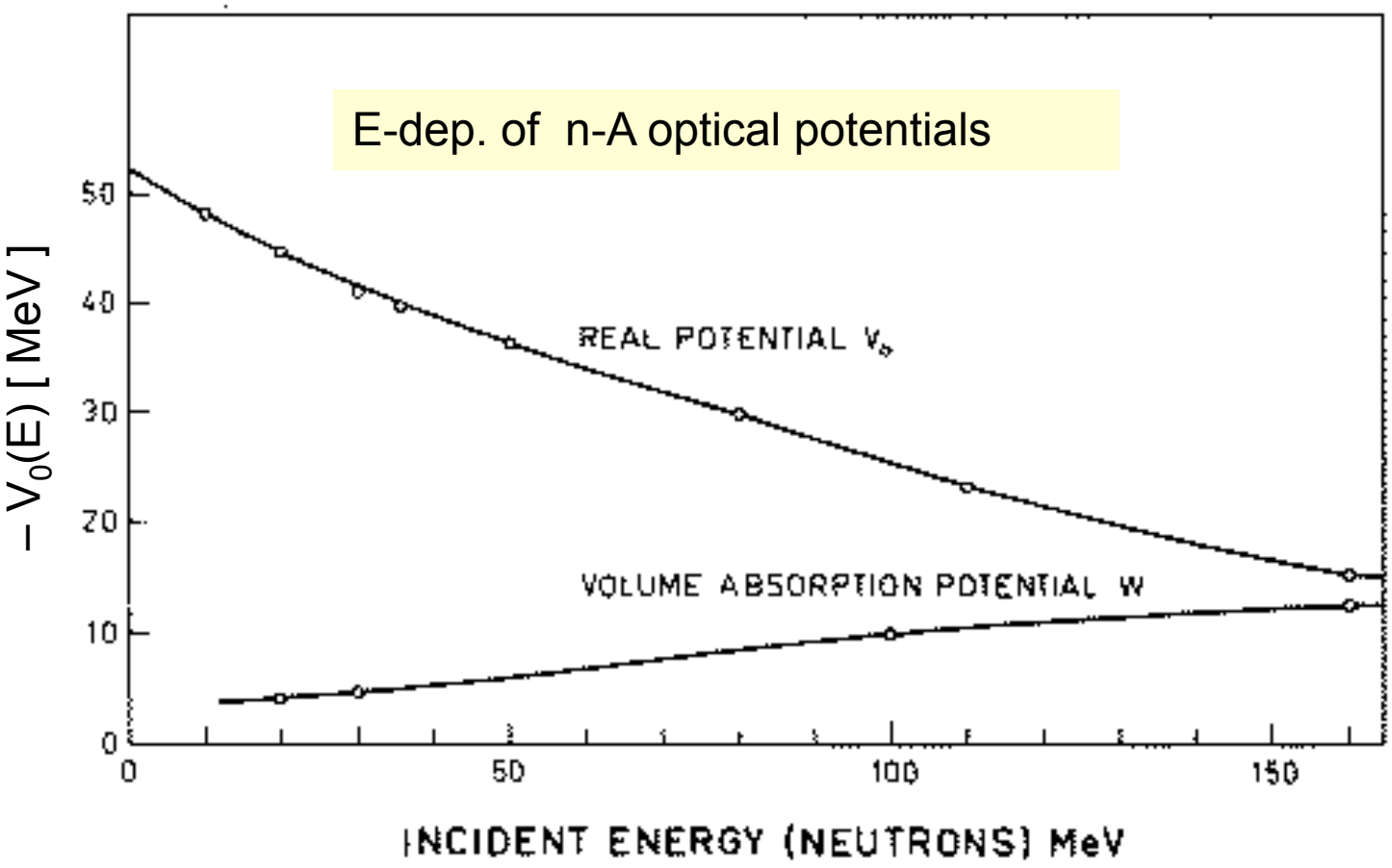


From a lecture by R. Casten

Spin-parity of odd nuclei



光学ポテンシャル



低エネルギーの中性子に対して虚数部分は小さい

フェルミ気体（フェルミ液体）

- 飽和密度
  - $\rho \approx 0.16\ \mathrm{fm}^{-3} \quad \Rightarrow \quad k_F \approx 1.35\ \mathrm{fm}^{-1}$
  - フェルミ・エネルギー $T_F = \dfrac{\hbar^2 k_F^2}{2m} \approx 40\ \mathrm{MeV}$

$\Rightarrow \quad k_F r \approx 1, \quad k_F a >> 1$ 非希薄、強結合フェルミ系

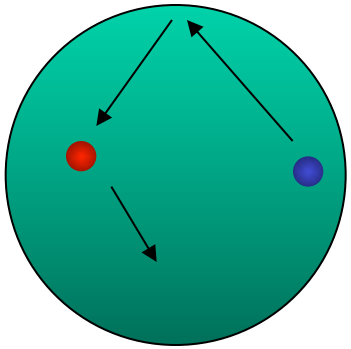
有効レンジ、 散乱長

- 核子が核内で動き回る時間周期

$$\tau_F \approx \frac{R}{v_F} \sim 10^{-22}\ \mathrm{s}$$

- 核子・核子衝突時間

$\tau_c >> \tau_F$ $\lambda >> R$



準粒子（quasi-particle)による記述

中性子共鳴散乱

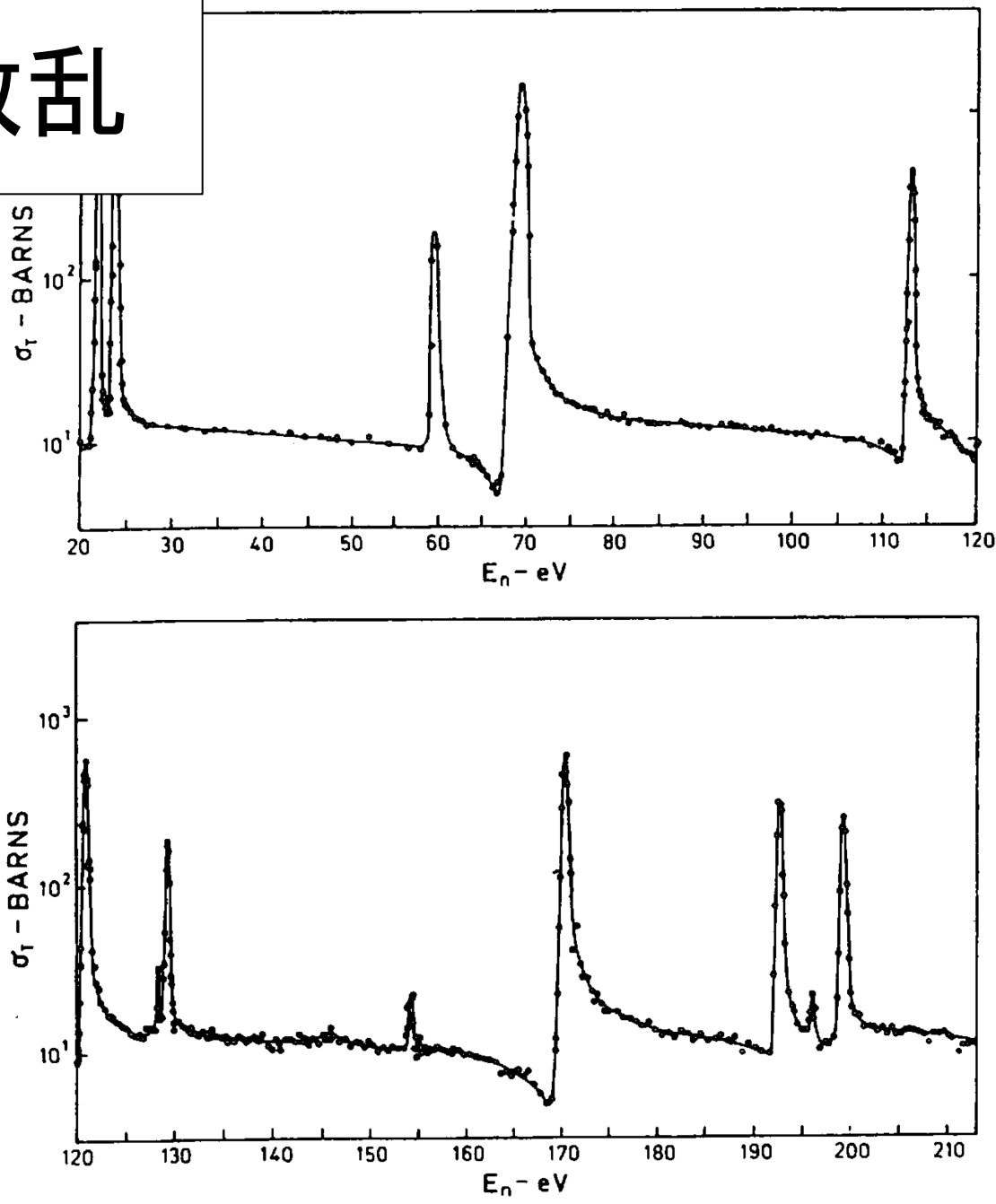
中性子にはクーロン反発力が働かないため、容易に原子核に衝突

低エネルギーの熱中性子(eVオーダー)による散乱実験によって多数の共鳴状態が観測

$$\tau_{\mathrm{comp}} >> \tau_c$$

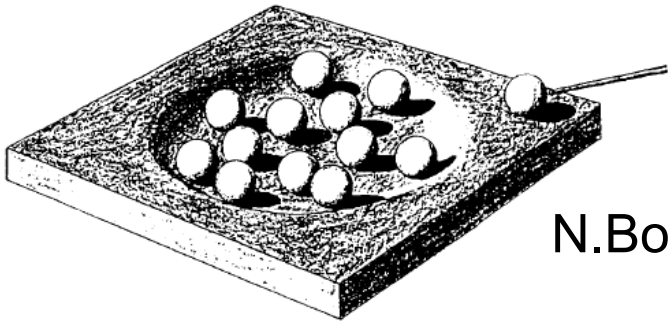
準粒子による記述は不可エネルギー分解能に限界

$$\Delta E > \hbar / \tau_c$$

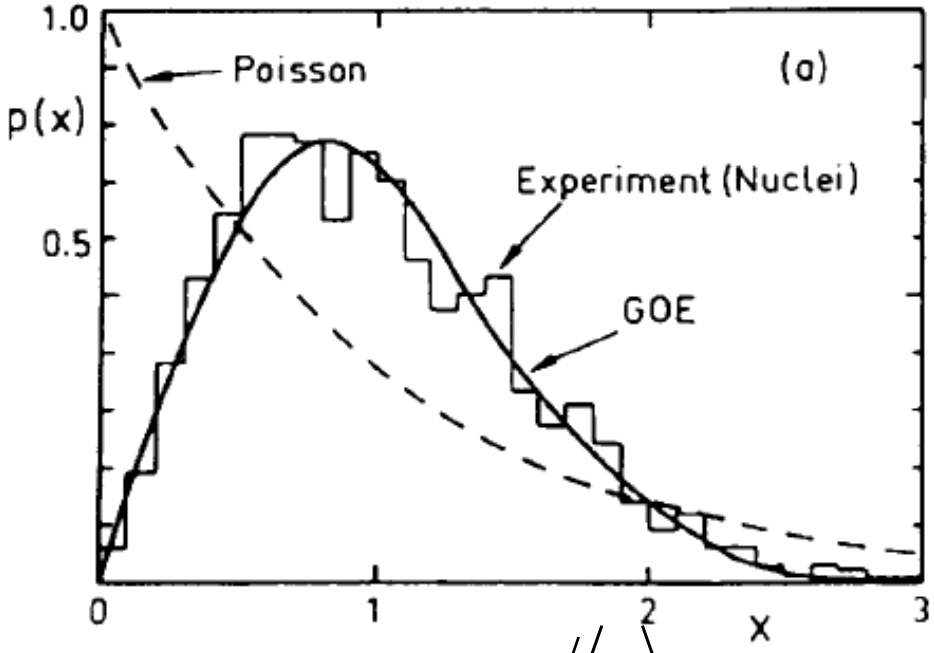


複合核模型 [Bohr 1936, Wigner, 1955]

- 熱中性子共鳴
  - 幅の小さい多数の共鳴状態 (s ~ eV, Γ ~ meV)
  - 準位間隔はウィグナー分布に従う(乱雑行列理論)
- 強結合・複雑系
  - 量子カオス的性質



N.Bohr (1936)



Bohigas (1989)

$$x = s / \langle s \rangle$$

原子核集団運動

- 集団励起モードの時間スケール
  - “周期” $\tau_{\mathrm{coll}} \sim \hbar / E_{\mathrm{ex}}$
  - “寿命” $\tau_{\mathrm{damp}} \sim \hbar / \Gamma$
  - Well-defined: $\tau_{\mathrm{coll}} < \tau_{\mathrm{damp}}$
  - 早い運動（短い時間） $\tau_c > \tau_{\mathrm{coll}} \sim \tau_F$
    - 巨大共鳴
    - 強い減衰
  - 遅い運動（長い時間） $\tau_c > \tau_{\mathrm{coll}} > \tau_F$
    - 低エネルギー振動モード
    - 核変形に伴う回転

早い集団励起の例：巨大四重極共鳴(GQR)

巨大共鳴：和則値(sum rule value)をほぼ100%尽くす状態

$$m_p = \sum_n E_n^p \left| \langle n | F | 0 \rangle \right|^2$$

和則解析：復元力は3次の和則値に比例

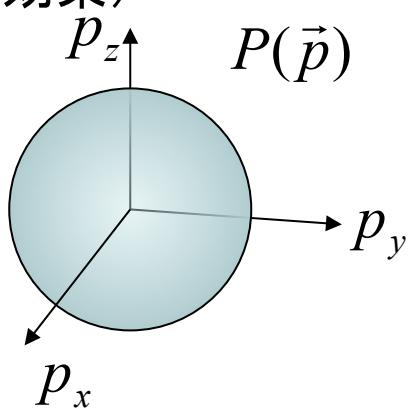
cf) Ring-Schuck, Nuclear Many-body problems (1980)

$$H = \frac{1}{2B}\pi^2 + \frac{1}{2}C\,\alpha^2$$

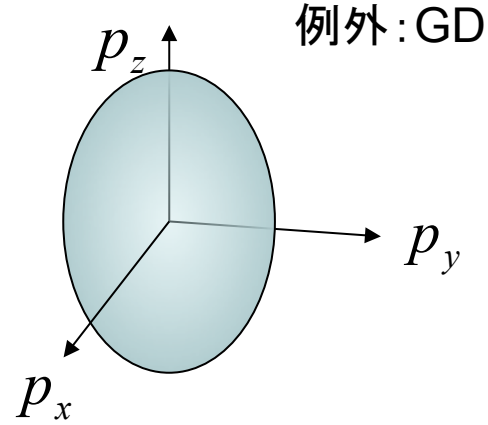
$$C \sim m_3 \sim \langle T \rangle$$

形状変形が運動量空間のフェルミ球を変形させる→エネルギー増加

（量子フェルミ効果）



例外：GDR



低エネルギーの集団運動では、フェルミ球を球形に保とうとする

遅い集団励起：表面振動モード

- 低エネルギー振動励起モード
  - 表面振動モード（球形核）

$$H = \sum_{\lambda\mu}\left(\frac{1}{2B_\lambda}\pi_{\lambda\mu}^2 + \frac{1}{2}C_\lambda\alpha_{\lambda\mu}^2\right)$$

$$\Rightarrow \sum_{\mu}\left(\frac{1}{2B_2}\pi_{2\mu}^2 + \frac{1}{2}C_2\alpha_{2\mu}^2\right)$$

  - 古典的非回転液滴模型

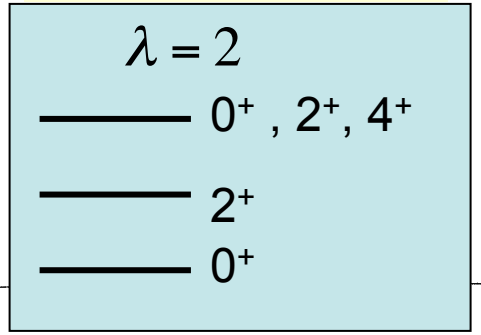
$\lambda = 2$

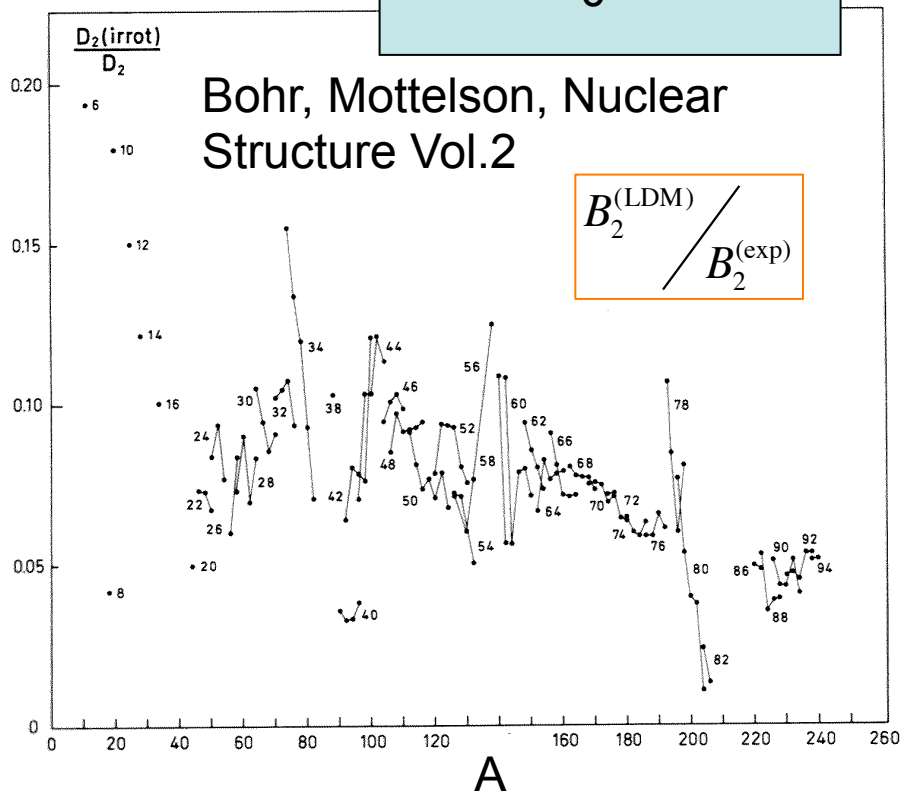
$$C_2 = \pi^{-1}a_S A^{2/3} - \frac{3Z^2e^2}{10\pi R_0}$$

$$B_2 = \frac{1}{2}M\rho_0 R_0^5$$

実験と非整合

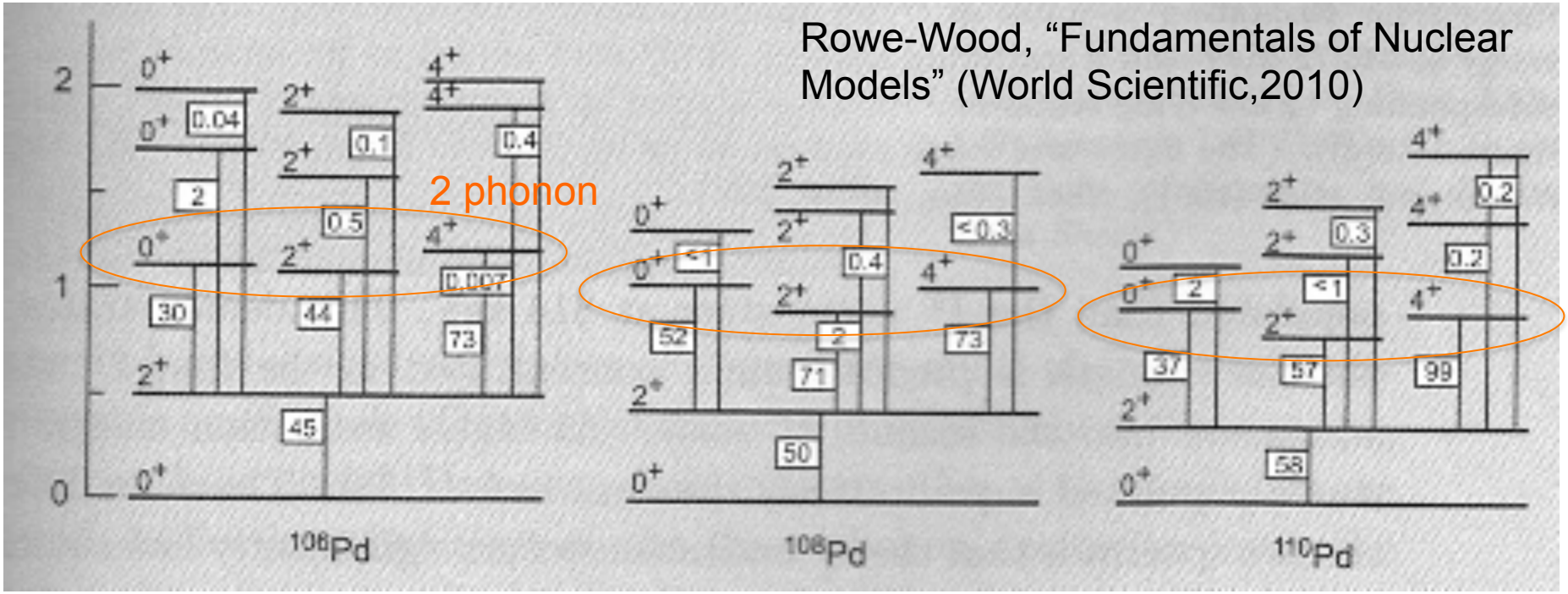
四重極振動



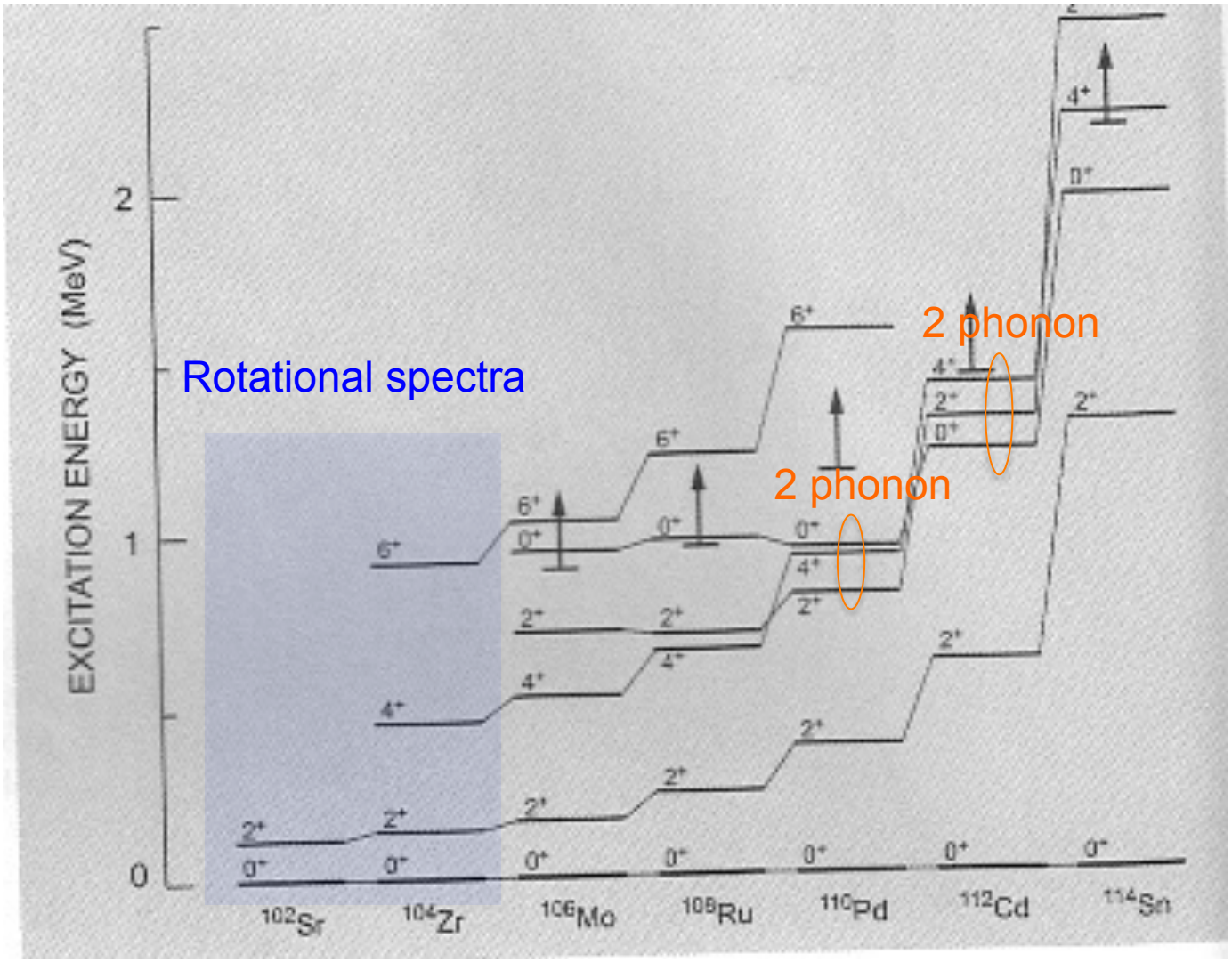


四重極振動励起

- 一重閉殻に比較的近い原子核(N,Z:偶数)
  - 例：Pd (Z=46 [=50–4])
  - 1振動子(1 phonon)状態（$J^{\pi} = 2^{+}$）
  - 2振動子(2 phonon)状態（$J^{\pi} = 0^{+}, 2^{+}, 4^{+}$）



閉殻 → 開殻



Z = 38 40 42 44 46 48 50

フォノン凝縮による核変形

$\left|\Phi_0\right\rangle$ 球形の基底状態

$B^+_{2^+}\left|\Phi_0\right\rangle$ 1-phonon状態 (2^+)

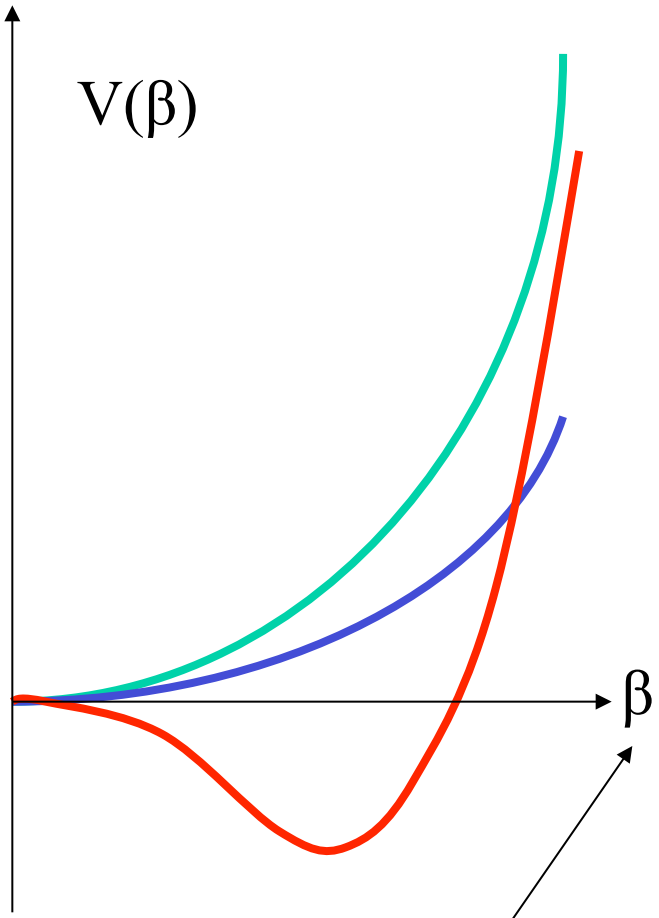
$\left[B^+_{2^+}B^+_{2^+}\right]^L_M\left|\Phi_0\right\rangle$ 2-phonon状態 (L^+)

閉殻➔開殻

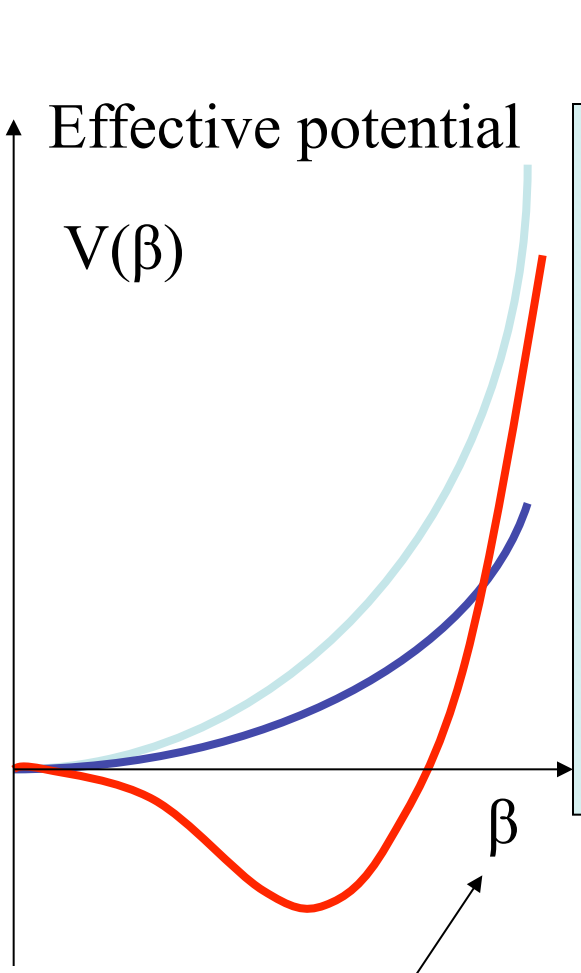
$$\left|\Phi_{\mathrm{def}}\right\rangle \approx \exp(cB^+_{2^+})\left|\Phi_0\right\rangle$$

$$\beta \sim \left\langle\Phi_{\mathrm{def}}\left|B_{2^+}\right|\Phi_{\mathrm{def}}\right\rangle$$

$$\sim \left\langle\Phi_{\mathrm{def}}\left|r^2Y_{20}(\hat{r})\right|\Phi_{\mathrm{def}}\right\rangle$$ 変形（秩序パラメータ）

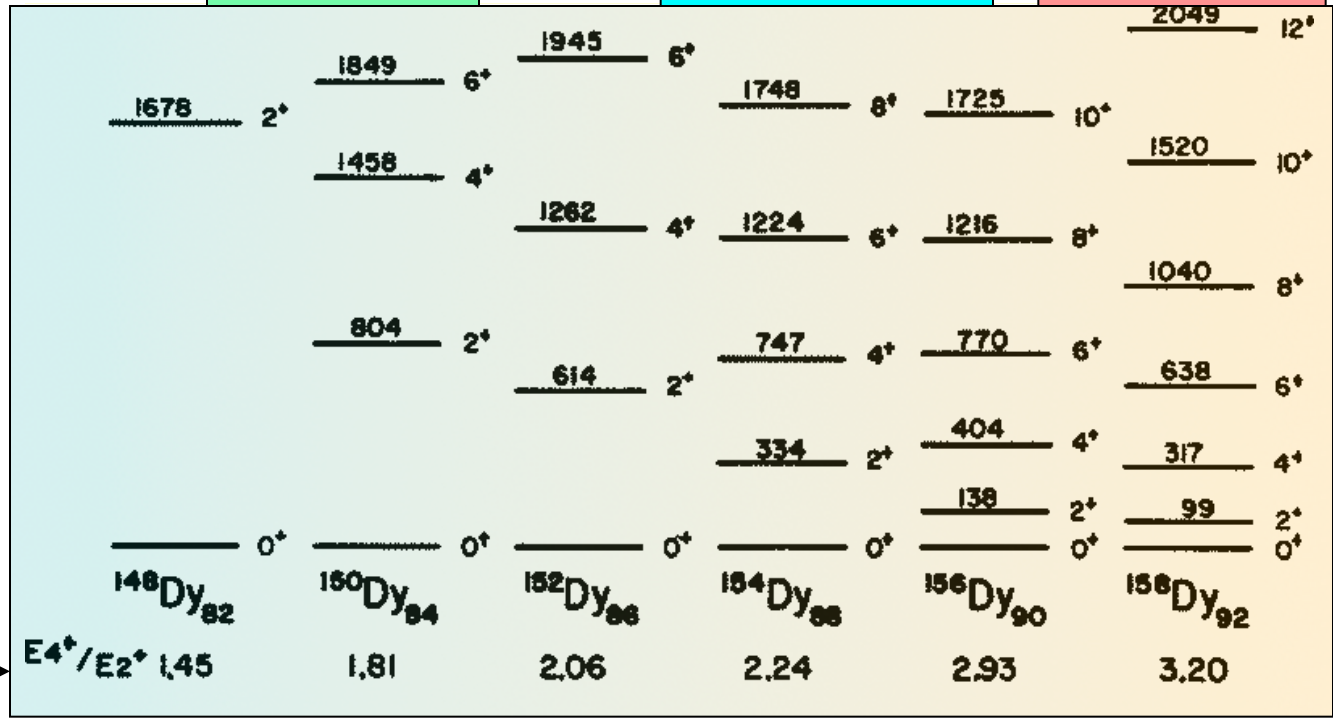


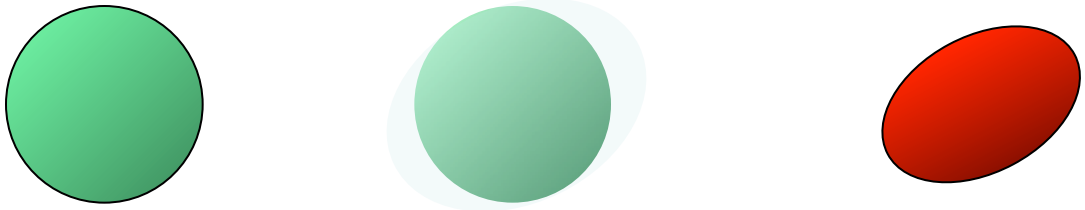
形状相転移



Quadrupole deformation
(order parameter)

spherical | transitional | deformed





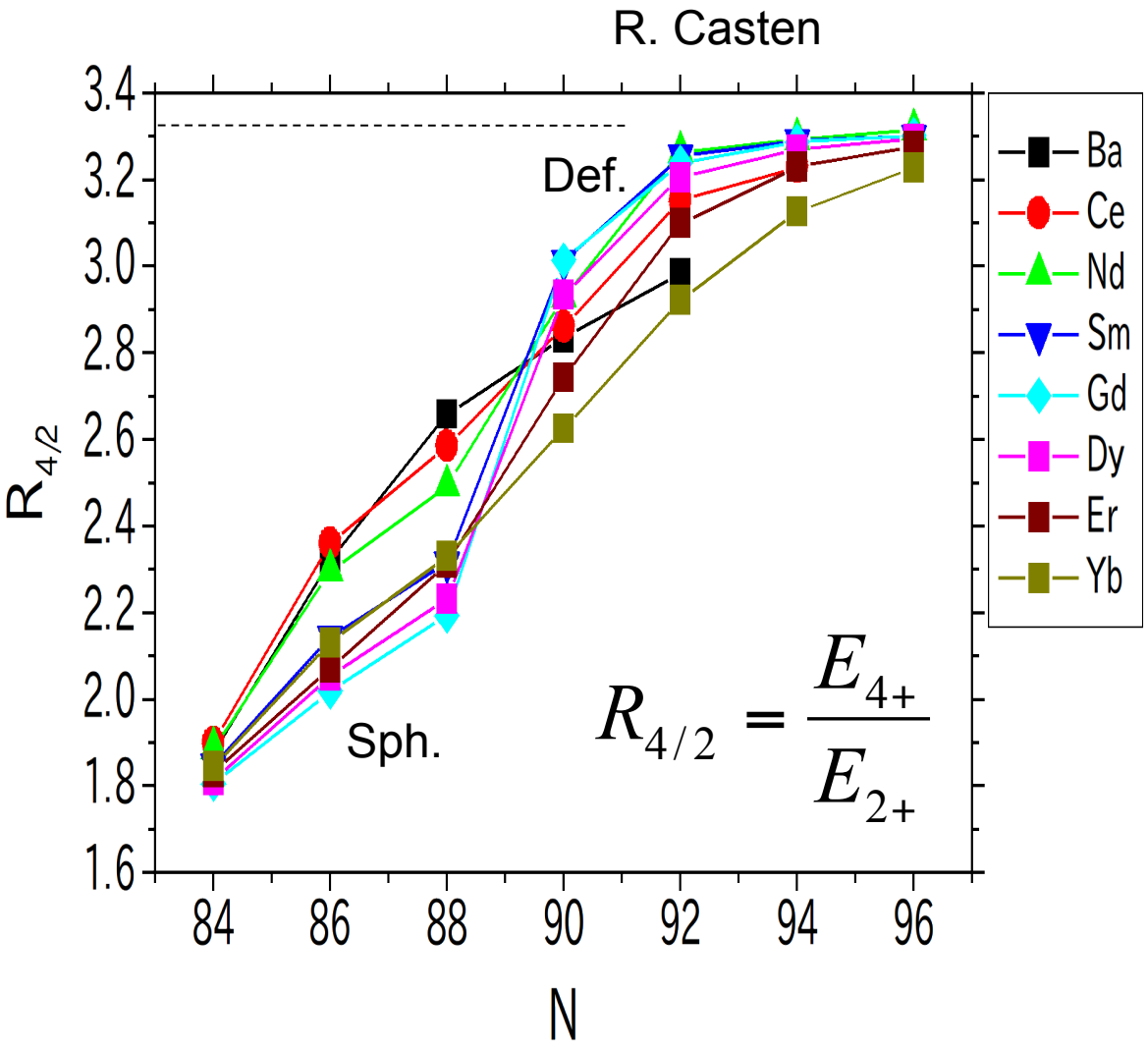
Spontaneous Symmetry Breaking (SSB)

$R_{4/2}$ でみる変形の成長（実験データ）

$$E_I = \frac{I(I+1)}{2\Im}$$

$$\Downarrow$$

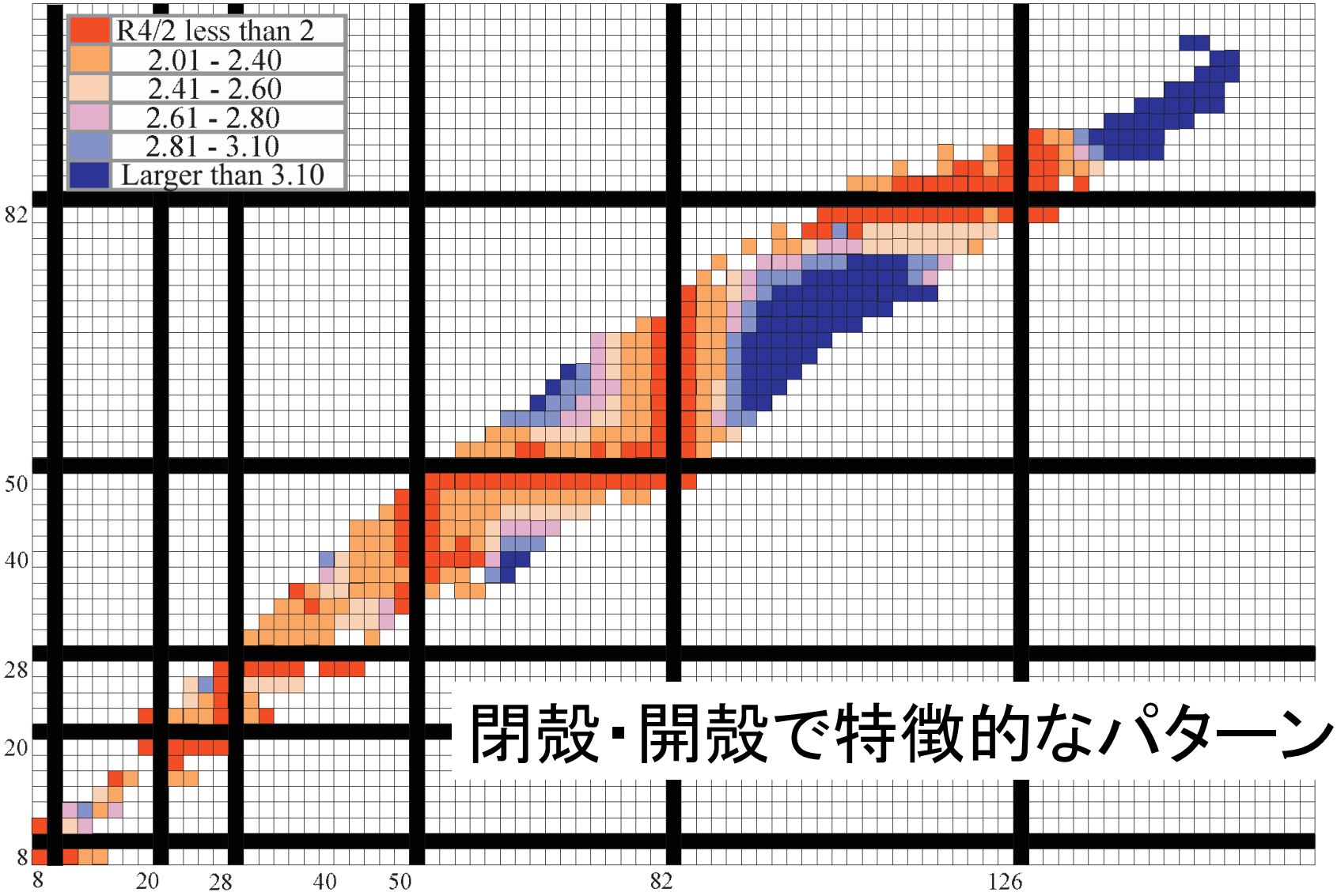
$$R_{4/2} \equiv \frac{E_4}{E_2} = \frac{20}{6} = 3.33\cdots$$



Onset of deformation →

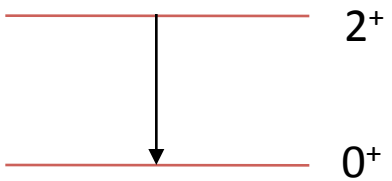
核図表(偶々核)における $R_{4/2}$

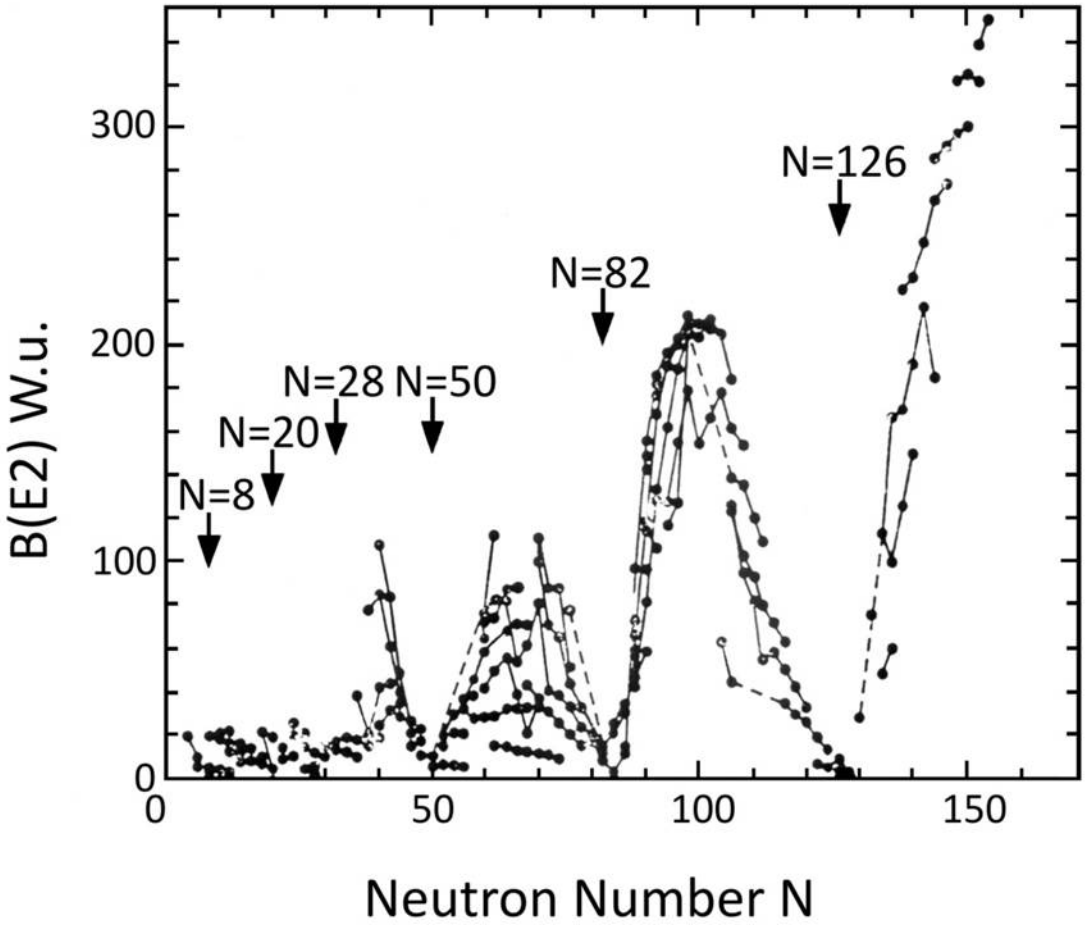
Courtesy: R. Casten



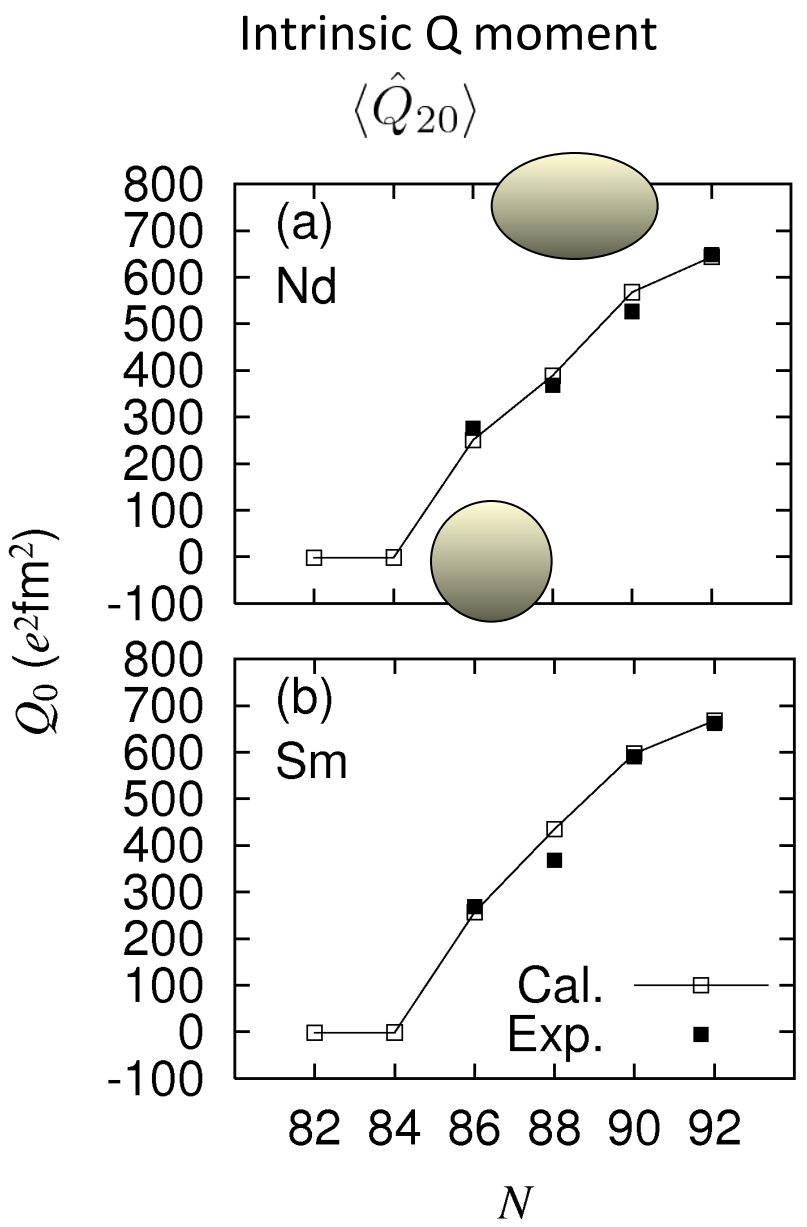
閉殻・開殻で特徴的なパターン

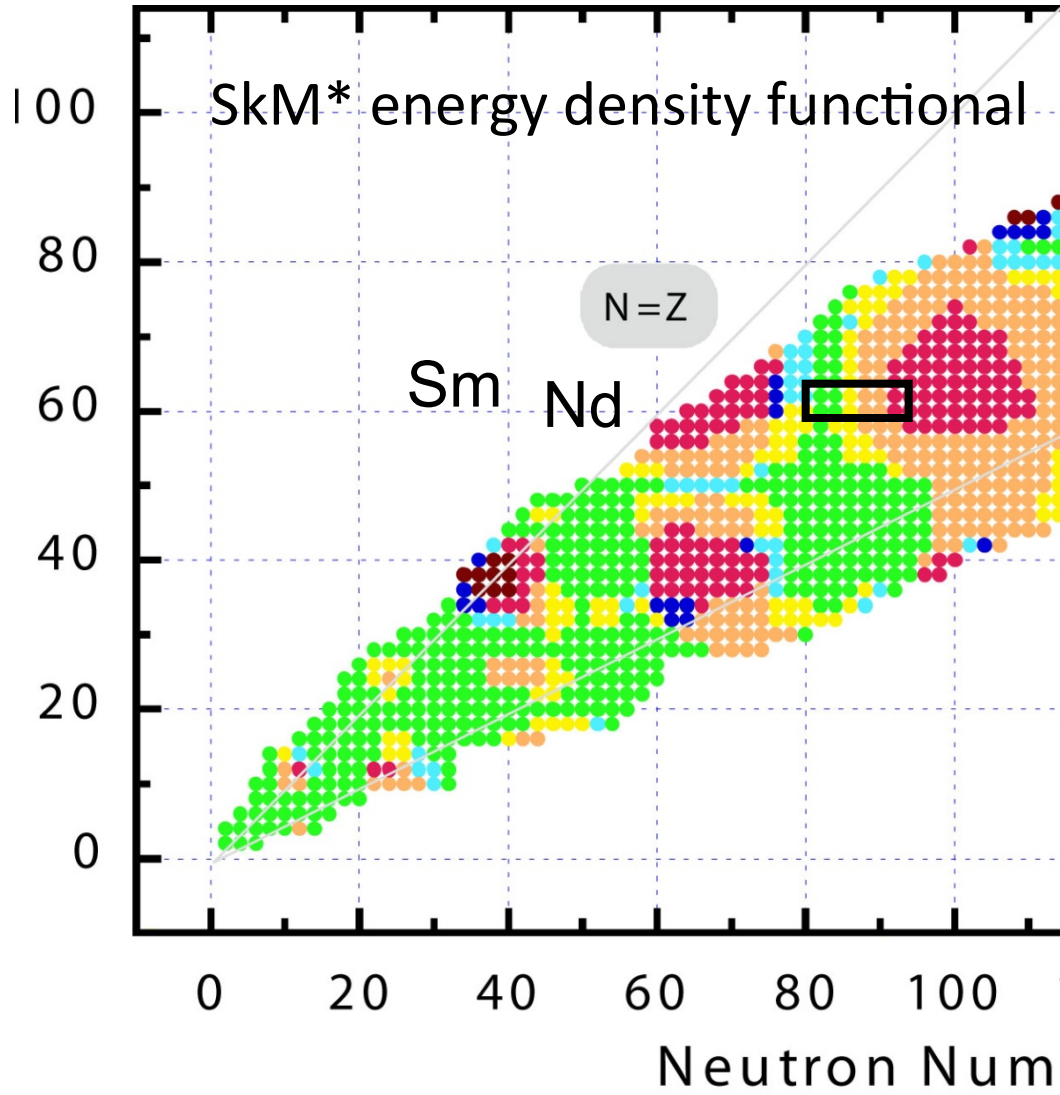
$B(E2: 0^+_1 \rightarrow 2^+_1) \propto \langle 2^+_1 || E2 || 0^+_1 \rangle^2$





密度汎関数計算による核変形の再現・予言





(時間依存)密度汎関数理論 [(TD)DFT]

- エネルギー密度汎関数

$$E\left[\rho_q(t),\tau_q(t),\overleftrightarrow{J}_q(t),\vec{j}_q(t),\vec{s}_q(t),\vec{T}_q(t);\kappa_q(t)\right]$$

kinetic　spin-current　current　spin　spin-kinetic　pair density

- Time-dependent BdG Kohn-Sham eq.

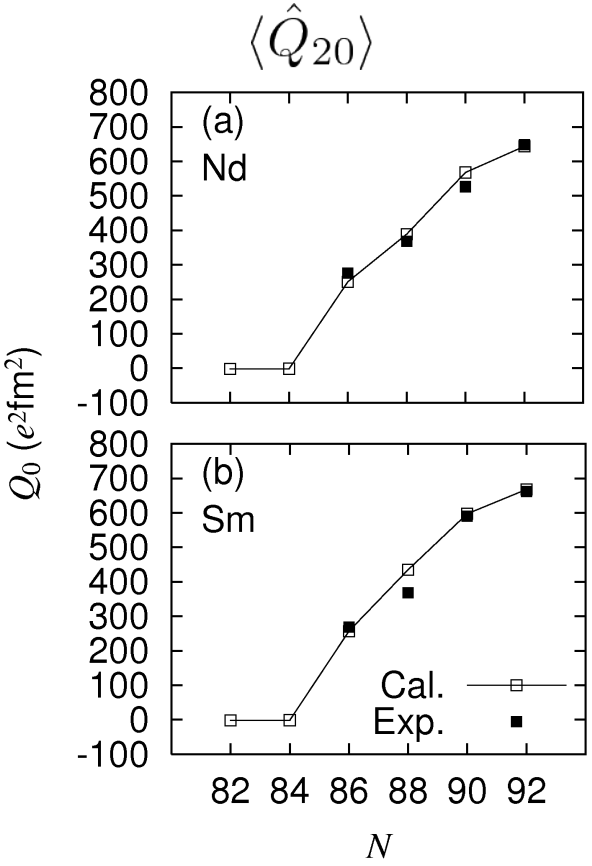
$$i\frac{\partial}{\partial t}\begin{pmatrix}U_\mu(t)\\V_\mu(t)\end{pmatrix}=\begin{pmatrix}h(t)-\lambda & \Delta(t)\\-\Delta^*(t) & -\left(h(t)-\lambda\right)^*\end{pmatrix}\begin{pmatrix}U_\mu(t)\\V_\mu(t)\end{pmatrix}$$

時間依存密度汎関数計算：光吸収断面積

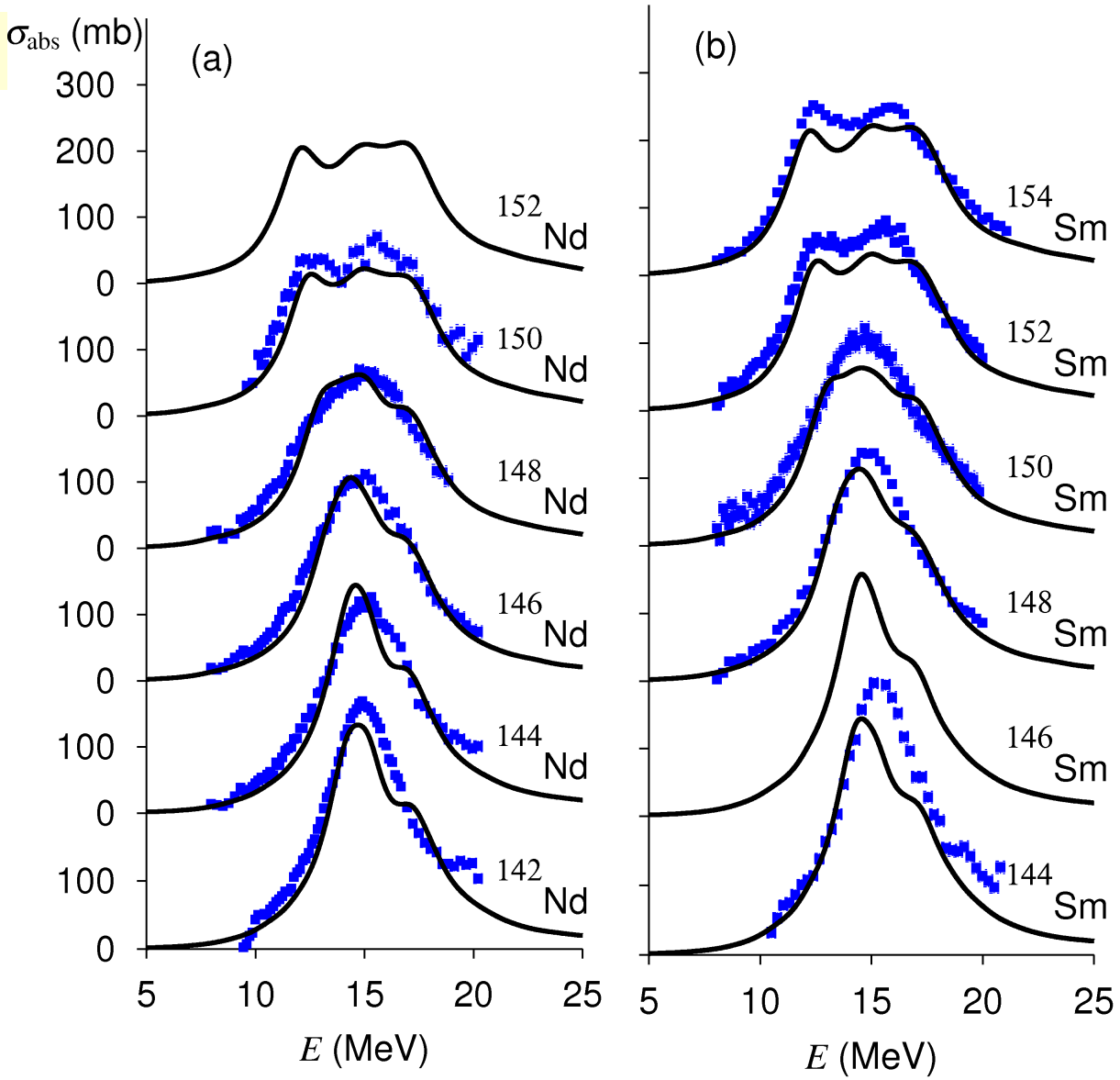
SkM* functional

(S ~ 30 MeV, K ~ 217 MeV)

Intrinsic Q moment



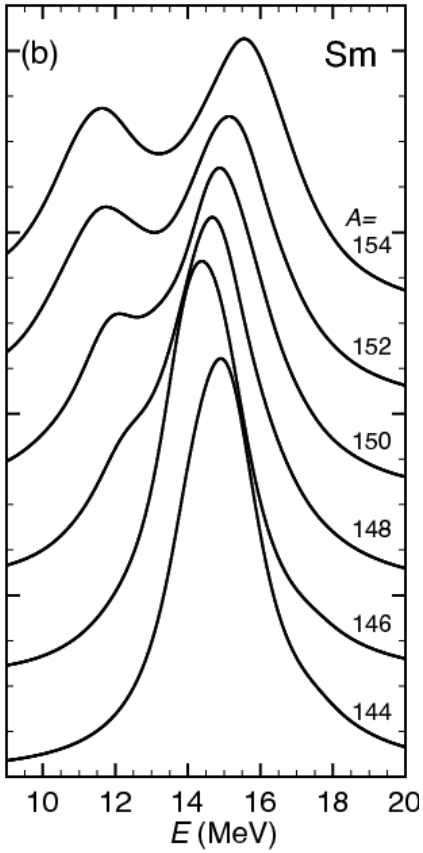
Yoshida, Nakatsukasa, PRC 83, 021304 (2011)

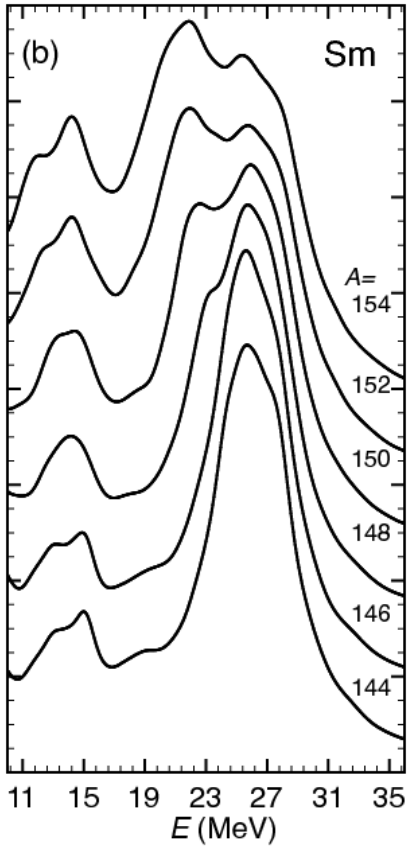


核変形と巨大共鳴(IS,IV; L=0~3)

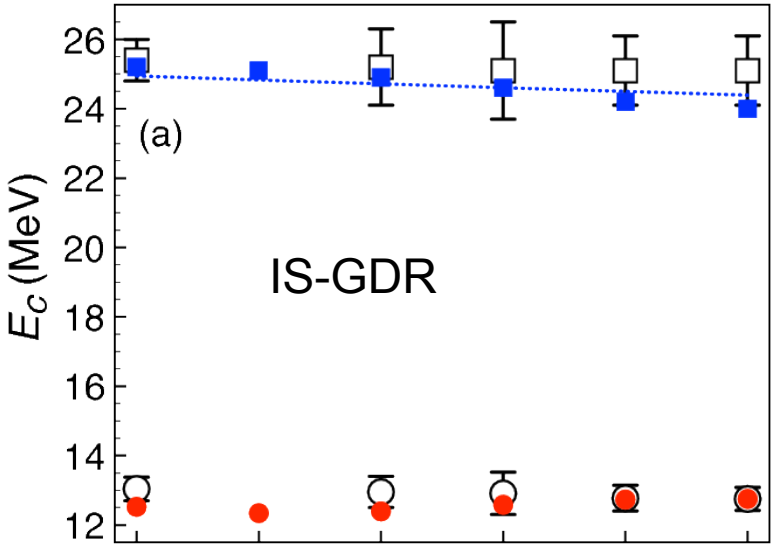
Yoshida and TN, PRC88 (2013) 034309
スパコン「京」の成果（hp120192）

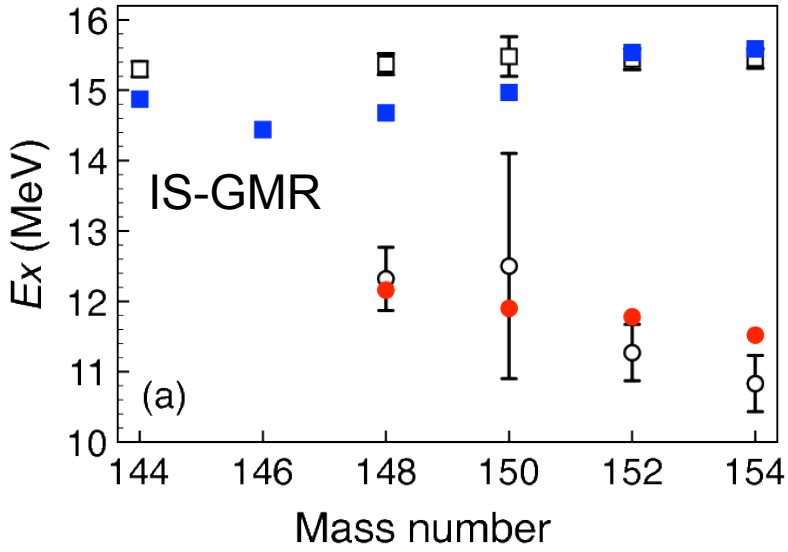
IS-GMR





IS-GDR



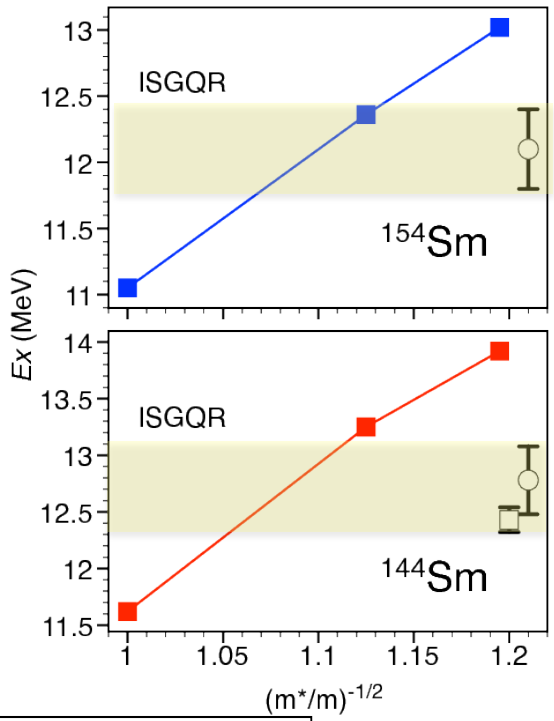


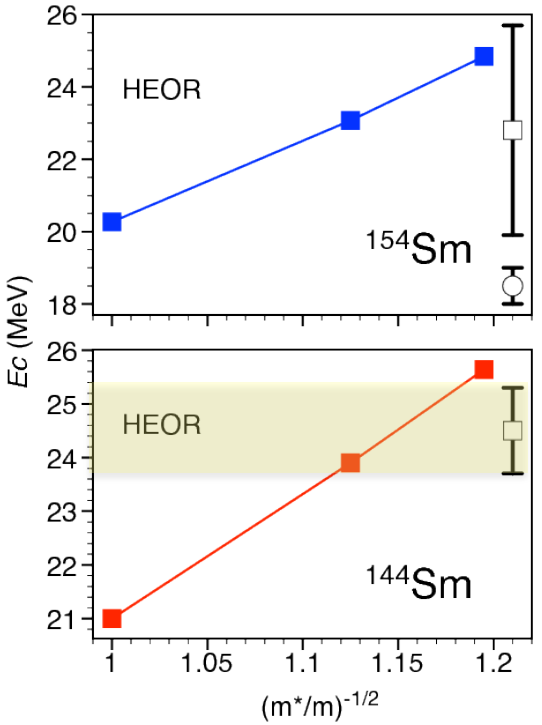
密度汎関数の比較

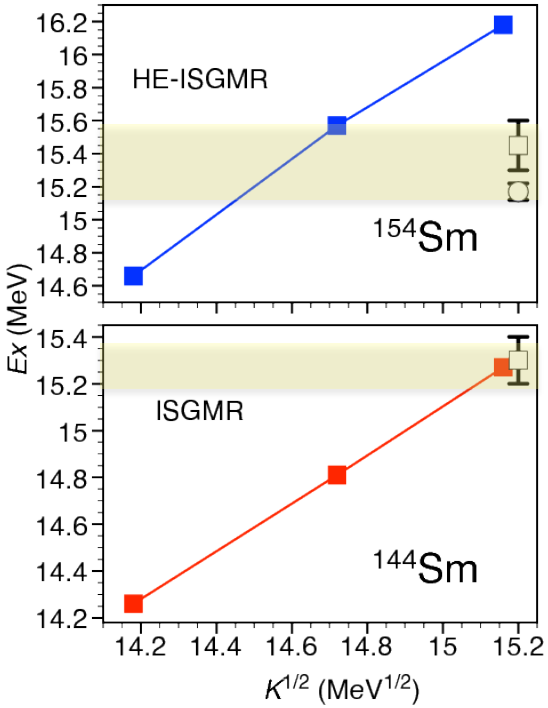
核子有効質量

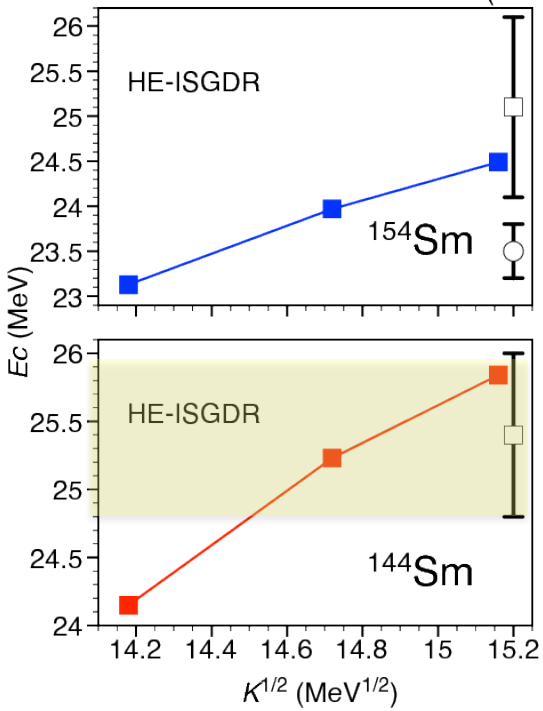
$$m^*/m = 0.8 \sim 0.9$$

（ISGQRのデータより）







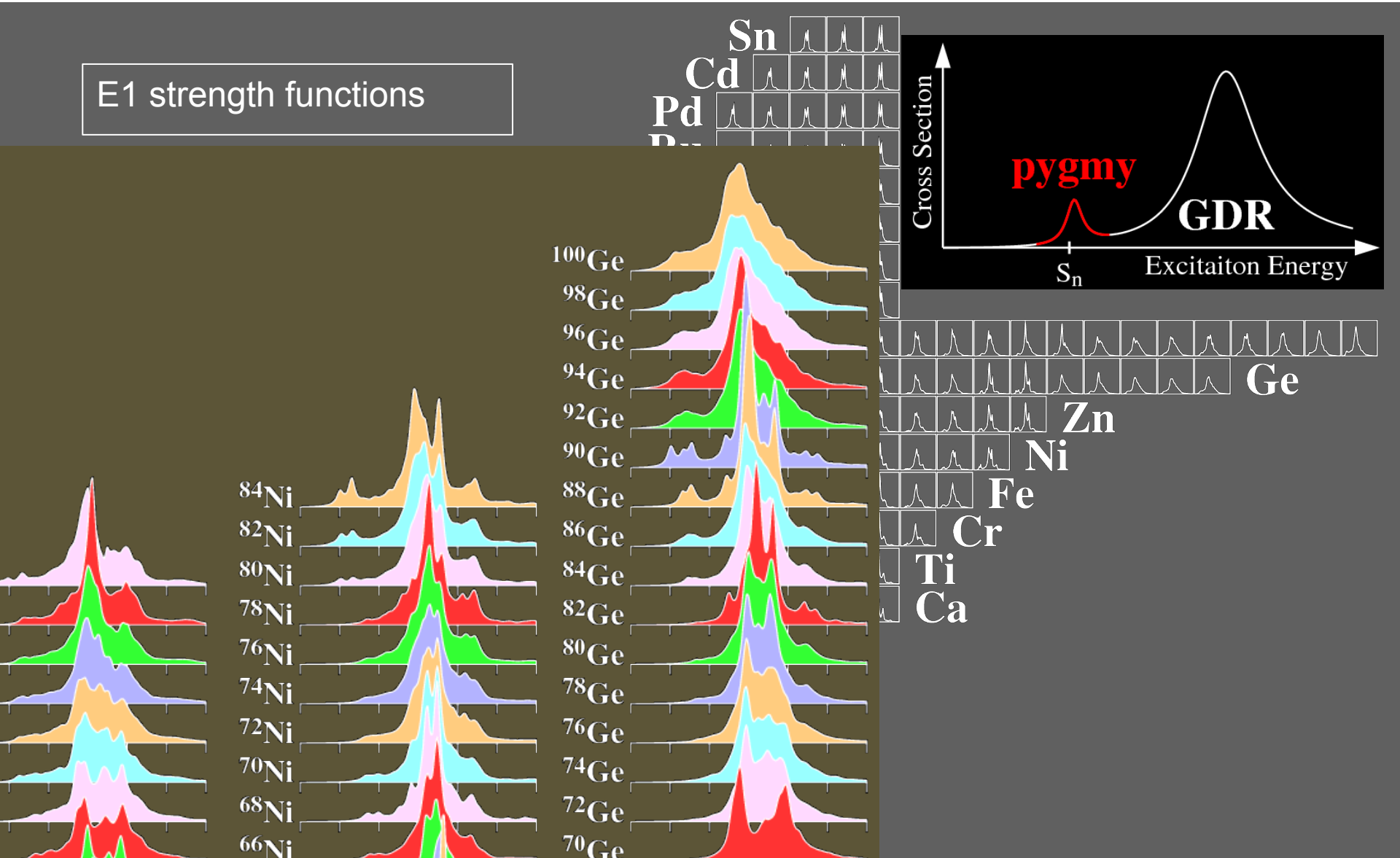


非圧縮率

$$K = 210 \sim 230 \text{ MeV}$$

Computational nuclear data tables

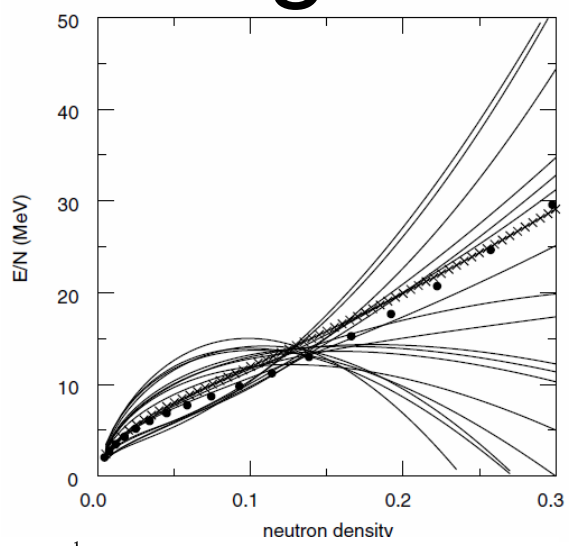
Inakura, T.N., Yabana, PRC 84, 021302 (R) (2011); arXiv: 1306.3089

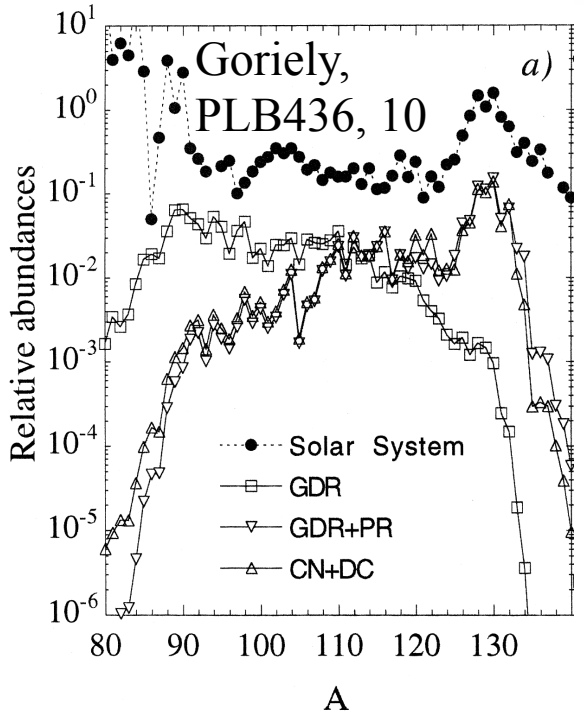


Issues in low-energy *E1* strength

Inakura, et al., arXiv: 1306.3089

- Does the observation constrain the neutron skin thickness and the neutron-matter EOS?
  - Yes, but we need to go to very neutron rich!
  - ^{84}Ni is much better than ^{68}Ni
- Does it influence the r-process?
  - Significantly influence the direct neutron capture process near the neutron drip line
  - We need calculation with a proper treatment of the continuum.

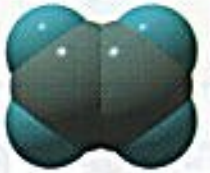
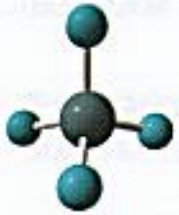




原子核の変形と対称性の自発的破れ

- 原子は“丸い”
  - 量子系
  - 零点運動エネルギーをなるべく下げる
- 分子は原子配置による変形
  - 古典系
- 原子核は分子とは違うメカニズムで変形
  - 量子系

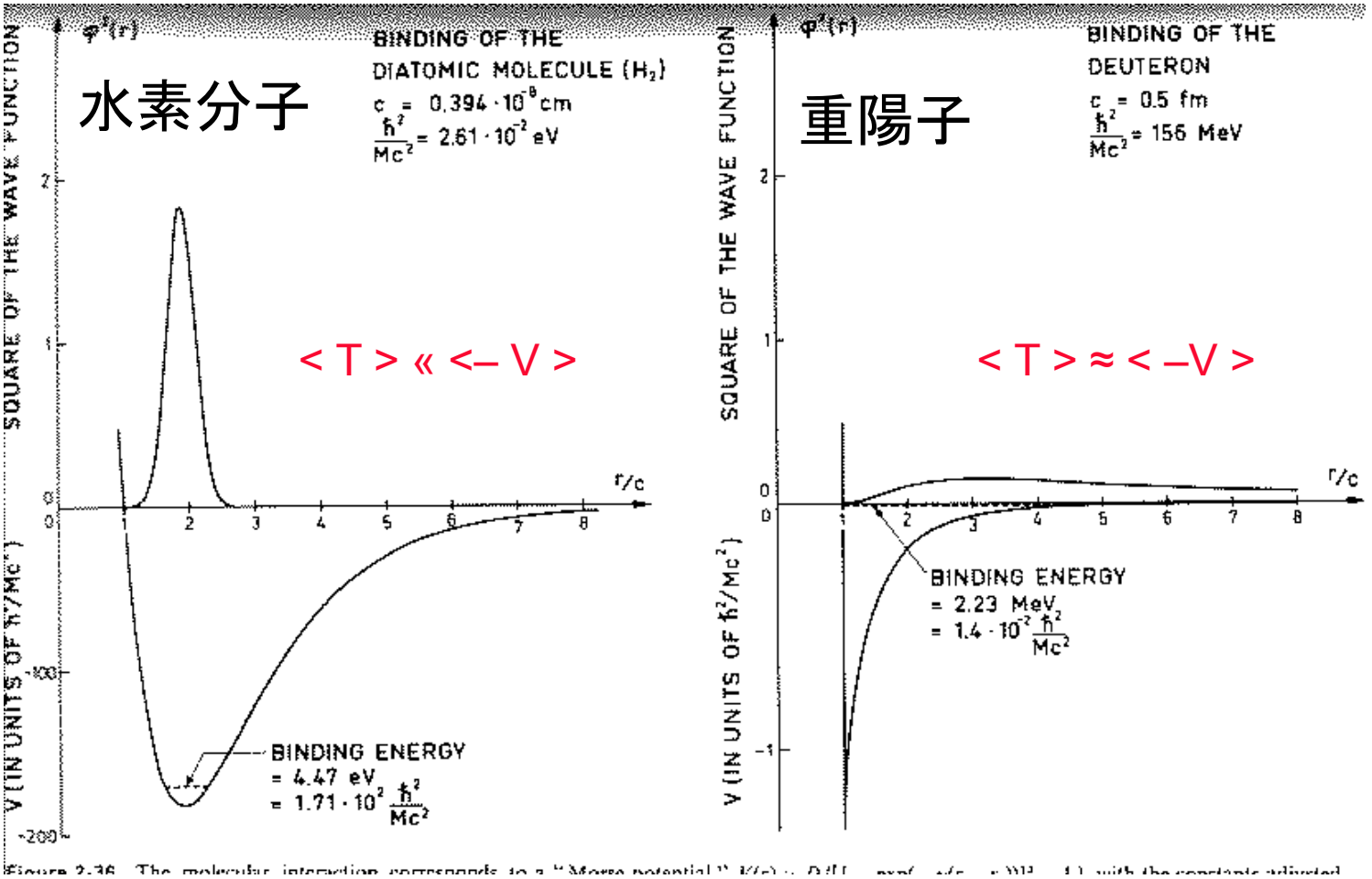
分子の変形

分子	水素	水	アンモニア	メタン	二酸化炭素	窒素	エチレン
分子式	H_2	H_2O	NH_3	CH_4	CO_2	N_2	C_2H_4
電子式	H:H	H:O:H	H:N:H (H)	H (H:C:H) H	:O::C::O:	:N⋮⋮N:	H:C::C:H (H H)
構造式	H-H	H-O-H	H-N-H (H)	H (H-C-H) H	O=C=O	N≡N	H-C=C-H (H H)
分子モデル							
立体構造							
	直線形	折れ線形	三角すい形	正四面体形	直線形	直線形	平面形

- 分子配置による変形(古典的)
  - 慣性能率は剛体値

核力と原子間力

Bohr, Mottelson, Nucl. Str. Vol.1



低温で結晶化

古典的

低温で液体

量子的

量子流体としての原子核

- 量子性の判定パラメータ
  - V_0: 相互作用の強さ
  - c: 相互作用レンジ

$$\Lambda = \frac{\hbar^2}{2Mc^2} \cdot \frac{1}{V_0}$$

- 典型的な系における値
  - 重い原子は以下よりもはるかに小さい値

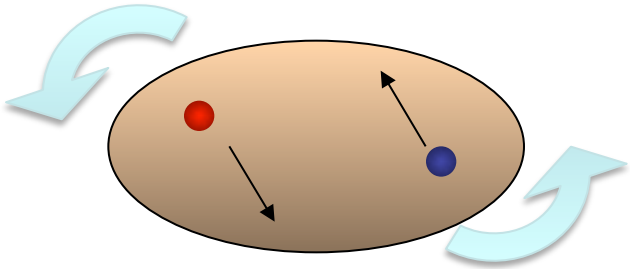
	Λ	絶対零度の相
水素(H)	0.06	固体
ヘリウム(^{3}He,^{4}He)	0.1~0.2	液体
核子(n,p)	0.5	液体

有限量子系・原子核における変形

- 変形は有限の時間 τ_{SSB} において実現
  - フェルミ運動の周期時間 τ_F より十分長い
  - 通常、核子衝突時間 τ_c よりも短い
  - 核子は変形した核内を自由に高速で運動

$$v_F \sim 0.3c$$

- τ_{SSB} より長い時間では、量子的零点運動（zero-point motion）によって球形の密度分布に
  - 有限の相関時間 τ_{SSB}
  - 回転運動（集団運動）の出現
  - 実験で観測（回転スペクトル）



Rotating objects in the universe

Nucleus is one of the fastest rotating many-body system.

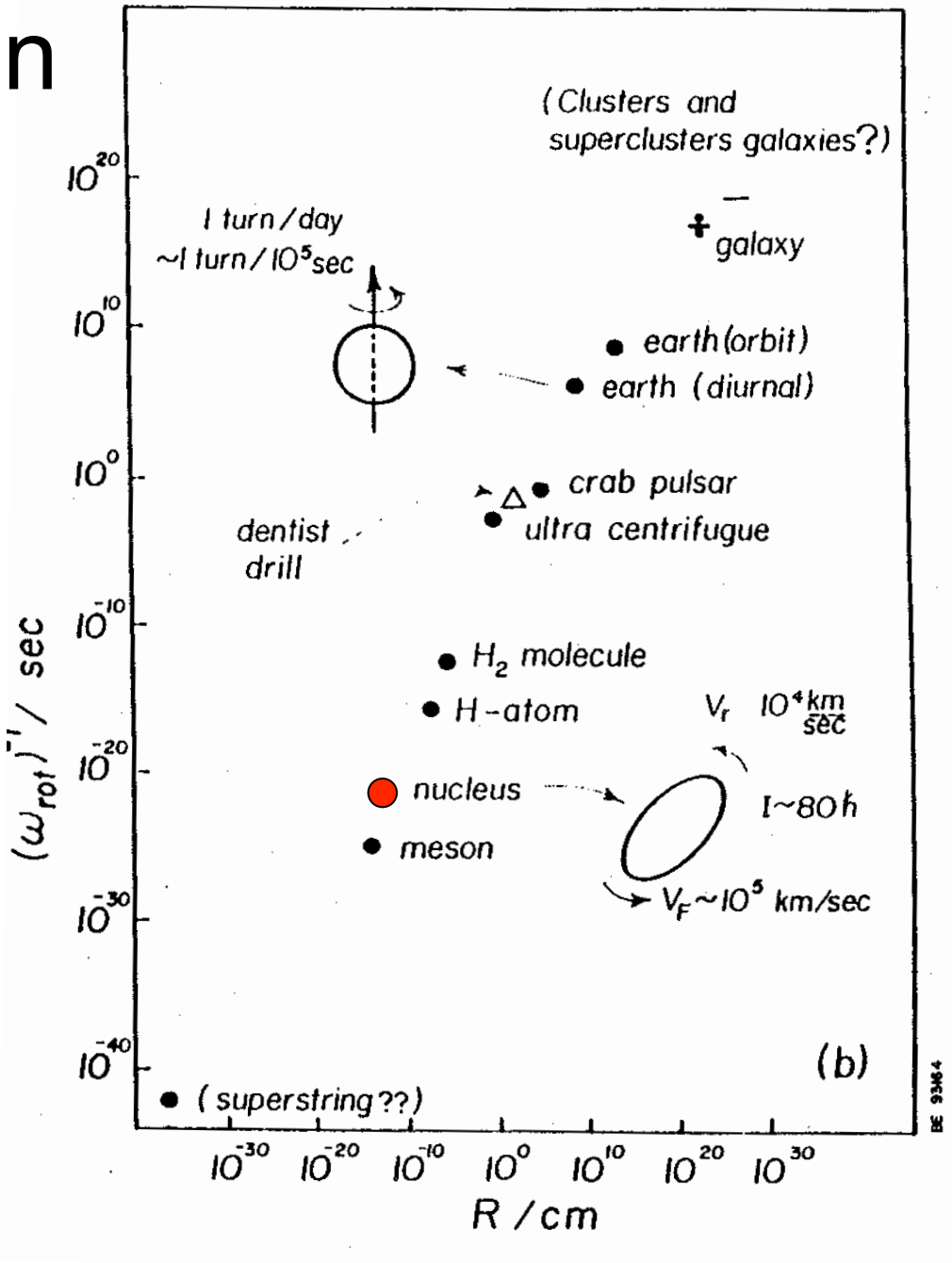
$$\frac{R_0\omega_{\mathrm{rot}}}{v_{\mathrm{F}}} << 1$$ Low spin

"Perturbative" Coriolis effects

$$\frac{R_0\omega_{\mathrm{rot}}}{v_{\mathrm{F}}} \sim 1$$ High spin

Non-perturbative Coriolis effects

Structure change, band crossings



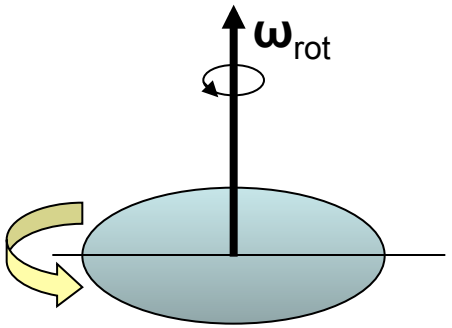
Cranking model
Picture in the rotating frame

Time-dependent Schrödinger equation

$$i\frac{\partial}{\partial t}\left|\Psi(t)\right\rangle = H\left|\Psi(t)\right\rangle$$

In the uniformly rotating frame with the rotational frequency **ω**

$$\left|\Psi(t)\right\rangle = e^{-i\boldsymbol{\omega}t\cdot\mathbf{J}}\left|\Phi(t)\right\rangle \qquad i\frac{\partial}{\partial t}\left|\Phi(t)\right\rangle = \left(H-\boldsymbol{\omega}\cdot\mathbf{J}\right)\left|\Phi(t)\right\rangle$$



Choose the rotational axis as x-axis: "1-dim. cranking"

$$H' \equiv H-\boldsymbol{\omega}\cdot\mathbf{J} \quad\Rightarrow\quad H' = H-\omega_{\mathrm{rot}}J_x$$

Cranking violates the time-reversal symmetry. However,

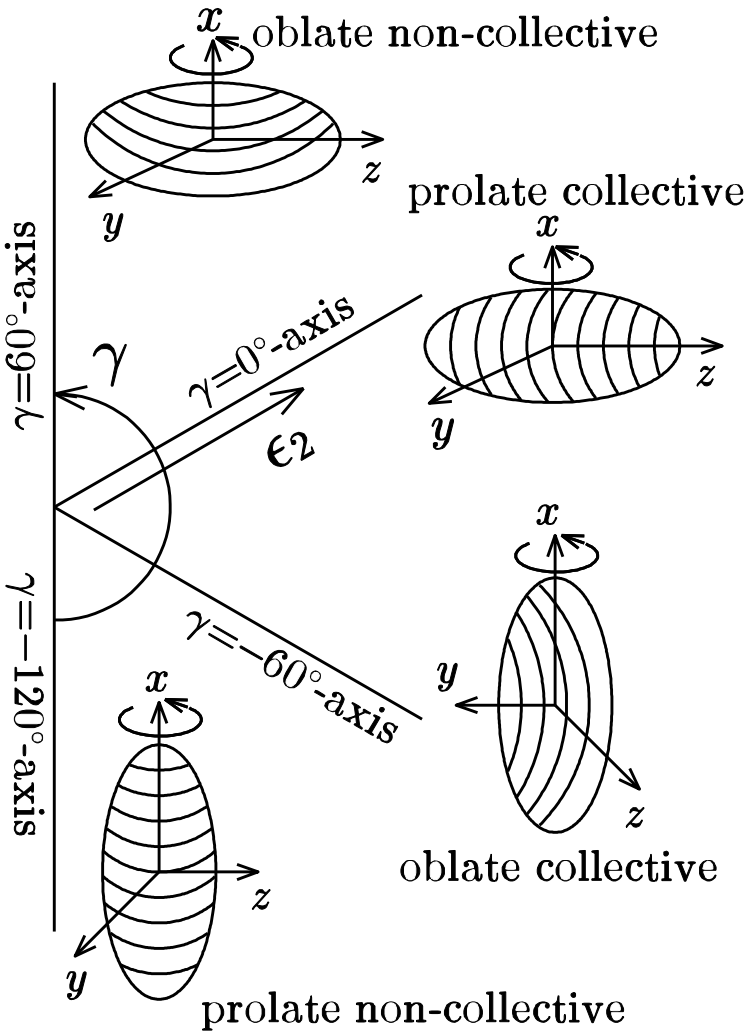
in case of quadrupole deformation, it conserves the parity and signature symmetry:

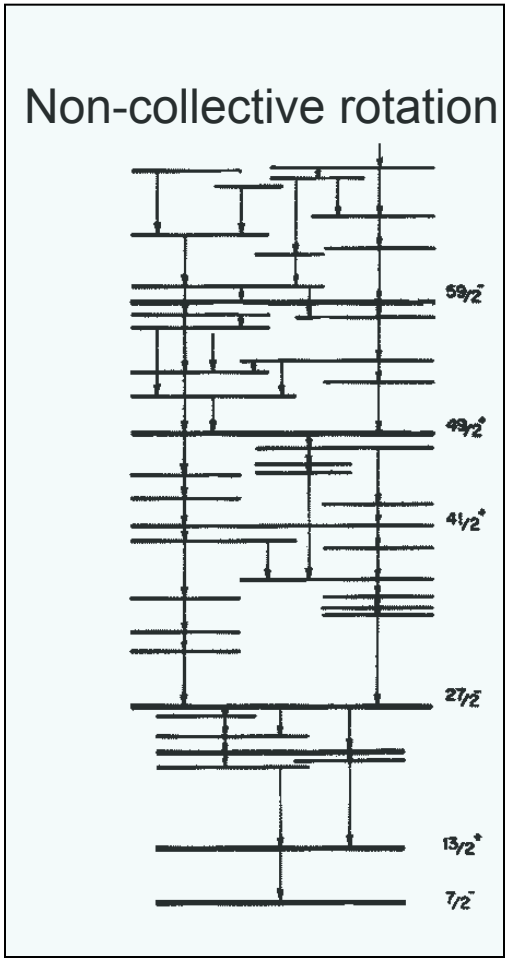
$$\hat{R}_x = e^{-i\pi J_x} \qquad r = e^{-i\pi\alpha}, \quad r = \begin{cases} \pm i\,, & \alpha = \mp 1/2 \\ \pm 1\,, & \alpha = \begin{cases} 0 \\ 1 \end{cases} \end{cases}$$

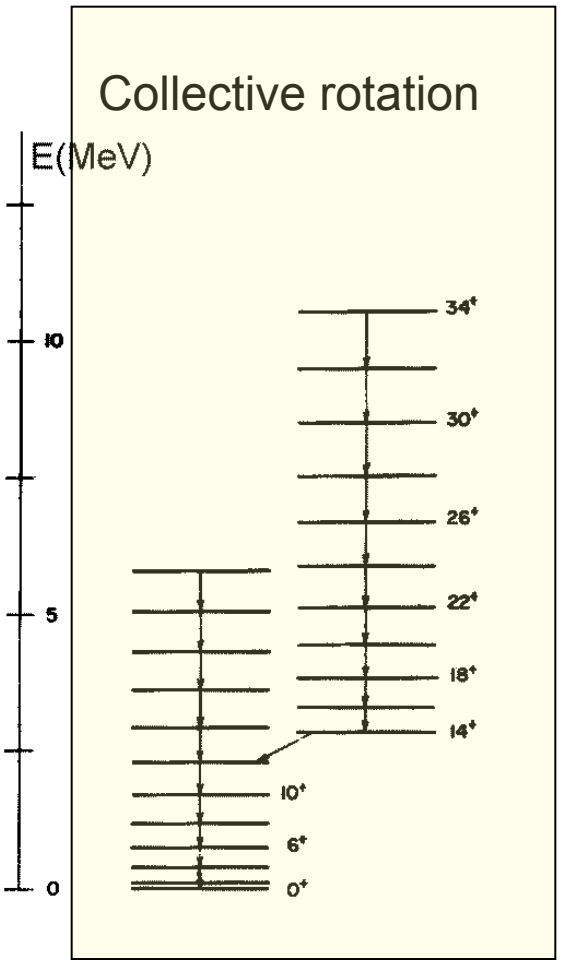
Experimentally, often defined as

$$\alpha = I \pmod 2$$

Collective and non-collective rotations







Cranking model is applicable to both cases.

Quasi-particle routhians

Quasi-particle eigen-energies of the "cranked" HFB equation

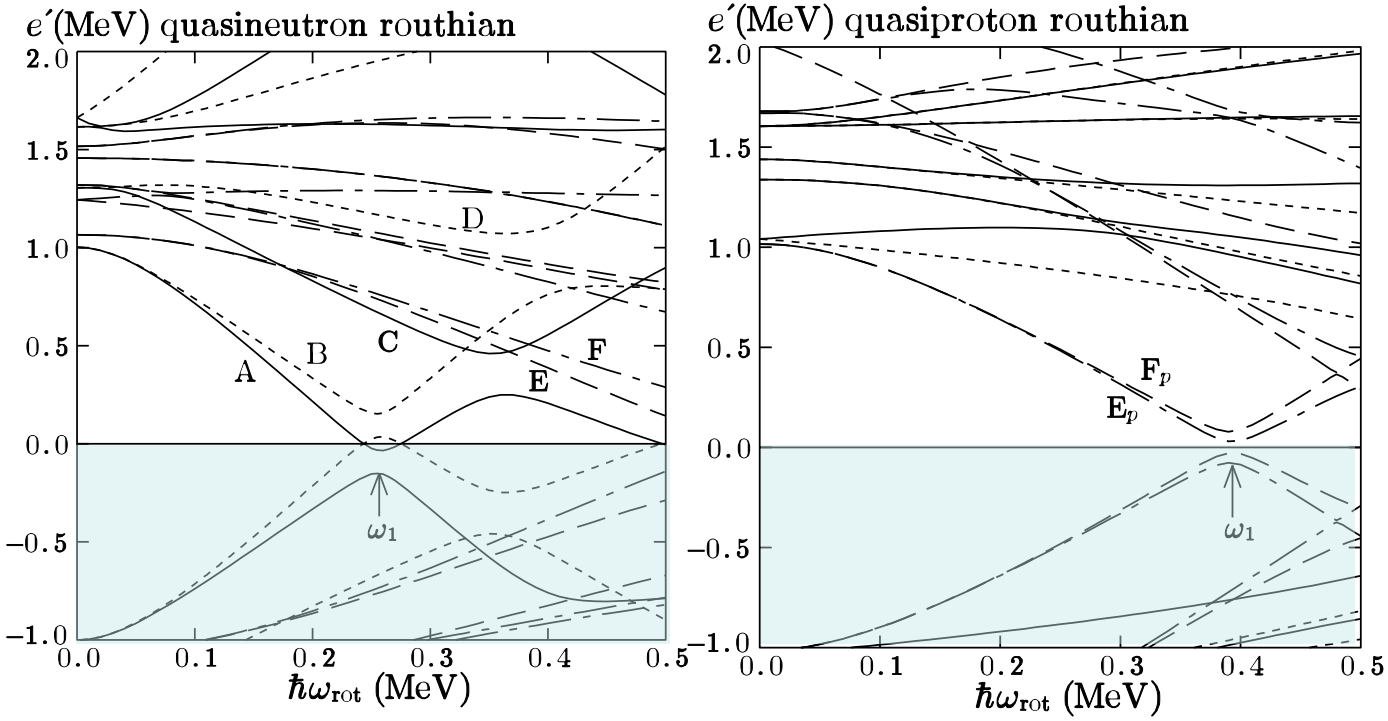
$$\begin{pmatrix} h-\lambda N-\omega_{\mathrm{rot}} j_x & \Delta \\ -\Delta & -(h-\lambda N-\omega_{\mathrm{rot}} j_x) \end{pmatrix} \begin{pmatrix} U \\ V \end{pmatrix} = e' \begin{pmatrix} U \\ V \end{pmatrix}$$

Even nuclei: qp vacuum → ground band $E' = 0$

2qp excitation $e'_A(\omega) + e'_B(\omega), \cdots$

Odd nuclei: 1qp exc. $e'_A(\omega), e'_B(\omega), \cdots$

QP routhians around ^{164}Er



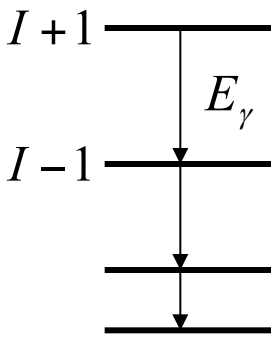
Negative-energy states are *fully occupied* in the vacuum.

Experimental routhians

Angular momentum → Rotational frequency

$$\omega_{\mathrm{rot}}(I) \equiv \frac{dE}{dI} \approx \frac{E(I+1)-E(I-1)}{I_x(I+1)-I_x(I-1)} \approx \frac{E_\gamma(I+1 \to I-1)}{2}$$

$$I_x(I) = \sqrt{(I+1/2)^2 - K^2}$$



Routhian and relative routhian

$$E'(\omega_{\mathrm{rot}}) = E(I) - \omega_{\mathrm{rot}} I_x(I) \approx \frac{1}{2}\left[E(I+1)+E(I-1)\right] - \frac{\omega_{\mathrm{rot}}}{2}\left[I_x(I+1)+I_x(I-1)\right]$$

$$e'(\omega_{\mathrm{rot}}) \equiv E'(\omega_{\mathrm{rot}}) - E'_{\mathrm{ref}}(\omega_{\mathrm{rot}})$$

Ground-state band as the reference band

$$I_x(\omega_{\mathrm{rot}}) = J_0\omega_{\mathrm{rot}} + J_1\omega_{\mathrm{rot}}^3$$

The Harris formula parameters are determined by fitting

$$E'_{\mathrm{ref}}(\omega_{\mathrm{rot}}) = -\int^{\omega_{\mathrm{rot}}} I_x(\omega)d\omega = E'_0 - \frac{1}{2}J_0\omega_{\mathrm{rot}}^2 - \frac{1}{4}J_1\omega_{\mathrm{rot}}^4$$

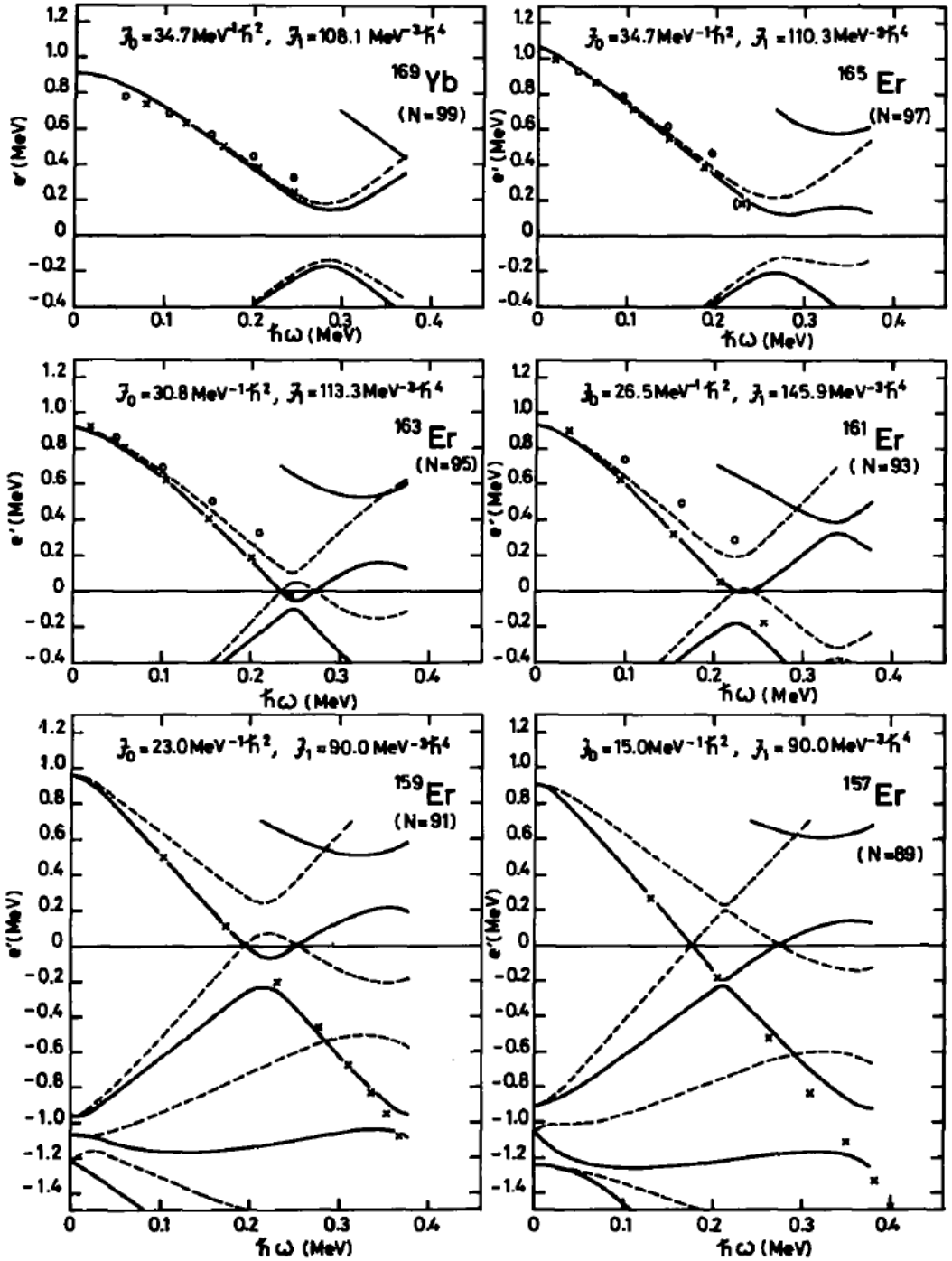
The “const.” is chosen so as to make the ground state (I=0) at zero energy.

$$E'_0 = \frac{1}{8J_0}$$

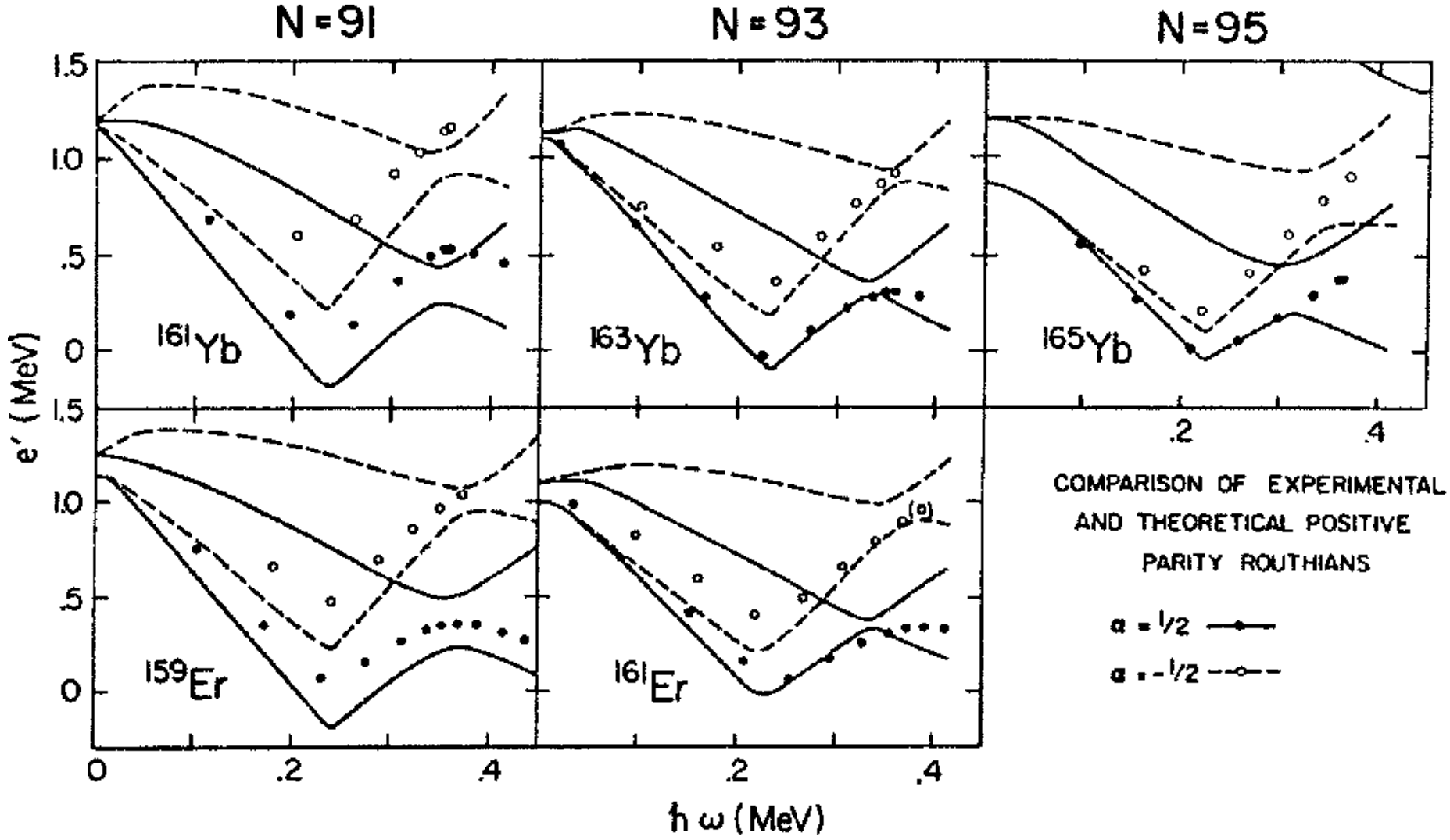
Routhian analysis

Bengtsson & Frauendorf, NPA327 (1979) 139.

Experimental quasi-particle routhians in odd rare-earth nuclei

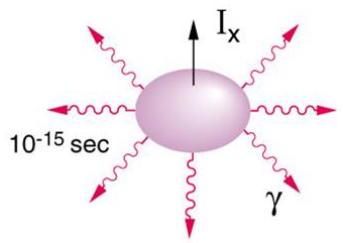


We may take, as the reference routhians, the experimental yrast routhians of neighboring even-even nuclei (or their average).



Back-bending phenomena

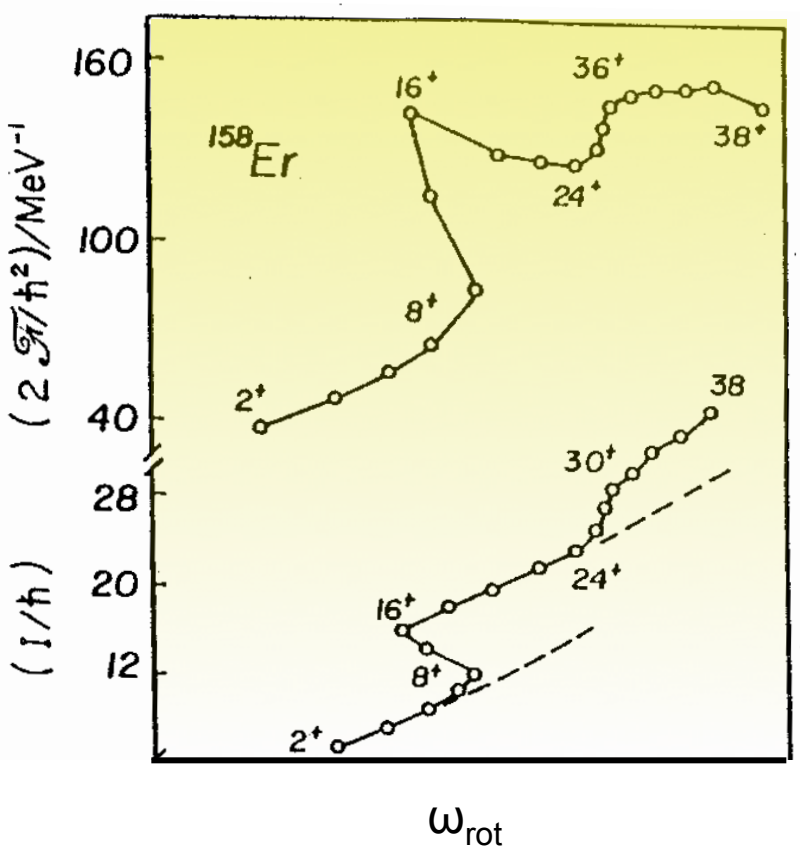
Nucleus loses its angular momentum by emitting gamma rays.

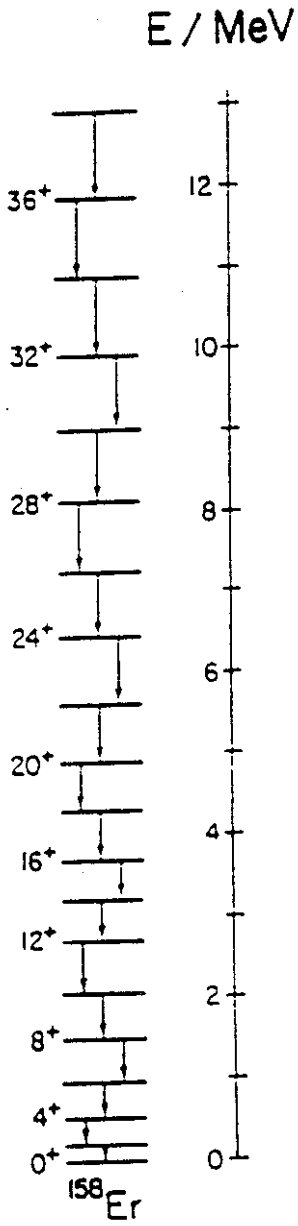


The ^{158}Er nucleus is spinning down, losing ΔI=2 each step.

But, then, at I=16, it spins up, even though losing the angular momentum.

"Nuclear glitch"



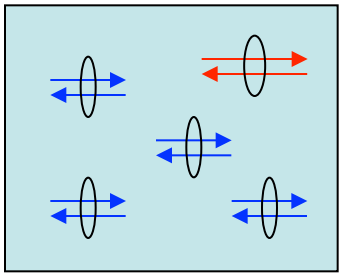


This phenomenon was first discovered in 1972 using the in-beam gamma-ray spectroscopy.

Structure change of the yrast states

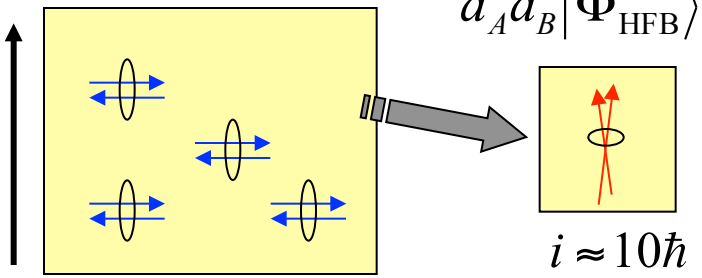
At low spin, the Cooper pair is condensed in the ground state.

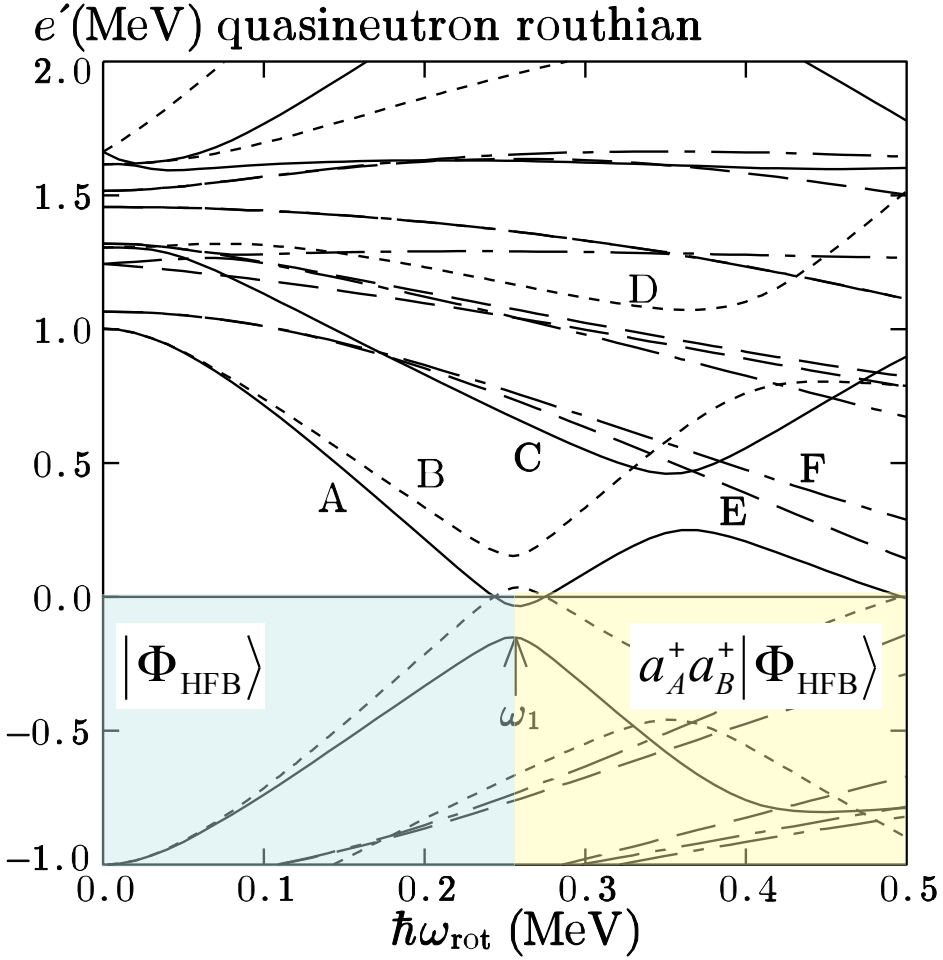
$$\left|\Phi_{\mathrm{HFB}}\right\rangle \approx \left(\sum_k \alpha_k c_k^+ c_{\bar{k}}^+\right)^{N/2} \left|0\right\rangle$$



Coriolis force

At frequency ω_c, one of the Cooper pair is broken up, due to the Coriolis anti-pairing effect.

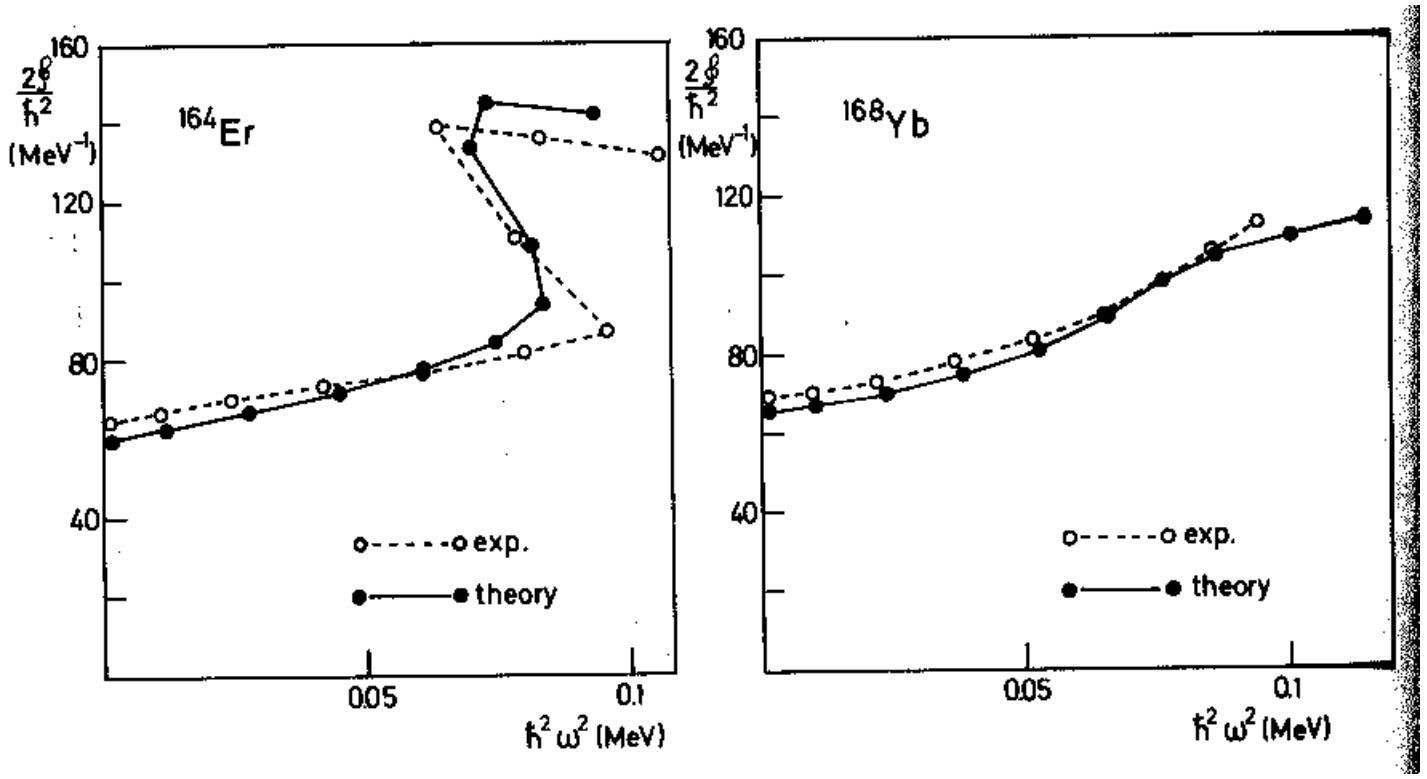




Without increasing ω_{rot}, the state gains about 10 units of spin values, by the alignment.

Cranked HFB model

The cranking model successfully describes the back-bending phenomena in many nuclei, with the proper strength of the Coriolis force.



Ring and Schuck, Nuclear Many-Body Problems (1980), Springer-Verlag

Systematic analysis

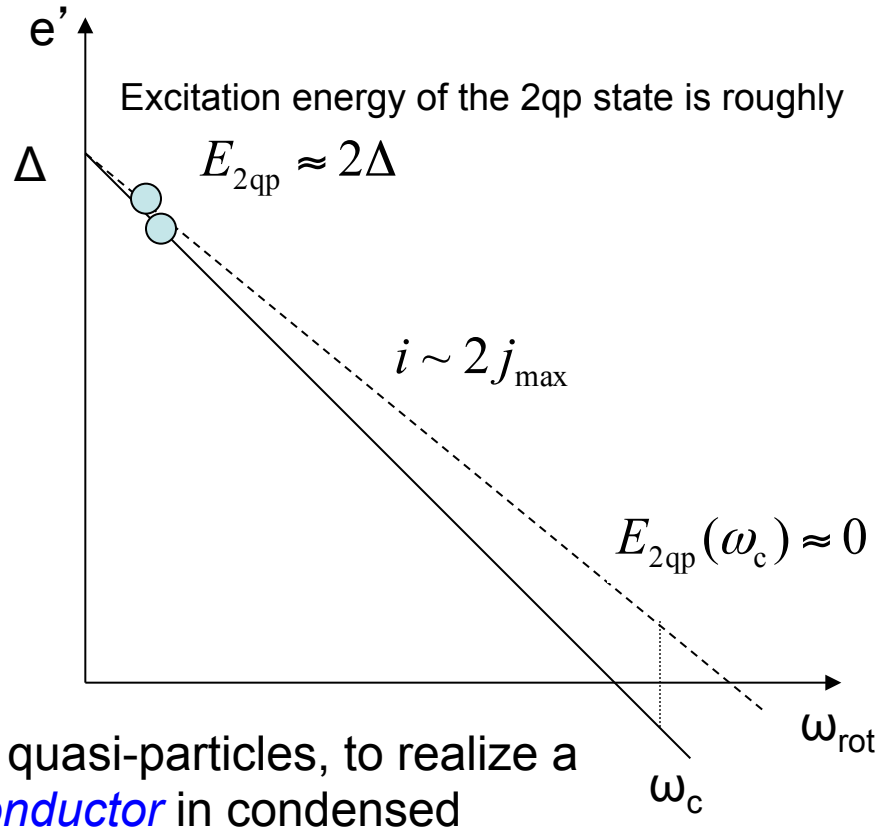
Systematic analysis of the back-bending frequency (by Garrett)

$$\omega_c^{\exp} \approx \frac{1.67\Delta}{j_{\max}}$$

where $j_{\max}$ is the largest j near the Fermi surface.

Simple picture in the right figure predicts

$$\omega_c \approx \frac{\Delta}{j_{\max}}$$

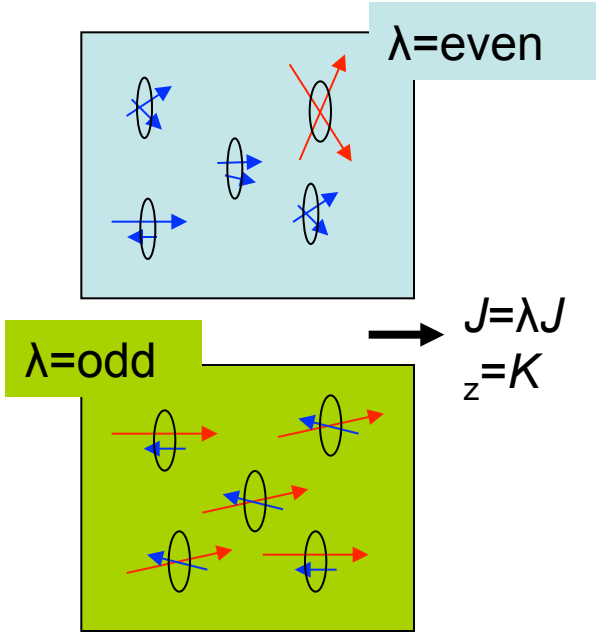


The Coriolis force pulls down the high-j quasi-particles, to realize a state analogous to the *gapless superconductor* in condensed matter.

This can be also regarded as the band crossing between the qp vacuum (0qp) and a 2qp state; g-band and s-band.

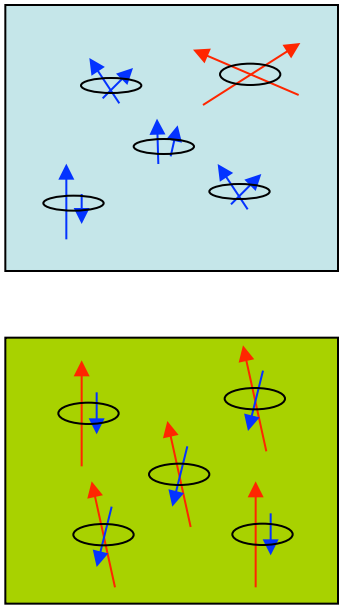
Collective states under rapid rotation

At low spin, many p-h pairs of spin λ contribute to the collective state.



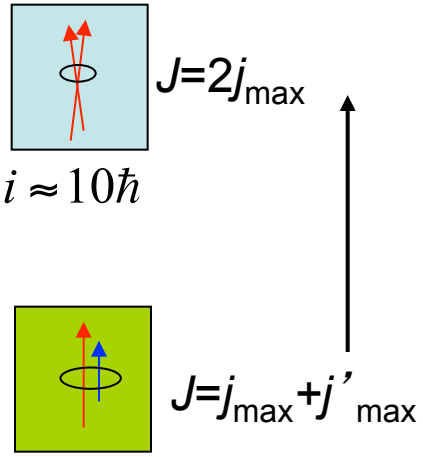
$$\left|\Phi_{\text{coll}}\right\rangle \approx \left(\sum_{ph} \alpha_{ph}\left(c_p^{+}c_h\right)_{\lambda K}\right)\left|\Phi_0\right\rangle$$

At high spin, each p-h pair is aligned by the Coriolis force, to produce an aligned phonon.



$$\left|\Phi_{\text{coll}}^{\text{aligned}}\right\rangle \approx \left(\sum_{ph} \alpha_{ph}\left(c_p^{+}c_h\right)_{\lambda\lambda}\right)\left|\Phi_0\right\rangle$$

At even higher spin, one of the p-h pairs is completely aligned, by escaping from the λ-coupling.

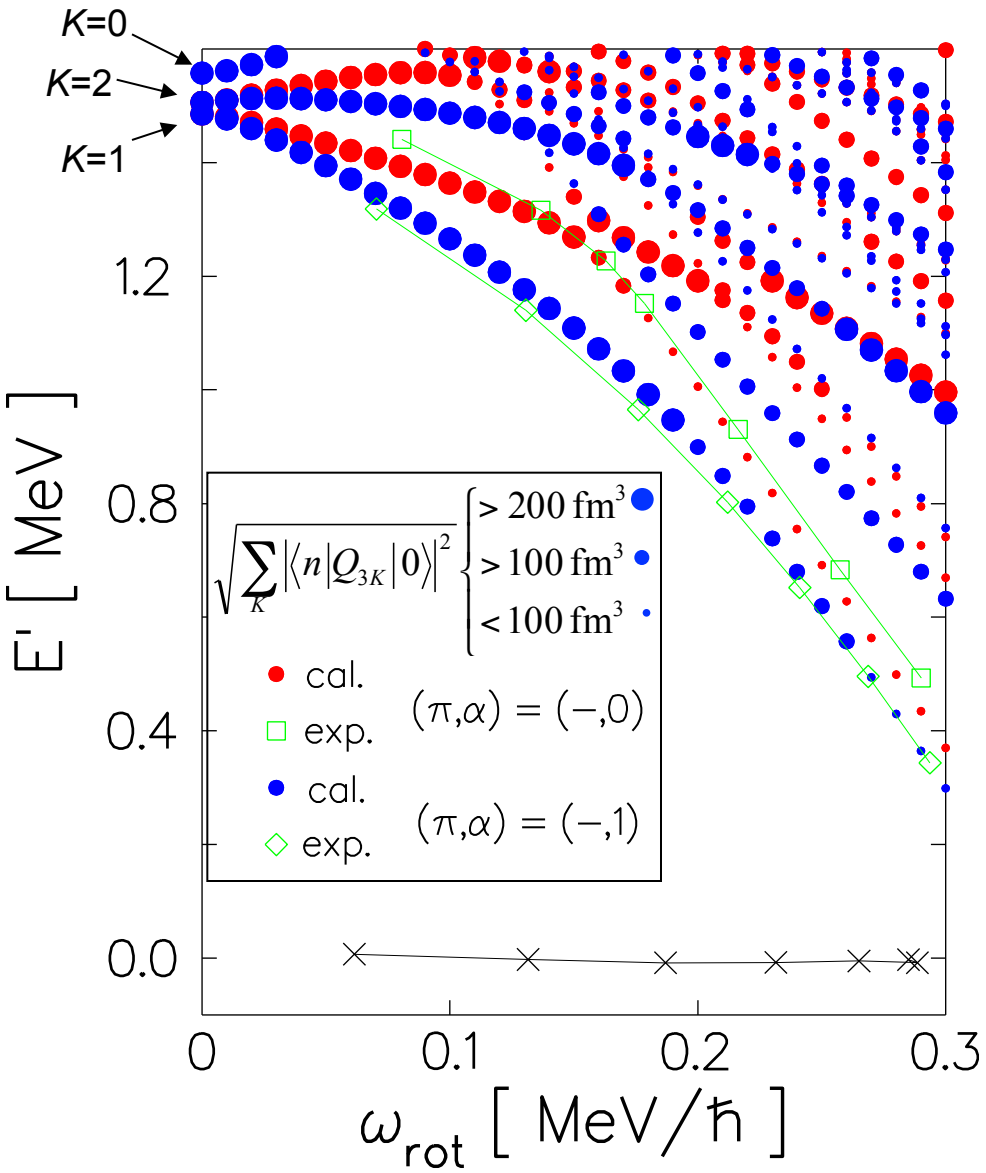


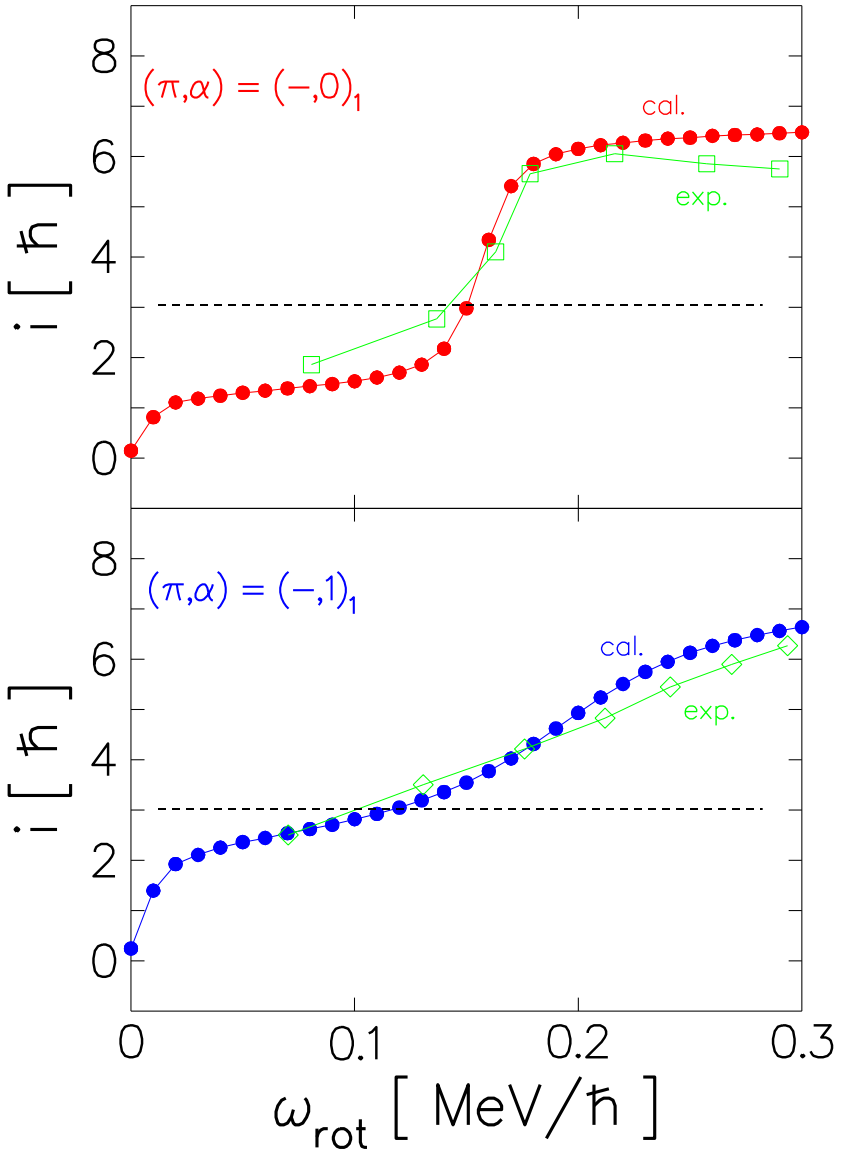
$i \approx 5 \sim 10\hbar$

$a_A^{+}a_B^{+}\left|\Phi_{\text{HFB}}\right\rangle$

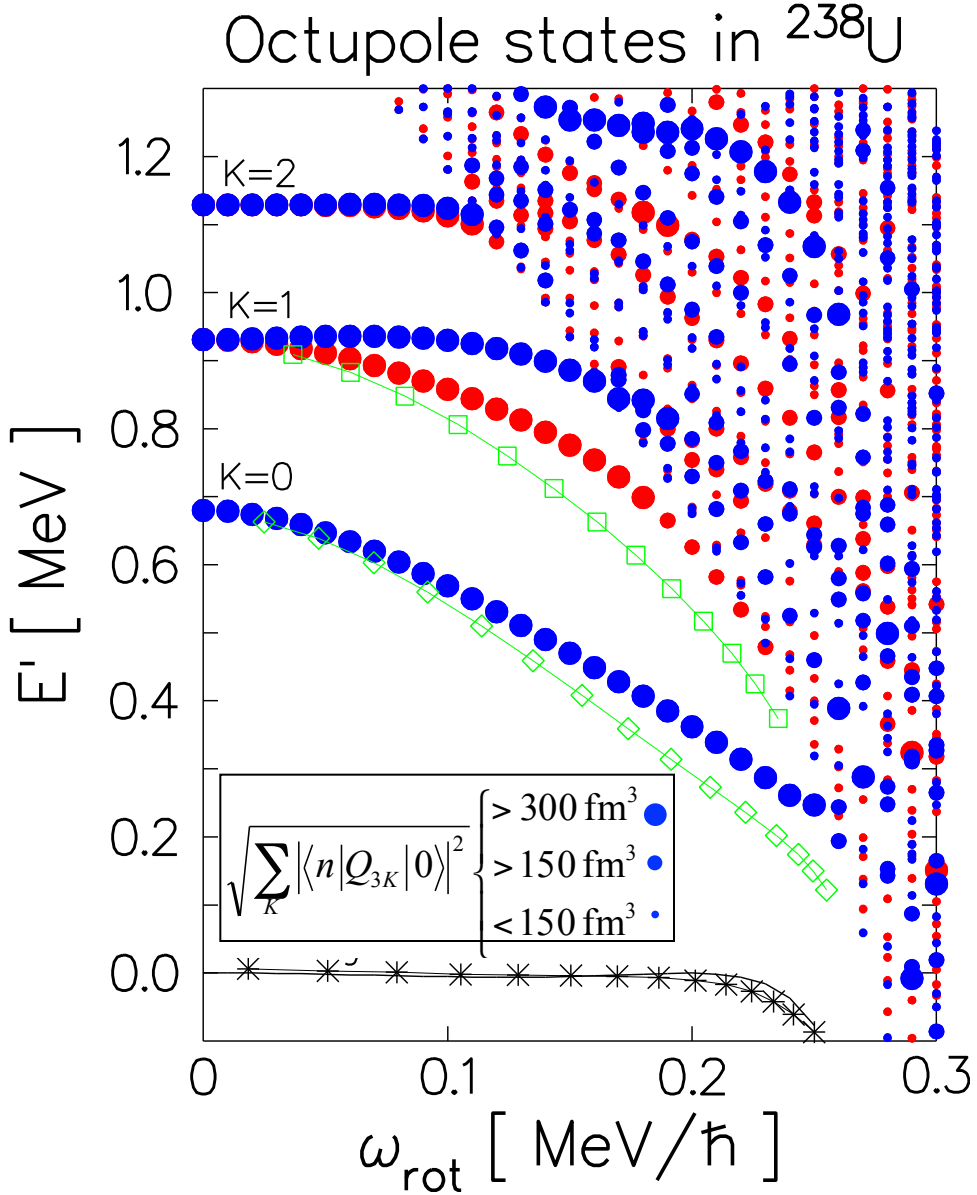
Octupole vibrations in ^{164}Yb

T.N., Act. Phys. Pol. B27 (1996) 59

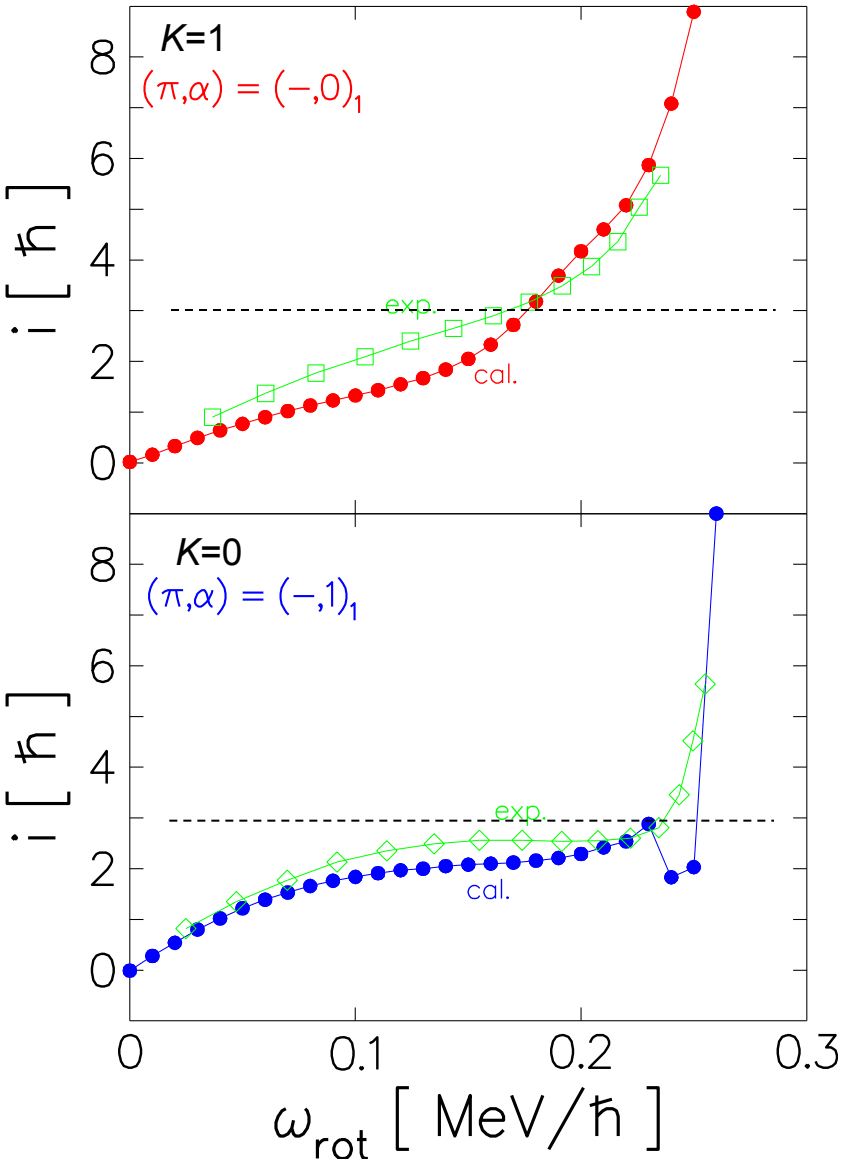




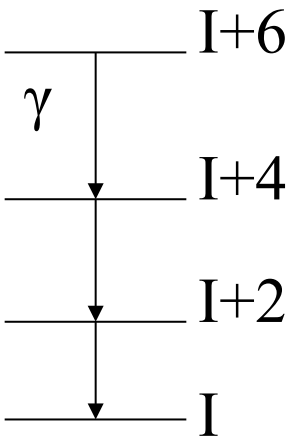
Octupole vibrations in ^{238}U



T.N., Act. Phys. Pol. B27 (1996) 59



In 1986, the first superdeformed band was discovered in ^{152}Dy.



1986 @Daresbury, UK

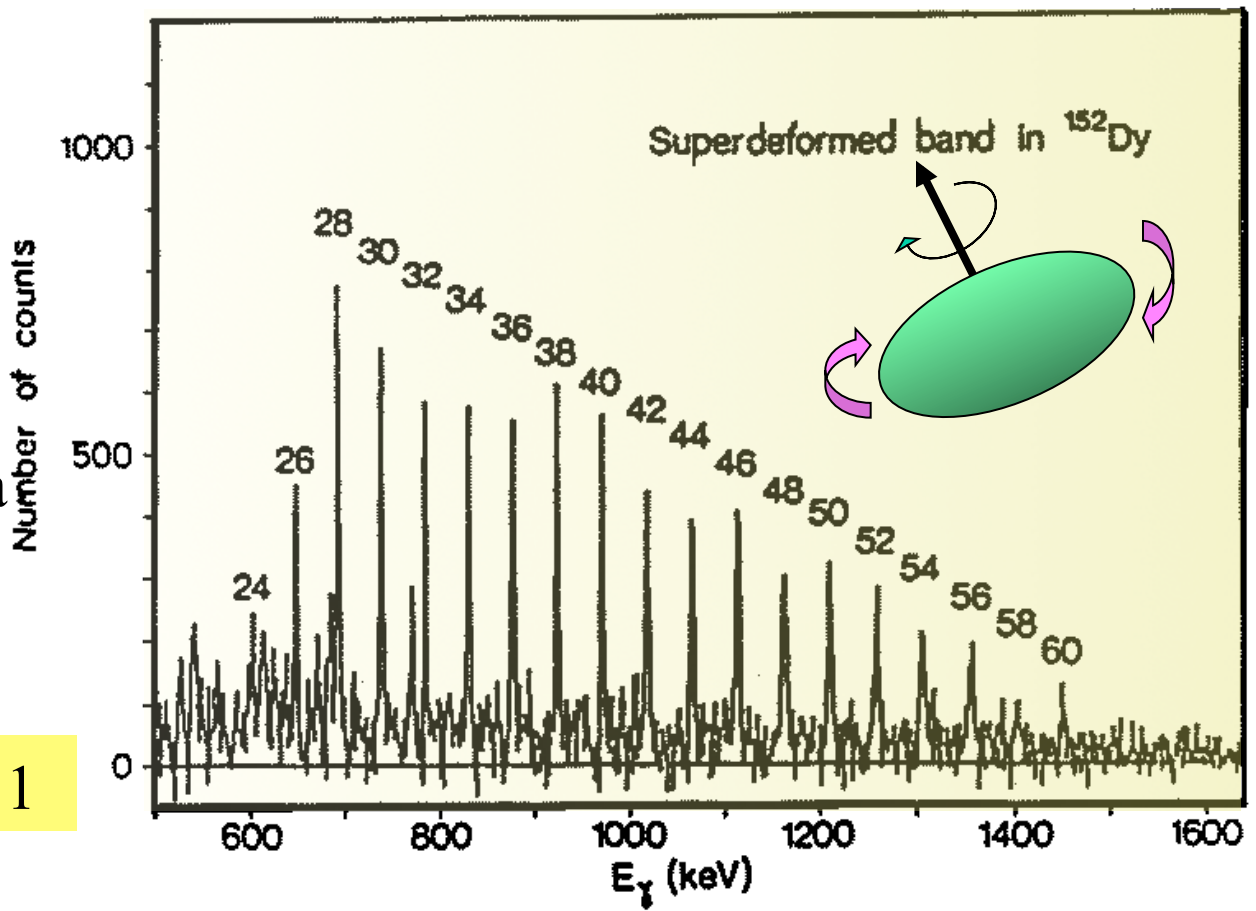
P.J. Twin et al, PRL **57** (1986) 811

J.D. Garret et al, Nature **323** (1986) 395.

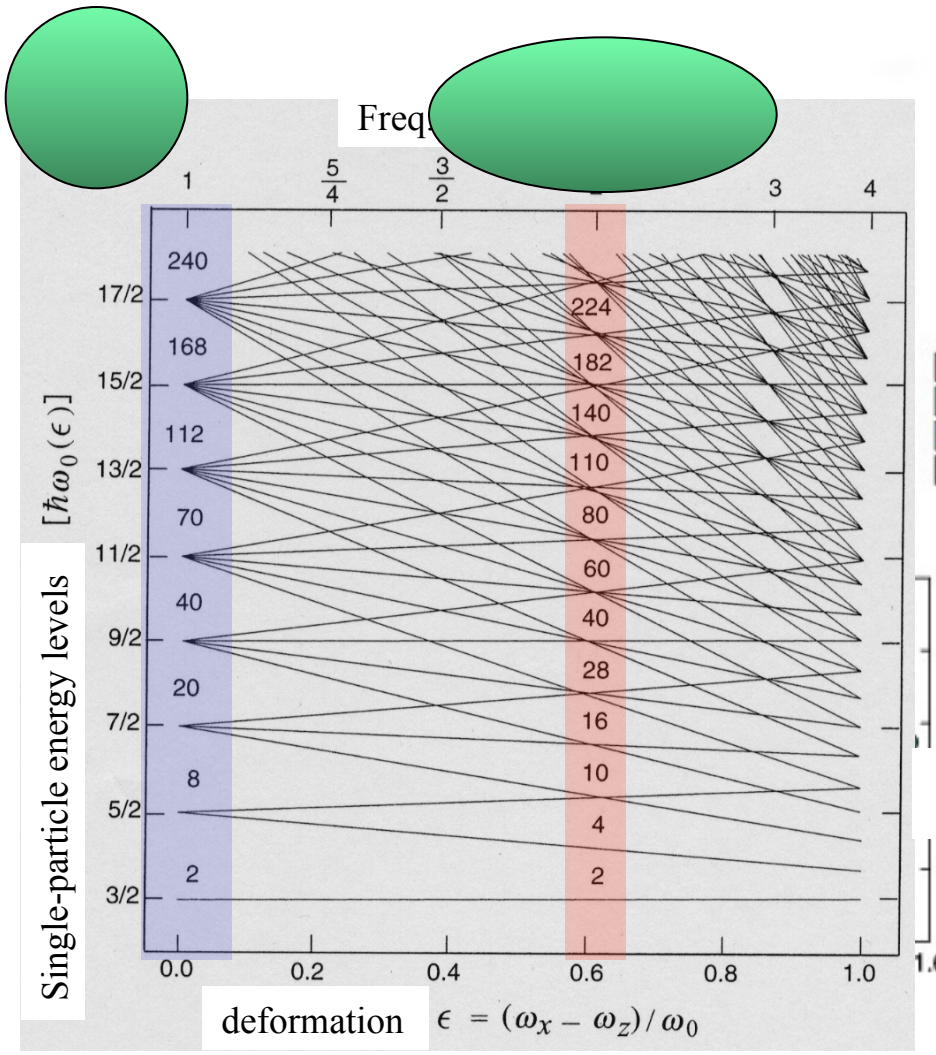
- Large moment of inertia
- Large intraband B(E2)

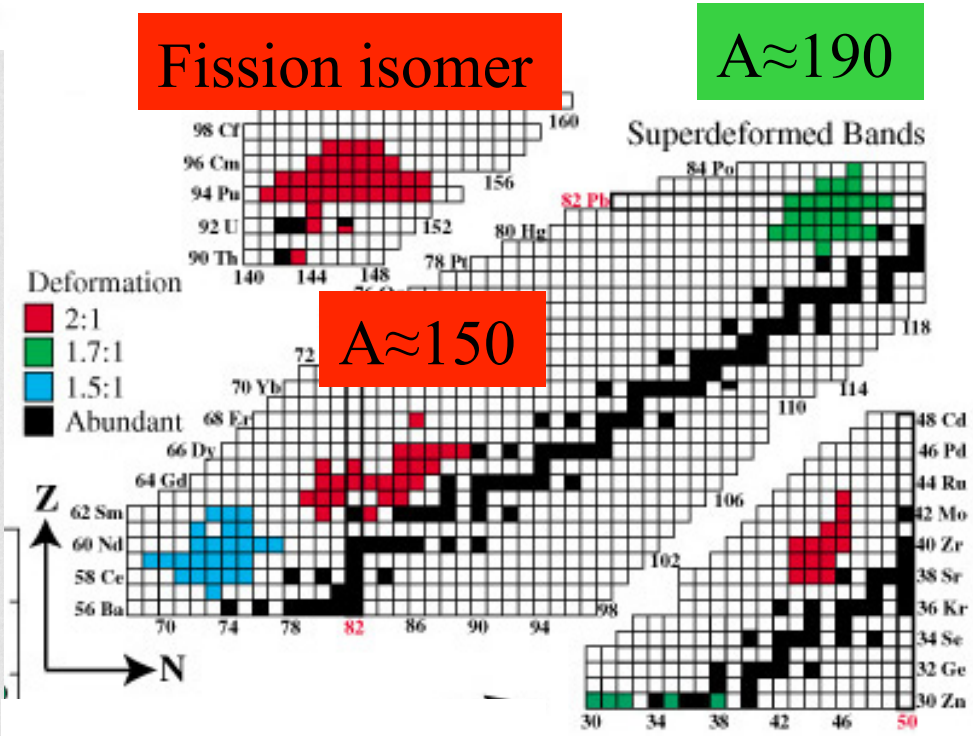
B(E2)≈2000 W.u.

Major : Minor axes ~ 2:1



超変形状態は“大変形閉殻配位”

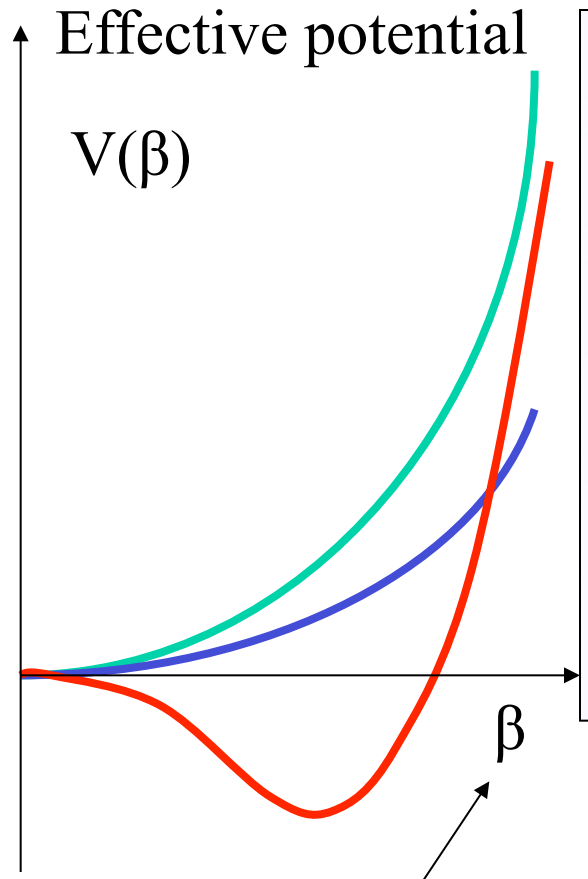




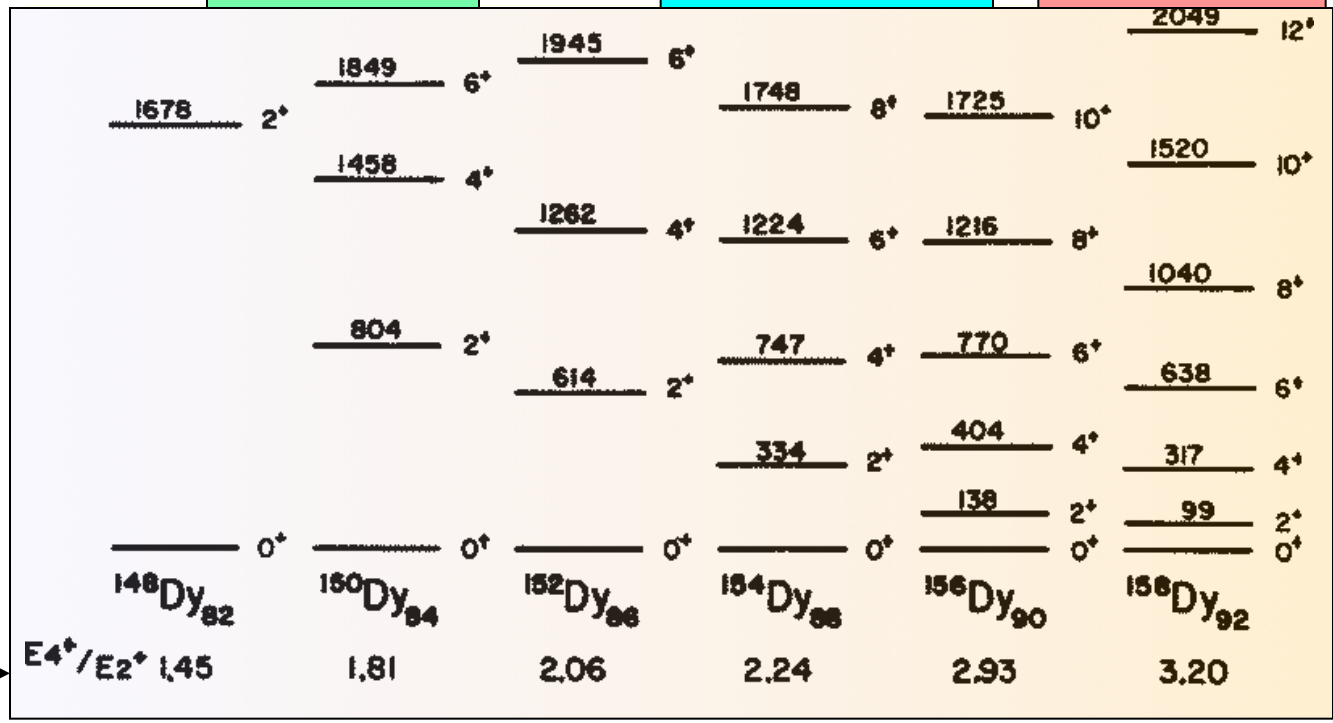
閉殻 → 開殻へ

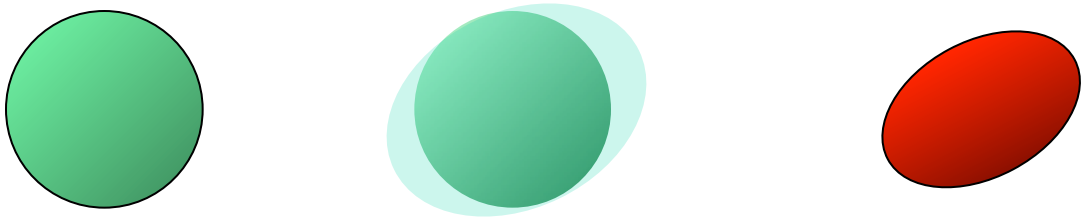
形状相転移(球形閉殻 → 開殻)

spherical | transitional | deformed



Quadrupole deformation
(order parameter)





Spontaneous Symmetry Breaking (SSB)

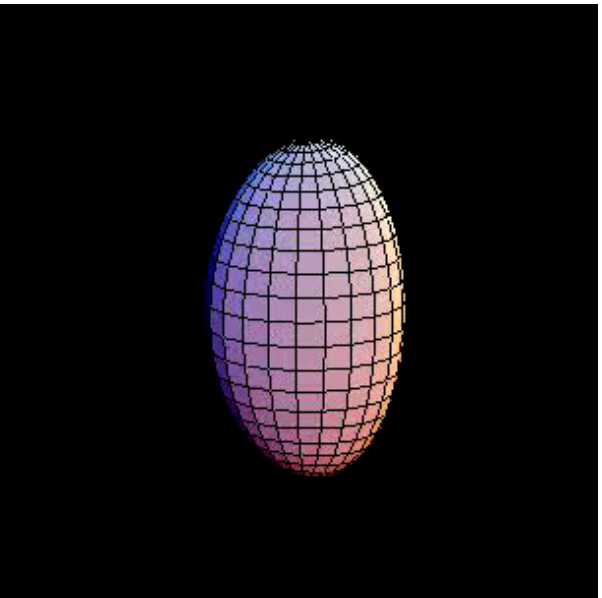
Banana-(Y_{31}-type) shape phase transition in open-shell SD states

T.N., S.M., K.M., Prog. Theor. Phys. **87** (1992) 607.

Increase of valence nucleons

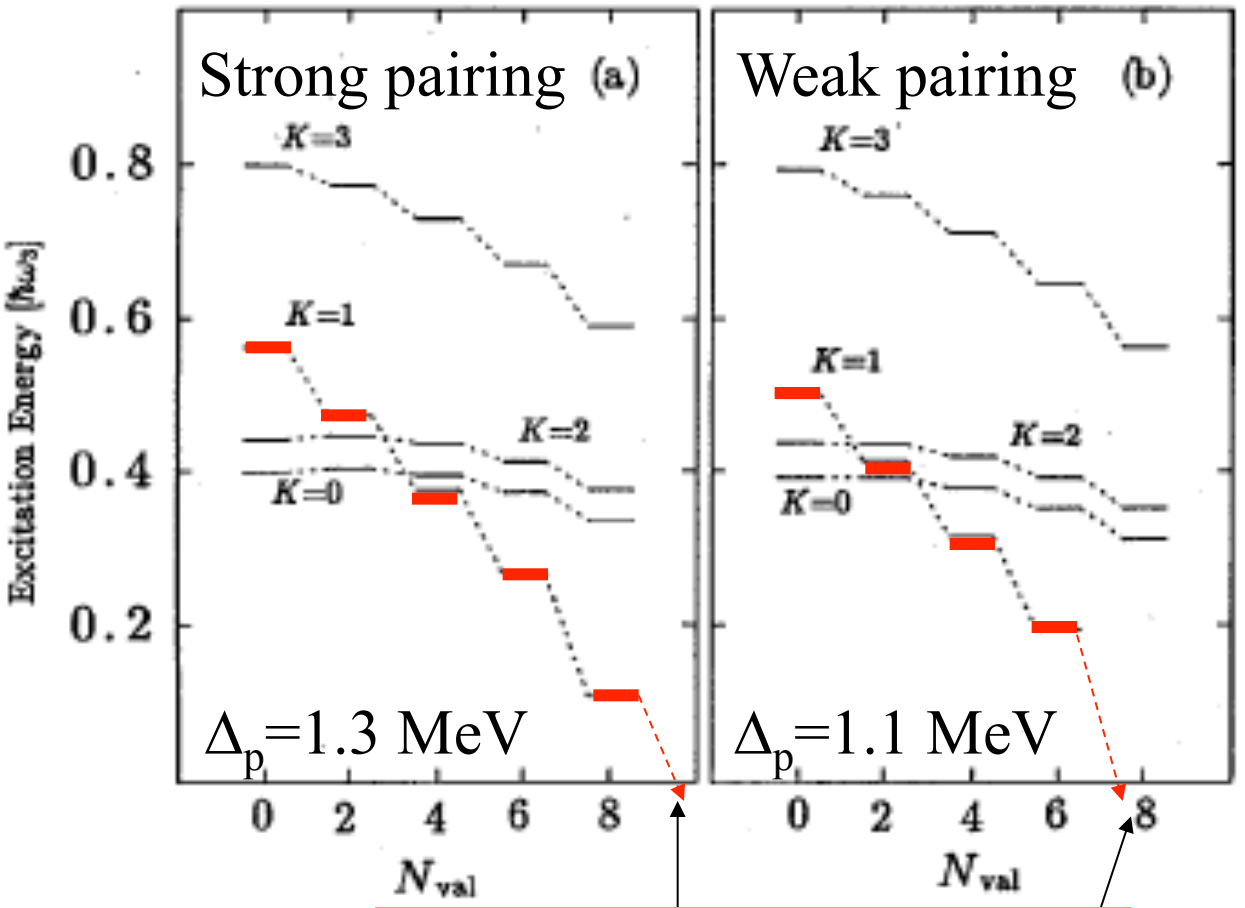
⇓

Banana-super-deformation



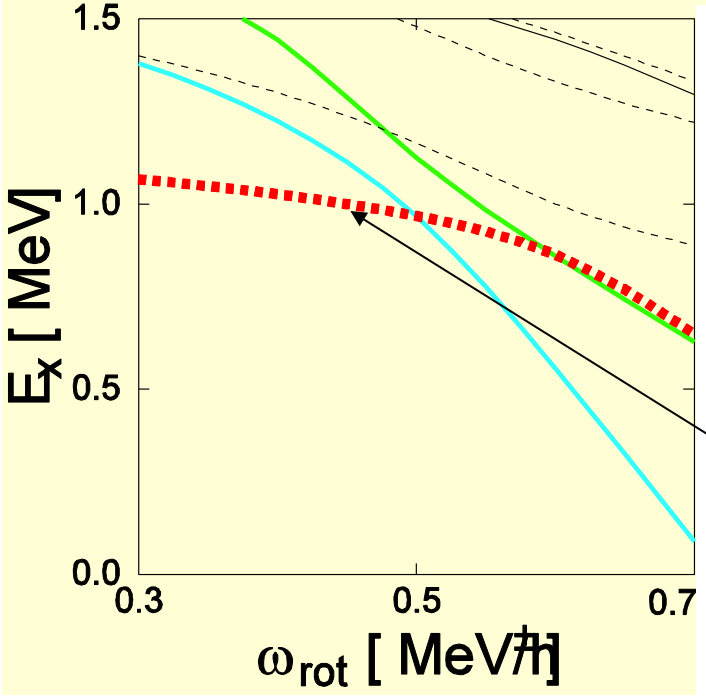
HO+QRPA

$Z=80+2$, $N=80+N_{val}$



SSB towards banana shape

RPA routhians for SD ^{152}Dy

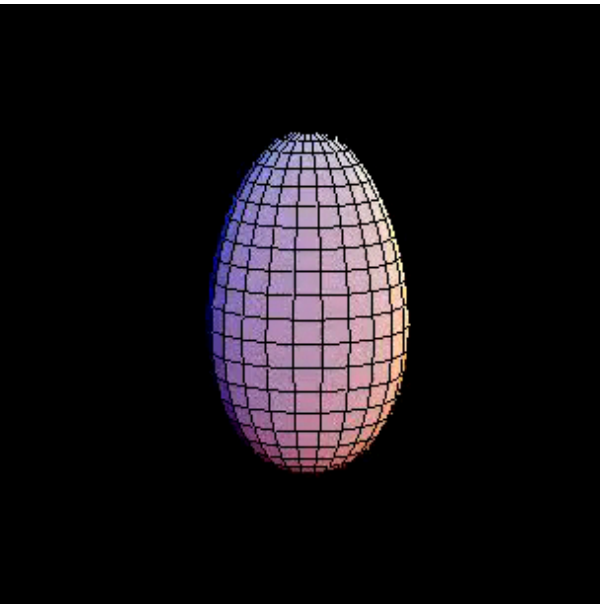


Excitation energy in the rotating frame relative to the ground-state SD band.

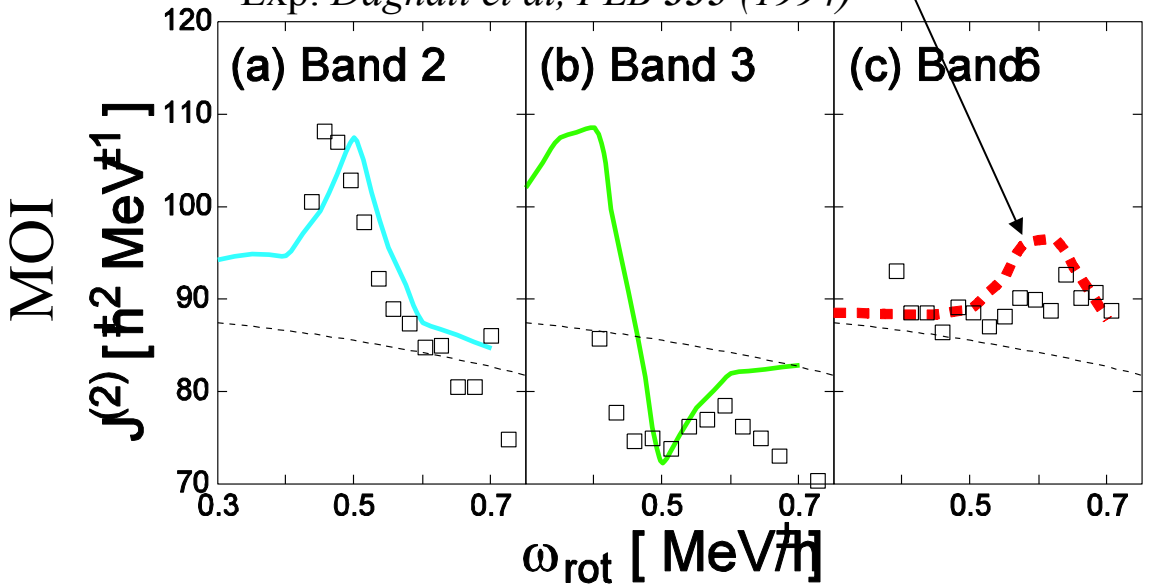
RPA in the rotating shell model predicted an excited SD band in ^{152}Dy is the K=0 octupole vibrational band.

*T.N., Mizutori, Matsuyanagi, Nazarewicz, PL**B343** (1995) 19*

Octupole band with K=0 (Y_{30})



Exp: *Dagnall et al, PLB **335** (1994)*

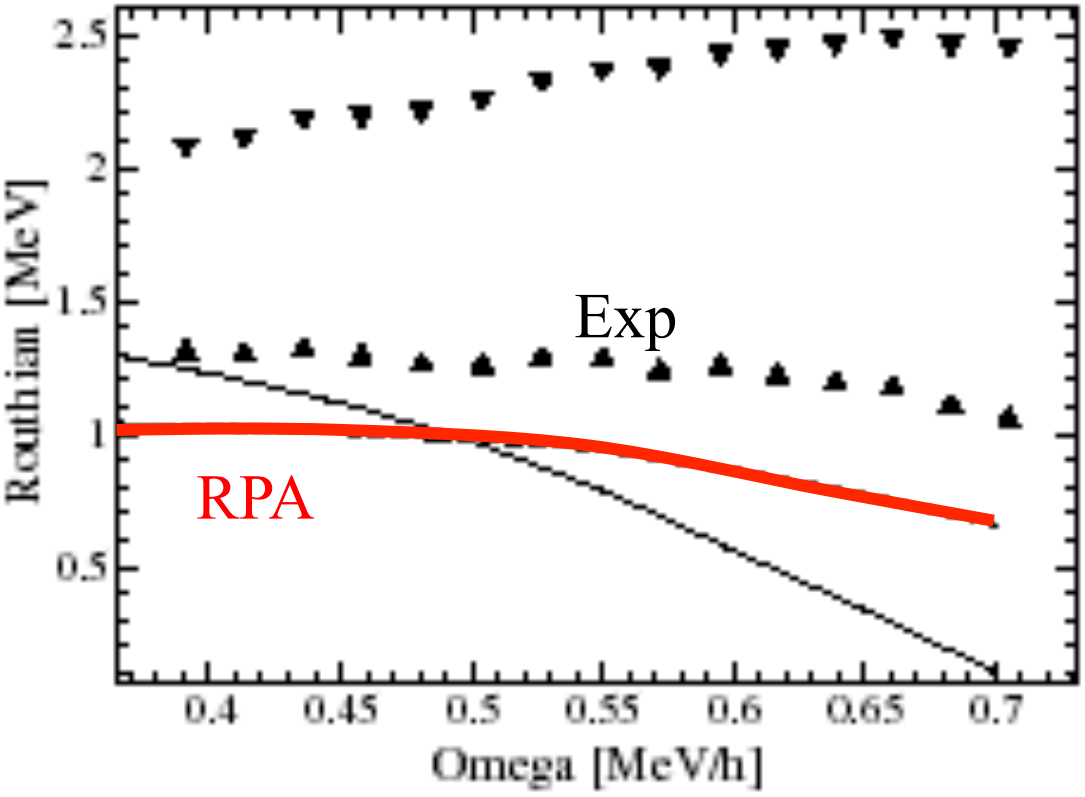


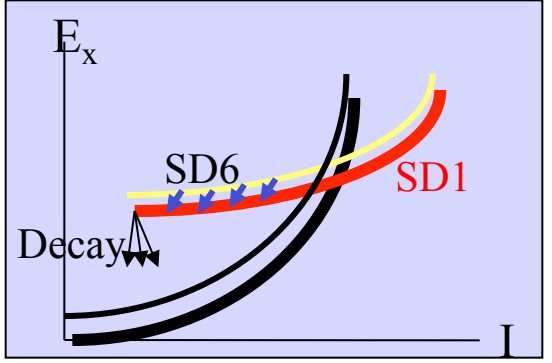
Octupole Vibration in Superdeformed $^{152}_{66}Dy_{86}$

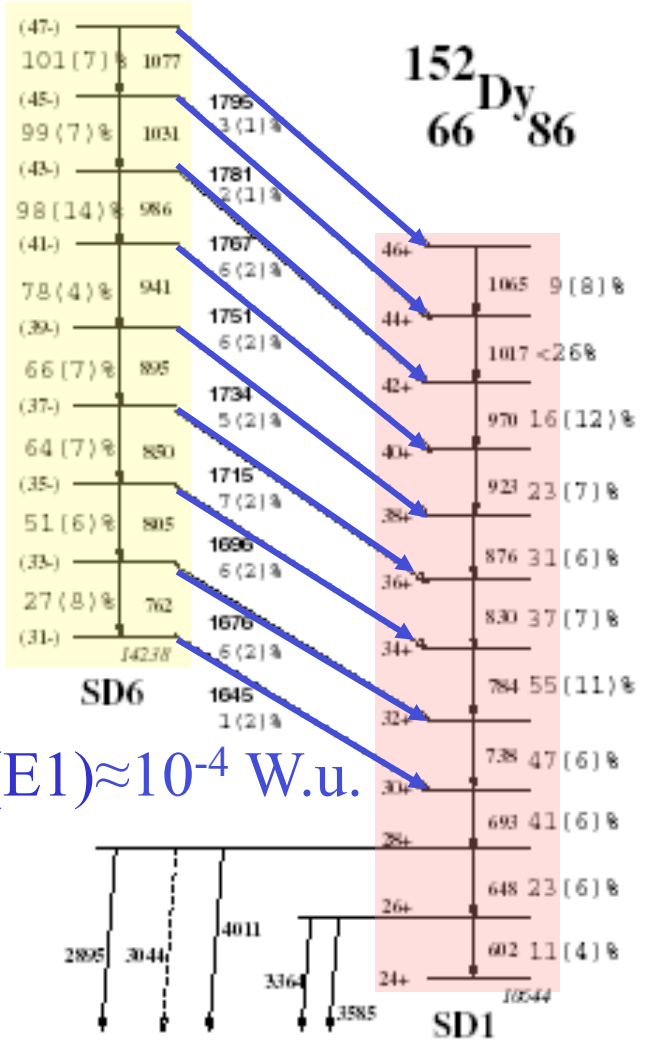
T. Lauritsen,[1] R. V. F. Janssens,[1] M. P. Carpenter,[1] P. Fallon,[2] B. Herskind,[3] D. G. Jenkins,[1] T. L. Khoo,[1] F. G. Kondev,[1] A. Lopez-Martens,[4] A. O. Macchiavelli,[2] D. Ward,[2] K. Abu Saleem,[1] I. Ahmad,[1] R. M. Clark,[2] M. Cromaz,[2] T. Døssing,[3] A. M. Heinz,[1] A. Korichi,[4] G. Lane,[2] C. J. Lister,[1] and D. Seweryniak[1]

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[3]*Niels Bohr Institute, DK-2100, Copenhagen, Denmark*
[4]*C.S.N.S.M, IN2P3-CNRS, bat 104-108, F-91405 Orsay Campus, France*
(Received 7 June 2002; published 31 December 2002)

Nine transitions of dipole character have been identified linking an excited superdeformed (SD) band in ^{152}Dy to the yrast SD band. As a result, the excitation energy of the lowest level in the excited SD band has been measured to be 14 238 keV. This corresponds to a 1.3 MeV excitation above the SD ground state. The levels in this band have tentatively been determined to be of negative parity and odd spin. The measured properties are consistent with an interpretation in terms of a rotational band built on a collective octupole vibration.

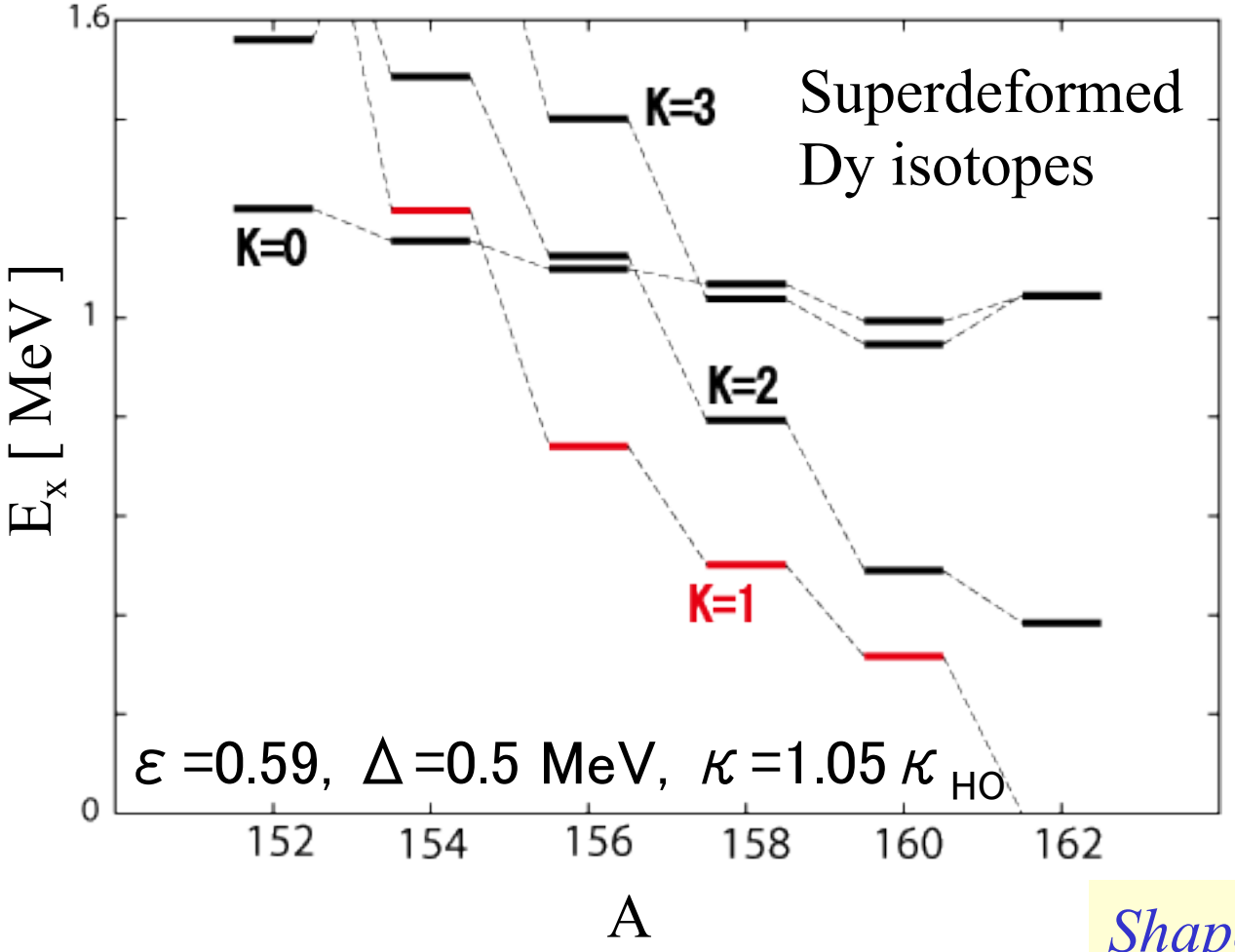






More realistic calculation

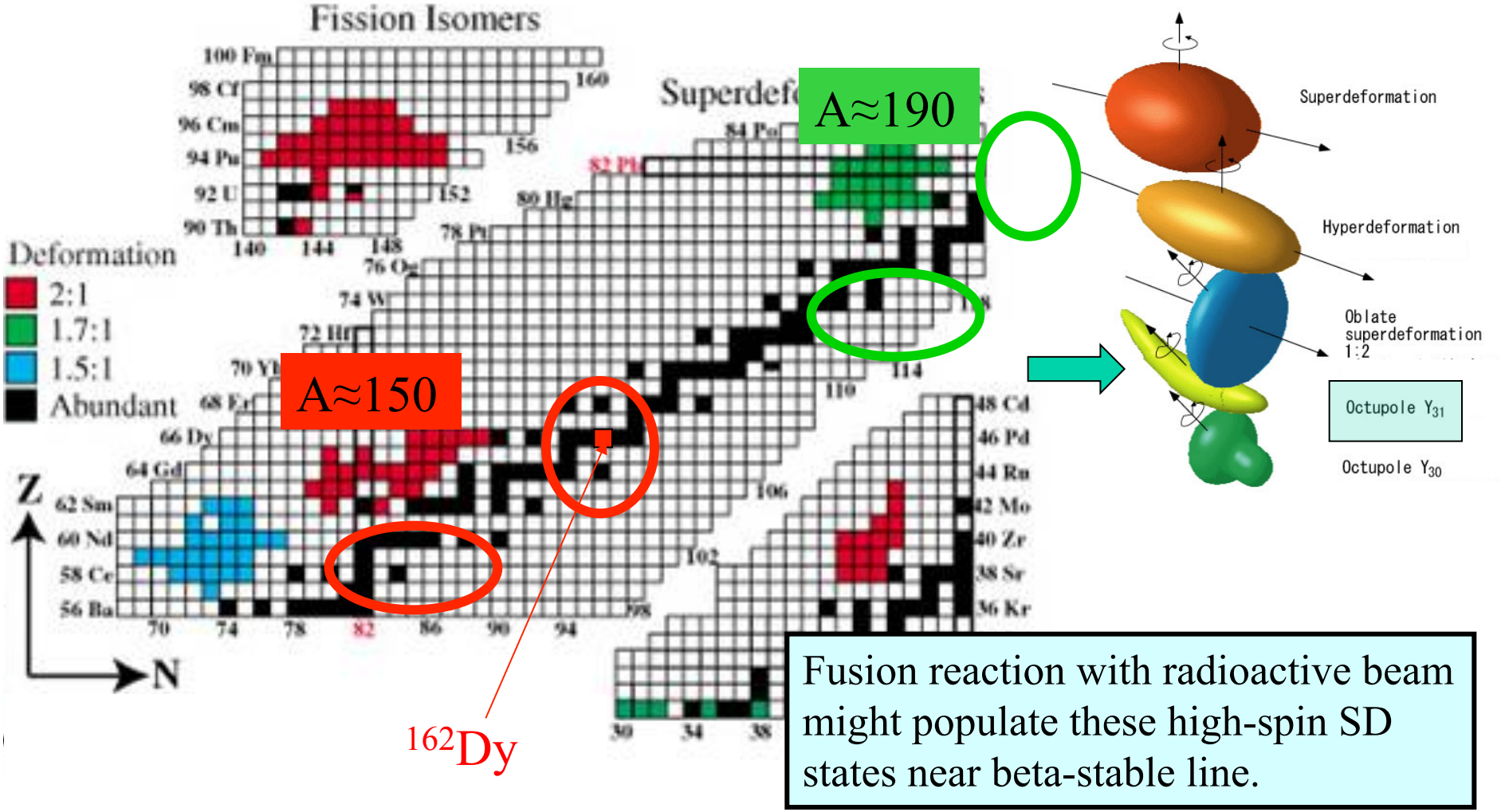
Nilsson+BCS+QRPA



Shape transition to banana-super-deformation

Where are they?

Increasing (decreasing) valence neutrons (protons) by 8-10 leads to regions near beta-stable line



Fusion reaction with radioactive beam might populate these high-spin SD states near beta-stable line.

まとめ

- 原子核の性質
  - 強い量子性、フェルミ多体系
  - 異なる時間スケールと異なる描像
  - 有限の相関時間における対称性の自発的破れ
- 高速回転・超変形と形状相転移
  - 回転運動の出現
  - 強いコリオリ相関による様々な現象
  - 超変形閉殻・開殻配位における形状相転移