

# 反応実験屋のための核構造学

## 1. 量子多体系の集団現象

多様で複雑な核構造と核反応現象の統一的理解をめざして

## 2. 超低温での集団励起スペクトル

有限量子系における対称性の自発的破れと回復

## 3. 安定核および不安定核での対相関

真空とその励起モード, 密度汎関数理論

## 4. 高速回転する原子核と超変形状態

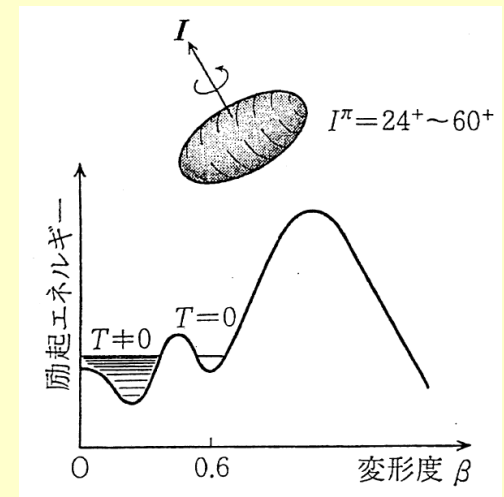
回転系シェルモデル, 超変形シェル構造

## 5. 大振幅集団運動の微視的理論

時間変化する平均場の理論, Bohr-Mottelsonモデルの微視的導出

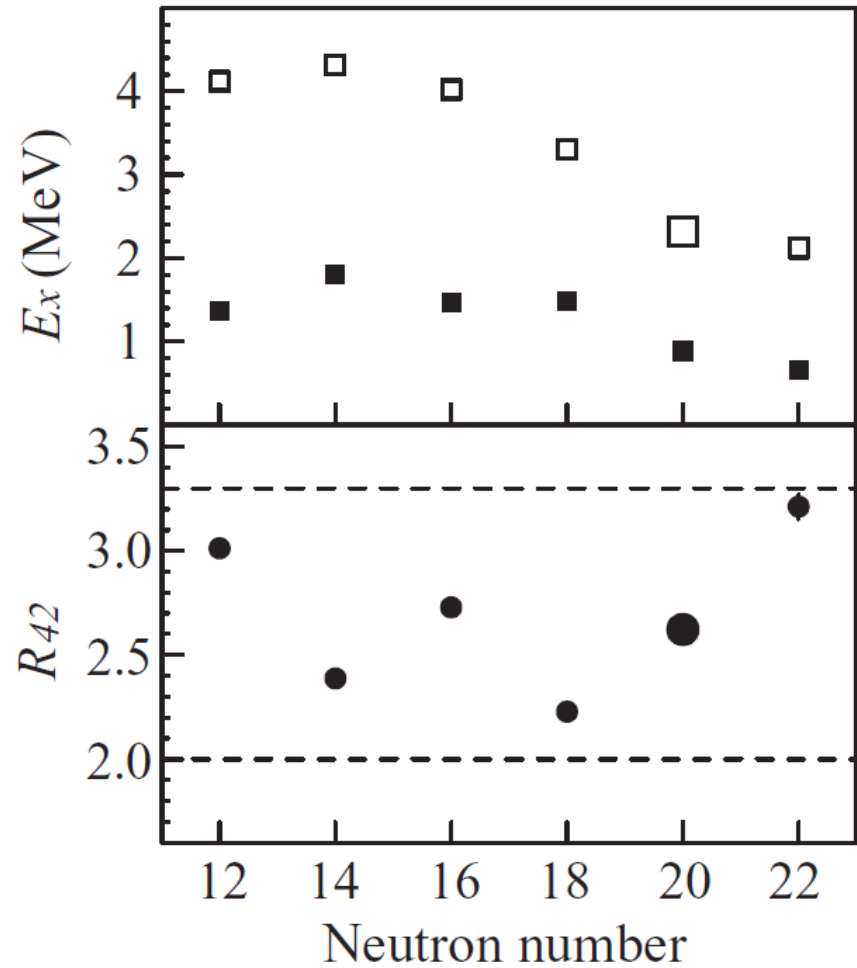
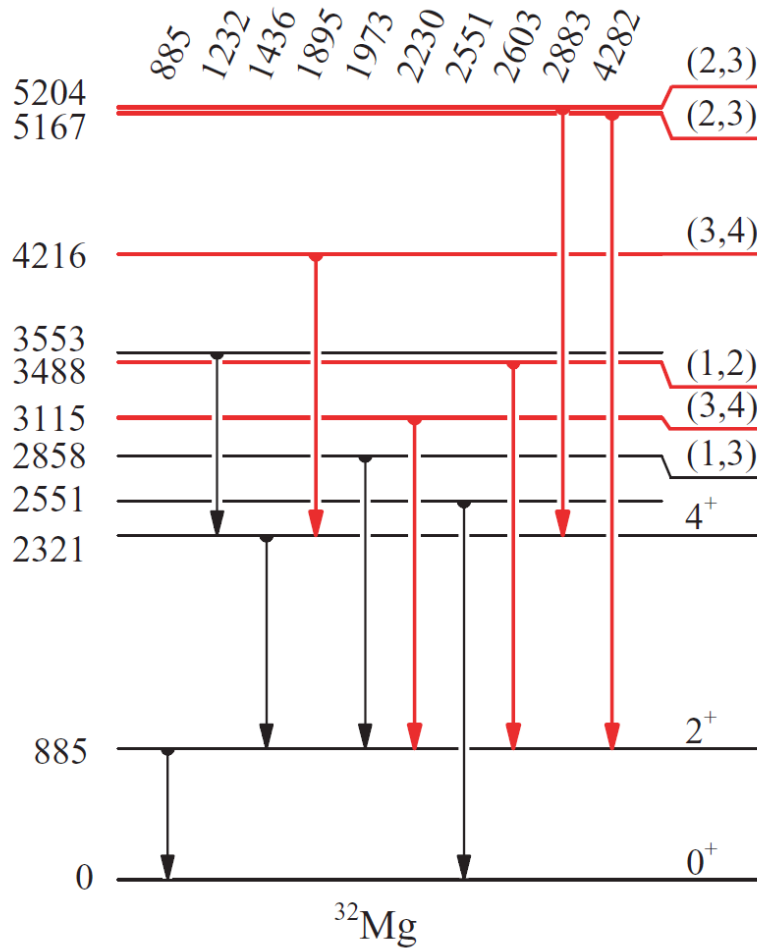
## 6. 不安定核 (エキゾチック核) 研究の将来

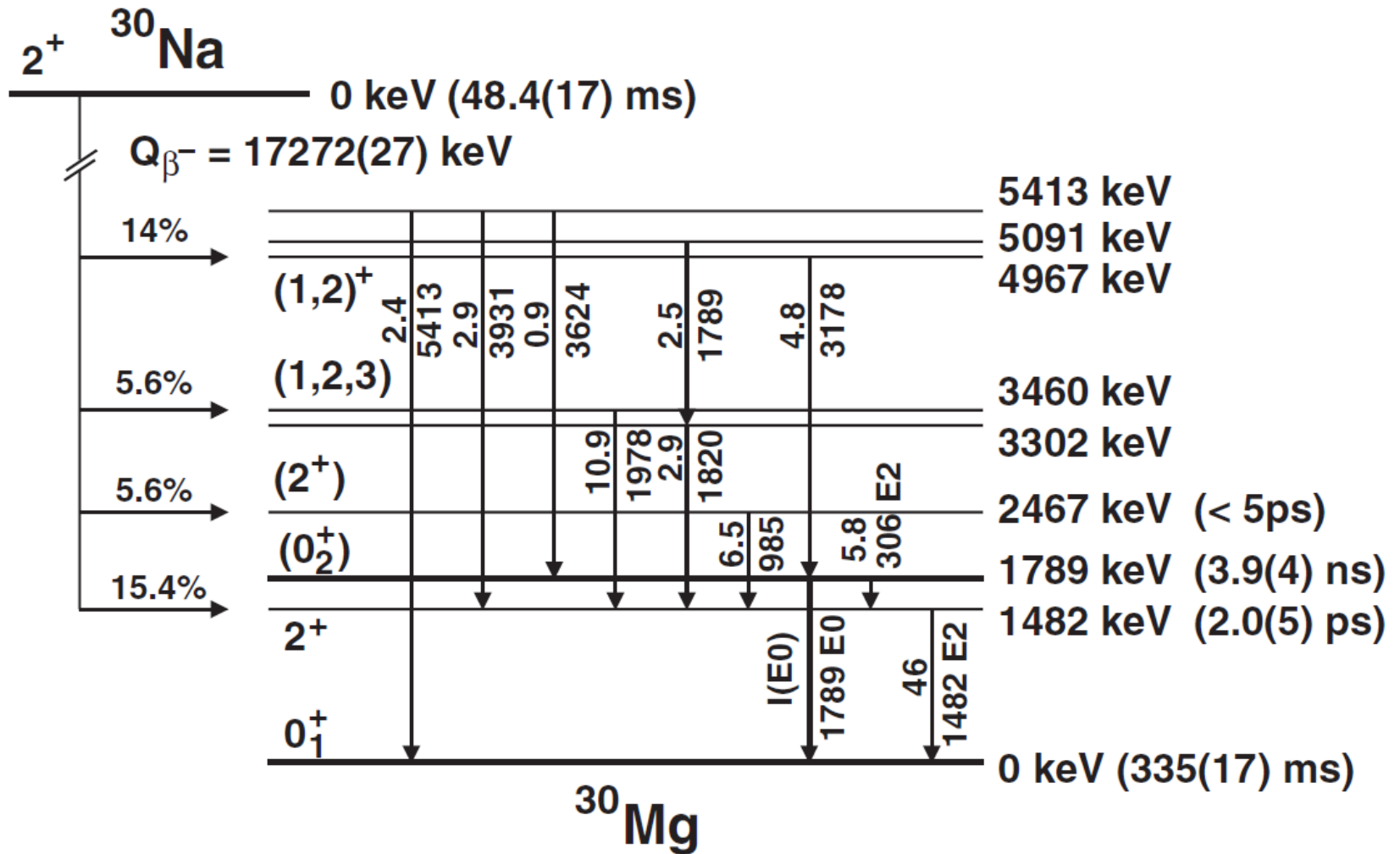
束縛状態と連続状態の統一的記述にむけて



# 32Mgとその周辺の低励起スペクトル

Takeuchi et al. Phys. Rev. C 79 (2009) 054319





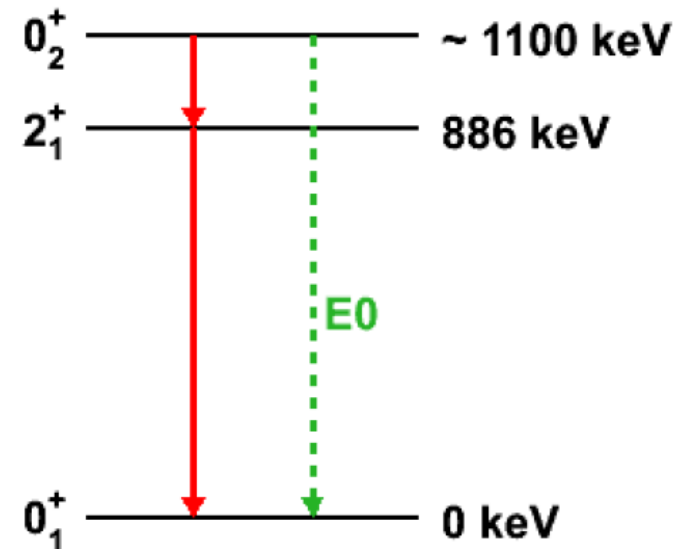
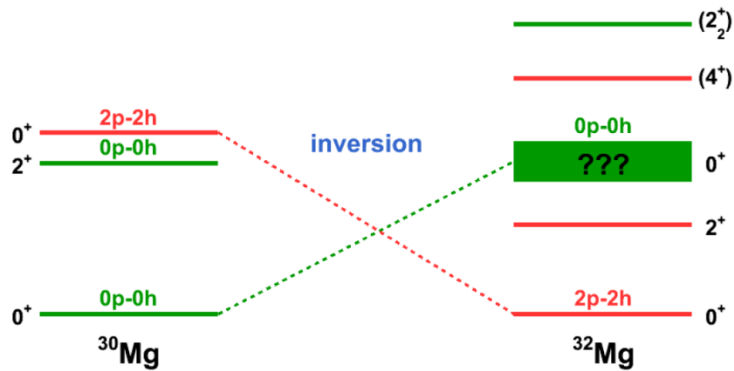
# Shape Coexistence in the Island of Inversion: The $0_2^+$ state in $^{32}\text{Mg}$

Kathrin Wimmer

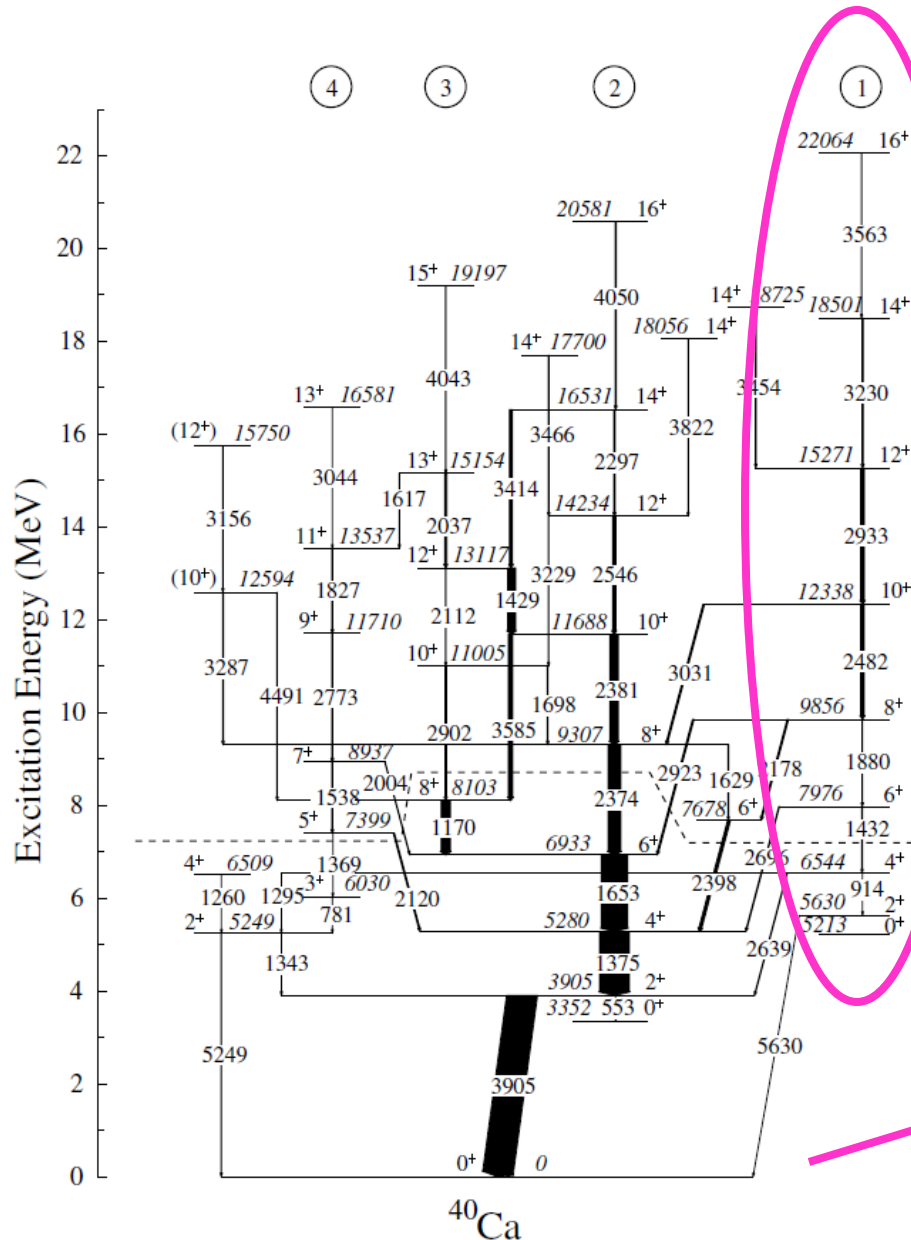
Physik Department E12, Technische Universität München

December 17, 2009

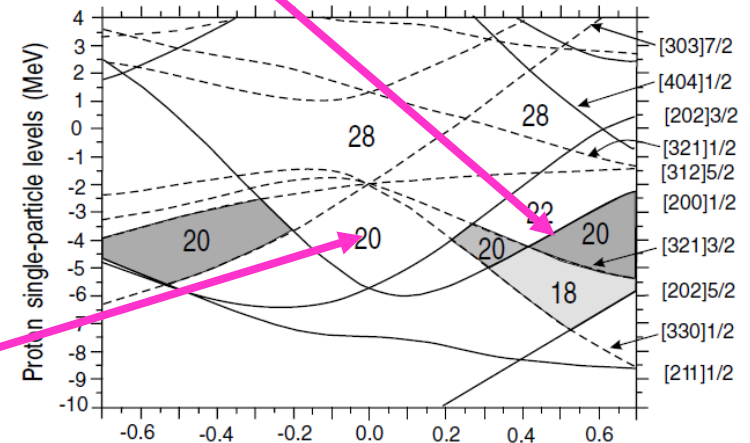
## The $t(^{30}\text{Mg},p)^{32}\text{Mg}$ reaction

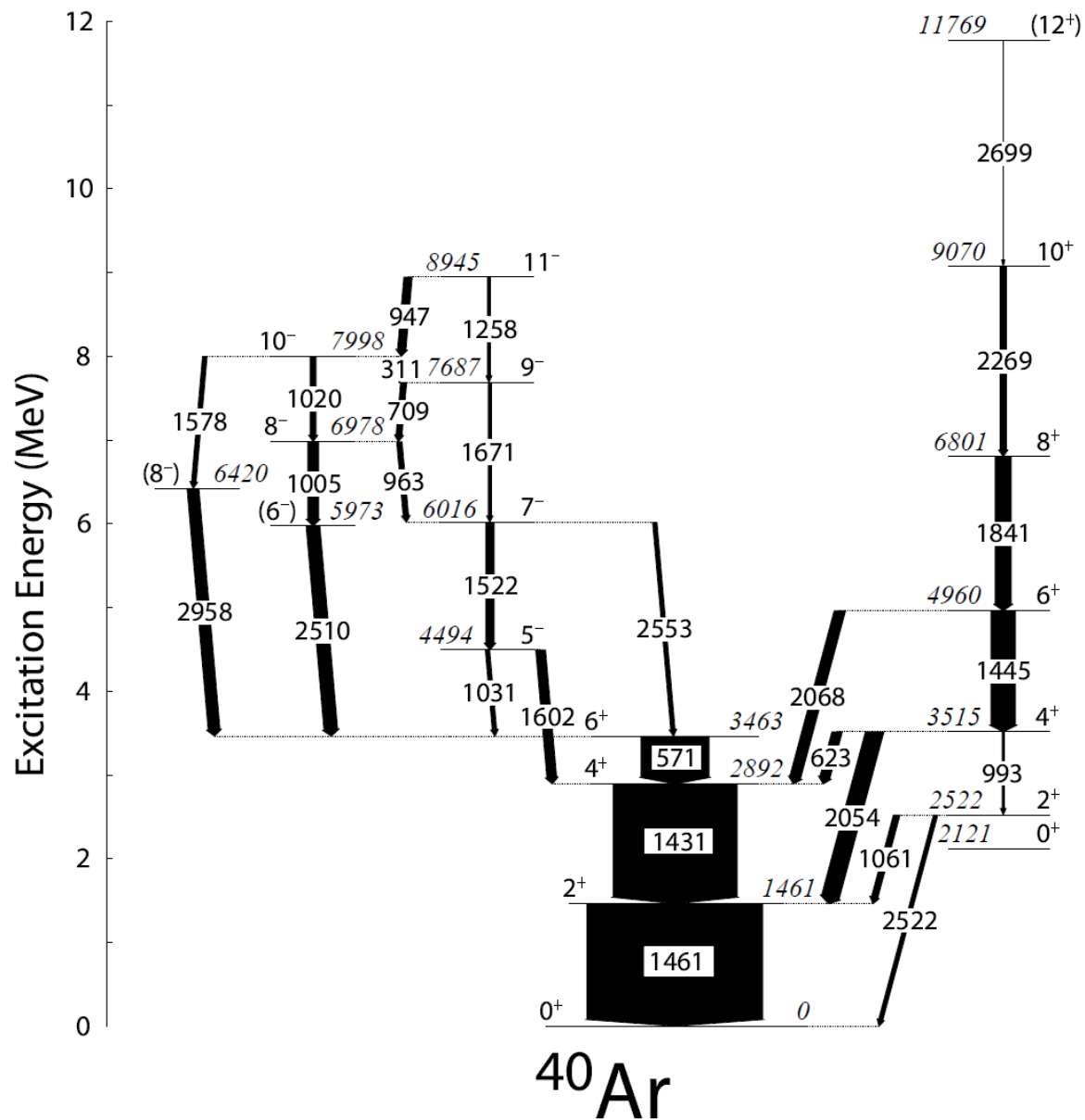


# Superdeformation in the Doubly Magic Nucleus $^{40}\text{Ca}_{20}$

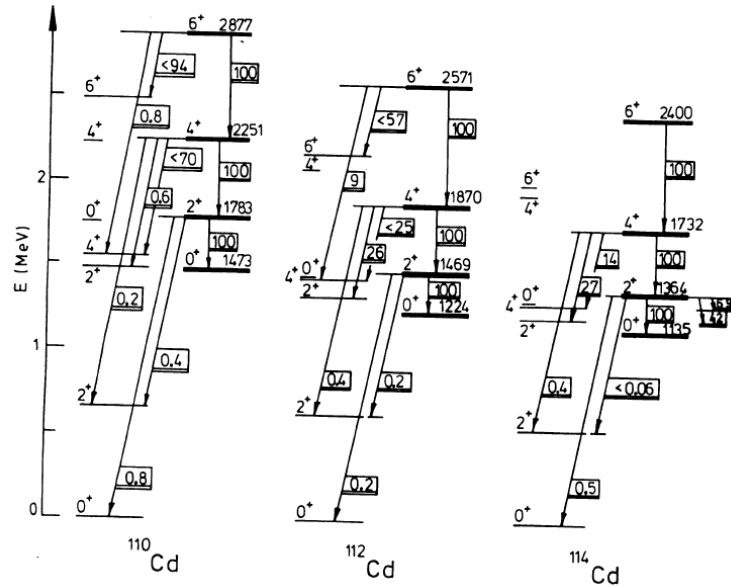
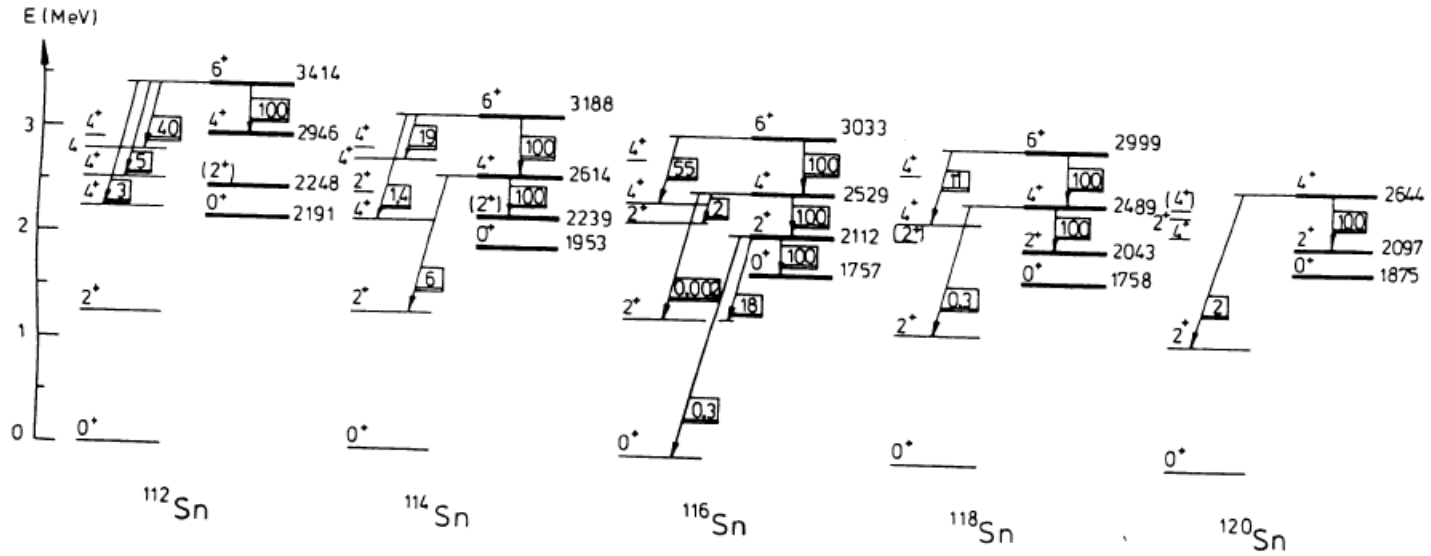


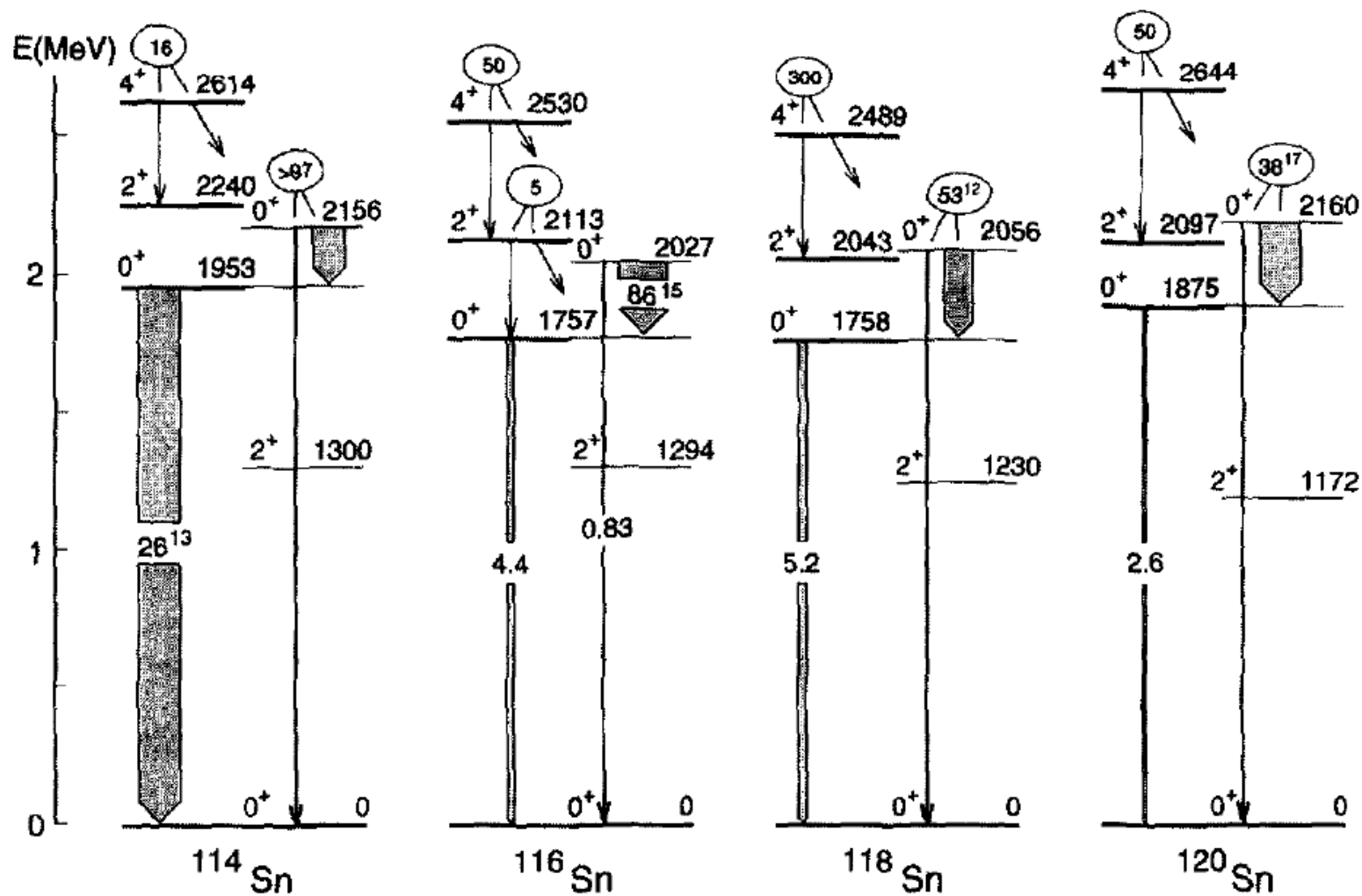
E. Ideguchi, et al.,  
 Phys. Rev. Lett. 87 (2001) 222501





# 球形の閉殻は容易に2p2h励起して変形する

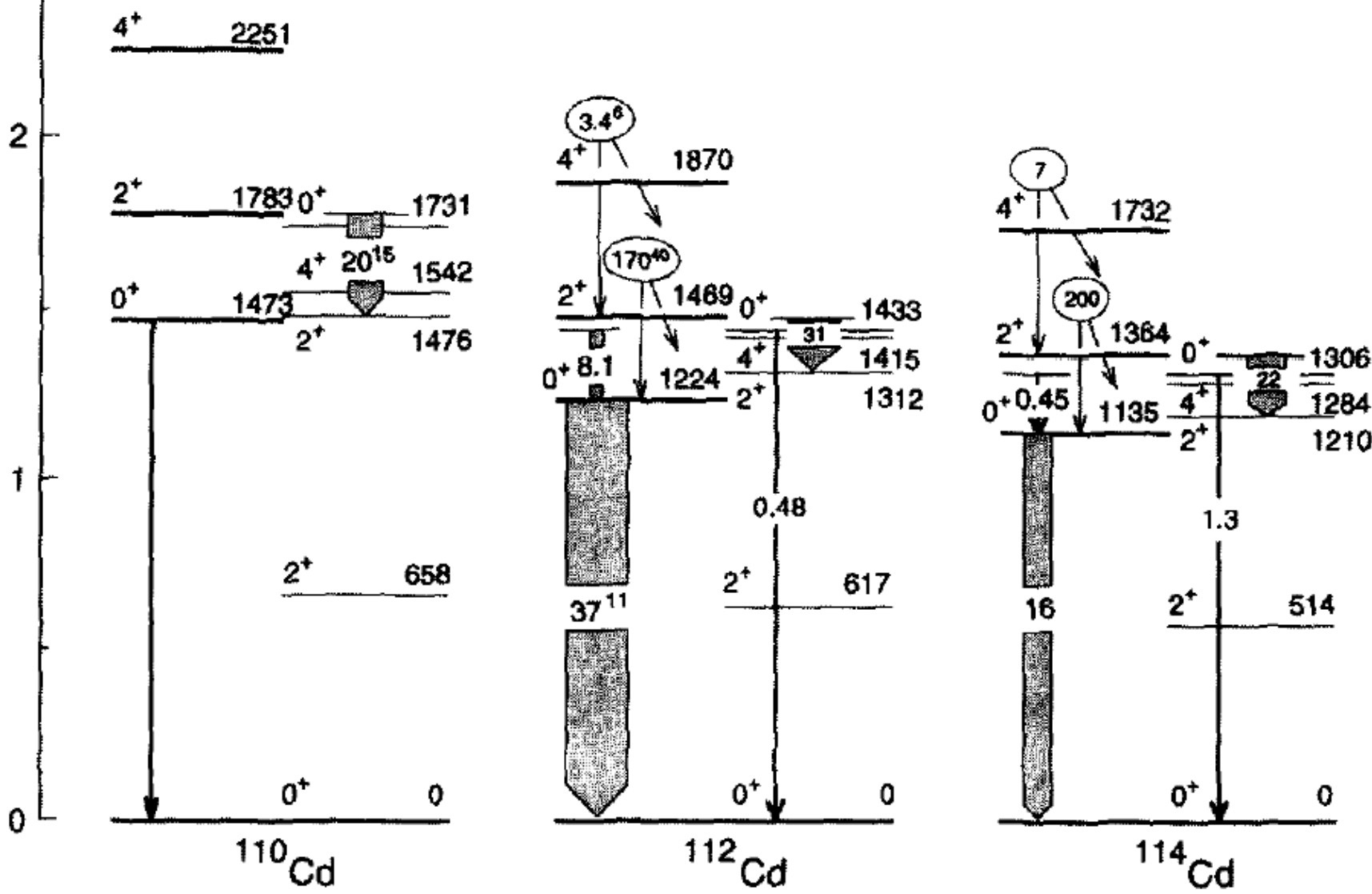


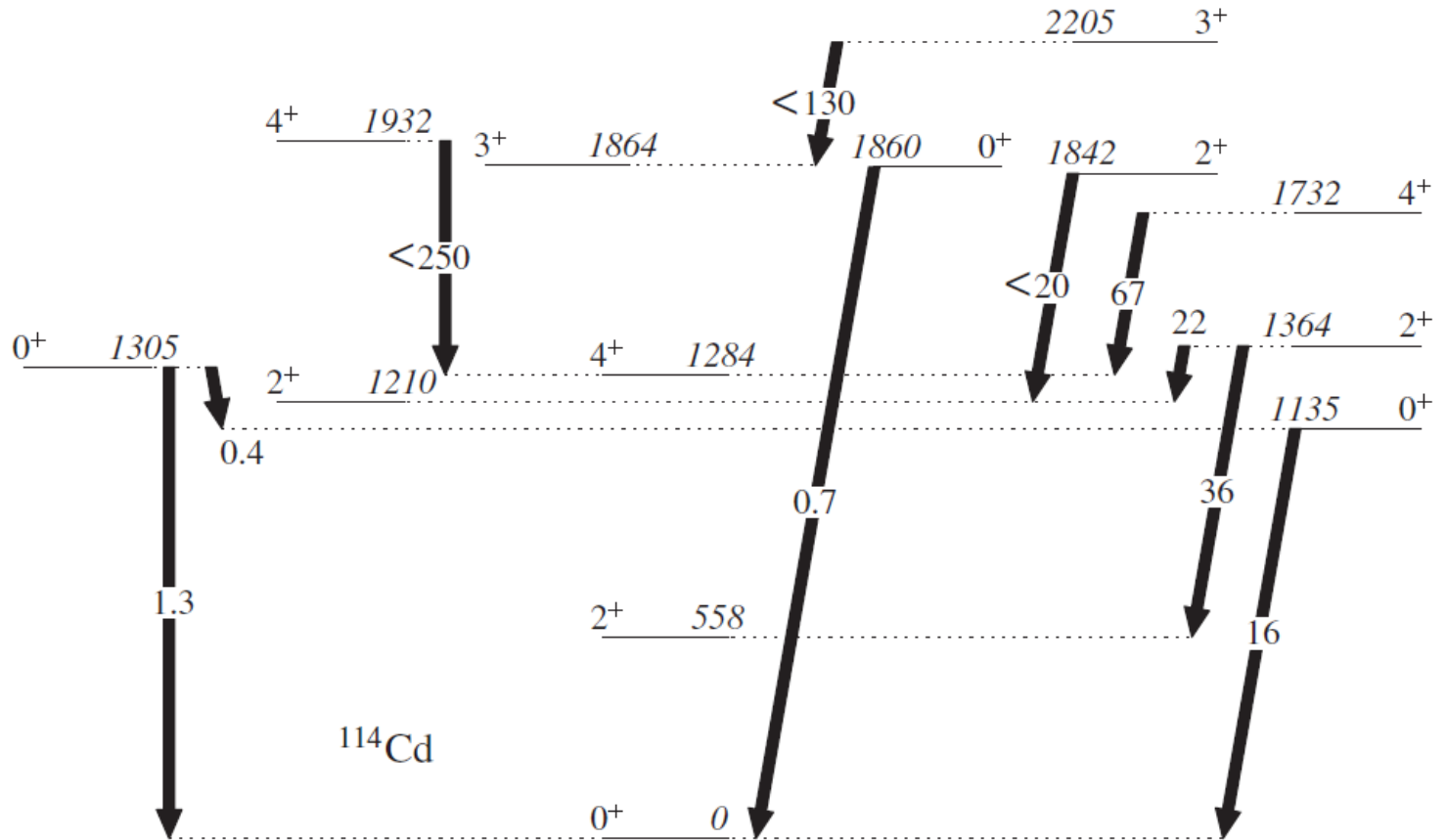




E(MeV)

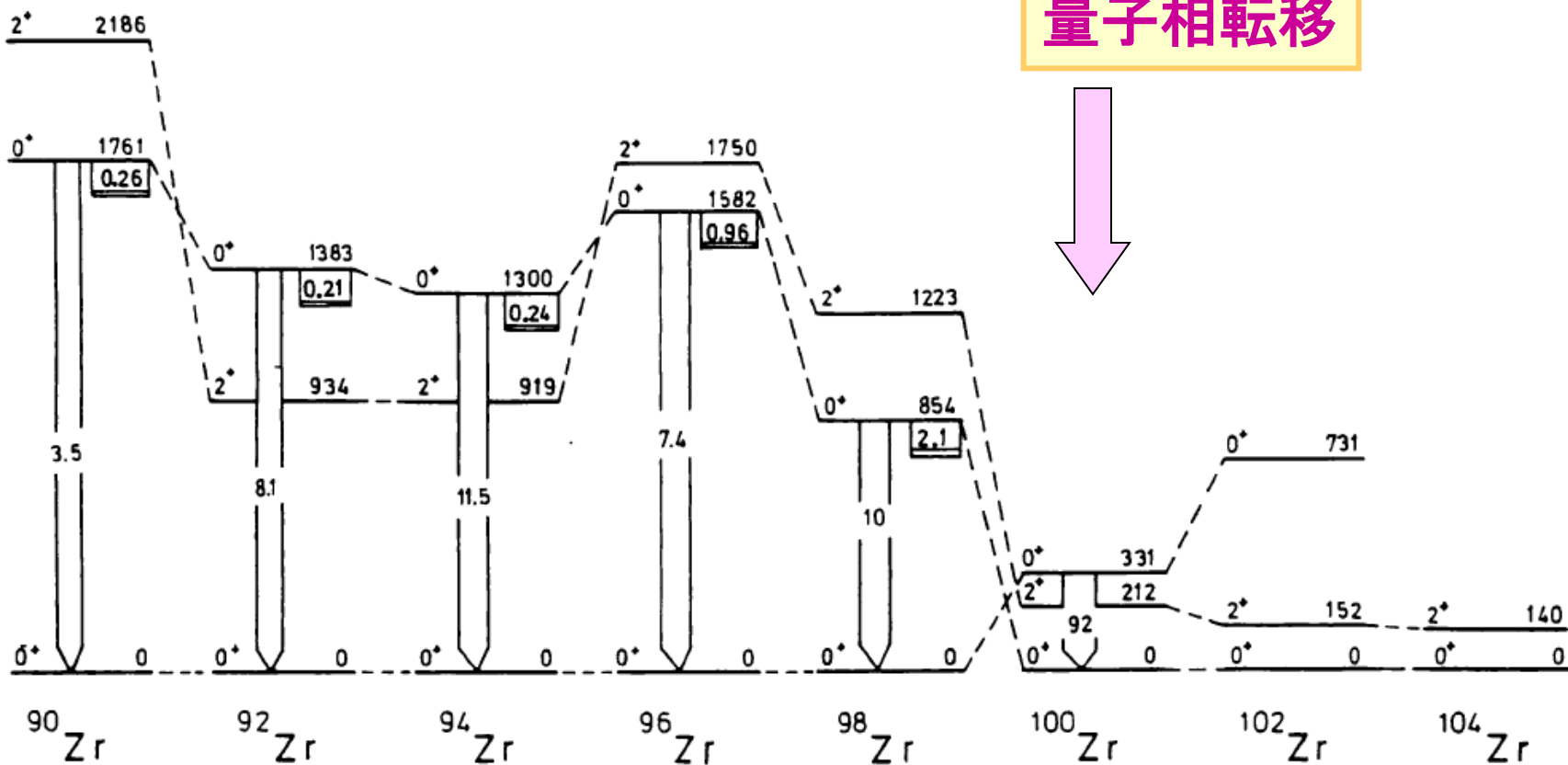
$\rho^2 \times 10^3$





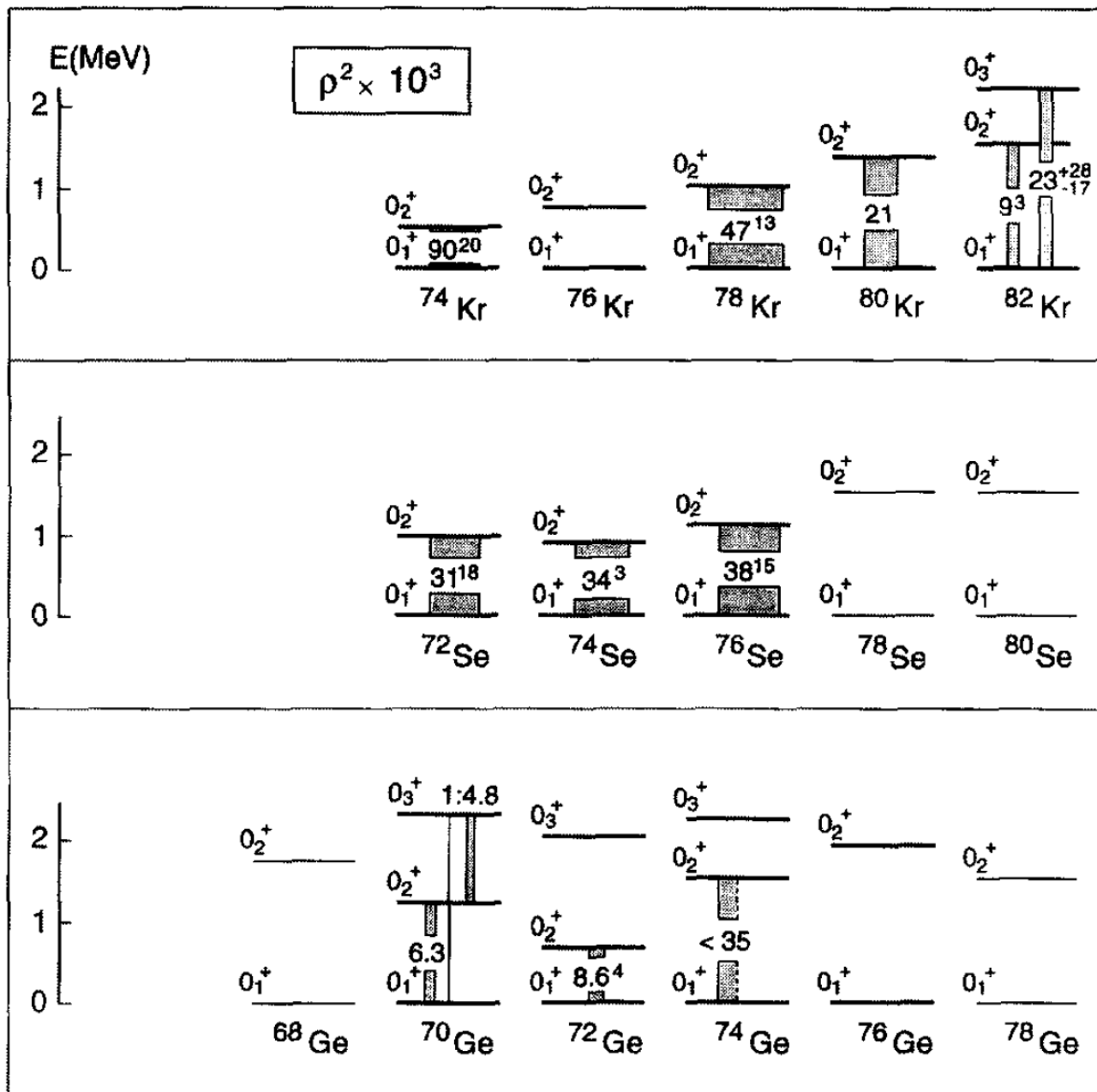
**Figure 6.** Values of  $10^3 \rho^2(E0)$  for  $^{114}\text{Cd}$ . Vertical arrows represent transitions between ‘normal’ states (the ground-state band and levels to the left), whereas diagonal arrows correspond to transitions between normal and intruder states (levels to the right of the ground-state band). Large  $\rho^2(E0)$  values arise due to mixing of configurations with different deformations [22].

# Zr isotopes の低励起スペクトル



N=50

N=60

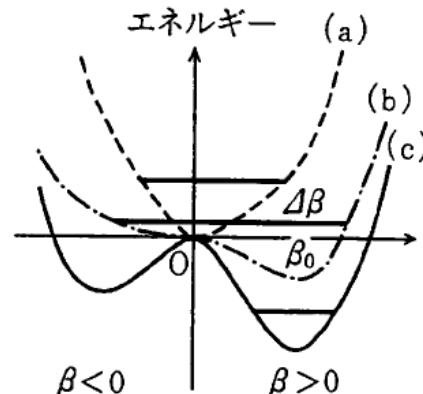


# Quantum Phase Transition

## ゆるやかな量子相転移(真空の構造変化)

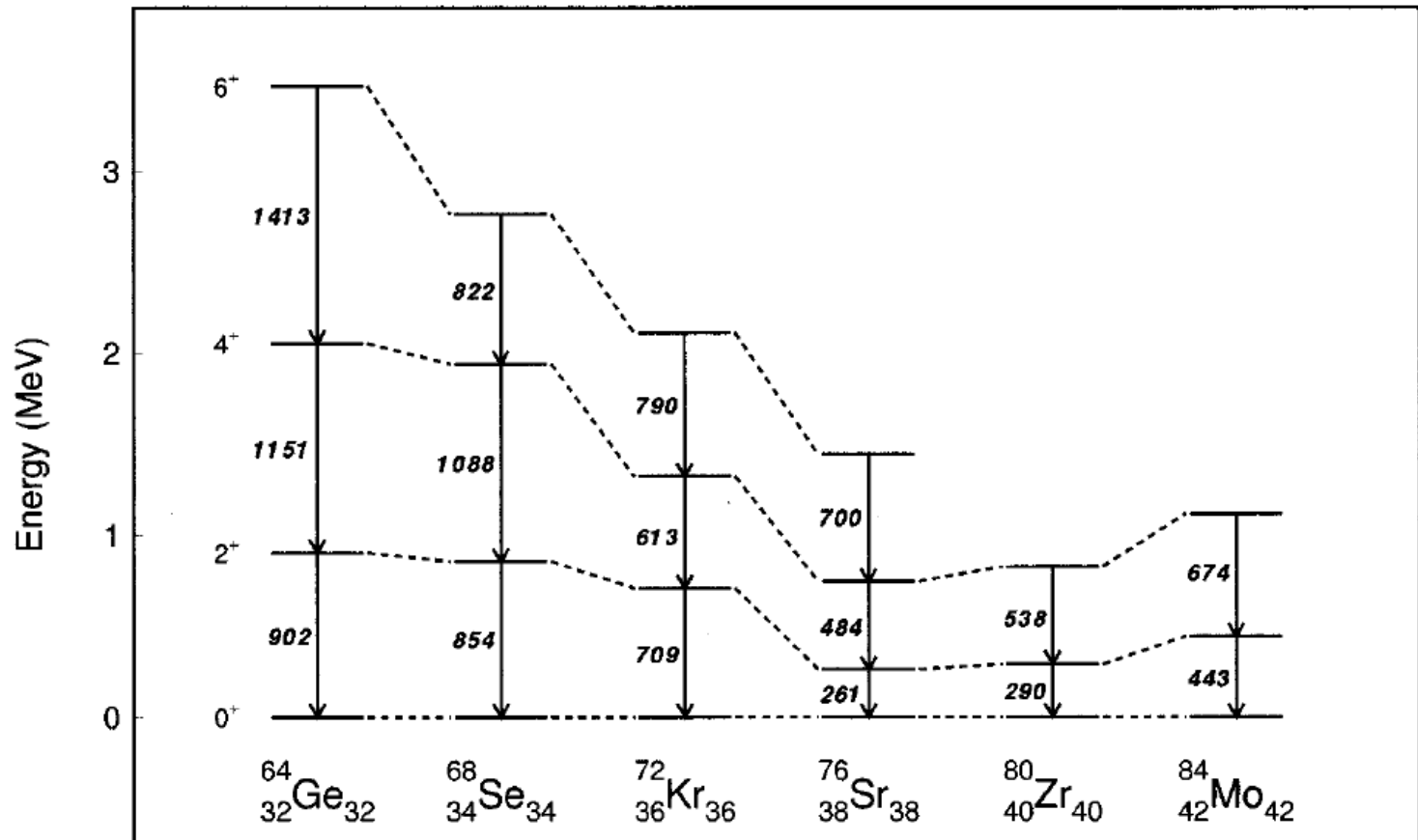
有限系の特徴

温度ゼロ



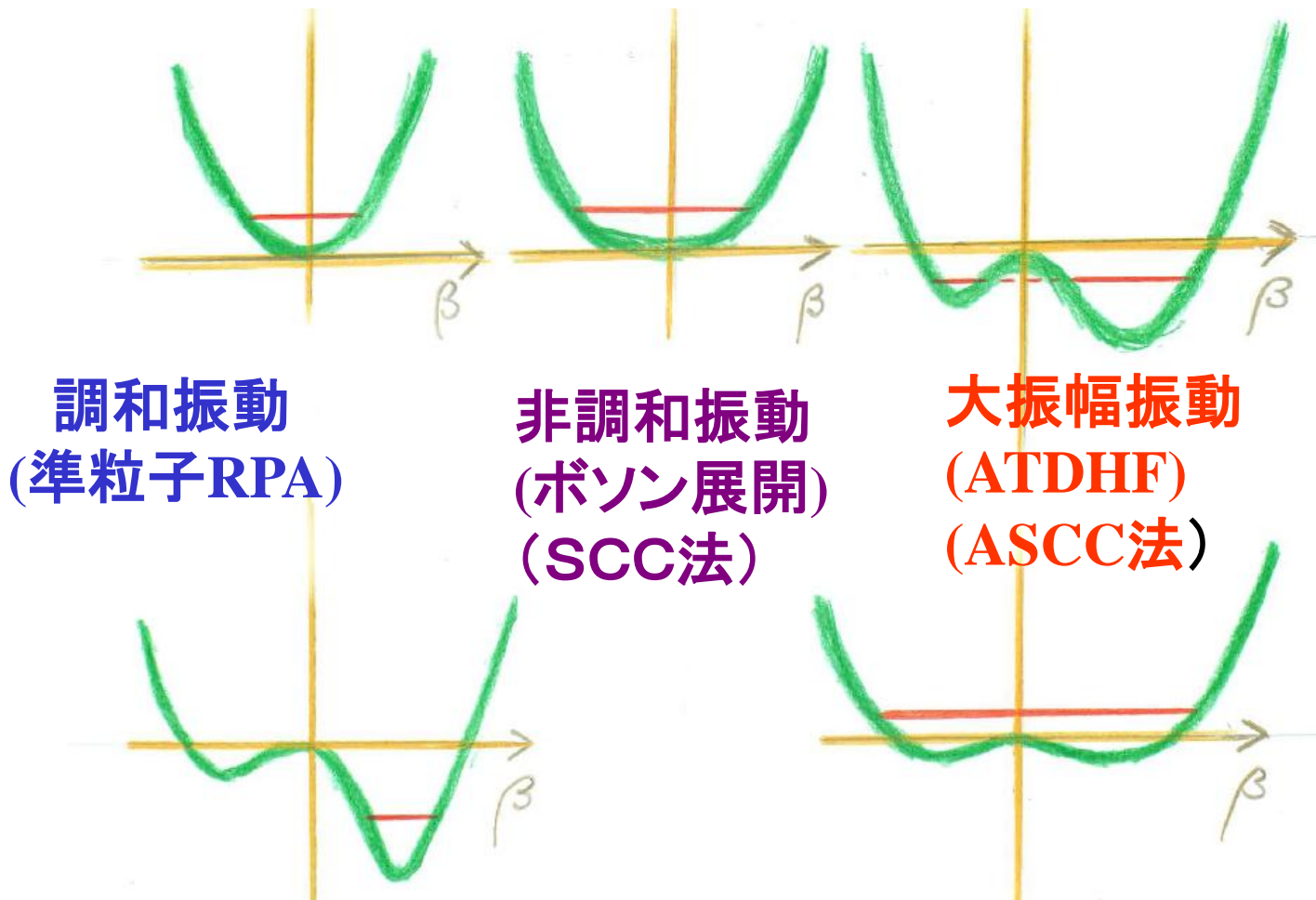
	<u>2428</u> 4 <sup>+</sup>	<u>2400</u> 8 <sup>+</sup>	<u>2438</u> 8 <sup>+</sup>	<u>2304</u> 10 <sup>+</sup>	<u>2286</u> 12 <sup>+</sup>	<u>2613</u> 14 <sup>+</sup>
		<u>1849</u> 6 <sup>+</sup>	<u>1945</u> 6 <sup>+</sup>	<u>1748</u> 8 <sup>+</sup>	<u>1725</u> 10 <sup>+</sup>	<u>2049</u> 12 <sup>+</sup>
	<u>1678</u> 2 <sup>+</sup>	<u>1458</u> 4 <sup>+</sup>				<u>1520</u> 10 <sup>+</sup>
			<u>1262</u> 4 <sup>+</sup>	<u>1224</u> 6 <sup>+</sup>	<u>1216</u> 8 <sup>+</sup>	
		<u>804</u> 2 <sup>+</sup>		<u>747</u> 4 <sup>+</sup>	<u>770</u> 6 <sup>+</sup>	<u>1040</u> 8 <sup>+</sup>
			<u>614</u> 2 <sup>+</sup>			<u>638</u> 6 <sup>+</sup>
				<u>334</u> 2 <sup>+</sup>	<u>404</u> 4 <sup>+</sup>	<u>317</u> 4 <sup>+</sup>
					<u>138</u> 2 <sup>+</sup>	<u>99</u> 2 <sup>+</sup>
	<u>0</u> 0 <sup>+</sup>	<u>0</u> 0 <sup>+</sup>	<u>0</u> 0 <sup>+</sup>	<u>0</u> 0 <sup>+</sup>	<u>0</u> 0 <sup>+</sup>	<u>0</u> 0 <sup>+</sup>
	<sup>148</sup> Dy <sub>82</sub>	<sup>150</sup> Dy <sub>84</sub>	<sup>152</sup> Dy <sub>86</sub>	<sup>154</sup> Dy <sub>88</sub>	<sup>156</sup> Dy <sub>90</sub>	<sup>158</sup> Dy <sub>92</sub>
$\frac{E(4^+)}{E(2^+)}$	1.45	1.81	2.06	2.24	2.93	3.20

# Zr80 領域の陽子過剰N=Z核の低励起スペクトル



D. Bucurescu et al., Phys. Rev. C 56 (19 97) 2497

# 非線形振動

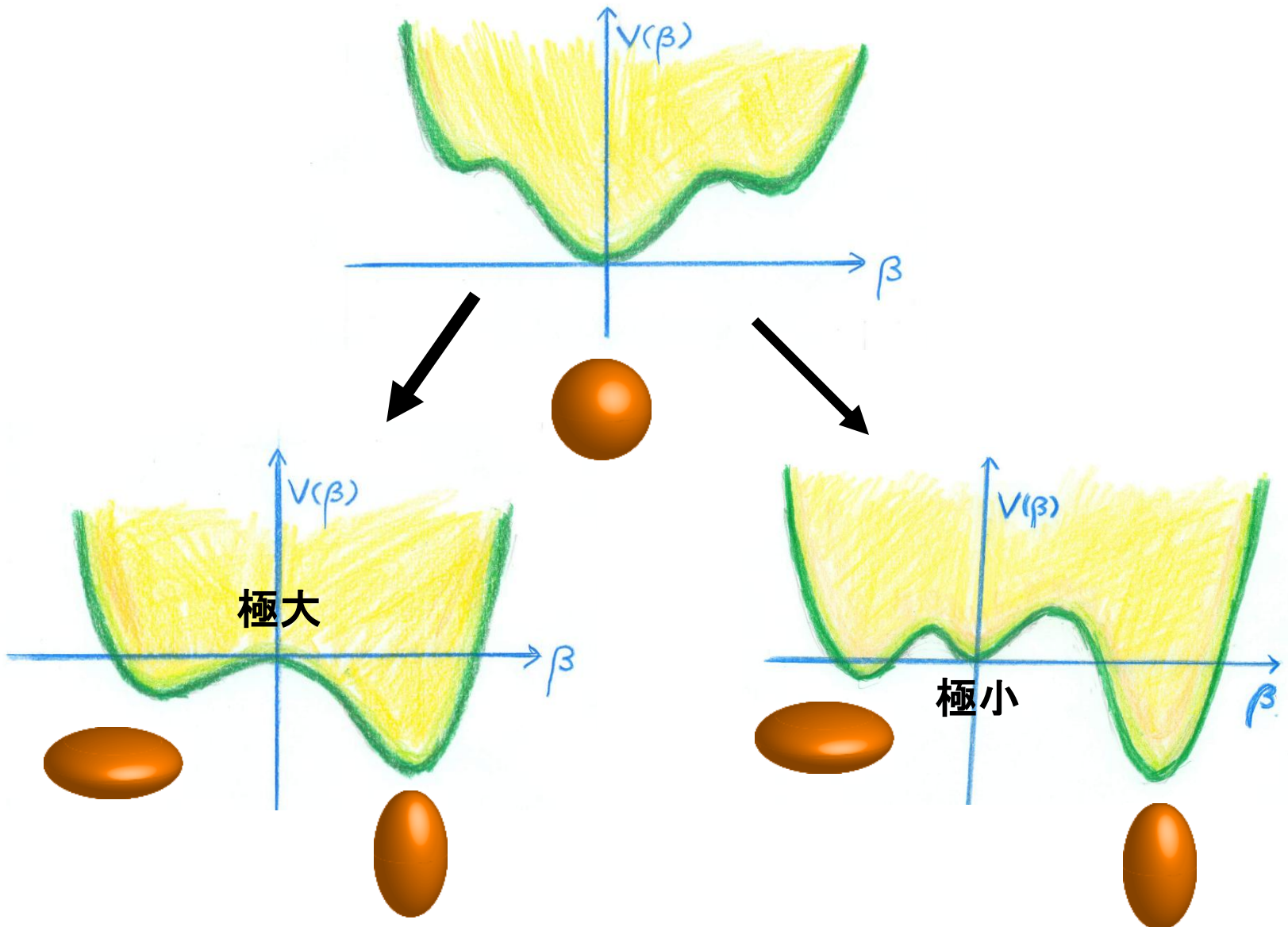


調和振動  
(準粒子RPA)

非調和振動  
(ボソン展開)  
(SCC法)

大振幅振動  
(ATDHF)  
(ASCC法)

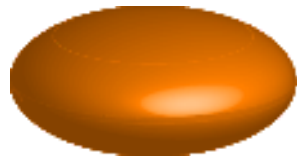
# 變形共存現象



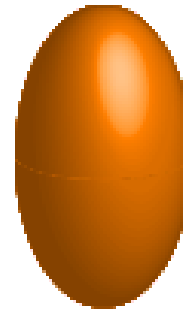


問い なぜ原子核はオブレート変形よりプロレート変形を好むのですか？

オブレート-プロレート非対称性の起源は何ですか。



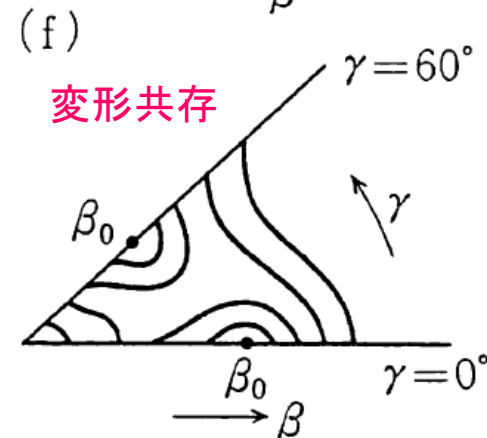
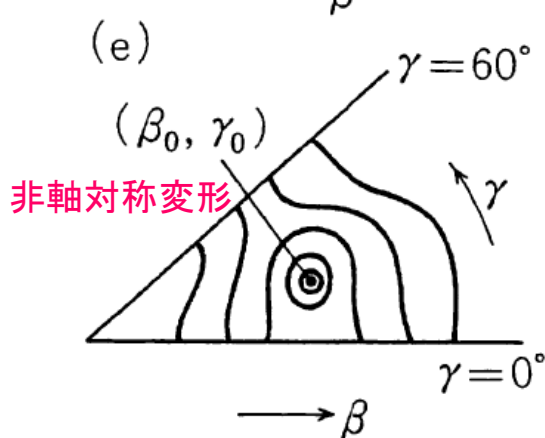
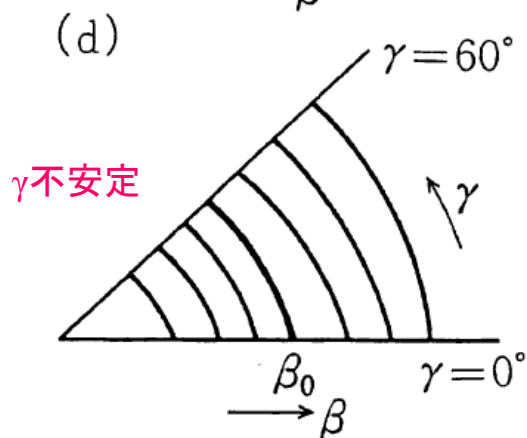
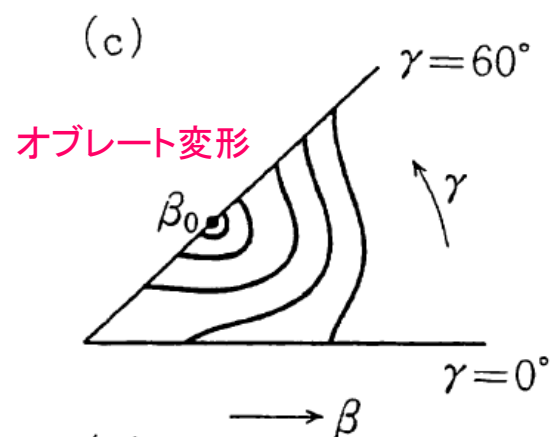
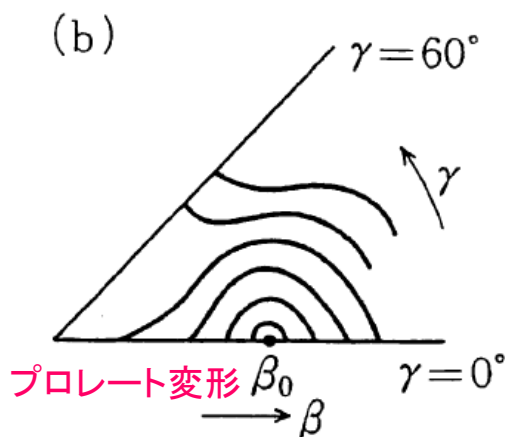
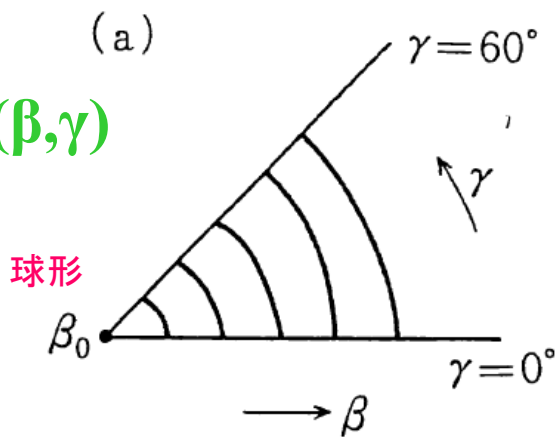
Oblate



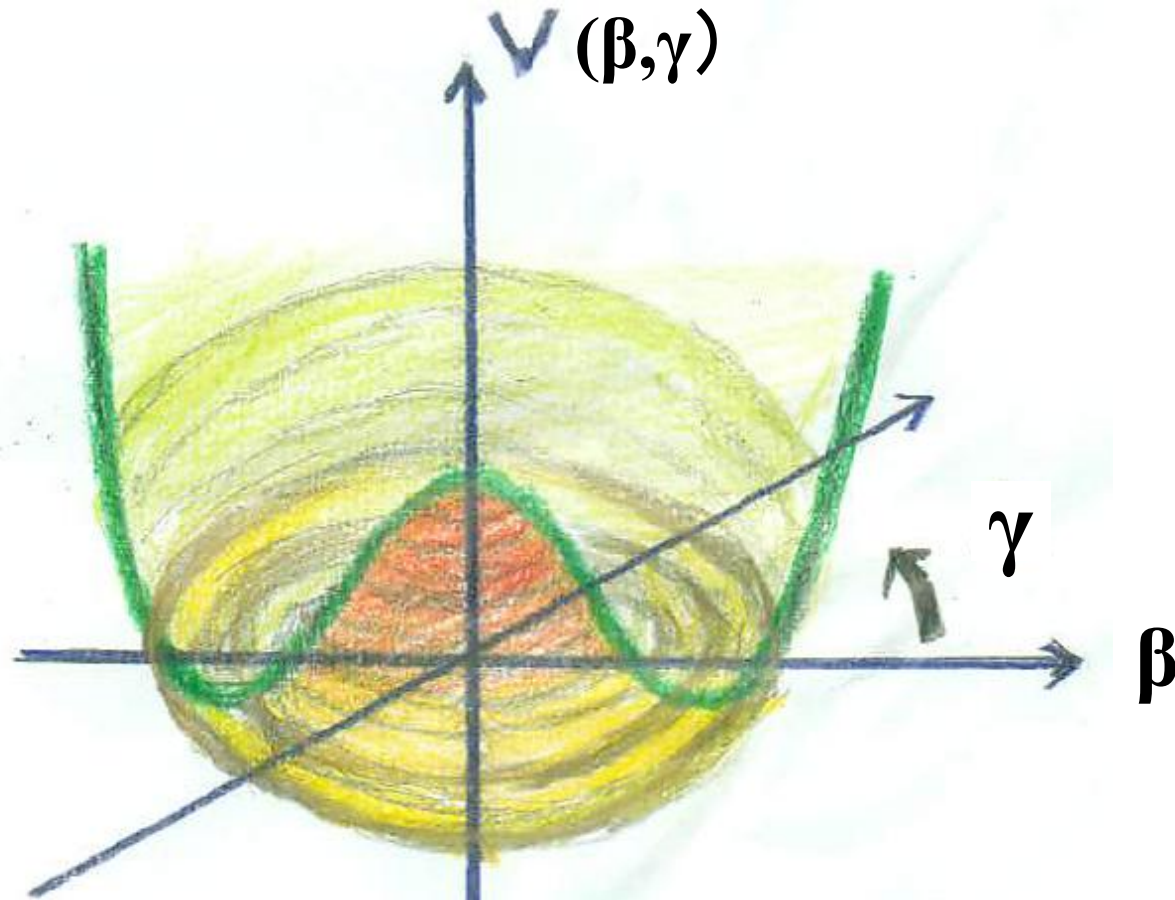
Prolate

$$H_{\text{coll}} = \frac{1}{2} B_{\beta\beta}(\beta, \gamma) \dot{\beta}^2 + B_{\beta\gamma}(\beta, \gamma) \dot{\beta} \dot{\gamma} + \frac{1}{2} B_{\gamma\gamma}(\beta, \gamma) \dot{\gamma}^2 + \frac{1}{2} \sum_{\kappa=1,2,3} \mathcal{I}_{\kappa}(\beta, \gamma) \omega_{\kappa}^2 + V(\beta, \gamma)$$

$V(\beta, \gamma)$



# Wilets-Jean $\gamma$ -unstable model



The excitation spectrum is quite different from the well-known rotational pattern.

# Nuclear Constitution and the Interpretation of Fission Phenomena

DAVID LAWRENCE HILL\*

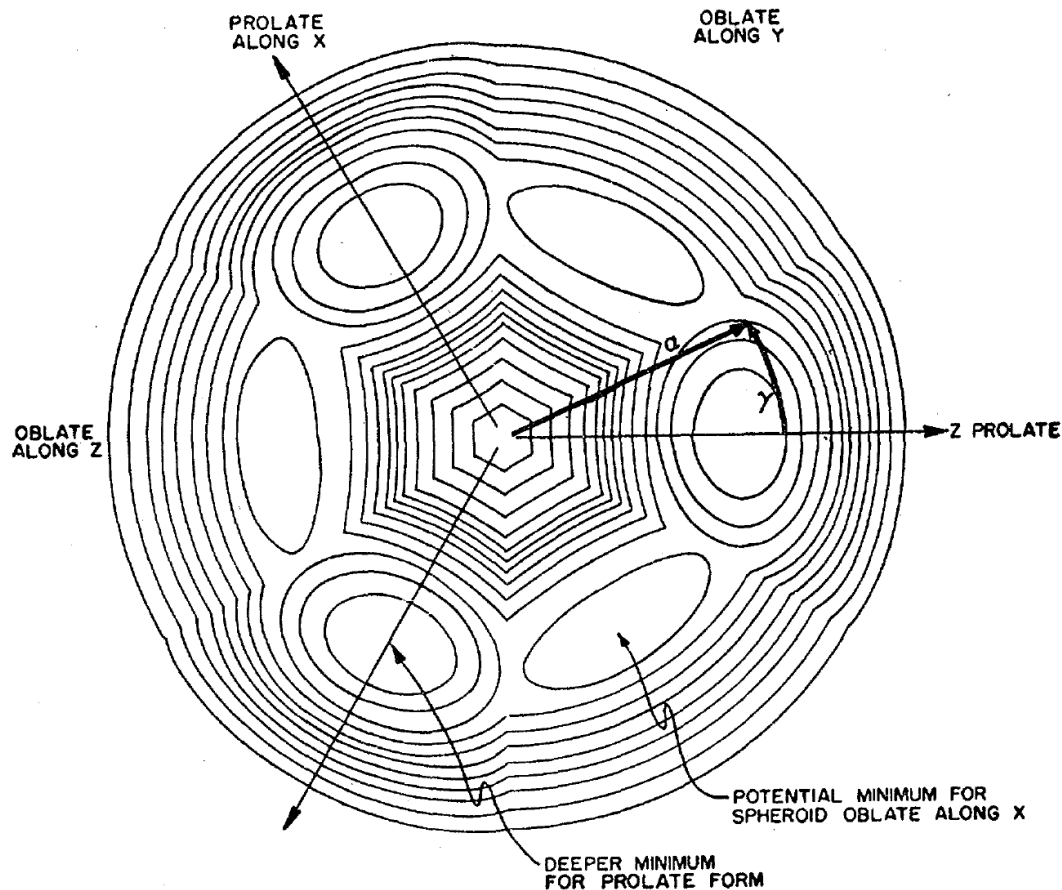
*Vanderbilt University, Nashville, Tennessee, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

AND

JOHN ARCHIBALD WHEELER†

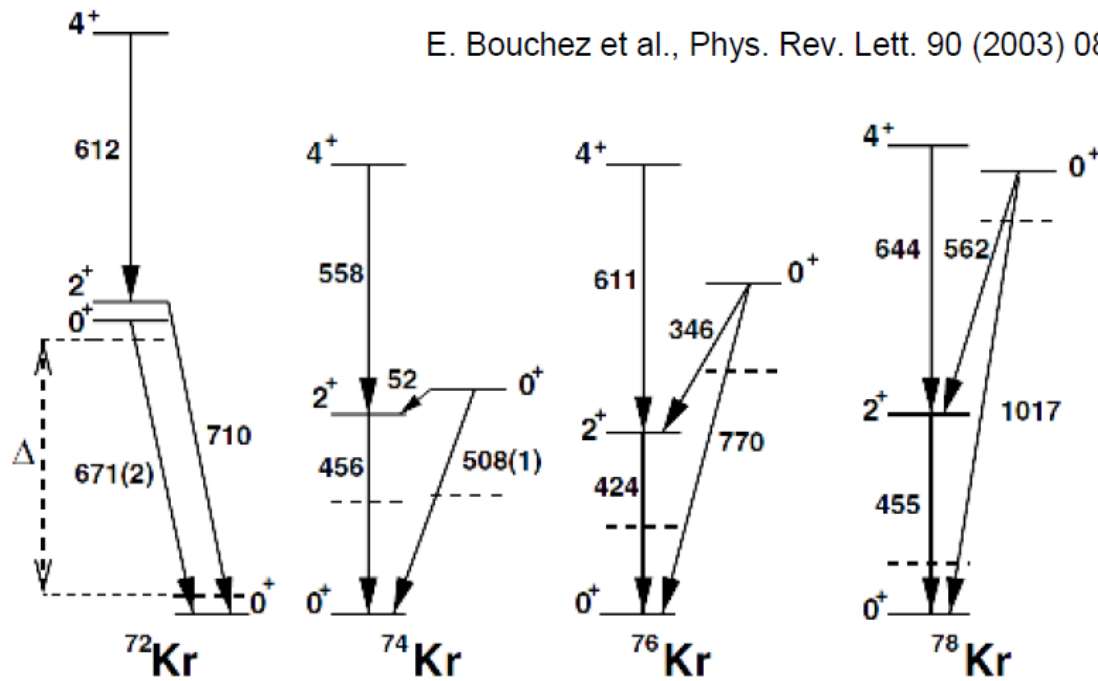
*Princeton University, Princeton, New Jersey, and Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

(Received October 14, 1952)



# Oblate- prolate shape coexistence phenomena in proton-rich Kr isotopes

E. Bouchez et al., Phys. Rev. Lett. 90 (2003) 082502



$\rho^2(E0)$  0.072(6) 0.085(19) 0.079(11) 0.047(13)

oblate



prolate

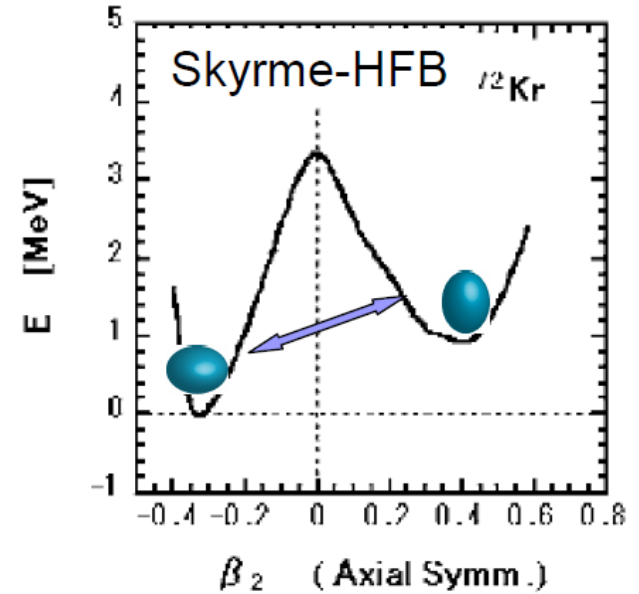
◆ Low-lying excited 0+ states

◆ Irregularities of the excitation spectra

◆ Systematics of the excited 0+ energies and E0 transition strengths

◆ Spectroscopic quadrupole moments

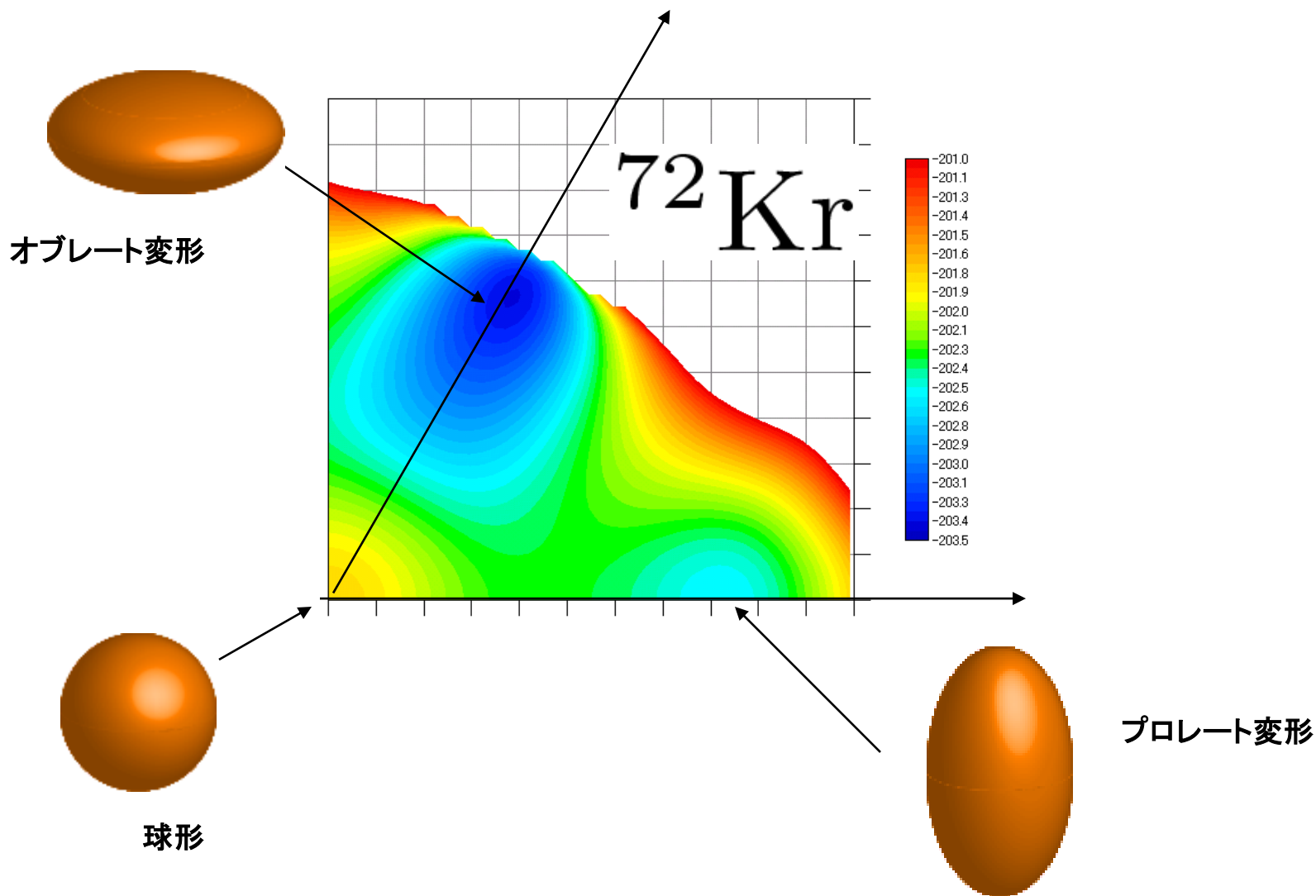
M. Yamagami et al., NPA 693(2001) 579



Shape mixing by tunneling between the local minima

Shape transition from the oblate ground state in 72Kr to the prolate ground state in 74,76,78Kr

# 複数の真空(平均場)の間の巨視的トンネル現象 オブレート・プロレート変形共存現象



$^{64}\text{Ge}$

$^{68}\text{Se}$

$^{72}\text{Kr}$

$^{76}\text{Sr}$

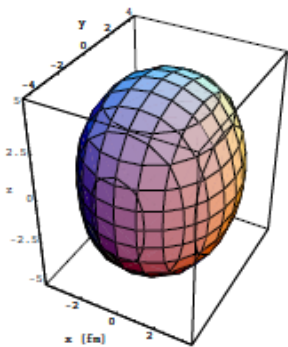
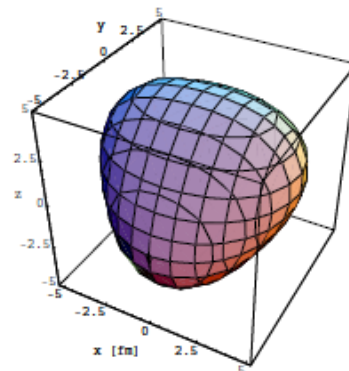
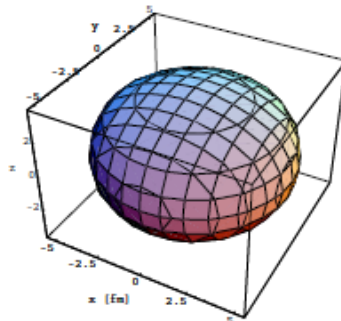
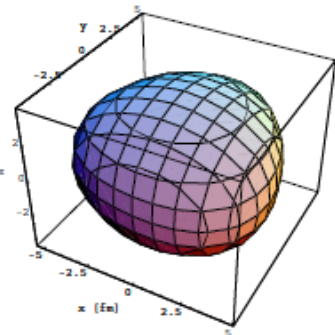
$^{80}\text{Zr}$

triangular (g.s.)

oblate (g.s.)

tetrahedral

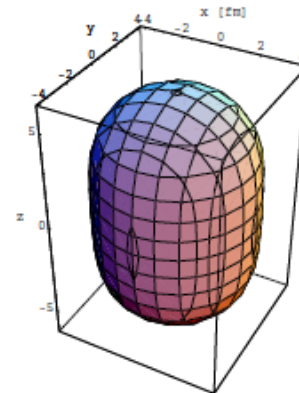
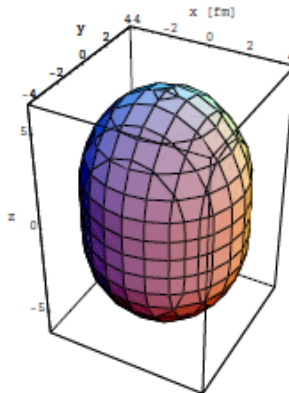
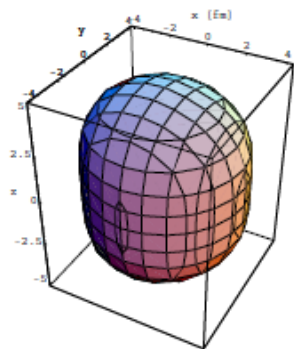
triaxial (g.s.)



prolate

prolate (g.s.)

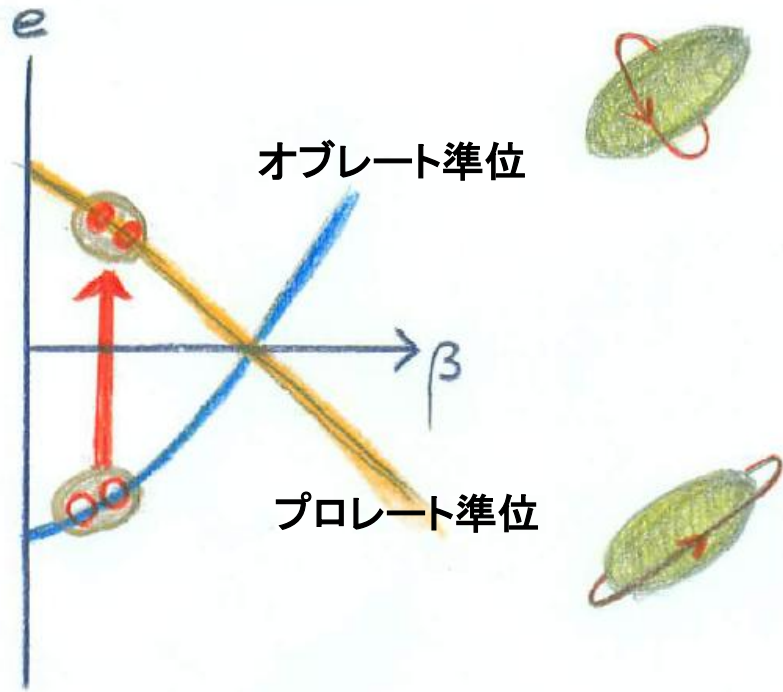
prolate (g.s.)







# 閉殻が2p2h励起すると ..... 変形する



常識に反するようだが....

ひとたび、閉殻が励起すると  
対相関と四重極相関は  
コヒーレントに作用する

$$|K^\pi = 0_{\text{ground}}^+\rangle = \alpha|i\bar{i}\rangle + \beta|j\bar{j}\rangle,$$

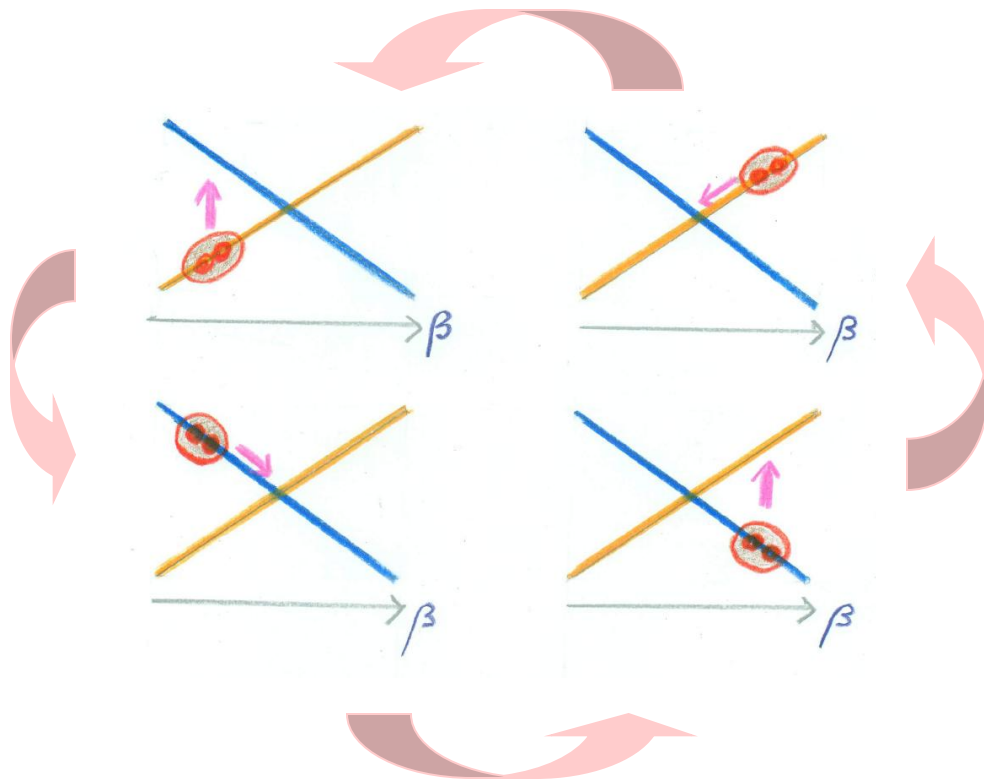
$$|K^\pi = 0_{\text{excited}}^+\rangle = -\beta|i\bar{i}\rangle + \alpha|j\bar{j}\rangle.$$

$$\langle K^\pi = 0_{\text{excited}}^+ | \sum_i (r^2 Y_{20})_i | K^\pi = 0_{\text{ground}}^+ \rangle = 2\alpha\beta (\langle j | r^2 Y_{20} | j \rangle - \langle i | r^2 Y_{20} | i \rangle)$$

ペアの空間構造の違い  $\longrightarrow$  四重極対相関も重要

# ペア密度の4重極振動

ペア密度揺らぎと4重極変形揺らぎがカップルするメカニズム

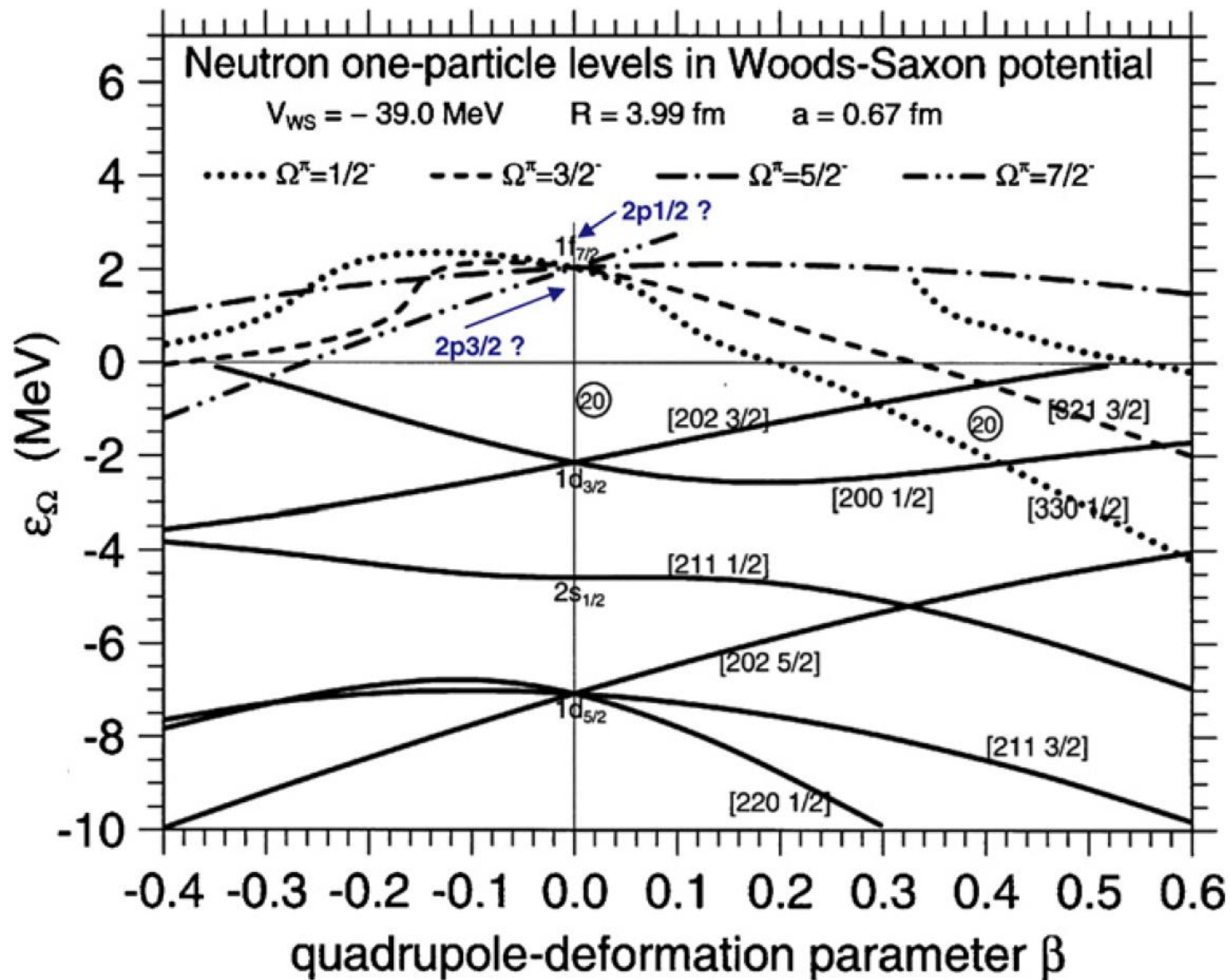


BCS描像

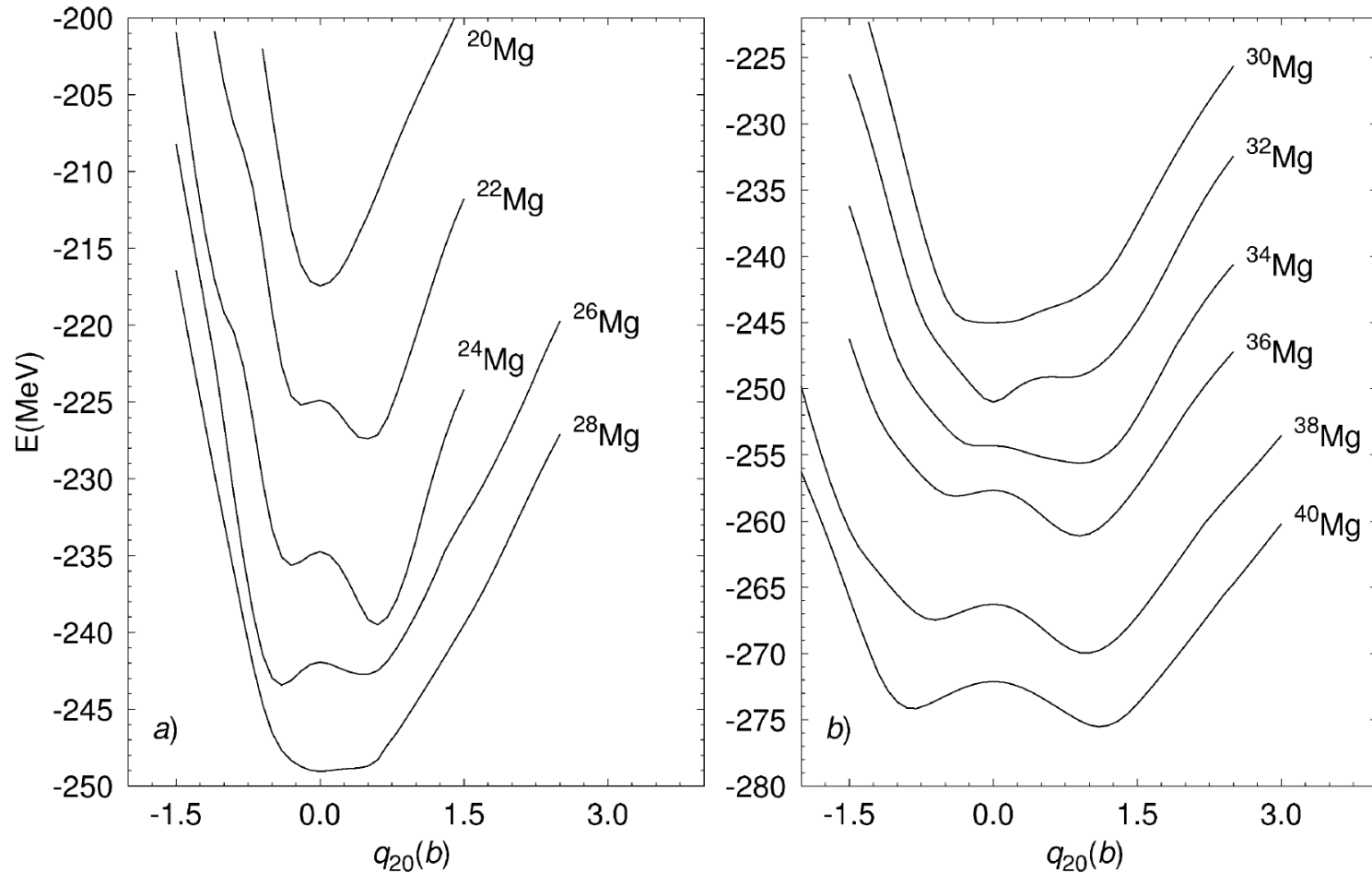


Di-neutron描像





# Mg isotopesの変形ポテンシャル



R. Rodríguez-Guzmán<sup>1</sup>, J.L. Egido, L.M. Robledo

Nuclear Physics A 709 (2002) 201

## 変形パラメータは主軸系 (intrinsic系) で定義される

$$\beta_2 \cos \gamma = \frac{4\pi}{5} \left\langle \sum_{i=1}^A r_i^2 Y_{20}(\theta_i, \phi_i) \right\rangle \left\langle \sum_{i=1}^A r_i^2 \right\rangle^{-1},$$

$$\beta_2 \sin \gamma = -\frac{4\pi}{5} \left\langle \frac{1}{\sqrt{2}} \sum_{i=1}^A r_i^2 (Y_{22}(\theta_i, \phi_i) + Y_{22}^*(\theta_i, \phi_i)) \right\rangle \left\langle \sum_{i=1}^A r_i^2 \right\rangle^{-1}$$

二つの変形パラメータ $(\beta, \gamma)$ と3つのオイラー角 $\Omega$ を集団座標とみなすと、  
集団運動ハミルトニアンは

$$H_{\text{coll}} = \mathcal{T}_{\text{vib}}(\beta, \gamma) + \mathcal{T}_{\text{rot}}(\beta, \gamma, \Omega) + \mathcal{V}_{\text{coll}}(\beta, \gamma)$$

$$\mathcal{T}_{\text{vib}} = \frac{1}{2} B_{\beta\beta} \dot{\beta}^2 + \beta B_{\beta\gamma} \dot{\beta} \dot{\gamma} + \frac{1}{2} \beta^2 B_{\gamma\gamma} \dot{\gamma}^2$$

$$\mathcal{T}_{\text{rot}} = \frac{1}{2} \sum_{k=1}^3 \mathcal{I}_k \omega_k^2$$

# 曲がった空間での量子化

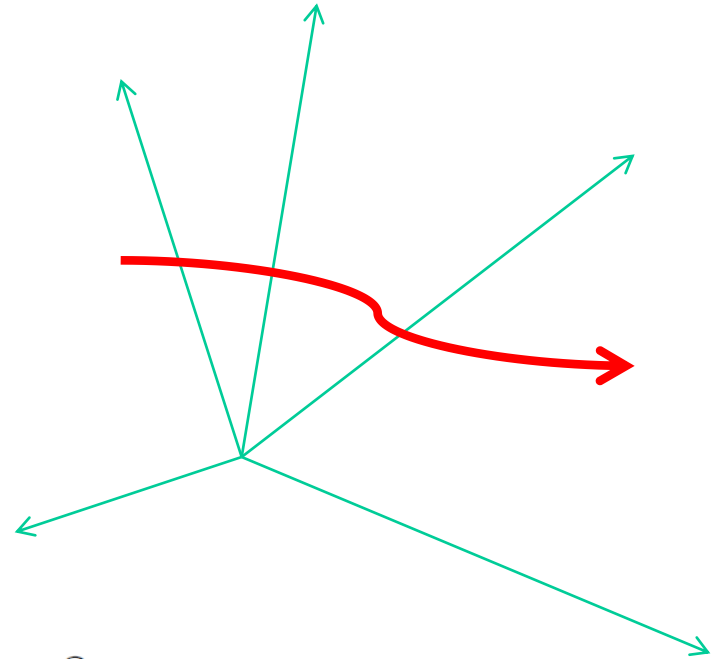
$$ds^2 = \sum_{i,j} g_{ij}(x) dx_i dx_j$$

$$\begin{aligned} T &= \frac{1}{2} \left( \frac{ds}{dt} \right)^2 \\ &= \frac{1}{2} \sum_{i,j} g_{ij}(x) \frac{dx_i}{dt} \frac{dx_j}{dt} \end{aligned}$$

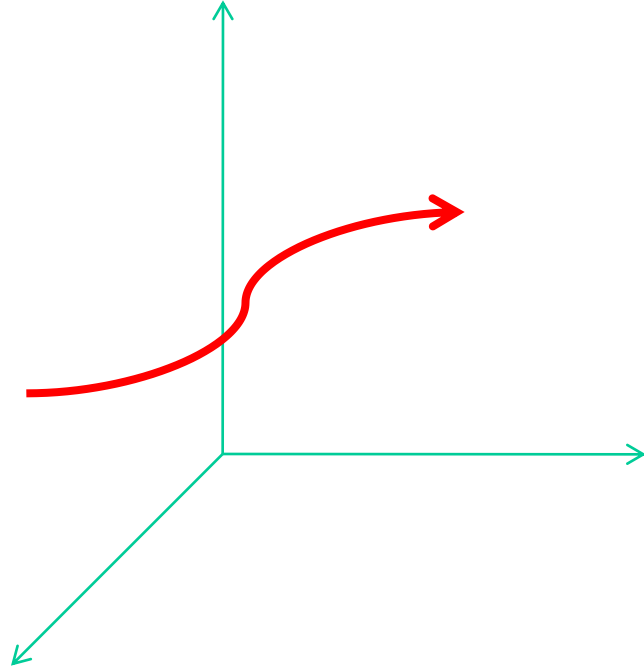
量子化



$$\hat{T} = -\frac{\hbar^2}{2} \frac{1}{\sqrt{g}} \sum_{i,j} \frac{\partial}{\partial x_i} \sqrt{g} g^{ij} \frac{\partial}{\partial x_j}$$



## 3D極座標での量子化



$$ds^2 = dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\varphi^2$$

$$(g_{ij}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & r^2 & 0 \\ 0 & 0 & r^2 \sin^2 \theta \end{pmatrix}$$

$$\det(g_{ij}) \equiv g = r^4 \sin^2 \theta$$

$$(g^{ij}) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/r^2 & 0 \\ 0 & 0 & 1/r^2 \sin^2 \theta \end{pmatrix}$$

$$\begin{aligned} \hat{T} &= -\frac{\hbar^2}{2} \frac{1}{\sqrt{g}} \left( \frac{\partial}{\partial r} \sqrt{g} \frac{\partial}{\partial r} + \frac{\partial}{\partial \theta} \frac{\sqrt{g}}{r^2} \frac{\partial}{\partial \theta} + \frac{\partial}{\partial \varphi} \frac{\sqrt{g}}{r^2 \sin^2 \theta} \frac{\partial}{\partial \varphi} \right) \\ &= -\frac{\hbar^2}{2} \left( \frac{\partial^2}{\partial r^2} + \frac{2}{r} \frac{\partial}{\partial r} + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \sin \theta \frac{\partial}{\partial \theta} + \frac{1}{r^2 \sin \theta} \frac{\partial^2}{\partial \varphi^2} \right) \end{aligned}$$

## 曲がった空間での量子化

運動エネルギー

$$T = \frac{1}{2} \sum_{ij} \underline{B_{ij}(q)} \dot{q}_i \dot{q}_j$$

metric

Pauli処方箋



$$\hat{H}_{\text{kin}} = -\frac{\hbar^2}{2} \frac{1}{\sqrt{\det B}} \sum_{ij} \frac{\partial}{\partial q_i} \sqrt{\det B} (B^{-1})_{ij} \frac{\partial}{\partial q_j}$$

$$B = \begin{pmatrix} B_{\text{vib}} & 0 \\ 0 & B_{\text{rot}} \end{pmatrix}$$

$$B_{\text{vib}} = \begin{pmatrix} B_{\beta\beta} & \beta B_{\beta\gamma} \\ \beta B_{\beta\gamma} & \beta^2 B_{\gamma\gamma} \end{pmatrix}$$

$$(B_{\text{rot}})_{ik} = \delta_{ik} \mathcal{I}_k, \quad k = 1, 2, 3$$

この理論的基礎付けは集団運動理論の根本問題のひとつ



# 量子化されたBohr-Mottelson の集団ハミルトニアン

$$\hat{H} = \hat{T}_{\text{vib}} + \hat{T}_{\text{rot}} + V_{\text{coll}}$$

$$\hat{T}_{\text{vib}} = -\frac{\hbar^2}{2\sqrt{wr}} \left\{ \frac{1}{\beta^4} \left[ \frac{\partial}{\partial\beta} \sqrt{\frac{r}{w}} \beta^4 B_{\gamma\gamma} \frac{\partial}{\partial\beta} - \frac{\partial}{\partial\beta} \sqrt{\frac{r}{w}} \beta^3 B_{\beta\gamma} \frac{\partial}{\partial\gamma} \right] \right. \\ \left. + \frac{1}{\beta \sin 3\gamma} \left[ -\frac{\partial}{\partial\gamma} \sqrt{\frac{r}{w}} \sin 3\gamma B_{\beta\gamma} \frac{\partial}{\partial\beta} + \frac{1}{\beta} \frac{\partial}{\partial\gamma} \sqrt{\frac{r}{w}} \sin 3\gamma B_{\beta\beta} \frac{\partial}{\partial\gamma} \right] \right\}$$

$$\hat{T}_{\text{rot}} = \frac{1}{2} \sum_{k=1}^3 \frac{\hat{J}_k^2}{\mathcal{I}_k}$$

## 積分の測度

$$\int d\tau_{\text{coll}} = \int d\Omega d\tau_0 \sqrt{wr} = \int_0^\infty d\beta \beta^4 \int_0^{2\pi} d\gamma |\sin 3\gamma| \int d\Omega \sqrt{wr}$$

$$w = B_{\beta\beta} B_{\gamma\gamma} - B_{\beta\gamma}^2 \quad r = B_1 B_2 B_3$$

## 回転運動の慣性モーメント

$$(B_{\text{rot}})_{ik} = \delta_{ik} \mathcal{I}_k, \quad k = 1, 2, 3$$

$$\mathcal{I}_k = 4B_k \beta^2 \sin^2(\gamma - 2k\pi/3)$$

行列式

$$\det B = \det B_{\text{vib}} \cdot \det B_{\text{rot}} = 4wr\beta^8 \sin^2 3\gamma$$

$$w = B_{\beta\beta} B_{\gamma\gamma} - B_{\beta\gamma}^2$$

$$r = B_1 B_2 B_3$$

# 集団波動関数

$$\Psi_{\alpha}^{IM}(\beta, \gamma, \Omega) = \sum_{K \in \Delta I} \psi_{\alpha K}^I(\beta, \gamma) \Phi_{MK}^I(\Omega)$$

振動運動の波動関数

回転運動の波動関数

$$\Phi_{MK}^I(\Omega) = \sqrt{\frac{2I+1}{16\pi^2(1+\delta_{K0})}} [D_{MK}^{I*}(\Omega) + (-1)^I D_{M-K}^{I*}(\Omega)]$$

オイラー角

$$(\phi', \theta', \phi) \equiv \psi$$

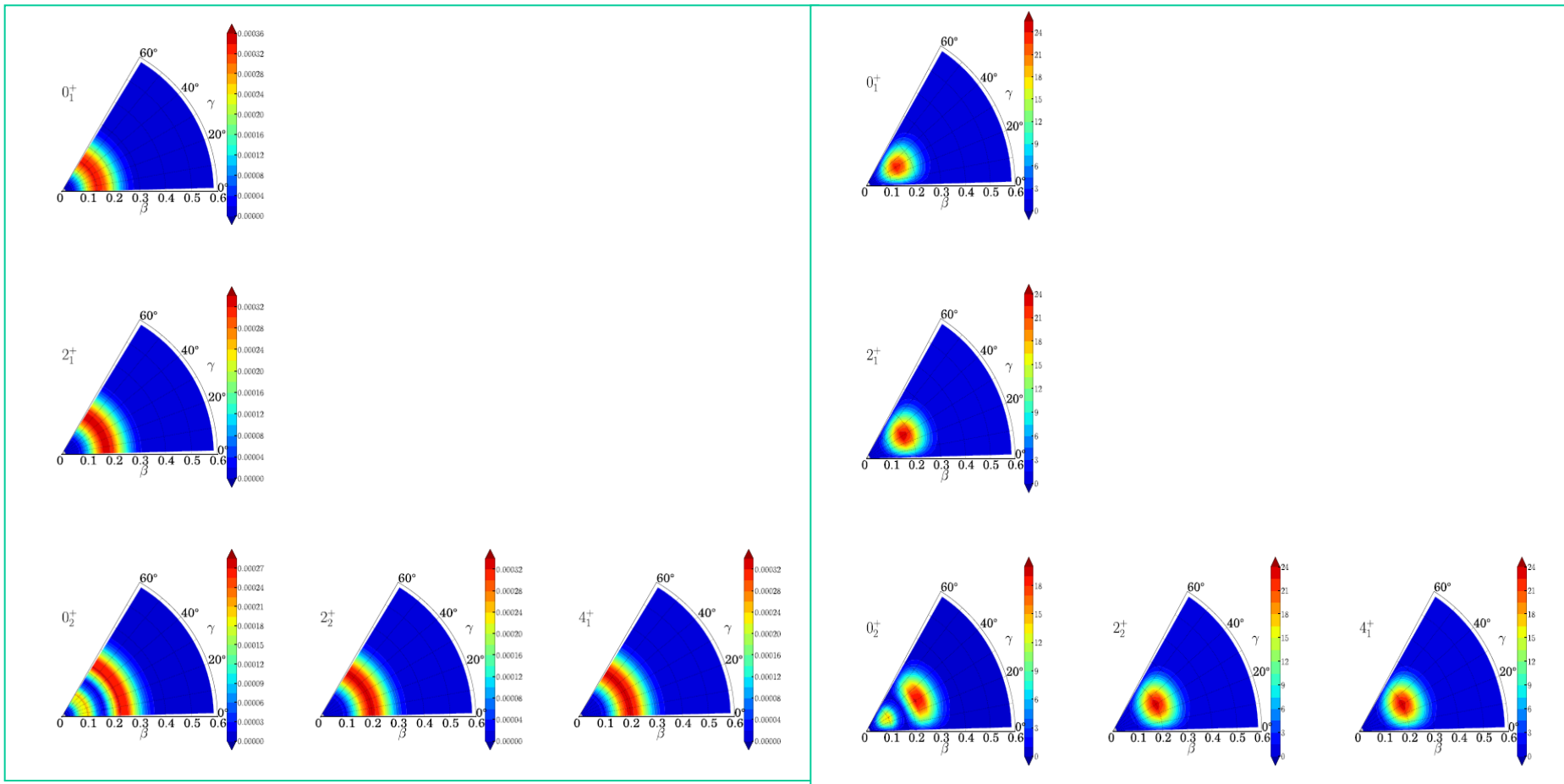
## 球形平衡点のまわりの小振幅振動(調和振動)の場合には

すべての慣性質量を同じ定数に置き換えることが出来て  
集団運動のSchrodinger方程式は

$$\left\{ \frac{\hbar^2}{2B_2} \left[ \frac{1}{\beta^4} \frac{\partial}{\partial \beta} \left( \beta^4 \frac{\partial}{\partial \beta} \right) + \frac{1}{\beta^2 \sin 3\gamma} \frac{\partial}{\partial \gamma} \left( \sin 3\gamma \frac{\partial}{\partial \gamma} \right) - \frac{1}{4\beta^2} \sum_{k=1}^3 \frac{L_k^2}{\sin^2 (\gamma - 2\pi k/3)} \right] + \frac{1}{2} C_2 \beta^2 \right\} \times \Psi(\theta_i, \beta, \gamma) = E \Psi(\theta_i, \beta, \gamma).$$

となる。これは5次元調和振動子に対するSchrodinger方程式に他ならない。  
これを一般的なBohr-Mottelsonモデルと混同してはいけない。

# Collective wave functions of 5D harmonic vibration

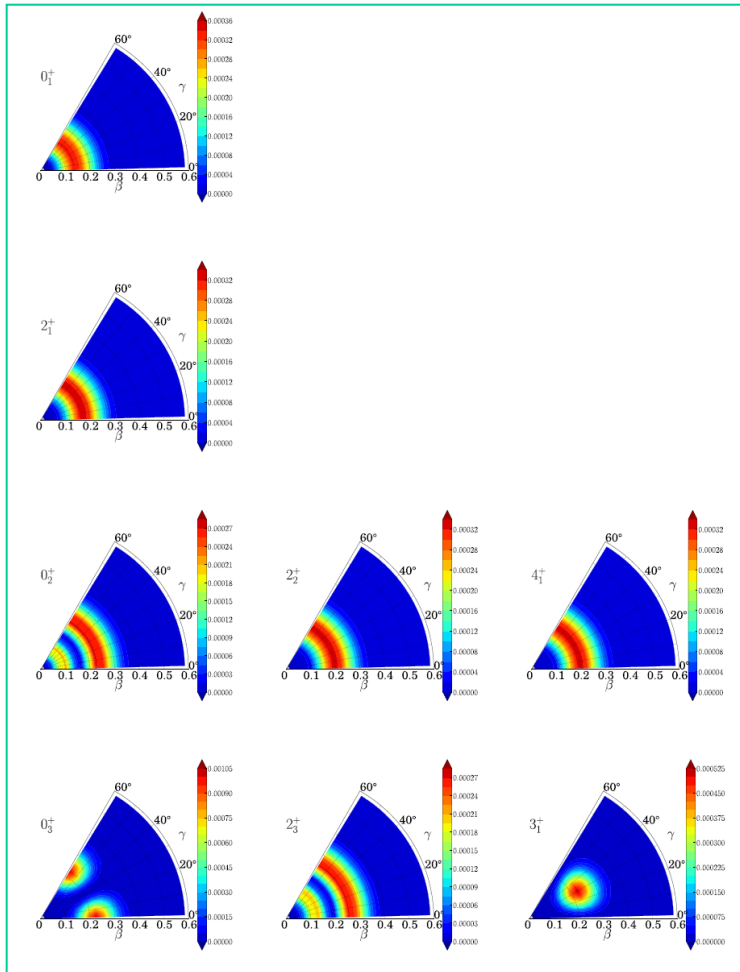


$$\beta^4 \sum_K |\Phi_{IK\alpha}(\beta, \gamma)|^2$$

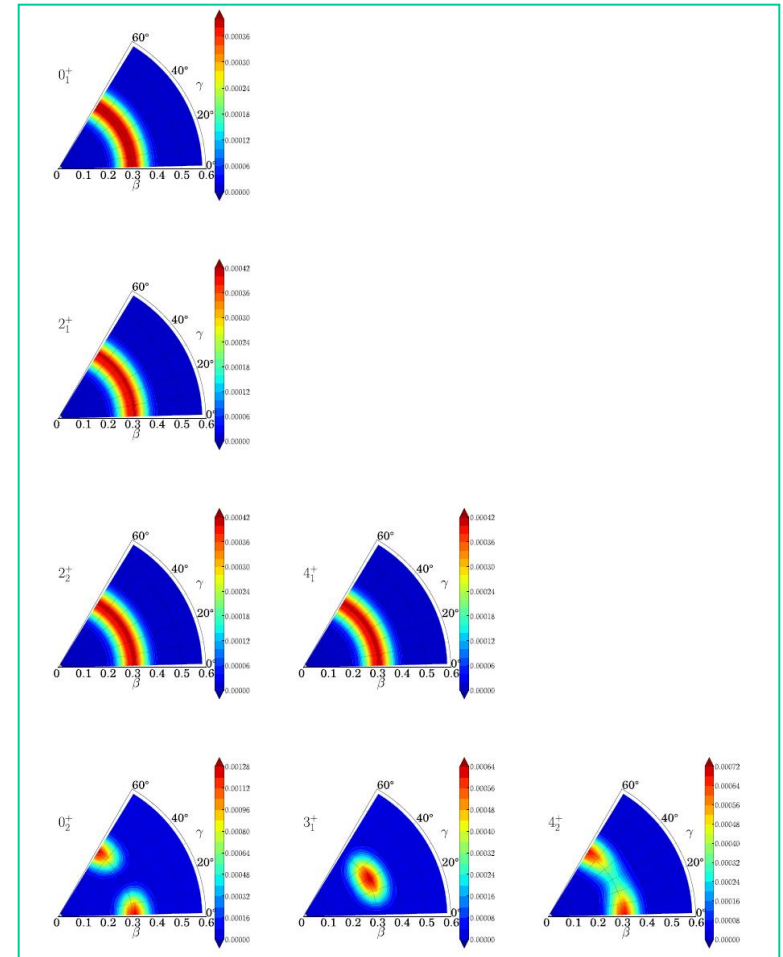
$$: 2\beta^4 \sqrt{W(\beta, \gamma)R(\beta, \gamma)} \sin 3\gamma \sum_K |\Phi_{IK\alpha}(\beta, \gamma)|^2$$

# Vibrational wave functions

$$\beta^4 \sum_K |\Phi_{IK\alpha}(\beta, \gamma)|^2.$$



**5D harmonic vibrations**

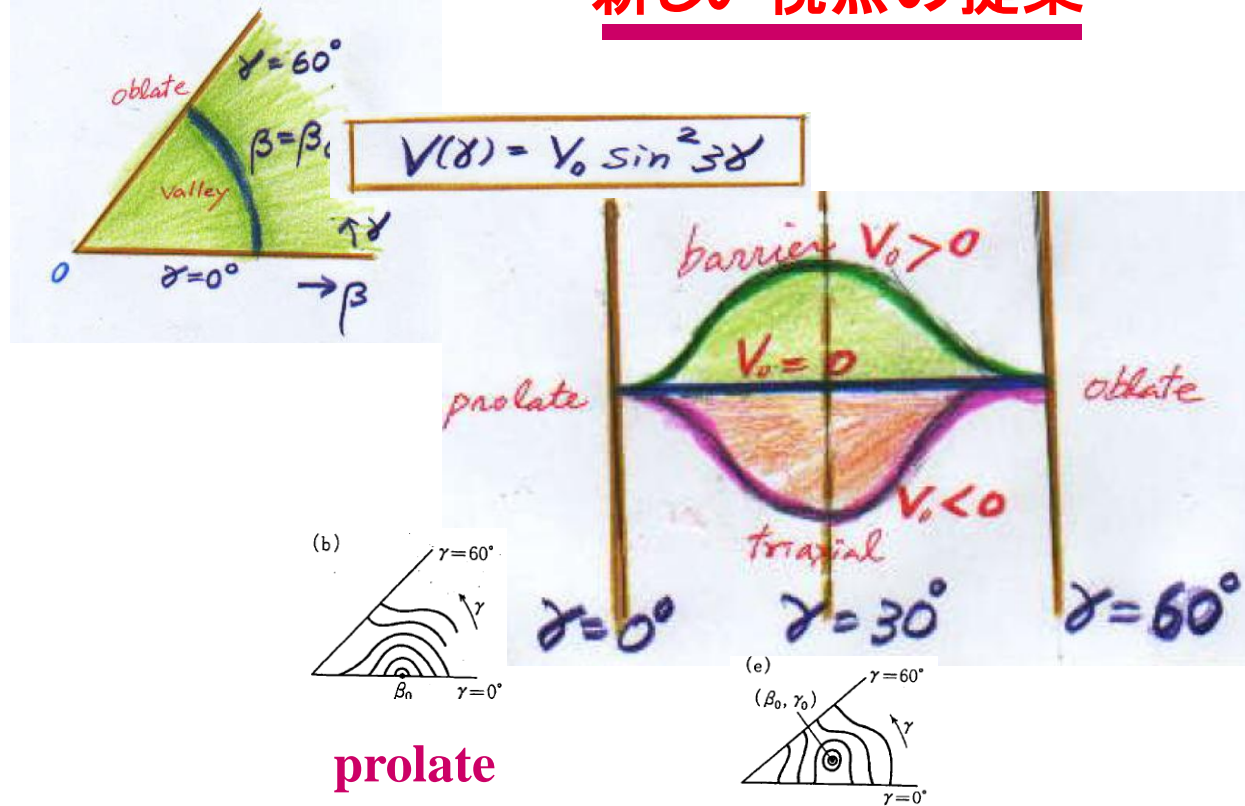


**Gamma-unstable vibrations**

球対称性が破れると多くの場合、prolateとoblateの2つの局所平衡点が現れる。そこで、

非軸対称変形、 $\gamma$ 不安定、oblate-prolate変形共存を統一적으로取り扱う

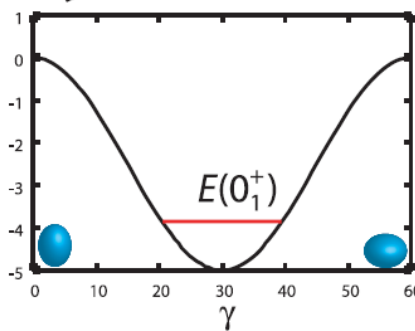
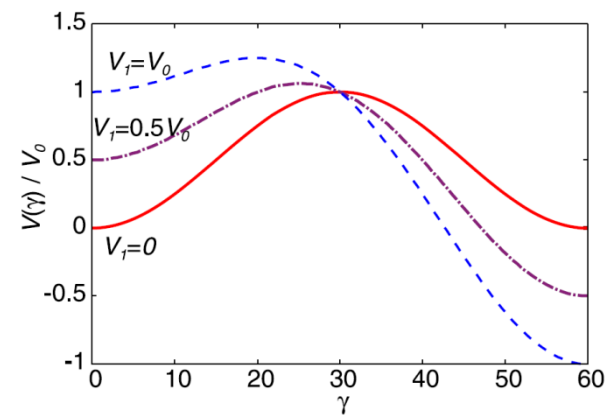
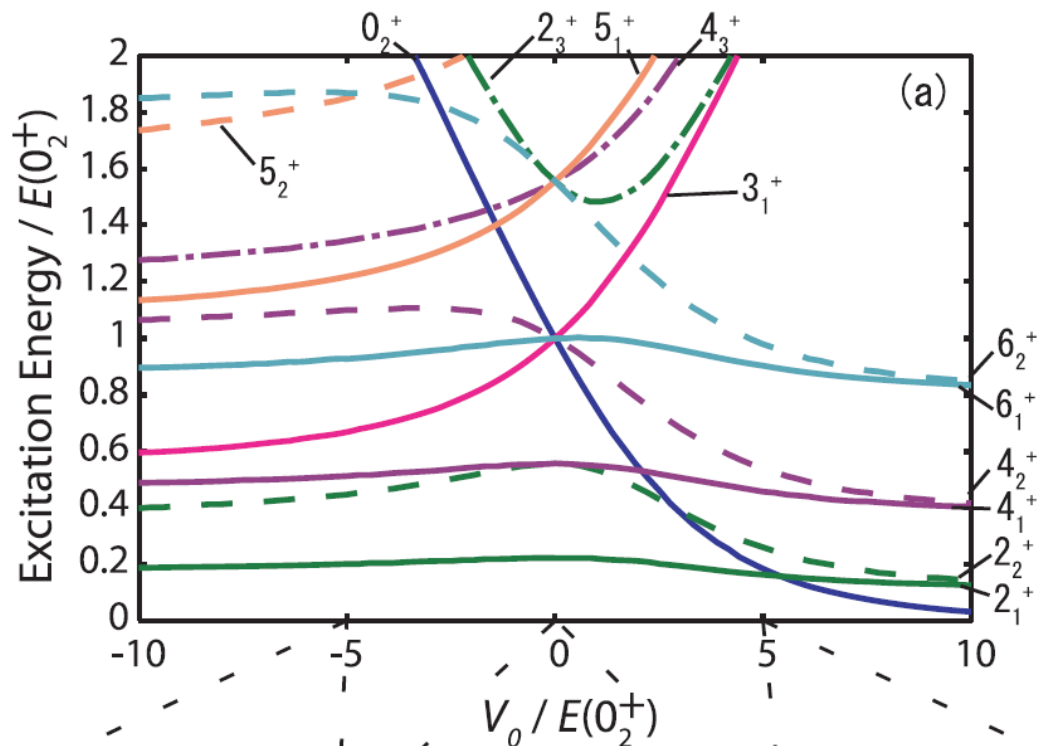
## 新しい視点の提案



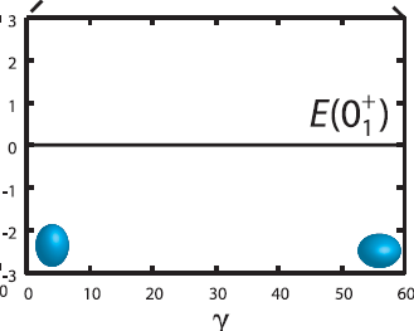
非軸対称変形

Oblate-prolate対称の極限から出発して、現実にはこの対称性がどの程度破れているか、という視点から実験データを分析しよう。

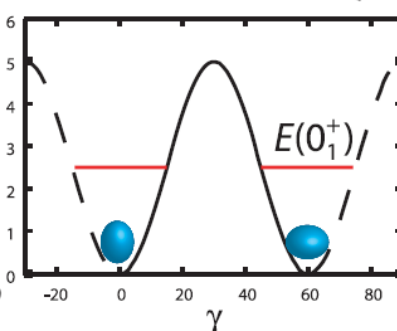
$$V(\gamma) = V_0 \sin^2 3\gamma + V_1 \cos 3\gamma$$



(b)



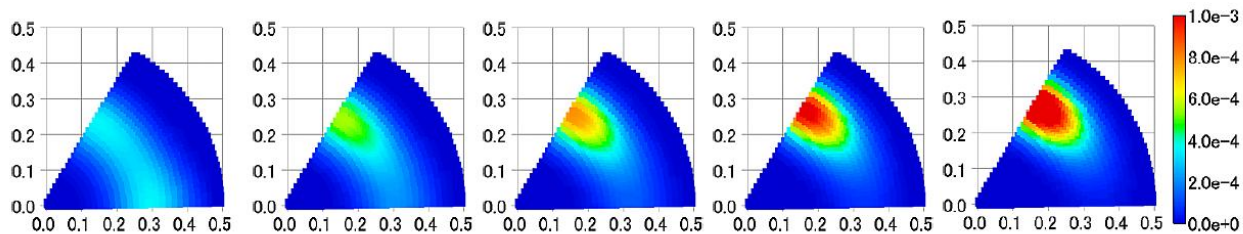
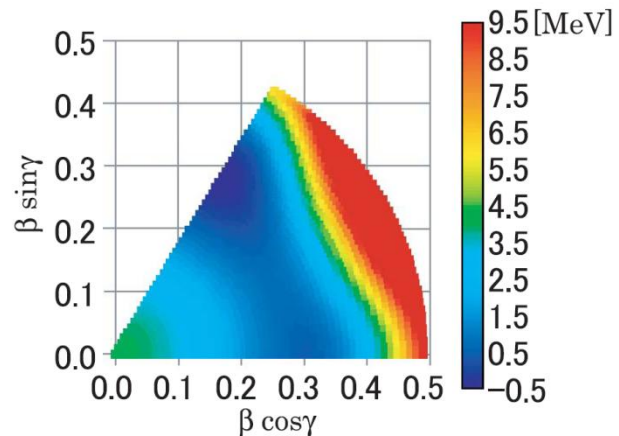
(c)



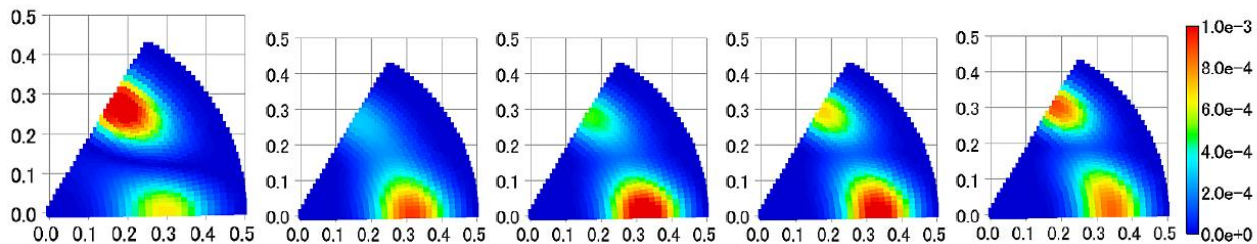
(d)



$$V(\beta, \gamma) = \frac{1}{2}C(\beta^2 - \beta_0^2)^2 - v_0\beta^6 \cos^2 3\gamma + v_1\beta^3 \cos 3\gamma + C_6\beta^6,$$



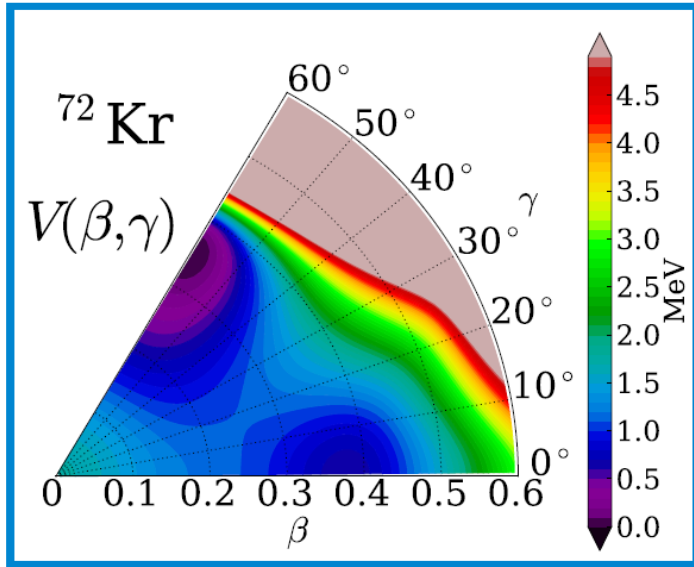
(a)  $0_1$  state    (b)  $2_1$  state    (c)  $4_1$  state    (d)  $6_1$  state    (e)  $8_1$  state



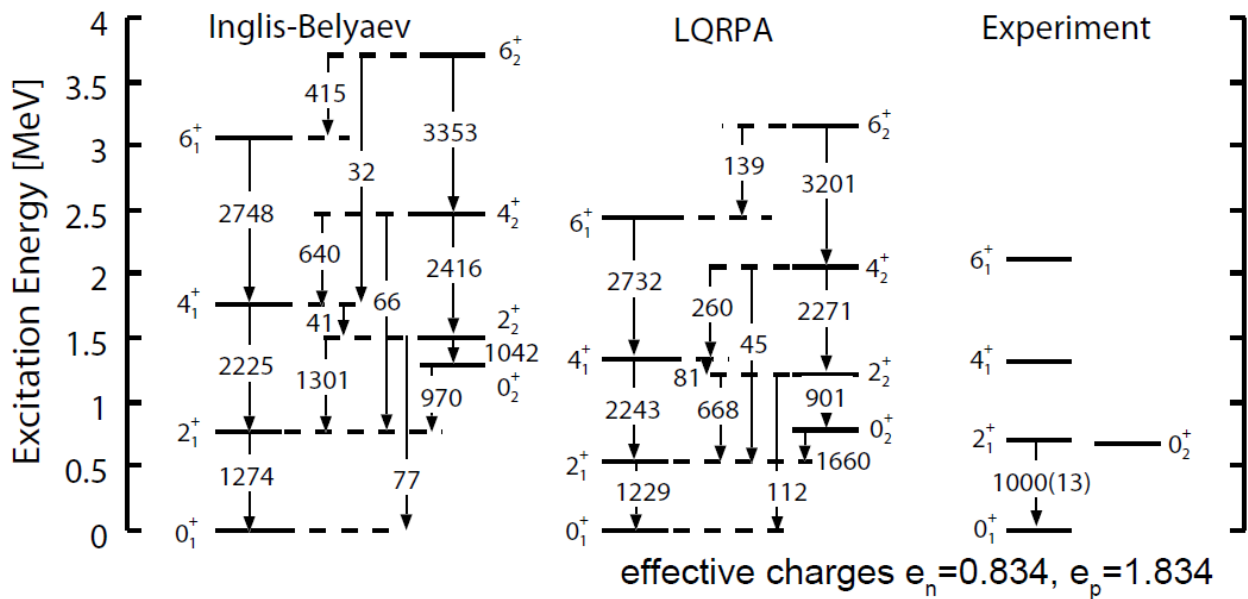
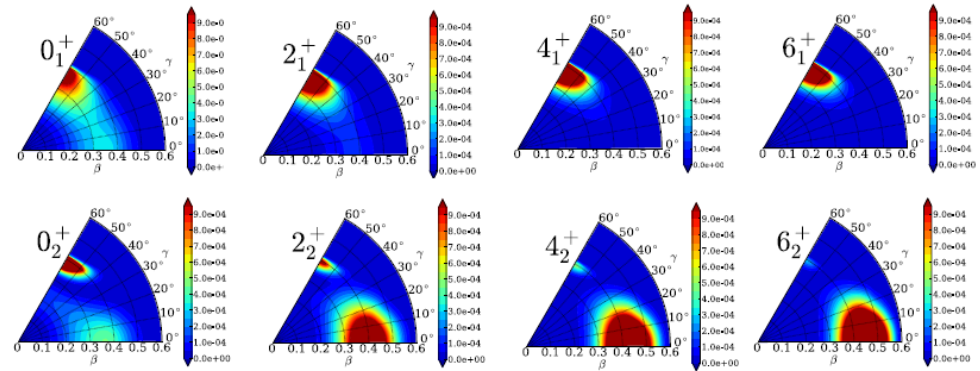
(f)  $0_2$  state    (g)  $2_2$  state    (h)  $4_2$  state    (i)  $6_2$  state    (j)  $8_2$  state

# Oblate-Prolate shape coexistence in $^{72}\text{Kr}$

K. Sato and NH, submitted to NPA, arXiv:1006.3694

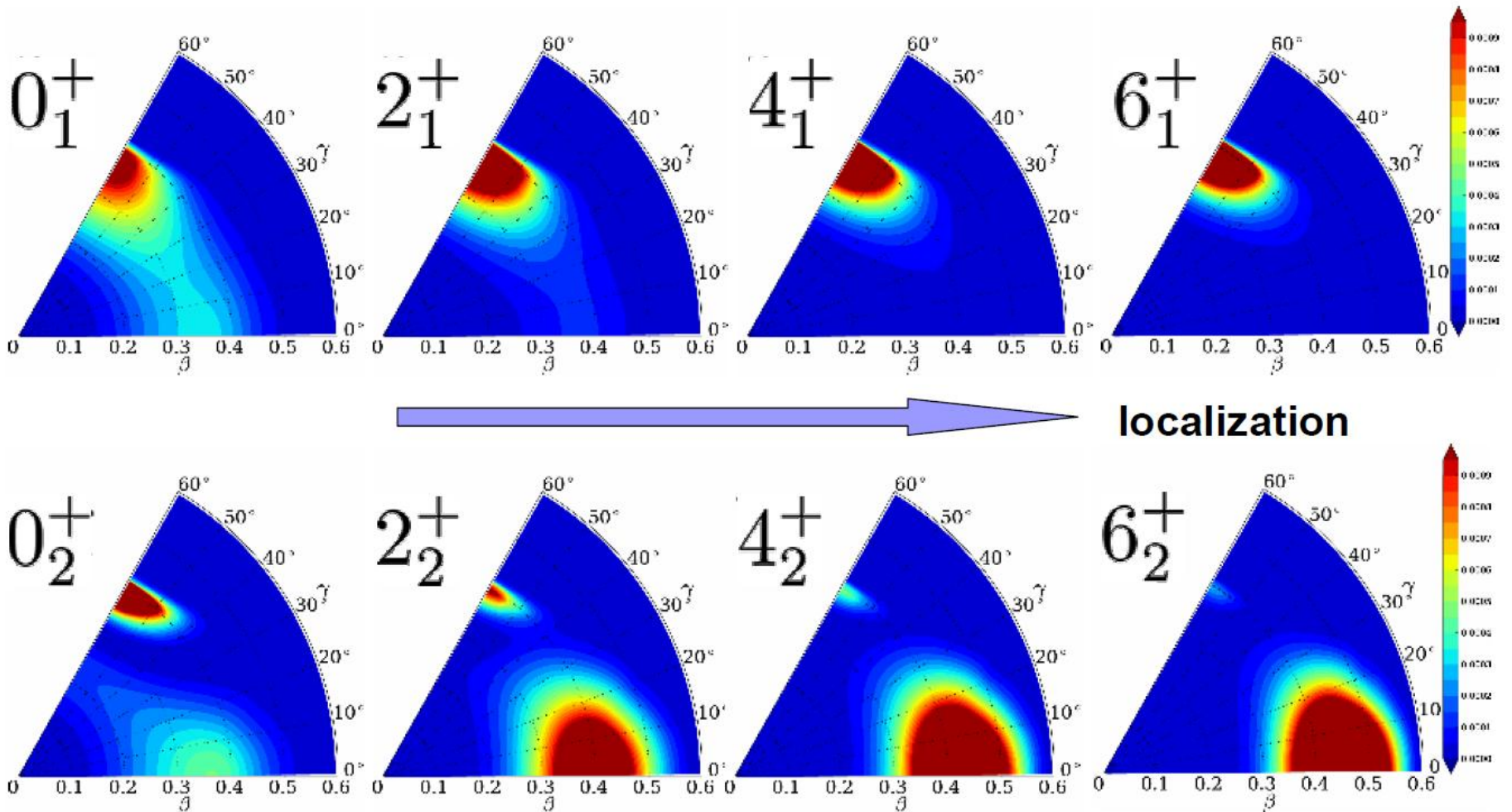


## Shape mixing in collective w.f.



Collective wave functions squared for <sup>72</sup>Kr

$$\beta^4 \sum_K |\Phi_{IKk}(\beta, \gamma)|^2$$

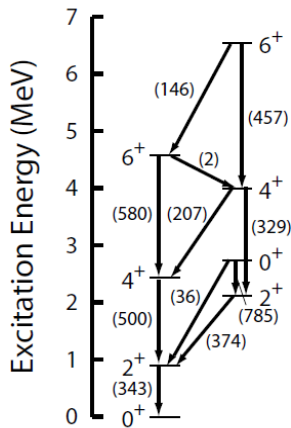
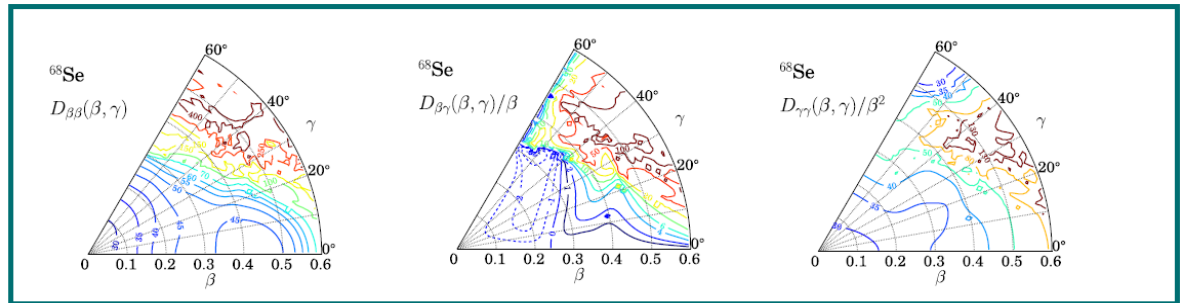
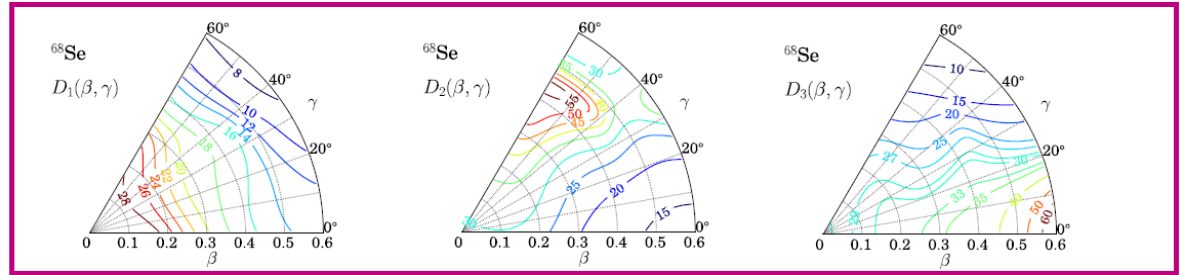
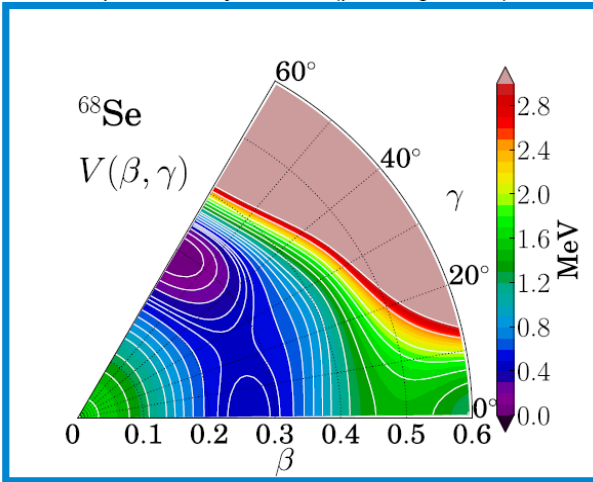


# Oblate-Prolate shape mixing in $^{68}\text{Se}$

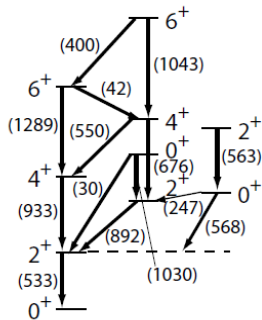
$$\mathcal{J}_k(\beta, \gamma) = 4\beta^2 D_k(\beta, \gamma) \sin^2 \gamma_k$$

arXiv:1004.5544

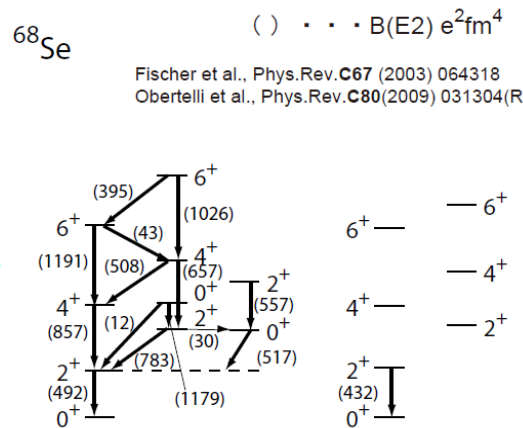
microscopic Hamiltonian: P0+P2+Q model  
 parameters adjusted to Skyrme HFB (SIII)  
 model space: 2 major shells (pf + sdg shells)



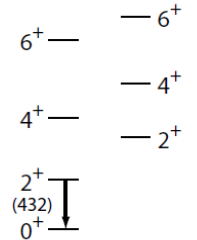
(1+3)D ASC



CHB+IB

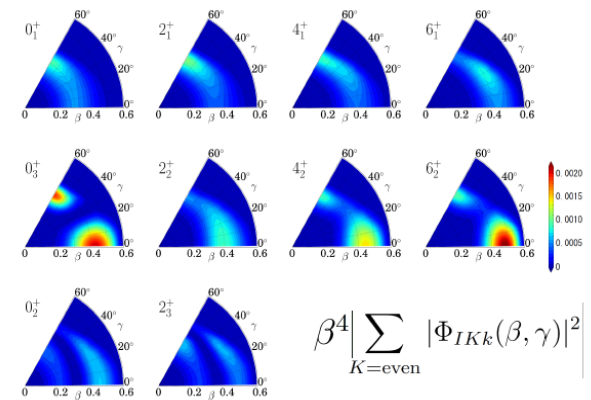


CHB+LQRPA



EXP

## Shape mixing in collective w.f.



$$\beta^4 \left| \sum_{K=\text{even}} |\Phi_{IKk}(\beta, \gamma)|^2 \right|$$



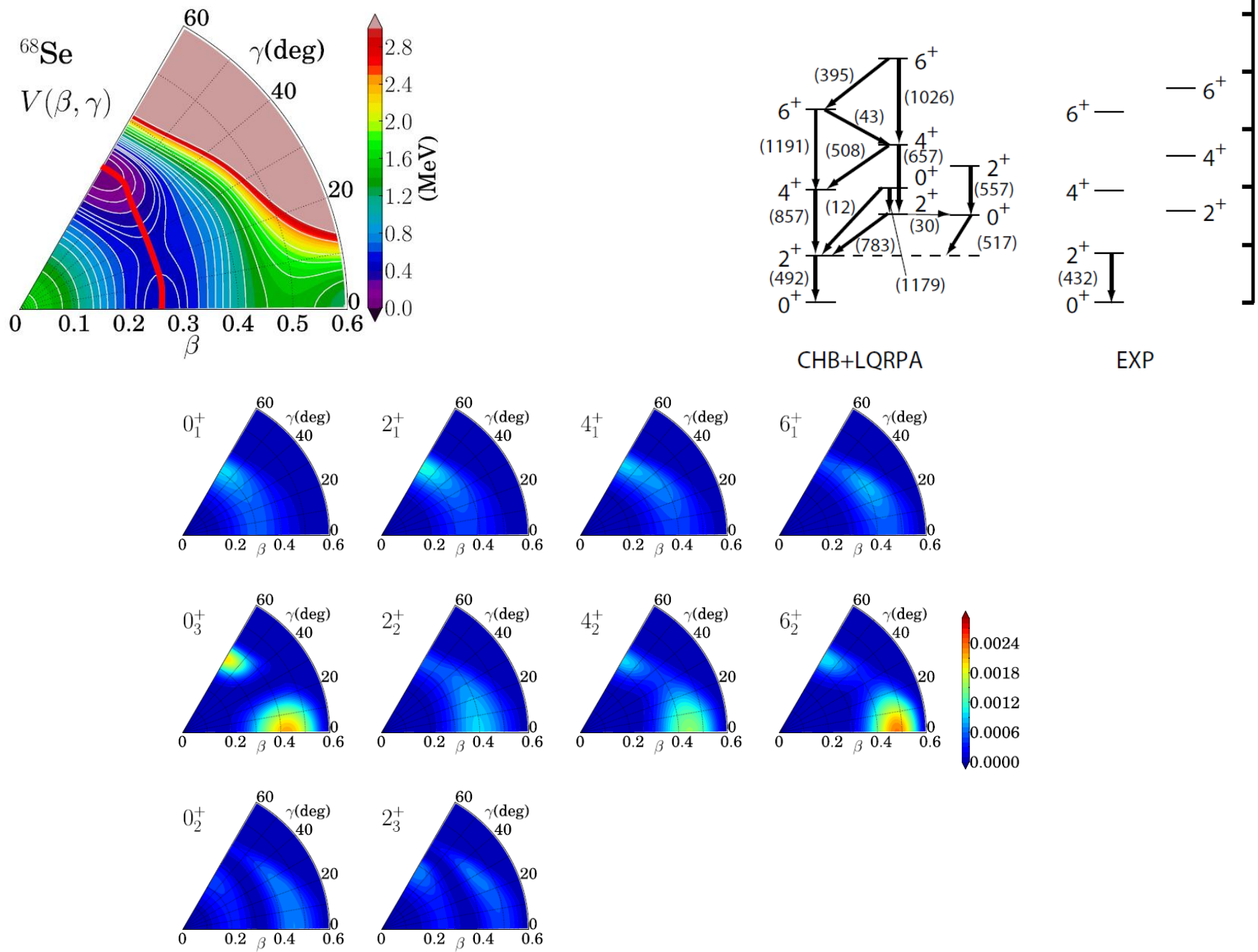
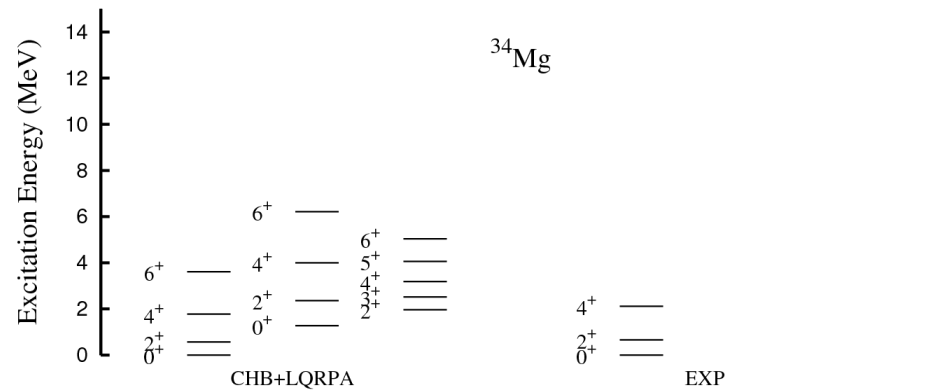
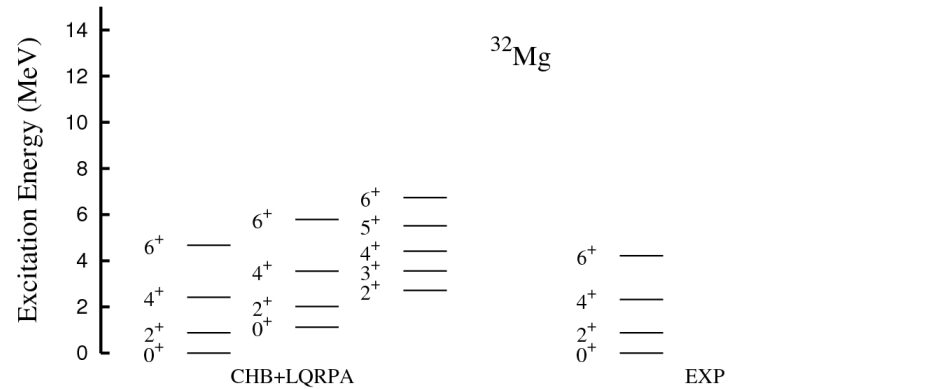
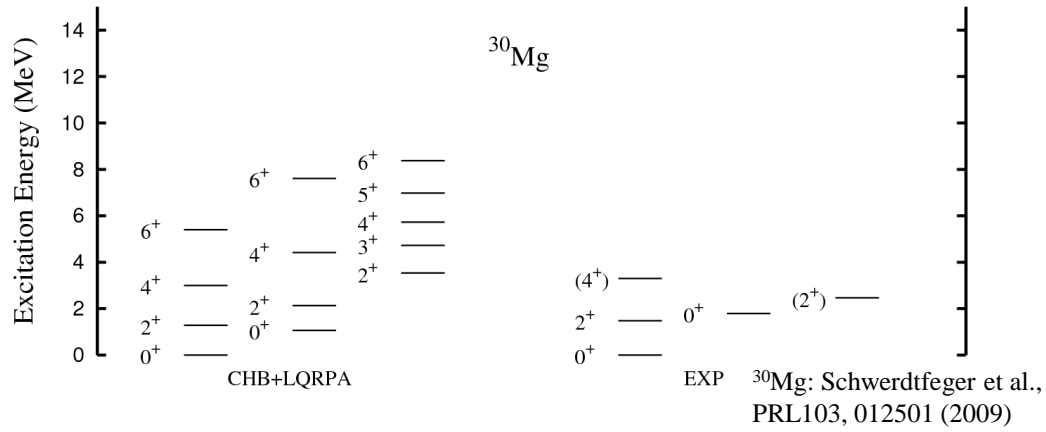
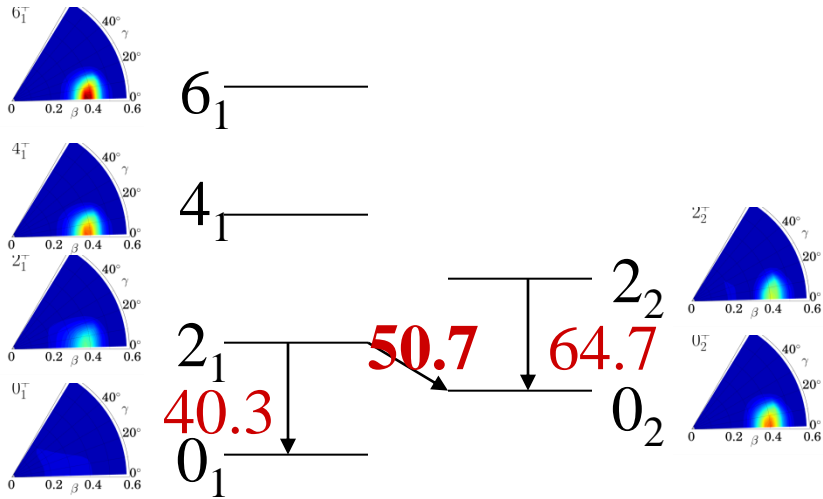


FIG. 11: (Color online) Vibrational wave functions squared  $\beta^4 |\Phi_{Ik}(\beta, \gamma)|^2$  calculated for  $^{68}\text{Se}$ .

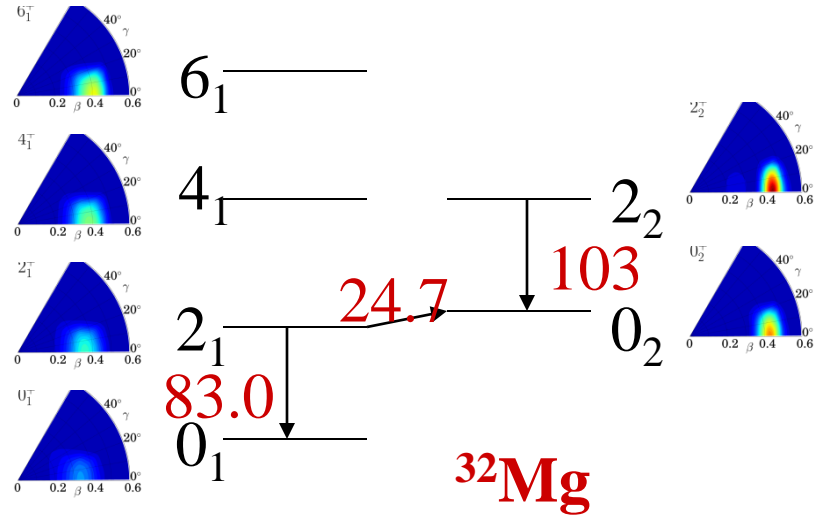
# Energy spectra



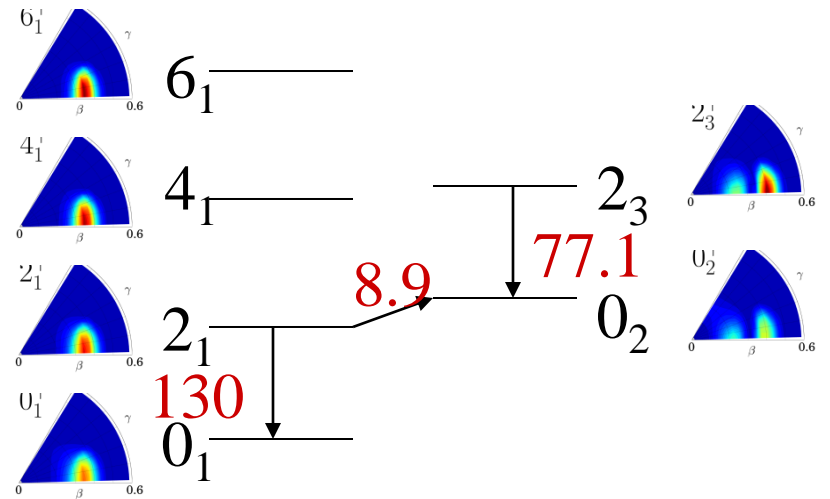
# Shape mixing properties



**$^{30}\text{Mg}$**

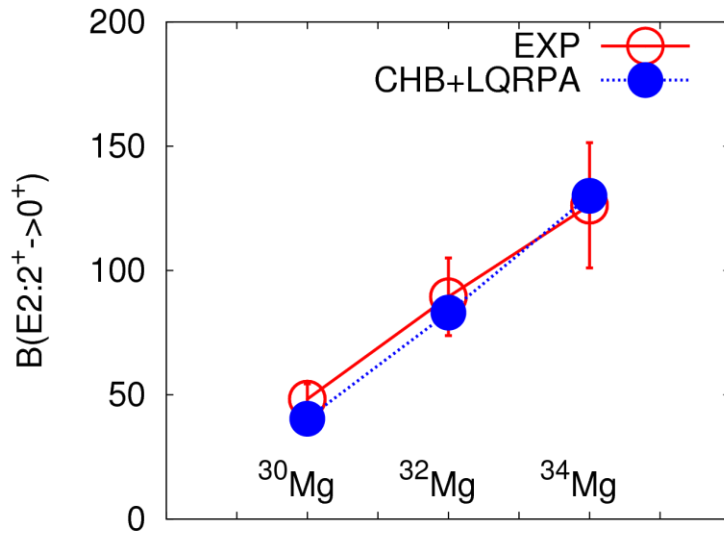
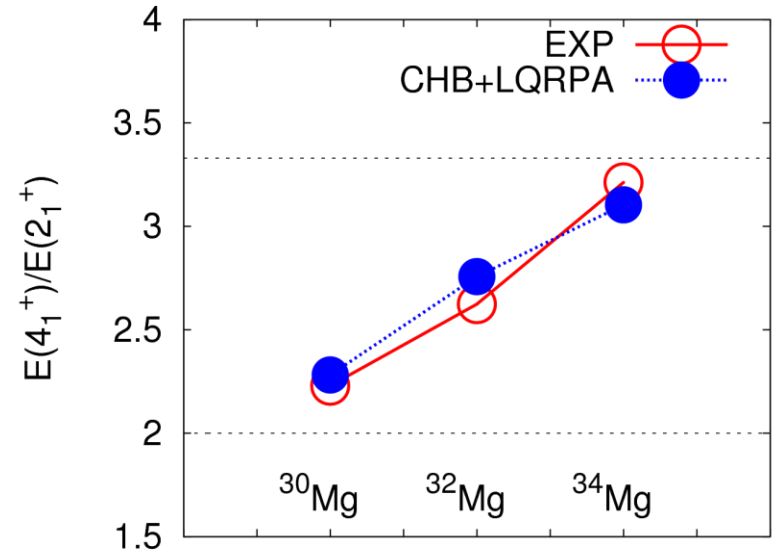
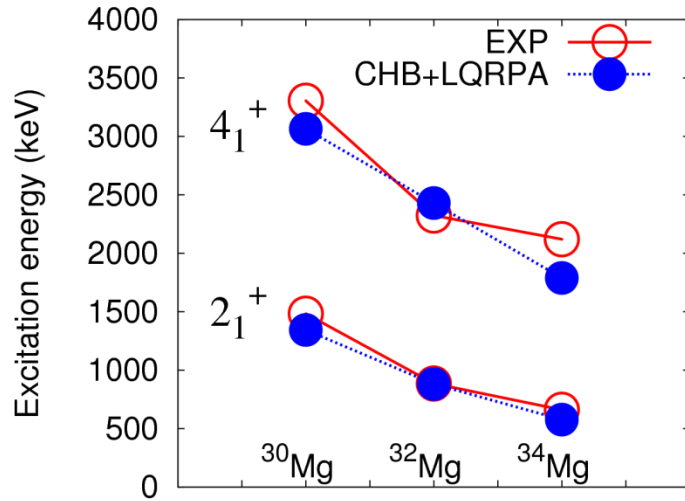


**$^{32}\text{Mg}$**



**$^{34}\text{Mg}$**

# Ground bands



$M_n/M_p / (N/Z)$

	$^{30}\text{Mg}$	$^{32}\text{Mg}$	$^{34}\text{Mg}$
$2^+ \rightarrow 0^+$	0.789	0.815	0.807

0.84(15)

EXP, Takeuchi et al.

$^{30}\text{Mg}$ : assume 3303 keV to be  $4^+$

$^{32}\text{Mg}$ : Takeuchi et al. PRC79 (2009) 054319

$^{34}\text{Mg}$ : Yoneda et al. PLB499 (2001) 233

$B(E2)$   $^{30}\text{Mg}$ : Niedermaier et al. PRL94 (2005) 172501

$^{32}\text{Mg}$ : Motobayashi et al. PLB346 (1995) 9

$^{34}\text{Mg}$ : Iwasaki et al. PLB522 (2001) 227.



# Unified model of Bohr and Mottelson

集団座標

集団運動量

平均場中の粒子のハミルトニアン

$$H = H_{coll}(\boldsymbol{\alpha}, \boldsymbol{\pi}) + H_{part}(\boldsymbol{r}, \boldsymbol{\alpha})$$

平均場の集団運動ハミルトニアン

粒子座標

$$H_{coll} = T_{coll}(\boldsymbol{\alpha}, \boldsymbol{\pi}) + V_{coll}(\boldsymbol{\alpha})$$

平均場の振動と回転の運動エネルギー

$$T_{coll} = T_{rot}(\boldsymbol{\alpha}, \boldsymbol{\pi}) + T_{vib}(\boldsymbol{\alpha}, \boldsymbol{\pi})$$

四重極変形の場合の古典的集団ハミルトニアン

$$H_{coll}^{(classical)} = \frac{1}{2} B_{\beta\beta}(\beta, \gamma) \dot{\beta}^2 + \frac{1}{2} B_{\beta\gamma}(\beta, \gamma) \dot{\beta} \dot{\gamma} + \frac{1}{2} B_{\gamma\gamma}(\beta, \gamma) \dot{\gamma}^2 + \frac{1}{2} \sum_{\kappa=1,2,3} \mathcal{J}_{\kappa}(\beta, \gamma) \omega_{\kappa}^2 + V_{coll}(\beta, \gamma)$$

これを量子化する(曲がった空間での量子化)

## Particle-Rotor coupling モデル

平均場の振動を凍結(freeze)する

$$\alpha \implies \alpha_0 \text{ (平衡点での値)}$$

$$T_{vib}(\alpha, \pi) \implies 0$$

$$H_{part-rot} = T_{rot}(\alpha_0, \pi) + H_{part}(\mathbf{r}, \alpha_0)$$

## Particle-Vibration coupling モデル

回転運動を無視する(平均場が変形している場合)

$$T_{rot}(\alpha, \pi) \implies 0$$

$$H_{part-vib} = T_{vib}(\alpha, \pi) + H_{part}(\mathbf{r}, \alpha)$$

## 粒子-振動結合ハミルトニアン

$$\begin{aligned} H &= H_{\text{coll}}(\pi, \alpha) + \sum_{i=1}^A \left( \frac{\mathbf{p}^2}{2m} + U(\mathbf{x}, \alpha) \right)_i \\ &= H_{\text{coll}}(\pi, \alpha) + H_{\text{particle}}(\mathbf{p}, \mathbf{x}, \alpha^0) + H_{\text{coupl}}(\mathbf{x}, \alpha) \end{aligned}$$

$$H_{\text{particle}}(\mathbf{p}, \mathbf{x}, \alpha^0) = \sum_{i=1}^A \left( \frac{\mathbf{p}^2}{2m} + U(\mathbf{x}, \alpha^0) \right)_i$$

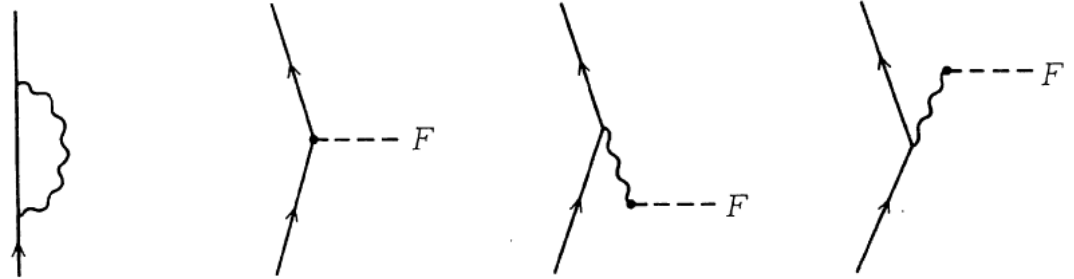
$$H_{\text{coupl}}(\mathbf{x}, \alpha) = \sum_{i=1}^A (U(\mathbf{x}, \alpha) - U(\mathbf{x}, \alpha^0))_i$$

$$U(r, \theta, \varphi, \alpha) = U^{(0)}(r) - R_0 \frac{\partial U^{(0)}}{\partial r} \sum_{\lambda\mu} Y_{\lambda\mu}(\theta, \varphi) \alpha_{\lambda\mu}^* + \dots$$

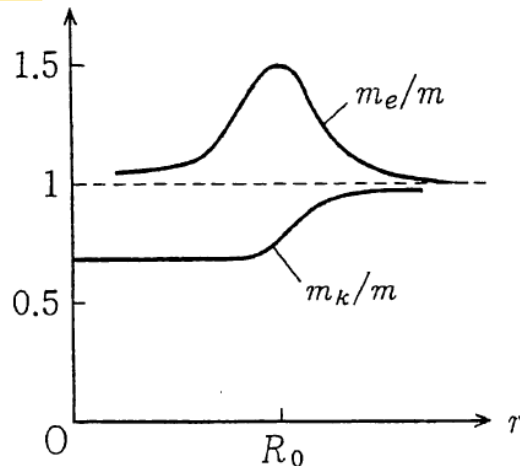
$$H_{\text{coupl}}(\mathbf{x}, \alpha) \cong - \sum_{i=1}^A \sum_{\lambda\mu} (k_{\lambda}(r) Y_{\lambda\mu}(\theta, \varphi) \alpha_{\lambda\mu}^*)_i$$

$$k_{\lambda}(r) = R_0 \frac{\partial U^{(0)}}{\partial r}$$

着物を着た1粒子モード



有効質量



有効結合結合定数

