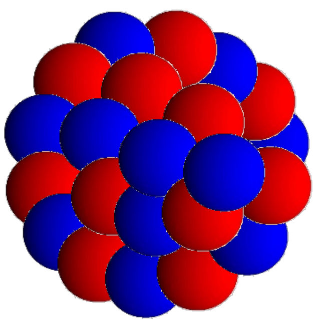
原子核基礎論B

原子核理論研究室（物2）
萩野浩一

シラバス

萩野
1. 原子核の集団運動とその微視的理解（3コマ）
2. 原子核反応論基礎（1コマ）
3. 核融合反応（1コマ）
4. 核分裂：現象論と微視的理論（1コマ）
5. ニホニウムと超重元素の物理（1コマ）

大西
6. 高温・高密度核物質外観（1コマ）
7. 高エネルギー重イオン衝突（2コマ）
8. 有限温度・密度における場の理論入門（2コマ）
9. QCD有効模型における相転移と相図（1コマ）
10. 有限温度・密度格子QCDと符号問題（1コマ）



シラバス（基礎論A）

5. 殻模型と魔法数（1コマ）
6. 平均場理論と核変形（3コマ）
7. 中性子過剰核の物理（2コマ）
8. 非束縛核と共鳴散乱理論（1コマ）

主に基底状態

→ 基礎論Bで

シラバス（基礎論B）

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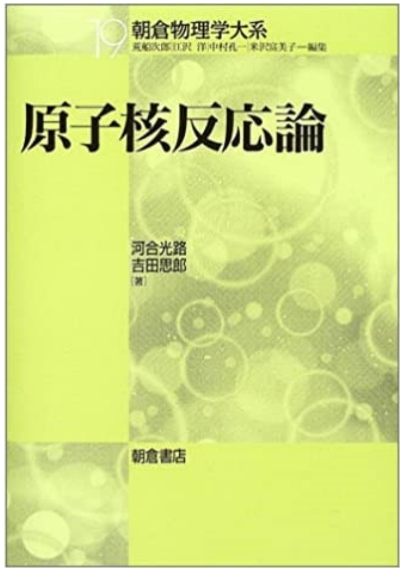
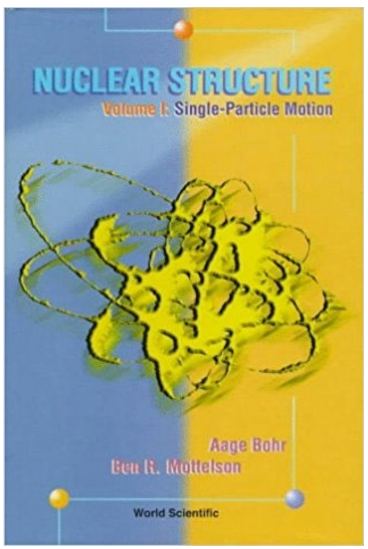
主に励起状態と核反応

成績:　　レポート80%、出席など20%

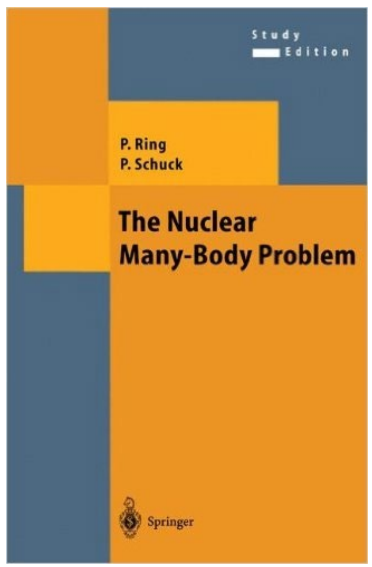
質問:　　適宜聞いて下さい。
チャットに書き込んでもOK。

参考書

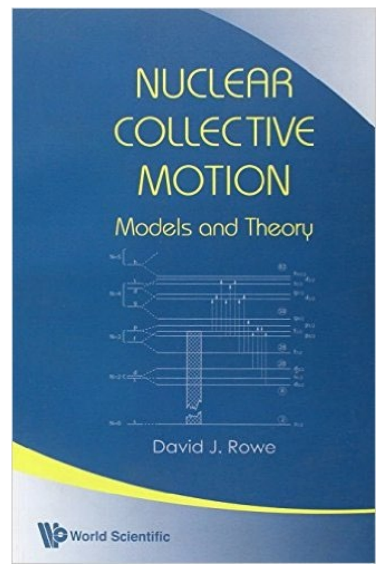




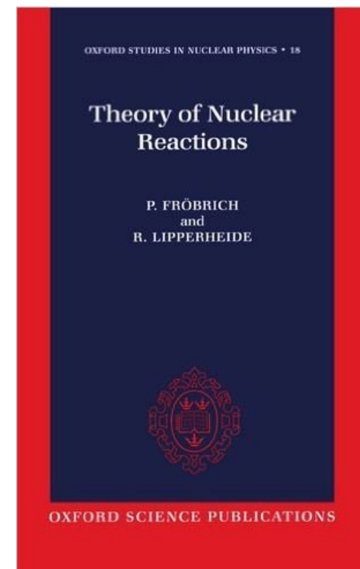
Bohr-Mottelson



Ring-Schuck



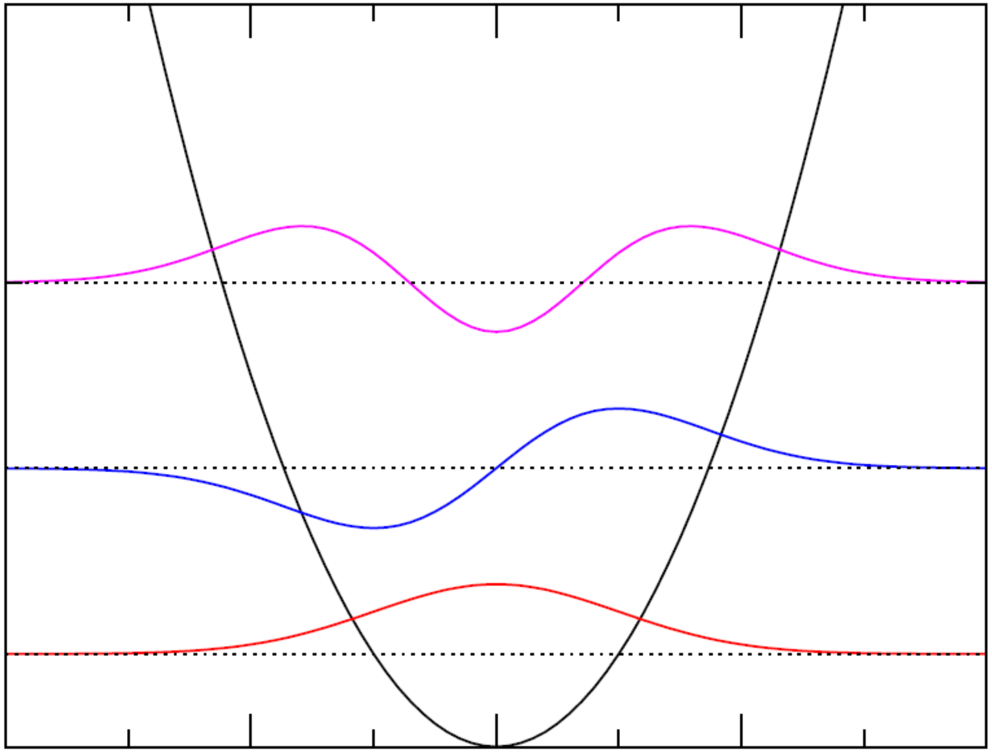
Rowe



Frobrich
-Lipperheide

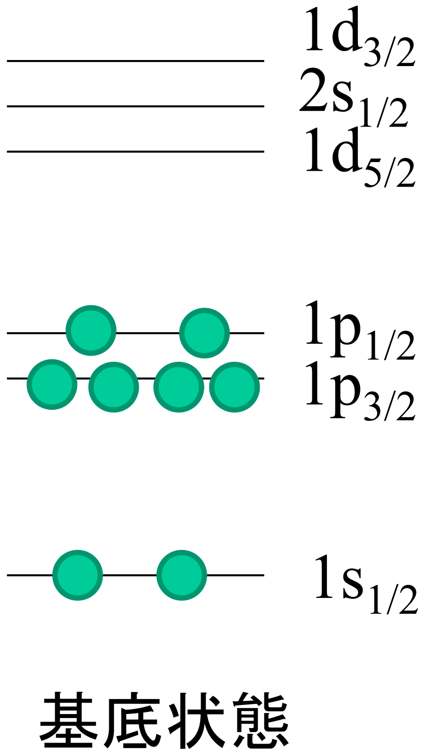
励起状態

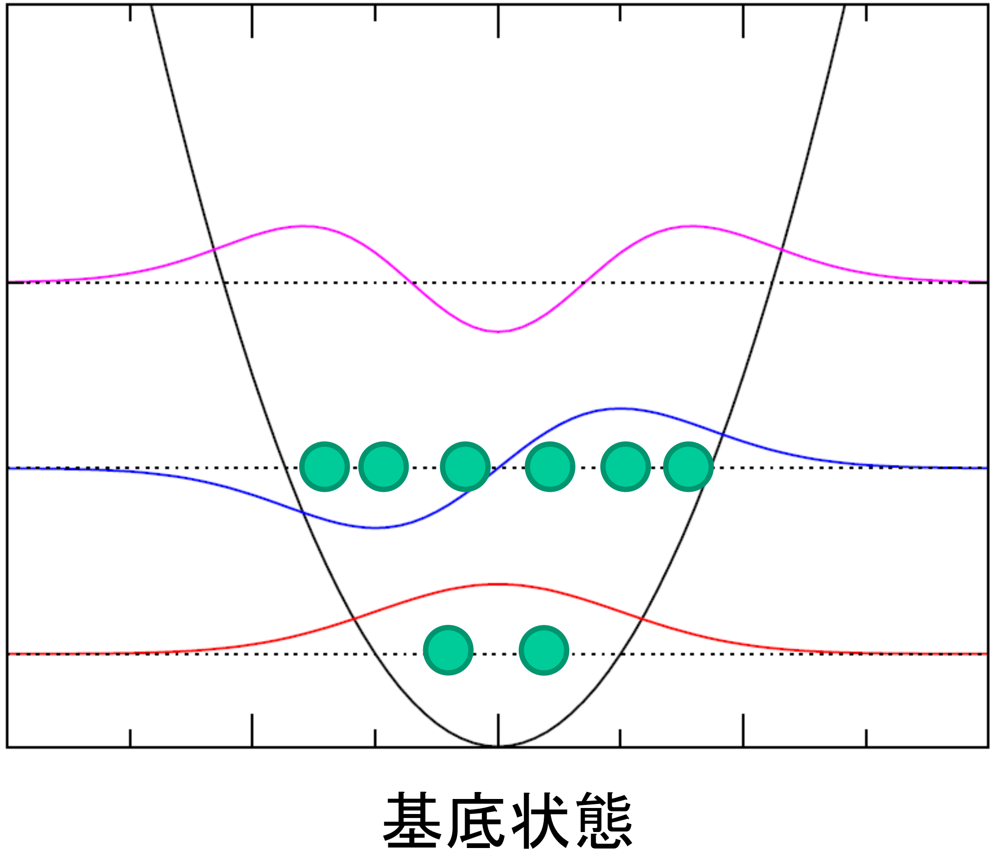
ポテンシャル中の1粒子の場合



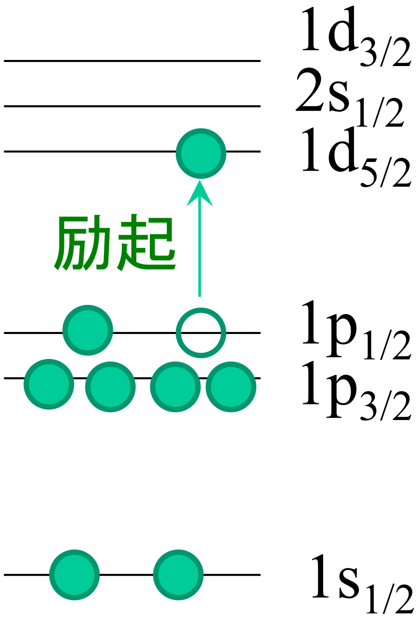
原子核の励起状態

多体系の場合





原子核の励起状態



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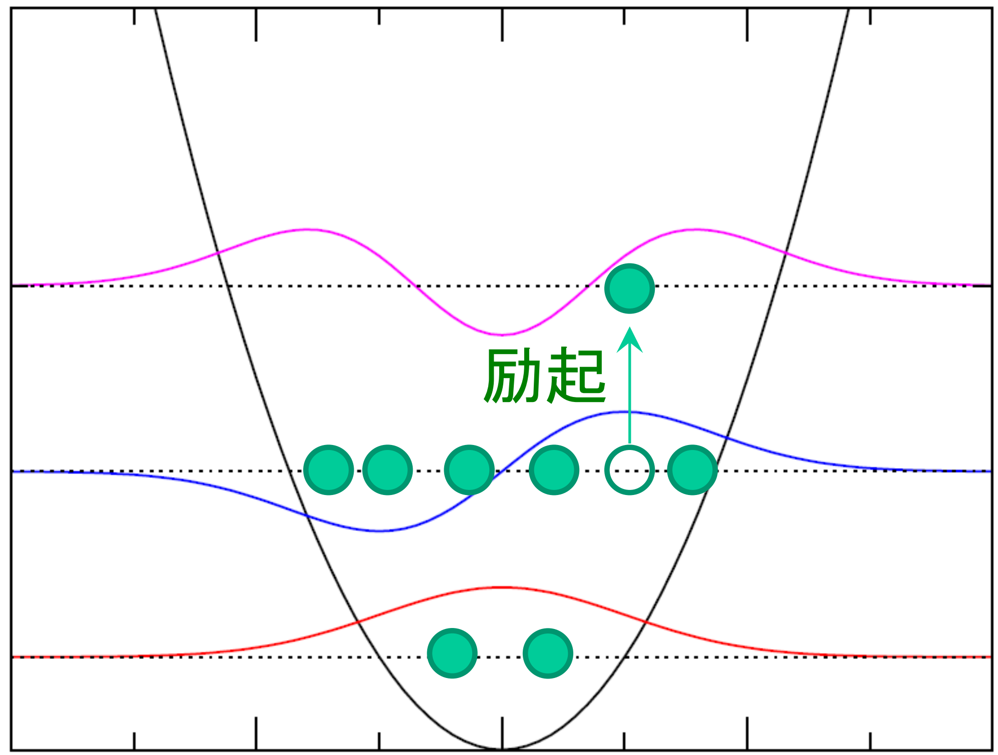

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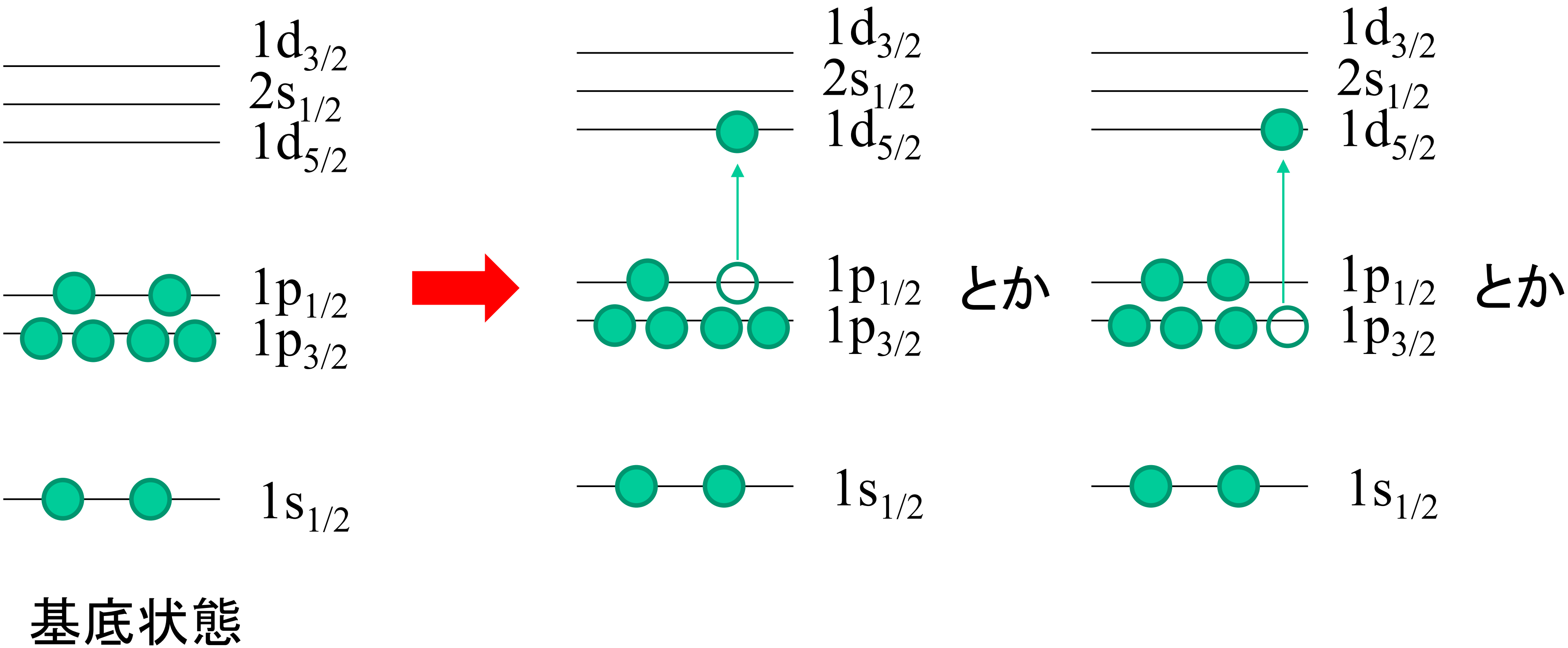
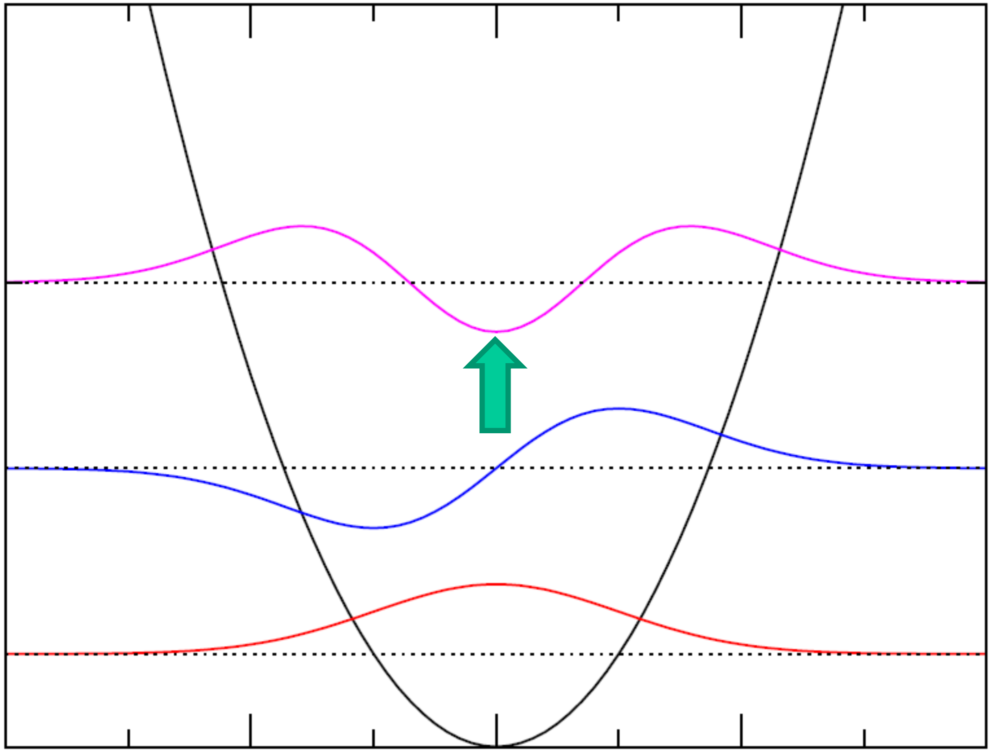


$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
基底状態
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
とか
$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
$1s_{1/2}$
とか



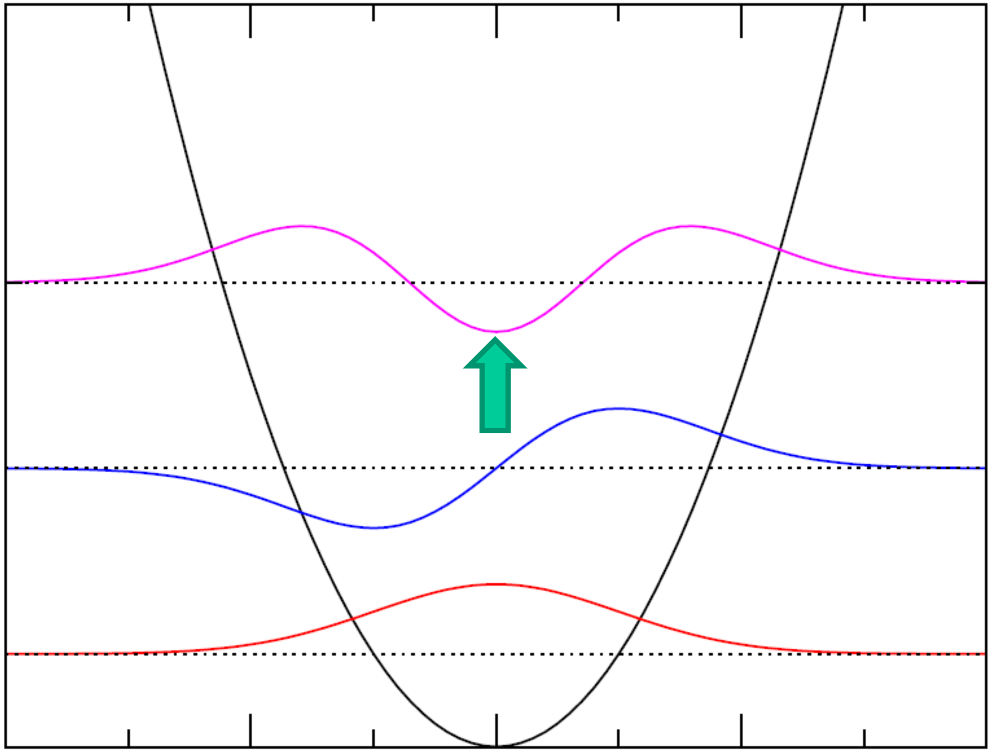
原子核では

$\hbar\omega \sim 41\,A^{-1/3}$ (MeV)

$\longleftarrow$ $R \sim 1.2\,\mathrm{A}^{1/3}$ (fm)

A = 16 だと 16.27 MeV

cf. 実際に、^{16}Oの16.2 MeV
に 1^- 状態



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← $R \sim 1.2\, \mathrm{A}^{1/3}$ (fm)

A = 16 だと 16.27 MeV

cf. 実際に、^{16}Oの16.2 MeV
に 1^- 状態

………でも実際にはこのようには理解できない励起状態
も多数存在する（集団励起）

Giant Dipole Resonance (GDR) 巨大双極子共鳴

光吸収のスペクトル

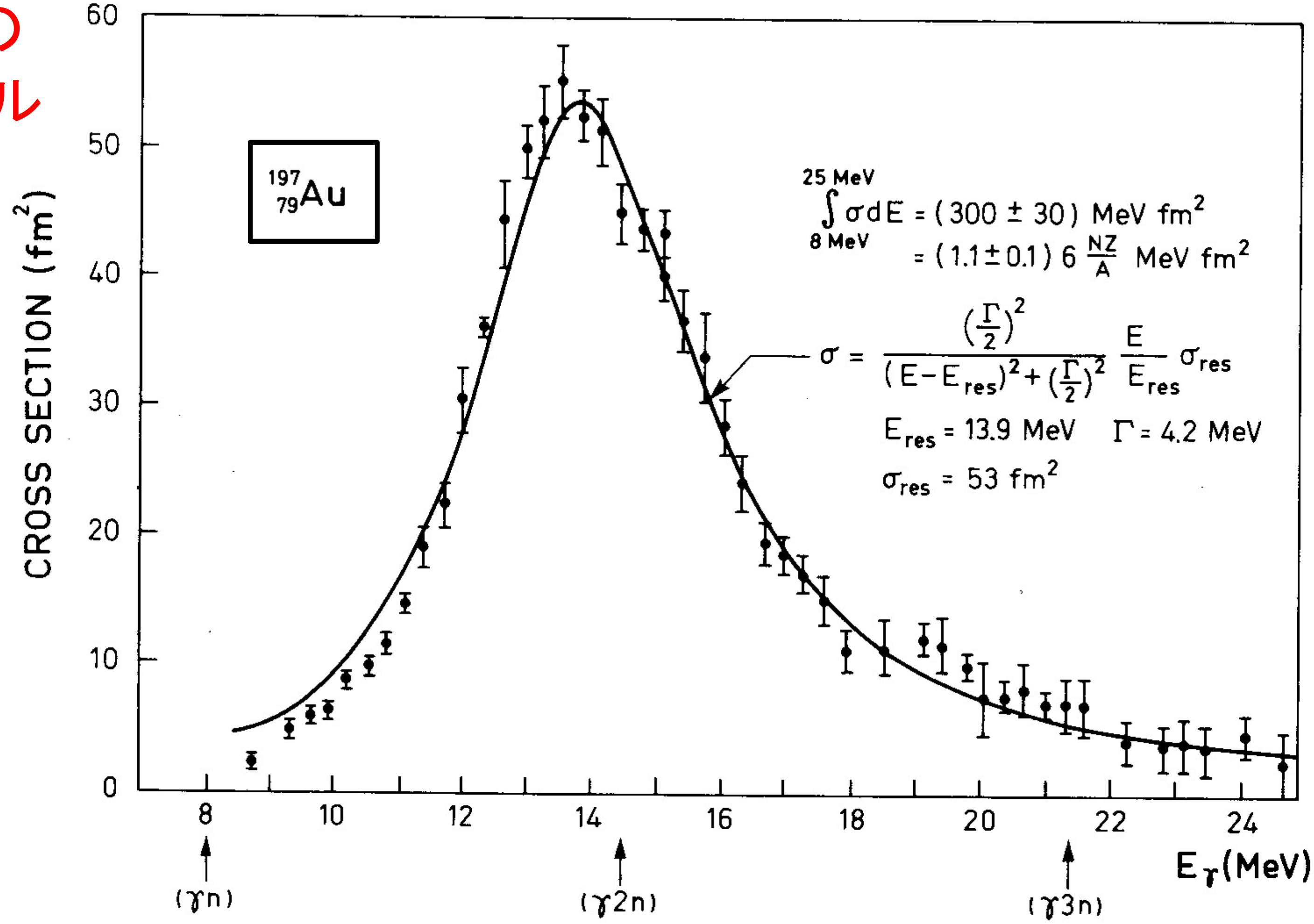


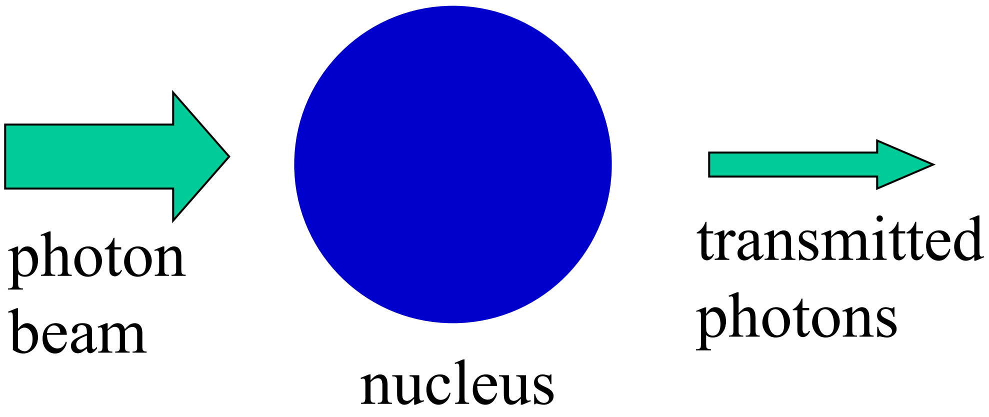
Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

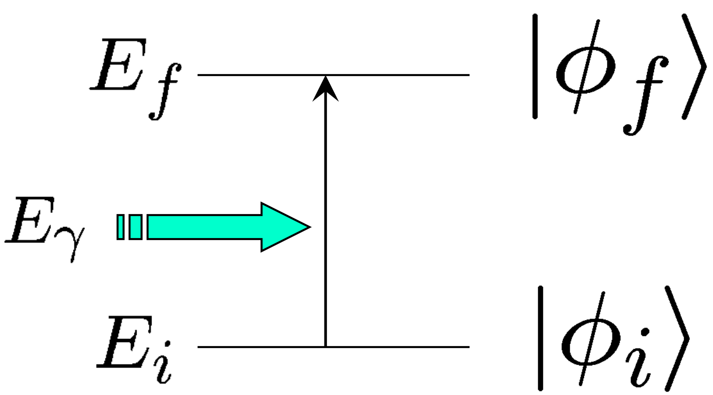
cf. $41 \times 197^{-1/3} = 7.05$ MeV

Collective Vibrations

How does a nucleus respond to an external perturbation?

i) Photo absorption cross section





The state is strongly excited when $E_f - E_i = E_\gamma$.

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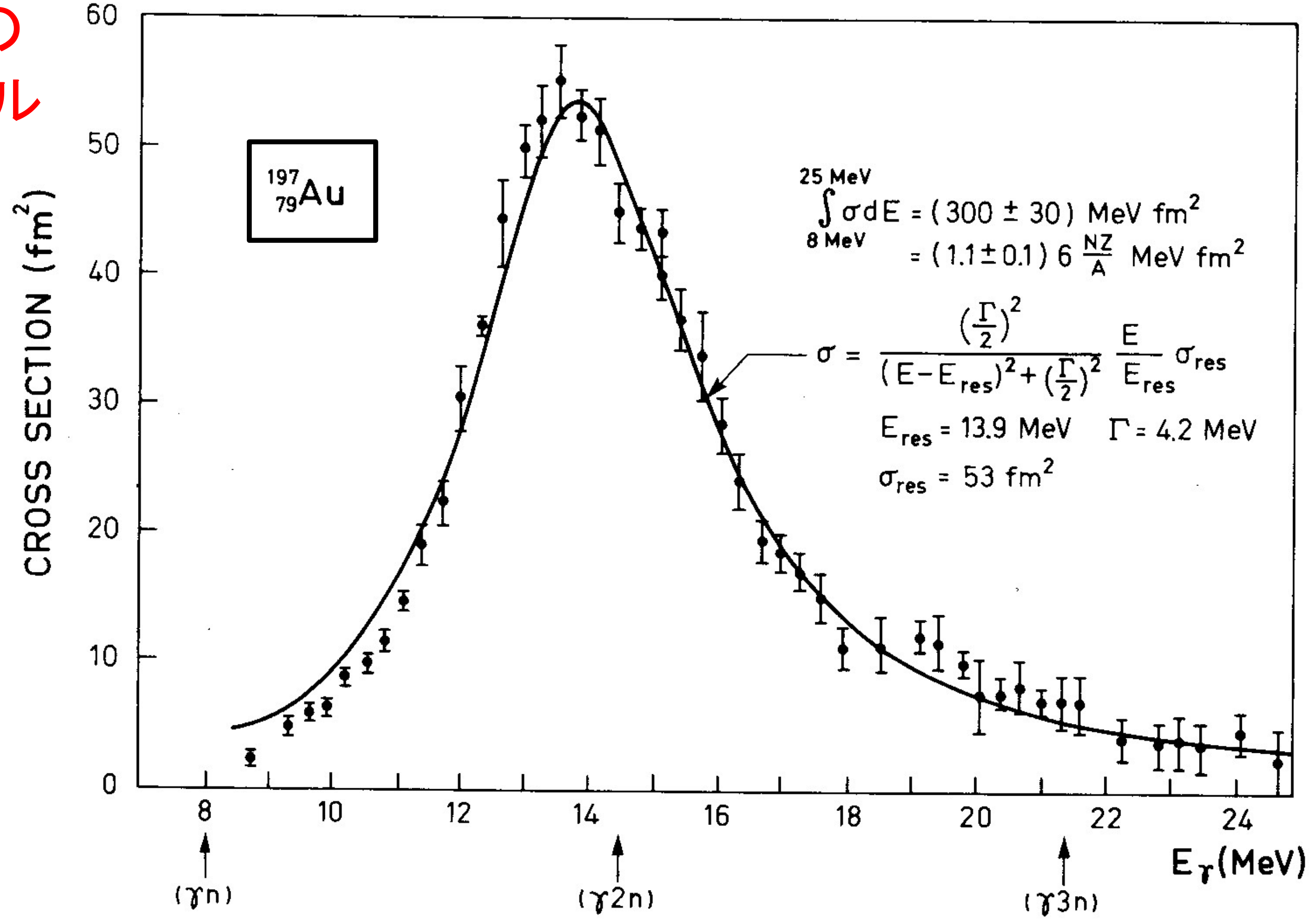
光吸収のスペクトル



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cf. $41 \times 197^{-1/3} = 7.05$ MeV

Remarks

i) Photon interaction ⟷ dipole excitation

$$H_{\text{int}} = \frac{1}{2m}\frac{e}{c}(\boldsymbol{p}\cdot\boldsymbol{A}+\boldsymbol{A}\cdot\boldsymbol{p})$$

$$\boldsymbol{A}(\boldsymbol{r},t) = \sum_{\boldsymbol{k}}\sum_{\alpha=1,2}\sqrt{\frac{2\pi c^2\hbar}{\omega V}}(a_{\boldsymbol{k}\alpha}\,\epsilon_\alpha\,e^{i\boldsymbol{k}\cdot\boldsymbol{r}-i\omega_k t}+h.c.)$$

$$e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \sim 1 \qquad \text{(dipole approximation)}$$

Remarks

i) Photon interaction ⟷ dipole excitation

E_γ = 10 MeV, R = 5 fm だと $kR \sim 0.25$

$$H_{\rm int} = \frac{1}{2m}\frac{e}{c}(\boldsymbol{p}\cdot\boldsymbol{A}+\boldsymbol{A}\cdot\boldsymbol{p})$$

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$$e^{i\boldsymbol{k}\cdot\boldsymbol{r}} \sim 1$$ (dipole approximation)

$$\sigma_{\rm abs}(E_\gamma) = \frac{4\pi^2e^2}{\hbar c}(E_f-E_i)|\langle\phi_f|\tilde{z}|\phi_i\rangle|^2\,\delta(E_\gamma-E_f+E_i)$$

$$\tilde{z} = \sum_p (z_p - Z_{cm})$$

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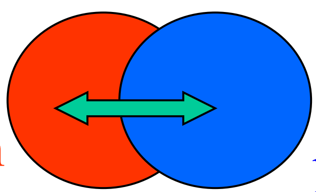
ii) Isospin

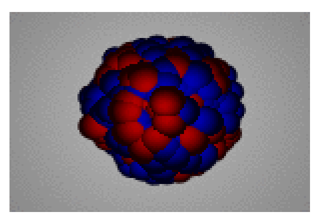
$$\tilde{z} = \sum_p (z_p - Z_{cm})$$

neutron

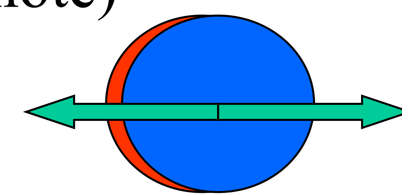


proton

Isovector type



(note)



Isoscalar dipole motion
⟷ c.m. motion (to the first order)

Remarks

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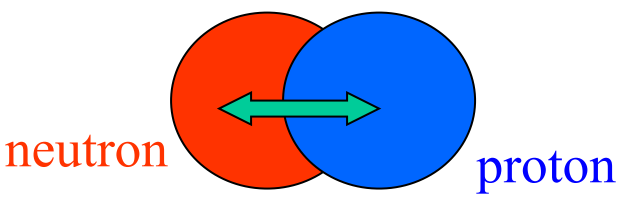
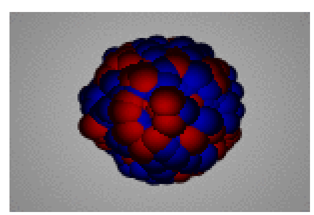
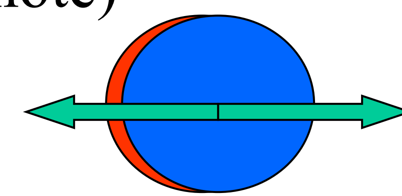


Isovector type



(note)



Isoscalar dipole motion
⟷ c.m. motion (to the first order)

iii) Collective motion

Motion of the whole nucleus rather than a single-particle motion

Giant Dipole Resonance (GDR) 巨大双極子共鳴

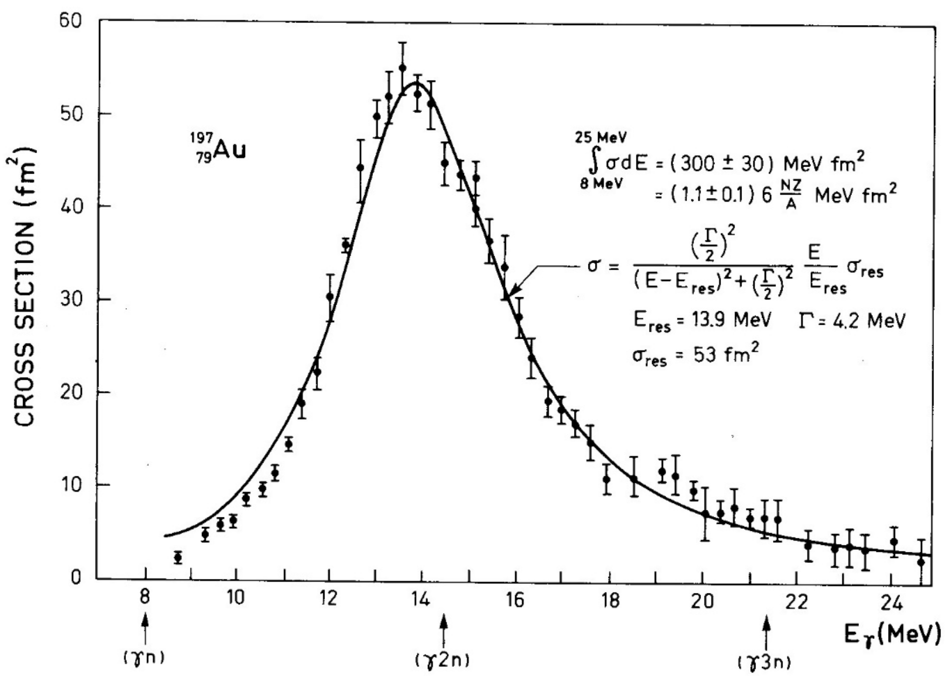


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

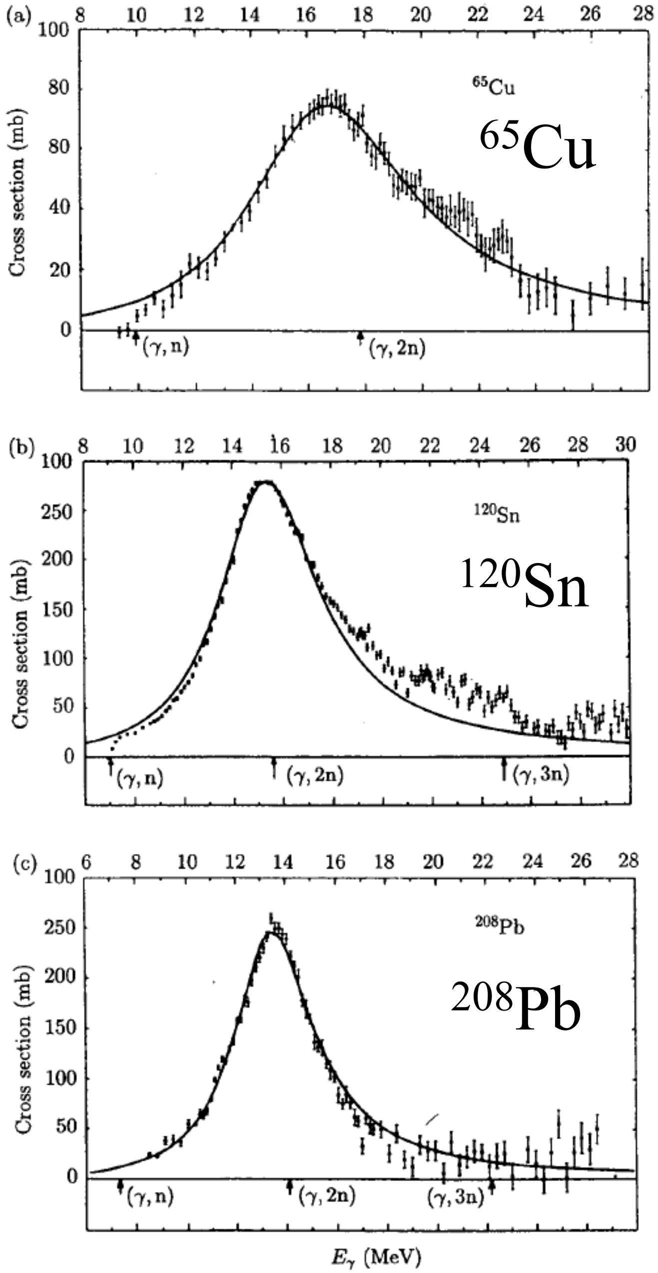
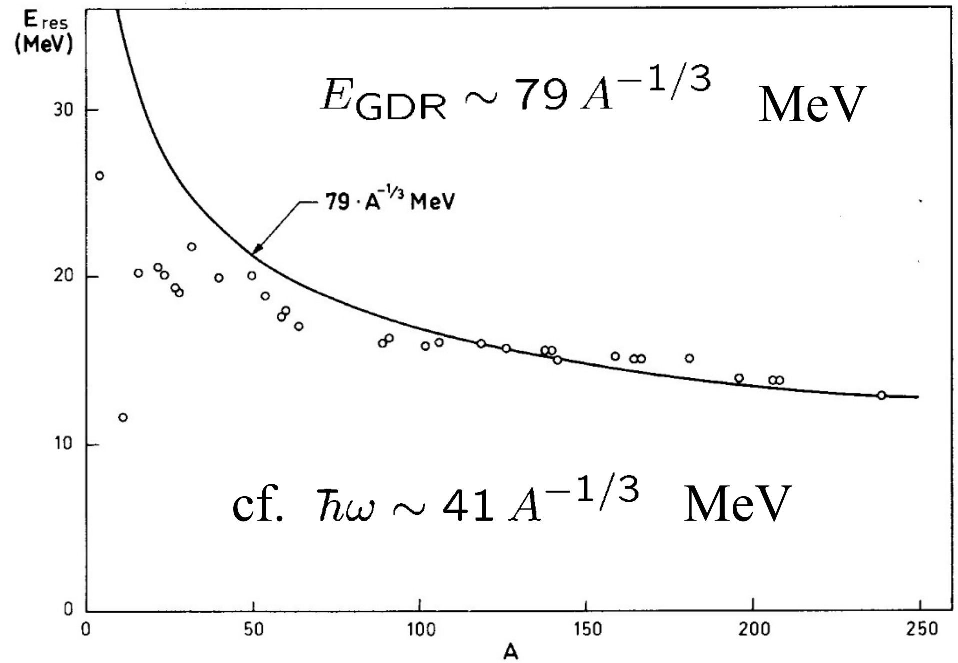
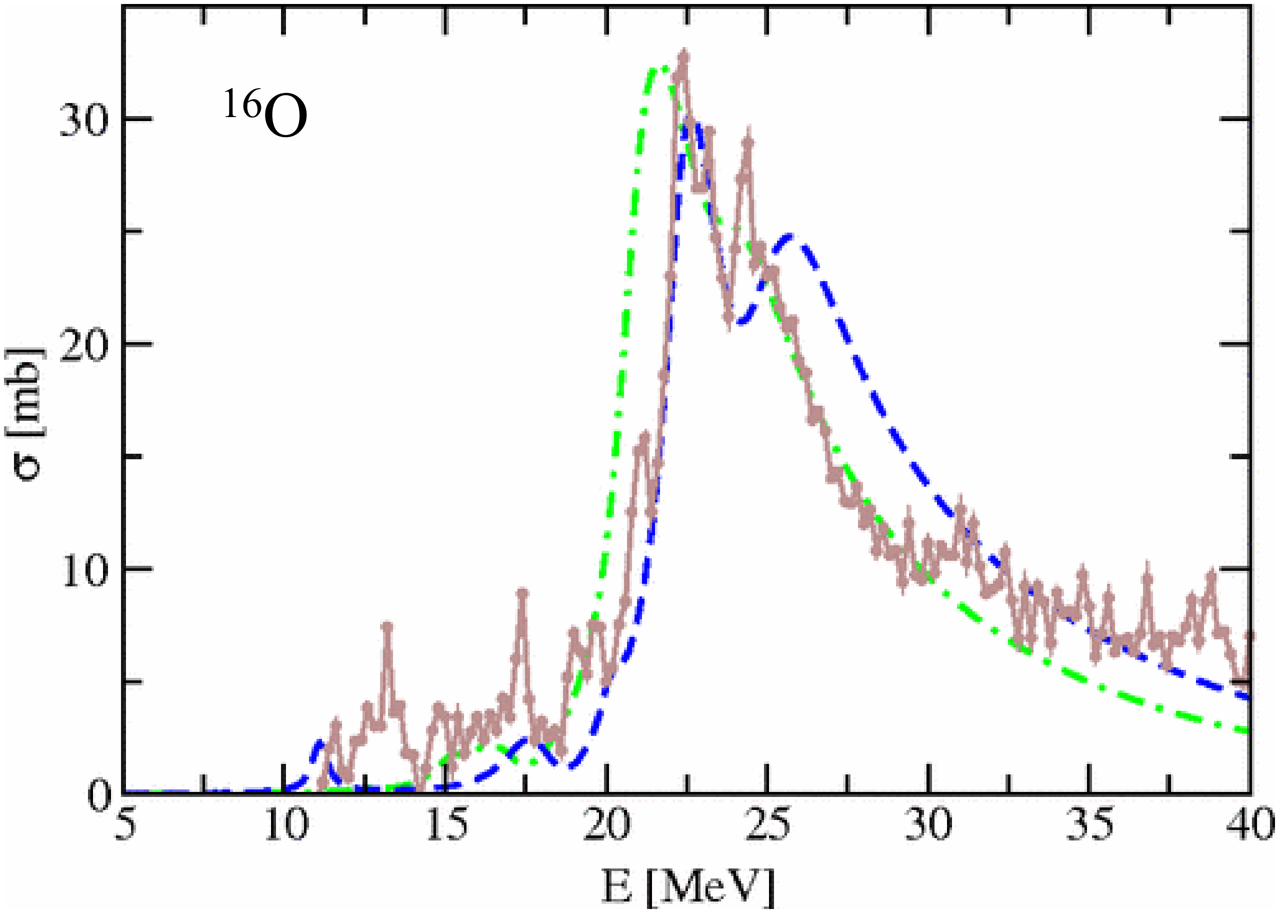


FIG. 1.2. The photo-neutron cross section $\sigma(\gamma, n)$ as a function of the photon energy for the three nuclei ^{208}Pb, ^{120}Sn and ^{65}Cu. Note that for these nuclei $\sigma(\gamma, n) \approx \sigma_{abs}(\gamma)$. From reference (BER75).



Bohr-Mottelson
"Nuclear Structure vol. II"

M.N. Harakeh and A. van der Woude,
"Giant Resonances"

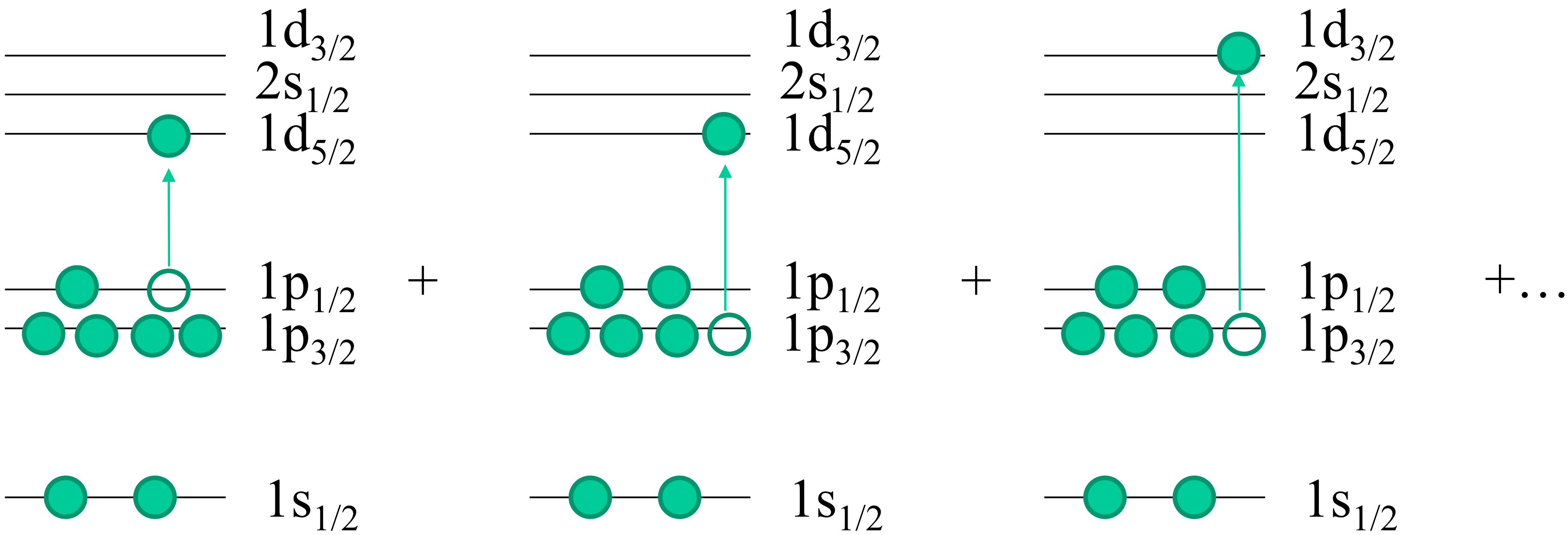


実験データ：茶色

N. Lyutorovich et al., Phys. Rev. Lett. 109 (2012) 092502

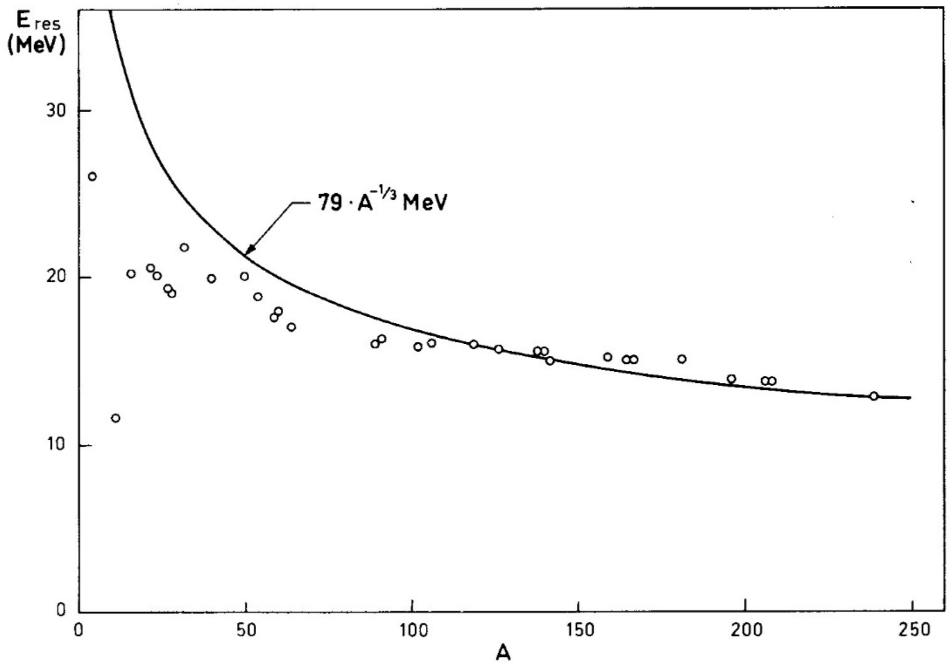
cf. $41 \times 16^{-1/3} = 16.27$ MeV

何故励起エネルギーが大きくなるのか？



様々な励起状態がコヒーレントに重ね合わさることにより「集団的」になる。→（次回もう少し詳しく）

残留相互作用が大きな役割



Bohr-Mottelson
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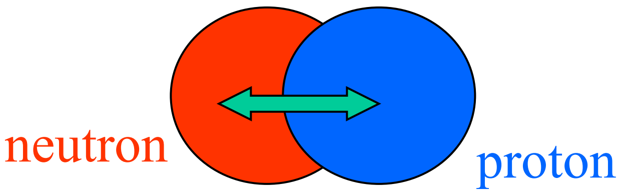

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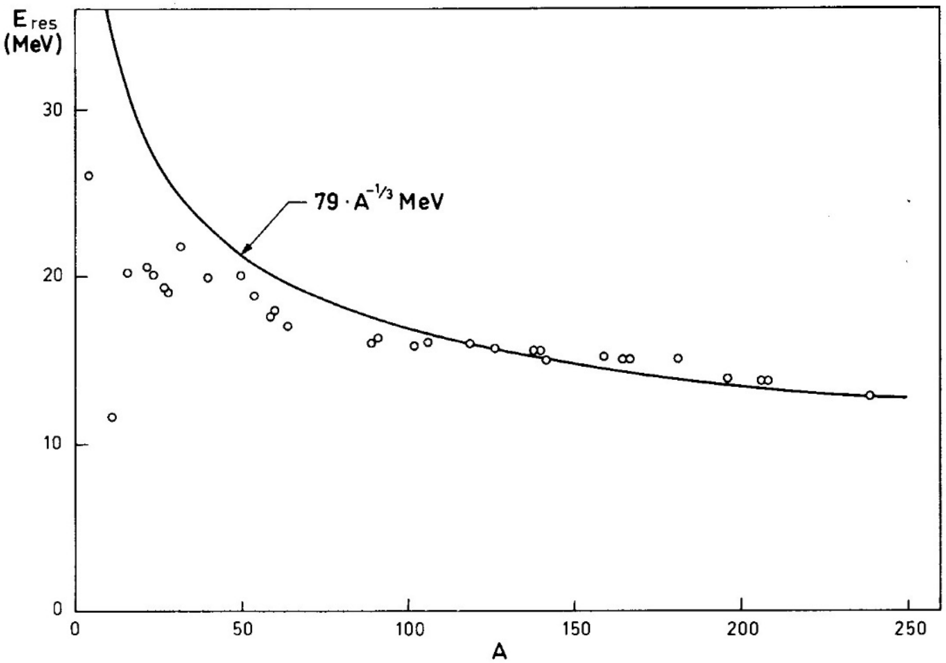
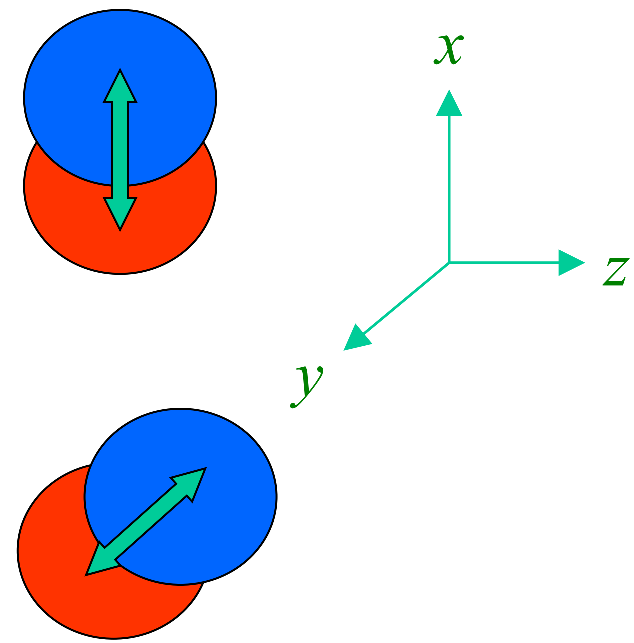
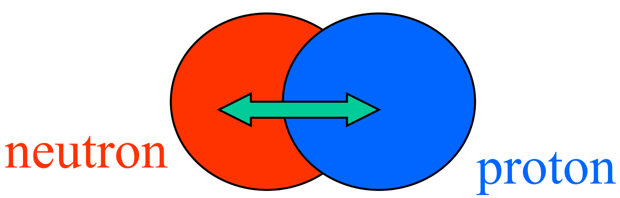


$$E_{\mathrm{GDR}} \propto A^{-1/3}$$

3つのモード



Bohr-Mottelson
“Nuclear Structure vol. II”



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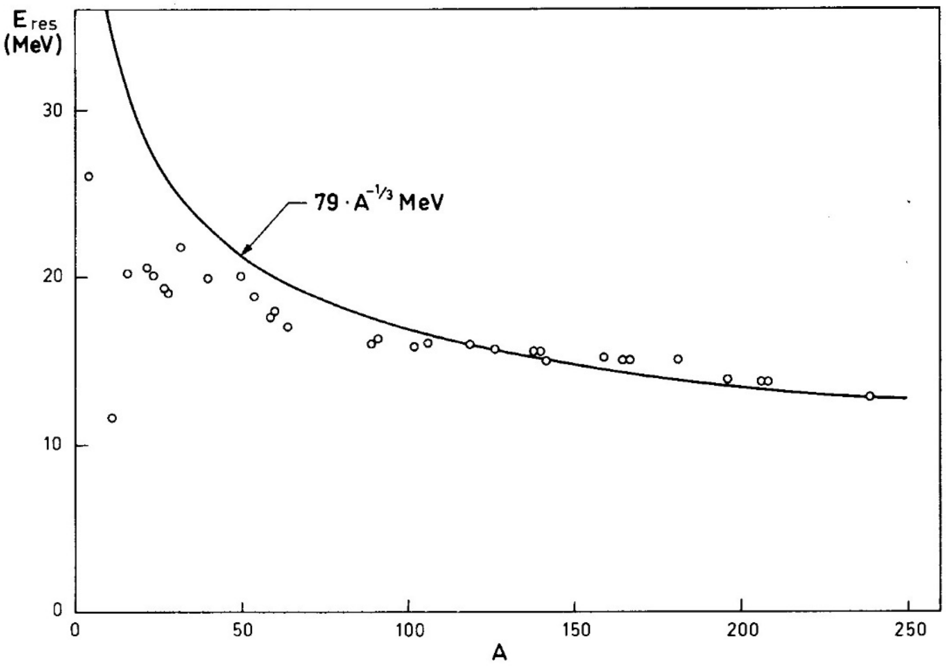
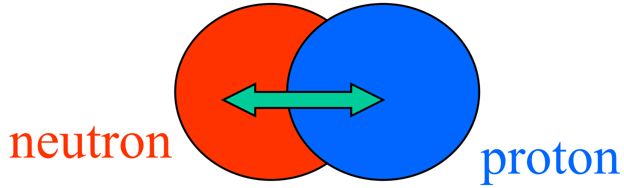


$$E_{\mathrm{GDR}} \propto A^{-1/3}$$
$$\propto 1/R$$

Bohr-Mottelson
"Nuclear Structure vol. II"

３つのモード



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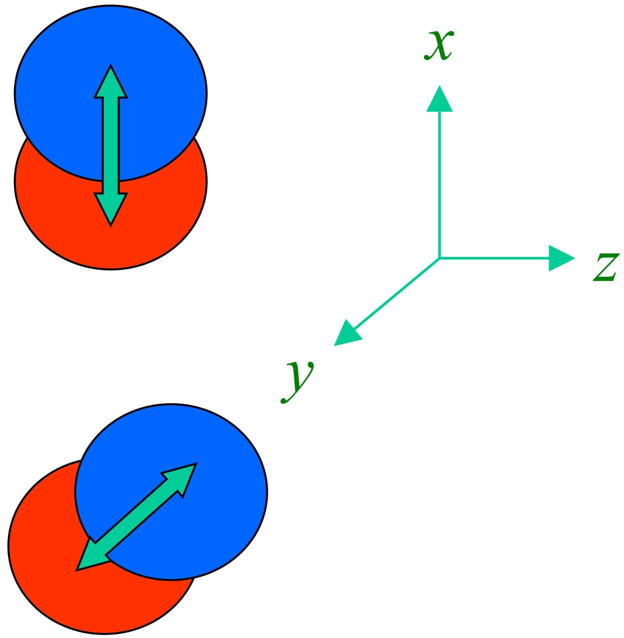


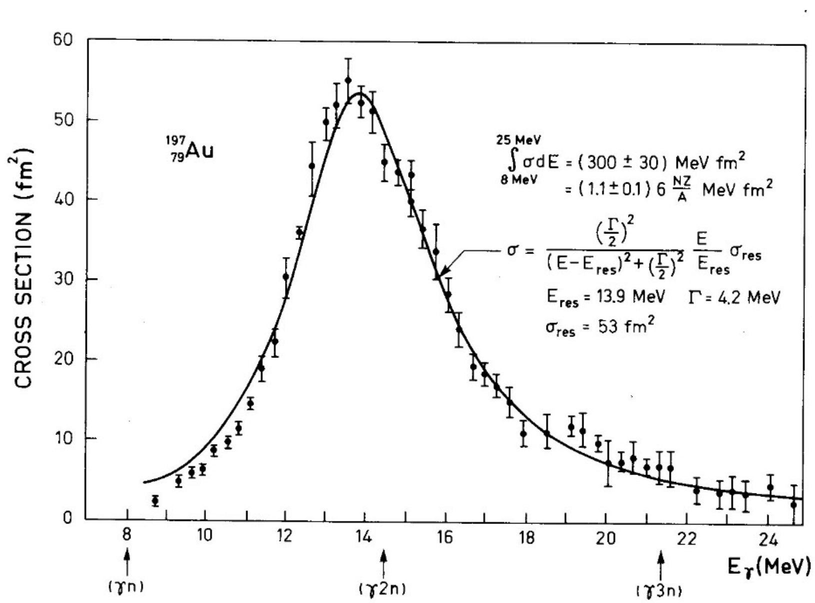
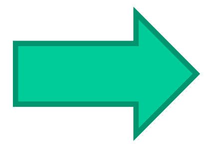
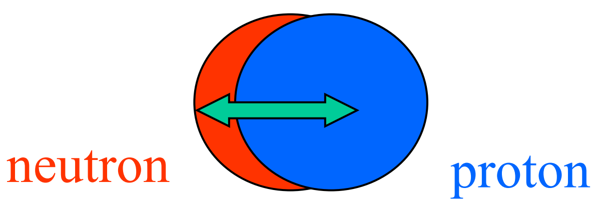


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

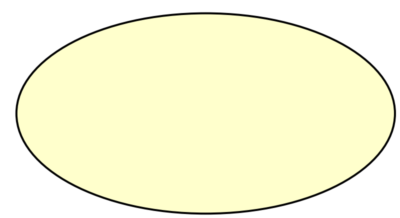


?

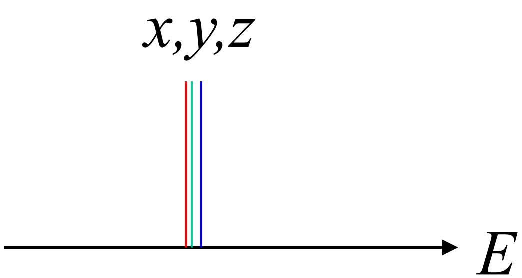


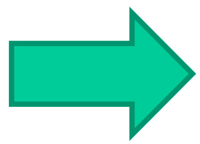
$$E_{\mathrm{GDR}} \propto 1/R$$

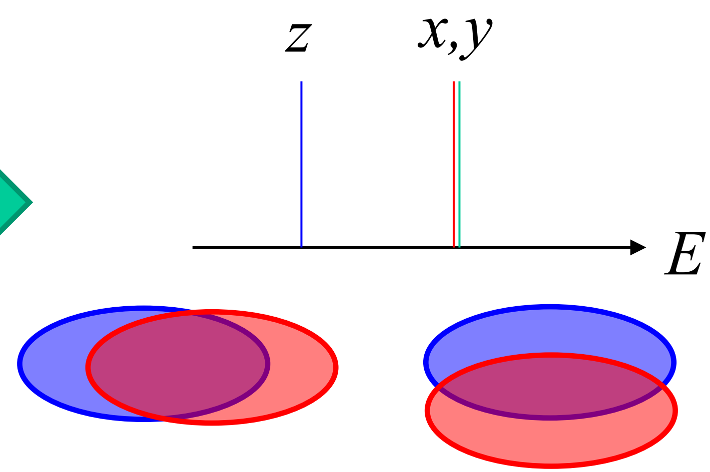
deformed nucleus



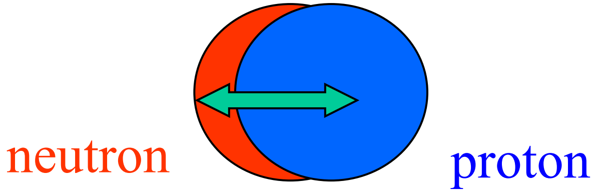
(prolate deformation)



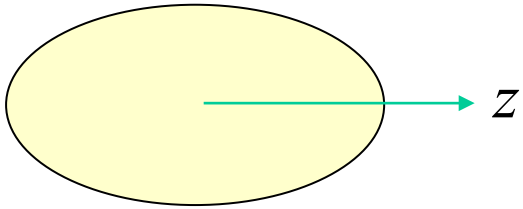




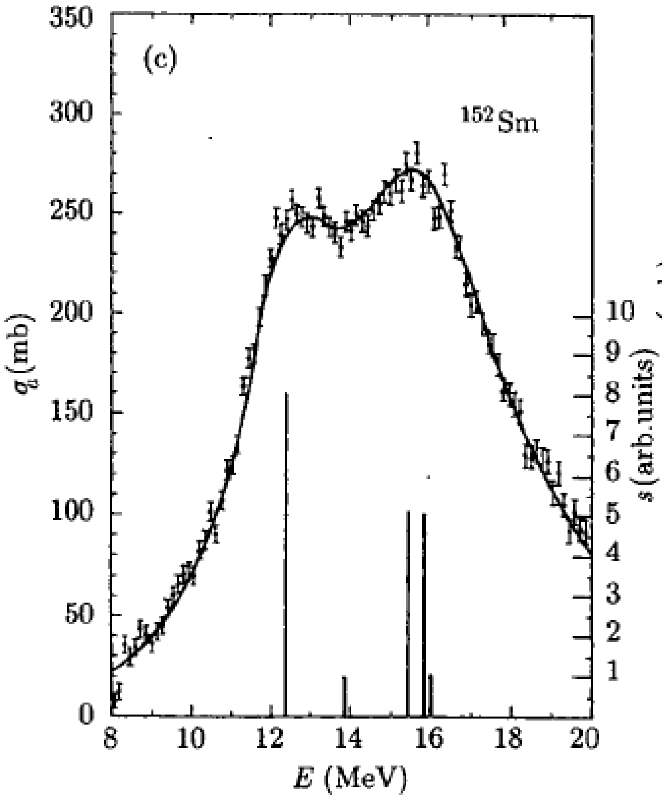
spherical nucleus

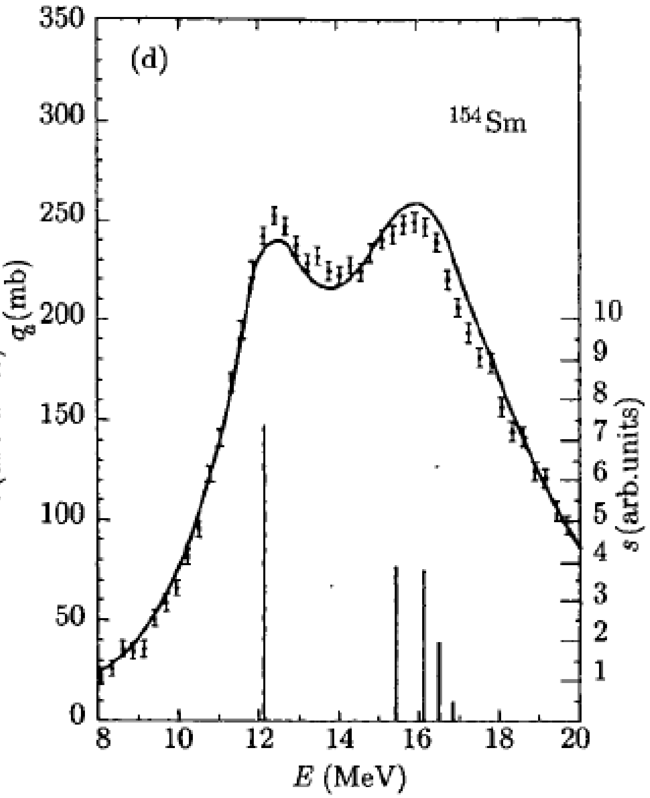


deformed nucleus



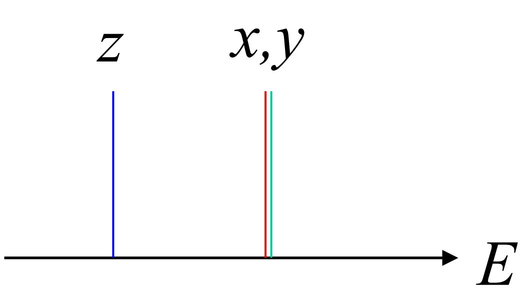
$$E_{\mathrm{GDR}} \propto 1/R$$



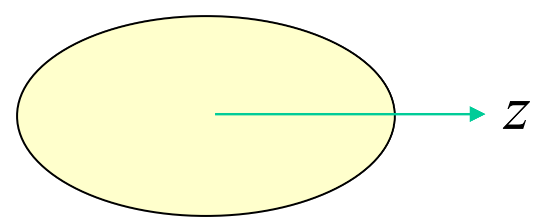


M.N. Harakeh and A. van der Woude, "Giant Resonances"

(prolate deformation)

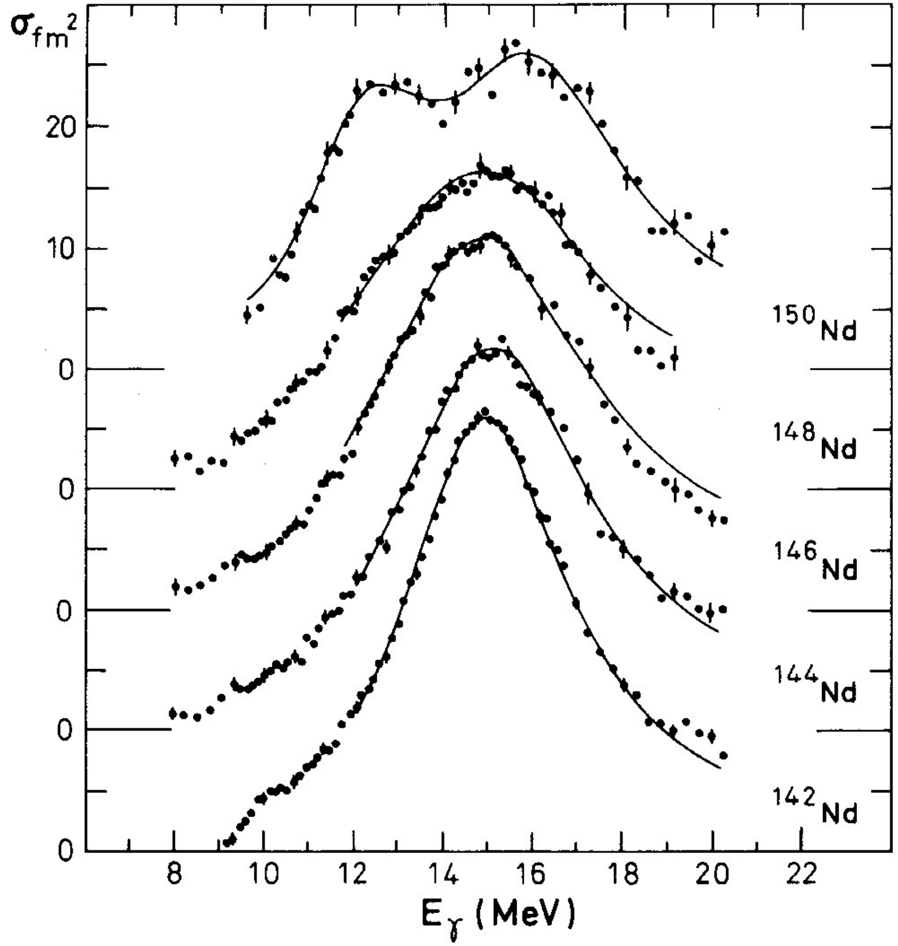


deformed nucleus



Deformation effect

$$E_{\mathrm{GDR}} \sim A^{-1/3} \sim 1/R$$



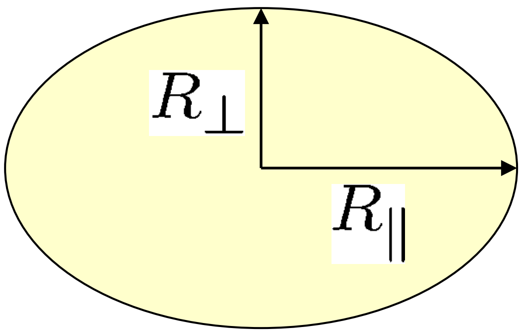
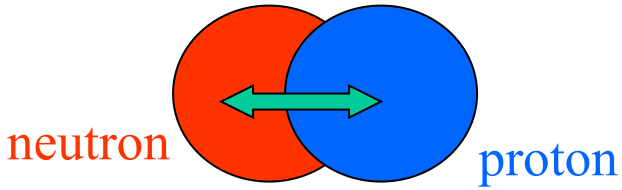


Figure 6-21 Photoabsorption cross section for even isotopes of neodymium. The experimental data are from P. Carlos, H. Beil, R. Bergère, A. Lepretre, and A. Veyssière, *Nuclear Phys.* **A172**, 437 (1971). The solid curves represent Lorentzian fits with the parameters given in Table 6-6.

Giant Dipole Resonances

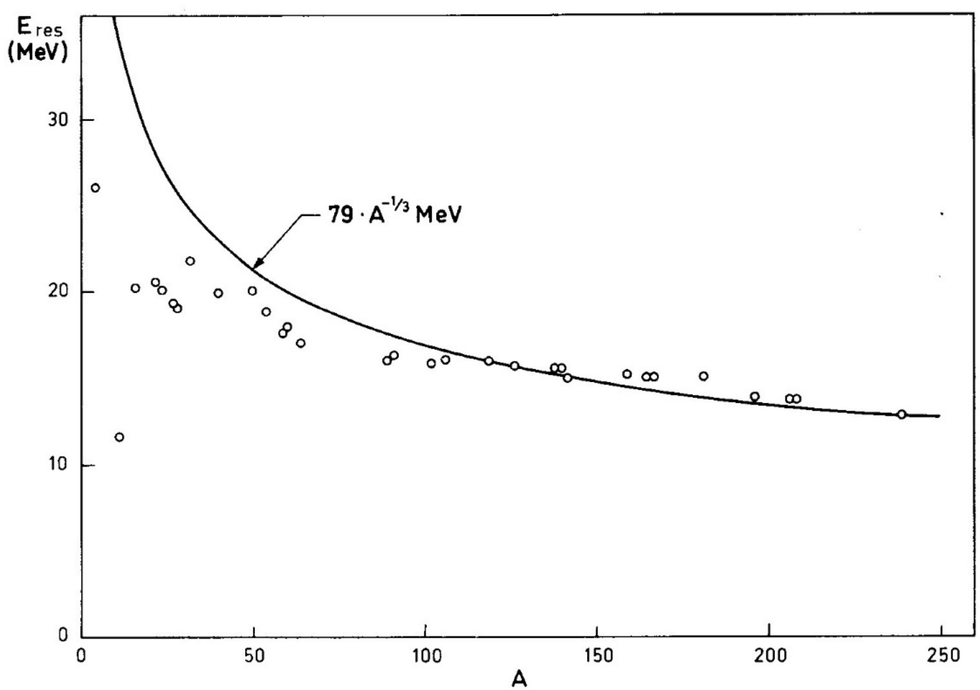
●Goldhaber-Teller type



$$\hat{Q} = rY_{1\mu}(\hat{\boldsymbol{r}})\tau_z$$

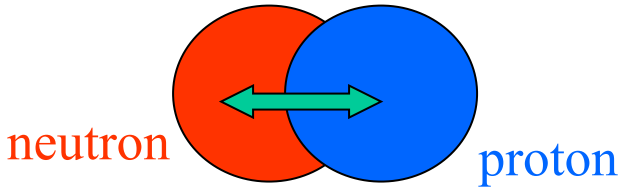
$\Rightarrow$ $\hbar\omega \sim A^{-1/6}$

$\Rightarrow$ Inconsistent with expt.
(except for light nuclei)



Giant Dipole Resonances

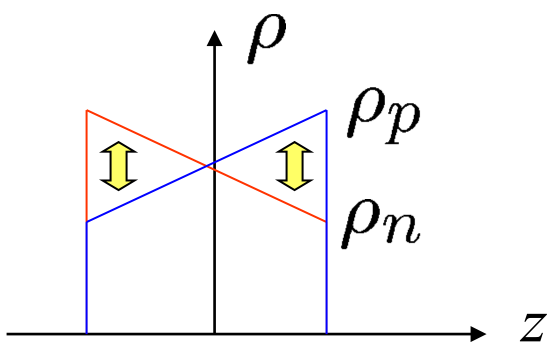
- Goldhaber-Teller type



$$\hat{Q} = rY_{1\mu}(\hat{\boldsymbol{r}})\tau_z$$

$$\Longrightarrow \hbar\omega \sim A^{-1/6}$$

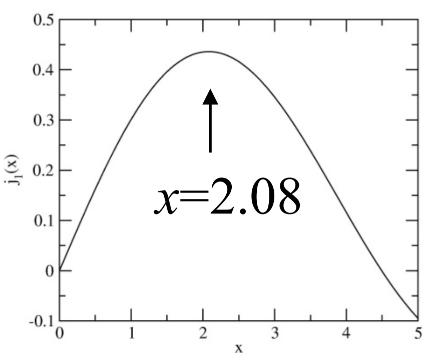
- Steinwedel-Jensen type



$$\hat{Q} = j_1(kr)Y_{1\mu}(\hat{\boldsymbol{r}})\tau_z$$

$$\Longrightarrow \hbar\omega \sim A^{-1/3}$$

$$kR = 2.08$$



$$j_1(x) = (\sin x - x\cos x)/x^2$$

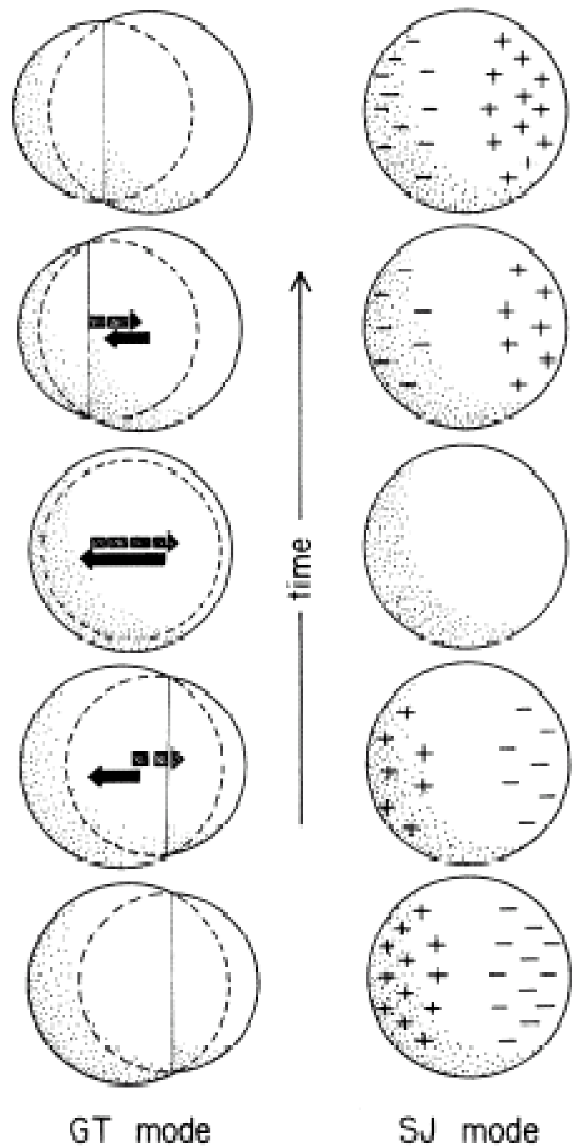


FIG. 1. Schematic drawings that serve to illustrate the the general features of the Goldhaber-Teller (Ref. 3) (GT) and Steinwedel-Jensen (Ref. 4) (SJ) dipole modes.

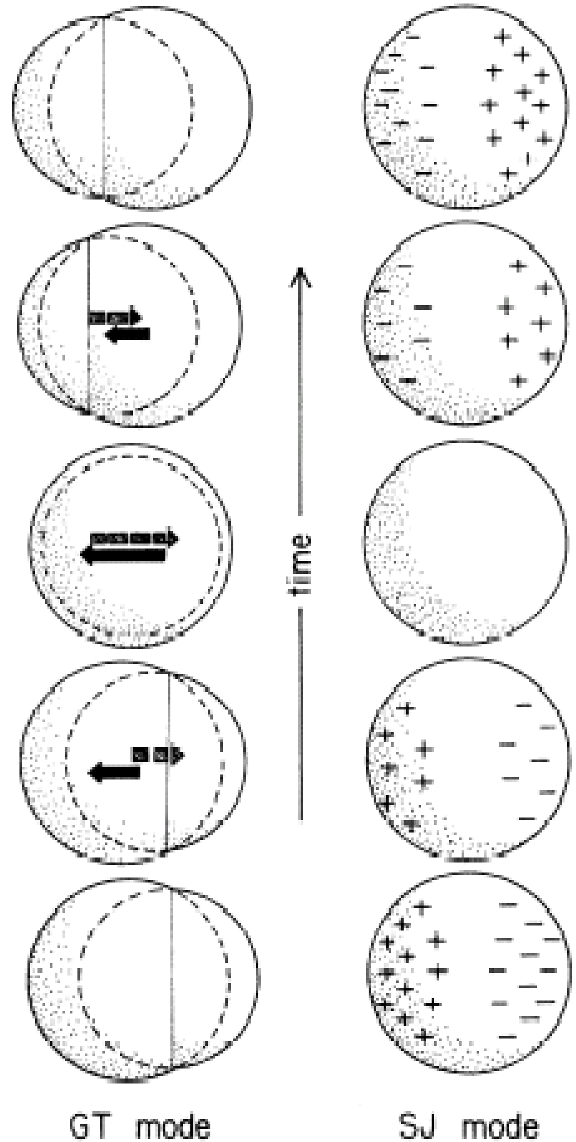
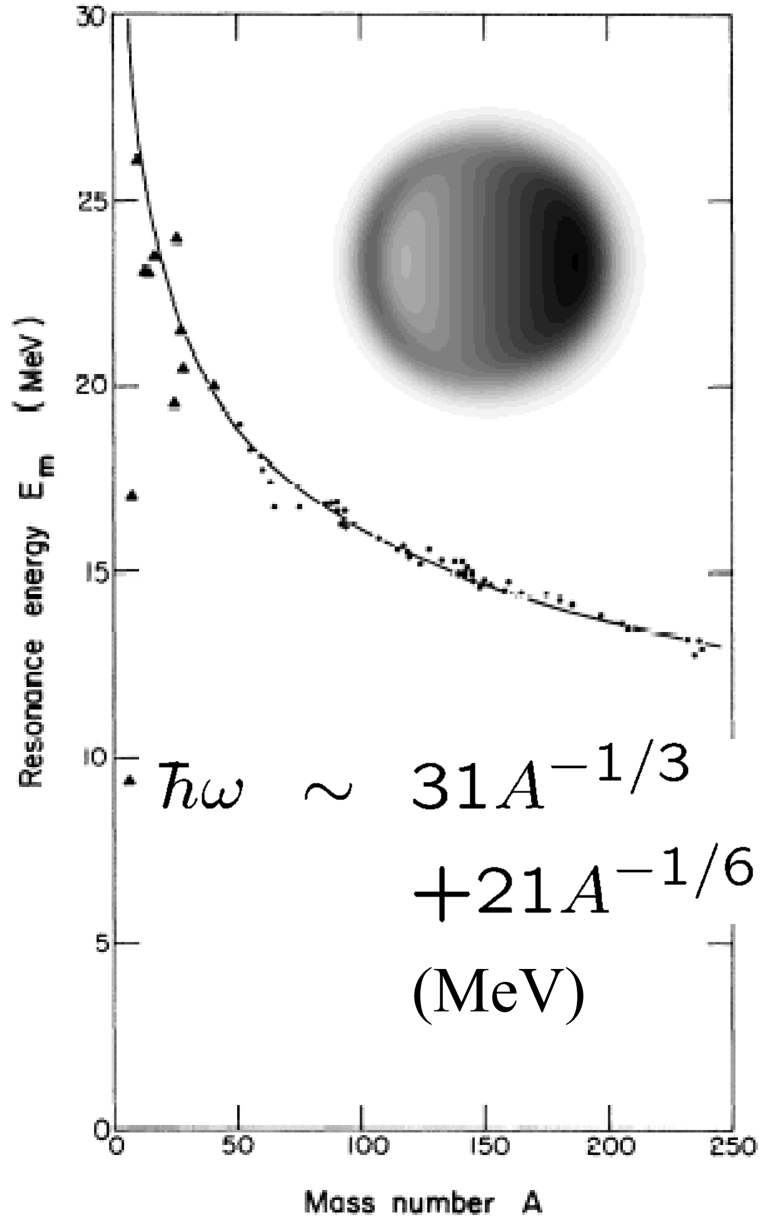


FIG. 1. Schematic drawings that serve to illustrate the the general features of the Goldhaber-Teller (Ref. 3) (GT) and Steinwedel-Jensen (Ref. 4) (SJ) dipole modes.

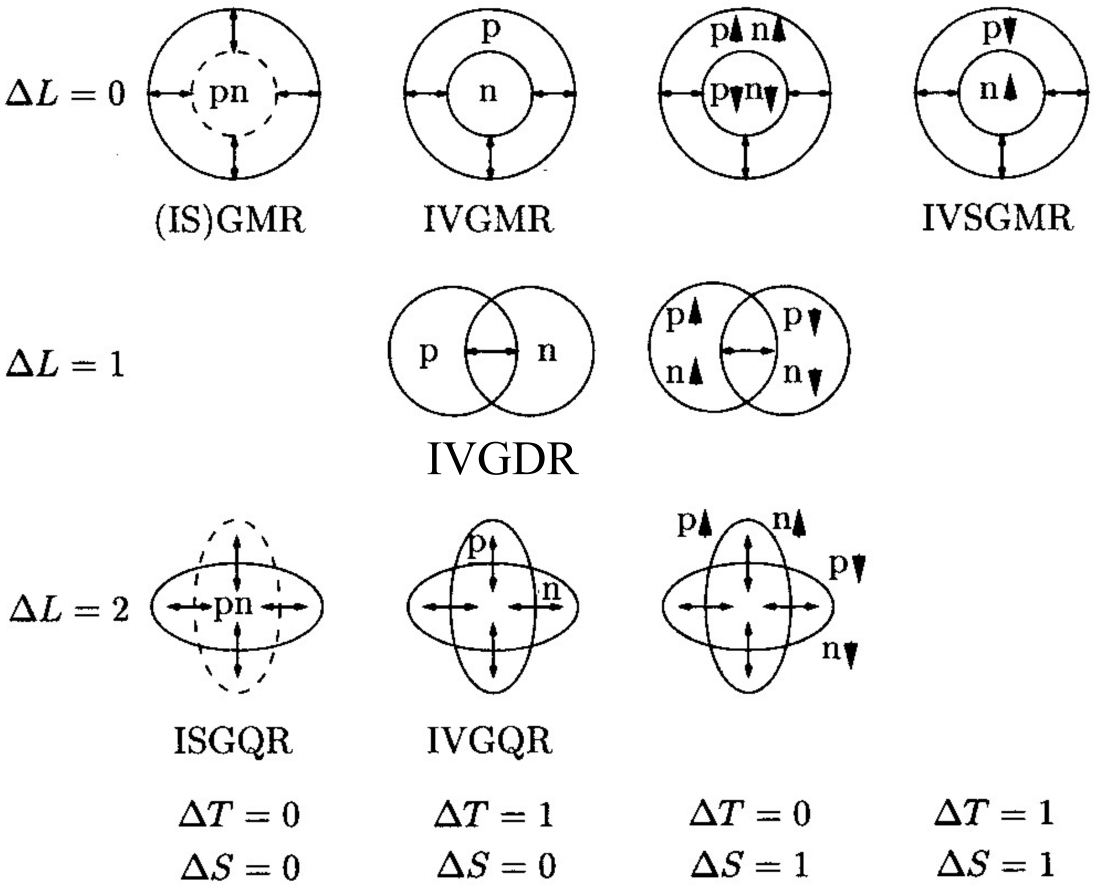


$$\hbar\omega \sim 31A^{-1/3} + 21A^{-1/6}$$ (MeV)

J.D. Myers et al., PRC15('77)2032

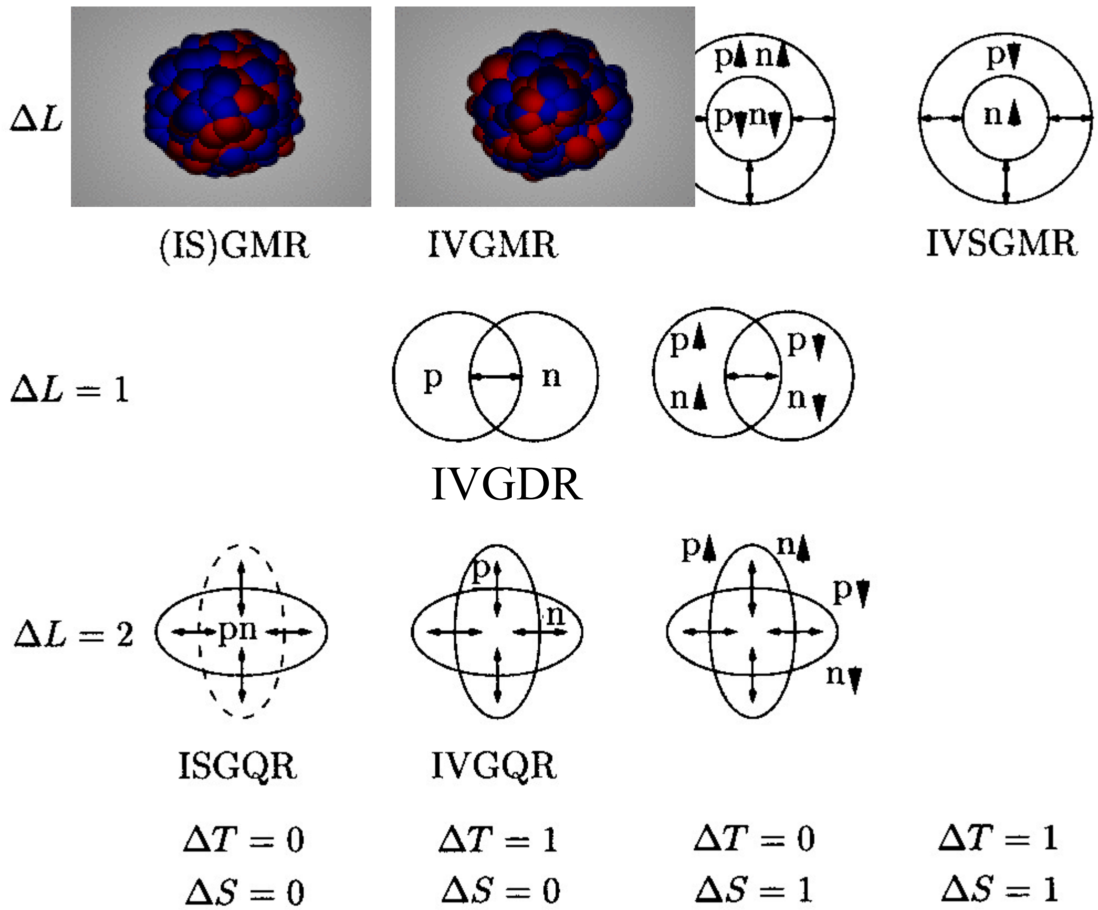
ii) Inelastic scattering

(e,e'), (p,p'), (α,α'), Heavy-ion → Higher multipolarities



ii) Inelastic scattering

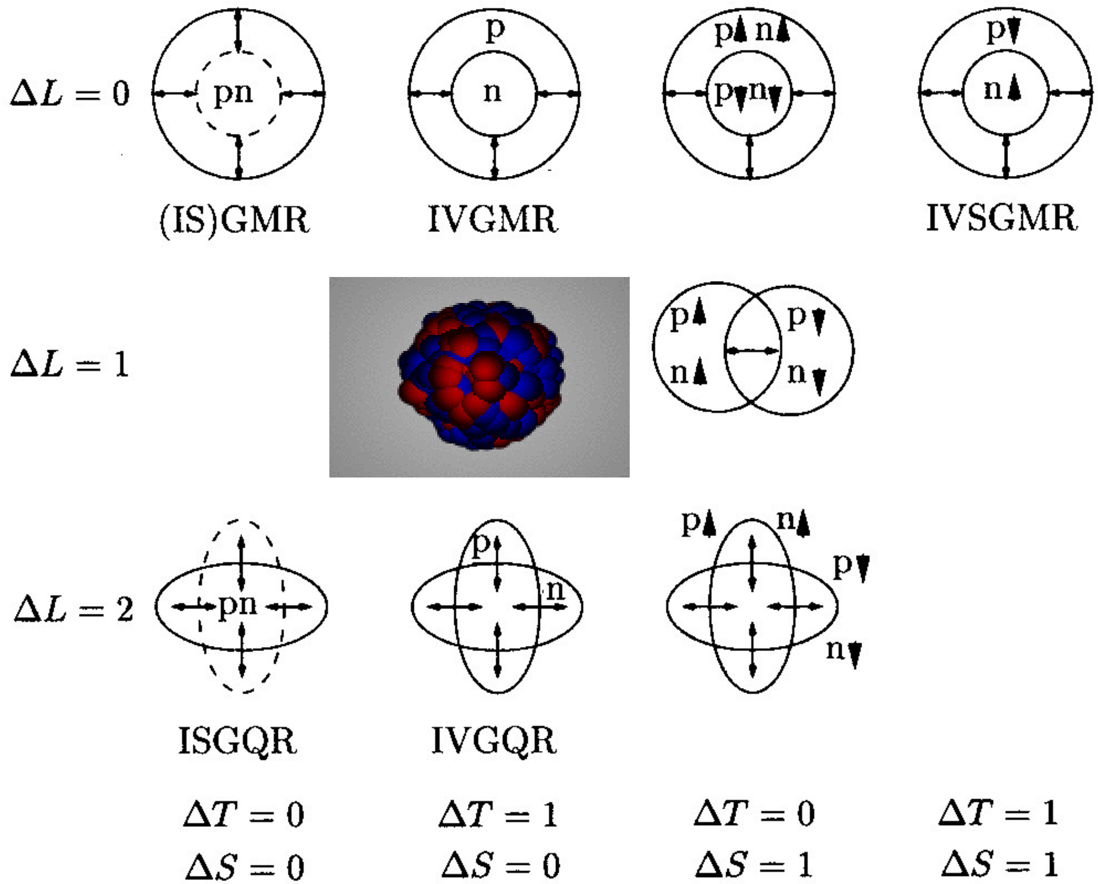
(e,e'), (p,p'), (α,α'), Heavy-ion → Higher multipolarities



movies: H.-J. Wollersheim,
https://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/index-s.html

ii) Inelastic scattering

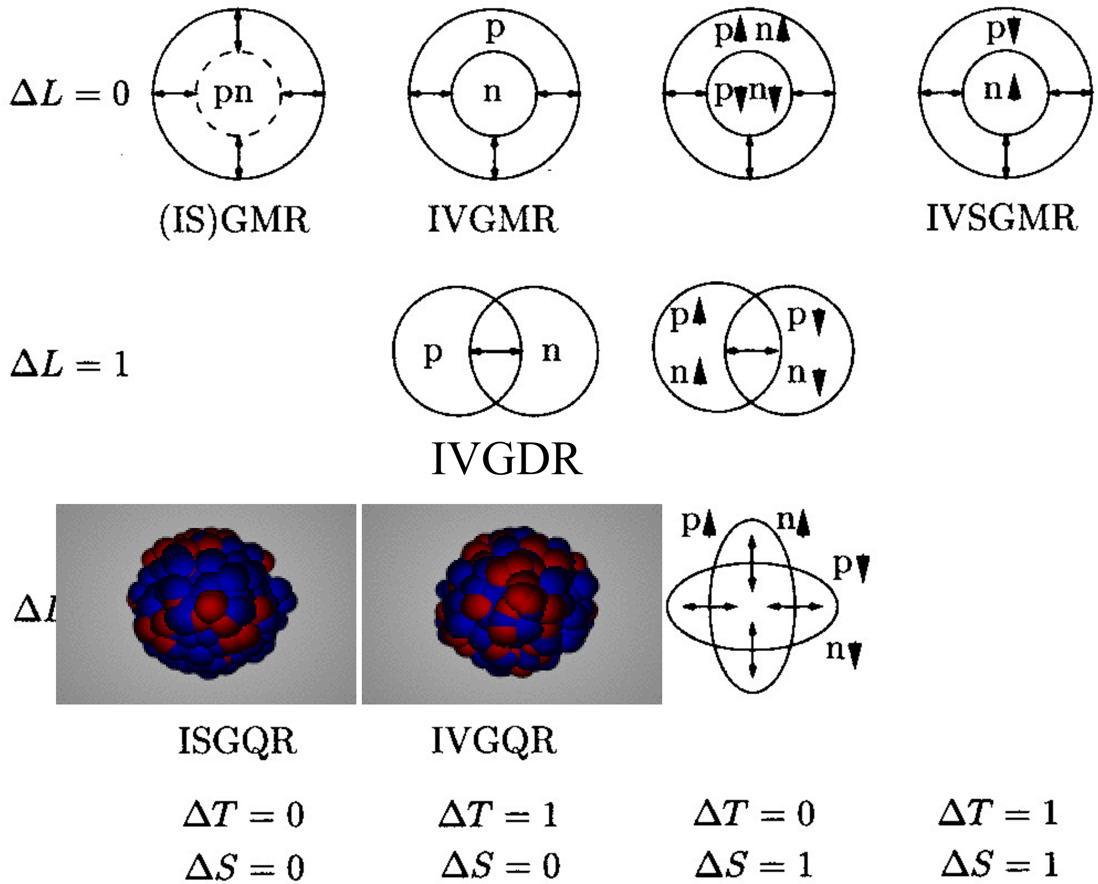
(e,e’), (p,p’), (α,α’), Heavy-ion → Higher multipolarities



movies: H.-J. Wollersheim,
https://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/index-s.html

ii) Inelastic scattering

(e,e'), (p,p'), (α,α'), Heavy-ion → Higher multipolarities

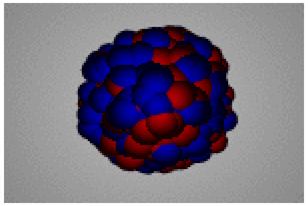


(note) $\Delta L = 2 \longrightarrow$

$$\Delta N = 2 \quad \text{Giant Resonance (GQR)}$$

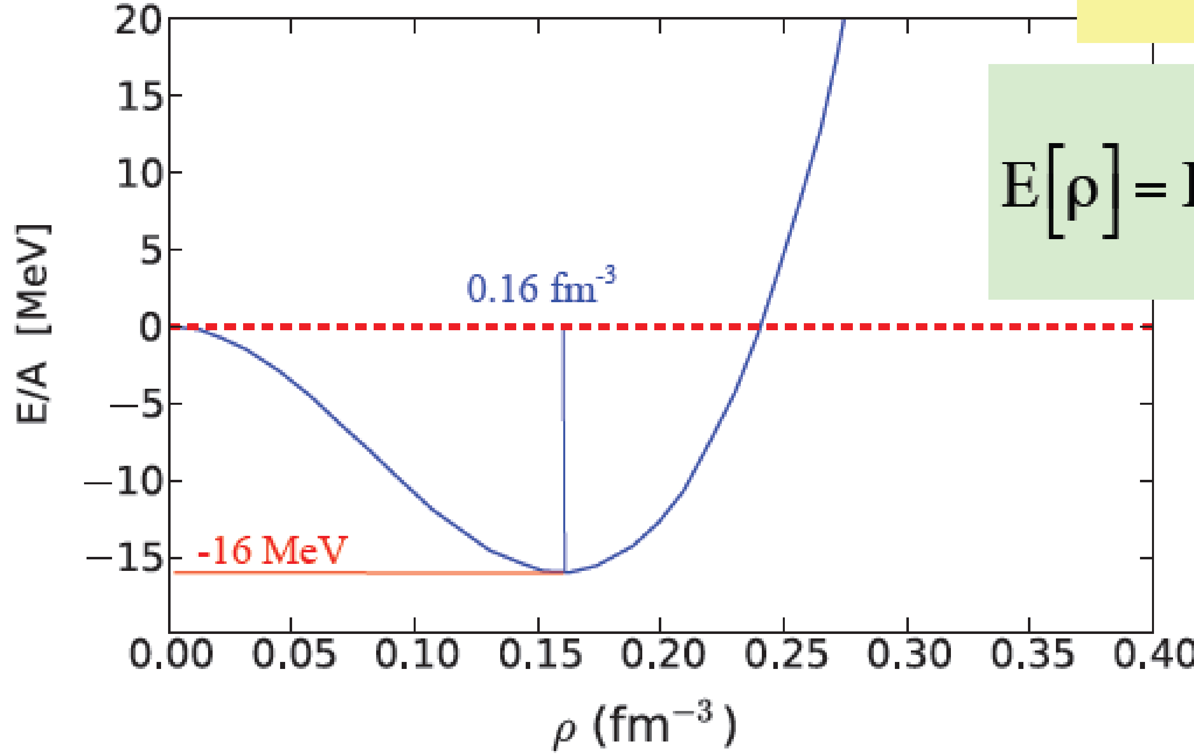
$$\Delta N = 0 \quad \text{Low-lying state}$$

EOS of infinite nuclear matter



$$K_\infty = 9\rho^2 \left. \frac{d^2 \left[E(\rho)/\rho \right]}{d\rho^2} \right|_{\rho_0}$$

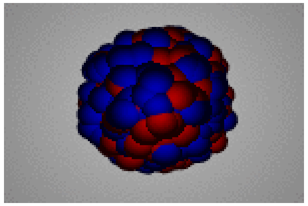
$$E[\rho] = E[\rho_0] + \frac{1}{18} K_\infty \left(\frac{\rho - \rho_0}{\rho_0} \right)^2$$



cf. 中性子星の大きさや重さ（MR曲線）

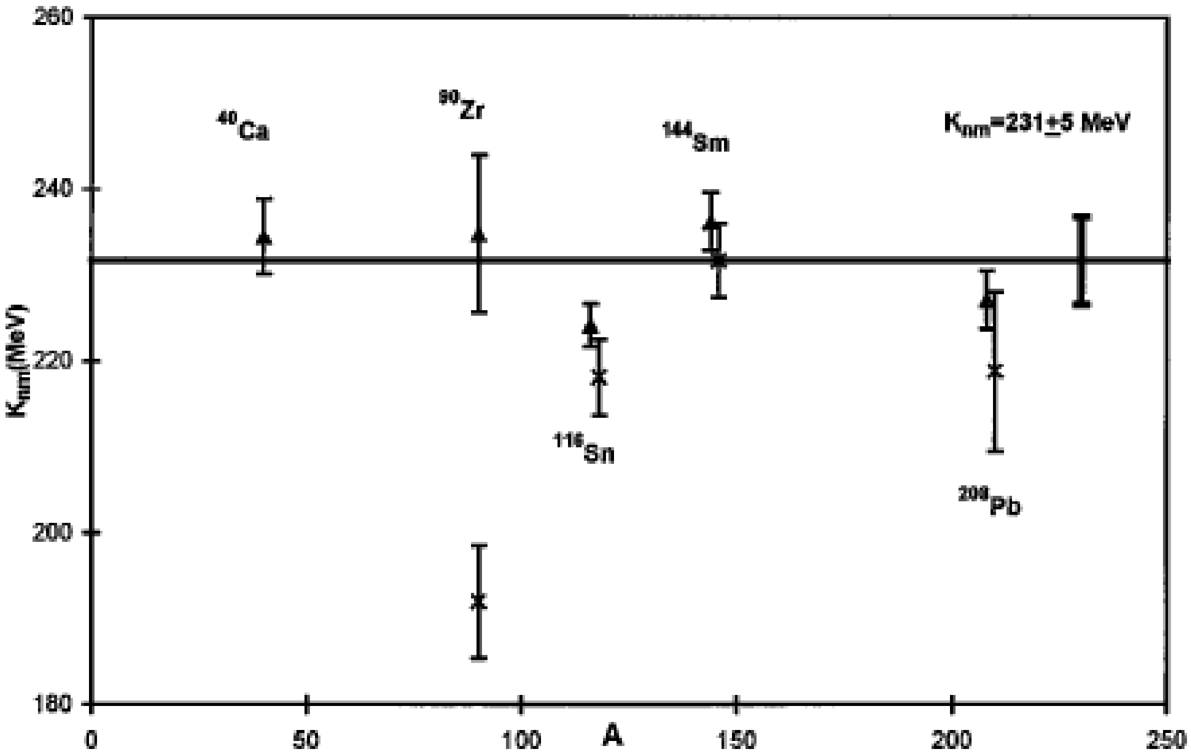
slide: Carlos Bertulani

Isoscalar giant monopole resonances (breathing mode)



$$E_{\mathrm{ISGMR}} \sim \sqrt{\frac{\hbar^2 K}{m\langle r^2\rangle}}$$

J.P. Blaizot,
Phys. Rep. 64 ('80) 171



K ~ 231 +/- 5 MeV

D.H. Youngblood, H.L. Clark, and Y.-W. Lui, PRL82 ('99) 691

レポート問題1（〆切：12月4日（土））

「振動状態」の量子力学的意味を考えるために $H|\psi_n\rangle = E_n|\psi_n\rangle$ で記述される系を考えよう。

1) 時刻 $t = 0$ で系が基底状態 (n=0) にいる場合、時刻 t において波動関数の2乗

$$\rho(x,t) = |\Psi(x,t)|^2$$

が t に依らないことを示せ。

2) 時刻 $t = 0$ で系が $\Psi(x, t=0) = \psi_0(x) + \alpha\psi_1(x)$ という状態にいるとき、時刻 t における

$$\rho(x,t) = |\Psi(x,t)|^2$$

を求めよ。ただし、$|\alpha|$ は1に比べて十分小さいとし、$|\alpha|^2$ の項は無視してよい。

このとき、$\delta\rho(x,t) \equiv |\Psi(x,t)|^2 - |\psi_0(x)|^2$

は t の関数として振動するが、その周期を求めよ。