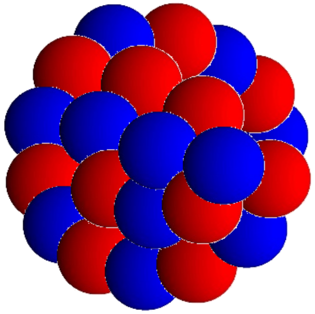
原子核基礎論B

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
→北沢
6. 高温・高密度核物質概観（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(2コマ)
6. 平均場理論と核変形(2コマ)
7. 原子核の対相関(2コマ)
8. 中性子過剰核の物理(1コマ)

主に基底状態

シラバス(基礎論B)

1. 原子核の集団運動とその微視的理解(3コマ)
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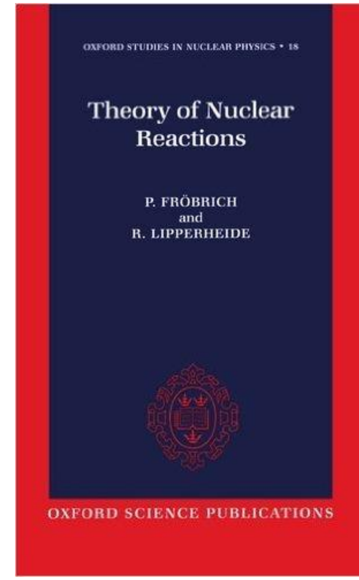
主に励起状態
と核反応

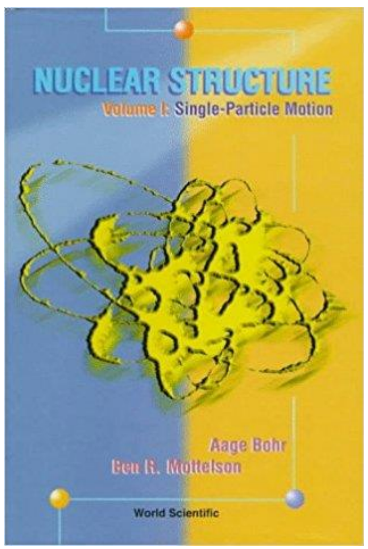
成績: レポート80%、出席など20%

質問: 講義中にも適宜聞いて下さい。

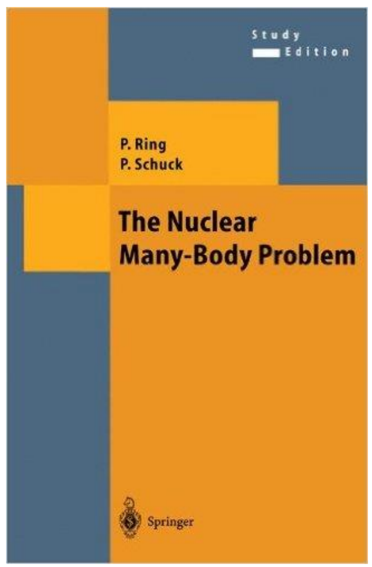
参考書



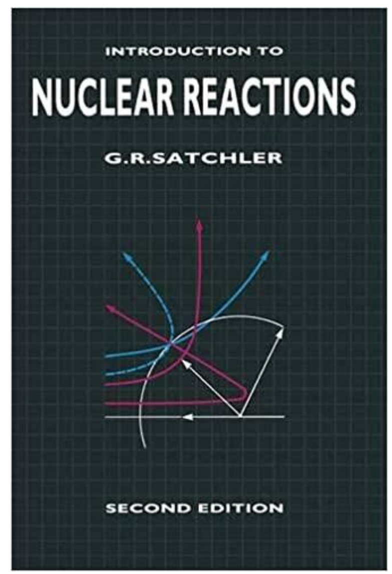
Frobrich-Lipperheide



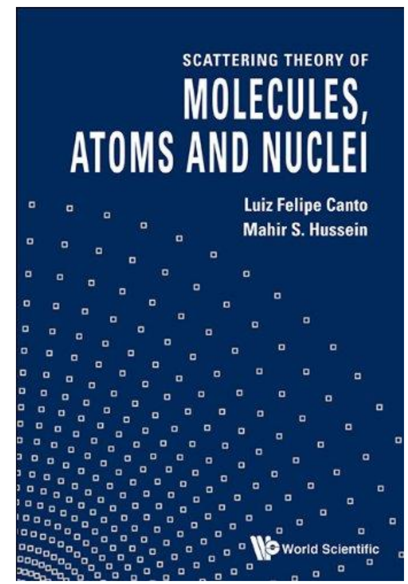
Bohr-Mottelson



Ring-Schuck



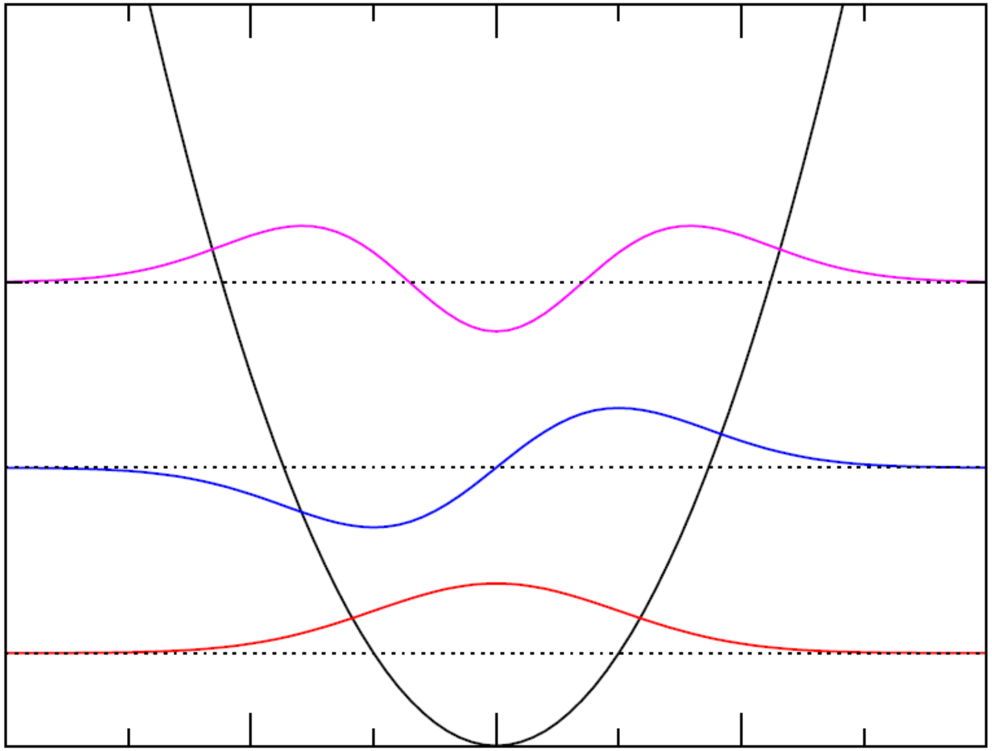
Satchler



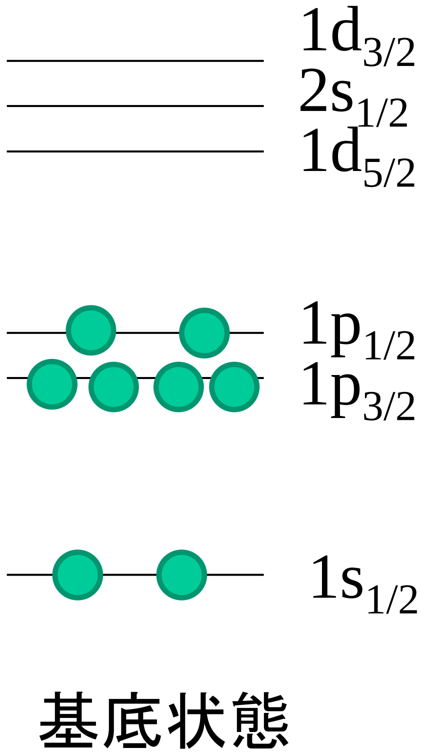
Canto-Hussein

励起状態

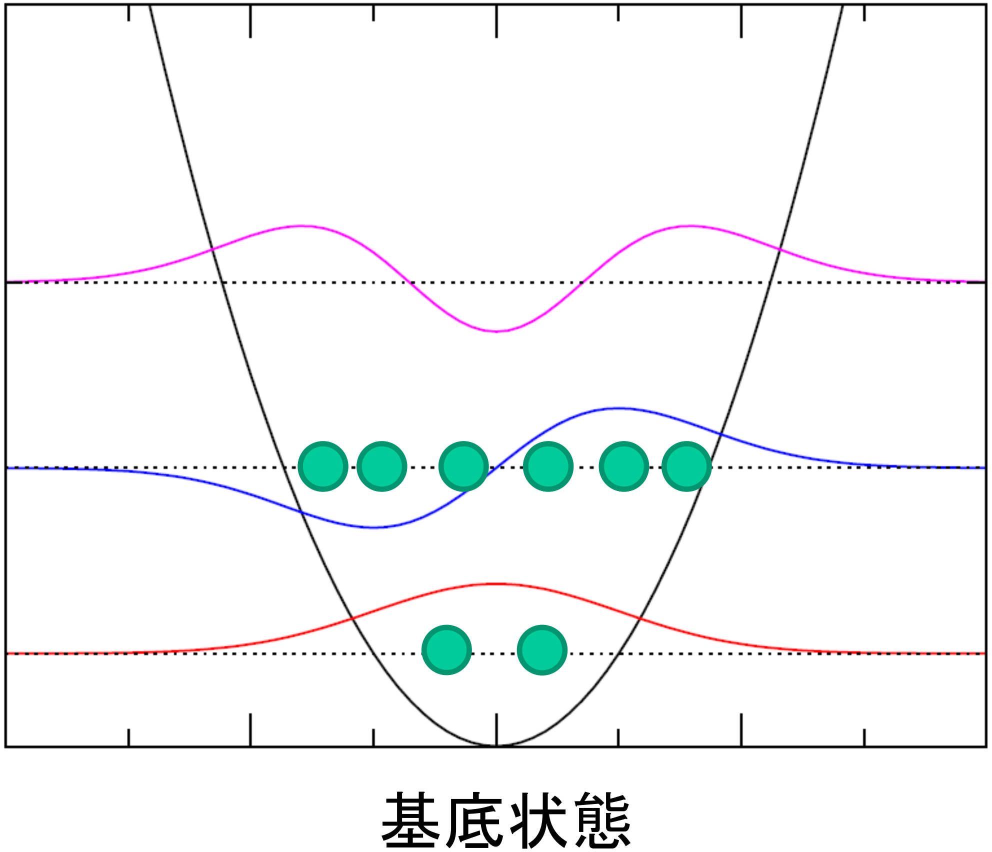
ポテンシャル中の1粒子の場合



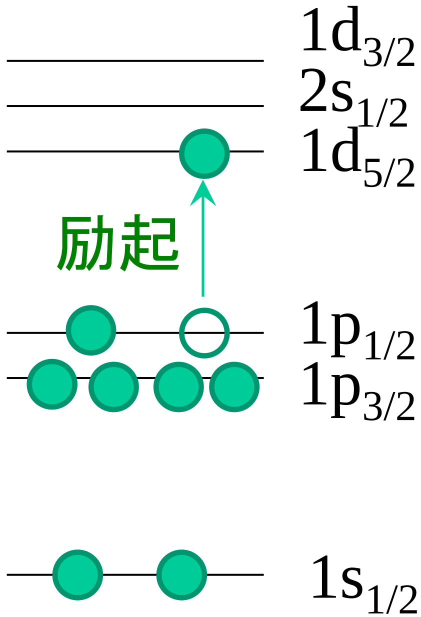
原子核の励起状態



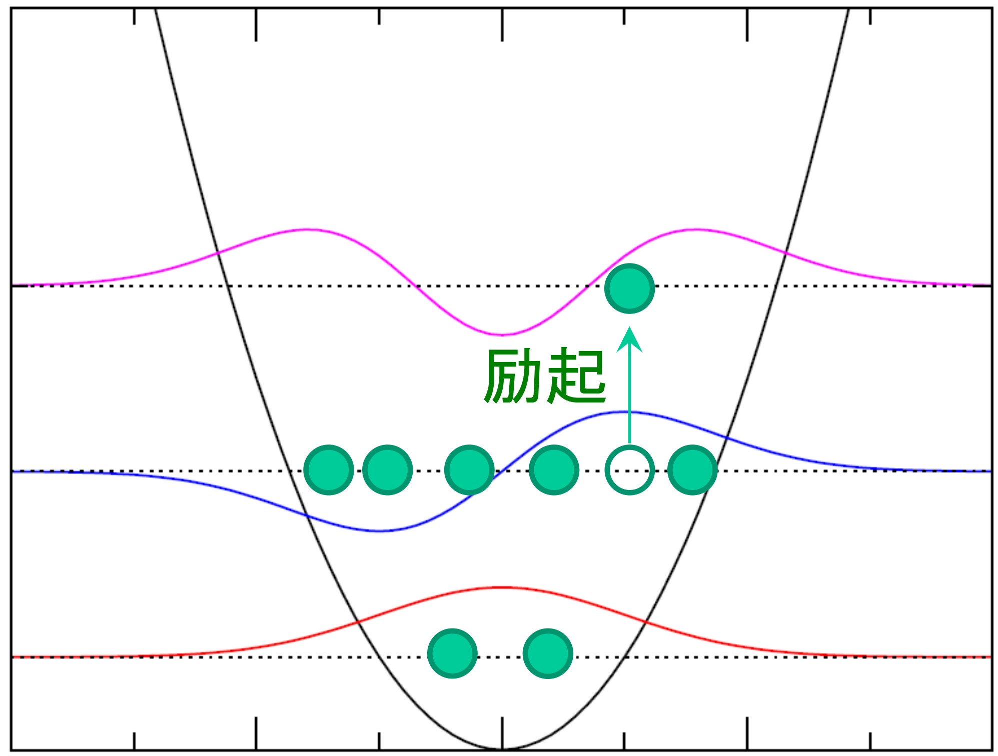
多体系の場合



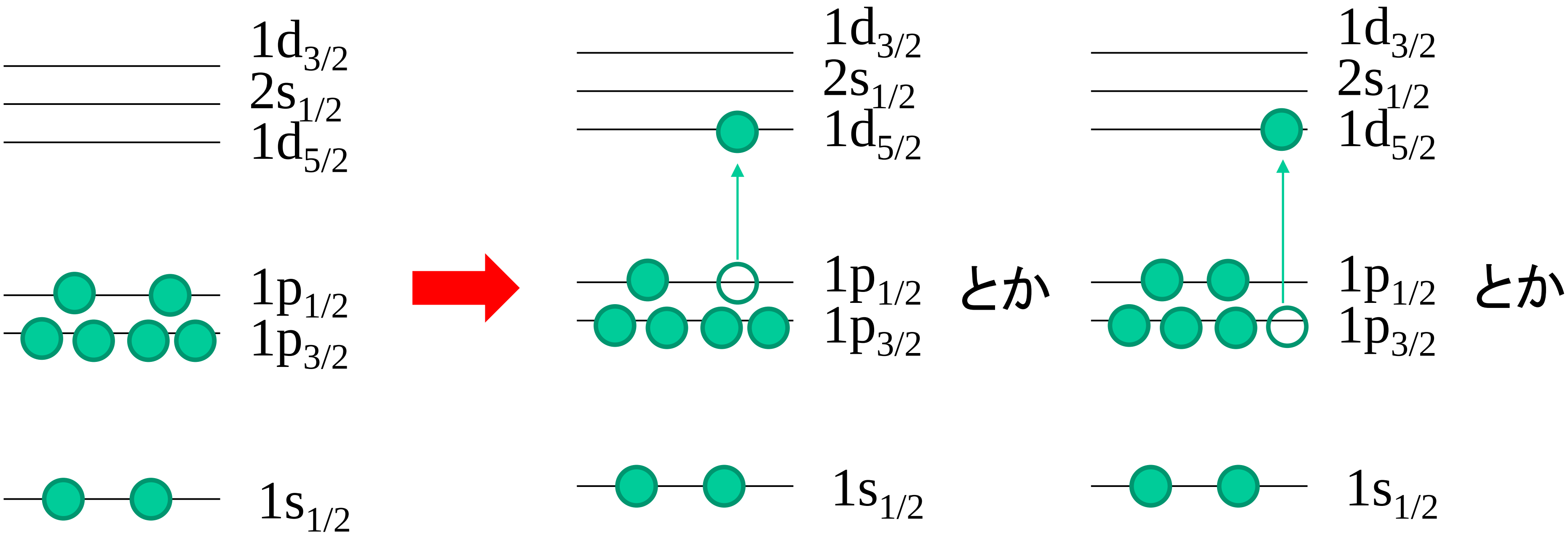
原子核の励起状態



多体系の場合



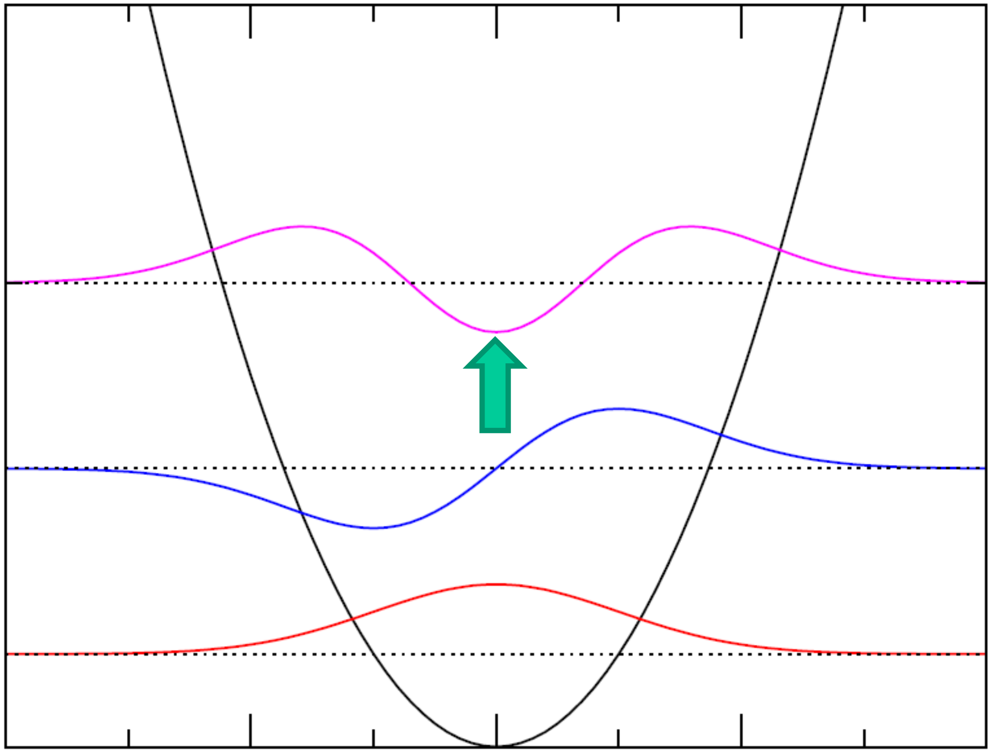
原子核の励起状態



基底状態

1粒子1空孔（1p1h）状態

粒子2個あげる励起や、複数個あげる励起も。
2p2h 状態、npnh状態。



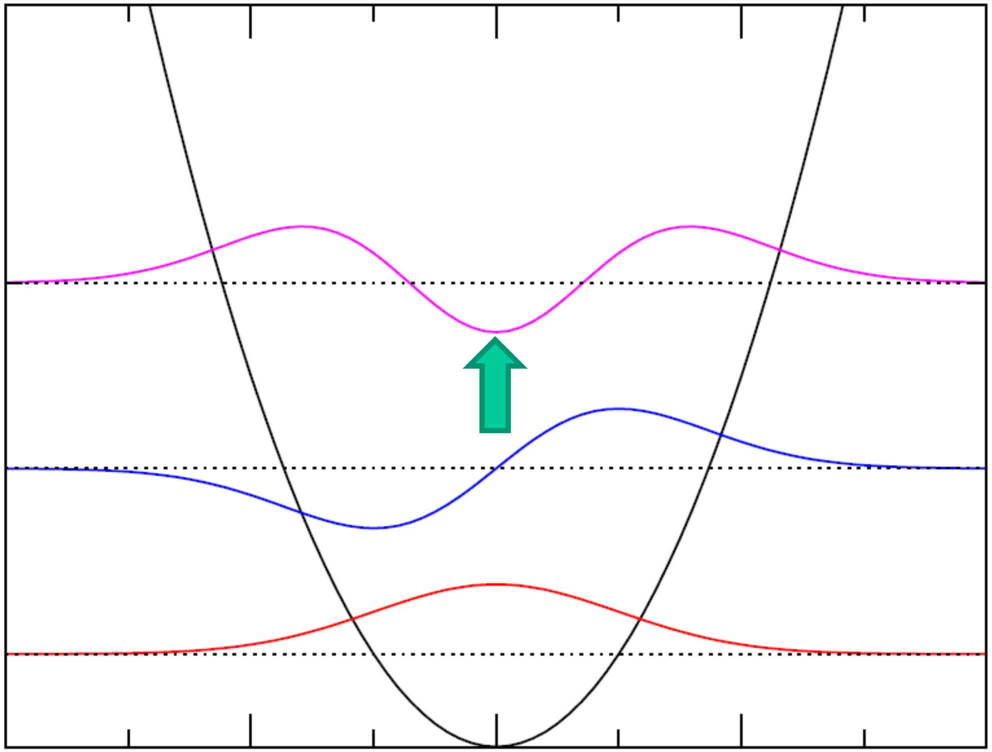
原子核では

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

$\longleftarrow$ $R \sim 1.2$ 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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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

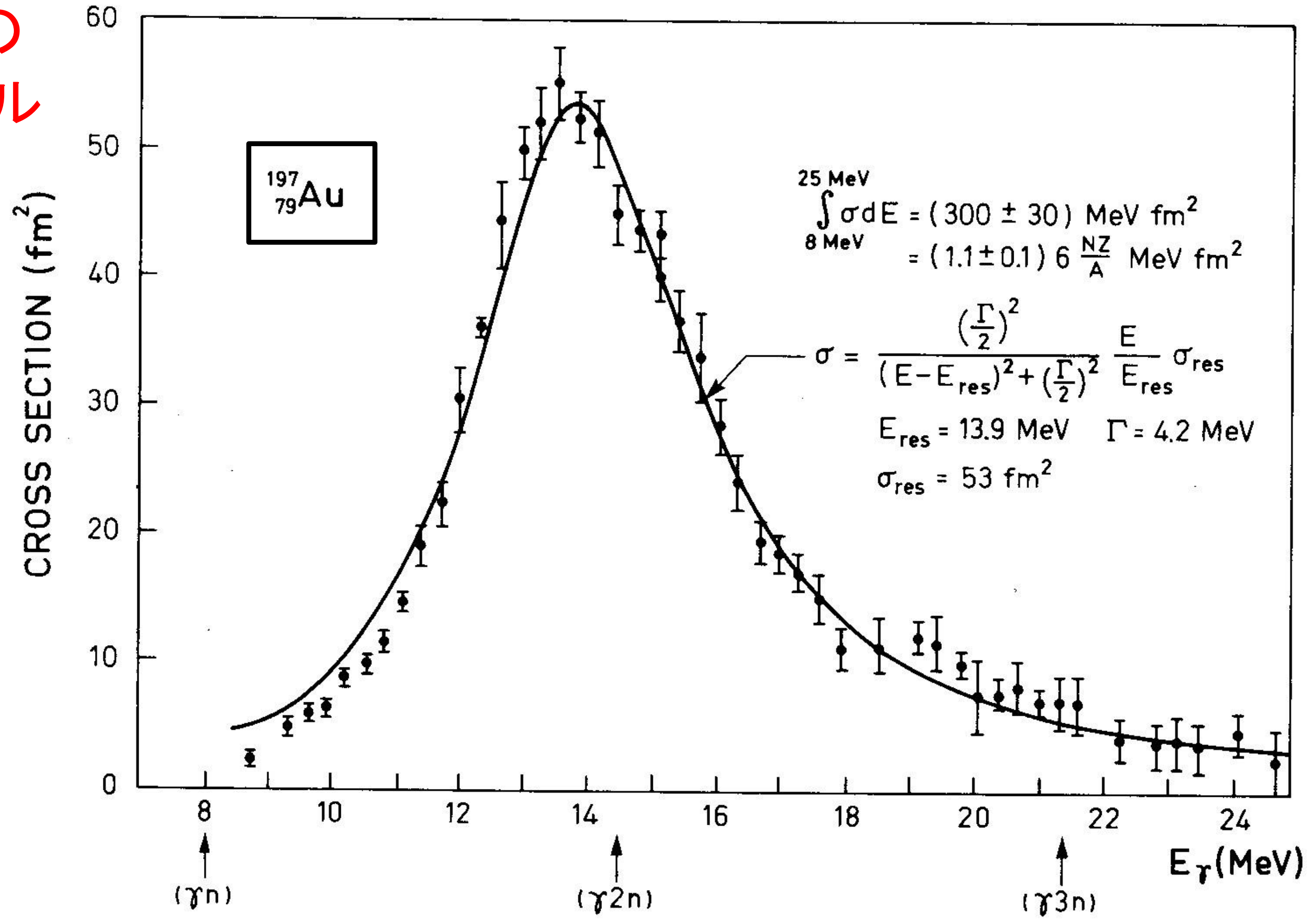


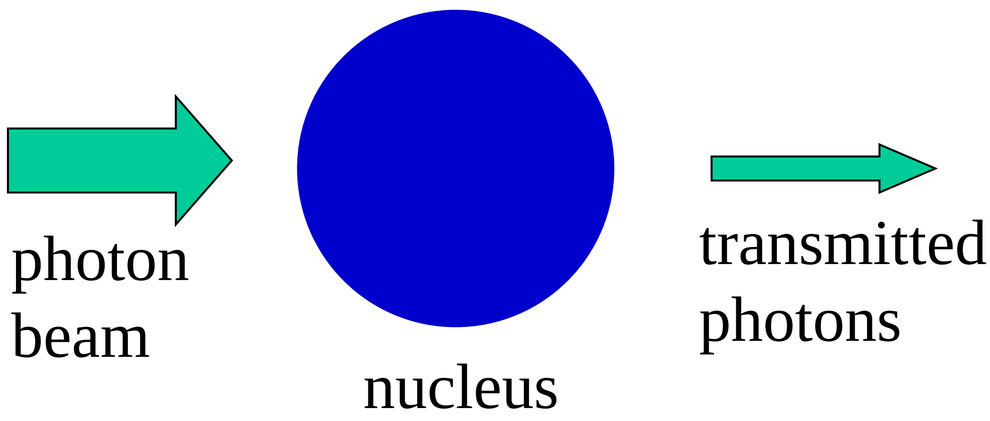
Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

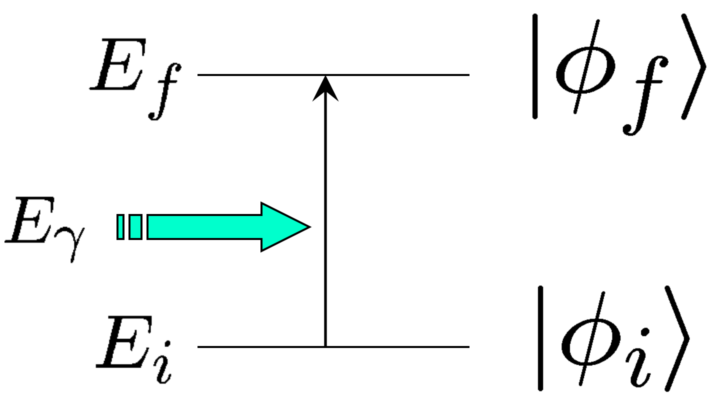
cf. 41 x $197^{-1/3}$ = 7.05 MeV

Collective Vibrations

How does a nucleus respond to an external perturbation?

i) Photo absorption cross section





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

Giant Dipole Resonance (GDR) 巨大双極子共鳴

光吸収の
スペクトル

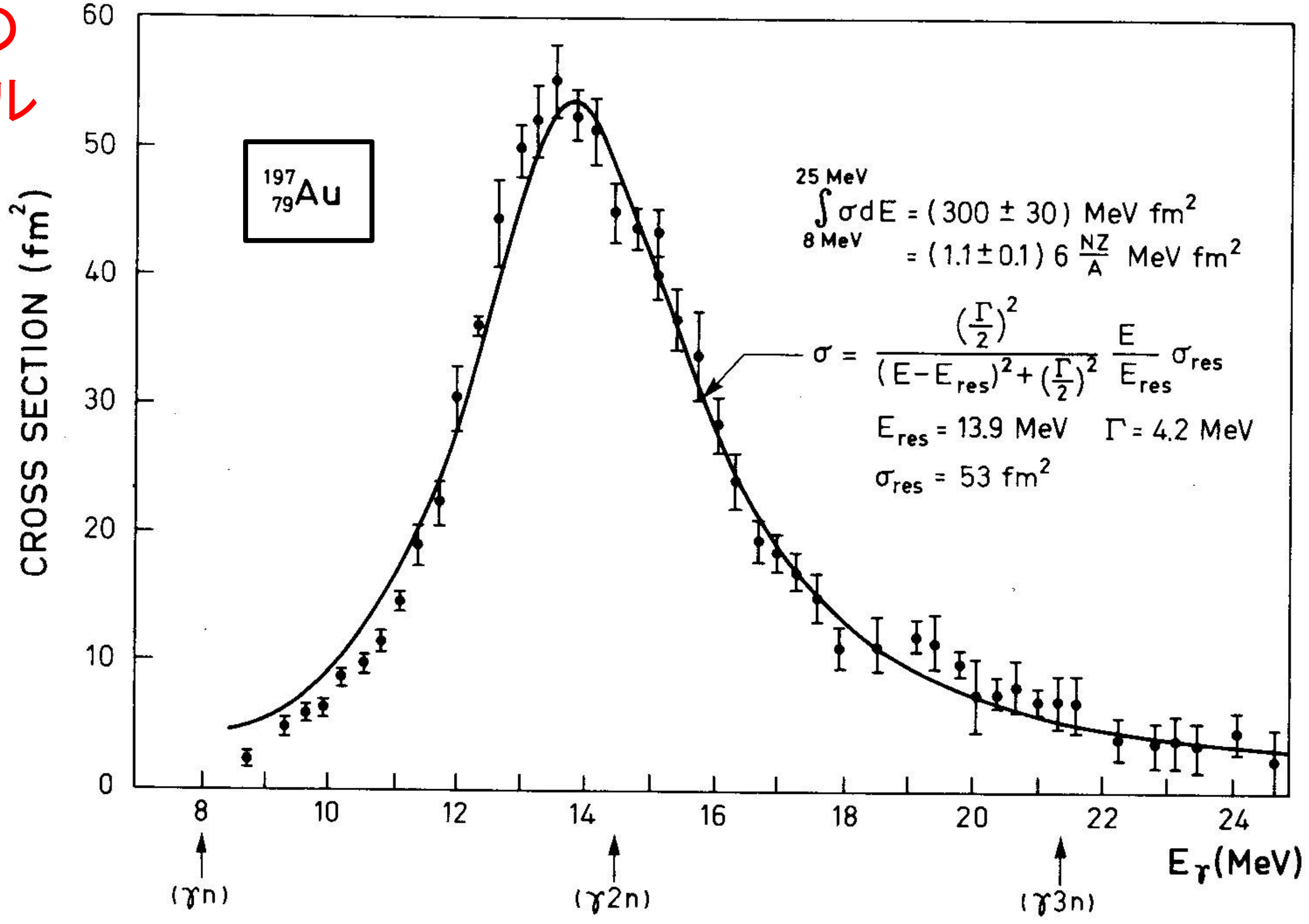


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

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

Remarks

i) Photon interaction $\longleftrightarrow$ dipole excitation

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

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

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

E_γ ~ 10 MeV, R~5 fm のときに、kR はどのくらいになるか？

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

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

E_γ ~ 10 MeV, R~5 fm のときに、kR はどのくらいになるか？

$$k = \frac{E_\gamma}{\hbar c} \sim \frac{10}{200}\ (1/fm) \rightarrow kR \sim 50/200 = 0.25$$

Remarks

i) Photon interaction ⟷ dipole excitation

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

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

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

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

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

Remarks

i) Photon interaction $\longleftrightarrow$ dipole excitation

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

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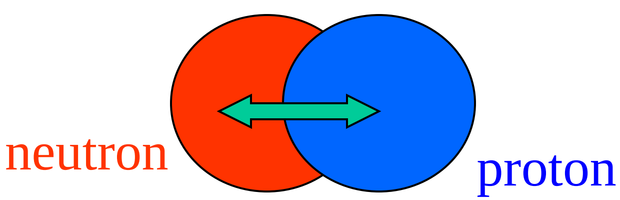
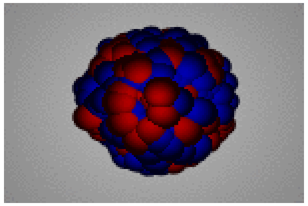
ii) Isospin

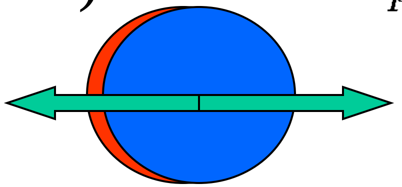
$$\tilde{z} = \sum_p (z_p - Z_{cm})$$



Isovector type



(note)



Isoscalar dipole motion

$\longleftrightarrow$ c.m. motion (to the first order)

Remarks

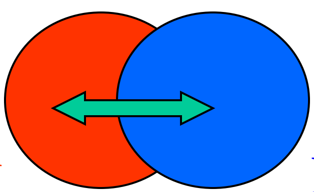
i) Photon interaction ⟷ dipole excitation

$$
\begin{aligned}
H_{\rm int} &= \frac{1}{2m}\frac{e}{c}(\boldsymbol{p}\cdot\boldsymbol{A}+\boldsymbol{A}\cdot\boldsymbol{p}) \\
\boldsymbol{A}(\boldsymbol{r},t) &= \sum_{\boldsymbol{k}}\sum_{\alpha=1,2}\sqrt{\frac{2\pi c^2\hbar}{\omega V}}\left(a_{\boldsymbol{k}\alpha}\,\epsilon_\alpha\, e^{i\boldsymbol{k}\cdot\boldsymbol{r}-i\omega_k t}+h.c.\right)
\end{aligned}
$$

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

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

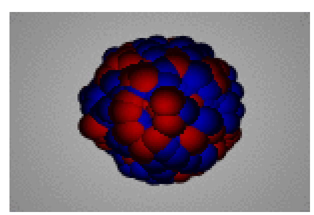
ii) Isospin



neutron

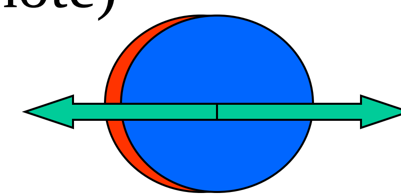
proton

Isovector type



(note)

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



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

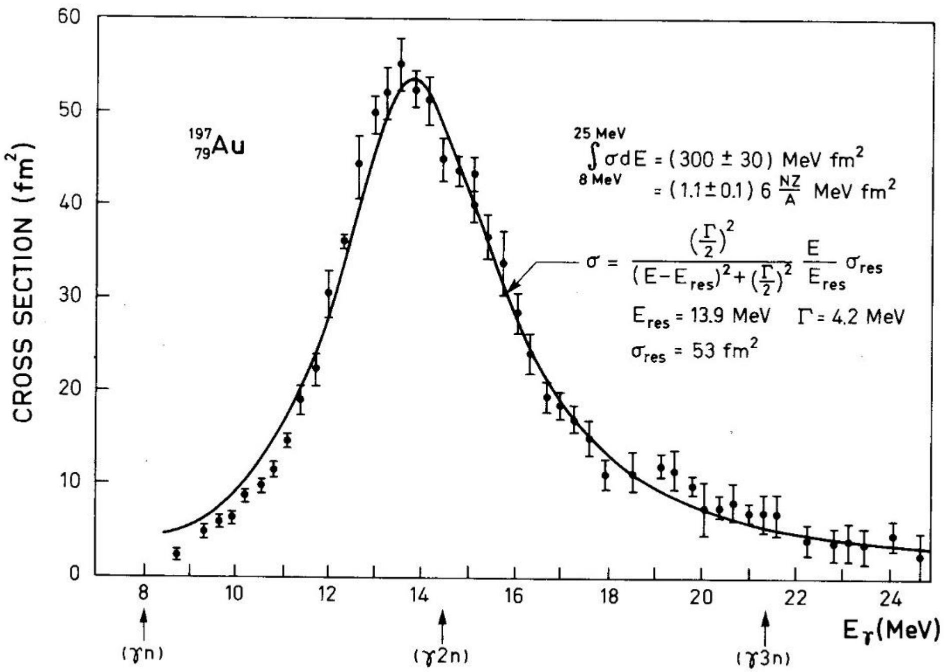


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

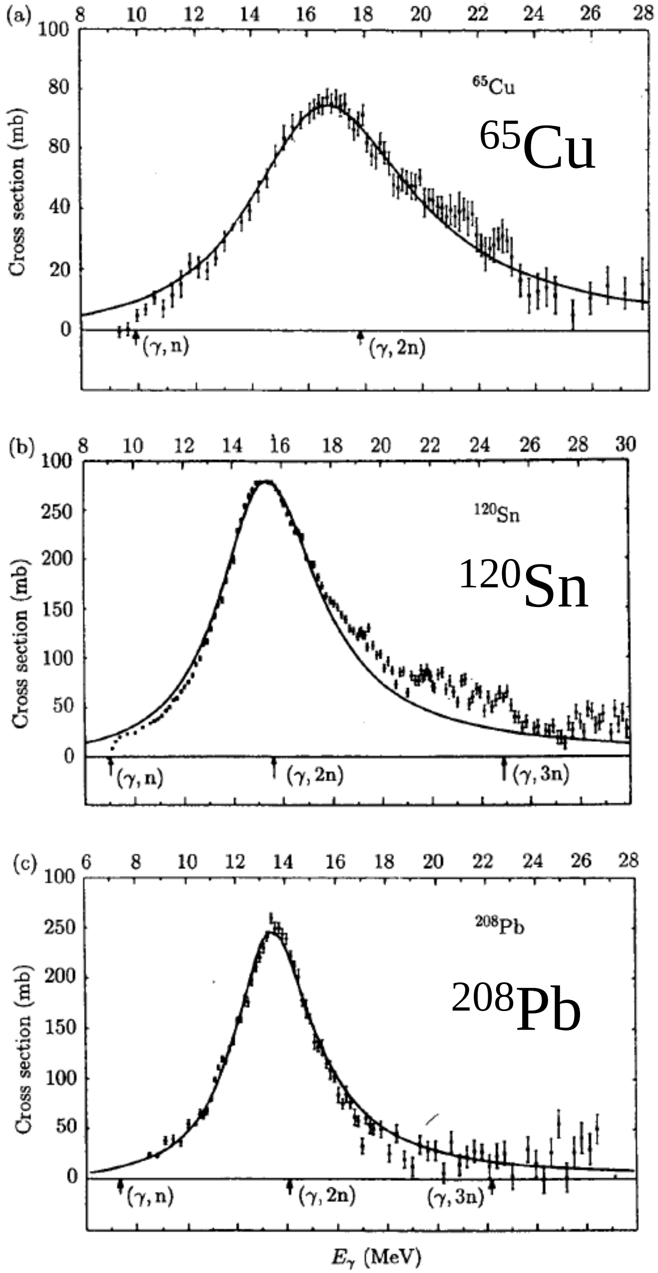
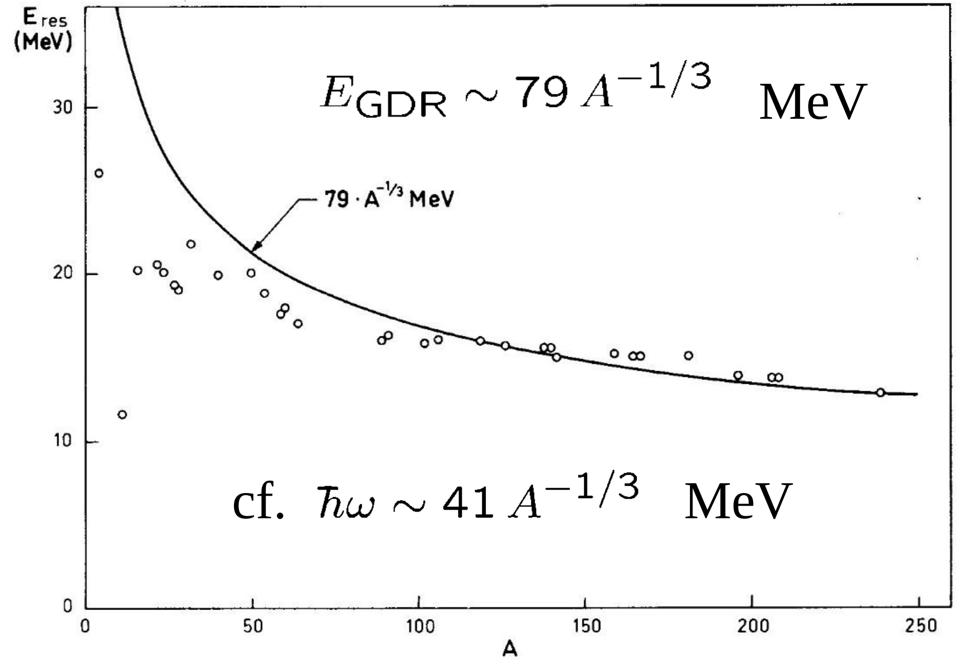
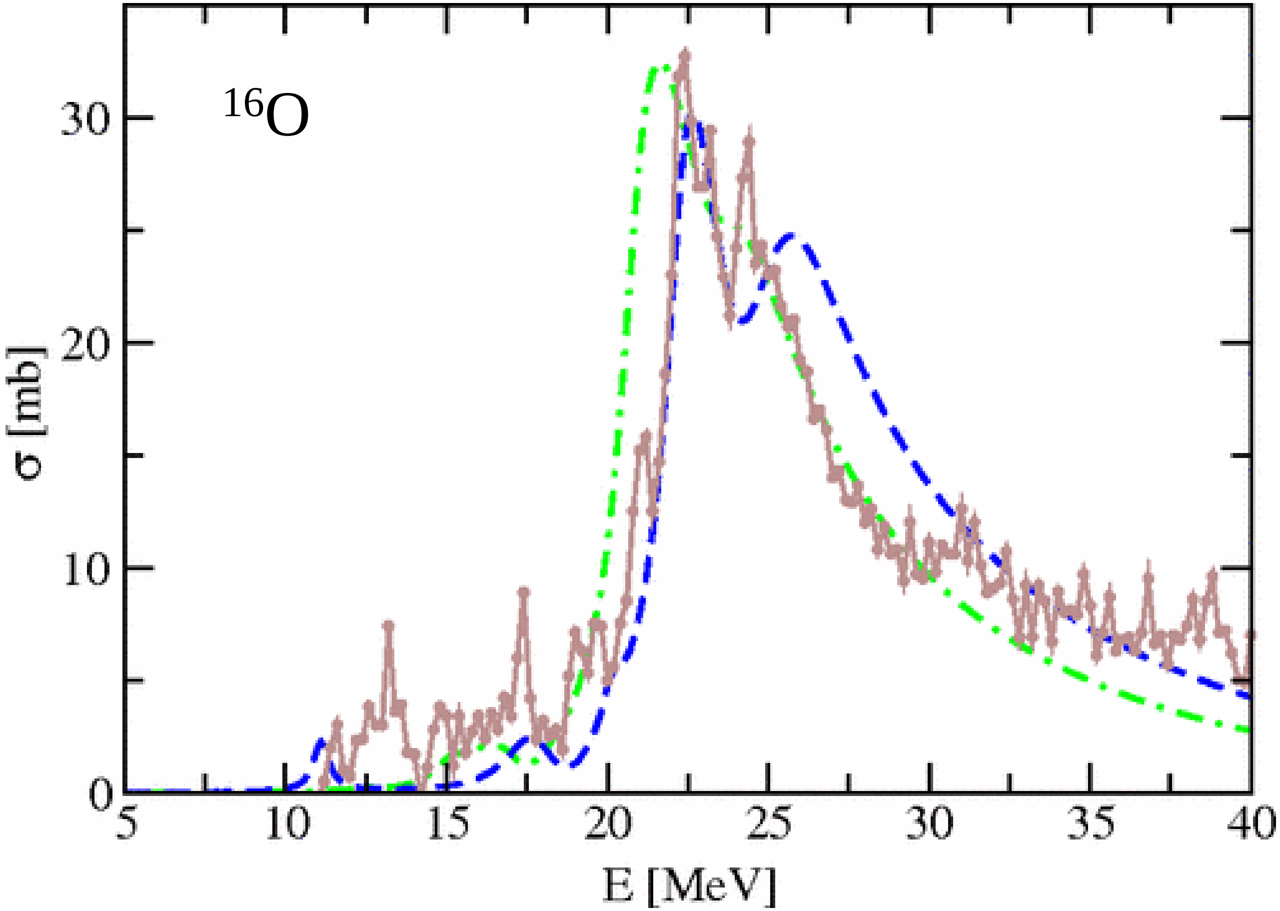


FIG. 1.2. The photo-neutron cross section $\sigma(\gamma, \mathrm{n})$ as a function of the photon energy for the three nuclei ^{208}Pb, ^{120}Sn and ^{65}Cu. Note that for these nuclei $\sigma(\gamma, \mathrm{n}) \approx \sigma_{abs}(\gamma)$. From reference (BER75).



Bohr-Mottelson
"Nuclear Structure vol. II"

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

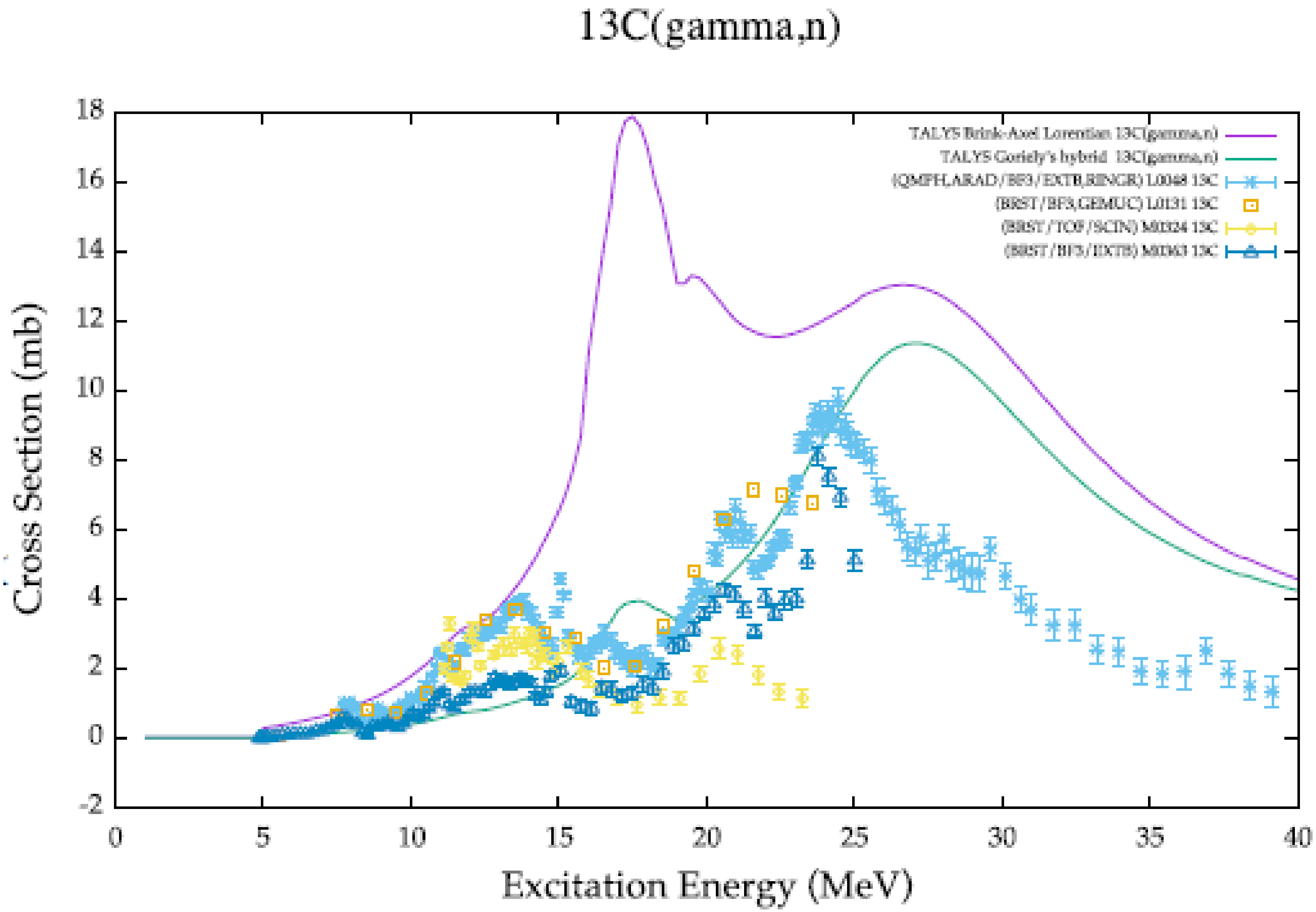


実験データ：茶色

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

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

ただし、軽い核（Fe, Ni 程度以下）のデータはまだ少ない
→ PANDRA プロジェクト（RCNP民井さん） 2022年～

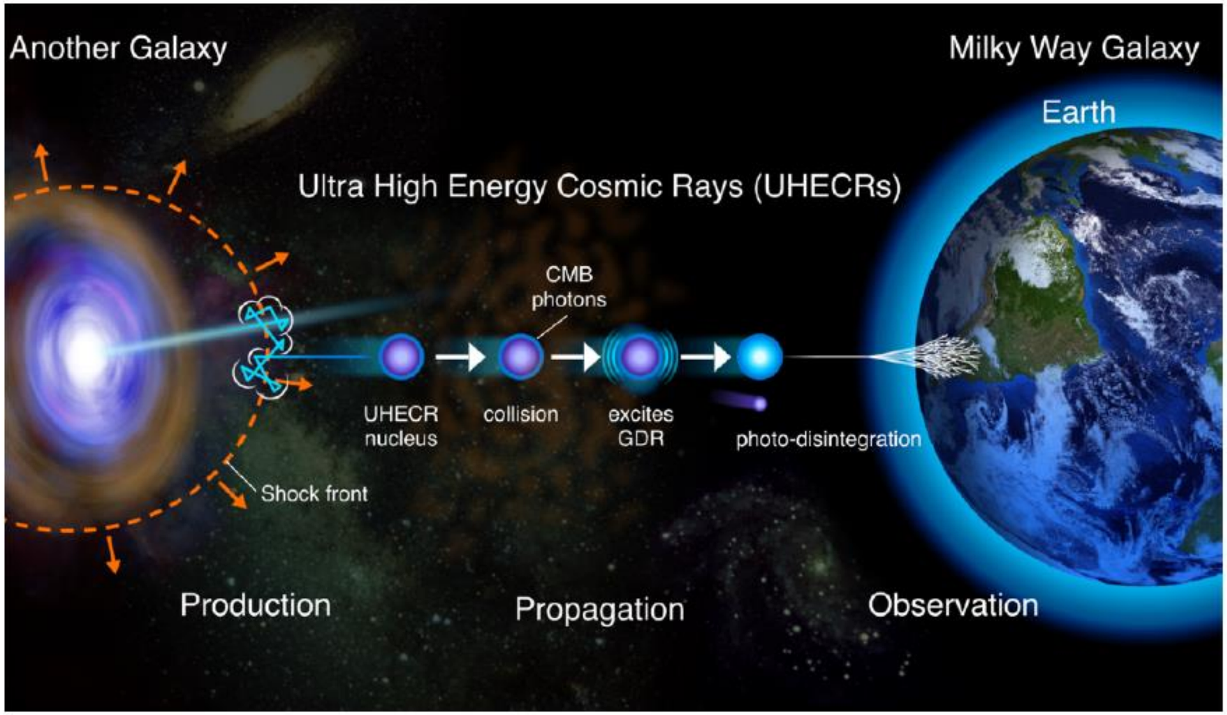


スライド：民井さん

- 実験データ同士の矛盾
- 軽い核の理論計算

PANDORA Project

Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics



スライド：民井さん

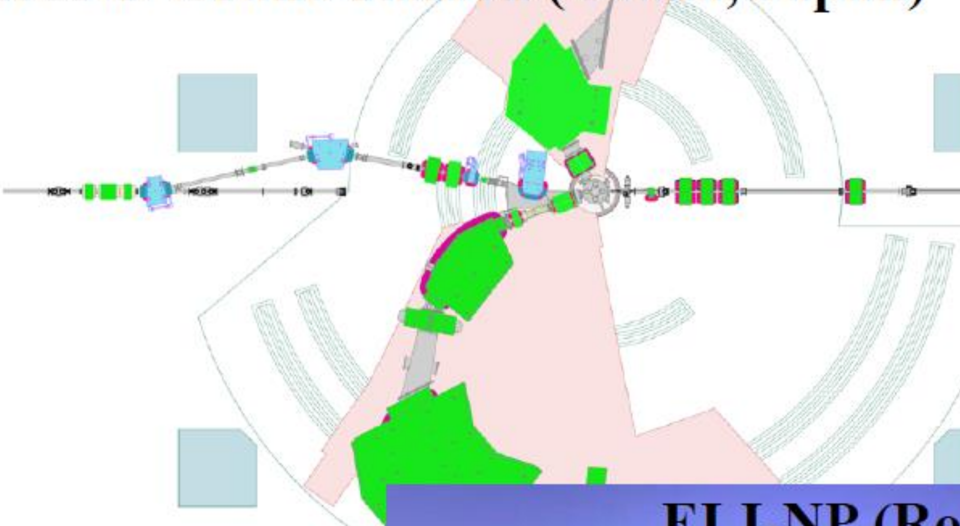
高エネルギー宇宙線の観測で、原子核のGDRが大きな不定性の原因になっている

PANDORA Project

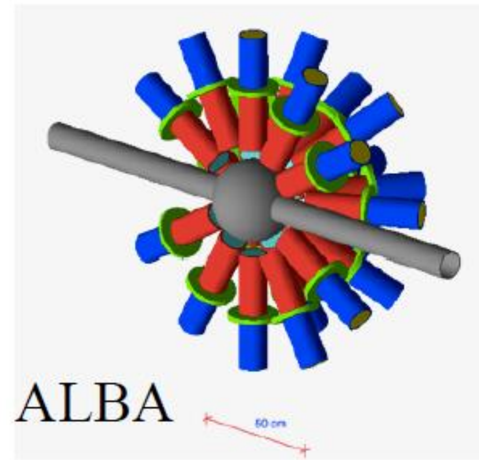
Photo-**A**bsorption of **N**uclei and **D**ecay **O**bservation for **R**eactions in **A**strophysics

Joint project among three experimental facilities with nuclear theories and astrophysical simulations

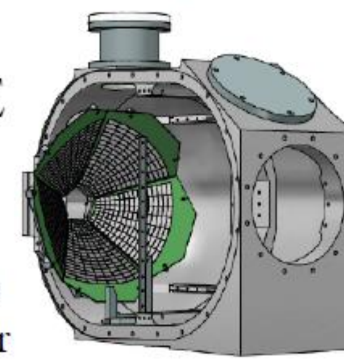
RCNP-Grand Raiden (Osaka, Japan)



iThemba LABS South Africa



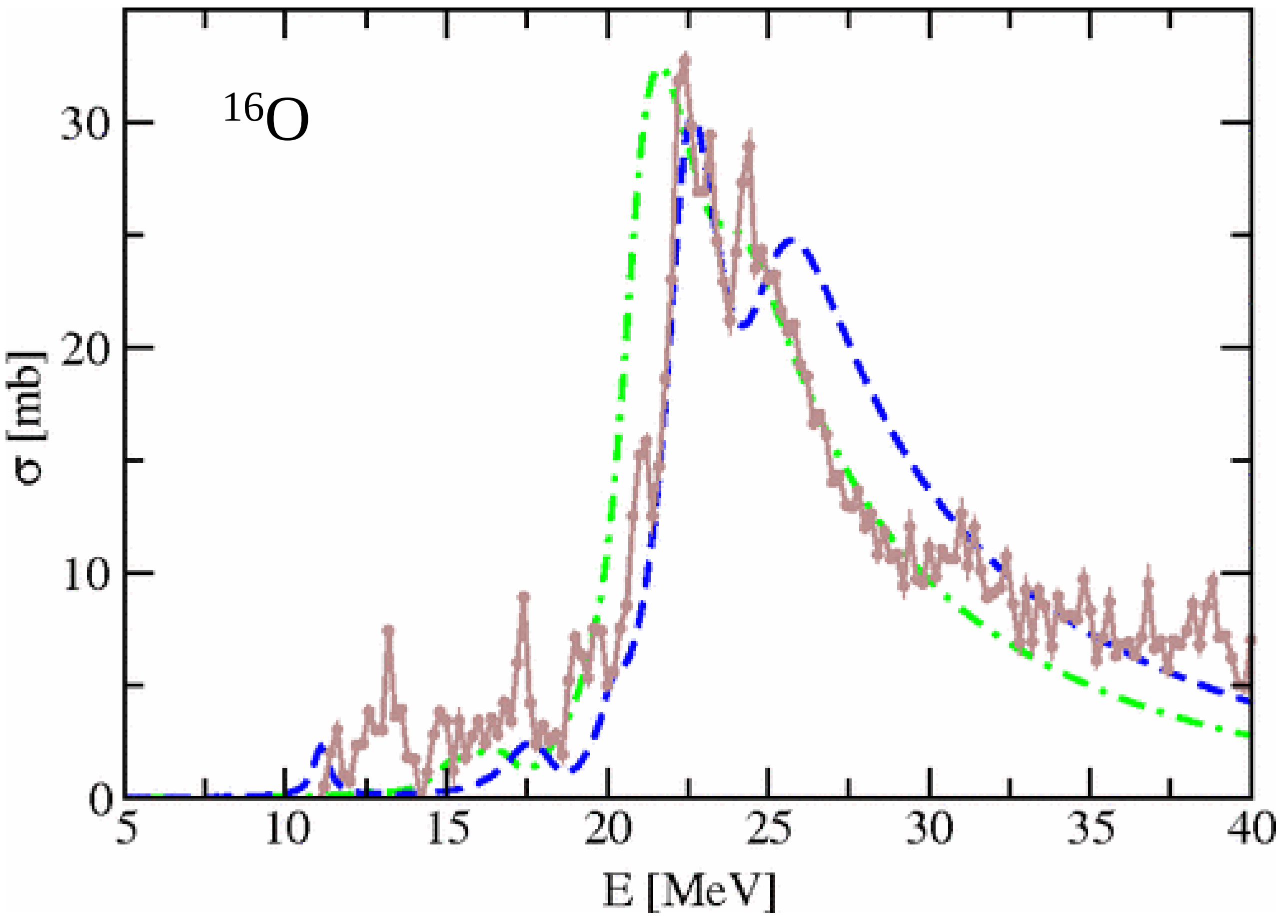
CAKE



decay charge particle detector array

complementary experimental techniques

スライド：民井さん

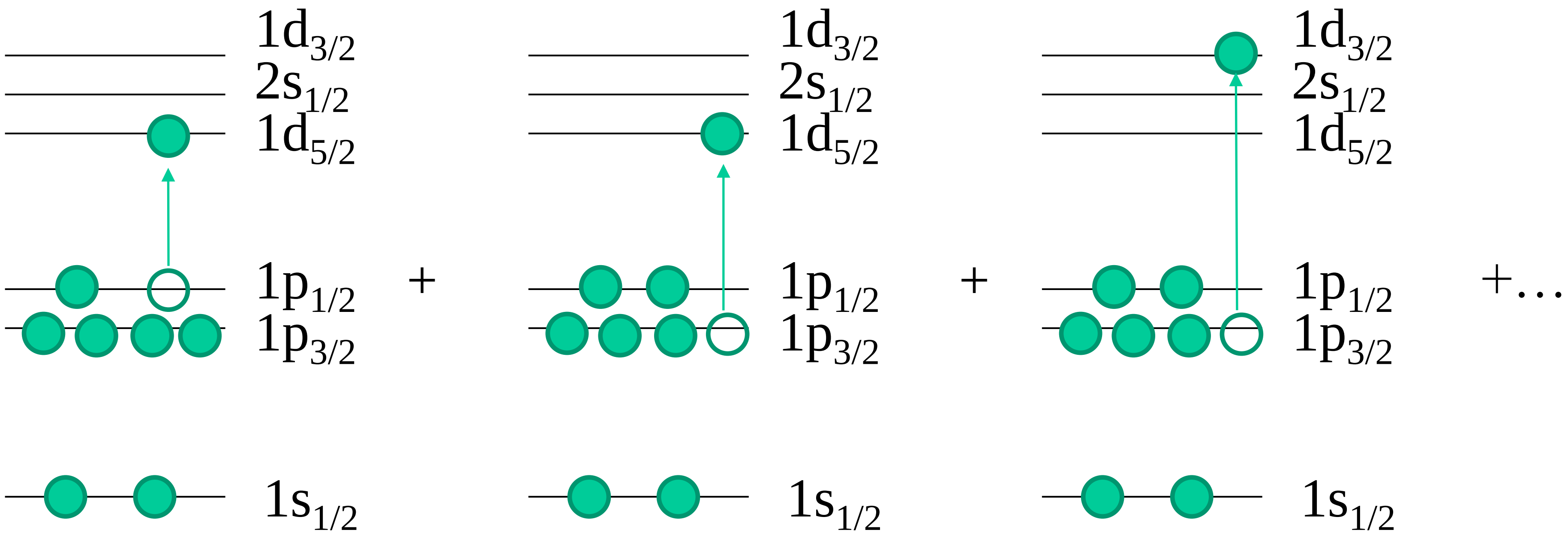


実験データ：茶色

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

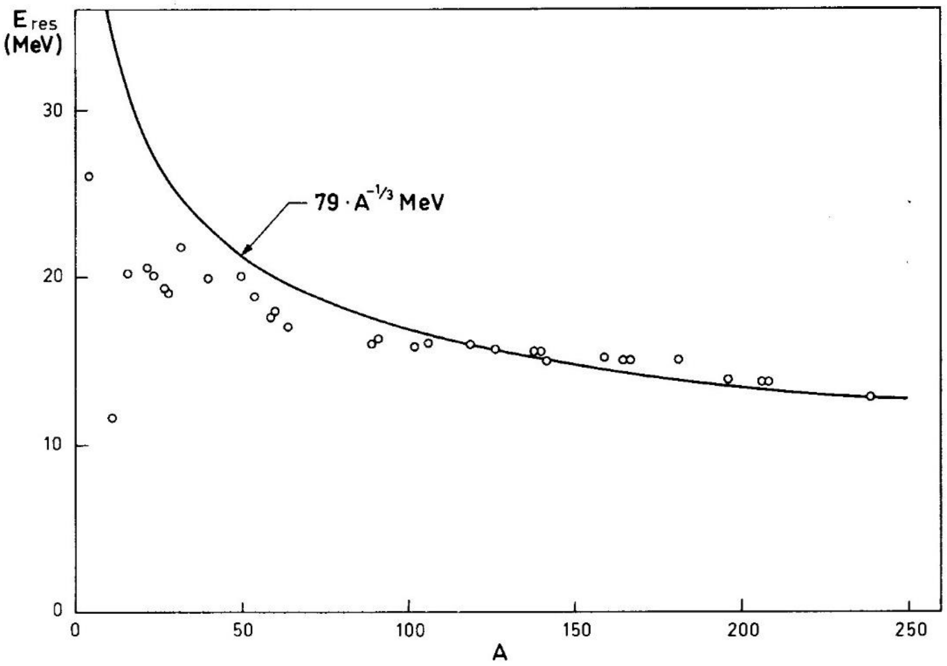
cf. $41 \times 16^{-1/3} = 16.27$ MeV

何故励起エネルギーが大きくなるのか？

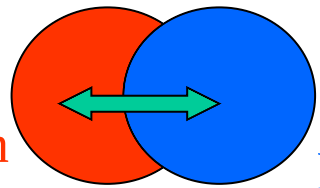


様々な励起状態がコヒーレントに重ね合わさることにより
「集団的」になる。→（次回もう少し詳しく）

残留相互作用が大きな役割



Bohr-Mottelson
“Nuclear Structure vol. II”



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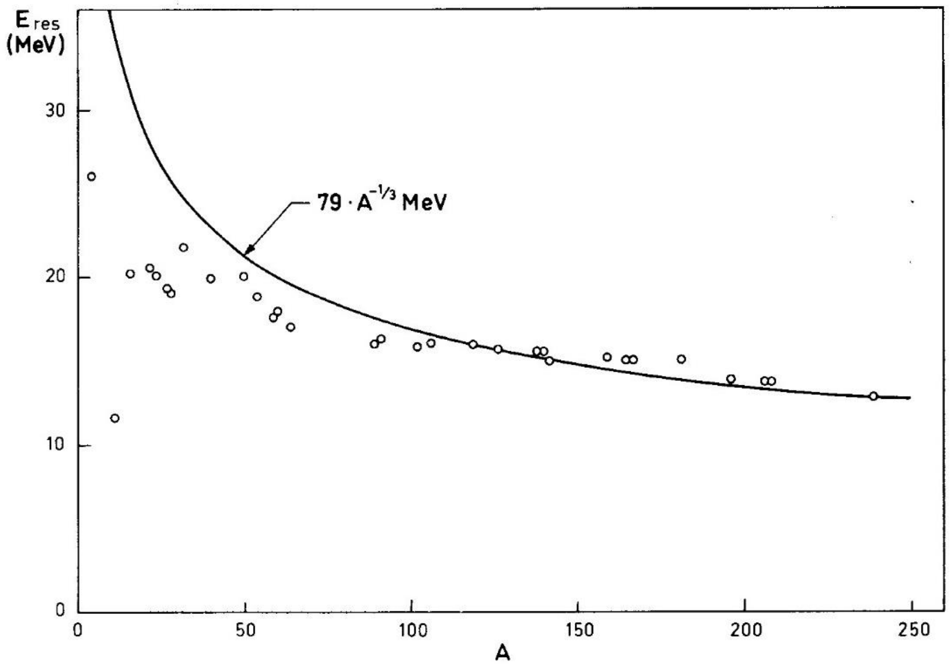
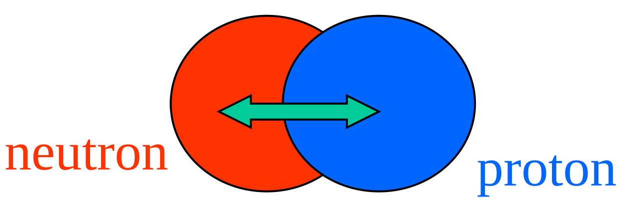


$$E_{\mathrm{GDR}} \propto A^{-1/3}$$

3つのモード

Bohr-Mottelson
"Nuclear Structure vol. II"



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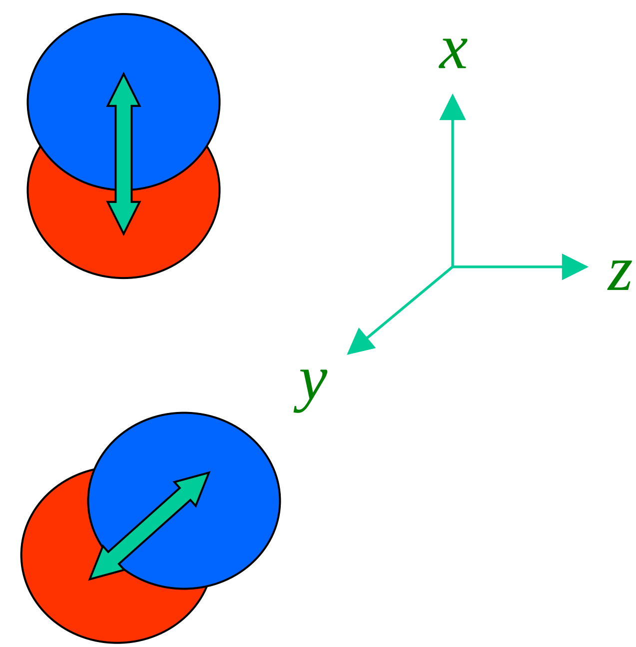
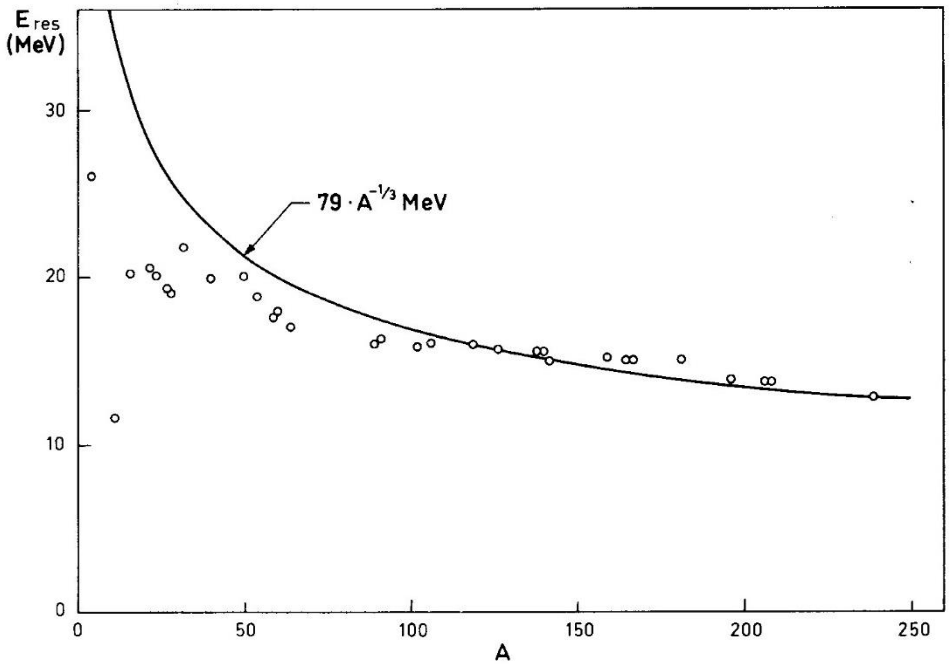
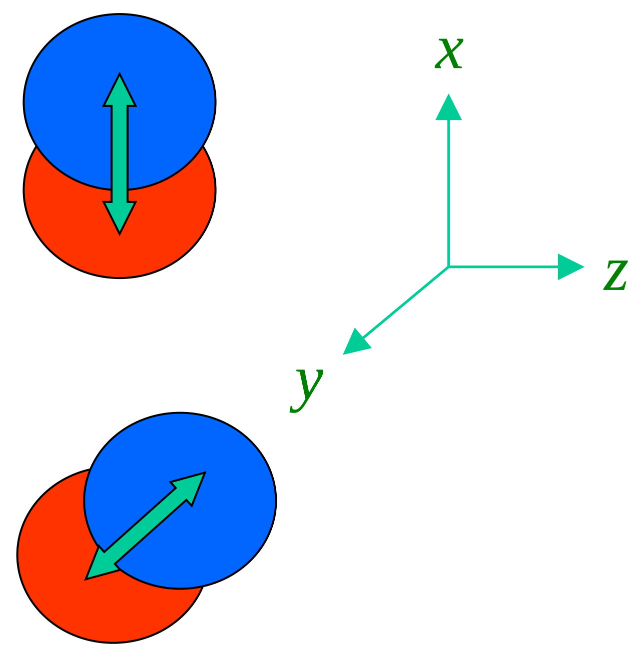


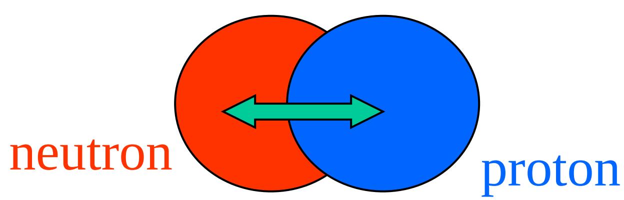


$$E_{\mathrm{GDR}} \propto A^{-1/3}$$
$$\propto 1/R$$

3つのモード



Bohr-Mottelson
"Nuclear Structure vol. II"



Isovector type

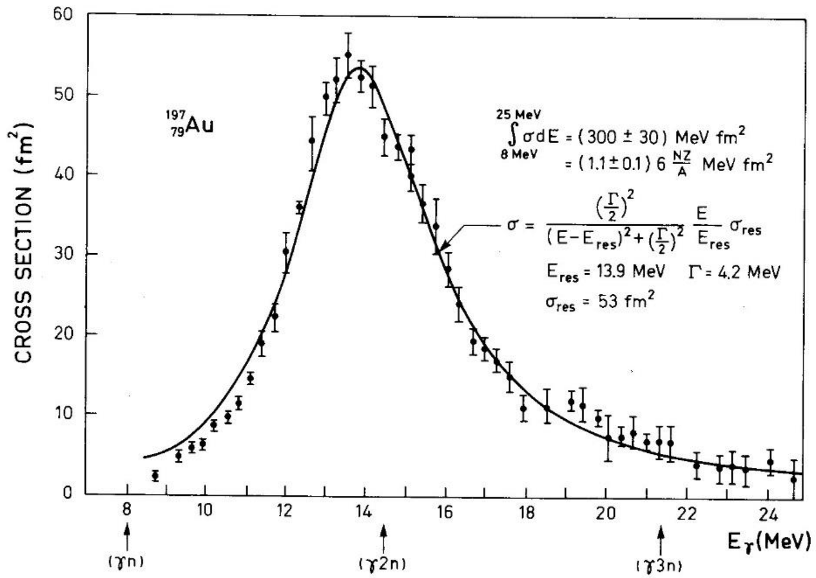
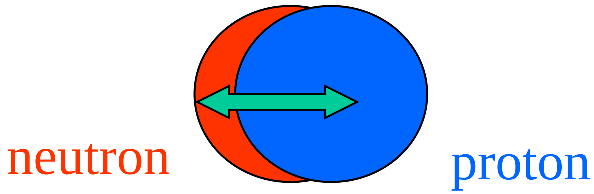
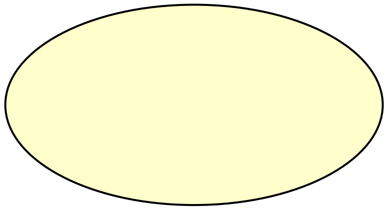


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

?

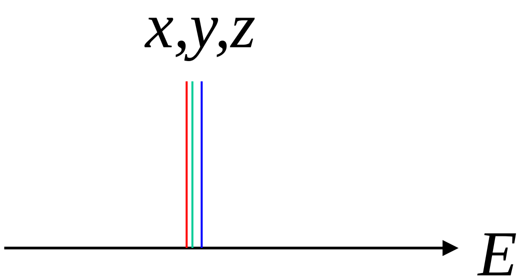


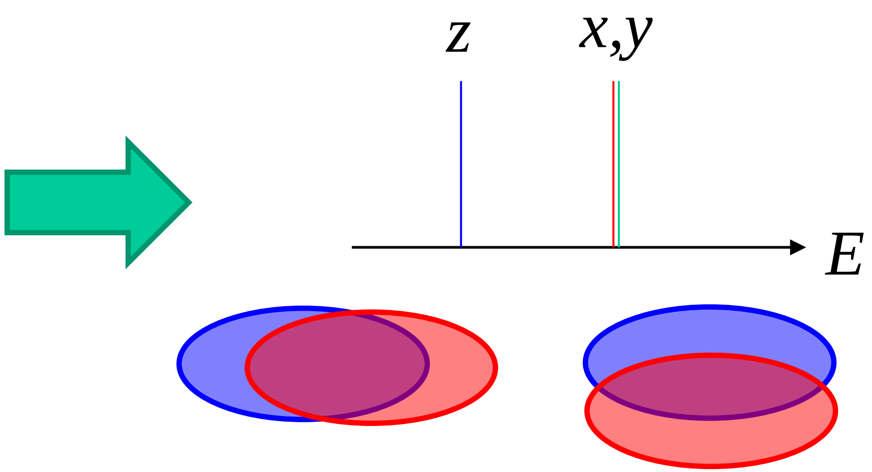
deformed nucleus



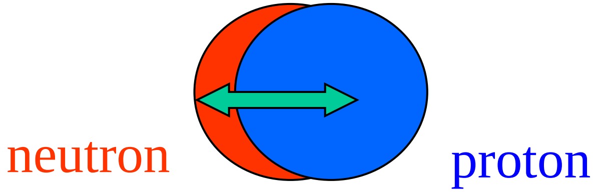
$$E_{\rm GDR} \propto 1/R$$

(prolate deformation)

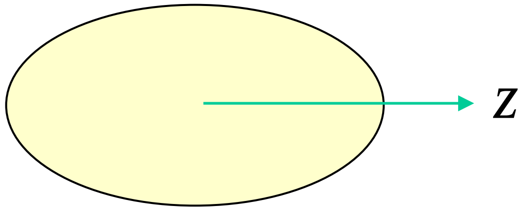




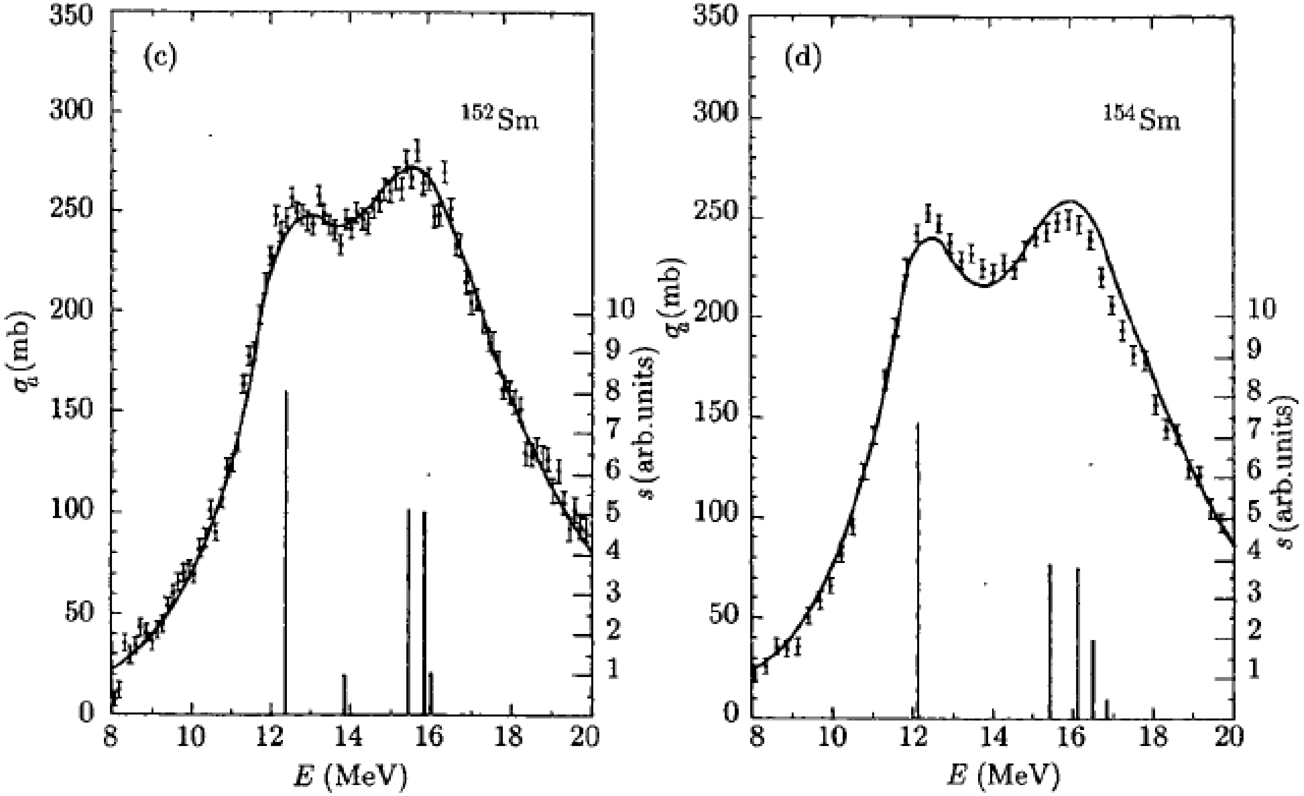
spherical nucleus



deformed nucleus

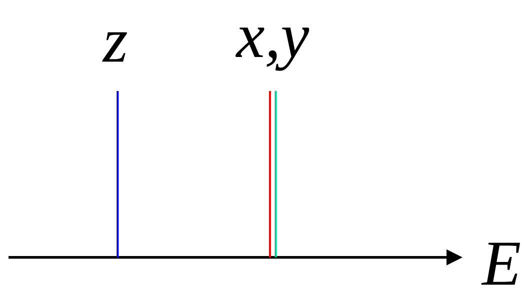


$$E_{\mathrm{GDR}} \propto 1/R$$

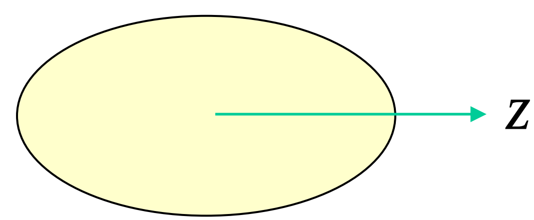


M.N. Harakeh and A. van der Woude, "Giant Resonances"

(prolate deformation)

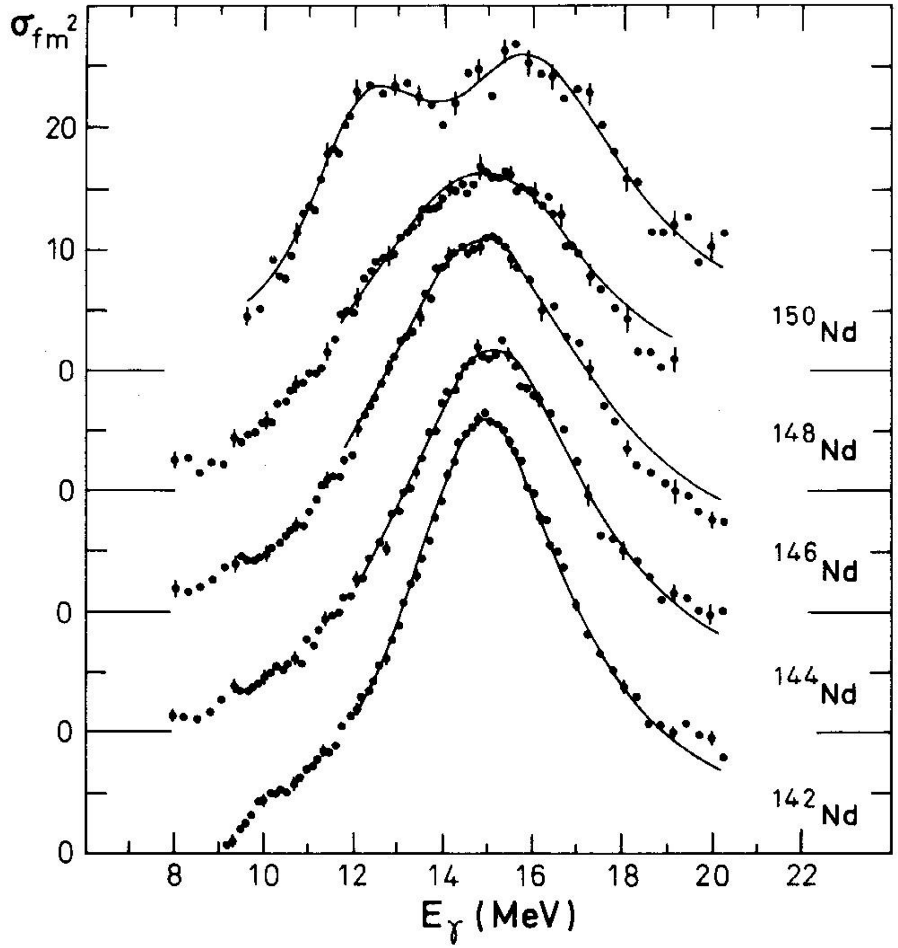


deformed nucleus



Deformation effect

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



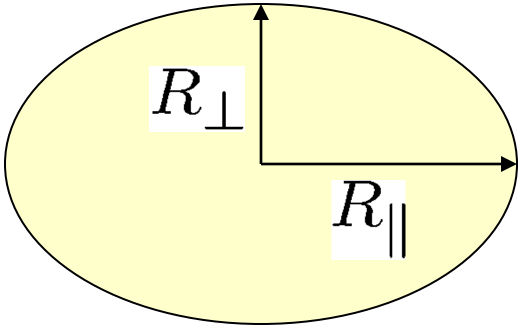
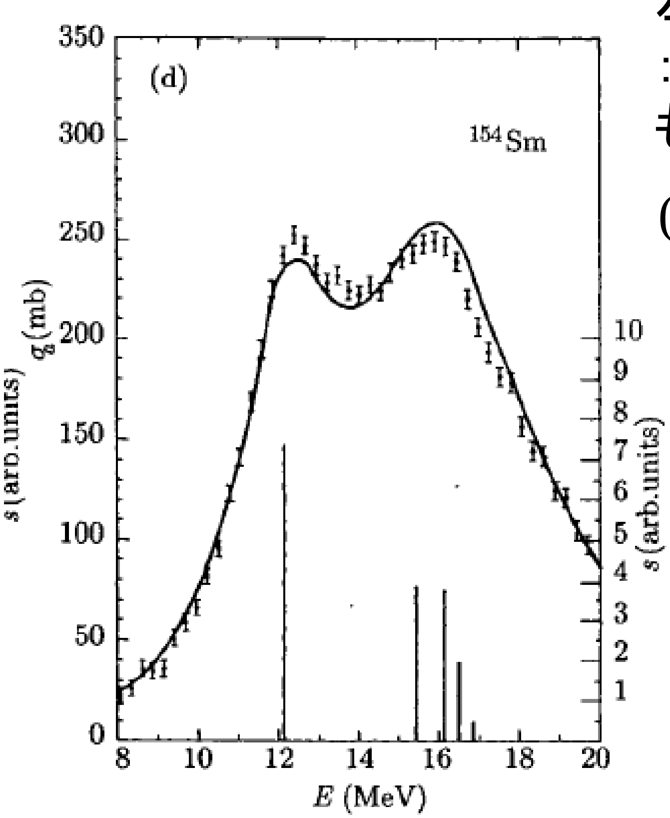


Figure 6-21 Photoabsorption cross section for even isotopes of neodymium. The experimental data are from P. Carlos, H. Beil, R. Bergère, A. Lepretre, and A. Veyssière, *Nuclear Phys.* **A172**, 437 (1971). The solid curves represent Lorentzian fits with the parameters given in Table 6-6.

レポート問題1（〆切：12月3日（土））



左に示す ^{154}Sm 核の光吸収断面積（巨大双極子共鳴：GDR）の実験データから ^{154}Sm 核の変形度を見積もってみよう。

(i) GDRのエネルギーはおおよそ $E \sim 79\ A^{-1/3}$ MeV となることが知られている。原子核の半径を $R_0 = r_0 A^{1/3}$ とすると、これは $E \sim 79\ r_0 / R_0$ MeV となることを示している。左の図は 12 MeVと 16 MeV にピークを持つが、$r_0 = 1.1$ fm としてそれぞれのエネルギーに相当する半径 R_0 の大きさを求めよ。（この場合、$R_0 = r_0 A^{1/3}$ にはならないことに注意せよ。）

(ii) (i) で求めた2つの半径（小さい方から R_1、R_2とする）が^{154}Sm の変形に起因すると仮定する。
このとき、半径が

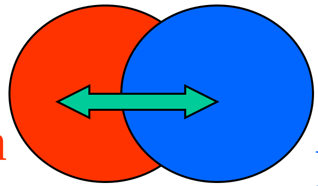
$$R(\theta) = R_0(1 + \beta Y_{20}(\theta)); \quad R_0 = r_0 A^{1/3}$$

で与えられるとし、$R_1 = R(\theta=\pi/2)$, $R_2 = R(\theta=0)$と考え、二つの半径の差 $R_2 - R_1$ の値から変形度 β を求めよ。

Giant Dipole Resonances

- <u>Goldhaber-Teller type</u>

neutron

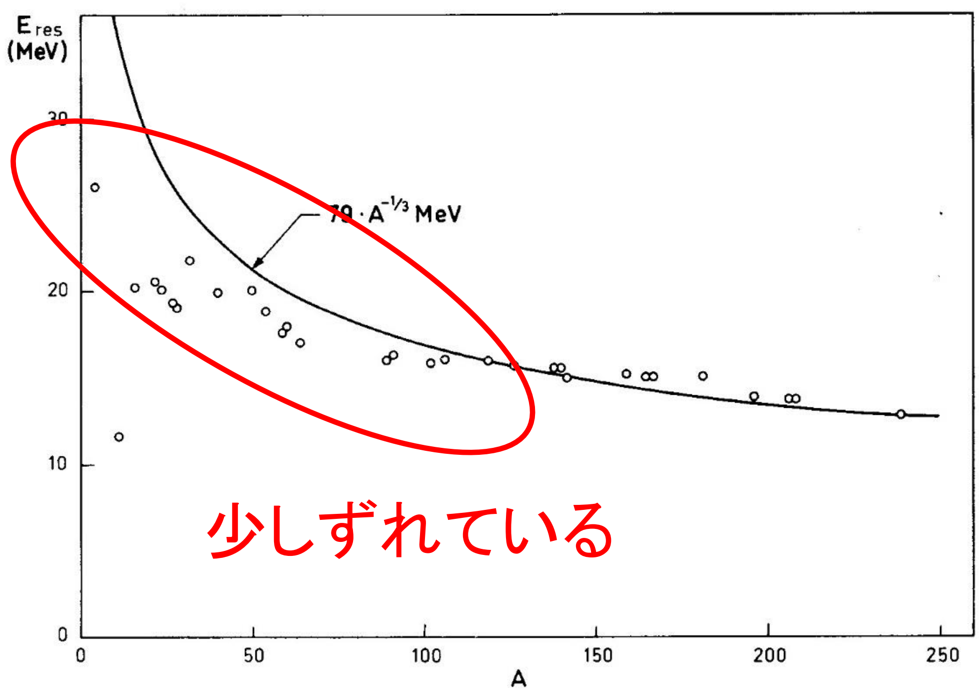


proton

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

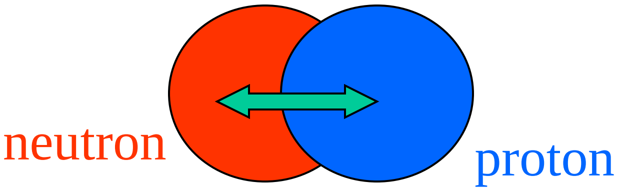
→ $\hbar\omega \sim A^{-1/6}$

⇒ Inconsistent with expt.
(except for light nuclei)



Giant Dipole Resonances

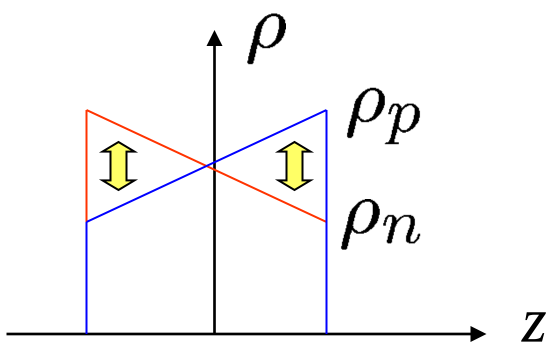
- Goldhaber-Teller type



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

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

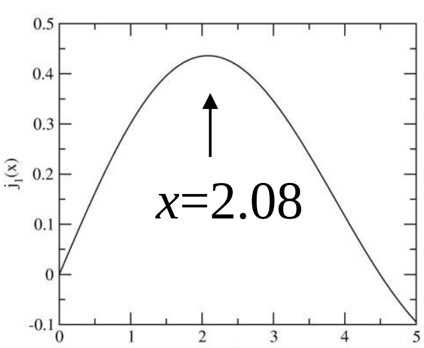
- Steinwedel-Jensen type



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

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

$$kR = 2.08$$



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

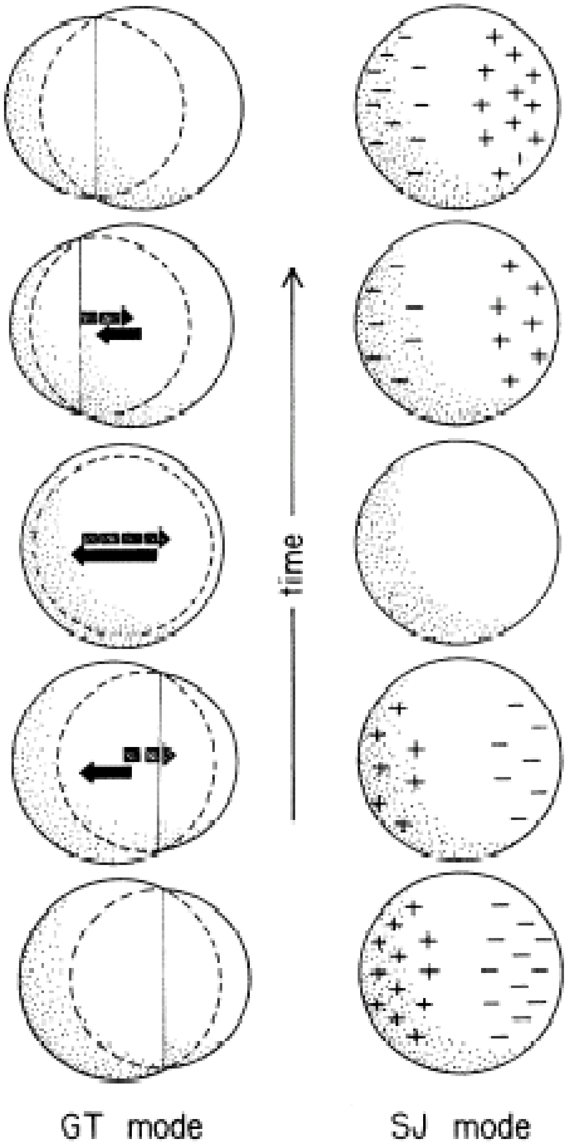


FIG. 1. Schematic drawings that serve to illustrate the the general features of the Goldhaber-Teller (Ref. 3) (GT) and Steinwedel-Jensen (Ref. 4) (SJ) dipole modes.

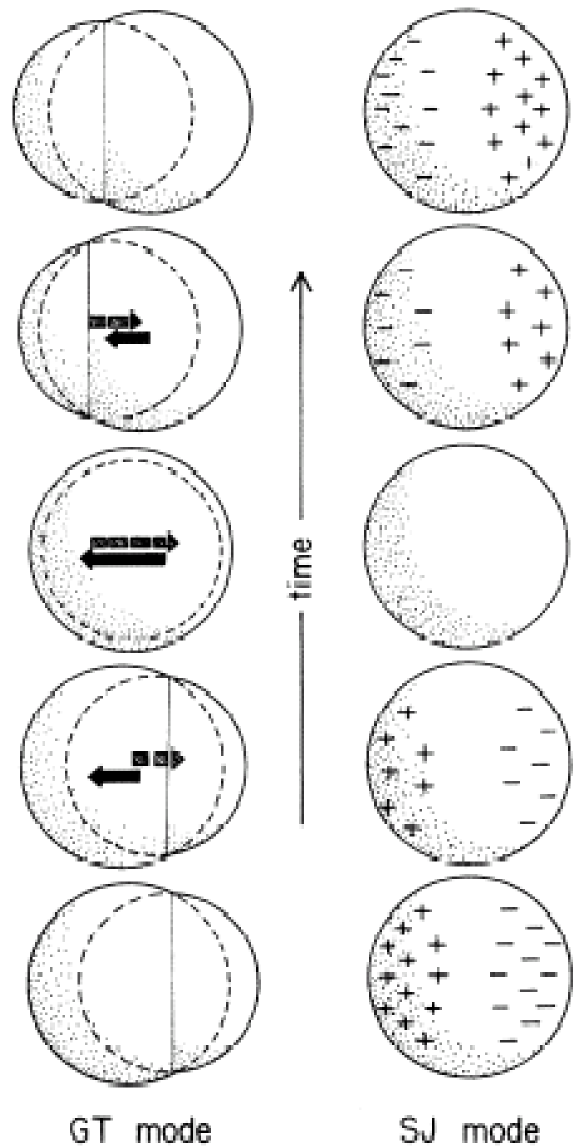
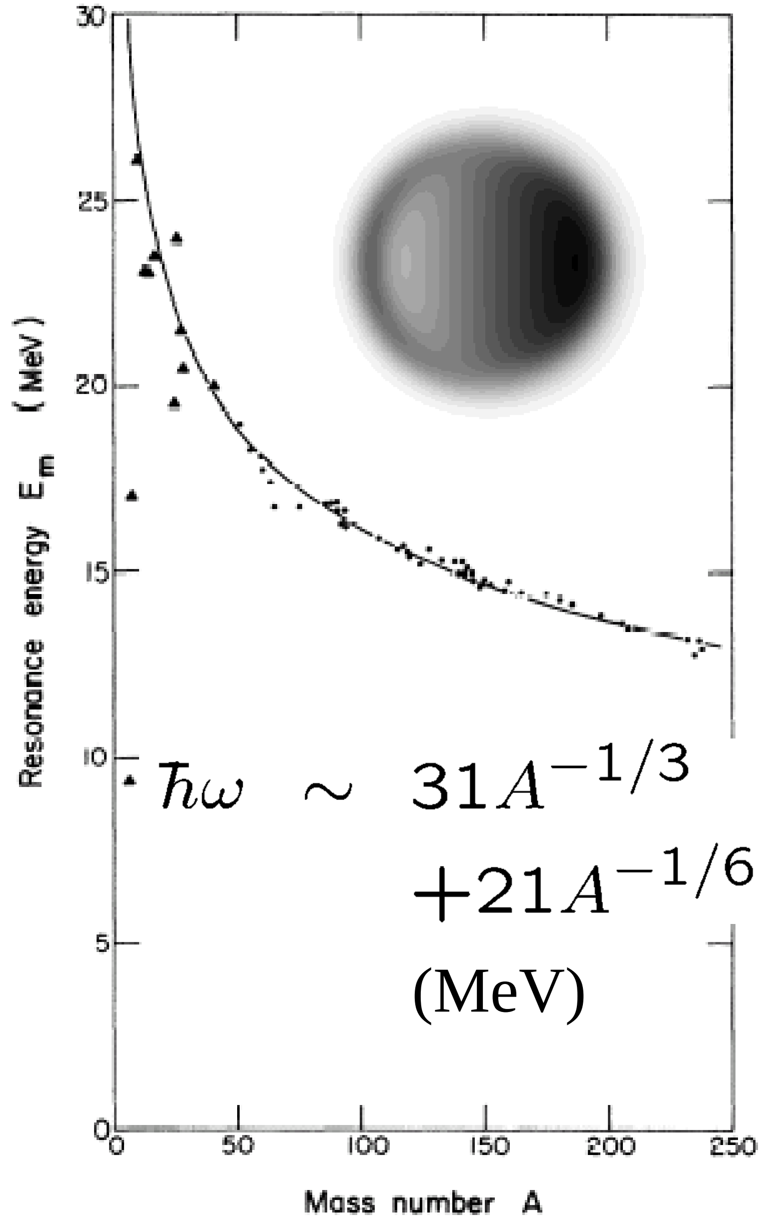


FIG. 1. Schematic drawings that serve to illustrate the the general features of the Goldhaber-Teller (Ref. 3) (GT) and Steinwedel-Jensen (Ref. 4) (SJ) dipole modes.

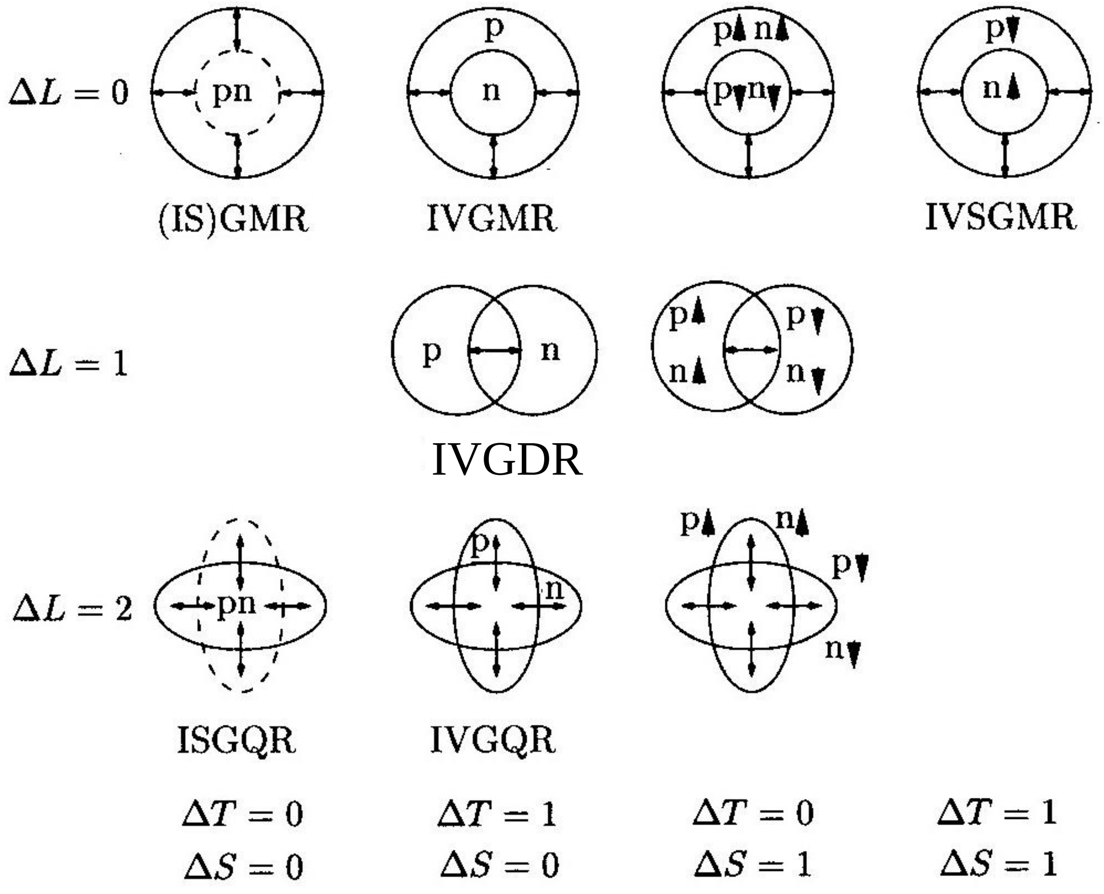


$$\hbar\omega \sim 31A^{-1/3} + 21A^{-1/6}$$ (MeV)

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

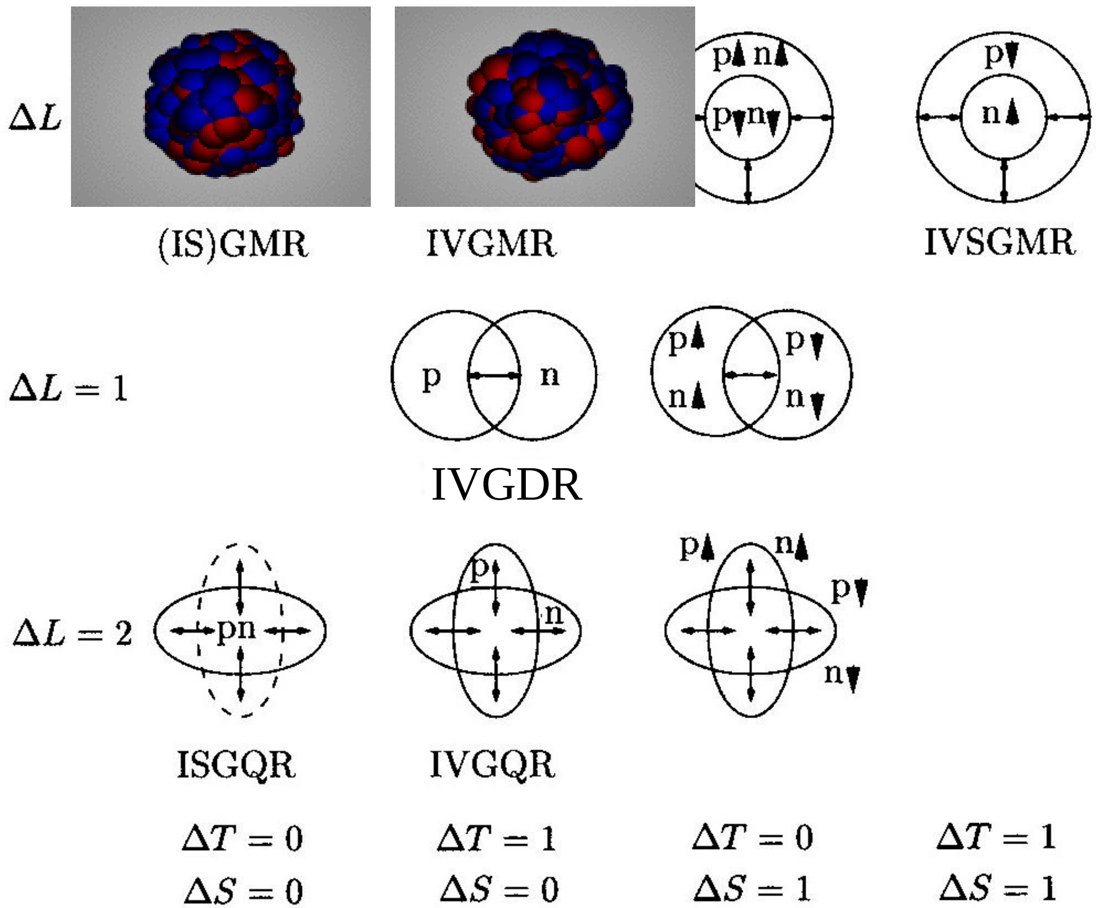
ii) Inelastic scattering

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



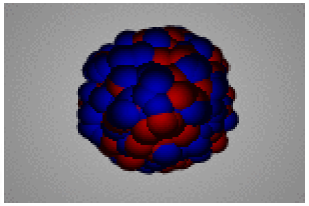
ii) Inelastic scattering

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



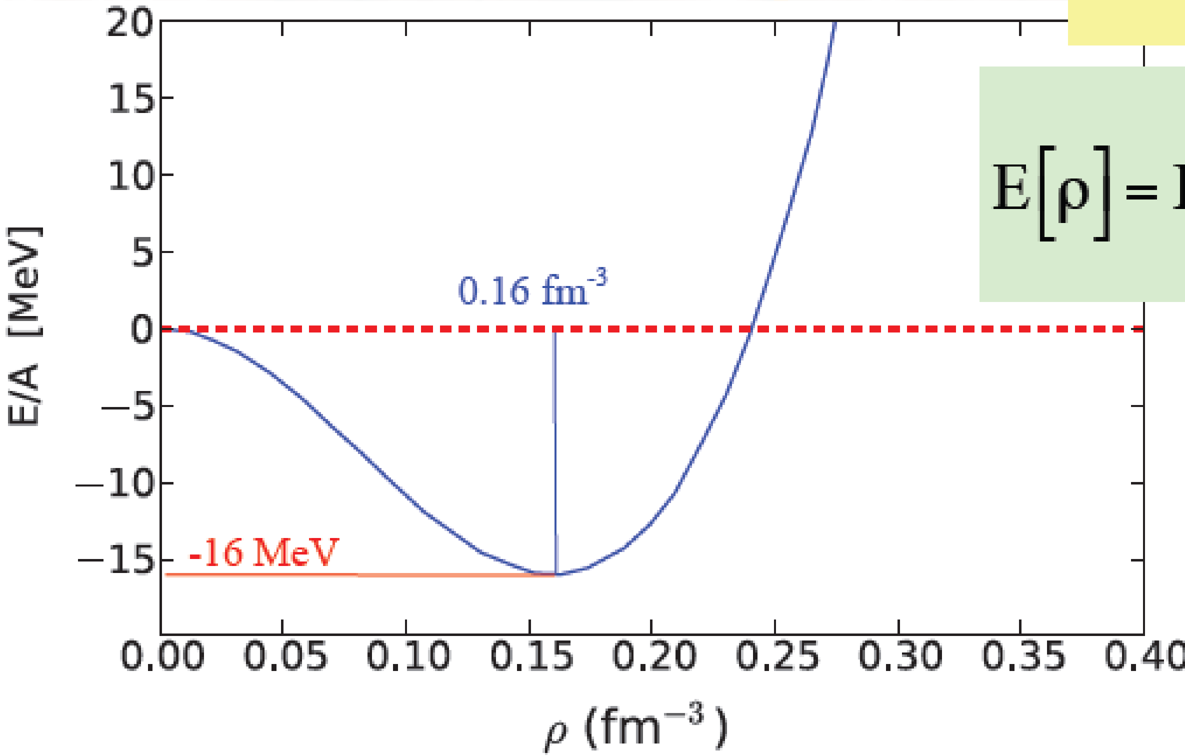
movies: H.-J. Wollersheim,
https://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/index-s.html

EOS of infinite nuclear matter



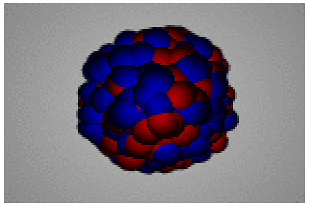
$$K_\infty = 9\rho^2 \frac{d^2\left[E(\rho)/\rho\right]}{d\rho^2}\bigg|_{\rho_0}$$

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



cf. 中性子星の大きさ
や重さ(MR曲線)

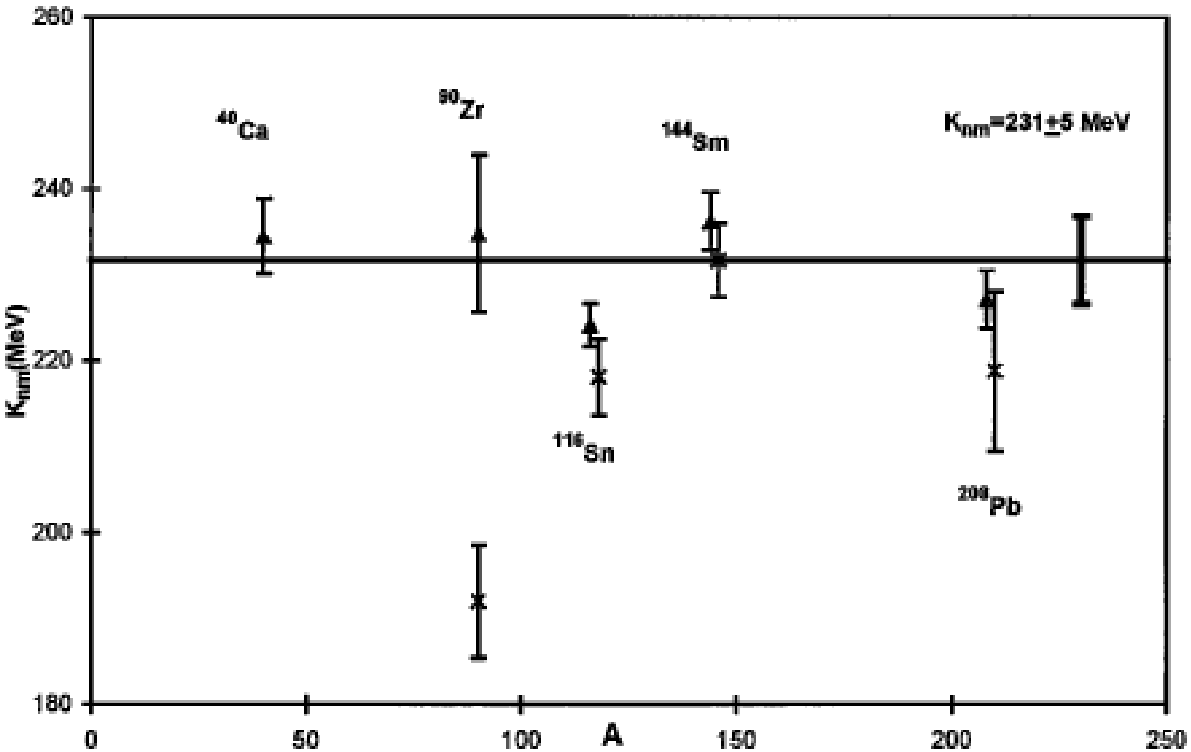
slide: Carlos Bertulani



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

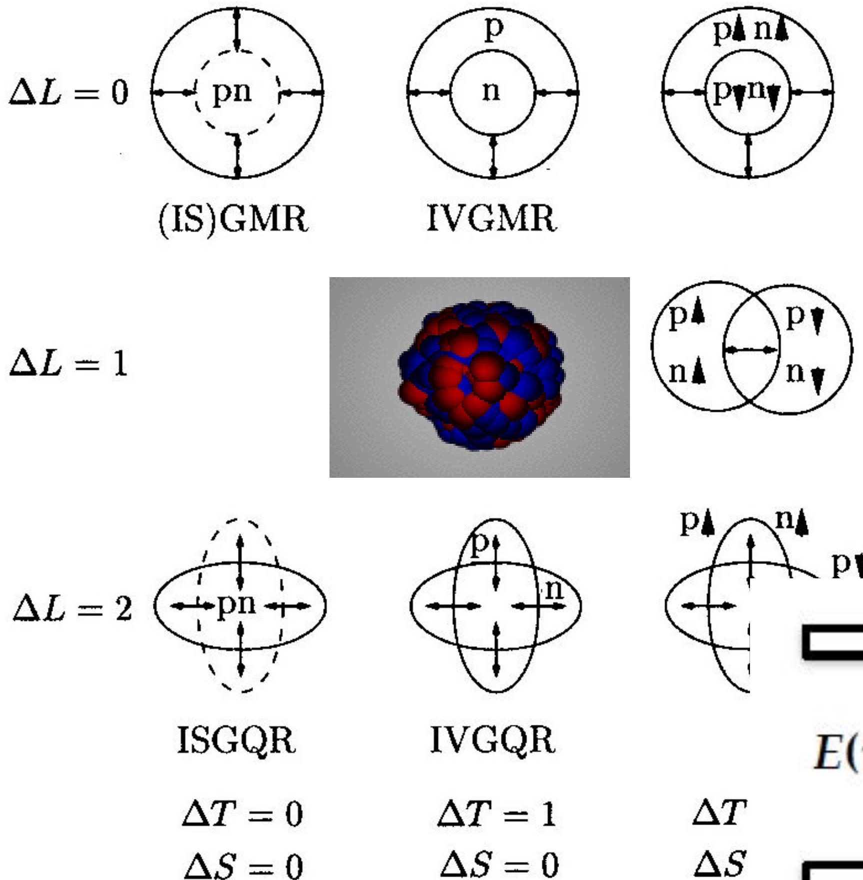


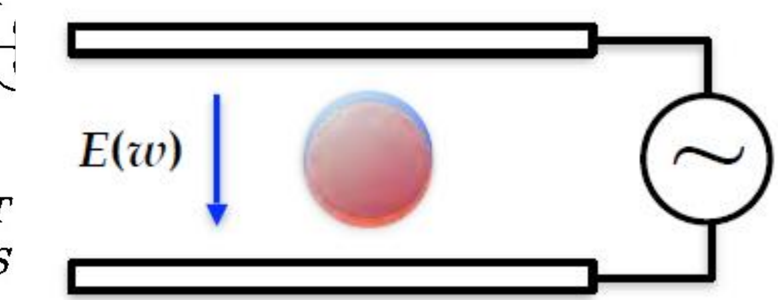
K ~ 231 +/- 5 MeV

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

ii) Inelastic scattering

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





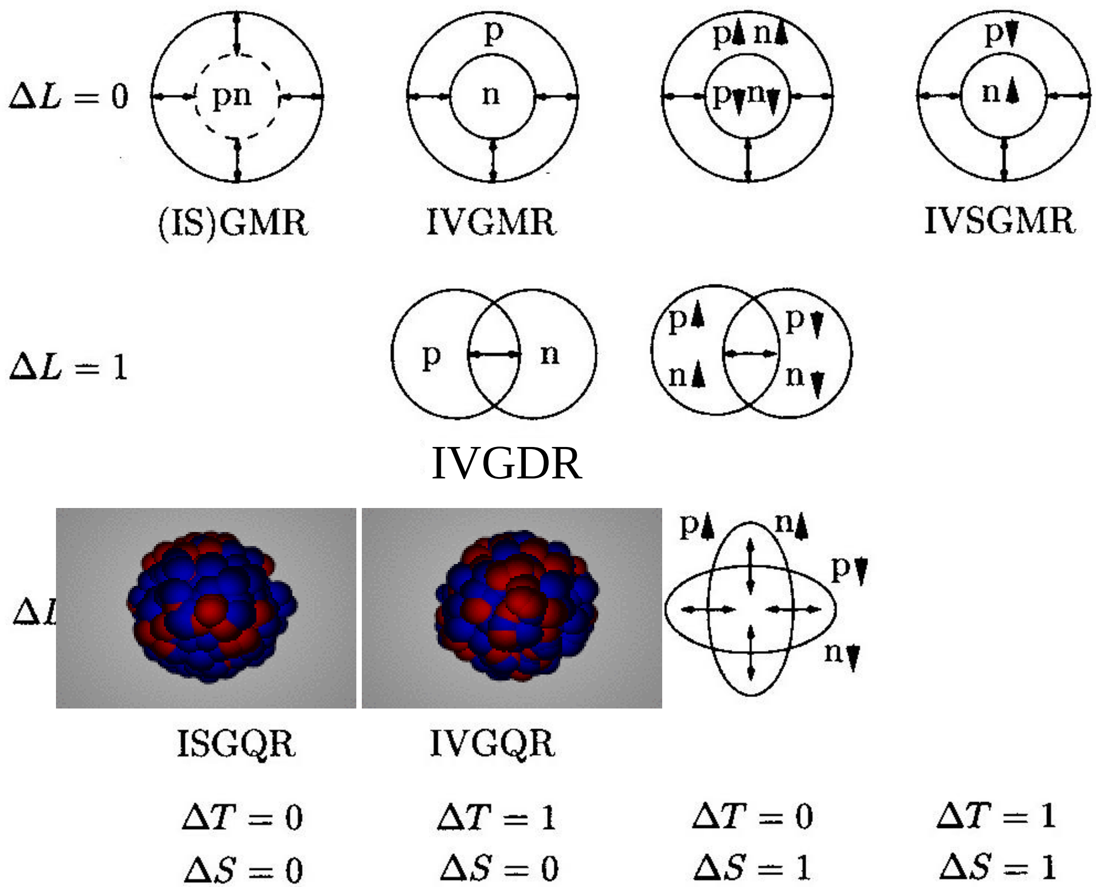
⇒ 原子核の
静電分極率
→対称エネルギー

図 : 民井さん

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

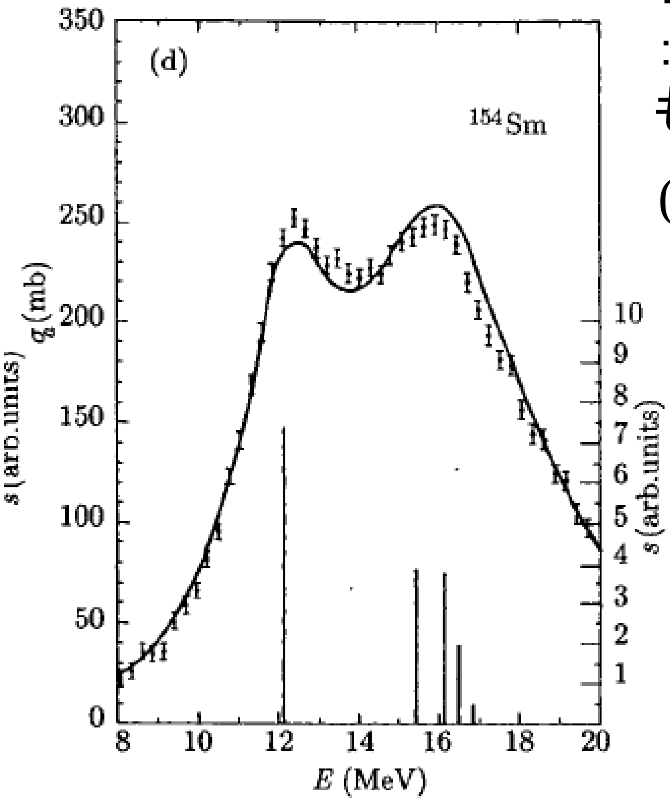


(note) $\Delta L = 2 \longrightarrow$

$\Delta N = 2$ Giant Resonance (GQR)

$\Delta N = 0$ Low-lying state

レポート問題1（〆切：12月3日（土））



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