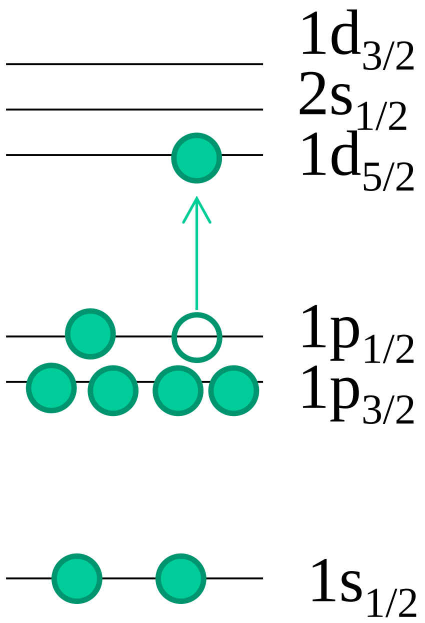
原子核の励起状態

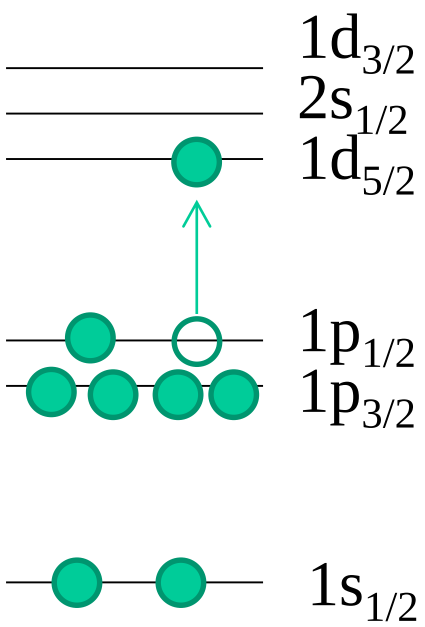
✓ 一粒子励起（一つの核子が励起に関与）



一粒子励起の例

原子核の励起状態

- ✓ 一粒子励起（一つの核子が励起に関与）
- ✓ 集団励起（多くの核子が集団として励起に関与）



一粒子励起の例

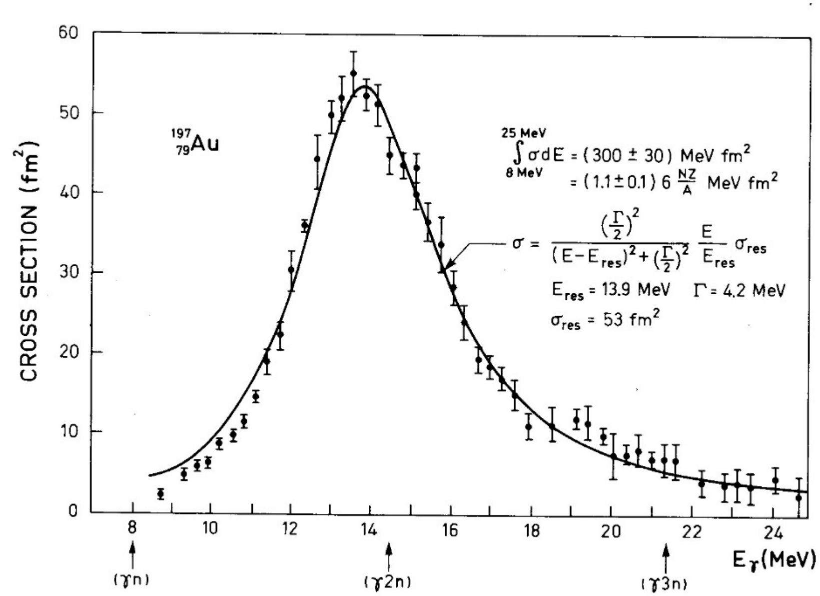
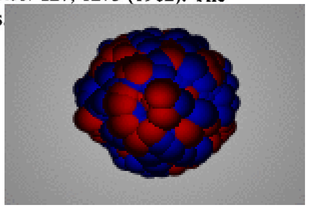
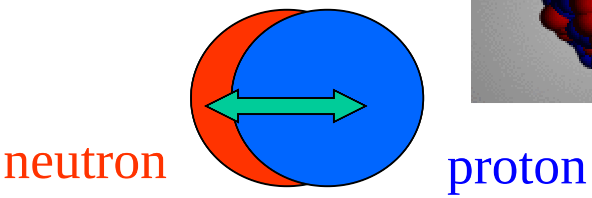


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.





集団励起の例：巨大双極子共鳴

原子核の励起状態

- ✓ 一粒子励起（一つの核子が励起に関与）
- ✓ 集団励起（多くの核子が集団として励起に関与）

集団励起を微視的に理解してみる
（集団励起をミクロに見てみるとどうなっているのか?）

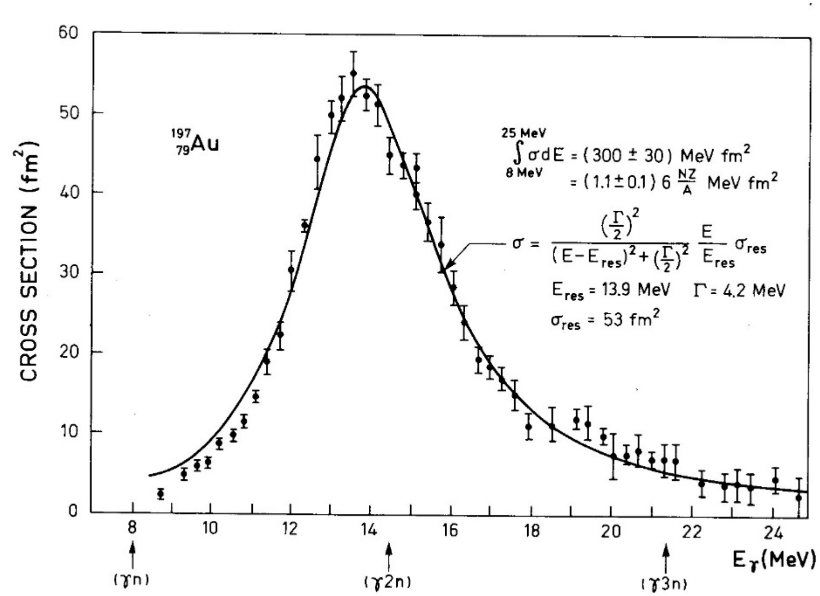
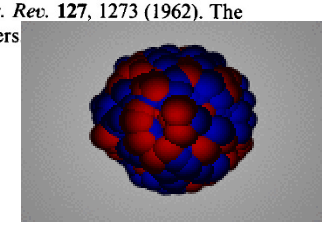
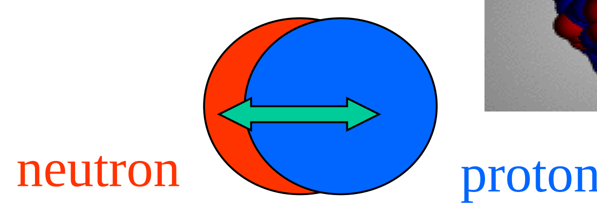


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

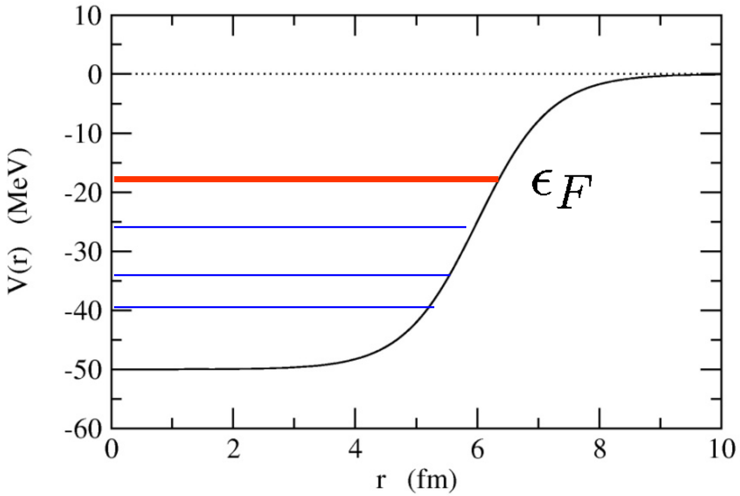




集団励起の例：巨大双極子共鳴

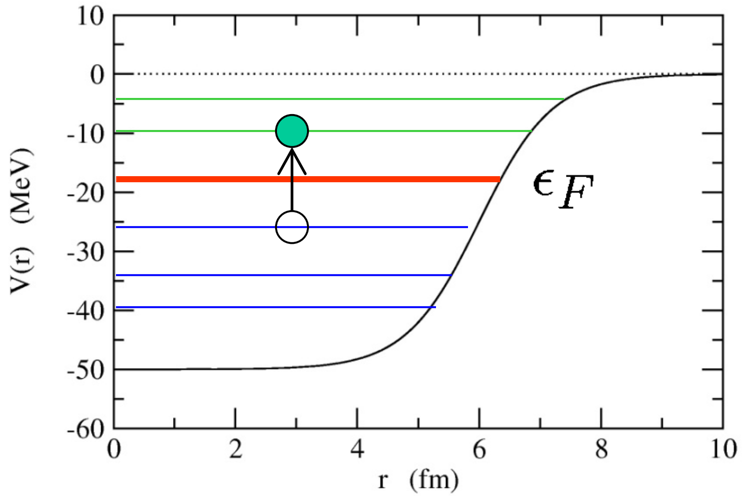
Particle-Hole excitations

Hartree-Fock state



$$|HF\rangle = \prod_h a_h^\dagger |0\rangle$$

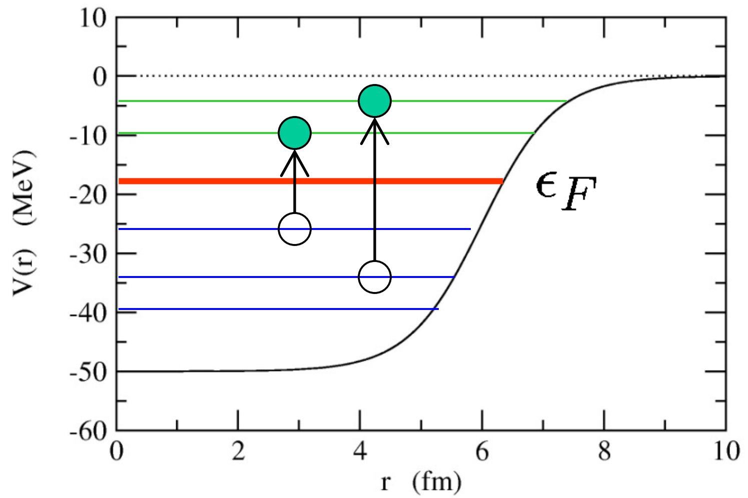
1 particle-1 hole (1p1h) state



$$a_p^\dagger a_h |HF\rangle$$

2 particle-2 hole (2p2h) state

$$a_p^\dagger a_{p'}^\dagger a_h a_{h'} |HF\rangle$$

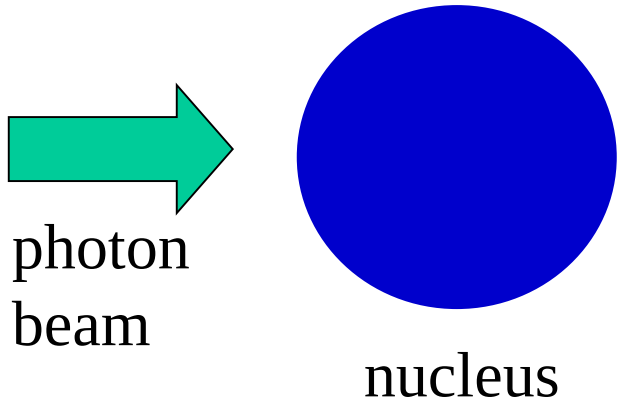


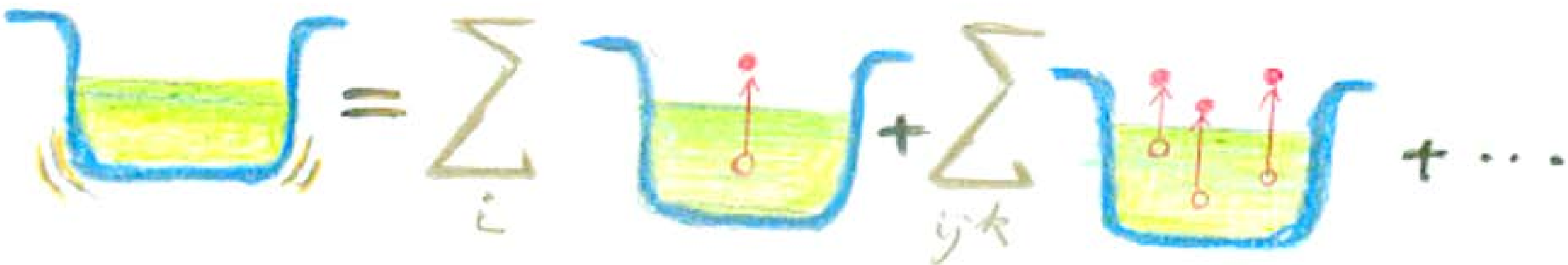
Tamm-Dancoff Approximation

Assume: $$|\nu\rangle = Q_\nu^\dagger|HF\rangle = \sum_{ph} X_{ph}\, a_p^\dagger a_h|HF\rangle \equiv \sum_{ph} X_{ph}|ph^{-1}\rangle$$

(superposition of 1p1h states)

原子核を外場により揺らしてみると何が起こるのか?





スライド: 松柳研一氏

Tamm-Dancoff Approximation

Assume: $|\nu\rangle = Q_\nu^\dagger|HF\rangle = \sum_{ph} X_{ph}\, a_p^\dagger a_h|HF\rangle$

$$\equiv \sum_{ph} X_{ph}|ph^{-1}\rangle$$

(superposition of 1p1h states)

$$H|\nu\rangle = E_\nu|\nu\rangle$$

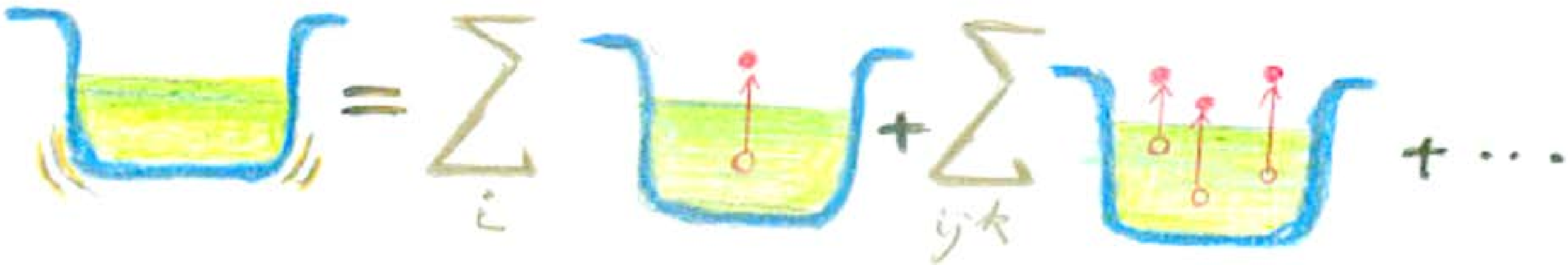
$$\sum_{p'h'} H_{ph,p'h'}X_{p'h'} = E_\nu X_{ph}$$

residual interaction

$$H_{ph,p'h'} = (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \langle ph'|\bar{v}|hp'\rangle$$

Tamm-Dancoff equation

残留相互作用の意味



スライド：松柳研一氏

$$V(\boldsymbol{r}) \sim \int d\boldsymbol{r}'\, v(\boldsymbol{r},\boldsymbol{r}')\rho(\boldsymbol{r}')$$

vibration: $\rho = \rho_0(\boldsymbol{r}) \to \rho_0(\boldsymbol{r}) + \delta\rho(\boldsymbol{r},t)$

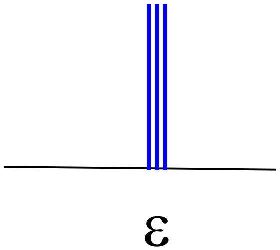
residual
interaction

TDA on a schematic model

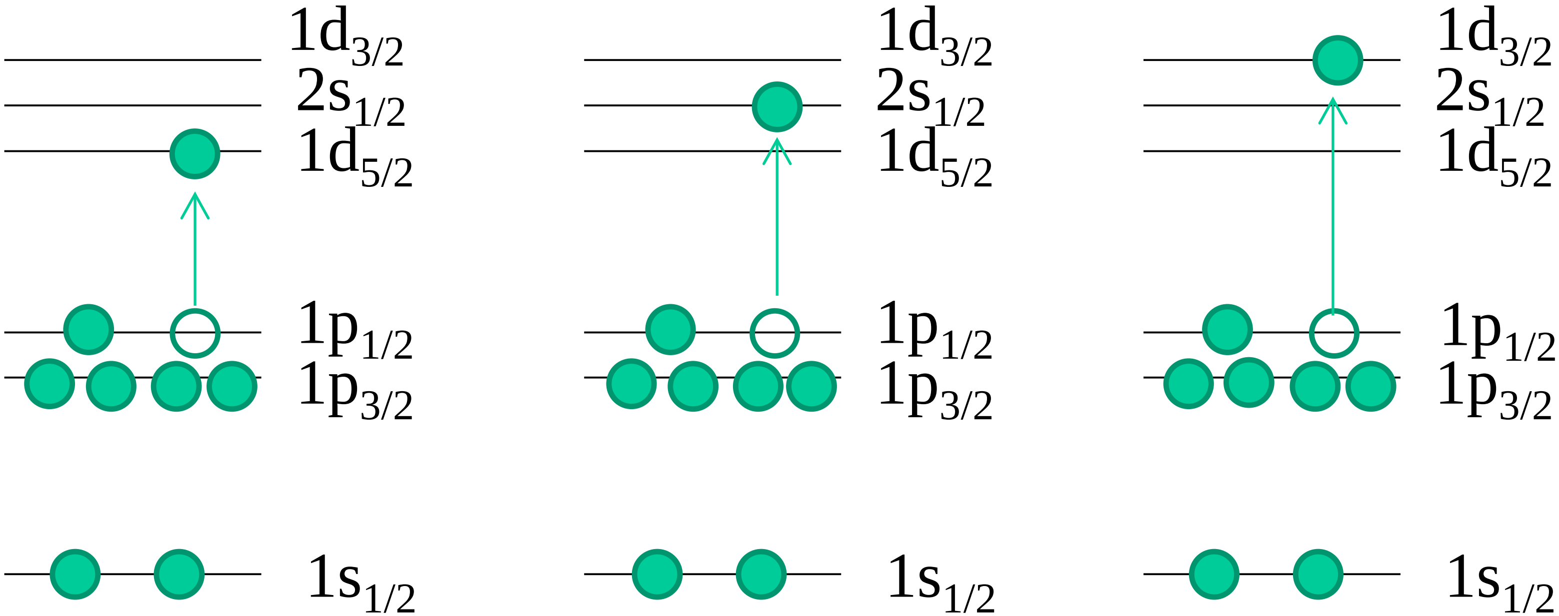
$$H_{ph,p'h'} = (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \langle ph'|\bar{v}|hp'\rangle$$

$$\epsilon_p - \epsilon_h = \epsilon, \quad \langle ph'|\bar{v}|hp'\rangle = g$$

for three ph configurations:



（例えば）



TDA on a schematic model

$$H_{ph,p'h'} = (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \langle ph'|\bar{v}|hp'\rangle$$

$$\epsilon_p - \epsilon_h = \epsilon, \qquad \langle ph'|\bar{v}|hp'\rangle = g$$

for three ph configurations:

$$H = \epsilon \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + g \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

→ Diagonalization:

$$\lambda = \epsilon, \epsilon, \underline{\epsilon + 3g}$$

TDA on a schematic model

$$\begin{pmatrix} \epsilon+g & g & g \\ g & \epsilon+g & g \\ g & g & \epsilon+g \end{pmatrix} \cdot \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = (\epsilon+3g) \cdot \frac{1}{\sqrt{3}} \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix}$$

全ての状態が同位相で寄与
＝コヒーレントな重ね合わせ

他の固有状態:

$$\begin{pmatrix} \epsilon+g & g & g \\ g & \epsilon+g & g \\ g & g & \epsilon+g \end{pmatrix} \cdot \frac{1}{\sqrt{6}} \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix} = \epsilon \cdot \frac{1}{\sqrt{6}} \begin{pmatrix} 1 \\ -2 \\ 1 \end{pmatrix}$$

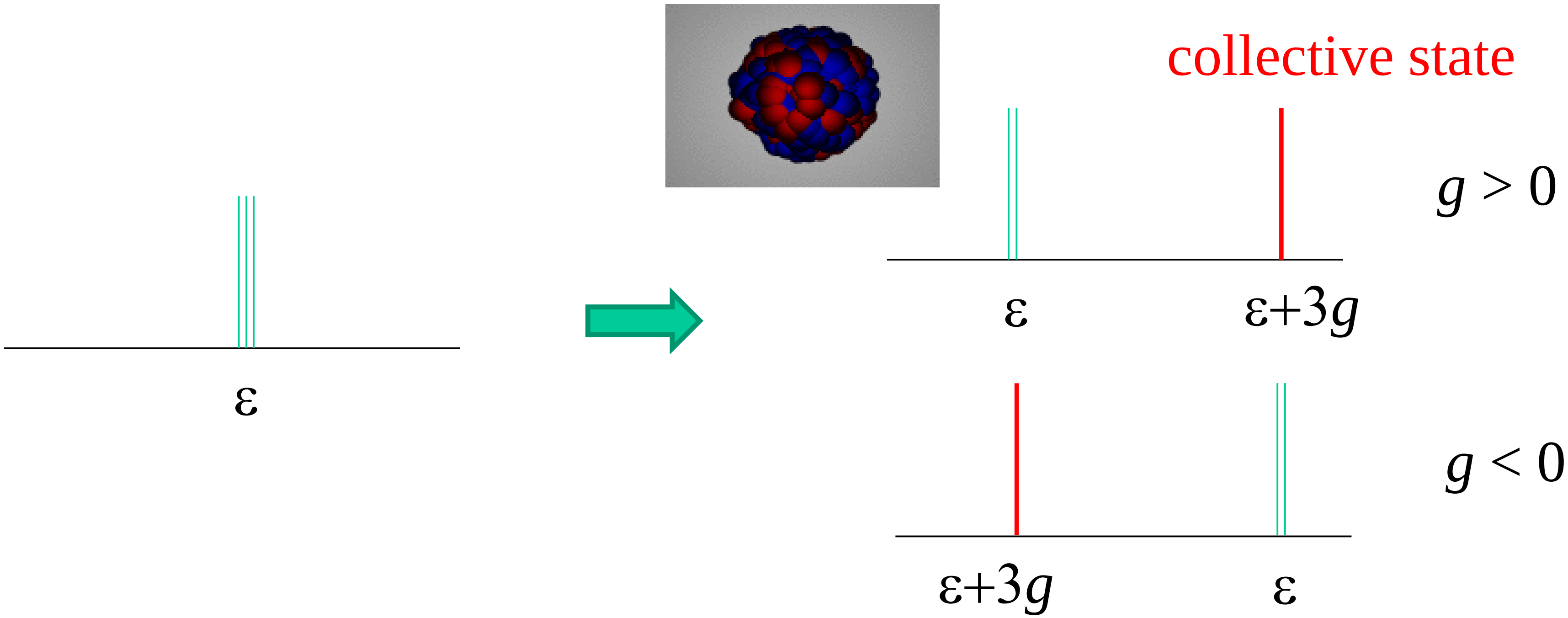
$$\begin{pmatrix} \epsilon+g & g & g \\ g & \epsilon+g & g \\ g & g & \epsilon+g \end{pmatrix} \cdot \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix} = \epsilon \cdot \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}$$

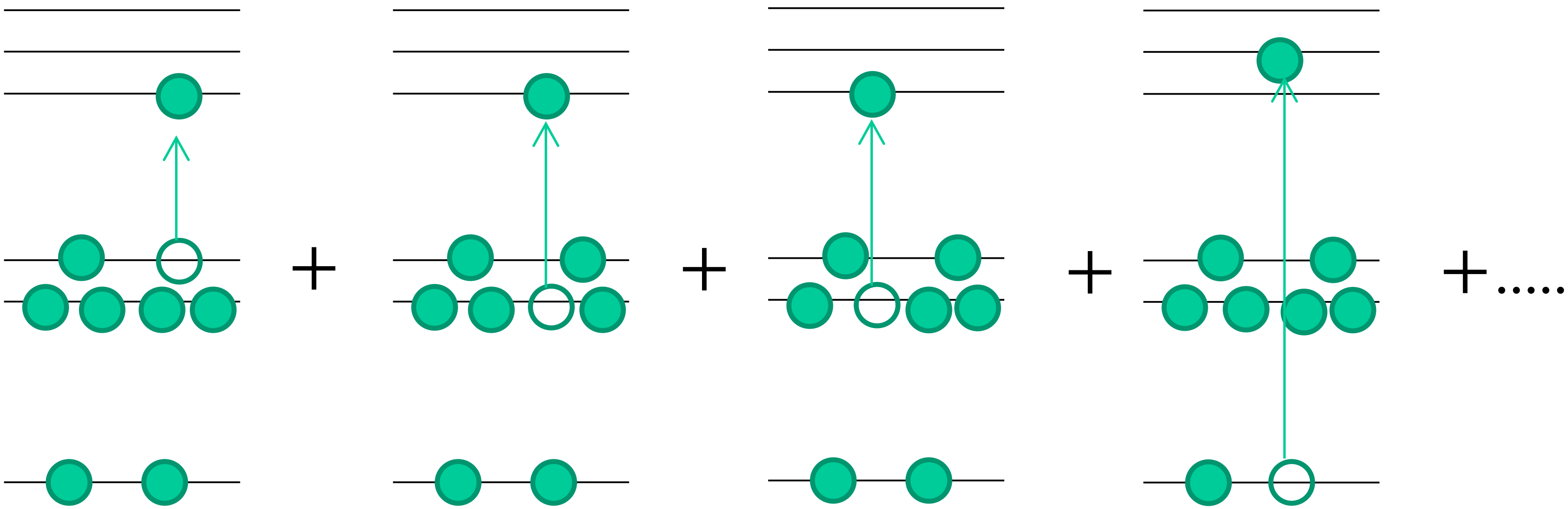
位相がそろっていない

TDA on a schematic model

$$H = \epsilon \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + g \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}$$

$\rightarrow$ Diagonalization: $\lambda = \epsilon, \epsilon, \underline{\epsilon + 3g}$

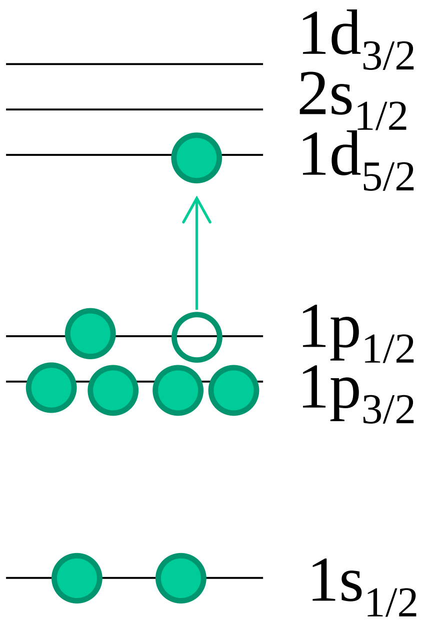




複数の粒子・空孔状態をコヒーレントに重ね合わせることによって
多数の核子が励起に関与していることを表現する

原子核の励起状態

- ✓ 一粒子励起（一つの核子が励起に関与）
- ✓ 集団励起（多くの核子が集団として励起に関与）



一粒子励起の例

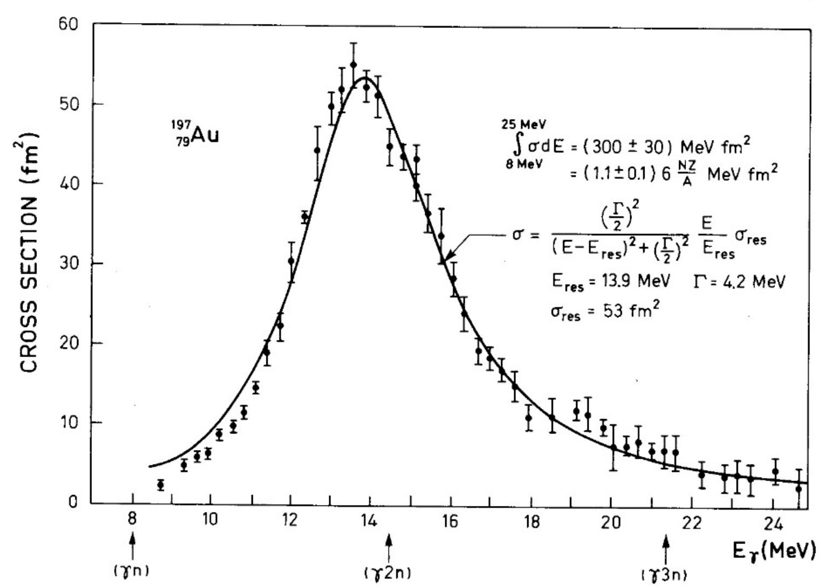
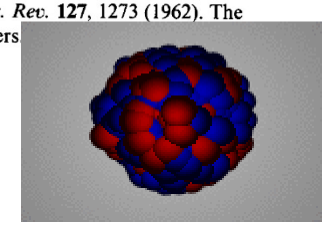
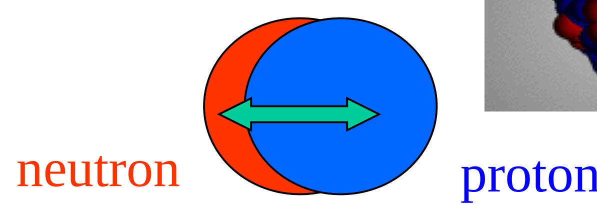


Figure 6-18 Total photoabsorption cross section for [197]Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

$$\sigma = \frac{\left(\frac{\Gamma}{2}\right)^2}{(E-E_{res})^2+\left(\frac{\Gamma}{2}\right)^2}\frac{E}{E_{res}}\sigma_{res}$$





集団励起の例：巨大双極子共鳴

Giant Dipole Resonance (GDR) 巨大双極子共鳴

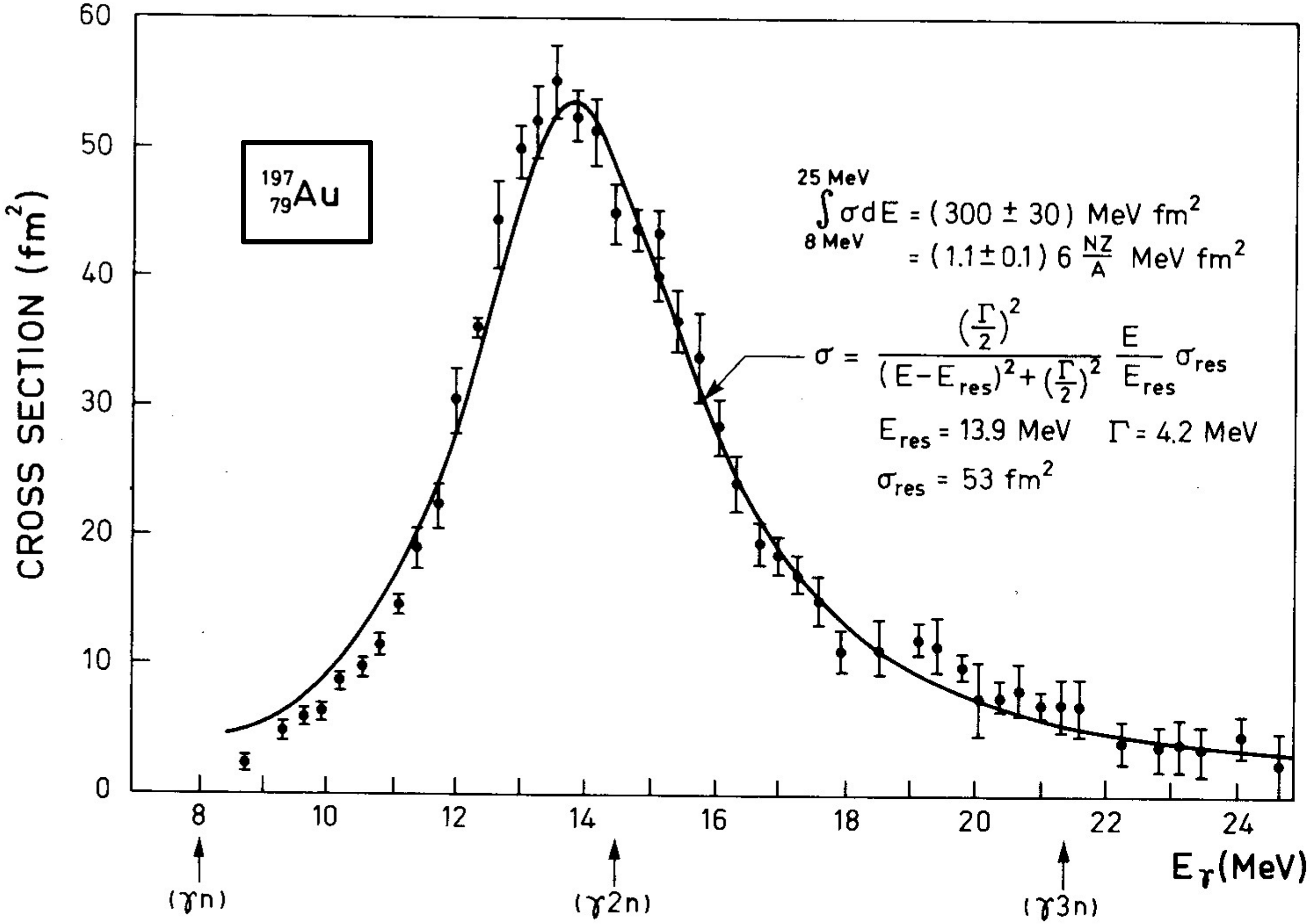


Figure 6-18 Total photoabsorption cross section for ^{197}Au. The experimental data are from S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, *Phys. Rev.* **127**, 1273 (1962). The solid curve is of Breit-Wigner shape with the indicated parameters.

cf. $41 \times 197^{-1/3} = 7.05$ MeV → 14 MeV

Iso-scalar type modes: $E < \epsilon_{ph} \rightarrow \lambda < 0$ (attractive)

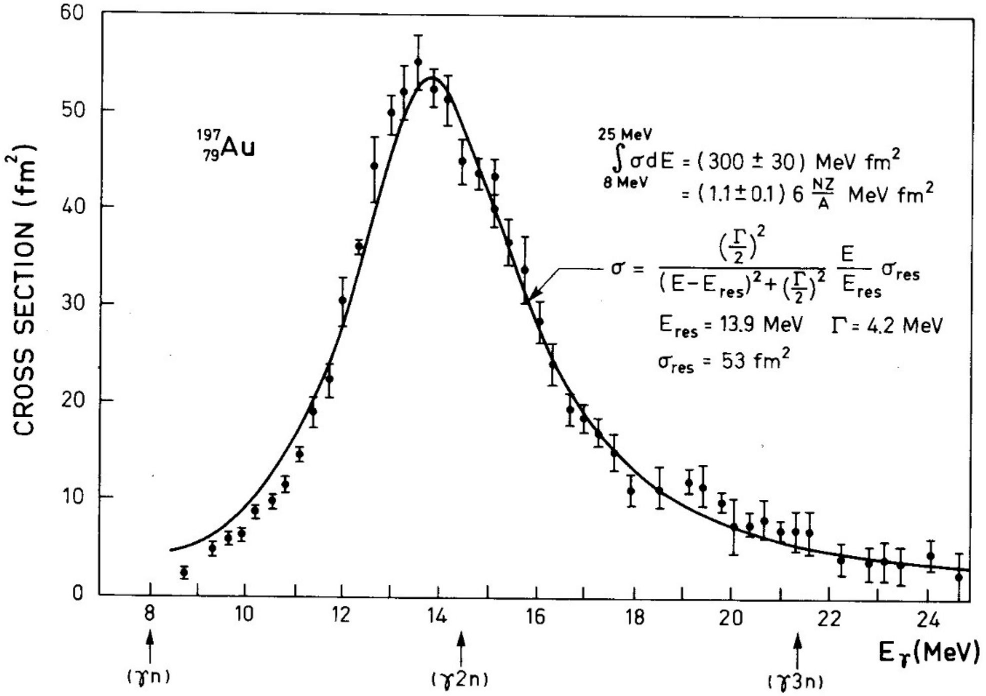
Iso-vector type modes: $E > \epsilon_{ph} \rightarrow \lambda > 0$ (repulsive)

Experimental systematics:

IV GDR: $E \sim 79A^{-1/3}$ (MeV) $\longleftrightarrow \epsilon_{ph} \sim 41A^{-1/3}$

IS GQR: $E \sim 65A^{-1/3}$ (MeV) $\longleftrightarrow \epsilon_{ph} \sim 82A^{-1/3}$

(note) single particle potential: $\hbar\omega \sim 41A^{-1/3}$ (MeV)



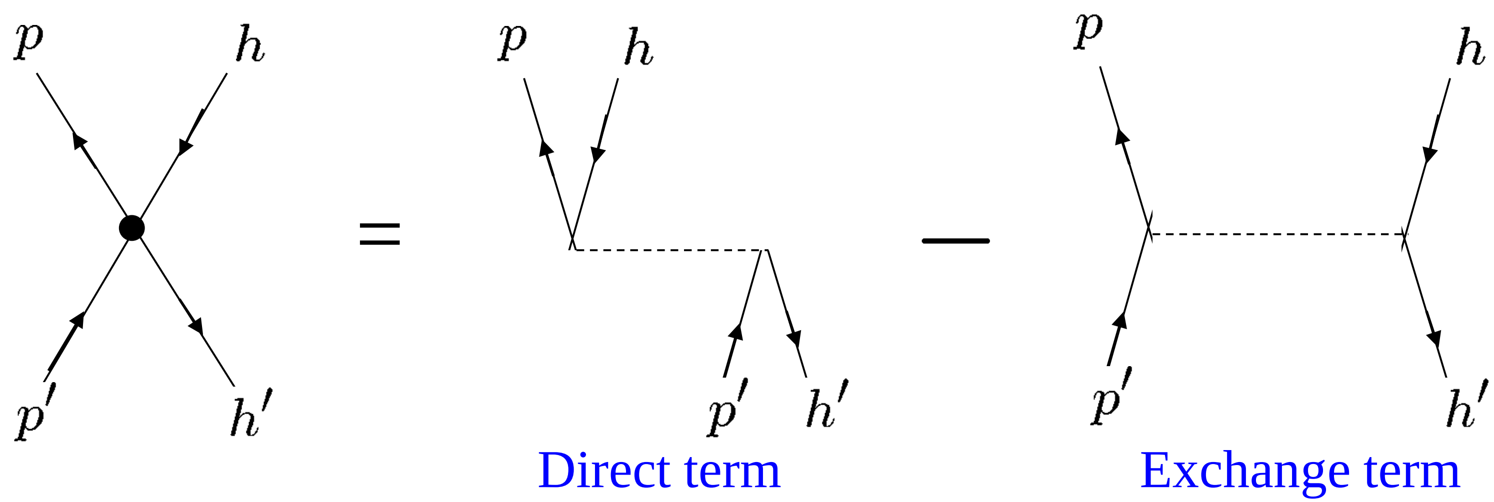
^{197}Au

$$E_{\rm GDR} = 14 \ \ ({\rm MeV})$$

$$\epsilon_{ph} \sim 41 \cdot 197^{-1/3}$$

$$\sim 7 \ \ ({\rm MeV})$$

$$\langle ph^{-1}|\bar{v}|p'h'^{-1}\rangle = \langle ph'|\bar{v}|hp'\rangle = \langle ph'|v|hp'\rangle - \langle ph'|v|p'h\rangle$$



$$\langle PP^{-1}|\bar{v}|PP^{-1}\rangle \sim \langle NN^{-1}|\bar{v}|NN^{-1}\rangle = D - E$$

$$\langle PP^{-1}|\bar{v}|NN^{-1}\rangle = D$$ (no charge exchange)

$$\langle IS|\bar{v}|IS\rangle = 2D - E \sim D$$

$$\langle IV|\bar{v}|IV\rangle = -E \sim -D$$

$$|IS\rangle \propto |NN^{-1}\rangle + |PP^{-1}\rangle$$

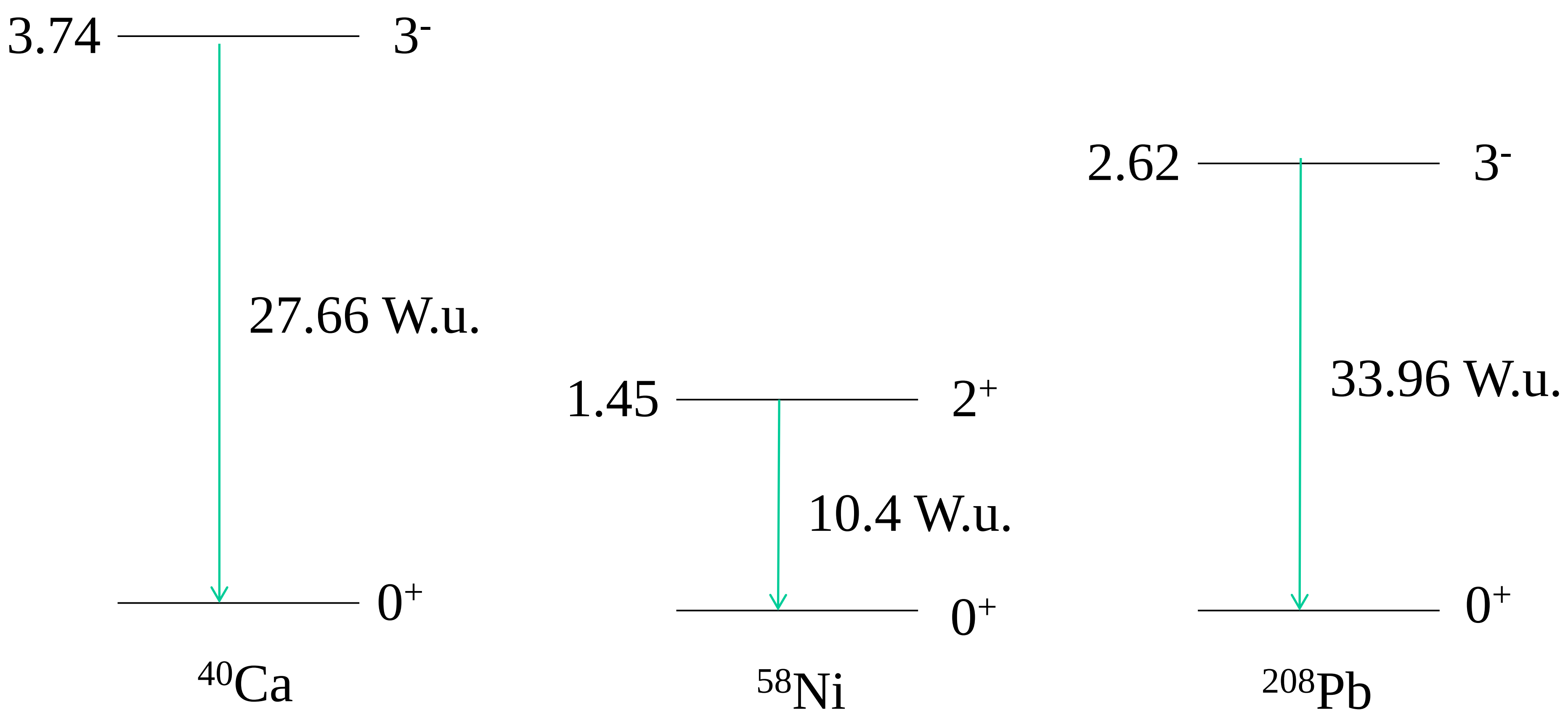
$$|IV\rangle \propto |NN^{-1}\rangle - |PP^{-1}\rangle$$

どれだけの核子が励起に関与しているのか?

Single-particle transition (Weisskopf unit)

$$B(E\lambda : I_i \to I_{gs}) = \frac{(1.2A^{1/3})^{2\lambda}}{4\pi}\left(\frac{3}{\lambda+3}\right)^2 \qquad (e^2\mathrm{fm}^{2\lambda})$$

exp data:



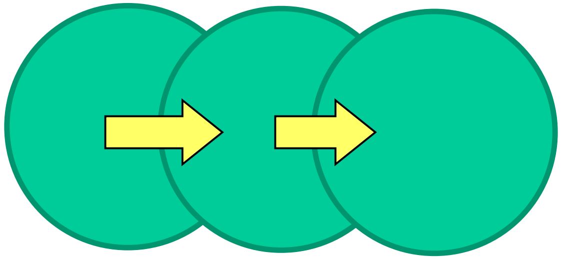
Spurious motion and RPA

Mean-Field Approximation ⟷ Broken symmetiries

- Center of mass localization (single center)
- Rotational motion

Restoration of broken symmetries

⇨ Zero energy mode (Nambu-Goldstone mode)



does not require an extra energy → zero energy mode

A drawback of TDA:

Zero modes appear at finite excitation energies.

$$|\nu\rangle = Q_\nu^\dagger|0\rangle = \sum_{ph} X_{ph}\, a_p^\dagger a_h|0\rangle \qquad \text{(TDA)}$$

A better approximation:

the random phase approximation (RPA)

$$|\nu\rangle = Q_\nu^\dagger|0\rangle = \sum_{ph}\left(X_{ph}\, a_p^\dagger a_h - Y_{ph}\, a_h^\dagger a_p\right)|0\rangle$$

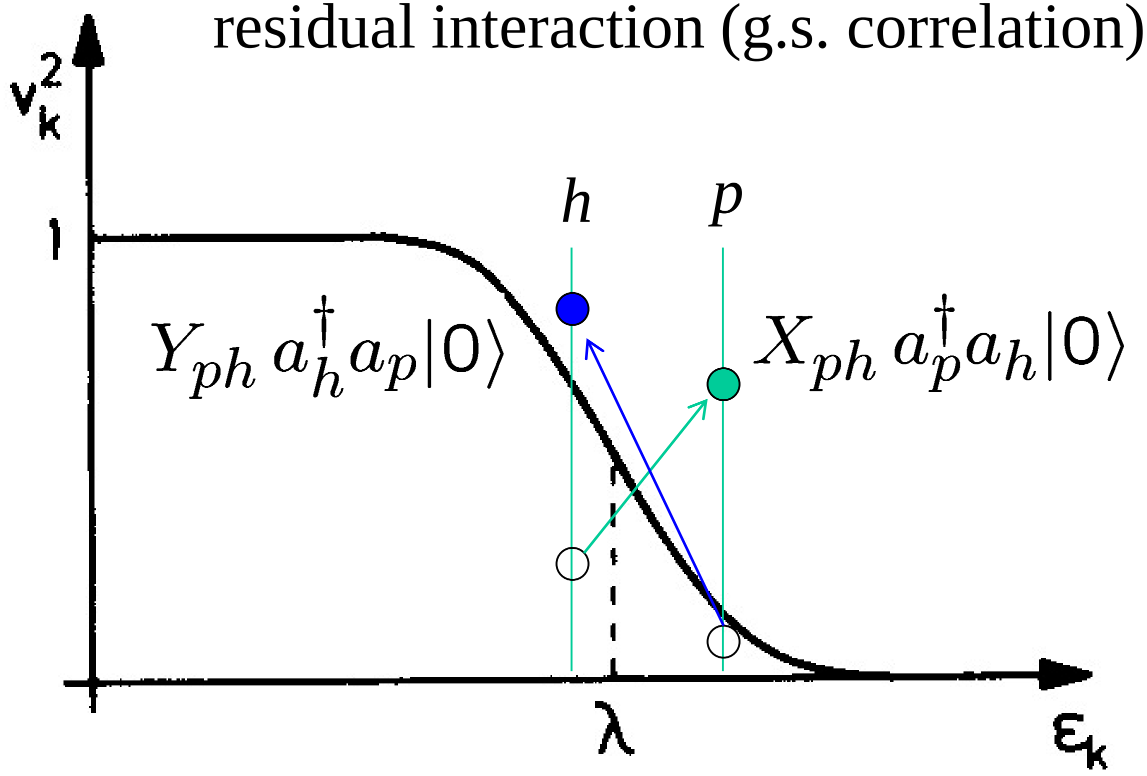
(superposition of 1p1h states)

A better approximation: **the random phase approximation (RPA)**

$$|\nu\rangle = Q_\nu^\dagger|0\rangle = \sum_{ph}\left(X_{ph}\, a_p^\dagger a_h - Y_{ph}\, a_h^\dagger a_p\right)|0\rangle$$

(superposition of 1p1h states)

smearing of Fermi surface due to the residual interaction (g.s. correlation)



A better approximation: **the random phase approximation (RPA)**

$$|\nu\rangle = Q_\nu^\dagger|0\rangle = \sum_{ph}\left(X_{ph}\,a_p^\dagger a_h - Y_{ph}\,a_h^\dagger a_p\right)|0\rangle$$

(superposition of 1p1h states)

$$[H, Q_\nu^\dagger] \sim E_\nu Q_\nu^\dagger$$

$$\langle HF|[\delta Q,[H,Q_\nu^\dagger]]|HF\rangle = E_\nu\langle HF|[\delta Q, Q_\nu^\dagger]|HF\rangle$$

→ coupled equations for X and Y

$$\langle HF|[\delta Q,[H,Q_\nu^\dagger]]|HF\rangle = E_\nu \langle HF|[\delta Q,Q_\nu^\dagger]|HF\rangle$$

$$Q_\nu^\dagger = \sum_{ph} X_{ph}\, a_p^\dagger a_h - Y_{ph}\, a_h^\dagger a_p \qquad \delta Q = a_h^\dagger a_p, \qquad a_p^\dagger a_h$$

RPA equation:

$$\begin{aligned}\sum_{p'h'} A_{ph,p'h'} X_{p'h'} + B_{ph,p'h'} Y_{p'h'} &= E_\nu X_{ph} \\ \sum_{p'h'} B^*_{ph,p'h'} X_{p'h'} + A^*_{ph,p'h'} Y_{p'h'} &= -E_\nu Y_{ph}\end{aligned}$$

$$\begin{aligned}A_{ph,p'h'} &= (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \langle ph'|\bar{v}|hp'\rangle \\ B_{ph,p'h'} &= \langle pp'|\bar{v}|hh'\rangle\end{aligned}$$

or

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix}\begin{pmatrix} X \\ Y \end{pmatrix} = E_\nu \begin{pmatrix} X \\ Y \end{pmatrix}$$

Spurious motion in RPA

Mean-Field Approximation ⟷ Broken symmetiries

- Center of mass localization (single center)
- Rotational motion

Restoration of broken symmetries

⇒ Zero mode (Nambu-Goldstone mode)

$$[H, \hat{O}] = 0$$

RPA

$$[H, Q_\nu^\dagger] \sim E_\nu Q_\nu^\dagger$$

$\hat{O}$ is a solution of RPA with E=0

$$Q^\dagger = \hat{O} = \sum_{ph} (O_{ph} a_p^\dagger a_h + O_{hp} a_h^\dagger a_p)$$

(note) $Q^\dagger_{\mathrm{TDA}} = \sum_{ph} O_{ph} a_p^\dagger a_h$ ⇒ $[H, Q^\dagger_{\mathrm{TDA}}] \neq 0$

Spurious motion in RPA

Mean-Field Approximation ⟷ Broken symmetiries

- Center of mass localization (single center)
- Rotational motion

Restoration of broken symmetries

⇒ Zero mode (Nambu-Goldstone mode)

RPA $[H, Q_\nu^\dagger] \sim E_\nu Q_\nu^\dagger$

if $[H, \hat{O}] = 0$

Then $\hat{O}$ is a solution of RPA with E=0

The physical solutions are exactly separated out from the spurious modes.

Comparison between Skyrme-(Q)RPA calculation and exp. data

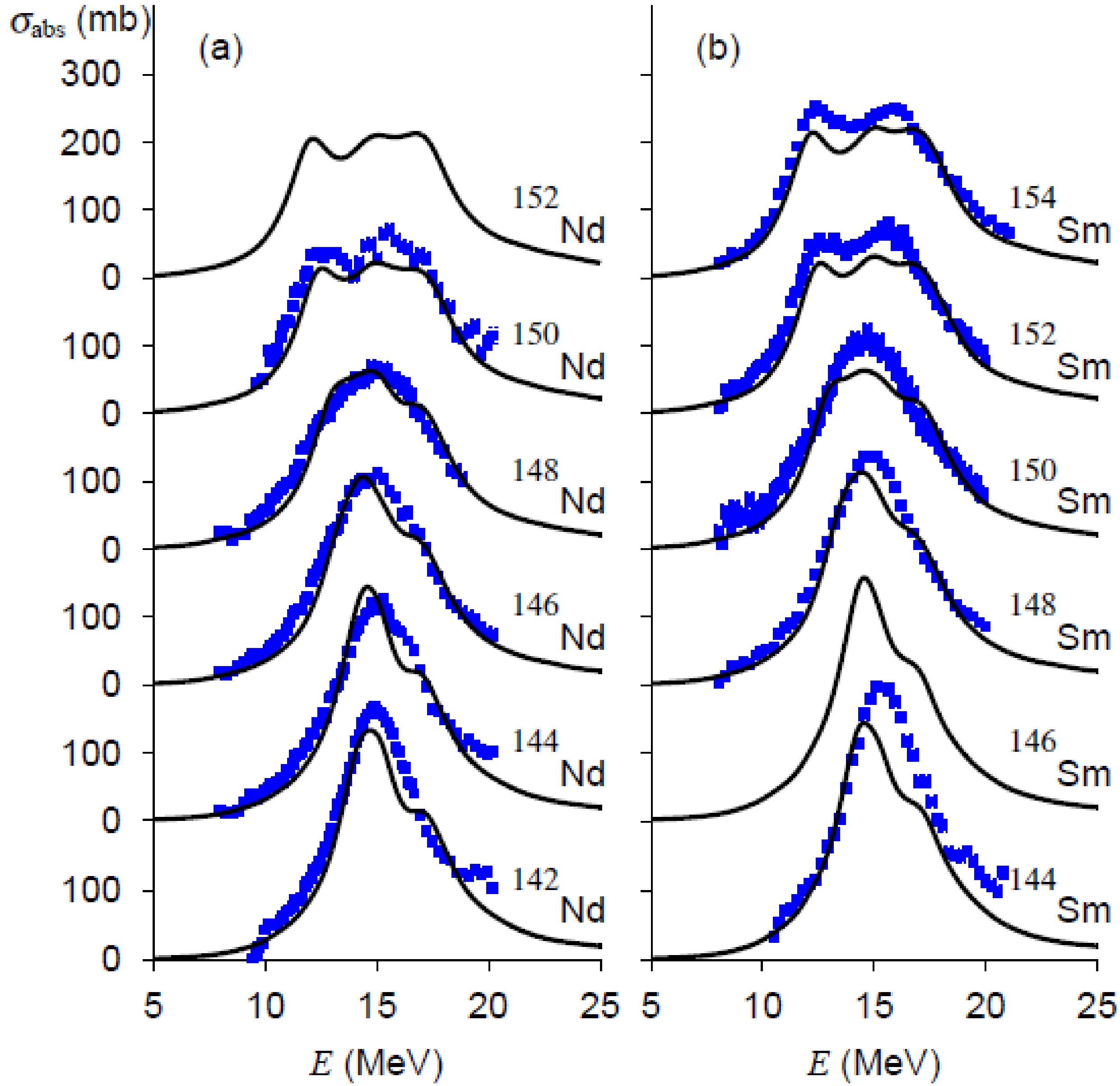


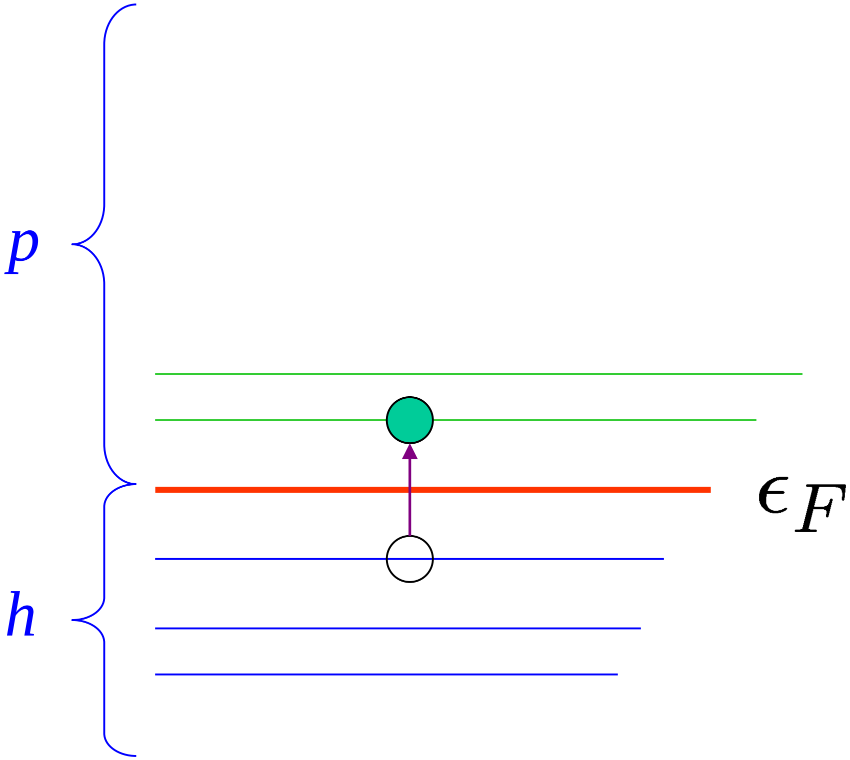
photo-absorption
cross section
(GDR)

K. Yoshida
and T. Nakatsukasa,
PRC83('11)021304

Tamm-Dancoff Approximation

Assume: $$|\nu\rangle = Q_\nu^\dagger |HF\rangle = \sum_{ph} X_{ph}\, a_p^\dagger a_h |HF\rangle \equiv \sum_{ph} X_{ph} |ph^{-1}\rangle$$

(superposition of 1p1h states)



h: all the occupied (bound) states

p: the bound excited states + continuum states

TDA on a schematic model

$$H_{ph,p'h'} = (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \langle ph'|\overline{v}|hp'\rangle$$

Separable interaction: $\langle ph'|\overline{v}|hp'\rangle = \lambda D_{ph} D^*_{p'h'}$

(separable interaction)

$$H\psi = E\psi; \qquad \psi = \sum_i C_i \phi_i$$

$$\longrightarrow \quad \sum_j H_{ij} C_j = E C_i; \qquad H_{ij} = \langle \phi_i | H | \phi_j \rangle$$

suppose $H_{ij} = \epsilon_i \delta_{i,j} + \lambda f_i^* f_j$ (separable form)

$$(\epsilon_i - E) C_i + \lambda f_i^* \underbrace{\sum_j f_j C_j}_{\equiv T} = 0$$

$$C_i = -\lambda \frac{T f_i^*}{\epsilon_i - E}$$

$$T = -\lambda \sum_j \frac{|f_j|^2}{\epsilon_j - E} T \quad \longrightarrow \quad \boxed{\frac{1}{\lambda} = \sum_i \frac{|f_i|^2}{E - \epsilon_i}}$$

(separable interaction)

$$H\psi = E\psi; \qquad \psi = \sum_i C_i \phi_i$$

$$\longrightarrow \sum_j H_{ij} C_j = E C_i; \qquad H_{ij} = \langle \phi_i | H | \phi_j \rangle$$

suppose $H_{ij} = \epsilon_i \delta_{i,j} + \lambda f_i^* f_j \longrightarrow$

$$\frac{1}{\lambda} = \sum_i \frac{|f_i|^2}{E - \epsilon_i}$$

$$H_{ph,p'h'} = (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \lambda D_{ph} D^*_{p'h'}$$

$$\longrightarrow \frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E - \epsilon_{ph}}$$

(TDA dispersion relation)

TDA on a schematic model

Separable interaction: $\langle ph'|\bar{v}|hp'\rangle = \lambda D_{ph} D^*_{p'h'}$

Tamm-Dancoff equation: $\sum_{p'h'} A_{ph,p'h'} X_{p'h'} = E X_{ph}$

$$A_{ph,p'h'} = (\epsilon_p - \epsilon_h)\delta_{ph,p'h'} + \langle ph'|\bar{v}|hp'\rangle$$

$$(\epsilon_{ph} - E) X_{ph} + \lambda D_{ph} \cdot T = 0 \qquad T \equiv \sum_{ph} D^*_{ph} X_{ph}$$

$$X_{ph} = -\lambda \frac{D_{ph} T}{\epsilon_{ph} - E}$$

$$T = \sum_{ph} D^*_{ph} X_{ph} = -\lambda \sum_{ph} \frac{|D_{ph}|^2}{\epsilon_{ph} - E} T$$

or

$$\frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E - \epsilon_{ph}}$$

(TDA dispersion relation)

Graphical solutions $$\frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E - \epsilon_{ph}}$$

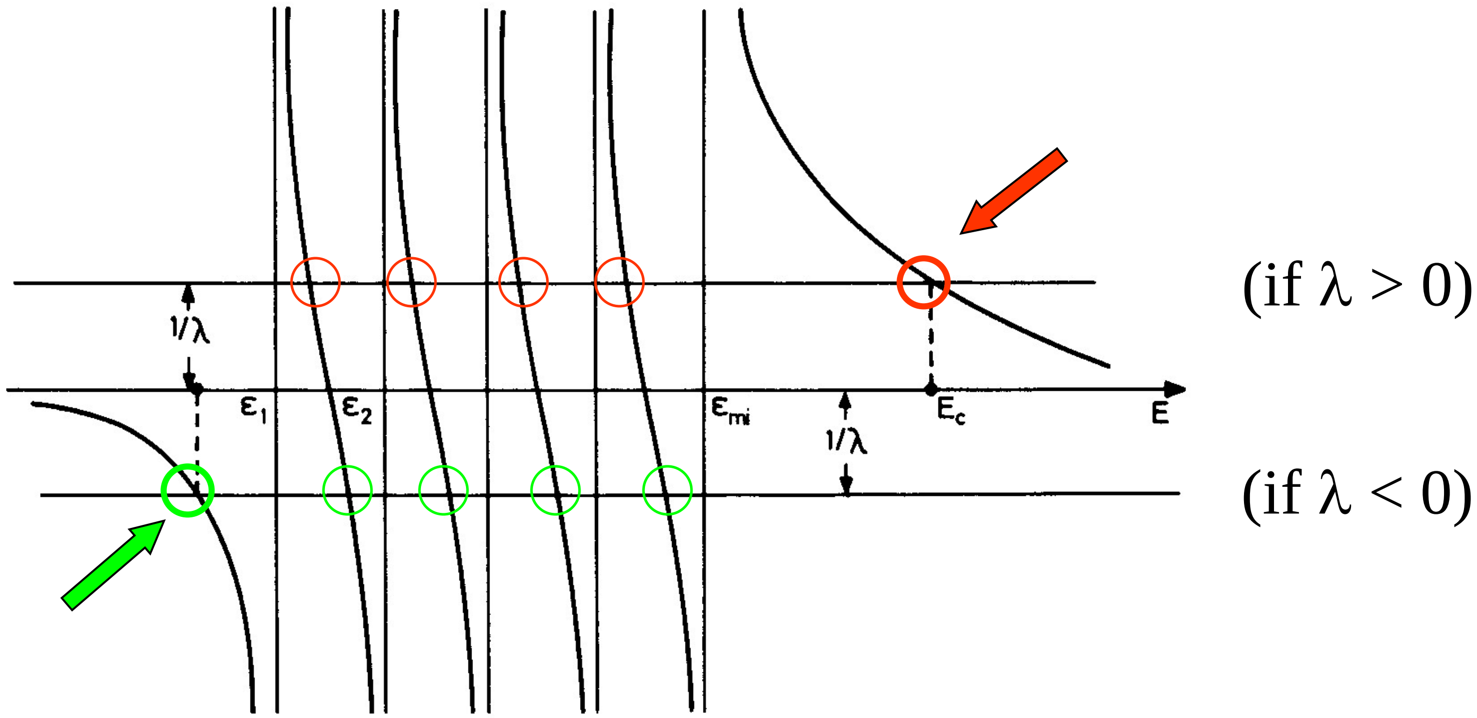


Figure 8.4. Graphical solution of Eq. (8.18).

(note) in the degenerate limit: $\epsilon_{ph} \sim \epsilon$

$$E = \epsilon + \lambda \sum_{ph} |D_{ph}|^2, \qquad |\nu\rangle = \sum_{ph} D_{ph} a_p^\dagger a_h |HF\rangle$$

coherent superpositon of 1p1h states

RPA on a schematic model

Separable interaction: $\langle ph'|\bar{v}|hp'\rangle = \lambda D_{ph} D^*_{p'h'}$

$$\frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E - \epsilon_{ph}} - \frac{|D_{ph}|^2}{E + \epsilon_{ph}}$$

(RPA dispersion relation)

Cf. TDA dispersion relation: $\frac{1}{\lambda} = \sum_{ph} \frac{|D_{ph}|^2}{E - \epsilon_{ph}}$

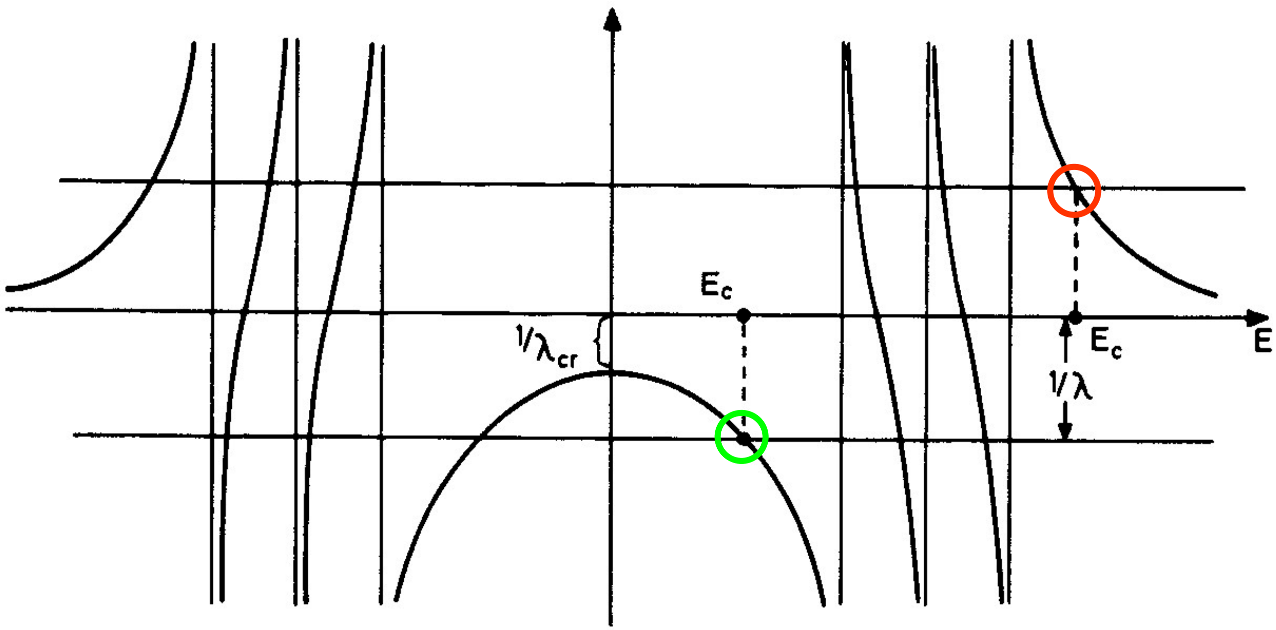
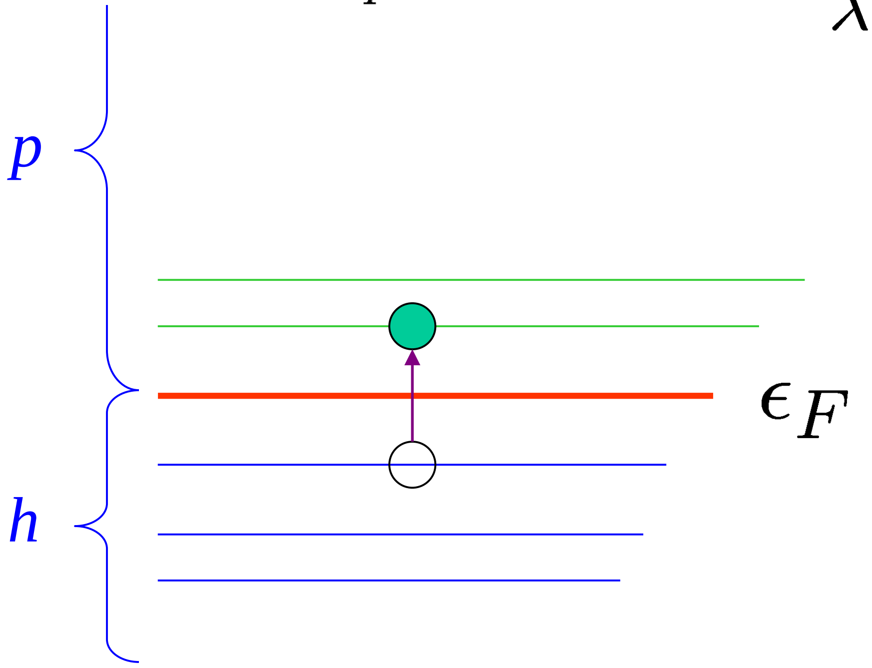


Figure 8.11. Graphical solution of the dispersion relation (8.135).

Continuum Excitations

$$\langle ph'|\bar{v}|hp'\rangle = \lambda D_{ph} D^*_{p'h'} \quad \Longrightarrow \quad \frac{1}{\lambda} = -\sum_{ph} \frac{|D_{ph}|^2}{\epsilon_p - \epsilon_h - E}$$



h: all the occupied (bound) states

p: the bound excited states + continuum states

$$\frac{1}{\lambda} = -\sum_{ph} \frac{|D_{ph}|^2}{\epsilon_p - \epsilon_h - E} = -\sum_{ph} \langle \phi_h | D^\dagger | \phi_p \rangle \frac{1}{\epsilon_p - \epsilon_h - E} \langle \phi_p | D | \phi \rangle$$

(note) $\hat{h}\phi_p = \epsilon_p \phi_p$

$$\frac{1}{\lambda} = -\sum_{ph} \langle \phi_h | D^\dagger \frac{1}{\hat{h} - \epsilon_h - E} | \phi_p \rangle \langle \phi_p | D | \phi \rangle$$

$$1 = \sum_i |\phi_i\rangle\langle\phi_i| = \sum_p |\phi_p\rangle\langle\phi_p| + \sum_h |\phi_h\rangle\langle\phi_h|$$

$$\frac{1}{\lambda} = -\sum_{h} \langle \phi_h | D^\dagger \frac{1}{\hat{h} - \epsilon_h - E} | \phi_p \rangle \left[1 - \sum_{h'} |\phi_{h'}\rangle\langle\phi_{h'}| \right] | D | \phi \rangle$$

particle 状態の和がなくなった