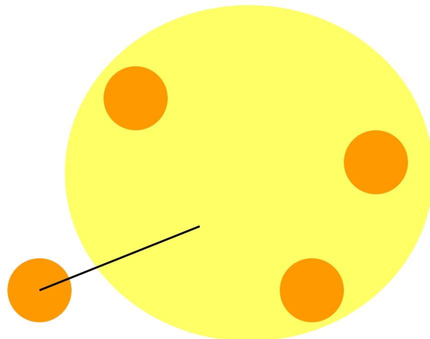
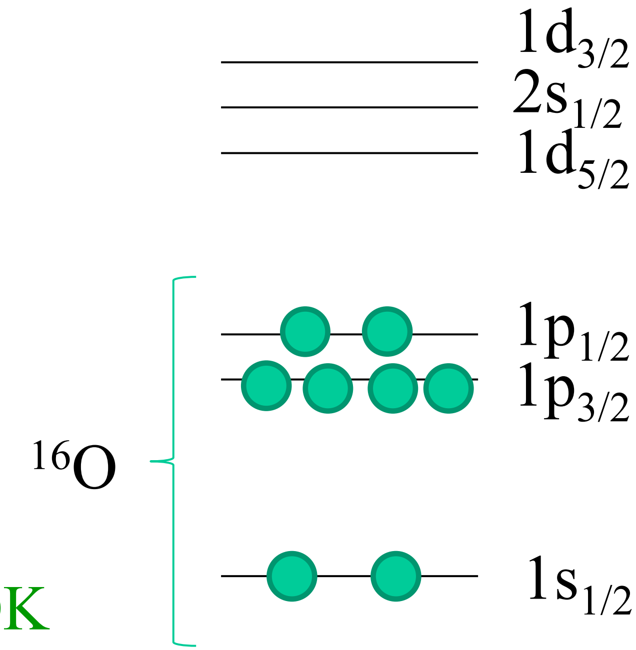
# 対相関

単純な平均場近似(独立粒子描像):





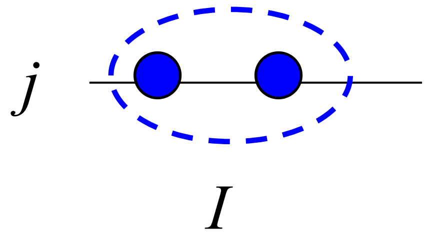

閉殻の場合はOK

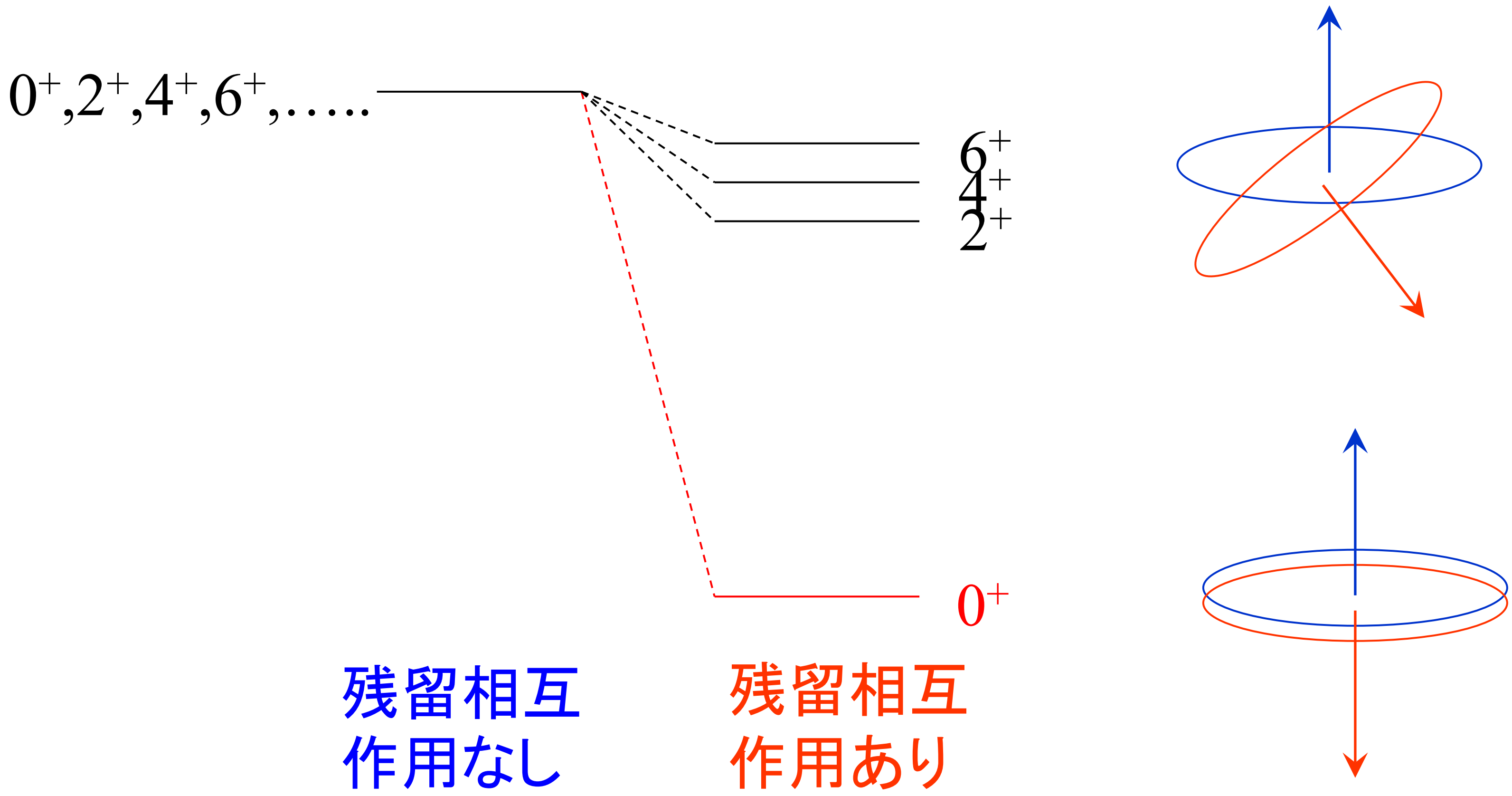
開殻原子核では「対相関」が重要

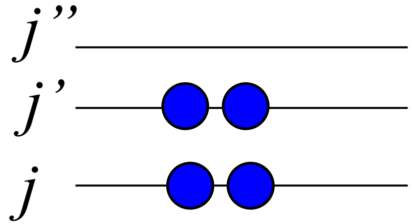
$$H=\sum_i T_i+\sum_{i<j} v_{ij} \rightarrow H=\sum_i (T_i+V_i)+\sum_{i<j} v_{ij}-\sum_i V_i$$

平均からのずれ
(残留相互作用)

$$v_{\mathrm{res}}(\boldsymbol{r},\boldsymbol{r}') \quad \sim -g\,\delta(\boldsymbol{r}-\boldsymbol{r}')$$

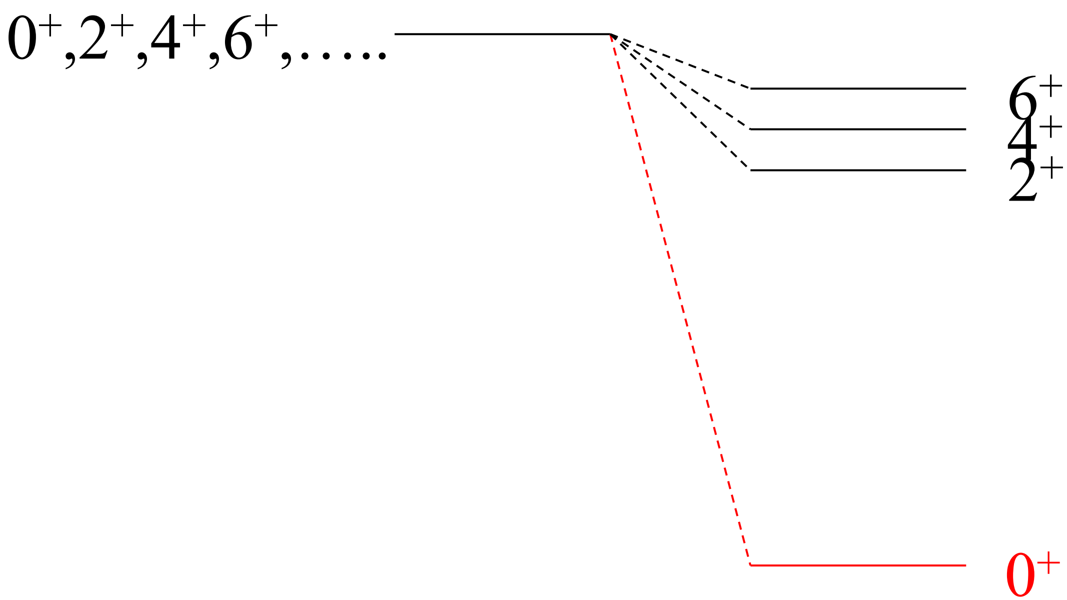





複数個のレベルに
複数個のペアがある問題

$$v_{\rm res}(\boldsymbol{r},\boldsymbol{r}') \sim -g\,\delta(\boldsymbol{r}-\boldsymbol{r}')$$



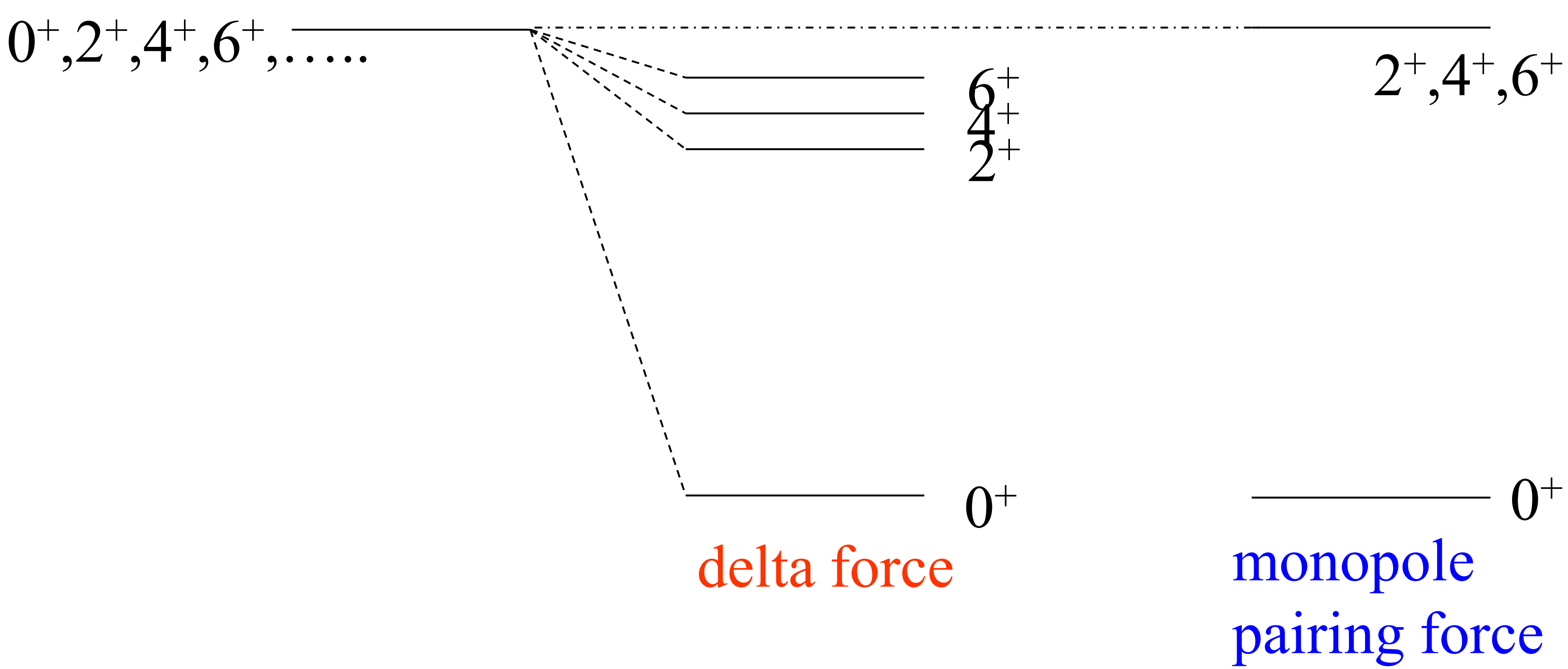

デルタ関数のままでもいいが、説明を簡単にするために
もう少し簡単にした相互作用を導入する。

# Simplified pairing interaction

$$V = -G\,P^\dagger P; \qquad P^\dagger = \sum_{\nu>0} a^\dagger_\nu a^\dagger_{\bar{\nu}}$$

$\bar{\nu}$ : the time reversed state of $\nu$

e.g., $|\nu\rangle = |njlm\rangle, \quad |\bar{\nu}\rangle = |njl-m\rangle$

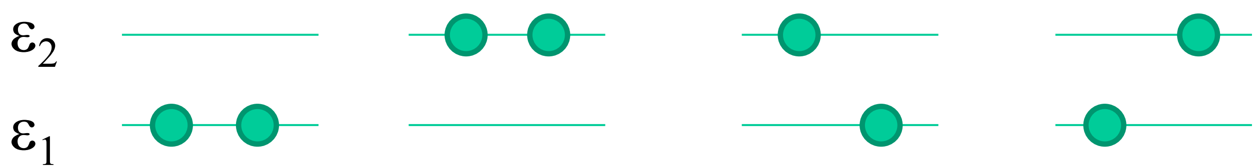


# Simplified pairing interaction

$$V = -G\,P^\dagger P; \qquad P^\dagger = \sum_{\nu>0} a^\dagger_\nu a^\dagger_{\bar{\nu}}$$

$\bar{\nu}$ : the time reversed state of $\nu$

$$H = \sum_k \epsilon_k (a^\dagger_k a_k + a^\dagger_{\bar{k}} a_{\bar{k}}) - G \left(\sum_{k>0} a^\dagger_k a^\dagger_{\bar{k}}\right)\left(\sum_{k>0} a_{\bar{k}} a_k\right)$$

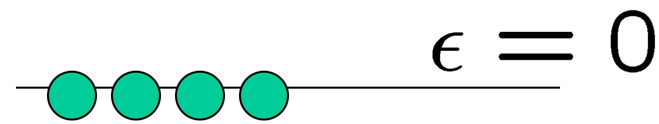



$$H = \begin{pmatrix} 2\epsilon_1 - G & -G & 0 & 0 \\ -G & 2\epsilon_2 - G & 0 & 0 \\ 0 & 0 & \epsilon_1+\epsilon_2 & 0 \\ 0 & 0 & 0 & \epsilon_1+\epsilon_2 \end{pmatrix}$$

$$\rightarrow \quad \Psi_{\rm g.s.} = C_1\Psi_1 + C_2\Psi_2$$

# Seniority Scheme

Particles in a single degenerate level




Degeneracy: $2\Omega$

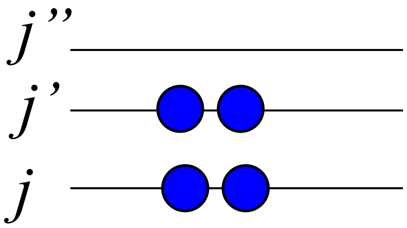
$$
\begin{aligned}
H &= -G\,P^\dagger P; \qquad P^\dagger = \sum_{m>0} a^\dagger_m a^\dagger_{-m} \\
&= -G\Omega A^\dagger A; \qquad A^\dagger = P^\dagger/\sqrt{\Omega}
\end{aligned}
$$

- Exact solution (Seniority scheme)

(note) $$[A, A^\dagger] = 1 - \frac{\hat{N}}{\Omega}, \qquad A|0\rangle = 0, \quad \hat{N}|0\rangle = 0$$

$$[\hat{N}, A^\dagger] = 2A^\dagger$$

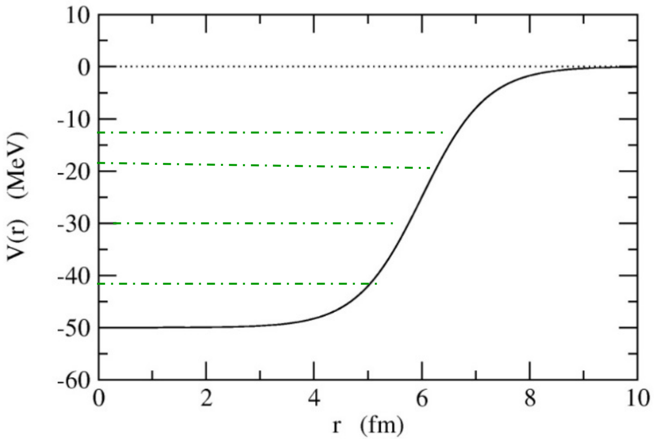
$$
\begin{aligned}
H A^\dagger|0\rangle &= -G\Omega\, A^\dagger|0\rangle \\
H(A^\dagger)^2|0\rangle &= -2G(\Omega - 1)\,(A^\dagger)^2|0\rangle \\
&\cdots \\
H(A^\dagger)^{N/2}|0\rangle &= -GN/4 \cdot (2\Omega - N + 2)\,(A^\dagger)^{N/2}|0\rangle
\end{aligned}
$$




複数個のレベルに
複数個のペアがある問題

# HF+BCS theory

①平均場近似をして核子の感じるポテンシャルを求める
（平均的な振る舞いをまず決める）




$$H = \sum_k \epsilon_k (a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - G \left( \sum_{k>0} a_k^\dagger a_{\bar{k}}^\dagger \right) \left( \sum_{k>0} a_{\bar{k}} a_k \right)$$

②各準位の占有確率を決める。
決め方は、残留相互作用も含めてエネルギーが最小になるようにする。

$$H = \sum_{\nu} \epsilon_\nu (a^\dagger_\nu a_\nu + a^\dagger_{\bar{\nu}} a_{\bar{\nu}}) - G \left( \sum_{\nu>0} a^\dagger_\nu a^\dagger_{\bar{\nu}} \right) \left( \sum_{\nu>0} a_{\bar{\nu}} a_\nu \right)$$

2体の相互作用
→ １体近似をする

cf. HF potential

$$V_H(\boldsymbol{r}) = \int v(\boldsymbol{r}, \boldsymbol{r}') \rho_{\mathrm{HF}}(\boldsymbol{r}') d\boldsymbol{r}$$

Solve the pairing Hamiltonian

$$H = \sum_{\nu} \epsilon_{\nu}(a_{\nu}^{\dagger}a_{\nu} + a_{\bar{\nu}}^{\dagger}a_{\bar{\nu}}) - G \left(\sum_{\nu>0} a_{\nu}^{\dagger}a_{\bar{\nu}}^{\dagger}\right) \left(\sum_{\nu>0} a_{\bar{\nu}}a_{\nu}\right)$$

in the mean-field approximation

- Mean-field approximation:

$$V = -G\, P^{\dagger}P \rightarrow -G\left(\langle P^{\dagger}\rangle P + P^{\dagger}\langle P\rangle\right) = -\Delta(P^{\dagger} + P)$$

$\Longleftrightarrow$ particle number violation

we consider $H' = H - \lambda\hat{N}$ instead of $H$ :

$$
\begin{aligned}
H' &= \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - G\hat{P}^\dagger \hat{P} \\
&\to \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta(\hat{P}^\dagger + \hat{P}) \\
&= \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta \sum_{k>0} (a_k^\dagger a_{\bar{k}}^\dagger + a_{\bar{k}} a_k)
\end{aligned}
$$

we consider $H' = H - \lambda\hat{N}$ instead of $H$ :

$$H' = \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - G\hat{P}^\dagger \hat{P}$$

$$\rightarrow \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta(\hat{P}^\dagger + \hat{P})$$

$$= \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta \sum_{k>0} (a_k^\dagger a_{\bar{k}}^\dagger + a_{\bar{k}} a_k)$$

- Transform *H'* in a form of

$$H' = \sum_{k>0} E_k(\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}})$$

we consider $H' = H - \lambda\hat{N}$ instead of $H$ :

$$H' = \sum_{k>0}(\epsilon_k - \lambda)(a^\dagger_k a_k + a^\dagger_{\bar{k}} a_{\bar{k}}) - G\hat{P}^\dagger\hat{P}$$
$$\to \sum_{k>0}(\epsilon_k - \lambda)(a^\dagger_k a_k + a^\dagger_{\bar{k}} a_{\bar{k}}) - \Delta(\hat{P}^\dagger + \hat{P})$$
$$= \sum_{k>0}(\epsilon_k - \lambda)(a^\dagger_k a_k + a^\dagger_{\bar{k}} a_{\bar{k}}) - \Delta\sum_{k>0}(a^\dagger_k a^\dagger_{\bar{k}} + a_{\bar{k}} a_k)$$

- Transform *H'* in a form of

$$H' = \sum_{k>0} E_k(\alpha^\dagger_k \alpha_k + \alpha^\dagger_{\bar{k}} \alpha_{\bar{k}})$$

g.s.: $\alpha_k|BCS\rangle = 0$

1st excited state: $|1_k\rangle = \alpha^\dagger_k|BCS\rangle$ at $E_k$

…. and so on.

## Bogoliubov transformation

$$\alpha^\dagger_\nu = u_\nu a^\dagger_\nu - v_\nu a_{\bar{\nu}}, \qquad \alpha^\dagger_{\bar{\nu}} = u_\nu a^\dagger_{\bar{\nu}} + v_\nu a_\nu$$

(Quasi-particle operator)

or $$a^\dagger_\nu = u_\nu \alpha^\dagger_\nu + v_\nu \alpha_{\bar{\nu}}, \qquad a^\dagger_{\bar{\nu}} = u_\nu \alpha^\dagger_{\bar{\nu}} - v_\nu \alpha_\nu$$

(note)

$$\{\alpha_\nu, \alpha_{\nu'}\} = 0, \qquad \{\alpha_\nu, \alpha^\dagger_{\nu'}\} = \delta_{\nu,\nu'}$$

$$\rightarrow \quad u_\nu^2 + v_\nu^2 = 1$$

# Bogoliubov transformation

$$\alpha_\nu^\dagger = u_\nu a_\nu^\dagger - v_\nu a_{\bar{\nu}}, \qquad \alpha_{\bar{\nu}}^\dagger = u_\nu a_{\bar{\nu}}^\dagger + v_\nu a_\nu$$

(Quasi-particle operator)

or $$a_\nu^\dagger = u_\nu \alpha_\nu^\dagger + v_\nu \alpha_{\bar{\nu}}, \qquad a_{\bar{\nu}}^\dagger = u_\nu \alpha_{\bar{\nu}}^\dagger + -v_\nu \alpha_\nu$$

$$H' = \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta \sum_{k>0} (a_k^\dagger a_{\bar{k}}^\dagger + a_{\bar{k}} a_k)$$

$$\rightarrow$$

using the quasi-particle operators:

$$
\begin{aligned}
H' \sim & \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta \sum_{k>0} (a_k^\dagger a_{\bar{k}}^\dagger + a_{\bar{k}} a_k) \\
= & \sum_{k>0} [(\epsilon_k - \lambda)(u_k^2 - v_k^2) + 2\Delta u_k v_k](\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}}) \\
& + \sum_{k>0} [2(\epsilon_k - \lambda) u_k v_k - \Delta(u_k^2 - v_k^2)](\alpha_k^\dagger \alpha_{\bar{k}}^\dagger + \alpha_{\bar{k}} \alpha_k)
\end{aligned}
$$

using the quasi-particle operators:

$$
\begin{aligned}
H' &\sim \sum_{k>0} (\epsilon_k - \lambda)(a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - \Delta \sum_{k>0} (a_k^\dagger a_{\bar{k}}^\dagger + a_{\bar{k}} a_k) \\
&= \sum_{k>0} [(\epsilon_k - \lambda)(u_k^2 - v_k^2) + 2\Delta u_k v_k](\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}}) \\
&\quad + \sum_{k>0} [2(\epsilon_k - \lambda) u_k v_k - \Delta(u_k^2 - v_k^2)](\alpha_k^\dagger \alpha_{\bar{k}}^\dagger + \alpha_{\bar{k}} \alpha_k)
\end{aligned}
$$

if $\quad 2(\epsilon_k - \lambda) u_k v_k - \Delta(u_k^2 - v_k^2) = 0$

then $\quad H' = \sum_{k>0} E_k (\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}})$

with $\quad E_k = (\epsilon_k - \lambda)(u_k^2 - v_k^2) + 2\Delta u_k v_k$

$$
\begin{aligned}
H' \; = \; & \sum_{k>0} [(\epsilon_k - \lambda)(u_k^2 - v_k^2) + 2\Delta u_k v_k](\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}}) \\
& + \sum_{k>0} [2(\epsilon_k - \lambda) u_k v_k - \Delta(u_k^2 - v_k^2)](\alpha_k^\dagger \alpha_{\bar{k}}^\dagger + \alpha_{\bar{k}} \alpha_k)
\end{aligned}
$$

$$
\begin{cases}
0 = 2(\epsilon_k - \lambda) u_k v_k - \Delta(u_k^2 - v_k^2) \\
1 = u_k^2 + v_k^2
\end{cases}
$$

$$
\boxed{
\begin{aligned}
u_\nu^2 &= \frac{1}{2}\left(1 + \frac{\epsilon_\nu - \lambda}{\sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}}\right) \\
v_\nu^2 &= \frac{1}{2}\left(1 - \frac{\epsilon_\nu - \lambda}{\sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}}\right)
\end{aligned}
}
$$

$$
\begin{aligned}
H' &= \sum_{k>0} [(\epsilon_k - \lambda)(u_k^2 - v_k^2) + 2\Delta u_k v_k](\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}}) \\
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\end{aligned}
$$

$$
\begin{aligned}
u_\nu^2 &= \frac{1}{2}\left(1 + \frac{\epsilon_\nu - \lambda}{\sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}}\right) \\
v_\nu^2 &= \frac{1}{2}\left(1 - \frac{\epsilon_\nu - \lambda}{\sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}}\right)
\end{aligned}
$$

$$
\begin{aligned}
E_k &= (\epsilon_k - \lambda)(u_k^2 - v_k^2) + 2\Delta u_k v_k \\
&= \sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}
\end{aligned}
$$

$$H' = \sum_{k>0} E_k(\alpha_k^\dagger \alpha_k + \alpha_{\bar{k}}^\dagger \alpha_{\bar{k}})$$

$$E_k = \sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}$$

Ground state wave function:

$$\alpha_k |BCS\rangle = 0$$

$$|BCS\rangle \propto \prod_{\nu>0} \alpha_\nu \alpha_{\bar{\nu}} |0\rangle$$

$$= \prod_{\nu>0} v_\nu \left(u_\nu + v_\nu \, a_\nu^\dagger a_{\bar{\nu}}^\dagger\right) \Big| 0 \Big\rangle$$

$$|BCS\rangle = \prod_{\nu>0} \left(u_\nu + v_\nu \, a_\nu^\dagger a_{\bar{\nu}}^\dagger\right) \Big| 0 \Big\rangle$$

Ground state wave function:

$$\alpha_k|BCS\rangle = 0$$

$$|BCS\rangle = \prod_{\nu>0}\left(u_\nu + v_\nu\, a^\dagger_\nu a^\dagger_{\bar{\nu}}\right)\Big|0\Big\rangle$$

(note) $\left\langle BCS|a^\dagger_\nu a_\nu|BCS\right\rangle = |v_\nu|^2$ : occupation probability

(note)

$$E'_{\rm BCS} = \langle BCS|H'|BCS\rangle \sim 2\sum_{\nu>0}(\epsilon_\nu - \lambda)v_\nu^2 - \frac{\Delta^2}{G}$$

(note) $\left(1 + \frac{v_\nu}{u_\nu}a^\dagger_\nu a^\dagger_{\bar{\nu}}\right)\Big|0\Big\rangle = \exp\left(\frac{v_\nu}{u_\nu}a^\dagger_\nu a^\dagger_{\bar{\nu}}\right)\Big|0\Big\rangle$

$$|\Psi\rangle \propto \exp\left(\sum_{\nu>0}\frac{v_\nu}{u_\nu}a^\dagger_\nu a^\dagger_{\bar{\nu}}\right)\Big|0\Big\rangle$$

(pair condensed wave function)

## Gap equation

$$\begin{cases} u_\nu^2 = \frac{1}{2}\left(1 + \frac{\epsilon_\nu - \lambda}{E_\nu}\right) \\ v_\nu^2 = \frac{1}{2}\left(1 - \frac{\epsilon_\nu - \lambda}{E_\nu}\right) \end{cases}$$

$$E_\nu = \sqrt{(\epsilon_\nu - \lambda)^2 + \Delta^2}$$

$$\begin{aligned} \Delta &= G\langle BCS|\hat{P}|BCS\rangle = G\sum_{\nu>0} u_\nu v_\nu \\ &= \frac{G}{2}\sum_{\nu>0}\frac{\Delta}{E_\nu} \end{aligned}$$

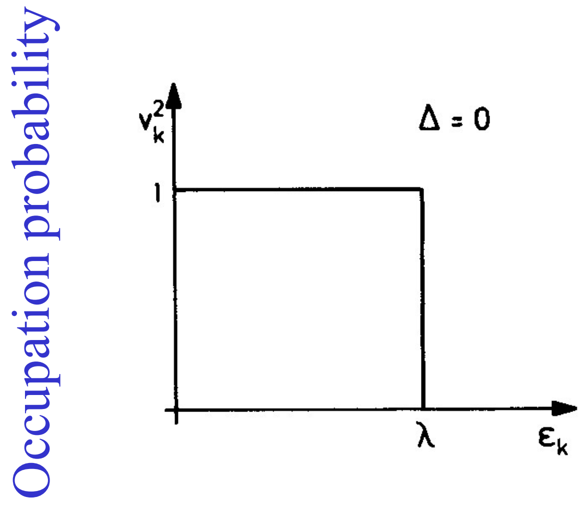
(Gap equation)

$$N = 2\sum_{\nu>0} v_\nu^2 \qquad \leftarrow \lambda$$

$$\Delta = \frac{G}{2} \sum_{\nu>0} \frac{\Delta}{E_\nu}$$

i) Trivial solution: always exists

$$\Delta = 0$$




$$\Delta = G \sum_{\nu>0} u_\nu v_\nu$$

$$\begin{aligned} v_\nu^2 &= 1 \quad (\epsilon_\nu \leq \lambda) \\ &= 0 \quad (\epsilon_\nu > \lambda) \end{aligned}$$

$$|\Psi\rangle = \prod_{\nu>0} a_\nu^\dagger a_{\bar{\nu}}^\dagger |0\rangle$$

$$\Delta = \frac{G}{2} \sum_{\nu>0} \frac{\Delta}{E_\nu}$$

i) Trivial solution: always exists

$$\Delta = 0$$

$G$ a/o $N \longrightarrow$ large

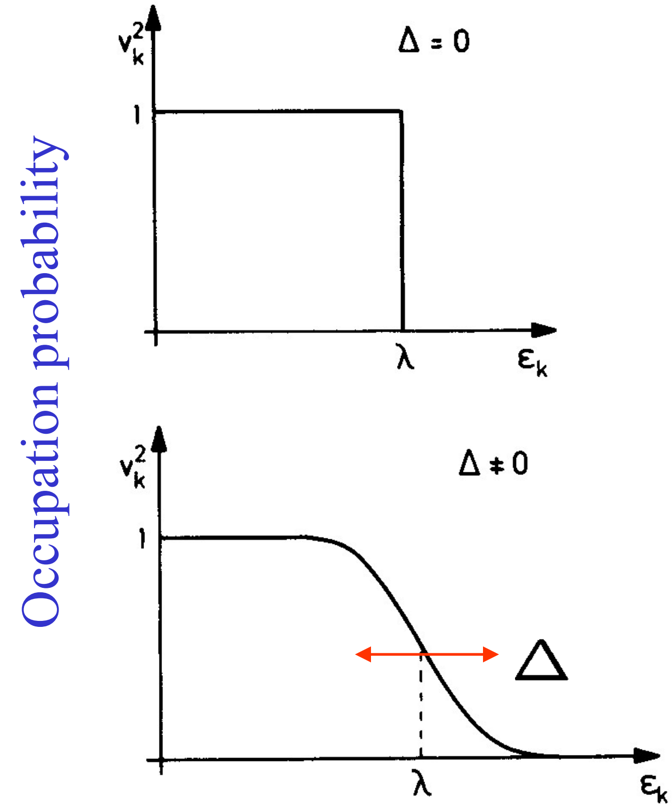
ii) Superfluid solution

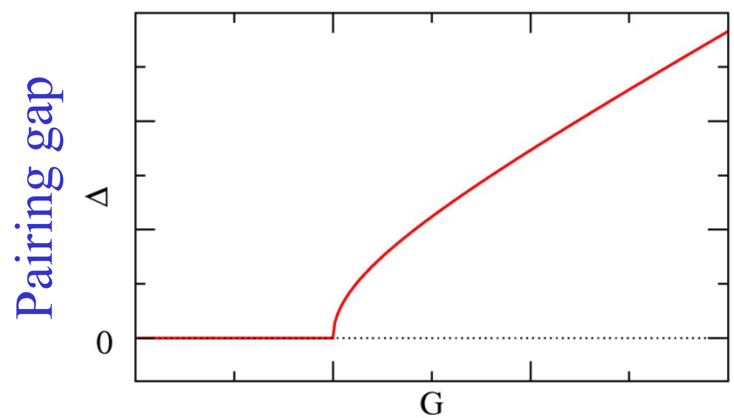
$$\Delta \neq 0$$

$$v_\nu^2 < 1$$

$$|BCS\rangle = \prod_{\nu>0} \left(u_\nu + v_\nu\, a_\nu^\dagger a_{\bar{\nu}}^\dagger\right)\left|0\right\rangle$$

Number fluctuation




Normal-Superfulid phase transition

# Quasi-particle excitations

$$H = \sum_\nu \epsilon_k (a_k^\dagger a_k + a_{\bar{k}}^\dagger a_{\bar{k}}) - G \left( \sum_{k>0} a_k^\dagger a_{\bar{k}}^\dagger \right) \left( \sum_{k>0} a_{\bar{k}} a_k \right)$$

ハミルトニアンを書き直すと:

$$H \sim E_{BCS} + \sum_k E_k \, \alpha_k^\dagger \alpha_k$$

$$E_k = \sqrt{(\epsilon_k - \lambda)^2 + \Delta^2}$$

$$\alpha_\nu^\dagger = u_\nu a_\nu^\dagger - v_\nu a_{\bar{\nu}}, \qquad \alpha_{\bar{\nu}}^\dagger = u_\nu a_{\bar{\nu}}^\dagger + v_\nu a_\nu$$

（ボゴリューボフ変換）

# Quasi-particle excitations

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$$\alpha_\nu^\dagger = u_\nu a_\nu^\dagger - v_\nu a_{\bar{\nu}}, \qquad \alpha_{\bar{\nu}}^\dagger = u_\nu a_{\bar{\nu}}^\dagger + v_\nu a_\nu$$

（ボゴリューボフ変換）

基底状態: $|\mathrm{BCS}\rangle$

1準粒子状態: $\alpha_k^\dagger|\mathrm{BCS}\rangle$　　奇核に対応

2準粒子状態: $\alpha_k^\dagger \alpha_{k'}^\dagger|\mathrm{BCS}\rangle$

- N +/- 2 の原子核
- 同じ原子核の励起状態に対応

# Quasi-particle excitations

$$H \sim E_{BCS} + \sum_k E_k \, \alpha_k^\dagger \alpha_k$$

$$\alpha_\nu^\dagger = u_\nu a_\nu^\dagger - v_\nu a_{\bar{\nu}}, \qquad \alpha_{\bar{\nu}}^\dagger = u_\nu a_{\bar{\nu}}^\dagger + v_\nu a_\nu$$

（ボゴリューボフ変換）

基底状態： $|\mathrm{BCS}\rangle$

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2準粒子状態： $\alpha_k^\dagger \alpha_{k'}^\dagger |\mathrm{BCS}\rangle$

- N +/- 2 の原子核
- 同じ原子核の励起状態に対応

$$E_k = \sqrt{(\epsilon_k - \lambda)^2 + \Delta^2} \geq \Delta$$

（エネルギー・ギャップ）

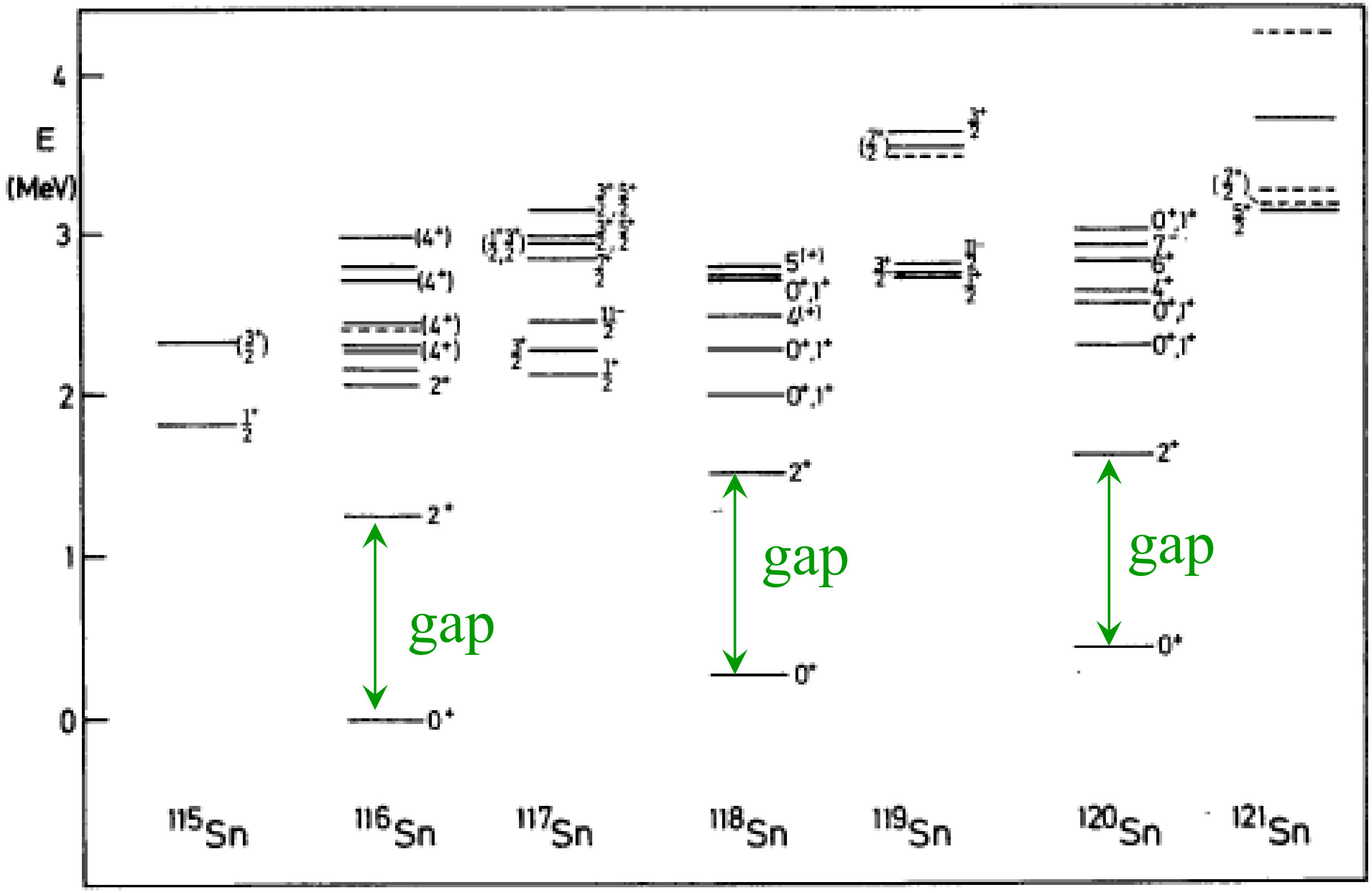



**Figure 6.1.** Excitation spectra of the $_{50}$Sn isotopes.

Ring-Schuck

# Effects of pairing on moment of inertia

$$E_I = \frac{I(I+1)\hbar^2}{2\mathcal{J}}$$

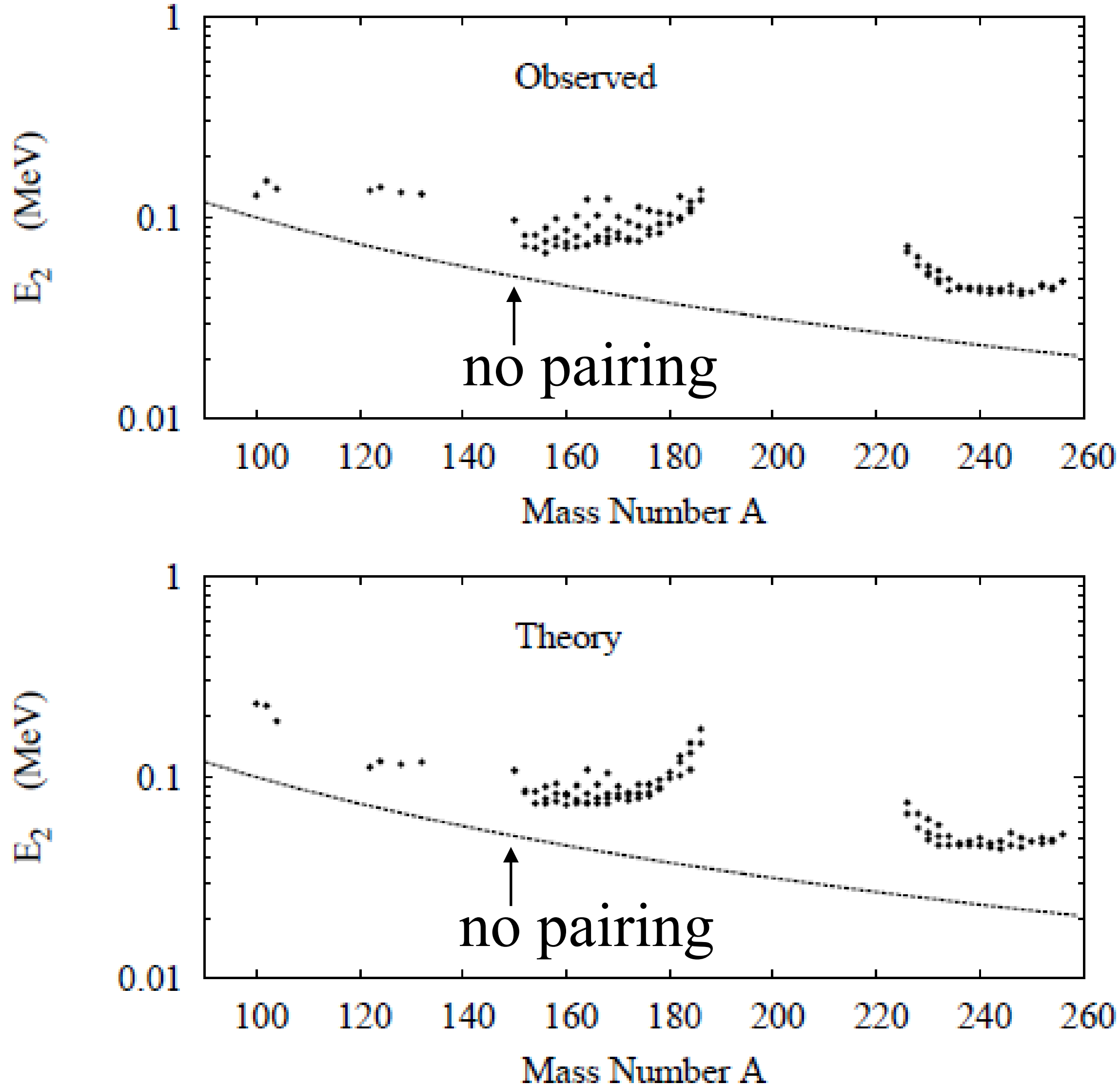
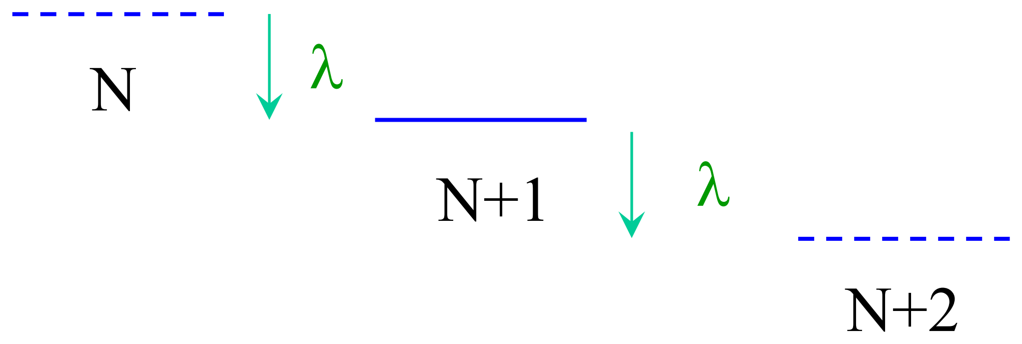



Fig. 9. Excitation energy of the first $2^+$ state in deformed nuclei. The line shows the prediction assuming a rigid rotor.

G.F. Bertsch, in "Fifty years of nuclear BCS"

# Even-odd mass difference and pairing gap

$$E(N+2,Z) = E(N,Z) + 2\lambda$$
$$E(N+1,Z) = E(N,Z) + \lambda + \Delta$$

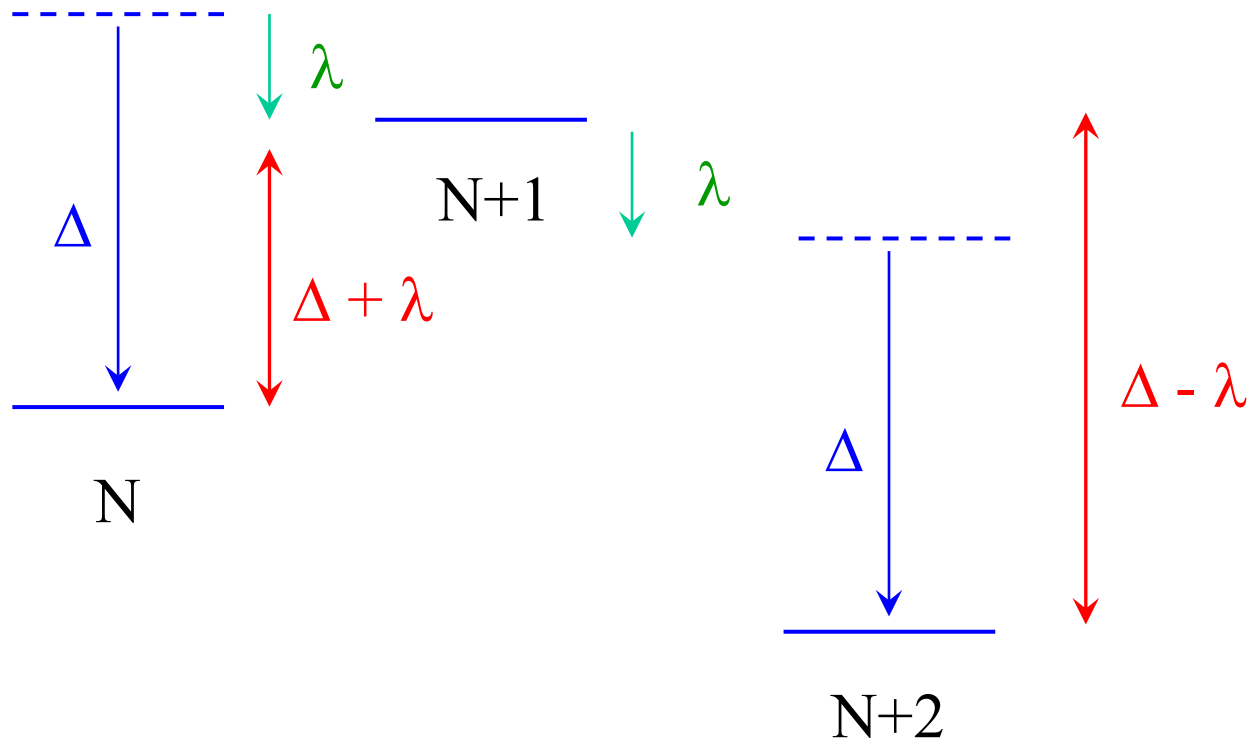



(note) $\lambda < 0$

$$-\Delta_n \sim [E(N+2,Z) - 2E(N+1,Z) + E(N,Z)]/2$$

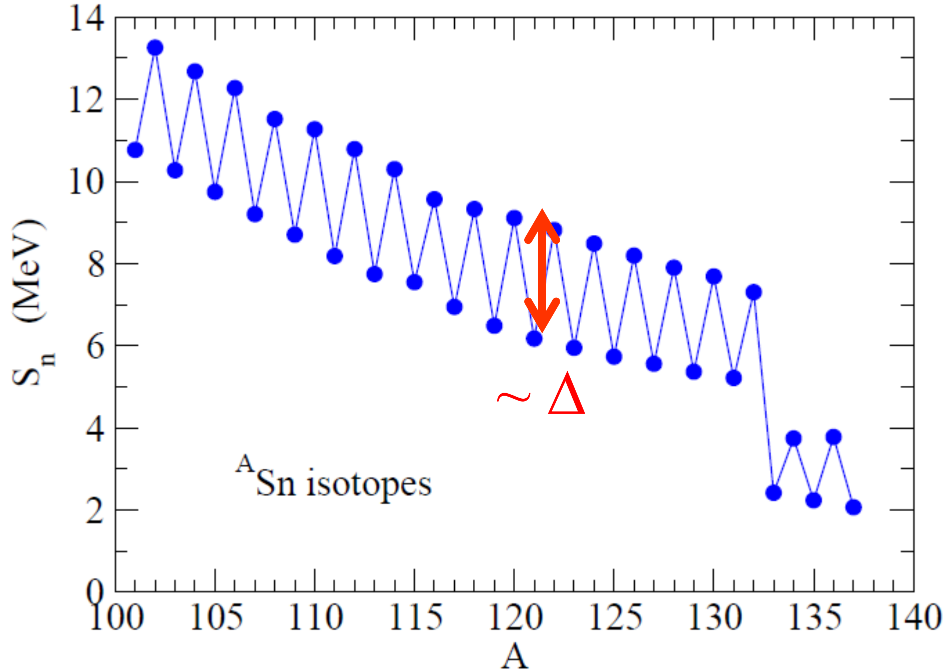
# Even-odd mass difference and pairing gap

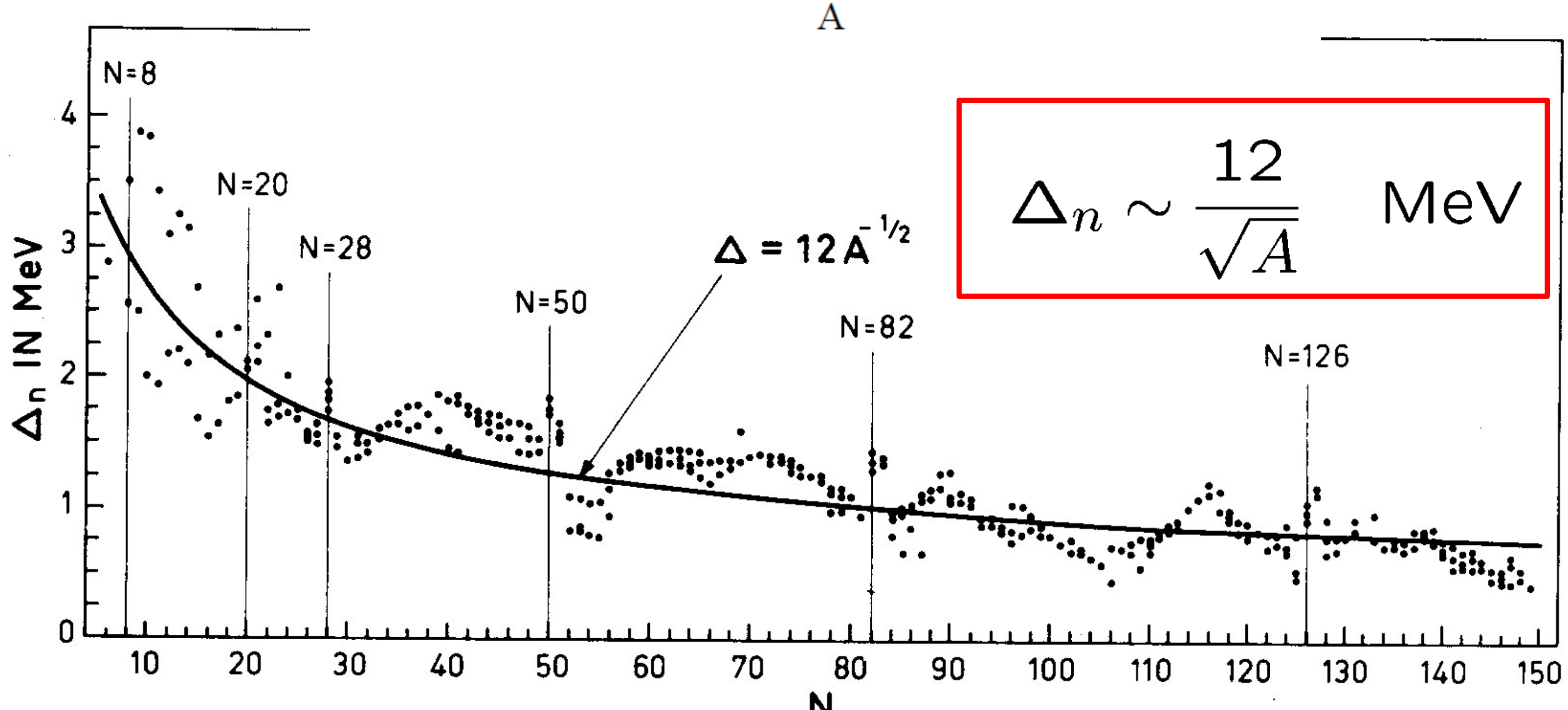
$$E(N+2,Z) = E(N,Z) + 2\lambda$$
$$E(N+1,Z) = E(N,Z) + \lambda + \Delta$$




(note) $\lambda < 0$

$$-\Delta_n \sim [E(N+2,Z) - 2E(N+1,Z) + E(N,Z)]/2$$




$$\Delta_n \sim \frac{12}{\sqrt{A}} \quad \text{MeV}$$

# 粒子数射影法

$$|BCS\rangle = \prod_{\nu>0} \left(u_\nu + v_\nu\, a^\dagger_\nu a^\dagger_{\bar{\nu}}\right)\Big|\,0\Big\rangle$$

様々な粒子数の状態が混ざっている $\quad |BCS\rangle = \sum_{N_k} C_{N_k} |N_k\rangle$

ただし、平均値だけは正しく設定されている:

$$\langle BCS|\hat{N}|BCS\rangle = N$$

粒子数射影: $\quad \hat{P}_N|BCS\rangle = C_N|N\rangle$

$$\hat{P}_N = \frac{1}{2\pi}\int_0^{2\pi} d\phi\, e^{i(\hat{N}-N)\phi}$$

# Hartree-Fock-Bogoliubov (HFB) Theory

HF+BCS 法: 2ステップ
（まず平均場を求め、次に占有確率）

$$\psi_k(\boldsymbol{r}), u_k, v_k$$

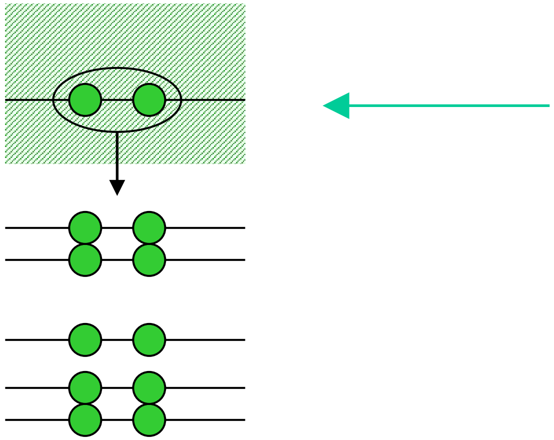
⇒ 改良：両方同時に行う
Hartree-Fock-Bogoliubov (HFB) theory:

波動関数と占有確率を同時に求める

$$U_k(\boldsymbol{r}), V_k(\boldsymbol{r})$$

cf. weakly bound systems
（ガスの問題）

$$\begin{pmatrix} \hat{h}(\boldsymbol{r}) - \lambda & \tilde{\Delta}(\boldsymbol{r}) \\ \tilde{\Delta}(\boldsymbol{r})^* & -\hat{h}(\boldsymbol{r}) + \lambda \end{pmatrix} \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix} = E_k \begin{pmatrix} U_k(\boldsymbol{r}) \\ V_k(\boldsymbol{r}) \end{pmatrix}$$



束縛

BCS法だと散乱状態をそのまま占有させるので、中性子が抜けていく（束縛核のまわりに中性子のガスができる）。

HFB法だと全体で束縛するということがもともと取り入れられているので中性子ガスは発生しない。