Pairing Correlation（対相関）

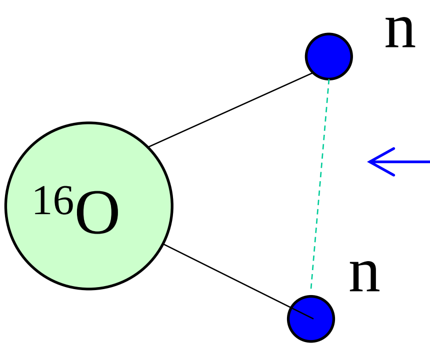
$$H = \sum_i T_i + \sum_{i<j} v_{ij} \rightarrow H = \sum_i (T_i + V_i) + \sum_{i<j} v_{ij} - \sum_i V_i$$

平均からのずれ
（残留相互作用）

残留相互作用は完全に無視してもよいのか?

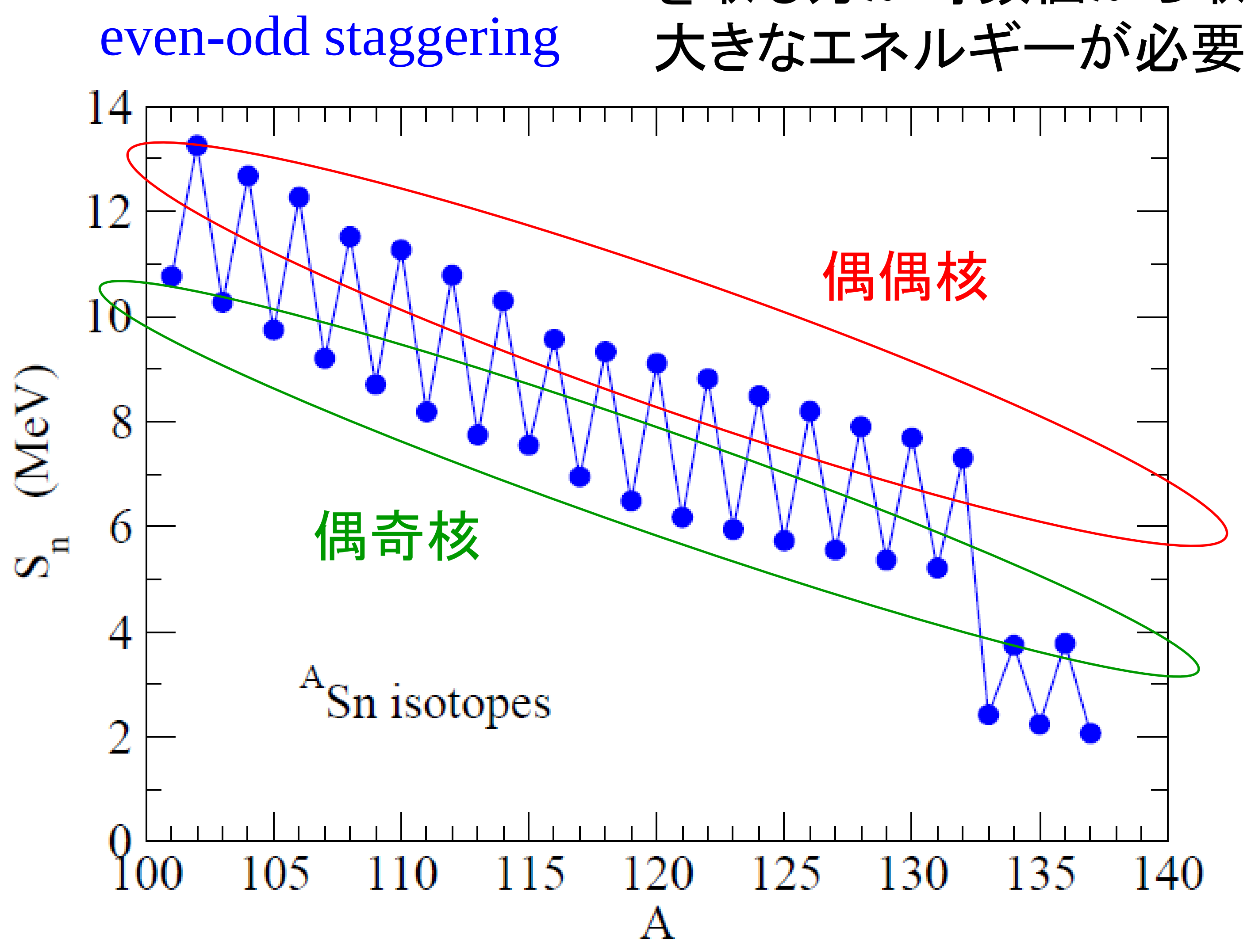
答え：no

開殻原子核では重要な役割を果たすことが知られている（ペアリング）



対相関エネルギー

偶数個の中性子から1つ中性子を取る方が奇数個から取るより大きなエネルギーが必要：対相関



1n separation energy: $S_n\,(A,Z) = B(A,Z) - B(A\text{-}1,Z)$

(参考)中性子誘起核分裂

$$n + {}^{235}U \longrightarrow {}^{236}U^* \longrightarrow \text{fission}$$

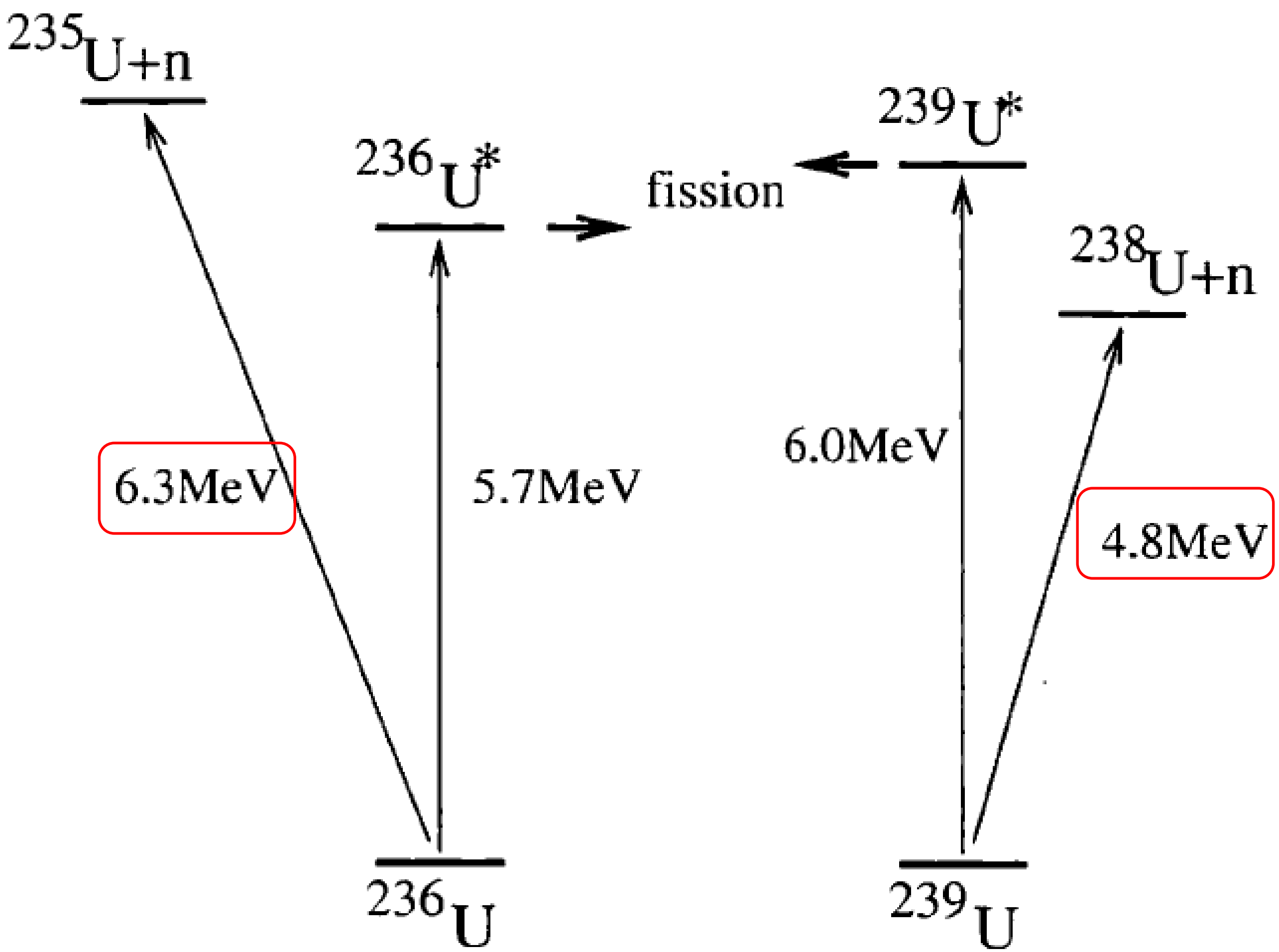


Fig. 6.6. Levels of the systems $A = 236$ and $A = 239$ involved in the fission of ^{236}U and ^{239}U. The addition of a motionless (or thermal) neutron to ^{235}U can lead to the fission of ^{236}U. On the other hand, fission of ^{239}U requires the addition of a neutron of kinetic energy $T_n = 6.0 - 4.8 = 1.2$ MeV.

対相関（ペアリング）

$$H=\sum_{i=1}^{A}\left(-\frac{\hbar^2}{2m}\boldsymbol{\nabla}_i^2+V_{\rm HF}(i)\right)+\frac{1}{2}\sum_{i,j}^{A}v(\boldsymbol{r}_i,\boldsymbol{r}_j)-\sum_i V_{\rm HF}(i)$$

簡単のために、残留相互作用としてデルタ関数を仮定してみる
（超短距離力）

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

摂動論で残留相互作用の効果を見積もってみる:

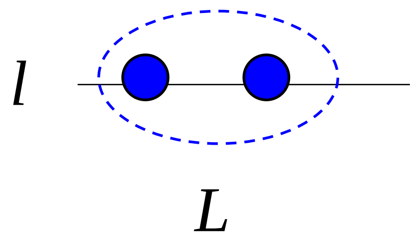
対相関(ペアリング)

$$H = \sum_{i=1}^{A}\left(-\frac{\hbar^2}{2m}\nabla_i^2 + V_{\rm HF}(i)\right) + \frac{1}{2}\sum_{i,j}^{A} v(\boldsymbol{r}_i, \boldsymbol{r}_j) - \sum_i V_{\rm HF}(i)$$

簡単のために、残留相互作用としてデルタ関数を仮定してみる
(超短距離力)

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

摂動論で残留相互作用の効果を見積もってみる:

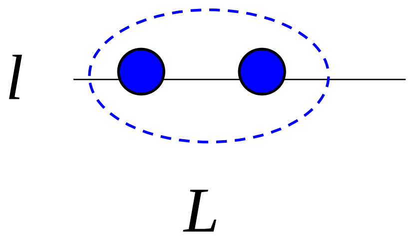


非摂動な波動関数:
角運動量 l の状態に中性子2個、それが
全角運動量 L を組んでいる

$$|(ll)LM\rangle = \sum_{m,m'} \langle lmlm'|LM\rangle \psi_{lm}(\boldsymbol{r})\psi_{lm'}(\boldsymbol{r}')$$

対相関（ペアリング）

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



$$|(ll)LM\rangle = \sum_{m,m'}\langle lmlm'|LM\rangle\psi_{lm}(\boldsymbol{r})\psi_{lm'}(\boldsymbol{r}')$$

⇩

残留相互作用によるエネルギー変化：

$$\begin{aligned}\Delta E_L &= \langle (ll)LM|v_{\rm res}|(ll)LM\rangle \\ &= -g\,I_r^{(l)}\,\frac{(2l+1)^2}{4\pi}\begin{pmatrix} l & l & L \\ 0 & 0 & 0\end{pmatrix}^2\end{aligned}$$

$$I_r^{(l)} = \int_0^\infty r^2dr\,(R_l(r))^4$$

$$\Delta E_L = -g\, I_r^{(l)} \frac{(2l+1)^2}{4\pi} \begin{pmatrix} l & l & L \\ 0 & 0 & 0 \end{pmatrix}^2 \equiv -g\, I_r^{(l)} \frac{A(ll;L)}{4\pi}$$

$A(ll;L)$	L=0	L=2	L=4	L=6	L=8
l = 2	5.00	1.43	1.43	---	---
l = 3	7.00	1.87	1.27	1.63	---
l = 4	9.00	2.34	1.46	1.26	1.81

$$\Delta E_L = -g\, I_r^{(l)} \frac{(2l+1)^2}{4\pi} \begin{pmatrix} l & l & L \\ 0 & 0 & 0 \end{pmatrix}^2 \equiv -g\, I_r^{(l)} \frac{A(ll;L)}{4\pi}$$

$A(ll;L)$	L=0	L=2	L=4	L=6	L=8
l = 2	5.00	1.43	1.43	---	---
l = 3	7.00	1.87	1.27	1.63	---
l = 4	9.00	2.34	1.46	1.26	1.81

$$\Delta E_L = -g\, I_r^{(l)} \frac{(2l+1)^2}{4\pi} \begin{pmatrix} l & l & L \\ 0 & 0 & 0 \end{pmatrix}^2 \equiv -g\, I_r^{(l)} \frac{A(ll;L)}{4\pi}$$

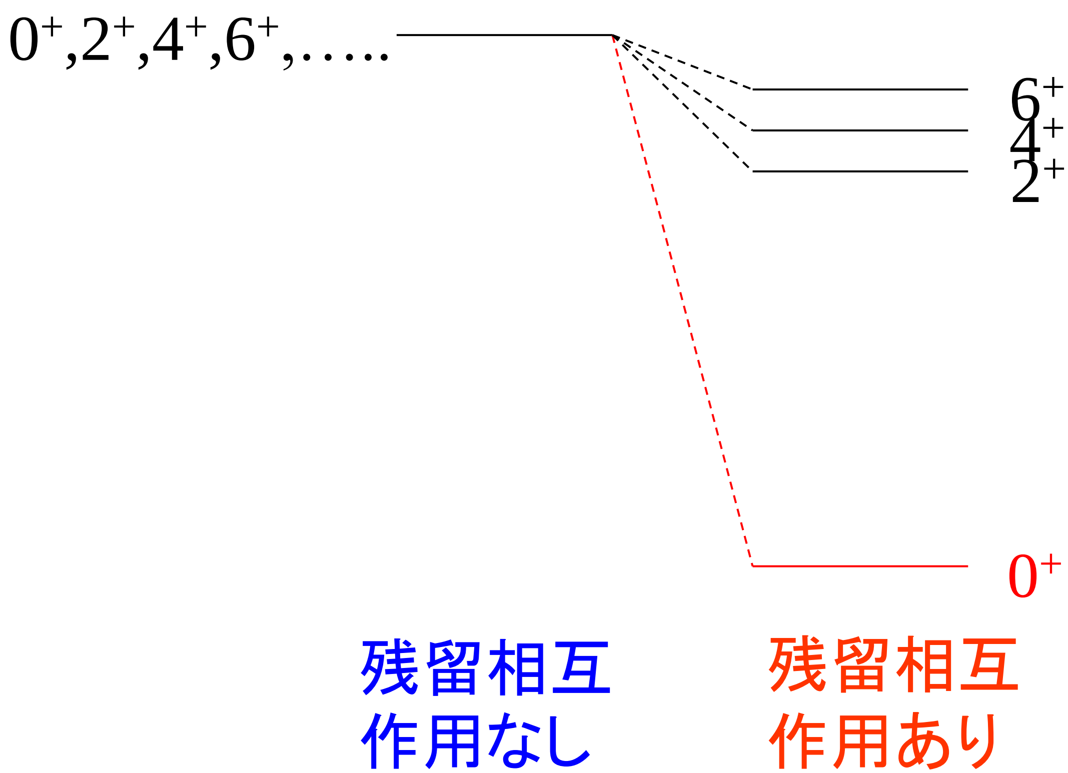
$A(ll;L)$	L=0	L=2	L=4	L=6	L=8
l = 2	5.00	1.43	1.43	---	---
l = 3	7.00	1.87	1.27	1.63	---
l = 4	9.00	2.34	1.46	1.26	1.81

$0^+, 2^+, 4^+, 6^+, \ldots\ldots$ ————

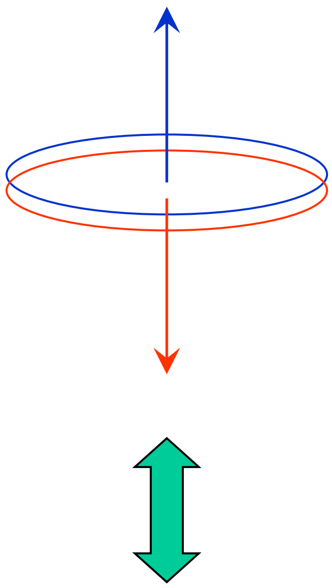
残留相互
作用なし

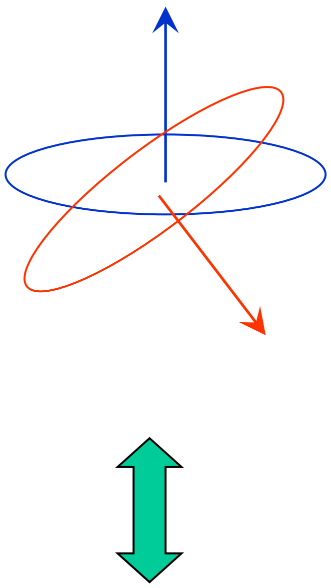
$$\Delta E_L = -g\, I_r^{(l)} \frac{(2l+1)^2}{4\pi} \begin{pmatrix} l & l & L \\ 0 & 0 & 0 \end{pmatrix}^2 \equiv -g\, I_r^{(l)} \frac{A(ll;L)}{4\pi}$$

$A(ll;L)$	L=0	L=2	L=4	L=6	L=8
l = 2	5.00	1.43	1.43	---	---
l = 3	7.00	1.87	1.27	1.63	---
l = 4	9.00	2.34	1.46	1.26	1.81



簡単な解釈:



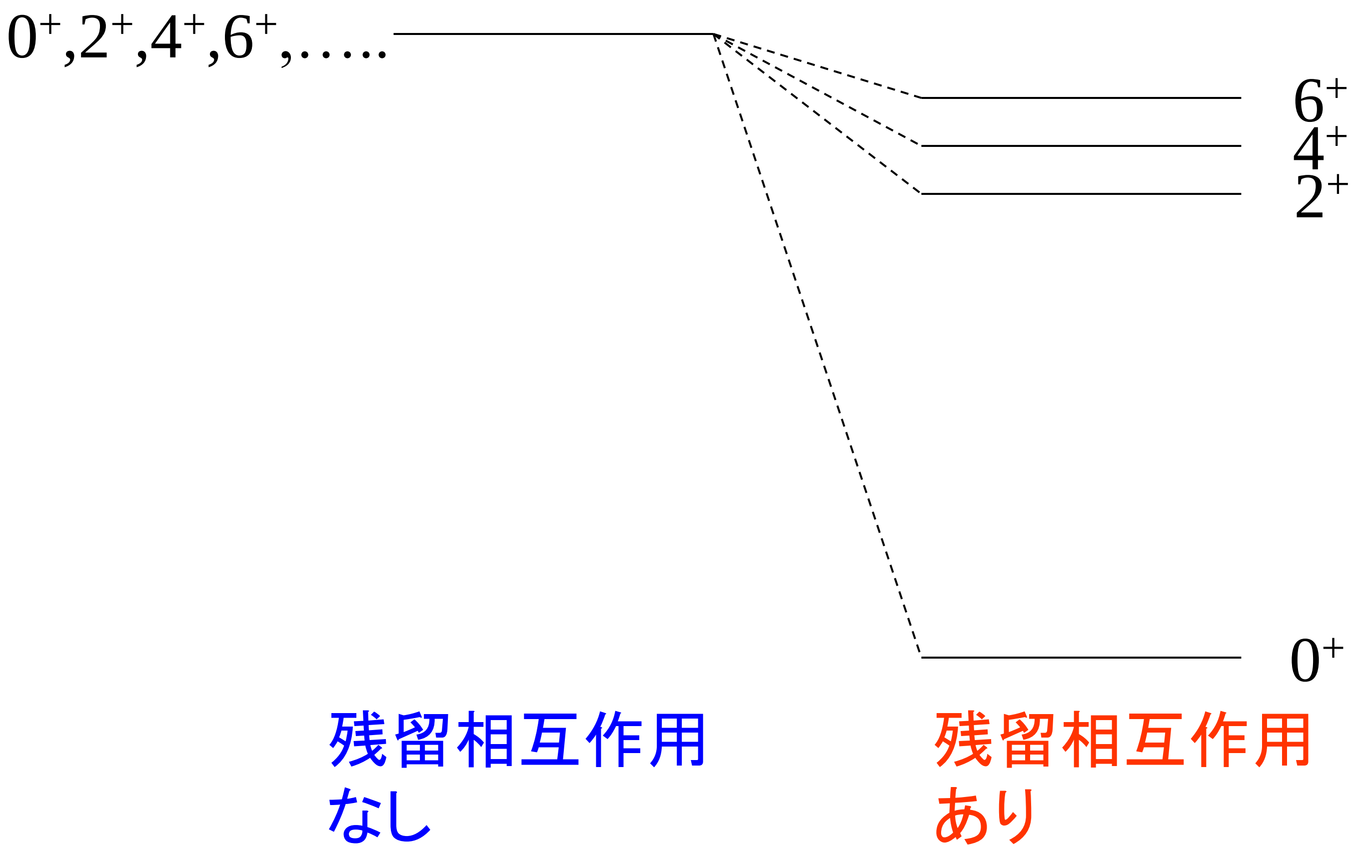


L=0 対

$L \neq 0$ 対

L=0 対に対して空間的重なりが最大（エネルギー的に得）

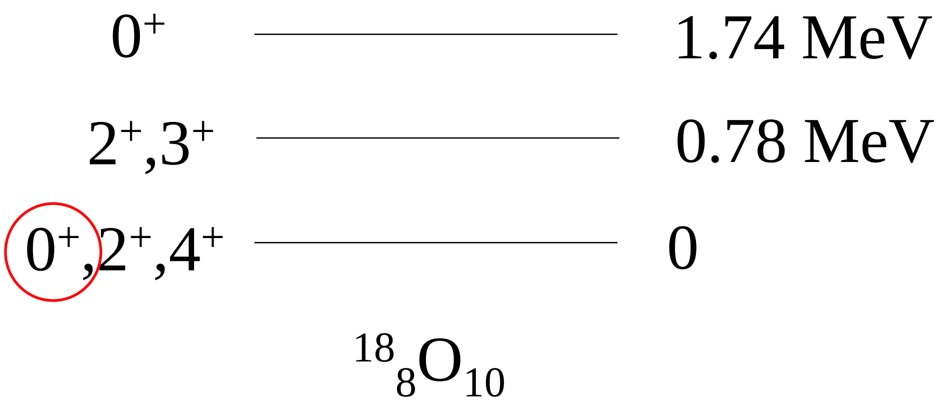
"対相関"



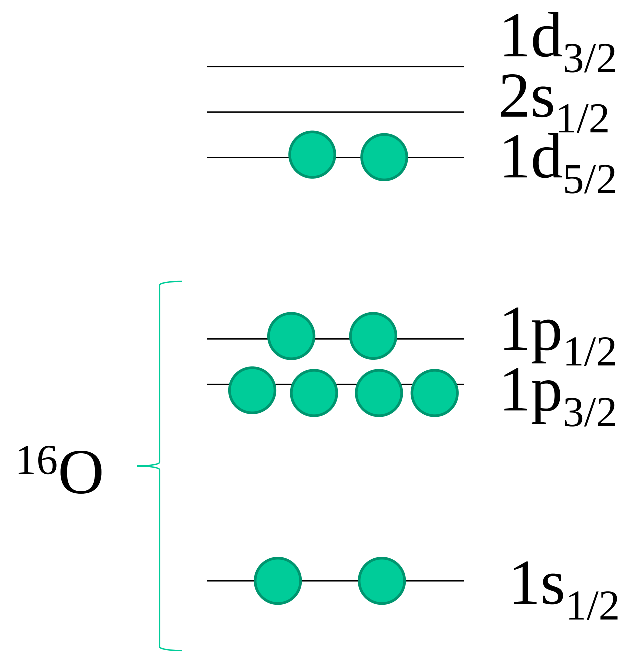
<u>原子核の基底状態のスピン</u>

- 偶々核:例外なしに 0^+
- 奇核: 最外殻核子の角運動量と一致

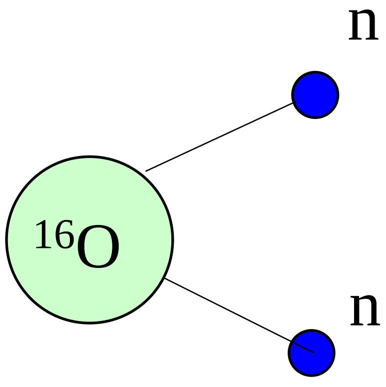
単純な平均場近似:



0^+
1.74 MeV
$2^+, 3^+$
0.78 MeV
$0^+, 2^+, 4^+$
0
$^{18}_{8}O_{10}$

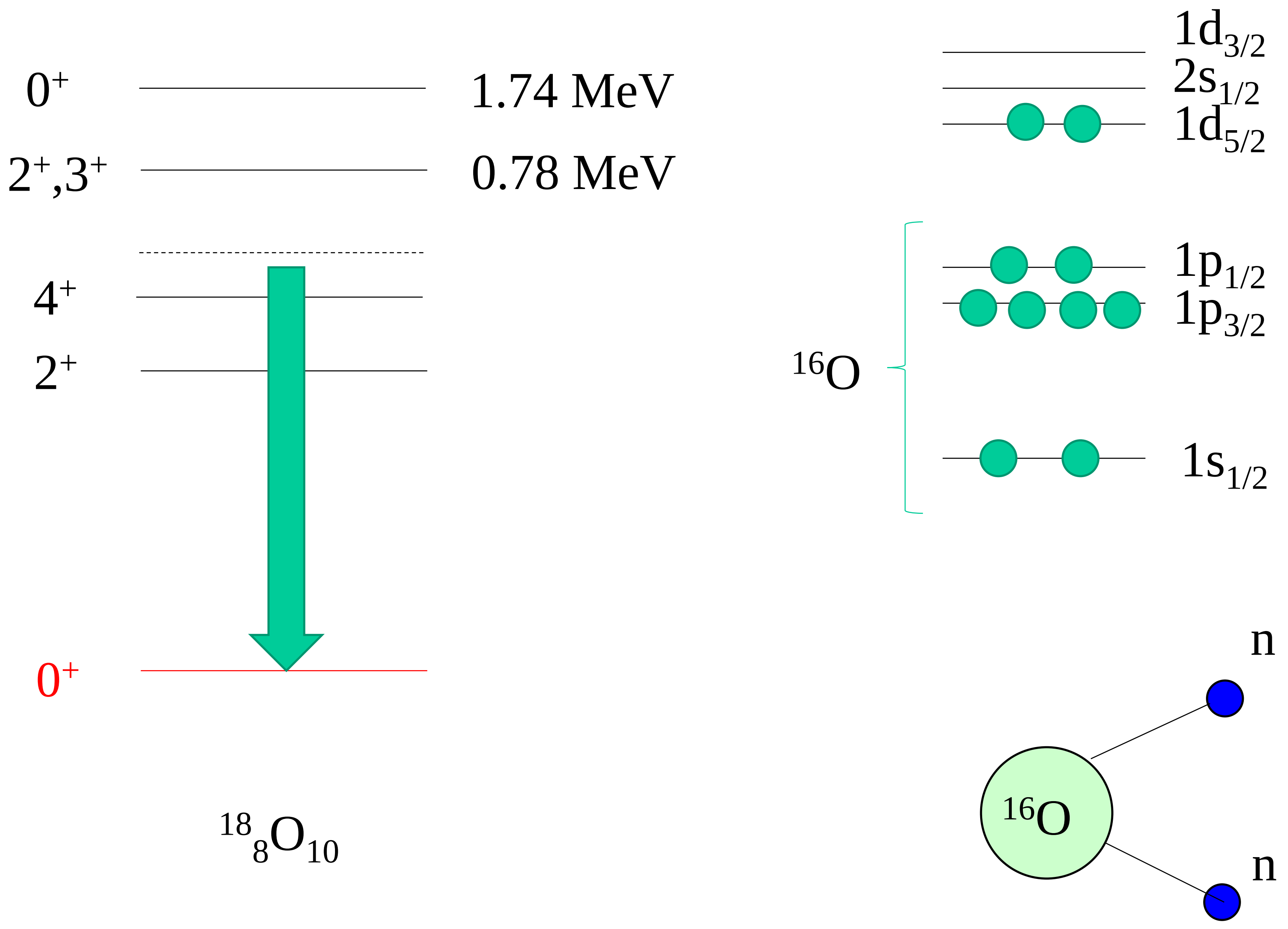


$1d_{3/2}$
$2s_{1/2}$
$1d_{5/2}$
$1p_{1/2}$
$1p_{3/2}$
^{16}O
$1s_{1/2}$



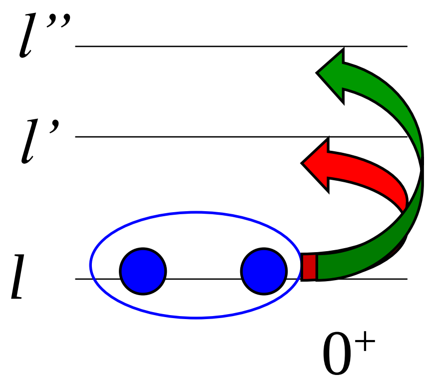
n
^{16}O
n

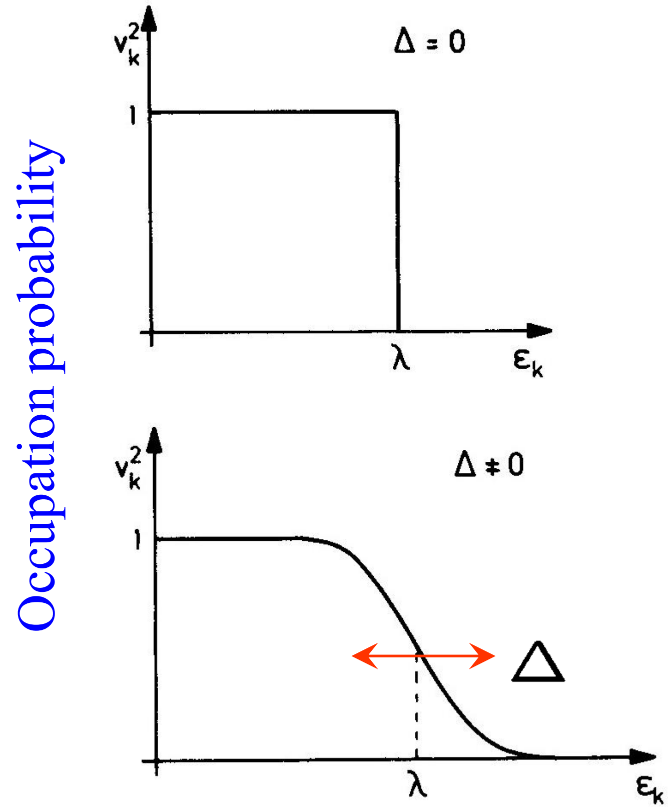
単純な平均場近似:



0+
1.74 MeV
2+,3+
0.78 MeV
4+
2+
0+
18 8 O 10
1d3/2
2s1/2
1d5/2
1p1/2
1p3/2
16O
1s1/2
n
16O
n

波動関数:

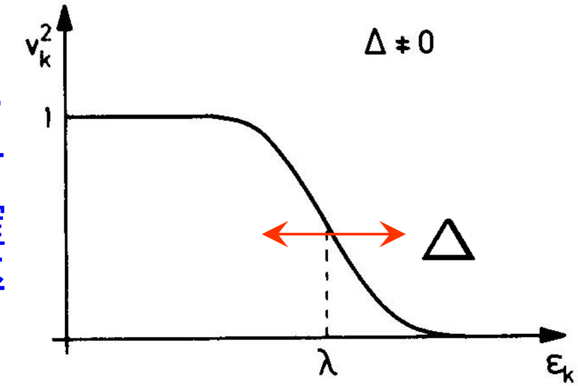




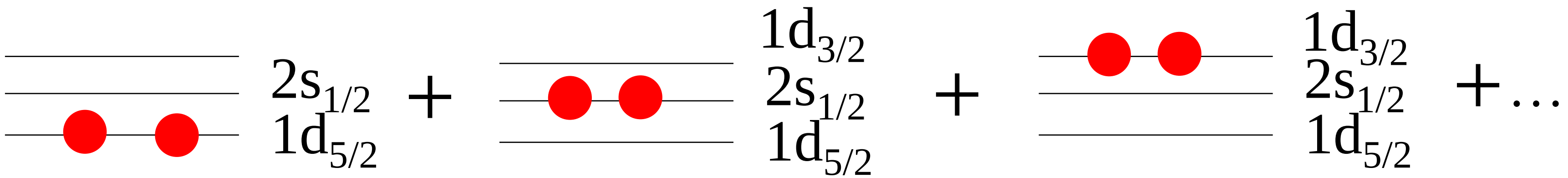
$$
\begin{aligned}
|\Psi_{0+}\rangle &= |(ll)L=0\rangle \\
&+ \sum_{l'} \frac{\langle (l'l')L=0|v_{\rm res}|(ll)L=0\rangle}{2\epsilon_l - 2\epsilon_{l'}} |(l'l')L=0\rangle + \cdots
\end{aligned}
$$

波動関数:

占有確率



$$|\Psi_{g.s.}\rangle =$$



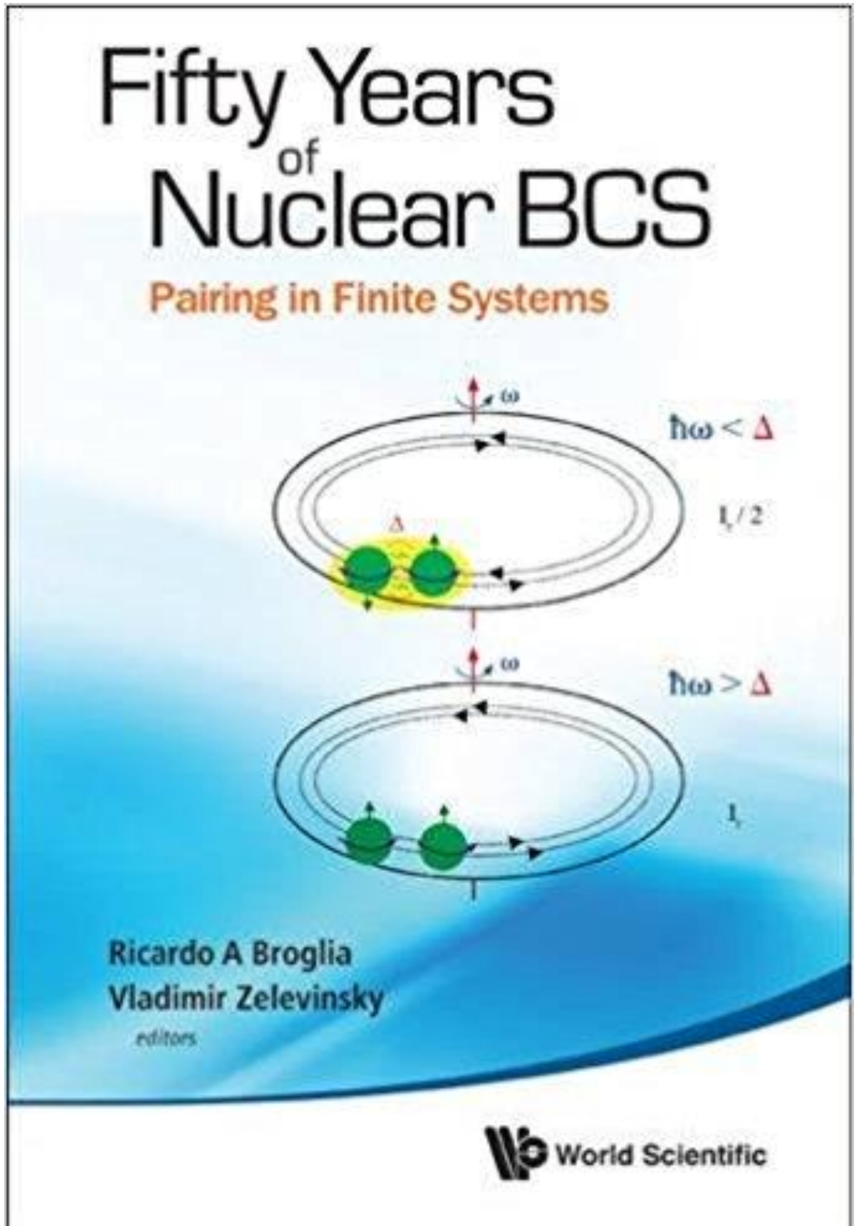
いろいろな配位を混ぜることによって対相関エネルギーを稼ぐ

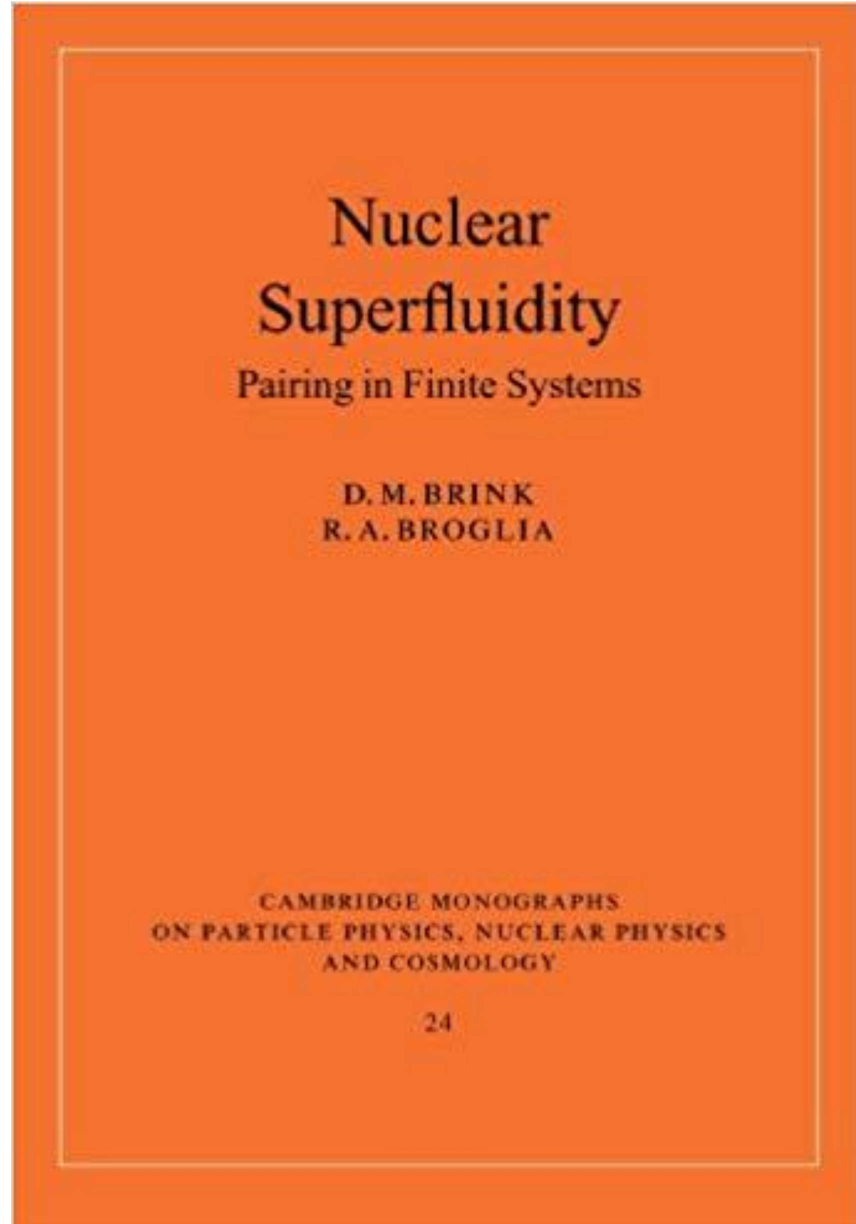
→ 各軌道は部分的にのみ占有されることになる

占有確率はエネルギーを最小化するように決定

cf. BCS 理論

超流動状態


Fifty Years of Nuclear BCS
Pairing in Finite Systems
ħω < Δ
ħω > Δ
Ricardo A Broglia
Vladimir Zelevinsky
editors
World Scientific

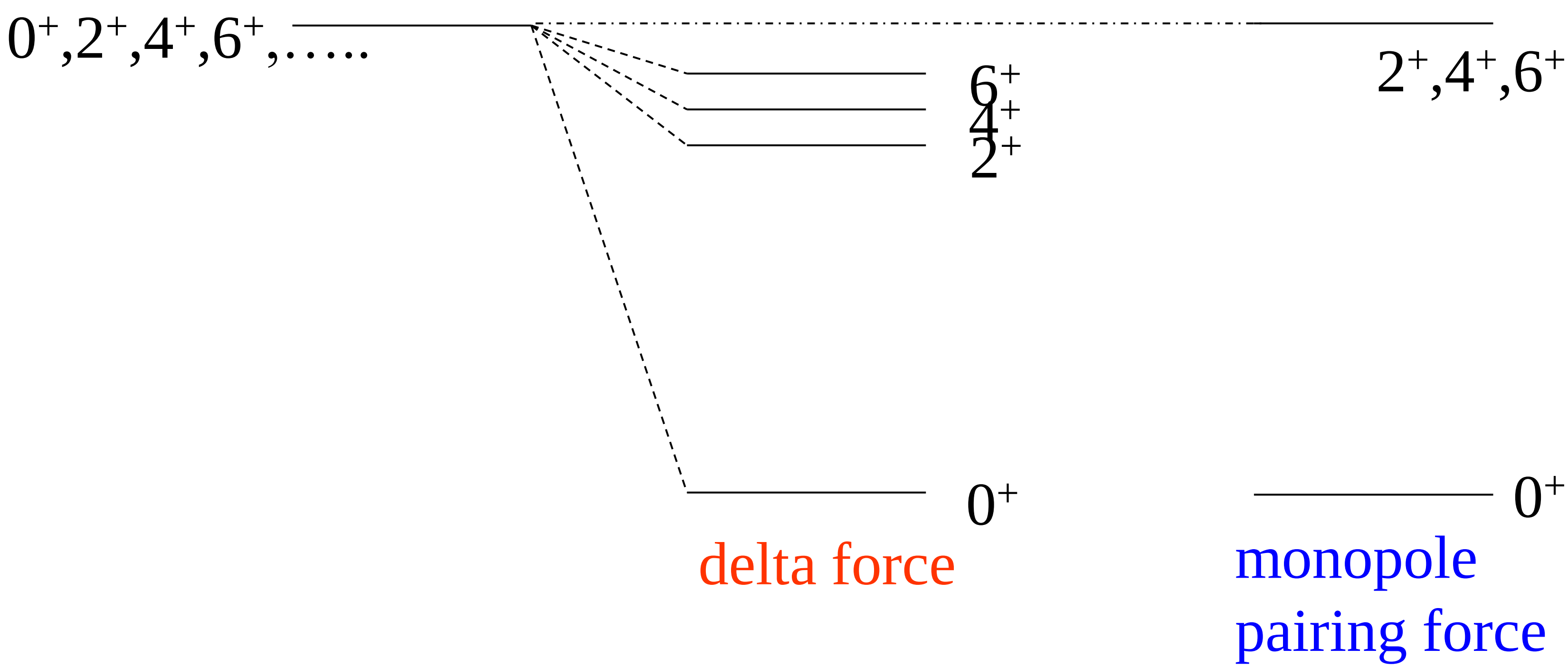

Nuclear Superfluidity
Pairing in Finite Systems
D. M. BRINK
R. A. BROGLIA
CAMBRIDGE MONOGRAPHS
ON PARTICLE PHYSICS, NUCLEAR PHYSICS
AND COSMOLOGY
24

以下では、簡単のために、単純化された対相関相互作用を用いる:

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

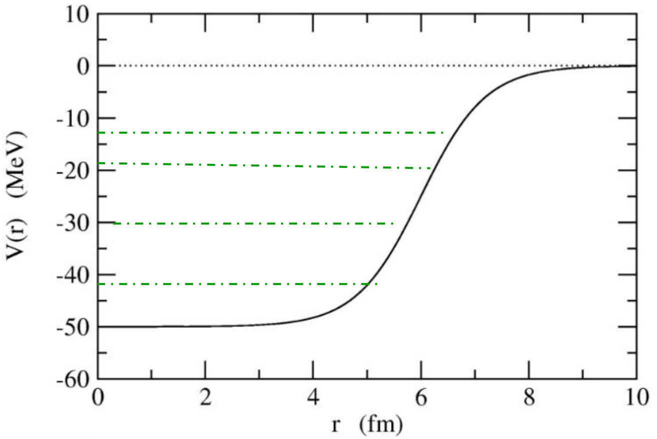
$\bar{\nu}$: the time reversed state of ν

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



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:

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

⟺ particle number violation

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

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

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

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

- 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 :

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

- Transform *H'* in a form of

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

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

1st excited state: $|1_k\rangle = \alpha_k^\dagger|BCS\rangle$ at E_k

…. and so on.

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

(note)

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

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

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

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

$$\rightarrow$$

using the quasi-particle operators:

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

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

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

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

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

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

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

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

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

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

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

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

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

(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)

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

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

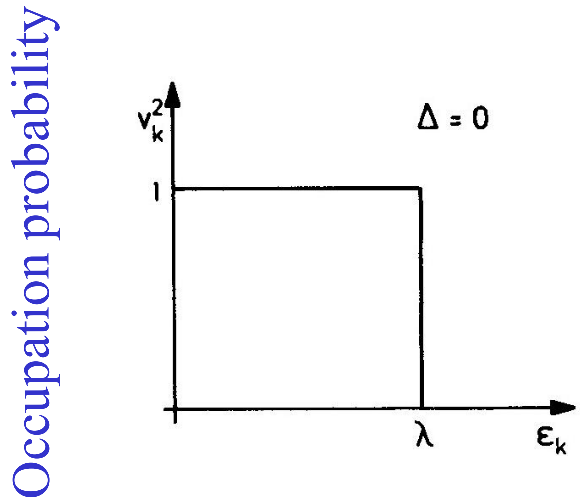
i) Trivial solution: always exists

$$\Delta = 0$$

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

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

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



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

i) Trivial solution: always exists

$$\Delta = 0$$

G a/o $N \longrightarrow$ large

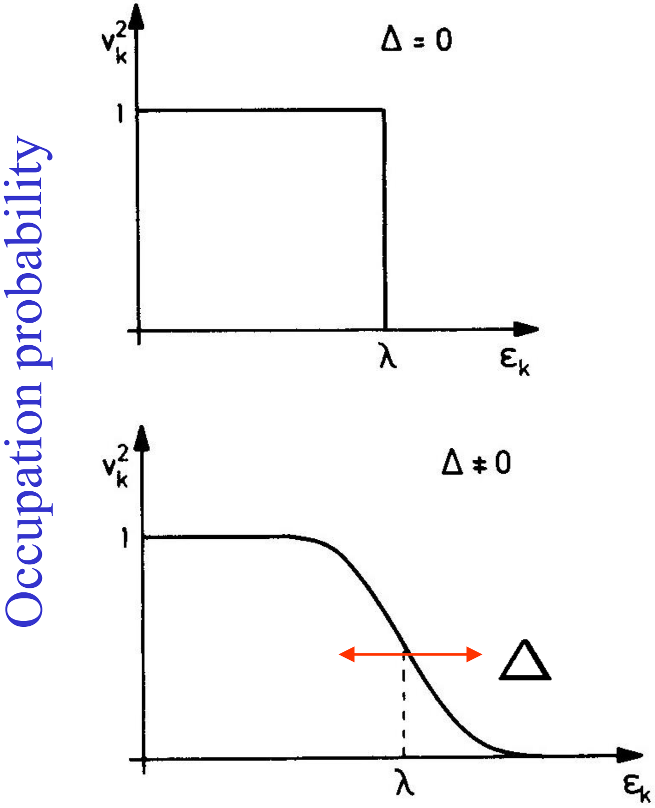
ii) Superfluid solution

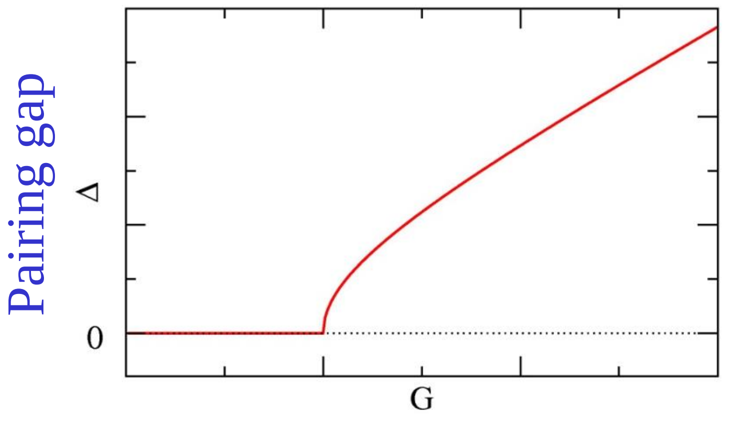
$$\Delta \neq 0$$

$$v_\nu^2 < 1$$

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

Number fluctuation



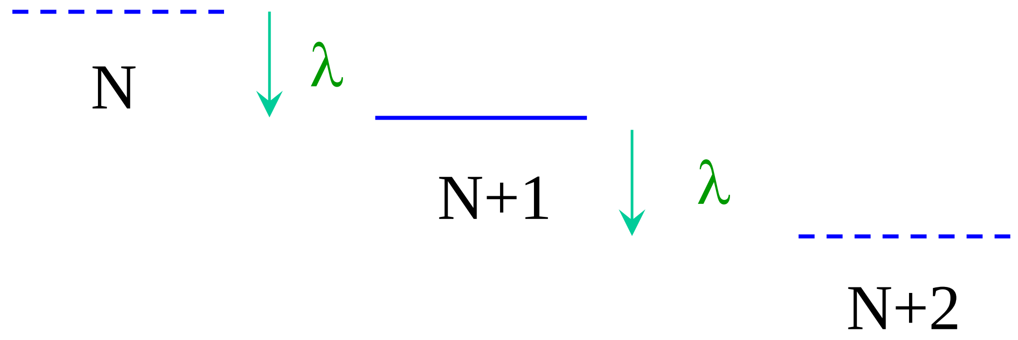


Normal-Superfulid phase transition

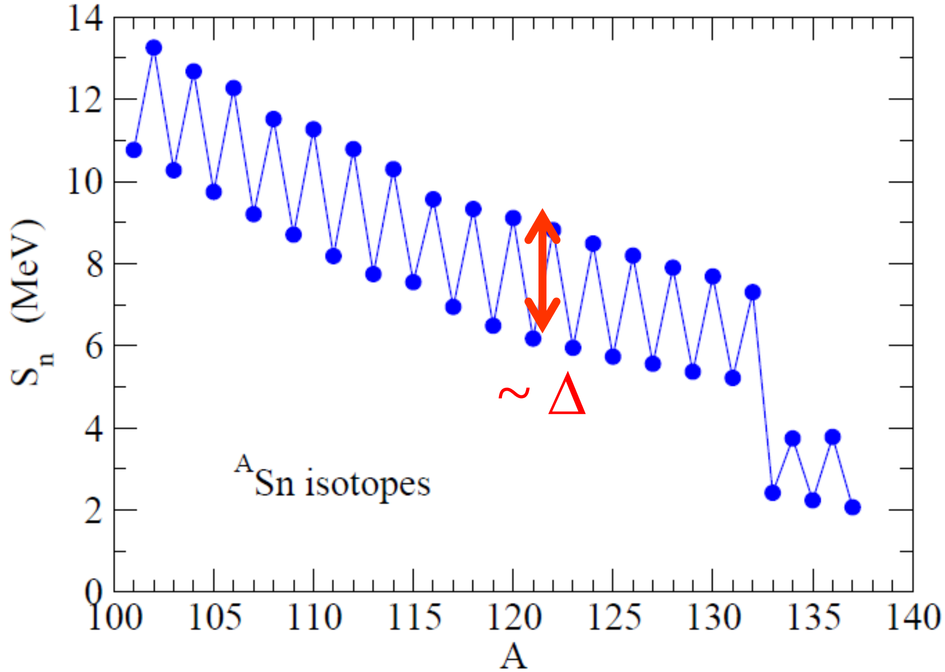
Even-odd mass difference and pairing gap

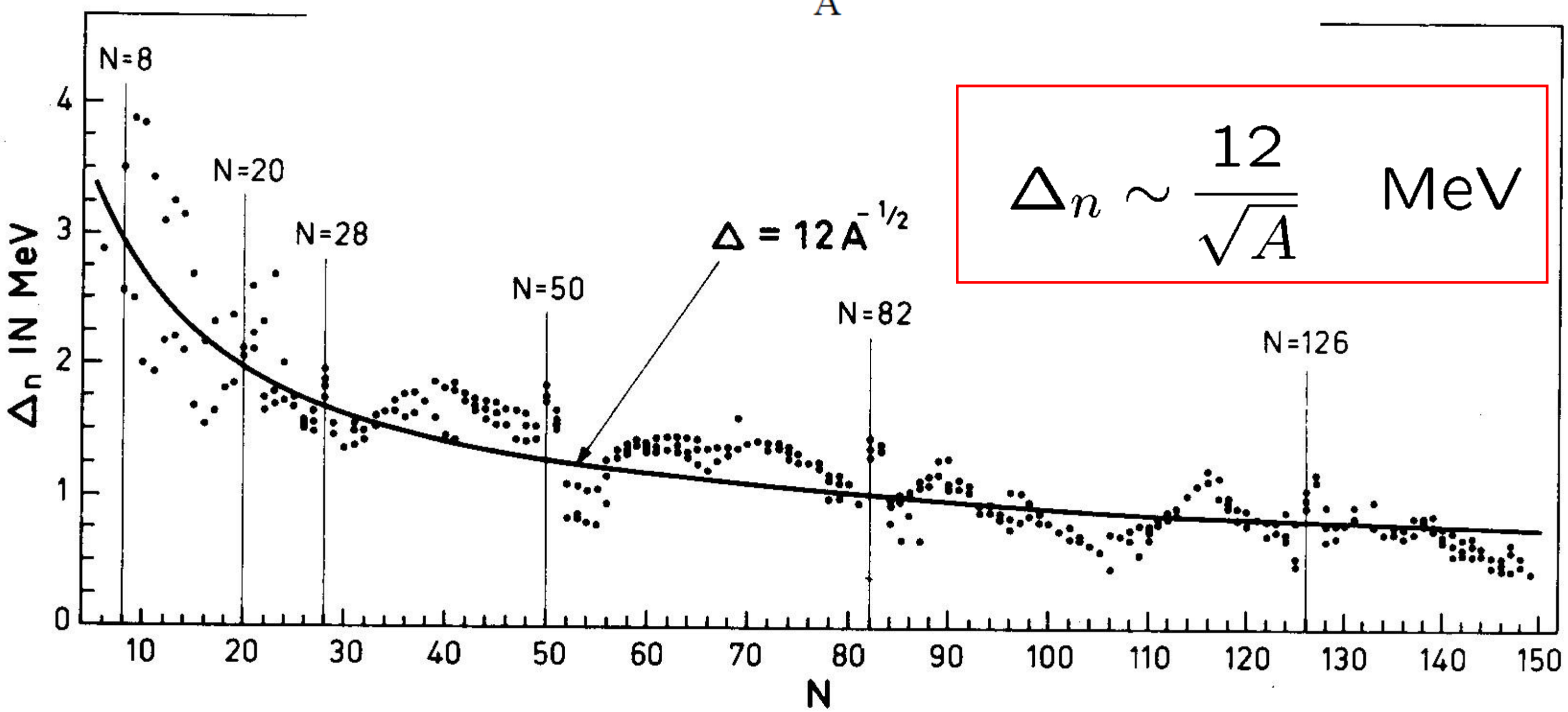
$$E(N+2,Z) = E(N,Z) + 2\lambda$$
$$E(N+1,Z) = E(N,Z) + \lambda + \Delta$$

(note) $\lambda < 0$



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



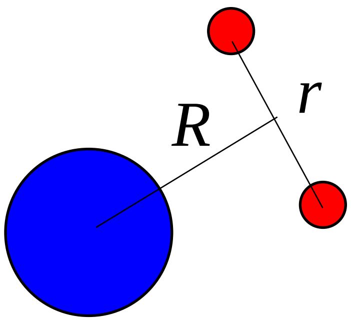


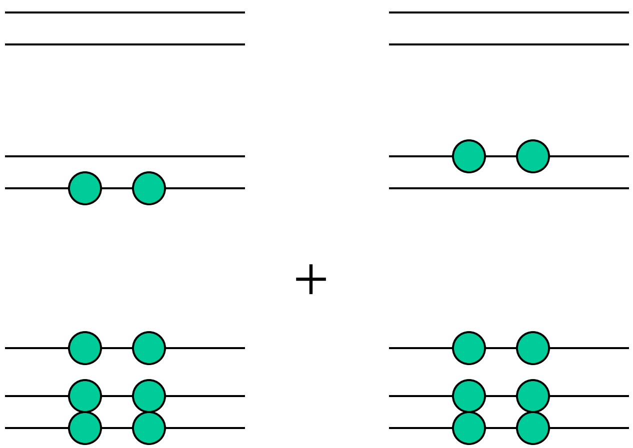
$$\Delta_n \sim \frac{12}{\sqrt{A}} \quad \text{MeV}$$

弱束縛核における対相関と2中性子ハロー核

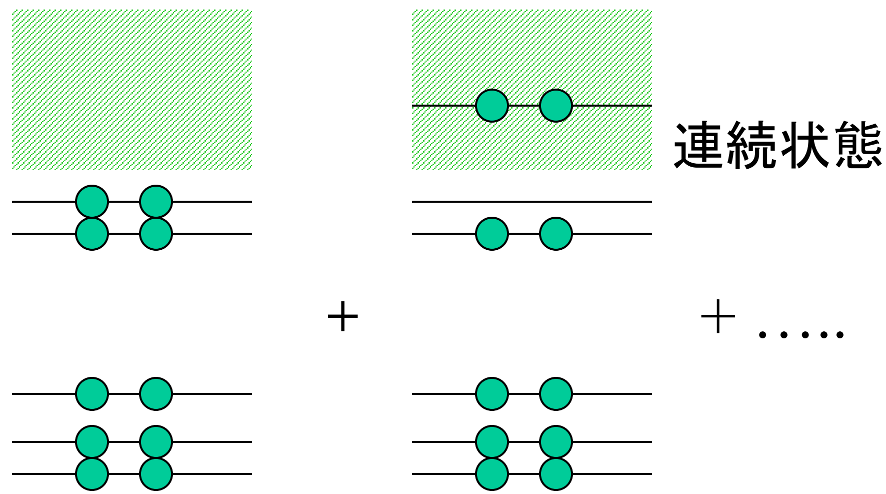
$$H = \sum_i T_i + \sum_{i<j} v_{ij} \rightarrow H = \sum_i (T_i + V_i) + \underbrace{\sum_{i<j} v_{ij} - \sum_i V_i}$$

平均からのずれ
（残留相互作用）





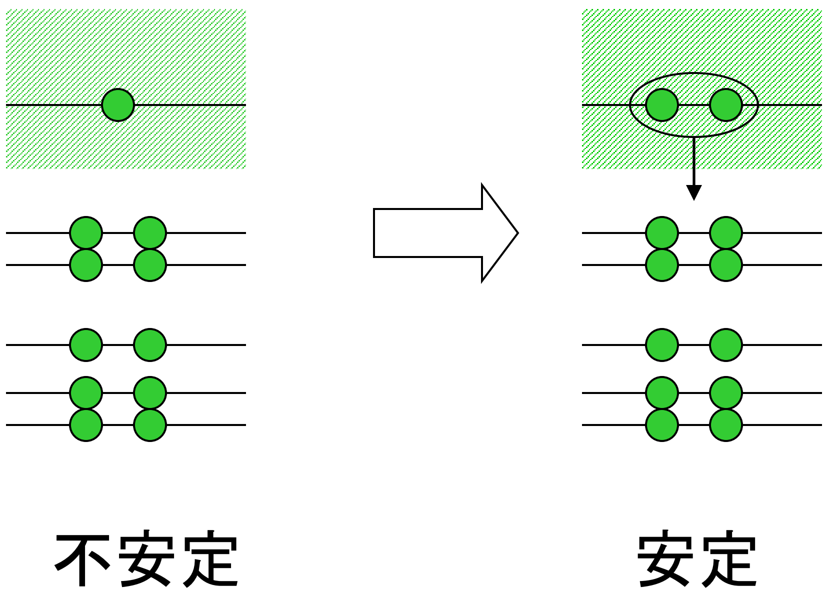
安定な原子核
→超流動(BCS)状態

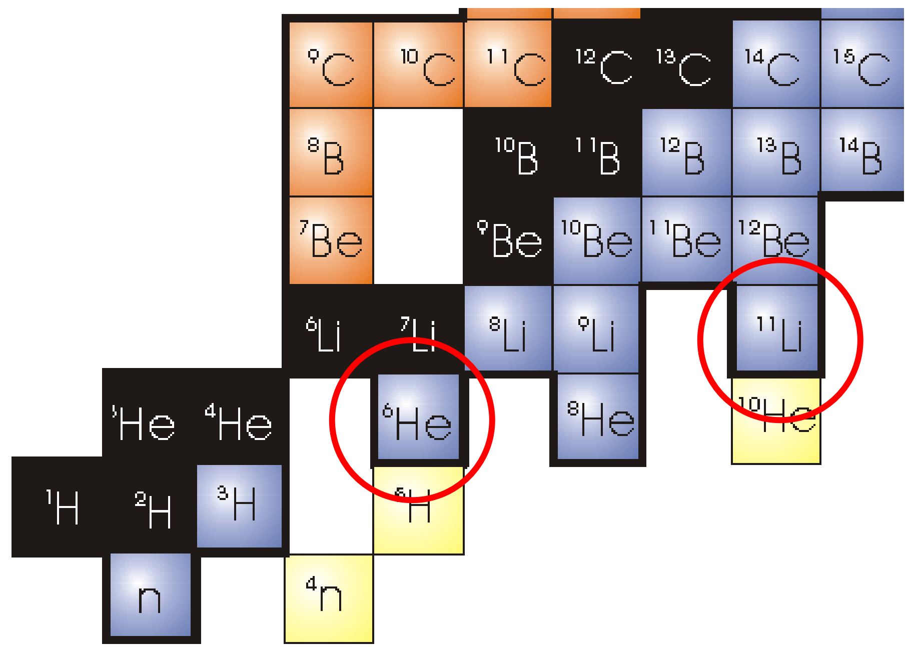


弱く束縛された系

ボロミアン原子核

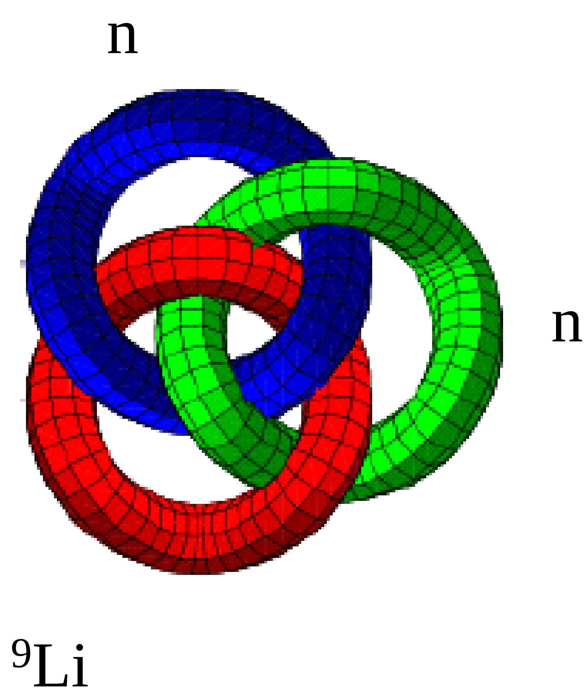
残留相互作用 → 引力

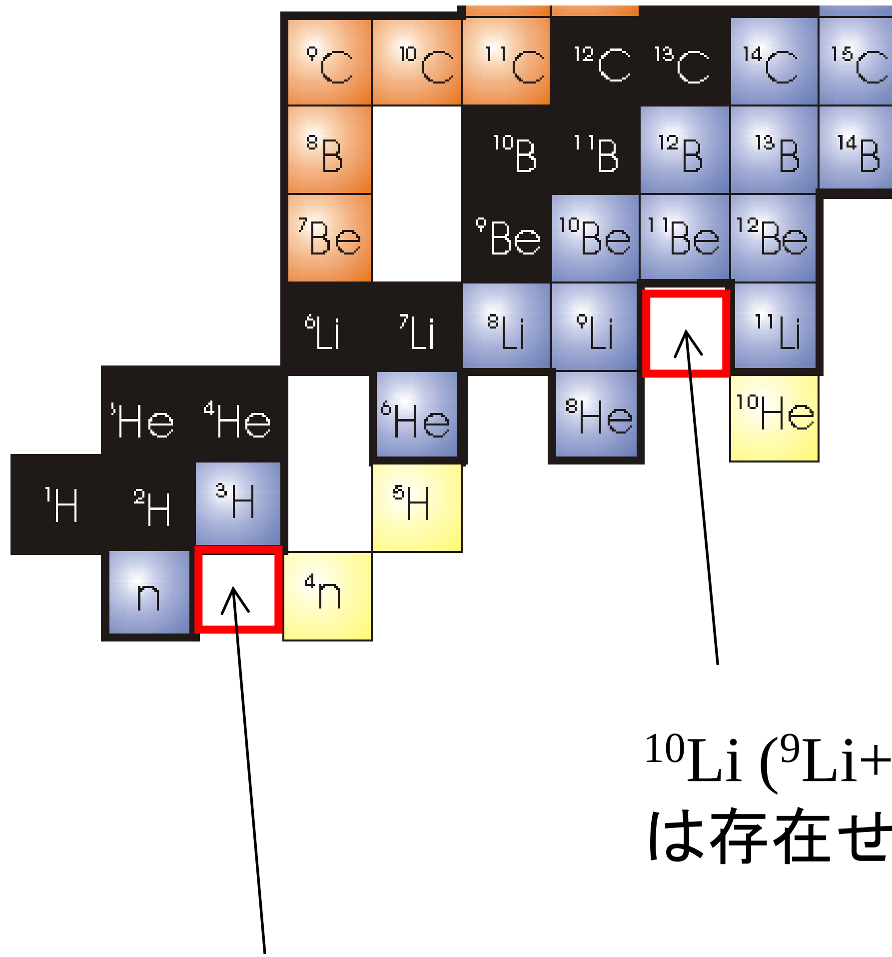




“ボロミアン核”

ボロミアン原子核





^{10}Li (^{9}Li+n)
は存在せず

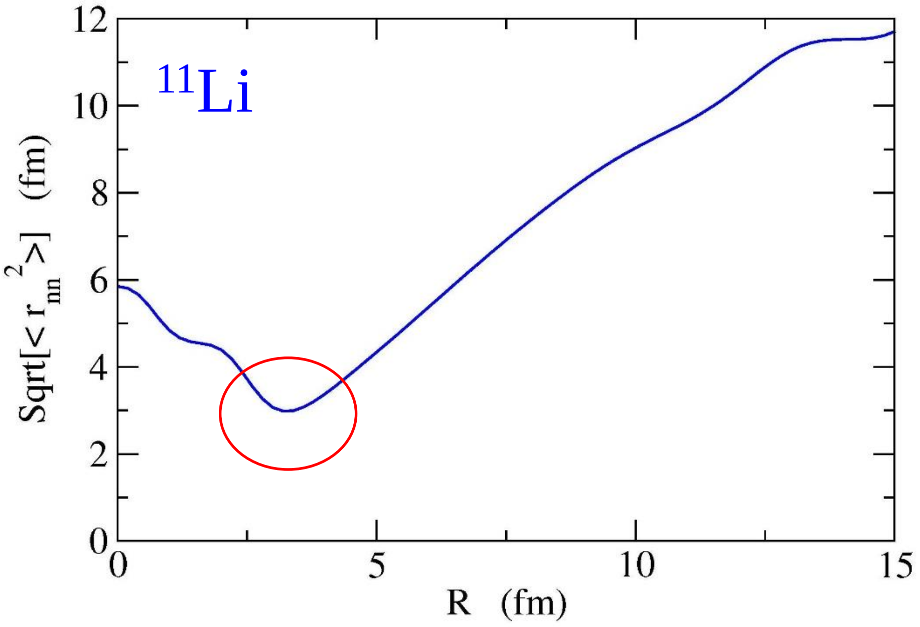
^{2}n (n+n) は存在せず

ボロミアン核

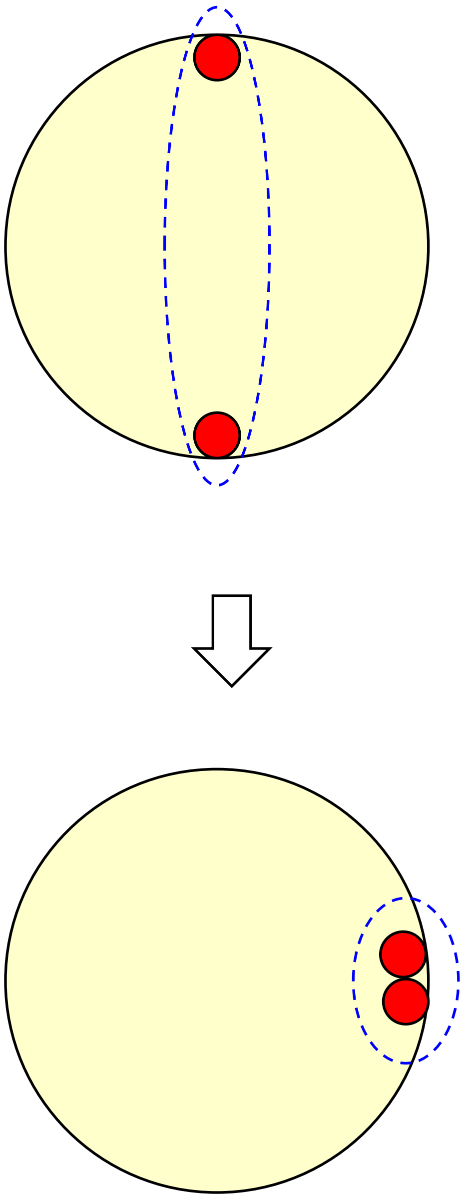
他にも、^{6}He が典型的な例

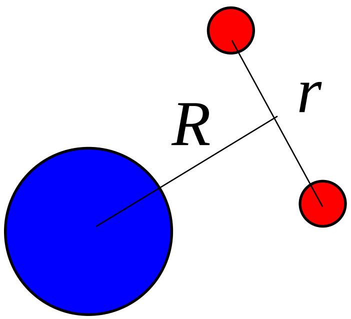
核子間相関（特にダイニュートロン相関）

Surface dineutron correlations



K.H., H. Sagawa, J. Carbonell, and P. Schuck,
PRL99('07)022506





"dineutron" 相関