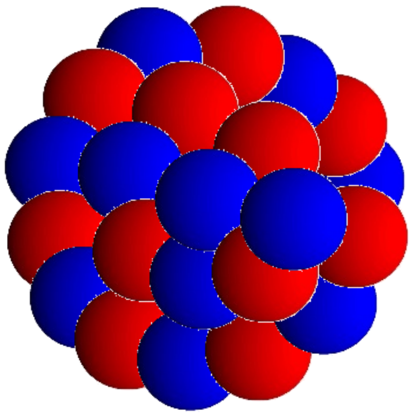
はじめに：核子多体問題について



原子核 ＝ 陽子と中性子の多体系

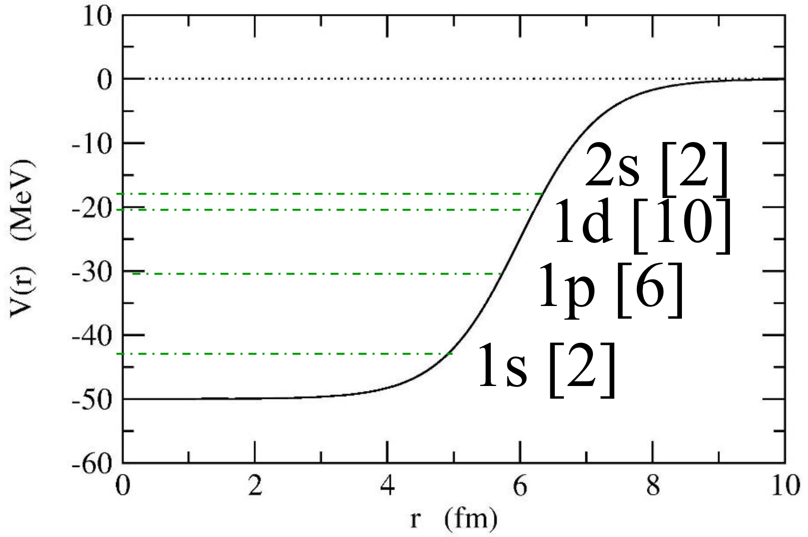
多体のハミルトニアン

$$H = \sum_i T_i + \underbrace{\sum_{i<j} v_{ij}}_{2\text{体力}} + \underbrace{\sum_{i<j<k} v_{ijk}}_{3\text{体力}}$$

このハミルトニアンを核子間のパウリ原理を考慮して
どのように(近似的に)解くのか？

原子核の殻模型

Shell Model: independent particle motion in a potential well



+ spin-orbit interaction

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r) - \epsilon\right]\psi(\boldsymbol{r}) = 0$$

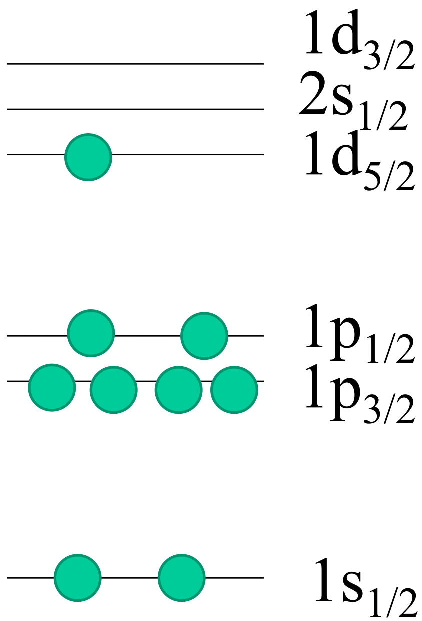
$$\psi(\boldsymbol{r}) = \frac{u_l(r)}{r}\mathcal{Y}_{jlm}(\hat{\boldsymbol{r}})$$

$$\mathcal{Y}_{jlm}(\hat{\boldsymbol{r}}) = \sum_{m_l, m_s} \langle l\ m_l\ 1/2\ m_s | j\ m \rangle Y_{lm_l}(\hat{\boldsymbol{r}})\chi_{m_s}$$

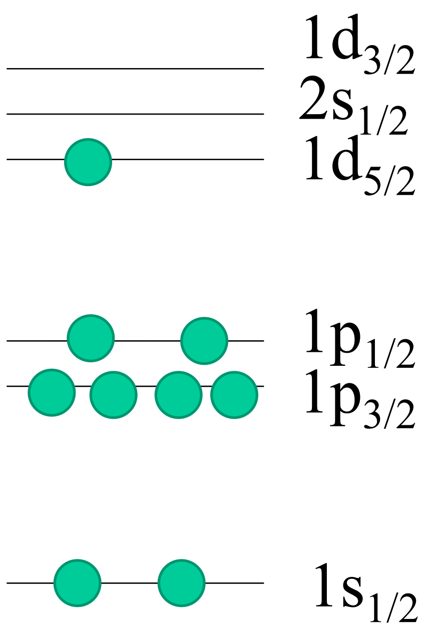
$$\boxed{H = \sum_k \epsilon_k a_k^\dagger a_k}$$

shell model

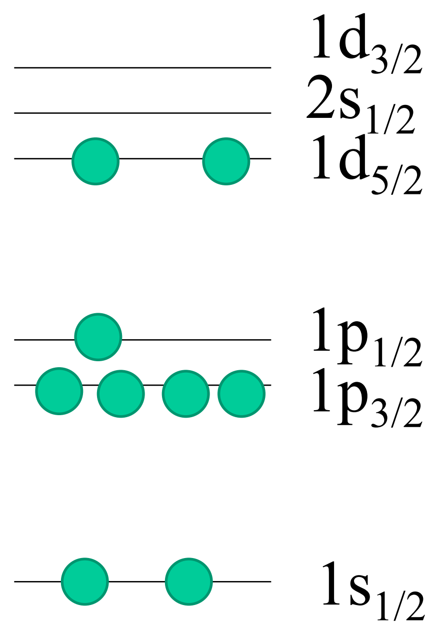
$$H = \sum_k \epsilon_k a_k^\dagger a_k$$



shell model $$H = \sum_k \epsilon_k a_k^\dagger a_k$$



configuration 1

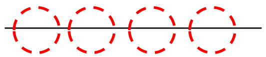


configuration 2

…… several others

angular momentum (spin) and parity for each configuration?

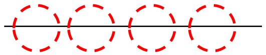
→ let us first investigate a single-j case an example: $j = p_{3/2}$



$p_{3/2}$

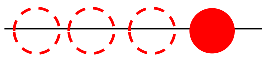
can accommodate 4 nucleons

(j_z= +3/2, +1/2, -1/2, -3/2)

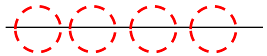


$p_{3/2}$ can accommodate 4 nucleons
(j_z= +3/2, +1/2, -1/2, -3/2)

i) 1 nucleon

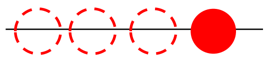


$p_{3/2}$

 $p_{3/2}$

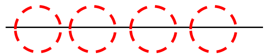
can accommodate 4 nucleons
(j_z= +3/2, +1/2, -1/2, -3/2)

i) 1 nucleon

 $p_{3/2}$

$I^{\pi} = 3/2^{-}$

(there are 4 ways to occupy this level)

 $p_{3/2}$

can accommodate 4 nucleons
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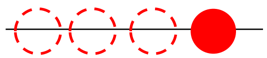
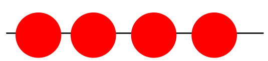
i) 1 nucleon

 $p_{3/2}$

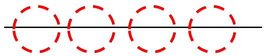
$I^{\pi} = 3/2^{-}$

(there are 4 ways to occupy this level)

ii) 4 nucleons

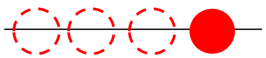
 $p_{3/2}$

$$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2 + \boldsymbol{j}_3 + \boldsymbol{j}_4$$

 $p_{3/2}$ can accommodate 4 nucleons

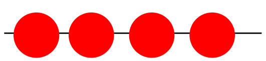
($j_z = +3/2, +1/2, -1/2, -3/2$)

i) 1 nucleon

 $p_{3/2}$ → $I^\pi = 3/2^-$

(there are 4 ways to occupy this level)

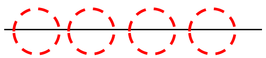
ii) 4 nucleons

 $p_{3/2}$ → $I^\pi = 0^+$

$$I = j_1 + j_2 + j_3 + j_4$$

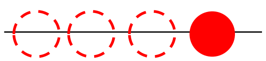
(there is only 1 way to occupy this level)

parity: (-1) x (-1) x (-1) x (-1) = +1

 $p_{3/2}$ can accommodate 4 nucleons

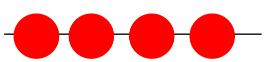
(j_z= +3/2, +1/2, -1/2, -3/2)

i) 1 nucleon

 $p_{3/2}$ $\Longrightarrow$ $I^\pi = 3/2^-$

(there are 4 ways to occupy this level)

ii) 4 nucleons

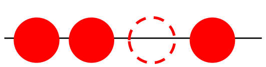
 $p_{3/2}$ $\Longrightarrow$ $I^\pi = 0^+$

(there is only 1 way to occupy this level)

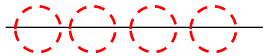
$$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2 + \boldsymbol{j}_3 + \boldsymbol{j}_4$$

parity: (-1) x (-1) x (-1) x (-1) = +1

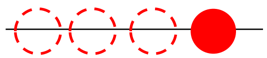
iii) 3 nucleons

 $p_{3/2}$

$$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2 + \boldsymbol{j}_3$$

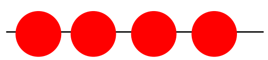
 $p_{3/2}$ can accommodate 4 nucleons
(j_z= +3/2, +1/2, -1/2, -3/2)

i) 1 nucleon

 $p_{3/2}$ → $I^{\pi} = 3/2^{-}$

(there are 4 ways to occupy this level)

ii) 4 nucleons

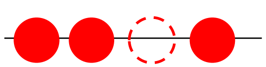
 $p_{3/2}$ → $I^{\pi} = 0^{+}$

$$I = j_1 + j_2 + j_3 + j_4$$

(there is only 1 way to occupy this level)

parity: (-1) x (-1) x (-1) x (-1) = +1

iii) 3 nucleons

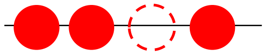
 $p_{3/2}$ → $I^{\pi} = 3/2^{-}$

$$I = j_1 + j_2 + j_3$$

(there are 4 ways to make a hole)

parity: (-1) x (-1) x (-1) = -1

iii) 3 nucleons



$p_{3/2}$

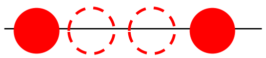
$I^{\pi} = 3/2^{-}$

$$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2 + \boldsymbol{j}_3$$

(there are 4 ways to make a hole)

parity: (-1) x (-1) x (-1) = -1

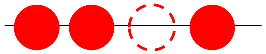
iv) 2 nucleons



$p_{3/2}$

$$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2$$

iii) 3 nucleons



$p_{3/2}$

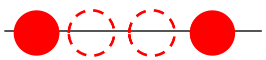
$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2 + \boldsymbol{j}_3$

$I^{\pi} = 3/2^{-}$

(there are 4 ways to make a hole)

parity: (-1) x (-1) x (-1) = -1

iv) 2 nucleons



$p_{3/2}$

$\boldsymbol{I} = \boldsymbol{j}_1 + \boldsymbol{j}_2$

there are 4 x 3/2=6 ways to occupy this level with 2 nucleons.

$I^{\pi} = 0^{+}$ or 2^{+} (= 1+5)

$3/2 + 3/2 \longrightarrow I = 0, \cancel{1}, 2, \cancel{3}$

anti-symmetrization

レポート問題4 : KULMSから提出、提出〆切 7/28（火）23:59

角運動量 j を持つ軌道（j は半整数）にフェルミオン2つを生成する以下の演算子を考える。

$$[a_j^\dagger a_j^\dagger]^{(JM)} = \sum_{m,m'} \langle jmjm'|JM\rangle \, a_{jm}^\dagger a_{jm'}^\dagger$$

ここで、J は2粒子系の全角運動量、M はその z 成分である。

フェルミオン演算子の反交換関係

$$\{a_{jm}^\dagger, a_{jm'}^\dagger\} = 0$$

及び Clebsch-Gordan 係数の性質

$$\langle jmjm'|JM\rangle = (-1)^{j+j-J}\langle jm'jm|JM\rangle$$

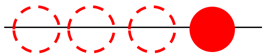
を用いて、角運動量 J は偶数の値しかとらないことを示せ。

レポート問題5: KULMSから提出、提出〆切　7/28（火）23:59

前問で、角運動量 j が整数のボゾンの場合、全角運動量 J がどのような値を取るか議論せよ。

$$[a_j^\dagger a_j^\dagger]^{(JM)} = \sum_{m,m'} \langle jmjm'|JM\rangle \, a_{jm}^\dagger a_{jm'}^\dagger$$

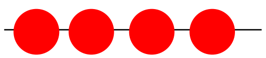
i) 1 nucleon



$p_{3/2}$ $\Rightarrow$ $I^\pi = 3/2^-$

(there are 4 ways to occupy this level)

ii) 4 nucleons



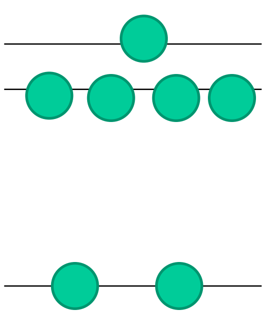
$p_{3/2}$ $\Rightarrow$ $I^\pi = 0^+$

(there is only 1 way to occupy this level)

$$I = j_1 + j_2 + j_3 + j_4$$

parity: (-1) x (-1) x (-1) x (-1) = +1

$\Downarrow$



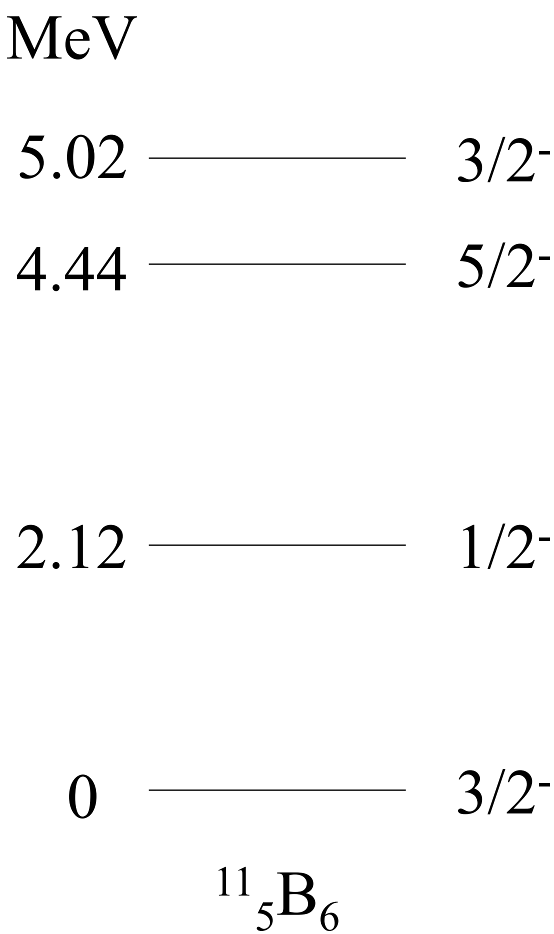
$1p_{1/2}$ $\rightarrow$ $I^\pi = 1/2^-$

$1p_{3/2}$ $\rightarrow$ $I^\pi = 0^+$

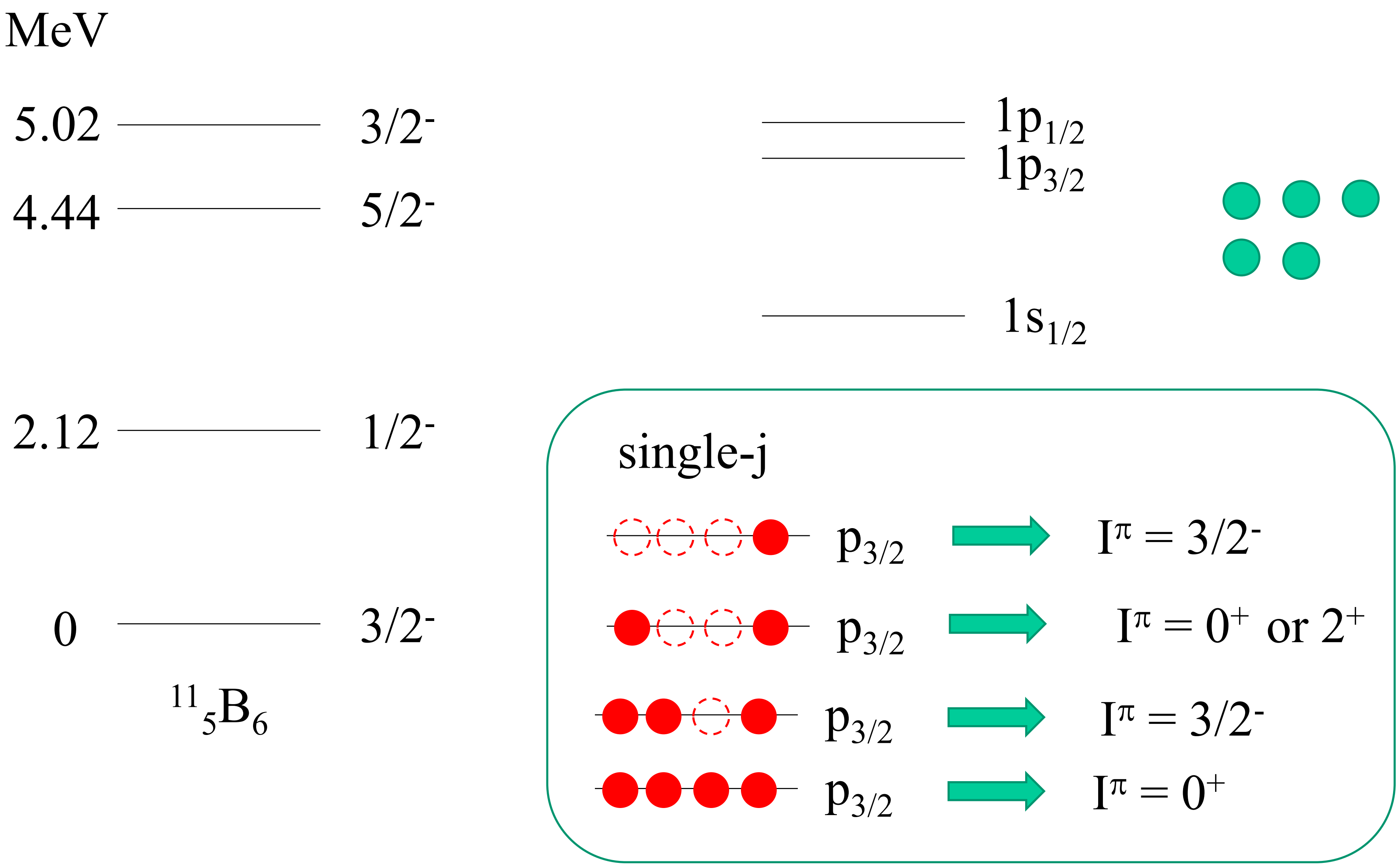
$1s_{1/2}$ $\rightarrow$ $I^\pi = 0^+$

in total,
$I^\pi = 1/2^-$

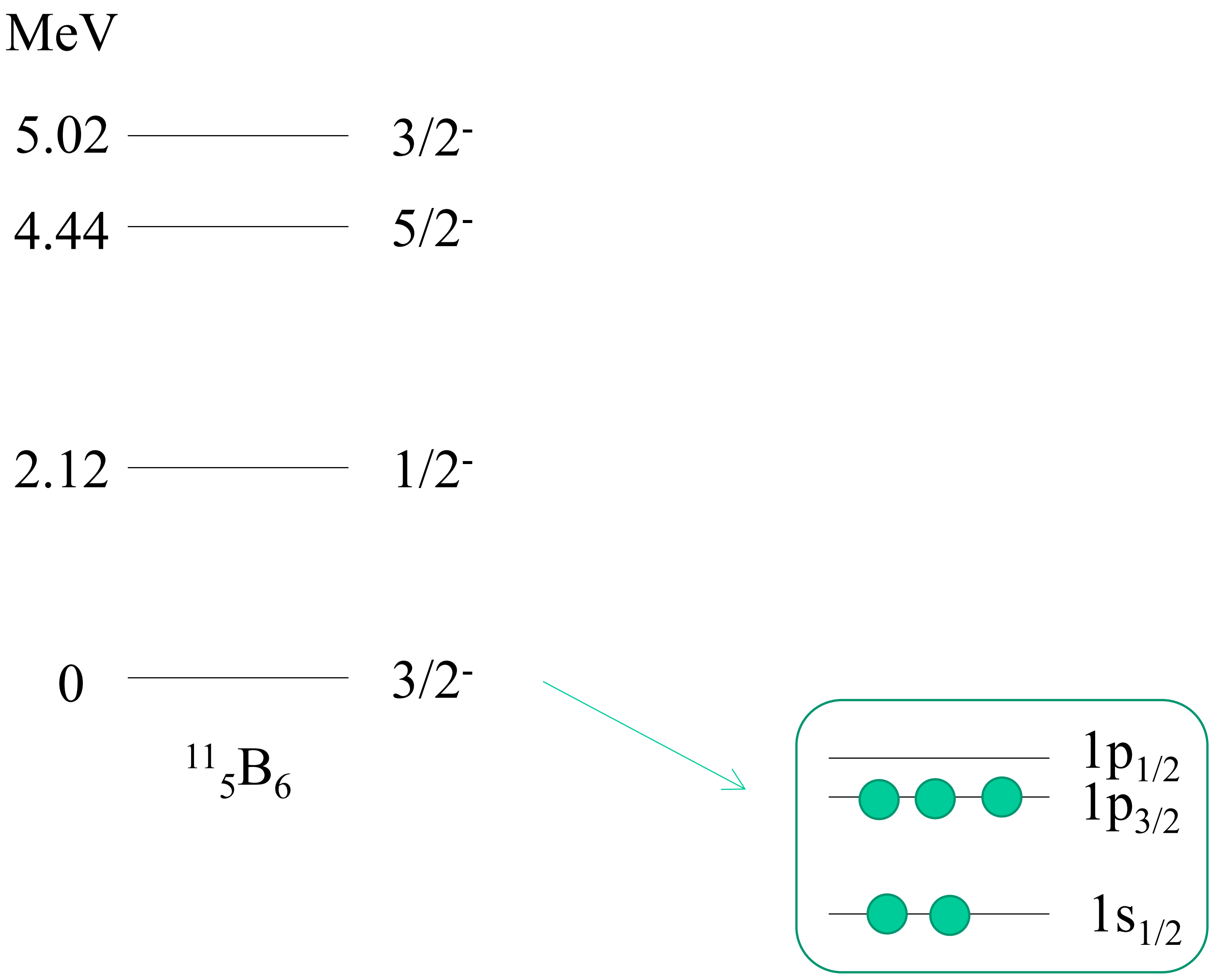
example: (main) shell model configurations for $^{11}_{5}B_6$



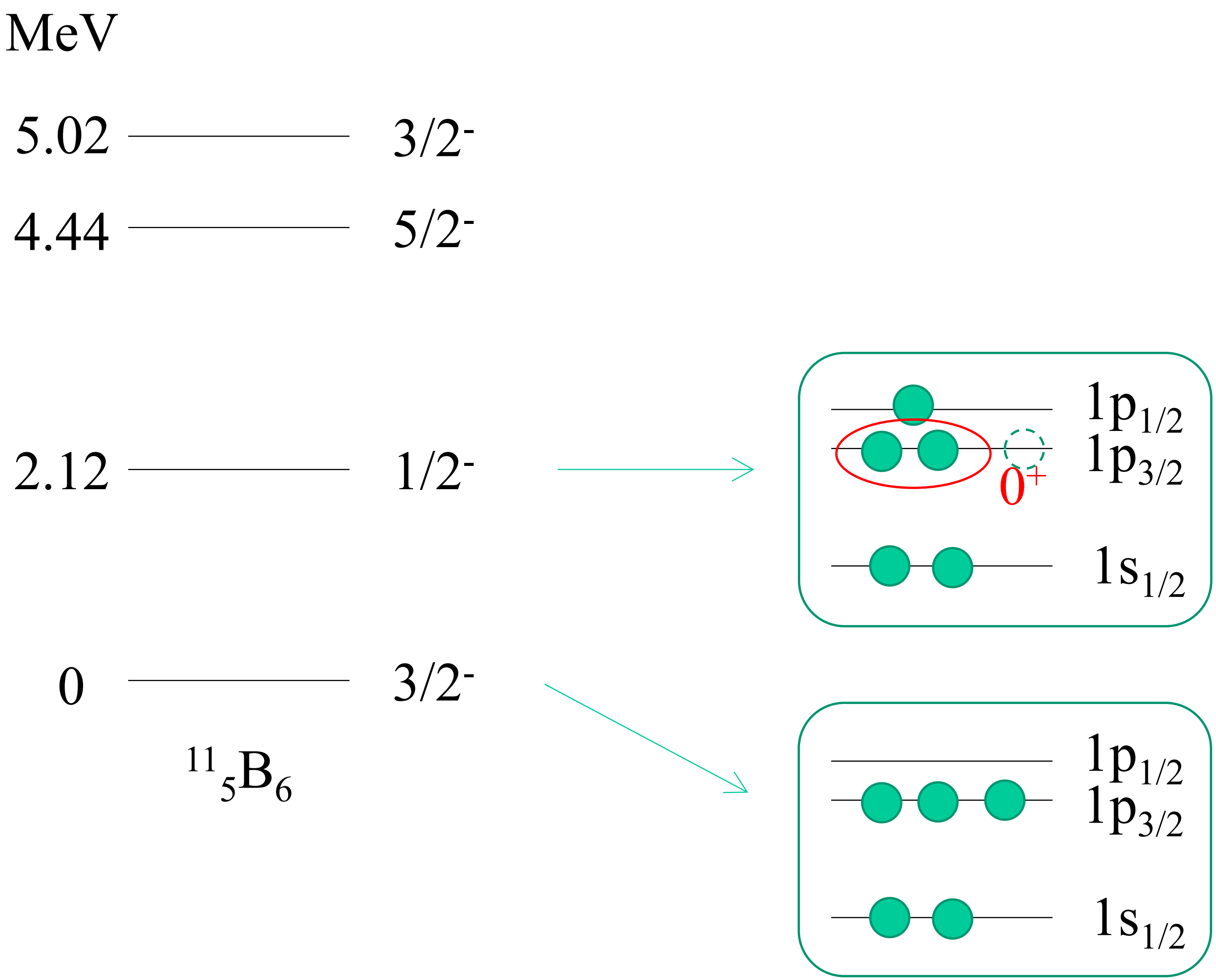
example: (main) shell model configurations for $^{11}_{5}B_{6}$



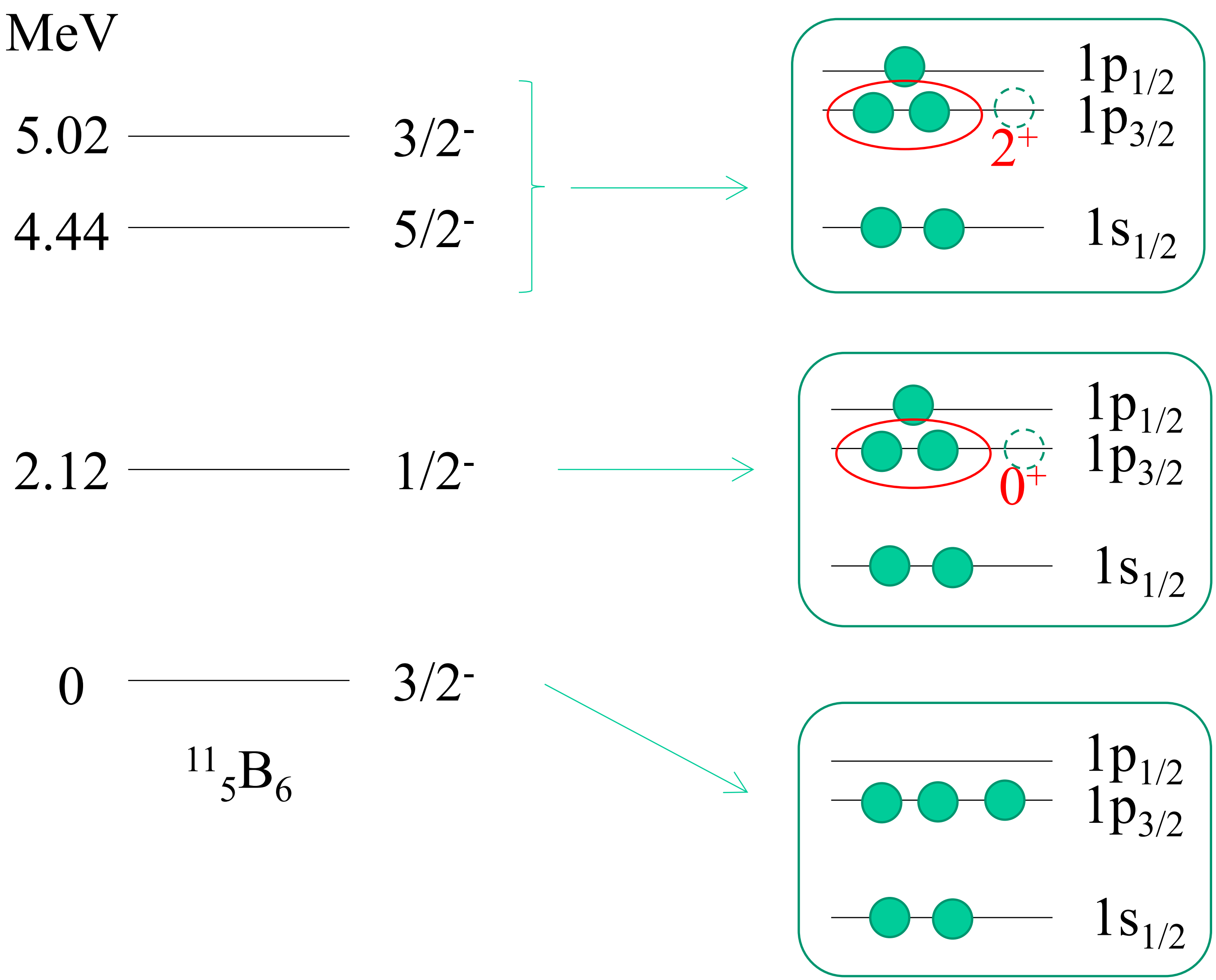
example: (main) shell model configurations for ${}^{11}_{5}B_6$



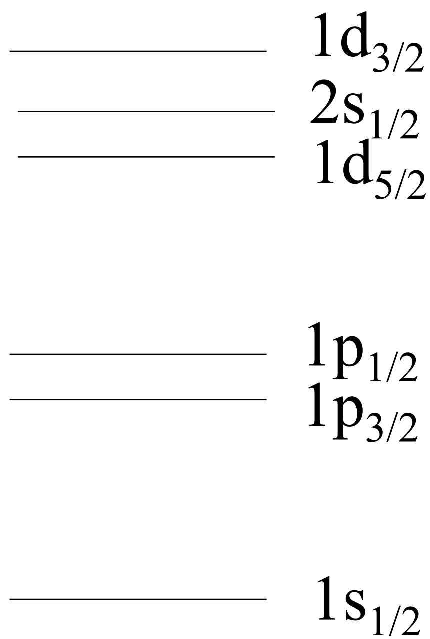
example: (main) shell model configurations for $^{11}{}_{5}B_{6}$

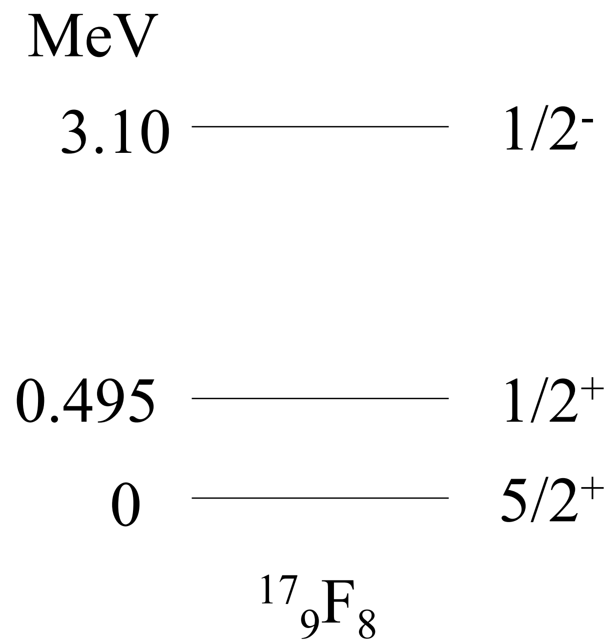


example: (main) shell model configurations for $^{11}_{5}B_6$



レポート問題6：$^{17}{}_{9}F_{8}$の基底状態の陽子の配位を殻模型を使って説明せよ。第一励起状態、第二励起状態はどうなるか？



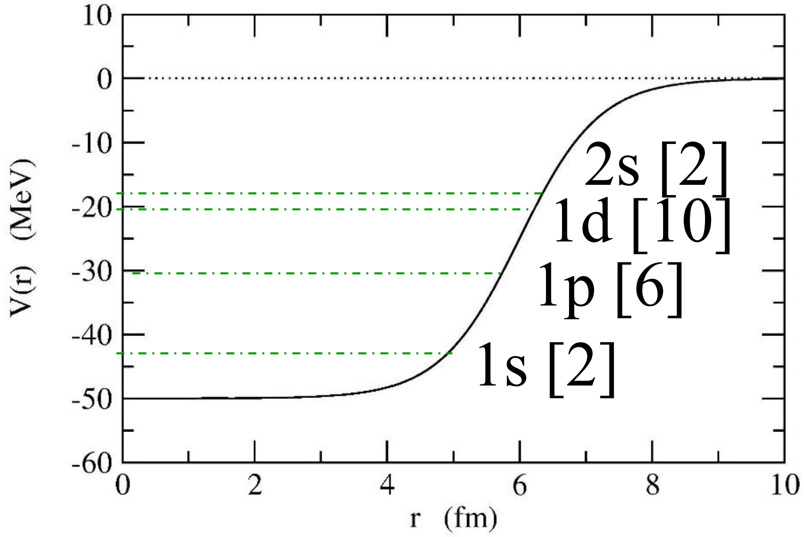


1粒子状態
ここに9つの陽子をつめる
（中性子は偶数なので考えなくてよい）

$^{17}{}_{9}F_{8}$のスペクトル

Extra binding for N or Z = 2, 8, 20, 28, 50, 82, 126 (magic numbers)

An interpretation: independent particle motion *in a potential well*

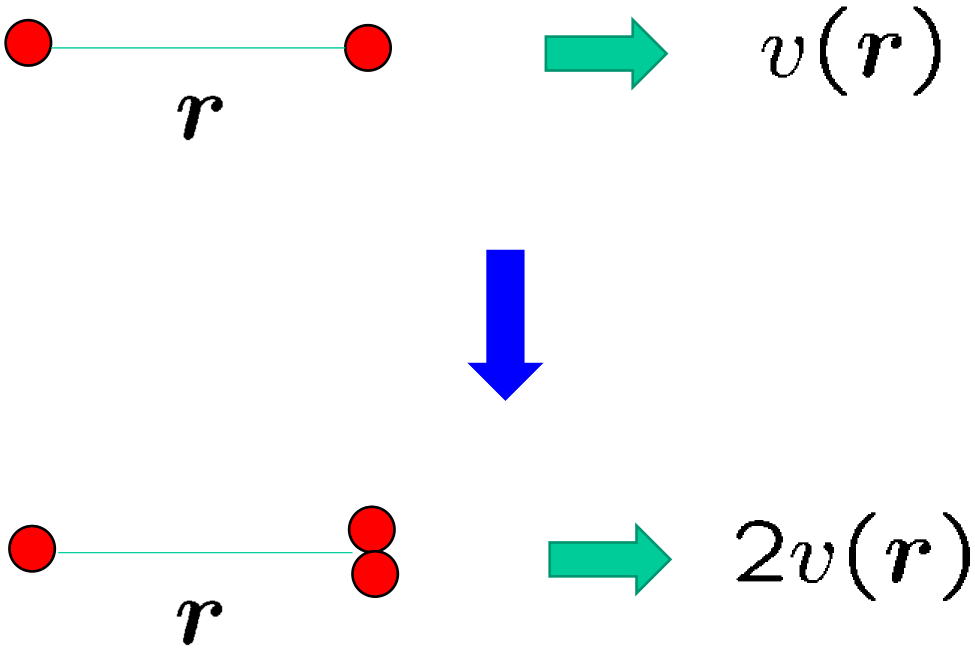


+ spin-orbit interaction

how to construct the potential well?

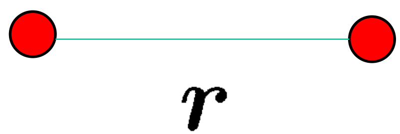
Mean-field (Hartree-Fock) Theory

nucleon-nucleon interaction



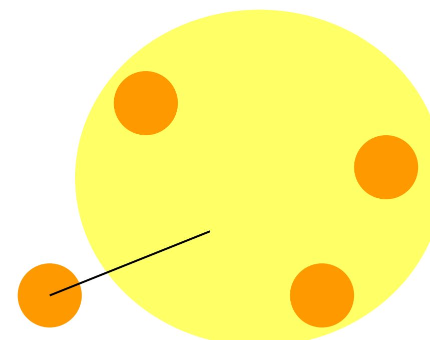
Mean-field (Hartree-Fock) Theory

nucleon-nucleon interaction



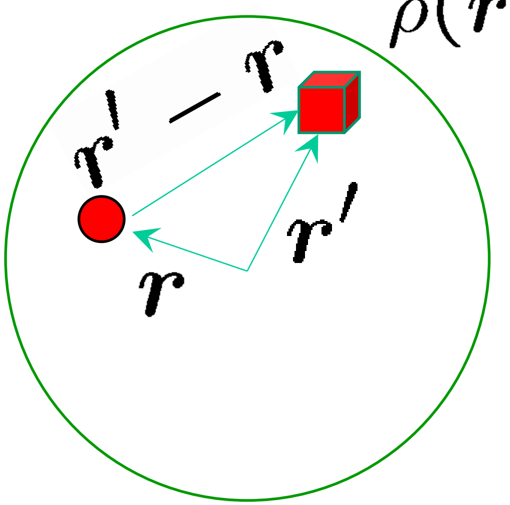
$$\Rightarrow \quad v(\boldsymbol{r})$$

平均場



interaction for a nucleon inside a nucleus:

$\rho(\boldsymbol{r}')d\boldsymbol{r}'$

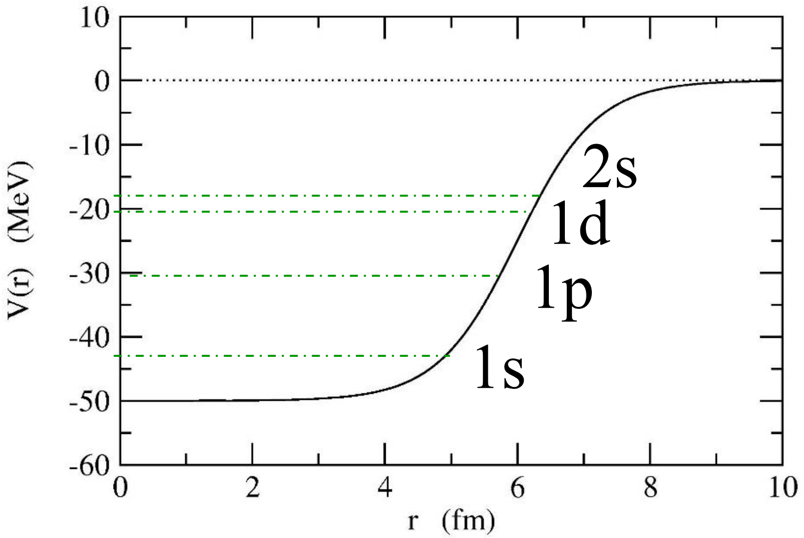


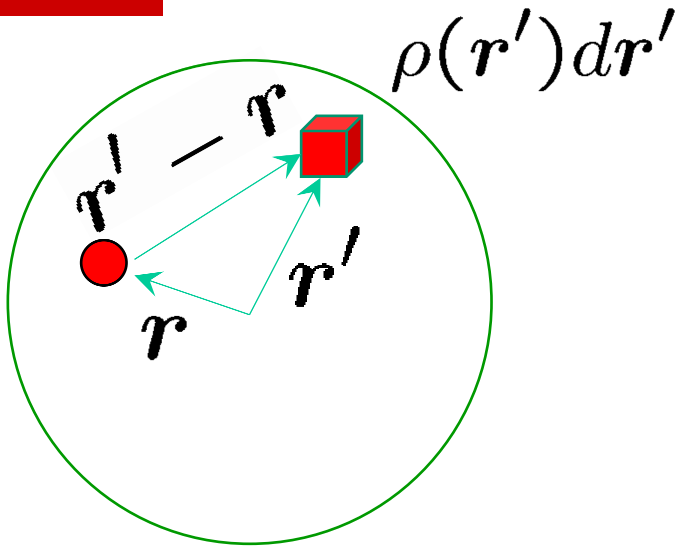
$$\Rightarrow \quad v(\boldsymbol{r}'-\boldsymbol{r})\cdot\underline{\rho(\boldsymbol{r}')d\boldsymbol{r}'}$$

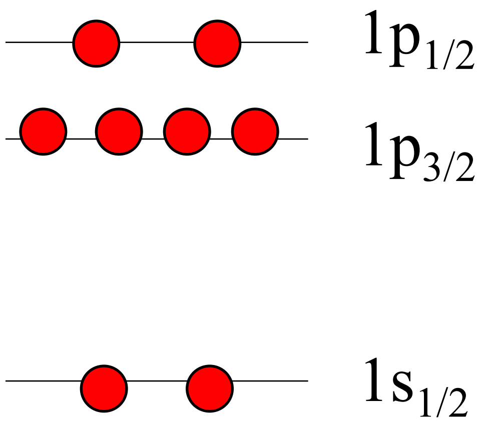
the number of nucleon at *r*'

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

Mean-field (Hartree-Fock) Theory





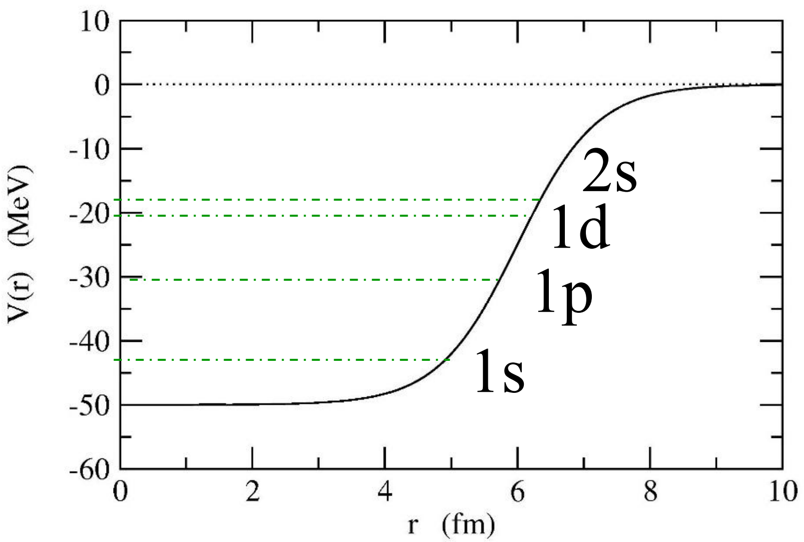


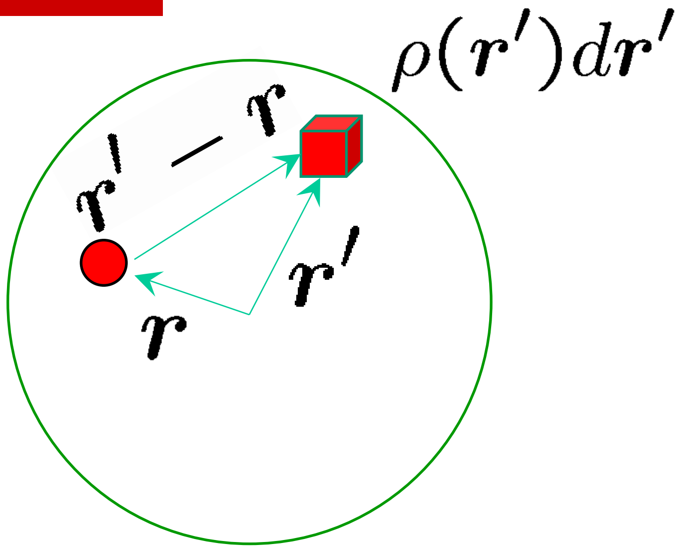
shell model

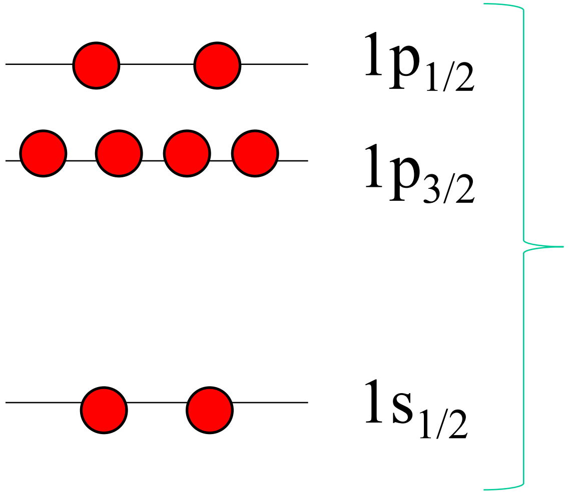
naively speaking,

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

Mean-field (Hartree-Fock) Theory







shell model

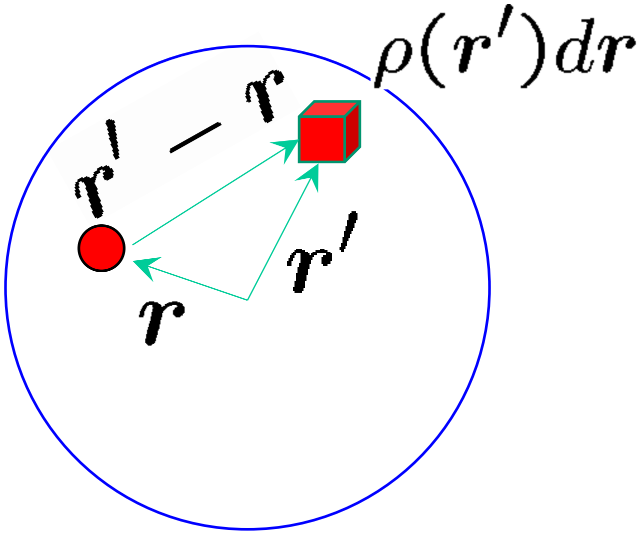
naively speaking,

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

independent motion

$$\rho(\boldsymbol{r}) = \sum_i |\psi_i(\boldsymbol{r})|^2$$

Mean-field (Hartree-Fock) Theory



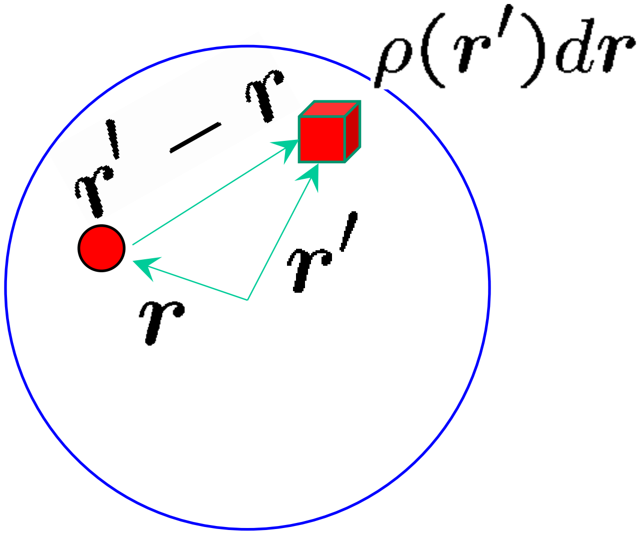
naively speaking,

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

$$\rho(\boldsymbol{r}) = \sum_i |\psi_i(\boldsymbol{r})|^2$$

$$0 = \left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + V(\boldsymbol{r}) - \epsilon_i\right]\psi_i(\boldsymbol{r})$$

Mean-field (Hartree-Fock) Theory



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the potential depends on the solutions

Mean-field (Hartree-Fock) Theory

$$0 = \left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + \int v(\boldsymbol{r} - \boldsymbol{r}') \left(\sum_j |\psi_j(\boldsymbol{r}')|^2 \right) d\boldsymbol{r}' - \epsilon_i \right] \psi_i(\boldsymbol{r})$$

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$\longrightarrow$ self-consistent solutions

Iteration: $\{\psi_i\} \to \rho \to V \to \{\psi_i\} \to \cdots$

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$$\rho(\boldsymbol{r}) = \sum_i |\psi_i(\boldsymbol{r})|^2, \quad V(\boldsymbol{r}) \sim \int v(\boldsymbol{r}-\boldsymbol{r}')\rho(\boldsymbol{r}')d\boldsymbol{r}'$$

repeat until the first and the last wave functions are the same.

"self-consistent solutions" 自己無撞着(むどうちゃく)解

Variational Principle (Rayleigh-Ritz method)

optimization $\longleftrightarrow$ variational principle

$$\boxed{\frac{\langle \Psi | H | \Psi \rangle}{\langle \Psi | \Psi \rangle} \geq E_{\mathsf{g.s.}}}$$

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H : many-body Hamiltonian

$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, \cdots) = \psi_1(\boldsymbol{r}_1)\cdot\psi_2(\boldsymbol{r}_2)\cdot\psi_3(\boldsymbol{r}_3)\cdots$$

$\longleftarrow$ many-body wave function for independent particles

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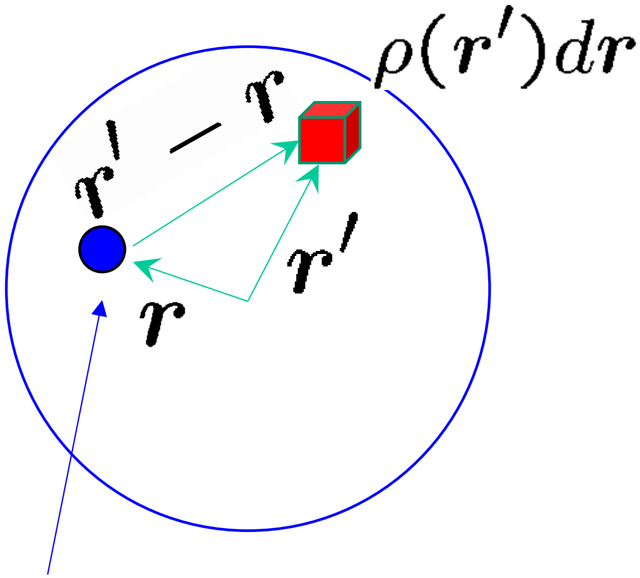
$$\left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + \int v(\boldsymbol{r}-\boldsymbol{r}')\rho(\boldsymbol{r}')d\boldsymbol{r}' - \epsilon_i\right]\psi_i(\boldsymbol{r}) = 0$$

change gradually the single-particle potential so that the total energy becomes minimum

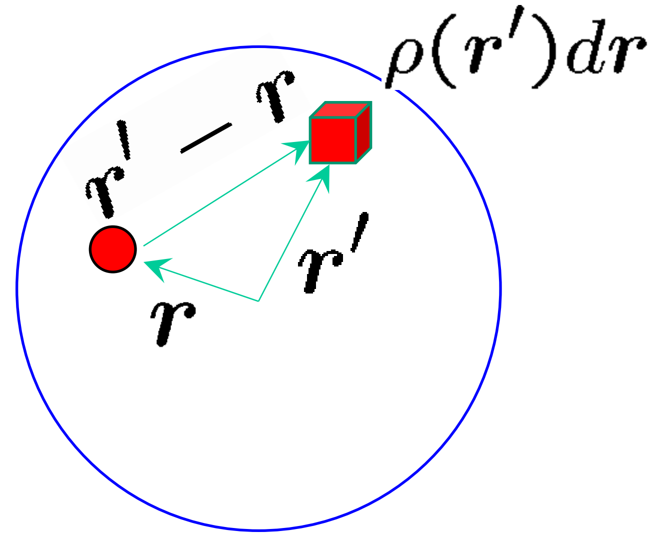
Mean-field (Hartree-Fock) Theory

<u>electro-static potential</u>



test charge

<u>nucleus</u>



interaction between identical particles

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

Mean-field (Hartree-Fock) Theory

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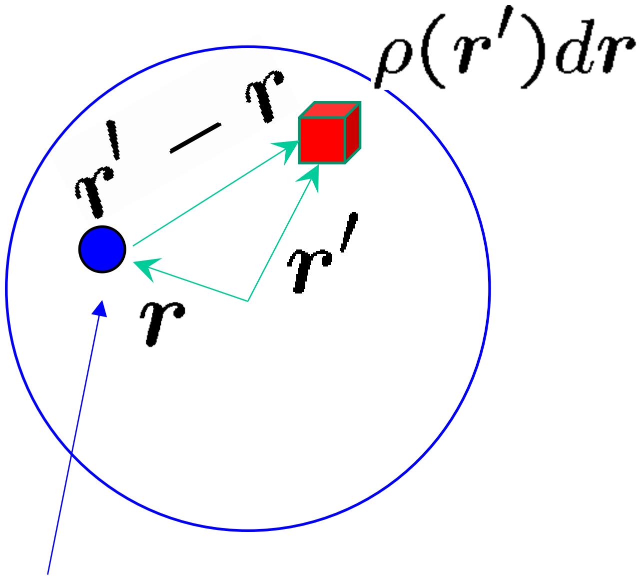

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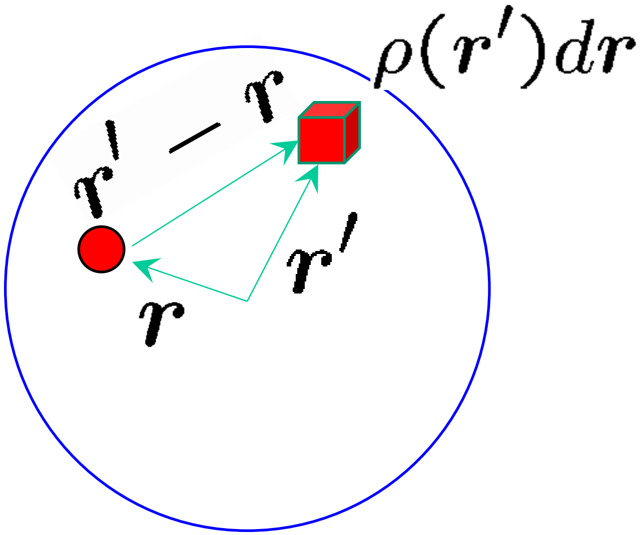

interaction between identical particles
$\longrightarrow$ needs anti-symmetrization

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

anti-symmetrization

nucleon: fermion

$$\Psi(x_1, x_2, x_3 \cdots) = -\Psi(x_2, x_1, x_3 \cdots)$$

$$\psi_1(x_1)\psi_2(x_2) \to \frac{1}{\sqrt{2}}[\psi_1(x_1)\psi_2(x_2) - \psi_2(x_1)\psi_1(x_2)]$$

Slater determinat

$$0 = \left[-\frac{\hbar^2}{2m}\nabla^2 + \int v(\boldsymbol{r} - \boldsymbol{r}')\left(\sum_j |\psi_j(\boldsymbol{r}')|^2\right) d\boldsymbol{r}' - \epsilon_i\right]\psi_i(\boldsymbol{r})$$

$$\psi_j^*(\boldsymbol{r}')\psi_j(\boldsymbol{r}')\psi_i(\boldsymbol{r}) \to \psi_j^*(\boldsymbol{r}')\psi_i(\boldsymbol{r}')\psi_j(\boldsymbol{r})$$

anti-symmetrization

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$$\psi_j^*(\boldsymbol{r}')\psi_j(\boldsymbol{r}')\psi_i(\boldsymbol{r}) \to \psi_j^*(\boldsymbol{r}')\psi_i(\boldsymbol{r}')\psi_j(\boldsymbol{r})$$

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$$-\int v(\boldsymbol{r}-\boldsymbol{r}')\left(\sum_j \psi_j^*(\boldsymbol{r}')\psi_i(\boldsymbol{r}')\right) d\boldsymbol{r}'\psi_j(\boldsymbol{r})$$

exchange term

Hartree-Fock theory

anti-symmetrization

$$
\begin{aligned}
0 &= \left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + \int v(\boldsymbol{r}-\boldsymbol{r}')\left(\sum_j |\psi_j(\boldsymbol{r}')|^2\right) d\boldsymbol{r}' - \epsilon_i\right]\psi_i(\boldsymbol{r}) \\
&\to \left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + \int v(\boldsymbol{r}-\boldsymbol{r}')\left(\sum_j |\psi_j(\boldsymbol{r}')|^2\right) d\boldsymbol{r}' - \epsilon_i\right]\psi_i(\boldsymbol{r}) \\
&\quad - \int v(\boldsymbol{r}-\boldsymbol{r}')\left(\sum_j \psi_j^*(\boldsymbol{r}')\psi_i(\boldsymbol{r}')\right) d\boldsymbol{r}'\psi_j(\boldsymbol{r}) \\
&= \left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + V(\boldsymbol{r}) - \epsilon_i\right]\psi_i(\boldsymbol{r}) + \int d\boldsymbol{r}' V_{\mathrm{NL}}(\boldsymbol{r},\boldsymbol{r}')\psi_i(\boldsymbol{r}')
\end{aligned}
$$

non-local potential

Non-local potentials

$$\boxed{\left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2+V(\boldsymbol{r})-E\right]\psi(\boldsymbol{r})+\int d\boldsymbol{r}'V_{\mathrm{NL}}(\boldsymbol{r},\boldsymbol{r}')\psi(\boldsymbol{r}')=0}$$

- Local equivalent potential

$$\left[-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2+V(\boldsymbol{r})-E\right]\psi(\boldsymbol{r})+\left[\frac{1}{\psi(\boldsymbol{r})}\int d\boldsymbol{r}'V_{\mathrm{NL}}(\boldsymbol{r},\boldsymbol{r}')\psi(\boldsymbol{r}')\right]\psi(\boldsymbol{r})=0$$

E-dep. potential

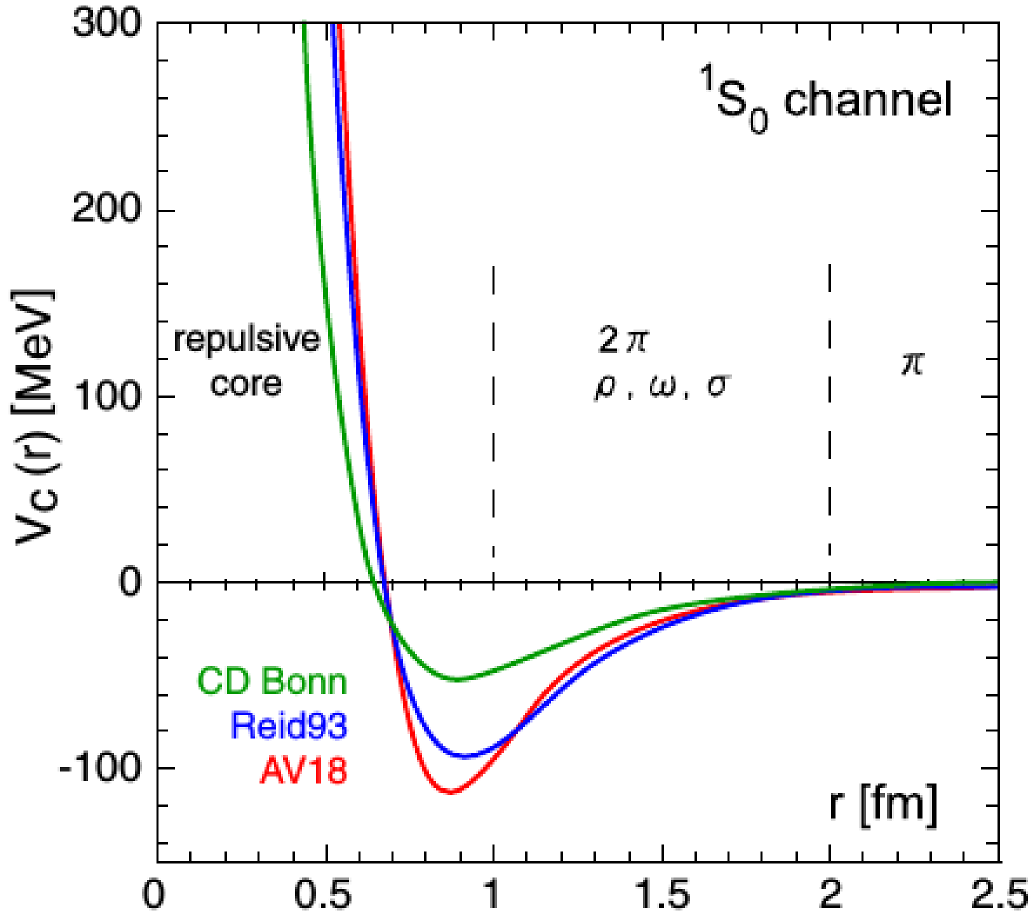
- Wigner 変換

$$V_W(\boldsymbol{r},\boldsymbol{p})=\int V_{\mathrm{NL}}(\boldsymbol{r}-\boldsymbol{s}/2,\boldsymbol{r}+\boldsymbol{s}/2)\,e^{i\boldsymbol{p}\cdot\boldsymbol{s}/\hbar}d\boldsymbol{s}$$

✓ momentum expansion
✓ effective mass approximation

cf. Perrey-Buck 型 $$V_{\mathrm{NL}}(\boldsymbol{r},\boldsymbol{r}')=U\left(\frac{1}{2}|\boldsymbol{r}+\boldsymbol{r}'|\right)\exp\left[-\left(\frac{\boldsymbol{r}-\boldsymbol{r}'}{\beta}\right)^2\right]$$

Bare nucleon-nucleon interaction



N. Ishii, S. Aoki, and T. Hatsuda,
PRL99, 022001 (2007)

Bruckner's G-matrix

Nucleon-nucleon interaction *in medium*

Nucleon-nucleon interaction with a hard core

⇨ HF method: does not work

← Matrix elements: diverge

…..but the HF picture seems to work in nuclear systems

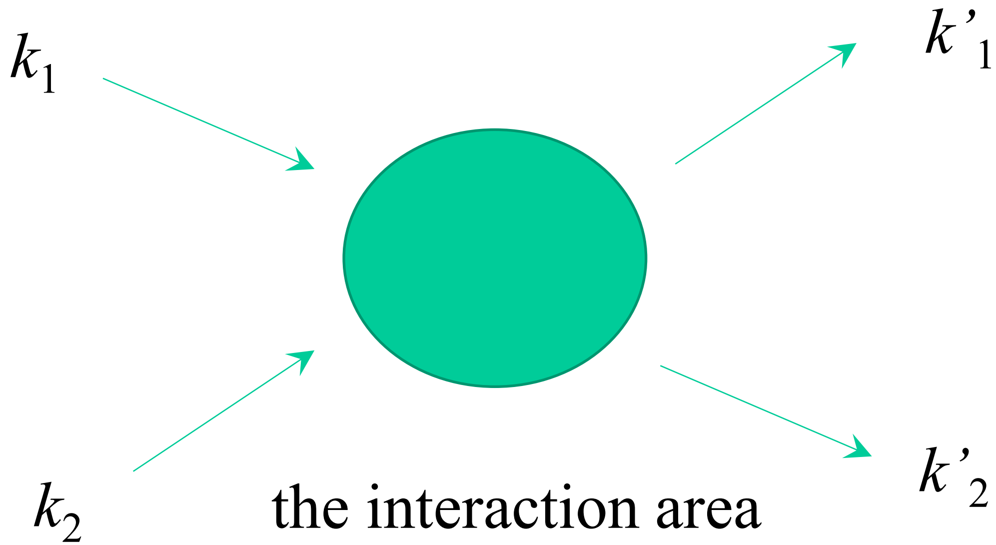
cf. magic numbers

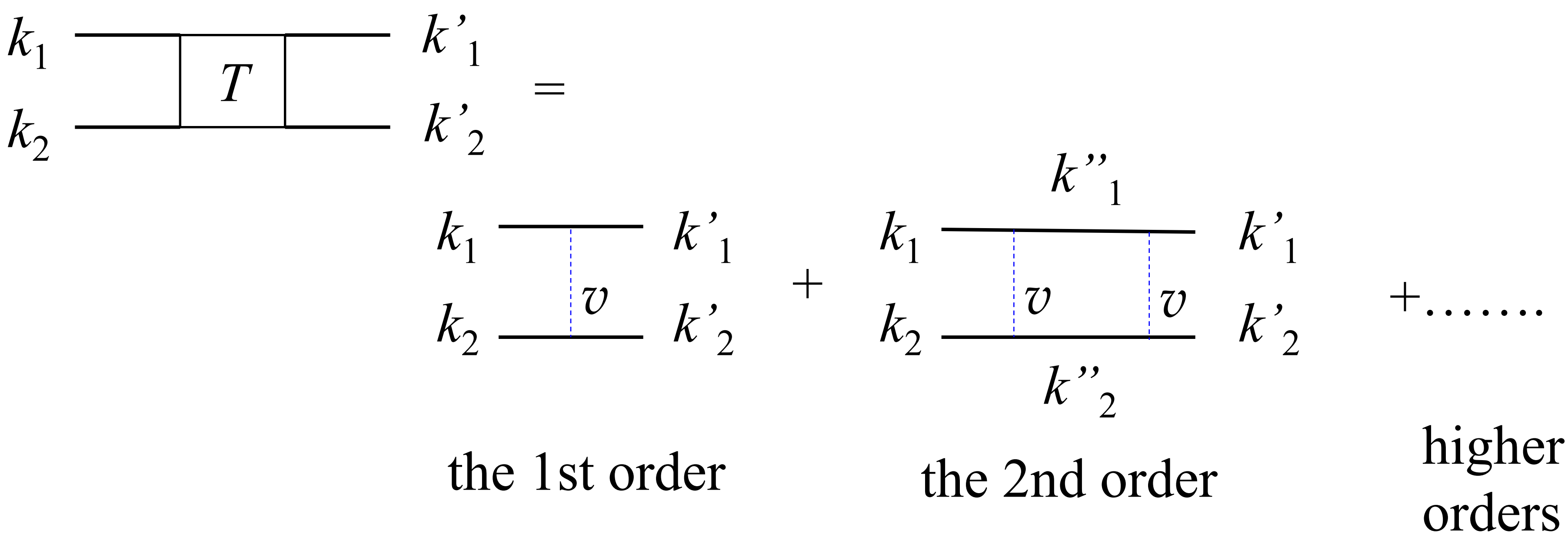
Solution: a nucleon-nucleon interaction *in medium* (effective interaction) rather than a bare interaction

⇧

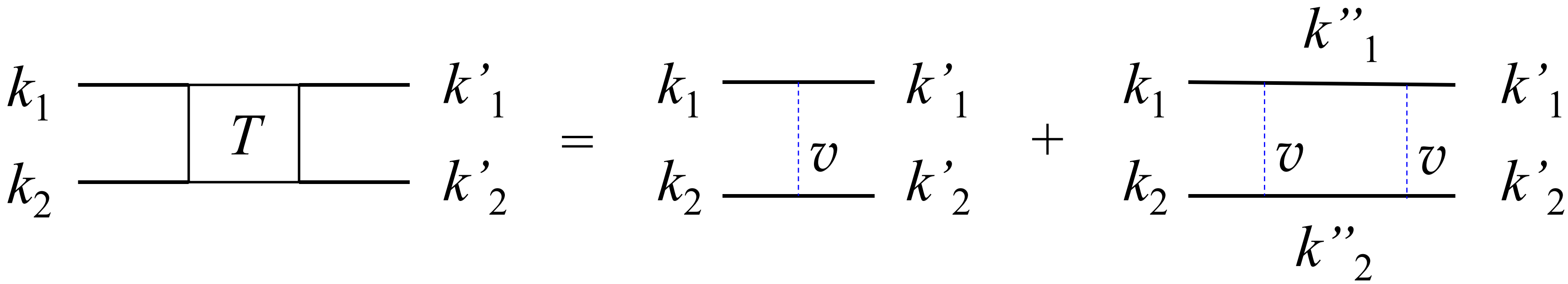
Bruckner's G-matrix

- Firstly, two-body (multiple) scattering *in vacuum*





➢ Firstly, two-body (multiple) scattering *in vacuum*



$$+\ldots\ldots$$

Lippmann-Schwinger equation

$$\boxed{T = v + v\frac{1}{E - H_0}T}$$

$$\left(-\frac{\hbar^2}{2m}\nabla^2 + V - E\right)\psi = 0$$

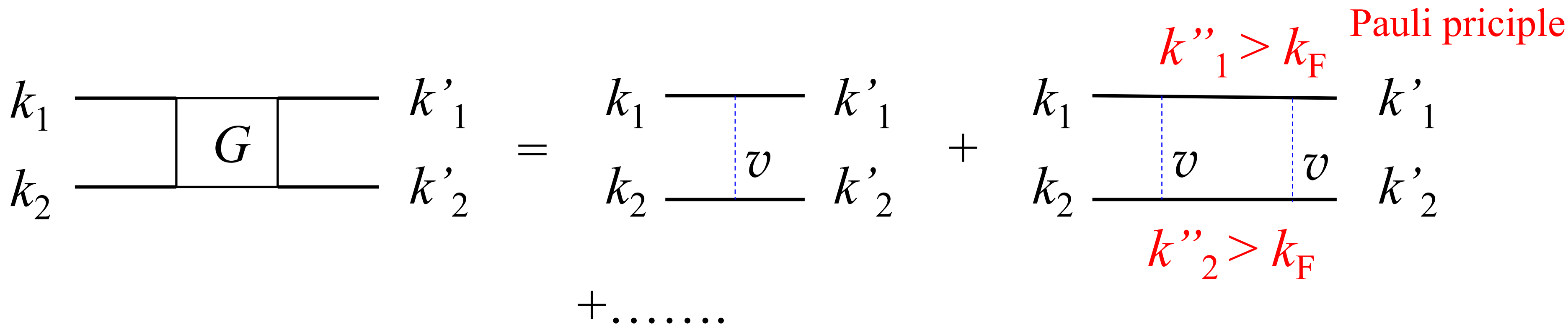
$$\Rightarrow \left(-\frac{\hbar^2}{2m}\nabla^2 - E\right)\psi = -V\psi$$

$$\Rightarrow \psi = \phi - \frac{1}{H_0 - E}V\psi \qquad H_0 = -\frac{\hbar^2}{2m}\nabla^2, \quad (H_0 - E)\phi = 0$$

$$\Rightarrow V\psi = V\phi - V\frac{1}{H_0 - E}V\psi \quad \underset{(V\psi = T\phi)}{\Rightarrow} \quad T = V - V\frac{1}{H_0 - E}T$$

核内における核子間相互作用（媒質効果）

➢ two-body (multiple) scattering *in medium*



Bethe-Goldstone equation

$$G = v + v\frac{Q_F}{E - H_0}G$$

*scattering: suppressed
because intermediate states have to have
$k > k_{\mathrm{F}}$ ⟶ independent particle picture

◆Hard core

$$G = v + v\frac{Q_F}{E - H_0}G \quad \Longleftrightarrow \quad G = \frac{v}{1 - v\,\frac{Q_F}{E-H_0}}$$

Even if v tends to infinity, G may stay finite.

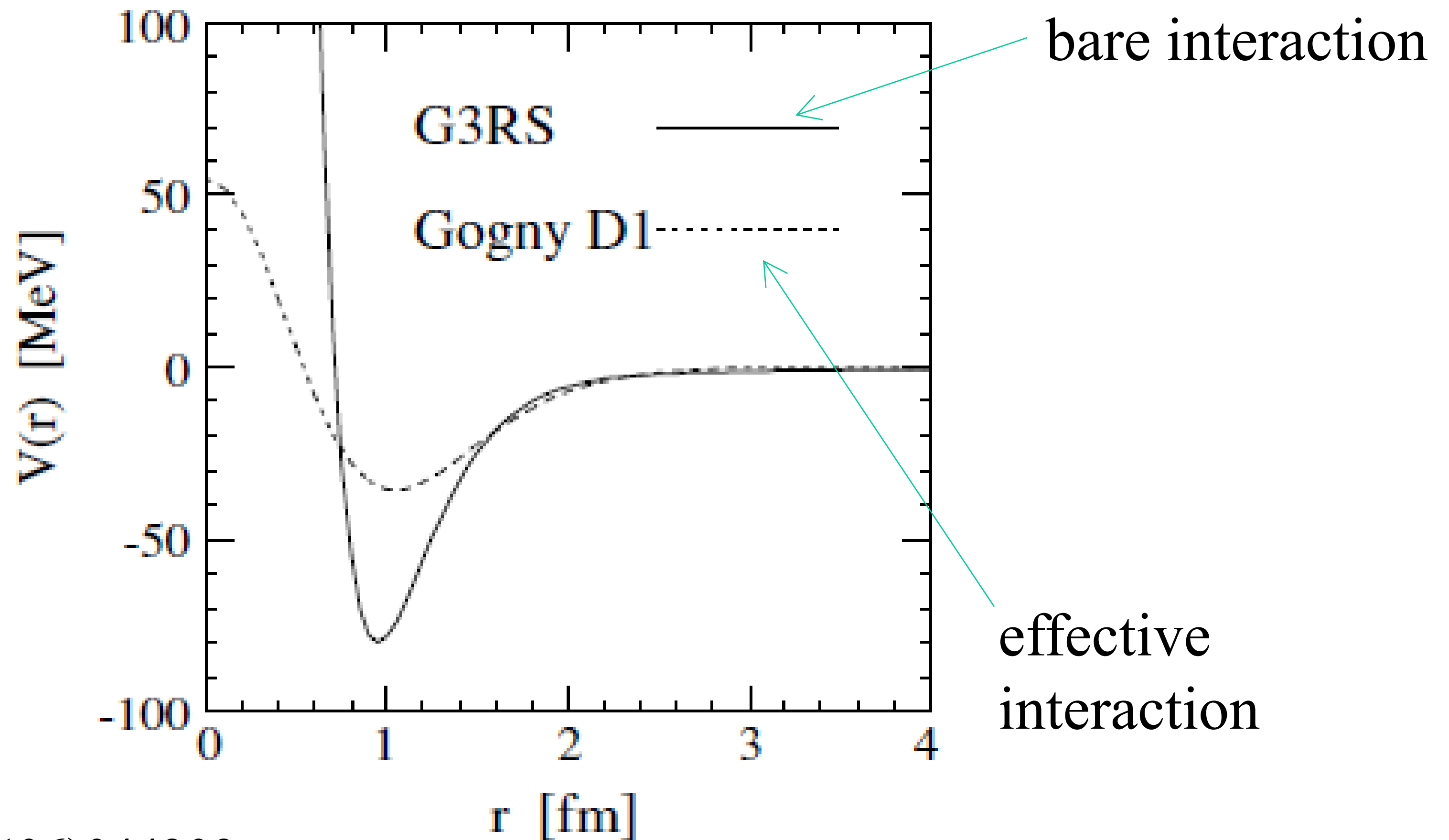


figure from
M. Matsuo,
Phys. Rev. C73('06)044309

◆Hard core

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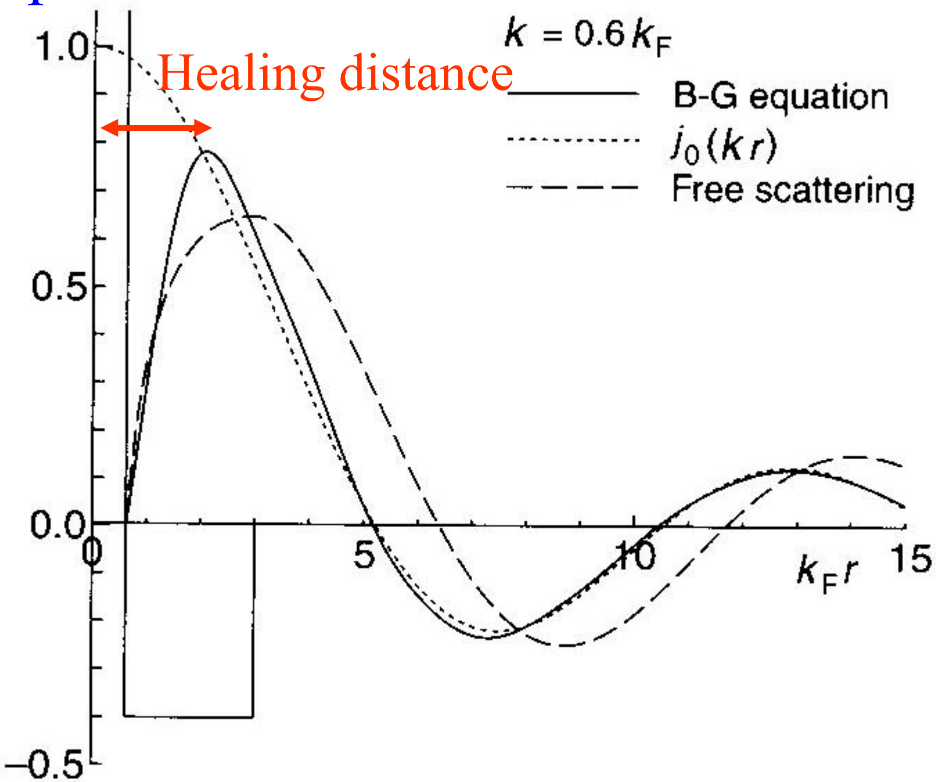
Even if v tends to infinity, G may stay finite.

◆Independent particle motion



→ use G instead of v in mean-field calculations