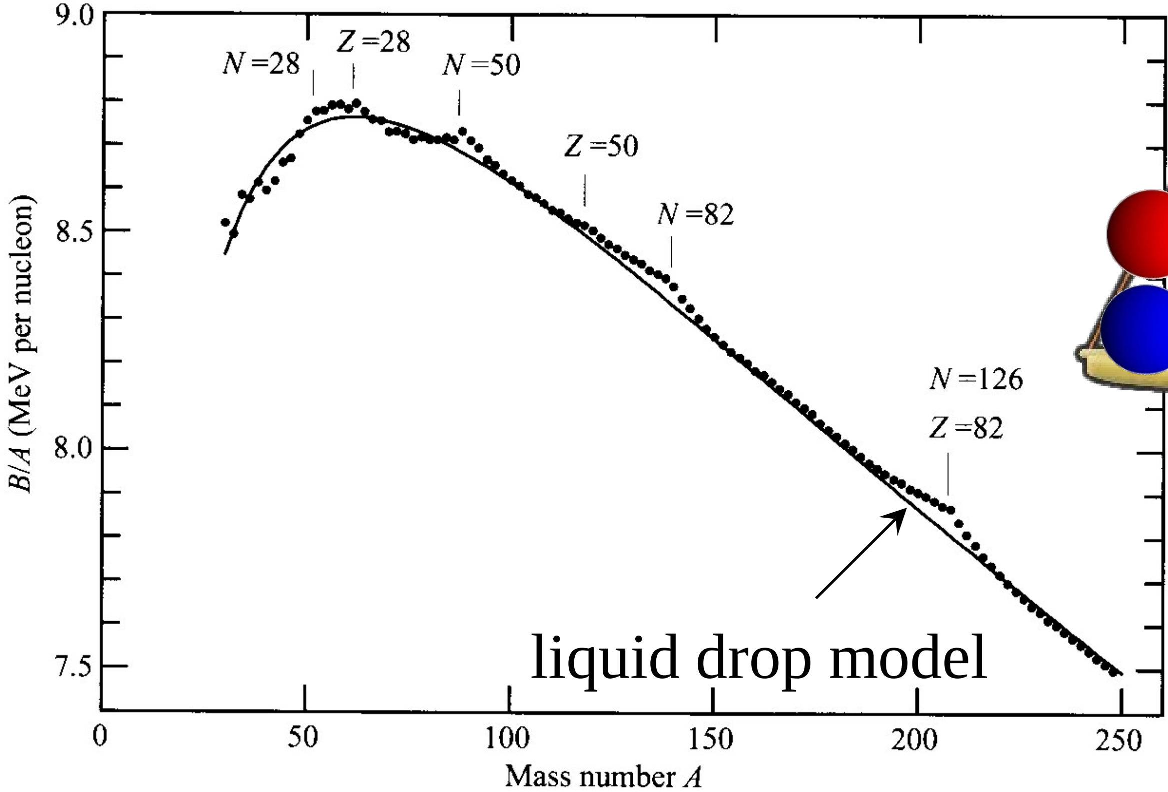
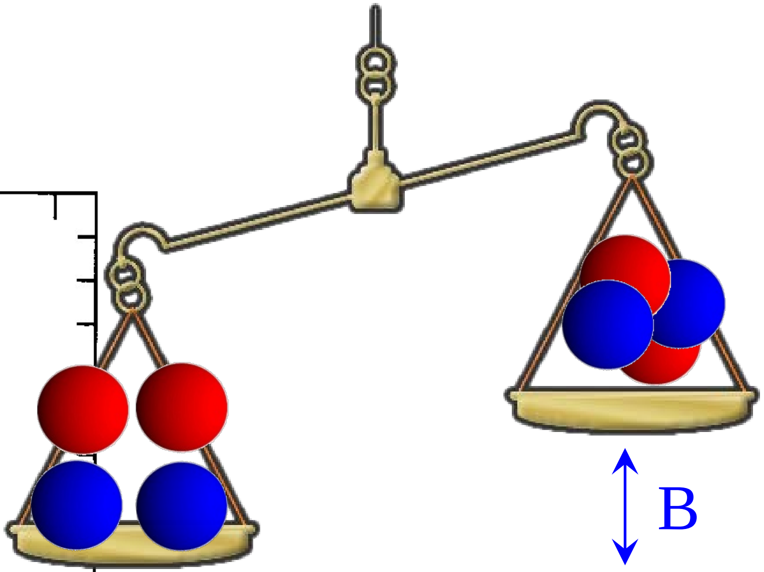
Magic Numbers





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

⇨ Very stable

${}^{4}_{2}He_{2}$, ${}^{16}_{8}O_{8}$, ${}^{40}_{20}Ca_{20}$, ${}^{48}_{20}Ca_{28}$, ${}^{208}_{82}Pb_{126}$

成績のつけかた

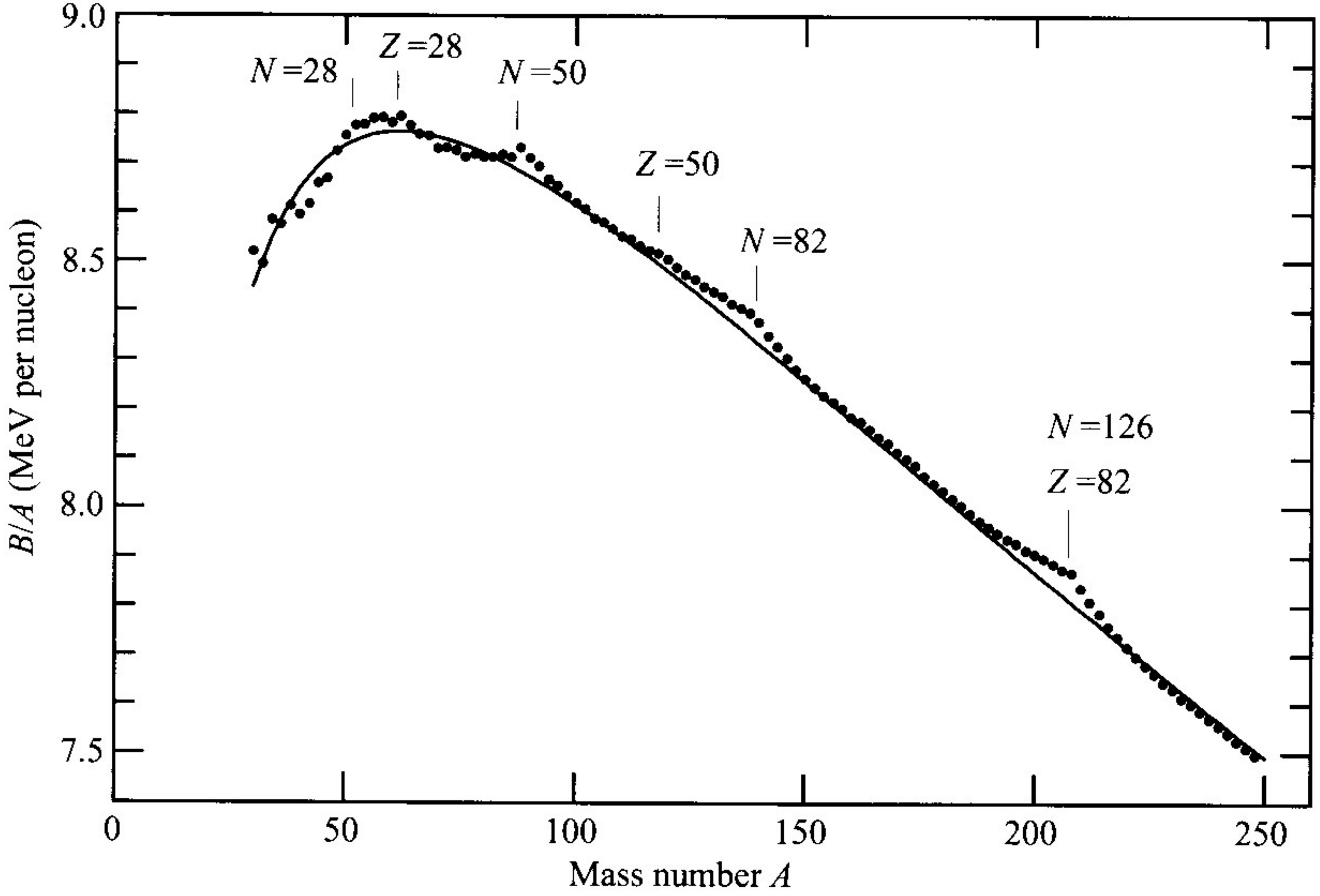
期末レポート（必須）＋出席点

質問をした日は出席点１。
質問を考えながら講義を聴いてください。

成績の基準：レポートが良く書けていて、出席点３以上
（３回以上質問をする） → A

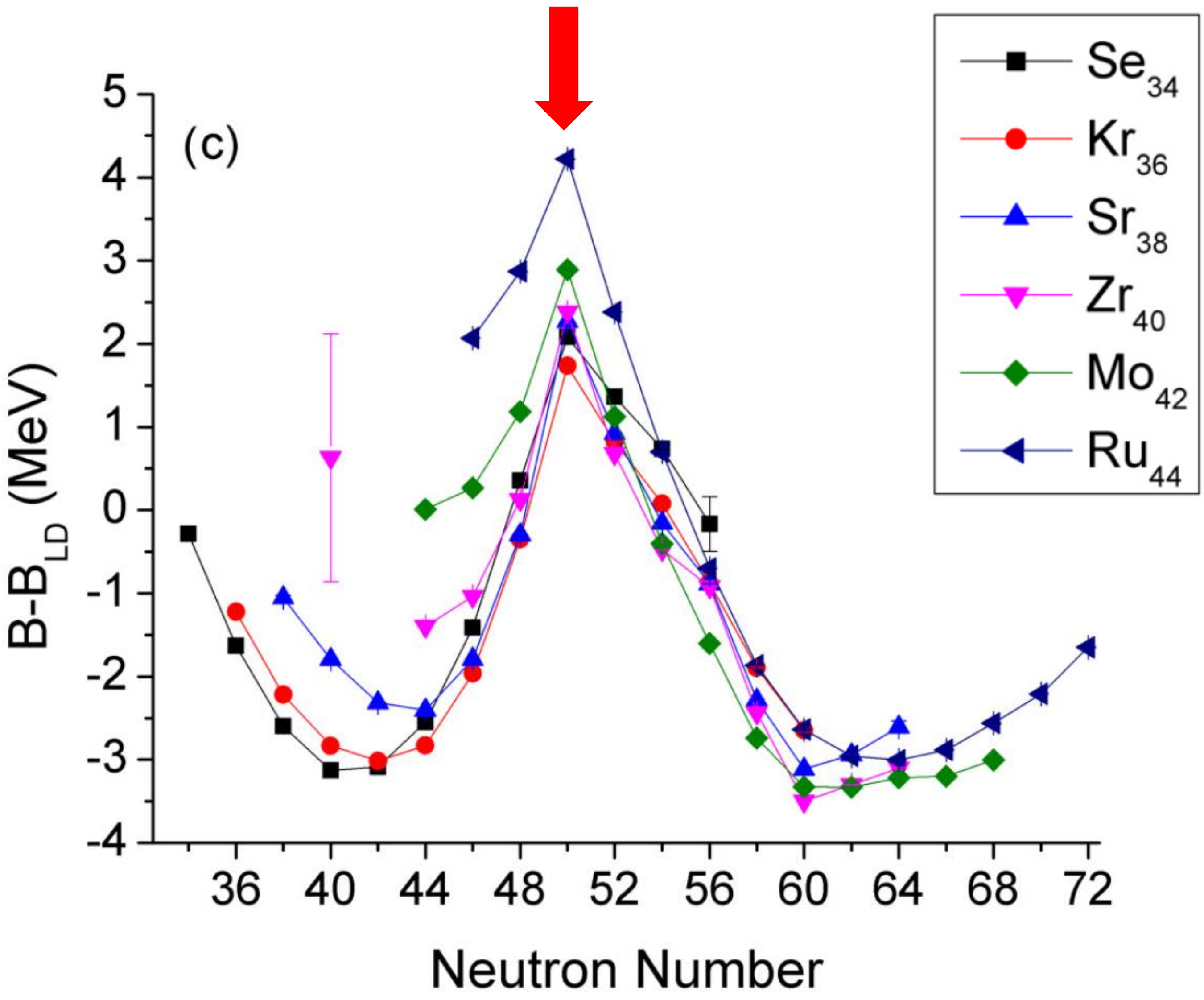
AAが欲しい場合は4回以上質問してください。

Magic Numbers



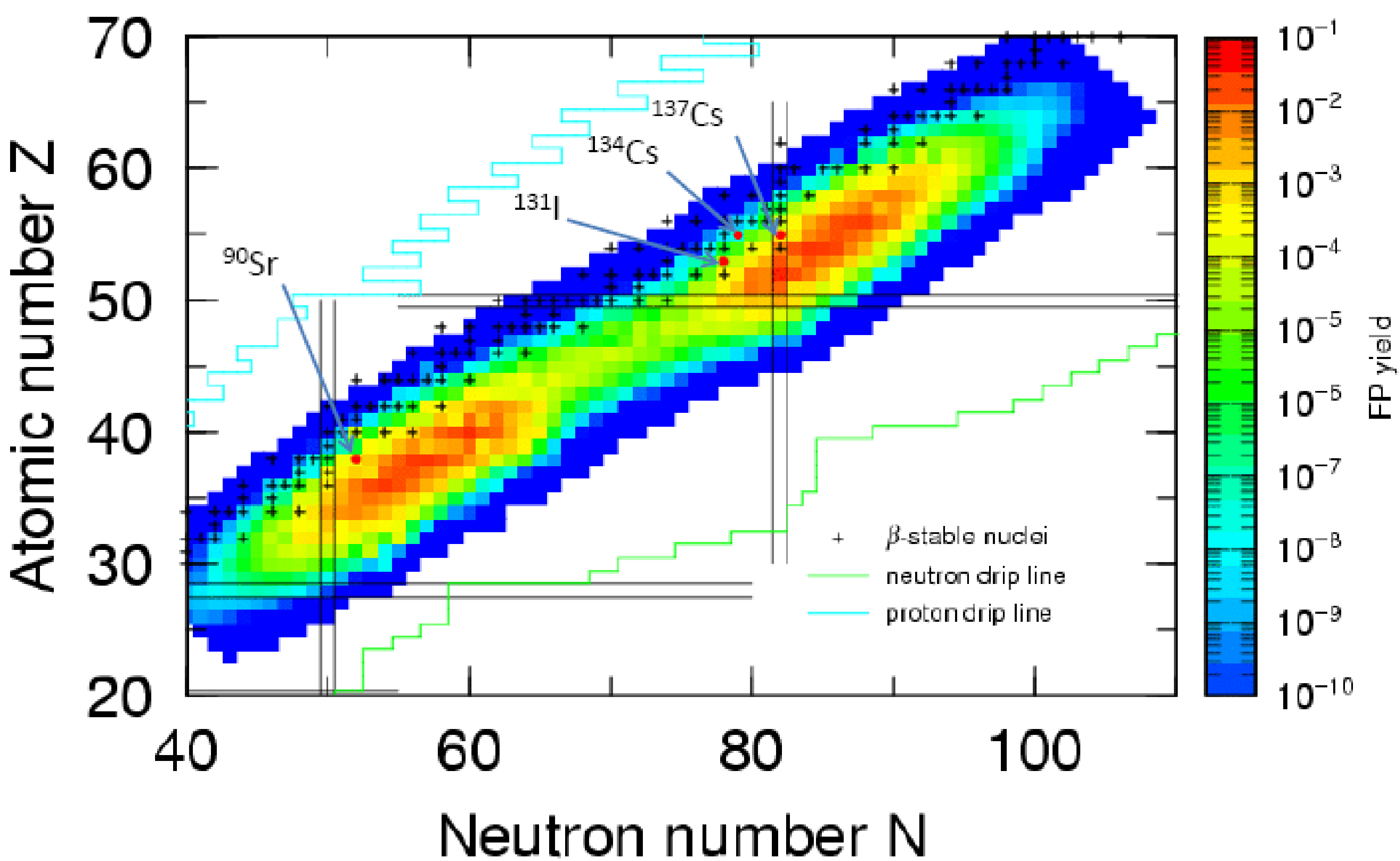
cf. N,Z = 2, 8, 20, 28, 50, 82, 126 (魔法数)に対して束縛エネルギー大

N = 50



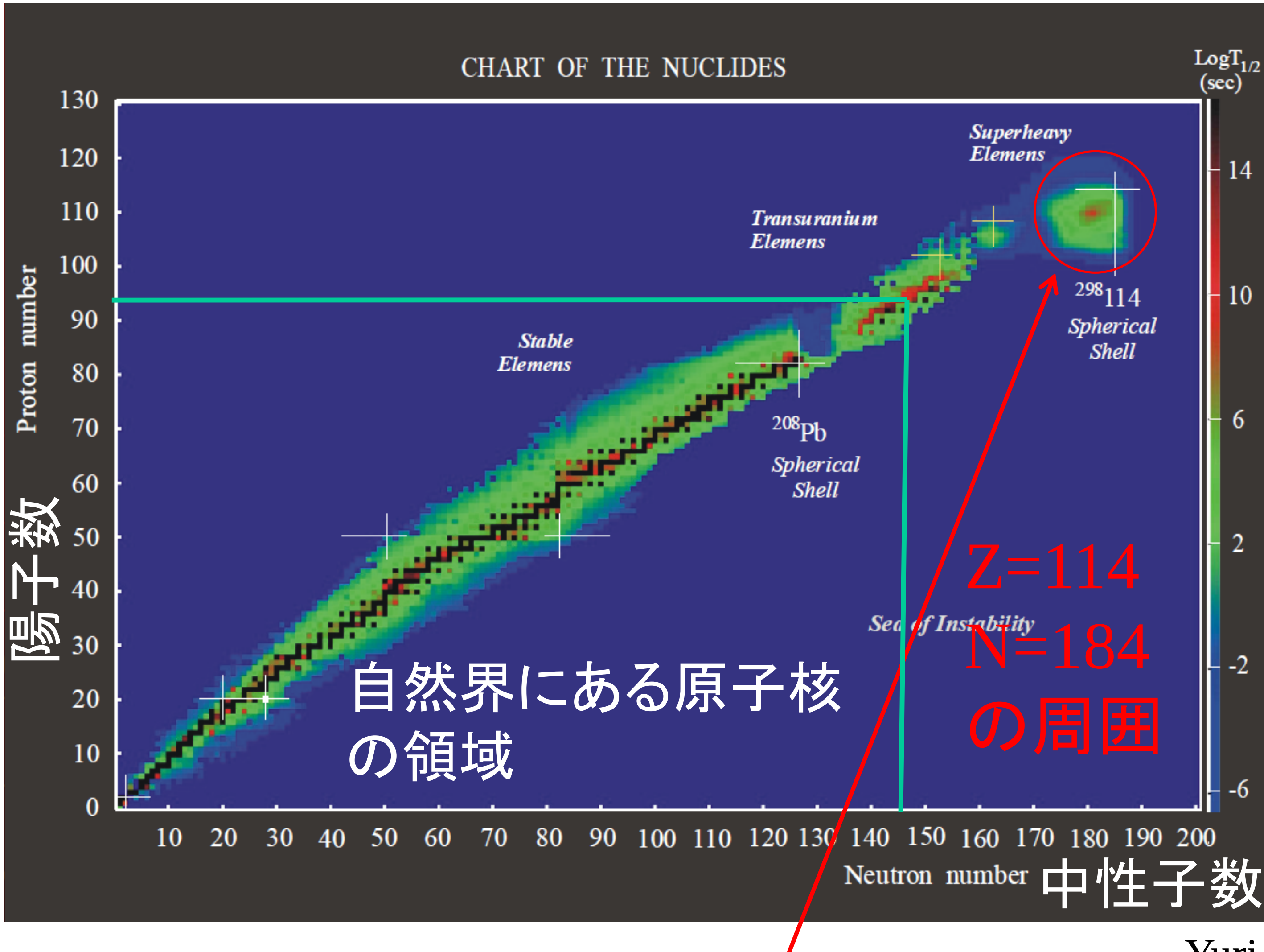
I. Bentley et al., PRC93 (‘16) 044337

Fission fragment mass distribution for n_{th} + ^{235}U reaction



非对称核分裂

超重元素(超重原子核)

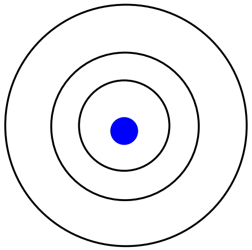


Yuri Oganessian

原子核の安定領域の理論的予言
「安定の島」

(note) 原子の魔法数 (貴ガス･希ガス)

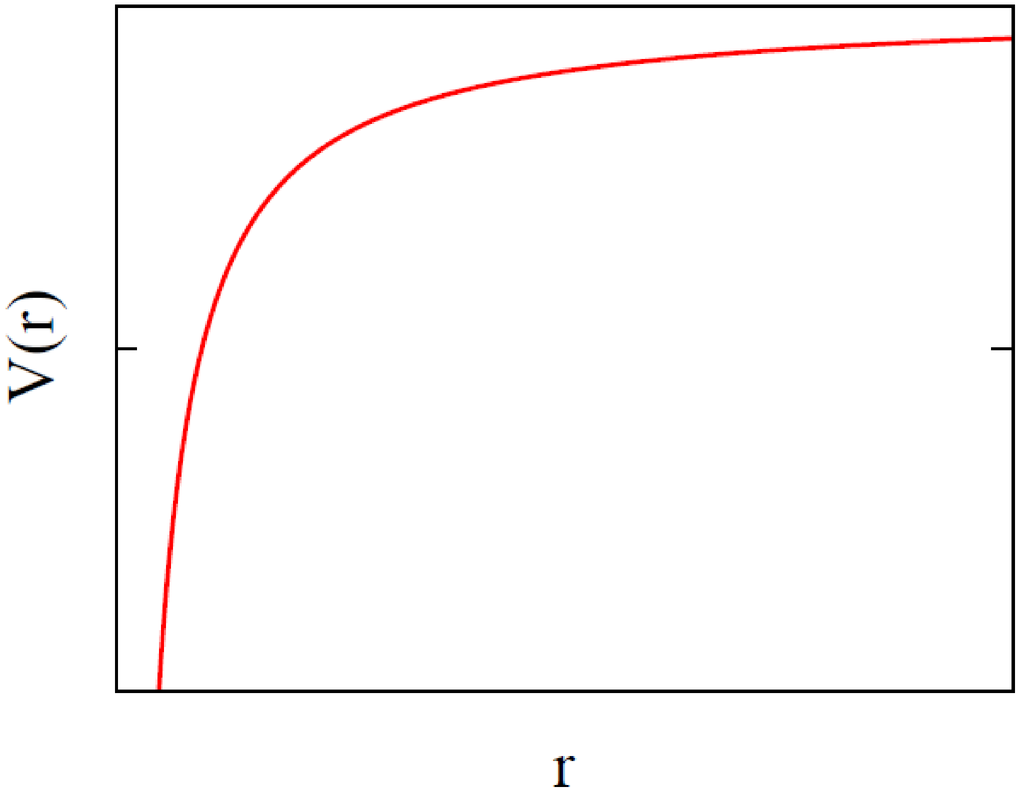
He (Z=2), Ne (Z=10), Ar (Z=18), Kr (Z=36), Xe (Z=54), Rn (Z=86)



電子の殻構造

Magic numbers

Hydrogen-like potential: $$V(r) = -\frac{Ze^2}{r}$$



$$E_n = -\frac{(Z\alpha)^2}{2n^2} mc^2$$

$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137}$$

$$n = n_r + l + 1$$

Magic numbers

Hydrogen-like potential: $$V(r) = -\frac{Ze^2}{r}$$

$$E_n = -\frac{(Z\alpha)^2}{2n^2} mc^2$$

3S 3P 3D

2S 2P

1S

$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137}$$

$$n = n_r + l + 1$$

Magic numbers

Hydrogen-like potential:

$$V(r) = -\frac{Ze^2}{r}$$

degeneracy = 2 * (2 l +1)

(spin x l_z)

$$E_n = -\frac{(Z\alpha)^2}{2n^2} mc^2$$

3S [2] 3P [6] 3D [10]

$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137}$$

2S [2] 2P [6]

$$n = n_r + l + 1$$

1S [2]

Magic numbers

Hydrogen-like potential:

$$V(r) = -\frac{Ze^2}{r}$$

degeneracy = 2 * (2 *l* +1)

(spin x l_z)

$$E_n = -\frac{(Z\alpha)^2}{2n^2} mc^2$$

3S [2] 3P [6] 3D [10]

$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137}$$

2S [2] 2P [6]

$$n = n_r + l + 1$$

1S [2] He

Magic numbers

Hydrogen-like potential: $$V(r) = -\frac{Ze^2}{r}$$

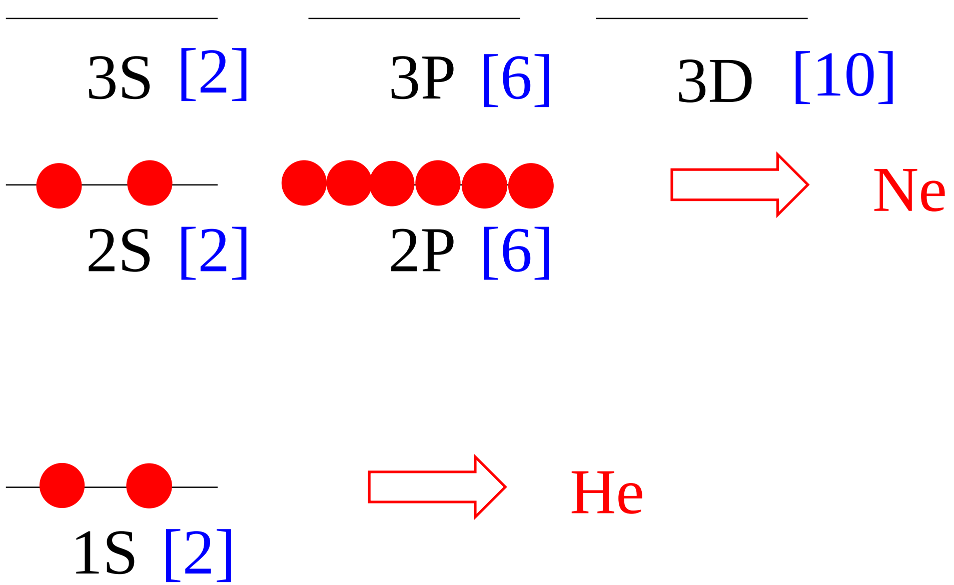
degeneracy = 2 * (2 *l* +1)

(spin x l_z)

$$E_n = -\frac{(Z\alpha)^2}{2n^2} mc^2$$

$$\alpha = \frac{e^2}{\hbar c} \sim \frac{1}{137}$$

$$n = n_r + l + 1$$



Magic numbers

Hydrogen-like potential: $$V(r) = -\frac{Ze^2}{r}$$

degeneracy = 2 * (2 l +1)

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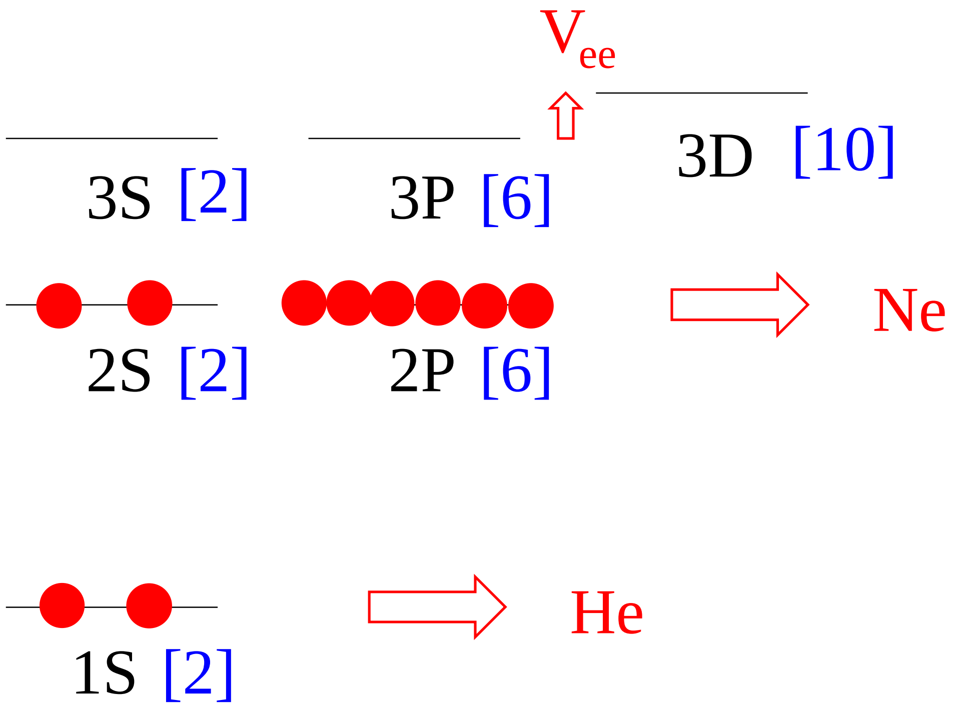

Magic numbers

Hydrogen-like potential: $$V(r) = -\frac{Ze^2}{r}$$

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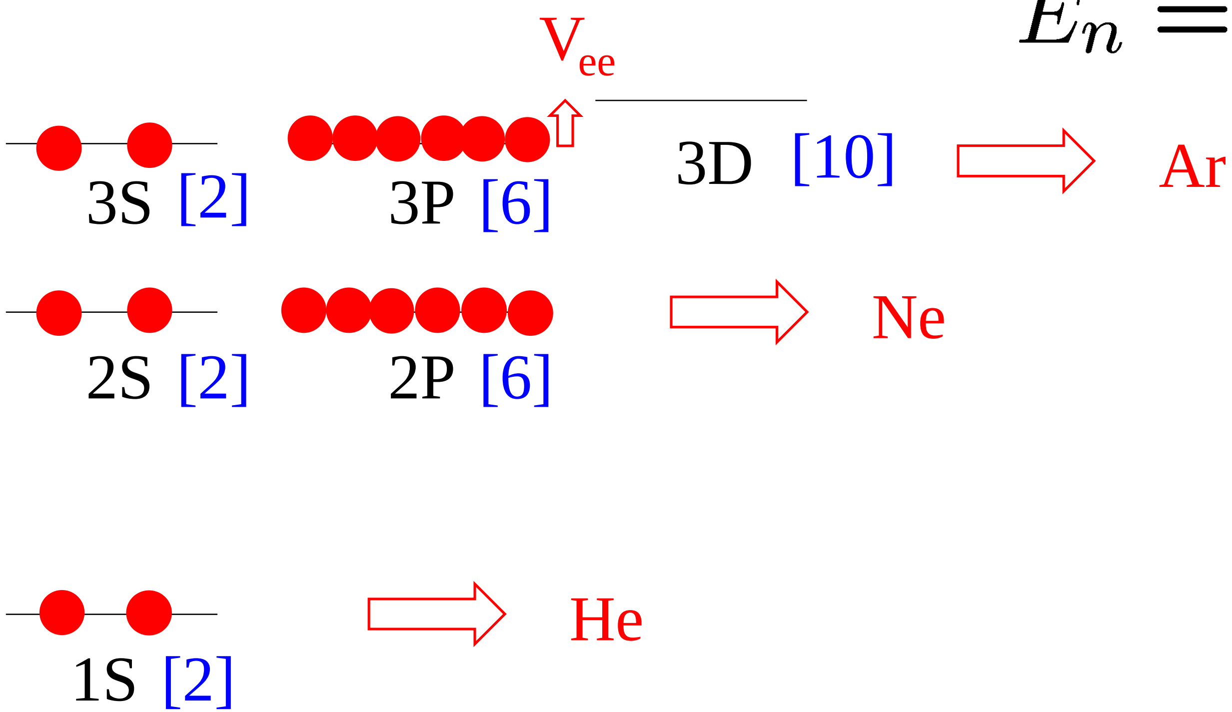
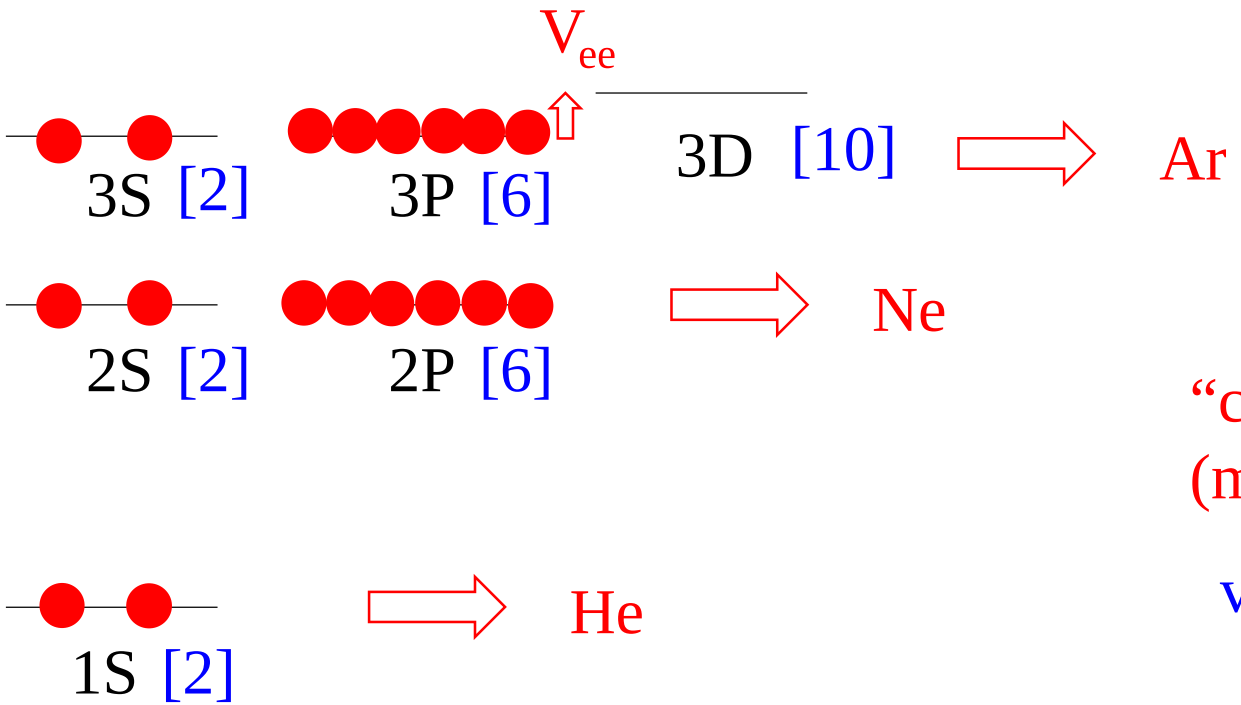


Magic numbers

Hydrogen-like potential: $$V(r) = -\frac{Ze^2}{r}$$

degeneracy = 2 * (2 *l* +1)

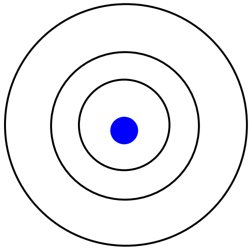


"closed shell"
(magic numbers)

very stable

(note) Atomic magic numbers (Noble gas)

He (Z=2), Ne (Z=10), Ar (Z=18), Kr (Z=36), Xe (Z=54), Rn (Z=86)

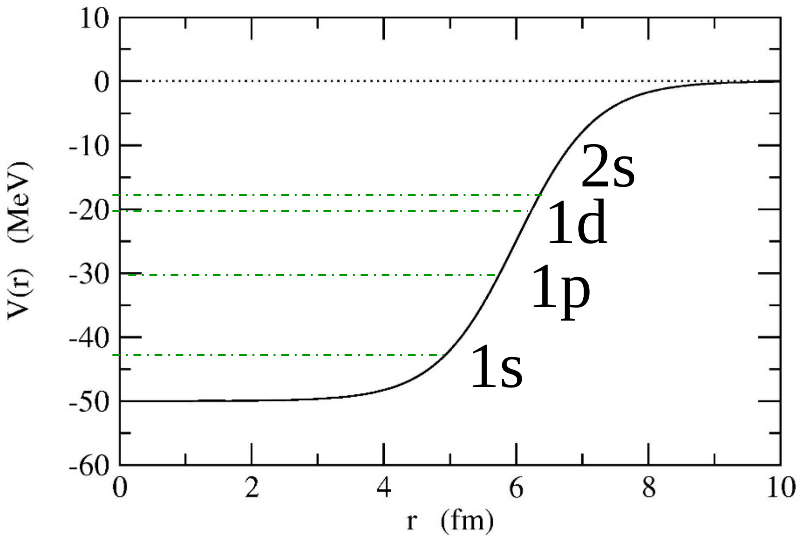


Shell structure

Similar attempt in nuclear physics: independent particle motion in a potential well

Woods-Saxon potential

$$V(r) = -V_0/[1 + \exp((r - R_0)/a]$$

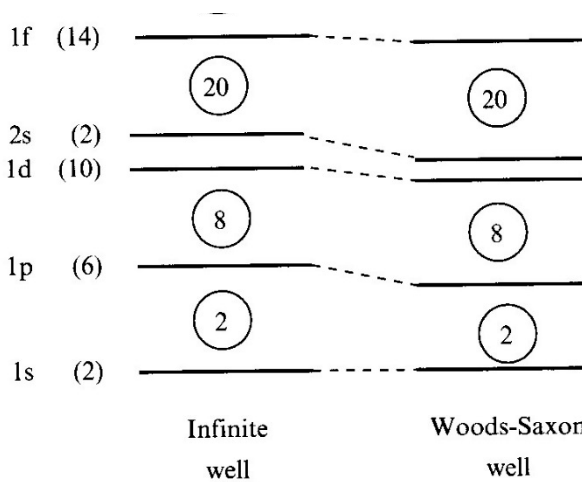


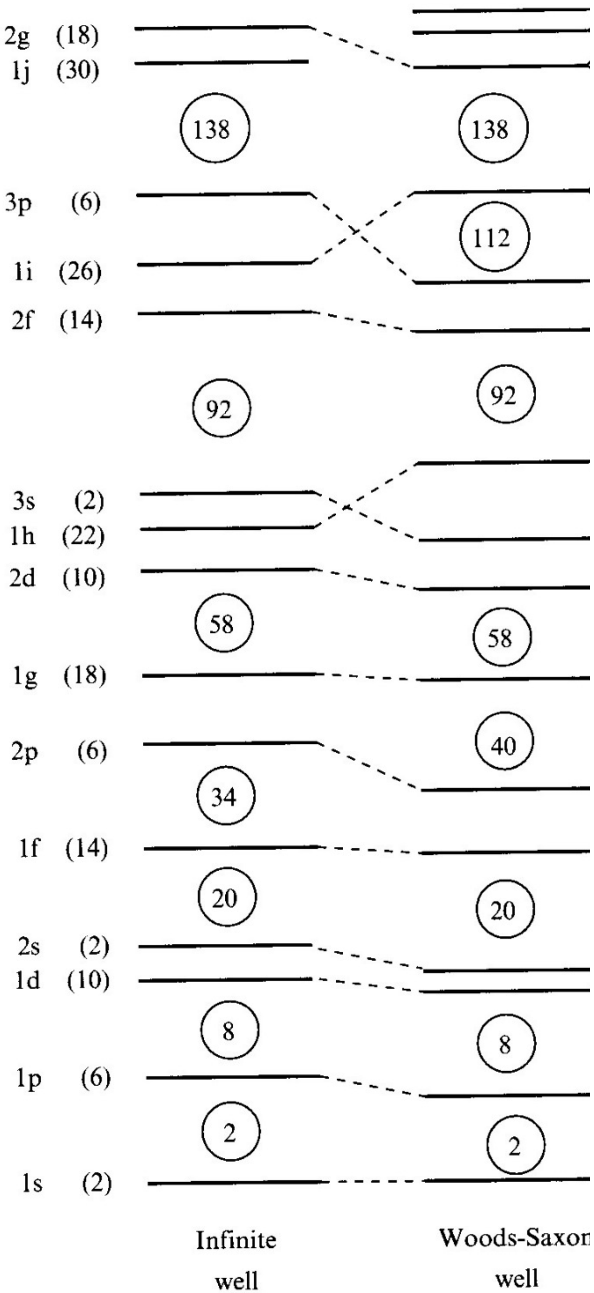
$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r) - \epsilon\right]\psi(\boldsymbol{r}) = 0$$

$$\psi(\boldsymbol{r}) = \frac{u_l(r)}{r} Y_{lm}(\hat{\boldsymbol{r}}) \cdot \chi_{m_s}$$

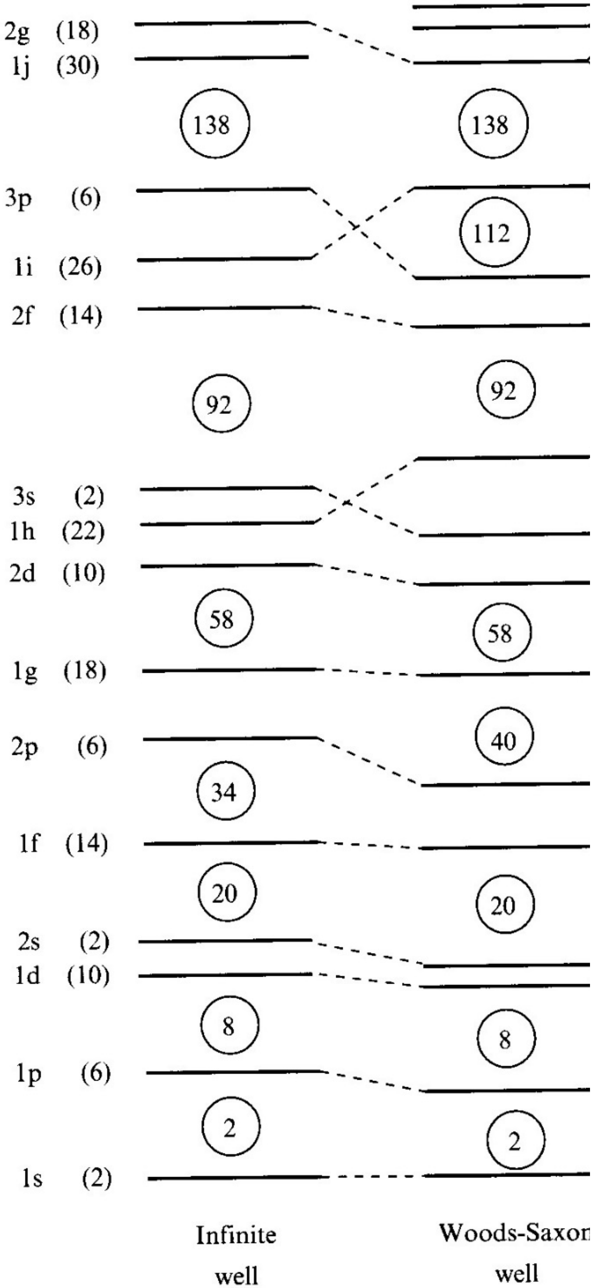
Nuclear magic numbers:

2, 8, 20, 28, 50, 82, 126



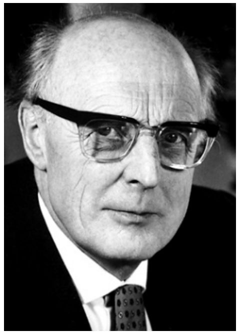


Nuclear magic numbers:
2, 8, 20, 28, 50, 82, 126



Woods-Saxon itself does not provide the correct magic numbers (2,8,20,28, 50,82,126).

Mayer and Jensen (1949):
Strong spin-orbit interaction

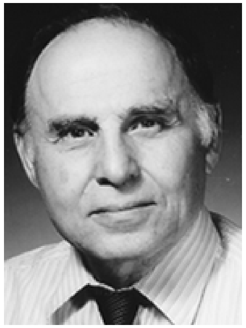


$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r) + V_{ls}(r)\boldsymbol{l}\cdot\boldsymbol{s} - \epsilon\right]\psi(\boldsymbol{r}) = 0$$

$$V_{ls}(r) \sim -\lambda \frac{1}{r}\frac{dV}{dr} \qquad (\lambda > 0)$$

ノーベル物理学賞

□ レーザー物理学 (2018)



アシュキン

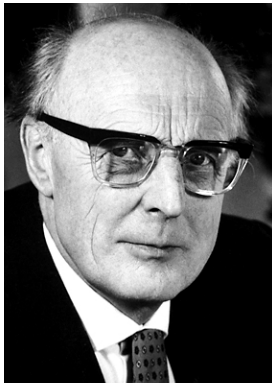
ムル

ストリックランド

□ 原子核物理学 (1963)

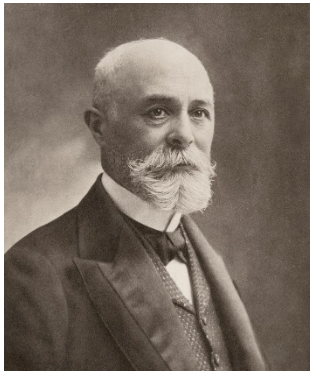
ウィグナー

メイヤー



イェンセン

□ 放射線物理学 (1903)



ベクレル

キュリー

キュリー

「お母さん、ノーベル賞をもらう」
シャロン・バーチ著
（工作舎）

仙台市民図書館

1　マリー・スクロドフスカ・キュリー
（1903：ノーベル物理学賞。放射能の研究
／1911：ノーベル化学賞。ラジウムの発見）

2　リーゼ・マイトナー
（核分裂を発見しながら1944年のノーベル化学賞をハーンに独り占めにされる）

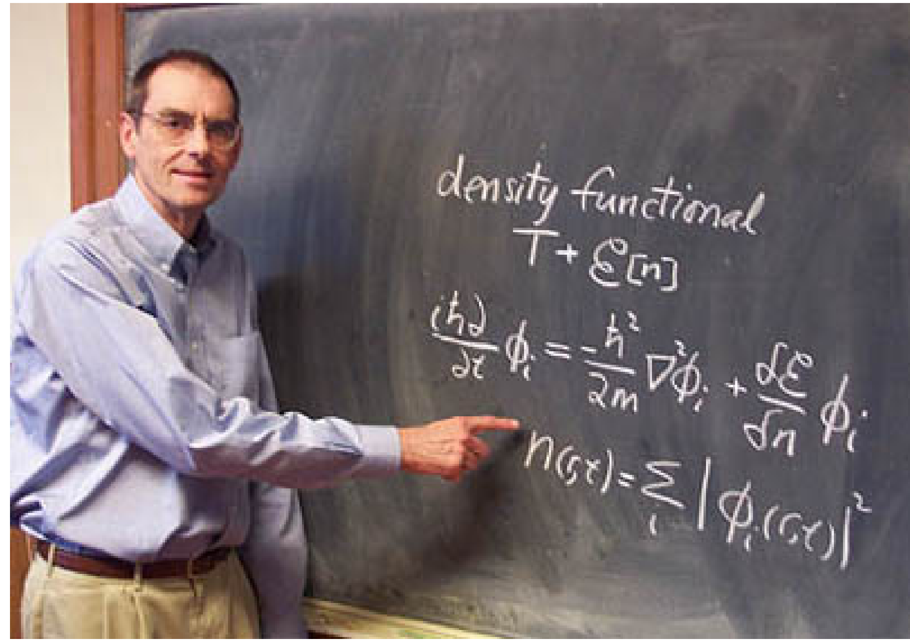
3　エミー・ネーター
（ノーベル賞に数学賞があればまちがいなく受賞に値した抽象代数学の天才）

7　マリア・ゲッペルト・メイヤー
（1963：ノーベル物理学賞。原子核の殻模型の研究）

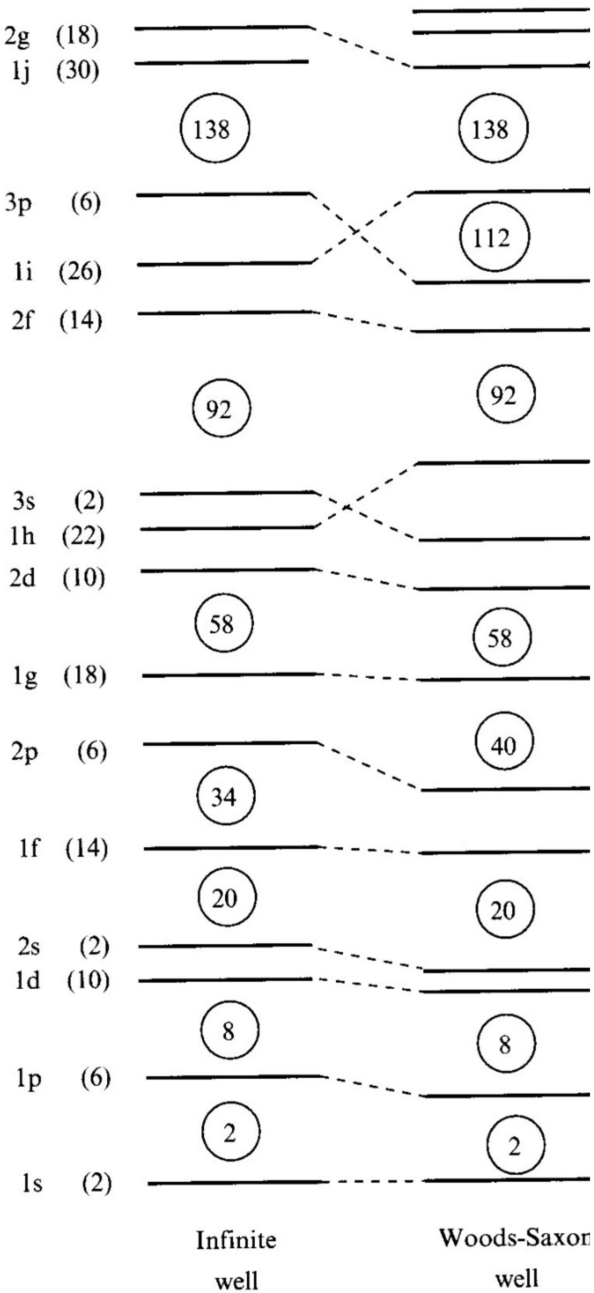
10　呉健雄
（パリティ非保存の実験的検証をしたが、1957年のノーベル物理学賞は李政道と楊振寧に）

14　ジョスリン・ベル・バーネル
（パルサーを発見したが、1974年の物理学賞は彼女の上司ヒューイッシュに）

Sharon Bertch McGrayne



George F. Bertsch
(University of Washington)



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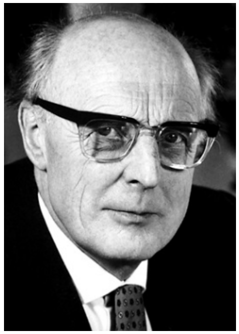


Mayer and Jensen (1949):

Strong spin-orbit interaction

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

$$V_{ls}(r) \sim -\lambda \frac{1}{r}\frac{dV}{dr} \qquad (\lambda > 0)$$

jj 結合殻模型

軌道運動とスピンは独立の自由度

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r) - \epsilon\right]\psi(r) = 0 \Longrightarrow \psi_{lmm_s}(\boldsymbol{r}) = \frac{u_l(r)}{r} Y_{lm}(\hat{\boldsymbol{r}}) \cdot \chi_{m_s}$$

スピン・軌道力

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

(note) $\boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s} \Longrightarrow \boldsymbol{l}\cdot\boldsymbol{s} = (\boldsymbol{j}^2 - \boldsymbol{l}^2 - \boldsymbol{s}^2)/2$

l と ***s*** を結合して ***j*** を組む。

→ *j* = *l* +/- 1/2

jj 結合殻模型

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r) - \epsilon\right]\psi(r) = 0 \Longrightarrow \psi_{lmm_s}(\boldsymbol{r}) = \frac{u_l(r)}{r} Y_{lm}(\hat{\boldsymbol{r}}) \cdot \chi_{m_s}$$

スピン・軌道力

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

(note) $\boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s} \Longrightarrow \boldsymbol{l}\cdot\boldsymbol{s} = (\boldsymbol{j}^2 - \boldsymbol{l}^2 - \boldsymbol{s}^2)/2$

l と ***s*** を結合して ***j*** を組む。

$$\boxed{\begin{aligned} \psi_{jlm}(\boldsymbol{r}) &= \frac{u_{jl}(r)}{r}\mathcal{Y}_{jlm}(\hat{\boldsymbol{r}}) \\ \mathcal{Y}_{jlm}(\hat{\boldsymbol{r}}) &= \sum_{m_l, m_s} \langle l\ m_l\ 1/2\ m_s | j\ m\rangle Y_{lm_l}(\hat{\boldsymbol{r}})\chi_{m_s} \end{aligned}}$$

$$\begin{aligned} \boldsymbol{j}^2|\mathcal{Y}_{jlm}\rangle &= j(j+1)\,|\mathcal{Y}_{jlm}\rangle \\ j_z|\mathcal{Y}_{jlm}\rangle &= m\,|\mathcal{Y}_{jlm}\rangle \\ \boldsymbol{l}^2|\mathcal{Y}_{jlm}\rangle &= l(l+1)\,|\mathcal{Y}_{jlm}\rangle \\ \boldsymbol{s}^2|\mathcal{Y}_{jlm}\rangle &= 3/4\,|\mathcal{Y}_{jlm}\rangle \end{aligned}$$

jj 結合殻模型

$\boldsymbol{l}$ と $\boldsymbol{s}$ を結合して $\boldsymbol{j}$ を組む。

$$\boxed{\psi_{jlm}(\boldsymbol{r}) \;=\; \frac{u_{jl}(r)}{r}\mathcal{Y}_{jlm}(\hat{\boldsymbol{r}})}$$

$$\begin{aligned}
\boldsymbol{j}^2|\mathcal{Y}_{jlm}\rangle &= j(j+1)\,|\mathcal{Y}_{jlm}\rangle \\
j_z|\mathcal{Y}_{jlm}\rangle &= m\,|\mathcal{Y}_{jlm}\rangle \\
\boldsymbol{l}^2|\mathcal{Y}_{jlm}\rangle &= l(l+1)\,|\mathcal{Y}_{jlm}\rangle \\
\boldsymbol{s}^2|\mathcal{Y}_{jlm}\rangle &= \frac{3}{4}\,|\mathcal{Y}_{jlm}\rangle
\end{aligned}$$

(note) $\boldsymbol{j} = \boldsymbol{l} + \boldsymbol{s} \quad \Longrightarrow \quad \boldsymbol{l}\cdot\boldsymbol{s} = (\boldsymbol{j}^2 - \boldsymbol{l}^2 - \boldsymbol{s}^2)/2$

$$\boxed{\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle = \frac{1}{2}\left(j(j+1) - l(l+1) - \frac{3}{4}\right)|\mathcal{Y}_{jlm}\rangle}$$

$$\begin{aligned}
\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle &= \frac{l}{2}\,|\mathcal{Y}_{jlm}\rangle \qquad (j = l + 1/2) \\
\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle &= -\frac{l+1}{2}\,|\mathcal{Y}_{jlm}\rangle \qquad (j = l - 1/2)
\end{aligned}$$

符号が逆！

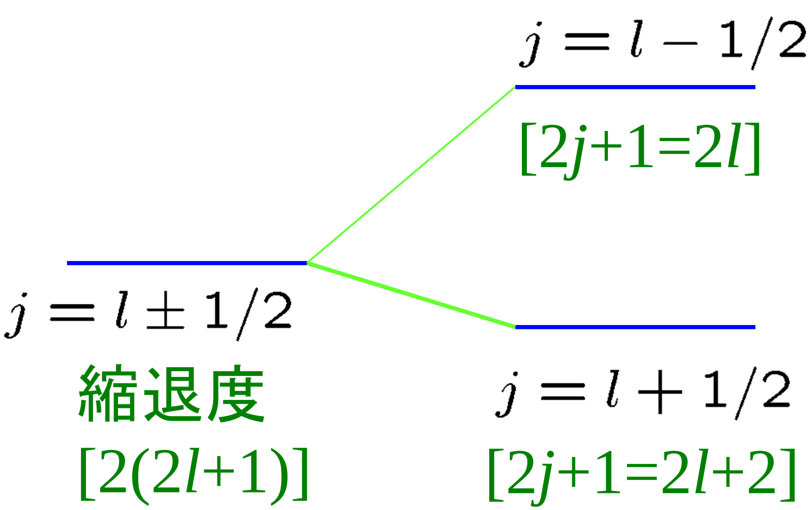
jj 結合殻模型

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

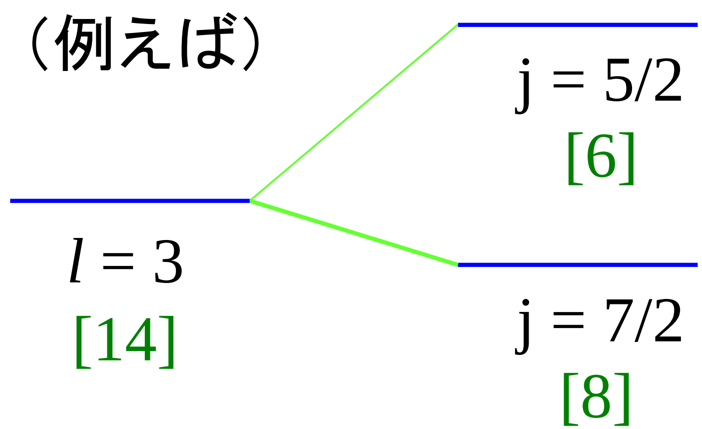
$$\begin{aligned}
\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle &= \frac{l}{2}|\mathcal{Y}_{jlm}\rangle \quad (j = l + 1/2) \\
\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle &= -\frac{l+1}{2}|\mathcal{Y}_{jlm}\rangle \quad (j = l - 1/2)
\end{aligned}$$

符号が逆！

$\boxed{j = l \pm 1/2 \quad \text{で準位が分離}}$



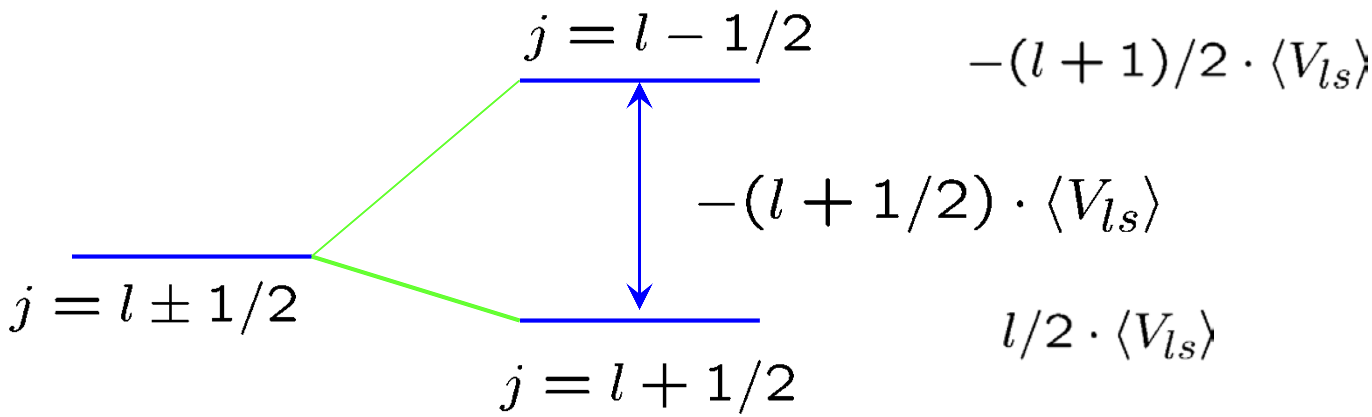
（例えば）



jj 結合殻模型

$$\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle = \frac{l}{2}|\mathcal{Y}_{jlm}\rangle \quad (j = l + 1/2)$$

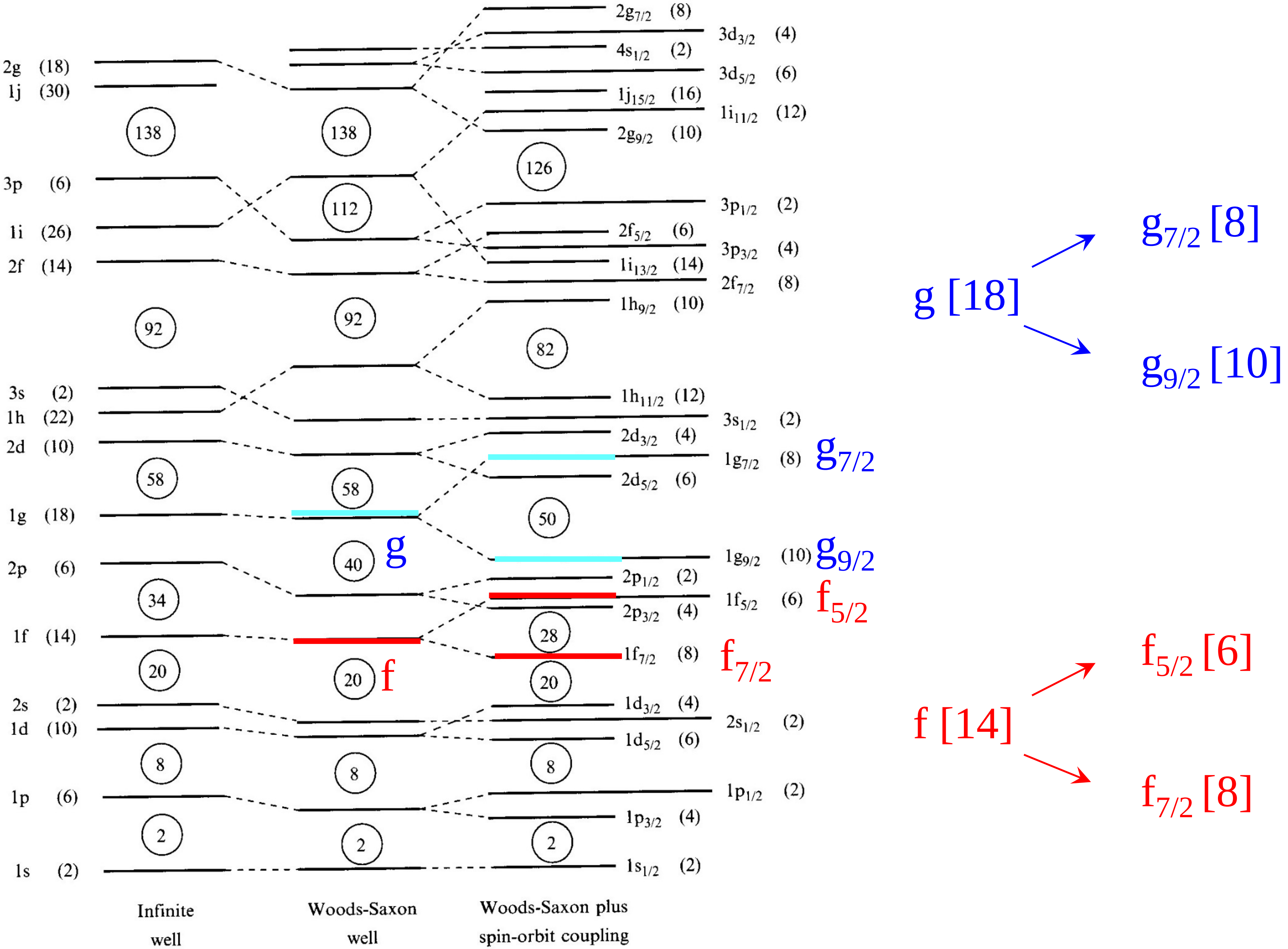
$$\boldsymbol{l}\cdot\boldsymbol{s}\,|\mathcal{Y}_{jlm}\rangle = -\frac{l+1}{2}|\mathcal{Y}_{jlm}\rangle \quad (j = l - 1/2)$$



$j = l \pm 1/2$ で準位が分離: *l が大きくなればなるほど分離は大*

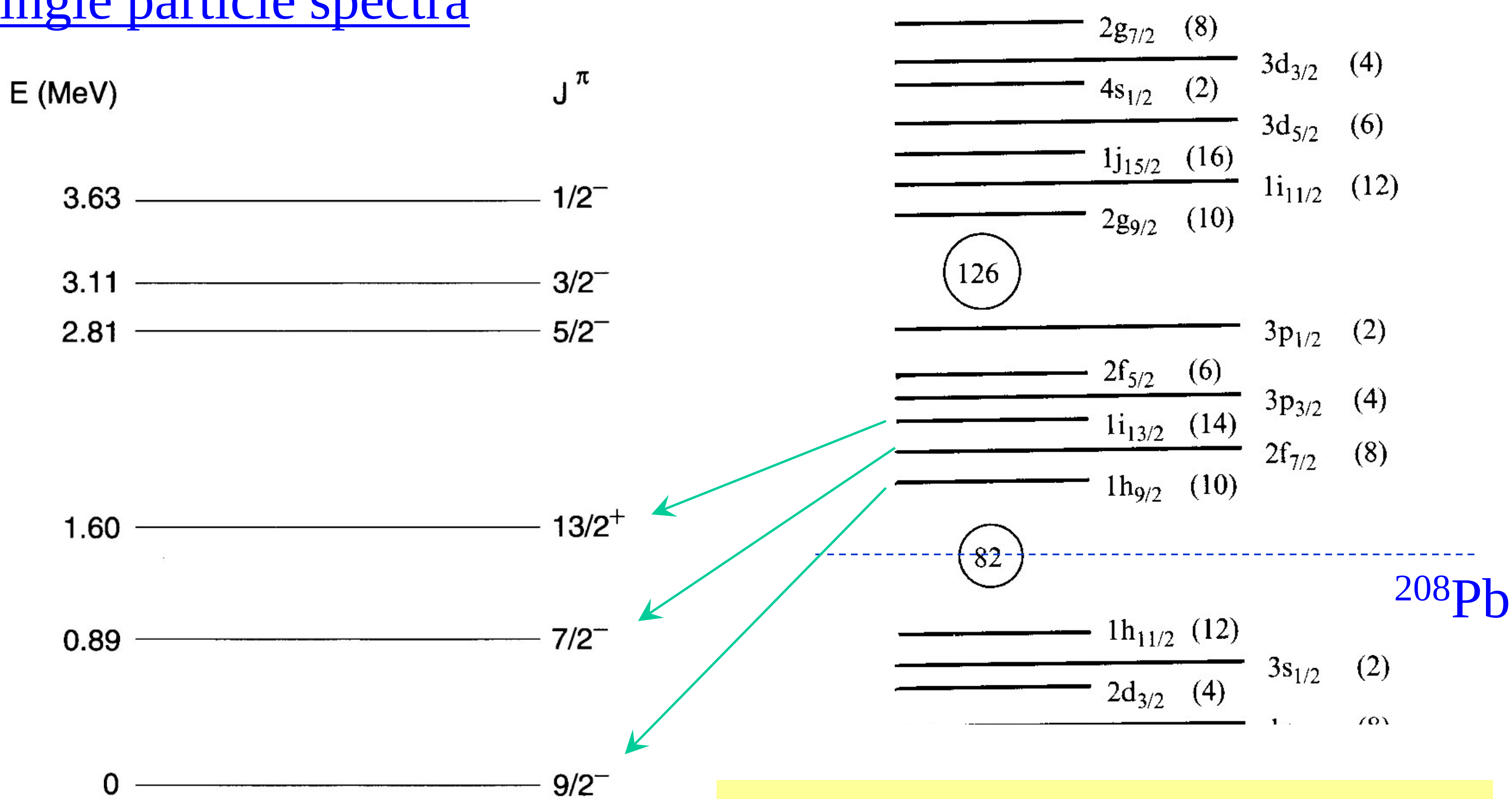
* ただし、スピン平均はゼロ:

$$+\frac{l}{2}(2(l+1/2)+1) - \frac{l+1}{2}(2(l-1/2)+1) = 0$$



2g (18)
1j (30)
138
3p (6)
1i (26)
2f (14)
92
3s (2)
1h (22)
2d (10)
58
1g (18)
2p (6)
34
1f (14)
20
2s (2)
1d (10)
8
1p (6)
2
1s (2)
Infinite well
138
112
92
58
g
40
20
f
8
2
Woods-Saxon well
$2g_{7/2}$ (8)
$3d_{3/2}$ (4)
$4s_{1/2}$ (2)
$3d_{5/2}$ (6)
$1j_{15/2}$ (16)
$1i_{11/2}$ (12)
$2g_{9/2}$ (10)
126
$3p_{1/2}$ (2)
$2f_{5/2}$ (6)
$3p_{3/2}$ (4)
$1i_{13/2}$ (14)
$2f_{7/2}$ (8)
$1h_{9/2}$ (10)
82
$1h_{11/2}$ (12)
$3s_{1/2}$ (2)
$2d_{3/2}$ (4)
$1g_{7/2}$ (8)
$g_{7/2}$
$2d_{5/2}$ (6)
50
$1g_{9/2}$ (10)
$g_{9/2}$
$2p_{1/2}$ (2)
$1f_{5/2}$ (6)
$f_{5/2}$
$2p_{3/2}$ (4)
28
$1f_{7/2}$ (8)
$f_{7/2}$
20
$1d_{3/2}$ (4)
$2s_{1/2}$ (2)
$1d_{5/2}$ (6)
8
$1p_{1/2}$ (2)
$1p_{3/2}$ (4)
2
$1s_{1/2}$ (2)
Woods-Saxon plus spin-orbit coupling
g [18]
$g_{7/2}$ [8]
$g_{9/2}$ [10]
f [14]
$f_{5/2}$ [6]
$f_{7/2}$ [8]

Single particle spectra



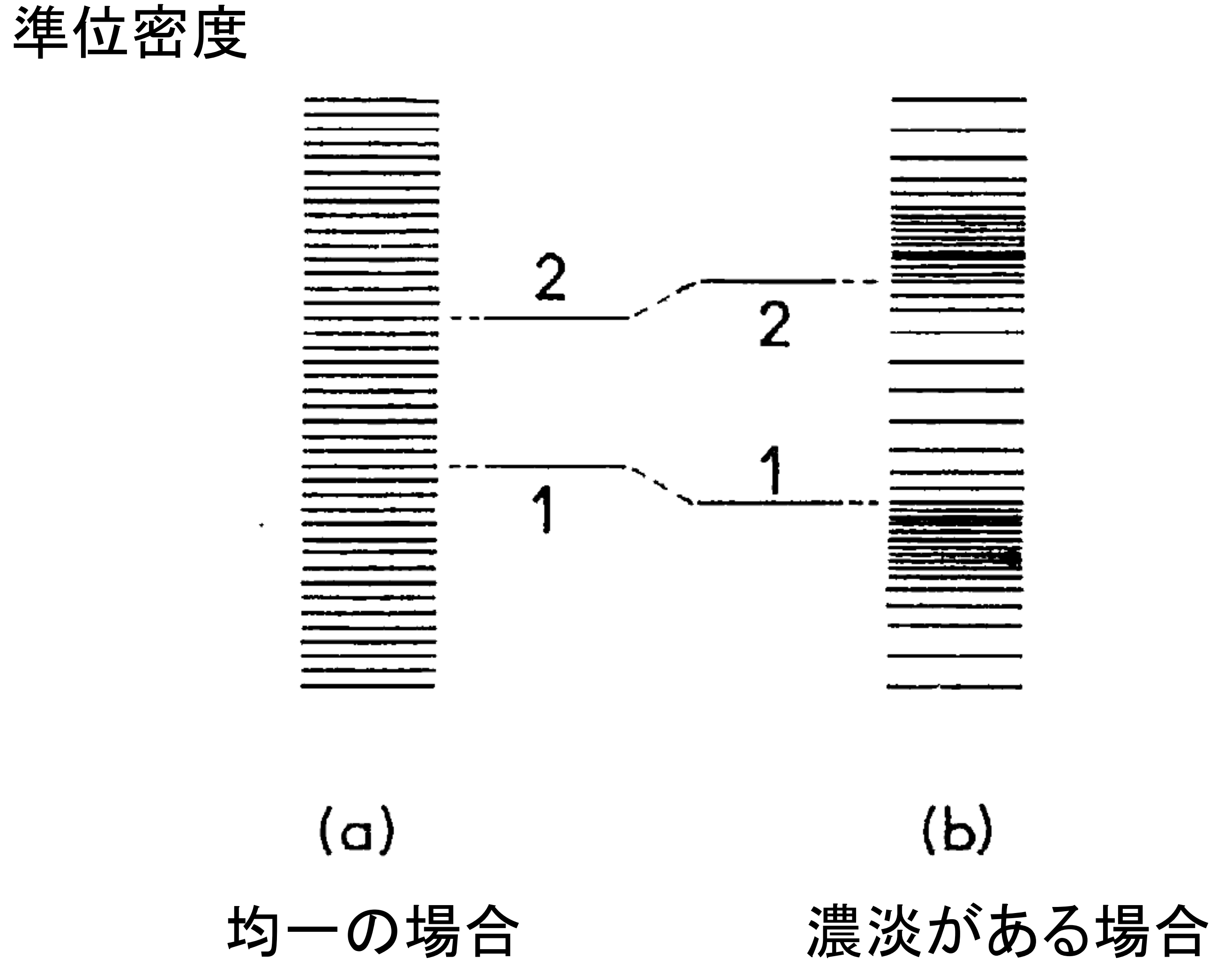
^{209}Bi (Z=83)

FIG. 3.6. Low-lying single-particle levels of ^{209}Bi.

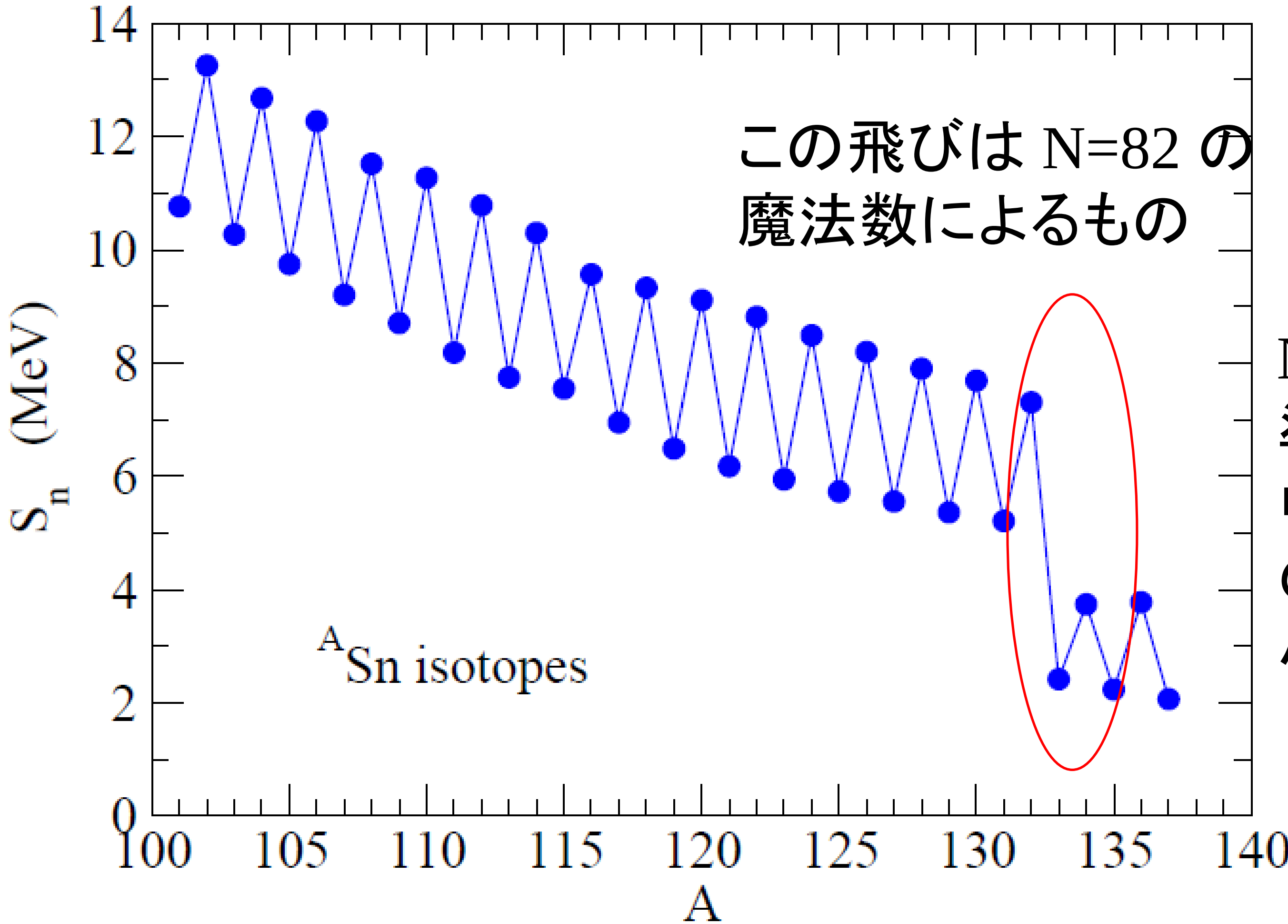
- How to construct V(r) microscopically?
- Does the independent particle picture really hold?

⇨ Later in this course

何故、閉殻の原子核は安定になるのか?



準位密度に濃淡があれば、下から数えて濃淡の終わりまで準位がつまると(図の1の場合)、均一の場合に比べてエネルギーが小さい



N=83から上の
準位がつまるため
中性子をとりのぞく
のにエネルギーが
小さくてすむ

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

生命誕生のための幸運な偶然

原子の魔法数

電子の数が 2, 10, 18, 36, 54, 86

不活性ガス：He, Ne, Ar, Kr, Xe, Rn

原子核の魔法数

陽子または中性子の数が

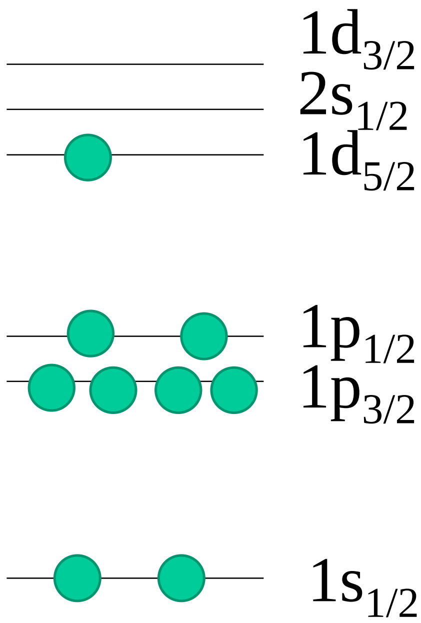
2, 8, 20, 28, 50, 82, 126 の時安定

- 例えば $^{16}_{8}O_{8}$（二重閉殻核）
- 酸素元素は元素合成の過程で数多く生成された
- しかし、酸素は化学的には「活性」
- 化学反応により様々な複雑な物質をつくり生命に至った

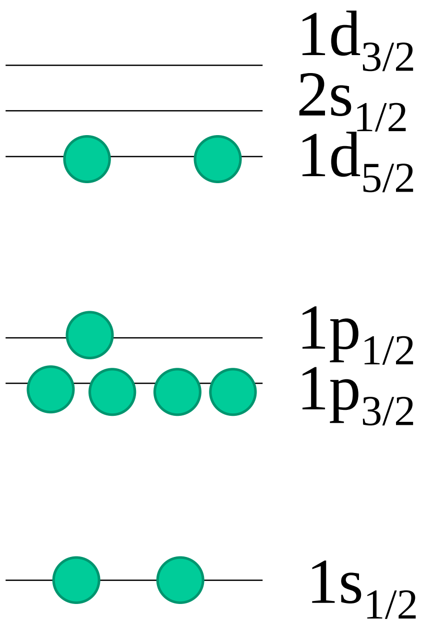
参考：望月優子　ビデオ「元素誕生の謎にせまる」　http://rarfaxp.riken.go.jp/~motizuki/contents/genso.html

single-j model

shell model



configuration 1



configuration 2

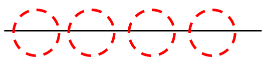
…… several others

angular momentum (spin) and parity for each configuration?

→ let us first investigate a single-j case single-j level: one level with an angular momentum j

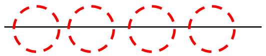
j

example: j = $p_{3/2}$

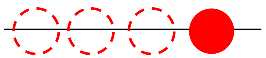


$p_{3/2}$

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

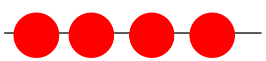
 $p_{3/2}$ can accommodate 4 nucleons (j_z= +3/2, +1/2, -1/2, -3/2)

i) 1 nucleon

 $p_{3/2}$ → $I^{\pi} = 3/2^{-}$

(there are 4 ways to occupy this level)

ii) 4 nucleons

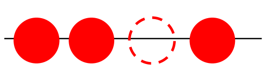
 $p_{3/2}$ → $I^{\pi} = 0^{+}$

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

(there is only 1 way to occupy this level)

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

iii) 3 nucleons

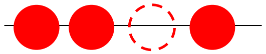
 $p_{3/2}$ → $I^{\pi} = 3/2^{-}$

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

(there are 4 ways to make a hole)

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

iii) 3 nucleons



$p_{3/2}$

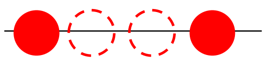
$\Rightarrow$ $I^\pi = 3/2^-$

$$I = j_1 + j_2 + j_3$$

(there are 4 ways to make a hole)

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

iv) 2 nucleons



$p_{3/2}$

$$I = j_1 + j_2$$

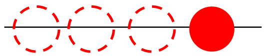
there are 4 x 3/2=6 ways to occupy this level with 2 nucleons.

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

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

anti-symmetrization

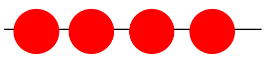
i) 1 nucleon



$p_{3/2}$ → $I^{\pi} = 3/2^{-}$

(there are 4 ways to occupy this level)

ii) 4 nucleons

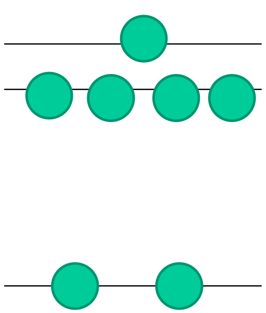


$p_{3/2}$ → $I^{\pi} = 0^{+}$

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

(there is only 1 way to occupy this level)

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



$1p_{1/2}$ → $I^{\pi} = 1/2^{-}$

$1p_{3/2}$ → $I^{\pi} = 0^{+}$

$1s_{1/2}$ → $I^{\pi} = 0^{+}$

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

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

cf. ${}^{12}C(e,e'K^{+}){}^{12}_{\Lambda}B$ ($={}^{11}B+\Lambda$)

MeV

5.02 $3/2^{-}$

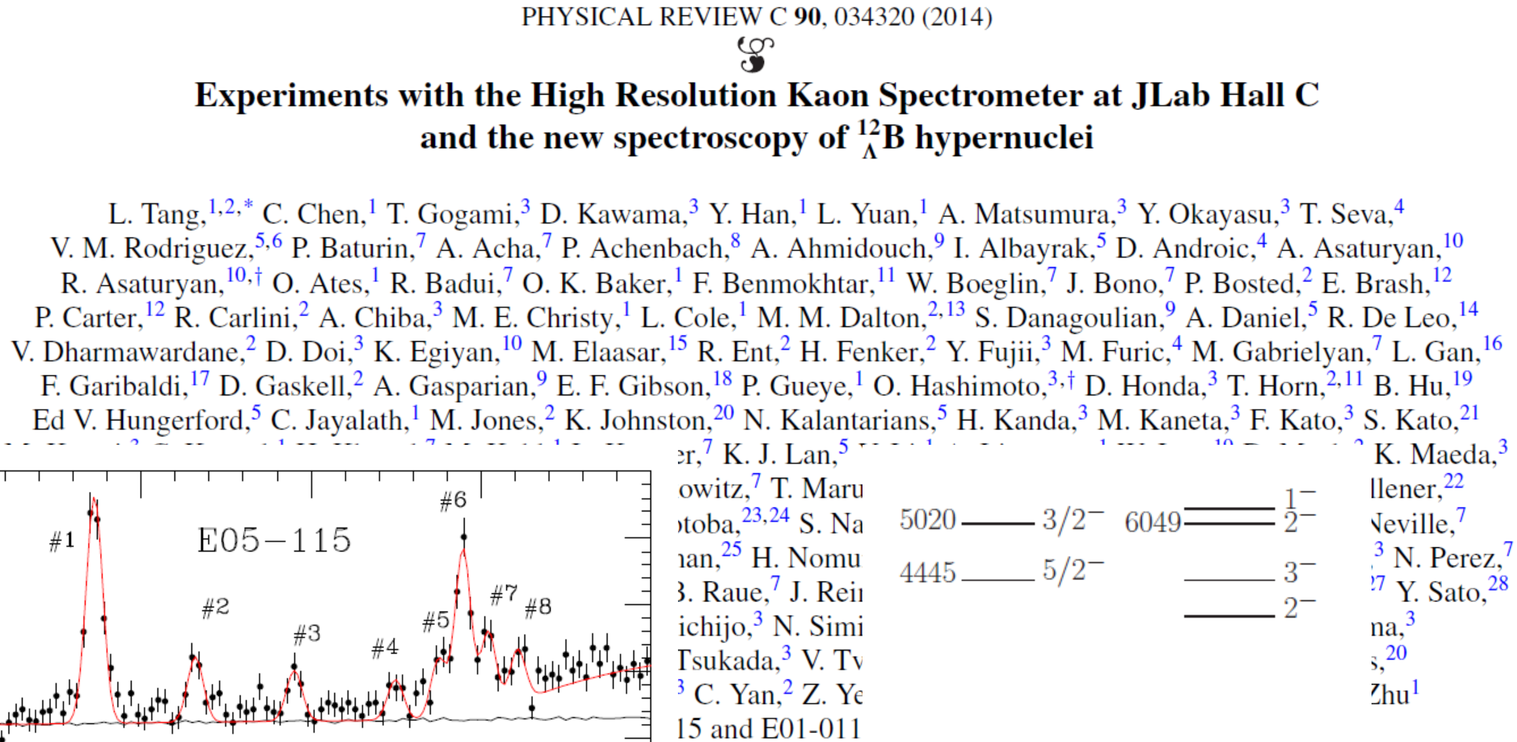
4.44 $5/2^{-}$

2.12 $1/2^{-}$

0 $3/2^{-}$

${}^{11}_{5}B_{6}$

cf. $^{12}C(e,e'K^+)^{12}_{\Lambda}B$ (=$^{11}B+\Lambda$)


PHYSICAL REVIEW C **90**, 034320 (2014)

Experiments with the High Resolution Kaon Spectrometer at JLab Hall C and the new spectroscopy of $^{12}_{\Lambda}B$ hypernuclei

L. Tang,[1,2,*] C. Chen,[1] T. Gogami,[3] D. Kawama,[3] Y. Han,[1] L. Yuan,[1] A. Matsumura,[3] Y. Okayasu,[3] T. Seva,[4]
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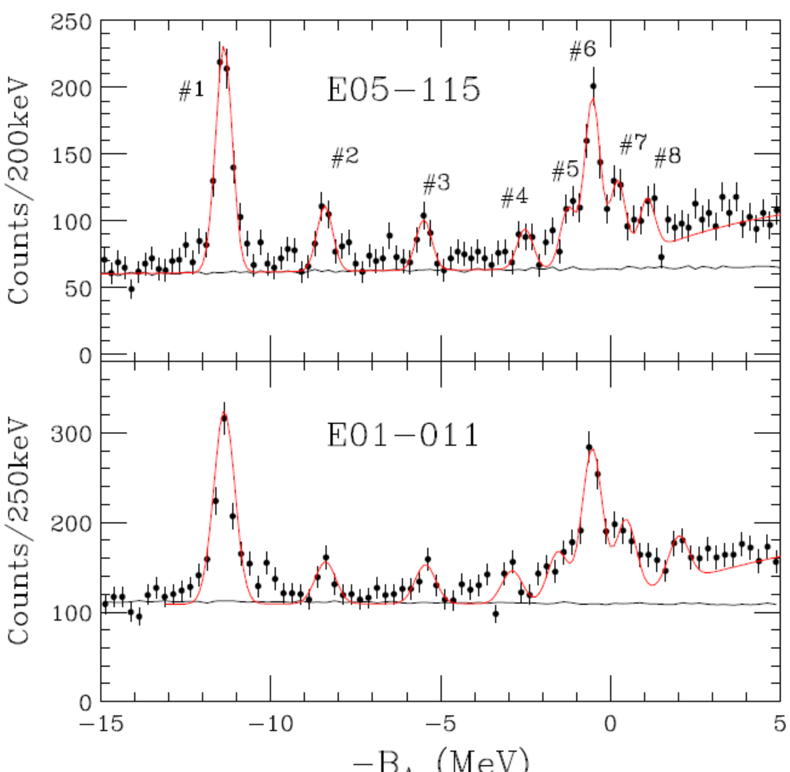
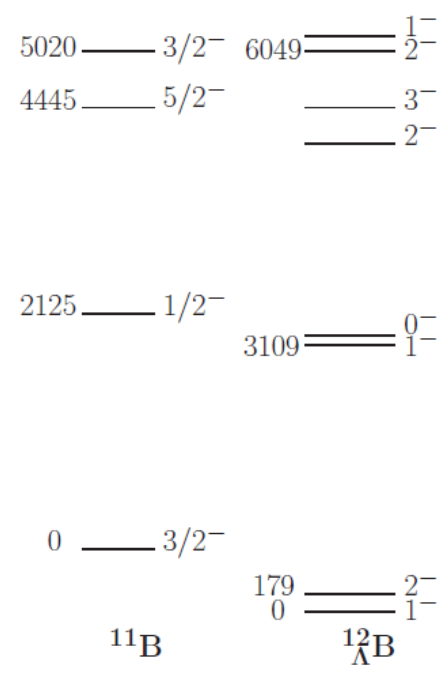
Ed V. Hungerford,[5] C. Jayalath,[1] M. Jones,[2] K. Johnston,[20] N. Kalantarians,[5] H. Kanda,[3] M. Kaneta,[3] F. Kato,[3] S. Kato,[21]
…er,[7] K. J. Lan,[5] … K. Maeda,[3]
…owitz,[7] T. Maru… …llener,[22]
…toba,[23,24] S. Na… …Neville,[7]
…an,[25] H. Nomu… …[3] N. Perez,[7]
…. Raue,[7] J. Rei… …[27] Y. Sato,[28]
…ichijo,[3] N. Simi… …na,[3]
…Tsukada,[3] V. Tv… …s,[20]
…[3] C. Yan,[2] Z. Ye… …Zhu[1]
…15 and E01-011





(b)

example: (main) shell model configurations for ^{11}B

cf. $^{12}C(e,e'K^+)^{12}_{\Lambda}B$ (=$^{11}B+\Lambda$)

MeV

5.02 $3/2^-$

4.44 $5/2^-$

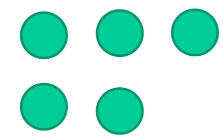
2.12 $1/2^-$

0 $3/2^-$

$^{11}_{5}B_{6}$

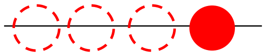
$1p_{1/2}$

$1p_{3/2}$

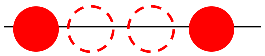


$1s_{1/2}$

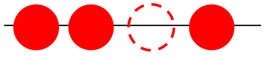
single-j



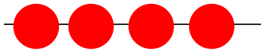
$p_{3/2}$ → $I^{\pi} = 3/2^-$



$p_{3/2}$ → $I^{\pi} = 0^+$ or 2^+



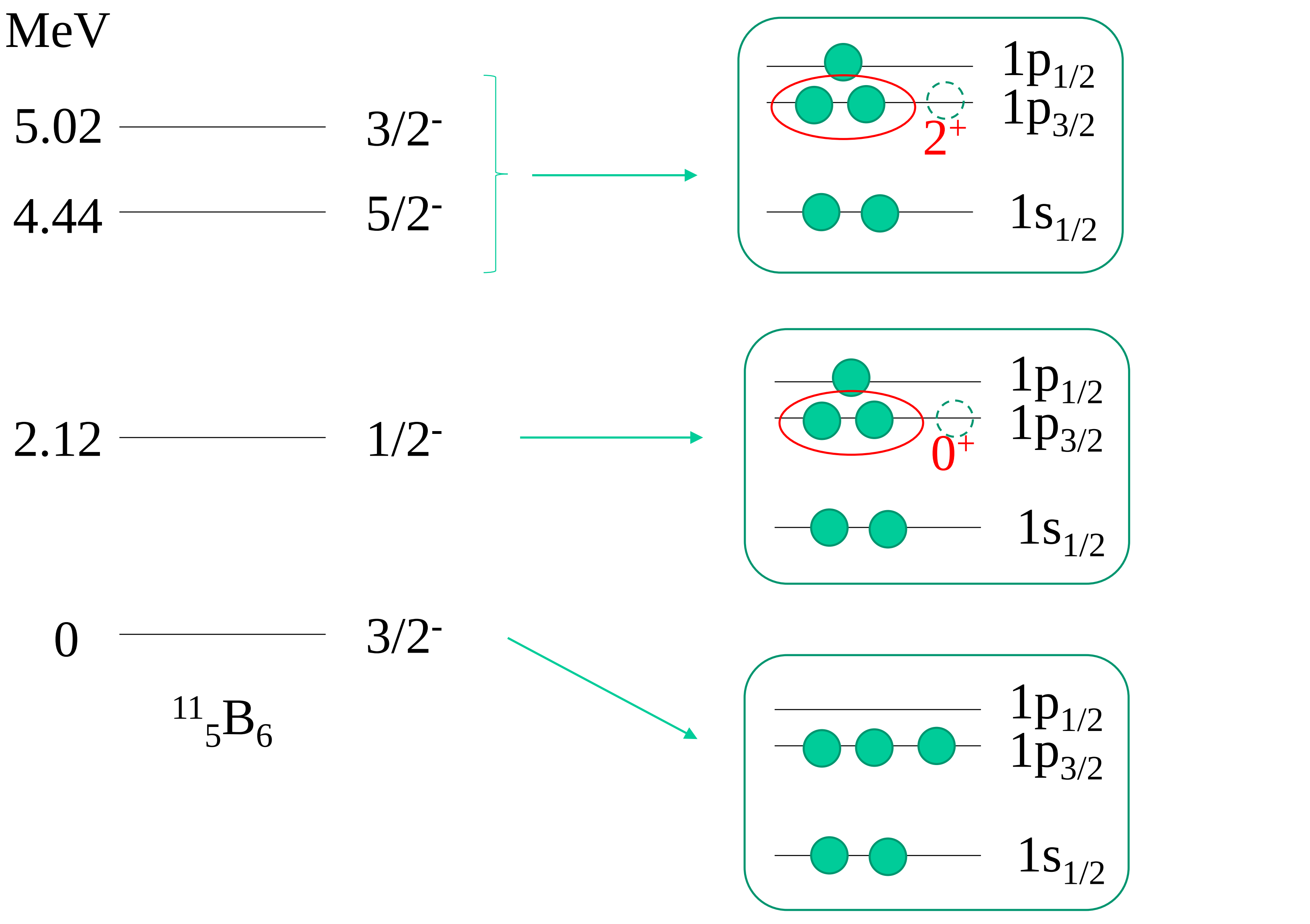
$p_{3/2}$ → $I^{\pi} = 3/2^-$



$p_{3/2}$ → $I^{\pi} = 0^+$

example: (main) shell model configurations for ^{11}B

cf. $^{12}C(e,e'K^+)^{12}_{\Lambda}B$ (=$^{11}B+\Lambda$)



another example: (main) shell model configurations for ^{17}F

MeV	
4.64	$3/2^-$
3.10	$1/2^-$
0.495	$1/2^+$
0	$5/2^+$

$^{17}_{9}F_{8}$

another example: (main) shell model configurations for ^{17}F