

▣ β 崩壊 $K > 17$

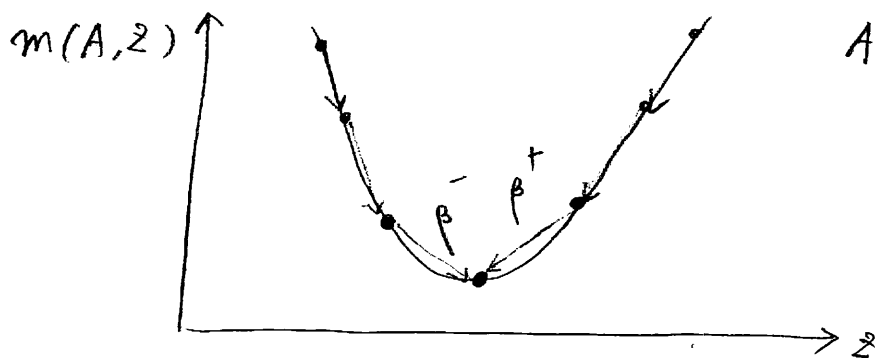
0. β 安定線

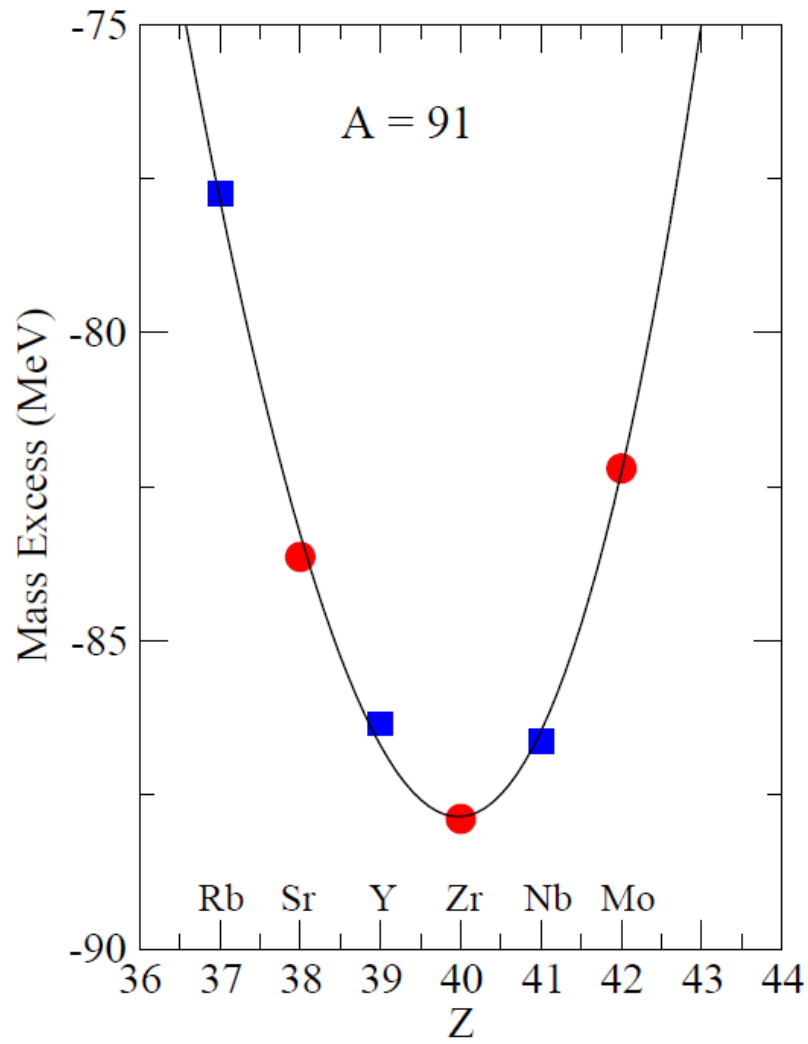
液滴模型

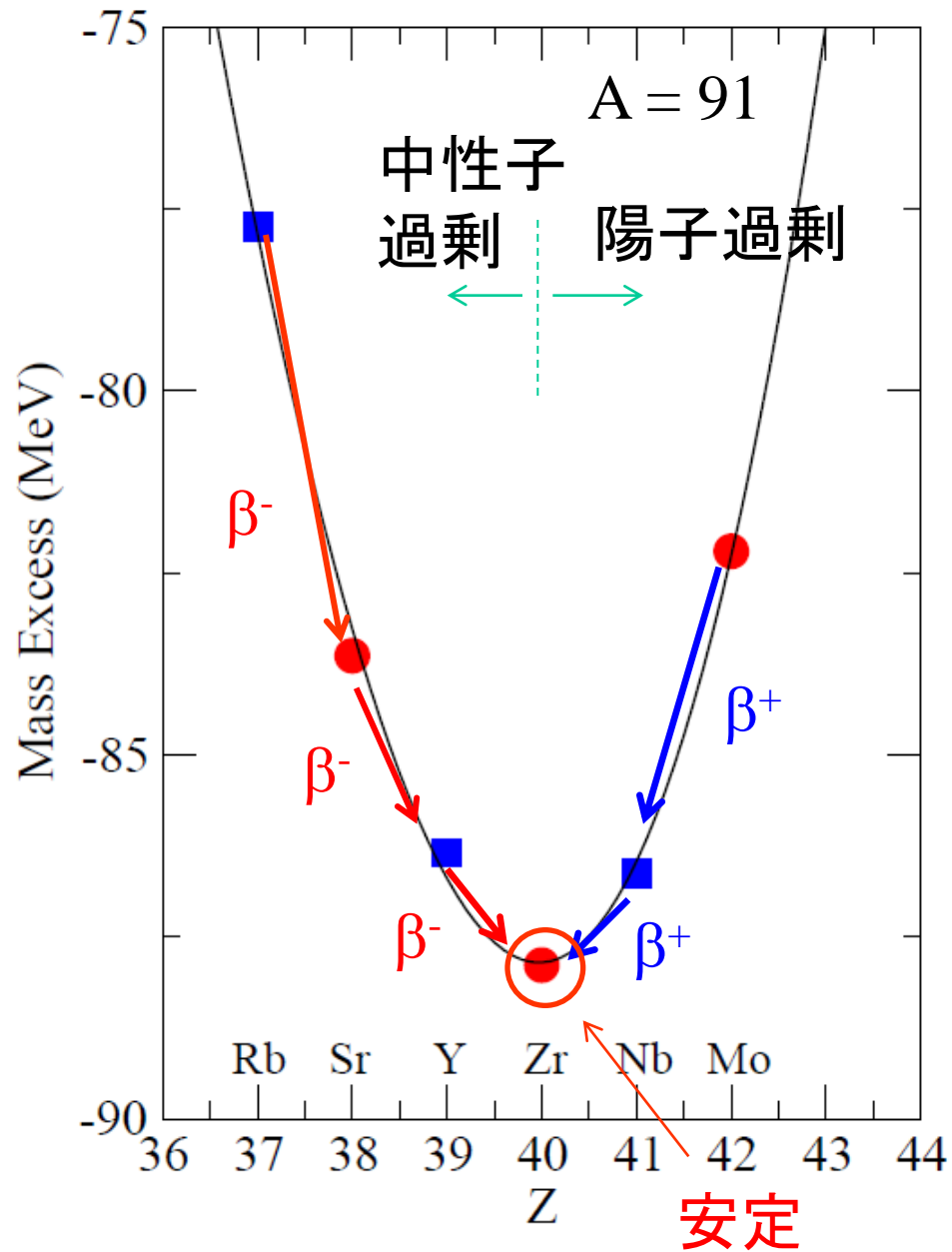
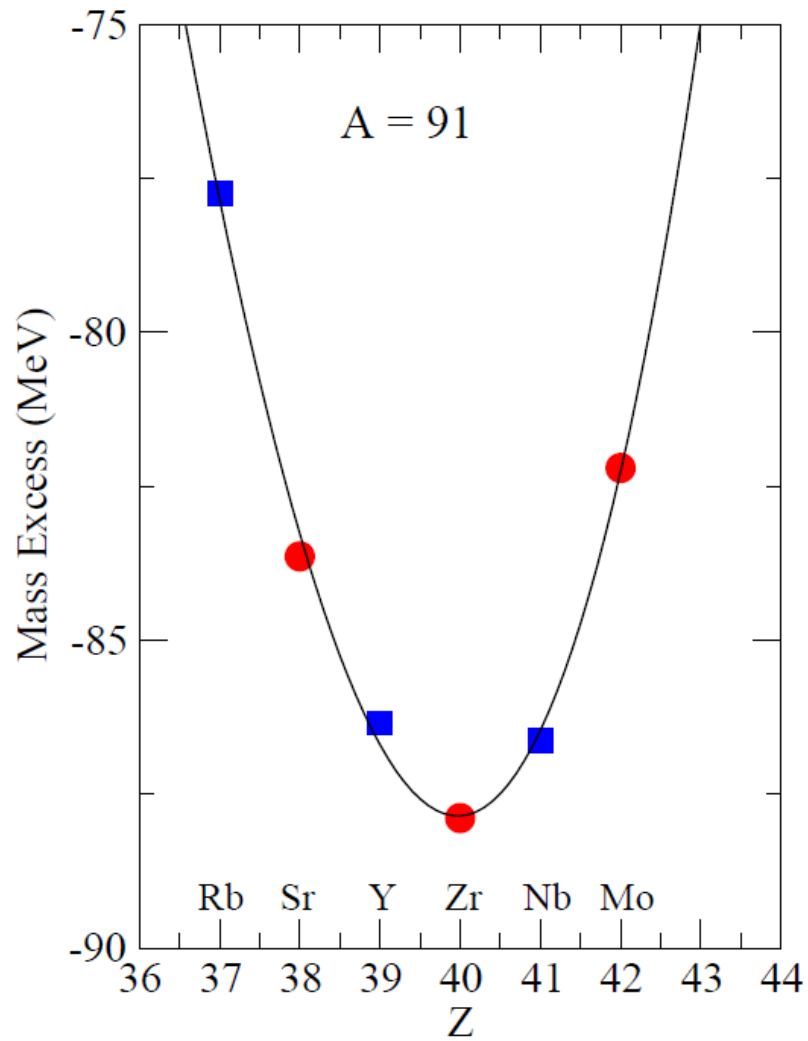
$$B(N, Z) = a_v A - a_s A^{2/3} - a_c \frac{Z^2}{A^{1/3}} - \underbrace{a_{sym} \frac{(N-Z)^2}{A}}$$

↓

$$m(A, Z) = f(A) + a_c \frac{Z^2}{A^{1/3}} + a_{sym} \frac{(A-2Z)^2}{A}$$







β線スペクトル

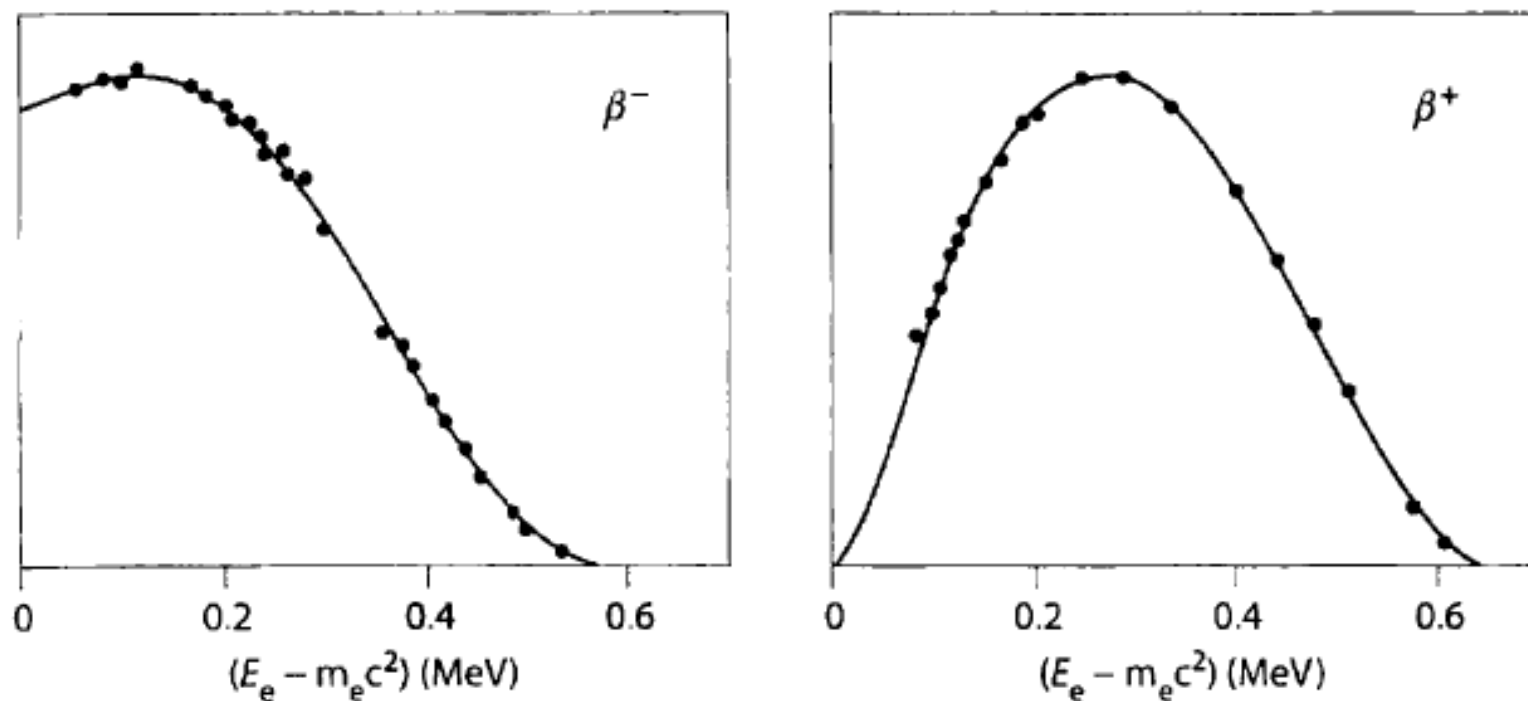
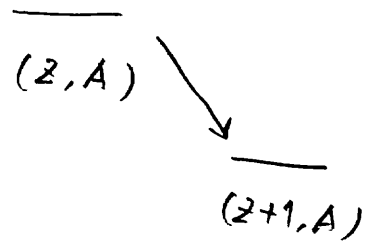
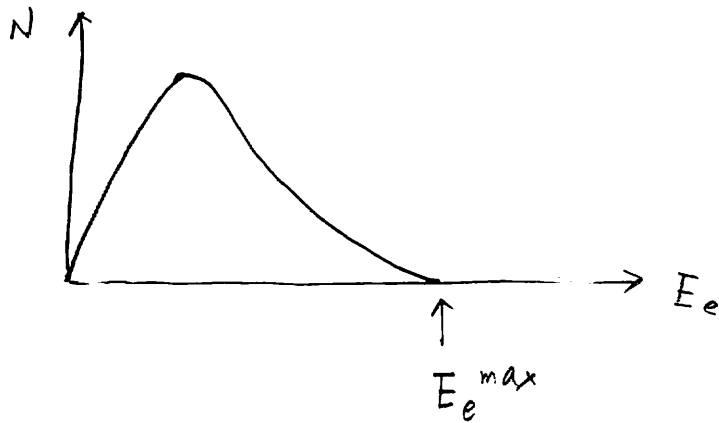
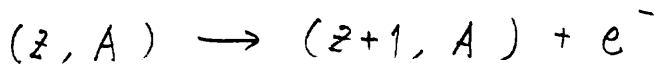


Figure 8.1 Energy distribution of the electron and positron in ^{64}Cu decay. The low energy part of the electron spectrum is enhanced due to the deceleration caused by the nuclear attraction. For the positron one has the opposite effect.

連続スペクトル

β崩壊について

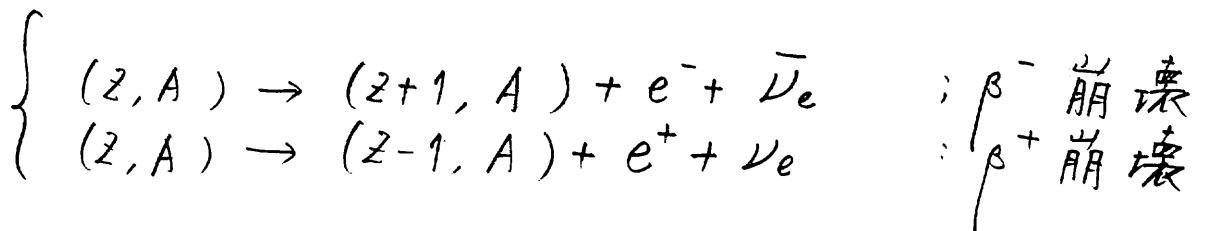
1. β線スピン外ルとニュートリノ



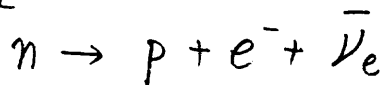
$$E_e^{max} \sim M(A, Z) c^2 - M(A, Z+1) c^2 - m_e c^2$$

連続分布 → 3体崩壊を示唆

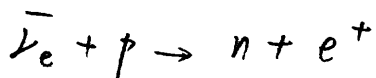
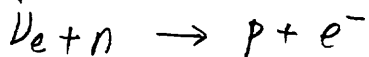
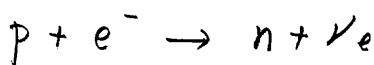
パウリ (1931): ニュートリノを仮定



素過程



ファストプロセス

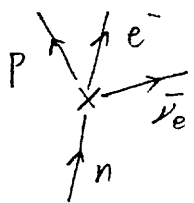


(電子捕獲)

ニュートリノ-原子核反応

2. β 崩壊の理論 (非相対論的, スピン無し模型)

$$H_\beta = g_F \int (\psi_p^\dagger(r) \psi_n(r)) (\psi_e^\dagger(r) \psi_{\bar{\nu}_e}(r)) dr + h.c.$$



$\psi_a^\dagger(r)$: 場所 r に a を生成 } させると $\Delta L = -2$
 \bar{a} を消滅 }

$\psi_e^\dagger \psi_{\bar{\nu}_e}$: $e^- + \bar{\nu}_e$ を生成

フェルミの Golden Rule:

$$\lambda = \frac{2\pi}{\hbar} \sum_{\text{終状態}} |\langle f | H_\beta | i \rangle|^2$$

• L 70トノ波動関数

$$\psi_e(r) = \frac{1}{\sqrt{V}} e^{iP_e \cdot r/\hbar}, \quad \psi_D(r) = \frac{1}{\sqrt{V}} e^{+iP_D \cdot r/\hbar}$$

$$P_D = -P_e$$

↓

$$\langle f | H_p | i \rangle = \frac{g_F}{V} \int [\psi_f^*(r) \textcircled{I_+} \psi_i(r)] e^{-i(P_e + P_D) \cdot r/\hbar} d^3r$$

$$e^{-i(P_e + P_D) \cdot r/\hbar} \sim 1 - \frac{i}{\hbar} (P_e + P_D) \cdot r + \dots$$

許容転移

(allowed transition)

1次禁止転移
(forbidden

transition)

$\Psi(r)$: 原子核の多体波動関数

• 選択則

$$\langle f | H_p | i \rangle \sim \frac{g_F}{V} \int [\psi_f^*(r) I_+ \psi_i(r)] d^3r$$

$\Delta I = 0$, パリティ変化なし

$$0^+ \rightarrow 0^+$$

・終状態の数

$$\sum_{\text{終状態}} = V^2 \int \frac{dP_e}{(2\pi\hbar)^3} \frac{dP_{\bar{\nu}_e}}{(2\pi\hbar)^3} \underbrace{\delta(E_e + E_{\bar{\nu}_e} - Q)}_{\text{エネルギー保存}}$$

$$= V^2 \frac{(4\pi)^2}{(2\pi\hbar)^4} \int P_e^2 dP_e P_{\bar{\nu}_e}^2 dP_{\bar{\nu}_e} \delta(E_e + \underbrace{E_{\bar{\nu}_e}}_{\substack{\parallel \\ cP_{\bar{\nu}_e}}}) - Q)$$

$$= V^2 \frac{(4\pi)^2}{(2\pi\hbar)^6} \int \underbrace{P_e^2 dP_e}_{\substack{\parallel \\ \frac{1}{c^2}(E_e^2 - m_e^2 c^4)}} \cdot \frac{1}{c^3} (cP_{\bar{\nu}_e})^2 d(cP_{\bar{\nu}_e}) \delta(cP_{\bar{\nu}_e} + E_e - Q)$$

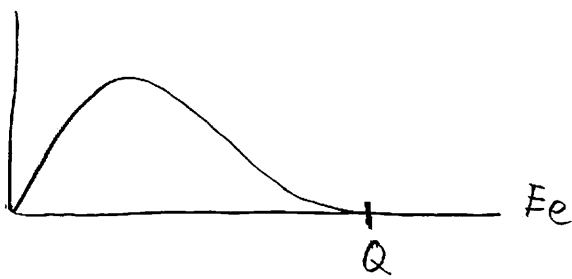
$$= V^2 \cdot \frac{(4\pi)^2}{(2\pi\hbar)^6} \cdot \int dP_e \cdot \frac{1}{c^5} (E_e^2 - m_e^2 c^4) (Q - E_e)^2$$

$$\hookrightarrow P_e = \frac{1}{c} \sqrt{E_e^2 - m_e^2 c^4} \quad \Downarrow \quad dP_e = \frac{E_e}{c \sqrt{E_e^2 - m_e^2 c^4}}$$

$$= V^2 \cdot \frac{(4\pi)^2}{(2\pi\hbar)^6} \cdot \int dE_e \frac{1}{c^6} (Q - E_e)^2 E_e \sqrt{E_e^2 - m_e^2 c^4}$$

$$\Downarrow \quad \lambda = \int dE_e \frac{d\lambda}{dE_e}$$

$$\frac{d\lambda}{dE_e} \propto |\langle f | H_{\beta} | i \rangle|^2 \cdot \underbrace{(Q - E_e)^2 E_e \sqrt{E_e^2 - m_e^2 c^4}}_{\substack{\downarrow \\ e^- \text{ のエネルギー分布}}}$$

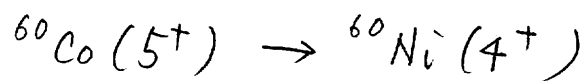


3. スピン導入 (ガモフ・テラ-遷移)

$$H_{\beta} = g_{GT} \int d\mathbf{r} \sum_{\text{spin}} [\psi_p^{\dagger}(\mathbf{r}) \vec{\sigma} \tau_+ \psi_n(\mathbf{r})] \\ \cdot [\psi_e^{\dagger}(\mathbf{r}) \vec{\sigma} \psi_{\nu_e}(\mathbf{r})]$$

$\Delta I = 1$, 10% 以上変化なし

$$0^+ \rightarrow 1^+$$



4. 相対論的な取り扱

$$H_{\beta} = \int d^4x \left\{ C_V (\psi_p^\dagger \gamma_\mu \psi_n) (\psi_e^\dagger \underbrace{\gamma^\mu}_{\text{ハリリ}} (1 + \underbrace{\gamma_5}_{\text{ハリリ}}) \psi_\nu) + h.c. \right. \\ \left. - C_A (\psi_p^\dagger \gamma_\mu \gamma_5 \psi_n) (\psi_e^\dagger \gamma^\mu \gamma_5 (1 + \gamma_5) \psi_\nu) + h.c. \right\}$$

"V-A 型"

$$\gamma_k = \begin{pmatrix} 0 & -i\sigma_k \\ i\sigma_k & 0 \end{pmatrix}, \quad \gamma_0 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$-i\gamma_k\gamma_5 = \begin{pmatrix} \sigma_k & 0 \\ 0 & -\sigma_k \end{pmatrix}, \quad -i\gamma_0\gamma_5 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

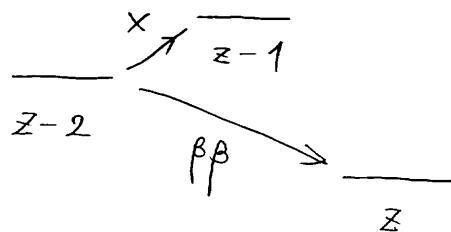
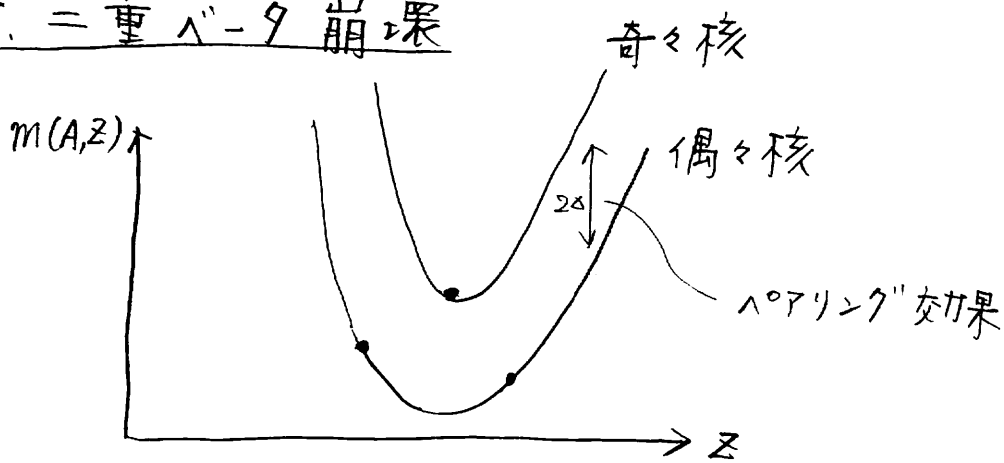
↑ ↓ "非相対論的極限":

$$\gamma_\mu \sim \delta_{\mu,0}, \quad \gamma_5 \sim 0, \quad -i\gamma_k\gamma_5 \sim \sigma_k \\ -i\gamma_0\gamma_5 \sim 0$$

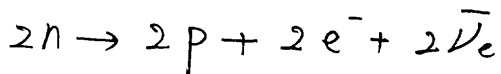
↓

$$H_{\beta} \sim \int d^4x \left\{ C_V (\psi_p^\dagger \psi_n) (\psi_e^\dagger \psi_\nu) + h.c. \right. \\ \left. + \underbrace{C_A (\psi_p^\dagger \vec{\sigma} \psi_n) \cdot (\psi_e^\dagger \vec{\sigma} \psi_\nu)}_{\text{GT}} + h.c. \right\}$$

5. 二重β崩壊

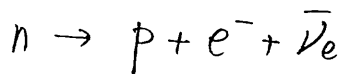


• $2\nu\beta\beta$

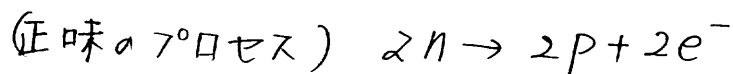
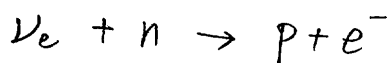


β崩壊が2回おこる

• $0\nu\beta\beta$



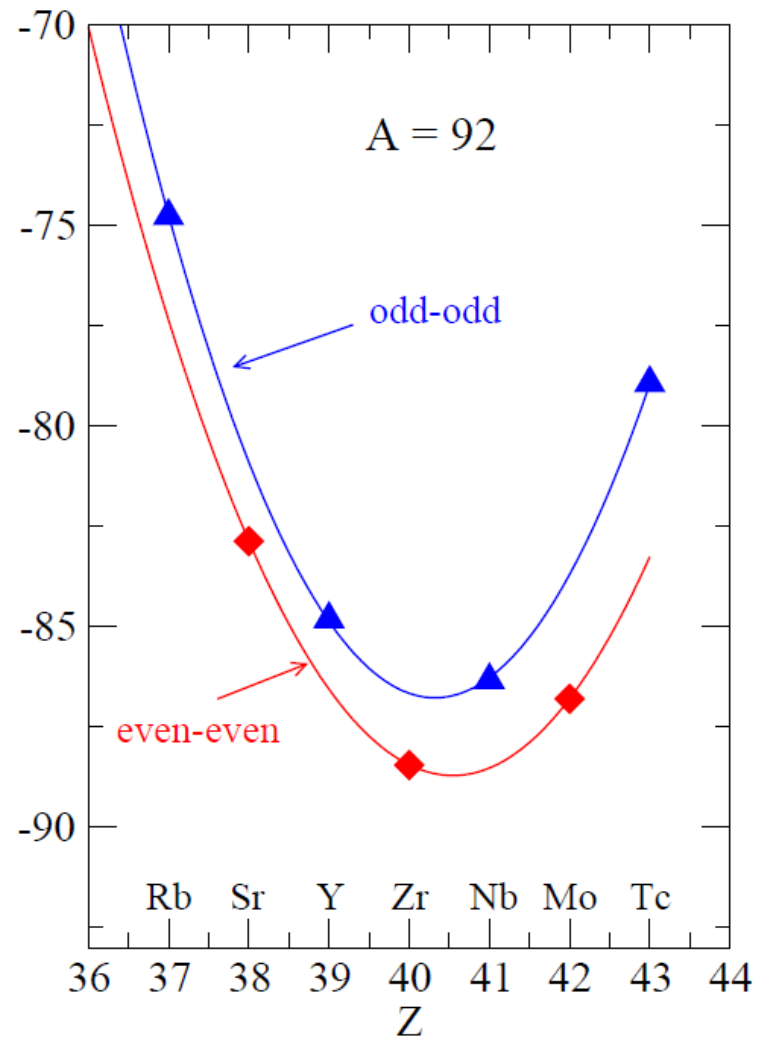
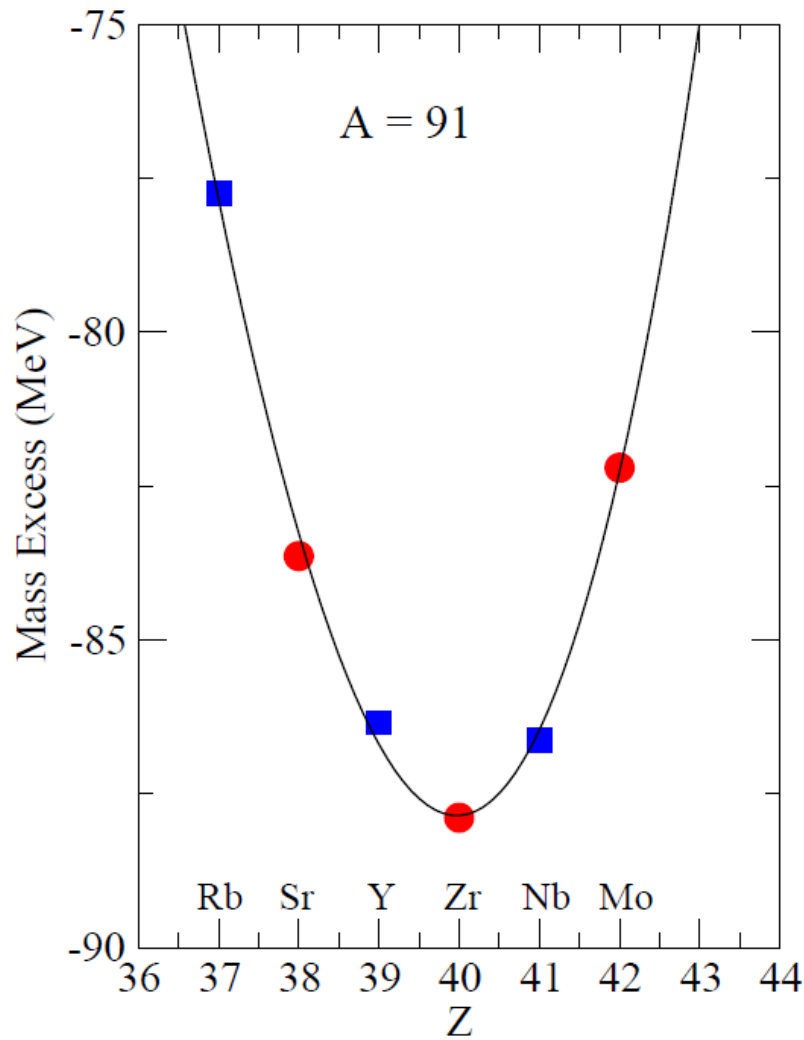
$\bar{\nu}_e = \nu_e$ 反ニュートリノ (反ニュートリノ)

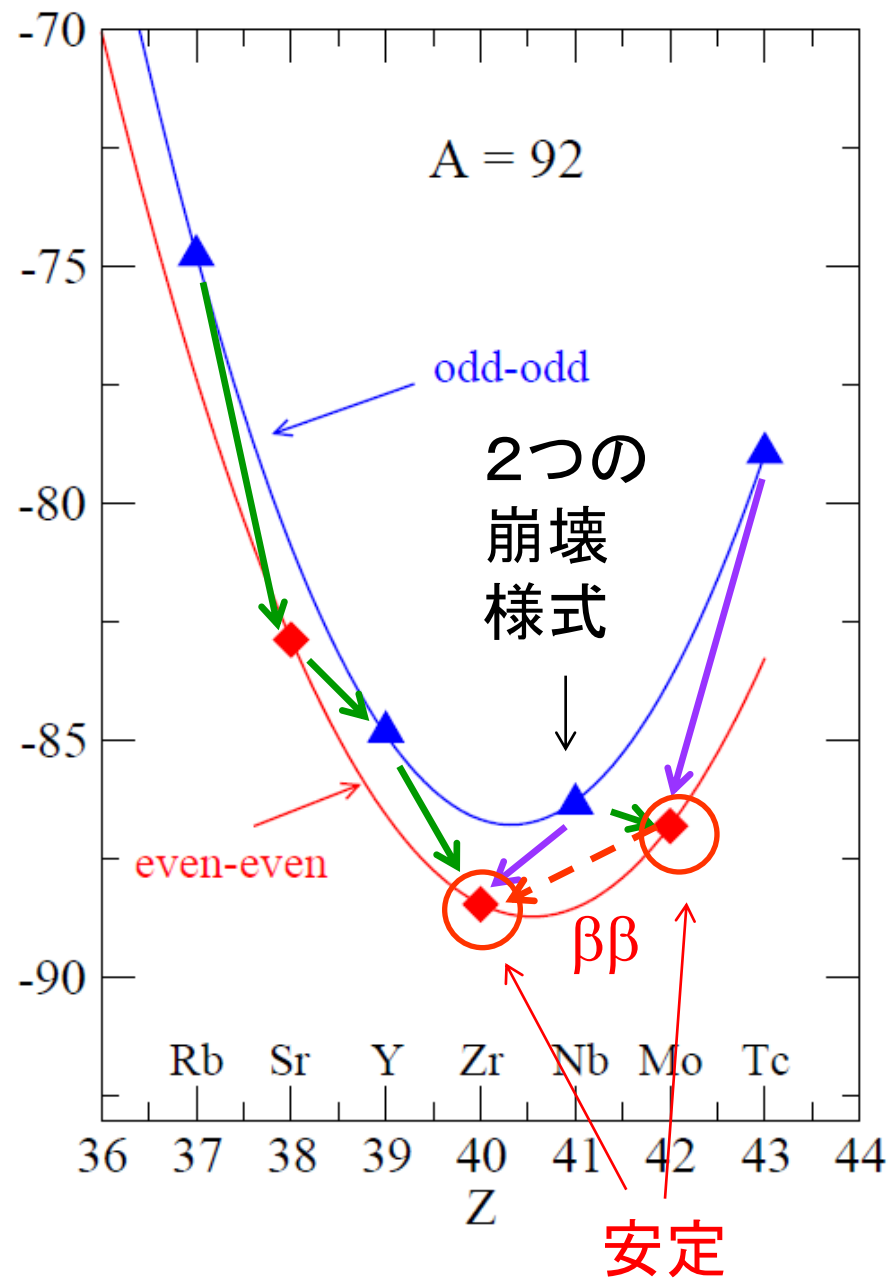
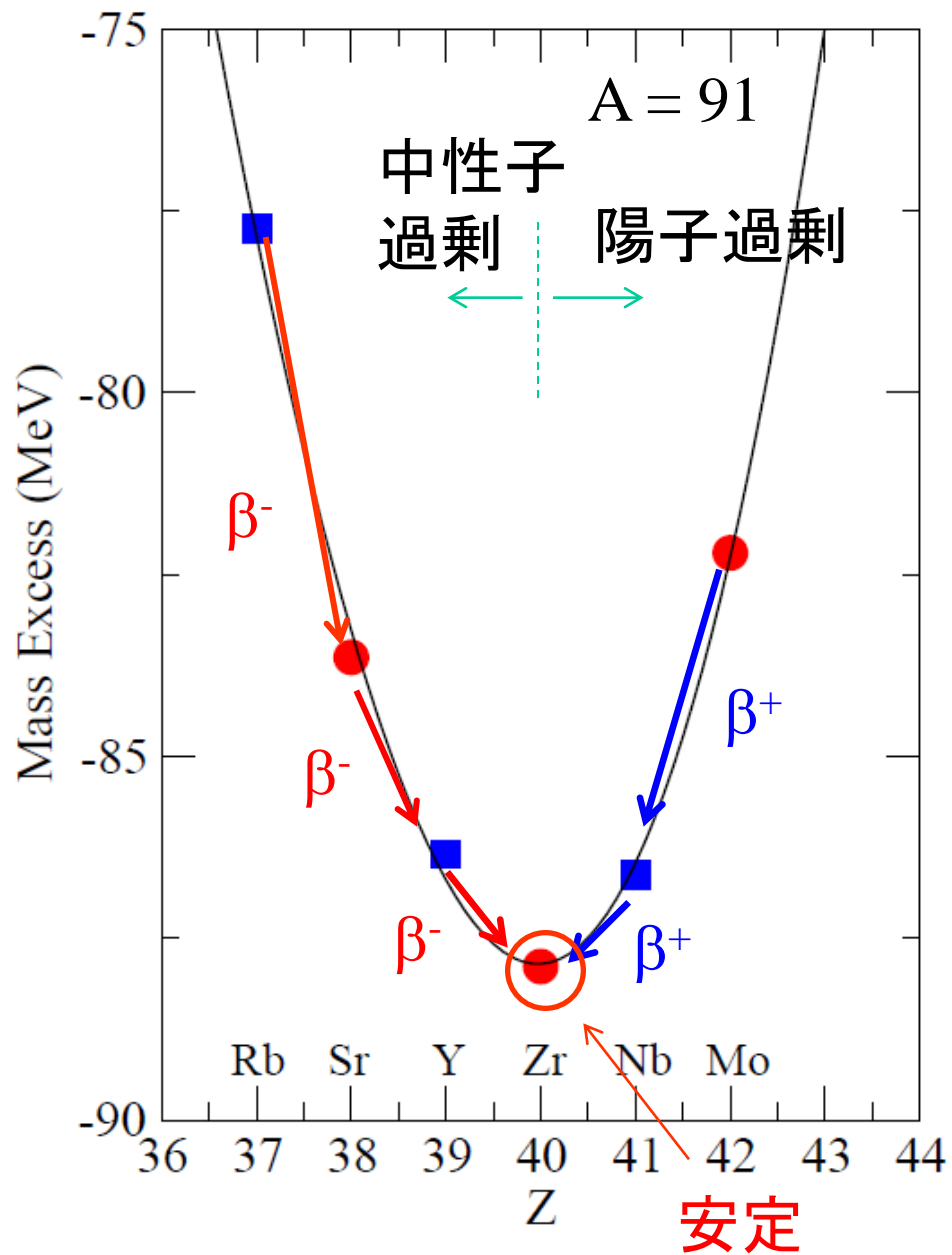


レプトン数非保存

KAMLANDで探索実験開始 (11秋~)

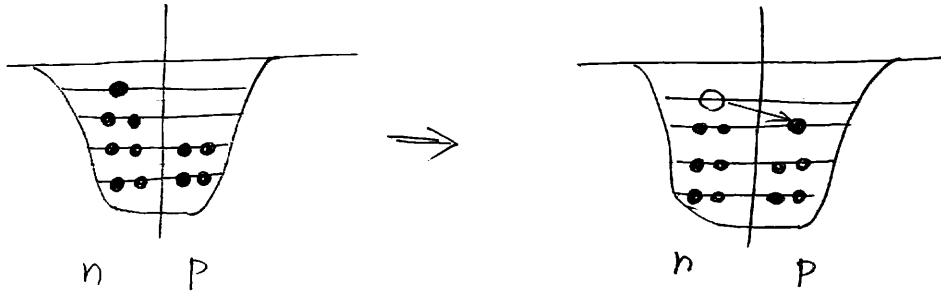
KAMLAND-ZEN



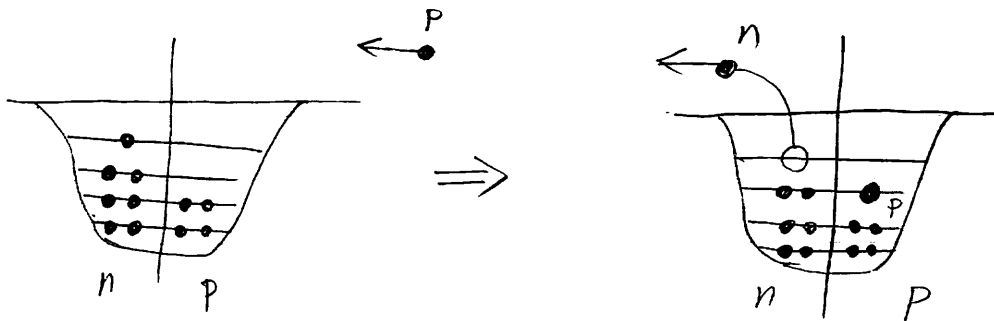


6. 荷電交換反応

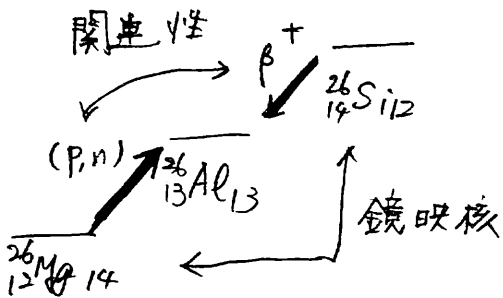
核内 T_z の β 崩壊



荷電交換反応 (p, n) 反応
 p を β^+ として n を出す反応



β 崩壊と同じ Ψ_i, Ψ_f
 同じ matrix element



$$\langle \Psi_f | T_z | \Psi_i \rangle$$

$$\text{or } \langle \Psi_f | \vec{\sigma} T_z | \Psi_i \rangle$$

他にも

ニュートリノ原子核反応

