Neutron Antineutron Oscillations in Nuclei

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Nuclear 'disappearance' lifetime

$$T_d(\mathrm{Fe}) > 7.2 \times 10^{31}\ \mathrm{yr} \quad (\mathrm{Soudan\ 2})$$

$$T_d(\mathrm{O}) > 1.8 \times 10^{32}\ \mathrm{yr} \quad (\mathrm{Super-Kamiokande})$$

set a lower limit on $n\bar{n}$ oscillation lifetime in free space

$$\tau_{n\bar{n}} > 1.3 \times 10^{8}\ \mathrm{sec} \quad (\Gamma_{\bar{n}} \sim 100\ \mathrm{MeV})$$

Here: exhibit origin of nuclear suppression by studying temporal evolution of $n\bar{n}$ oscillations in nuclei

Present talk

- Gal, PRC **61** (2000) 028201; refs. cited therein
- Friedman, Gal, Mares, NPA **761** (2005) 283, antiproton-nucleus potentials from X-rays and radiochemical data

Previous calculations

- Chetyrkin, Kazarnovsky, Kuzmin, Shaposhnikov, PLB **99** (1981) 358
- Alberico et al., PLB **114** (1982) 266, NPA **429** (1984) 445, NPA **523** (1991) 488
- Dover, Gal, Richard, PRD **27** (1983) 1090, PRC **31** (1985) 1423, NIM A **284** (1989) 13, PLB **344** (1995) 433
- Kondratyuk, JETP Lett. **64** (1996) 495
- Huefner, Kopeliovich, Mod. Phys. Lett. A **13** (1998) 2385

Mass matrix in nuclear matter - antineutrons annihilate

$$\begin{pmatrix} m & 0 \\ 0 & m - i\frac{\Gamma_{\bar{n}}}{2} \end{pmatrix} \qquad m_{\bar{n}} = m - i\frac{\Gamma_{\bar{n}}}{2} \qquad m_n = m$$

add oscillations, $\varepsilon = \tau_{n\bar{n}}{}^{-1}$: $\begin{pmatrix} m & \varepsilon \\ \varepsilon & m - i\frac{\Gamma_{\bar{n}}}{2} \end{pmatrix} \qquad \varepsilon << \Gamma_{\bar{n}}$

$$m_{\bar{n}} \approx m - i\frac{\Gamma_{\bar{n}}}{2} \qquad m_n \approx m - i\frac{2\varepsilon^2}{\Gamma_{\bar{n}}}$$

decay widths : $\gamma_{\bar{n}} = \Gamma_{\bar{n}} \qquad \gamma_n = \frac{4\varepsilon^2}{\Gamma_{\bar{n}}} = 4\frac{\varepsilon}{\Gamma_{\bar{n}}}\varepsilon << \varepsilon$

$$T_d = \gamma_n{}^{-1} \;\Rightarrow\; \tau_{n\bar{n}} = \varepsilon^{-1} = 2\left(\frac{T_d}{\Gamma_{\bar{n}}}\right)^{1/2}$$

seesaw mechanism : $\gamma_n \gamma_{\bar{n}} = 4\varepsilon^2 \qquad \begin{pmatrix} m & \varepsilon \\ \varepsilon & m \end{pmatrix} \qquad m_{\pm} = m \pm \varepsilon$

Temporal development

$$i\partial_t\psi_n = \varepsilon\psi_{\bar{n}} \quad i\partial_t\psi_{\bar{n}} = \varepsilon\psi_n - i\frac{\Gamma_{\bar{n}}}{2}\psi_{\bar{n}} \quad \Rightarrow \quad \left(\partial_t^2 + \frac{1}{2}\Gamma_{\bar{n}}\partial_t + \varepsilon^2\right)\psi = 0$$

$$\psi_j = \exp(i\omega_j t/2) \;\Rightarrow\; \omega^2 - i\Gamma_{\bar{n}}\omega - 4\varepsilon^2 = 0 \quad (\Gamma_{\bar{n}} = 0 \Rightarrow \omega = \pm 2\varepsilon)$$

$$\omega_{\bar{n}} = i\Gamma_{\bar{n}}\left(1 - 4\frac{\varepsilon^2}{\Gamma_{\bar{n}}^2} + \ldots\right) \;, \qquad \omega_n = i\frac{4\varepsilon^2}{\Gamma_{\bar{n}}}\left(1 + 4\frac{\varepsilon^2}{\Gamma_{\bar{n}}^2} + \ldots\right)$$

$$\omega = i\gamma \quad \Rightarrow \quad \gamma_{\bar{n}} \approx \Gamma_{\bar{n}} \;, \quad \gamma_n \approx \frac{4\varepsilon^2}{\Gamma_{\bar{n}}}$$

$T_d = \gamma_n^{-1}$? feedback mechanism from $\bar{n}$ channel?

Show that $\psi_{\bar{n}}$ remains small throughout 'oscillations':

$$\psi_n(t=0) = 1 \quad \psi_{\bar{n}}(t=0) = 0 \quad \Rightarrow \quad |\frac{\psi_{\bar{n}}}{\psi_n}| << 1 \;\text{ for all times } t$$

$$\psi_n(t) = \frac{\omega_{\bar{n}}}{\omega_{\bar{n}} - \omega_n} \exp\left(i\omega_n t/2\right) - \frac{\omega_n}{\omega_{\bar{n}} - \omega_n} \exp\left(i\omega_{\bar{n}} t/2\right)$$

$$\psi_{\bar{n}}(t) = \frac{2\varepsilon}{\omega_{\bar{n}} - \omega_n} \left[\exp\left(i\omega_n t/2\right) - \exp\left(i\omega_{\bar{n}} t/2\right)\right]$$

$$\omega_n \approx i\frac{4\varepsilon^2}{\Gamma_{\bar{n}}} \;, \quad \omega_{\bar{n}} \approx i\Gamma_{\bar{n}} \;, \quad \text{and for } t >> \Gamma_{\bar{n}}^{-1} \;:$$

$$|\psi_n(t)|^2 \to \exp\left(-4\frac{\varepsilon^2}{\Gamma_{\bar{n}}}t\right) \qquad |\psi_{\bar{n}}(t)|^2 \to \frac{4\varepsilon^2}{\Gamma_{\bar{n}}^2}\exp\left(-4\frac{\varepsilon^2}{\Gamma_{\bar{n}}}t\right)$$

Read disappearance rate from exponent:

$$\Gamma_d = \frac{4\varepsilon^2}{\Gamma_{\bar{n}}} \quad \Rightarrow \quad T_d = \Gamma_d^{-1} = \frac{1}{4}(\Gamma_{\bar{n}}\tau_{n\bar{n}})\tau_{n\bar{n}}$$

More rigorously:

$$\Gamma_d = \frac{-\partial_t\left(|\psi_n|^2 + |\psi_{\bar{n}}|^2\right)}{|\psi_n|^2 + |\psi_{\bar{n}}|^2}$$

For free-space oscillations: $\psi_n = \cos \varepsilon t, \quad \psi_{\bar{n}} = -i \sin \varepsilon t$

$$|\psi_n(t)|^2 + |\psi_{\bar{n}}(t)|^2 = 1 \;\Rightarrow\; \Gamma_d = 0$$

In matter show:

$$-\partial_t \left(|\psi_n|^2 + |\psi_{\bar{n}}|^2 \right) = \Gamma_{\bar{n}} \, |\psi_{\bar{n}}|^2 \quad \Rightarrow \; \Gamma_d = \Gamma_{\bar{n}} \frac{|\psi_{\bar{n}}|^2}{|\psi_n|^2 + |\psi_{\bar{n}}|^2}$$

$$\approx \Gamma_{\bar{n}} \left| \frac{\psi_{\bar{n}}}{\psi_n} \right|^2 \approx \frac{4\varepsilon^2}{\Gamma_{\bar{n}}}$$

Include spacial dependence and real potentials

$$i\partial_t \psi_n = -\frac{\Delta}{2m}\psi_n + U_n(r)\psi_n + \varepsilon\psi_{\bar{n}}$$

$$i\partial_t \psi_{\bar{n}} = -\frac{\Delta}{2m}\psi_{\bar{n}} + \left[U_{\bar{n}}(r) - iW(r)\right]\psi_{\bar{n}} + \varepsilon\psi_n$$

$$-\partial_t \int \left(\left|\psi_n\right|^2 + \left|\psi_{\bar{n}}\right|^2\right) d^3r = \int 2W \left|\psi_{\bar{n}}\right|^2 d^3r$$

Dependence on $U_n(r)$, $U_{\bar{n}}(r)$: implicit in wavefunctions

$$\left|\frac{\psi_{\bar{n}}}{\psi_n}\right|^2 \approx \frac{4\varepsilon^2}{\Gamma_{\bar{n}}^2 + 4(U_{\bar{n}} - U_n)^2} \;\Rightarrow\; \Gamma_d = \Gamma_{\bar{n}} \frac{4\varepsilon^2}{\Gamma_{\bar{n}}^2 + 4(U_{\bar{n}} - U_n)^2}$$

where $\Gamma_{\bar{n}},\ U_{\bar{n}},\ U_n$ are spacial averages, e.g.

$$\Gamma_{\bar{n}} = \frac{\int 2W \left|\psi_{\bar{n}}\right|^2 d^3r}{\int \left|\psi_{\bar{n}}\right|^2 d^3r}$$

$$T_d = (\Gamma_d/N)^{-1} = \frac{1}{4}\ \frac{\bar{\Gamma}_{\bar{n}}}{\Gamma_{\bar{n}}}\ (\bar{\Gamma}_{\bar{n}} \tau_{n\bar{n}})\ \tau_{n\bar{n}}\ , \quad \tau_{n\bar{n}} = 2\ (\Gamma_{\bar{n}} T_d)^{1/2} /\ \bar{\Gamma}_{\bar{n}}$$

where $\bar{\Gamma}_{\bar{n}} = \sqrt{\Gamma_{\bar{n}}^2 + 4(U_{\bar{n}} - U_n)^2}$

$$T_R = \bar{\Gamma}_{\bar{n}}^2/(4\Gamma_{\bar{n}})\ \text{suppression factor}\ (\mathrm{s}^{-1}) \;\Rightarrow\; T_d = T_R\ \tau_{n\bar{n}}^2$$

Estimates and calculations of T_R

LEAR and post-LEAR antiproton X-ray data analyses [Friedman, Gal, Mares, NPA **761** (2005) 283]:

$$U_{\bar{n}}(r=0) \approx -110 \text{ MeV} \;, \qquad \Gamma_{\bar{n}}(r=0) \approx 320 \text{ MeV}$$

Use surface half-values for averages:

$$T_R = 0.67 \times 10^{23}\ s^{-1} \qquad [U_n(r=0) = -60 \text{ MeV}]$$

Dover, Gal, Richard (1983-5) for a **similar** $\bar{n}$ potential:

$$T_R(\text{O}) = (0.8 \pm 0.1) \times 10^{23}\ s^{-1}, \;\; T_R(\text{Fe}) = (1.1 \pm 0.2) \times 10^{23}\ s^{-1} \;,$$

leading to:

$$\tau_{n\bar{n}} > (2.7 \pm 0.2) \times 10^8 \; s \; , \qquad \text{SK} \; - \; \text{O}$$

$$\tau_{n\bar{n}} > (1.4 \pm 0.2) \times 10^8 \; s \; , \qquad \text{Soudan 2} \; - \; \text{Fe}$$

Conclusion: somewhat larger lower limits on $\tau_{n\bar{n}}$ than deduced by experimenters, and a fairly small error.