

Neutron-antineutron in nuclei

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History

- $n - \bar{n}$ oscillation, see Mohapatra and others
- Meeting Maurice Goldhaber: 1982
- Controversy
 - Hot seminars on the subject
 - Nazarek and others



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PHYSICAL REVIEW

Limits on $n - \bar{n}$ Oscillations

A recent paper¹ reported an upper limit of $0.7 \times 10^{-10} \text{ yr}^{-1}$ for the rate of $n - \bar{n}$ transitions² in oxygen nuclei and deduced a corresponding lower limit of $2 \times 10^9 \text{ yr}$ for the free-neutron oscillation time, by use of a relation taken from Dover, Gal,³ and Richard.⁴ This is the latest in a series of papers (Refs. 11-17 of Ref. 1) which reflect the prevalent view that there is a direct relation between the $n - \bar{n}$ transition rates for free neutrons and for those inside a nucleus. This had led to the unjustified interpretation that improved tests

- Our results supported by Alberico et al., Kopeliovich et al.,

NEUTRON-ANTINEUTRON OSCILLATIONS IN NUCLEI

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S-D mixing in the deuteron

Rarita-Schwinger equations

$$\psi = \frac{u(r)}{r} |^3S_1\rangle + \frac{w(r)}{r} |^3D_1\rangle$$

$$-u''(r) + m V_{00} u(r) + m V_{02} w(r) = m E u(r) ,$$

$$-w''(r) + \frac{6}{r^2} w(r) + m V_{22} w(r) + m V_{02} u(r) = m E w(r) ,$$

$$V_{00} = V_c , \quad V_{22} = V_c - 2 V_T - 3 V_{LS} - 3 V_{LL} , \quad V_{02} = \sqrt{8} V_T .$$

Only about 5%, but crucial for the deuteron and many other nuclear states. See Ericson & Rosa-Clot and Blatt & Weisskopf



S-D mixing in charmonium

- At first, $J/\psi = 1S$, $\psi' = 2S$, $\psi'' = 1D$, etc.
- Leptonic coupling of ψ'' requires some S-wave admixture
- Usually

$$|S(^3D_1)\rangle \simeq \frac{\langle 2^3S_1 | \sqrt{8} V_T | 1^3D_1 \rangle}{E_0(2S) - E_0(1D)} |2^3S_1\rangle .$$

- Solving RS eqs. in specific models indicate some important 1S admixture: states with same node structure mix better
- Also

$$\psi^{(n)} \leftrightarrow D^{(*)} \bar{D}^{(*)} \leftrightarrow \psi^{(m)}$$

e.g., Cornell model

S-D mixing in muonium or hydrogen

- Quadrupole deformation of an atom such as (μ^+, e^-)
- Small effect in principle measurable in a gradient of electric field
- More delicate than in a $(Q\bar{Q})$ potential model, as the sum on intermediate states (if performed!), extends over the continuum

$$|D(\text{g.s.})\rangle = \sum_n \frac{\langle n^3D_1 | \sqrt{8} V_T | 1^3S_1 \rangle}{E_0(1S) - E_0(nD)} |n^3D_1\rangle .$$

- Sternheimer (Dalgarno & Lewis) equation

$$-w''(r) + \frac{6}{r^2} w(r) + m V_{22} w(r) + m V_{02} u_0(r) = m E_0 w(r) ,$$

- Good surprise: can be solved analytically, leading to a **compact expression** for the quadrupole moment of the ground state.

Deuteron lifetime

- Simplest nucleus. We restrict to *S*-wave, but including *D*-wave is straightforward
- Hulthen wave function

$$u(r) = N [\exp(-ar) - \exp(-br)] ,$$

with $a = 0.04570$ and $b = 0.2732 \text{ GeV}^{-1}$, and the proper behavior at $r \rightarrow 0$ and $r \rightarrow \infty$.

- **antineutron** component given by the Sternheimer equation

$$-w''(r) + m W w(r) - m E_0 w(r) = -m \gamma u(r) ,$$

with $E_0 = -0.0022 \text{ GeV}$ deuteron energy, $\gamma = 1/\tau(n\bar{n})$ strength of transition, and W complex potential of the $N\bar{N}$ interaction.

- **width** given by

$$-\frac{\Gamma}{2} = \int_0^\infty \text{Im } W |w(r)|^2 dr = -\gamma \int_0^\infty u(r) \text{Im } w(r) dr ,$$

Deuteron lifetime-2

- One gets (valid for other nuclei)

$$\Gamma \propto \gamma^2, \quad T = T_r \tau (n\bar{n})^2,$$

- where T_r is the **reduced lifetime** (in s^{-1} !).
- $N\bar{N}$ potential by Dover-Richard-Sainio (Khono-Weise, for instance, give similar results)

$$W(r) = V_{LR} - \frac{V_0 + i W_0}{1 + \exp[(r - R)/a]},$$

$$V_0 = W_0 = 0.5 \text{ GeV}, \quad a = 0.2 \text{ fm}, \quad R = 0.8 \text{ fm},$$

LR is the G -parity transformed of the NN potential,

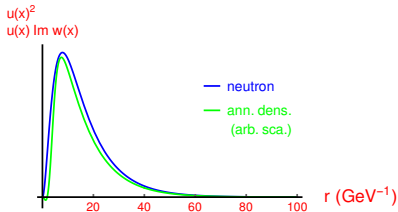
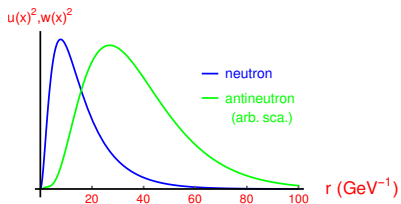
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$$T_r \simeq 3 \cdot 10^{22} \text{ s}^{-1}.$$

Thus $T \gtrsim 10^{33} \text{ yr}$ for the deuteron $\Rightarrow \tau(n\bar{n}) \sim 10^9 \text{ s}$.

Lifetime of the deuteron-3

- Spatial extension of n , \bar{n} and annihilation density
 $\propto \gamma u(r) \text{Im } w(r)$.



Lifetime of the deuteron-4

- Alternative formula

$$T_R \approx \frac{\langle V_n - \text{Re } V_{\bar{n}} \rangle^2 + \langle \text{Im } V_{\bar{n}} \rangle^2}{-2 \langle \text{Im } V_{\bar{n}} \rangle},$$

- is not too bad, but not too good either
- does not distinguish inner from outer neutrons
- works in the limit of **deep** binding!
- underestimates the rate of decay, especially in case of weakly-bound external neutrons

Lifetime of ^{16}O

- As an example of medium-size nucleus in proton-decay exp.
- See Dover, Gal, R., and Friedman & Gal, ...
- Shell-model with individual wave function for $s_{1/2}$, $p_{3/2}$, ... to reproduce the observed properties (mainly r.m.s.)
- See M. Bolsterli, E.O. Fiset, J.R. Nix, J.L. Norton (Los Alamos). Phys.Rev. C5 (1972) 1050-1077
- Summarized as an **effective neutron potential** for each shell, $V_n = V(n - ^{15}\text{O})$
- While $V_{\bar{n}}$ taken from \bar{p} -nucleus phenomenology (exotic atoms, low-energy scattering)
- **Same inhomogeneous** eqn. as for deuteron, for each shell

$$-u_{\bar{n}}''(r) + \frac{\ell(\ell+1)}{r^2} u_{\bar{n}}(r) + \mu W u_{\bar{n}}(r) - \mu E_0 u_{\bar{n}}(r) = -\mu \gamma u_n(r),$$

Results for ^{16}O and ^{56}Fe

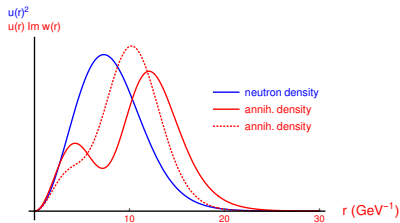
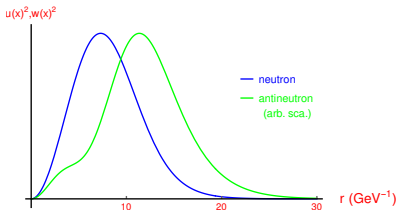
TABLE I. Reduced lifetime T_R (in units of 10^{23} sec^{-1}) for the neutrons in ^{16}O .

Orbit lj	$s_{1/2}$	$p_{3/2}$	$p_{1/2}$	Average
Model I (Ref. 18)	1.63	1.11	0.94	1.2
Model II (Ref. 19)	1.21	0.85	0.75	0.8

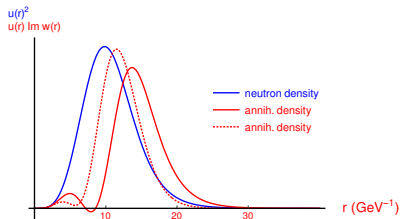
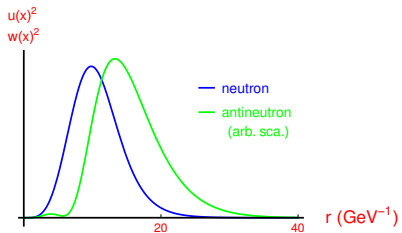
TABLE II. Reduced lifetime T_R (units 10^{23} sec^{-1}) for the neutrons in ^{56}Fe

Orbital lj	T_R (Model II)	T_R (Model I)
$s_{1/2}$	1.68	3.32
$p_{3/2}$	1.50	2.75
$p_{1/2}$	1.54	2.92
$d_{5/2}$	1.26	2.04
$2s_{1/2}$	1.09	1.60
$d_{3/2}$	1.33	2.29
$f_{7/2}$	0.98	1.34
$2p_{3/2}$	0.57	0.64
Average	1.13	1.69

Results for ^{16}O and ^{56}Fe



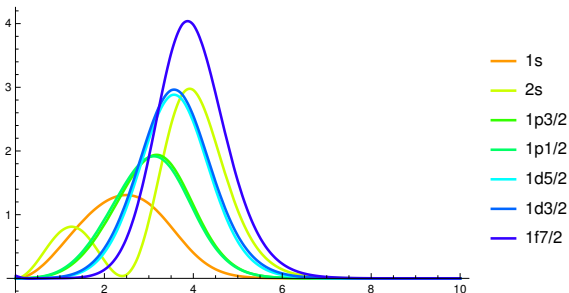
Results for ^{16}O and ^{56}Fe



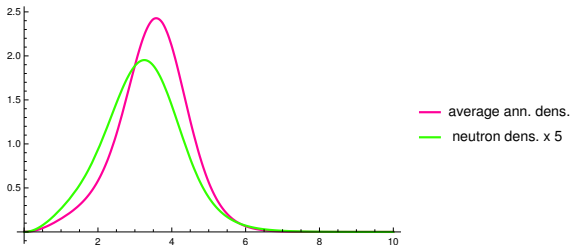
Results for ^{40}Ar

- Same strategy: start from realistic individual neutron wf (K. Bennaceur and M. Bender who use the method of Phys.Rev. C5 (1972) 1050-1077)
- Adopt a \bar{n} -nucleus potential deduced from \bar{p} -atoms and \bar{p} -scattering
- Estimate the induced \bar{n} -wf for each shell
- And the corresponding annihilation densities

Results for ^{40}Ar



Results for ^{40}Ar



Conclusions

- Oscillations **mainly outside**
- Subsequent annihilation **mainly at the surface**
- So minimal risk of dramatic medium renormalization of the basic process
- Good knowledge of the antinucleon-nucleus interaction in this region
- Nuclei with **neutron skin** or neutron halo favored
- $T_R \sim 10^{23} \text{ s}^{-1}$ in $T(\text{nucleus}) = T_r \tau_{n\bar{n}}^2$