Calculation of the Suppression Factor for Bound Neutron-Antineutron Transformation

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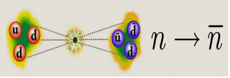
Theoretical Innovations for Future Experiments
Regarding Baryon Number Violation
August 3, 2020



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History

- $n - \bar{n}$ oscillation, see Mohapatra and others
- P.G.H. Sanders 1980; Dover et al. 1982
- Controversy
  - Hot seminars on the subject
  - Nazaruk and others

New limit on the neutron–antineutron transitions

V.I. Nazaruk [1]
Institute for Nuclear Research of the Academy of Sciences of Russia, 60th October Anniversary Prospect 7a, 117312 Moscow, Russia

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Editor: P.V. Landshoff

Abstract

We reexamine the problem of extracting a lower limit on the free-space $n\bar{n}$ oscillation time τ_{min} from the nuclear annihilation lifetime. It is shown that the $n\bar{n}$ transitions in the medium are suppressed only by a factor 0.5. As a result we get $\tau_{min} = 3 \times 10^{31}$ yr, which increases the previous limit by 31 orders of magnitude.

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

A recent paper[1] reported an upper limit of 0.7 $\times 10^{-30}$ yr^{-1} for the rate of $n \to \bar{n}$ transitions[2] in oxygen nuclei and deduced a corresponding lower limit of 2×10^7 s for the free-neutron oscillation time, by use of a relation taken from Dover, Gal, and Richard.[3] 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 $n \to \bar{n}$ 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

W.M. ALBERICO, A. DE PACE and M. PIGNONE
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and
Dipartimento di Fisica Teorica, Università di Torino, Torino, Italy

Received 11 June 1990

Quadrupole deformation of atoms

- 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.

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

Deuteron lifetime

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

$$u(r) = N\,[\exp(-a\,r) - \exp(-b\,r)]\ ,$$

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

- antineutron component given by the Sternheimer equation

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

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

- width given by

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

Deuteron lifetime-2

- One gets (valid for other nuclei)

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

- 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)

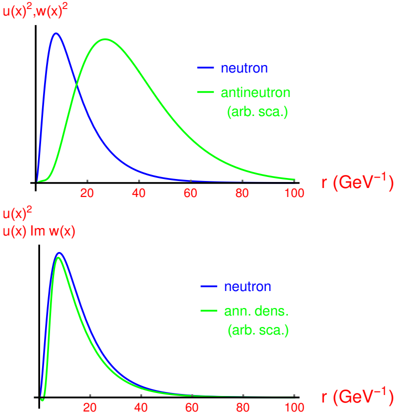
$$W(r) = V_{LR} - \frac{V_0 + i\, W_0}{1 + \exp[(r - R)/a)} ,$$
$$V_0 = W_0 = 0.5\,\text{GeV} , \quad a = 0.2\,\text{fm} , \quad R = 0.8\,\text{fm} ,$$

  LR is the G-parity transformed of the NN potential,
-
$$T_r \simeq 3\, 10^{22}\,\text{s}^{-1} .$$

  Thus $T \gtrsim 10^{33}$ yr for the deuteron $\Rightarrow \tau(n\bar{n}) \sim 10^9$ s.
- Sanders: $2.5\, 10^{22}\,\text{s}^{-1}$

Lifetime of the deuteron-3

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



Lifetime of the deuteron-4

- Recent recalculations
- Oosterhof et al., see previous speaker, using effective field theory
- Phys. Rev. Lett. **122**, no.17, 172501 (2019) [arXiv:1902.05342],
- T_R about 2.5 times smaller
- Haidenbauer et al. (Chin. Phys. C **44**, no.3, 033101 (2020), arXiv:1910.14423 [hep-ph]),
- also using effective field theory,
- agree with the old calculation of the 80s.
- To be fixed!

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Lifetime of the deuteron-5

- Alternative formula

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

- 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, $V_n = V(n - {}^{15}\mathrm{O})$
- 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

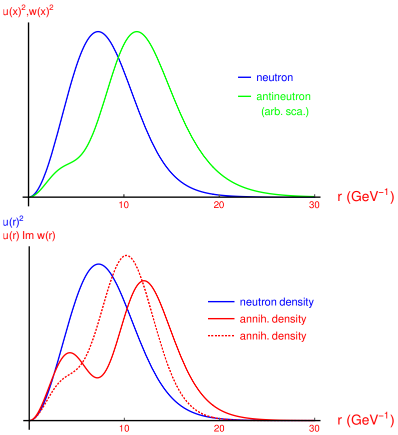
TABLE I. Reduced lifetime T_R (in units of 10^{23} sec^{-1}) for the neutrons in ^{16}O.

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

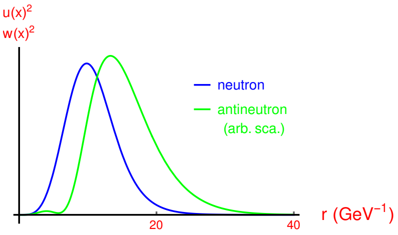
TABLE II. Reduced lifetime T_R (units 10^{23} sec^{-1}) for the neutrons in ^{56}Fe

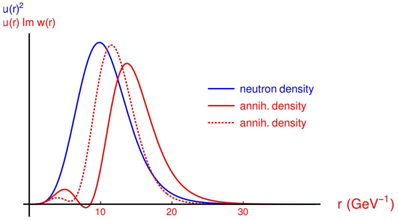
Orbital lj	T_R (Model II)	T_R (Model I)
$s_{1/2}$	1.68	3.32
$p_{3/2}$	1.50	2.75
$p_{1/2}$	1.54	2.92
$d_{5/2}$	1.26	2.04
$2s_{1/2}$	1.09	1.60
$d_{3/2}$	1.33	2.29
$f_{7/2}$	0.98	1.34
$2p_{3/2}$	0.57	0.64
Average	1.13	1.69

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



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

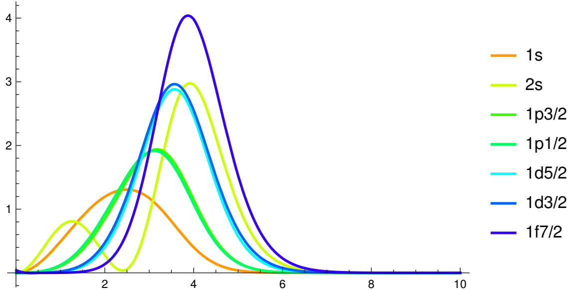




Results for $^{40}\mathrm{Ar}$

- Same strategy: start fromm 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



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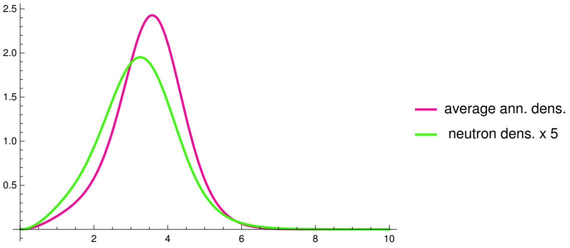
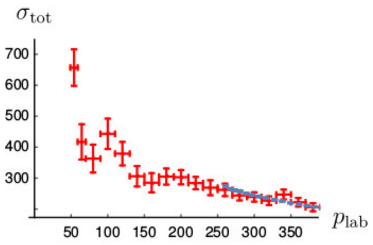
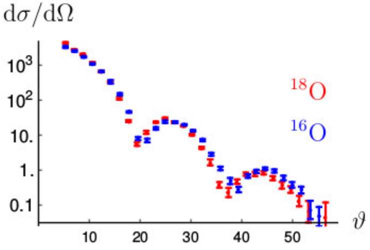
Results for $^{40}\mathrm{Ar}$



Isospin considerations

- The formalism involves $\bar{n}$-A interaction
- Most data deal with $\bar{p}$-A
- $\exists$ some indirect indication by PS184 (right)





- $\exists$ a few data on $\bar{n}$, in particular by the OBELIX collaboration.
  Left: $\bar{n}p$ vs. $\bar{p}p$ total cross section

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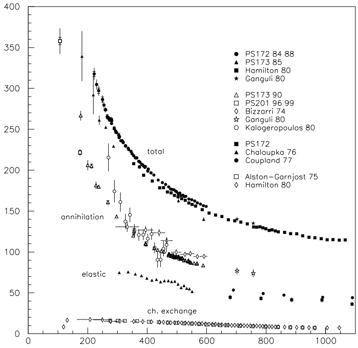
Isospin considerations

- Before the discovery of the antiproton at Berkeley, one expected

$$\sigma_{\rm ann} < \sigma_{el} < \sigma_{\rm c.e.}(\bar{p}p \to \bar{n}n)$$

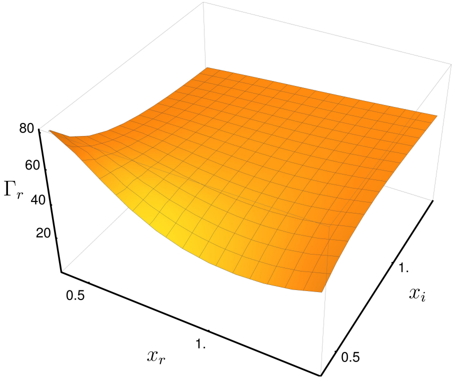
- The reverse is obtained. Much cancellation

$$\mathcal{M}_{\rm c.e.} \propto \mathcal{M}(I=0) - \mathcal{M}(I=1)$$



Stability of T_R

- More $\bar{n}$ attraction $\to$ more annihilation but also more suppression. So T_R remains remarkably constant.
- Test on deuteron $V_r - i\, V_i \to x_r\, V_r - i\, x_i\, V_i$



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
- Framework solid, results stable
- $T_R \sim 10^{23}\,\mathrm{s}^{-1}$ in $T(\mathrm{nucleus}) = T_r\,\tau^2_{n\bar{n}}$