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AUTHOR(S): ALBERT G. PETSCHKE

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Neutron-Oscillation Experiments
using Ultracold Neutrons

Albert G. Petschek*
Los Alamos National Laboratory

Abstract

The figure of merit for a neutron oscillation experiment using ultracold neutrons is shown to be competitive with that for beam experiments.

* Also at New Mexico Institute of Mining and Technology

I. Introduction

Neutron oscillation experiments can be performed in three environments. Neutrons in nuclei can be observed in large quantities for long times but the interaction with the rest of the nucleus inhibits the oscillations and introduces theoretical uncertainties. Neutrons in beams can be observed also, but require evacuation and magnetic field elimination from large volumes. Hence the third method, involving confining neutrons (ultracold neutrons) in bottles has received considerable attention. This includes unpublished calculations (Ramsay, 1983; Fidecaro, 1983), proposals (Yoshiki, 1980), preprints (Marsh and McVoy, 1983) and publications (Kazarnovskii et al., 1981; Chetyrkin et al., 1981).

An advantage one might expect from the use of bottled neutrons is that the confining volume will generally be smaller than the volume of a beam tube used in a beam experiment. Thus smaller volumes need to be evacuated and rendered field free. Also the detector might be smaller. The confining time of neutrons can approach the neutron lifetime, which far exceeds the flight time in any feasible beam experiment. Thus a single neutron can be observed for a long time.

Disadvantages are that, because of the very low energy (< 0.25 μeV) of neutrons that can be confined and the difficulty of producing and manipulating such neutrons, the densities that can be achieved are very low. Also the coherence between the neutron and antineutron is destroyed after a few collisions with the wall.

Whereas in a beam experiment, the $\bar{n}$ annihilation rate per n is proportional to the square of the flight time, for the bottle experiment it is proportional to the product of the coherence time and the confining time. This product is far less than the square of the confining time.

II. Neutron Densities

Previous discussion of the feasibility of bottle $n\bar{n}$ experiments used densities of 0.1 cm^{-3} or less. At present we believe we can achieve much higher densities. The following calculation, due to T. Dombeck, applies to Be, which confines neutrons to 7 m s^{-1} . For bottles with maximum confining velocity v_m , all the following densities should be multiplied by $(v_m/7 \text{ m s}^{-1})^3$. The published density claimed at Argonne was 0.12 cm^{-3} (Brun et al. 1980). Reanalysis using a lower detector efficiency gave 0.15 cm^{-3} . A funnel plate at ZING gave an increase of a factor 3. As the final density depends only on the peak neutron flux we can scale by the ratio of protons/pulse ZING $\rightarrow$ LAMPF $5 \cdot 10^{13}/1.0 \cdot 10^{12} = 50$ and the ratio of the number of neutrons per proton $= 1.5$, due to LAMPF's higher energy. Improvements in the cold moderator and guide tube should give a factor ~ 8 . Altogether then $0.15 \cdot 3 \cdot 50 \cdot 1.5 \cdot 8 = 250 \text{ cm}^{-3}$. Further improvements might result from better moderator coupling ($\times 4$) a howitzer moderator ($\times 2$), CH_4 rather than H_2 ($\times 2$, but with safety problems) and use of a uranium booster target ($\times 3$). On the other hand, transport losses to the bottle might reduce the flux by about a factor 10. Fill rates for

these densities are estimated to be $2 \text{ } \ell\text{s}^{-1}$.

It is the increase in density by a factor of over 10^3 that makes it again attractive to investigate ultracold neutrons for the $\bar{n}\bar{n}$ experiment, especially as a bottle and filling mechanism are likely to be built for a neutron electric dipole moment experiment.

III. Wall Potentials

Ultracold neutrons are confined because the effective potential is repulsive. For neutrons the potential is known for many substances (e.g. Golub and Pendlebury, 1979). For antineutrons the scattering length cannot be measured for lack of low energy $\bar{n}$ beams. However, antiprotonic atoms allow measurement of the interaction between antiprotons and nuclei. These interactions have been interpreted in terms of $\bar{p}$ -nucleon scattering lengths. Assuming charge symmetry and ignoring the poorly established difference between $\bar{p}p$ and $\bar{p}n$ potentials, one can then calculate the $\bar{n}$ nucleus optical potential (Dover, Gal and Richards, 1983) from which one can calculate a scattering length. For example for Fe, Dover, Gal and Richards give Woods-Saxon parameters $R = 4.933 \text{ fm}$, $a = 0.52$ and a well depth $249 + 107i \text{ MeV}$ (Model I) or $107 + 222i \text{ MeV}$ (Model II). These lead to scattering lengths of $-6.27 + 1.43i \text{ fm}$ and $-6.21 + 1.08i \text{ fm}$ respectively.

The connection between the scattering length f and the potential in material with a density N nuclei cm^{-3} is $V = -2\pi\hbar^2 Nf/M$ where M is the neutron mass. Taking a density $8.8 \cdot 10^{22} \text{ atoms cm}^{-3}$ gives antineutron potentials $0.143 - 0.0327i \text{ } \mu\text{eV}$ and $0.142 -$

0.02461 μeV for models I and II respectively. These numbers are more or less appropriate to Ni, a material often used for bottles because the neutron potential is exceptionally high, 0.25 μeV . We shall see, however, that for the $n\bar{n}$ experiment it is better to have the n and $\bar{n}$ potentials similar, rather than have one very high.

IV. Confinement

There are several ways to discuss the behavior of the $n\bar{n}$ system in a bottle:

a. Consider the neutrons as wave packets, bouncing back and forth in the bottle. Account must then be taken of the difference in the phase shift and amplitude on reflection between neutron and antineutron. The effective free time (flight time) of the neutron is the time required to accumulate a relative phase shift of 1. This is the approach we shall take.

b. Consider energy eigenfunctions of the $n\bar{n}$ system in the bottle. Because of $\bar{n}$ absorption (and also because of the finite neutron lifetime) these eigenvalues are complex. Since the interaction of the neutron and antineutron with the wall are very different, the wave function at a particular eigenvalue is predominantly either neutron or antineutron, whereas in field-free space the n and $\bar{n}$ amplitudes are the same. The effective flight time can be deduced from the antineutron amplitude in the dominantly neutron wave function. This is the approach taken by Marsh and McVoy.

c. Solve the time dependent Schroedinger equation starting with a pure neutron wave function. This is the approach I took in an internal Los Alamos memorandum. The $\bar{n}$ amplitude then reaches a saturation value after the effective free time.

d. Find uncoupled neutron and antineutron wave functions in the bottle. These will have different energies, and the energy difference, just like that due to a magnetic field, gives an effective free time.

All these approaches are correct and can be shown to lead to essentially the same result. The gravitational potential complicates all of them, especially since it turns out that the lowest energy neutrons are the most valuable.

If k_1 is the wave number in the vacuum and

$$k_2 = [k_1^2 - 2 MV/\hbar^2]^{1/2}$$

the wave number in the wall, then the reflection coefficient is

$$R = R_e^1 = -(k_2 - k_1)/(k_2 + k_1)$$

which clearly approaches -1 for small k_1 . Thus the absorption by the wall approaches zero for small incident energies and the phase shift on reflection approaches π for both neutrons and antineutrons.

Using the Model I potential and the fact that the time between bounces is $2 v/g$, gives for the effective flight time of an antineutron bouncing on a horizontal surface $2 v g^{-1} (1 - \bar{R}^2)^{-1} = 2.4$ s, nearly constant up to an energy of 0.04 μ eV and then diminishing slowly. See Table 1. Increase in bounce time balances decrease

TABLE 1

Reflection Parameters for Neutrons and Antineutrons

Antineutron Potential $\bar{V} = 0.143 - 0.327i$ μeV . Neutron Potential V

Energy (μeV)	Velocity (m/s)	$\bar{R}$	$\bar{\theta}$	$\frac{1}{(1-\bar{R}^2)\bar{v}}$ (s/m)	$\frac{2\bar{v}}{g(1-\bar{R}^2)}$ (s)	$V = 0.25 + 0i$ μeV			$V = 0.14 + 0i$ μeV		
						θ	$\frac{1}{(\theta-\bar{\theta})v}$ (s/m)	$\frac{2v}{g(\theta-\bar{\theta})}$ (s)	θ	$\frac{1}{(\theta-\bar{\theta})v}$ (s/m)	$\frac{2v}{g(\theta-\bar{\theta})}$ (s)
10^{-4}	.1585	.994	-3.09	620	2.43	-3.10	- .607	-2.37			
.01	1.385	.941	-2.62	6.32	2.48	-2.74	-5.92	-2.32	-2.60	43.9	17.2
.02	1.959	.915	-2.39	3.13	2.45	-2.57	-2.88	-2.26	-2.36	20.7	16.3
.04	2.77	.872	-2.05	1.51	2.36	-2.32	-1.36	-2.13	-2.01	9.12	14.3
.08	3.92	.786	-1.51	.67	2.09	-1.94	- .59	-1.86	-1.43	3.12	9.8
.12	4.80	.655	-.994	.37	1.72	-1.61	- .34	-1.59	- .78	.95	4.5
.16	5.54	.447	-.575	.23	1.41	-1.29	- .25	-1.59			
.20	6.19	.301	-.414	.18	1.39	- .93	- .32	-2.46			

in reflection coefficient. If the neutron potential is $0.25 \mu\text{eV}$, the reciprocal rate of phase shift $2 v g^{-1}(\bar{\theta} - \theta)^{-1}$ is nearly constant at 2.3 s and then diminishes slowly. Thus if the vertical walls are very far away and if the lid of the bottle is high enough (about 1.5 m at $0.14 \mu\text{eV}$) the effective neutron flight time is 2.3 s.

For confinement between vertical walls, the collision rate increases with velocity and $(1 - \bar{R}^2)$ and $(\bar{\theta} - \theta)$ also increase with velocity. The effective flight time is therefore inversely proportional to the energy. We have roughly $(1 - \bar{R}^2)^{-1} v^{-1} = 0.62(0.1 \mu\text{eV}/E) \text{ s/m}$ and $(\bar{\theta} - \theta)^{-1} v^{-1} = 0.60 (0.1 \mu\text{eV}/E) \text{ s/m}$ where E is the energy. These must be multiplied by the box dimension L to give the effective flight time. The ratio of this effective flight time to the average time between wall collisions is, $2.6(E/0.1 \mu\text{eV})^{-1/2}$. For energies above $E = 0.024 \mu\text{eV/m L}$ collisions with the vertical surfaces are more important, below that energy the horizontal surface has a larger effect, and the effective free time is essentially constant.

It is happenstance that the absorption times (involving $\bar{R}$) and the dephasing times (involving $\bar{\theta} - \theta$) are about equal. Choosing a material for which the neutron potential is closer to the real part of the $\bar{n}$ potential will increase the dephasing times so that dephasing becomes insignificant. Since neutron scattering lengths cover a wide range, it should be easy to arrange for a neutron potential equal to the real part of the $\bar{n}$ potential if the latter can be accurately ascertained and is less than about 0.25

μeV.

In a rectangular box, we can treat reflections in each orthogonal direction independently, using an energy corresponding to the normal velocity, if reflections are specular. Otherwise, only the energy is conserved and angles vary. According to Robson (1976) and Steyerl (1977), specular reflection dominates for very smooth surfaces.

V. Antineutron Annihilation Rate

To simplify the following discussion, assume specular reflection. Also neglect neutron decay and suppose that the real parts of the n and $\bar{n}$ potential in the wall have been matched so that dephasing can be neglected and only $\bar{n}$ absorption need be considered. Schroedinger's equation then becomes

$$i \frac{\partial}{\partial t} \begin{pmatrix} \phi \\ \bar{\phi} \end{pmatrix} = \begin{pmatrix} 0 & \delta \\ \delta & i/2T \end{pmatrix} \begin{pmatrix} \phi \\ \bar{\phi} \end{pmatrix}$$

where ϕ and $\bar{\phi}$ are n and $\bar{n}$ amplitudes, δ is the $n\bar{n}$ coupling and T is the mean life of an antineutron determined by the wall annihilation rate. On our assumptions, in a square lidless box

$$T^{-1} = T_z^{-1} + (v_x^2 + v_y^2)/(C_h L)$$

where $T_z = 2.4$ s, $C_h = 12$ m s⁻¹, v_x and v_y are horizontal velocity components and L is the horizontal dimension of the box. Neglect of the magnetic field level splitting in Schroedinger's equation is justified if $B \mu_n/\hbar = 10^4$ Gauss⁻¹ s⁻¹ · $B \ll T_z^{-1}$ or $B < 10^{-5}$

Gauss.

With a time dependence $\phi \propto e^{-at}$ we find eigenvalues $a = (2T)^{-1}$ for the predominantly $\bar{n}$ wave function and $a = 2T\delta^2$ for the predominantly neutron wave function, the one of interest. Here $\delta \ll T$ has been assumed. A neutron introduced into the box will, after a transient of length $2T$ settle into the predominant neutron wave function with antineutron relative amplitude $2T\delta$. The number of neutrons will decay at a rate $2a = 4T\delta^2$ and this must be the rate of $\bar{n}$ annihilation. Hence, the average over the neutron distribution function of T is of interest.

The neutron distribution function will be flat over the energy range of ultracold neutrons if a turbine or similar injection device was used. It may be far from flat if neutrons are injected directly from a moderator. Take it to be flat then

$$\langle T \rangle = v_m^{-3} \int_0^{v_m} dv_x \int_0^{v_m} dv_y \int_0^{v_m} dv_z [T_z^{-1} + (v_x^2 + v_y^2)(C_h L)^{-1}]^{-1},$$

where v_m is the maximum confined velocity. The integral is greatly simplified by replacing $\int_0^{v_m} dv_x \int_0^{v_m} dv_z$ by $2\pi \int_0^{v_m} v dv$. Then

$$\begin{aligned} \langle T \rangle &\approx v_m^{-3} \int_0^{v_m} 2v dv [T_z^{-1} + v^2 C_h^{-1}]^{-1} \int_0^{v_m} dv_z \\ &= C_h L v_m^{-2} \ln(1 + v_m^2 T_z C_h^{-1} L^{-1}). \end{aligned}$$

With $v_m = 5.2$, corresponding to $0.14 \mu\text{eV}$ and other parameters as given, and with L in meters

$$\begin{aligned}\langle T \rangle &= 0.45L \ln(1 + 5.4 L^{-1}) \text{ s} \\ &= 0.83 \text{ s at } L = 1 \text{ m.}\end{aligned}$$

Had gravity been ignored and a lidded box been taken, the almost identical result $\langle T \rangle = 3 C_h L v_m^{-2}$ would have been obtained.

At a density of 100 n cm^{-3} (corresponding to $0.14 \text{ } \mu\text{eV}$ wall potential) in a 1 m^3 box, there would be 10^8 neutrons and an annihilation rate of $10^8 \cdot 4 \cdot 0.83 \cdot \delta^2$ per second, or $3.3 \cdot 10^8 \delta^2$ per second. For $\delta = 10^{-7}$, the average interval between annihilation is $3 \cdot 10^5 \text{ s}$ or 4 days. It is customary to define a figure merit, equal to the annihilation rate over δ^2 . We have obtained $3.3 \cdot 10^8$, compared to a range of 10^6 to 10^{10} for other proposed experiments (Anderson, 1982).

The main uncertainty in the calculation comes from the $\bar{n}$ scattering length. It is difficult to see how to design or interpret an $n\bar{n}$ experiment with ultracold neutrons without a reliable value for the scattering length.

Enhancements of the experiment might be obtained by trapping neutrons to $0.25 \text{ } \mu\text{eV}$, expanding and cooling them and then transporting them into the bottle in which the experiment is to be done. This would allow one to use neutrons well below the confining energy which have long effective free times as well as volumes greater than the 2 m^3 determined by a fill rate of $2 \text{ } \ell\text{s}^{-1}$ and neutron lifetime of 1000 s . The use of large flat bottles is to be preferred since the $\bar{n}$ loss due to vertical motion is constant. Since the effective free time of about 1 s is only a few bounces, schemes involving the use of only part of the wall as an n anni-

hilator probably won't work. The figure of merit for this experiment is competitive with that for other proposed experiments.

If the further improvements in neutron density (a factor of 5-50) suggested in Sec. II can be realized, then the experiment is as good or better than any yet proposed.

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