LE JOURNAL DE PHYSIQUE-LETTRES

J. Physique — *LETTRES* 44 (1983) L-321 - L-326

1^{er} MAI 1983, PAGE L-321

Classification

Physics Abstracts

13.40F — 14.20 — 29.25

New application of the superthermal Ultra-Cold Neutron source. I — The search for the neutron electric dipole moment

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(Reçu le 13 décembre 1982, révisé le 21 février 1983, accepté le 15 mars 1983)

Résumé. — Une source « super-thermique » de neutrons ultra-froids qui contient une solution diluée d'hélium 3 dans l'hélium 4 peut permettre la recherche du moment dipolaire électrique du neutron sans limiter l'angle solide des neutrons incidents. De même, on peut ainsi éviter des pertes de neutrons dues à différentes causes.

Abstract. — A superthermal Ultra-Cold Neutron source containing a dilute solution of polarized ^3He in ^4He can provide a method for carrying out the search for the neutron electric dipole moment which will not place any limits on the solid angle of the incoming neutrons and eliminate losses due to several causes.

As recent experiments [1-3] have confirmed the principles of the superthermal source of Ultra-Cold Neutrons [4-6] it now seems appropriate to consider some new techniques for applying the extremely high UCN densities [7] made available by this source. In this paper we discuss a new method for searching for the neutron electric dipole moment (edm) using UCN.

UCN are neutrons with energies so low ($\sim 10^{-3}$ K) that they are totally reflected from many materials at any angle of incidence and hence can be stored in material bottles for times approaching the β decay lifetime [8, 9].

In the superthermal UCN source [1-7] neutrons with wavelength $\lambda_c \sim 10$ Å can scatter from liquid ^4He , emit a phonon and come to rest, while neutrons in a small band around λ_c can be scattered into a small energy interval around zero (UCN). If this process takes place inside a vessel whose walls are a good UCN container the resulting UCN buildup to a density given by

$$\zeta_{\text{UCN}} = Q_u \tau \quad (1)$$

where Q_u is the production rate of UCN per cm^3 per second and τ is the storage time of UCN in the vessel resulting from wall losses, β decay and ^4He upscattering [6]. Equation (1) represents the saturation density achieved after several storage times, τ . Because of the weakness of the interaction between the UCN and the ^4He (relaxation times $\gtrsim 500$ s due to ^4He upscattering

have been observed [1]), the UCN are not in thermal equilibrium and the UCN density (1) is not limited to what would be achieved if the neutrons were in thermal equilibrium with the source. In addition, UCN are produced by incoming neutrons regardless of their direction so the production rate, Q_u , will increase with the solid angle of the incoming neutrons [4, 7].

The search for a neutron edm [10-12] using UCN requires the storage of polarized UCN in a vessel which is subject to parallel electric and magnetic d-c fields and a perpendicular magnetic field rotating about the d-c fields. The existence of an edm would be demonstrated by a change in the spin flip probability produced by the rotating magnetic field, due to the reversal of the direction of the electric field with respect to the d-c magnetic field. With current technology the effect is detected by looking for a change in the number of UCN exiting the storage chamber through a polarization analyser.

At present it is thought to use the superthermal UCN source more or less as a conventional source for storage experiments — the UCN accumulated in the source being periodically admitted to the experimental storage chamber. As the search for the parity and time-reversal violating neutron electric dipole moment (edm) [10-12] requires polarized neutrons, the UCN must enter and exit the experimental chamber through one or more polarizers which introduce losses in addition to those associated with the transport of the UCN (usually through several windows) and the volume dilution factor. Currently used polarizers [10, 13] require rather high magnetic fields and thus must be located outside the magnetic shields used to produce the low-field environment required for the edm search. In this paper we describe a method that will enable the entire edm experiment to be performed inside the liquid helium of the superthermal source, thus eliminating the above mentioned losses.

We now note that the well known large neutron absorption cross section for ^3He is due almost entirely to the $J^\pi = 0^+$ excited state of ^4He , that is with the neutron and ^3He spins directed oppositely [14]. Thus polarized ^3He selectively absorbs neutrons of one spin only and has long been considered as a possible neutron polarizer [15]. Thus if a small amount of polarized ^3He were dissolved in the superfluid ^4He in a superthermal UCN source, UCN polarized parallel to the ^3He polarization would selectively accumulate in the liquid helium. The storage time would now be a function of the neutron spin with $\tau_+/\tau_- = \kappa > 1$ an experimentally adjustable parameter. Can such an arrangement also be used to detect magnetic resonance transitions of the stored UCN, thus eliminating the need to remove the UCN from the storage chamber by passing them through a polarizer?

To answer this question we consider what happens when we apply a constant magnetic field, B_0 (parallel to the ^3He spins) as well as a perpendicular rotating magnetic field, B_1 , to the system, which is also exposed to a steady flux of neutrons. There will thus be a steady rate of production of UCN so that at times between t' and $t' + dt'$ there will be $Q_u dt'/2$ UCN produced per unit volume in each of the spin states. At time t , these neutrons will be distributed so that

$$Q_u \frac{dt'}{2} [P_{+-}(t - t') + P_{--}(t - t')]. \quad (2)$$

UCN will be in the $| - \rangle$ spin state and the number in the $| + \rangle$ state will be given by (2) with $(+) \leftrightarrow (-)$, where $P_{ij}(t)$ is the probability that a UCN in state $| i \rangle$ at $t = 0$ will be in the state $| j \rangle$ at t , including the effects of UCN losses. Thus the total number of UCN, per unit volume in the state $| - \rangle$ at time t is given by the integral of (2) with respect to t' over the interval $t' = t_0$ to $t' = t$, where t_0 is the time at which the UCN production is switched on with the chamber empty. In order to calculate the steady state conditions we set $t_0 = -\infty$ and write

$$N_-(t) = \frac{Q_u}{2} \int_0^\infty dx [P_{+-}(x) + P_{--}(x)]. \quad (3)$$

In the presence of the magnetic fields and spin dependent UCN absorption the Schroedinger equation can be written

$$|\psi(t)\rangle = a(t)|+\rangle + b(t)|-\rangle, \quad (4)$$

$$i\dot{a} = (\omega_0 - i\gamma_+) a/2 + \beta e^{-i\omega t} b, \quad (5)$$

$$i\dot{b} = \beta e^{i\omega t} a - (\omega_0 + i\gamma_-) b/2,$$

where $\beta = \mu B_1/\hbar$, $\omega_0/2 = \mu B_1$, $\gamma_{\pm} = 1/\tau_{\pm}$, ω is the frequency of the rotating magnetic field and μ is the neutron magnetic dipole moment. The solution of (5) yields

$$P_{+-}(t) = \frac{\beta^2}{|f|^2} e^{-\bar{\gamma}t} [e^{\gamma t} + e^{-\gamma t} - 2 \cos xt], \quad (6)$$

$$P_{+-}(t) + P_{--}(t) =$$

$$= \frac{e^{-\bar{\gamma}t}}{4|f|^2} [e^{-\gamma t}(A+B) + e^{\gamma t}(A-B) + 2C \cos xt - 2D \sin xt], \quad (7)$$

with

$$A = |f|^2 + \lambda, \quad C = |f|^2 - \lambda, \quad B = 2\Omega x + \gamma y, \quad D = 2\Omega y + \gamma x \quad (8)$$

$$\lambda = \Omega^2 + \gamma^2/4 + 4\beta^2, \quad \gamma = \gamma_- - \gamma_+, \quad \bar{\gamma} = (\gamma_+ + \gamma_-)/2$$

$$\Omega = \omega - \omega_0, \quad f = [\Omega^2 + 4\beta^2 - \gamma^2/4 - i\gamma\Omega]^{1/2} \equiv x + iy.$$

In the case $\gamma_+ = \gamma_-$ (6) reduces to the well known « Rabi » transition [16] probability as it should. Substituting (7) into (3) we find

$$\gamma_- N_-(t) = \frac{Q_u}{2} \left[\frac{\alpha^2 + (1+\kappa)^2/4 + 2(1+\kappa)\zeta^2}{\alpha^2 + (1+\kappa)^2(4\zeta^2/\kappa + 1)/4} \right] \equiv \frac{Q_u}{2} S_-(\alpha) \quad (9)$$

with $\zeta = \beta/\gamma_+$, $\alpha = \Omega/\gamma_+$, $\kappa = \gamma_-/\gamma_+$.

$S_-(\alpha)$ has a peak at $\alpha = 0$ falling off to $S_- = 1$ for large α . The width and height of the peak depend on ζ and κ .

The expression (9) gives the steady state rate of absorption of UCN by ^3He , in the ideal case of 100 % ^3He polarization, neglecting the contribution of loss mechanisms other than ^3He absorption to γ_- . In principle this effect could be used to detect the resonance directly as each UCN absorbed releases a triton and proton with 746 keV total energy and liquid ^4He is an excellent scintillator releasing ultra-violet radiation [17]. Thus a quasi-steady state experiment would be possible; with constant rotating field frequency we could look for changes in the steady state counting rate associated with changing the relative direction of the electric and magnetic fields. In this case the signal due to the UCN would be swamped by that due to absorption of the incoming neutrons so it will be necessary to switch off the incoming beam periodically to allow data taking, thus reducing the overall experimental sensitivity.

Neglecting this effect we calculate the sensitivity of such an experiment by finding the maximum value of $dS_-/d\alpha$ from (9) and maximize this with respect to ζ^2 and κ . The result is

$$(dS_-/d\Omega)_{\max} = -\gamma_+/16 \quad (10)$$

at $\alpha = 2$, when $\kappa = 3$, $\zeta^2 = 3/2$.

Another method of performing the experiment would be to measure the total number of neutrons remaining in the helium after a given time by inserting a detector into the storage

chamber. In the steady state the total number of UCN in the chamber is given by the sum of equation (3) and the equation obtained from it by the interchange $(+) \leftrightarrow (-)$.

Defining

$$S_-(\alpha) = 1 + \eta(\alpha), \quad (11)$$

we find from (9) that

$$S_+(\alpha) = 1 - \eta(\alpha). \quad (12)$$

By combining (9), (11), (12) we find

$$\gamma_- N_- + \gamma_+ N_+ = \frac{Q_u}{2} [S_+(\alpha) + S_-(\alpha)] = Q_u, \quad (13)$$

as it must. In the steady state the total loss rate equals the total production rate. From (9), (11), (12) we find for the total UCN density

$$\begin{aligned} N = N_+ + N_- &= \frac{Q_u}{2} [(1 + \eta)/\gamma_- + (1 - \eta)/\gamma_+] \\ &= \frac{Q_u}{2 \gamma_+ \kappa} [1 + \kappa + (1 - \kappa) \eta(\alpha)]. \end{aligned} \quad (14)$$

To find the optimum operating conditions we proceed as before. The result is

$$\left(\frac{\partial N}{\partial \Omega} \right)_{\max} = - \frac{Q_u}{2 \gamma_+} \left(\frac{0.045}{\gamma_+} \right) \quad (15)$$

at $\alpha = 2.62$, $\kappa = 4.24$, $\zeta^2 = 2.12$.

The measurement would be carried out by allowing the density to build up for a period of time, then inserting a detector into the storage chamber, the incoming neutrons being switched off during the relatively short counting time. In this technique the UCN density builds up under the influence of the magnetic (and electric) fields contrary to current methods where the buildup takes place in a separate chamber, involving a volume dilution factor.

The time scale of the approach to steady state conditions can be seen, by considering the slowest term in (7), to be given by

$$\tau_1 \lesssim [\bar{\gamma} - |\gamma|]^{-1}, \quad (16)$$

which yields $\tau_1 \lesssim [1.35 \gamma_+]^{-1}$ for conditions (12) and $\tau_1 \lesssim [1.49 \gamma_+]^{-1}$ for the conditions (15), that is somewhat shorter than the filling time of a conventional superthermal source (for 100 % ^3He polarization $\gamma_+ = \gamma_0$, the loss rate of UCN due to all causes other than the ^3He).

The sensitivity of the conventional method, applying the rotating field in two short pulses (Ramsey method [16]) is given by an expression analagous to (15) but with the number in brackets replaced by 0.18, i.e. four times larger. However, this will be reduced by the volume dilution factor (~ 2 to 3) so that the sensitivity of the two methods as measured by the slope of the resonance curve will not be too different in the two methods. Of course it would be possible to produce polarized UCN starting with a beam of polarized $10 \text{ \AA}$ neutrons but in general this will place severe restrictions on the input solid angle and the UCN will have to leave the apparatus through a polarizer to detect the transition [18]. The main advantage of the method proposed here is the fact that it allows the use of a large solid angle of incoming neutrons and eliminates the losses due

to transmission through pipes, windows and polarizing foils, and the volume dilution factor. It has been estimated [7] that one can achieve UCN densities of 2×10^4 UCN/cm³ in a superthermal source operating at a practical distance (inside the moderator) from a primary source with a thermal (300 K) flux of 5×10^{14} n/cm²/s. This is comparable to 200 UCN/cm³ which is expected if an identical superthermal source were located outside the shielding at the end of a loss-free guide. This increase in density should result in at least a factor of 10 increase in sensitivity of the edm experiment.

A value of $\kappa = 4.24$ (15) would require a ³He polarization of 62 % if other UCN losses did not play a role. In the above comparison with the conventional method we assumed γ_+ was the same in both cases, i.e. $\gamma_+ = \gamma_0$ so a ³He polarization less than 100 % will result in a loss of relative sensitivity for the methods under discussion. For example a 90 % polarization of ³He will result in an increase of 25 % of γ_+ for $\kappa = 4.24$.

³He polarizations on the order of 70-80 % have already been obtained by laser optical pumping [19] and in solid ³He [20] and it seems that still higher polarization can be achieved by cryogenic techniques [20, 21]. Wall relaxation times of 40 hours have been measured for dilute solutions of polarized ³He in ⁴He [22].

Ultra-violet scintillations in ⁴He have been measured [17] by coating the walls of the chamber with a wavelength shifter. For the present experiment it would be necessary to develop a deuterated wavelength shifter with suitable UCN reflection properties, or to cover the wavelength shifter with a thin layer of material transparent to u-v but reflecting for UCN. The scintillations due to β decays in the walls activated by the incoming neutrons should not be too much of a problem. They can contribute as little as 10^{-4} of the UCN counting rate.

At the low temperatures under consideration here it seems unlikely that a conventional UCN detector can be used. However silicon resistance bolometers as constructed by Frossati *et al.* [23] are sensitive enough to allow the detection of single neutrons and work is in progress to develop these devices as neutron detectors [21]. Another possibility would be to use a superconducting bolometer [24].

Although several technical developments are necessary before realizing the methods proposed here, it is evident that the use of a dilute solution of polarized ³He in the « superthermal » UCN source will allow the search for the neutron electric dipole moment to be carried out making use of the maximum possible solid angle of incoming neutrons and without any losses due to polarizer foils, volume dilution, etc., thus offering the possibility of higher sensitivity than other methods. The method seems most attractive for a pulsed neutron source where one can work quite close to the core and the incident neutrons can be easily shut off.

Acknowledgments.

I would like to thank G. Frossati, R. Gähler, K. A. Steinhauser, J. Morse and J. T. Jenkin for helpful discussions.

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