ULTRA-COLD NEUTRONS

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Since their first production in 1968 Ultra-Cold Neutrons (UCN) have been used in the most sensitive search for the P and T violating neutron electric dipole moment (edm) and the most accurate measurement of the neutrons's β decay lifetime. The main advantage of UCN in these and similar experiments derives from the fact that UCN can be stored for long periods of time in material and magnetic bottles thus allowing significantly longer measurement times than classical beam experiments.

We present a short summary of the physics of UCN, intended to serve as an introduction to the talks of Doyle and Lamoreaux at this conference.

1. Introduction

Ultra-cold Neutrons (UCN) are best characterized by the property of total reflection at all angles of incidence from many material surfaces. The interaction of slow neutrons with atomic nucleii is effectively repulsive for most materials (the main exception being Hydrogen) because for most nucleii the neutron wave function makes many oscillations in the attractive potential well of the nuclear-neutron interaction with the result that the conditions on the well parameters (depth and range) for an effective attraction are very stringent and are met for only a small number of nucleii.[1] Neutrons interacting with condensed matter see the nucleii in the material as a sort of forest of short range potential spikes each of which produce a spherical scattered wave. The sum of all these scattered waves is a plane wave with a $\vec{k}$ vector altered from that of the incident plane wave. Thus the interaction of the neutron with matter can be described by an index of refraction or alternatively by an effective potential which is given by the volume average of the potential spikes of the individual nucleii:

$$V = \frac{2\pi\hbar^2 Nb}{m_n} = \frac{157 \cdot \rho_{g/cm^2} \cdot b_{ferm}}{A} \tag{1.1}$$

where ρ_{g/cm^2} is the material density, b_{ferm} the nuclear scattering length in *fermis*, m_n the neutron mass and A the atomic weight of the material. The extension of equ. 1.1 to mixtures of elements or isotopes is obvious. Thus neutrons with wavelengths long enough that no diffraction can occur see the surface of a solid or liquid as a potential step and will be totally reflected if their kinetic energy in the direction perpendicular to the surface satisfies:

$$E_{\perp} = E_{tot} \sin^2\theta < V \tag{1.2}$$

and neutrons with $E_{tot} < V$ will be totally reflected for all angles of incidence and will be referred to as Ultra-cold neutrons (UCN). The phenomenon of total reflection for neutrons with $E_{tot} > V$ has found widespread application in the construction of neutron guides, capable of transporting neutrons over large distances with little loss of intensity and in many other neutron optical devices. [2]. $V \sim 100nev$ for many materials reaching as high as $335nev$ for ^{58}Ni. UCN with an energy of $100nev$ have a velocity $\sim 5m/s$ and a wavelength $\sim 500\mathring{A}$. The interaction of a neutron with the earth's gravitational field is $100nev/m$ and the neutron magnetic interaction is $100nev$ in a field of $16kGauss$.

During the process of total reflection the neutron wave function penetrates into the reflecting surface and has the form of a decaying exponential (evanescent wave). The result is that the neutrons can interact (with a small probability) with the nucleii of the material, leading to losses of UCN due to absorption of the neutrons by the nucleii or to an increase of the neutrons' kinetic energy due to the transfer of energy from the thermal excitations of the nucleii in the material. This latter process means that the neutrons will no longer be in the UCN energy range and at the next encounter with the surface the neutrons will no longer satisfy (1.2). Theoretical values of the loss probability per bounce due to these processes are on the order of 10^{-4} for many materials, reaching 10^{-5} for pure Carbon and Beryllium at room temperature. Experimentally observed loss rates tend to be higher than the theoretical values with the discrepancy being attributed to impurities, most often Hydrogen.

It was Fermi who first realized that neutrons moving with a small enough velocity normal to the surface could undergo total reflection and he and his co-workers demonstrated this experimentally in 1946 [3]. Altough many people attribute the idea that neutrons with a low enough total energy could be totally reflected at any angle of incidence to Fermi, it was Zeldovich [4] who first put this idea into print in 1959, pointing out the practical difficulties associated with the fact that $V/kT \sim 10^{-5}$. In 1968 Shapiro pointed out the advantages of a stored gas of UCN for the search for the neutron's electric dipole moment (edm), namely the long measurement time in comparison to the then current beam experiments[5]. This was followed by the almost simultaneous observation of UCN by Shapiro's group[6] at Dubna and by Steyerl in Munich[7]. Following this a paper by Okun[8] pointed out the attractiveness of UCN for the measurement of the neutron lifetime, the poorest known lifetime of any of the common particles. The advantage of UCN is that if extraneous losses can be made small enough the neutron lifetime can be measured with a single (neutron) detector, in contrast to beam experiments which need two detectors, one for at least one decay product and the second for determining the number of decaying neutrons. In the years following Steyerl[9] and his co-workers devoted themselves to developing applications of UCN in neutron optics and condensed matter physics while the Dubna group, a group formed around the ILL, and the Leningrad group pursued the application to the neutron edm and lifetime experiments.

The following years were taken up by much technical development work and studies of the behaviour of UCN. Most of the technical effort was in the Soviet Union while in the West a major part of the effort went into trying to get recognition and financial suppport from the appropriate committees. For a more complete discussion of this work see ref.[1]. Here we mention a few representative works[10][11][12][13]. The first result for the neutron edm using UCN was published in 1980 by the Leningrad group[14] followed in 1984 by the first result from the ILL group[15]. The ILL group published some preliminary results on the β decay lifetime in 1986[16] and a definitive value in 1989[17].

2. UCN and superfluid He: The 'superthermal' source of UCN

In this section we will try to explain the principles and review the present experimental situation of the 'superthermal' UCN source[1], which, in principle, is capable of producing higher phase space densities than those sources which are limited by Liouville's theorem (applied to the neutrons alone) to be $\leq$ the phase space density in the reactor moderator or cold source. The UCN source at the ILL[11], used in the edm and lifetime experiments, is an example of such a source based on the slowing down of faster neutrons by a 'neutron turbine'.

We consider a closed vessel with walls made of an ideal UCN reflector and filled with a medium containing only two energy levels (separated by an energy Δ) with a potential $V_m \ll V$, the potential of the wall material, at a temperature T so that $\Delta \gg T \gg E_{UCN}$. If the walls are transparent to neutrons of energy $E \sim \Delta$, and the vessel is placed in a neutron flux containing neutrons of this energy, there will be a constant rate of production of UCN due to downscattering of the incident neutrons in the vicinity of Δ:

$$P(E_{UCN}) = \Sigma(E \rightarrow E_{UCN})\,\Phi_o(E) \tag{2.1}$$

with $\Sigma(E \rightarrow E_{UCN})$, the macroscopic cross section for energy loss from E to E_{UCN}, and $\Phi_o(E)$ the incident neutron flux. In the steady state, if there were no losses the UCN density ρ would build up to where the production rate was equal to the upscattering rate which is proportinal to the Boltzmann factor $e^{-\Delta/T}$. Thus under these conditions we would expect a UCN density $\rho \propto Pe^{\Delta/T}$, increasing exponentially as the temperature decreases. In a real system there are always losses (*e.g.* we can never avoid the β decay lifetime) characterized by an overall UCN storage time, τ. In this case we would have $\rho = P\tau$ as the steady state UCN density.

How can we achieve such a system in practice? One possibility is to make use of the neutron scattering properties of superfluid ^4He. This material has an absorption cross section of zero and is a completley coherent neutron scatterer. This means that the neutrons can only exchange energy and momentum with the liquid when the values of energy and momentum exchange lie along a curve $\omega(k)$, *i.e.* the dispersion curve ($\hbar\omega$ =energy transfer, $\hbar k$ = momentum transfer). Then we see that a free neutron at rest can only absorb an amount of energy E_c, from the liquid, where E_c is given by

$$E_c = \frac{\hbar^2 k_c^2}{2m_n} = \hbar\omega(k_c) \tag{2.2}$$

For Helium $k_c \approx .7\mathring{A}^{-1}$ and $E_c \approx 11K$. By the same reasoning only a neutron with energy E_c can come to rest as a result of an interaction with the liquid and only a neutron whose energy is in the neighborhood of E_c can scatter into the UCN energy range. Thus we see that the probability of an upscattering event for a UCN in the liquid will be $\sim e^{-E_c/T}$ just as in the case of a two level system. However there are some differences between the superfluid and the ideal two level system.

1. Neutrons with energy E_c can scatter to energies larger than the UCN energy range, but this has no significant effect.

2. There are other upscattering processes - higher order processes involving more than one excitation. The most important of these being 2 phonon scattering, *i.e.* a phonon instead of being absorbed can be scattered with a lower energy, the lost energy being transferred to the neutron followed in importance by roton scattering. The 2 phonon process has been shown to result in a an upscattering rate $1/\tau_{up} \propto T^7$, with its strength depending on the three phonon interaction.

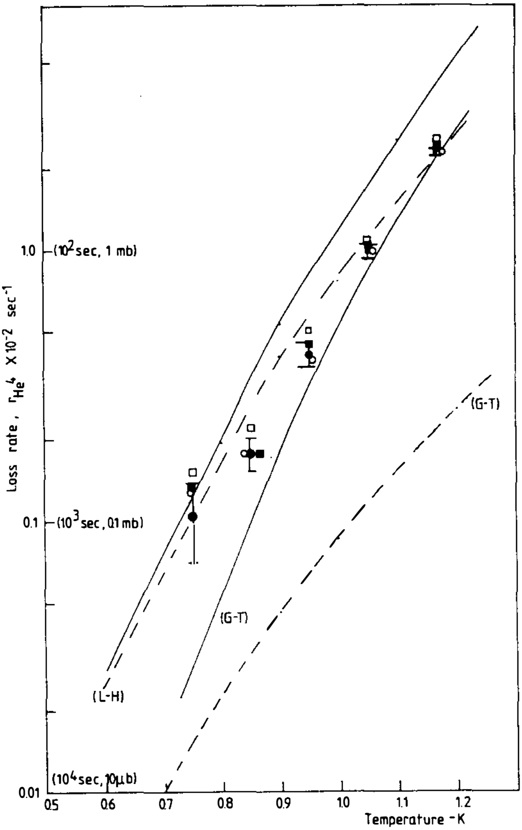

Fig. 1. Measured and calculated values of UCN loss rate due to the interaction with superfluid *Helium*^{4} as a function of temperature. The numbers in brackets on the vertical scale give the corresponding storage times and total cross sections for 4.6 m/s UCN respectively. The different point styles indicate the results of different procedures to correct for the systematic errors. Their spread is an indication of the uncertainties from that source. Dashed lines show the results for the two phonon scattering process calculated using Landau's Hamiltonian (L-H) and by Griffin and Talbot (G-T), [*Phys. Rev.* B24, 5075 (1981)]. Solid lines show the total loss rate (including one phonon and roton cotributions) using these two approaches. From ref.[20].

For liquid ^4He equation 2.1 can be written as:

$$P(E_u)\,dE_u = \Phi_o(E_c)\,N\sigma_{coh}\sqrt{\frac{E_u}{E_c}}\alpha S(k_c)\,dE_u = \Phi_o(E_c) \times 10^{-7} dE_u\ UCN\ cm^{-3}\ \sec^{-1} \quad (2.3)$$

where $\Phi_o(E_c)$ is the incident flux per unit energy at E_c, N the atomic density of the Helium, σ_{coh} the coherent cross section of the Helium, E_u the UCN energy, E_c and k_c the critical energy and wave vector (see equation 2.2), $\alpha = |v_n/(v_n - v_g)|$ with v_n the neutron velocity and $v_g = \partial\omega(k_c)/\partial k_c$ the phonon group velocity at k_c. $S(k_c)$ is the structure factor for superfluid Helium at k_c.

For a thermal flux of $10^{14}\ n/cm^2/\sec$ we expect

$$\rho_{UCN} = 1.3 \times 10^3 \tau \quad (2.4)$$

for a UCN storage time τ.

For storage times of several hundred seconds this represents a formidable UCN density but its achievement would require the installation of several liters of liquid Helium at a temperature below $1\,K$ inside a high flux reactor. However impressive UCN densities can also be achieved at the end of a guide tube as is planned for the neutron lilfetime experiment (see Doyle, this volume and ref. [18]) and for initial work on the edm experiment (see Lamoreaux, this volume and ref.[19]).

The rate for UCN upscattering by the 2 phonon scattering process has been calculated to be

$$\frac{1}{\tau_{2p}} = 7.7 \times 10^{-3} \cdot T^7 \sec^{-1} \quad (2.5)$$

Measurements of the temperature dependence of the upscattering in pure ^4He have shown a somewhat smaller upscattering rate than expected (fig. 1)[20]. The discrepancy is thought to be due to the momentum dependence of the three phonon interaction which was neglected in the upscattering calculations. This conjecture is born out by some calculations of Halley and Korth[21] and by preliminary measurements of the spectrum of UCN upscattered out of the Helium[22]. The measured intensity of the upscattered neutrons is a measure of the UCN density in the Helium and is consistent with calculations. In effect, measurements of the upscattering rate allow us to look into the Helium and measure the UCN density there. This observation has confirmed the calculations of the losses in the UCN extraction system used in the prototype experiments[23].

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