The Ultra Cold Neutron Production at KENS

H. Yoshiki
National Laboratory for High Energy Physics, Oho, Tsukuba, 305 Japan

1. Introduction

Golub and Pendlebury[1)] proposed the super-thermal helium converter to produce ultra cold neutrons (UCN) from a cold (9Å) neutron source. In the ordinary thermal reactors, the heat, in the order of a few watts/gram, is dissipated inside the reactor, therefore it is difficult to install such a device except on the external cold beam line. This reduces the initial cold neutron flux integrated over the solid angle by a factor of 10^4.[2)] The recent success of solid methane moderator at KENS[3)] suggests that the heat produced at the target and the radiating heat can be put well under control. It looks therefore that the neutron spallation source is not only suited for TOF measurements by its pulsed beam structure as quoted often, but for gaining an enormous amount of solid angle, e.g. to install the helium converter next to the target.

2. The cross sections

When a cold neutron is led into super-thermal helium, there is a certain chance that the neutron emits a phonon reducing its energy and momentum into the UCN region. For the sake of our calculation, by UCN we define that its energy lies below $E_{max} = 7.6 \times 10^{-7}$eV. At this energy the reflectivity of UCN from beryllium becomes 1%. The beryllium is known to have the highest potential barrier among metals used for the UCN confinement. There are two solutions for the incident cold neutron energy, E_{in}, which produces a UCN having E_{max} : E_{in} = 1.013 and 1.061 meV corresponding θ=0 and 180° UCN production. The excitation function of the super-thermal helium was compiled from the experimental results to our best knowledge. Any E_{in} between these two values produces UCN below E_{max}. The cross section of the neutron-phonon interaction in Born approximation is given by Cohen and Feynman[4)]. It was assumed that the initial state of the helium is in its ground state and the matrix element between the initial and final states is equated to the liquid structure factor given by Reekie and Hutchison[5)]. We divided the UCN energy between 0 and E_{max} into 40 equal bins and the differential cross sections were computed at the center of each bin. Since the differential cross sections have poles when $E_{in} = 1.043 \pm .006$ meV, care must be taken neither to loose the accuracy nor the computation time too much in this region. The 40 sets of differential cross sections were tabulated then onto a disk. The total cross section vs. the incident neutron energy is shown in Fig 1.

3. Mote Carlo calculation

Using the tabulated differential cross sections, a Monte Carlo calculation was performed to determine the average store time of UCN in a box of differnt shape, material, surface contamination, with differnt degree of contamination. In regard to the contamination, we were specially interested in that with hydrogen and deuterium. We briefly quote here our findings. 1) The rounder the shape of the container, the longer the store time. 2) When the surface is covered with 10^{15} hydrogen/cm^2, the store time is about 200 sec in a SiO_2 box of $(0.3m)^3$. This number and other sources of information seem to support the theory that the present experimental limit on the store time is due to the hydrogen contamination. 3) If the hydrogen is replaced by the deuterium, due to its larger mass and smaller scattering cross section, the store time becomes about eight times as large.

4. The test apparatus

In order to verify what have been described in the previous sections, the test of UCN production by means of super-thermal helium has been planned (Fig 2). The vessel to contain super-thermal helium will be fabricated out of single piece of Al block whose inner wall is plated with Ni. The size of the vessel is 8cm in diameter, 30cm in length. The figure shows the main part of the cryostat. The upper part is the 4.2°K helium bath in which commercial liquid helium is stored. The outer radiation shield is anchored to this. Through a needle valve the liquid of this bath will be transfered to a 1°K bath below, whose atomosphere will be pumped out through an orfice, to bring down the liquid to the desired temperature. The inner radiation shield is anchored to this bath. The liquid which is partly super-thermal will be led to the vessel through a super-leak, eliminating

He^3 in the process. A He^3 pot attached to the vessel will cool down the He^4 in the vessel to 0.5°K. He^3 will be pumped out and recirculated through the system. A horizontal valve which is not shown in the figure will be pressed down against the opening of the vessel during the time UCNs are produced and is lifted when they are counted by a thin windowed He^3 counter attached to the verticl pipe. The counting rate determined by the present (October, 1980) KENS performance (Mizuki, this meeting) will be only 0.5 UCN/sec. But this is expected to be improved.

5. Check of Neutron Oscillations making use of UCN

Apart from electric dipole moment measurement of the neutron and other topics related to UCN, we discuss the possibility of detecting this phenomenon by means of UCN in this section. Recently Mohapatra and Marshak[6-7] discussed the phenomenology of neutron-antineutron oscillations within a frame work of gauge models with sponteneously broken local B-L symmetry which leads to large $\Delta B=2, \Delta L=0$ nucleon transition amplitudes. A proposal was made to detect this effect by Wilson[7] using thermal neutrons of $\Phi=5\times10^{13}$ neutrons/sec for a period of $t=10^{-2}$ sec. Kamae[8] proposed a similar experiment at a lower neutron energy using a cold neutron source recently installed at KEK. For both experiments it is important to degauss the earth's magnetic field to the order of 10^{-2} gauss along the beam paths of meters or tens of meters. For both experiments the counting rate $R/\text{sec}/(\delta m)^2$ is Φt^2, where δm is explained below.

δm is the $\Delta B=2$ transition mass between $|n\rangle$ and $|\bar{n}\rangle$ states, which are placed in a magnetic field B only. The new eigenstates of the $|n\rangle-|\bar{n}\rangle$ complex, $|n_1\rangle$, $|n_2\rangle$, are then,

$$|n_1\rangle=\cos\theta.|n\rangle+\sin\theta.|\bar{n}\rangle=(|n\rangle+|\bar{n}\rangle.\delta m/(\mu B+\sqrt{(\mu B)^2+(\delta m)^2})).\cos\theta \quad (1a)$$

$$|n_2\rangle=-\sin\theta.|n\rangle+\cos\theta.|\bar{n}\rangle=(|\bar{n}\rangle-|n\rangle.\delta m/(\mu B+\sqrt{(\mu B)^2+(\delta m)^2})).\cos\theta \quad (1b)$$

where μ is the magnetic moment of the neutron and θ is the mixing angle, a relation $\tan 2\theta=\delta m/\mu B$ thereby holds. The corresponding mass values, m_1, m_2, are

$$m_1, m_2 = m_0\pm\sqrt{(\mu B)^2+(\delta m)^2}. \quad (2)$$

Mohapatra and Marshak[7] found $\delta m\lesssim10^{-20}$eV, whereas for B=1 gauss, μB becomes as large as $\sim6.3\times10^{-12}$eV.

Supposing the state was a pure $|n\rangle$ state at t=0, the state vector

$|\tilde{n}(t)\rangle$ in terms of $|n\rangle$ and $|\bar{n}\rangle$ will be,

$$|\tilde{n}(t)\rangle\cong(|n\rangle+2i\theta\sin\Delta mt/2.e^{-i\Delta mt/2}|\bar{n}\rangle).e^{im_1t}, \quad (3)$$

where $\Delta m=m_1-m_2$. The probability to observe $|\bar{n}\rangle$ at t, is

$$|\langle\bar{n}|\tilde{n}(t)\rangle|^2=1/2.(\delta m/\mu B)^2.(1-\cos 2\sqrt{(\mu B)^2+(\delta m)^2}\ t). \quad (4)$$

The maximum effect of oscillation can be seen when the argument of cos-term becomes π, and for the measurment periods proposed like above (10^{-2} sec), B is most preferably in the order of $10^{-2}\sim10^{-3}$ gauss. This is why the earth's magnetic field must be degaussed to this order in the above experiments(fig 3).

Major problems of the n-$\bar{n}$ oscillation experiments with UCN are 1) the phase-shifts produced each time they are reflected from the metal walls, which will mar the relative phase between $|n\rangle$ and $|\bar{n}\rangle$ in eq.(3), and 2) the question of absorption from the wall. The relative phase between $|n\rangle$ and $|\bar{n}\rangle$ in eq.(3) is illustrated in fig 3. If they are reflected in time interval of $\langle\Delta t\rangle$, however, $|\bar{n}\rangle$ is most likely to start a random walk, changing its directions in relative phase angles as shown in fig 4. The step of random walk in this case is $\theta\Delta m\langle\Delta t\rangle$, therfore after t, the square of distance from the starting point to the last point is,

$$N(t) = (\theta\Delta m\langle\Delta t\rangle)^2.t/\langle\Delta t\rangle\cong(\delta m)^2\langle\Delta t\rangle.t. \quad (5)$$

The effect of absorption is not included in eq(5). If the absorption to the wall takes place at a rate of Γ/sec, eq(5) must be modifed to

$$N(t) \cong (\delta m)^2\langle\Delta t\rangle\ (1 - e^{-\Gamma t})/\Gamma. \quad (6)$$

The production and absorption rates of $\bar{n}$ per unit time becomes equal after $t\gg\Gamma^{-1}$. If we assume that all absorbed $\bar{n}$'s are detected, the number of $\bar{n}$'s up to time T is,

$$\int_0^T N(t)\Gamma dt = (\delta m)^2(\Delta t).T, \quad (7)$$

if $T\gg\Gamma^{-1}$. Eq(7) times Φ, the inflow of source neutrons to the system per unit time, is the number of $\bar{n}$ observed in unit time. In this calculation the use of the area reserved for the neutron irradiation therapy is envisaged. Since the average velocity υ of UCN is about 3 m/sec, in a box of about $(30\text{cm})^3$ in dimension, $\langle\Delta t\rangle$ is in the order of 10^{-1} sec. Γ can be defined as the absorption coefficient per bounce divided by $\langle\Delta t\rangle$ and not well known. After a reasonable estimate, we assume that the absorption coefficient is ~20%, or $\Gamma^{-1}\sim0.5$sec. On the other hand UCN can be stored as long as about several hundreds of seconds therefore $T \gg \Gamma^{-1}$ holds.

Fig.5 shows an example of UCN source to meet such experimental requirements. As was pointed out in sec.1, the use of wide solid angle against the cold neutron sources of solid methane is to be noted. Further, the use of reflectors around the super-thermal bath should enhance the flux of cold neutrons through the converter. With this set-up, it should produce 2×10^5 UCN/sec at KENS assuming the reflector gain of 20%. This type of set-up should be incorporated into a UCN target station independently from other stations. In this case the counting rate $R/sec/(\delta m)^2$ will be $10^7/sec/(\delta m)^2$. The UCN target station will be a very efficient source of UCN in improving the upper bound of the electric dipole moment as well.

References

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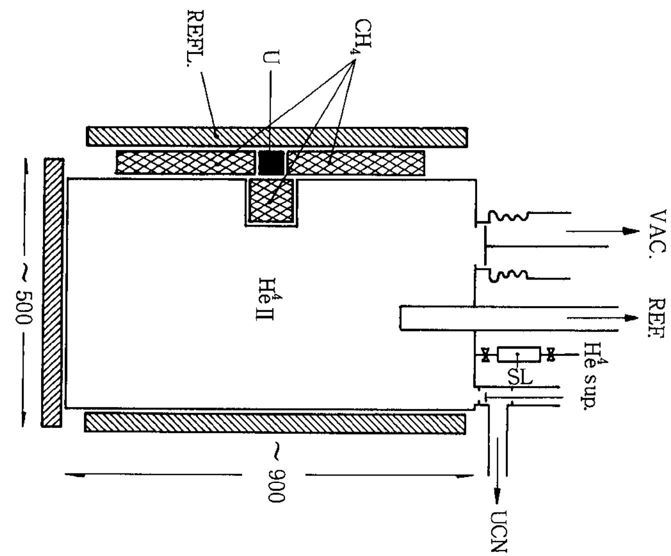

Fig. 5

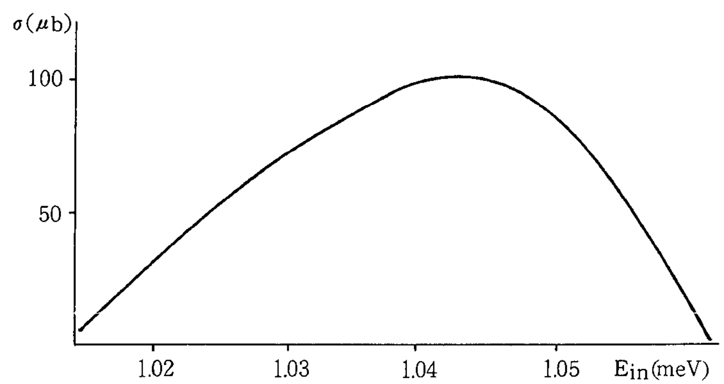

Fig. 1

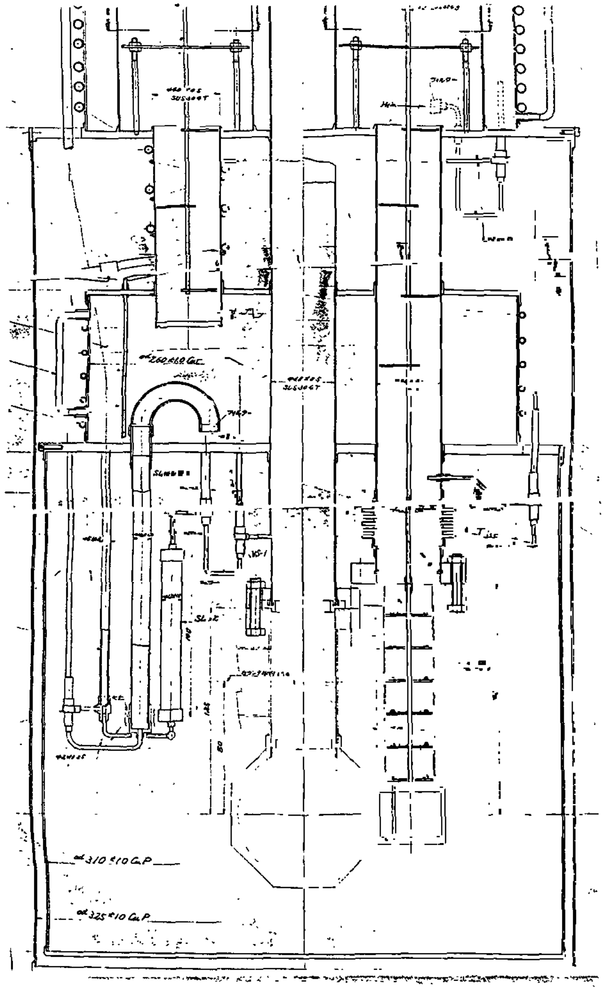

Fig. 2

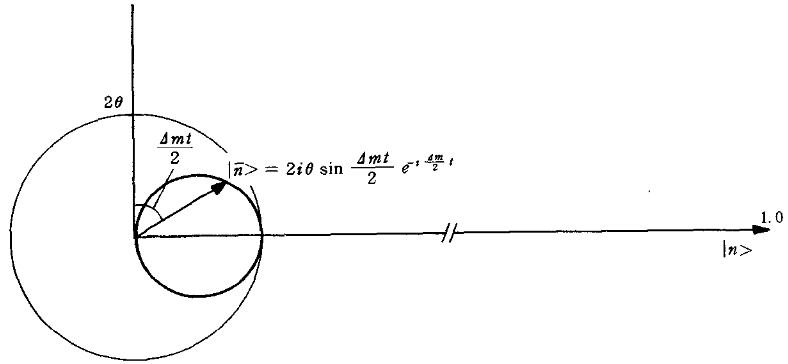

Fig. 3

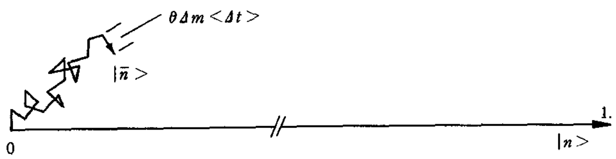

Fig. 4