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Ultracold Neutron Production and Storage in Superfluid ^{4}He

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A cross-section model for neutron scattering in liquid ^{4}He at temperatures down to 0.1 K is developed, in which some fundamental excitations in superfluid and normal ^{4}He are described in terms of phonon-roton (quasiparticle) excitation at temperatures below 2.17 K, density(sound) one at all temperatures up to 4.2 K and recoil scattering from a free ^{4}He atom for high incident energies of a neutron. The cross-section model is analyzed quantitatively by comparison with experimental results, both double-differential and total, for many different values of temperature and neutron energy. Scattering cross-sections in the vicinity of 1 meV for temperatures below 1 K are calculated to estimate ultracold neutron production, since a 1 meV neutron can exchange its energy and momentum entirely with those of a created phonon in liquid ^{4}He. Furthermore it is shown that lowering temperature below about 0.5 K significantly suppresses upscattering of an ultracold neutron due to phonon absorption and hence results in disappearance of an ultracold neutron by neutron β-decay only. Consequently the number density of ultracold neutrons attainable at 0.1 K is determined in the case of no significant upscattering and no wall loss. For instance, it is estimated to be 4.2x10^4 cm^{-3} with neutron energies below 0.335 μeV for an incident neutron flux of 1.9x10^9 cm^{-2}s^{-1}meV^{-1} at 1 meV.

KEYWORDS: ultracold neutron, liquid helium, superfluid, cold neutron, superthermal source

§1. Introduction

Ultracold neutrons(UCNs) are defined to be neutrons with energies of the order of 0.1 μeV or less, i.e. in neutron velocity below about 5 m/s. Such a neutron can undergo total reflection at material surface: for instance, ^{58}Ni has an effective UCN potential of 0.335 μeV. Hence UCNs can be accumulated and stored in a closed metallic bottle until they disappear by neutron β-decay with a lifetime of 887.6 s.[1] This may provide a new research field such as fundamental physics studies of neutron β-decay and electric dipole moment, UCN scattering from condensed matters and relevant new technologies.[2]

For this purpose, it is necessary to produce UCNs as many as possible. Various methods of UCN production have been developed and applied by means of the following concepts: for instance,[3] deceleration by the gravity, down-scattering in a cryogenic moderator and use of a mechanical neutron turbine. Among these, use of pure superfluid ^{4}He at temperatures T lower than 1 K has been expected to be most promising. The idea is that 1 meV neutrons may be down scattered into UCNs by creating phonons in liquid ^{4}He, since there are some advantages of a rigorously zero absorption cross section, a well-defined phonon-roton dispersion relation and no significant upscattering of UCNs at lower T. A number of papers on this subject have been published: for instance, the possibility of a strong UCN source[4] and the application of UCN storage in a vessel for experiments in fundamental physics.[5]

The purpose of the present paper is to study theoretically the UCN production and storage in superfluid ^{4}He. A cross-section model for neutron scattering in liquid ^{4}He at any T down to 0.1 K[6] is fully utilized. A discussion is centered on the UCN production by down-scattering of a 1 meV cold neutron and the maximum density of UCNs to be expected at low T.

§2. Cross Section Model

Neutron scattering in liquid ^{4}He at all T between 0.1 and 4.2 K has been recently described in terms of a cross-section model.[6] It is based on the following experimental results.[7,8] At low momentum transfer κ below 0.8 Å^{-1}, a dynamic structure factor $S(\kappa,\omega)$ shows a sharp peak which broadens with increasing T but remains well-defined above T_λ=2.17 K. The peak position persists at almost the same energy for T below and above T_λ. At higher κ up to about 3.6 Å^{-1}, $S(\kappa,\omega)$ at $T < T_\lambda$ has a sharp peak plus a broad component. As T increases, the magnitude of the peak is reduced rapidly until it vanishes at T_λ. The broad one still exists above T_λ as being nearly independent of T.

The above experimental findings may be interpreted microscopically in terms of a model consisting of two kinds of excitations:[9] a density-mode excitation related a non-condensate component and a quasiparticle (phonon-roton) excitation due to a condensate component. In superfluid ^{4}He, the density and quasiparticle excitations are strongly coupled through the Bose condensate, which leads to a common phonon-roton dispersion curve with an energy $\hbar\omega_R(\kappa)$. At low κ, the sharp excitation arises from a collective density mode among all the atoms lying in and above the condensate. At higher κ, the sharp peak in $S(\kappa,\omega)$ comes from the quasiparticle excitation while the broad one from the density mode. These two excitations are coupled through the Bose condensate fraction $\Delta(T) = 0.1\{1-(T/T_\lambda)^{3/2}\}$ for $T \le T_\lambda$

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and $= 0$ for $T > T_\lambda$.[9)]

Consequently the double-differential cross section for neutron scattering in liquid ^{4}He is expressed as

$$\frac{d^2\sigma}{dEd\Omega} = b^2\frac{k}{k_0}\left[\Delta(T)S(\kappa)S_{C,S}(\kappa,\omega)\right.$$
$$\left.+\{1-\Delta(T)\}S(\kappa)S_{N,S}(\kappa,\omega)\right] \qquad (1)$$

where b is the scattering length of a bound ^{4}He atom, k and k_0 are, respectively, the wave numbers for scattered and incident neutron, $S(\kappa)$ is the static structure factor,[10)] and $S_{X,S}(\kappa,\omega)$ $(X = C, N)$ are the dynamic structure factors for a condensate($X = C$) and a non-condensate($X = N$) component. Each of $S_{X,S}(\kappa,\omega)$ is further expressed by the sum of down- and up-scattering processes to take into account of the above-mentioned excitations. The cross-section model has been found to be in satisfactory agreement with experimental results, both double-differential[7,11)] and total,[5,12)] for many different values of temperature and neutron incident energy.

§3. Ultracold Neutron Production

For a specific down-scattering for an incident neutron energy $E_0 \sim 1$ meV and $T < 1$ K, Eq.(1) is reduced to

$$\frac{d^2\sigma}{dEd\Omega} = b^2\frac{k}{k_0}S(\kappa)\Delta(T)\frac{1}{\pi\hbar}\exp\left[q^2\alpha c - \hbar\omega^+/2k_BT\right]$$
$$\times\frac{q^2\alpha}{(\omega^+)^2+(q^2\alpha)^2}\Big|_{\mathrm{C}} + b^2\frac{k}{k_0}S(\kappa)\{1-\Delta(T)\}\frac{1}{\pi\hbar}$$
$$\times\exp\left[q^2\alpha c - \hbar\omega^+/2k_BT\right]\frac{q^2\alpha}{(\omega^+)^2+(q^2\alpha)^2}\Big|_{\mathrm{N}} \qquad (2)$$

where $q^2 = \kappa^2\{1/S(\kappa) - \hbar\omega_R(\kappa)/(\hbar^2\kappa^2/2m)\}$, $\omega^+ = -\omega + \omega_R(\kappa)$, and $c = \alpha m/k_BT$ with the mass m of a ^{4}He atom. The general explicit expression for Eq.(1) together with all the definitions of model parameters such as α are given in ref.6.

Equation (2) indicates two excitations by condensate and non-condensate components and both are peaked when $\omega^+ = 0$, i.e. at an energy transfer $\hbar\omega$ equal to $\hbar\omega_R(\kappa)$. This condition is satisfied at the intersection of $\hbar\omega_R(\kappa)$[8)] and a free neutron dispersion curve as $E_0 = \hbar^2k_0^2/2m$, which is shown in Fig.1. It can be seen from Fig.1 that only a 1 meV neutron can meet with the condition to be able to exchange its energy and momentum entirely with those of a created phonon. Furthermore, lowering T leads to smaller value of phonon width $2q^2\alpha$,[9)] thus producing stronger UCNs. This is significant in the condensate component rather than in the non-condensate one, since the former has much longer lifetime of a phonon(i.e. smaller width $2q^2\alpha$). Consequently it follows that superfluidity at low T plays an essential role in producing UCNs.

The inelastic scattering processes in liquid ^{4}He at 1 K are shown in Fig.2 for E_0= 1.03 meV and 0.1 μeV. The former indicates an UCN production at $\hbar\omega$= 1.03 meV and κ= 0.704 Å^{-1}, while the latter shows an inverse process as upscattering of an UCN into a cold neutron. As has been recognized,[9)] lowering T reduces the number of phonons in liquid ^{4}He, thus resulting in no significant UCN upscattering. This is clearly shown in Fig.3 in terms of total scattering cross sections at many different temperatures.[5,12)] Also shown in Fig.3 is an effective absorption cross section due to the neutron β-decay with a lifetime of τ_β= 887.6 s.[1)] It is obvious that lowering T below 0.8 K results in much less(or negligible) upscattering of UCNs. Namely there is a possibility to obtain a high density of UCNs.

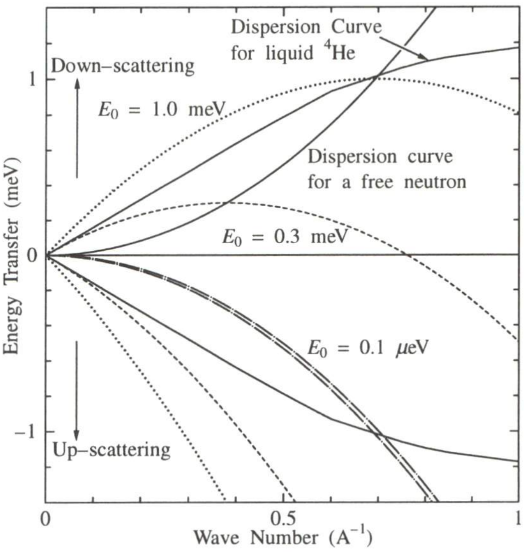

Fig.1. Dispersion curves for liquid ^{4}He and a free neutron, together with the regions covered by the laws of energy-momentum for neutron incident energies E_0= 1 meV, 0.3 meV and 0.1 μeV.

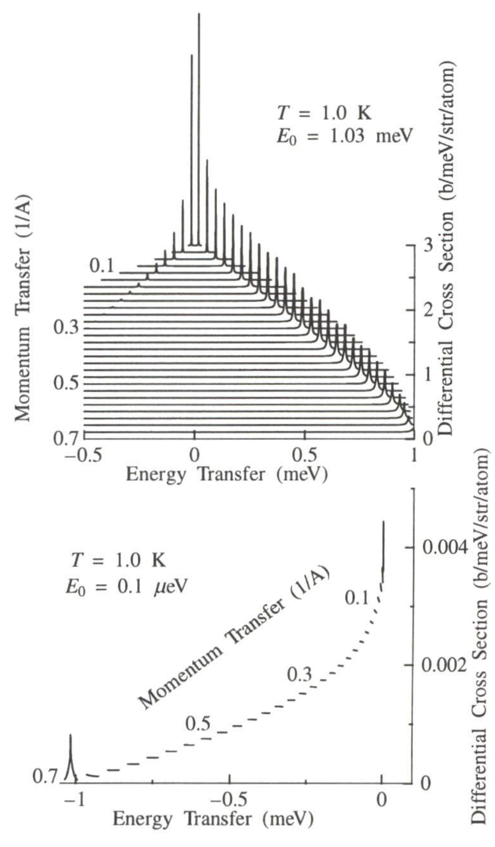

Fig.2. Inelastic scattering in liquid ^{4}He at 1 K for E_0= 1.03 meV(top) and 0.1 μeV(bottom).

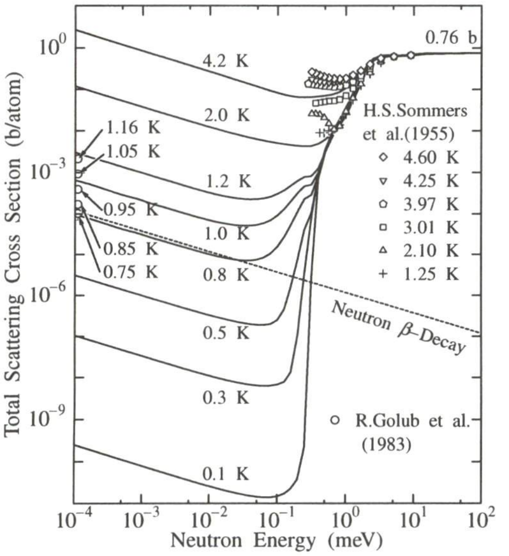

Fig.3. Total scattering cross sections $\sigma_s(E_0)$ of liquid ^{4}He and absorption cross section due to neutron β-decay.

Figure 4 shows a total cross section of UCN production defined by

$$\sigma_U(E_0) = \int_0^{E_U} dE \int_{4\pi} d\Omega \frac{d^2\sigma(E_0 \to E, \mu)}{dEd\Omega} \quad (3)$$

where E_U= 0.335 μeV is taken. As T is decreased, the peak magnitude of $\sigma_U(E_0)$ increases, but the peak area given by an integral of $\sigma_U(E_0)$ with respect to E_0 around 1 meV remains almost constant. For instance, it is 1.17x10^{-6} b·meV/atom at 0.1 K where $\sigma_s(E_0)$= 3.48x10^{-2} b/atom and $\sigma_U(E_0)$= 5.45x10^{-5} b/atom at E_0= 1.03 meV. It follows from this that an UCN production is an extremely rare event with a mean free path of about 5 km in liquid ^{4}He at 0.1 K.

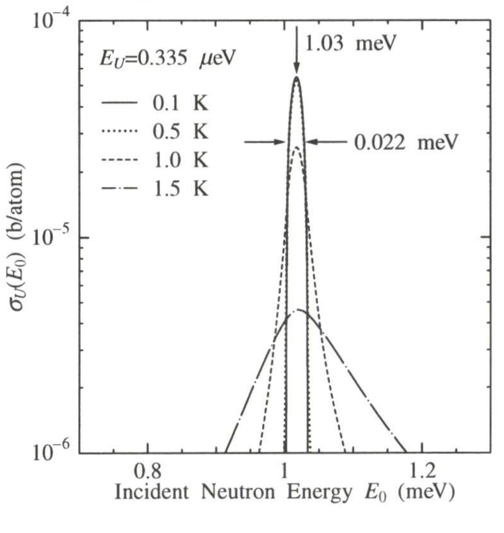

Fig.4. Total scattering cross sections $\sigma_U(E_0)$ of UCN production for liquid ^{4}He at 0.1, 0.5, 1.0 and 1.5 K.

§4. Ultracold Neutron Storage

The maximum UCN density to be expected may be evaluated as follows. Assuming that an UCN disappears only by neutron β-decay, not by UCN loss due to upscattering with a phonon, leakage from a liquid ^{4}He system and absorption by impurities, then it is possible to determine the energy spectrum $\rho(E)$ of UCNs:

$$\frac{1}{\tau_\beta}\rho(E) = \int dE_0 \phi(E_0) \int_{4\pi} d\Omega N_0 \frac{d^2\sigma(E_0 \to E, \mu)}{dEd\Omega} \quad (4)$$

where $\phi(E_0)$ is the energy spectrum of incident neutrons and N_0 is the number density of ^{4}He with 2.2x10^{22} cm^{-3} at 0.1 K. Hence the total UCN density ρ_U is given by $\rho_U = \int_0^{E_U} \rho(E)dE$. It is estimated to be 4.2x10^4 UCNs/cm^3 at 0.1 K for ϕ_0= 1.9x10^9 cm^{2}s^{-1}meV^{-1} at 1 meV (total ϕ_0 of 1.0x10^{10} cm^{2}s^{-1}).[13] This magnitude is about 500 times larger than the experimentally achieved one of about 90 UCNs/cm^3 at ILL.[3]

§5. Concluding Remarks

Production and storage of UCNs in superfluid ^{4}He have been discussed physically and quantitatively. The discussion is based on the cross-section model which has been recently developed for liquid ^{4}He at any temperatures down to 0.1 K. The results thus obtained are clear and easy to understand since a concept of a single down-scattering of a 1 meV neutron into an UCN is used.

In the actual development of a superthermal source based on superfluid ^{4}He, such a limited situation may not be expected. For this, the following studies are now in progress: generation of a basic data library as group-constant sets at many different T, a multigroup neutron transport analysis to estimate a maximum UCN density in the source, enhancement of an UCN density by an appropriate cryogenic moderator/reflector such as liquid D_2 and a possibility of magnetic confinement of more UCNs. These results will be reported in the near future.

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