



Ultra cold neutron production by multiphonon processes in superfluid helium under pressure

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ABSTRACT

Cold neutrons are converted to ultra cold neutrons (UCN) by the excitation of a single phonon or multiphonons in superfluid helium. The dynamic scattering function $S(q, \hbar\omega)$ of the superfluid helium strongly depends on pressure, leading to a pressure-dependent differential UCN production rate. A phenomenological expression for the multiphonon part of the scattering function $s(\lambda)$ describing UCN production has been derived from inelastic neutron scattering data. When combined with the production rate from single phonon processes this allows us to calculate the UCN production for any incident neutron flux. For calculations of the UCN production from single phonon processes we propose to use the values $S^* = 0.118(8)$ at saturated vapour pressure and $S^* = 0.066(6)$ at 20 bar. As an example we will calculate the expected UCN production rate at the cold neutron beam for fundamental physics PF1b at the Institut Laue Langevin. We conclude that UCN production in superfluid helium under pressure is not attractive.

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1. Introduction

Current projects to increase the density of ultra cold neutrons (UCN) available for physics experiments employ neutron converters of superfluid helium (He-II) [1–3] and solid deuterium [4–8]. In these materials cold neutrons with energies in the order of meV may be scattered down to the neV energy range by the excitation of a single phonon or multiphonon in the converter. The inverse process is suppressed by the Boltzmann factor if the converter is kept at sufficiently low temperature. We consider UCN production in He-II, for which first publications have focused on the single phonon process, where incident 8.9 Å neutrons are scattered down to the UCN energy range [9,10]. Later two publications [11,12] have set out to calculate the expected UCN production rate from processes involving the emission of two or more excitations but reached contradicting results.

The purpose of this article is to provide on the one hand a physical-model-based extrapolation to short wavelengths of scattering data relevant for UCN production. On the other hand we consider for the first time UCN production in He-II under pressure. This is motivated by the pressure dependence of the properties of He-II, in particular its dispersion curve and density. Application of pressure to He-II increases the velocity of sound, such that the dispersion curves of He-II and of the free neutron

cross at shorter neutron wavelength. For neutron beams from a neutron guide coupled to a liquid deuterium cold source, the differential flux density $d\Phi/d\lambda$ in the range 8–9 Å normally increases for decreasing wavelength. Pressure also increases the density of He-II. These two facts may lead to the expectation that the single phonon UCN production rate increases with pressure. Furthermore, the multiphonon contributions might be favourably affected by application of pressure. This justifies to investigate whether pressure may provide an UCN source superior to a converter at saturated vapour pressure (SVP).

The first part of this paper presents some general expressions for the UCN production rate in He-II as given in an internal note in 1982 by Pendlebury [13] and in Ref. [11]. In the second part we consider UCN production due to multiphonon excitations both for SVP and for 20 bar, using inelastic scattering data for He-II measured at 0.5 K [14]. We give a formula approximating the contribution from multiphonon processes to the UCN production rate. This might be useful to calculate, for any given spectrum of incident neutrons, the expected UCN production rate. As an example, this is done here for the cold neutron beam PF1b at the Institut Laue Langevin.

2. UCN production rate, general expressions

UCN production in superfluid helium is due to coherent inelastic scattering of the incident cold neutrons with energy E (and wavenumber k) down to energies E' (k'). The maximum

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final energy is defined by the wall potential of the converter vessel (252(2) neV for beryllium) with respect to the Fermi potential of He-II (18.5 neV at SVP): $V_c = 233(2)$ neV. The production rate per unit volume is given by

$$P_{\text{UCN}}(V_c) = \int_0^\infty dE \int_0^{V_c} N \frac{d\phi}{dE} \cdot \frac{d\sigma}{dE'}(E \rightarrow E') dE' \quad (1)$$

where $d\phi/dE$ is the differential incident flux, N the helium number density, and $d\sigma/dE'$ the differential cross-section for inelastic neutron scattering. The latter is given by

$$\frac{d\sigma}{dE'} = 4\pi b^2 \frac{k'}{k} S(q, \hbar\omega) \quad (2)$$

where b is the bound neutron scattering length of ^4He , $\hbar\omega = E - E'$, $q = k - k'$, and $S(q, \hbar\omega)$ is the dynamic scattering function evaluated for values on the dispersion curve of the free neutron. Details of calculation can be found in Ref. [11] where the general result is given in Eq. (9). We may write

$$P_{\text{UCN}}(V_c) = N \sigma V_c \frac{k_c}{3\pi} \int_0^\infty \frac{d\phi}{d\lambda} s(\lambda) \lambda d\lambda \quad (3)$$

where $\sigma = 1.34(2)$ barn [15] is the bound neutron scattering cross-section of ^4He , $\hbar k_c = \sqrt{2m_n V_c}$, and

$$s(\lambda) = \hbar \int S(q, \hbar\omega) \delta(\hbar\omega - \hbar^2 k^2 / 2m_n) d\omega \quad (4)$$

defines the UCN scattering function as function of the incident neutron wavelength λ , making use of $q = k = 2\pi/\lambda$, valid for $k' \ll k$. We divide it into a single and a multiphonon part, $s(\lambda) = s_I(\lambda) + s_{II}(\lambda)$.

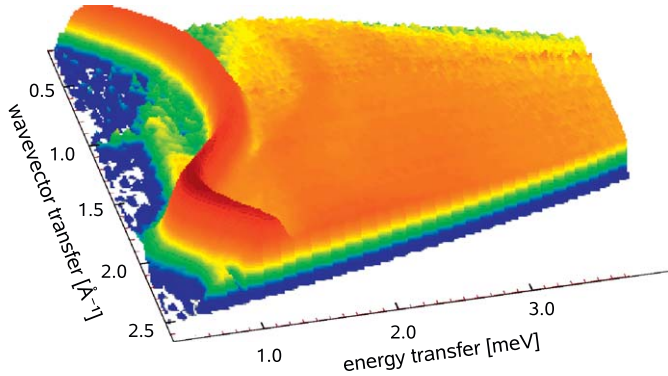


Fig. 1. Visualisation of $S(q, \hbar\omega)$, for helium at $T = 0.5$ K and 20 bar, measured by Ref. [14].

The single phonon contribution can be approximated by $s_I(\lambda) = S^* \delta(\lambda^* - \lambda)$, where $\lambda^* = 2\pi/q^*$ is the neutron wavelength at the intersection of the dispersion curves of the free neutron and the helium ($q^* = 0.706 \text{ Å}^{-1}$ for SVP), and $S^* = \hbar \int_{\text{peak}} S(q^*, \hbar\omega) d\omega$ denotes the intensity due to single phonon emission. Evaluation of the single-phonon UCN production rate yields

$$P_I(V_c) = N \sigma \left(\frac{V_c}{E^*} \right)^{3/2} \frac{\lambda^*}{3} \beta S^* \frac{d\phi}{d\lambda} \Big|_{\lambda^*} \quad (5)$$

where $E^* = \hbar^2 q^{*2} / 2m_n$, and the Jacobian factor

$$\beta = \frac{\frac{dE_n}{dq} \Big|_{q^*}}{\frac{dE_n}{dq} \Big|_{q^*} - \frac{dE_{\text{He}}}{dq} \Big|_{q^*}}$$

accounts for the overlap of the two dispersion curves, $E_n(q)$ and $E_{\text{He}}(q)$. For a beryllium-coated converter at SVP this results in

$$P_I(V_c) = 4.97(38) \times 10^{-8} \frac{\text{A}}{\text{cm}} \frac{d\phi}{d\lambda} \Big|_{\lambda^*} \quad (6)$$

The differential multiphonon UCN production rate in the same units is given by

$$\frac{dP_{II}(V_c)}{d\lambda} = N \sigma V_c \frac{k_c}{3\pi} \frac{d\phi}{d\lambda} \lambda s_{II}(\lambda) \quad (7)$$

which depends explicitly on the form of $s_{II}(\lambda)$ which is discussed below.

3. UCN production rates from scattering data

The scattering function Eq. (4) can be extracted from inelastic scattering measurements. This has been done here for data previously measured by Andersen and colleagues, on the IN6 time-of-flight spectrometer at the Institut Laue Langevin, at SVP and at 20 bar. Parts of this data have already been published earlier in Refs. [14,18–21]. For the present purpose we have treated and rebinned all of the raw data to obtain a higher resolution in q and to cover the complete accessible q -range. Existing data points from previous publications were used as reference for our analysis. A typical measurement of the dynamic scattering function $S(q, \hbar\omega)$ is shown in Fig. 1.

The plane is divided into slices with width $\Delta q = 0.2 \text{ Å}^{-1}$. Fig. 2 shows $S(q, \hbar\omega)$ for two representative values of q . From each such slice we extract one value of $s_{II}(\lambda)$, with λ fixed by the condition $\hbar/\lambda = \sqrt{2m_n \hbar\omega}$. For this purpose the energy is binned with width

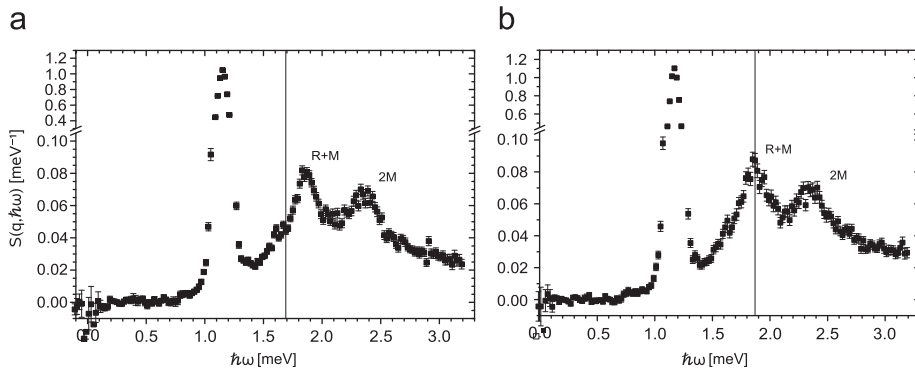


Fig. 2. $S(q, \hbar\omega)$ at SVP for (a) $q = 0.90 \text{ Å}^{-1}$ and (b) $q = 0.95 \text{ Å}^{-1}$. The vertical lines indicate the energy of an incident neutron with $E = \hbar^2 q^2 / 2m_n$ that can be down-scattered to the UCN energy range. The width of the single phonon excitation is dominated by the finite resolution of the instrument. The roton–maxon (R+M) and two maxon (2M) resonances at higher energies are significantly lower in intensity.

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