UCN production in superfluid helium

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Ultra- cold neutrons(UCN) are produced in superfluid helium by single- and multiphonon excitation. The UCN production rate density R_{II} via multiphonons is larger than that by one phonon excitation R_I depending on the shape of the incident neutron spectral flux density $d\phi/d\lambda(\lambda)$. R_{II} exceeds R_I by about 20% for $d\phi/d\lambda$ peaking at 4 Å. For a thermal n spectrum, whose shape matches better with the multiphonon scattering function s_{II}, the relative contribution of R_{II} is correspondingly larger.

When cold and thermal neutrons pass through a volume of superfluid helium at very low temperature (ca. 0.4 K) as in the Mark3000 apparatus [1], ultra- cold neutrons(UCN) of very high density can be produced by one- and multiphonon processes, respectively. Since the ^{4}He absorption cross section is zero, the storage time is limited only by the neutron life time, the ^{4}He purity and the storage volume wall absorption cross section. High ^{4}He purity and low absorption are obtained by filling the storage volume through a superleak (compressed Al_2O_3 powder with 200 Å grain size) and sputtering the walls with Be, respectively.

The macroscopic double differential cross section for neutron downscattering in superfluid helium from the energy $T...T+dT$ to the UCN energy $T^{'}...T^{'}+dT^{'}$ is given by

$$d^2\Sigma/(d\Omega\, dT^{'}) = n_{^4He}\sigma_b\, k^{'} s(q,\hbar\omega)/(4\pi\, k),$$

where $n_{^4He} = 2.185\cdot 10^{22} cm^{-3}$ is the ^{4}He atom density, $\sigma_{\rm b} = 1.34\cdot 10^{-24}$ cm^2 the bound nuclear cross section, k and $k^{'}$ the initial and final n momenta and $s = s_I + s_{II}$ the scattering functions due to single- phonon and multiphonon excitation, respectively, depending on the momentum transfer $q = |\vec{k} - \vec{k}^{'}|$ and energy transfer $\hbar\omega = T - T^{'}$. $s_{II}(q,\hbar\omega)$ of 0.5K superfluid helium has been measured recently [2]. However, the covered $\hbar\omega$ range was too small to be used for calculating the UCN production in a wide T range.

The differential UCN production rate density $d^2R = d^2(R_I + R_{II}), R_I$ and R_{II} being the single- and multiphonon contributions, results to be

$$d^2R = d\phi\cdot\, d\Sigma, \qquad (1)$$

where $d\phi$ is the differential incoming n flux density.

When UCN are produced, the momentum and energy transfer are to a good approximation equal to the initial n momentum k and energy T, respectively, both described by the incident n wavelength λ. $s_I(\lambda)$ consists just of a sharp peak at $\lambda = \lambda^* = 8.99$Å, the crossing point of the free n and the acoustical phonon dispersion curves, with $s_I(\lambda^*) = 0.15K^{-1}, \delta\lambda = (d\lambda/dq)\delta q = 0.27$ Å width(fig. 2a) and $\delta q = 2k_c, k_c$ being the UCN momentum corresponding to T_c, where $T_{\rm c} = 2.73$ mK is the critical UCN energy inside the Be coated storage volume filled with helium. Because of the δ function type $s_I(\lambda), d^2R_I$(cf. eq.(1)) can be integrated over T and $T^{'}$ yielding

$$R_I = d\phi/d\lambda(\lambda^*)(\lambda^*/3)\alpha\, n_{^4He}\sigma_b S_I(q^*)(T_c/T^*)^{3/2}$$

[3], where $d\phi/d\lambda$ is the incident n spectral flux density. $q^* = 0.7$Å^{-1} and $T^* = 11.85$ K are the n momentum transfer and energy, $\alpha = 1.45$ is a numerical factor due to the dispersion curve slopes, all at $\lambda^*, S_I(q^*) = 0.105$ the one phonon structure factor at q^* [4] (fig. 1),respectively. $S_I(q^*)$ can be written as $S_I(q^*) = s_I(\lambda^*)(dT/d\lambda)(\lambda^*)\delta\lambda$.

d^2R_{II}(cf. eq(1)) integrated over $T^{'}$ is given by

$$dR_{II}/d\lambda = n_{^4He}\sigma_b\sqrt{2E_0}T_c^{3/2}/(3\pi\hbar\, c)d\phi/d\lambda(\lambda)\,\lambda\, s_{II}(\lambda)$$

with $E_0 = 1.09\cdot 10^{13}$ K the n rest energy.

s_{II} is given by $s_{II} = (dS_{II}(q)/dq)(dq/dT) = (dS_{II}(q)/dq)q^{-1}\, 2.08\cdot 10^{-2}K^{-1}$ with q in Å^{-1}, where $S_{II}(q)$ is the multiphonon structure factor(fig. 1). Thus, from the derivative of $S_{II}(q)$ we obtain $s_{II}(\lambda)$(fig. 2a).

The differential production rate densities $dR_I/d\lambda$ and $dR_{II}/d\lambda$ depend on the differential flux $d\phi/d\lambda$, which is given by
$d\phi/d\lambda = (\Phi\lambda_0(dN/dch)/\int_0^\infty \lambda(dN/dch)d\lambda$, where Φ is the thermal equivalent flux, e. g., $\Phi = 2\cdot 10^8 cm^{-2}s^{-1}$ at HMI [5], $\lambda_0 = 1.8$Å and dN/dch, e. g., the measured counts per time channel, respectively(fig. 2b), yielding $d\phi/d\lambda = 959.4\, dN/dch\, cm^{-2}s^{-1}$Å^{-1}. The resulting $dR/d\lambda = d(R_I + R_{II})/d\lambda$ vs λ is shown in fig. 2c. The integrals are $R_I = 6.4\cdot 10^{-2}\, cm^{-3}s^{-1}$ and $R_{II} = 7.5\cdot 10^{-2}\, cm^{-3}s^{-1}$, respectively. For a thermal $d\phi/d\lambda$ with a maximum matching with that of s_{II}, R_{II} exceeds R_I correspondingly more.

References

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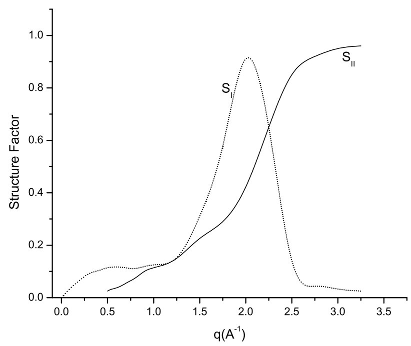

Fig. 1: Structure factor in superfluid helium due to one-(S_I) and multiphonon(S_{II}) excitation vs momentum transfer q [4]

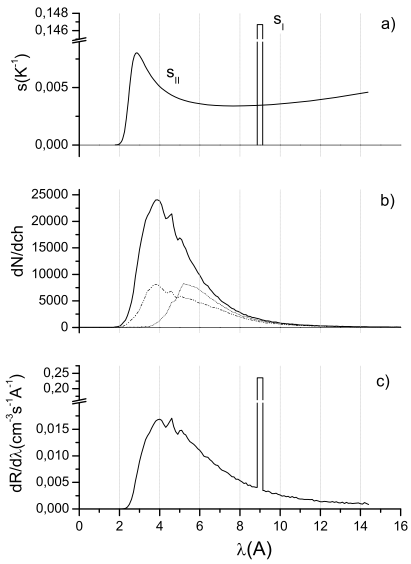

Fig. 2: a: One-phonon (s_I) and multiphonon(s_{II}) scattering functions vs incident neutron wavelength λ. b: Count rate of the n spectral flux density measurement at the HMI cold n guide end vs λ [5]. The dotted lines denote measurements with the counter displaced in the horizontal plane by ± 1 cm from the maximum flux density. c: Resulting spectral UCN production rate density vs λ.