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Fizeau effect for neutrons

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It is shown that local-field effects in the neutron optical potential produce a nonvanishing Fizeau effect and that the magnitude of the effect is particularly large for cold neutrons with wavelengths $\lambda \gtrsim 13$ Å.

In a recent article Arif *et al.*[1] have attempted to measure the Fizeau effect for thermal neutrons transmitted through a moving slab using a perfect-crystal neutron interferometer. When the slab is moving in a direction parallel to its boundaries (so that there is no motion of the boundaries themselves) the phase shift due to the motion of the slab is[1] proportional to dV/dE, where V is the optical potential that describes the effective interaction of the neutrons with the slab and E is the incident-neutron energy. In the elementary theory[2,3] V is given by the mean value of the Fermi pseudopotential,

$$V=\left(\frac{2\pi\hbar^2}{m}\right)\rho b \ , \tag{1}$$

where m is the neutron mass, ρ the number of nuclei per unit volume, and b the average bound coherent scattering length per nucleus. If b is independent of E, then $dV/dE=0$ and the Fizeau phase shift vanishes.[4–7] This was found[1] to be consistent with the experimental results for a fused-quartz slab and an incident-neutron wavelength $\lambda=1.268$ Å, which gave an upper bound

$$\left|\frac{dV}{dE}\right| \leq 2.1\times10^{-8} \ . \tag{2}$$

It has been suggested[5,6] that a nonvanishing Fizeau effect will occur near a neutron resonance, where b has a significant energy dependence. The purpose of the present paper is to call attention to the fact that V also becomes energy dependent when one takes into account the local-field effects that are neglected in the approximate result (1). In this case one finds[8–10] that the real part of the optical potential is given by

$$V=\left(\frac{2\pi\hbar^2}{m}\right)\rho b(1+J) \ , \tag{3}$$

in which the local-field correction is given for an isotropic medium by

$$J=\frac{2\pi\rho b}{k}\int_0^\infty [1-g(r)]\sin(2kr)dr \ , \tag{4}$$

where k is the incident-neutron wave vector and $g(r)$ the pair-correlation function for the atoms that comprise the medium. Since $E=(\hbar k)^2/2m$, we see that

$$\frac{dV}{dE}=\left(\frac{2\pi\rho b}{k}\right)\frac{dJ}{dk} \ . \tag{5}$$

The qualitative behavior of J is dominated by the repulsive core of the interatomic potential so that a rough estimate can be obtained by putting

$$g(r)=\begin{cases}0, & r<a,\\ 1, & r>a,\end{cases} \tag{6}$$

in which case[9]

$$J=J_0\sin^2(ka)/(ka)^2, \tag{7}$$

where

$$J_0=2\pi\rho b a^2 \ . \tag{8}$$

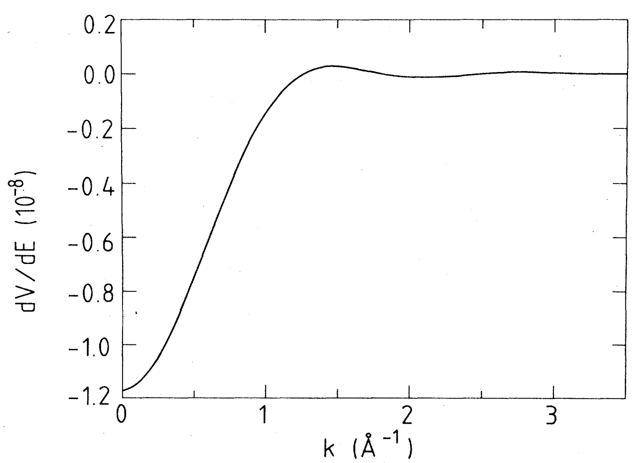

FIG. 1. Energy derivative of the neutron optical potential as a function of the neutron wave vector as calculated from (9) for fused quartz.

Hence, it follows from (5) that

$$\frac{dV}{dE}=2[J_0^2/(ka)^4]\sin(ka)[ka\cos(ka)-\sin(ka)] \quad . \quad (9)$$

For fused quartz (amorphous SiO_2) $\rho=0.022$ molecules/Å^3, $b=15.76$ fm/molecule, and $a=2.5$ Å, so that $J_0=1.3\times10^{-4}$. The corresponding results for dV/dE calculated from (9) are shown in Fig. 1. It is seen that dV/dE has a pronounced negative peak at $k=0$ and an oscillating tail for $k\gtrsim1$ Å^{-1}. These features are qualitatively consistent with our earlier results[9] calculated directly from (4) for various monatomic liquids using experimentally determined pair-correlation functions. The value of dV/dE at $k=0$ in Fig. 1 is -1.2×10^{-8}, which is of the same order of magnitude as the experimental upper bound (2). However, for the wave vector $k=2\pi/\lambda=4.955$ Å^{-1}, at which this upper bound was measured,[1] the expression (9) gives $dV/dE=-3.3\times10^{-12}$.

In conclusion, the above analysis shows that the Fizeau effect provides a direct method for the experimental investigation of local-field effects in the neutron optical potential and that these effects will be most easily observed using cold neutrons with $k\lesssim0.5$ Å^{-1} and $\lambda=2\pi/k\gtrsim13$ Å. Such measurements would be of particular importance, since it has recently been shown[11] that local-field effects often produce a significant correction to the values of b measured by neutron gravity refractometry.

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