Measurement of the reflection of ultracold neutrons from the surface of materials with a large capture cross section

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The energy dependence of the reflection of ultracold neutrons from the surface of strongly absorbing Cd^{113} and Gd^{155} elements is measured. The "metallic" reflection of neutrons was observed in Gd^{155} for which the real part of the potential for interaction with neutrons is much smaller than the imaginary part.

Gurevich and Nemirovskiĭ[1] called attention to the fact that the reflection of neutrons from the vacuum- (absorbing medium) interface increases, as it does in optics, when strong neutron absorbers are used. In optics this effect is known as "metallic" reflection of light.[2,3] Reflection becomes noticeable when the path length of light in the medium is on the order of, or less than, the wavelength.

The amplitude of the neutron wave reflected from the interface, as we know, is given by

$$r = \frac{p_\perp - p'_\perp}{p_\perp + p'_\perp} \tag{1}$$

where $p_\perp$ and $p'_\perp = \sqrt{p_\perp^2 - 2mU}$ are respectively the components of the neutron momentum normal to the interface in the vacuum and in the material, and

$$U = U_r + iU_i = \frac{p_r^2}{2m} - i\frac{p_i^2}{2m} = \frac{\hbar^2}{2m} 4\pi \sum_j N_j b_j \tag{2}$$

is the potential of the interaction of a neutron with the medium.[4] Here N_j is the number of nuclei of species j per unit volume of the medium, b is the complex length of the scattering of a neutron by the nuclei of the medium, and m is the neutron mass.

We see from the two expressions given above that if b is purely imaginary and $p_\perp^2 \sim 2m|U|$, the reflection coefficient $R = |r|^2$ is nonvanishing and if $p_\perp^2 \ll 2m|U| R \to 1$. Since according to the optical theorem $\mathrm{Im}b = \sigma p/2h$, where σ is the total cross section for interaction of a neutron with the medium, and p is the neutron momentum in the medium, at low energies an increase in the absorption leads to an increase in the reflection coefficient.

An exact expression for the general reflection coefficient was given in the lectures by Frank[5]

$$R = 1 - \frac{2\sqrt{2}p_\perp \{(p_\perp^2 - p_r^2) + [(p_\perp^2 - p_r^2)^2 + p_i^4]^{1/2}\}^{1/2}}{p_\perp^2 + [(p_\perp^2 - p_r^2)^2 + p_i^4]^{1/2} + \sqrt{2}p_\perp \{(p_\perp^2 - p_r^2) + [(p_\perp^2 - p_r^2)^2 + p_i^4]^{1/2}\}^{1/2}}. \tag{3}$$

At low neutron energies $p_\perp \ll p_i$ and very strong absorption $p_i \gg p_r$ Eq. (3) yields an expression for the reflection coefficient

$$R = 1 - 2\sqrt{2}\frac{p_\perp}{p_i} = 1 - \frac{4p_\perp}{\hbar N\sigma}, \tag{4}$$

i.e., Eq. (13) of Ref. 1. The last relation in (4) can be found with allowance for (2) and the fact that $\mathrm{Re}\, p'_\perp = p_i/\sqrt{2}$ in the given limit.

For elements with a large capture cross section, the scattering length changes appreciably even at thermal neutron energies because of the presence of close-lying resonances. The energy evolution of the scattering length is given by[6]

$$b = b_0 + \sum_i \frac{2\Gamma_{ni}(E - E_i)g_i}{k_i[4(E - E_0)^2 + \Gamma_i^2]} - i\sum_i \frac{\Gamma_{ni}\Gamma_i g_i}{k_i[4(E - E_i)^2 + \Gamma_i^2]}, \tag{5}$$

where b_0 is the potential scattering length, Γ_i and Γ_{ni} are the total and neutron resonance widths at an energy E_i, g_i is a statistical factor, and k_i is the wave vector for the energy E_i.

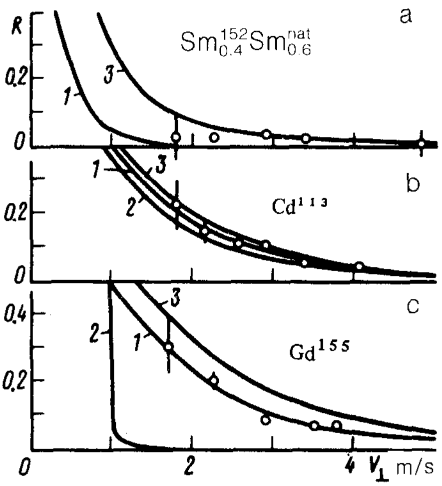

FIG. 1. Experimental data and calculated curves for the reflection of neutrons from the corresponding metals. 1—The potential is calculated in accordance with the amplitudes given in (6); 2—the same, but with Im$b = 0$; 3—the amplitudes were taken from (6), with a 50-Å oxide layer of the appropriate element.

We studied experimentally the energy dependence of the reflection of ultracold neutrons from the surface of Cd^{113} and Gd^{155}, two strong neutron absorbers.

The following procedure was used to carry out the measurements. A collimated ultracold neutron beam was aimed at a 45° angle at a stainless-steel mirror onto which a thin layer ($3–5\times10^3$ Å) of the metal to be tested was vacuum deposited. The neutrons reflected from the mirror were guided along a mirror neutron duct to the input of a time-of-flight correlation spectrometer.[7,8] The energy dependence of the reflection coefficient was determined by the ratio of the spectra of neutrons reflected from the material under study and from the stainless-steel mirror, whose reflection coefficient differs, as we know,[9] from unity by no more than 10^{-3} over the spectral range used by us. Figure 1 is a plot of the experimental and calculated curves for the reflection of neutrons from the velocity component normal to the surface. To obtain reliable results, we had to prepare, before each evaporation of the test material, a mirror substrate that did not reflect neutrons. Such a substrate was fabricated by depositing on it a mixture of samarium isotopes (Sm^{152} 40% + Sm^{nat} 60%). Such a composition was chosen because of the requirement that Re $\Sigma_j N_j b_j = 0$, and that the imaginary part of the potential would be small enough to prevent an appreciable "metallic" reflection of neutrons. Figure 1 shows that the reflection of neutrons from such a mixture over the range of experimentally feasible energies is within 3%. Also shown in this figure are the reflections of neutrons from the surfaces of Cd^{113} and Gd^{155} mirrors, as well as the relevant calculated curves obtained under various assumptions regarding the form of the potential of the reflecting layer. We used the following scattering lengths which were calculated on the basis of (5) and the known composition of the isotopic mixtures:

$$\begin{array}{ll} Sm^{152}_{0.4} + Sm^{nat}_{0.6} & b = (0.06 - 0.59) \\ Cd^{113} & b = (-6.88 - 4.13) \\ Gd^{155} & b = (0.67 - 13.07)\,. \end{array} \qquad (6)$$

For Gd^{155} we see a pure neutron reflection due to the imaginary part of the potential. For Cd^{113} we have $\mathrm{Re}b > \mathrm{Im}b$, and the component $\mathrm{Im}b$ in the reflection is small. In addition to the condition $\mathrm{Im}b \gg \mathrm{Re}b$, a second condition $p_\perp \ll p_i$, where Eq. (4) holds (here $R \to 1$), is satisfied at $v_\perp < 1$ m/s for the isotopes actually existing in nature and for their possible mixtures. This situation was unattainable in the experiments described above.

The measurements were carried out using the ultracold-neutron channel of the IR-8 reactor of the I.V. Kurchatov Institute of Atomic Energy.[10] The experiments are described in more detail in Ref. 11.

The results of measurements of the integrated reflection of ultracold neutrons from strongly absorbing materials were previously described in Refs. 12 and 13.

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