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Diffraction and Mirror Reflection of Ultracold Neutrons

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Ultracold-neutron diffraction by a ruled grating was observed. The measured peak positions, linewidths, and intensities agree with expectation. Mirror reflection experiments yielded, for glass, a reflection curve sensitive to surface contamination, and for gold coating, a typical interference pattern.

We report on experimental investigations of the diffraction of ultracold neutrons (UCN) from an optically ruled grating and on their reflection from neutron mirrors. Diffraction of thermal neutrons by a ruled grating has been observed first by Kruz and Rauch.[1] The motivation behind the present studies was to gain insight into anomalies observed in the containment of UCN's in "neutron bottles" which have thus far persistently yielded shorter containment times than expected.[2,3] We are especially interested in the idea of an "intrinsic coherence length of the neutron wave train," about which there has been much speculation.[4]

In the apparatus used (which may be called "gravity diffractometer") we utilize the fact that the motion of UCN's is strongly affected by gravity since the neutron gravitational potential of $\approx 10^{-7}$ eV per meter of height is of the same order as the kinetic energies considered. Furthermore, we take advantage of the special features of the flight parabola for beam focusing in two spatial dimensions.

Figure 1 shows the principal arrangement. A continuous beam of neutrons slowed down by the "neutron turbine"[5] at the Forschungs Reactor Munich (with a thermal flux of 10^{13} cm^{-2} s^{-1}) is channeled by neutron guides to a horizontal entrance slit. Two beam stops, arranged symmetrically to the slit, select a horizontal UCN beam with small vertical divergence. The neutrons with initial velocity of approximately 3 m/s fall along parabolic trajectories and hit a first vertical mirror consisting of Ni-coated glass. After further reflections from a horizontal and a second vertical mirror with adjustable vertical and horizontal positions, the neutrons pass the exit slit at the maximum height of their ascending flight parabola. The highest point is chosen because it is the focusing point where the spatial beam width is a minimum, being equal to the entrance slit width of 2 cm, provided that the initial divergence and velocity spread are sufficiently small. After passing the exit slit, the neutrons are allowed to acquire some energy by falling in a slightly convergent, vertical guide tube, in order to be able to penetrate the Al window (0.1 mm) of the BF_3 detector (with depleted ^{10}B content), which would totally reflect neutrons with $v < 3.2$ m/s. Along the full flight path the beam is confined to a lateral width of 10 cm by

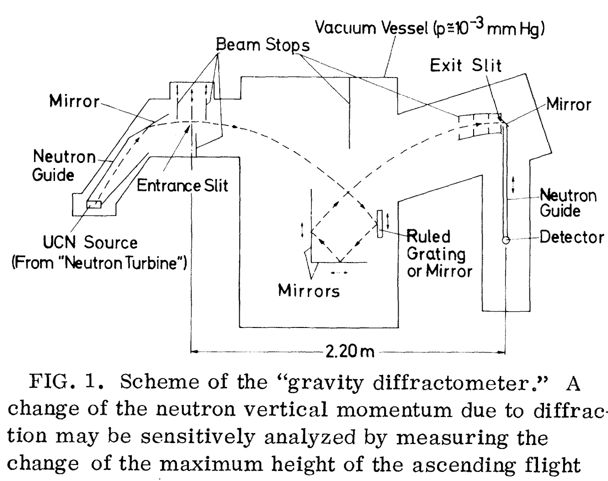

FIG. 1. Scheme of the "gravity diffractometer." A change of the neutron vertical momentum due to diffraction may be sensitively analyzed by measuring the change of the maximum height of the ascending flight parabola.

vertical glass mirrors.

The vertical guide tube including the exit slit and detector may be moved vertically for scanning the beam profile. The resolution curve measured in this way proves to be nearly triagonal as expected for the convolution of the identical rectangular resolution functions for entrance and exit. The full width at half-maximum of 3 cm (corresponding to 3 neV of energy resolution for the vertical motion) is only slightly broadened as compared to the 2 cm of slit width, because of the finite beam divergence and velocity spread. This indicates that reflections (typically, 10–50) along the flight path, mainly from the lateral mirror plates, have little effect on the resolution, although beam attenuation of ~20%/m takes place due to diffuse reflections.

In spite of the high instrumental resolution, the peak counting rate of 180 counts/h (at a background of about 35 counts/h) is quite appreciable because, as in the "gravity refractometer" after Maier-Leibnitz,[6] a fairly wide interval of horizontal velocities and a significant beam divergence may be used without deterioration of resolution.

In the diffraction experiments, the first vertical mirror was replaced by a mechanically ruled, plane reflection grating (effective size 10×20 cm^2, 1200 grooves/mm, with a grating profile chosen in such a way as to obtain blazing condition in first-order diffraction for wavelength $\lambda \approx 1500$ Å). Nickel coating was provided in order to ensure total neutron reflection. In the diffraction process the component of wave number parallel to the grating surface changes by $2\pi n/t$, where n is the order of diffraction and t the groove spacing. The corresponding momentum transfer may again be analyzed sensitively by a vertical intensity scan. The measurement (Fig. 2) shows the diffraction orders $n = 1$, 0, and -1, where $n = -1$ designates first-order diffraction with reversed grating, i.e., reversed grating profile. The intensity in the predominant peak for $n = 1$ is nearly as expected, while the other orders are less intense since the blazing condition is not satisfied for them. The linewidths may be fully explained by the experimental resolution which is slightly deteriorated for $n \neq 0$ due to the finite size of the grating. This effect occurs because the grating causes a definite momentum transfer, but eventually the energy transfer is analyzed.

From the absence of a detectable line broadening beyond the instrumental resolution, it may be concluded that any "intrinsic neutron coherence length" should be at least of the order of 10^2 groove spacing, i.e., 10^6 Å or more, which is $\gtrsim 10$ times larger than previous lower limits reported by Shull.[7]

The diffractometer was also used to study the reflection of UCN's from mirrors. For this purpose, the intensity reflected from the horizontal sample mirror was measured as a function of h, the neutron height of fall. The reflection curve obtained for low-alumina boron-free float glass (Fig. 3) shows the typical steep edge at the critical height of fall, $h_{\rm cr} = 93.6$ cm, which agrees with the calculation of the limit of total reflection for the glass composition used. However, the measured slope is significantly steeper than predicted by the simple theory for reflection from a potential step. On the other hand, the data may

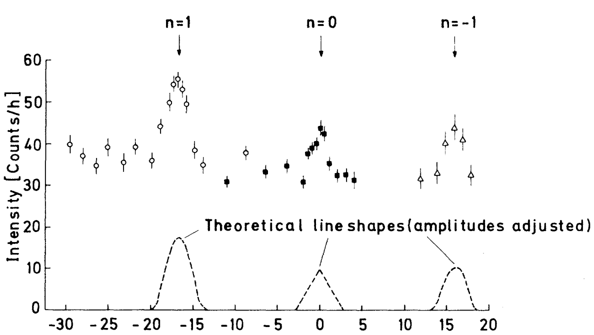

FIG. 2. The measured diffraction peaks for the ruled grating, plotted vs the height of the exit slit relative to that of the entrance slit, are compared to the theoretical line shapes for the instrumental resolution. Background is included.

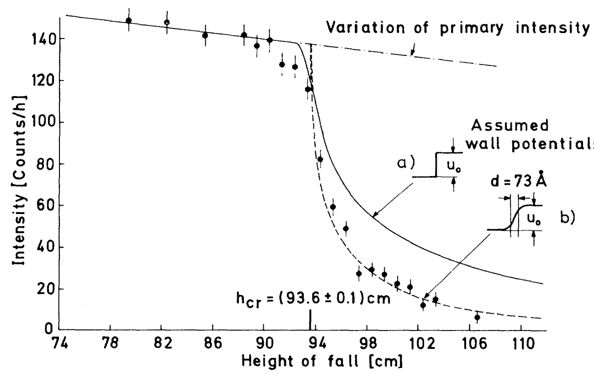

FIG. 3. Measured intensity reflected from a glass mirror (points) compared to theoretical curves for (a) a step function, and (b) a smoothed step function for the wall scattering potential. ---, calculation for monoenergetic neutrons; ——, calculation for the instrumental resolution. Assumption (b) may be a model for a hydrogenous surface contamination.

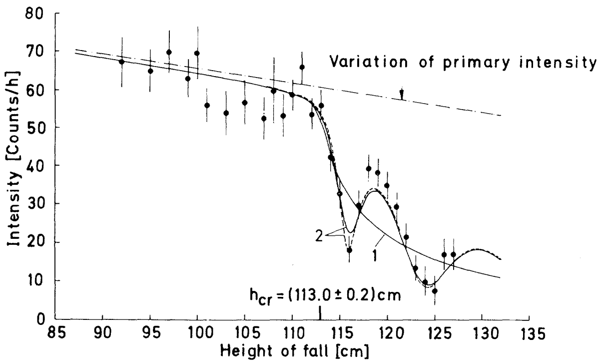

FIG. 4. Intensity reflected from a glass mirror with gold coating (points) showing interference pattern characteristic of thin films. The data are compared to calculations for thick homogeneous gold showing no interference (curve 1), and for a thin homogeneous gold film (2680 Å) on homogeneous glass exhibiting the observed patter (curves 2). ---, calculation for monoenergetic neutrons; ——, calculation for the instrumental resolution.

be well described by the choice of a "soft potential" of the form $u(z) = u_0/[1 + \exp(z/d)]$, where z is the coordinate normal to the wall and d is a measure of the thickness of the transition region. For this potential with real u_0 the reflectivity is given by $R = |\sinh[\pi d(k-k')]/\sinh[\pi d(k+k')]|^2$, where k and k' are the components of wave vector perpendicular to the wall in vacuum and deep in the medium, respectively. A good fit to the data is achieved for $d = 73 \pm 3$ Å. This seems to be a plausible result if the transition region is assumed to be associated with a physisorbed hydrogenous surface layer, e.g., of H_2O with a concentration diminishing with depth. Similar quantities of hydrogen have been observed on various technically "clean" substances,[8] and they would be sufficient to account for the empirical UCN containment lifetimes, at least at room temperature,[8-12] resulting from the large cross section of hydrogen for inelastic neutron scattering. The method of neutron reflection used in the present work to probe the shape of the surface potential is similar to a suggestion by Golub and Pendlebury[13] where, however, a spatially constant change of wall potential due to impurity was considered.

Additional measurements with a nickel mirror (for which h_{cr} is more than twice the value for glass) showed that the slope of the intensity curve for glass (Fig. 3) in the subcritical region is determined solely by the slight variation of beam losses due to the variation of the length of flight path.

Similar reflection experiments were carried out with a mirror consisting of a thin gold film evaporated on glass. Figure 4 shows the measuring data which exhibit the typical interference pattern sensitive to the film thickness.[14] The fitted numerical value $d = 2680 \pm 60$ Å for the film thickness agrees with the evaporation data.

It may be stated as a conclusion that apparently no "anomalies" must be invoked to understand our experimental results both on the diffraction and reflection of ultracold neutrons, but that the data are well explained by ordinary wave mechanics.

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