PROPAGATION OF NEUTRON BEAMS

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1. INTRODUCTION

In my view, the topic of this talk, "propagation of neutron beams", has two general aspects. One refers to the fundamental characteristics of propagation of the neutron as a matter wave, the other is connected with the specific problem of guiding slow neutrons, say, from a neutron source like a reactor, to the experimental site, or from one place in an apparatus to another. Evidently, the first and more fundamental of these aspects is very complicated, and it will be the subject of several other contributions at this meeting. It comprises not only phenomena like scattering or absorption, which occur when a beam of neutrons traverses matter, but it may even touch upon the very old puzzle of quantum mechanics as to the "reality" of a matter wave. To my knowledge, no one has ever given a completely satisfactory answer to that question.

In the present talk I shall concentrate mainly on the much easier problems of slow neutron guidance and confinement. The techniques used for these purposes are based on collective neutron interactions with matter, or with gravitational or magnetic fields. Within the restricted framework of the specific applications considered, these interactions may be described by the simple concept of an index of refraction.

2. INDEX OF REFRACTION AND NEUTRON MIRRORS

Refraction is well known as a common phenomenon for any radiation like sound, light, x-rays, electrons, or neutrons. From a microscopical point of view, refraction by matter may be described as a collective effect of coherent-elastic scattering in the forward direction. The elementary scattering centres may be atoms, nuclei, or other systems like small air bubbles in water as a source of sound wave scattering. The usual procedure of coherent superposition of the wavelets originating from all the scattering centres with the wave incident from outside the matter, then leads to a modification of the incident wavenumber k_o by an index of refraction n so that the wavenumber within the medium is $k = nk_o$. This result holds for any wave form and any shape of the region filled with matter. For nuclear scattering of slow neutrons the refractive index is given by

$$n = (1 - 4\pi N\langle b_{coh}\rangle/k_o^2)^{1/2},$$

where b_{coh} is the coherent-scattering amplitude for the bound nucleus, and N is the number of nuclei per unit volume. The averaging refers to such cases where, on a microscopic scale, the medium consists of a mixture of atoms or isotopes with different scattering lengths, similarly as the "coherent"-scattering length refers to averaging the nuclear interaction over different relative orientations of neutron and nuclear spin, where applicable. In cases where the scattering distribution is non-isotropic, as in light or x-ray scattering, or in neutron scattering by paramagnetic atoms, the relevant scattering amplitude is that for forward scattering, i. e., b should be replaced by -f(0). Incoherent scattering effects including inelastic scattering and absorption may be incorporated in an imaginary part of the refractive index.

For neutrons or other massive particles the kinetic energy $E_{(o)}=\hbar^2k^2_{(o)}/2M$ (M: mass) is proportional to the wavenumber squared, in the non-relativistic limit. Thus, refraction may be visualized as an effect of a "scattering potential" (or "optical potential") $U = 2\pi\hbar^2N\langle b_{coh}\rangle/M$, chosen in such a way that $E = E_o - U$.

In the framework of this picture it is very easy to extend the concept of neutron refraction also to situations where further interactions must be considered. Examples are the gravitational potential Mgz, where z is the height measured from an arbitrary origin, or the interaction energy $\pm\mu B$ of the neutron magnetic dipole moment $\vec{\mu}$ with a magnetic induction $\vec{B}$, where the sign depends on the mutual orientation of field and neutron spin. Numerically, $Mg = 10^{-7}$ eV/metre and $\mu = 6 \times 10^{-8}$ eV/tesla. Thus, the combined effect of these interactions may be expressed as a spatially variable index of refraction

$$n(r) = \{1 - [U(\vec{r}) + Mgz \pm \mu B(\vec{r})]/E_o\}^{1/2}.$$

Further interaction terms, for instance due to the weak interaction, could be included in the same way.

The slow neutron scattering potential is positive for most substances (which corresponds to a phase shift of $-\pi$ on scattering), thus $n < 1$. This is a necessary condition for the possibility of total reflection. Therefore, a slow neutron incident on a flat "mirror" of appropriate material will be totally reflected, provided that the angle of incidence, referred to the surface normal, lies in the range $\theta > \arcsin n$. This corresponds to the plausible condition that the kinetic energy of motion perpendicular to the surface should not exceed U, so that wave propagation within the medium is impossible. For the bulk of substances, U is of the order of 10^{-7} eV, therefore total reflection of thermal neutrons with typical energies $E_o \approx 25$ meV ($\lambda \approx 1.8$ Å) occurs only at very small glancing angles $\gamma = \pi/2 - \theta \leq (U/E_o)^{1/2} < 10^{-2}$. On the other hand, for neutrons with ultralow energies ("ultracold neutrons") E_o and U are comparable, and such neutrons may be totally reflected even at any angle of incidence. This is the basis for the possibility to store these neutrons in closed cavities ("neutron bottles") for fairly long times, presently up to 650 s /1/.

When slow neutrons interact with a magnetized ferromagnet, double refraction occurs because the index of refraction differs for the two possible neutron spin orientations relative to the internal induction $\vec{B}$. This phenomenon is widely used for slow neutron polarization and polarization analysis, choosing appropriate ferromagnetic mirrors for which $U + \mu B$ is large but $U - \mu B$ is nearly zero. Then only one spin state is totally reflected at glancing incidence while the other is not refracted and eventually absorbed in the mirror substance. Instead of reflection also the transmission through thin ferromagnetic films may be employed to obtain a polarized neutron beam, and this method is particularly useful for ultracold neutrons where a divergent beam may be polarized with 98 % efficiency by perpendicular transmission through thin monocrystalline iron films /2/.

The force experienced by a neutron in an inhomogeneous magnetic field, $F = \mp\mu \text{ grad } |B| = E_o \text{ grad } n^2$ may also be used for mirror reflection or beam focussing in appropriate magnetic field configurations /3, 4/. I shall mention one example later.

The beam divergences usable in all devices based on total mirror reflection are determined by the angular range of total reflection, which is quite small for thermal neutron energies. A possibility to overcome this limitation, the so-called "supermirror", has been developed and demonstrated by Schoenborn et al. /5/ and Mezei /6/. It consists in using

Bragg reflection from a synthetic, one-dimensional crystal made up of thin evaporation layers with alternating scattering potentials, in much the same way as dielectric multilayer systems used as high-reflectance mirrors in light optics. In Mezei's version the lattice parameter varies smoothly across the multilayer arrangement. In this way a wide wavelength band may be Bragg-reflected. Such devices are very efficient polarizers and fairly good reflectors (with about 70 % reflectivity) over an angular range exceeding the range of usual total reflection by a factor of two.

3. NEUTRON GUIDE TUBES

The phenomenon of total reflection may be utilized for neutron beam transport in "neutron guide tubes", in a similar way as light can be conducted in light pipes. A neutron guide tube /7/ consists of an evacuated tube surrounded by mirror walls of high surface quality, usually made of float glass with a thin nickel coating. Nickel is chosen as reflecting material because of its relatively high scattering potential of about 2×10^{-7} eV.

The use of guide tubes offers the advantage over non-reflecting beam tubes, that fairly large distances between neutron source and experiment can be bridged without significant loss in luminosity. This is very important for time-of-flight measurements where long flight paths are necessary for good resolution, but also for background considerations. The background due to γ-rays and epithermal neutrons from the source can be practically eliminated by a guide tube because the glancing angle for these radiations would be extremely low, and direct sight to the source may be avoided completely by appropriate curvature.

A great number of guide tubes have been installed until now at various Institutes. For instance, guide tubes with a total length of over 500 m provide thermal and cold neutron beams for a variety of instruments at the High-Flux Reactor, Grenoble.

A further application of neutron guide tubes is the guide for polarized neutrons /8/, which consists of magnetized ferromagnetic mirror walls. The advantage of a polarizing guide over a simple mirror consists in the possibility to provide larger beam divergences.

4. PECULIARITIES OF VERY-SLOW NEUTRON PROPAGATION

Now I want to draw your attention to some peculiarities of low-energy neutron propagation, connected with the effects of gravity and static magnetic fields. In applying the concept of refraction to inhomogeneous magnetic fields one must be aware of the limitation of this simple picture. It provides an adequate phenomenological description only as long as the neutron spin orientation relative to the field is a constant of motion, i. e., if the spin is able to follow adiabatically changes of field orientation along the neutron trajectory. The criterion for this is that the Larmor precession frequency in the local magnetic field should be significantly larger than the frequency of field rotation as "sensed" by the moving particle. This condition is usually satisfied for slow neutrons except possibly in critical regions where the magnitude of the field is small and its orientation changes rapidly. In such circumstances spin flip relative to the field may occur, and the simple formalism of an index of refraction breaks down.

The effect of gravity or magnetic fields is most pronounced for neutrons of very low energy, although the gravitational interaction has also been observed with thermal neutrons, using interferometric techniques /9/. Since the fields usually vary very slowly in space on a scale determined by the neutron wavelength, the WKBJ approximation as well as Ehrenfest's theorem of quantum theory provide a transition to classical mechanics. Thus, a neutron should describe the same trajectories under the influence of these potentials as a classical particle. This means, for instance, that a very slow neutron should describe a parabolic trajectory in the earth's gravitational field, but this result can also be obtained from the variation of the refractive index with height, similarly as light rays are curvilinear in media with a gradient of the refractive index.

The free fall of neutrons in the gravitational field has been utilized extensively for precise measurements of scattering lengths for slow neutrons /10/, making use of the fact that the energy of vertical motion accumulated by a particle upon falling through a given vertical distance may be determined very accurately. Thus, in the gravity refractometer built by Koester in Garching cold neutrons start from the reactor source horizontally at a height determined by a narrow entrance slit, and after having travelled for about 100 m they hit a horizontal mirror surface at a variable vertical distance H below the entrance slit. Then the limiting height H_{crit} for total reflection is simply related to the mean scattering length of the constituent atoms of the mirror. One of the results of such measurements is that the gravitational acceleration is the same for the neutron as for any other particle within an accuracy of less than 10^{-3}, which sets an upper bound to speculations about a possible spin dependence of gravity which would be the consequence of a postulated "gravitational dipole moment" /11/.

As another example of utilization of gravity, Fig. 1 shows the scheme of a gravity diffractometer for ultracold neutrons /12/. This instrument was used to study the diffraction of neutrons with wavelengths of about 1000 Å from a ruled grating. The neutrons again start horizontally from an entrance slit, fall in the gravitational field and are reflected from various mirrors in much the same way as in a billiard game. They first hit the vertical grating. After two further reflections from a horizontal and a vertical mirror they travel upwards and are collected by an exit slit at the heighest point of their flight parabola. The highest point is chosen because it is the focussing point for the beam which is much wider along other parts of the trajectory. In the diffraction process at the grating the neutrons gain vertical momentum, $2\pi\hbar m/d$ (d: groove spacing, m: order of diffraction), which may be measured by the change of the vertex height of the analyser flight parabola. One result of the experiment was a lower limit of 10^6 Å for an "intrinsic coherence length of the neutron wave train". This does not contradict the expectation of an infinite coherence length (apart from effects due to the finite neutron lifetime), derived from the simple consideration that the solutions of the Schroedinger equation in free space are plane waves without spatial limitation.

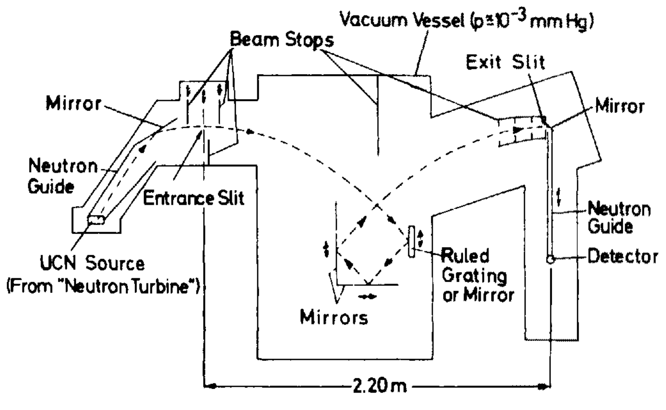

Fig. 1 Scheme of the neutron gravity diffractometer at Garching

Another example where the effect of gravity is significant is the problem of image formation with ultracold neutrons, say, with the futuristic aim of a neutron microscope. The variable refractive index of space in the presence of gravity, and its dependence on wavelength lead to chromatic aberration of space, which must be corrected for in an optical system. One possibility of compensation is provided by a "zone mirror" /13/, where diffraction and reflection at a concave reflecting zone plate are combined to achieve achromatism.

Let me conclude with an interesting example of the influence of magnetic fields on neutron propagation in the "neutron storage ring" developed and successfully tested by a group of the University of Bonn /14/. This device consists in a superconducting ring magnet as shown schematically in Fig. 2. The magnet generates a toroidal hexapole field with higher multipole components. Due to the magnetic dipole interaction very slow neutrons may be trapped in the toroidal region, and they were observed to circle around the ring until they disappear due to β-decay. It is hoped that magnetic storage in this or other forms may ultimately provide an improved value for the free neutron lifetime.

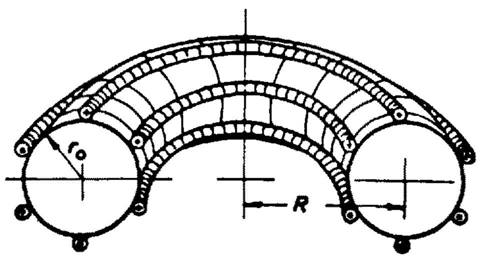

Fig. 2 Simplified scheme of a magnetic storage ring for neutrons

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