REACTORS AND PHYSICS EDUCATION

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Abstract

This paper will discuss some ideas for using neutrons in physics education, including experiments which demonstrate diffraction and optical refraction, divergence imaging, Zeeman splitting, polarization, Larmor precession, and neutron spin-echo.

Introduction

There are about 325 test, research, and training reactors currently in service. One of the main roles which has evolved for these reactors is research and training in nuclear engineering and reactor operation. However, it is relatively rare to see them used for education and training in other branches of science and engineering, even though many are now used for research encompassing practically all scientific disciplines. Thermal neutron beams of quite modest flux (10^9 $m^{-2}.s^{-1}$) make excellent educational tools for teaching some basic aspects of physics, in particular. With a simple chopper and fairly inexpensive optical bench equipment of the type typically found in undergraduate physics laboratories, dual wave-particle experiments may be used to give some "hands-on" reality to quantum mechanics, for example. These types of pedagogical experiments have been pioneered, in particular, by Professors Cliff Shull (at the M.I.T. reactor), Peter Egelstaff (using an Am/Be source at the University of Guelph), and Sam Werner (at the Missouri University Research Reactor).

Examples of Introductory Experiments

The basic kitset consists of a thermal neutron beam running parallel to a length of optical bench on which devices such as diaphragms can be placed using standard optical mounts. The beam may be white or monochromatic. Diaphragms can be made from plasticized boron carbide sheets with holes of various sizes punched in them. Several simple but instructive experiments can be done with this basic kit, using a scintillator and Polaroid camera as the imaging device. A series of photographs of the beam with different attenuators (such as stacks of 1 mm plexiglass) or absorbers (such as Cd) in place gives an introduction to neutron transmission and absorption. The addition of a pinhole images divergence, rather than intensity, and shows the difference between flux and brightness. The divergence in the beam may be made anisotropic and varied by using pairs of rectangular diaphragms spaced by different distances; moving the pinhole allows the divergence to be observed at different points in the beam. A more interesting variation with a monochromatic beam is to place a Stern-Gerlach magnet around the beam and observe the Zeeman splitting of the beam into two beams; since $2s+1$ beams would be expected, this confirms that the neutron spin is $s = ½$. The use of a video camera makes these survey experiments much easier and is probably cheaper than instant film in the long run.

A monochromatic beam finely collimated in one dimension allows neutron refraction to be demonstrated. Figure 2 shows the arrangement. For a material with average number density N of scatterers with scattering amplitude b, the neutron refractive index is

$$n = 1 - \frac{Nb\lambda^2}{2\pi} \tag{1}$$

where λ is the wavelength. This is an interesting formula because it is an optical (wave) quantity which may be derived using particle considerations, starting with $½ mv^2$ as the neutron energy, where m is the mass and v the velocity of the neutron[1]. A simple application of Snell's law shows that there will be an angle of critical reflection

$$\theta_c = \lambda \left(\frac{Nb}{\pi}\right)^{½} \tag{2}$$

below which all neutrons will be totally reflected. For Ni, this angle is 17.45 milliradian per nm of wavelength.This may be demonstrated by setting a Ni mirror to an angle smaller than this and scanning the detector through the reflecting position.

This effect is the basis of neutron guides.

More Advanced Experiments

The reflection experiment demonstrates refraction at low angles, where the variation in speed of the neutron in different materials generates the effect. If the mirror is replaced by a crystal (pyrolytic graphite or mica, for example), high angle diffraction may be demonstrated. For a given incident angle, θ, between the incident beam and the crystal, scanning the detector will show strongly scattered intensity whenever the Bragg condition

$$n\lambda = 2d \sin\theta \tag{3}$$

is satisfied. Here, n is the order of the reflection and d the spacing between atomic planes in the crystal; if d is known the wavelength may be deduced. Repeating the measurement for different values of θ allows the intensity in the beam, $N(\lambda)$, to be measured as a function of wavelength for each wavelength band $\Delta\lambda$. After correcting for standard instrumental effects such as geometrical area of the beam intercepted by the crystal and for the (known) crystal reflectivity as a function of wavelength, this measurement allows verification of the fact that the beam spectrum from the reactor is Maxwellian:

$$N(\lambda)\,\Delta\lambda = \lambda^{-6} \exp(-h^2/2\lambda^2 mkT)\,\Delta\lambda \tag{4}$$

Here, h is Planck's constant, k is Boltzmann's constant, and T is the absolute temperature.

Figure 3 shows the arrangement for the Bragg diffraction measurement. Also shown in the figure are a simple chopper and an oscilloscope whose timebase is synchronized with the chopper. The chopper is a 400 mm diameter aluminum disk painted with a neutron absorber such as Gd_2O_3 paint, leaving just one or two clear windows which pass pulses of neutrons as they pass through the beam; only modest speeds (1500 - 2000 RPM) are required. With the detector in the correct position to detect Bragg scattering, the oscilloscope will show the time each detected pulse arrives relative to the time of chopping. This may be converted to a particle velocity, v, using the distance from chopper to detector. The experiment thus simultaneously uses a wave phenomenon to measure the wavelength, λ, and a particle phenomenon to measure the momentum, mv, of the neutron. The value of Planck's constant may be derived from the experiment by using the de Broglie relation

$$h = mv\lambda \tag{5}$$

Finally, polarized neutrons open the way to many simple and fascinating experiments that demonstrate fundamental physical ideas related to magnetism and magnetic resonance. Thin-film multilayer magnetic mirrors which act as efficient neutron polarizers or analyzers are now available and may be mounted in a collimated beam as an insertion device. It is worth noting that, for the experiments to be considered here, very high polarization efficiency is not needed, and a simple setup giving a polarization of order 0.9 (easily achievable) is satisfactory. Linear polarization effects familiar from optics are easily demonstrated, but the most interest experiments use precessing polarization.

Figure 4(a) shows a typical setup in which the beam entering from the left is already polarized. The spin-turn device labelled $\pi/2$ is a flat coil wound from 1 mm wire on an aluminum plate about 5 mm thick and larger and wider than the beam. Such devices are easily made and set up[2]. When appropriately energized it interchanges the x and z components of the neutron spin, where z is the direction of the magnetic field in which the polarized beam is travelling, leaving the y component alone. This is equivalent to rotating the spin direction from parallel (or antiparallel) to z to perpendicular to z:

$$(x,y,z) \rightarrow (\pm z, -y, \pm x) \tag{6}$$

The spin will precess about the field at the Larmor frequency so that, as the neutron travels in the field, the polarization direction will have rotated to a phase angle

$$\psi = (4\pi|\gamma|\mu_n m\lambda/h^2) \int \boldsymbol{H}\cdot d\boldsymbol{l} \tag{7}$$

after traversing a path with field integral $\int \boldsymbol{H}\cdot d\boldsymbol{l}$. As the analyzer/detector combination is moved along the beam, the detected intensity will be modulated as $\cos\psi$. However, the further the distance, the lower the modulation depth, since different velocities in the beam will precess at different rates, eventually washing out the signal.

The concept of spin echo can be demonstrated by adding two more spin-turn coils to the arrangement, as shown in figure 4(b). The π coil is physically the same as the $\pi/2$ coil but is energized differently[2]. Its action on the spin components is

$$(x,y,z) \rightarrow (x,-y,-z) \quad (8)$$

which is equivalent to the action of a spin flipper. (These coils alone may be used between a polarizer/analyzer combunation to demonstarte linear polarization.) The arrangement is symmetric about the π coil, so that whatever precession takes place in the first part is reversed exactly in the second part. A spread in velocity in the beam no longer matters and the full initial polarization is recovered at the analyzer.

Many other experiments are possible with the simple equipment described in this paper, which is intended only to stimulate further thought on the use of neutron beams in physics education.

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References

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2. J. B. Hayter, *Z. Physik* **B31**, 117 (1978)

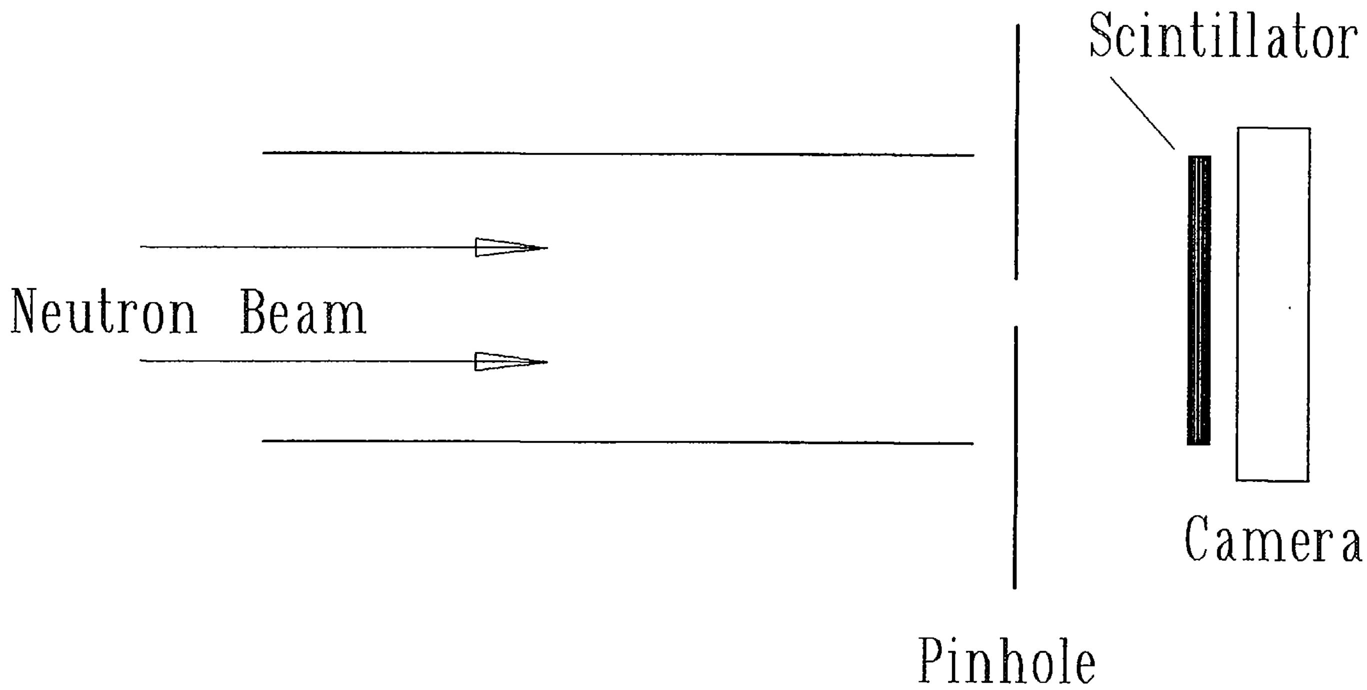


Figure 1

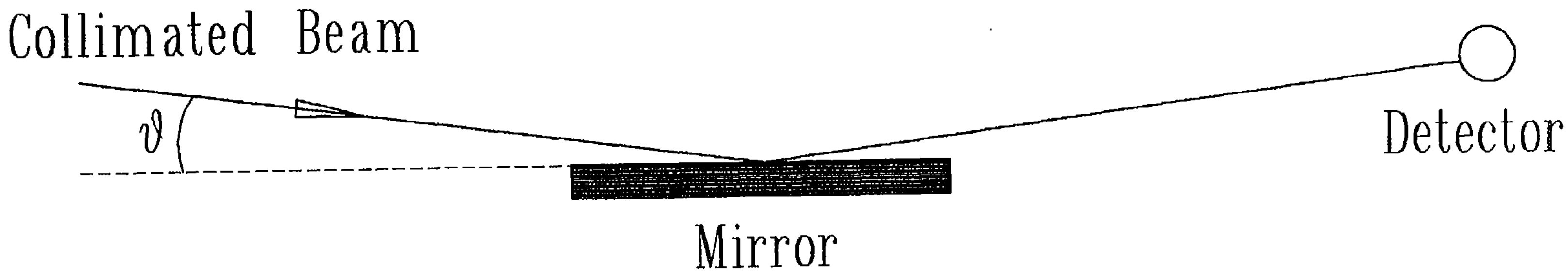
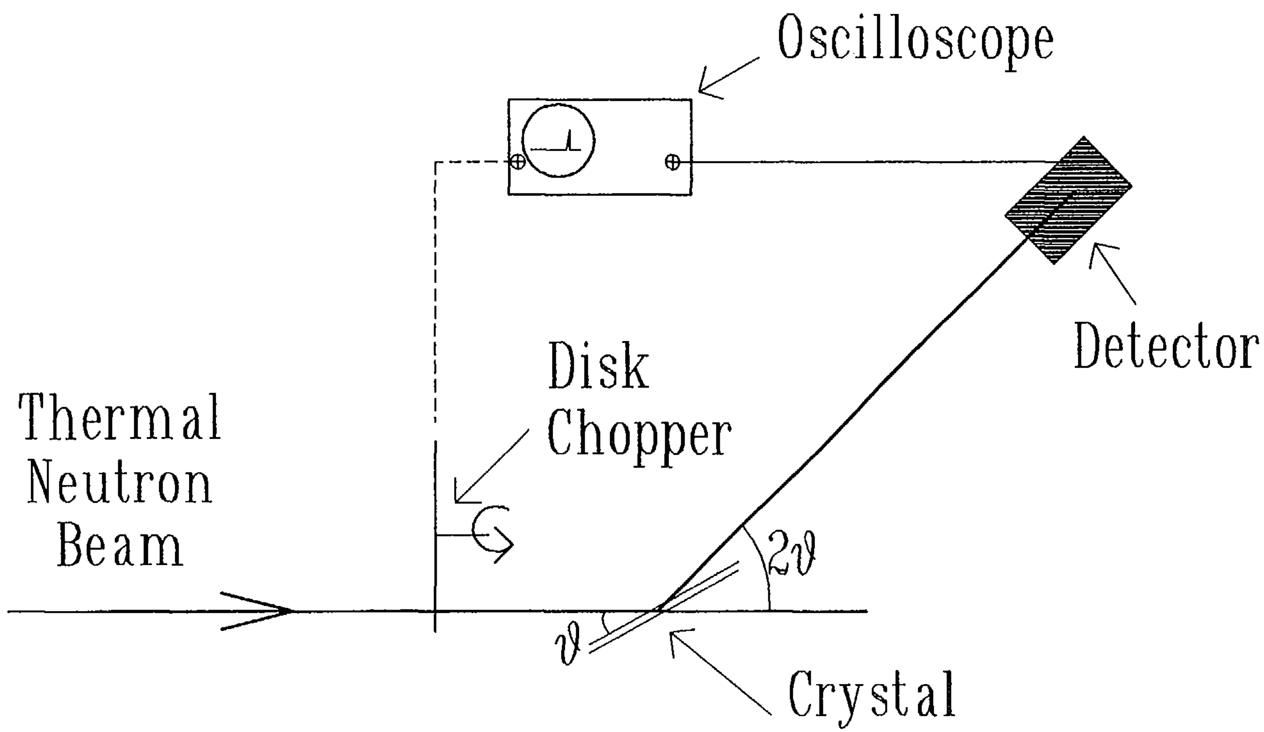


Figure 2



Oscilloscope
Detector
Disk
Chopper
Thermal
Neutron
Beam
2ϑ
ϑ
Crystal

Figure 3

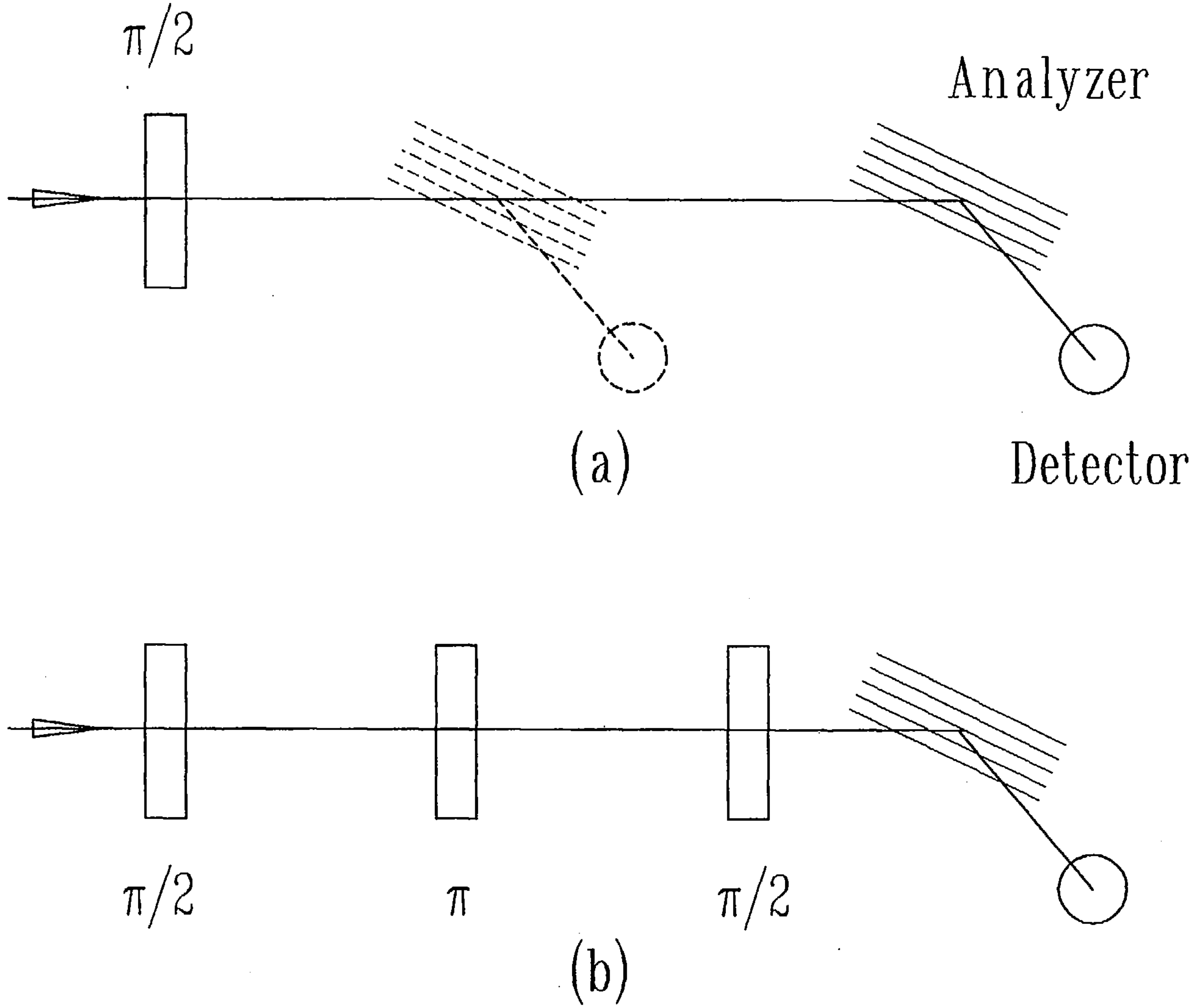


Figure 4