Neutron beam handling by inelastic interaction with time-dependent magnetic fields

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ABSTRACT: Two different methods of energy transfer to neutrons by time-dependent magnetic fields are experimentally demonstrated. The first method involves a change of the neutrons potential energy during the passage through the field region. The second method involves a change of the neutrons potential energy during the passage through the field region. The second method involves a spin-flip in an external magnetic field by an rf-flipping device. All experiments were performed on high-resolution perfect crystal spectrometers. Applications of these methods for active monochromatization and beam handling are discussed.

Introduction

One of the most important objectives of neutron optics is to increase the percentage of neutrons in a beam which are in a distinct space, time or velocity interval. Most devices which are used today are passive in the sense that they select particles with the desired properties. Compared with the optics of charged particles and atoms, where effective cooling systems have been invented[1,2], the handling of neutron beams is more difficult due to the weak interacting potentials. Therefore, active devices that involve inelastic action on the neutrons are still a challenging problem.

Among the active neutron optical components that can change the energy of thermal and cold neutrons are special moderators[3], different techniques for the production of ultracold neutrons[4,5,6,7] and fast moving crystals[8]. Another class of active neutron optical components makes use of the interaction of the neutrons magnetic moment with time-dependent magnetic fields[9]. Here methods with spinflip[10,11] and without[12,13] can be distinguished.

Energy change without spinflip

When a neutron moves in a homogeneous magnetic field whose strength varies in time, the potential energy of the particle changes as

$$\frac{dU}{dt} = \pm \mu \frac{dB}{dt}, \tag{1}$$

where $\mu = 0.966 \times 10^{-26}\ \mathrm{JT}^{-1}$ is the neutrons magnetic moment, and the sign depends on the spin orientation compared with the field vector. This effect can be used for the acceleration and deceleration of neutrons and has been demonstrated recently[13]. The experimental arrangement (Fig. 1) consists of two aligned C-shaped electromagnets which produce a field varying sinusoidally in time. The frequency of the oscillation is matched to the time of flight through a magnet, in the sense that this time corresponds to one-half (modus A) or one-fourth period (mode B). The phase difference between the two field regions was:

$$\Delta\varphi = \frac{l\,\pi}{4\,(1 + \mathrm{d})}\,; \tag{2}$$

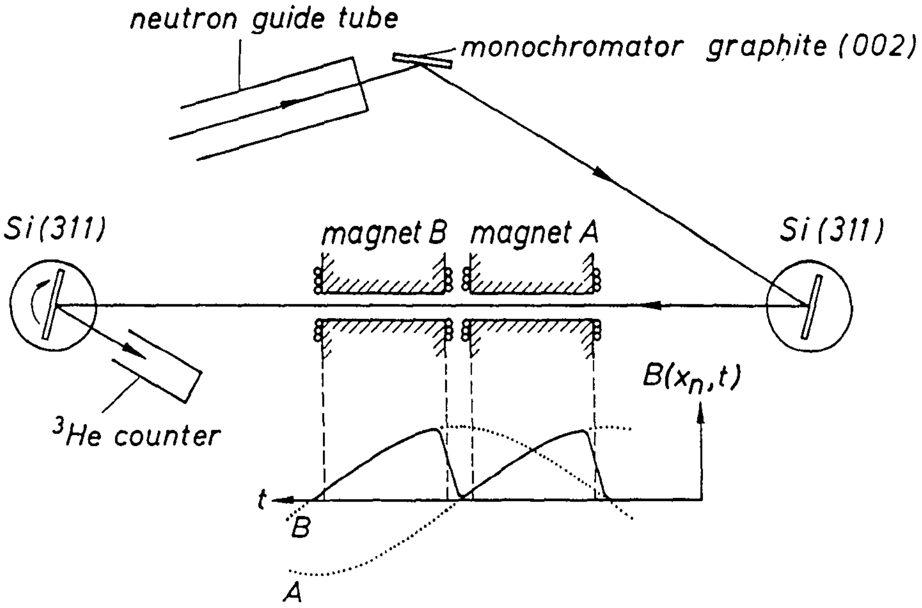

Fig. 1 Outline of the experimental set-up. Neutrons passing through the air gap of the two electromagnets experience two consecutive energy changes. The field amplitudes of the magnets (dotted lines) and the field amplitude at the location of one selected particle (solid line) are shown.

(l = 105 mm is the length of one magnet and d = 25 mm is the distance between them) in mode A and twice this value in mode B. The field amplitude in this experiment was limited due to material constraints to 0.4 T. The measurements were performed at a wavelength of 3.23 Å at the High Resolution Double Crystal Spectrometer (instrument S21) of the ILL, Grenoble. The counting of the particles was accomplished in eight time channels corresponding to different phases of the oscillating fields.

It was found that for those time channels where the neutron had to pass a field-inverting region between the magnets, the beam was partially depolarized (31%), whereas for measurements where no field inversion between the magnets happens (only in mode A), all particles experienced a full change of energy. The results are shown in Fig. 2. Although the fields were too weak to generate a double-peaked curve, the data are in full agreement with the expected values and demonstrate clearly the predicted effect with an energy transfer $\Delta E = \pm 2\mu B_{max} = \pm 58.4$ meV.

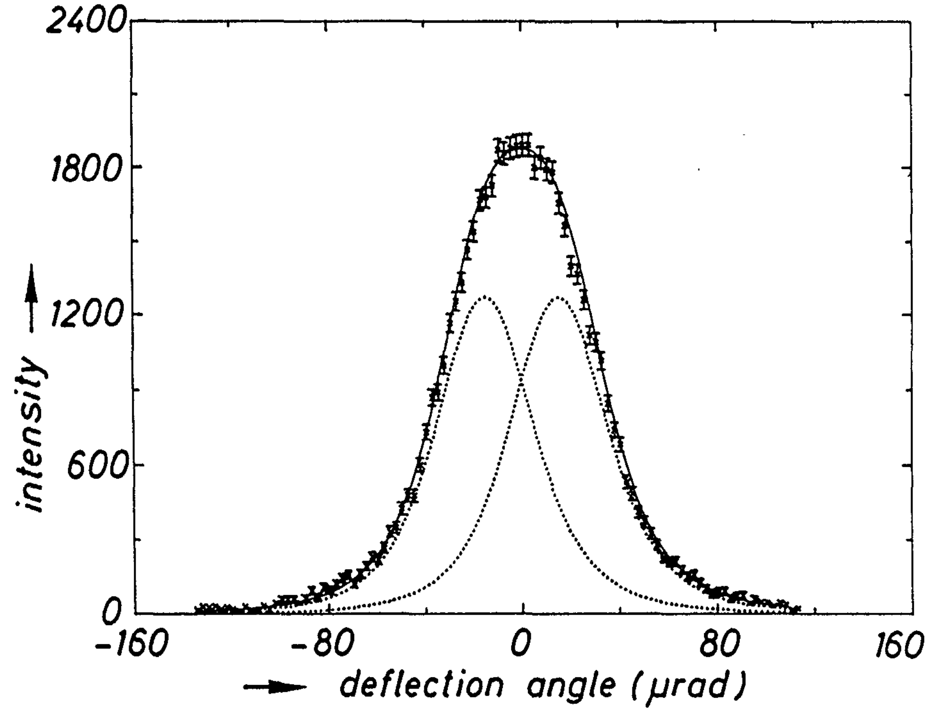

Fig. 2 Rocking curve of channel 5, mode A (maximum energy shift without depolarization). The dotted lines correspond to the two spin states.

Energy change with spinflip

Another method of changing the energy of the neutron by time-dependent magnetic fields consists in the inelastic action of an rf-flipper, as it was predicted almost two decades ago[14] and verified later on by using a backscattering spectrometer[10]. For the flipping action two conditions have to be fulfilled: (i) the "frequency resonance" condition

$$2\mu B_0 = \hbar\omega \; ; \tag{3}$$

and (ii) the "amplitude resonance" condition

$$B_1 = \frac{\pi\hbar v_n}{\mu l} \; . \tag{4}$$

Here B_0 is the static and $B_1(\ll B_0)$ the oscillating field, v_n the neutron velocity and l the length of the field region. If a gradient is applied to the static field, the amplitude resonance condition can be relaxed. This makes possible a broadband action of the flipper in the energy range of cold neutrons.

The inelastic action of such a gradient flipper has been demonstrated in an experiment at a perfect crystal spectrometer of the DIDO reactor of the KFA Jülich (Fig. 3). The results are shown in Fig. 4. The peaks corresponding to the two spin states can be separated. The measured energy transfer, $\Delta E = 0.240(5)$ µeV, corresponds well to the calculated value $\Delta E = h\nu = 0.243$ µeV for $\nu = 58.97$ MHz ($\overline{B}_0 = 2.022$ T). In another experiment with polarization analysis, the flipping efficiency has been compared with theory[15] and the agreement has been confirmed. By a careful shaping of the magnetic fields, the wavelength dependence of the flipper action for the energy shift can be optimized[16].

Applications

There are many proposals for various beam handling systems that make use of the energy change demonstrated in the experiments described above. For example, systems for dynamical spin polarization[17] and for the storage of neutrons in a total reflecting ring or in a crystal resonator have been considered[11].

Probably the most challenging application of inelastically acting devices are active monochromators that selectively accelerate and decelerate neutrons and, therefore, increase the flux in a distinct energy interval. Due to Liouville's theorem, this can only be done with pulsed sources. Clearly the energy changes obtained so far with active neutron optical devices based on interaction with time-dependent magnetic fields are not yet in the order of magnitude that can be useful for most neutron scattering experiments. For this purpose multistage systems have to be constructed, which are not only expensive, but also include the problem of depolarization. A monochromator using the energy shift of rf-flippers has been described[18]. Comparable to this is a multistage system based on magnets as described in the first experiment. This would be analogous to the accelerator design of Wideroe with the electric dipole fields replaced by magnetic quadrupole fields[13].

Up to now we have considered only magnetic fields where the region of the accelerating gradient is fixed in space. This is not the case in the traveling wave monochromator[12]. A schematic drawing of such a system is shown in Fig. 5. For this system no small-scale version can be constructed. Therefore, we present some results of computer simulations.

A comparison of the intensity gain which can be achieved with different types of potentials is shown in Fig. 6. The various types of potentials considered in this comparison are (the primed variables refer to the moving potential frame):

a) An oscillator potential with constant width 2w.

$$V(x) = \pm\, \mu B_{max} \left(\frac{x'^2}{w^2} \right) . \qquad (5)$$

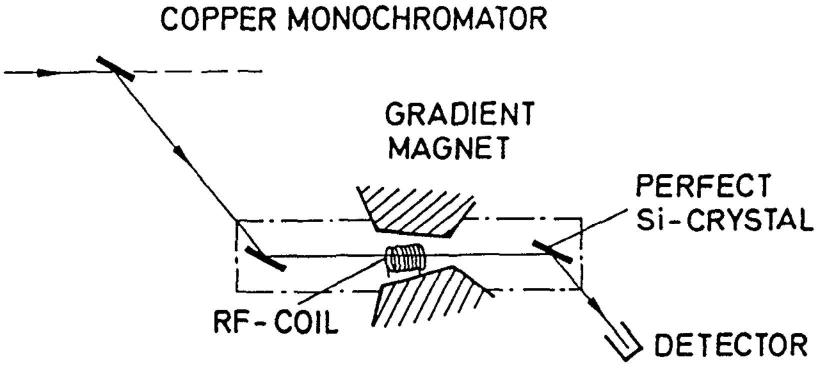

Fig. 3 Sketch of the experimental set up of the spinflip experiment.

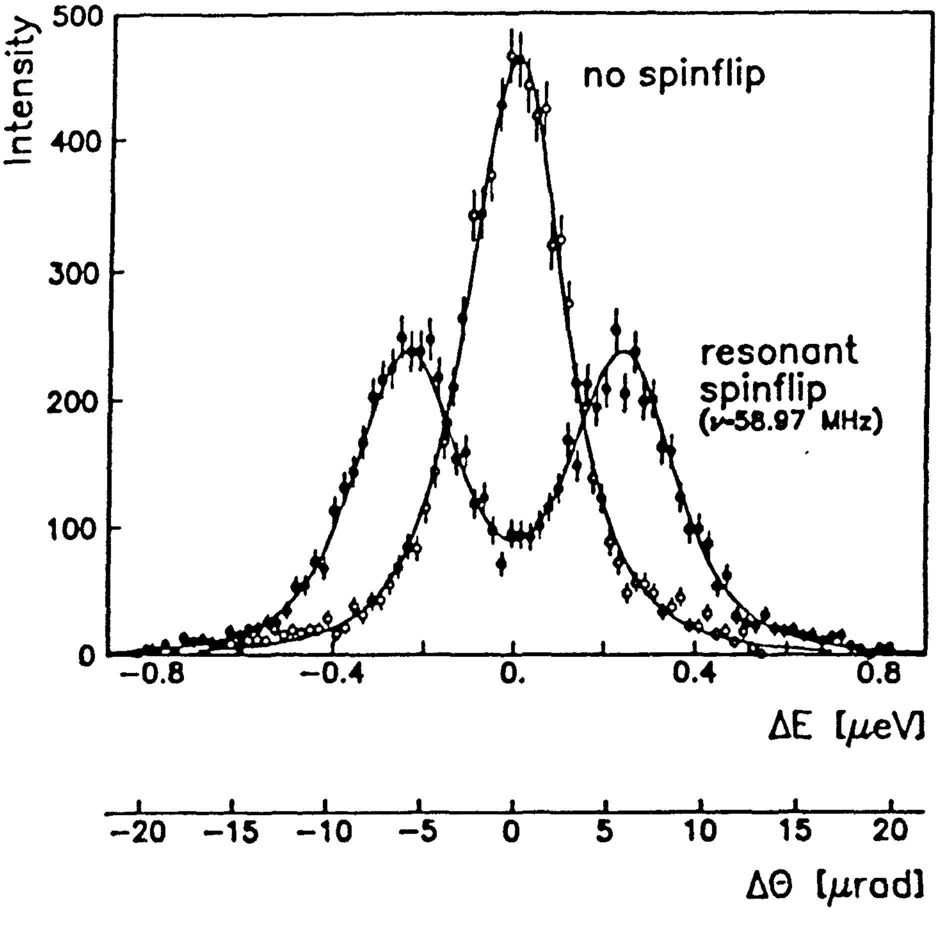

Fig. 4 Splitting of the rocking curve due to the inelastic action of the rf-flipper.

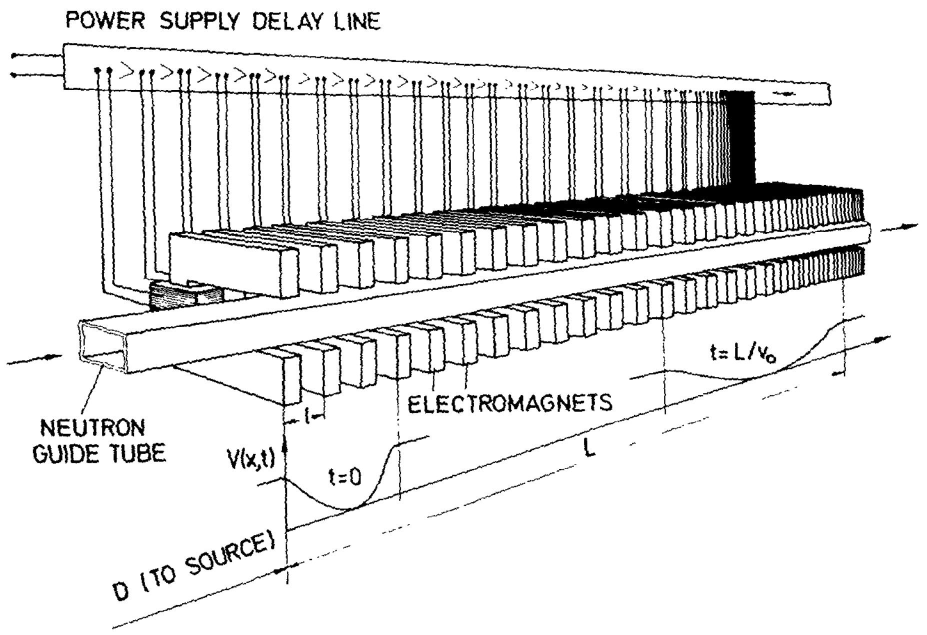

Fig. 5 Proposed scheme of a traveling wave monochromator.

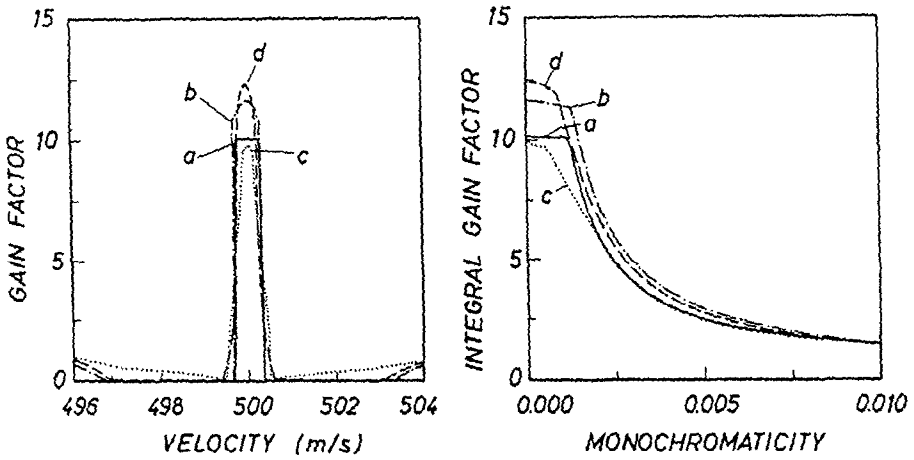

Fig. 6 Comparison of the expected gain factors and integral gain factors for traveling wave monochromators with different kinds of magnetic potentials. For details of the shaping of the potentials, see text. Common parameters: distance-source monochromator D = 10 m, length of monochromator L = 20 m, mean neutron velocity v_0 = 500 m/s, pulse length τ = 50 μs, magnetic field amplitude B_{max} = 1 T.

In this case the phase space evolution of the particle trajectories is a simple rotation. Therefore, the analytical treatment of the problem is facilitated.

b) An expanding oscillator potential with width 2w(t). A given neutron with velocity v'_{max} that was emitted in the center of the pulse remains on the edge of the potential, which is the point of highest force. This allows, in principle, arbitrarily wide velocity intervals to be monochromatized.

c) A sinusoidal potential with constant width. This is the type of potential that is the easiest to produce from the technological point of view.

d) An expanding potential with trapezoidal form.

$$V(x',t) = \left\{ \begin{array}{ll} -\mu B_{max} & |x'| \leq a(t) \\ -\mu B_{max} \dfrac{b(t) - |x'|}{b(t) - a(t)} & a(t) < |x'| \leq b(t) \\ 0 & b(t) < |x'| \end{array} \right\} . \tag{6}$$

Three conditions determine the time evolution of the distances a and b: a(0) = 0; b(t) has to fulfill the same condition as w(t) in case b); and a particle that was emitted in the middle of a pulse reaches a(t) when its velocity is $v' = 0$.

In general the gain factors g are not constant over the velocity interval Δv. Therefore, we define the integral gain factor g_I:

$$g_I(\Delta v) = \frac{1}{\Delta v} \int_{-\frac{\Delta v}{2}}^{\frac{\Delta v}{2}} g(v')\, dv' . \tag{7}$$

For very monochromatic beams ($\Delta E/E < 0.1\%$), an expanding trapezoidal potential is best. From the point of feasibility, sinusoidal and oscillator potentials have to be preferred.

Most of the systems for beam handling described in this paper are competing with instruments based on moving crystal and mirrors. The advantage of magnetic devices is the absence of any moving parts; the main disadvantage is the high power consumption. A lot of technological problems have to be solved before a large-scale active monochromator for thermal or cold neutrons can be realized. For very cold and ultracold neutrons, the design parameters are much easier to fulfill.

Acknowledgements

Work supported by the Austrian *Fonds zur Förderung der wissenschaftlichen Forschung* (project S42/02).

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