Monochromatization of polarized neutrons by the method of spatial spin resonance

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A description is given of a magnetic monochromator for polarized neutrons which is capable of separating out from the spectrum of thermal neutrons narrow monochromatic lines of different prescribed halfwidths $\Delta\lambda_{1/2}/\lambda$. The aperture ratio of the monochromator is not less than 90%; the readjustment from one wavelength to another is attained by varying the direct current which gives rise to the activating magnetic field H_0 of the resonator. The use of multilayer iron-cobalt polarizing mirrors included in the design of the monochromator ensures that the polarization of a nonmonochromatic neutron beam is ~96%.

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1. INTRODUCTION

In 1962 one of us[1] predicted a new form of magnetic resonance for polarized neutrons—spatial spin resonance (SSR) the existence of which was later verified experimentally. The idea of SSR consists of the circumstance that when polarized netrons pass through a system of mutually perpendicular magnetic fields $\mathbf{H}_0$ and $\mathbf{H}_1$ constant in time a resonant spin flip of neutrons characterized by velocity v_r occurs along a segment of length L. The field $\mathbf{H}_0$ is parallel to the polarization vector of the neutrons and determines the frequency of Larmor precession:

$$\omega_0=\gamma_n H_0, \tag{1}$$

where γ_n is the gyromagnetic ratio for the neutron. The field $\mathbf{H}_1$ changes its sign in space along the segment L with a period $2a$ and is directed at right angles to the field $\mathbf{H}_0$. Such a configuration of the field $\mathbf{H}_1$ makes it variable in time in the coordinates of the moving neutron with a frequency

$$\omega=\pi v/a, \tag{2}$$

which depends on the velocity. From this it is clear that the resonance velocity of the neutron is given by

$$v_r=\gamma_n H_0 a/\pi. \tag{3}$$

Thus, only those neutrons experience a spin reversal the velocity of which satisfies condition (3), and, as was shown in Ref. 2, the halfwidth of the line is given by

$$\Delta v_{1/2}/v=1.59a/L. \tag{4}$$

If now with the aid of a nonadiabatic spin flipper one again reverses the spins of all the neutrons of the spectrum and analyzes the resultant picture with the aid of an analyzing mirror, one can separate out a monochromatic beam of neutrons which have undergone a resonant spin flip.

2. CONSTRUCTION OF THE MONOCHROMATOR

The magnetic monochromator consists (Fig. 1) of a polarizer 3 and an analyzer 9, between which there are situated: a nonadiabatic spin flipper 7 and a magnetic resonator 8. For the polarizer and analyzer we have utilized iron-cobalt polarizing mirrors which guarantee that the polarization of the neutron beam is ~ 96%. The system nonadiabatic spin flip enables one to produce a beam of neutrons with a polarization which is antiparallel to the magnetization of the analyzer with an efficiency of ~ 100%.

The magnetic resonator consists of an electromagnet which produces the activating field $\mathbf{H}_0$, between the poles of which there is situated a device which enables one to obtain a field $\mathbf{H}_1$ which alternates in sign along a spatial coordinate. The electromagnet had poles of dimensions 1700× 200 mm and a gap of 82 mm; power was supplied from a stablized source of constant current which maintained the magnitude of the activating field with an accuracy up to 10^{-4}. The field $\mathbf{H}_1$ which is periodic in space was produced by means of an aluminum foil of 0.015 mm thickness, placed between glass plates of 3 mm thickness in the form of an accordion through which a direct current was passed. The glass plates had windows through which the neutron beam was passed. The width of the foil was $h=28$ mm, while the total length of the resonator was $L_0=964$ mm. With the aid of clamp contacts it is possible to connect the required length of resonator, thereby varying the halfwidth of the selected line according to relation (4). In order to

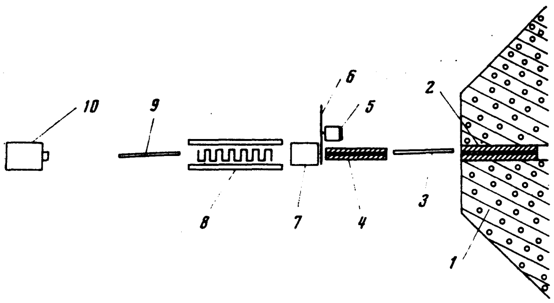

FIG. 1. Diagram of the arrangement: 1—biological shield of the reactor, 2—collimator, 3—polarizing mirror, 4—collimator, 5—electric motor, 6—cadmium disk with a slit, 7—nonadiabatic spin flipper, 8—magnetic resonator, 9—analyzing mirror, 10—detector.

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readjust the resonator with respect to wavelength it is sufficient, as can be seen from (3), to vary the magnitude of the activating field H_0.

3. EXPERIMENTAL CHARACTERISTICS OF THE MONOCHROMATOR

In order to evaluate the operation of the magnetic monochromator the time-of-flight method of analyzing the spectrum being produced was employed. With the aid of a mechanical modulator which consists of a rotating cadmium disk with a slit (Fig. 1) the beam of thermal neutrons was periodically interrupted, and the signal from the detector entered the multichannel analyzer LP4000 which has 512 channels.

The measurements were conducted in the following manner:

1. The nonadiabatic spin flipper was set up in the parallel position, the activating field H_0 was switched on and the spectrum produced by the polarizing and the analyzing mirrors (the H_1 field of the resonator was switched off) was recorded.

2. The nonadiabatic spin flipper was placed in the antiparallel position (in this case a beam of neutrons was produced with its polarization antiparallel to the magnetization of the analyzer), the needed value of the field H_0 was selected in accordance with the required wavelength and the field H_1 was switched on. The spectrum was recorded for different values of H_1.

In Ref. 2 it was shown that the magnetic resonator has resonance properties not only with respect to the parameter H_0, but also with respect to the magnitude of the field H_1 which changes sign, with the approximate resonance value of the current flowing through the foil being given by the expression

$$I_r \approx \frac{\pi h v_r}{0.4\gamma_n L} = \frac{h}{0.4} H_1, \tag{5}$$

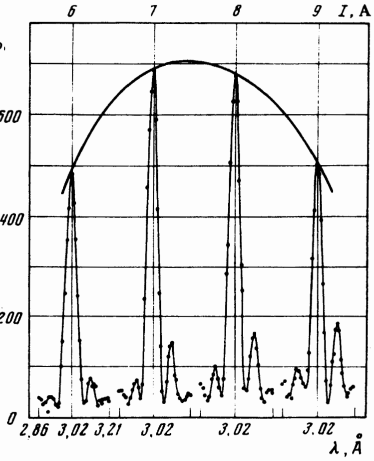

FIG. 2. Variation of the amplitude of a monochromatic line of halfwidth $\Delta\lambda_{1/2}/\lambda = 2.0\%$ and of wavelength $\lambda = 3.02$ Å as a function of the current producing the field H_1 (N_p is the number of pulses).

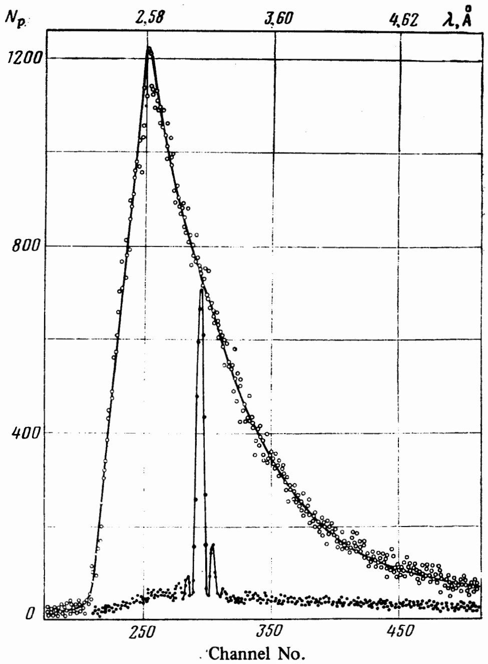

FIG. 3. A monochromatic line of halfwidth $\Delta\lambda_{1/2}/\lambda = 2.0\%$ picked out at a wavelength of $\lambda = 3.02$ Å with the aid of a magnetic monochromator from the thermal neutron spectrum with $\lambda_{\max} = 2.59$ Å, produced by Fe–Co mirrors.

where h is the width of the foil, L is the length of the resonator being utilized, v_r is the resonance value of the neutron velocity.

The value of I_r was determined more accurately by the experimental method of comparing the amplitudes of spectra recorded for different values of I chosen in the neighborhood of the value of I_r calculated by means of formula (5).

Figure 2 demonstrates the dynamics of the variation of the amplitude of a resonance line as a function of the current through the aluminum foil for a spectrum obtained for $L = L_0/4 = 241$ mm and $H_0 = 75$ Oe. The wavelength at which a monochromatic line is picked out is in accordance with relation (3) equal to $\lambda = 3.02$ Å. From this graph one can experimentally determine the value of the current $I_r = 7.5$ A, and this corresponds, in accordance with (5), to the value of the field $H_1 = 1$ Oe, and one can also estimate the halfwidth of the line which agrees with the calculated value and is equal to $\Delta\lambda_{1/2}/\lambda = 2.0\%$.

The overall picture of the operation of the monochromator is given in Fig. 3. Here is shown a spectrum produced by the mirrors when the field H_1 is switched off, together with the spectrum obtained with the aid of SSR with the resonator parameters indicated above. From this was determined the probability of resonance spin flip, which, as can be seen from the curves reproduced above, is close to 100%. Analogous results were obtained for other values of the resonance wavelength and of the resolving power of the apparatus. It should also be noted that the resolving power of the time-of-flight technique was chosen in each case approximately equal to one half of the halfwidth of the spectrum produced $0.5\Delta\lambda_{1/2}/\lambda$. The aperture ratio of the apparatus should be regarded as being not less than 90%, since losses on reflection from a Fe-Co mirror do not exceed 3–5% if one takes into account the fact that the monochromator involves both a polarizer and an analyzer.

Among the shortcomings of the apparatus one should include the presence of a background due to the less than 100% polarization of the neutron beam (Fig. 3). For a line of halfwidth $\Delta\lambda_{1/2}/\lambda = 2.0\%$ picked out at the maximum of the given spectrum at a wavelength of $\lambda = 2.59$ Å, the signal to background ratio is equal to 2.5. This ratio, naturally, becomes worse if we go to longer wavelengths or better resolving power. One should note the presence in the spectrum produced with the aid of the monochromator of higher order maxima which spoil the shape of the line being selected.

The monochromator described above can find application in experiments in which it is necessary to retain a high aperture ratio for the apparatus together with a good resolving power. A not unimportant advantage is the possibility of a smooth adjustment of the line being produced with respect to the wavelength by means of a simple variation in the value of the direct current. The apparatus also enables us to produce with the aid of a number of contacts a rapid discrete change in the resolving power.

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[1] G. M. Drabkin, Zh. Eksp. Teor. Fiz. 43, 1107 (1962) [Sov. Phys. JETP **16**, 781 (1963)].
[2] G. M. Drabkin, V. A. Trunov and V. V. Runov, Zh. Eksp. Teor. Fiz. 54, 362 (1968) [Sov. Phys. JETP 27, 194 (1968)].

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Mesic atoms of light nuclei in the field of resonant electromagnetic radiation

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We consider the influence of resonant electromagnetic radiation on the characteristics of light mesic atoms (^{1}H, ^{2}H, ^{3}He, and ^{6}Li). The conditions are investigated under which the populations of the hfs sublevel populations become equalized in the case of linearly polarized radiation. We calculate the dependence of the critical external field (at which saturation is reached) on the collision and Doppler widths of the level. The degree of muon polarization produced when the mesic atom interacts with circularly polarized resonant radiation is determined. It is noted that the most strongly polarized is the muon in the mesic atoms of hydrogen isotopes. The effect of resonant electromagnetic radiation on the rate of nuclear fusion in the $pd\mu$ molecule is also considered. It is shown that the yield of the fusion-reaction channel can be changed by 20% as a result of this action.

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1. It is known that a nucleus captures a muon from the K-shell of the mesic atom. If the nucleus has zero spin, then the 1s level is split by the hyperfine interaction of the magnetic moments of the meson and the nucleus. The spin of the muon + nucleus system takes on two values $F = j \pm \frac{1}{2}$ (j is the spin of the nucleus), and the probability of μ capture in light nuclei depends essentially on the hyperfine-structure (hfs) state from which the capture takes place.[1,2] The presence of the hyperfine interaction influences also the polarization properties of the muon, which in turn influences the asymmetry of the angular distribution of the electrons (neutrons) produced as a result of the decay (capture) of the bound muon.[3,4] The actual magnitude of these effects depends strongly on the combination of the weak-interaction constants and the sublevel population of the hyperfine structure. It is therefore of interest to study the decay (capture) properties of the bound muon by varying the hfs sublevel population in a definite manner. A convenient mechanism for varying the population is, for example, the interaction of the mesic atom with intense electromagnetic radiation from a laser, at a frequency that is resonant with the hyperfine-splitting frequency of the 1s level. High-power lasers that are tunable in a rather large frequency range have by now been developed.[5] This range includes the hyperfine-splitting frequencies of the mesic atoms of five light isotopes: ^{1}H, ^{2}H, ^{3}H, ^{3}He, and ^{6}Li. Some characteristics of the indicated isotopes are shown in Table I.

2. Consider at first the interaction of a system of mesic atoms with linearly polarized laser radiation whose frequency is close to the hyperfine-splitting frequency ω_{12} (we assume for the sake of argument that

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