Adiabatic method of separated oscillating fields

V. F. Ezhov, S. N. Ivanov, V. M. Lobashev, V. A. Nazarenko, G. D. Porsev, O. V. Serdyuk, A. P. Serebrov, and R. R. Tal'daev

Institute of Nuclear Physics, USSR Academy of Sciences
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An improvement on Ramsay's well-known magnetic resonance method of separated oscillating fields is proposed. The new adiabatic method of separated oscillating fields makes it possible to obtain resonances with a depth that is independent of the velocity dispersion in the beam. In the case of a fully polarized beam, the depth of the resonance obtained by the new method is 100%.

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Magnetic-resonance methods for the determination of the magnetic moments of particles—the Rabi method and the Ramsay method[1]—are well known. In both methods, the depth of the resonance is determined by the distribution of the particle velocities in the employed beam, since the probability of reorientation of the magnetic moment of the particle depends on the time of flight through the alternating-field region. We describe here a proposed and experimentally verified new adiabatic method of separated oscillating fields, with a depth of resonance that is independent of the dispersion of the velocities in the beam and is determined only by the product of the degree of polarization of the beam and the efficiency of the analyzer.

To explain the method, we consider the motion of a particle spin in Ramsay's method. We consider the point of resonance, i.e., when $\omega=\omega_0$, where ω is the frequency of the rotating or oscillating field H_1, and ω_0 is the Larmor-precession frequency of the magnetic moment in the field H_0.

It is convenient to carry out the analysis in a coordinate frame rotating with frequency ω. In this frame, the vector H_1 is at rest and the vector H_0 goes over into $\Delta H_0=H_0-\omega/\gamma$, which is equal to zero at the resonance point (γ is the gyromagnetic ratio). The motion of the magnetic moment of the particle in the rotating coordinate system reduces to two successive rotations of the magnetic moment of the particle through 90° in a plane perpendicular to H_1, as shown in Fig. 1a. On leaving the field system, the orientation of the magnetic moment is reversed by a proper choice of the field H_1. However, the angle of rotation of the magnetic moment will be slightly different for particles with different

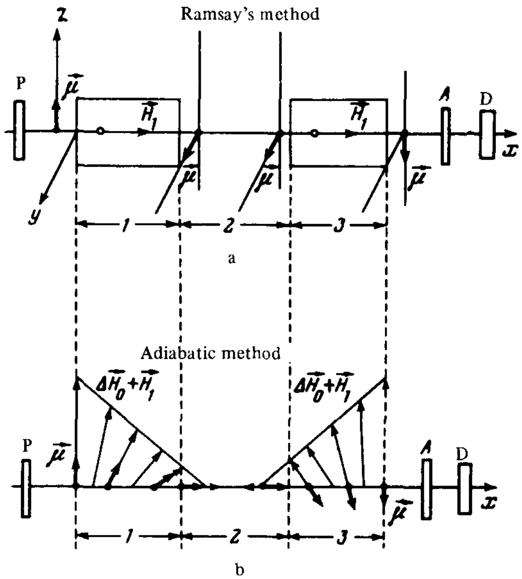

FIG. 1. Motion of magnetic moment of a neutron in a magnetic-resonance spectrometer in a coordinate system rotating with frequency ω. 1 and 3—regions of action of the field H_1, 2—region of the homogeneous field H_0, P and A—polarizer and analyzer, D—detector. Figure b shows the case when the fields H_1 in regions 1 and 3 are in antiphase.

velocities, decreasing, as it were the polarization of the beam and accordingly decreasing the depth of the resonance.

To eliminate this decrease, it is proposed in the adiabatic method to produce an inhomogeneous constant magnetic field in the regions where the field H_1 acts, and to make the field H_1 much stronger than in the Ramsay method. In the rotating coordinate frame, the summary field vector $\Delta\mathbf{H}_0+\mathbf{H}_1$ will be rotated in succession as the particle passes through regions 1 and 3, as shown in Fig. 1b. If the rate of rotation is much less than the frequency of the precession of the magnetic moment about $\Delta\mathrm{H}_0+\mathrm{H}_1$, then the magnetic moment will follow adiabatically the direction of the vector and will turn out to be directed along $\mathbf{H}_1$ on leaving the region 1, regardless of the particle velocity. Thus, the depth of the resonance turns out to be complete and independent of the velocity dispersion in the beam. The adiabaticity condition which connects the form of the gradient of the inhomogeneous field and the magnitude of the field H_1 must be satisfied for all velocities in the beam, and is given by

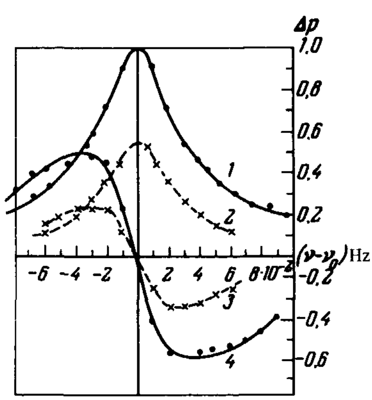

FIG. 2. Change in the probability of reversal of the magnetic moment as a function of the deviation from resonance, when the phase is shifted by 0 and 180° (curves 1 and 2) or 90 and 270° (curves 3 and 4). The curves corresponding to the Ramsay method are shown dashed.

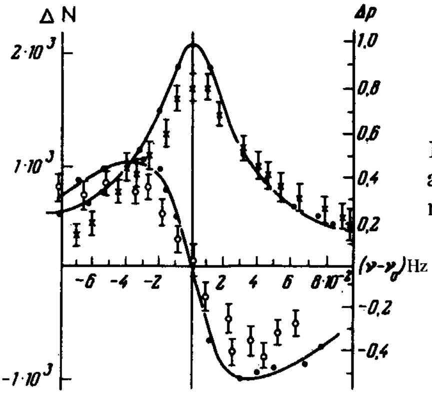

FIG. 3. Comparison of the calculated curves and the experimental points for the adiabatic method.

$$v_x \frac{dH_0(x)}{dx} << \gamma \frac{\left\{H_1^2 + \left[H_0(x) - \frac{\omega_0}{\gamma}\right]^2\right\}^{3/2}}{H_1} .$$

The inhomogeneous field most suitable for the realization of the adiabatic method is of the form $H_0(x) = ax/\sqrt{1-bx^2}$. This expression is obtained for $H_0(x)$ by solving the adiabaticity equation presented above. The parameters a and b depend on the degree of satisfaction of the adiabaticity condition, on the value of the field H_1, and on the particle velocity.

The probability of reversal of the magnetic moment in the adiabatic method can be easily obtained and, as expected, is independent of the time τ required to pass through regions 1 and 3:

$$P = \frac{\nu_1^2}{(\nu_0 - \nu)^2 + \nu_1^2} \sin^2 [\pi(\nu - \nu_0) T - \delta/2] .$$

Here ν_0 is the frequency of the Larmor precession about H_0, ν is the frequency of the rotating field H_1, ν_1 is the frequency of the precession about H_1, T is the time of stay in the region 2, δ is the phase shift between the fields H_1 in regions 1 and 3. It should be noted that the coefficient in front of the sign function is in fact equal to unity, inasmuch as in the adiabatic method the amplitude of the employed field H_1 is quite large and $\nu_1 \gg \nu - \nu_0$.

We consider now the adiabatic method as applied to a spectrometer intended to search for the electric dipole moment of a neutron with the aid of ultracold neutrons,[2] and used in fact to check out the method. It is known that sensitivity of the spectrometer is expected to be larger than that of the usual transit variant,[3] owing to the increase of the time of interaction of the neutrons with the field, which is attained by using in region 2 a trap in which the ultracold neutrons, being reflected many times, are contained for a sufficiently long time. However, the presence of the trap makes the situation worse for the Ramsay method, in the sense of the influence of the velocity dispersion, for in this case the velocities of the individual particles along the x axis in the regions

1 and 3 turn out to be uncorrelated, in contrast to the transit variant. Therefore the use of the adiabatic method, which eliminates completely the influence of the velocity dispersion, is particularly profitable here. In addition, it should be noted that the adiabatic method not only increases the depth of the resonance, but also ensures a maximum of the derivative $\partial P/\partial \nu$ at the point of resonance for curves of the dispersion type (at $\delta = 90$ and $270°$), which is also of considerable importance. In a sufficiently low vicinity of the resonance, the derivative is equal to $J_0 \Pi A T_{av}$, where T_{av} is the average time of stay of the neutron in the trap, while A and Π are the analyzing ability of the analyzer and the polarizing efficiency of the polarizer, respectively; J_0 is the detector counting rate in the absence of the action of the field H_1.

Figure 2 shows the calculated curves for the adiabatic method of separated oscillating fields and for the Ramsay method. The calculation was carried out by the Monte Carlo method for the magnetic-resonance spectrometer described in[2]. The average storage time of the ultracold neutrons in the spectrometer trap was 4.6 sec. A comparison shows that the amplitude of the resonance and the slope of the curve at $\delta = 90$ or $270°$ are better by a factor 1.8 for the adiabatic method. Figure 3 shows the experimental results obtained by using the adiabatic method of separated oscillating fields. The comparison with the calculation (solid curve) shows that the adiabatic method could not be fully realized (the amplitude of the resonance was not complete), but the experimental comparison of the methods at the point of resonance has shown that the amplitude of the resonance is indeed smaller by a factor 1.8 in the Ramsay method. The possible causes of the incomplete realization of the adiabatic method may be the penetration of the stray field H_1 into region 2 and to a number of other factors that call for a more detailed analysis.

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