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Physica B 356 (2005) 182–186

PHYSICA B

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A pulsed neutron Ramsey's method

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Abstract

A Ramsey's method with pulsed neutrons is proposed. A Ramsey signal, which is a neutron spin rotation about a static magnetic field for a time interval between two separated oscillatory fields, is observed as a function of a neutron time of flight (TOF) in this method. The neutron spin rotation or the RF oscillation is used as a clock of the neutron velocity measurement which ranges from cold to epithermal neutron energies. This method together with the TOF measurement can be used for neutron inelastic scattering experiments. In addition, this method can be applied to the measurement of magnetic and pseudomagnetic fields in matter, and also to neutron spin manipulation for spin dependent scattering.

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Keywords: Polarized neutron; NMR; Pulsed neutron; Neutron spectrometer

1. Ramsey's method

In 1956, Ramsey developed a precision nuclear magnetic resonance (NMR) by means of two separated oscillatory fields [1]. In the Ramsey's method, a spin rotation in a static magnetic field for a time interval between the two separated oscillatory fields, which are represented as $2H_1 \cos \omega t$, is measured, which enable us to obtain a very accurate NMR. $2H_1$ denotes an oscillatory field amplitude and ω a frequency. The two oscillatory fields are perpendicular to a static field, which hold the nuclear spin. The static field is denoted as H_0. An oscillating field can be represented as a sum of clockwise and counter-clockwise rotating fields, $H_1(\exp(\mathrm{i}\omega t) + \exp(-\mathrm{i}\omega t))$. In a rotating frame of the frequency ω, the nuclear spin sees an effective magnetic field, which is represented as

$$\boldsymbol{H}_{\mathrm{eff}} = \boldsymbol{H}_0 - \omega/\gamma + \boldsymbol{H}_1. \tag{1}$$

At $\omega = \omega_0$, the effective field on the nuclear spin becomes $\boldsymbol{H}_1$ and then the neutron spin rotates around $\boldsymbol{H}_1$. Here, $\omega_0 = \gamma H_0$. γ is the gyromagnetic ratio of the nuclear spin.

In the Ramsey's method, the oscillatory field is applied to the nuclear spin for a time interval of t_{r}

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doi:10.1016/j.physb.2004.10.073

so that the nuclear spin becomes perpendicular to the static field, namely the equation $\gamma H_1 t_r = \pi/2$ is satisfied as it is shown in the left side of Fig. 1. After switching off the oscillatory field, the nuclear spin rotates around the static field for a time interval of t_{phase} as it is shown in the right side of Fig. 1. The phase difference between the nuclear spin rotation and the oscillatory field becomes $\phi = -\pi/2 + (\omega_0 - \omega)t_{\mathrm{phase}}$, and then the second oscillatory field is applied. The phase of the second oscillatory field is coherent with the first oscillatory field. In the second oscillatory field, the nuclear spin rotates back to the direction of the static field as it is shown in Fig. 2.

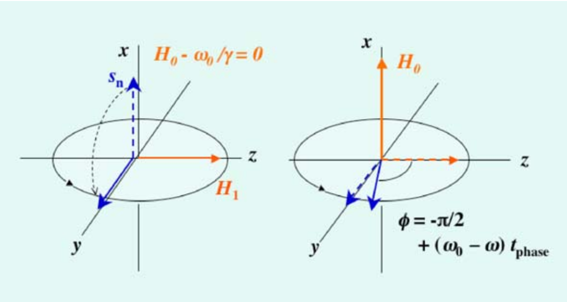

Fig. 1. Nuclear spin (s_n) rotation in an oscillatory field and a static field. In a rotating frame of the resonance frequency ω_0, the nuclear spin sees only the oscillating field as a static field H_1 and then rotates by $\pi/2$ under the condition $\gamma H_1 t_r = \pi/2$. After the rotation, the H_1 field is switched off and then the nuclear spin rotates about the static field H_0.

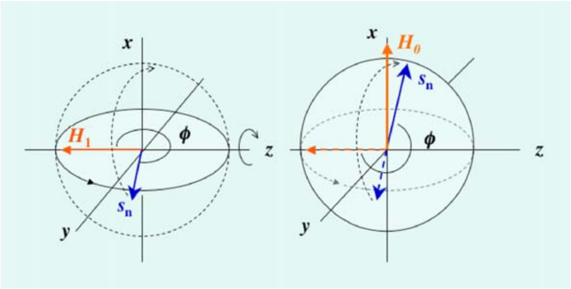

Fig. 2. Nuclear spin rotation in the second oscillatory field. A plane where the nuclear spin rotates under the static field rotates by $\pi/2$ under the second H_1 field.

After the $\pi/2$ rotation around the second H_1 field, the angle of the nuclear spin with the direction of the static field (x-axis) becomes $\phi - 3\pi/2$. Therefore, the projection component of the nuclear polarization P_n on the static field is represented as

$$P_R = P_n \cos(\omega_0 - \omega)t_{\mathrm{phase}}, \tag{2}$$

which is held by the static field and then analyzed.

If we apply the Ramsey's method to a neutron beam, the time interval of t_{phase} is a neutron time of flight (TOF), which depends on the neutron velocity. When the neutron beam is pulsed, we can analyze the neutron spin rotation as a function of the neutron TOF. In the present paper, we use a neutron Ramsey signal, which is shown in Eq. (2), for the measurements of

1. the neutron velocity, and
2. a pseudomagnetic field in matter, which has a neutron energy dependence,

between the two oscillatory fields. The first measurement can be applied to a neutron inelastic scattering spectrometer. Here, we refer this spectrometer as Ramsey interferometer for dynamics explorations with neutrons, (RAIDEN).

2. Comparison with neutron spin echo

The neutron spin echo (NSE), which is applied to a neutron spectrometer, also uses the neutron spin rotation during passing through a magnetic field [2]. An energy transfer upon neutron scattering is found in a rotation phase change in the NSE measurement. But, the phase dispersion, which arises from an energy distribution of incident neutrons from a steady neutron source like the reactor, obscures the effect of the velocity change. A phase echo compensates the velocity dependent phase dispersion by means of a π coil, which satisfies the condition $\gamma H_1 t_r = \pi$, in the NSE measurement. A new proposal of neutron spin echo for a pulsed neutron source also uses the phase echo [3]. In the NSE spectrometers, the difference between neutron spin rotation phases in two precession fields is analyzed in terms of a Fourier time and a neutron energy transfer.

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