Inversion of magnetization of a nuclear spin system by ultrasound in adiabatic fast passage

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Adiabatic fast passage of ultrasound is used to obtain inversion of the spin levels of Na^{23} nuclei in NaCl. The maximum inversion coefficient is 0.65. The method makes it possible to estimate the spin-phonon coupling constant and appears to be most suitable for the study of metals.

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We have investigated experimentally the inversion of the magnetization of the nuclear spin system of Na^{23} nuclei in single-crystal NaCl with the aid of adiabatic fast passage (AFP) of ultrasound. This experiment is the acoustic analog of electromagnetic AFP. However, the use of only acoustic action makes it possible to violate the Boltzmann distribution of the level population and thus obtain information on the spin-spin interaction in cubic crystals.[1] The AFP phenomenon can also serve as a basis for the development of an acoustic maser operating on nuclear levels.

Population inversion with the aid of acoustic AFP was reported earlier in[2]. That experiment, however, in which the inversion obtained was quite small (about 16%), cannot serve as the basis for a theoretical interpretation or practical applications.

Our investigations were made with single-crystal NaCl in the form of a cylinder of 7 mm diameter and 23 mm length. The cylinder axis coincided with the [100] axis. The ultrasound source was x-cut quartz of resonant frequency 20 MHz, excited by a 50-watt pulsed generator.

The magnitude and direction of the nuclear spin system were determined from the free induction signal produced after applying to the sample a 90° electromagnetic sounding pulse. To register the signal we used phase detection and a memory device. The acoustic passage was produced by sweeping the ultrasound oscillations from 20294 to 20278 kHz at the resonant frequency 20286 kHz of the Na^{23} nuclei in a field $H_0 = 9007$ Oe, corresponding to a transition with $\Delta m = \pm 2$.

We investigated the dependences of the magnetization of the nuclear system on the passage time (τ) and on the converter voltage, maintaining constant the delay between the end of the passage and application of the sounding pulse. The dependence of the magnetization on τ at different voltages (U_0) on the quartz crystal is shown in Fig. 1. At a constant $\tau = 2$ sec and $U_0 = 600$ V we obtained maximum inversion of the magnetization, amounting to 65% of the initial value (Fig. 2).

Corroborating the inversion of the spin population by the ultrasound is the time dependence of the recovery of the initial magnetization after the end of the acoustic passage (Fig. 3).

As shown by Goldman,[3] the magnetization losses in AFP experiments are determined by the following factors:

1) The loss due to insufficient adiabaticity of the passage: it is inversely proportional to the probability (W) of the transition induced by the exciting field.

2) The loss of magnetization due to spin lattice relaxation (T_1), or

$$l_n\left(\frac{|M_{\text{init}}|}{|M_{\text{fin}}|}\right) = AW^{-1}\left(\frac{dH}{dt}\right) + BT_1^{-1}\left(\frac{dH}{dt}\right)^{-1},$$

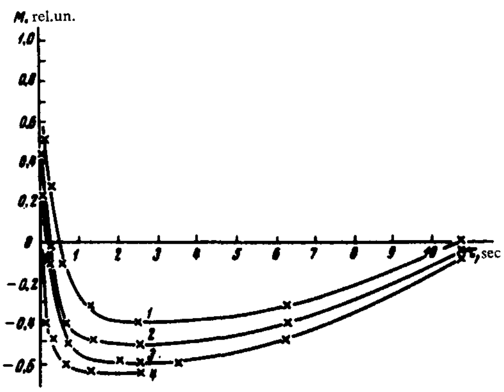

FIG. 1. Dependence of the magnetization on the time of passage at $U_0 = 100$, 200, 300, and 600 V (curves 1, 2, 3, and 4, respectively).

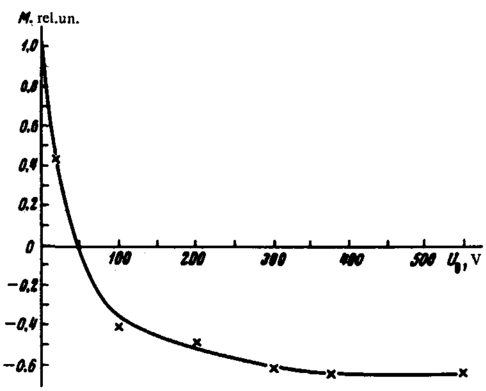

FIG. 2. Dependence of the magnetization on the amplitude of the voltage on the piezoelectric converter.

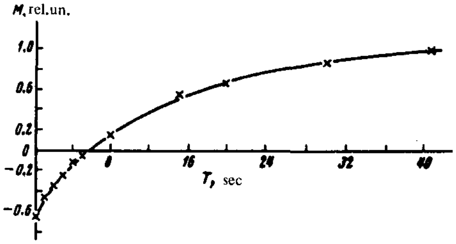

FIG. 3. Recovery of magnetization after the termination of the acoustic pulse.

where M is the spin-system magnetization, while A and B are constants that are different for each substance and are independent of the excitation method. In the case of electromagnetic and acoustic excitation we have respectively $W^{(em)} \sim H_1^2$ and $W^{(a)} \sim G_{ij}^2 \epsilon_i^2$, where H_1 is the electromagnetic field intensity, G_{ij} are the elements of the spin-phonon interaction tensor, and ϵ_i is the amplitude of the ultrasonic deformation. The elements of the tensor G_{ij} can be estimated from the condition that the magnetization losses be the same under electromagnetic (em) and acoustic (a) excitation. Our experiments on (em) and (a) excitation yielded $G_{11} \sim 10^{-15}$ cgs esu, using the well known expressions for $W^{(em)}$ and $W^{(a)}$.[4]

$$W^{(a)}_{m,\,m+2} = \frac{1}{64}\, g(\nu)\left(\frac{A}{\hbar}\right)^2 (I - m)(I - m - 1)(I + m + 1)(1 + m + 2) G_{11}\, \epsilon_1$$

$$W^{(em)}_{m,\,m+1} = \frac{1}{4}\, \gamma_n^2 H_1^2 g(\nu)(I - m)(I + m + 1).$$

It appears that the acoustic method used by us for the inversion of nuclear spin levels is most suitable for use in conducting media, where the RF excitation is limited to the depth of the skin layer.

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