Appearance of negative spin temperature in the presence of a nonresonant acoustic stimulus

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An inversion of the nuclear-spin system of ^{27}Al was observed in a ruby in the presence of steady-state, nonresonant, acoustic saturation at frequencies of 5–70 MHz. It is shown that the interaction of ultrasound with the nuclear-spin system occurs via the nonresonance (relaxation) absorption of ultrasonic-wave energy by the spin system of Cr^{3+} ions.

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The inversion of the nuclear-spin system under steady-state conditions in the presence of an acoustic stimulus that is nonresonant with the spin-transition frequencies was detected for the first time. It is shown that the interaction of ultrasound with the nuclear-spin system occurs via nonresonance (relaxation) absorption of ultrasonic-wave energy by the spin system of paramagnetic ions.

Negative spin temperatures of nuclear systems are usually achieved as a result of interaction of the two spin systems.[1] A continuous electromagnetic or acoustic stimulus on this nuclear-spin system decreased the population difference of its nuclear Zeeman levels.[2]

We report in this paper a population inversion of all the nuclear Zeeman levels of ^{27}Al in a ruby produced as a result of a continuous, nonresonance, ultrasonic excitation.

The experiments were conducted using samples with Cr^{3+}-ion concentrations of $\sim$0.01–0.05 at.% at $T \sim 1.6$–4.2 K. The NMR signals were recorded by an autodyne circuit using a coil wound around a cylindrical sample. The optical C axis of the crystal was perpendicular to the generatrix of the cylinder, and the angle θ between the direction of the C axis and the constant, external, magnetic field H_0 could be varied. The longitudinal acoustic oscillations were excited in the sample by a quartz piezoeletric transducer cemented to one of the plane-parallel ends of the cylinder. The propagation direction of ultrasonic waves, which coincided with the direction of the radiofrequency field H_1, was perpendicular to the direction of the constant field H_0. The amplitude of the strain produced in the sample was monitored by the capacitive method.[3] To obtain the maximum strain amplitudes, we selected an ultrasound frequency that corresponded to the mechanical resonance of the sample. The intensity H_1 was chosen in such a way that saturation of the NMR signals was avoided. The NMR signals of all transitions ($I = 5/2$) were observed at a specified value of $H_0 \sim 0.8$ T by sweeping the frequency of the autodyne oscillator. The frequencies of transitions with $\Delta m \pm 1$ were in the range 8.0–9.6 MHz, and the frequencies of transitions with $\Delta m = \pm 2$ were in the range 16–20 MHz.

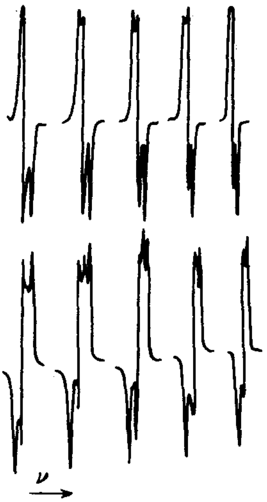

FIG. 1. NMR spectrum of ^{27}Al in Al_2O_3:Cr^{3+} (0.01 at.%). Top–without pumping. Bottom–with nonresonance acoustic excitation.

At $T\sim 1.6$ K and a relative strain $\epsilon_0\sim 5\times 10^{-5}$ in a sample with $c\sim 0.01$ at.%, the NMR signals, which corresponded to a population inversion of all the spin transitions, were observed in the entire investigated frequency range (4 MHz to 70 MHz) of ultrasonic pumping (Fig. 1). As T increased to 2.2 K, the inversion effect disappeared even when ϵ_0 increased to 2×10^{-4}. The time for establishing equilibrium in the inverted system after the pumping was turned on depended on the level of the power supply; this time was different in all the transitions. The time for establishing equilibrium is

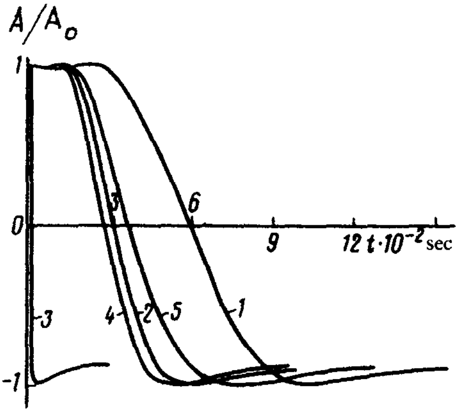

FIG. 2. Variation of the NMR signal intensities A/A_0 after turning on the acoustic pumping (numbering of the transitions is as follows: 1, $-\frac{5}{2}\longleftrightarrow -\frac{3}{2}$; 2, $-\frac{3}{2}\longleftrightarrow -\frac{1}{2}$; 3, $-\frac{1}{2}\longleftrightarrow +\frac{1}{2}$; 4, $+\frac{1}{2}\longleftrightarrow +\frac{3}{2}$; 5, $+\frac{3}{2}\longleftrightarrow +\frac{5}{2}$.

similar for the NMR of the $\pm\frac{5}{2}\longleftrightarrow\pm\frac{3}{2}$ and $\pm\frac{3}{2}\longleftrightarrow\frac{1}{2}$ transitions (Fig. 2). The time for establishing equilibrium after the pumping was turned off depended on the duration and power of the acoustic stimulus. When these values were sufficiently high to establish dynamic equilibrium, the recovery of the spin system after the pumping was turned off was the same in all the NMR transitions. When dynamic equilibrium was not established in the spin system, i.e., the acoustic stimulus was insufficient, the recovery was qualitatively identical in the NMR transitions, but it occured at different rates; the quickest recoverey of the equilibrium occurred in the $\frac{1}{2}\longleftrightarrow-\frac{1}{2}$ transition and the slowest in the $\pm\frac{5}{2}\longleftrightarrow\pm\frac{3}{2}$ transitions.

The nonresonance inversion effect exhibits angular anisotropy. As θ increases, the establishment rate and the inversion coefficient decrease for a given ϵ_0 value (Fig. 3). After θ increased to 25°, the inversion no longer occurred even at $\epsilon_0 \geqslant 2\times10^{-4}$.

The effect disappeared when ϵ_0 decreased to 2×10^{-6}; however, a change in the population of the nuclear Zeeman levels, which is qualitatively described by the existing theories,[2] was observed at the resonance frequencies of the NMR transitions with $\Delta m = 2$ and $\Delta m = 1$. The samples with a 0.03 at .% concentration of Cr^{3+} ions had only a nonresonance variation of the population, which no longer exhibited anisotropy. Such effect was observed earlier.[4]

We should note that attempts to detect such effect in the presence of electromagnetic saturation produced negative results. A noticeable change in the intensities of the NMR signals was not observed as a result of nonresonant pumping at $H_1 \| H_0$ and $H_1 \perp H_0$ field polarizations to 30 V in the NMR loop.

The nonresonance inversion cannot be explained only by the relaxation processes in the nuclear-spin system of the ^{27}Al, since the currently available data show that all nuclear transitions are inverted under steady-state conditions because of variation of the electron spin system.[1] Although the observed experimental results cannot be rigorously accounted for at this time, we can propose the following mechanism on the basis of the existing data and models.[5–7]

An inversion can be represented as a two-stage process. The first stage involves nonresonance (relaxation) absorption of the sonic-wave energy by the dipole-dipole

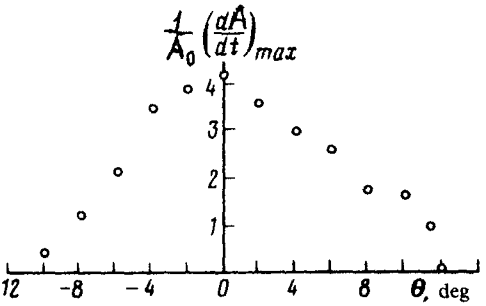

FIG. 3. Angular anisotropy of the rate of the intensity variation of the central NMR transition in the presence of acoustic pumping.

system of the Cr^{3+} electron spins, which, as shown in Ref. 5, occurs when $\omega_a \sim \omega_{ss}$, where ω_{ss} is the average frequency of spin-spin interactions. The ultrasonic wave in this case modulates the distance between the electron spins. This gives rise to the inverted temperature of the spin-spin system of Cr^{3+} ions, which causes an inversion of the nuclear Zeeman system of ^{27}Al because of the thermal contact between the systems.[8] The modulation of the distance is the main difference between the ultrasonic and the electromagnetic stimulus. An absence of the nonresonance inversion in the electromagnetic saturation favors the proposed mechanism.

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[1] V. A. Atsarkin, Usp. Fiz. Nauk **126**, 3 (1978) [Sov. Phys. Usp. **21**, 725 (1978)].

[2] V. A. Golenishchev-Kutuzov, V. V. Samartsev, N. K. Solovarov, and B. M. Khabibullin, Magnitnaya kvantovaya akustika (Magnetic Quantum Acoustics), Nauka Moscow, 1977.

[3] Kh. G. Bogdanova, Yu. V. Vladimirtsev, V. A. Golenishchev-Kutuzov, and N. A. Shamukov, Prib. Tekh. Eksp. No. 5, 166 (1969).

[4] I. I. Sadykov, VII Vsesoyuznoe soveshchanie po kvantovoĭ akustike. Tezisy dokladov (7th All-Union Conference on Quantum Acoustics. Summaries of Papers), Khar'kov, 1972, p. 157.

[5] N. G. Koloskova, U. Kh. Kopvillem, and B. I. Kochelaev, In:Fizicheskie problemy spektroskopii (Physical Problems of Spectroscopy), Vol. 2, Nauka, Moscow, 1963, p. 91.

[6] Yu. V. Vladimirtsev, V. A. Golenishchev-Kutuzov, and U. Kh. Kopvillem, Fiz. Tverd. Tela **9**, 361 (1967) [Sov. Phys. Solid State **9** 276 (1967)].

[7] Sh. F. Murtazin, Fiz. Tverd. Tela **7** 1690 (1965) [Sov. Phys. Solid State **7**, 1368 (1965-66)].

[8] L. L. Buishvili, Zh. Eksp. Teor. Fiz. **49**, 1868 (1965) [Sov. Phys. JETP **22**, 1277 (1965)].

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