Acoustic spin locking

V. A. Golenishchev-Kutuzov, V. A. Kirsanov, and V. F. Tarasov
Kazan' Physicotechnical Institute, Academy of Sciences of the USSR

(Submitted 6 March 1984)
Pis'ma Zh. Eksp. Teor. Fiz. **39**, No. 9, 407–409 (10 May 1984)

Acoustic spin locking has been achieved experimentally for the first time. This locking is an excitation of quadrupole quasienergy levels in a rotating coordinate system by sound waves.

One of the most interesting aspects of the nuclear acoustic resonance stems from the quadrupole mechanism for the interaction of the spin system with the sound waves. No components of the magnetic moment I are excited in the plane perpendicular to the static magnetic field H_0 in this case. Instead, there are processing transverse components of the nuclear electric quadrupole moment[1] Q. The resulting electric field is too weak to be detected experimentally. In a rotating coordinate system, on the other hand, quasienergy levels should arise with a spectrum determined by the interaction of the quadrupole moment Q with the alternating gradient of the electric field produced by the acoustic deformations.[2] This situation is fundamentally different from that of electromagnetic excitation, in which the quasienergy is of a Zeeman nature in the rotating coordinate system and is determined by the interaction of the transverse component of I with the rf field H_1.

That quasienergy levels actually exist in the rotating coordinate system during electromagnetic excitation has been proved by the observation of a resonance[3] and a stimulated induction[4] in these levels. The quantization of the spin system in a rotating coordinate system is directly related to the spin-locking effect, in which the relaxation time of the nonequilibrium transverse component of the magnetic moment, $T_{1\rho}$, is determined by the rate of energy exchange between the spin system and the lattice. It is for this reason that we have $T_{1\rho} \sim T_1$, where T_1 is the spin-lattice relaxation time in the laboratory coordinate system. Kessel'[5] has derived a theory on the possible excitation by resonant sound waves of a spin-system state analogous to a spin-locking state.

0021-3640/84/090491-03$01.00

These events can be proved experimentally by measuring the time $T_{1\rho}$ in the case of acoustic excitation. If there is a quantization of the spins in the field of the acoustic wave, then for $I = 3/2$ we have, according to Ref. 6,

$$\frac{1}{T_{1\rho}} = \frac{\omega_L^2 / T_D + 0{,}6(4\omega_a / |\Delta m|)^2 / T_Q}{\omega_L^2 + 0{,}6\,(4\omega_a / |\Delta m|)^2}, \tag{1}$$

where $\omega_L = \gamma H'_L$, H'_L is the local field created at the nucleus by the adjacent spins, T_D is the spin-lattice relaxation time of the dipole-dipole subsystem, $\omega_a = (3eQS_{11}\epsilon_1)/[16I(2I-1)\hbar]$, S_{11} is the acoustic strain amplitude, eQ is the electric quadrupole moment of the nucleus, *T_Q is the relaxation time of the quadrupole quasienergy, and m is* the magnetic quantum number. According to (1), as ω_a is increased, the time $T_{1\rho}$ should tend toward T_Q if $\omega_a \gg \omega_L$. If $\omega_a \ll \omega_L$, $T_{1\rho}$ is determined by T_D.

In the case of acoustic excitation, however, no transverse components of I are produced, and the customary methods for measuring $T_{1\rho}$ are of no use. We have accordingly developed a new method for measuring $T_{1\rho}$. When the acoustic exciting pulse is applied (Fig. 1a), its frequency is shifted by an amount $\Delta\omega$, greater than the line width, from the resonant value ω_0 (Fig. 1b). Over a time $\tau \ll T_1$ the frequency difference decreases adiabatically to zero, and the spin system goes into a state of energy quantization in the rotating coordinate system which is analogous to a spin locking. After the time T, the frequency difference is reintroduced adiabatically, and the acoustic pulse is turned off. As a result, the magnetization of the spin system flips; the magnitude of this magnetization depends on the time T. We then apply a 90° electromagnetic pulse, and we observe the free-induction signal (Fig. 1c). By studying the T dependence of the signal amplitude we can determine $T_{1\rho}$.

The present experiments were carried out at room temperature on the spin system

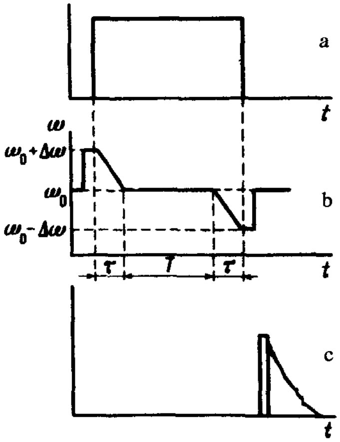

FIG. 1. Time evolution of the exciting pulses. a—Sound pulse; b—modulated frequency of the sound pulse; c—90° electromagnetic pulse and free-induction signal.

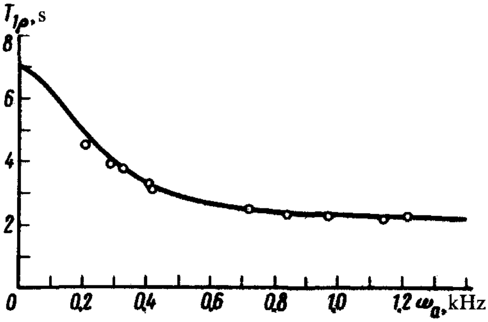

FIG. 2. Dependence of $T_{1\rho}$ on ω_a.

of ^{23}Na nuclei in a NaCl single crystal. Longitudinal sound waves were excited at 20 MHz by a quartz piezoelectric transducer; this frequency corresponds to transitions with $\Delta m = \pm 2$ in the resonant magnetic field. Figure 2 shows the experimental values found for $T_{1\rho}$ for various values of ω_a. We see that $T_{1\rho}$ decreases to 2 s with increasing acoustic strain amplitude. Shown for comparison by the solid curve in Fig. 2 is the theoretical dependence of $T_{1\rho}$ on ω_a calculated from Eq. (1) with $T_D = 7$ s and $T_Q = 2$ s. These results show that the nonequilibrium state of the spin system excited by the acoustic waves does not decay under the influence of the spin-spin relaxation processes, whose characteristic time is $T_2 = 400\,\mu$s; this state is instead preserved for a time comparable to $T_1 = 14$ s. This result is evidence that in the rotating coordinate systems there is a quasienergy whose relaxation time, $T_Q = 2$ s, differs from T_D and T_1. We might note that the condition for a strong resonant acoustic field, $\omega_a > \omega_L = 0.71$ kHz, was satisfied in these experiments.

Control experiments carried out under the same conditions revealed that when the acoustic contact between the piezoelectric transducer and the sample is broken the exciting pulse has no effect of any sort on the spin system.

It can thus be asserted that an acoustic spin locking has been achieved in these experiments; i.e., quadrupole quasienergy levels have been excited in the rotating coordinate system and maintained for a time T_1.

[1] A. R. Kessel', Yadernyĭ akusticheskiĭ rezonans (Nuclear Acoustic Resonance), Nauka, Moscow, 1969.
[2] A. R. Kessel' and M. M. Shakirzyanov, Fiz. Tverd. Tela (Leningrad) **19**, 1535 (1977) [Sov. Phys. Solid State **19**, 899 (1977)].
[3] A. G. Redfield, Phys. Rev. **98**, 1787 (1955).
[4] A. E. Mefed and V. A. Atsarkin, Pis'ma Zh. Eksp. Teor. Fiz. **25**, 233 (1977) [JETP Lett. **25**, 215 (1977)]; Zh. Eksp. Teor. Fiz. **74**, 720 (1978) [Sov. Phys. JETP **47**, 378 (1978)].
[5] A. R. Kessel' and M. M. Shakirzyanov, Zh. Eksp. Teor. Fiz. **83**, 1100 (1982) [Sov. Phys. JETP **56**, 624 (1982)].
[6] M. M. Shakirzyanov, Candidate's Dissertation, KGU, Kazan', 1978.

Translated by Dave Parsons
Edited by S. J. Amoretty