Observation of magnetoacoustic solitons in $KMnF_3$ single crystals in the neighborhood of NMR

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The first experimental evidence of self-induced acoustic transparency (SIAT) produced as a result of transmission of short, acoustic pulses through a magnetically ordered crystal is presented. Their soliton nature is proved theoretically.

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Measurements aimed at observing self-induced acoustic transparency (SIAT) were performed using $KMnF_3$ single crystals at $T = 4.2$ K. These were prepared in the form of parallelepipeds whose faces are parallel to the cubic axes. The longitudinal acoustic pulses $\tau_p = 0.05$–0.4 μsec were excited on one surface of the sample and detected on the opposite surface by a superheterodyne receiver with a 25-MHz bandwidth and a sensitivity of $\sim 10^{-14}$ W for a decoupling of the transmitting and receiving channels of ≈ 100 db. The magnetic field H_0 was applied to the (001) plane of the sample and the acoustic wave propagated along the [001] axis. The operating frequency was 642.3 MHz. To facilitate observation and simplify the calculations, all the observed effects were recorded from a pulse that was transmitted once through the crystal (Fig. 1).

The transmission of pulses ($\tau_p = 0.26$ μsec) depended on their power ($\mathscr{P}_a$) (Fig. 2). The oscillogram 1 corresponds to an acoustic pulse that was transmitted through the sample at some distance from the resonance. At $\mathscr{P}_a < 5$ mW we observed an absorption of ultrasound (a_n) due to acoustic NMR of Mn^{55} in a magnetic field $H_0 = 6100$ G($H_{0\,res} = 5900$ G) (oscillogram 2).

A highly diffuse signal of small amplitude was recorded in the interval 5 mW $< \mathscr{P}_a < 40$ mW. The propagation rate of the pulse in this case decreased fourfold compared with that of sound (oscillograms 3, 4, and 5). At $\mathscr{P}_a = \mathscr{P}_{thresh} = 40$ mW we observed a contraction and a sharp decrease in damping of the ultrasound pulse (oscil-

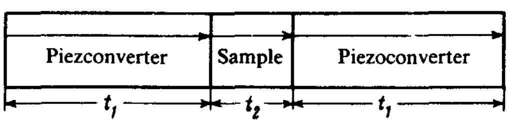

FIG. 1. t_1 and t_2 represent the transit time of a pulse through the piezoconverter and the sample, respectively. $t_1 = 2.19$ μsec and $t_2 = 0.87$ μsec before the development of SIAT.

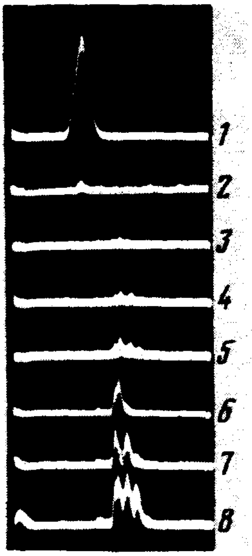

FIG. 2. Dependence of the transit time of pulses through the sample on their power.

logram 6), which can be interpreted as the onset of a stationary, solitary wave (a soliton). A second soliton appeared beginning at $\mathscr{P}_a \approx 0.2$ W, and the first soliton in this case contracted by a factor of 2. The third soliton was produced at $\mathscr{P}_a \approx 1$ W. The ratio of the threshold ultrasound power, which produces one, two, and three solitons, respectively, is equal to 1:5:25. The production regime of solitons could be observed only on the right wing of the curve for resonance absorption of ultrasound. For $H_0 < H_{0\,\mathrm{res}}$ the production of solitons could not be recorded experimentally.

To explain this effect, we shall analyze a bound, electron-nuclear, magnetic spin system with allowance for magnetoelastic interaction, which, as is known, is determined by two types of normal modes.[1] Limiting ourselves to a consideration of only the "transverse" mode, whose frequency depends on H_0, and only the neighborhood of the NMR frequency ($\omega \sim \omega_Y < \omega_{\mathrm{AFMR}}$), the corresponding dispersion law can be represented in the form

$$(\Omega^2 - \kappa^2)(\Omega^2 - 1) - \delta^2\kappa^2 = 0, \tag{1}$$

where $\Omega = \dfrac{\omega}{\omega_Y}$, $\kappa = \dfrac{v_e K}{\omega_Y}$, $\delta = \dfrac{C_0}{v_e}\Gamma (Sr)^{1/2}$ is the repulsion of branches for $\kappa = 1$, $\omega_Y = \omega_N\left(1 + \dfrac{H_{Ne}}{H_B}\right)^{1/2}$, $C_0 = \left(\dfrac{2b_1}{\rho}\right)^{1/2}$ $S, r = \dfrac{H_{Ne}H_{me}}{H_B + N_{Ne}}$, $H_B = \dfrac{H_0^2}{2H_E} - \frac{1}{2} H_A \sin^2\Phi \cos 4\psi$, $\Gamma = \sin 2\psi \sin\Phi$.

$\Phi = \arcsin\left(\dfrac{4}{7 + \cos 4\psi}\right)^{1/2}$, ω_N is the "unbiased" NMR frequency,

$H_{Ne} = Am_0(T), H_{me} = b_1/M_0$ are the effective fields of the hyperfine and magnetoelastic interactions, respectively, ψ is the angle between the H_0 and [100] directions, and v_e is the velocity of longitudinal sound.

If H_0 is higher than the sublattice-reversing field, assuming that the nuclear subsystem is slightly nonlinear, we can obtain (by using a known method[2]) a nonlinear parabolic equation for the envelop of the complex amplitude of elastic strain:

$$i U_z + P(\kappa) U_{tt} + q(\kappa) |U|^2 U = 0, \tag{2}$$

where
$$P(\kappa) = \frac{1}{2v_e \omega_Y}\left(\frac{d\Omega}{d\kappa}\right)^{1/3} \frac{d^2\Omega}{d\kappa^2}, \quad q(\kappa) = -\frac{2\omega_Y^3 S(\delta \Gamma r)^2}{v_e^2(\Omega^2 - 1)^4}\kappa^4 \tag{3}$$

and $v_q = v_e \dfrac{d\Omega}{d\kappa}$ is the group velocity.

The soliton solutions of Eq. (2) exist if $Pq > 0$. As follows from Eq. (3), this inequality occurs only for the lower branch of the spectrum $[\Omega(\kappa) < 1]$, which accounts for the experimentally observed "brightening" of the medium only on the right wing of the absorption curve. In the case of a square input pulse of duration τ_p, the expression for the acoustic-flux power, which is needed for production of solitons, has the form[2]

$$\mathcal{P}_m(\kappa) = \frac{\pi^2 \omega_Y^2 \Omega^2}{\tau_p^2}\left(m - \frac{1}{2}\right)^2 v_q \frac{P}{q}, \qquad m = 1, 2 \ldots \tag{4}$$

i.e., the power needed to produce one, two, etc. solitons can be represented as a square of the odd numbers. This is in qualitative agreement with the measurements of the relative thresholds for the onset of two and three solitons. A disagreement with the experimental data is apparently attributable to a large damping of the ultrasound in the nuclear subsystem. The absolute value of $\mathcal{P}_1(\kappa)$ is also in reasonable agreement with the experimental values. In fact, if we assume that

$$H_0 = 6\cdot 10^3\,\text{Oe}, \quad H_A = 2.9\,\text{Oe}, \quad H_{Ne} = 2.26\,\text{Oe}, \quad H_E = 8.68\cdot 10^5\,\text{Oe},$$

$$M_0 = 300\,\text{G}, \quad b_1 = 10^6\,\text{erg/cm}^3, \quad v_e = 5.35\cdot 10^5\,\text{cm/sec}, \quad \rho = 4.3\,\text{g/cm}^3$$

$$T_2 = 5\cdot 10^{-7}\,\text{sec}, \quad \frac{\omega_N}{2\pi} = 687\,\text{MHz}, \quad \tau_p = 4\cdot 10^{-7}\,\text{sec}, \quad \psi = 45°, \tag{5}$$

then we obtain $\mathcal{P}_1(\kappa = 1) = 5 \times 10^{-2}\,\text{W/cm}^2$.

The thresholds for other orientations of H_0, particularly in the (111) plane, are of the same order of magnitude.

In spite of a large damping, the optimum conditions for production of solitons in our experiments corresponded to a considerable delay of the transmitted signal: $v_q \approx 0.25\, v_e$. Such a delay for the numerical values (5) should occur at $\kappa = 1.002$. Using the relation $\mathscr{P}_m(\kappa) = \frac{1}{2}\left(\frac{\delta}{\kappa - 1}\right)^3 \mathscr{P}_m(1)$, which is valid in the region $\frac{1}{2}\ \delta < \kappa - 1 < 1$, we have: $\mathscr{P}_1(1.002) = 0.5\mathscr{P}_1(1)$. Although a further decrease of v_q is connected with a decrease of $\mathscr{P}(\kappa)$, it is limited by the effect of damping which is disregarded in the theory.

The maximum effect was observed in a 4.7-mm-long sample. This is apparently attributable to the fact that the solitons do not have time to form in a short sample and cannot escape in the form of solitons in a long sample because of damping. We observed the formation of solitons only for pulses $\tau_p = 0.3$–$0.4\ \mu$sec, i.e., with a shorter duration than the irreversible time of spin relaxation ($T_2 = 0.48\ \mu$sec).

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