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GENERATION OF ULTRASOUND WITH THE AID OF A NUCLEAR SPIN SYSTEM

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Coherent spontaneous electromagnetic radiation of a system of $N \gg 1$ particles was first considered theoretically and observed experimentally by Bloch [1]. By now, such coherent signals have been observed in nuclear and electronic spin systems [1,2], and also on electric dipole moments [3,4].

The possibility of generating ultrasound with the aid of a spin system was demonstrated theoretically in [5]. We report in this paper observation of this phenomenon on the spin system of In^{115} nuclei in InSb. According to [5], a spin system in a superposition state should generate coherent phonons, a fact used to detect this state. Insofar as we know, this is the first report of observation of ultrasound generation with the aid of coherent spontaneous transitions of a spin system.

Coherent spontaneous generation of phonons by a spin system was observed in a stationary mode (signal of stimulated phonon induction, SPI). As in experiments on ordinary Bloch induction, the spin system was brought into the coherent state with the aid of an alternating magnetic field of intensity H_0. However, unlike ordinary experiments on Bloch induction, in this investigation we observed generation of phonons by a spin system.

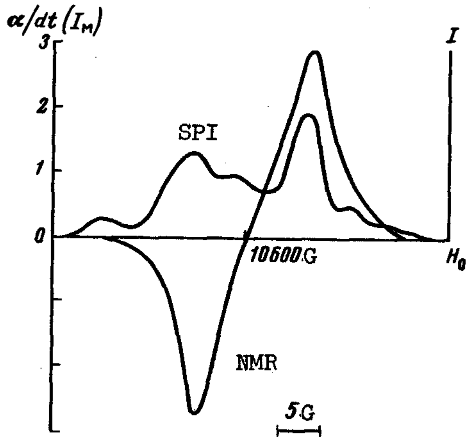
An InSb sample was placed in a constant magnetic field H_0 = 10 600 G, in which the In^{115} nuclei form an equidistant spectrum with a splitting frequency $\nu_0 = 10^7$ Hz.

The sound generated in the sample was transformed with the aid of a quartz converter into an electromagnetic signal, which was detected with a sensitive receiver. The power conversion coefficient was $\alpha = 2 \times 10^{-1}$. The sample (volume $V = 2$ cm^3, length 2 cm, and with plane-parallel end surfaces of area $S = 1$ cm^2) constituted an acoustic resonator with $Q = 5 \times 10^3$ at the frequency $\nu_0/2$. Inasmuch as the sample dimensions greatly exceeded the wavelength of the sound of frequency ν_0, but were much smaller than the wavelength of the electromagnetic exciting generator, there should have been effectively generated in the resonator, besides the SPI signal of frequency ν_0, also a signal of two-quantum SPI of frequency $\nu_0/2$. This circumstance was used by us for a reliable separation of the exciting and receiving circuits (we recorded the sound at $\nu_0/2$). A spectrogram of the SPI signal is shown in the figure.

According to [5], the intensity of the SPI signal is given by the formula

$$I = I_0 9^{-1}[S(S+1)]^2 N^2 \sin^2\theta \, \mathrm{th}^2(\hbar\omega_0/2kT), \tag{1}$$

$\omega_0 = 2\pi\nu_0$, $S = 9/2$ - spin of In^{115} nucleus, I_0 - intensity of spontaneous emission of an iso-



Spectrograms of signal of stimulated phonon induction I and the corresponding NMR signal I_M, in arbitrary units.

lated particle per unit solid angle, $\Delta\omega = \omega_0 - \omega$, $\omega_1 = \gamma H_1$,

$$\sin\theta = |\omega_1| T_2^2 \Delta\omega [1 + (T_2 \Delta\omega)^2 + \omega_1^2 T_1 T_2]^{-1}, \tag{2}$$

$\gamma = 933.1$ Hz/G, T_1 and T_2 - respectively the times of longitudinal and transverse relaxation of In^{115}. All other symbols are standard.

A characteristic feature of (2) is that sin θ has two maxima, at $\Delta\omega = \pm T_2^{-1}[1 + \omega_1^2 T_1 T_2]^{\frac{1}{2}}$, which yields at $\omega_1^2 T_1 T_2 \gg 1$:

$$\Delta\omega = \pm\, \omega_1 (T_1 T_1^{-1})^{1/2}, \quad (\sin\theta)_{max} = 1/2\, (T_2 T_1^{-1})^{1/2}. \tag{3}$$

Maxima on the experimental curve are observed at

$$\Delta\omega = \pm\, \pi 25 \times 10^3 \text{ Hz}.$$

A remarkable feature of this behavior of sin θ is the possibility of determining important kinetic parameters of the quantum systems T_1 and T_2 by spectroscopic methods. For In^{115} in InSb we have $T_2 = 10^{-4}$ sec [6]. Curve 1 was plotted at T = 4.2°K. Calculation by means of (3) yields $T_1 \sim 1$ sec.

Analysis has shown that spontaneous two-quantum decay of an isolated particle accompanied by production of $\nu_0/2$ phonons is due to the joint action of spin-phonon and anharmonic interactions, described respectively by the Hamiltonians $\mathcal{H}_{sp}$ and $\mathcal{H}_{anh}$:

$$\begin{aligned} \mathcal{H}_{sp} &= \sum_{\alpha\beta v} G_{\alpha\beta v} S_\alpha S_\beta \delta_v; \quad \alpha, \beta = x, y, z; \\ \mathcal{H}_{anh} &= \sum_{vwu} F_{vwu} \delta_v \delta_w \delta_u; \quad v, w, u = k_1, k_2, \ldots, \end{aligned} \tag{4}$$

where $G_{\alpha\beta v}$ and F_{vwu} - respectively the spin-phonon and anharmonic interaction tensors, and (α, β) and (v, w, u) - respectively the indices for the coordinates and the wave vectors [4].

From (4) we get in second order of perturbation theory:

$$I_0 = 9\hbar\omega_0^3\omega_D^4\Delta\omega_0 Q^2G_1^2G_2^2[2^2(2\pi)^7v^{14}q^4V^2]^{-1}, \tag{5}$$

where G_1 and G_2 are the averaged values of $G_{\alpha\beta\gamma\xi}$ and $G_{\alpha\beta\gamma}$, $G_1 = 2\pi 10^{-18}$ erg, $G_2 = R2a^3N/3!(2\sqrt{2})^3$ [7], $R \sim 10^{13}$ erg/cm^3, $a = 6.45$ Å, ω_D is the Debye frequency of InSb, $\Delta\omega_0 = 5\pi 10^4$ rad/sec - width of absorption line of In^{115}, $v = 4.25 \times 10^5$ cm/sec - speed of sound, and $q = 5.8$ g/cm^3 - density of sample. Calculations by means of (5) and (1) with allowance for the coefficient α yield $I \sim 10^{-15}$ W at the maximum, coinciding with the experimental value of this quantity. We note also that in the described phenomenon we registered for the first time spontaneous two-quantum transitions of a quantum system. When $T_1 \to T_2$ and when impurities with strong spin-phonon interaction are used (such as paraelectrics), the SPI phenomenon can be used for effective generation of sound.

In our experiment the InSb sample acted as a phonon quantum generator [8] (PQG) at the coherent spontaneous transitions of the crystal lattice, and the pumping of the population was "automatically realized" as a result of the nuclear spin-lattice relaxation, while the emission intensity was set by the amplitude of the applied alternating magnetic field. Unlike the usual PQG [7], the present generator operates at any spin temperature $\infty > T_S \gtrless 0$, this being connected with the use of zero-point oscillations in the generation process. This example points to the promising nature of using zero-point oscillations in quantum and nuclear electronics. It is obvious that the principle of phonon generation realized by us can be used to excite other quasiparticles with the aid of various zero-point oscillations in any frequency range.

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CHARGE EXCHANGE OF PROTONS ON ALKALI-ELEMENT ATOMS

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The effective cross sections for charge exchange of protons on atoms (the reaction $H^+ + A \to H(n, l) + A^+$, where n and l are the principal and orbital quantum numbers) were measured recently in states with different values of n and l. A characteristic feature of charge exchange in an excited state at low energies (1 - 10 keV) is the presence of several maxima on the plot of the cross section against the energy [1]. The appearance of ad-