Role of incoherent phonons in resonant interaction of ultrasound with a nuclear spin system

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Direct acoustic magnetic resonance and acoustic saturation of NMR are investigated in InSb and CsI. Anisotropy of acoustic saturation of NMR is observed for the first time ever. The feasibility of correctly determining the spin-phonon coupling constants and the incoherent-phonon lifetime is demonstrated.

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According to prevailing ideas concerning the mechanisms of the interaction of ultrasound with a spin system, both the intensity of the direct nuclear acoustic resonance (NAR) and the factor of the acoustic saturation of NMR (ASNMR)[1] should have a definite dependence on the angle. In all the preceding ASNMR studies, however, no angular dependence was observed at all,[2,3] whereas the NAR results do yield the expected dependence. Moreover, the so-called "defect" mechanism was proposed[4] to explain the absence of the angular dependence.

We report here the first observation of the anisotropy of ASNMR in two crystals, InSb and CsI, interpret the results, and note the feasibility of correctly determining the constants of the spin-phonon coupling and of the phonon lifetime from the ASNMR data.

The experiments were performed on a universal spectrometer that made it possible to investigate, in one and the same sample, both NAR and acoustic saturation of NMR in a stationary regime at frequencies 10–20 MHz and temperatures 4.2–300 K.[5] To measure the extremely weak NAR absorption, $\alpha_n \sim 10^{-7}$–10^{-9} cm^{-1}, the end faces of

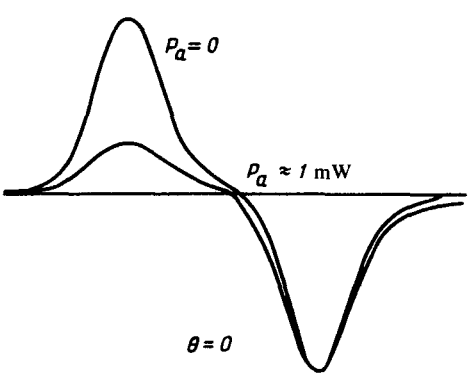

FIG. 1. Plot of NMR signal from ^{115}In at two values of the acoustic power fed to sample: $T_1 = 0.8$ sec (77 K), $\nu_a = 10$ MHz, $\nu_s = 5.03$ MHz, $\Delta\nu_m = 30$ kHz.

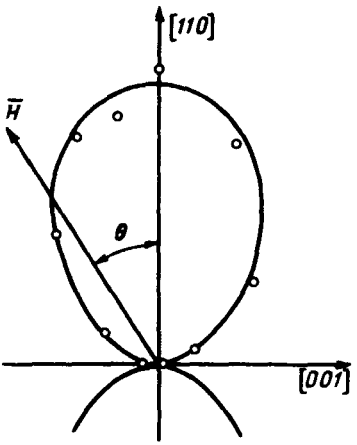

FIG. 2. Angular dependence of NAR of ^{115}In at ultrasound propagation and polarization directions [1$\bar{1}$0] and [110] respectively.

the samples were made plane parallel within 2 μm/cm, so that an acoustic $Q\sim(3-5)\times10^{-3}$ was obtained. This corresponds to sound absorption $\alpha_0\sim10^{-3}$ cm^{-1}. At the same time, to increase the sensitivity and lower the noise level, we used an original procedure.[5] By modulating the magnetic field with a square-wave current, we were able to record simultaneously the sound-saturated and the unsaturated NMR lines when the frequencies ν_a of the acoustic pump, ν_s of the NMR sensor, and $\Delta\nu_m$ of the modulation were connected by the relation $\nu_a/2-\nu_s=\pm\Delta\nu_m$ (Fig. 1). Figure 2 shows the experimental points and the expected angular dependence of the NAR of ^{115}In for the transitions $\Delta m=\pm2$ ($\alpha_n\sim\cos^2\theta$). The NMR saturation factors (A/A_0) are shown in Fig. 3, as functions of the acoustic power fed to the sample for two sample orientations ($Q=5.5\times10^4$) corresponding to the maximum ($\theta=0$) and minimum ($\theta=\pi/2$) values of the NAR absorption. With increasing Q ($Q=10^3$) the anisotropy vanishes (Fig. 3). It is seen from the data of Figs. 2 and 3 that a definite correlation exist between the angular dependences of NAR and ASNMR.

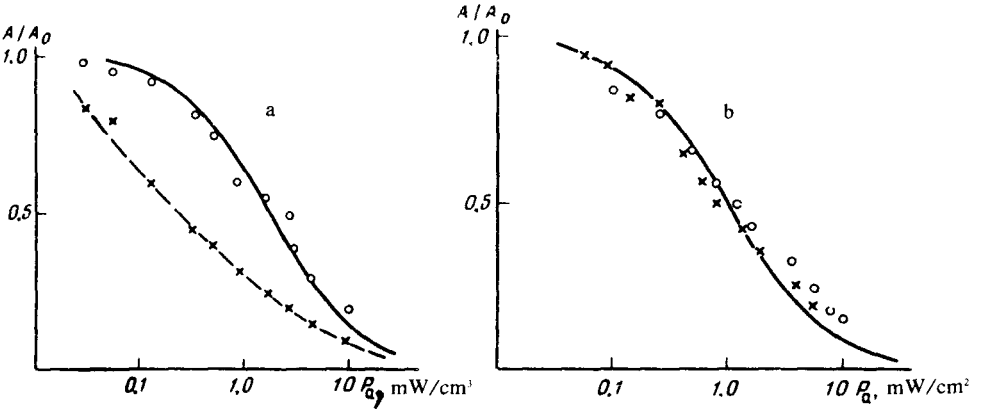

FIG. 3. Saturation factors of NMR at two values of the acoustic Q of the sample, 5.5×10^4 (a) and 10^3 (b). The points (X) and (0) correspond to the maximum and minimum NAR absorption. Solid curve—theoretical plot of $A/A_0=(1+W'_{in}T_1)^{-1}$.

The results can be obtained by recognizing that in real crystals the ultrasound energy of the beam is subject at the indicated frequencies to rather strong scattering because of diffraction effects, crystal imperfections, and inaccuracy in the mechanical finish of the sample.[6] Consequently besides the coherent beam phonons that cause the expected angular dependence, a part is played in the resonant absorption of the spin system by incoherent (diffusely scattered) phonons that lead to a partial or predominant isotropic saturation of the NMR. It follows from our data that the densities of the incoherent and coherent phonons are commensurate even at the maximum attainable Q of the sample. We note that the foregoing reasoning makes it easy to explain the total saturation of the entire spin system even at a relatively small beam volume, as observed in[7]. Taking into account the probabilities of the acoustic transitions due to either coherent (W_c) or incoherent (W_{in}) phonons, and taking into account the distributions of the strain amplitude along the beam,[2] we can write

$$\frac{A}{A_0} = \frac{\eta}{\sqrt{(1 + W'_{in} T_1)(1 + W''_c T_1 + W''_{in} T_1)}} + \frac{1 - \eta}{1 + W'_{in} T_1}, \quad (1)$$

where $\eta = V_n/V_0$, V_n and V_0 are the volumes of the beam of the sample, respectively, T_1 is the spin-lattice relaxation time. To calculate the spin-phonon coupling constants in NAR and ASNMR S_{ij} it is necessary to know the proability W_c. It can be obtained from (1) after first calculating W_{in} at the same input power, when $W_c = 0(\theta = \pi/2)$. An estimate of the spin-lattice coupling constants for ^{115}In nuclei on the basis of measurements by both procedures (NAR and ASNMR) gives results that are in full agreement.

The ASNMR has made it also possible to estimate the lifetime of the incoherent phonons. It can be shown that the ratio of the scattered power (P_{in}) to the input power (P_a) is $P_{in}/P_a = 1 - \tau_c/\tau_{ph}$, where τ_c is the beam decay time, and τ_{ph} is the lifetime of the incoherent phonons. The average energy of the incoherent phonons in the sample is therefore $\langle E \rangle = \tau_{ph} P_{in} = (\tau_{ph} - \tau_c) P_a$. Using values of P_a corresponding to the same saturation level at different Q values, $Q = 5.5 \times 10^4$ and $Q = 10^3$ we can obtain τ_{ph}, whose value for InSb turned out to be 4×10^{-3} sec.

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