

Fig. 3

A confirmation of this hypothesis is the noticeable decrease of the spin-lattice relaxation time when  $T > T_c$  in  $Nb_3Al$ , which is also ascribed to fluctuations [5].

It should be noted that a temperature dependence similar to that obtained by us was observed for the susceptibility of  $Nb_3Sn$  [6]. It was assumed there that the maximum on the  $\chi(T)$  curve is due to the martensitic transformation that occurs in  $Nb_3Sn$  at 40°K. One cannot exclude the possibility that in our case the deviation of  $\chi$  from the  $T^{-1}$  dependence is due to a martensitic transformation. However, NMR investigations of the  $Nb_3Al_{1-x}Ge_x$  system [7] show that the  $^{27}Al$  line does not vary noticeably with the temperature, thus casting doubts on the martensitic-transition hypothesis.

In addition, as noted above, a decrease of the spin-lattice relaxation time  $T_1$  at temperatures below critical is observed at the same time for  $Nb_3Al$ , where no martensitic transition takes place.

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#### FORBIDDEN ACOUSTIC NUCLEAR SOLID-STATE EFFECT IN CsI SINGLE CRYSTALS

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Submitted 28 September 1972

*ZhETF Pis. Red.* **16**, No. 9, 525 - 528 (5 November 1972)

In [1] we obtained dynamic polarization of  $Li^7$  nuclei in an  $LiF$  crystal by ultrasonic modulation of the internuclear dipole-dipole interaction at the sum

and difference precession frequencies of the nuclei  $\text{Li}^7$  and  $\text{F}^{19}$ . According to the selection rules applicable in this case, the acoustic transitions excited thereby are connected with simultaneous reorientation of two different spins (of  $\text{Li}^7$  and  $\text{F}^{19}$ ) and are "acoustically allowed" [2], so that the change of the nuclear polarization observed in the  $\text{LiF}$  crystal under the influence of the ultrasound can be called "allowed acoustic solid-state effect." The possibilities of the acoustic solid-state effect, however, are not limited to modulation of the magnetic dipole interaction, since a variety of mechanisms for the interaction of the nuclei with the ultrasonic waves exist in acoustic nuclear resonance (ANR). In particular, the most effective for heavy nuclei is the "quadrupole" mechanism due to the interaction of the dynamic gradients of the local electric field with the quadrupole moment of the nucleus [3]. On the other hand, in crystals in which one of the nuclear spins interacts strongly with the lattice because of the quadrupole spin-phonon coupling, the dynamic polarization of the nuclei can result from excitation of acoustic transitions connected with the existence of non-secular terms of the dipole-dipole interaction, corresponding to the mixing of different non-equivalent spin states [2]. Although such transitions are forbidden for pure states [2], their probability in a system of interacting spins may turn out to be much larger than the probability of the allowed acoustic transitions. These transitions, and the acoustic solid-state effect due to them, will be called "forbidden."

In the present study we obtained dynamic polarization of  $\text{Cs}^{133}$  nuclei by exciting forbidden transitions of this type with ultrasound in a pure  $\text{CsI}$  crystal. This crystal contains two different nuclear spins, of  $\text{I}^{127}$  and  $\text{Cs}^{133}$ , with different gyromagnetic ratios  $\gamma_{\text{I}}$  and  $\gamma_{\text{Cs}}$ , the  $\text{I}^{127}$  nuclei being strongly coupled with the lattice by a quadrupole spin-phonon interaction (relaxation time  $T_{1\text{I}} \approx 0.01$  sec), and the  $\text{Cs}^{133}$  nuclei are anomalously weakly coupled ( $T_{1\text{Cs}} \approx 500$  sec). Under these conditions, calculation yields for the maximum change of the stationary polarization of  $\text{Cs}^{133}$  under the influence of ultrasound of frequency  $|q|\omega_{\text{I}} \pm \omega_{\text{Cs}}$ , corresponding to one of the forbidden transitions, the relation

$$(P_{\text{Cs}}^{\text{st}})_{\text{max}} = |q| \omega_{\text{I}} / \omega_{\text{Cs}}, \quad (1)$$

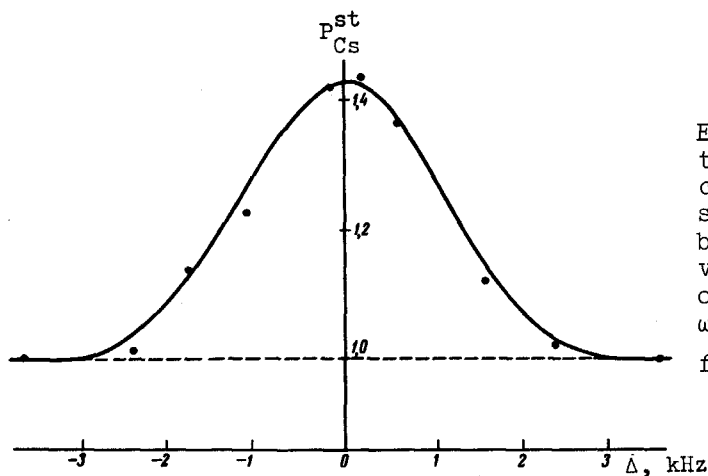
where  $\omega_{\text{I}} = \gamma_{\text{I}} H_0$  and  $\omega_{\text{Cs}} = \gamma_{\text{Cs}} H_0$  are the Larmor precession frequencies of the nuclei  $\text{I}^{127}$  and  $\text{Cs}^{133}$  in an external magnetic field  $H$ , and  $q = \pm 1$  or  $\pm 2$  is a quantity determined by the selection rule for the allowed quadrupole transitions in the  $\text{I}^{127}$  spin system and corresponds to a change of the magnetic quantum number  $m_{\text{I}}$  by  $\Delta m_{\text{I}} = q$ . It follows from (1) that the maximum attainable enhancement of polarization in the system in question, following excitation of forbidden transitions at a frequency  $\omega_2 \equiv 2\omega_{\text{I}} - \omega_{\text{Cs}}$ , is twice as large as the maximum dynamic polarization due to the allowed acoustic transitions [1, 2]. The probability of the latter is determined by the expression [2]

$$W_{\text{allow}} \approx \gamma_{\text{I}}^2 \gamma_{\text{Cs}}^2 \hbar^2 g_a(\nu) s_0^2 / r^6, \quad (2)$$

where  $\hbar$  is Planck's constant,  $r$  is the internuclear distance,  $s_0$  the amplitude of the deformation in the ultrasonic wave, and  $g_a(\nu)$  is a function of the shape of the corresponding ANR line. The probability of forbidden transitions in a  $\text{CsI}$  crystal can be estimated from the relation [2]

$$W_{\text{qforb}} \approx W_{\text{q}} (H_{\text{loc}} / H_0)^2, \quad (3)$$

where  $H_{\text{loc}}$  is the local field induced at the  $\text{Cs}^{133}$  nucleus by the dipole moments of the  $\text{I}^{127}$  nuclei,  $W_{\text{q}} = R^2 g_a(\nu) s_0^2$  is the probability of the usual allowed quadrupole transitions with  $\Delta m_{\text{I}} = q$  in the  $\text{I}^{127}$  system at the frequency  $|q|\omega_{\text{I}}$ , and



Enhancement of stationary polarization of  $\text{Cs}^{133}$  nuclei in single-crystal  $\text{CsI}$  by longitudinal ultrasonic waves of frequency deviating by an amount  $\Delta$  from the theoretical value of the difference frequency of the forbidden transition,  $(2\omega_I - \omega_{\text{Cs}})/2 = 6.954$  MHz in a magnetic field  $H = 6.0$  kG.

$R$  is the effective quadrupole spin-phonon coupling constant for the  $\text{I}^{127}$  nuclei. Expressions (2) and (3) make possible a comparative estimate of the probabilities  $W_{\text{allow}}$  and  $W_{\text{q forb}}$  at one and the same deformation amplitude  $s_0$ . In a fixed field  $H_0 \sim 10$  kG this yields at  $\Delta m = \pm 2$  ( $r = 4.11 \text{ \AA}$ ,  $R = 10^9 \text{ sec}^{-1}$  [5]) the ratio  $W_{2\text{forb}}/W_{\text{allow}} \approx 10^3$ . Thus, the forbidden acoustic solid-state effect in the  $\text{CsI}$  crystal should predominate strongly over the allowed one.

We performed the experiment at room temperature using the pulse apparatus described in [4]. The polarization of the  $\text{Cs}^{133}$  nuclei was determined from the change of the initial free-precession signal amplitude. The precession signals of the  $\text{Cs}^{133}$  nuclei were excited by short electromagnetic pulses, making it possible to observe a series of signals of monotonically decreasing amplitude. In the interval between the series, longitudinal ultrasonic oscillations were excited in the  $\text{CsI}$  sample, with a frequency  $\omega$  that was varied within the converter bandwidth relative to the theoretical value of the difference frequency of the forbidden transition  $\omega_2 = 2\omega_I - \omega_{\text{Cs}} = 6.954$  MHz in a magnetic field  $H_0$  of approximately 6 kG. The investigated  $\text{CsI}$  sample was a cylinder of 12 mm diameter and  $\sim 40$  mm length, cut along the  $[100]$  axis, which was in turn oriented perpendicular to  $\vec{H}_0$ . An X-cut quartz plate was fastened to the flat face of the sample, and a voltage up to 750 V was applied to it. The opposite face of the sample was cleaved to produce in it a diffuse ultrasonic field.

The results of the experiment are shown in the figure in the form of a plot of the relative stationary polarization  $P_{\text{Cs}}^{\text{st}}$  of the  $\text{Cs}^{133}$  nuclei, which is proportional to the observed initial amplitude of the precession signals, against the deviation  $\Delta$  of the ultrasound frequency  $\omega/2\pi$  from the theoretical value of the difference frequency  $\omega_2/2\pi$ . As seen from this figure, in a frequency band of width  $\delta \approx 2.5$  kHz there is observed an acoustic enhancement of the polarization of the  $\text{Cs}^{133}$ , up to 50% at the center of the line of the forbidden solid-state effect, coinciding with the theoretical value  $\omega_2$ . The relative error of these measurements did not exceed 5%. Thus, the observed effect (which vanishes when the acoustic contact between the converter and sample is broken) actually corresponds to dynamic polarization of the  $\text{Cs}^{133}$  nuclei due to excitation of acoustic forbidden transition. The probability of these transitions at the center of the solid-state-effect line ( $\Delta = 0$ ), obtained from the experimental curve corresponds to  $0.5 \times 10^{-3} \text{ sec}^{-1}$ , which agrees in order of magnitude with the theoretical value calculated from formula (3) using the known parameters of the  $\text{CsI}$  crystal.

In conclusion, the authors thank I.G. Mikhailov for collaboration and V.I. Smushkov for supplying the CsI samples.

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# RADIATION OF A BIELECTRON (BI-HOLE) IN A BiI<sub>3</sub> CRYSTAL AT LOW TEMPERATURES

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Submitted 11 July 1972; resubmitted 28 September 1972

ZhETF Pis. Red. 16, No. 9, 528 - 531 (5 November 1972)

We have investigated the radiation spectrum of the inverse hydrogen-like line series of BiI<sub>3</sub> crystals in the temperature interval 1.6 - 10°K, using a large-dispersion (1.9 Å/mm) diffraction spectrograph. The luminescence was excited by a DRSh-500 mercury lamp through an optical filter. The luminescence was recorded photographically.

The emission spectrum of BiI<sub>3</sub> crystals at low temperatures is complex and has not yet been uniquely interpreted [1, 2]. We have studied in greater detail the bright  $n = 6$  resonant emission line and its first phonon replica with frequency 112 cm<sup>-1</sup>, which falls in a spectral region free of other emission lines. The use of a large-dispersion spectral instrument has revealed, in our opinion, a new interesting fact.

It is seen already at 4.2°K that the phonon replicas are broader than the resonant emission lines and have an asymmetrical shape, with a wing on the high-energy side. When the temperature is raised to 8°K, the widths of the phonon replica lines and their asymmetries increase even more. Preliminary results show that the phonon replica lines broaden linearly with rising temperature (see the figure). The resonant emission line also broaden somewhat, but their shape remains unchanged. It is seen from the figure that when the crystal is cooled to  $T = 1.6^\circ\text{K}$  the phonon line becomes narrow and almost symmetrical. This "symmetrization" of the phonon replica shows that its asymmetric shape is not due to superposition of other emission lines.

The phonon replicas are observed against a continuous emission background that starts with the resonant emission lines  $n = 5$  and  $n = 6$  and stretches,

Micrograms of phonon replica ( $\nu_6 - \omega_2$ ) emission lines of a BiI<sub>3</sub> crystal at 1.6, 4.2, and 8°K. The half-widths of the  $n = 6$  resonant emission line at the same temperatures are shown for comparison.

