# DOUBLE $Cr^{53}$ - $Al^{27}$ ACOUSTO-MAGNETIC RESONANCE IN RUBY

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This is the first time that acoustic nuclear magnetic resonance (ANMR) from a small number of nuclei has been detected by another spin system with a large number of nuclei ($Cr^{53}$ in $Al_2O_3:Cr^{3+}$). This results in an unprecedented sensitivity in the measurement of the sound absorption coefficient due to the ANMR, $\sigma \sim 10^{-10}$ $cm^{-1}$. This is also the first time that ANMR on a paramagnetic-ion nucleus has been observed and the gain of the spin-phonon interaction due to the coupling between nuclear spin and the electron shell of the paramagnetic ion has been estimated.

The experiment is based on the idea that saturation of the $Cr^{53}$ system with sound increases the longitudinal relaxation time of the $Al^{27}$ nuclei, the number of which in the sample exceeds that of the $Cr^{53}$ by a factor $10^3$. Thus, the $Cr^{53}$ ANMR signal is revealed by the decrease of the intensity of the ordinary NMR from $Al^{27}$. The $Al^{27}$ NMR signal decreases not because the energy of the ultrasound enters into the $Al^{27}$ spin system, but because the channel of the longitudinal relaxation of the $Al^{27}$ nuclei via the $Cr^{3+}$ ions is apparently the reservoir of the magnetic dipole-dipole interactions $Cr^{3+} \leftrightarrow Cr^{3+}$ [1]. The ANMR on $Cr^{53}$ raises the temperature of the dipole-dipole system [1] and increases greatly the longitudinal relaxation time of the $Al^{27}$ nuclei, and by the same token decreases the NMR signal of the $Al^{27}$ nuclei. Owing to the ratio of the frequencies of the NMR of the $Cr^{53}$ nucleus to the average frequency of the dipole-dipole interactions $Cr^{3+} \leftrightarrow Cr^{3+}$, a further increase takes place in the sensitivity of the measurement of $\sigma$, by a factor $[\nu(Cr^{53})/\nu(Cr^{3+} \leftrightarrow Cr^{3+})]^2 = 10^2$, and altogether, taking the concentration into account, by a factor $10^5$.

Double acousto-magnetic nuclear-nuclear resonance was observed at 4.2°K in a polished single-crystal $Al_2O_3$ laser rod, containing 0.1

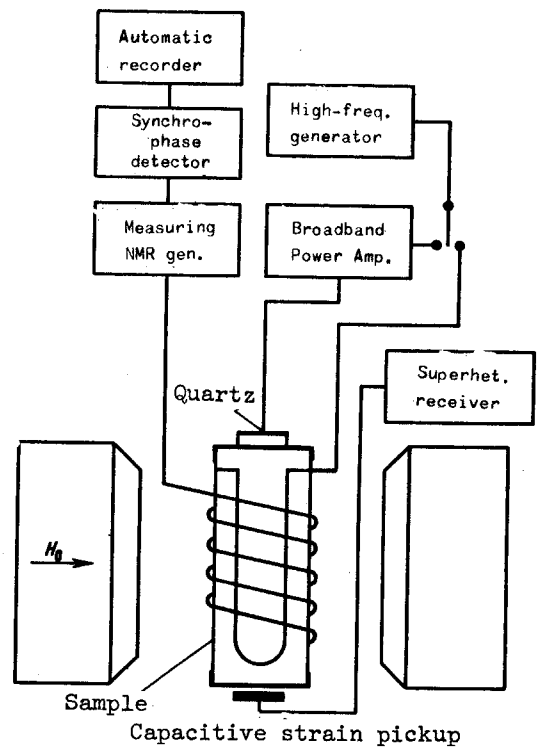


Fig. 1. Block diagram of double-resonance spectrometer.

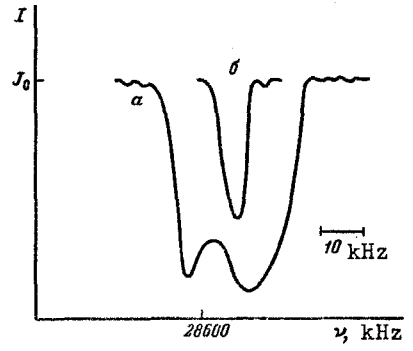


Fig. 2. a - NMR signal from $Cr^{53}$ nuclei, b - ANMR signal from $Cr^{53}$ nuclei. Switching speed of exciting electromagnetic field 340 Hz/sec.

at.% $Cr^{3+}$ ions. The NMR measuring generator was tuned to 3570 kHz. The magnitude of the static magnetic field ($H_0$ = 3210 G), parallel to the optical $C_3$ axis of the crystal, was adjusted to obtain from the synchronous detector a maximum signal corresponding to the maximum of the first derivative of the NMR line of the $Al^{27}$ nucleus (nuclear spin transition $|1/2\rangle \leftrightarrow |3/2\rangle$ with frequency 3570 kHz). The magnitude of this signal $I_0$ is indicated in Fig. 2. At a constant value of the field $H_0$, a change in the magnitude of the signal was subsequently observed at the maximum of the first derivative of the NMR line of the $Al^{27}$ nuclei under the influence of an additional alternating magnetic field perpendicular to $H_0$ (switch of high-frequency generator in position A, Fig. 1) or an ultrasonic field (switch in position B). Figure 2 shows plots of the signal at the maximum of the first derivative against the frequency of the alternating magnetic field (a) and against the ultrasound frequency (b). Curve (a) corresponds to the transition $|-1/2\rangle \leftrightarrow |-3/2\rangle$ of the $Cr^{53}$ nucleus (abundance 10%), pertaining to the $Cr^{3+}$ ion spin state $|1/2\rangle$. It was obtained at an alternating magnetic field amplitude $H \sim 0.01$ G. It should be noted that the frequency of this transition, $\nu_0$ = 28610 kHz, is practically independent of $H_0$, and the width at half-intensity is $\Delta\nu_1 = 4 \times 10^{-4}$ $sec^{-1}$. This agrees qualitatively with the results of [2,3]. Curve (b) corresponds to the same transition of the $Cr^{53}$ nucleus, but in the case of acoustic saturation.

The line width of the ANMR line of $Cr^{53}$, plotted by the described method, turned out to be on the order of $\Delta\nu_p \sim 6 \times 10^3$ $sec^{-1}$ (Fig. 2b).

The physical reason for the narrowness of the ANMR line of $Cr^{53}$ compared with the line width of the ordinary NMR of the $Cr^{53}$ nucleus is not completely clear. It is possible that it is due to the motion of the nuclei under the influence of the acoustic oscillations, which can lead to an averaging of the inhomogeneities of the internal field. Let the spin-phonon and spin-photon interaction operators for $Cr^{53}$ be characterized respectively by the constants $\epsilon G$ and $g\beta H$, where $\epsilon$, G, g, and $\beta$ are respectively the relative alternating deformation, the spin-phonon interaction tensor, the g-factor, and the nuclear magneton. When the acoustic and magnetic saturations of the NMR signal of $Al^{27}$ are equal we get $G = kg\beta H\epsilon^{-1}$, where k is the coefficient of amplification of the field H at the $Cr^{53}$ nucleus due to the polarization of the $Cr^{3+}$ electron shell [4]. In our case $k \sim 10$ and $\epsilon \sim 10^{-6}$, and consequently $10^{-18}$ erg (deformation units)$^{-1}$. The sound absorption coefficient due to the $Cr^{53}$ nuclei amounts to only $\sigma \sim \pi\Delta n\nu_0\Delta\nu_1^{-1}G^2\rho^{-1}v^{-2}\hbar^{-1} = 10^{-10}$ $cm^{-1}$, where $\Delta n$ - population difference, $v = 10^6$ cm/sec - speed of sound, and $\rho = 4$ g/$cm^3$ - crystal density. The value of G exceeds by $10^2$ times the ordinary value of the spin-phonon interaction of the nucleus in the diamagnetic crystal. The effect of the amplification of the ANMR due to the contact coupling was predicted theoretically in [5].

To screen the sample and the NMR circuit against the penetration of the high-frequency voltage exciting the force, the ends of the sample were metallized with allowance for the depth of the skin layer and placed in screens. When the quartz was replaced by a dielectric, the NMR of $Al^{27}$ did not change when electromagnetic excitation was turned on.

Additional proof that the observed effect is indeed caused by sound is the sharp difference between the widths of the lines of ANMR of $Cr^{53}$ in the case of electromagnetic and acoustic excitation.


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## DOUBLE FERROMAGNETIC RESONANCE


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Let a ferromagnetic sample be situated in a constant magnetic field $H_0$ and in the radiation field of two close microwave frequencies $\omega_1$ and $\omega_2$. A photon incident on the ferrite excites in it a spin wave with energy equal to the photon energy, and with a zero wave vector (homogeneous precession).

Owing to this process, saturation can be reached in any region of the FMR line at a sufficiently large amplitude of the microwave field. This saturation can be observed when plotting the absorption curve, by varying the frequency $\omega_2$ of the so-called detecting microwave radiation, the amplitude of which is such that parametric excitation of the undamped spin waves by this field is impossible. The ferromagnetic-resonance line recorded in this manner is the usual curve with a dip in the vicinity of the saturation point (see the figure). The dip is due to the interaction between the parametrically-excited spin waves saturating the spin system and the homogeneous precession excited by the detecting field. We shall call this phenomenon double ferromagnetic resonance (DFMR). Using the expansion of the magnetization vector in plane waves [1] and a successive-approximation method, we can obtain from the