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NMR STUDY OF HEAT TRANSFER IN RUBY (Al2O3, Cr3+) AT VERY LOW TEMPERATURES

M. Chiba*, M. Chapelier and M. Rotter*
DPh-G/PSRM - CEN Saclay - B.P. N°2, 91190 Gif-sur-Yvette, France

1. INTRODUCTION.- Ruby is one of the good candidates to study the behaviour of a nuclear spin system at low temperatures such a nuclear magnetic ordering in the laboratory frame in the presence of external magnetic field, if the nuclear spin system is well isolated from the lattice. The energy levels of the electron spin of Cr3+ and those of the nuclear spin of 27Al are already well-known [1]. The levels of 27Al have several crossing points if the c-axis is parallel to the external magnetic field. We report here preliminary results of relaxation times of 27Al quadrupole resonance at zero field after enhancement of the signal by demagnetization from 2 kG to zero field. The minimum observed temperature of the 27Al nuclear spin system was 3 mK. The relaxation times were quite long at low bath temperatures and the isolation from the lattice was found to be very good.

2. EXPERIMENTS AND DISCUSSIONS.- The experiments were performed on a single crystal of ruby (Al2O3 : Cr3+) with the concentration Cr3+/Al = 150 ppm and the size of 4 x 11 x 12.5 mm3. The sample was placed in a mixing chamber of a 3He - 4He dilution refrigerator. The measurements were done at the temperatures from 900 mK down to 6 mK. The temperatures were calibrated by Tc of metallic Pt powder at 250 kHz with the use of Korrina equation. The external magnetic field H0 was applied parallel to c-axis: The energy level diagrams of the electron spin of Cr3+ and the nuclear spin of 27Al with H0 // c-axis are shown in figures 1 and 2. An NMR coil was wound around the sample so that the rf magnetic field Hr // c-axis. Working frequencies were between 300 kHz and 800 kHz, because the nuclear quadrupole resonance (NQR) signals at zero field are observed at two frequencies of 356 kHz and 712 kHz.
The NQR and NMR signals were detected by using a Robinson box with low level oscillations. Fast increase of the $^{27}$Al relaxation time was observed with decreasing temperature. Therefore no measurements were done below 80 mK. When a demagnetization from 2 kG was done, an enormous enhancement of the NQR and NMR signals was observed after experiencing zero field. This fact means that the electrons spin system is cooled by the demagnetization and that at zero field the nuclear quadrupole system couples to the electron dipole system which causes the cooling of the nuclear spin system. The minimum observed temperature of the nuclear quadrupole system was estimated to be 3 mK by using Curie law in comparison with a signal strength at thermal equilibrium with the lattice.

The relaxation times of nuclear quadrupole system of $^{27}$Al in ruby were measured at two NQR frequencies of 356 kHz and 712 kHz after enhancement of the signal by demagnetization from 2 kG. As the mixing time between the electron and the nuclear spin systems was less than several hundred milliseconds and relaxation times were much longer, one can consider that the coupling between electron and nuclear spin systems is strong and that the temperatures of these two systems are always equal at zero field. Therefore one can measure the temperature of electron dipole system by monitoring NQR signal. At zero field the ground states of Cr$^{3+}$ are $|\pm 3/2\rangle$ and actually there is no population at the states $|\pm 1/2\rangle$. Therefore strong coupling between nuclear and electronic system was unexpected. Probably there is a small mixing of $|\pm 1/2\rangle$ states by terms of the spin Hamiltonian which do not commute with D-term. The relaxation times $\tau$ measured at 712 kHz are plotted in figure 3. Those measured at 356 kHz showed the same behaviour. The variation of $\tau$ with the bath temperature $T$ shows better fitting with $\exp(\Delta/kT)$ than $T$-law, which suggests Orbach process /2/ of electron spin system through the upper levels $|\pm 3/2\rangle$. The value $\Delta/k$ determined from the straight line in figure 2 is 700 mK, while the zero field splitting between the state $|\pm 3/2\rangle$ and $|\pm 1/2\rangle$ is 550 mK. The consistency between these two values is unfortunately not so good.

At low temperatures the isolation between the nuclear spin system and the lattice was found to be very good. Therefore one can expect to cool the nuclear spin system of $^{27}$Al in ruby by the following process. First, the nuclear spin system is cooled by means of dynamic nuclear polarization for a high magnetic field parallel to c-axis. Second, the nuclear spin system is further cooled by demagnetization down to the crossing point B in figure 2. There is a possibility of nuclear ordering in the laboratory frame in the presence of an external magnetic field. One can have two more possibilities of nuclear ordering at the crossing point A and at zero field. In this experiment the precise orientation of a crystal is very important, otherwise additional splittings appear at points A and B.

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References

/1/ As for the energy levels of spin in ruby, see for example Brodbeck, C.M., Lee, S. and Niebur, H.H., Phys. Rev. B 10 (1974) 844 and references therein