About nuclear spin kinetics in solid ^{3}He at magnetic field

D.A.Tayurskii [a,b,1], H.Suzuki [a],

[a] *Physics Department, Kanazawa University, Kanazawa, 920-1192, Japan*
[b] *Physics Department, Kazan State University, Kazan, 420008, Russia*

Abstract

It is shown that the nuclear spin system of solid ^{3}He in paramagnetic phase can not be divided into two almost independent subsystems (the Zeeman reservoir and the exchange reservoir) in case when the Zeeman energy exceeds the heat energy. The introduced representation about spin excitons in nuclear system of solid ^{3}He at a rather high magnetic fields allows to eliminate the reasons for the appearance of strong thermodynamic coupling between subsystems. The preliminary calculations give the evidence that an effective cooling of solid ^{3}He nuclear spin system can be achieved at NMR saturation and show that important information about the validity of taking into account the spin-spin interactions of different nature can be obtained from nuclear spin lattice relaxation measurements at these conditions.

Key words: solid ^{3}He; NMR; spin kinetics; multiple spin exchange

The magnetic properties of solid ^{3}He have been under intensive studying during many years [1], [2], [3], [4] and a big progress has been achieved in the understanding of magnetic ordered phases. At the same time there were no such investigations for paramagnetic phase. Probably it is connected with the fact that due to the most strong spin-spin interactions - exchange and multiple exchange interactions between nuclear spins [3] - the NMR lineshape is extremely narrowed and it should not be any resonance frequency shift in the magnetically disordered state. In this work we show that investigations of nuclear spin kinetics of solid ^{3}He in paramagnetic phase at a rather high magnetic fields can provide an interesting physical information.

1. Spin excitations

The Hamiltonian for nuclear spin system of solid ^{3}He in external magnetic field $\mathbf{H}_0$ directed along z-axes can be written in quite general form as:

$$H = H_Z + H_{ss} \tag{1}$$

where

$$H_Z = \gamma_n \hbar \sum_j I_j^z H_0 \tag{2}$$

represents the Hamiltonian of the Zeeman interactions of spins whose gyromagnetic ratio is denoted as γ_n. The Hamiltonian of spin-spin interactions H_{ss} may include usual exchange interactions between spins, multiple spin exchange interactions and dipole-dipole interaction although the strength of the latter is very small. Namely the exchange energy is of order 1 mK whereas the dipole energy ia about 10^{-4} mK. The explicit form of H_{ss} is not important now and can be found in literature.

We are interested here in studying only the paramagnetic phase of solid ^{3}He. It denotes that temperatures above 1 mK should be considered. At magnetic fields well above 2 T the Zeeman energy exceeds all other magnetic energies as well as the heat energy $\frac{\gamma_n \hbar H_0}{k_B T} >> 1$ so the ground state of the spin system corresponds to the alignment of all spins along external magnetic field direction. Any excited state can be considered in

[1] E-mail: dtayursk@mi.ru, [a]present address

terms of some elementary spin excitations. They are not magnons in full sense because their energy is determined mostly by the Zeeman energy. Spin-spin interactions lead to the appearance of an energy zone for such excitations. When the condition $\frac{\gamma_n \hbar H_0}{k_B T} >> 1$ is satisfied the number of these spin excitations is small and they can be considered as non-interacting bosons. The average energy of spin excitons is equal to

$$\varepsilon = \hbar(\gamma H_0 + J_0) \tag{3}$$

where J_0 has the sense of some mean-field and depends on the nature of spin-spin interactions as well as lattice symmetry.

2. Thermodynamics of spin system

It is very well known success of the spin temperature concept in magnetic resonance description. Usually two temperatures - the Zeeman temperature and the spin-spin temperature - are introduced as the thermodynamics parameters conjugative to the Zeeman energy (H_Z) and the energy of spin-spin interactions (H_{ss}) because in the high temperature limit ($\frac{\gamma_n \hbar H_0}{k_B T} << 1$) the subsystems described by the Hamiltonians H_Z and H_{ss} are statistically independent. The latter denotes that one can change the state of one subsystem (for example, the magnetization of system or the Zeeman energy) without changing the state of the second. But at low temperatures this independence disappears and a strong thermodynamic coupling between subsystems appears. The reasons of this coupling appearing as well as the possible choices of thermodynamic parameters were investigated in [5], [6], [7] for the case of paramagnetic solids with dipolar interactions between spins.

Here we apply the approach developed in [5], [6], [7] for investigations of nuclear spin kinetics of solid ^{3}He in paramagnetic phase. The NMR saturation and nuclear spin-lattice relaxation in solid ^{3}He can be described in the terms of above spin excitations. The interaction with radio-frequency field leads to creation (annihilation) of a spin exciton and annihilation (creation) of a photon. The probability distribution of such a process is given by the normalized NMR lineshape. So the spin excitons with the energy

$$\varepsilon_{max} = \hbar(\gamma H_0 + M_1) \tag{4}$$

are created with the maximal probability. Here M_1 stands for the first moment of NMR lineshape. The values of M_1 and J_0 are essential different. It is mostly easy to see in the case of isotropic exchange interaction which gives no any contribution to the first moment of NMR lineshape but produce non-zero molecular field. Such an energy disbalance leads to the appearing of very strong thermodynamic coupling between magnetization of system and the energy of spin-spin interactions because every elementary act of the resonant absorption of a photon has to be accompanied by the energy transfer of order $J_0 - M_1$ to the subsystem of spin-spin interactions. In the similar manner the interactions between nuclear spins of ^{3}He with other degrees of freedom (phonons, vacancy waves, tunneling excitations) can be considered. The only difference is the dependence of the corresponding lineshape (probability distribution) on the wave vector of spin exciton $\mathbf{k}$ and the first moment in Eq. 4 should be written as $M_{1\mathbf{k}}$. Again the statistical independence of the Zeeman reservoir and the exchange reservoir considered, for example, in [1], [2] is broken and the times of nuclear spin-lattice relaxation depend strongly on difference between J_0 and $M_{1\mathbf{k}}$.

Our calculations show that when the condition $\frac{\gamma_n \hbar H_0}{k_B T} >> 1$ is satisfied the saturation of NMR line can lead to the essential cooling of the whole spin system of solid ^{3}He. For example, the steady-state solution of the obtained kinetic equations [8] gives the final value of spin temperature

$$T \sim \frac{J_0}{k_B} exp \frac{\gamma_n \hbar H_0}{k_B T} << T_0 \tag{5}$$

which is very low compared to the initial one T_0.

Also it follows from our calculations [8] that the values of nuclear spin relaxation becomes very sensitive to the nature of spin-spin interactions as well as the lattice dimension and geometry through the dependence of difference $J_0 - M_{1\mathbf{k}}$ on spin exciton wave vector $\mathbf{k}$. So the nuclear spin relaxation measurements for bulk solid ^{3}He as well as for 2D solid ^{3}He films at the condition $\frac{\gamma_n \hbar H_0}{k_B T} >> 1$ can give essential information about the role of different types of spin-spin interactions in solid ^{3}He magnetism.

References

[1] P.M.Richards, Phys. Rev. **137** (1965) A1327.

[2] R.A.Guyer, R.C.Richardson, I.I.Zane Rev. Mod. Phys. **43** (1971) 532.

[3] M.Roger, J.H.Hetherington, J.M.Delrieu, Rev. Mod. Phys. **55** (1983) 2.

[4] M.C.Cross, D.S.Fisher, Rev. Mod. Phys. **57** (1985) 881.

[5] B.I.Kochelaev, D.A.Tayurskii, Sov. Phys. Solid State **30** (1988) 1769.

[6] D.A.Tayurskii Sov. Phys. Solid State **30** (1988) 1995, *ibid* **31** (1989) 1890.

[7] D.A.Tayurskii, Physica Status Solidi B **152** (1989) 645.

[8] D.A.Tayurskii, H.Susuki, to be published.