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^{11}B-NMR Study of SmB$_6$ under Pressure

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We present first experimental results of ^{11}B-NMR of SmB$_6$ under applied pressure. From measurement of nuclear spin–lattice relaxation time (T_1) we find that with applied pressure the value of activation gap E_g is decreasing. This decrease is larger than in case of other experimental techniques. We suppose that the enhancement of $1/T_1$ in temperature range 20–100 K with applied pressure reflects not only a suppression of hybridization gap, but also changes in spin correlations.

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1. Introduction

The intermetallic compound SmB$_6$ is one of the most famous compounds in terms of the physics of intermediated valence state, heavy fermion systems and the Kondo insulators. The Kondo insulator systems are characterized by a small gap in density of states close to the Fermi level. In SmB$_6$ the narrow gap arises from the hybridization between the narrow $4f$ and conduction band ($5d$). The ground state of Sm in SmB$_6$ is mixture of Sm^{2+} ($4f^6$ state) and Sm^{3+} ($4f^5 5d$) ions in the ratio 0.3 to 0.7, which gives an effective $4f$ valence of about 2.7 [1]. The properties of this system are governed by several energy scales. In temperature range from ≈ 70 K to 15 K the properties are characterized by hybridization gap $E_g \approx$ 10–20 meV [2] and the system is semiconducting. Between 15 K and 5 K an in-gap band with activation energy $E_d \approx$ 3–5 meV (situated below the conduction band) was observed by several experimental measurements [3–5]. Several models of in-gap states have been proposed [6–8], however the nature of the in-gap states is still under discussion. Below about 5 K the electrical conductivity is constant due to small conductivity channel in the E_d band. Experiments under applied pressure show that the insulating gap closes at pressure ≈ 40 kbar and above ≈ 60 kbar long range magnetic order appears [2, 9].

2. Experimental

In this paper we present first experimental results of ^{11}B-NMR studies of SmB$_6$ under applied pressure. The single crystal of SmB$_6$ was prepared using the floating zone melting technique. The ratio between resistivity at liquid helium and room temperature is 4 orders of magnitude. In order to increase penetration of radio frequency signal to the sample as well as to avoid the uncertainty of magnetic field due to demagnetization effect, we crushed the single crystal into fine powder. The ^{11}B-NMR measurements were carried out by using spin-echo technique with a phase-coherent pulsed spectrometer. The measurements of nuclear spin–lattice relaxation time were performed in temperature range from 1.6 K to 250 K. For measurements under pressure 16.5 kbar we used a piston-cylinder-type pressure cell. Pressure was examined using measurement of resistivity of manganin wire. As pressure medium we used Daphne oil 7373.

The crystal structure of SmB$_6$ is simple cubic CsCl-type with Sm ions located at the corner sites and boron octahedron at the body center of cube. In case of ^{11}B ($I = 3/2$) NMR spectrum we observed for powder sample three peaks with quadrupole splitting of ν_Q = 570 kHz. Within experimental uncertainty, quadrupole splitting is independent of temperature and applied pressure up to 16.5 kbar.

3. Results and discussion

Figure 1 shows the $1/T_1$ as a function of temperature for different applied pressures. For comparison we show

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also data of first NMR measurements at ambient pressure by Takigawa et al. [10]. Our data are in good agreement with that of Takigawa above 20 K and difference below 20 K comes from fact that in this temperature range the $1/T_1$ is sample dependent [10]. The hyperfine interaction of ^{11}B moments with $4f$ electrons of Sm is dominant in relaxation process at temperatures above 20 K and leads to an activation type of temperature dependence. On the contrary to high temperature region the relaxation rate at low temperatures is strongly field dependent [1]. In this paper we are interested in temperature range above 20 K. In our experiment we observed an increase of $1/T_1$ at applied pressure in temperature range between 20 K and $\approx$ 100 K (see Fig. 1). Using a simple approximation $\sim \exp(-E_g/2k_BT)$ [10] we received values of E_g equal to 7.5 meV (at 1 bar, solid line) and 5.5 meV (at 16.5 kbar, dashed line). The fitting errors are 1.9% at 1 bar and 3.7% at 16.5 kbar, which are much smaller than change of $1/T_1$ (around 20%) in the temperature range 20–100 K. The value of E_g at 1 bar is in good agreement with other NMR experiments [1, 10]. However, the decrease of E_g with increasing applied pressure is quite large in comparison with other experimental methods [2, 9]. One of the possible explanations is that pressure brings about not only the decrease of E_g, but also changes in spin correlations. Since the system approaches magnetic order phase with increasing pressure as indicated by previous reports [9, 11], low energy spin fluctuations which contribute to the T_1 relaxation may be enhanced in the low temperature region.

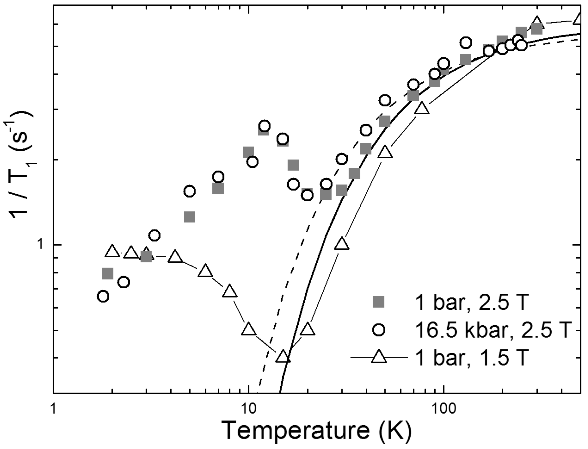

Fig. 1. Temperature dependences of the ^{11}B nuclear spin–lattice relaxation time in SmB_6 at ambient pressure (full squares) and under pressure of 16.5 kbar (open circles). The solid (1 bar) and dashed (16.5 kbar) lines show a fit of data using exponential dependence $\sim \exp(-E_g/2k_BT)$ [10]. For comparison we insert data (open triangles) from Ref. [10].

Another interesting feature is that $1/T_1$ tends to decrease compared with the data at ambient pressure, in contrast to the pressure effect seen below 100 K. Similar behavior is observed in some Ce-based heavy fermion systems [12, 13], namely $4f$ local moments become more itinerant with pressure, which seems opposite to the usually expected pressure effect for the Sm-based compounds. However, this decrease in $1/T_1$ at high temperatures is very small and therefore it is necessary to confirm this feature by measurements at higher pressures.

To find the critical pressure of long range magnetic order as well as the semiconductor–metal transition, experiments at higher pressures using anvil-type pressure cell are needed.

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