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Liquid-He-free 10-T superconducting magnet for neutron scattering

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Abstract. A new type of superconducting magnet, which is directly cooled by two 4-K GM cryocoolers (i.e. liquid-He-free), has been developed for neutron-scattering experiments. The magnet consists of a split pair of a (Nb, Ti)$_3$Sn inner coil and a NbTi outer coil. The gap between the coils is 29 mm, and the upper and lower coils are supported by three rings made of Al alloy (4.5, 7.5, and 8 mm in thickness) and a plate of Al alloy (42.5° in angle). The total thickness of the Al alloy in the neutron path is 52 mm, and the transmission of the beam is about 60% for neutrons with 20 meV. The room-temperature bore is 51 mm in diameter, and in this bore one of the sample-cooling systems (4-K cryocooler or liquid-He-free dilution refrigerator) is inserted. The maximum field of 10 T is very stably obtained. Some results on the magnetism of strongly correlated electron systems obtained with this cryomagnet are presented.

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Strongly correlated electron systems have presented much interesting novel physics. Applying a magnetic field in these systems further induces dramatic changes of their physical and magnetic properties. Manganites show an insulator to metal transition under a magnetic field, called colossal magnetoresistance (CMR), accompanying complex magnetic phase transitions. In heavy-fermion systems peculiar metamagnetic transitions occur under a high magnetic field. Antiferromagnetism of high-T_c superconducting materials induced by a strong magnetic field is particularly interesting. To study the magnetism of these systems, neutron-scattering experiments under a high magnetic field of 10-T class are indispensable.

For neutron-scattering experiments under high magnetic fields, however, there are several technical difficulties. To keep the incident and scattered beam paths over a wide angle in the horizontal plane, a split-pair magnet is required. This inevitably lowers the maximum central field. The materials which support the upper and lower coils substantially reduce the transmission of neutrons. Strong stray fields from the split-pair magnet will cause serious problems in the interaction with various magnetic parts of the spectrometers. The interaction of the stray field with the massive shielding materials may induce huge and dangerous forces.

Superconducting magnets are conventionally cooled by liquid He. However, there are several shortcomings in this type. The cryosystems to preserve liquid He and to keep the magnet cool are rather complex. When a quench of the magnet occurs in the 10-T class magnet, sudden evaporation of a large amount of liquid He may be dangerous. Furthermore, the liquid He which needs to run a large cryomagnet of this class is very costly. Recently, liquid-He-free type, i.e. cryocooler-cooled superconducting magnets have become familiar in physical researches. For this advance, developments of high-performance cryocoolers and current leads using a high-T_c superconductor were essential. The superconducting magnets of this type have advantages for the points mentioned above; that is, the system is compact, safe, and easy to handle, and the running cost is low. The only problem is that the cooling power and efficiency to keep the magnet at low temperatures are still low compared to the case of liquid He. This problem, however, will be improved further in the future.

Here the cryocooler-cooled-type superconducting magnet of the 10-T class has been applied to neutron scattering for the first time. This new magnet has been operated very stably on triple-axis spectrometers.

1 Specifications

The system is shown in Fig. 1. This cryomagnet consists of a cryostat, a split-pair magnet of (Nb, Ti)$_3$Sn and NbTi coils, Bi(2223) bulk current leads, two 4-K GM cryocoolers, GFRP (glass fiber reinforced plastics) pipes to support the coil system, and so forth. The outer diameter of the system is 600 mm, the height is 760 mm, and the total weight is 280 kg. The room-temperature bore is 51 mm in diameter.

The magnet is a set of the (Nb, Ti)$_3$Sn inner coil and the NbTi outer coil. The upper and lower coils are of the same size; i.e. this split-pair magnet is symmetric. The gap for the neutron beam is 29 mm at the position of the room-

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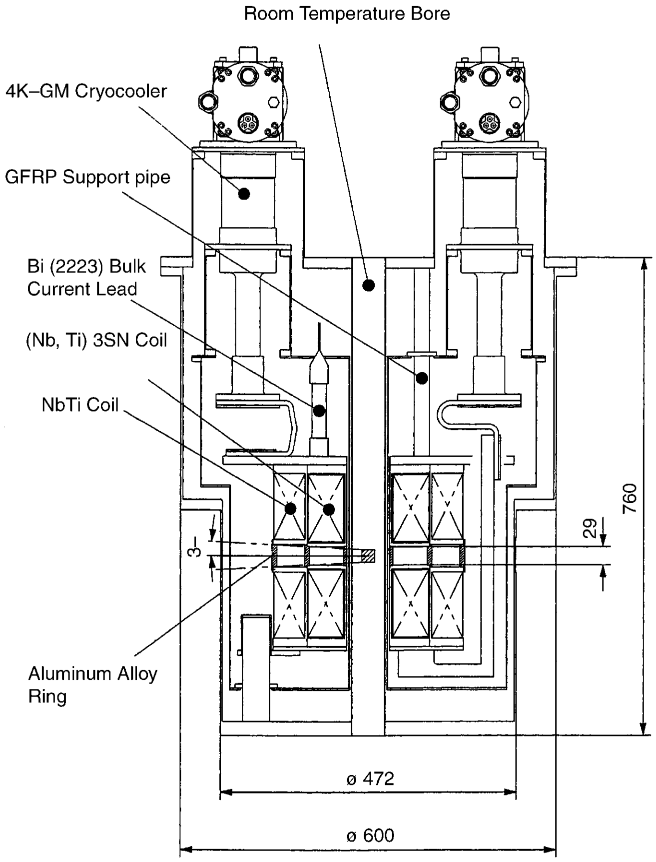

Fig. 1. Vertical sectional view of the cryocooler-cooled 10-T split-pair magnet

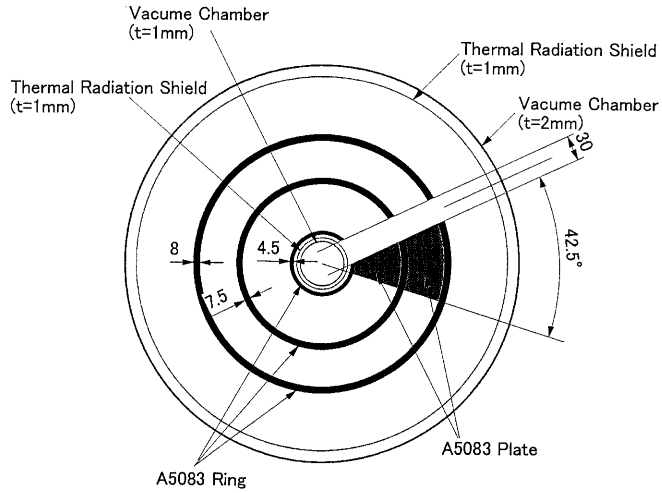

Fig. 2. Horizontal sectional view at the coil gap

temperature bore, and the magnet can be inclined with an angle of 3° for crystal-axis alignments. The further details of the coils are as follows: the (Nb, $Ti)_3Sn$ coil – the inner diameter 78 mm, the outer diameter 191 mm, the height 106 mm, the gap between the upper and lower coils 45 mm, the maximum field 12.01 T; and the NbTi coil – the inner diameter 201 mm, the outer diameter 300 mm, the height 104 mm, the gap 50 mm, the maximum field 5.82 T. The critical temperature of these coils is estimated at 6.3 K.

The axial compression force between these upper and lower coils is about 765 kN ($\sim 76.5 \times 10^3$ kgf). This force is supported by three Al alloy (A5083) rings and a plate of 42.5° in angle, as shown in Fig. 2. Thus there exist only Al alloys in the gap. The total thickness of these Al alloys, including those of the thermal radiation shield and of the vacuum chamber, is 52 mm. A higher transmission can be obtained by the use of a window for the incident beam (the width is 30 mm and the height is 29 mm) as shown in Fig. 2. In this case, the total thickness of the Al alloys is 32 mm.

The Bi(2223) high-T_c superconductor was used for the bulk current leads to minimize thermal conduction. The inner diameter of this lead is 20 mm and the outer diameter is 23 mm. The length is 140 mm. Each end of these current leads is an electrode made by the Ag plasma spray method. A contact resistance between the Bi(2223) lead and the Ag electrode is below $10^{-6}\ \Omega$ at 77 K.

The cryocoolers used are two heavy-duty two-stage GM cycle cryocoolers (the 1st stage 30 W and the 2nd stage 0.9 W). One of them cools the upper coil, and the other cools the lower coil. The temperature of the 1st stage of these cryocoolers almost saturates at around 35 K in about 8 h, and that of the 2nd stage reaches 3.3 K in about 52 h.

After the cooling, the field of 10 T was attained with the current of 151 A. Typically the current is increased to 151 A at a sweep rate of 0.175 A/s; accordingly the excitation up to 10 T is attained within 15 min. The operation at 10 T shows that the system is very stable at this maximum field over a long time. The magnetic field is stabilized better than 0.01%. The field homogeneity is better than 0.4% for 10-mm dsv (diameter spherical volume). In a test in which the cryocoolers were stopped at 10 T, the magnet was quenched after 10 min passed – at around the critical temperature of 6.3 K. Then this magnet (protected by diode circuits) warmed to about 40 K. When the cryocoolers were restarted the magnet was cooled again to 3.5 K in 3.5 h.

2 Neutron scattering

This magnet is being used on the triple-axis spectrometers TAS-2 (at the thermal guide) and LTAS (at the cold guide) in the JRR-3M. The stray field at the side surface of the cryostat is about 0.5 T, and that field at the bottom is around 1 T. These fields drop to a 0.01-T (100-G) level at 1 m from the coil center. The goniometer just below the magnet was therefore fully remade using nonmagnetic materials of stainless steels and brasses. Stepping motors of this goniometer were also replaced by ultrasonic motors. Furthermore, several parts of the spectrometer were changed to non-magnetic ones. The monochromator shielding and the analyzer and detector shieldings were reconstructed using stainless steels.

The transmission of neutrons of around 20 meV is about 60% when the beam passes through the whole Al alloys placed in the beam path. This is enough to get elastic scattering intensities from crystal and magnetic structures. Inelastic scattering experiments are also possible. When the window for the incident beam is used, the transmission becomes higher at about 75%.

In the room-temperature bore, one of the sample-cooling systems is set – a 4-K cryocooler or a dilution refrigerator. This dilution refrigerator is also a liquid-He-free type, and was made in the course of the development of 'mK cryocoolers' by Koike et al. [1]. The refrigerator for this magnet can cool the sample to 50 mK. With these instruments, experiments under high magnetic fields and at very low temperatures are now easily performed.

Researches are concentrated on magnetic transitions under high magnetic fields of strongly correlated electron systems. As an example, the result of the high-T_c superconducting material $La_{2-x}Sr_xCuO_4$ ($x = 0.12$) is shown [2]. In these copper-oxide superconductors dynamical spin fluctuations are definitely observed at incommensurate reciprocal positions, and thus it has been considered that the magnetic interactions are crucial to their superconductivity. Recently, however, at around $x = 0.12$ static (or quasistatic) long-ranged antiferromagnetic correlations were found coexisting with the superconductivity. Since then, this antiferromagnetism has attracted great attention in connection with the stripe ordering of spins and charges. To investigate these features further the antiferromagnetic correlations of the system were measured under fields up to 10 T applied perpendicular to the CuO_2 plane. Under these magnetic fields, the superconductivity of this sample is severely suppressed; on the other hand, the static magnetic correlations are considerably enhanced by as much as 50% of that at 0 T (Fig. 3). The result obtained can be interpreted as the suppression of the dynamical spin fluctuations – the field increases the weight of the spin fluctuations with low energies, which are observed as the quasistatic magnetic correlations. As another mechanism the antiferromagnetic ordering induced by vortices is pointed out. After our experiment some work has been performed on similar systems. These experiments will open new windows in understanding of the correlations between the magnetism and the superconductivity.

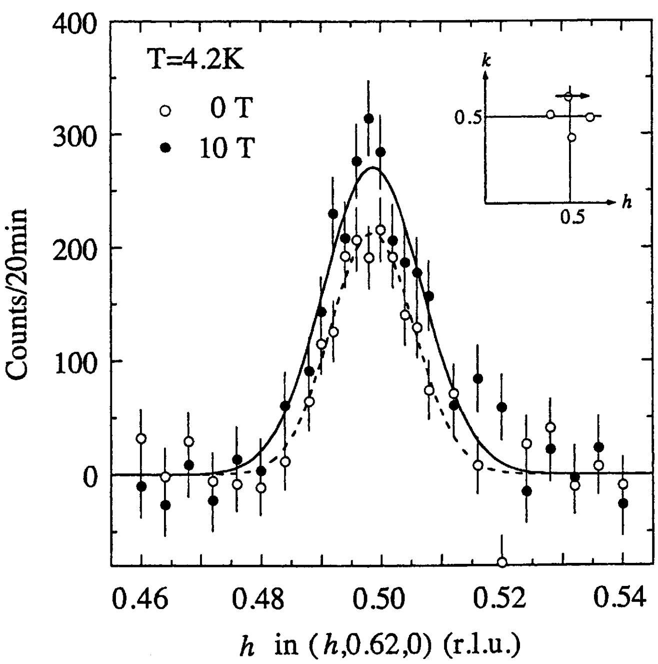

Fig. 3. Intensities of the incommensurate antiferromagnetic peak of $La_{2-x}Sr_xCuO_4$ ($x = 0.12$) measured at 4.2 K

Up to now, several other experiments have been performed using this magnet with the liquid-He-free cryocooler. Metamagnetism of the typical heavy-fermion system $CeRu_2Si_2$ was studied. The experiment revealed that the antiferromagnetic spin fluctuations in the heavy-fermion state are gradually destroyed by a magnetic field and the ferromagnetism is induced dramatically at the metamagnetic transition of 7.7 T. There, a divergent enhancement of dynamical (quasielastic) ferromagnetic correlations were observed for the first time [3]. In the Haldane systems NDMAZ ($Ni(C_5H_{14}N_2)_2N_3(ClO_4)$) and NDMAP ($-(PF_6)$) magnetic transitions have been studied. For NDMAP an antiferromagnetic ordering was observed under the field of 6 T at 0.2 K when the Haldane state was collapsed. Magnetic excitations in the antiferromagnetic state are also observed [4]. Novel magnetic orderings were found in DyB_2C_2 under fields. The results clearly indicate that these magnetic structures are correlated with quadrupole ordering. A complex magnetic phase diagram was clarified [5]. These and other new findings have been or will be published elsewhere.

3 Summary

A cryocooler-cooled split-pair superconducting magnet has been developed for neutron-scattering experiments. The maximum field of 10 T is very stably obtained over a long period. With the experience of this 10-T magnet, the same type of magnet with a higher field (the target is 15 T) is now under construction.

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Note added in proof

Recently we have changed the material of the Al alloy rings, which support the upper and lower coils, from A5083 to A6061. The thicknesses of these three rings were reduced to 3, 4, and 4 mm from 4.5, 7.5, and 8 mm. The transmission was increased to about 75% from 60% for neutrons of 20 meV.

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