

Flux pinning property in a single crystal $\text{NdBa}_2\text{Cu}_3\text{O}_y$ superconductor

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Abstract

The critical current density J_c and the apparent pinning potential U_0^* in a single crystal $\text{NdBa}_2\text{Cu}_3\text{O}_y$ superconductor which shows a broad peak effect are investigated by measuring a DC magnetization and its relaxation. The field-induced pinning mechanism does not explain the temperature dependence of peak field B_p and dip field B_d . The experimental results of J_c and U_0^* are compared with the theoretical analysis based on the flux creep-flow model, taking the distribution of the flux pinning strength into account. The number of flux lines in the flux bundle (g^2), the most probable value of pinning strength (A_m) and distribution width (σ^2) are determined so that a good fit is obtained between the experimental and theoretical results. The behavior of these parameters is discussed in correspondence to the disorder transition of flux lines.

Keywords: $\text{NdBa}_2\text{Cu}_3\text{O}_y$ superconductor, Peak effect, Flux creep-flow model, Field-induced pinning, Disorder transition of flux lines.

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1 Introduction

Among high-temperature superconductors, $\text{REBa}_2\text{Cu}_3\text{O}_y$ (RE denotes a rare earth element, RE-123) is one of the most interesting materials to study, as it is considered to be a strong candidate for practical applications. In particular, RE-123 with RE = Nd and Sm fabricated under a low oxygen partial pressure exhibits high T_c and large J_c values [1, 2] than Y-123 superconductors. In single crystal RE-123 superconductors, it has been reported that the critical current density J_c has a broad peak due to the pinning of a low T_c phase in which RE sites are substituted by Ba [3, 4]. There are two proposed mechanisms on the peak effect: one is the field-induced pinning [5] and the other is the disorder transition of flux lines [6].

Although the substituted regions are superconducting at low fields and may not strongly contribute to the flux pinning, those become normal state at high fields and may contribute strongly to the flux pinning. This is the mechanism of the field-induced pinning to explain the peak effect. On the other hand, the increase of J_c with magnetic field is considered to originate from other mechanism in the disorder transition model. In this model, the increase of J_c is attributed to a rearrangement of flux lines so as to fit to randomly distributed pinning centers initiated by the disorder in the flux line lattice. The corresponding movement of flux lines at the rearrangement is considered to be the shear, and a softening of the shear modulus C_{66} is considered to take place at the disorder transition. The softening influences the number of flux lines in the flux bundle, g^2 , since g^2 is proportional to C_{66} .

The flux creep-flow model is useful for an investigation of the pinning property and the corresponding behavior of flux lines, such as g^2 . In this model, another

important parameters used for the characterization as well as g^2 are the most probable value of pinning strength (A_m) and distribution width of pinning strength (σ^2). The detailed explanation of the model and these parameters will be given later.

In this paper, the relation between the apparent pinning potential U_0^* and the critical current density J_c is investigated to find out the mechanism of the peak effect in a single crystal $\text{NdBa}_2\text{Cu}_3\text{O}_y$ superconductor. For this purpose the flux creep-flow model is used and the behavior of the parameters, g^2 , A_m and σ^2 is argued. Then, a discussion is given on the mechanism of the peak effect.

2 Experiment

Specimen was a flux-grown $\text{NdBa}_2\text{Cu}_3\text{O}_y$ single crystal superconductor. The sample dimension was $1.60 \times 1.45 \times 0.65 \text{ mm}^3$ and the critical temperature T_c was 96.0 K, which was determined by temperature dependence of zero-field-cooled (ZFC) and field-cooled (FC) magnetization by a Quantum Design SQUID magnetometer. The magnetization in a magnetic field along the c -axis was measured at different temperatures. The critical current density J_c was estimated from a measured magnetization hysteresis using the Bean model. The irreversibility field was determined by the field at which J_c was reduced to $1 \times 10^6 \text{ A/m}^2$. The E - J characteristic was estimated from a relaxation of magnetization over a range of electric field from 10^{-12} to 10^{-8} V/m and also the apparent pinning potential U_0^* is estimated from a relaxation of magnetization.

3 Flux creep-flow model

The E - J characteristics can be calculated using the flux creep-flow model [7]. The pinning potential U_0 is the important quantity to determine the characteristics and is given by

$$U_0 = \frac{0.835g^2k_B J_{c0}^{1/2}}{(2\pi)^{3/2}B^{1/4}}, \quad (1)$$

where J_{c0} is the virtual critical current density in the creep-free case. Equation (1) holds for a superconductor of thickness d larger than the longitudinal flux bundle size, $L = (Ba_f/2\pi\mu_0J_{c0})^{1/2}$, where a_f is the flux line spacing.

Here, the temperature and magnetic field dependence of the virtual critical current density, J_{c0} , is expressed as

$$J_{c0} = A \left[1 - \left(\frac{T}{T_c} \right)^2 \right]^m B^{\gamma-1} \left(1 - \frac{B}{B_{c2}} \right)^\delta, \quad (2)$$

where A , m , γ and δ are the pinning parameters. It is considered that the flux pinning strength is distributed in practical superconductors. For simplicity, it is assumed that only A in Eq. (2) is distributed in the form:

$$f(A) = K \exp \left[-\frac{(\log A - \log A_m)^2}{2\sigma^2} \right], \quad (3)$$

where A_m is the most probable value, K is a constant determined by the condition of normalization and σ^2 is a constant representing the degree of distribution width.

The E - J characteristics are calculated using the flux creep-flow model with the pinning parameters A_m , m , γ , δ , g^2 and σ^2 , and the critical current density J_c is estimated with the electric field criterion of $E_c = 1 \times 10^{-9}$ V/m. Also, U_0^* is estimated by the relaxation of the DC magnetization. For further details of

the numerical calculation, see [8].

4 Results and Discussion

In Fig. 1, the observed magnetic field dependence of the critical current density J_c is shown in the temperature region of 50 -94 K. The broad peak was observed in the temperature region of 60-88 K. The observed irreversibility field B_i , peak field B_p and dip field B_d at which J_c takes a minimum value are shown in Fig. 2. It is found that the field B_d is almost constant with temperature, while the peak field B_p increases with temperature, takes a maximum at 77.3 K, and then, decreases with increasing temperature. B_p and B_d disappear above 80 K due to the flux creep. If the peak effect originated from the field-induced pinning mechanism, B_d would decrease monotonically with increasing temperature reaching zero at the low T_c phase as shown by the dot line.

In Fig. 3(a), experimental results of field dependences of the apparent pinning potential U_0^* and the critical current density J_c at 40 K, where the peak effect is not observed, are shown. In this case, U_0^* increases with magnetic field in spite of a monotonous decrease of J_c . The theoretical results of U_0^* and J_c are also shown in Fig. 3(a). The parameters used in the theoretical calculation are: $A_m = 9.73 \times 10^8$, $\gamma = 0.87$, $\sigma^2 = 0.01$, $m = 2.05$ and $\delta = 2.0$, and g^2 is assumed to increase with increasing magnetic field, as shown in Fig. 3(b). It is found that the agreement is good between theoretical and experimental results. The monotonous decrease of J_c is simply explained by a monotonous decrease of J_{c0} as in Eq. (2).

Fig. 4(a) shows the results at 77.3 K. U_0^* and J_c increase with magnetic field in

the magnetic field range of 0.2-1.5 T. However, U_0^* decreases in spite of further increase of J_c in the field range of 1.5-2.0 T. Magnetic field dependence of parameters A_m , g^2 and σ^2 obtained so as to get a good agreement, are shown in Fig. 4(b). The other parameters used in this theoretical calculations are: $\gamma = 0.85$, $m = 2.05$ and $\delta = 2.0$. A_m and g^2 increase up to 1.5 T with increasing magnetic field, and then g^2 decreases, in spite of increase of A_m up to 2.0 T, and from 2.0 T, A_m is constant. At 1.5 T, σ^2 has a maximum value.

The enhancement of A_m is directly related to the enhancement of J_c , and hence, can be explained by the both mechanisms. Above 2 T A_m is constant and this is consistent with the decrease of J_c . The change of σ^2 can also be explained by the both mechanisms. In the field region of $B < B_d$, σ^2 is expected to be small, as the distribution of the flux pinning strength has a sharp peak around a small value. In the field region of $B > B_p$, the similar thing take place around a strong pinning force, resulting in a small σ^2 again. In the intermediate region, weakly pinning regions and strongly regions coexist, resulting in a large σ^2 . Hence, the behavior of g^2 is important to specify the correct mechanism.

In the field region of 0.2-1.5 T, g^2 increases with magnetic field. This is consistent with the behavior at 40 K. However, g^2 decreases with increasing magnetic field for 1.5-2.0 T. It is not possible to explain the reduction of g^2 by the field-induced pinning mechanism. The reduction of g^2 means the reduction of C_{66} , i.e., the softening of flux lines. This results show that the disorder transition occurs in the field range between B_d and B_p .

5 Summary

To investigate the pinning mechanism of the peak effect of a single crystal $\text{NdBa}_2\text{Cu}_3\text{O}_y$ superconductor, the behavior of pinning parameters were investigated. The following results are obtained.

1. At 40 K, where the peak effect is not observed, the monotonous decrease of J_c is simply explained by a monotonous decrease of J_{c0} as in Eq. (2). At 77.3 K, the enhancement of A_m is directly related to the enhancement of J_c , and hence, can be explained by the both mechanisms. The peak of σ^2 is also explained by the two mechanisms. The reduction of g^2 can be explained only by the softening of flux lines, which is considered by the disorder transition of flux lines.
2. The field-induced pinning mechanism does not explain the temperature dependences of the peak field B_p and the dip field B_d .
3. From the above reasons, it is concluded that the peak effect originates from the disorder transition of flux lines.

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Fig. 1 Magnetic field dependence of J_c at various temperatures.

Fig. 2 Temperature dependence of B_i , B_p and B_d .

Fig. 3(a) Magnetic field dependence of U_0^* and J_c at 40 K.

Fig. 3(b) Magnetic field dependence of g^2 at 40 K.

Fig. 4(a) Magnetic field dependence of U_0^* and J_c at 77.3 K.

Fig. 4(b) Magnetic field dependence of A_m , g^2 and σ^2 at 77.3 K.

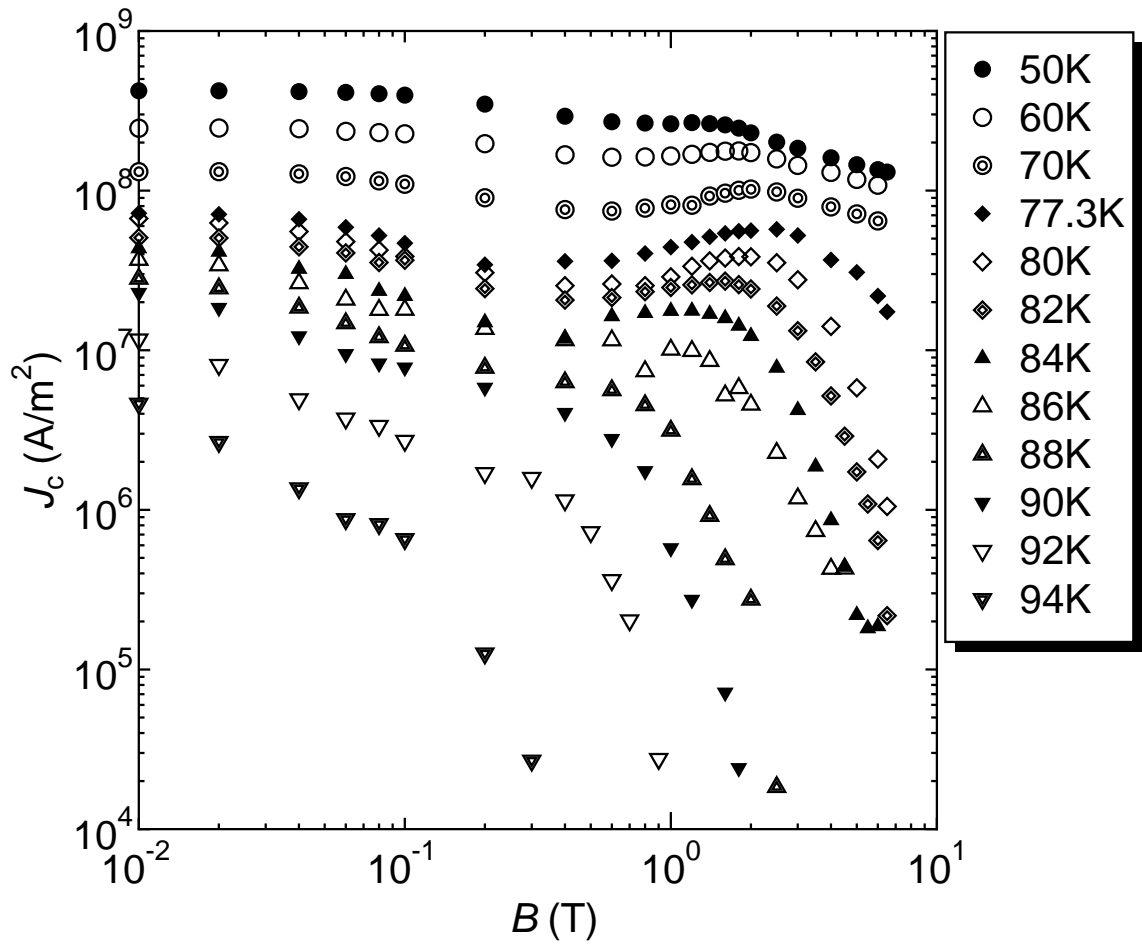


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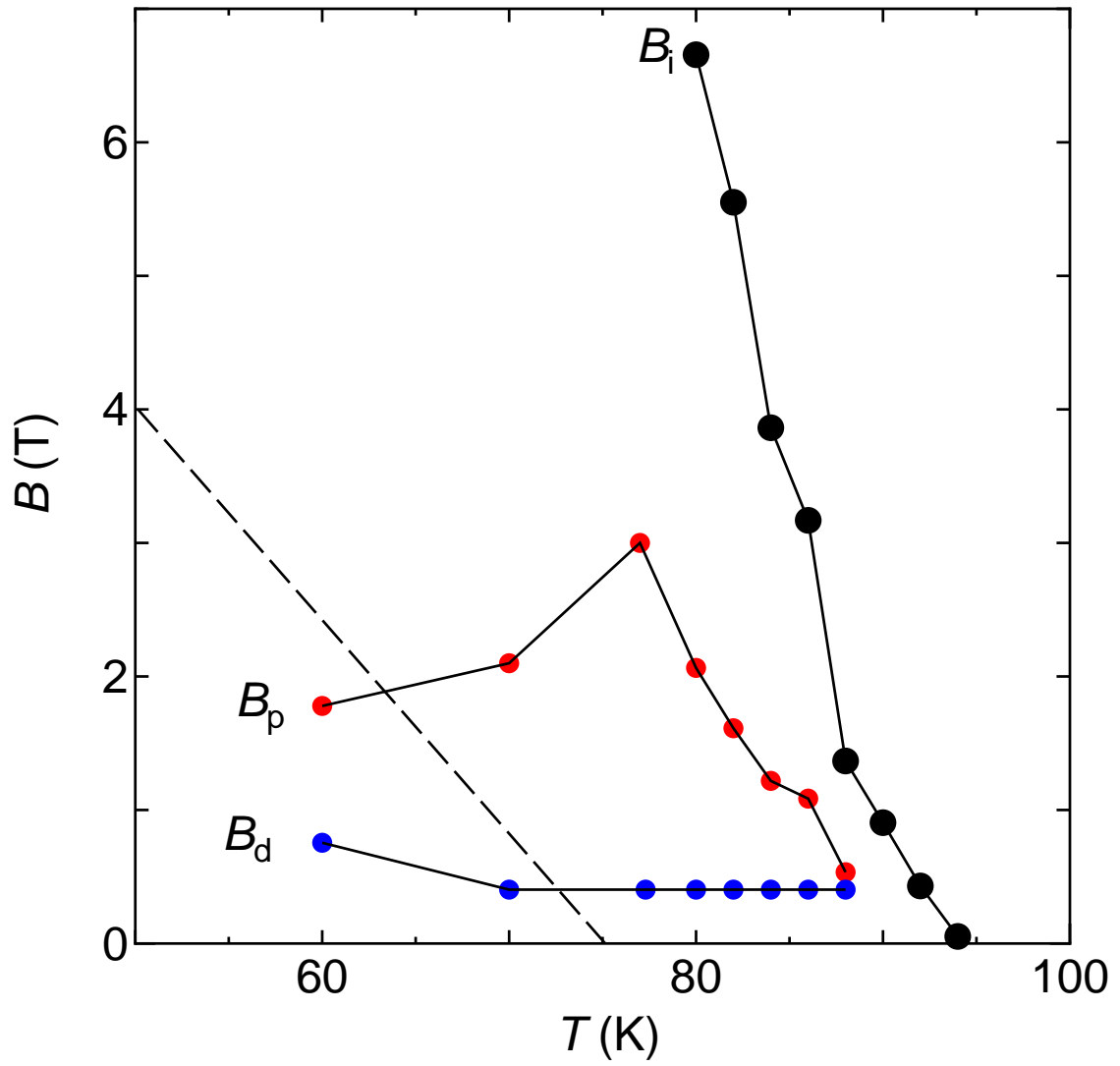


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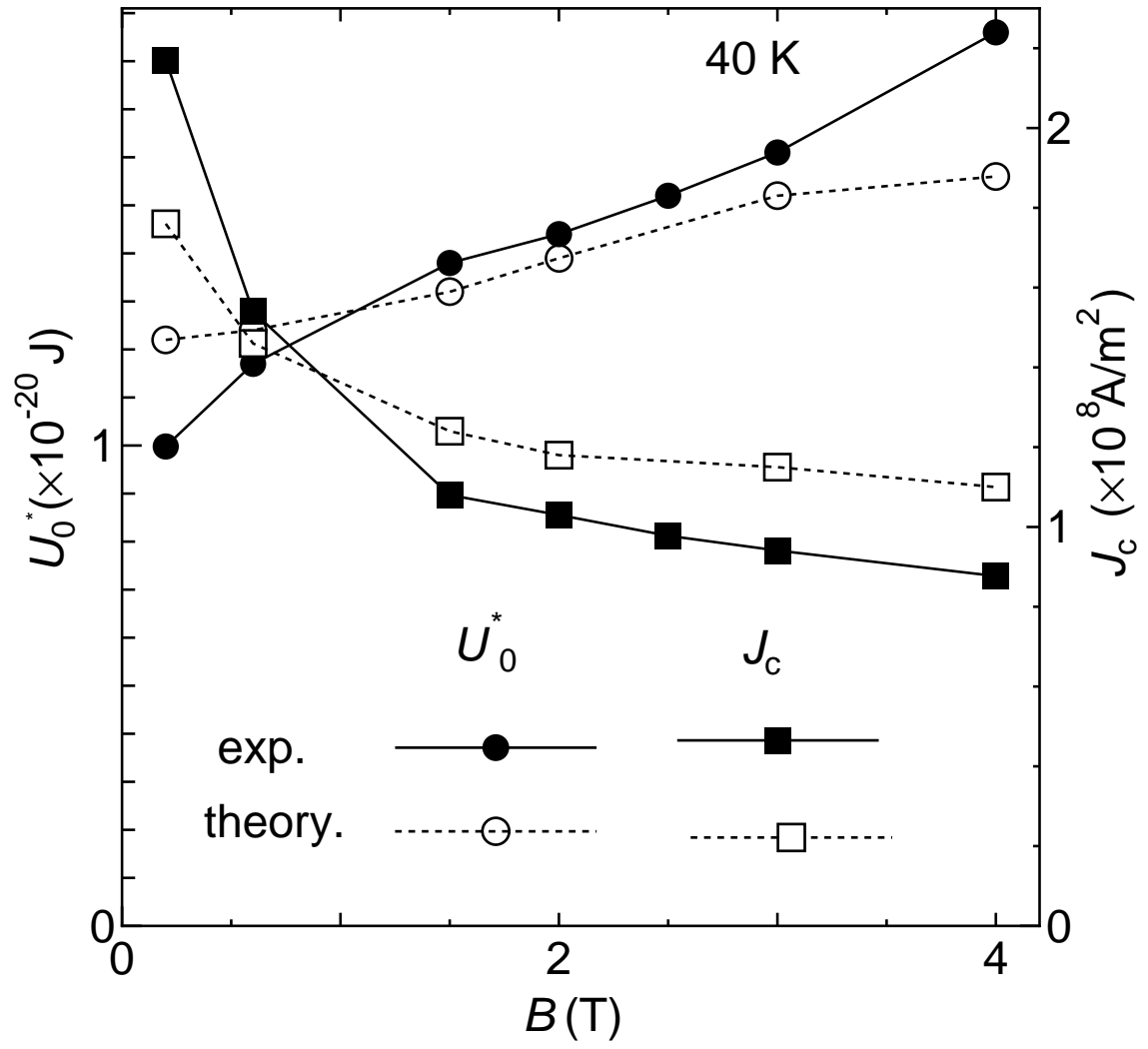


Fig. 3(a): M. N. Hasan *et al.* PCP-10/ISS2004

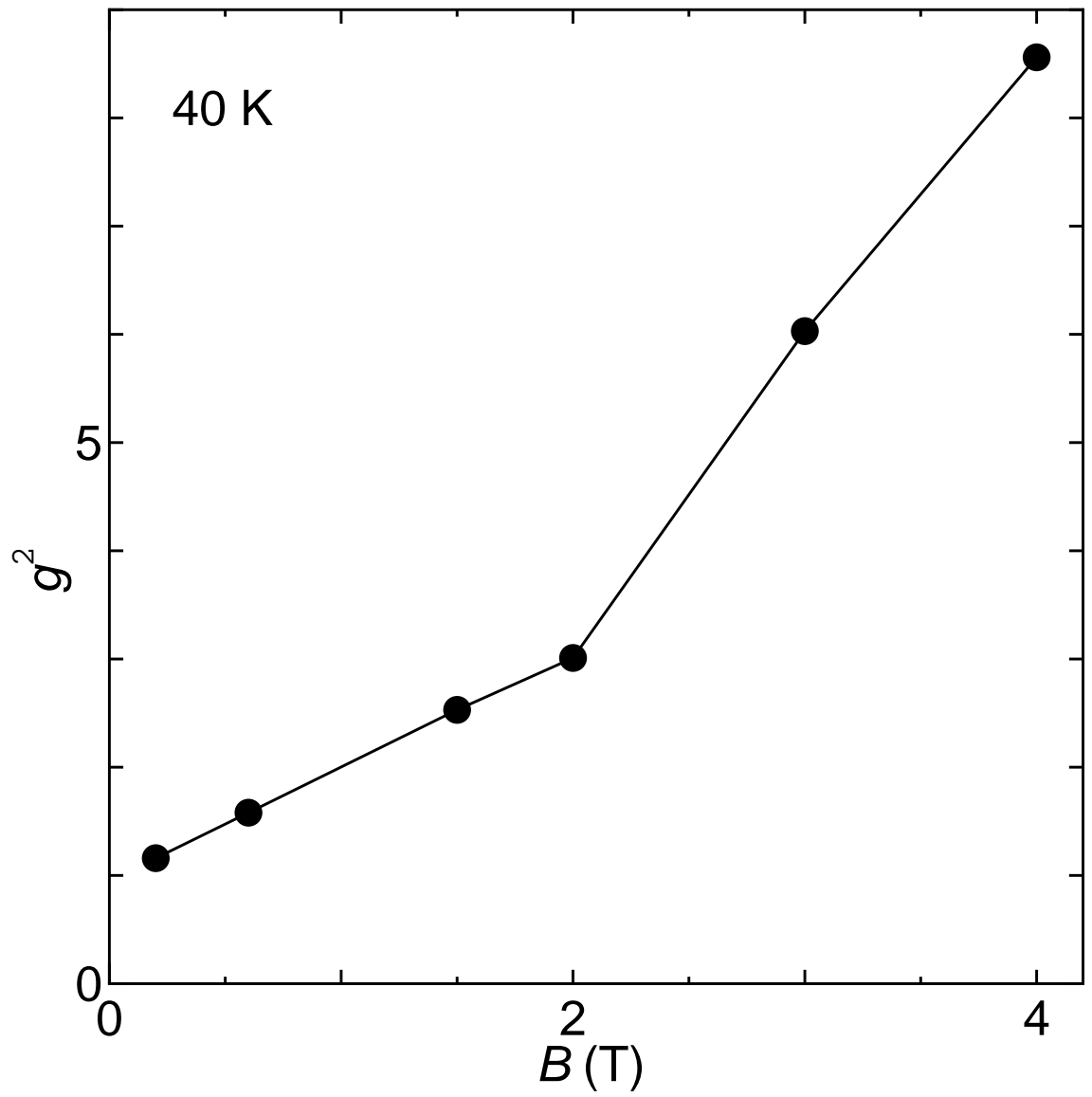


Fig. 3(b): M. N. Hasan *et al.* PCP-10/ISS2004

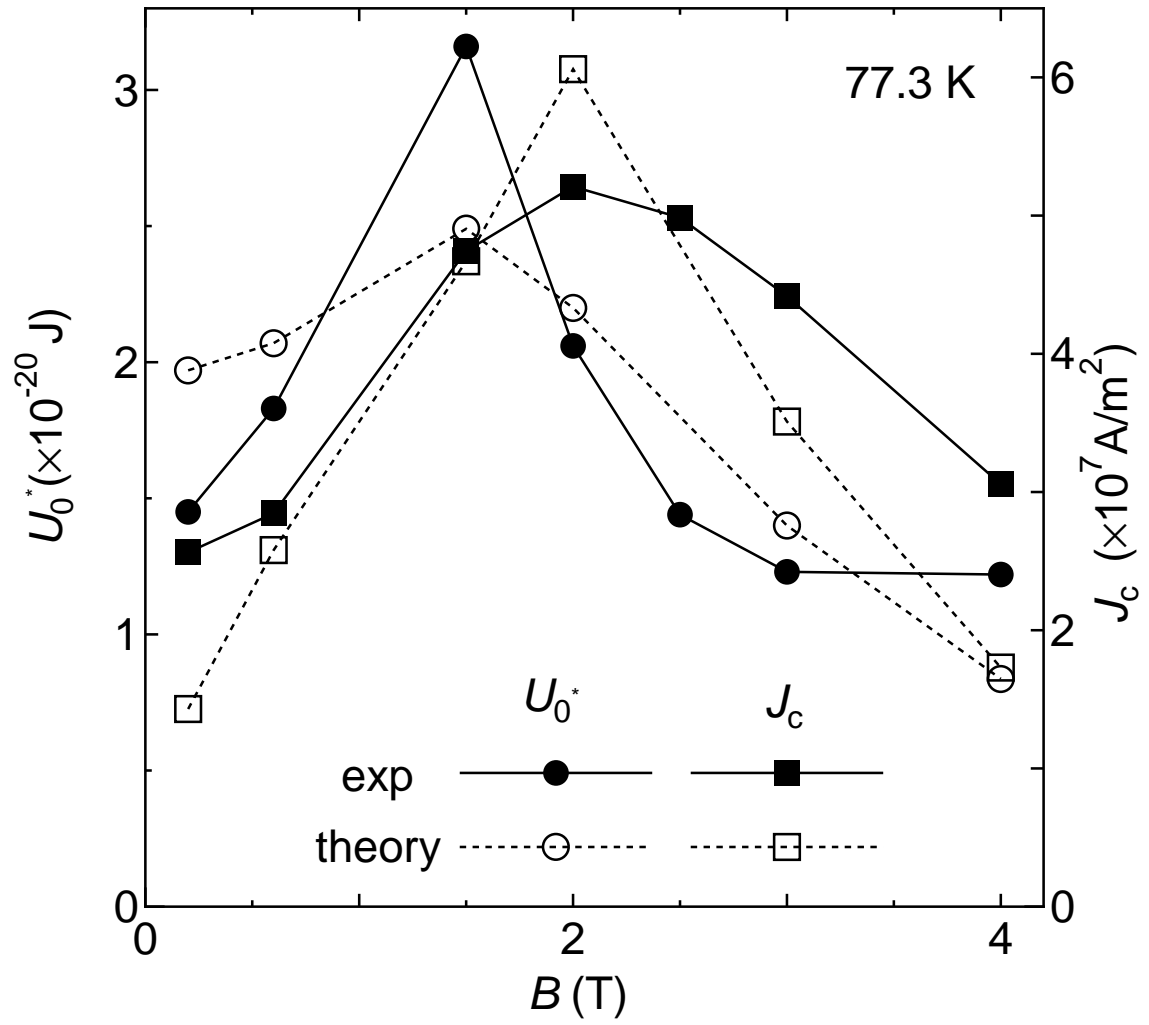


Fig. 4(a): M. N. Hasan *et al.* PCP-10/ISS2004

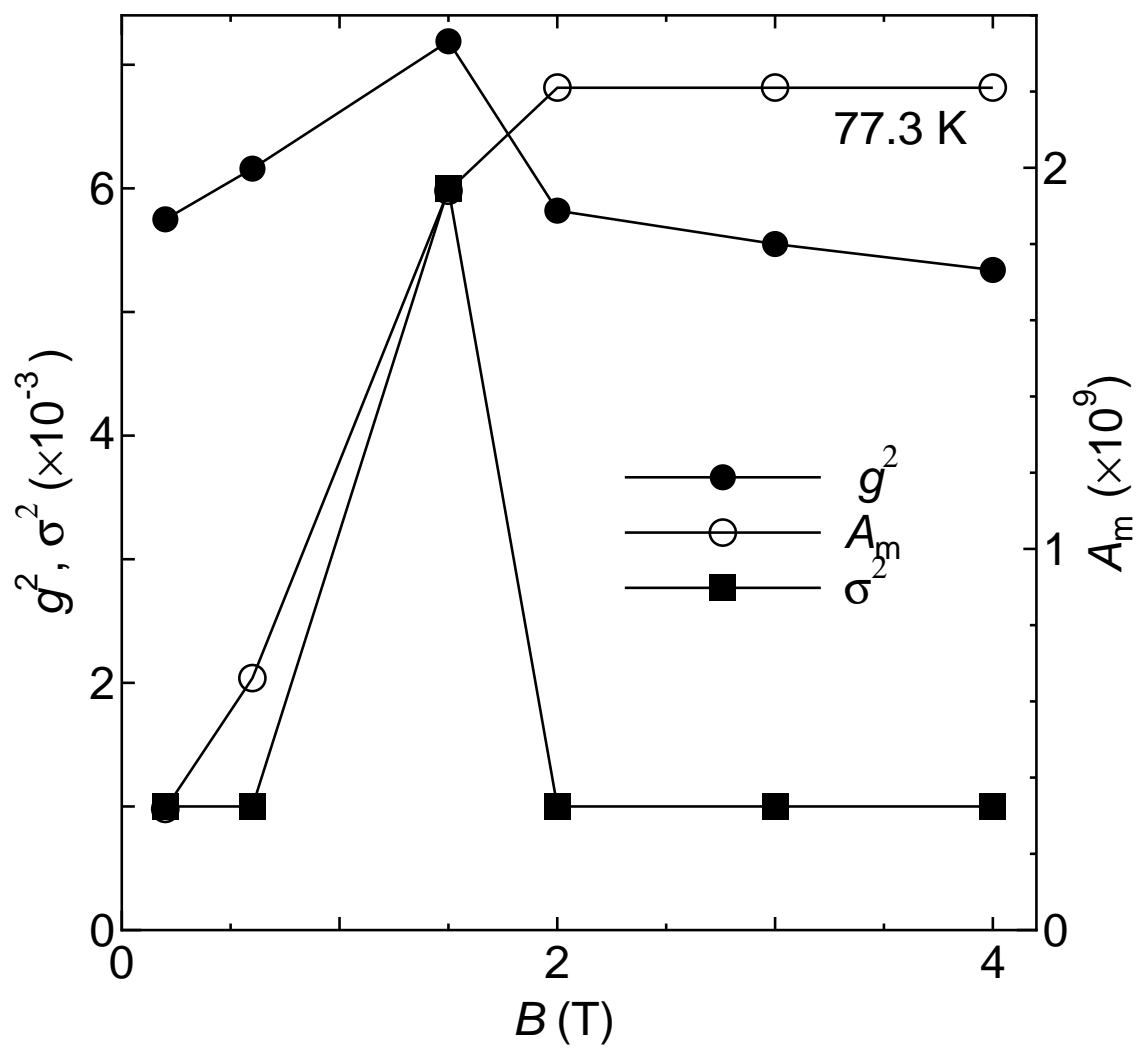


Fig. 4(b): M. N. Hasan *et al.* PCP-10/ISS2004