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H_{c2} of $MgCNi_3$ Determined From the Specific Heat and Resistivity Measurements

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H_{c2} of $MgCNi_3$ has been determined from the specific heat C and resistivity ρ measurements *in the same sample*. The results from ρ are nearly identical with those determined from the anomaly in C. Furthermore, utilizing the relation $\gamma(H) \propto H$ and the value of $d\gamma/dH$, the obtained value of H_{c2} is the same as that by the WHH model, if the spin paramagnetic effect and the spin–orbit interaction are taken into account. The results of this comparison have strong implications on the order parameter of $MgCNi_3$.

KEY WORDS: $MgCNi_3$; H_{c2}; specific heat; order parameter; mixed state.

Very recently, several new superconductors with possible ferromagnetic spin fluctuations have been reported [1–3]. Among them, $MgCNi_3$ has highest $T_c \leq 8$ K. $MgCNi_3$ can be regarded as fcc Ni with only one quarter of Ni replaced by Mg and with C sitting on the octahedral sites. With the structure so similar to that of ferromagnetic Ni, the occurrence of superconductivity in $MgCNi_3$ is really surprising. Supposed that ferromagnetic fluctuations exist in a superconductor, p-wave order parameter is generally expected. Therefore, $MgCNi_3$ could have been a p-wave superconductor with highest T_c. Accordingly, there has been theoretical speculation about p-wave pairing in $MgCNi_3$ [4]. Specific heat (C) [5] and NMR experiments [6], however, provided evidence of the full energy gap (possibly due to s-wave pairing) in $MgCNi_3$. On the other hand, there were tunneling spectra suggesting an unconventional pairing state [7].

The upper critical field H_{c2} is one of the important fundamental properties of a type II superconductor. It is related to important parameters like the coherence length ξ and many magnetic properties. The value of H_{c2} is also one of the crucial criteria for applications of the superconducting magnets. H_{c2} of $MgCNi_3$ was reported in Ref. 8 by resistivity (ρ) measurements. H_{c2} can also be deduced from the magnetic field dependence of C. It is of interest to see if the values of H_{c2} by distinct techniques are consistent with each other. Moreover, the magnetic field dependence of the linear coefficient γ in C from the electronic contribution was reported to be proportional to H in $MgCNi_3$, and this was taken as one of the strong evidences for s-wave pairing [5]. This conclusion in principle could be further examined by the relevant data of H_{c2}. In this paper, both C and ρ were measured *using the same sample*. This would allow eliminating any possible uncertainty from individual samples leading to more conclusive results.

The $MgCNi_3$ sample was prepared on the basis of procedure described in Ref. 1, and the X-ray diffraction pattern revealed the nearly single phase of $MgCNi_3$ structure. It is well known that T_c significantly depends on the real carbon content in the nominal $MgCNi_3$ [1,9]. Magnetization, specific heat, and resistivity measurements all showed a superconducting onset at about 7 K in the present sample, while thermodynamic T_c determined from $C(T)$ was 6.4 K. $C(T)$ was measured using a ^{3}He thermal relaxation

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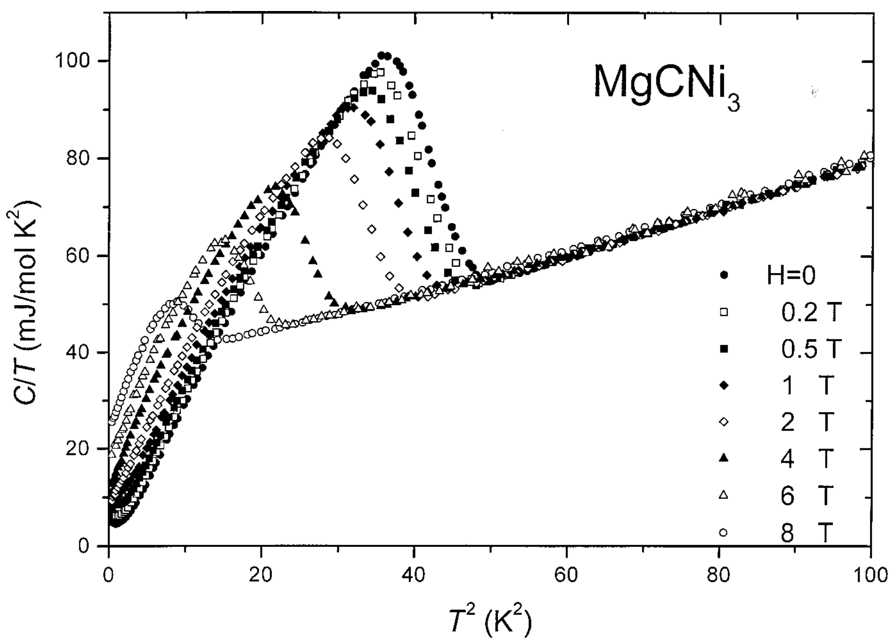

Fig. 1. $C(T, H)/T$ vs. T^2 of $MgCNi_3$ for $H = 0$–8 T.

calorimeter from 0.6 to 10 K with magnetic fields H up to 8 T. Detailed description of the specific heat measurements can be found in Ref. 10. Resistivity $\rho(T)$ was measured by the four-probe method. The change of H was applied at $T = 12$ K for both ρ and C measurements, and the data were taken in field cooling.

$C(T)$ of $MgCNi_3$ with $H = 0$–8 T is shown in Fig. 1 as C/T vs. T^2. The superconducting anomaly at $H = 0$ is much sharper than that in Ref. 1, indicating high quality of the sample, and clearly persists even with H up to 8 T. It is noted that C/T shows an upturn at very low temperatures. This upturn disappears in high H, which is a manifestation of the paramagnetic contribution like the Schottky anomaly. The normal state $\gamma_n = 33.6$ mJ mol K^2 and the Debye temperature $\Theta_D = 287$ K can be extracted from data in Fig. 1 [5]. To derive $H_{c2}(T)$ from $C(T, H)$, it is of interest to figure out $\Delta C(T, H) = C(T, H) - C_{lattice}(T) - \gamma_n T$. $T_c(H)$ is thus determined by the conservation of entropy around the transition in the $\Delta C/T$ vs. T plots at various H. The case of $H = 0$ has been demonstrated in Ref. 5.

Figure 2 shows the transition of $\rho(T)$ in H up to 8 T. The normal state $\rho(T)$ of the present sample is slightly smaller than that in Ref. 8. It is noted that H did not broaden the transition width, probably due to the low temperatures investigated here. T_c determined by the criterion of 50% of the normal state ρ just above T_c.

H_{c2} vs. T, resulting from both C and ρ measurements, is shown in Fig. 3. As expected T_c determined

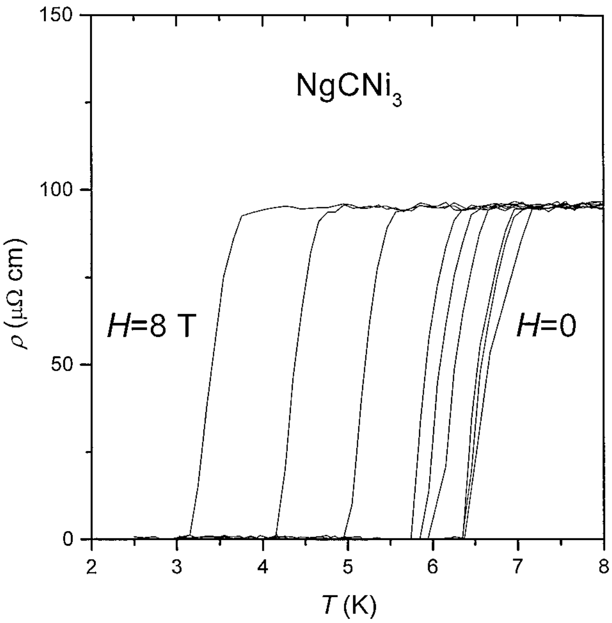

Fig. 2. $MgCNi_3$ $\rho(T)$ in H near the transition. The applied magnetic fields from right to left are 0, 0.1, 0.2, 1, 1.5, 2, 4, 6, 8 T, respectively.

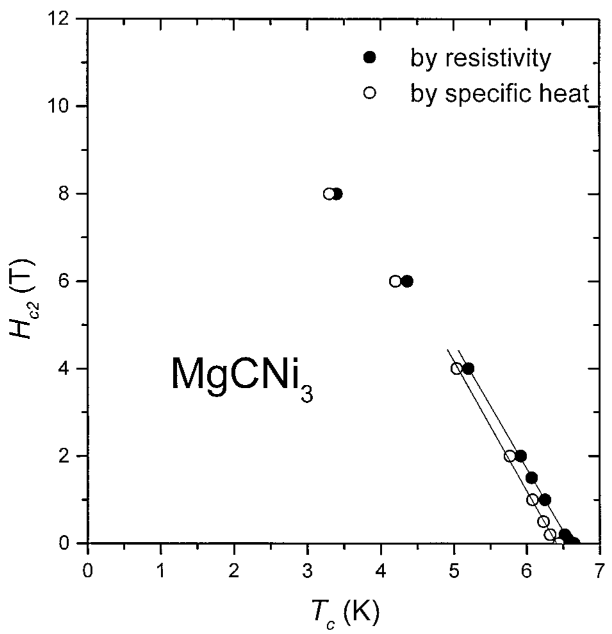

Fig. 3. H_{c2} of MgCNi$_3$. Open and solid circles denote the results from C and ρ measurements, respectively. The straight lines are the linear fits of data with $H \leq 4$ T (roughly corresponding to $0.8 \leq T/T_c < 1$). The zero field data were excluded for the fitting.

by C is slightly lower than that by ρ . Other than that, both techniques yielded very similar results. $H = 8$ T lead to about 50% of T_c suppression. The data show a downward curvature in Fig. 3 as in conventional superconductors. The slopes $(dH_{c2}/dT)_{T_c}$ derived from the linear fit of both C and ρ data for $0.8 \leq (T/T_c) < 1$ are very close to each other. The values of $(dH_{c2}/dT)_{T_c}$ are 2.96 ± 0.08 and 2.88 ± 0.03 T/K from C and ρ measurements, respectively. These values are slightly larger than that of 2.67 T/K in Ref. 8. The relation of $H_{c2} \approx 0.69 T_c (dH_{c2}/dT)_{T_c}$, which does not take into account the effects of the spin–orbit interaction and the spin paramagnetic term [11], was used in Ref. [8] to estimate H_{c2} at $T = 0$. In this way, it led to $H_{c2} = 13.2 \pm 0.7$ T in the present sample. However, failure to include the spin–orbit and the spin paramagnetic effects is known to significantly overestimate H_{c2}. To derive H_{c2} accurately, one has to utilize the numerical analysis, which is beyond the scope of this paper. However, certain plausible assumption can be made. It is found that the physical properties of MgCNi$_3$ are very similar to those of Nb$_{0.5}$Ti$_{0.5}$ [5]. It seems plausible for both compound to have a similar relation between H_{c2} and $(dH_{c2}/dT)_{T_c}$. According to Ref. [11], $H_{c2} \approx 0.59 T_c (dH_{c2}/dT)_{T_c}$ for Ni$_{0.5}$Ti$_{0.5}$. Following this relation, $H_{c2} = 11.2 \pm 0.6$ T in the present sample. It is intriguing to derive H_{c2} from $\gamma(H)$. The high field $\gamma(H)$ can be estimated from the linear extrapolation to $T = 0$, and is found to be proportional to H with $d\gamma/dH = 2.91$ mJ mol K^2 T, which is slightly smaller than the estimate by $\delta C(T,\ H)/T$ at $T = 0.6$ K [5]. For $\gamma_n = 33.6$ mJ mol K^2, $H_{c2} = 11.5 \pm 0.6$ T can be estimated, amazingly close to the above value estimated from the T_c transition in H. Estimates of H_{c2} for the present sample are summarized in Table I.

Table I. Estimates of H_{c2} in MgCNi$_3$ by Different Approaches

Estimate approaches	H_{c2} (T)
T_c transition by C and ρ measurements	
Spin–orbit interaction and spin paramagnetic effect not included	13.2 ± 0.7
Spin-orbit interaction and spin paramagnetic effect included	11.2 ± 0.6
$d\gamma/dH$	11.5 ± 0.6

In conclusion, we have estimated H_{c2} from the T_c transition in H by C and ρ measurements. Both lead to identical value of H_{c2}. Furthermore, this value is consistent with that derived from linear $\gamma(H)$ with respect to H. Since $\gamma(H) \propto H$ is characteristic of conventional superconductors (see discussions in Refs. 12–14), the results presented in this paper have intriguing implications on the order parameter of MgCNi$_3$.

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