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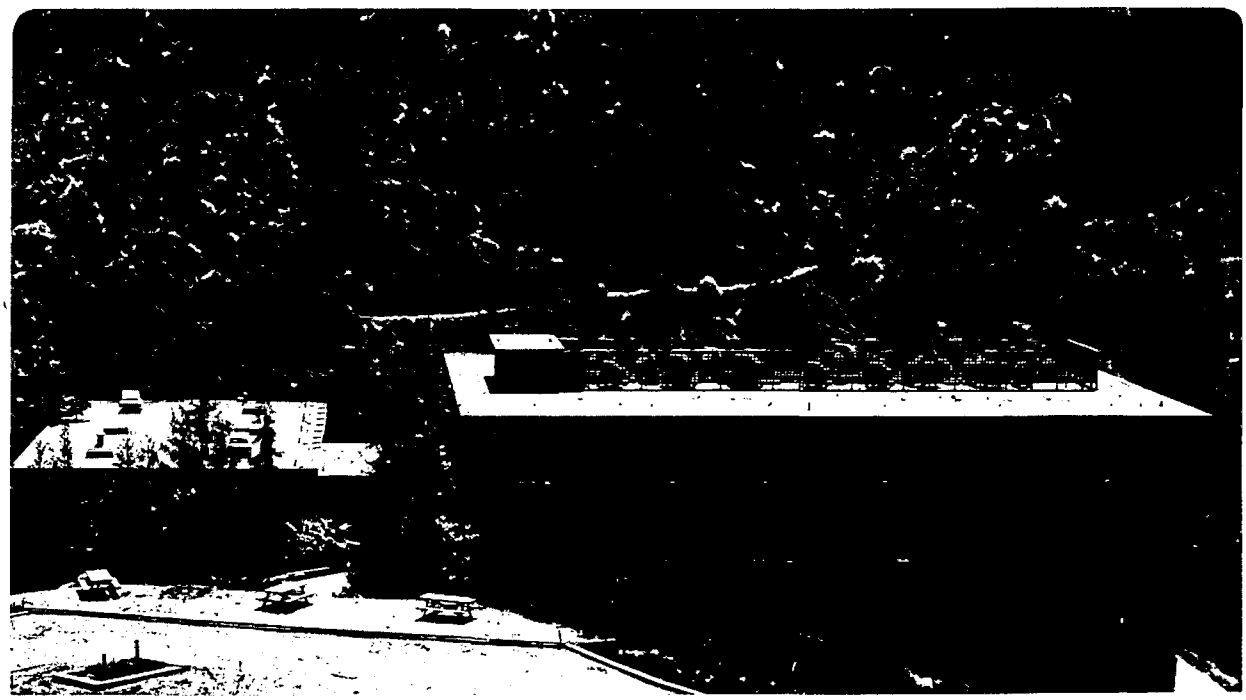
Specific Heat of URu_2Si_2: Effect of Pressure and Magnetic Field on the Magnetic and Superconducting Transitions

R.A. Fisher, S. Kim, Y. Wu, N.E. Phillips, M.W. McElfresh, M.S. Torikachvili, and M.B. Maple

July 1989



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SPECIFIC HEAT OF URu_2Si_2: EFFECT OF PRESSURE AND MAGNETIC FIELD ON THE MAGNETIC AND SUPERCONDUCTING TRANSITIONS

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ABSTRACT

Specific heats were measured in the range $0.3 \leq T \leq 30K$ for $0 \leq H \leq 7T$ and $P=0$, and for $H=0$ and $0 \leq P \leq 6.3$ kbar. For $H=0$ and $P=0$, the measurements were extended to 0.15K. Above the superconducting transition the $H=0$ and 7T data can be superimposed. For the magnetic transition near $T_0=18K$, T_0 increased with increasing P accompanied by a broadening and attenuation of the specific heat anomaly. The superconducting transition near $T_c=1.5K$ was broadened, attenuated and shifted to lower temperatures for both increasing P and H. The superconducting transition is similar to that of UPt_3, and both the temperature dependence of the superconducting state specific heat and the derived parameters are consistent with an unconventional polar-type pairing.

URu_2Si_2 orders magnetically at T_0~18K and becomes a bulk superconductor at T_c~1.5K with the two types of order co-existing at lower temperatures [1,2]. Neutron scattering measurements [3] have confirmed this co-existence, and have been used to derive a magnetic moment per U-atom of $(0.03 \pm 0.01)\mu_B$ in an antiferromagnetically ordered state below 1K. Based on a fit of the specific heat (C) on the low-temperature side of T_0 to $A_0\exp(-\Delta/T)$, Maple et al. [4] suggested that the transition at T_0 is due to a charge- or spin-density wave (CDW or SDW) state that opens a BCS-like gap over part of the Fermi-surface. The onset of superconductivity at T_c causes the formation of another gap in the remainder of the Fermi-surface. In this paper we report further measurements of specific heat in magnetic fields (H) and measurements under pressure (P). Previous measurements of C in the range $0.2 \leq T \leq 300$K and $0 \leq H \leq 8$T have been reported [1,2,4-6].

Measurements were made on a polycrystalline sample using a semi-adiabatic heat pulse method. For the measurements of specific heat under pressure, a beryllium-copper alloy cell was used with pressure determined from the superconducting transitions of <u>in-situ</u> discs of Sn and Pb. (Because of the higher ratio of cell-to-sample heat capacity at the higher temperatures, the specific heat data are not as precise as those at lower temperatures.)

Figure 1 is an overview of C/T vs T for H=0 and 7T at P=0. In the temperature region above T_c, the specific heat is H-independent, while below T_c, 7T suppresses the superconductivity. Above the sharp transition at T_0, the rounded feature near 25K is from a crystal-field state [6] (two doublets split by 75K). The solid line is a composite of the crystal field (C_{cf}) [6] and lattice (C_l) specific heats. C_l was derived from a fit (see Fig. 1 for parameters) to the data above T_0 after subtracting C_{cf}. It would be expected to be only a rough approximation at low temperatures, but it does have reasonable agreement with the specific heat for $ThRu_2Si_2$ [1].

A plot of the electronic specific heat (C_e) is shown in Fig. 2 as $(C-C_{cf}-C_l)/T$ vs T. Following Maple et al. [4], the low-temperature side of the transition at T_0 was fit to $A_1T+A_0\exp(-\Delta/T)$ with parameters given in the figure. Above T_0, C_e=52.1T and near 10K C_e=35.8T, indicating that 31% of the Fermi-surface develops a gap as a result of the magnetic ordering. The entropy (S) associated with the anomaly minus $\int_{10}^{18} 35.8dT$ is 0.16Rln2. The total electronic entropy at 18K is 0.25Rln2.

With increasing pressure, the magnetic transition moves to higher temperatures, broadens and decreases slightly in amplitude. The data are plotted in Fig. 3 where the insert shows the linear increase of T_0(max) with pressure. McElfresh et al. [7] have found similar behavor for the resistivity at pressures to 15 kbar.

With increasing pressure, as shown in Fig. 4, the maximum in specific heat associated with the superconducting transition decreases and shifts to lower temperatures, as does the onset temperature. The insert to Fig. 4 illustrates a linear dependence of T_c(max) on pressure. For P=5.8 and 6.3 kbar the maximum is so broadened that it is not evident that the sample remains superconducting.

Magnetic fields have an effect on the specific heat in the superconducting region similar to that of pressure. As shown in Fig. 5, the anomaly at T_c is shifted to lower temperatures and decreases in amplitude with increasing H, however, the onset temperature of the transition remains essentially unchanged. At 7T the superconductivity appears to have vanished. In the insert to Fig. 5, H vs T_c(max) has a similar staight line behavior to that found by Schlabitz et al. [1] in their magnetic measurements of the upper critical fields (H_{c2}). [From their measurements $H_{c2}(0)$=7.5T and T_c~0.4K at 7T.]

Figure 6 is a plot of C/T vs T below 2K for H=0 and 7T. The vertical dashed line at T_c=1.17K is an ideal entropy-conserving construction for the H=0 data, while the dot-dash line is an extrapolation of a T-T^2 fit to the 7T data which gives an entropy balance between the normal and superconducting states. As observed by others [1,4], just below the maximum in C/T the data can be fit by $C=\gamma(0)T+A_2T^2$ for H=0. The ideal $\Delta C(T_c)/\gamma(T_c)T_c$=0.80 which is well below the weak coupling BCS value of 1.43. These results are similar to those found for UPt_3 [8]. Assuming, as for UPt_3, that $\gamma(0)$ represents gapless superconductivity, and following the analysis in Ref. 8, the superconducting fraction $f_s=[1-\gamma(0)/\gamma]$=0.872. Using $1/f_s$ as a normalizing factor, $\Delta C(T_c)/f_s\gamma(T_c)T_c$=0.92 and $A_2T_c/f_s\gamma$=1.9 which are in good agreement with corresponding values found for UPt_3 [8]. This behavior suggests an unconventional polar-type superconductivity according to a theory by Monien et al. [9].

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FIGURE CAPTIONS

Fig. 1. C/T vs T in H=0 and 7T showing the superconducting and magnetic transitions. The solid line is a composite of lattice and crystal field specific heats.

Fig. 2. $C_e/T=[C-C_{cf}-C_l]/T$ vs T in H=0.

Fig. 3. C/T vs T in the magnetically ordered region showing the effect of P.

Fig. 4. C/T vs T in the superconducting region showing the effect of P.

Fig. 5. C/T vs T in the superconducting region showing the effect of H.

Fig. 6. C/T vs T in the superconducting region for H=0 and 7T showing entropy-conserving constructions and the linear behavior of C/T vs T below T_c for H=0.

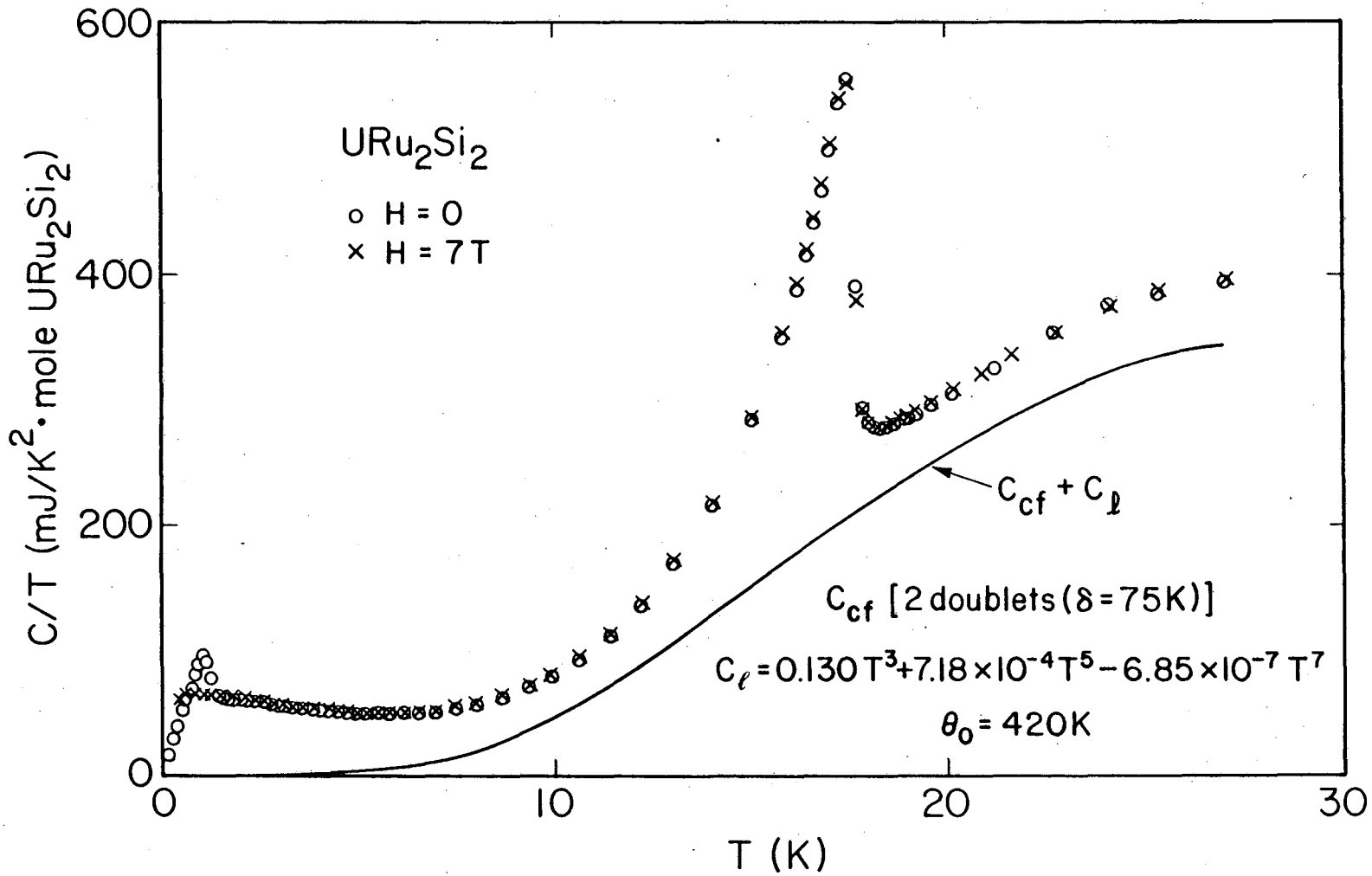

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FIG 1

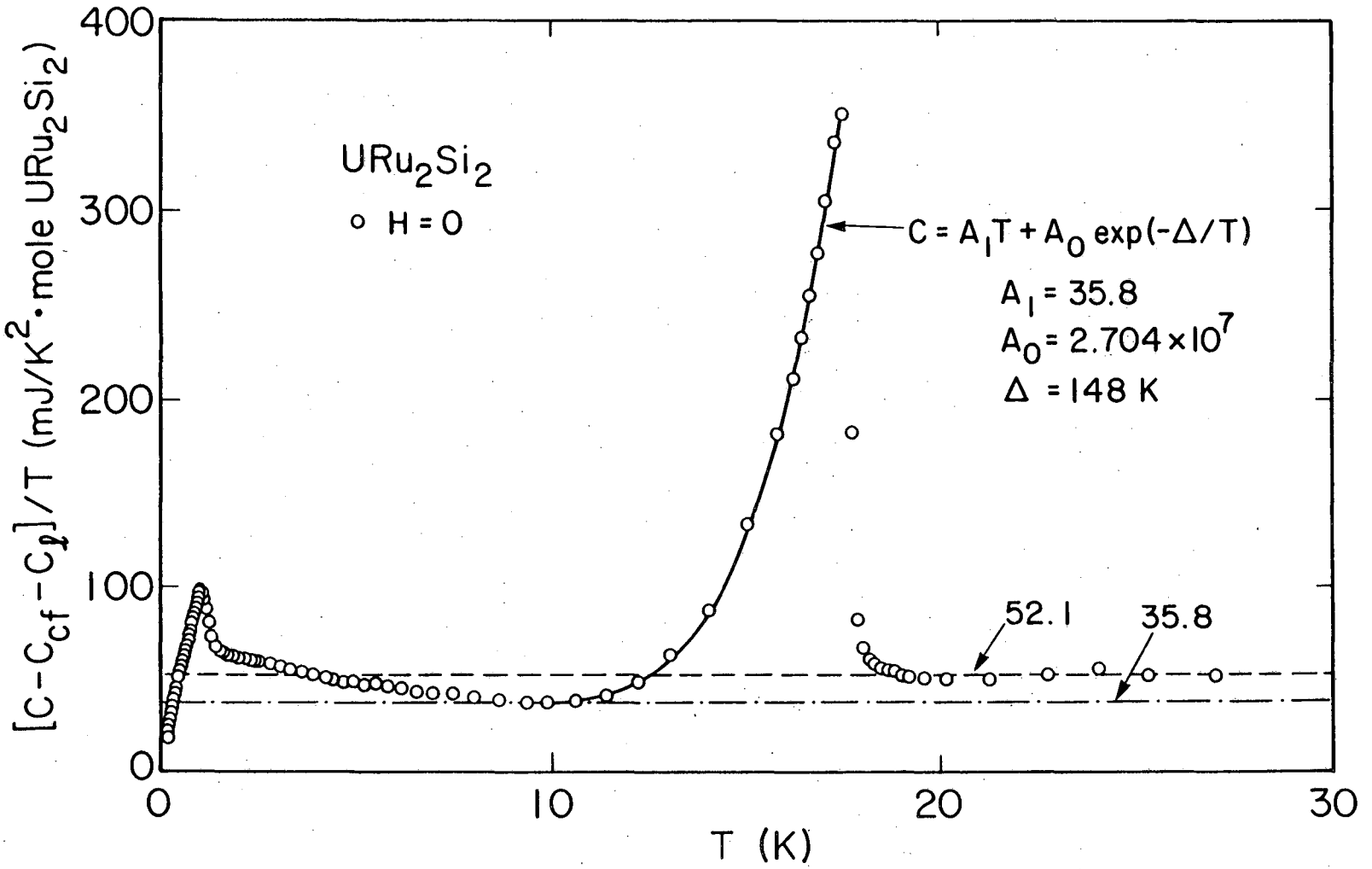

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FIG 2

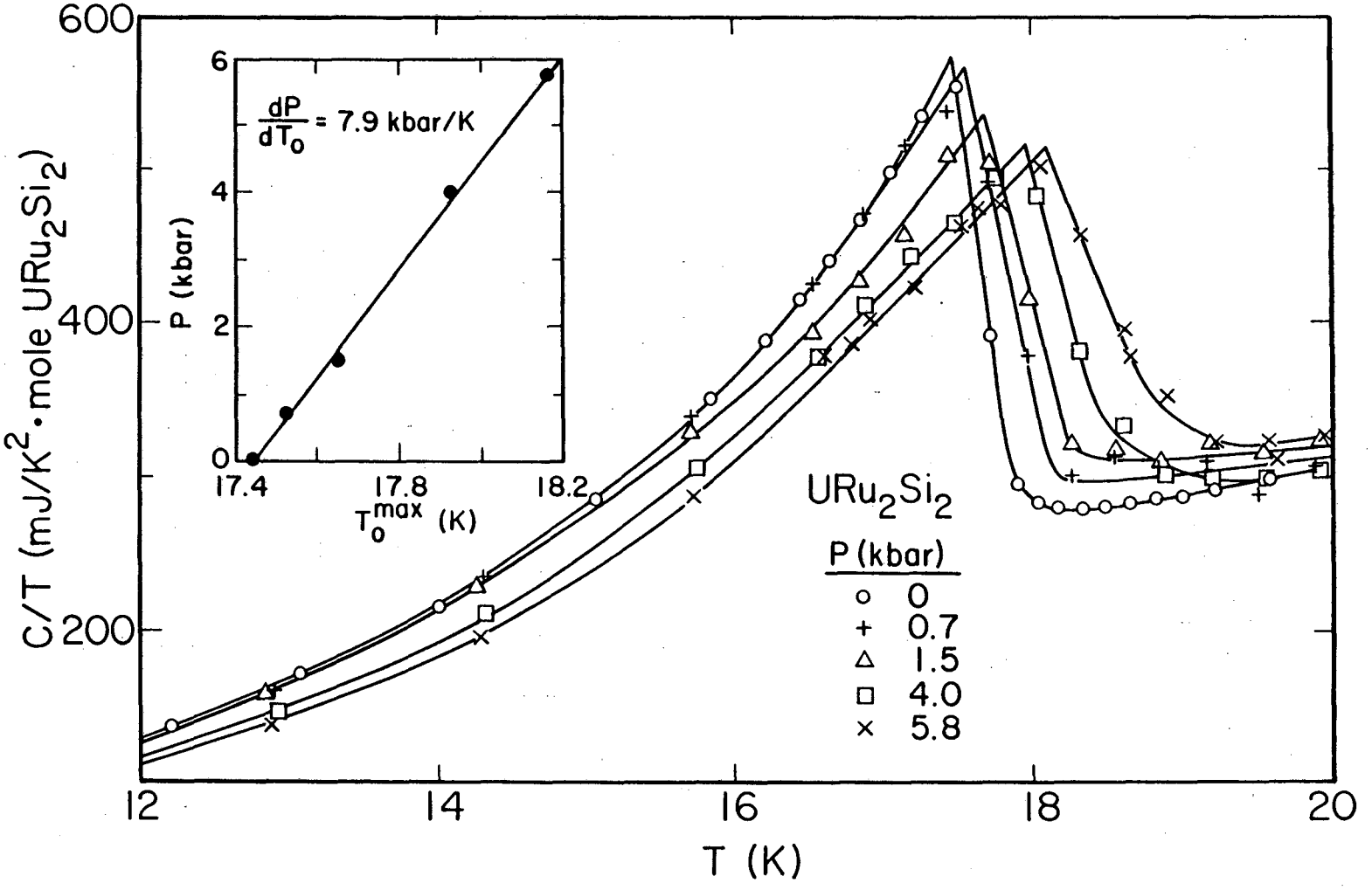

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FIG 3

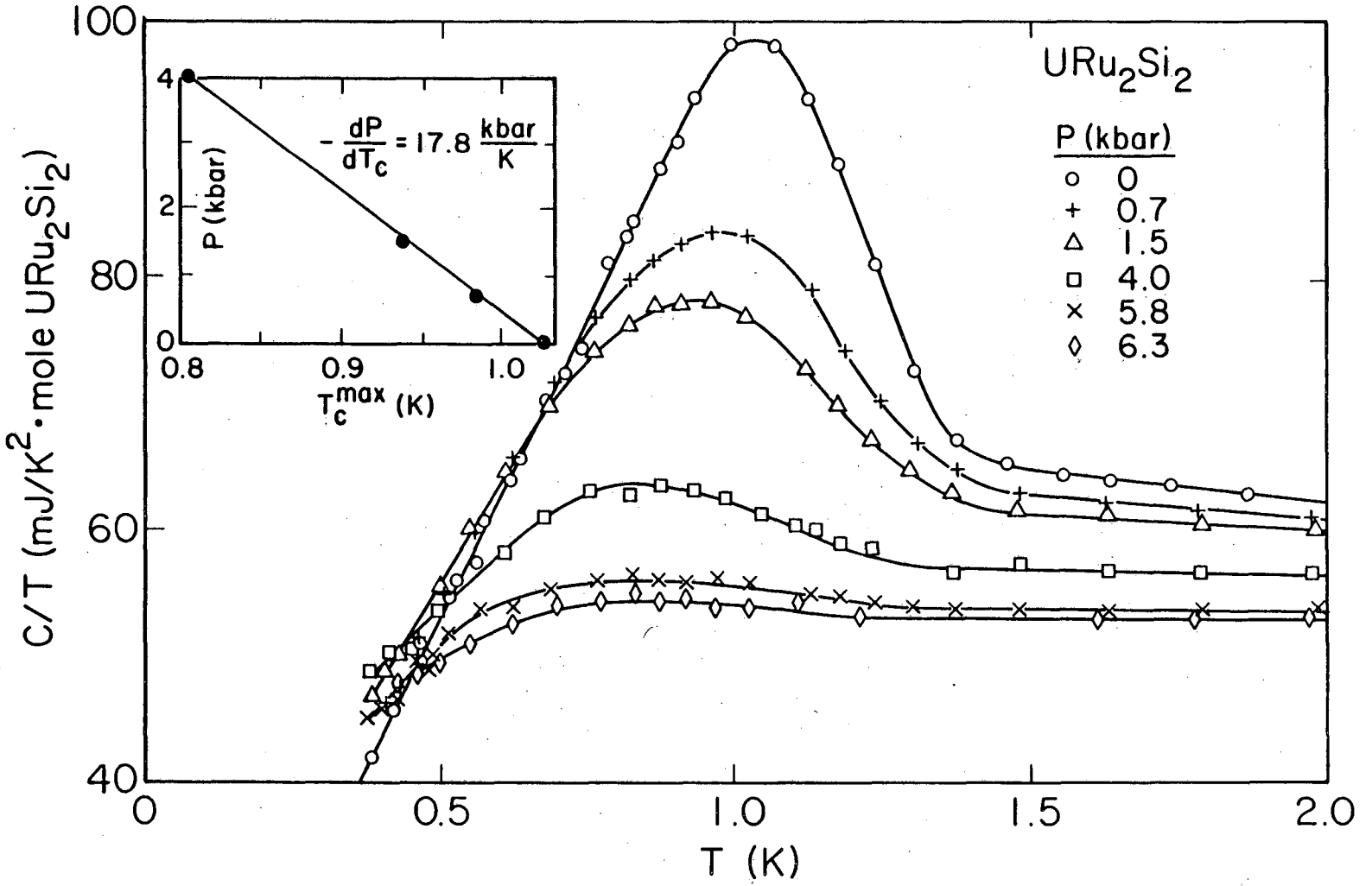

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FIG 4

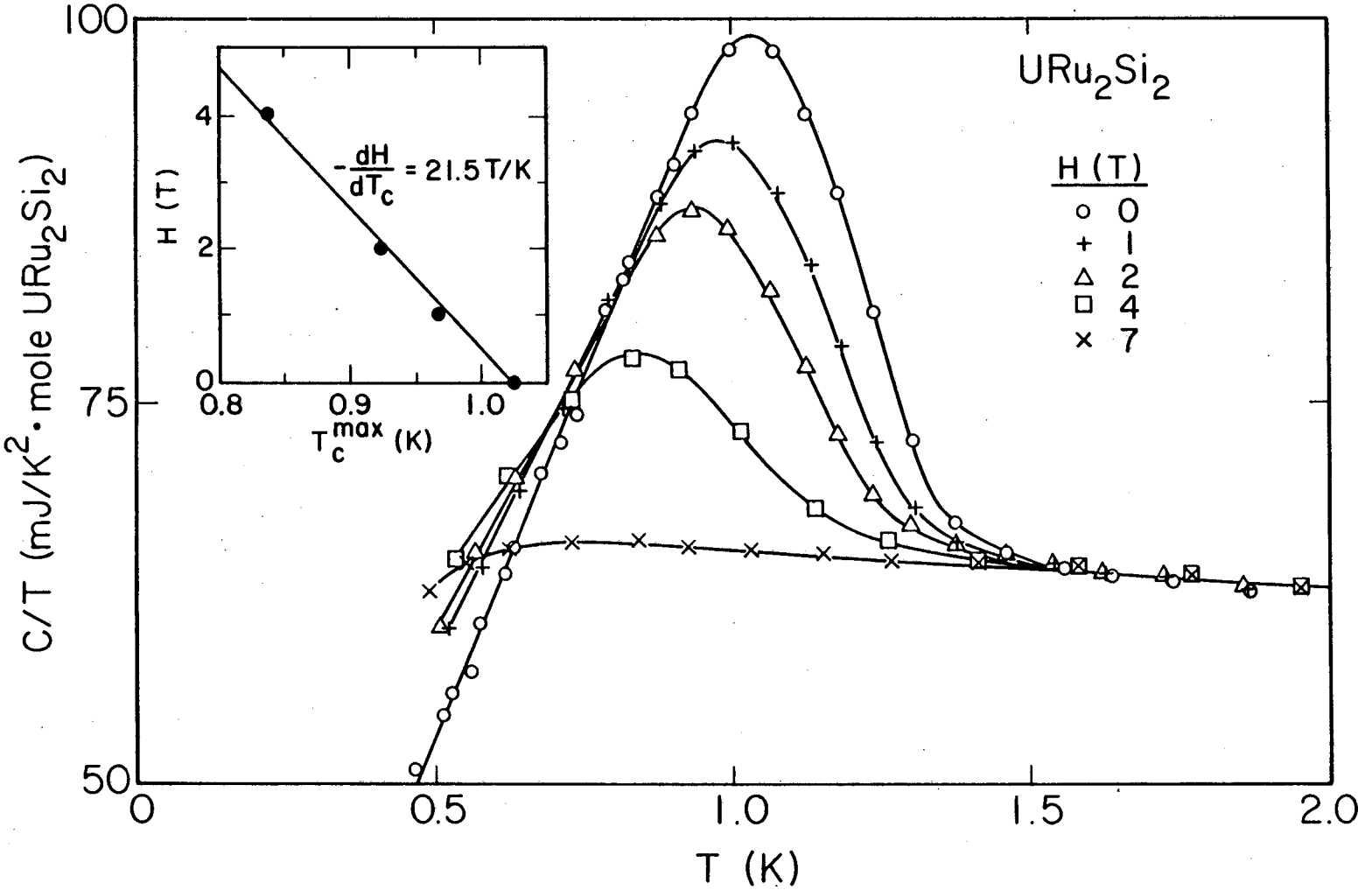

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FIG 5

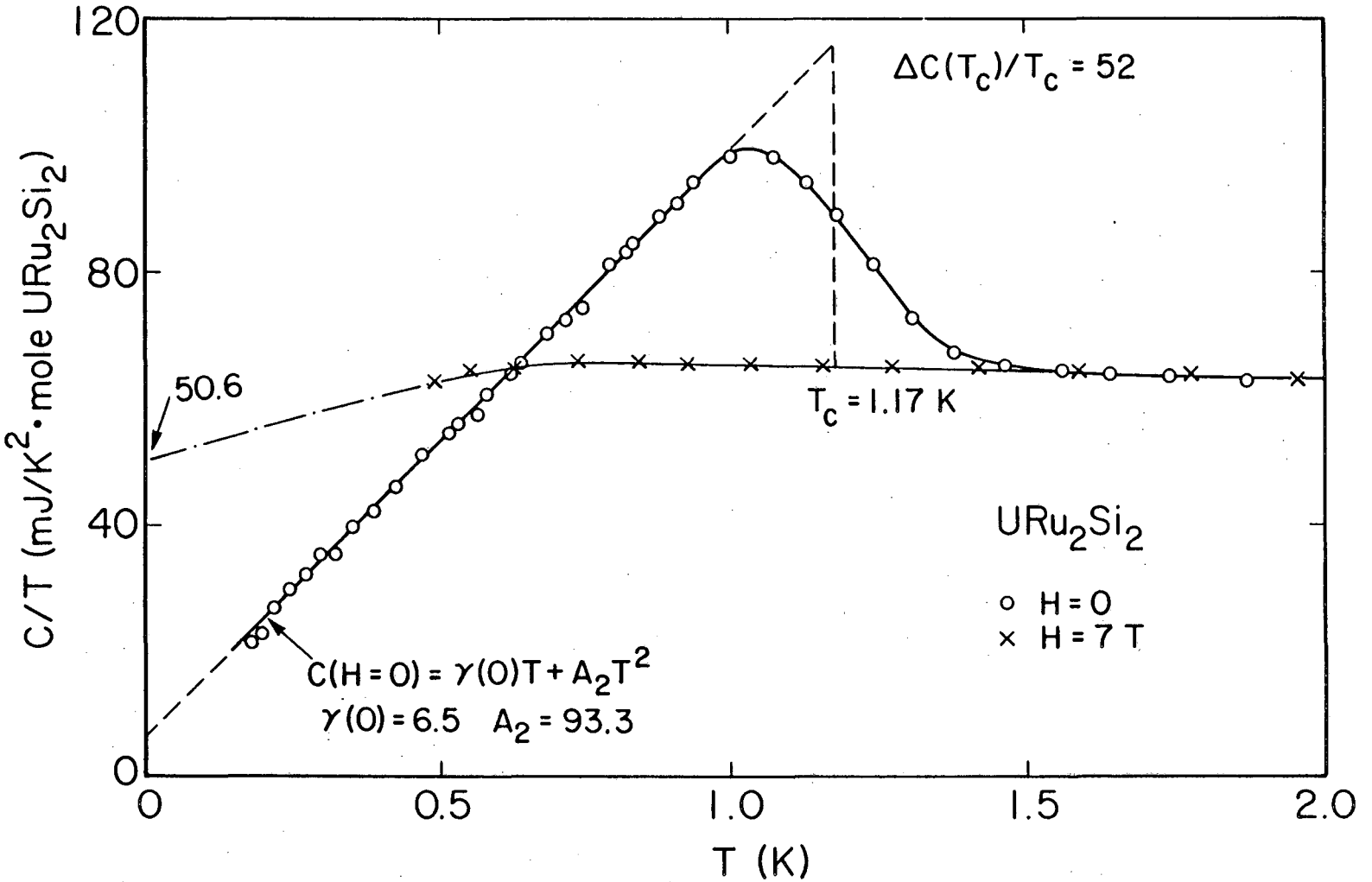

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FIG 6

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