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ABSTRACT

We report measurements of the upper critical field, H_{c2}, inclined at various angles with respect to the c-axis in the heavy fermion superconductor UPt_3. The angular anisotropy observed near $T_c = 0.53$K cannot be explained quantitatively by presently available theoretical expressions which consider either isotropic or anisotropic pairing. In addition, we find that the anisotropy apparently disappears at T ~200 mK, only to reemerge at lower temperatures with an opposite sense. We have also studied H_{c2} in the basal plane of this hexagonal crystal and find no angular dependence within the limits of our measurements.

The heavy fermion superconductor, UPt_3, has attracted considerable recent attention because of the wide range of unusual physical properties it exhibits.[1] The presence of the $T^3 \ln T$ term in its specific heat at low temperatures,[1] measurements of the upper critical field[2] and thermal conductivity,[3] and the power law behavior with temperature of the attenuation of longitudinal ultrasound[4] have led to the speculation that the superconductivity in UPt_3 involves anisotropic pairing. Recent measurements of the attenuation of transverse sound[5] present further evidence of this anisotropy and suggest that the superconducting state is a polar phase[6] with a line of zeroes in the basal plane. An additional method of characterizing the superconducting state is to look for similar anisotropic effects in the upper critical field. If the superconducting state consists of quasiparticles paired in an $l > 0$ angular momentum state, then one expects a spontaneous anisotropy which could be different from the underlying crystal symmetry.[7]

Measurements to date of the upper critical field, H_{c2}, in single crystals of UPt_3 have been confined to the major crystal axes and only extend down to $T \sim 150$ mK.[2] In this paper, we report new results on the angular dependence of H_{c2} between the c-axis and the basal plane, down to T = 10 mK. We also report measurements for various directions in the basal plane for which no anisotropy is observed.

The present experiments were performed on two single crystals of UPt_3 which came from the same batch as the samples in Ref. 5. The crystals were mounted on rotatable copper holders which were bolted on to the sample slug of a top-loading dilution refrigerator. Current and voltage leads were attached by means of silver epoxy. Typical sample dimensions were (0.15x0.5x2.0) mm^3, and the long axis was always held perpendicular to the magnetic field so as to minimize the effect of demagnetization factors on the intrinsic rotational

anisotropy. Current densities of less than 0.2 A/cm^2 were employed in measurements with a transformer-coupled bridge at 17 Hz. Data was collected by stepping the field in small steps at constant temperature. The 10%-90% transition width was ~150 Oe.

The various parameters we measure for the two samples are shown in Table I along with their comparison to the values given by other groups. The variation of the resistivity below 1K follows the form $\rho = \rho_o + AT^n$ with $n = 1.6 \pm 0.1$, in agreement with the results obtained by Chen et al. [2] We deduce an electron mean free path l=1800Å from the value of ρ_o.

We plot in Fig. 1 critical fields parallel and perpendicular to the hexagonal c-axis, $H_{c2\parallel}$ and $H_{c2\perp}$, respectively. The slopes at T_c are the largest yet observed for UPt_3 (see Table I), from which we determine a superconducting coherence length $\xi = 110$Å. In addition, the positive curvature observed by Chen et al.[2] for $H_{c2\perp}$ is less pronounced in Fig. 1 and is completely absent in $H_{c2\parallel}$. At lower temperature, $H_{c2\parallel}$ and $H_{c2\perp}$ not only approach each other, but cross at $T \approx 200$ mK. Although $\frac{dH_{c2\perp}}{dT}|_{T_c}$, is only 60% of $\frac{dH_{2\parallel}}{dT}|_{T_c}$, $H_{c2\perp}(T \to 0)$ is enhanced by 23% over $H_{c2\parallel}$ $(T \to 0)$.

It has been suggested [8] that the disappearance of the anisotropy, as must occur for critical field curves which cross, only can arise in the presence of an $l > 0$ pairing interaction. There also may be additional information in the angular dependence of H_{c2} in the basal plane. Gorkov and Burlachkov[7] have calculated the critical fields for anisotropic states possible for various crystal symmetries. Unfortunately, they find that no changes should be observed when the field is rotated in the basal plane of a hexagonal crystal. Our measurements, shown in Fig. 2, are consistent with this prediction. It is possible, however, that there may be delicate mechanisms present which are washed out by warming the sample above T_c while top-unloading to change the orientation of the samples.

The crossing of the curves for the critical field is not confined to the two perpendicular directions shown in Fig. 1. We have followed the disappearance of the anisotropy through the crossing point at various intermediate angles. This data is shown explicitly in Fig. 3, where the lines drawn are guides to the eye. Note the change in the sense in which the critical field varies as a function of angle, as one goes through the crossing point. This is a new result which we are unable to understand within the framework of any of the present day theories and should place important constraints on future work.

Angular dependence similar to that shown in Fig. 3 was also studied near T_c. In Fig. 4, we plot the slope near T_c obtained at various angles by fitting a straight line to the data points above 450 mK. We have analyzed these results near T_c using two models, one for isotropic pairing and the other which considers an anisotropic p-wave pairing interaction. Both these models are in the clean limit, which should be applicable to our samples as $l \gg \xi$.

In the standard WHH approach, the anisotropy in H_{c2} near T_c arises basically from the angular dependence of the effective mass.[9] For a hexagonal crystal this dependence is given by,[10]

$$H_{c_2}(\theta) \sim (\sin^2\theta + \varepsilon^2\cos^2\theta)^{1/2}$$

where $\varepsilon^2 = \frac{m_\perp}{m_{||}}$ is the ratio of the effective masses perpendicular and parallel to the c-axis. The solid line in Fig. 4 is a least squares fit to such an expression, which yields $\frac{m_\perp}{m_{||}} = 1.7$. This value is comparable with the results of susceptibility measurements.[11]

Hirschfeld and Sauls[12] recently have obtained expressions for a p-wave superconductor with a uniaxial Fermi surface and considering weak anisotropy in both the pairing interaction

and the effective mass. For the polar phase they find,

$$H_{c2}(\theta) \sim \sin^2\theta(1-\xi\cos^2\theta)\alpha_{||} + \cos^2\theta(1+\frac{\xi}{2}[\sin^2\theta-\cos^2\theta])\alpha_{\perp}$$

where $\xi = \frac{(m_{\perp}-m_{||})}{m_{||}}$, and $\alpha_{||}$ and $\alpha_{\perp}$ measure the strength of the pairing interaction parallel and perpendicular to the c-axis, respectively. The dashed line in Fig. 4 is a result of fitting the experimental results to the polar state. We obtain the best fit values $\xi = 0.45$ and $\alpha_{||}/\alpha_{\perp} = 1.3$.

In considering both these models we have neglected several effects. Spin-orbit coupling is known to be important in heavy mass superconductors. In addition, although the zero temperature critical field is not Pauli-limited[2], the spin paramagnetism could affect anisotropy near T_c. It is conceivable that incorporating these processes in the above theories will improve agreement with the experimental results near T_c.

We can only speculate at the mechanisms for the H_{c2} curves to cross at low temperature. Recent neutron scattering studies[13] of single crystals of UPt_3 indicate the presence of large antiferromagnetic spin fluctuations, restricted to the basal plane. The anisotropy in these fluctuations may be related to our observations of anisotropy in the upper critical field.If the pairing is triplet and if the correlation is ferromagnetic in nature, then the suppression of antiferromagnetic fluctuations by the external field should enhance H_{c2} in the basal plane, as observed. In addition to influencing the spin fluctuations, the magnetic field could have a perturbing effect on several other parameters in the superconducting state. Since the values for H_{c2} at low temperatures are extremely large, the magnetic energy is an appreciable fraction of the characteristic energy scale set by the "coherence temperature"[14] in UPt_3. In such a situation there can be a significant modification of the electron g-factor, the spin-orbit coupling

energy, and the energy gap.[15]

The fact that we observe the crossing of $H_{c2\perp}$ and $H_{c2\parallel}$, whereas previous results indicated no such behavior down to 150 mK, possibly implies an interesting sample dependence. On the other hand, it has been suggested[12] that the curvature observed near T_c in the work of Chen et al.[2] is due to the orienting effect of their larger current density on the order-parameter. A similar effect could have perturbed the low temperature behavior.

In summary, we find that as a function of angle out of the basal plane, the larger the critical field slope $\frac{dH_{c2}}{dT}$ at T_c, the smaller the limiting value $H_{c2}(T\rightarrow 0)$. At $T \approx 200$ mK, H_{c2} is independent of angle. We also find that H_{c2}(T) is insensitive to rotation in the basal plane, which appears to be a manifestation of UPt_3's hexagonal symmetry.

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FIGURE AND TABLE CAPTIONS

Table I: The two single crystals of UPt_3 described in this paper, compared with the results of other groups (Ref. 2). The slopes near T_c and the upper critical field as $T \rightarrow 0$ are the largest yet reported. Columns 6 and 7 come from fitting the normal state resistivity to $\rho = \rho_o + AT^{1.6}$. We also note the anisotropy in ρ at room temperature.

Fig. 1: The upper critical field, H_{c2}, in (filled circles) and perpendicular to (open circles) the basal plane. The current is along $\hat{b}$ and always perpendicular to H. The curves for intermediate angles also cross at T~200 mK.

Fig. 2: The upper critical field, H_{c2}, as a function of temperature appears independent of angle in the basal plane, a probable consequence of UPt_3's hexagonal symmetry. The current is along $\hat{c}$ and always perpendicular to H.

Fig. 3: The variation of H_{c2} with the angle θ out of the basal plane in 50 mK increments for 50 mK$\leq$T$\leq$350 mK. The anisotropy changes sense at T~200 mK. The solid lines are guides to the eye.

Fig. 4: The variation of the slope near T_c with the angle out of the basal plane. The solid line is a fit to the standard isotropic model and the dashed line to a p-wave model, polar phase (see text).

TABLE I

Sample	Current Density J, A/cm^2	T_c K	ρ(300K) $\mu\Omega$-cm	$\frac{\rho(300K)}{\rho(1K)}$	ρ_o $\mu\Omega$-cm	A $\frac{\mu\Omega\text{-cm}}{K^{1.6}}$	$[dH_{c2}/dT]_{T_c}$ kOe/K ||	$[dH_{c2}/dT]_{T_c}$ kOe/K ⊥	H_c (T=0) kOe ||	H_c (T=0) kOe ⊥
1	J||c ~ 0.1	0.53	125	155	0.20	0.54	77.6	45.1	-	28.1
2	J||b ~ 0.2	0.53	230	110	0.59	1.44	77.2	45.9	21.1	25.9
Chen et al	J||c ~ 2.0	0.52	165	150	~0.4	~0.7	63	40	~18	~18
Rausch-schwable et al.	-	0.49	-	-	-	-	60	40	~19	~19

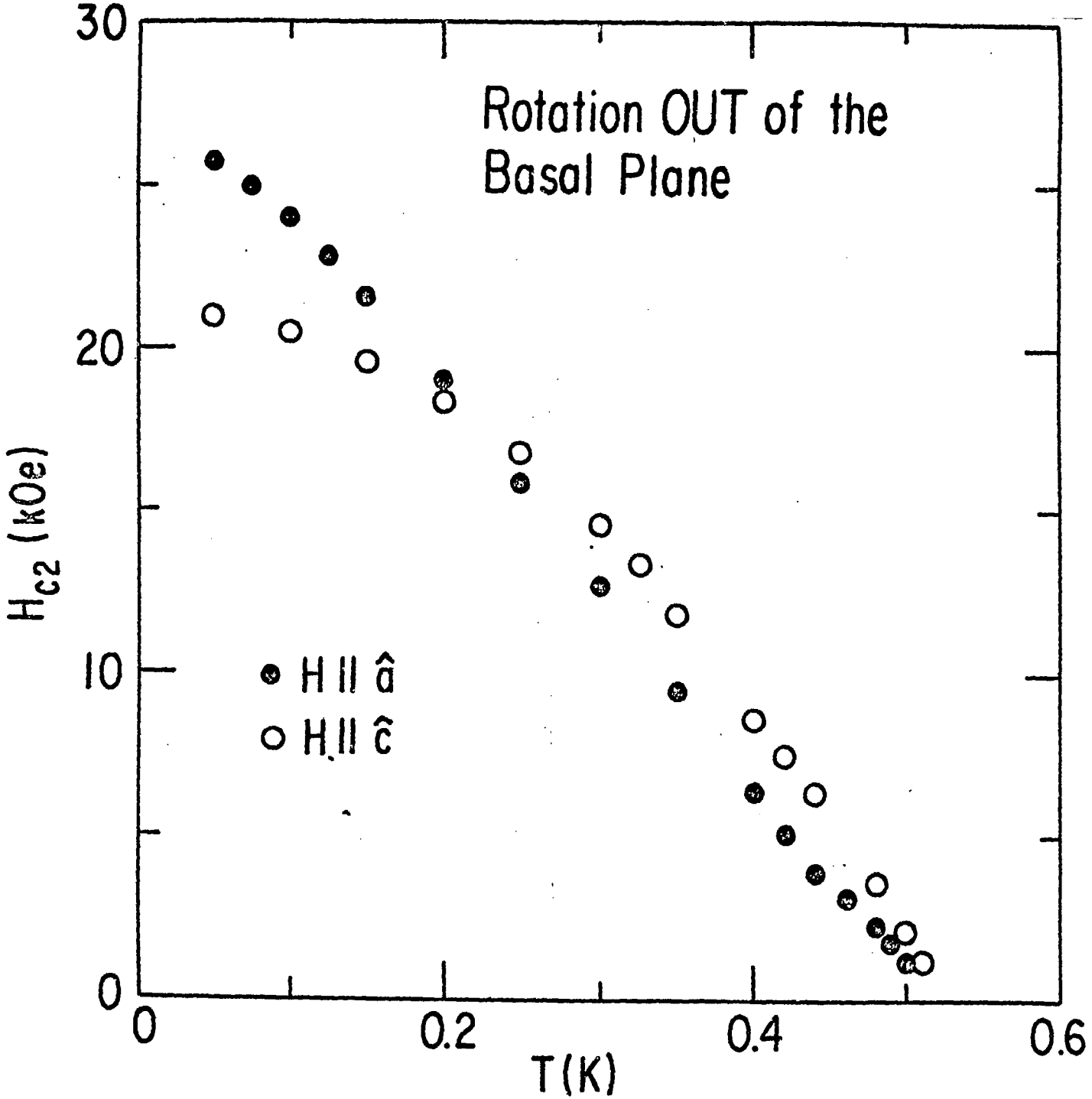
Rotation OUT of the
Basal Plane
H ∥ â
H ∥ ĉ
H_{c2} (kOe)
T(K)
30
20
10
0
0
0.2
0.4
0.6

FIG. 1

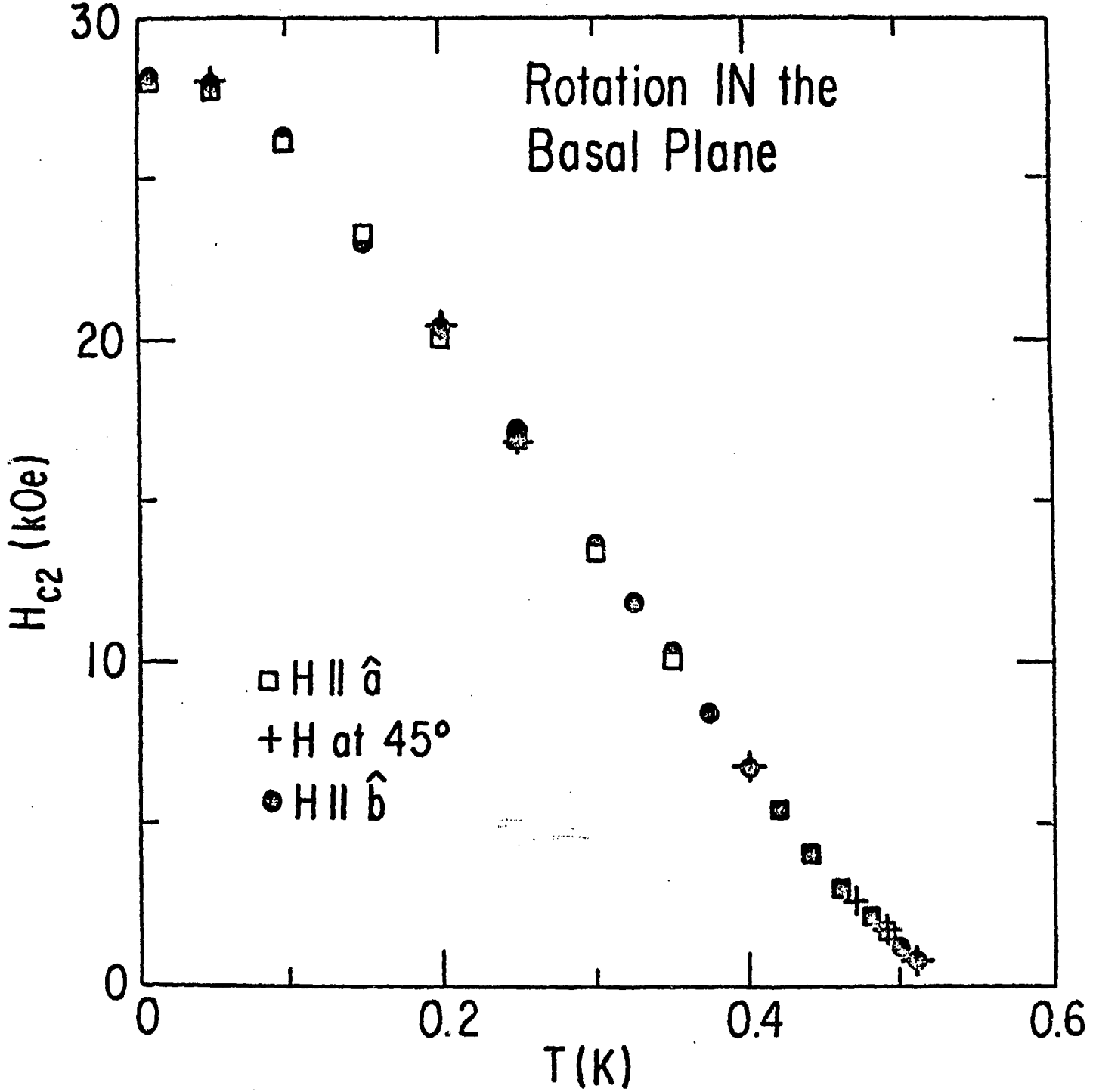
Rotation IN the
Basal Plane
H ∥ â
+ H at 45°
H ∥ b̂
H_{c2} (kOe)
T (K)
0
10
20
30
0
0.2
0.4
0.6

FIG. 2

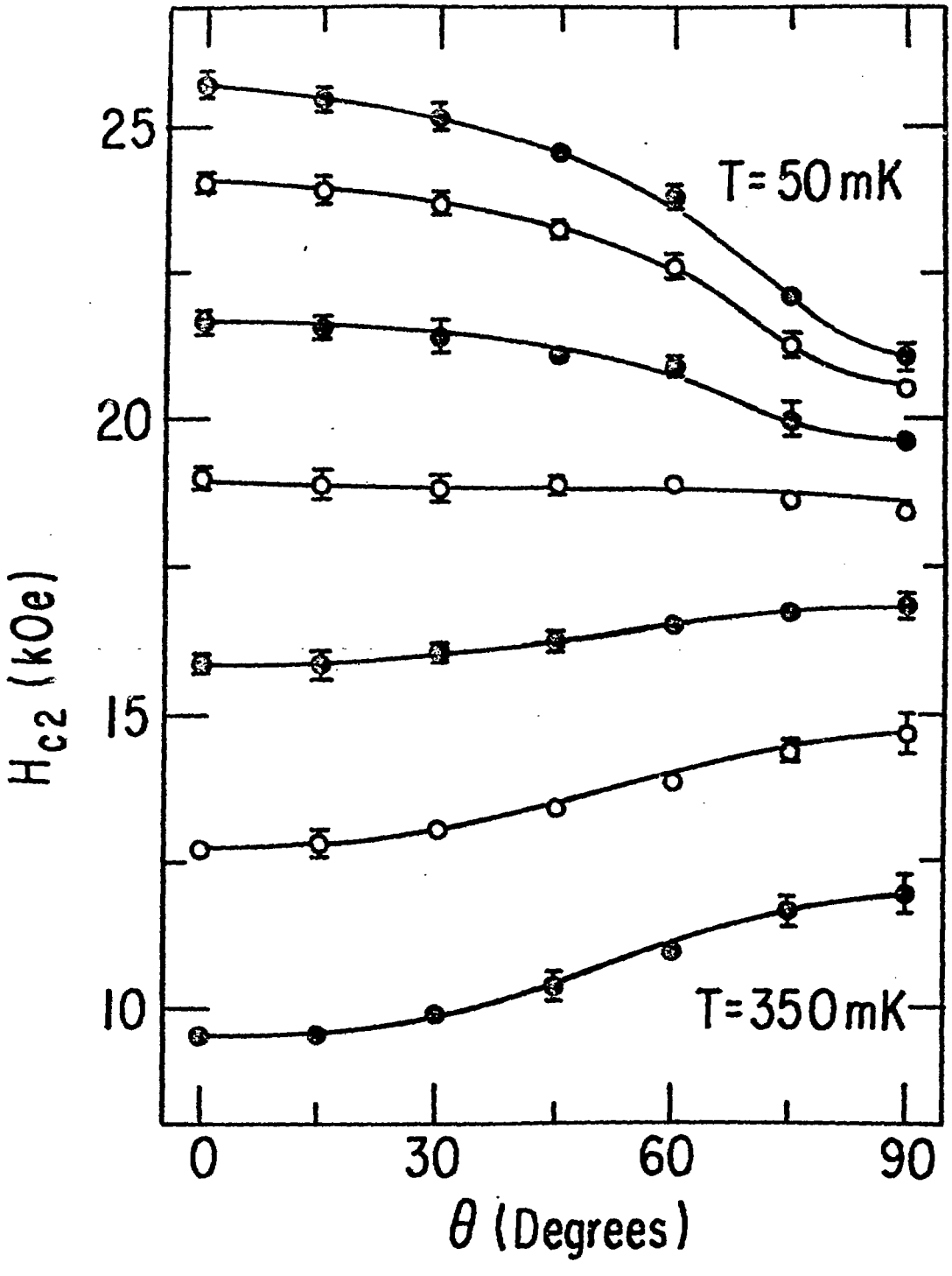

FIG. 3

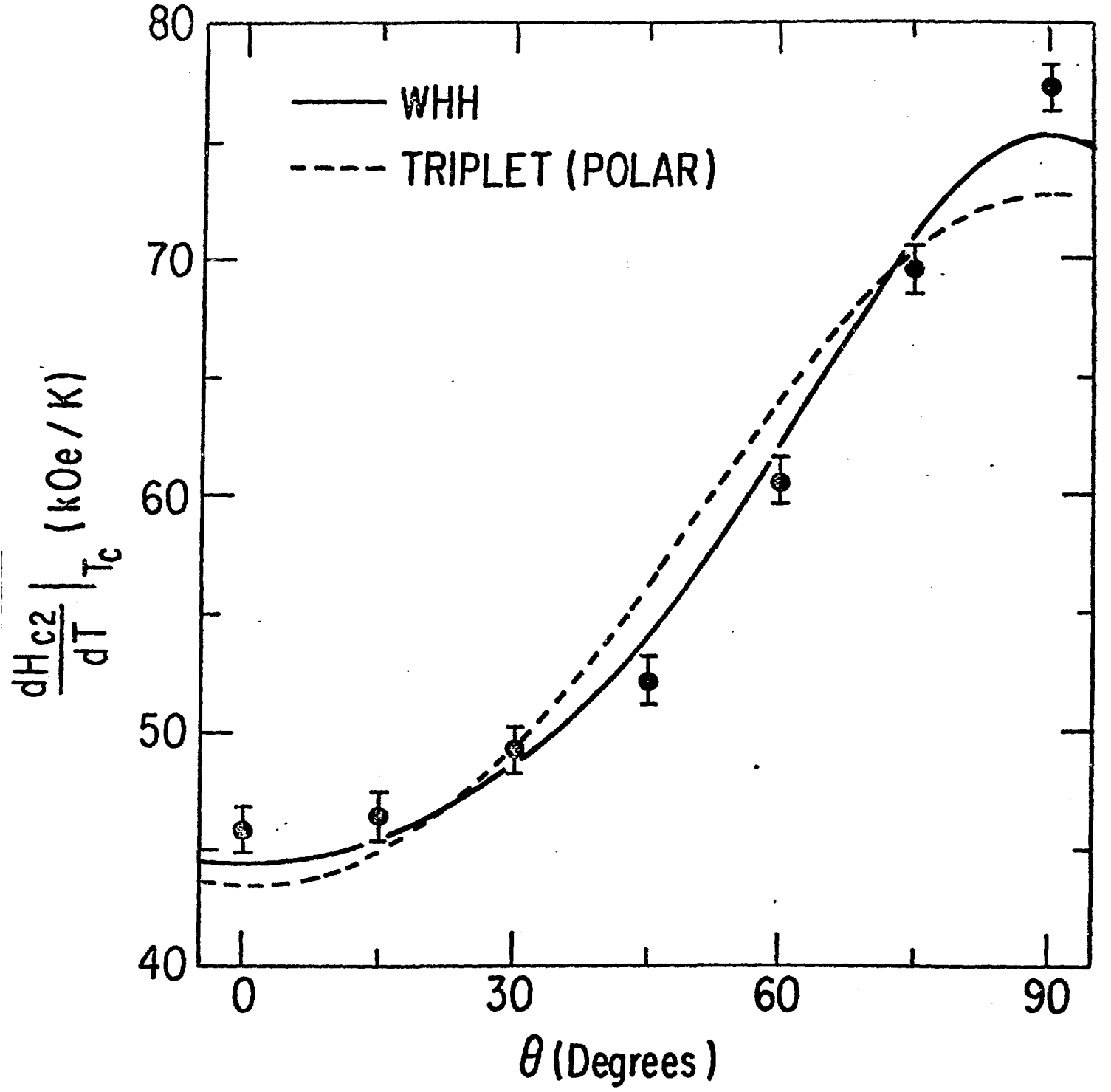
80
70
60
50
40
0
30
60
90
WHH
TRIPLET (POLAR)
$\frac{dH_{c2}}{dT}\Big|_{T_c}$ (kOe / K)
θ (Degrees)

FIG. 4