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Publication Date
1987

LBL-22814 c.2

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Presented at the Fifth International Conference on Valence Fluctuations, Bangalore, India, January 5-9, 1987 and to be published in the Proceedings

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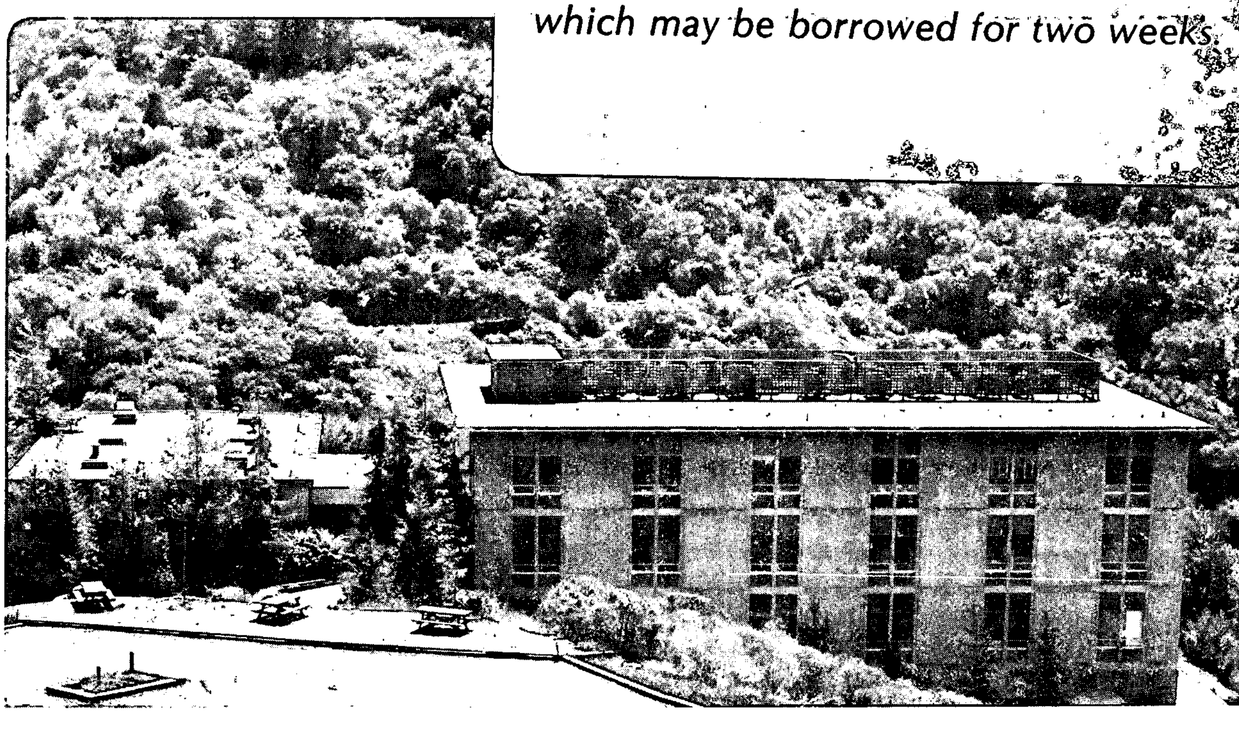
January 1987



Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LOW-TEMPERATURE SPECIFIC HEAT OF UBe_{13}

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The specific heats (C) of the heavy-fermion superconductors, $CeCu_2Si_2$, UPt_3 and UBe_{13}, show significant sample-to-sample variations in both the normal and superconducting states (C_n and C_s, respectively). For some samples, $C_s/T \neq 0$ at T=0. This has been interpreted as evidence for gapless superconductivity [1-3], and, in the case of UPt_3, as evidence of a gap over part of the Fermi surface [4], but could also indicate simply that some of the material remains normal. Measurements of C are reported here for four polycrystalline samples of UBe_{13} of differing quality, gauged by transition temperature (T_c) and width (δT_c). There is a strong correlation of C_s/T at T=0 with T_c and δT_c. The data also give some information on extrapolation of C_n to T=0.

Fig. 1 shows C/T below 1K in magnetic fields (H) of 0 and 7.5T. Cubic

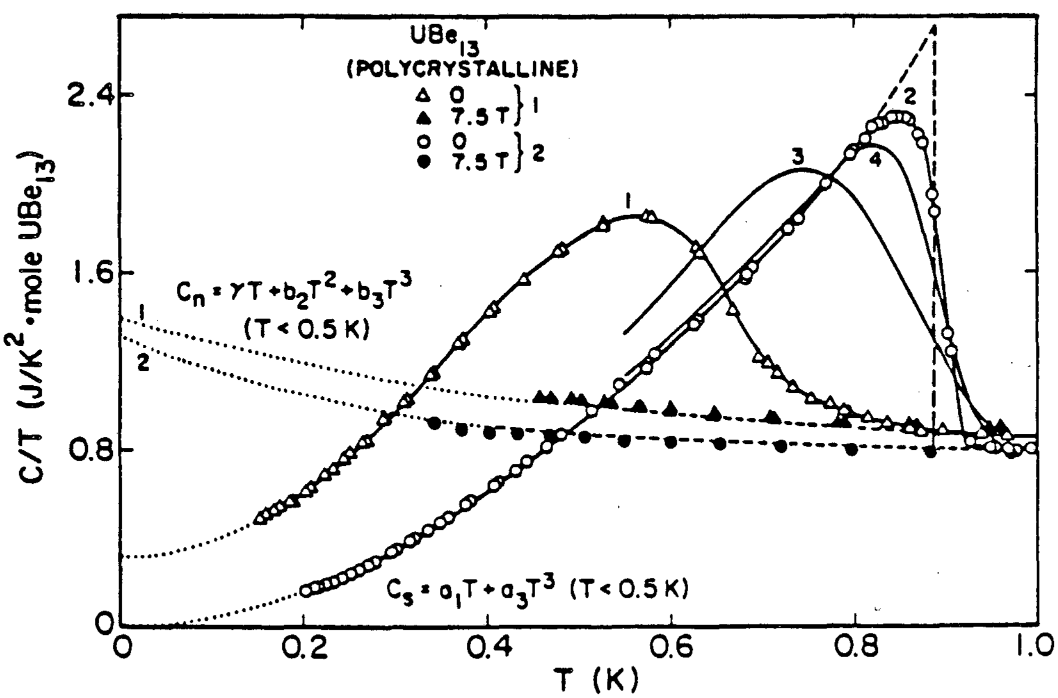

Fig. 1. C for four samples of UBe_{13} below 1K.

spline fits of the H=0 data for samples 3 and 4 are displayed near and below T_c. Above T_c, 7.5T has only a small effect on C; below T_c it suppresses the transition at the lowest T investigated, 0.35K. The light dashed curves represent probable values of C_n/T at H=0. They are parallel to C/T at 7.5T, but shifted by the small (barely perceptible) amount necessary to coincide with C/T at H=0 just above T_c. The dotted extrapolations to T=0 are by the 3-term polynominals indicated in Fig. 1, with two coefficients chosen to force a match to the dashed curves and the third chosen to give the same high-T entropy as that derived from C_s. Values of γ derived by this process are given in Table 1 for all four samples. Just above T_c, C_n/T is nearly constant but increases slowly with decreasing T. The experimental data display a more rapid increase below T_c, and a still more rapid increase is required below 0.35K (in the region of the extrapolation) to conserve entropy.

The heavy dashed vertical line for sample 2 is the idealized, entropy-conserving construction for a sharp transition at T_c. (Similar constructions for the other samples are omitted for clarity.) Table 1 lists values of T_c and δT_c, the difference between T_c and T at the onset of superconductivity.

C_s data at H=0 for the four samples are plotted in Fig. 2. From least-squares fits, the straight lines in the insert, it is evident that C_s for all samples is well represented by $C_s = a_1T + a_3T^3$. (Table 1 lists a_1 and a_3.) The positive deviation from this form at low-T for sample 4 has a T^{-2} dependence and may reflect a contribution from impurities. A small upturn of C/T at low-T for sample 2 is perhaps also due to impurities, but the effect is too small to permit analysis of the T dependence. The solid curves in Fig. 2 represent $a_1T + a_3T^3$ plus the additional T^{-2} term for sample 4. The strongly sample dependent a_1 correlates with T_c and δT_c: For samples 2 and 4, with the higher T_c and lower δT_c, $a_1 = 0$. We conclude that the linear term is not an intrinsic property of UBe_{13}. The T^3 dependence of C_s, which contrasts with

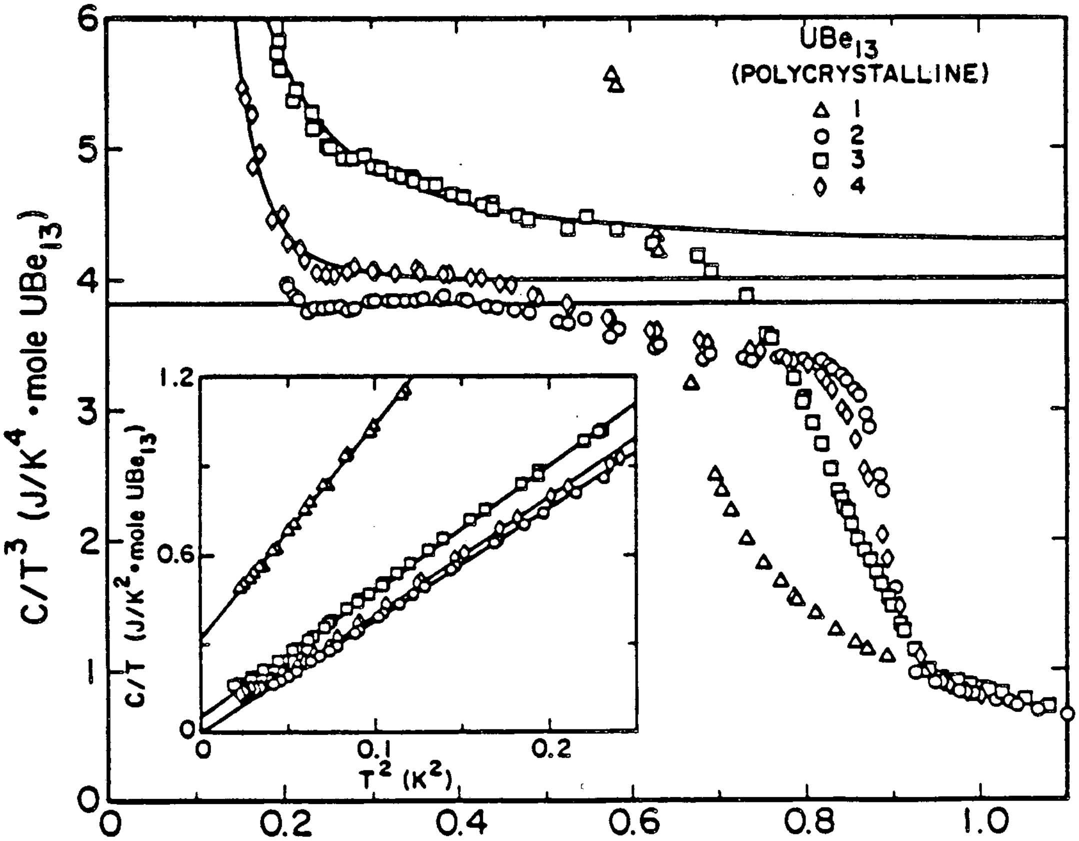

Fig. 2. Limiting low temperature behavior of C for UBe_{13}.

Table 1. Properties Characterizing Four UBe_{13} Samples below T_c. Units: a_1 and γ in $J/K^2 \cdot mole$; a_3 in $J/K^4 \cdot mole$; C(1K) and S(1K) in $J/K \cdot mole$.

Samples	δT_c(K)	T_c(K)	γ	a_1	a_3	f_s	r	C(1K)	S(1K)
2	0.03	0.89	1.31	0	3.82	1	2.4	0.789	0.904
4	0.07	0.89	1.40	0	4.00	1	2.1	0.790	0.891
3	0.11	0.84	1.34	0.06	4.25	0.96	2.0	0.861	0.971
1	0.15	0.68	1.39	0.31	7.32	0.78	2.0	0.855	1.058

the BCS exponential dependence on T, has been observed previously for UBe_{13}, and has been interpreted in terms of p-wave pairing [5]. Power laws in T for C_s have also been found for $CeCu_2Si_2$ and UPt_3 and have been interpreted as arising from points or lines on the Fermi surface with zero gap [1-3]. In addition to the power law for C_s, there is a new feature for samples 2 and 4 -- a small but significant departure from T^3 behavior near 0.5K, corresponding approximately, especially for sample 2, to a change in the value of a_3. This effect is also present for a sample studied by the Darmstadt group [2] (Fig. 7b). The fact that the same effect is seen in three samples from two separate sources, and in two laboratories with independent measuring techniques, demonstrates that it is a real, intrinsic property of UBe_{13}. (Samples 1 and 3 do not show this "transition" region, perhaps because of a lowered quality.) An intriguing possibility is that this feature is related to the second transition [6] in $(U,Th)Be_{13}$ that persists for UBe_{13}.

BCS theory gives $r \equiv [(C_s-C_n)/C_n(T_c)] = 1.43$. Taking "ideal" values of C_s-C_n (derived from constructions like that for sample 2 in Fig. 1), r = 2.4 for sample 2, close to reported values [2,5] and typical for strong coupling superconductors. For sample 4, r = 2.1. For samples 1 and 3, r < 2, but, assuming the a_1T term in C_s is due to material remaining normal, r would be corrected to 2.0 for both. The superconducting fraction of the sample at T=0, $f_s \equiv 1-a_1/\gamma$, and corrected values of r are given in Table 1.

Fig. 3 shows C_n/T vs. T from 1 to 20K for samples 1 and 2 at H=0, and sample 2 at 7.5T. In the region of the broad maximum in C_n (1-5K) the samples differ somewhat, while above 5K, C_n is nearly the same for each. Between 5

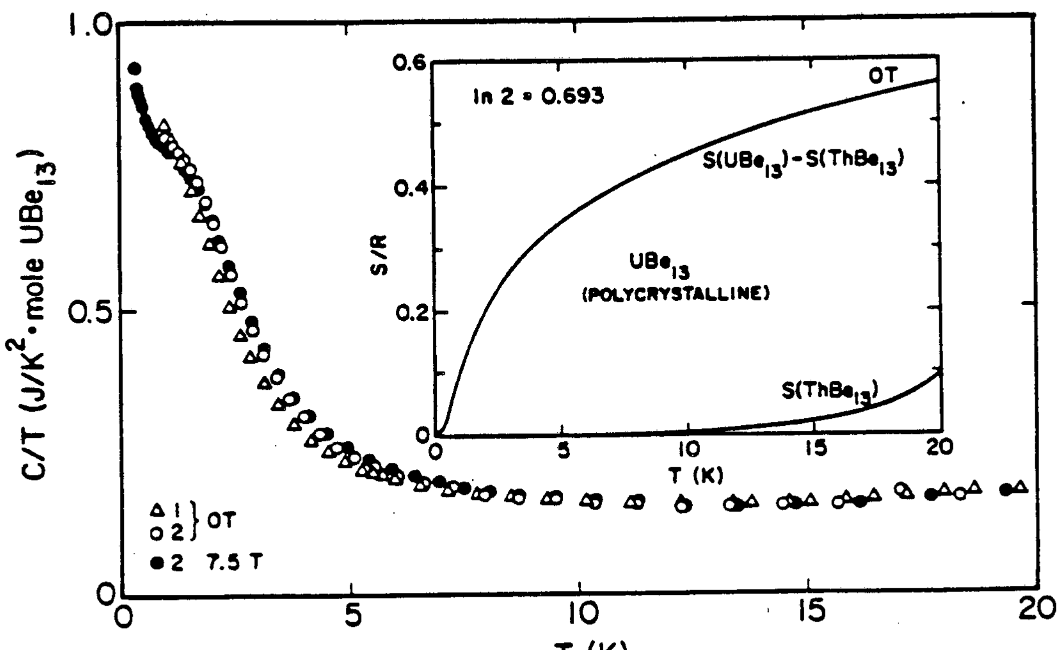

Fig. 3. C and S for UBe_{13} at 0 and 7.5T to 20K.

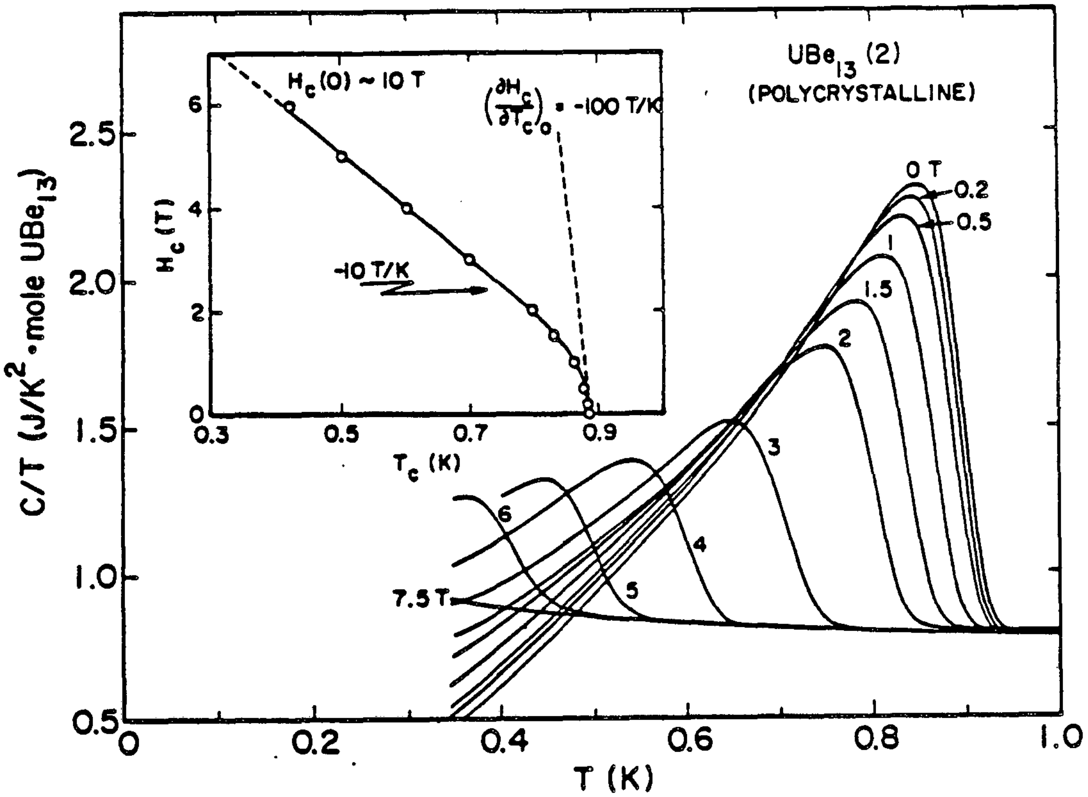

Fig. 4. H_c vs. T_c for UBe_{13} as measured by C in fields to 7.5T.

and 20K, C_n/T has a weak T dependence with a minimum near 12K. Stewart [1] has reviewed measurements of C in this T-range. The insert shows the electronic entropy calculated by subtracting the entropy for $ThBe_{13}$ [7].

Fig. 4 shows cubic spline fits of C/T vs. T for sample 2 in fields to 7.5T. (Precision of the data is similar to that in Fig. 1.) T_c vs. H_c is shown in the insert — T_c was taken as T at the midpoint of the transition, and these values of T_c are not equal to those in Table 1. Initially $(\partial H_c/\partial T_c)$ is -100T/K (at least) and for higher H is linear at -10T/K. At T=0, H_c extrapolates to 10T. Similar calorimetric results have been reported [8].

Work at Berkeley was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy under Contract DE-AC03-76SF00098. Work at Los Alamos was supported by the U.S. Department of Energy.

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