

given by Sommerfeld and Bethe. A detailed description of the method of measurement and additional results on other ferromagnetic metals and some nickel-copper alloys will be presented in a later communication.

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### Specific Heat of 96-Percent He<sup>3</sup> below 1°K\*

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WE have extended our previous measurements<sup>1</sup> of the specific heat of liquid He<sup>3</sup> (He<sup>3</sup> content 96 percent, 4-percent He<sup>4</sup>) by observations down to 0.57°K. Calorimetric techniques as previously described<sup>1,2</sup> were used, the calorimeter holding 13-mm<sup>3</sup> liquid He<sup>3</sup>. The calorimeter was cooled to temperatures below 1°K by a paramagnetic salt, the thermal connection being through a superconducting thermal valve which could be opened or closed magnetically, as described elsewhere.<sup>3</sup> Temperatures were measured with a carbon resistance thermometer calibrated against temperatures obtained from the susceptibility of the paramagnetic salt. Our preliminary results are shown in Fig. 1, which includes also our previous results obtained between 1.3°K and 2.3°K. The probable estimated error is  $\pm 10$  percent. Details of the corrections which had to be applied for evaporation of the liquid during the heating cycles, etc., will be described in a fuller publication later. It might be noted that the largest corrections (at 1.3°K) totaled 17 percent of the observed specific heats. The lower limit of temperature of observation was deter-

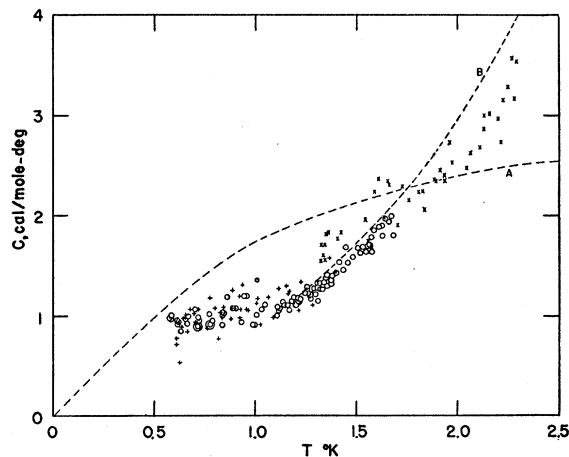


FIG. 1. The specific heat,  $C_{sat}$ , in cal/mole-deg of liquid He<sup>3</sup> (96-percent He<sup>3</sup>) as a function of the absolute temperature  $T$  in °K. The crosses **X** give our previously reported results,<sup>1</sup> the circles and crosses **+**, the new observations. The curve *A* gives the specific heat for an ideal Fermi-Dirac gas ( $T_{deg}=4.85^\circ\text{K}$ ). The curve *B* gives the formula  $C_{sat}=0.68T+0.27^\circ\text{K}$  cal/mole-deg derived from the vapor-pressure data [J. G. Daunt, Phil. Mag. Suppl. **1**, 209 (1952)].

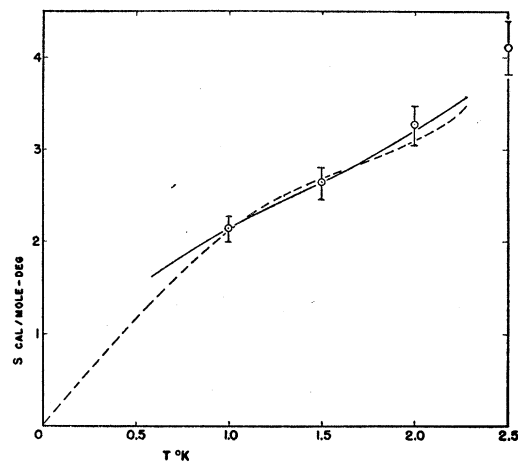


FIG. 2. The entropy  $S$  in cal/mole-deg of pure liquid He<sup>3</sup> as a function of the absolute temperature  $T$  in °K. The full curve gives the entropy curve derived from the measured specific heat. The circles give the values computed by Abraham *et al.* (see reference 5), the broken curve the computed entropy from the vapor-pressure data by Chen and London (see reference 6).

mined in these experiments by the effective range of the type of resistance thermometer which we employed.

It will be seen from Fig. 1 that our new data between 1.3°K and 0.57°K form a smooth continuation of the specific heat curve at higher temperatures which we reported previously.<sup>1</sup> Although there is some scatter in the individual points, it seems clear that there is no marked anomaly of a discontinuous or  $\lambda$ -type nature over the whole range of observation. It is of interest to note, however, the marked flattening of the curve between 0.6°K and 1°K and the fact that no obvious extrapolation of the curve can be made to  $T=0^\circ\text{K}$ .

We have drawn curve *A* also in Fig. 1, the specific heat to be expected for an ideal Fermi-Dirac system of particles of spin  $\frac{1}{2}$  with molecular weight and number density appropriate to liquid He<sup>3</sup>. It is clear by comparing curve *A* with the experimental results that the specific heat of liquid He<sup>3</sup> cannot be approximated by that of an ideal Fermi-Dirac gas, a conclusion which we had previously reached.<sup>1</sup> Moreover, from the fact that the observed specific heat in the range 0.57°K to 1.7°K lies everywhere well below that of the Fermi-Dirac model (curve *A*), it appears that one should conclude that the pairing off or the correlation between the nuclear spins must either be completely removed at temperatures of 0.6°K and up, or that nearly all the spins must still be paired off even at temperatures as high as 2°K. The latter alternative is unacceptable in view of the classical behavior recently observed for the paramagnetic susceptibility of the He<sup>3</sup> spin system in the temperature range 1.2°K to 2.8°K by Fairbank *et al.*<sup>4</sup>

In order to gain further insight concerning the thermal behavior of liquid He<sup>3</sup>, we have made computations of the entropy as a function of temperature. Since our observed specific heat does not allow any clear extrapolation to  $T=0^\circ\text{K}$  we have computed only entropy differences. To obtain Fig. 2, however, we have arbitrarily assumed an exact value for the entropy of pure He<sup>3</sup> at 1.5°K and our results are shown by the full curve. The value chosen for  $S_{liq}$  at 1.5°K was 2.63 cal/mole-deg obtained from the vapor-pressure measurements by Abraham *et al.*<sup>5</sup> We wish to emphasize that although the specific heat measurements of Fig. 1 are for a 96 percent He<sup>3</sup> mixture, our computed entropy of Fig. 2 is, within the accuracy given by the experimental errors, that for pure liquid He<sup>3</sup>. That this is so is evident from the fact that the entropy value of 2.63 cal/mole deg, chosen for  $T=1.5^\circ\text{K}$ , does not include the entropy of mixing. (The classical entropy of mixing for a 96 percent He<sup>3</sup> mixture would be 0.15 cal/mole-deg.)

It is of interest to note in Fig. 2 that the entropy *versus* temper-

ature curve goes through a point of inflexion at about 1.25°K. This inflexion, however, does not appear to mark any significant anomaly. A similar inflexion was computed and London<sup>6</sup> in their re-evaluation of the vapor pressure data of Abraham *et al.*<sup>5</sup> Moreover, between 1°K and 2.3°K our observed entropy confirms approximately the values<sup>5,6</sup> obtained from the vapor pressure data and from the density data.<sup>7</sup> Below 1° however, the slope of the observed entropy curve does not support the computations either of Abraham *et al.*<sup>5</sup> or of Chen and London.<sup>8</sup>

We have considered in detail the contributions to the entropy of the 4-percent He<sup>4</sup> present (which should show a  $\lambda$  temperature at 0.2°K)<sup>8</sup> and of terms stemming from the possible temperature dependency of the heat of mixing, and have found them to be small. Detailed discussion of these results, as well as of the general procedures involved in the measurements, must be deferred to a later publication.

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### Anomalous Optical Absorption Limit in InSb

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TANENBAUM and Briggs<sup>1</sup> have recently encountered an anomalous dependence of the optical absorption limit on impurity content in InSb. They find that the room-temperature absorption limit of an intrinsic sample lies at 7.0 microns while that of a relatively impure sample lies at 3.2 microns. They suggest that the transmission in the region from 3.2 to 7.0 microns is due to an impurity effect. Optical measurements have also been carried out at this laboratory.<sup>2</sup> We find, for example, in agreement with Tanenbaum and Briggs, that the absorption limit of an *n*-type sample containing  $5 \times 10^{18}$  electrons/cm<sup>3</sup> lies at 3.2 microns, while that of an intrinsic sample lies at 7.2 microns. We believe, however, that there is a natural explanation for the anomalous

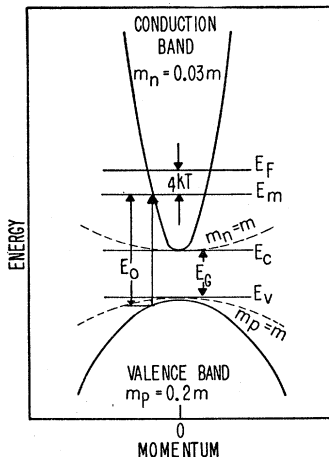


FIG. 1. Energy-momentum diagram of InSb based on  $m_n = 0.03m$  and  $m_p = 0.2m$  giving the position of the Fermi level and that of the lowest unfilled level in the conduction band for an *n*-type sample containing  $5 \times 10^{18}$  electrons/cm<sup>3</sup>. The corresponding energy-momentum curves for a semiconductor for  $m_n = m_p = m$  is shown in dotted lines.

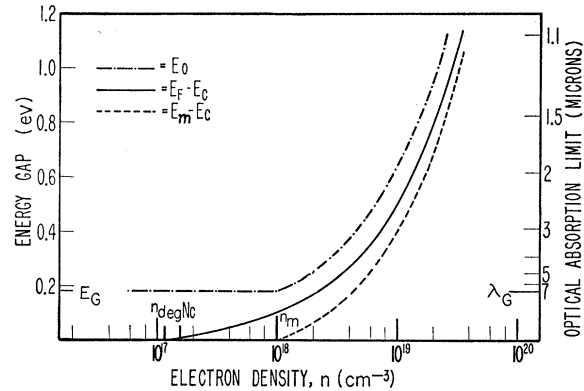


FIG. 2. The dependence of the Fermi level, the lowest unfilled level in the conduction band, and the optical energy gap on charge carrier density in *n*-type InSb.

behavior of the absorption limit which is based on the very small effective mass of the electrons in InSb, rather than on some specific impurity effect.

By assuming that the thermal-energy gap at room temperature is equal to 0.18 eV, the optical energy gap for intrinsic materials, Tanenbaum and Maita<sup>3</sup> obtain a value of  $0.083m$  for the geometric mean of the effective masses of the electrons and holes in InSb. In addition, by assuming a  $T^{-3}$  law for the hole mobilities at high temperatures, they obtain a value of approximately 85 for  $(\mu_n/\mu_p)_L$ , the ratio of electron to hole mobilities in the lattice scattering range of temperatures. Using the relation  $(\mu_n/\mu_p)_L = (m_p/m_n)^{5/2}$  we obtain values of  $0.03m$  and  $0.2m$  for the effective masses of electrons and holes, respectively, in InSb. The very small effective mass of the electrons in InSb results from a sharp curvature at the bottom of the conduction band and is associated with a small effective density of states and with a small degeneracy concentration ( $N_c = 1.6 \times 10^{17}/\text{cm}^3$  and  $n_{\text{deg}} = 1.2 \times 10^{17}/\text{cm}^3$  at 300°K). Consequently, InSb becomes degenerate at relatively low electron densities, and in a degenerate sample the height of the Fermi level above the bottom of the conduction band,  $E_F - E_c$ , increases very rapidly with increasing electron density.

The optical absorption limit of a degenerate *n*-type sample involves vertical transitions from the filled band to the lowest unfilled level  $E_m$  in the conduction band, which lies approximately  $4kT$  below the Fermi level (Fig. 1). The optical energy gap  $E_0$  is therefore given by the energy separation between  $E_m$  and the corresponding level in the filled band which, assuming spherical energy surfaces, lies  $(m_n/m_p)E_m$  below the top of the filled band, and is not just simply given by the minimum separation between the bands  $E_G$ .  $E_m$  is located at the bottom of the conduction band, i.e.,  $E_F - E_c$  is equal to  $4kT$  at an electron density of  $n_m = 6.5N_c = 1.0 \times 10^{18}/\text{cm}^3$ .<sup>4</sup> For *n*-type InSb,  $E_0$  should therefore be equal to  $E_G$  when the electron density is smaller than  $n_m$  and approximately equal to  $E_G + (1 + m_n/m_p)(E_F - E_c - 4kT)$  when the electron density is larger than  $n_m$ . For *p*-type InSb, on the other hand,  $E_0$  should be equal to  $E_G$  for hole densities smaller than  $1.7 \times 10^{19}/\text{cm}^3$ , and approximately equal to  $E_G + (1 + m_p/m_n)(E_v - E_F - 4kT)$  for hole densities larger than  $p_m$ .

The theoretical dependence of  $E_0$  on charge-carrier density for *n*-type InSb is given in Fig. 2. For the *n*-type sample containing  $5 \times 10^{18}$  electrons/cm<sup>3</sup>, we obtain a theoretical optical energy gap of 0.4 eV which is in agreement with the value of 0.39 eV corresponding to the observed optical absorption limit at 3.2 microns.

InSb appears to be the only semiconductor investigated thus far in which the anomalous behavior of the absorption limit is observed. This may be attributed to the fact that the effective masses of the charge carriers in other semiconductors are much larger than the effective mass of the electrons in InSb, so that a much larger carrier density is needed to make them degenerate.