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► **To cite this version:**

B. Gibson, D. Ginsberg. SPECIFIC HEAT OF SUPERCONDUCTING In-Mn ALLOYS. Journal de Physique Colloques, 1978, 39 (C6), pp.C6-872-C6-873. 10.1051/jphyscol:19786388 . jpa-00217856

HAL Id: jpa-00217856

<https://hal.science/jpa-00217856>

Submitted on 4 Feb 2008

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SPECIFIC HEAT OF SUPERCONDUCTING In-Mn ALLOYS⁺

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Résumé.- Nous avons déterminé la discontinuité de la chaleur spécifique des alliages In-Mn à la transition supraconductrice. En comparant nos résultats avec les prédictions basées sur la théorie de Shiba concernant les spins classiques dans les supraconducteurs, nous concluons que la théorie classique ne décrit pas nos résultats de manière adéquate, mais il se pourrait qu'un traitement complet par la mécanique quantique puisse le faire.

Abstract.- We have measured the discontinuity in the specific heat of In-Mn alloys at the superconducting transition. By comparing our results with predictions based on the theory of Shiba for classical spins in superconductors, we conclude that the classical theory does not adequately describe our results, but a fully quantum-mechanical treatment may do so.

INTRODUCTION.- In an attempt to understand the properties of superconductors containing magnetic impurities from the 3-d part of the periodic table, we have measured the specific heat of In alloyed with small amounts of Mn. Abrikosov and Gor'kov developed the first quantitative theory describing the effects of magnetic impurities on superconductors/1/. This was a lowest order perturbation theory, and it is not surprising that it is only qualitatively correct for the 3-d magnetic elements, which interact strongly with the conduction electrons. Shiba developed an exact theory, applicable to strongly interacting impurities/2/. From our measurements we determine the size of the discontinuity in the specific heat at the superconducting transition, and we compare our results with calculations based on the Shiba theory/3/. In developing this theory Shiba made the major simplification of treating the impurities as classical spins. Müller-Hartmann and Zittartz (MHZ) have attempted to treat the problem while retaining the full quantum-mechanical nature of the spins/4/. Unfortunately the problem is so difficult that they have so far been unable to rigorously extend their results beyond the limit of very small impurity concentration. We will use predictions of MHZ to assess the importance of the quantum-mechanical effects which are not treated in the Shiba theory.

Previous data for the specific heat of superconductors with 3-d magnetic impurities have been obtained for Zn-Mn alloys/5/, and the results indicate

that the Shiba theory underestimates the effect of magnetic impurities on the specific heat of superconductors.

TECHNIQUES.- Because of the low solubility of Mn in In, our alloys are made by quench-condensing the material on very thin substrates backed by superfluid He. The sample films, which have thicknesses ranging from 2800 to 5200 Å, are not allowed to warm up until after all the data have been taken.

The heat capacity, C' , of the sample is measured by using ac calorimetry. Heat at average power P is provided to the sample by means of ac current flowing in a thin-film heater. The power is $2P(\cos\omega t/2)^2 = P(1 + \cos\omega t)$, and the temperature of a thermometer attached to the sample responds sinusoidally with an amplitude T_{ac} . If the frequency of the applied power is high enough so that the sample does not come into thermal equilibrium with the surrounding heat bath and yet is low enough so that the heater-sample-thermometer system remains in internal thermal equilibrium, then $T_{ac} = P/\omega C'$. By precisely measuring T_{ac} , and by knowing P and ω , we can determine the total heat capacity of the heater-sample-thermometer system with great precision.

RESULTS AND CONCLUSIONS.- Figure 1 shows some typical data from our experiment. The scatter of the data about the fitted lines is only a few parts in ten thousand. The thicknesses of the films are determined by optical interferometry, and are used to transform our heat capacity data into values of the specific heat C . The results are shown graphically in figure 2, where they are normalized to the re-

⁺ This work was supported in part by the Department of Energy Contract EY-76-C-02-1198

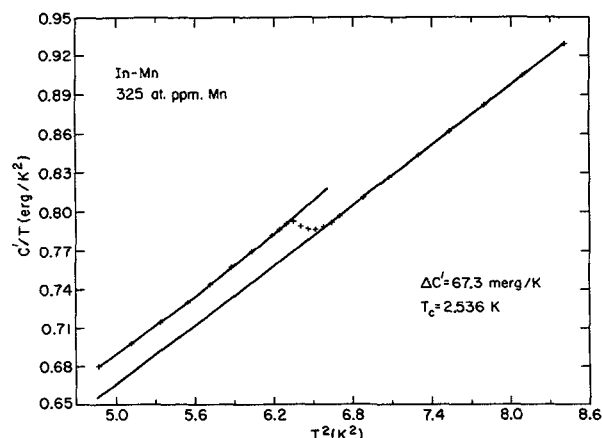


Fig. 1 : The total heat capacity of sample plus addenda, divided by the temperature T . The '+'s are the data points. The line is the best fit of C' to $AT + BT^3$ for the data above the transition. The curve is the best fit of C' to $A + BT + DT^3$ for the data below the transition.

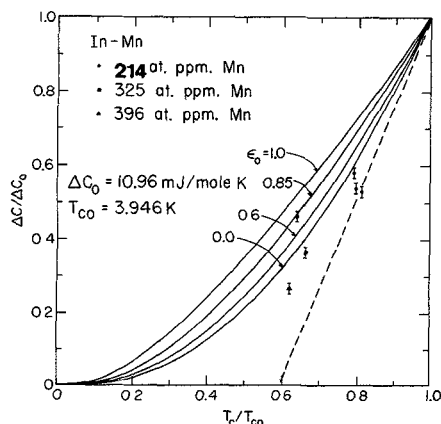


Fig. 2 : The discontinuity in the specific heat at the superconducting transition, ΔC , plotted against the transition temperature, T_c . The axes are normalized to the values for the pure superconductor, ΔC_0 and T_{c0} , which are the averages of four samples of pure In which were examined. The error bars do not take into account the uncertainties in the values of ΔC_0 and T_{c0} , which are approximately 10 % and < 1 %, respectively. The curves represent the theoretical predictions, based on the theory of Shiba. ϵ_0 is a parameter/3/ in the theory lying between 0 and 1, related to the strength of the interaction between the magnetic impurity and the conduction electrons of the superconductor. The straight line represents the maximum initial slope predicted by MHZ.

sults for pure In. It should be noted that our results for four pure In films show scatter that is greater than what we estimate to be our experimental uncertainty ; this may mean that the discontinuity in the specific heat of pure In films is highly de-

pendent on the degree of disorder of the film/6/. In comparing our results with the predictions of the Shiba theory we find that, as in the case of Zn-Mn/5/ the classical theory seems to underestimate the magnitude of the effect of magnetic impurities on this superconducting property. Comparison with the MHZ theory, as shown in figure 2, indicates that a fully quantum-mechanical treatment may explain our results.

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