Superconducting Properties of Cobalt Disilicide

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A solid rod of cobalt disilicide was found to have a superconducting transition temperature close to 1.4°K, a critical field gradient of 146 gauss per degree at the transition point, an ice-point resistivity of 16.5 micro-ohm cm and a residual resistivity of about 16 percent of the ice-point value.

INTRODUCTION

IN a recent paper[1] one of us reported the discovery of superconductivity in the Co−Si system, the transition being observed at about 1.39°K in a powdered cobalt-silicon specimen of approximate composition 1 Co+3 Si. Since from x-ray analysis this specimen appeared to consist of a mixture of the compound $CoSi_2$ and free silicon, it was deduced that $CoSi_2$ became superconducting. Against this, however, it was observed that a powder specimen composed solely of $CoSi_2$ remained normal down to 1.27°K, the lowest temperature then available. It was concluded, therefore, that the true transition temperature of $CoSi_2$ lay below 1.27°K, and that superconductivity appeared at 1.39°K in $CoSi_2$+Si owing to a rise in transition temperature caused by strain or some other effect of the free silicon. This hypothesis was later confirmed by measuring the pure $CoSi_2$ powder down to 1.1°K which revealed a superconducting transition at about 1.22°K.

The importance of this result, that a superconductor might be formed by combining a ferromagnetic metal with a nonmetal, made it imperative to check the above conclusions by measuring the various superconducting properties of a homogeneous, *solid* sample of the new material. In this paper we describe recent experiments in which detailed magnetic and electrical data were obtained down to 1.1°K for a solid rod of cobalt disilicide and which confirmed beyond doubt the superconducting behavior of this compound.

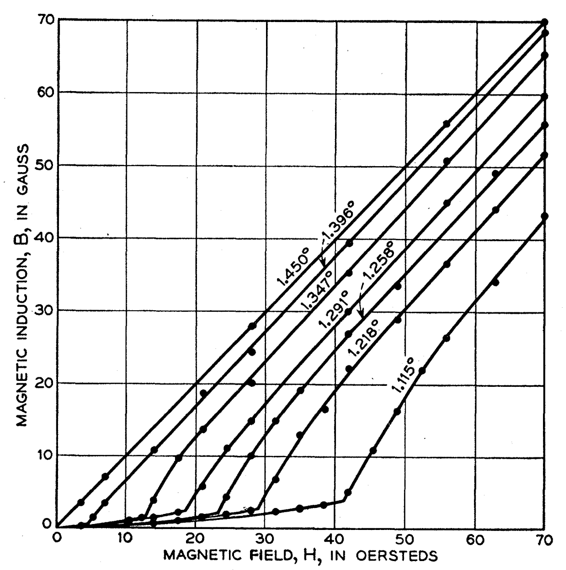

FIG. 1. Variation of magnetic induction with applied magnetic field at various temperatures for a cobalt disilicide rod.

EXPERIMENTAL DETAILS

Several rods of about 8 cm in length and 6 mm in diameter were prepared by casting molten $CoSi_2$ in quartz tubes. A dark blue oxide film was removed from the surface of the rods using 280 carborundum paste, exposing a blue-grey surface in which crystal grains of about 0.1- to 1.0-mm edge could readily be observed. In both the magnetic and electrical measurements the specimens were placed in thin-walled Lucite capsules and lowered into a magnetic apparatus of the type described elsewhere,[2] with, however, the following modifications. To permit reliable critical field data to be obtained from the magnetic induction measurements, a detector coil consisting of a 2-cm length, single layer of enamelled 50-gauge wire containing 755 turns was wound directly upon a specimen rod at about a central position. For electrical resistance measurements, current and potential leads were attached to another specimen by forming each lead from eight

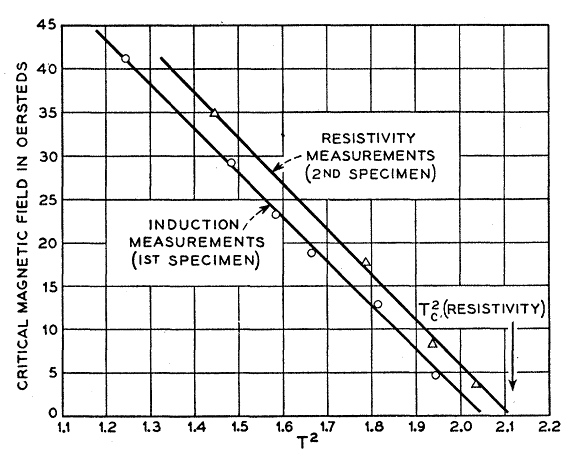

FIG. 2. Plot of magnetic field at which steep rise occurs in magnetic induction (circle points) and electrical resistance (cross points) for a cobalt disilicide rod *versus* T^2.

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[1] B. T. Matthias, Phys. Rev. **87**, 380 (1952).

[2] B. T. Matthias and J. K. Hulm, Phys. Rev. **87**, 799 (1952).

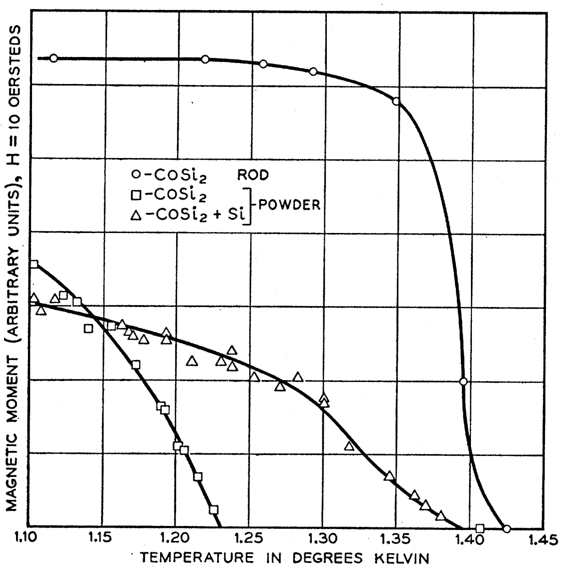

FIG. 3. Temperature variation of magnetic moment for rod and powder samples of $CoSi_2$ and powder sample of $CoSi_2+Si$, ($H=10$ oersteds).

turns of bare 32-gauge copper wire wound tightly around the specimen and tacked with solder at one point. There was a negligible contact resistance between the specimen and these leads over the whole temperature range of measurement.

RESULTS AND DISCUSSION

(A) Magnetic Measurements

Magnetic induction—magnetic field curves obtained for a typical cobalt disilicide rod at various temperatures are shown in Fig. 1. Despite the slow approach to the complete normal state observed at higher fields, which probably indicates a rather poor Meissner effect, the beginning of the transition is quite well marked at each temperature, and it seems reasonable to identify the field at which a steep rise occurs with the thermodynamic critical field of the material. This is borne out by the fact that the field thus obtained is quite accurately proportional to T^2, as is shown by the circle points in Fig. 2. We therefore write the field equation for the particular sample in the form

$$H_c=104.5[1-(T)^2/(1.43)^2] \text{ gauss},$$

which result suggests that $CoSi_2$ must be classified as a relatively soft superconductor from a magnetic point of view.

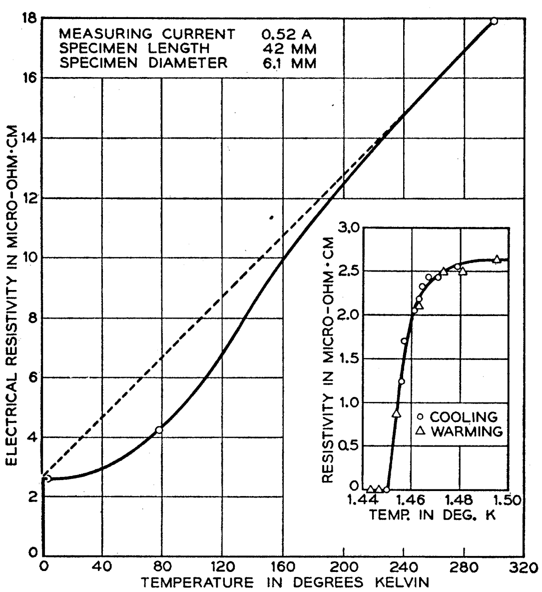

FIG. 4. Temperature variation of electrical resistivity of cobalt disilicide.

The temperature variation of the magnetic moment of the above rod sample in a field of 10 gauss is compared in Fig. 3 with the corresponding magnetic moment for the powder samples of $CoSi_2$ and $CoSi_2+Si$ in which the superconducting studies were first carried

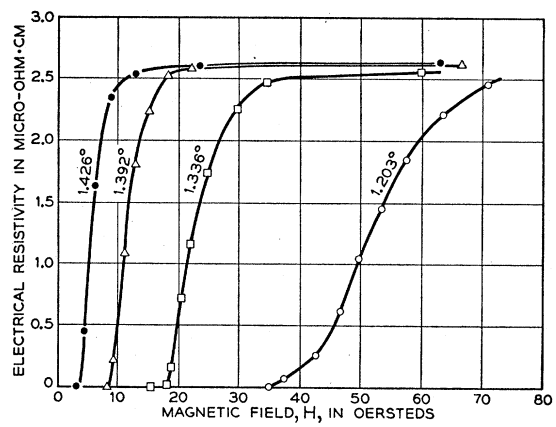

FIG. 5. Isothermal electrical resistance—magnetic field curves for cobalt disilicide.

out.[1] Since x-ray evidence and the residual resistivity data (next section) suggest that neighboring phases in the cobalt-silicon system are probably less than one percent soluble in $CoSi_2$, it seems that the differences of transition temperature between the $CoSi_2$ rod and the $CoSi_2$ powder of Fig. 3 are more likely to be due to differences of strain rather than differences in composition.[3]

(B) Electrical Measurements

The electrical resistivity of a $CoSi_2$ rod taken from the same batch of castings as the magnetic specimen of Sec. (A) was measured in zero magnetic field at room temperature, liquid nitrogen temperatures, and in the range from 4.2° down to 1.1°K, with the results shown in Fig. 4. As regards the high temperature resistivity, we may draw attention to the metallic behavior of the

[3] This assumption seems to be confirmed by Dr. S. Geller's observation that x-ray line broadening was observed to a greater extent in the solid rod than in the powdered sample.

sample despite the presence of 67 atomic percent of silicon, the ideal resistivity at the ice-point, about 13.9 micro-ohm cm, being comparable with that of pure metallic elements. The resistivity was constant between 4.2° and 1.5°K at about 16 percent of the ice-point value, which in comparison with corresponding data on solid solution alloys suggests that the deviation from stoichiometric composition was probably less than 1 percent.

The enlarged portion of Fig. 4 indicates that in zero field quite a sharp superconducting transition was observed at 1.455°K. The curves for restoration of resistance by a magnetic field at temperatures below the transition point were also studied and as shown in Fig. 5 were found to be of a rather gradual type. However, a plot of the field at which the first trace of resistance was restored against T^2 (cross points, Fig. 2) gave a straight line parallel to the critical field line obtained from induction measurements. Thus, allowing for the fact that the transition temperature of the electrical resistivity specimen (1.455°) is slightly higher than that of the magnetic specimen (1.432°K), the field at which resistance begins to be restored is probably quite close to the thermodynamic critical field in the present case.

CONCLUSION

Cobalt disilicide crystallizes in the calcium fluoride structure, in which, to our knowledge, no other superconducting compound has previously been found. Although this structure is usually regarded as typical for ionic compounds,[4] the present work indicates a clear exception in the case of $CoSi_2$. It remains to be seen whether similar exceptions are provided by other isomorphous intermetallic compounds such as $NiSi_2$ and $AuAl_2$, but it may be remarked for the present that neither of these compounds showed magnetic evidence of superconductivity down to 1.1°K.

We are grateful to E. Corenzwit for help in cryogenics, to D. H. Wenney and K. M. Olsen for casting the $CoSi_2$ rods, and to S. Geller for performing x-ray analyses.

[4] A. F. Wells, *Structural Inorganic Chemistry* (Clarendon Press, Oxford, 1945), p. 275.

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Variational Principles for Three-Body Scattering Problems*

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Several stationary expressions for the direct and the exchange scattered amplitudes in three-body collisions are derived.

I. INTRODUCTION

THREE-BODY scattering problems have been solved approximately either by a Born approximation[1] or by variational methods involving a differential operator.[2] We shall discuss here several generalizations for three-body problems of the variational principle proposed by Schwinger[3] for two-body problems.

Important prototypes of three-body scattering problems are those involving the scattering of electrons by hydrogen atoms and the scattering of neutrons by deuterons. In both these cases the indistinguishability of the scattered particle and one of the scatterers creates some special difficulties due to the symmetry conditions imposed on the solution by the Pauli principle. In this paper we shall assume that two of the particles are identical and that exchange effects are consequently important.

In Sec. II of this paper we formulate the problem and indicate how a knowledge of the direct and exchange scattered amplitude enables us to satisfy the Pauli principle without explicitly working with symmetrical or antisymmetrical wave functions. In Sec. III we derive a stationary expression for the direct scattered amplitude, and in Sec. IV we derive a stationary expression for the exchange scattered amplitude.

Finally, we derive in Sec. V still another stationary expression for the scattered amplitudes which is more likely to converge to the correct solution when the trial field is the iterated unperturbed field.

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[1] For a resume of the literature see N. F. Mott and H. S. W. Massey, *Theory of Atomic Collisions* (Clarendon Press, Oxford, 1949), second edition.

[2] W. Kohn, Phys. Rev. **74**, 1793 (1948); S. S. Huang, Phys. Rev. **76**, 477 (1949); H. S. W. Massey and B. L. Moiseiwitsch, Proc. Roy. Soc. (London) **A205**, 483 (1951); M. Verde, Helv. Phys. Acta, **22**, 339 (1949); A. Troesch and M. Verde, Helv. Phys. Acta **24**, 39 (1951).

[3] J. Schwinger, hectographed notes on nuclear physics, Harvard University, unpublished.