The Atomic Heat and Critical Magnetic Field of Superconducting Cadmium

J. R. Clement
Naval Research Laboratory, Washington, D. C.

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Recent calorimetric measurements by Samoilov[1] on cadmium below 1°K have shown an inconsistency between calorimetric data and caloric results deduced thermodynamically from a critical magnetic field equation of parabolic analytic form. Samoilov[1] notes that a rather large linear temperature term is required in the superconducting atomic heat if a parabolic equation is to give correctly the difference between the atomic heats in the normal and superconducting states; yet the calorimetric data for the superconducting state indicate that no such term is actually present. The magnitude of this discrepancy appears to be well beyond the range of experimental error. A similar inconsistency in the data for indium has recently been resolved[2] by assuming that the critical field equation is of cubic analytic form, $H_c=H_0[1-at^2+(a-1)t^3]$, where H_c is the magnetic field which just destroys superconductivity at temperature T, H_0 is the value of this field at $T=0$°K, t is the reduced temperature T/T_c, T_c is the transition temperature in zero magnetic field, and a is a dimensionless constant near unity.

If one takes $464.5T^3/(300)^3$ cal/mole deg for the lattice heat and $1.70\times10^{-4}T$ cal/mole deg for the normal electronic heat, in agreement with Samoilov's conclusions from his normal state data, and $T_c=0.555$°K, one finds, following an analysis similar to that described for indium,[2] that $a=1.20$ and $H_0=29.7$ gauss. In Fig. 1 calorimetric data[1] are compared with calculated curves obtained by adding to the lattice heat, $464.5T^3/(300)^3$ cal/mole deg, electronic heats deduced from the cubic critical field equation. The electronic heat deduced for the normal state is $1.70\times10^{-4}T$ cal/mole deg, the same as that found by Samoilov[1] from his normal state calorimetric data, and that deduced for the superconducting state is $[1.70\times10^{-4}T/2a][15(a-1)^2t^4-20a(a-1)t^3+6a^2t^2+6(a-1)t]$ cal/mole deg. The lack of agreement between the curve and the three superconducting data at lowest temperatures may be due to experimental error since Samoilov notes that there was "an irregularity in the course of the resistance of the (leaded phosphor bronze) thermometer below 0.4°K." Measured critical field data[3-5] are compared with the cubic equation in Fig. 2.

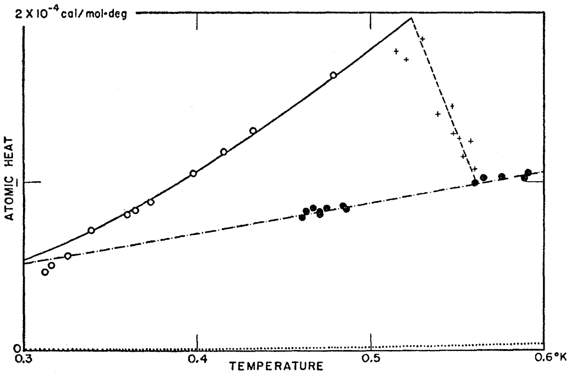

Fig. 1. Comparison of measured calorimetric data with results deduced thermodynamically from a critical magnetic field equation of cubic analytic form. Data obtained by Samoilov (reference 1): ○ in the superconducting state; ● in the normal state; + "in the transition phase." Smooth curves calculated for: —— superconducting state; –·– normal state; ···· lattice; - - - "transition phase" (approximate, assuming that the transition occurs in an earth's field of about 0.6 gauss and that the temperature rises obtained in the calorimetric measurements are always 0.04°K).

A reasonably consistent description of the caloric and magnetic properties of cadmium has thus been obtained, just as for indium, by assuming that the critical magnetic field equation is of cubic analytic form rather than the simpler parabolic form. Certainly these results are not to be interpreted as conclusive evidence that the critical field equation is of exactly cubic form. One can conclude only that the cubic equation is a sufficiently good approximation to the true equation to lead to a consistent description of caloric and magnetic properties within the limitations of experimental error, over the temperature range for which both kinds of data are now available.

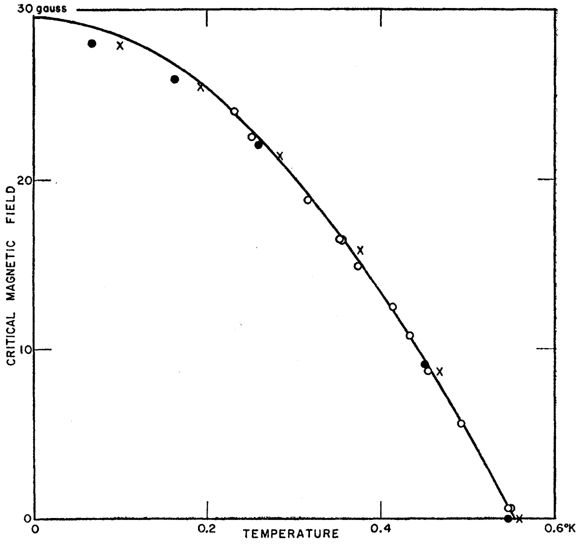

Fig. 2. Comparison of measured critical magnetic field data with a smooth curve calculated from a cubic equation with constants deduced from calorimetric data. Data of: ○ Steele and Hein (reference 3). Curve calculated from parabolic equations reported by: ● Samoilov (reference 4); × Goodman and Mendoza (reference 5).

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[2] J. R. Clement and E. H. Quinnell, Phys. Rev. **92**, 258 (1953).

[3] M. C. Steele and R. A. Hein (unpublished). (The author is indebted to Dr. Steele and Dr. Hein for permission to include their data in this report.)

[4] B. N. Samoilov, Doklady Akad. Nauk. S.S.S.R. **81**, 791 (1951).

[5] B. B. Goodman and E. Mendoza, Phil. Mag. **42**, 594 (1951).

The Interaction Cross Section of Hydrogen and Heavier Elements for 450-Mev Negative and 340-Mev Positive Pions*

S. J. Lindenbaum and Luke C. L. Yuan
Brookhaven National Laboratory, Upton, New York

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The hydrogen interaction cross section for pions of kinetic energies up to about 150–200 Mev have been measured by Anderson, Fermi, and others.[1-4] An investigation of the behavior of these cross sections for negative and positive ions from 150 Mev to about 700 Mev is now in progress using fast scintillation counter telescopes in the external meson beams of the 2.3-Bev Brookhaven Cosmotron.

This letter will report the cross sections obtained for 450-Mev negative and 340-Mev positive pions. The experiment was performed in two different beams using the arrangement shown in Fig. 1. First, the cross sections were determined using the negative 500-Mev π beam analyzed by the Cosmotron magnet. The beam was then analyzed a second time by a momentum selective triple monitor telescope with a deflecting magnet between the second and third counters. A fourth large liquid counter was then placed in quadruple coincidence with the monitor.

In the second arrangement, a direct beam at 32° from the forward direction diagonally through a straight section (without passing through the Cosmotron magnetic field) was defined and momentum analyzed by a similar magnetically selective quadruple telescope.

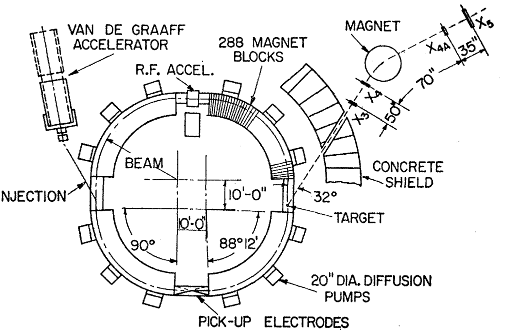

FIG. 1. The schematic arrangement of the scintillation counter telescope in the direct beam produced by the Brookhaven 2.3-Bev cosmotron. X_3 and X_4 are $2\frac{1}{2}$-inch diameter diphenolacethylene crystal counters, X_{4A} is a $1\frac{1}{2}$-inch crystal and X_5 is a 6-inch liquid scintillator. The beam intensity was approximately 10^{10} protons per pulse.

In order to determine the composition of the beams, copper range curves were taken, and it was found that both beams consisted of about 90 percent negative pions and 10 percent negative muons and electrons.

Transmission measurements on polyethylene, carbon, and copper yielded the cross sections,[5] shown in Table I. The results obtained by using several lengths of absorbers came out to be the same within the errors for the two arrangements employed. In the case of hydrogen, a relatively good (6°–13° mean acceptance angle) geometry was used and varied sufficiently to show that the geometry was good enough so that the possible errors due to acceptance of secondaries were smaller than the other errors. In the case of carbon and copper the geometry was chosen to be just poor enough to avoid contributions from shadow scattering. A study of the effects of the variation of the geometry revealed an approximate plateau in the cross section as a function of geometry above the shadow and Coulomb scattering limits. Hence, these results should essentially represent the cross section for all interactions other than shadow scattering. All the listed cross sections have been corrected for the contamination of the beam.

TABLE I. Total interaction cross sections for 450-Mev negative pions.

Element	Cross section in millibarns	Percentage of geometrical cross section using $R=1.37A^{\frac{1}{3}}\times10^{-13}$ cm
Hydrogen	25 ± 3	$46\pm\ 5.7$
Carbon	186 ± 22	$61\pm\ 7$
Copper	730 ± 109	77 ± 11.5

The results show considerable transparency for carbon and copper for negative pions at 450 Mev, and one can deduce the approximate average cross section per nucleon using Serber's[6] model of the nucleus. The results thus deduced are shown in Table II, where the hydrogen result is also listed for comparison.

TABLE II. Average cross section per nucleon for 450-Mev negative pions computed from the observed transparency of carbon and copper.

Element	Computed average cross section per nucleon	Observed hydrogen cross section
Carbon	26 ± 4	25 ± 3
Copper	25 ± 5	

If we compare the hydrogen result with that of Anderson, Fermi, *et al.* ($\sigma_\pi=60\pm6$ mb at 217 Mev) we see that the negative pion cross section has decreased by a factor of about 2.5 from 217 Mev to 450 Mev, indicating a fairly sharp peak in the energy dependence curve of $\sigma_{\pi^-\rightarrow p}$. Although Brueckner's resonance calculations[7] on the pion-nucleon interactions do not appear to agree with Fermi's latest data,[4] they give a calculated total cross section of about 20 mb when extended to 450 Mev, which is not in serious disagreement with our experimental result. Chew is also extending his calculations[8] to higher energies.

Also in Anderson's and Fermi's measurements[1] the hydrogen cross section for positive pions seems to be still increasing at the highest energy measured (135 Mev, $\sigma_{\pi^+\rightarrow p}=125-150$ mb) and the magnitude of the cross section was about 2.5 times that for the negative pions. In order to ascertain whether there exists a peak in the energy dependence of the hydrogen cross sections for positive pions similar to that for negative pions, we have also measured the hydrogen cross section for 340-Mev positive pions.

The second experimental arrangement in the 32° direct beam described above was used to accept all positive particles of the proper momentum emanating from the target at 32° from the forward direction. The high resolution ($2-3\times10^{-9}$ sec) circuitry normally employed in all our measurements automatically eliminated the proton component in the beam because of its longer time of flight through the telescope. The beam composition was also determined by a copper range curve.

An analysis of the range curve confirmed the elimination of the proton component by time of flight and demonstrated that the beam contained about 92 percent positive pions and about 8 percent positive muons and electrons.

Transmission measurements on the polyethylene-carbon difference were performed for a relatively good geometry (mean acceptance angle = 10°). The cross section of hydrogen for 340-Mev positive pions, after corrections for muon and electron contaminations in the beam, was determined to be 48 ± 9 mb. This value when compared to the result of Anderson, Fermi *et al.* ($\sigma_{\pi^+\rightarrow p}=125-150$ mb at 135 Mev) shows that the positive-pion cross section has decreased by a factor of close to 3 from 135 to 340 Mev. The extension of Brueckner's resonance calculations yields value of 66 mb for the positive-pion hydrogen cross section at 340 Mev.

The sharp drop in the hydrogen cross section for both positive and negative pions evidenced in these results and other preliminary measurements (not yet published) enhances the possibility of a resonance or near-resonance interaction.

A detailed description and analysis of the experiment will be presented in the near future.

The authors are greatly indebted to the entire Cosmotron staff, for their assistance and cooperation in this work. We are especially grateful to Dr. G. K. Green and Dr. J. P. Blewett for their valuable advice and cooperation in setting up the proper Cosmotron conditions for this experiment. We also wish to thank Dr. E. O. Salant for his interest and valuable discussions during the course of this experiment.

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Internal Conversion Electrons from Coulomb Excited Ta and W

TORBEN HUUS AND JØRGEN H. BJERREGAARD
Institute for Theoretical Physics, University of Copenhagen, Copenhagen, Denmark

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INTERESTING information can be obtained about the lowest-lying levels in heavier nuclei when these are excited by means of the electrical field of impinging particles which have an energy too low for barrier penetration. In recent investigations[1,2] of such