THE ELECTRICAL RESISTANCE OF CERIUM AT LOW TEMPERATURES AND HIGH PRESSURES

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Submitted to JETP editor December 14, 1961

J. Exptl. Theoret. Phys. (U.S.S.R.) **42**, 1173-1182 (May, 1962)

The temperature dependence of the resistance of two cerium samples is measured between 10° and 300°K at normal pressure and at pressures up to 10,000 kg/cm^2. The measurements are made in a bomb in which the pressure in the working chamber is fixed by a screw. The magnitude and nature of the resistance change for transitions due to temperature and due to pressure are shown to be identical; the pressure transition is not complete up to 10,000 kg/cm^2. The resistance of fcc′-cerium increases linearly with temperature between 50° and 300°K, with $\rho_0^{-1}\Delta\rho/\Delta T = 3.12 \times 10^{-3}$ deg^{-1}. Between 10 and 40°K the temperature dependent part of the resistance is proportional to T^2. The resistance anomaly at 12.5°K found by other authors is not observed. It is suggested that the branches of the phase diagram of cerium below room temperature are parallel. An approximate value is obtained for the temperature at which the jump in ρ at the fcc → fcc′ transition disappears.

IN spite of the continued interest in the properties of cerium—a rare-earth metal whose face-centered cubic lattice undergoes an isomorphous transition on lowering the temperature or increasing the pressure—a number of important questions remain unexplained.

From detailed studies of the structure at different temperatures and pressures, of the phase diagram, of the temperature dependence and partly of the pressure dependence of the thermal, electrical and magnetic properties it is sufficiently firmly established that the face-centered cubic lattice (fcc) of cerium goes over into a similar, but compressed lattice (fcc′) with an 8% volume reduction at low temperatures or at high pressures. This transition is very spread out and shows great hysteresis, the magnitude of which decreases with increasing temperature.[1] There is another transition in cerium at 12.5°K, as many authors have suggested, into the antiferromagnetic state. However, there were no direct indications of this until very recently. The magnitudes of the jumps in specific heat, magnetic susceptibility, and electrical resistance at both transitions are strongly dependent on the specimen history, and this is ascribed qualitatively to the possible presence of the metastable hexagonal close-packed phase (hcp), traces of which were found in a number of specimens at room temperature.

Two papers have recently appeared which further clarified this problem. McHargue and Yakel[2] carried out a detailed x-ray investigation of cerium between room and helium temperatures (at 5—10° intervals). They established that previously annealed cerium specimens, on cooling, start to change to the hcp phase non-isothermally at 263°K; at 96°K the remainder of the fcc phase (about 20%) starts to change to fcc′, and below 77°K the hcp → fcc′ transition starts and this does not go to completion. On heating, the transitions go in the reverse direction, but start at higher temperatures. All the transitions are spread over a considerable temperature interval.

It was found that plastic deformation suppresses the fcc → hcp transition, and if this is carried out at a temperature below 263°K it decreases the corresponding concentration of hcp phase. On the other hand, in agreement with the suggestions made earlier by a number of authors, McHargue and Yakel found that many repeated coolings from room temperature (cycles) increase the amount of the hcp phase at the temperature to which the cooling was carried out; after a hundred cycles to 4.2°K the hcp phase concentration reached 90%.

Wilkinson et al[3] carried out neutron diffraction studies of cerium at temperatures of 300, 77, 43, and 4.2°K. Their results on the phase composition for an annealed specimen and for thermal cycles agree with the data of McHargue and Yakel.[2] However, the effect of decreasing the amount of hcp phase for plastic deformation of a specimen was weaker. They measured the paramagnetic

scattering, the decrease of which on the formation of the fcc′ phase is connected with the change in the electronic configuration of the cerium atom. They concluded from the analysis carried out that there is one magnetic electron in the 4f ($2F_{5/2}$) state in the fcc and hcp phases, but this electron is missing in the fcc′ phase, i.e., the fcc → fcc′ and hcp → fcc′ transitions correspond to an electronic transition from a bound state to the conduction band.

Wilkinson et al[3] relate the magnetic moment calculated from the change in scattering above and below 12.5°K and the presence of additional peaks in the neutron diffraction pictures at helium temperatures, which disappear at 12.5°K, to a transition of cerium to the antiferromagnetic state below this temperature. Comparison of the intensities of the additional reflections with the phase analysis data shows that they refer to the hcp phase (antiferromagnetism is excluded in the fcc′ phase). These conclusions agree with the data of Parkinson and Roberts[4] on the heat capacity of cerium and of Lock[5] on the magnetic susceptibility. These authors found that the magnitude of the magnetic part of the entropy and the susceptibility at 12.5°K is on the first cooling 50% of the maximum value reached after many repeated coolings. In the work of Wilkinson et al the concentration of hcp phase at 4.2°K was 50% after the first cooling and 84% after a hundred, and this agrees well with the data of Parkinson and Roberts and of Lock.

James, Legvold, and Spedding[6] measured the electrical resistance of four cerium specimens between 4.2°K and room temperature. They observed a considerable change of resistance at the fcc ⇄ fcc′ transition and a noticeable break in the resistance behavior at 11—14°K. It was found that the amount of the hcp phase increases on repeated thermal cycling, and as we have seen, this was later confirmed and explains the increase in resistance over the whole temperature range and the increase in the anomaly at 12.5°K with an increase in the number of cycles. However, the magnitude and character of the resistance discontinuity for the fcc ⇄ fcc′ temperature transition differed considerably from data on the transition under pressure.

It seemed to be of undoubted interest to repeat the electrical resistance measurements on cerium over a wide range of low temperatures and to study the influence of pressure on the temperature dependence of resistivity. We had it in mind to obtain the resistance of fcc′ cerium over the whole temperature range of the measurements and to compare the character of the fcc ⇄ fcc′ transitions under pressure and under a change of temperature.

1. APPARATUS

We used the method developed for studying the electrical and galvanomagnetic properties of metals at low temperatures and high temperatures.

Figure 1 shows a section of the high pressure bomb with the specimen. All parts of the bomb are made of beryllium bronze, heat treated to a hardness of 38—40 Rockwell-C. The separate parts used are those customarily used in high pressure practice. The seal is fitted with four miniature electrical leads.[7] The pressure in the working chamber of the bomb is applied at room temperature with the help of a 30-ton hydraulic press. The pressure is measured on the press manometer and by the piston displacement.

A mixture of dehydrated oil and kerosene is used as the pressure transmitting medium and achieves hydrostatic conditions. We chose the concentration of oil following special experiments, so that the mixture should solidify completely at room temperature in the required pressure range. After the pressure was produced in the chamber, the bomb piston was secured in the working position by a nut, bearing on the shoulder of the piston rod transmitting the force. We obtained a pressure of 10,000 kg/cm^2 in such a bomb many times. The bomb with the specimen under hydrostatic pressure was suspended on a secure frame in a Dewar vessel filled with the refrigerant. We determined the pressure in the bomb at the temperature of the refrigerant by means of a special

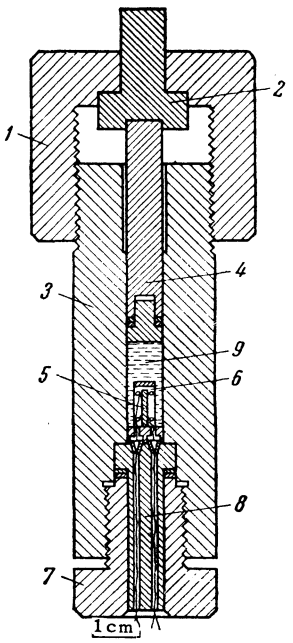

FIG. 1. High pressure bomb: 1—nut, 2—rod transmitting the load from the press, 3—bomb case, 4—working piston with Bridgman packing, 5—specimen being studied, 6—specimen holder, 7—supporting screw of the seal, 8—seal, 9—pressure transmitting medium.

calibration: the resistance of a manganin gauge in the working chamber of the bomb was measured at room temperature for different pressures, and for a few fixed pressures at liquid nitrogen temperature in our bomb and at varying pressure in the apparatus described by Likhter.[8] The pressure in the bomb fell by 26% on cooling to 77°K. Such a method of working under pressure at low temperatures has the advantage that hydrostatic conditions are preserved to a considerable extent on slow cooling, if the surrounding medium does not undergo a polymorphic transition with a change of volume. At present no sufficiently plastic solid is known suitable for achieving hydrostatic conditions when a unidirectional force is applied at temperatures below liquid nitrogen. On the other hand, the virtue of the method is both the relatively small size of the bomb and the extent to which it is self-contained, so that the usual low temperature technique, with a small quantity of refrigerant can be applied. The main drawback of the method is that it is not possible to vary the pressure at low temperature gradually, and this narrows its range of applicability. The introduction of a superconducting manometer into the bomb considerably removes the disadvantage of the unreliability in the measurement of the pressure at low temperatures.

The cerium samples were mounted on the Plexiglas holder which rests on the seal. A soft Dewar was used as cryostat. The temperature was measured with a copper-constantan thermocouple, soldered to the bomb and previously calibrated. Corrections were applied for the difference in temperature between the specimen and the outer surface of the bomb due to the temperature drift. We estimate that the systematic error in the value of the resistance in the region of the maximum temperature drift is about 5% of the measured value. The resistance of the specimen was measured with the usual compensation method using a KL-48 potentiometer and a F-16 photocell amplifier.

2. RESULTS OF THE MEASUREMENTS

We measured the temperature dependence of the electrical resistance of two cerium specimens (V and VI) between 10°K and room temperature at pressures up to 10,000 kg/cm^2.

The original cerium contained: neodymium—less than 0.75%; praesodymium—less than 0.75%; iron—0.2%; cadmium, lead, tin, and bismuth—less than 0.001% each. The specimens were 1 mm diameter cylindrical rods 10 mm long, cut on a lathe under a layer of kerosene. Current and potential leads of copper wire were welded to the specimens by discharging a condenser bank.

Specimen V was first studied under pressure. In addition, the pressure dependence of both specimens was studied for a fixed temperature dependence. Table I shows the results of measurements of the resistance at the fcc $\rightleftarrows$ fcc′ transition under hydrostatic pressure at room temperature.

These results agree with the data of other authors. We note, for example, the satisfactory agreement between our data and the R(P) curve obtained by Lifshitz et al[9] for a cerium specimen containing 0.02% iron.

Data on the history of the specimens is shown in Table II, and smoothed curves of the temperature dependence of the resistivity ρ between 10° and 300°K for different pressures are shown in Fig. 2. In calculating the magnitude of ρ no account was taken of the volume change of cerium with temperature or pressure.

In the first three cycles of specimen V and the last two of specimen VI the specimens were naturally under different pressures in different temperature ranges. The pressures at the extremes of the ranges are shown in Table II. The pressure changes do not affect the conclusions drawn.

If we take the end temperatures of the fcc → fcc′ and fcc′ → fcc transitions as the branching points of the $\rho(T)$ curves, then the width of the wings of the hysteresis loop for both specimens is 65°K, in-

Table I

Cerium specimen	Measurement No.	P_1—pressure of the beginning of the transition on increasing the pressure, kg/cm^2	P_2—pressure of the beginning of the transition on reducing the pressure, kg/cm^2	$P_m = \frac{P_1+P_2}{2}$, kg/cm^2	$\frac{\rho_{fcc}}{\rho_{fcc'}}$ (extrapolated to P = 0)	P_{max} kg/cm^2
V	1	7 500	6 000	6 750	1.51	10 600
V	2	7 600	5 750	6 675	1.54	9 100
V	3*	7 500	5 900	6 700	1.56	9 100
	mean	7 530	5 885	6 710		
VI	1**	8 000	5 200	6 600	1.51	10 000

*After one cooling cycle to 10°K under a pressure of 9,100 kg/cm^2. Cooling to 77°K was carried out in the fcc′ phase.

**After six cycles of cooling without pressure and under pressure. Cooled to 50°K in the fcc′ phase.

Table II

Cerium specimen	Cycle No.	T_{min}, °K	Time of cooling, hours	Time of heating, hours	Pressure, kg/cm² (T=300°K)	Pressure, kg/cm² (T=T_{min})
V after applying pressure three times at 300° K	1*	10	5	50	9 100	6 230
	2**	77	4.5	5	9 100	6 700
	3***	10	24	20	4 700	3 220
	4	10	~8	—	1	1
VI after preparation	1	10	3.5	10	1	1
	2	50	5	20	1	1
	3	10	20	<0.5	1	1
	4	20	<0.5	20	1	1
	5	60	4	20	1	1
	6	50	24	10	4 750	3 360
	7****	50	4	10	10 000	7 070

*The region 10–77°K was traversed twice.
**The pressure was removed before the cooling cycle.
***The pressure was reached by reducing the preceding pressure at room temperature.
****The pressure was reached by increasing the preceding pressure at 300°K; the pressure for the fcc → fcc′ transition was maintained for 20 hours.

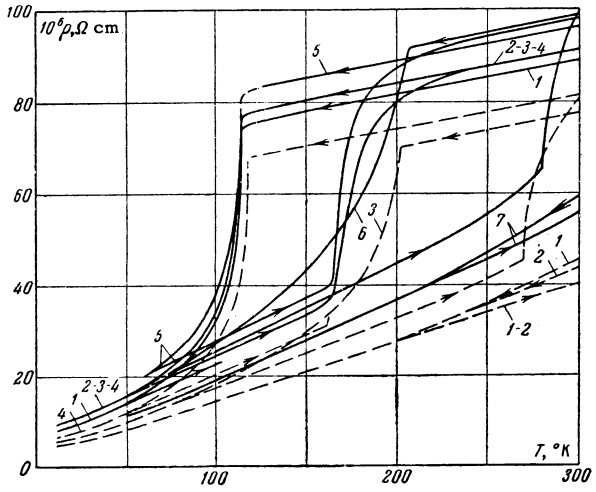

FIG. 2. Resistivity of cerium. Dashed curves–specimen V, full curves–specimen VI. The number on the curves indicates the cycle number.

creasing with a pressure of $(4-5) \times 10^3$ kg/cm² to about 120°. However, the main change of resistance at the fcc ⇄ fcc′ transitions in cycles at atmospheric pressure takes place in a narrow temperature range: in the first 10° after the start of the fcc → fcc′ transition the resistance decreases by more than $0.7\,\Delta\rho$, where $\Delta\rho$ is the difference in resistance between the descending and ascending branches of the $\rho(T)$ dependence at the corresponding temperature. The steepness of the change in $\rho(T)$ decreases under pressure and is $0.4\,\Delta\rho$ in 10°. In 10° the pressure change in the apparatus is ~ 60 kg/cm² and cannot be the reason for the decrease in steepness.

The dashed curves 1 and 2 and the continuous curve 7 of Fig. 2 refer to cerium specimens which were in the fcc′ phase over the whole temperature range, having passed into it at room temperature under pressure. For specimen V, which had three cooling cycles (Table II), the result below 230°K is independent of cycle number. Complete reversibility of resistance was found for both specimens below 180°K. Above 50°K in the region of reversibility and almost up to room temperature on the heating curve, the resistance of fcc′ cerium increases practically linearly with temperature and $\rho_0^{-1}(\Delta\rho/\Delta T) = 3.12 \times 10^{-3}$ deg^{-1} for both specimens, where ρ_0 is the resistance at 293°K after heating up. The $\rho(T)$ curves above the branching points at 180°K are, as can be seen, the tail of a very drawn out wing of the hysteresis loop, corresponding to temperatures above room temperature. The difference in the values of ρ at room temperature at the beginning and at the end of the cycle is ~ 10% in the first cycle for specimen V. The difference could be reduced to 5–6% for the second cycle and for specimen VI by maintaining the specimen under a pressure of $(8-9) \times 10^3$ kg/cm² for 20 hours. It can be concluded from the history of the specimens and from these results that the heating curves refer to relatively pure fcc′ phase.

Regarding the results obtained at atmospheric pressure and at pressures up to 5000 kg/cm², we should point out the linear temperature dependence of the resistivity of cerium in the fcc phase between room temperature and the fcc → fcc′ transition point, obtained on all cycles with practically the same coefficient $\Delta\rho/\Delta T = 7.2 \times 10^{-8}$ Ω-cm-deg^{-1}, and the practically linear dependence of the heating curves in the fcc′ phase from the branching point to the fcc′ → fcc transition point, obtained on the same cycles but with a larger value of the coefficient; the mean value of $\Delta\rho/\Delta T$ changes from 1.45 to 1.9×10^{-7} Ω-cm-deg^{-1} depending on the cycle number.

We have compared our results at atmospheric pressure with the data of James, Legvold, and Spedding (JLS) for specimens III and IV.[6] Our specimens showed a considerably steeper drop in resistance at the fcc ⇄ fcc′ transitions and also a lower value for the resistance at tempera-

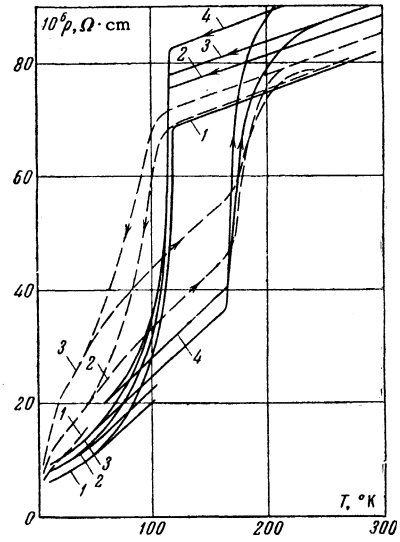

FIG. 3. Resistivity of cerium at atmospheric pressure. Full curves—our data: 1—specimen V, cycle 4; 2—specimen VI, cycle 1; 3—specimen VI, cycles 2-4; 4—specimen VI, cycle 5. Dashed curves—JLS data:[6] 1—specimen III, cycle 1; 2—specimen III, cycle 3; 3—specimen IV, cycle 3.

tures below 100°K (Fig. 3). Although we also observed an increase in the room temperature resistance after several cooling cycles, no definite dependence of ρ_0 on the number of cycles follows from our data. ρ_0 also increased while the specimens were being stored between separate experiments.

Resistivity measurement of specimen VI on the third and fourth cycles was made for different heating and cooling rates. No immediately significant effect was found (in the cooling and heating cycle) on the $\rho(T)$ curve when the heating rate was changed almost 50 times. After the end of the cycle the resistance of the specimen at room temperature increased by 5.5% after 10 days.

We studied the resistance of cerium carefully at different pressures in the range 10—20°K, in which an anomaly was expected. The results of the measurements are shown in Fig. 4. All the curves show a weak temperature dependence of ρ. In specimen V there was no anomaly of resistance with a magnitude of the effect greater than 0.5% of the value measured above 10.3°K (the lower limit of the measurements). The maximum departure of the experimental points from the smooth curve was 0.4% at 3250 kg/cm^2 and less than 0.2% at 1 kg/cm^2. No anomaly was found either in specimen VI on the first cooling cycle, but on the third cycle there is possibly a very small break in the $\rho(T)$ curve at 12.5°K; the maximum departure of the resistance from the smooth curve is 0.2% (the maximum scatter of the experimental points for specimen VI is not more than 0.1%). According to JLS's data the anomaly was noticeable on the first cycle. Our specimens showed a lower absolute value of ρ, which increased with cycle number. This increase is greater than the change of resistance with increase of pressure, as a simple calculation shows. An appreciable residual resistance was found for all specimens at 10°K. Specimen V, cooled from room temperature in the fcc′ phase had a residual resistivity on the first cycle equal to 10% of of $\rho_{fcc'}$ at room temperature. The temperature dependent part of the resistance of all specimens increases as T^2 in the range 10—40°.

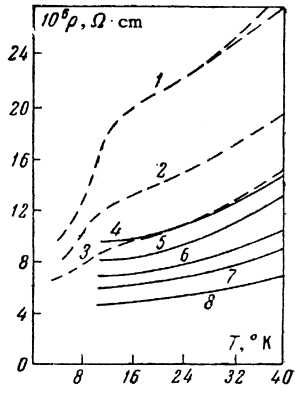

FIG. 4. Resistivity of cerium. Dashed curves—JLS data:[6] 1—specimen IV, cycle 3; 2—specimen III, cycle 3; 3—specimen III, cycle 1. Full curves—our data: 4—specimen VI, cycle 3; 5—specimen VI, cycle 1; 6—specimen V, cycle 4; 7—specimen V, cycle 3 (P = 3250 kg/cm^2); 8—specimen V, cycle 1 (P = 6300 kg/cm^2).

From our data we calculated points of the phase diagram* of the fcc $\rightleftarrows$ fcc′ transition (the transition points are considered the beginning of the rapid resistance change).

The temperature of the fcc′ → fcc transition at atmospheric pressure agrees well with the data of McHargue and Yakel[2] but this is not so with the temperature of the fcc → fcc′ transition. Figure 5 shows the temperatures and pressures of the transitions obtained by us and by other authors. The phase diagram constructed from all the points shows that the fcc → fcc′ and fcc′ → fcc transition curves below room temperature are practically parallel to one another with $\Delta T_m = 50°$, $\Delta P_m = 2200$ kg/cm^2 and $(\Delta P/\Delta T) = 44$ kg/cm^2-deg. The last value agrees with the value of $(\Delta P/\Delta T)_m$ obtained by a number of authors.[9-11] It seems to us that the low temperature part of the diagram shown in Fig. 5 is more nearly correct than the diverging branches of the fcc → fcc′ and fcc′ → fcc transitions at lower temperatures in the work of Ponyatovskiĭ[1] and of Lifshitz et al[9] or the converging branches in the work of Herman and Swenson.[11]

*Since there are definite fcc → fcc′ and fcc′ → fcc transitions, differing in temperatures and pressures, we use the term "phase diagram" provisionally.

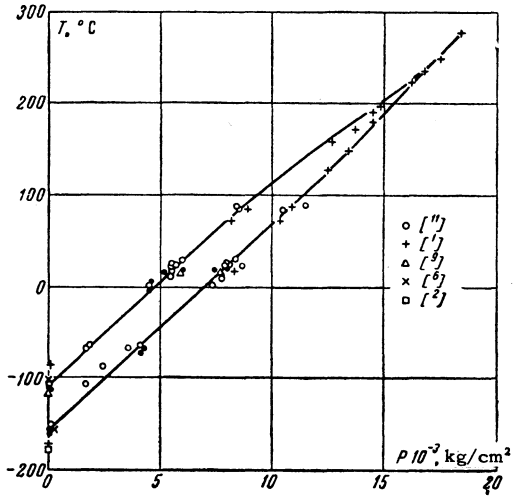

FIG. 5. The phase diagram of cerium according to our data (●) and the data of other authors.

3. DISCUSSION OF THE RESULTS

From the results obtained, the almost complete identity of the resistance change at the fcc $\rightleftarrows$ fcc′ transitions with temperature and with pressure follows. The discontinuity of resistance at the fcc $\rightleftarrows$ fcc′ transition due to temperature change at atmospheric pressure is in the main just as sharp as the discontinuity for the transition under pressure. There is good agreement also in the absolute magnitudes of the resistance change for the transitions: the values of $\rho_{fcc}/\rho_{fcc'}$ extrapolated to room temperature were 1.53 for specimen V and 1.52 for cycles 2—4 and 1.47 for cycle 5 of specimen VI. This agrees with data for $\rho_{fcc}/\rho_{fcc'}$ obtained in our experiments on pressure and with the work of Livshitz et al [9] and extrapolated to zero pressure (Table I). In both cases $\rho_{fcc'}$ is the part of the resistance hysteresis loop between the branching point and the beginning of the fcc′ → fcc transition. It is interesting to note that these results are independent of specimen history. Calculating $\rho_{fcc}/\rho_{fcc'}$ from JLS led to a considerably smaller value; for example this ratio was 1.04 for specimen IV on the third cycle (Fig. 3). The authors explain the considerable increase of resistance they found over the whole range of measurements with increase in cycle number and the cooling period after heating, just by the increase in the content of hcp phase which did not go over to the fcc′ phase at nitrogen temperatures. However, even in the framework of such an explanation there is quantitative disagreement between the data of JLS at hydrogen temperatures and the data on the concentration of hcp phase as a function of cycle number obtained in [2] and [3]. We pointed out at the beginning of this article that there is no such disagreement for the data on heat capacity and magnetic susceptibility.

If it is considered that the results of the determination of the phase composition of cerium as a function of temperature and specimen history, obtained in [2] and [3], are applicable to our results, then it can be assumed that the fcc and hcp phases have the same or very similar $\rho(T)$ dependence. This is confirmed by the drawn-out temperature range of the fcc → hcp transition and the equality of the ratios $\rho_{fcc}/\rho_{fcc'}$ in the temperature and pressure transitions, as shown above. This result also does not contradict the general considerations. Since, according to McHargue and Yakel [2] the hcp → fcc′ transition takes place at a lower temperature than the fcc → fcc′ transition, while the fcc′ → hcp transition takes place over a wide temperature range, including the temperature of the fcc′ → fcc transition, the hysteresis loop of the $\rho(T)$ curve should have and does have wings, the magnitude of which depends on the concentration of hcp phase, i.e., on the specimen history.

As a result of the equality of the relative changes of resistance at the fcc $\rightleftarrows$ fcc′ temperature transition and at the transition under pressure, both transitions can be regarded as complete. However, the branching of the $\rho(T)$ curves under a pressure of $(9—10) \times 10^3$ kg/cm^2 is indisputably evidence of the existence of untransformed fcc phase at these pressures at room temperature. Ponyatovskiĭ who measured the temperature diagram of the fcc → fcc′ transition and confirmed that the transition ended at P = 10,000 kg/cm^2, could not determine whether any amount of untransformed fcc phase remained in his specimens.

It can be seen in Fig. 2 that with increasing cycle number the loop-shaped $\rho(T)$ curves shift almost additively in the direction of larger resistances. The magnitude of the shift is roughly equal to the residual resistivity at 10°K. It is difficult to explain such a shift by the appearance of hcp phase, since it contradicts the assumption that $\rho_{fcc} \approx \rho_{hcp}$. It is possible that lattice defects which arise at each fcc → fcc′ transition, because of the large compression, are the reason for the shift.

From the larger ratio $(\Delta\rho/\Delta T)_m$ for the $\rho(T)_{fcc'}$ curves compared with $\rho(T)_{fcc}$ and the near linearity of the latter with temperature, a value for the temperature T_0 at which $\rho_{fcc}(T_0) = \rho_{fcc'}(T_0)$ can be obtained by extrapolation to high temperatures, i.e., the discontinuity of ρ at the fcc $\rightleftarrows$ fcc′ transition in cerium disappears.

We made a graphical extrapolation for five $\rho(T)$ curves: cycles 3 and 4 of specimen V and cycles 2—4, 5, and 6 of specimen VI and obtained $T_0 = 578°K$. Evidently there is a pressure P_0 at which the fcc′ phase is formed, the upper limit of the temperature range of existence of which is equal to T_0 and the resistivity $\rho_{fcc'}(T_0) = \rho_{fcc}(T_0)$ Ponyatovskiĭ, who determined the phase diagram of cerium at high temperatures and pressures, found that at $P_0 = 18{,}000$ kg/cm^2 and $T_0 = 553°K$ hysteresis and the heat of transition for fcc $\rightleftarrows$ fcc′ become zero [1] (Fig. 5). Considering the range of our extrapolation, the extent of the agreement between the values of T_0 is quite remarkable.

Over a wide temperature range, the resistance of fcc′ cerium has a temperature coefficient of the same order as most metals. The difference in the absolute values of ρ of the fcc′ phase for specimens V and VI may be connected with the existence in specimen VI of some amount of hcp phase formed during the six preceding cooling cycles and not transforming into the fcc phase under pressure, and with differences in the magnitudes of the pressure. However, it is to some extent also produced by different lattice defects and errors in determining the geometrical dimensions of the specimens (ρ/ρ_0 is nearly the same for both specimens). The last two reasons concern the differences of $\rho(T)$ in all phases. If it is assumed that all the residual resistance of specimen V on the first cycle is due to impurities and defects ($\Delta\rho = 4.3 \times 10^{-6}$ Ω-cm), then without these, at room temperature, $\rho_{fcc'} = 36 \times 10^{-6}$ Ω-cm.

Using the above value of $\rho_{fcc}/\rho_{fcc'}$ the resistivity of fcc cerium free of defects and impurities is calculated to be $\rho_{fcc} = 55 \times 10^{-6}$ Ω-cm at room temperature.

It is difficult to explain the absence of a resistance anomaly at 12.5°K in our specimens just by an insufficiently low measuring temperature. We suggest that the reason lies rather in the fuller fcc → fcc′ transition in our specimens, which is connected with their history. The lower absolute values of ρ for our specimens at hydrogen temperatures and the much smaller $\rho(T)$ wings at the fcc → fcc′ transition, compared with the data for the JLS specimens (Fig. 3) point to the existence of a smaller concentration of hcp phase in our specimens below 100°K, which undergoes the antiferromagnetic transition at 12.5°K.

In conclusion I must thank Corresponding Member L. F. Vereshchagin for his interest in the work and for his valuable advice, A. I. Likhter for discussion of the results and V. A. Sukharov for help with the measurements.

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Translated by R. Berman
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