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Electrical resistance of nickel in the range 300–725 K and 0–2 GPa

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The electrical resistance R of Ni has been measured as a function of temperature T and pressure p over the range 300–725 K and 0–2 GPa (0–20 kbar). In contrast to recent reports, we see no anomalies in $R(p)$ at 300 K, and we see no change in sign in dR/dp at the Curie temperature T_C. The pressure coefficient of R was -1.82×10^{-2} GPa^{-1} at 300 K, increasing with T to a peak value of -2.5×10^{-2} GPa^{-1} at T_C, above which it rapidly decreased to a value 20% below the room-temperature value. The data are analyzed using simple models; the resistivity at constant volume is found to deviate significantly from the constant-p data above T_C and a small anomaly is detected in $d(\ln R)/dp$ that could possibly be an effect of band-structure changes at T_C.

I. INTRODUCTION

In a series of papers, Yousuf *et al.*[1–3] have reported measurements of the electrical resistivity ρ of nickel under pressures p up to 5 GPa (50 kbar) and at temperatures T from 300 to 680 K, well above the Curie temperature $T_C \simeq 630$ K. Their results showed two surprising features: (a) The pressure coefficient $\beta\,[=d(\ln\rho)/dp]$ changed sign above T_C and (b) at 293 K there was a significant increase in $|\beta|$ at 2.5 GPa. The former result implies large changes in the band structure of Ni at T_C, which should have important consequences for the theory of the structural, transport, and magnetic properties of Ni; the latter observation seems to verify the existence of a second-order phase transition reported[4–6] to occur between 1 and 2.5 GPa.

In view of the importance of the results an independent verification should be of some value, and in particular we wanted to repeat these measurement under truly hydrostatic conditions. It is well known[7–9] that resistance measurements performed in solid pressure transmitting media (such as those used[1] by Yousuf *et al.*) are not very accurate at pressures below 2–3 GPa, which could explain the second anomaly. Also, it would be interesting to see whether the enormous, linear increase in β with T (or, equivalently, the increase in $d\rho/dT$ with p) reported continues beyond 700 K.

We have therefore measured the resistance R as a function of T between 290 and 725 K under hydrostatic pressure along several isobars in the range 0–2 GPa on four Ni samples with different properties. Contrary to the results of Yousuf *et al.* we do not find dR/dp to change sign at T_C at any p below 2 GPa. We have also measured[9] R up to 5 GPa at 293 K, and we find R to be a smooth function of p, with β values in good agreement with other literature data[5,10,11] and with no anomalies. Due to the nonoverlapping ranges in p above 300 K we can not rule out that β actually does change sign at T_C above 2 GPa, but we strongly suspect that all anomalies observed by Yousuf *et al.* are artifacts caused by the use of a solid pressure transmitting medium.

In Sec. II we describe our experimental setup and, in particular, a new oven used, in some detail. In Sec. III we present our results for $R(T,p)$; we also discuss some of the experimental difficulties encountered, since this might be of some help in future experiments. Finally, the experimental results and their implications are discussed in Sec. IV.

II. EXPERIMENTAL DETAILS

All measurements were carried out in a piston-and-cylinder device, 70 mm in inside diameter, with the necessary force being produced by a 60-MN hydraulic press. T and p were measured *in situ*, using a Chromel-Alumel thermocouple and a calibrated Manganin gauge,[12] respectively. We did not correct T for the (small) effect of pressure[13] on the thermocouple. The pressure transmitting medium used was a silicone oil (Dow Corning DC200, viscosity grades 1 or 5 mm^2/s), known to be stable to above 900 K under pressure[14] and hydrostatic to above 1.5 GPa at room temperature,[15] and significantly higher above.[14,15]

A specially designed oven, shown in Fig. 1, was used to obtain high temperatures in the pressure cell. The oven, also used in other recent experiments,[16] was constructed from an Al_2O_3 rod with 12 axial holes near the periphery. A heater wire (0.15-mm-diam Kanthal A alloy) was wound through these holes (see upper part of the figure) and fixed in place using ceramic cement (Cerastil C-10). A central axial hole, 4 mm in diameter, was obtained using an ultrasonic grinder. The oven was thermally insulated by a layer of spun silica wool and inserted into a Pyrex tube to minimize heat losses (lower part of the figure). In use, the specimen investigated was placed in the central third of the oven, while its outer parts were filled with silica wool to provide thermal insulation and stop convection currents, and thus to minimize temperature gradients. Since the walls of the Teflon pressure cells used soften appreciably above 450 K most measurements were performed as isobaric temperature sweeps between 300 and >700 K at a rate of 5–20 K/min. However, by adding further insulation around the oven con-

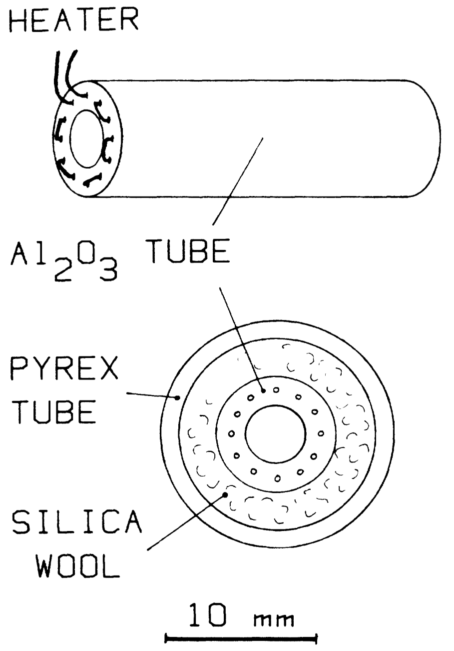

FIG. 1. Oven design used in the high-pressure experiments.

tinuous operation at 700 K was possible without heating the cell walls above 370 K, and isothermal measurements of $R(p)$ could thus also be carried out up to this temperature.

R was calculated from the voltage drops over the sample and over a 10 mΩ standard resistor connected in series, respectively, at a direct current of <0.1 A. Since no thermoelectric effects were noticed when testing the system in air, current reversal was not used in the early runs, but this feature was added later as discussed below.

Four different Ni specimens with different purities and from two different sources were studied (see Table I) in order to see any effects of the physical state of the material. Specimen A was obtained from Goodfellows Metals, England, while all other samples were bought in the form of wire, 1 mm in diameter, from Koch-Light Ltd., England. Specimen B was taken from the same piece of wire as the samples studied previously[10] and was hammered to a foil, 0.1-mm thick, being etched in dilute HCl (to remove traces of Fe) and annealed at 1000 K between hammerings. Identically treated samples from the same source were studied up to 5 GPa at 293 K by Andersson *et al.*[9] C and D finally, were from a new batch of wire and were drawn to a final diameter of <0.5 mm. To avoid contamination, drawing was carried out in small steps, using simply a set of pliers, with intermediate anneals at 1000 K. Since the end parts were cut off after drawing and the actual sample never touched with any tools, the original purity should have been preserved. The data for sample C, however, indicated a rather low dR/dT, characteristic of an impure sample; this might also be connected with an unusually large scatter in R above 500 K, possibly indicating a problem with the potential contacts. A comparison with the data of Laubitz *et al.*[17] confirms the high purity of sample D, and the resistance ratios $R(600\ \mathrm{K})/R(300\ \mathrm{K})$ for the four samples follow the trend expected from the differences in purity. We did not measure the residual resistance ratio (RRR) $\mathcal{R}=R(273\ \mathrm{K})/R(4\mathrm{K})$, since the same information is given by $R(600\ \mathrm{K})/R(300\ \mathrm{K})$, nor did we measure the absolute value of ρ. (A comparison with Ref. 17 gives estimates of 8, 14, 9, and 190 for the RRR's of samples A–D, respectively.) We concentrate here on the data for the purest specimen, D.

Each specimen was shaped as a short helix and annealed for more than 3 h at 1000 K before being inserted into the oven. To improve heat transfer the helix diameter was adjusted such that the sample pressed lightly on the inner surface of the oven. Four fine Ni wires were spot welded to each specimen to serve as current and potential leads, and these were soldered to copper wires well outside the oven and near the cell wall. Care was taken to ensure that all Ni-Cu contacts were kept at the same temperature, and in no case did we observed thermoelectric effects that could be traced to these contacts.

We also measured $T_C(p)$ using an inductive method. A short piece of wire (specimen E in Table I) from the same spool as samples C and D was bent into a square loop and annealed for 3 h at 1000 K. Two orthogonal coils were wound onto the sides of this transformer core, and the output voltage from the transformer measured as a function of T using a lock-in amplifier. T_C could then be found as the temperature at which this voltage dropped to some stable, near-zero, high-T value, with a precision of better than 0.2 K.

TABLE I. Physical properties of the specimens studied.

Sample	Stated purity (%)	Diameter (mm)	R at 300 K (mΩ)	$\frac{R(600\ \mathrm{K})}{R(300\ \mathrm{K})}$	T_C (K)
A	99	0.25	120.4	3.276	624±1
B	99.997	0.1×1.5^{a}	38.20	3.386	630±1
C	99.997	0.45	16.47	3.304	632±2
D	99.997	0.5	10.07	3.528	630±1
E	99.997	1.0			629.8 ± 0.2^{b}
Ref. 17	99.999			3.531	

[a] Annealed hammered foil.

[b] Measured inductively.

III. EXPERIMENTAL RESULTS

A. Curie temperature versus pressure

The Curie temperature T_C was measured in two ways, either from $R(T)$ or by the inductive method. A well-defined anomaly was always found in R at T_C, and from the position of this anomaly T_C could be determined to within better than 1 K. At $p=0$, T_C was in excellent agreement with literature data (see Table I), but to our surprise we found a nonlinear dependence on p: T_C first decreased with increasing p, with a minimum 2–5 K below $T_C(0)$, then increased rapidly such that at $p>0.75$ GPa it was again in excellent agreement with literature[18] data. The same behavior was found using the inductive method. We do not believe this to be an intrinsic effect, however. Instead, it was probably caused by thermal gradients between sample and thermocouple: The sample was always in good thermal contact with the oven wall (see above), while the thermocouple was brought in through the center of the oven with only the thermopoint in contact with the wall. The viscosity of the pressure medium increases[19] very rapidly with increasing p, and the effects observed were probably caused by convection cooling of the thermocouple wires (inside or outside the oven) at low pressures, where the viscosity is still low. From the data at $p=0$ and at $p>0.75$ GPa we find an average $dT_C/dp=0.31$ K/GPa (uncorrected for the pressure effect on the thermocouple[13]), in excellent agreement with literature data.[18]

B. Electrical resistance

Figure 2 shows R versus T for specimen D between 300 and 700 K, at 0.1 and 2 GPa. The two curves of R versus T are similar, and, in particular, R is "linear" in T above T_C in both cases, with no noticeable change in dR/dT with p, in contrast to the results of Yousuf *et al.*[1–3] This fact is shown more clearly by Fig. 3, in which we show experimental data for $R(T)$ at various pressures on an expanded scale between 600 and 700 K for the same specimen, for which we measured $R(T)$ over this range in T during 21 runs at 16 different pressures. Similar results were obtained for all samples studied, and in no case could we ever observe any significant change in dR/dT with pressure below 725 K, the highest T normally reached; in two runs we extended the range to 800 K with the same result. All data shown in Fig. 3 were collected while increasing T. Above 600 K, T was always changed at the rate ±10 K/min, and a small hysteresis, equivalent to a ΔT of 1–3 K, was usually observed. Below this, T was swept more rapidly (±20 K/min) and the hysteresis was larger. As discussed above, T_C also seemed to vary nonlinearly with p. To correct for this effect all data for T below 0.8 GPa were multiplied by a correction factor proportional to $(T-300)$ K, chosen such as to make T_C linear in p.

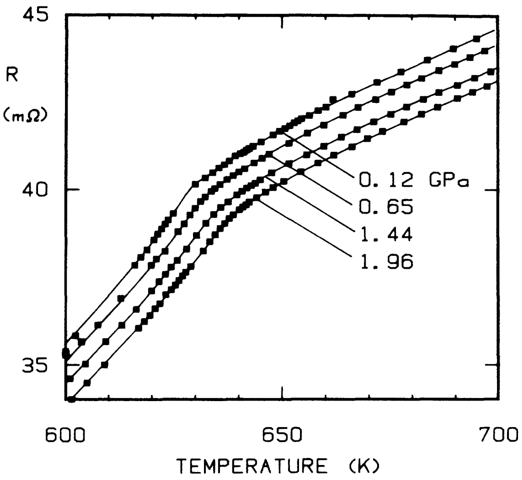

FIG. 3. R vs T between 600 and 700 K at the pressures indicated.

Direct isothermal measurements of $R(p)$ were also made on the same specimen at 300, 600, and 700 K, and we show in Fig. 4 the results obtained at 700 K (squares:

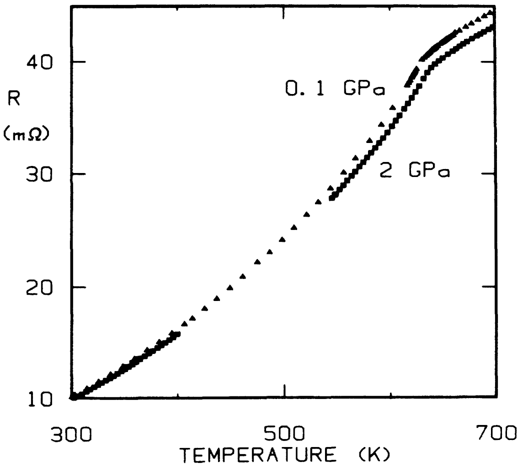

FIG. 2. R vs T of specimen D at 0.1 and 2 GPa.

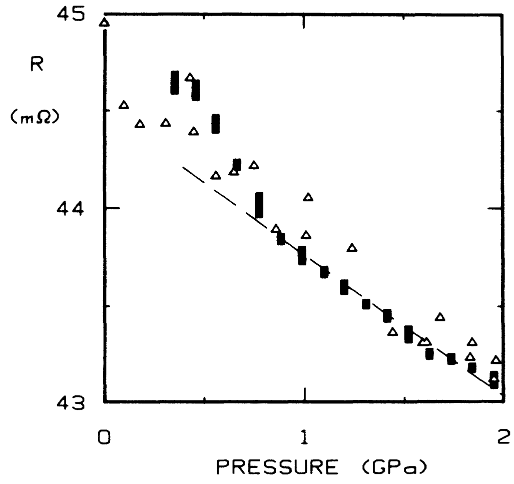

FIG. 4. R vs p at 700 K. Squares and the dashed line, results from isothermal experiment; triangles, interpolated data from isobaric experiments.

the data have been corrected to constant T using the known dR/dT, since the actual T varied by up to ±2 K during the measurement). While dR/dp is, indeed, negative at all p, it does not appear to be constant. Above 0.8 GPa a linear function of p can be fitted to the data with a relative rms deviation of 0.06% (dashed line), but below 0.7 GPa R is significantly larger. Anomalies such as this were observed in all isothermal runs above 450 K. Again, we do not believe that these anomalies reflect the true behavior of $R(p)$, but only the effect of convection cooling of the thermocouples; unfortunately, for the isothermal runs we have no way of correcting the resulting error in the apparent T. (Note that this effect did not noticeably change dR/dT at constant p, only the vertical spacing between curves of the type shown in Fig. 3.) In Fig. 4 we also show as a comparison the data from all isobaric sweeps for the same specimen, interpolated to 700 K (triangles). The scatter in the data is very much larger in this case, as expected, but the agreement between the two sets of data is excellent. Much of the scatter observed is due to the hysteresis mentioned above.

The false resistance anomaly shown in Fig. 4 was not the only one observed. Similar results were also observed for specimens $A-C$. For specimen C much larger, repeatable anomalies, involving drops in R of up to 20% with increasing p and a positive dR/dp above, were noted above 450 K between 0.5 and 0.8 GPa. Although we first ascribed these anomalies to some previously unknown phase transition, we later traced them to the thermoelectric effects at the junctions between the Ni sample and the Ni potential leads, which presumably were less pure. These anomalies all vanished when current reversal was used in later experiments. True anomalies in R (indicating sample damage) were only observed when changing p near 300 K above 1.2 GPa, where the pressure medium is known to be solid; for example, in the last run on specimen D we decreased p from 1.6 GPa at 295 K and observed a sharp step change of 1.6% in R at 1.2 GPa, corresponding to the glass transition pressure[15] of the medium.

It is evident from Figs. 2 and 3 that the pressure coefficient β does not change sign at T_C. In Fig. 5 we show our experimental values for $d(\ln R)/dp$ ($=\beta+\kappa/3$, where $\kappa=5.3\times10^{-3}$ GPa^{-1} is the compressibility[20]) as a function of T for sample D, together with most available literature data.[3,5,10,11,21–23] The open squares denote the results obtained in the isothermal runs in the range 0–1.2 GPa at 300 K, and above 0.75 GPa at 600 and 700 K. Our 300-K result $d(\ln R)/dp=-1.82\times10^{-2}$ GPa^{-1} is smaller than our previous result[9,10] but agrees well with the various literature results, except for those of Yousuf *et al.*[1–3] and Hiraoka.[23] (We do not show the value obtained by Andersson *et al.*[9] since this is virtually identical to that found by Villain *et al.*[11]) Below room temperature $d(\ln R)/dp$ seems to approach a constant value of about -1.95×10^{-2} GPa^{-1}, implying $\beta=-2.1\times10^{-2}$ GPa^{-1}.

In the range 600 to 725 K we made a large number of isobaric runs, and here we have calculated $d(\ln R)/dp$ at several temperatures by fitting interpolated data for R from the various runs to linear functions of p; these results are indicated by the closed squares in Fig. 5. Between 300 and 600 K a smaller number of measurements were made, and these were done at high heating or cooling rates ($\geq\pm20$ K/min), resulting in a larger scatter and hysteresis than for the high-T data. Furthermore, the low-p T correction might not be very accurate here, and above 1.2 GPa the pressure medium solidifies at some (unknown) temperature between[15] 350 and 500 K, probably adding a strain component to the resistivity of the specimen (see above). We thus cannot obtain accurate values for $d(\ln R)/dp$ in this range. No data are shown for specimens $A-C$ due to the various experimental problems discussed above; however, for all these samples $d(\ln R)/dp$ was in the range $(-1.8$ to $-2.0)\times10^{-2}$ GPa^{-1} near 300 K.

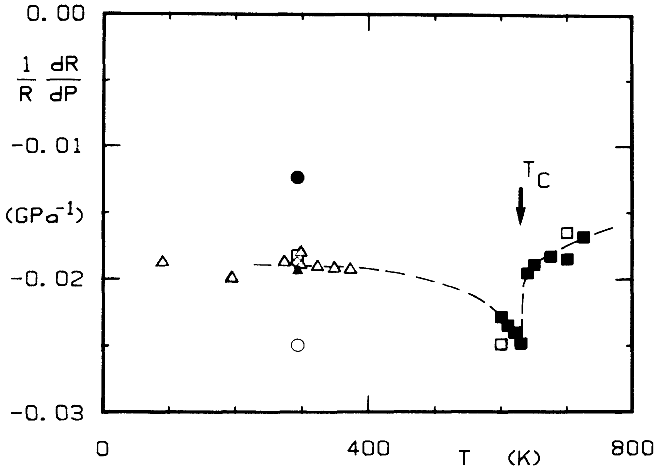

FIG. 5. Pressure coefficient of R vs T. Symbols denote the following: ■, this work, isobaric runs; □, this work, isothermal runs; ●, Yousuf *et al.* (Refs. 1–3). △, Bridgman (Refs. 5, 21, and 22); ◇, Sundqvist (Ref. 10); ○, Hiraoka (Ref. 23); ▲, Villain *et al* (Ref. 11). Dashed line is a guide for the eye only.

IV. DISCUSSION AND CONCLUSIONS

A. Phase transitions under pressure

The present work was undertaken mainly to check the results of Yousuf *et al.*[1–3] that (a) β changes dramatically near 2.5 GPa at 295 K, and (b) that β changes sign at T_C. As shown elsewhere,[9] we find no evidence for the first of these points; $R(p)$ is a smooth function of p up to 5 GPa at 293 K, with a small positive d^2R/dp^2, in contrast to the strong negative curvature found by Yousuf *et al.* We believe that the results of Yousuf *et al.* were caused by inhomogenous strain induced in their samples through the use of a solid pressure-transmitting medium. This also explains their very low value of β (see Fig. 5). As pointed out elsewhere,[7–9] great caution is necessary when evaluating high-pressure data for R obtained in solid pressure-transmitting media, and true hydrostatic conditions are always essential to obtain accurate quantitative data. However, the present work has also shown that high-T measurements under hydrostatic conditions can be very difficult and must be performed very carefully in order to give accurate and repeatable results. In particular, when large temperature gradients are present, the experimentalist must be aware that convection can produce large, unexpected effects in the data.

As to the second point, we have not, strictly speaking, ruled out the effect suggested by Yousuf *et al.* We have shown that, under hydrostatic conditions, there is no change in sign in β at T_C below 2 GPa. We have no new information on β near T_C above 2 GPa, in the range studied by Yousuf *et al.* There have been several reports of high-p anomalies in various physical properties of nickel, such as κ^4, ρ^5, and specific heat capacity;[6] however, these reports have not been verified by later work, and it is generally assumed that there are no high-p phase changes within the accessible pressure range. On the other hand, since nickel is known[24] to exist in a hexagonal form at $p=0$, and an fcc$\rightarrow$hcp transition under extreme pressures has been predicted[25] theoretically, we can not rule out that some type of phase transformation might occur at $p>2$ GPa and $T>400$ K, possibly only (or preferably) under nonhydrostatic conditions. We do, however, find this possibility unlikely, and we believe that the observed[1-3] change in sign in β is also due to the nonhydrostatic conditions of that particular experiment.

TABLE II. Electrical resistivity of Ni vs T. ρ_{expt} are data from Ref. 17, ρ_p are the same data corrected for thermal expansion, and ρ_V are corrected to constant volume $[V=V(T=0)]$. (Resistivities are in $\mu\Omega$ cm.)

T (K)	ρ_{expt}	ρ_p	ρ_V
90	0.762	0.760	0.759
100	0.986	0.984	0.982
125	1.585	1.582	1.575
150	2.237	2.233	2.216
200	3.703	3.699	3.652
250	5.384	5.381	5.276
300	7.237	7.237	7.048
400	11.814	11.832	11.323
500	17.704	17.757	16.62
600	25.554	25.670	23.57
630	28.862[a]	29.007[a]	
650	30.142	30.304	27.0[a]
700	32.237	32.436	29.0
800	35.637	35.916	31.2
900	38.676	39.045	32.8
1000	41.496	41.963	34.1
1100	44.166	44.741	35.0
1200	46.728	47.421	35.9

[a] T_C.

B. *P* and *T* dependence of the resistivity of nickel

The main new results of this investigation are the data for $d(\ln R)/dp$ near and above T_C, in a range where we know of no reliable previous data. Since the resistivity of Ni is not well understood, these data might be of some importance. First, they can be used to calculate the T dependence of ρ under isochoric (constant-volume) conditions, which is what is usually found from theoretical calculations, and second, $\beta(T)$ itself might give some insight into the conduction mechanisms.

We have made a brief, approximate calculation of the constant-volume resistivity ρ_V, taking data for ρ from ref. 17, thermal expansion data from Ref. 26, and using (extrapolated) data for $V(p)$ from Refs. 4 and 20, correcting the raw data for ρ for thermal expansion but not taking into account any change in κ with T, nor in β with p. The results for $V=V(T=0)$ are shown in Table II. The difference between ρ and ρ_V is surprisingly large at high T, due to the small κ and the large thermal expansion. (At 650 K, $p\simeq 5$ GPa is necessary to bring V down to the same value as at $p=0$ at 0 K.) $d\rho_V/dT \ll d\rho/dT$ at very high T, with a large, negative component proportional to T^2 in ρ_V, possibly due to band-structure effects. However, we shall not discuss ρ_V further here. Due to the various extrapolations and approximations used we estimate that the correction to isochoric conditions might be in error by up to 50% at the highest T shown, making quantitative discussions of ρ_V rather pointless. Better data for κ to 20 GPa are necessary to obtain accurate data for ρ_V.

For Ni, ρ is a sum of several contributions, none of which is very well known or understood. Schematically we can write

$$\rho=(\rho_0+)\rho_{ep}+\rho_{ee}+\rho_{\text{mag}} , \tag{1}$$

where ρ_0 is caused by impurity scattering and the other three terms are caused by scattering of electrons by phonons, electrons, and magnetic disorder, respectively. Yousuf *et al.*[3] have discussed the last three terms and their T and p dependence in some detail, and found excellent agreement between calculated resistance data and their experimental data for β (at 295 K) and $R(T)$. However, since our β (and all other literature data; see Fig. 5) is more than 50% larger than theirs, their calculation is in error by the same amount. Near T_C they find $\rho_{ee}\simeq\rho_{ep}<\rho_m$; since $\rho_{ee}\sim T^2$ this is unlikely, in view of the large negative T^2 dependence actually observed in ρ_V at high T. Finally, for ρ_{ep} they use basically Mott's two-band s-d model, which is also known[27] to be doubtful.

Since so little is known about $\rho(T,p)$, any discussion of our results must also be very uncertain. What we can try to do is to analyze the data for $\beta(T)$, and to see, for example, if we can extract values for the pressure dependence of ρ_{ep} and the magnetic component ρ_{mag}. We assume ρ_0 is negligible, since we work at high T, and we also exclude the term ρ_{ee}. Although a large term $\sim T^2$ is observed[28] in ρ (and ρ_V) at low T, no such term is evident at high T, where $d^2\rho/dT^2$ is actually negative, and ρ_{ee} should thus be too small to be important for β.

The cusp in $d(\ln R)/dp$ near T_C is due to the p dependence of T_C, which must be taken into account. Let us assume that the term giving rise to the critical cusp in ρ can be written $\rho^*=Af(T/T_C)$, where A gives the magnitude and f is a dimensionless function that is independent of volume. The pressure dependence of T_C then gives rise to an additional term Q in β, where

$$Q=-(T/\rho T_C)(dT_C/dp)(d\rho^*/dT) . \tag{2}$$

In the simplest possible model $\rho^*=\rho$; we have no terms ρ_{ee} or ρ_{mag}, but the critical behavior in $\rho(T)$ is entirely due to the effect of the shifts in the spin-up and spin-down Fermi surfaces on ρ_{ep} near T_C. We now define $\alpha=d(\ln\rho_{ep})/dp$ (and thus $\beta=\alpha+Q$), and we calculate $Q(T)$ from (2) using known data; we can then fit this function to the experimental data for β [or, equivalently, $d(\ln R)/dp$] to find α. The results are shown in the upper part of Fig. 6; the solid line shows the fitted function, while the dashed lines show the values corresponding to α. We have used all experimental points shown above 100 K in this fit, both the present results and literature data (cf. Fig. 5). Note that we have averaged Q numerically over a range of 8 K at each actual T in the calculation, corresponding to the change in T_C over the experimental range of 2 GPa; if only the data at $p=0$ are used the cusp at T_C sharpens appreciably. The agreement between experimental and calculated values (solid line) is clearly very good. Note also, however, that we cannot obtain a good fit near T_C unless we assume a small change in α at T_C; the values obtained from the fitting procedure are $\alpha=-1.0\times10^{-2}$ GPa^{-1} below T_C and -1.4×10^{-2} GPa^{-1} above. (In the figure we have, of course, added $\kappa/3$.) We note that more than one-half of the room temperature value of β in this model is simply due to the pressure dependence of T_C, with the "true" α very small.

In a more realistic model we must include ρ_{mag}. Joynt[29] has calculated $\rho_{\text{mag}}(T)$ theoretically and found $\rho_{\text{mag}}(T_C)\simeq7$ $\mu\Omega$ cm; on the other hand, Yousuf *et al.*[3] find $\rho_{\text{mag}}(T_C)=20.654$ $\mu\Omega$ cm, using Joynt's theory, and there is clearly a very large uncertainty in the value for ρ_{mag}. Since we need both ρ_{mag} and $d\rho_{\text{mag}}/dT$ in our calculation we have arbitrarily chosen to integrate Joynt's data for $d\rho_{\text{mag}}/dT$ from his Fig. 2 numerically to obtain $\rho_{\text{mag}}(T)$; we then find $\rho_{\text{mag}}(T_C)\simeq10$ $\mu\Omega$ cm, with ρ_{ep} $(=\rho-\rho_{\text{mag}})$ a linear function of T. Defining now $\gamma=d(\ln\rho_{\text{mag}})/dp$, putting $\rho^*=\rho_{\text{mag}}$ in (2), and fitting the experimental data to

$$\beta=\alpha(\rho_{ep}/\rho)+\gamma(\rho_{\text{mag}}/\rho)+Q\ , \tag{3}$$

using the same averaging procedure as before, we find the results shown in the lower part of Fig. 6. Here the solid line shows the results corresponding to the total $d(\ln R)/dp$ (or β) and the dashed line the sum of the first two terms in (3); as before, the difference between the two curves corresponds to the effect of the shift in T_C with p. The fit is marginally less good than the previous one, but it is probable that this depends to a large part on the inaccuracy in the assumed values for ρ_{mag} and $d\rho_{\text{mag}}/dT$, especially below 400 K. Again we find that we cannot obtain a good fit unless α (or γ) is allowed to change near T_C; if we assume γ to be independent of T and equal to the value $\gamma=-0.5\times10^{-2}$ GPa^{-1} obtained below T_C, we find $\alpha=-1.9\times10^{-2}$ GPa^{-1} below T_C and -2.5×10^{-2} GPa^{-1} above.

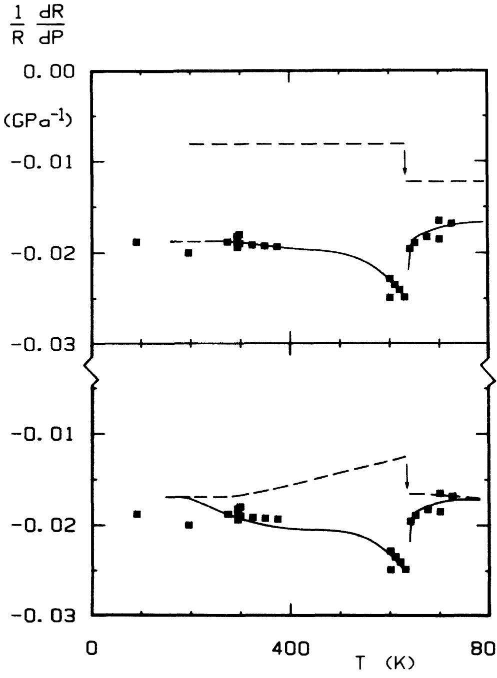

FIG. 6. Results of the fits to the two models discussed (see text). Upper part: $\rho=\rho_{ep}$ only, lower part: $\rho=\rho_{ep}+\rho_{\text{mag}}$. The solid lines are the fits to the total expressions, the dashed lines show the results excluding the effect of the change in T_C with p. Experimental points are the same as in Fig. 5.

From Fig. 6 we see that the pressure dependence of T_C determines most of the T dependence of β, while the actual numerical results depend on the model used. In the figure there is little difference between the models, but from a physical point of view the latter one seems preferable: Using the simplest model possible we would expect[30] $d(\ln\rho_{ep})/d(\ln V)=-\alpha/\kappa=2\gamma_G\simeq4$, or $\alpha\simeq-2.2\times10^{-2}$ GPa^{-1} at all T (γ_G is here the Grüneisen parameter). Well above T_C, α should equal that for Pd, which metal is quite similar to Ni; we can compare our value $\alpha=-2.5\times10^{-2}$ GPa^{-1} with the literature values -2.21×10^{-2} (Ref. 5) and -2.06×10^{-2} GPa^{-1} (Ref. 31). For ρ_{mag} we find to a first (free-electron) approximation, using Joynt's[29] model, $\rho_{\text{mag}}\sim VN(E_F)/\langle V_F^2\rangle$ or $\gamma\simeq-1.3\times10^{-2}$ GPa^{-1}, in fair agreement with the experimental result. The change in α, $\Delta\alpha\simeq-5\times10^{-3}$ GPa^{-1}, at T_C is small and should be very sensitive to the assumptions made above; it is not improbable that another choice of $d\rho^*/dT$ could eliminate $\Delta\alpha$. However, if real $\Delta\alpha$ could be explained as an effect of the change in the Fermi surface topology as the spin-up and spin-down surfaces coalesce; such a change in $d(\ln R)/dP$ is clearly seen when Au-Cu alloys[32] order. From the theory of Barnard[32,33] we would expect a simultaneous change $\Delta S\simeq-3$ μV K^{-1} in the thermoelectric power S at T_C, but any such is completely swamped by the larger $\Delta S\simeq+15$ μV K^{-1} at T_C arising from magnetic interactions.[17]

In conclusion, we find a surprisingly good agreement between the experimental data presented here for $\beta(T)$ and very simple theoretical models. We see no dramatic changes in β at T_C, indicating large band-structure changes in the material, but there might be a small discontinuous change arising from a topological transition on the Fermi surface. We also note that our data have important consequences for the constant-volume electrical resistivity of Ni. Since there is still no good theory for the transport properties of the ferromagnetic transition metals, we feel that it would be of some interest to attempt to make an exact calculation of the electron-phonon resistivity (and other transport properties) of nickel as a function of T (and, if possible, V), taking into account the changes in band structure with temperature.

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