values. This expansion apparently occurs in order for the t_{2g} orbital to form a covalent "bridge" between the $p\pi$ orbitals on the different F^- centers. While a small expansion was found in earlier point-charge crystal-field calculations,[4] such a covalent bridge further serves to minimize the energy of the system in much the same (well-known) way that the covalent bonding bridge is established between the metal $3d$ and ligand $2s$ and $2p\sigma$ in the e_g-symmetry case. Some of these effects are shown in Fig. 3 where e_g and t_{2g} spin-density contours are plotted in the $z = 0$ plane. The large induced spin density at the fluorine site is evident for the e_g case. The t_{2g} contour map shows the weaker $p\pi$ spin-density arrangement about the fluorine sites and the expanded spin density into the region between the ligands.

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ELECTRICAL RESISTIVITY OF NICKEL NEAR THE CURIE POINT*

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Emphasis is placed on the temperature dependence of the magnetic resistance R_{mag} in the region $10^{-4} \lesssim |\epsilon| \lesssim 10^{-2}$, where $\epsilon = (T - T_c)/T_c$. The temperature dependence of dR_{mag}/dT is found to be the same, within experimental error, as that of the specific heat, both above and below T_c. The anomalous behavior in the region $0 \lesssim \epsilon \lesssim 5 \times 10^{-3}$ reported by Craig, Goldburg, Kitchens, and Budnick is not observed.

Studies of transport properties offer the possibility of significantly enhancing our knowledge of microscopic processes near second-order phase transitions. The importance of such studies is well documented, together with a historical sketch of developments in the field, in the recent review article by Craig and Goldburg.[1] The theory of critical transport properties is virtually unexplored and appropriate experimental data are sparse. An exception to the latter deficiency is provided by existing data on the electrical resistivity of nickel. Measurements within $|\epsilon| \sim 5 \times 10^{-3}$ of T_c have been reported by Kraftmakher[2] and measurements within $|\epsilon| \sim 5 \times 10^{-4}$ of T_c have been reported by Craig and co-workers.[3] In both instances, a divergence in the temperature derivative of the magnetic resistivity at T_c was observed. This divergence was found to resemble (quantitatively[2,3] for $\epsilon \gtrsim 5 \times 10^{-3}$ and qualitatively[2] for $-\epsilon \gtrsim 5 \times 10^{-3}$) the divergence in the magnetic specific heat.[4,5] The theoretical basis of such a correspondence has been discussed by Mannari[6] and by Fisher and Langer,[7] and will be further discussed below.

A second and perhaps more dramatic effect reported by Craig and co-workers[3] is a distinct change in the temperature dependence of dR_{mag}/dT at approximately $\epsilon = 5 \times 10^{-3}$. It was observed that this is the temperature at which the (temperature dependent) magnetic coherence length $\xi(T)$ approximately equals the phonon-limited mean free path of the conduction electrons. Craig and Goldburg[1] suggested that this effect marks the transition from the hydrodynamic regime to the critical regime predicted by dynamic scaling theory. Hargitai[8] has suggested that the origin of the anomaly lies in a strong temperature dependence of the phonon-limited mean free path in the vicinity of T_c.

In this Letter we report new results which cor-

roborate in essence, if not in detail, the form of dR_{mag}/dT for $|\epsilon| \gtrsim 5\times10^{-3}$ reported in Refs. 2 and 3, but deny the existence of anomalous behavior in the range $10^{-4} \lesssim \epsilon \lesssim 5\times10^{-3}$.

To ensure unambiguous results near T_c, special attention was given to sample preparation and temperature control. The samples were mounted in a hermetically sealed calorimeter which was in turn immersed in a molten salt bath. This apparatus enabled us to make extremely slow temperature sweeps through T_c and to maintain the samples at a uniform temperature with measured gradients of less than 50 mdeg K over the length of the sample. Near T_c, where it was necessary to have closely spaced data points, drift rates of 1°K/hr were used; while further away rates were increased to 5°K/hr.

Samples were prepared for dc resistivity measurements by swaging nickel foils from starting materials of five-9's purity, and also of three-9's purity for the purpose of determining the effects of sample purity. The final sample configurations consisted of nickel filaments 0.05 $\times$0.005$\times$50 cm insulated with Fiberglas tubing and wound loosely on a mandrel. The samples were annealed in situ for periods ranging from 1 to 30 days before each run. The measuring current (~10 mA), provided by a heavy-duty wet-cell battery, was measured to be stable to 1 part in 10^5. The sample voltage and the voltages from the temperature-monitoring Chromel-Alumel thermocouples were measured with a resolution of 3 parts in 10^6 and a linear accuracy of 1 part in 10^5.

A method of sliding averages was used to calculate both the first and second derivatives of $R(T)$. Specifically, the method consisted of fitting a parabola to a set of adjacent experimental points, calculating the derivative of the fitted curve at the middle point, and then calling this value the derivative of the experimental curve at that point. By sliding the parabola along the experimental curve and choosing new sets of points, derivatives at each experimental point could be determined. In the region near T_c, where the derivative changes most rapidly, data were taken at progressively smaller temperature intervals. By taking points at 20 mdeg intervals, a least-squares fit to seven points could be made and still not sample more than 0.15°K of the R versus T curve. These techniques enabled us to obtain accuracies of better than 1% and 10%, respectively, for dR/dT and d^2R/dT^2 near T_c and considerably higher accuracies further from T_c where a larger range of temperature could be used in the calculation without loss of information.

In the analysis of our results, we attempt to fit the data to the following functional which is commonly used to fit critical divergences:

$$dR/dT = (A/\lambda)(|\epsilon|^{-\lambda}+1)+B, \quad T>T_c,$$
$$= (A'/\lambda')(|\epsilon|^{-\lambda'}+1)+B', \quad T<T_c. \quad (1)$$

In the limit $\lambda \to 0$ (or $\lambda' \to 0$), this equation represents a logarithmic divergence. When trying to determine the value of the critical exponent λ (or λ'), we had the usual problem of the sensitivity of λ (or λ') to the value chosen for T_c. A common procedure has been simply to take T_c as the temperature where dR/dT has a maximum. This is not necessarily the best choice. The smearing of the transition caused by thermal gradients, internal strains, and (in our case) the method of data analysis will cause some sort of averaging over a region as large as 0.3°K. When one considers the nonsymmetric nature of the singularity, with the second derivative being roughly five times larger immediately above T_c than immediately below (see Figs. 1 and 2, and discussion below), it is obvious that the position of the maximum of dR/dT need not be at T_c, but is probably slightly below T_c (~0.1°K in the present work). Determination of T_c from other experiments on the same sample, such as magnetic susceptibility, do not solve this problem since these measurements suffer similar broadening problems.[9]

A typical plot of $R(T)$ together with dR/dT is shown in Fig. 1. The solid-line curves are fits to Eq. (1) with $\lambda = 0.1$ and $\lambda' = -0.3$ and $T_c = T_{max} + 0.1$°K,[10] where T_{max} is the temperature of the maximum in dR/dT. If A, B, and λ of Eq. (1) and the corresponding primed quantities are assumed constant or only weakly temperature dependent, the data analysis is simplified by considering

$$d^2R/dT^2 = -Ae^{-(\lambda+1)}, \quad T>T_c,$$
$$= -A'e^{-(\lambda'+1)}, \quad T<T_c. \quad (2)$$

A typical plot of d^2R/dT^2 vs $\Delta T(=T-T_c)$ for $T > T_c$ from the present work is shown in Fig. 2 (on both linear and log-log grids) and compared with the results of Craig et al.[3] The important feature to note is that the anomalous increase in the strength of the divergence observed by Craig et al. is not observed in any of our results. Instead we observe that the data fit the power law

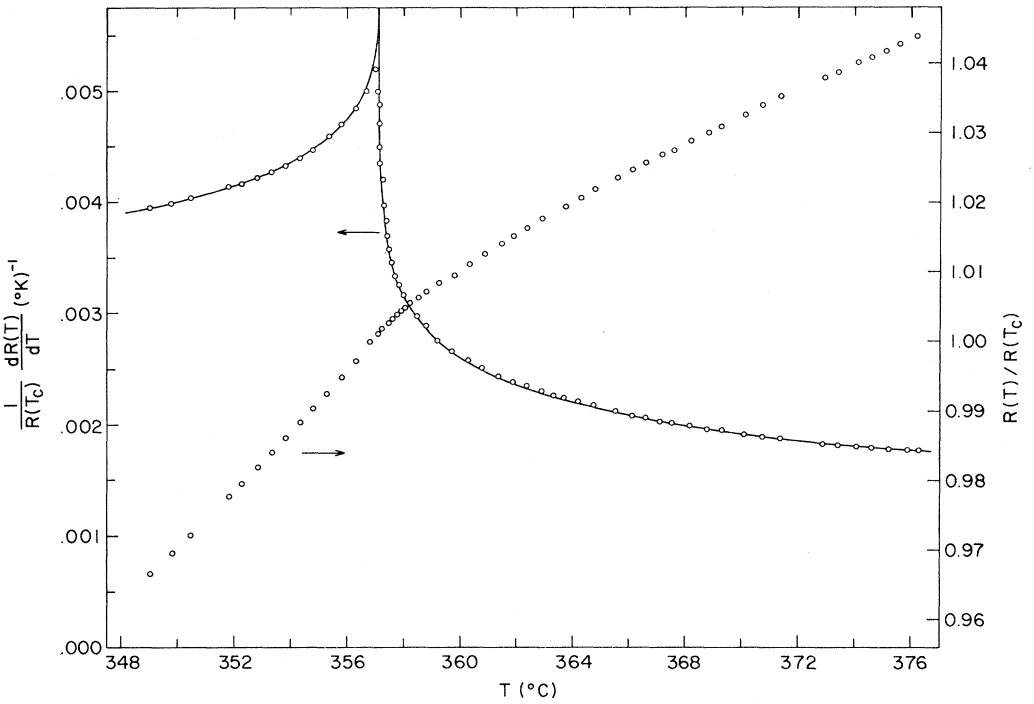

FIG. 1. Electrical resistivity $R(T)$ of nickel and dR/dT versus temperature in the region of the Curie point T_C. The solid lines represent fits of Eq. (1) to the data as discussed in text. For the sake of clarity only a small fraction of the data points is shown.

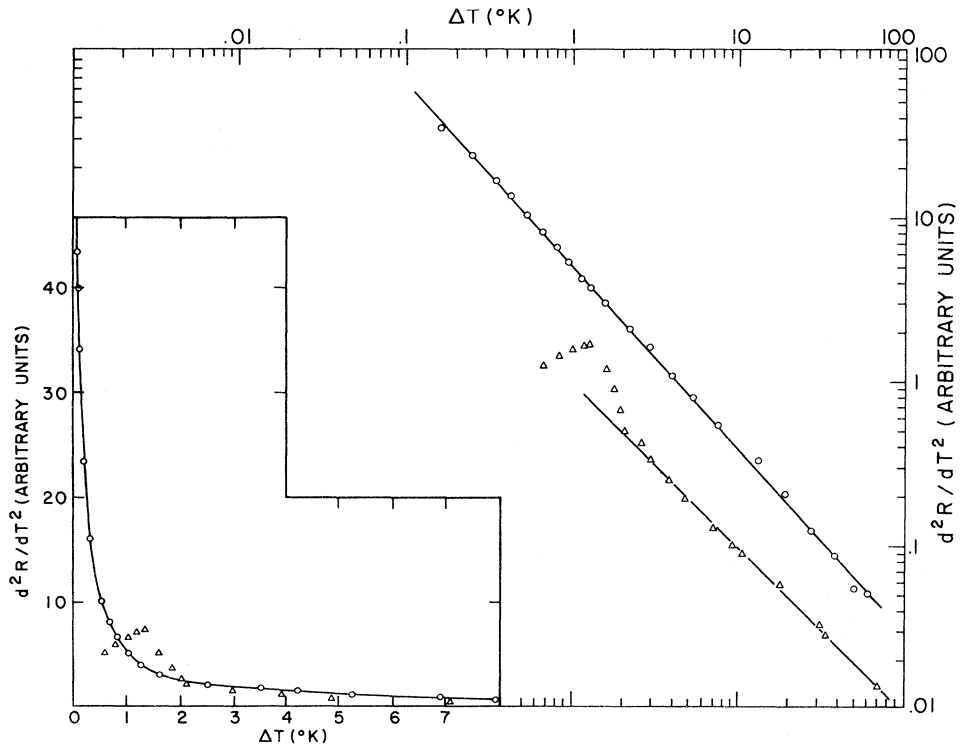

FIG. 2. Second derivative d^2R/dT^2 vs $\Delta T(=T-T_C)$ close to the Curie point. Circles: present data. Triangles: data of Craig, Goldburg, Kitchens, and Budnick (Ref. 3). In the linear plot the data of Craig et al. are normalized to the present data at $\Delta T = 10°K$. In the log-log plot the data of Craig et al. have been displaced for clarity. The slopes of the lines through the present data and the data by Craig et al. are −1.1 and −1.0, respectively.

relation one order of magnitude closer to T_c. Data in the region $\Delta T < 0.1°K$ are meaningless in this plot because of the temperature broadening of the dR/dT peak discussed above.

The behavior of dR/dT was found to be identical whether the sample purity was three-9's or five-9's or whether the sample was annealed at 450°C for 1 day or 30 days. Essentially identical results were obtained whether data were taken while increasing or decreasing the temperature through T_c (hysteresis referred to the temperature axis was smaller than 50 mdeg). The values of the exponents in Eq. (1), determined from studies of numerous samples, are the following:

$$\lambda = 0.1 \pm 0.1, \text{ for } 3\times10^{-4} \lesssim \epsilon \lesssim 0.1;$$

$$\lambda' = -0.3 \pm 0.1, \text{ for } -0.01 \lesssim \epsilon \lesssim -3\times10^{-4}. \quad (3)$$

These exponents are, within the quoted uncertainty, identical to the exponents obtained for the specific-heat divergence in nickel by Handler, Mapother, and Rayl[4] ($\alpha = 0.0 \pm 0.1$, $\alpha' = -0.3 \pm 0.1$) and by Maher and McCormick[5] ($\alpha = 0.104 \pm 0.050$, $\alpha' = -0.262 \pm 0.060$).

In discussing the anomalous effect reported in Ref. 3, Craig and Goldburg[1] cite an apparently similar effect observed by Cadieu and Douglass[11] in the temperature dependence of the coefficient of expansion in (single crystal) gadolinium. Cadieu and Douglass observe a change in the strength of the divergence at a temperature where $\xi(T) \sim l_i$ where l_i is the impurity-limited mean free path. We suggest that such an effect is related to the severe crystal anisotropy in Gd. The addition of impurities will smear the anisotropy of the momentum eigenstates of the conduction electrons, which in turn could be expected to affect the magnetic properties when $l < \xi(T)$. Such effects should be unimportant in Ni, which is highly isotropic.

We turn now to the second feature of the present results, namely the apparently precise correspondence between the exponents of divergence of the magnetic specific heat C_{mag} and of dR_{mag}/dT both above and below T_c. Mannari[6] and Fisher and Langer[7] have discussed the relationship between C_{mag} and dR_{mag}/dT in the framework of models in which the magnetic resistance arises effectively from scattering of conduction electrons (in a single band) by static spin fluctuations. They show that the short-range static spin-spin correlations above T_c give the principal contributions both to the energy $U_{mag}(T)$ and to the resistance $R_{mag}(T)$. Hence the dominant singularities at T_c in $C_{mag} \sim dU_{mag}/dT$ and in dR_{mag}/dT should closely resemble each other. The arguments can be restated in terms of the temperature dependence of the wave-vector-dependent spin-spin correlation function $\Gamma(k, T)$ for finite, non-zero values of k. The neutron-scattering results on iron and nickel[12,13] bear out the general behavior expected for $\Gamma(k, T)$; in particular, the occurrence of a maximum at fixed k at temperatures above T_c. On the other hand, Langer and Fisher indicated that below T_c an additional source of resistance might arise from the long-range order and they suggested that this would most probably yield a dominant singularity in dR_{mag}/dT different from that in C_{mag}. Our results do not bear out this suggestion since we still find a close correspondence in the exponents of C_{mag} and dR_{mag}/dT below T_c. This probably indicates an effective scattering mechanism somewhat more subtle than the direct electron-static-spin form assumed.

A physical point missing from the above discussion, which might be important in the case of nickel, is one made some time ago by Mott.[14] The argument is based on the assumption that a significant fraction of the electrical resistivity arises from interband processes[15] wherein an s (or p) electron from the conduction band is scattered (by a phonon, an impurity, or another electron) into a hole in the d band. In nickel such transitions can occur for electrons with either spin direction for $T \gg T_c$, but for $T \ll T_c$ conduction electrons with spins parallel to the direction of the magnetization cannot make transitions to the d band, since the spin-up band is full. Such (density of state) effects can be felt even above T_c due to the presence of spin fluctuations of wave vector larger than the electronic wavelength. Electrons in the vicinity of such fluctuations would see, at least on a time scale small compared with the lifetime of the fluctuations, a local density of $d\uparrow$ states which is characteristic of the ordered phase. It is clear that one would expect a gradual transition through T_c which would be reflected in $R_{mag}(T)$. A complete treatment of spin scattering must therefore explicitly discuss the possible importance of such band-structure effects.

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HELICITY OF ANTINEUTRINOS EMITTED BY NUCLEI*

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The helicity of antineutrinos emitted in nuclear transitions has been measured by determining the circular polarization of gamma rays emitted by a gaseous source of Hg^{203} and resonantly scattered by Tl^{203} nuclei. The antineutrinos and electrons preceding these gamma rays are known to travel approximately opposite to the gamma quanta. The helicity of neutrinos emitted following electron capture has been remeasured using the same apparatus.

The helicity of neutrinos involved in nuclear processes was determined by Goldhaber, Grodzins, and Sunyar.[1] Although a similar direct determination of the helicity of antineutrinos has never been made, there is experimental evidence suggesting that the antineutrino has helicity $\Theta_{\bar{\nu}} = +1$,[2] in agreement with the two-component theory of the neutrino.[3-5] It has recently been shown by this author that the practical difficulties in determining the helicity of the antineutrino through a method parallel to that employed by Goldhaber, Grodzins, and Sunyar can be overcome through the proper choice of an isotope for the experiment.[6]

If the total kinetic energy of the antineutrino and the electron is nearly equal to the gamma-transition energy, the gamma ray can be resonantly scattered by the daughter nucleus only if, in general, both the preceding leptons traveled in directions approximately opposite to the gamma quantum. The circular polarization of the resonance-scattered gamma rays can be approximately given to be[6,7] $P = -A(\bar{v}/c - \Theta_{\bar{\nu}})$, where A represents the beta-gamma circular-polarization angular-correlation coefficient, $\bar{v}$ is the average speed of electrons in the beta spectrum, and $\Theta_{\bar{\nu}}$ is the helicity of the antineutrinos. In actual practice, the circular polarization tends to be less, due to the direction and velocity distribution of the antineutrinos and electrons that precede the resonance-scattered gamma rays. Moreover, uncertainties in P may arise due to lack of information on the beta-neutrino angular correlation.

A gaseous source of Hg^{203} at a pressure of about 0.1 atm is used in the experiment. Hg^{203} decays with a 47-day half-life, by beta emission of maximum kinetic energy 208 keV followed by gamma rays of 279-keV energy. The gamma radiation is passed through a transmission-type polarimeter of average transmission length approximately 4 mean free paths, operated at magnetization cycles of 10 sec. The gain shift of the photomultiplier output due to reversal of the