the present LH values are used in the calculations. (It is not true that the results would be insensitive to any possible variation of the constants of comparable magnitude.) Also, since the term involving the Thomas, Driscoll, and Hipple experiment is only about 20 percent of ΔE, closer study shows that this correlation is not critical. Thus, despite the well-founded theoretical objections to using this extremely accurate experiment, it can probably be included without serious error.

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Volume Magnetostriction in Nickel and the Bethe-Slater Interaction Curve

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THE volume magnetostriction at high fields in ferromagnets can be related to the pressure dependence of the magnetization through the thermodynamic identity:

$$(\partial\omega/\partial H)_p = -(\partial(VM)/\partial p)_H, \tag{1}$$

where $\omega = \Delta V/V_0$. There are reasons for expecting a negative field dependence for the volume magnetostriction in nickel. (1) Recent experiments by Jones and Stacey[1] on the influence of pressure on magnetization show an increase in magnetization of the order of 10 percent at a pressure of 10 000 atmospheres which suggests that the left side of Eq. (1) should have negative sign. (2) Kornetzki[2] has related the volume magnetostriction to the pressure dependence of the Curie point in the following way:

$$\frac{1}{\theta}\frac{\partial\theta}{\partial p} = \frac{1}{T}\frac{\partial\omega}{\partial H} \bigg/ \left(p\frac{\partial\sigma}{\partial T} - \frac{3\alpha}{K}\frac{\partial\omega}{\partial H}\right), \tag{2}$$

where p and σ are the density and specific magnetization respectively, α is the thermal expansion, and K is the volume compressibility. The second term in the denominator may be neglected compared to the first, and it is seen that the latter is always negative. Patrick[3] finds $\partial\theta/\partial p$ to be positive which would require $\partial\omega/\partial H$ to be negative. It is considered improbable that the sign would change between room temperature and the Curie point. (3) The exchange interaction in ferromagnetic materials is usually represented by the "Bethe-Slater" curve shown in Fig. 1. There should be at least a qualitative correlation between the Curie points and the values of the ordinates for given metals on the curve (irrespective of the model employed), which lends support to the placement of nickel to the right of the maximum and would thus be in agreement with the observed effects of pressure and with the above supposition regarding the sign of the volume magnetostriction.

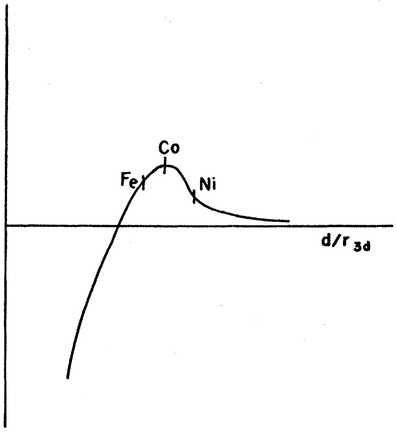

FIG. 1. The Sommerfeld and Bethe representation of Slater's interaction parameter in which the exchange energy J is plotted as a function of the ratio of the interatomic distance to the calculated radius of the $3d$ shell.

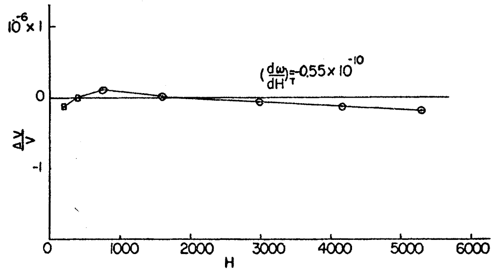

FIG. 2. Volume magnetostriction of nickel (isothermal) plotted as a function of applied magnetic field.

Previous investigators[4] have studied the volume magnetostriction of nickel using liquid dilatometers. All report positive values for $\partial\omega/\partial H$. Doring has pointed out the need for applying corrections to allow for expansions resulting from magnetocaloric heating, but his corrections are much larger than the measured quantities. By its very nature the liquid dilatometer as a method of measurement makes it difficult to eliminate errors due to magnetocaloric effects which in nickel are significant even at room temperature. The refinement of the resistance strain gauge method for the measurement of very small magnetostriction effects[5] suggested the desirability of repeating these measurements with the new technique. In our measurements, three gauges are mounted in the three principal directions of a rectangular parallelepiped shaped sample of approximate dimensions 22×6×6 mm and connected in series to form one arm of a Wheatstone bridge of which the other three arms are strain gauges that are placed in the same field as the sample. The gauges are in good thermal and magnetic contact with the electromagnet; the latter is essential in order to minimize form effect and other volume effects due to incomplete saturation. A series of thin-gauge high-permeability strips separate the sample from the magnet pole piece so that it will not be subject to constraints. Strains are measured by amplifying the unbalance of the bridge in a chopper amplifier and recording the output on an Esterline-Angus recording milliammeter. In this manner we can note the return to thermal equilibrium after magnetization. The relaxation time is very short, but it may be pointed out that this method may be used indirectly to observe the magnetocaloric effect by noting the thermal expansion during this period. Field changes are made by an arrangement which permits the current in the magnet coils to remain constant. By this arrangement and using this method, it is felt that we have nearly eliminated errors in the measurement due to extraneous thermal effects.

The results of our measurements on nickel are plotted in Fig. 2. It is seen that we do in fact obtain a negative slope for the volume magnetostriction as a function of magnetic field. The measured slope is 0.55×10^{-10} which we estimate to be accurate to approximately 10 percent. The agreement between our measurements and the more recent experiments on pressure effects appears to support the view that the exchange interaction in ferromagnetics can be represented by a curve of the type first suggested by Slater and given by Sommerfeld and Bethe. A detailed description of the method of measurement and additional results on other ferromagnetic metals and some nickel-copper alloys will be presented in a later communication.

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Specific Heat of 96-Percent He^3 below 1°K*

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We have extended our previous measurements[1] of the specific heat of liquid He^3 (He^3 content 96 percent, 4-percent He^4) by observations down to 0.57°K. Calorimetric techniques as previously described[1,2] were used, the calorimeter holding 13-mm³ liquid He^3. The calorimeter was cooled to temperatures below 1°K by a paramagnetic salt, the thermal connection being through a superconducting thermal valve which could be opened or closed magnetically, as described elsewhere.[3] Temperatures were measured with a carbon resistance thermometer calibrated against temperatures obtained from the susceptibility of the paramagnetic salt. Our preliminary results are shown in Fig. 1, which includes also our previous results obtained between 1.3°K and 2.3°K. The probable estimated error is ±10 percent. Details of the corrections which had to be applied for evaporation of the liquid during the heating cycles, etc., will be described in a fuller publication later. It might be noted that the largest corrections (at 1.3°K) totaled 17 percent of the observed specific heats. The lower limit of temperature of observation was determined in these experiments by the effective range of the type of resistance thermometer which we employed.

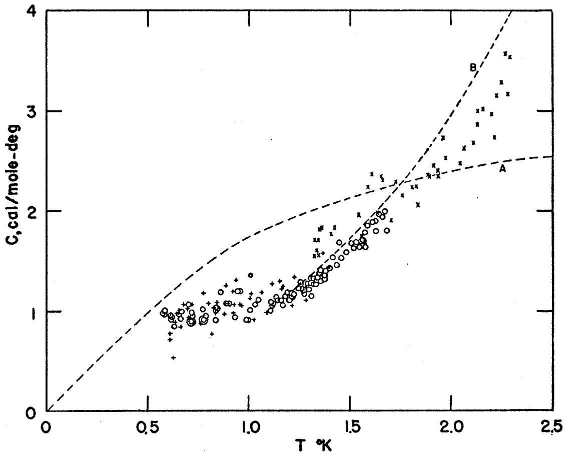

FIG. 1. The specific heat, $C_{\rm sat}$, in cal/mole-deg of liquid He^3 (96-percent He^3) as a function of the absolute temperature T in °K. The crosses **×** give our previously reported results,[1] the circles and crosses **+**, the new observations. The curve A gives the specific heat for an ideal Fermi-Dirac gas ($T_{\rm deg}=4.85$°K). The curve B gives the formula $C_{\rm sat}=0.68T+0.2T^3$ cal/mole-deg derived from the vapor-pressure data [J. G. Daunt, Phil. Mag. Suppl. **1**, 209 (1952)].

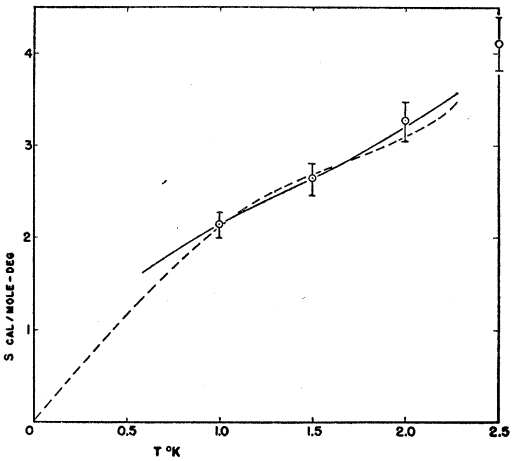

FIG. 2. The entropy S in cal/mole-deg of pure liquid He^3 as a function of the absolute temperature T in °K. The full curve gives the entropy curve derived from the measured specific heat. The circles give the values computed by Abraham *et al.* (see reference 5), the broken curve the computed entropy from the vapor-pressure data by Chen and London (see reference 6).

It will be seen from Fig. 1 that our new data between 1.3°K and 0.57°K form a smooth continuation of the specific heat curve at higher temperatures which we reported previously.[1] Although there is some scatter in the individual points, it seems clear that there is no marked anomaly of a discontinuous or λ-type nature over the whole range of observation. It is of interest to note, however, the marked flattening of the curve between 0.6°K and 1°K and the fact that no obvious extrapolation of the curve can be made to $T=0$°K.

We have drawn curve A also in Fig. 1, the specific heat to be expected for an ideal Fermi-Dirac system of particles of spin $\frac{1}{2}$ with molecular weight and number density appropriate to liquid He^3. It is clear by comparing curve A with the experimental results that the specific heat of liquid He^3 cannot be approximated by that of an ideal Fermi-Dirac gas, a conclusion which we had previously reached.[1] Moreover, from the fact that the observed specific heat in the range 0.57°K to 1.7°K lies everywhere well below that of the Fermi-Dirac model (curve A), it appears that one should conclude that the pairing off or the correlation between the nuclear spins must either be completely removed at temperatures of 0.6°K and up, or that nearly all the spins must still be paired off even at temperatures as high as 2°K. The latter alternative is unacceptable in view of the classical behavior recently observed for the paramagnetic susceptibility of the He^3 spin system in the temperature range 1.2°K to 2.8°K by Fairbank *et al.*[4]

In order to gain further insight concerning the thermal behavior of liquid He^3, we have made computations of the entropy as a function of temperature. Since our observed specific heat does not allow any clear extrapolation to $T=0$°K we have computed only entropy differences. To obtain Fig. 2, however, we have arbitrarily assumed an exact value for the entropy of pure He^3 at 1.5°K and our results are shown by the full curve. The value chosen for $S_{\rm liq}$ at 1.5°K was 2.63 cal/mole-deg obtained from the vapor-pressure measurements by Abraham *et al.*[5] We wish to emphasize that although the specific heat measurements of Fig. 1 are for a 96 percent He^3 *mixture*, our computed entropy of Fig. 2 is, within the accuracy given by the experimental errors, that for *pure* liquid He^3. That this is so is evident from the fact that the entropy value of 2.63 cal/mole deg, chosen for $T=1.5$°K, does not include the entropy of mixing. (The classical entropy of mixing for a 96 percent He^3 mixture would be 0.15 cal/mole-deg.)

It is of interest to note in Fig. 2 that the entropy *versus* temper-