Effect of pressure on the de Haas–van Alphen effect in nickel

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Experimental results are presented of the measurement of the de Haas–van Alphen effect in paramagnetic nickel at pressures up to 1 kbar. It is concluded that small parts of the Fermi surface are altered.

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Measurement of the changes of the corresponding parts of the Fermi surface (FS) under pressure would make it possible to check on the models of the electron spectrum of transitions metals.

Many parameters of these models have different sensitivities to changes of the distance between the atoms.[1] A change in the relative position of the *s* and *d* bands as a function of the volume leads, for example, to transfer of the conduction electrons from one hand to another and to a change of the FS. The de Haas—van Alphen (dHvA) effect is a convenient and reliable tool for obtaining such information.

In this article we report preliminary data on the measurements of the dHvA effect of a 3*d* transition metal—nickel—under pressure. In the ferromagnetic state, nickel has an fcc structure and a rather simple FS. The Fermi level of nickel passes inside the *d* band, below its ceiling. Figure 1 shows a section through the FS of nickel in the symmetry plane $(1\bar{1}0)$, obtained by calculation and given in[2].

As shown by Sukhoparov and Templeton, the modulation procedure[3] is perfectly suitable for the measurement of the dHvA effect with the aid of a fixed-pressure chamber.[4] We used a similar procedure to measure at 1.5 K, at a pressure up to 11 kbar, the dHvA effect in single-crystal samples of Ni$(\alpha \equiv \rho_{360\mathrm{K}}/\rho_{4.2\mathrm{K}_3} \approx 3000)$, cut in the form of 1×1×3 mm parallelepipeds in cham-

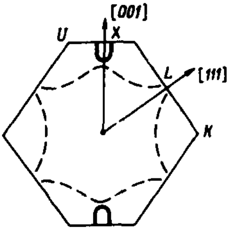

FIG. 1. Section through the Brillouin zone of the nickel by the (100) plane. The dashed line corresponds to the "spin up" sheet of the Fermi surface and the solid line to "spin down."

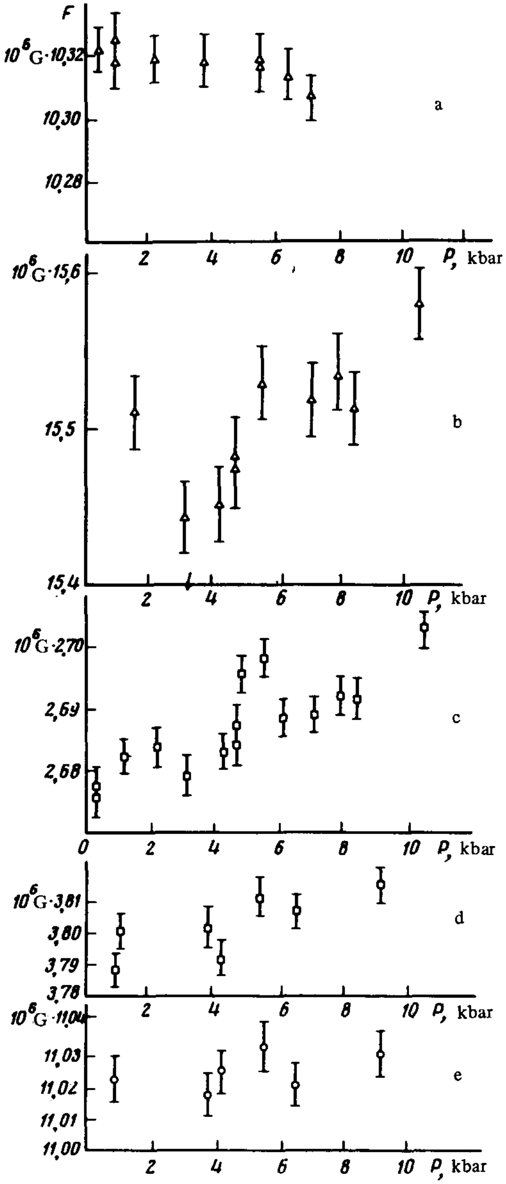

FIG. 2. Change of frequency F on the pressure. The letter indices on the figures and in Table I identify the section to which the particular frequency belongs.

bers of the type used in[4] with a kerosene-oil mixture as the pressure-transmitting medium. The entire system of receiving and modulation coils was located inside the chamber. A magnetic field up to 80 kOe was produced by a superconducting solenoid. The sample axis coincided with that of the solenoid.

The oscillations were measured for three samples with different direction of the sample axes relative to the field (H||[111],H||[100] and H||[112]). For the [111] sample in the field interval 10–80 kOe and at all pressures, oscillations were distinctly observed, with a frequency corresponding to the intersection of the (111) plane and the "neck" that joins, in the repeated-electron-band

TABLE I.

Plane containing S_{extr}	Part of Fermi surface				
	Spin neck ↑		Spin ellipsoid ↓		
	$(111)_c$	$(112)_d$	$(111)_b$	$(112)_e$	$(100)_a$
$\frac{d\ln S_{extr}}{dp}$ 10^{-4} kbar^{-1}	8.0 ± 1.2	6.6 ± 2.5	6.6 ± 2.5	1.5 ± 0.8	− 0.8 ± 0.8

model, the quasi-spherical parts of the *s*-surface of the sixth zone for the "spin up" sheet of the FS (point *L* on Fig. 1). In Fields 60–80 kOe, additional oscillations were superimposed, corresponding to the extremal section (111) of the ellipsoid of the *d*-holes of the fourth zone for the "spin down" sheet with center at the point *X*.

The oscillations in the [100] sample were observed in the field interval 35–80 kOe and likewise in the entire pressure interval. These oscillations are connected with the same ellipsoid, but correspond to an extremal section parallel to the (100) plane.

At a fixed orientation H||[112], which is intermediate between the two mentioned above, oscillations were observed starting with ~35 kOe and corresponded to the intersection of the "neck" with the (112) plane. At a field ~45 kOe, additional oscillations from the *d*-hole ellipsoid were superimposed on the observed picture.

The frequencies of all these oscillations at zero pressure agree with the data of[2] within the limits of the accuracy with which the sample axes were set relative to the field direction.

Figure 2 shows plots of the oscillation frequencies against pressure. All the plots in the pressure interval 0–10 kbar are linear and the corresponding slopes are very small. The corresponding derivatives with respect to the pressure are given in Table I. The results were reduced by least squares. Figure 2 shows the variance of the derivation of the points from a straight line, while the table gives the variance of the baric coefficients.

The quantity $d\ln S(100)/dp$ is very small and apparently does not exceed the sum of the random and systematic (due to the possible inclination of the sample axis under pressure) errors. Individual measurement runs with this sample yielded values of the derivative from -1.6 to 0.1×10^{-4} kbar^{-1}.

In addition, measurement of the smallest changes of the dHvA frequencies in ferromagnets are made difficult also by the existence of a distinct "reflection" effect due to the presence of a ferromagnet in the field of the superconducting solenoid, the influence of which in the dHvA oscillations was noted in[5].

We have introduced no correction for the pressure-induced change in the demagnetizing factor and in the magnetization at saturation. The internal field was estimated at 6500 Oe. The independence $d\ln S/dp$ of the magnetic field when the latter was changed by a factor of eight confirms the justification of this procedure.

After completing this work, we were informed of preliminary measurement data of some of these sections in nickel, reported by Anderson, Schirber, *et al.* at a conference on magnetism and magnetic materials in the USA in 1975.[6] By measuring the phase shift of the dHvA oscillations in liquids under pressure (up to 25 kbar) various values of $d\ \ln S_{el}(111)/dp$, namely $(-4\pm2)\times10^{-4}$ kbar^{-1} in liquid helium and $(6\pm1)\times10^{-4}$ kbar^{-1} in solid helium. For $d\ \ln S(100_h)/dp$ they obtained the value $(1.2\pm0.3)\times10^{-4}$ kbar^{-1} only in solid helium (no phase shift was obtained in liquid helium). The authors indicate that they cannot explain the discrepancies in their results and are planning to repeat the measurements.

It follows that the anisotropy of the hole ellipsoid increases under pressure: its minor section hardly changes, while its major section increases.

Unfortunately, at present there is still no quantitative model of describing the FS of nickel at $P=0$. At the same time, there are enough physical arguments indicating that pressure alters a large number of the parameters of the band structure and changes them in different manners. Experimental data on the effective pressure on the Fermi surface of nickel are therefore urgently needed.

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