a maximum not far from the Curie temperature. For the higher magnetostriction constants h_3, h_4 and h_5 contradictory results have been reported [34, 35, 16, 32, 36]. Some of these results must be ascribed to errors in the analysis of the experimental data, introduced by an incorrect application of the angle correction between **M** and **H** [37, 22]. Such incorrect procedures become manifest by a field dependence of these constants like $1/H$ and a temperature dependence equal to that of K_1. Recent data on the magnetostriction constants of nickel report values for the higher magnetostriction constants that are small at room temperature and at 77 °K and that are independent of the external magnetic field [38]. The values for the third magnetostriction constant h_3 are at the two temperatures in agreement with the results for the pressure dependence of the first magnetic anisotropy constant [22]. In case of iron a similar agreement has not yet been obtained.

The effect of pressure on the magnetostriction constants of nickel and iron is clearly present in the first magnetostriction constant of iron. For the other magnetostriction constant no change with pressure could be found [22].

IV. **Recent theoretical models.** — At this point we return to the origin of the magnetic anisotropy energy in nickel and iron. Furey has treated the anisotropy problem for nickel using improved energy bands, provided by Hodges e.a. [39], in which hybridization between the 3 d-bands and the conduction bands also has been considered. Since there are remarkable points of similarity between Furey's work and the experimental data, we briefly deal here with some of the keypoints of this work.

1. The main contributions to the magnetic anisotropy energy arise from special points in the Brillouin zone where energy bands are degenerate in absence of the spin-orbit interaction. These points are situated on the $\Gamma - X$ and $\Gamma - L$ directions.

2. The full eigenvalue problem has been solved in the neighbourhood of these directions in **k** space for different orientations of the magnetization. The energy shifts, due to a rotation of the magnetization, turn out to be largest near the point X and do not have the same sign for all bands. Some typical d-bands in this important region are shown in figure 3. In calculating the anisotropy energy the summation of the energy shifts has been performed over the unoccupied states.

3. The partial cancellation of the contributions of the different bands to the magnetic anisotropy energy is strongly affected by the occupation of the relevant states. A description of these occupations in terms of Fermi distribution functions results in a rapid variation of the magnetic anisotropy energy with temperature.

4. The calculated value for the magnetic anisotropy energy is very sensitive to the position of the Fermi level with respect to the minority spin d-bands. A second calculation, in which the Fermi level was lowered with an amount of 0.006 eV, resulted in a 25 percent lower value for the first magnetic anisotropy constant.

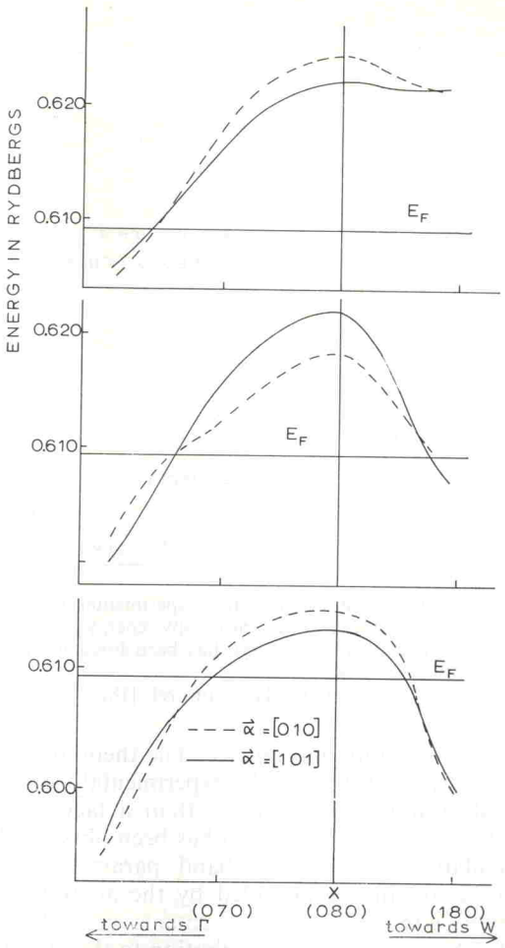

FIG. 3. — Energy bands of nickel near the point X in the Brillouin zone for two orientations of the magnetization. (After Furey ref. [12]).

By mentioning these four points we intend to call attention for this outstanding work which also deals with the orbital contribution to the magnetization and with the magnetostriction of nickel.

The energy shifts in the bands near the point X upon rotation of the magnetization have been revealed by the De Haas-Van Alphen studies on the hole pockets near this point. The X_5 levels that are responsible for these hole pockets, that vary in size upon rotation of the magnetization, turn out to yield essential contributions to the anisotropy in the energy. For a discussion of these De Haas-Van Alphen measurements we may refer to the review article by Gold [40].

To compare the results of Furey's work on the temperature dependence of the magnetic anisotropy energy with the experimental data, the differences in the free energy F_A have been determined between two orientations of the magnetization, parallel to the [100] and [110] directions, respectively, by integrating the experimental torque curves and applying a correction for the magneto-elastic energies and for the anisotropy in the magnetization. For nickel, where an expansion of the anisotropy energy in the direction cosines of the magnetization is questionable at low temperature from experimental as well as from theoretical points of view, this procedure must be preferred. Figure 4 shows the experimental and theoretical data

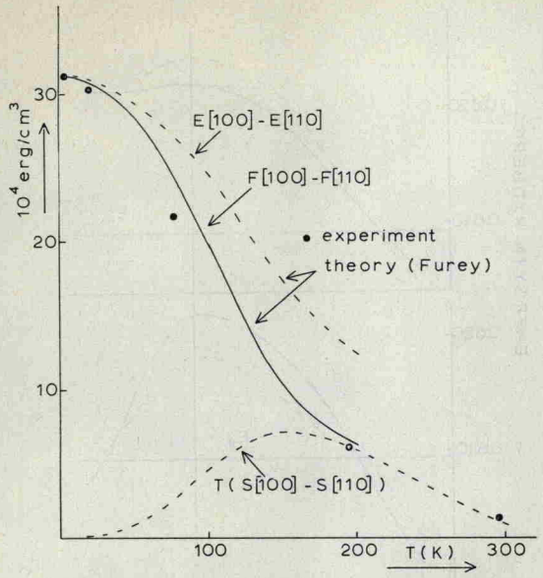

FIG. 4. — Comparison between the experimental temperature dependence of the magnetic anisotropy energy and Furey's calculations. The theoretical curve has been fitted to the experimental value at 0 °K.
(Experimental data from ref. [18]).

on the temperature dependence. The theoretical curve has been fitted at 0 °K to the experimental value. This value does not differ by more than a factor of two from the theoretical value that has been obtained from a calculation with use of band parameters and a spin-orbit parameter provided by the analysis of the De Haas-Van Alphen measurements near the point X [41]. An appreciable contribution to the anisotropy energy has been found to arise from the entropy term in the free energy. These entropy data have been taken from Furey's work directly and have not been fitted to the experiments. It should be emphasized that various contributions of different sign built up the magnetic anisotropy energy. A change in sign for K_1 at high temperature is quite reasonable within this theory. The experimental situation around this change in sign is not fully clear [30, 42, 43] ; it requires an accurate knowledge of the magneto-elastic contribution to the experimental value of K_1 [18].

In the very recent work of Mori also band calculations on the anisotropy energy of nickel and iron are presented. This work contradicts that of Furey in so far that for nickel contributions of degenerate states to the anisotropy energy are found to be less important. The experimental facts, present in the complicated low temperature structure, support the work of Furey.

The behaviour of the anisotropy energy of iron indicates that states very close to the Fermi level are not dominating and that degeneracy plays a less important role here. An actual calculation of K_1 by perturbation theory has to deal with the uncertain values for the bandwidth and the spin-orbit parameter, as has been stressed by Asdente and Delitala [11].

A quantitative interpretation of the effects of pressure on the anisotropy energy lies beyond the possibilities of the present theories and we have to restrict the discussion on this point to some qualitative remarks. The anisotropy energy usually follows in the band model from fourth order perturbation calculation and it is determined by the spin-orbit parameter and the energy differences between the relevant bands. Assuming an increase of the bandwidth with increasing pressure as a general rule, one finds the energy denominators in the fourth order perturbation calculation to become larger, resulting in lower values for the fourth order energy corrections. This is of course a very poor model since we have no precise knowledge of the energy bands and their shifts under pressure. An interpretation of the pressure effect is perhaps most successful for nickel, where only a few bands in a small region of the zone have to be known. It might be argued that the degeneracy in this small region of the zone is lifted to some extent under pressure. From these arguments a decrease of the anisotropy energy with pressure may be expected, which is in accordance with the experimental results. The increase in the pressure effect for nickel to lower temperatures may be attributed to an increasing sharpness of the Fermi distribution functions. The cancellation of the different contributions to the anisotropy energy is more sensitive to a small shift in the energy bands, introduced by pressure, if the Fermi level is sharper. In a case where states near the Fermi level are not of special importance for the anisotropy energy, like for iron, a strong temperature dependence of the pressure effect in the low temperature region is not to be expected.

Only a few words will be devoted to the magnetostriction problem. It is remarkable that for nickel two phenomena that both are related with the spin-orbit interaction, the anisotropy energy and the magnetostriction, are so different in character. No spectacular effects are present in the magnetostriction at low temperature. This suggests that the above discussed contributions from degenerate states are not dominant in the magnetostriction problem. This conclusion follows from Furey's work indeed. A meaningful calculation of the magneto-elastic energy could not be given since there are large fluctuations in the contributions to this energy over the Brillouin zone.

V. **Further developments.** — Finally we deal with some features of the magnetic anisotropy energy of nickel that ask for further investigations.

In order to calculate the magnetic anisotropy energy of nickel drastic assumptions had to be made and several contributions, one order of magnitude smaller than those from the energy shifts near the point X, have been neglected. This occurred for instance with contributions from states near the point L and with the effects, due to a change in the occupation of the energy bands upon rotation of the magnetization. This change in the occupation of states, caused by the spin-orbit interaction, has been discussed by Slonczewski [44] in a comment on Fletcher's calculation of the magnetic anisotropy energy of nickel. Furey pointed out that for the improved band structure he used this surface correction is at least one order smaller than the other contributions. These corrections can be important, however, for a discussion on the fine structure in the anisotropy energy. In particular a band, passing the Fermi level at the zone