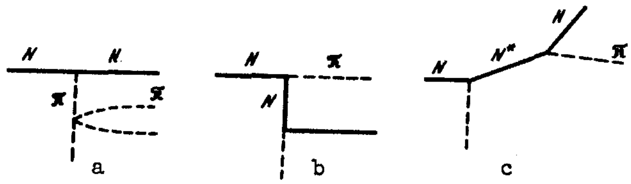

Fig. 2

From the point of view of the MPM, three types of diagrams are important in our case (see Fig. 2). Diagrams 2a and 2b describe "true" peripheral production of a proton and pion, the contribution of diagram 2a being decisive in this case. Figure 3 (curve 1) shows the correlation due to the peripheral production of the proton and pion.

Diagram 2c describes resonant production of a proton and pion. Figure 3 (curves 2 and 3) shows the correlations due to the 1236 and 1920 isobars, respectively. These correlations were calculated using the results and technique of [3]. We see that in the case of resonant production we can obtain an "inverse" asymmetry in the N(ϕ) distribution. Curve 4 of Fig. 3 describes the summary correlation for the diagrams of Fig. 2 and agrees well with experiment.

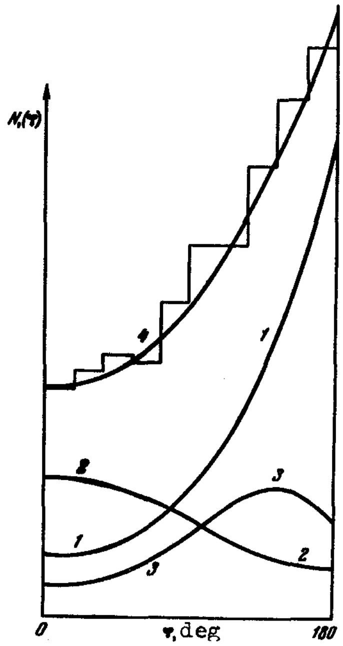

Fig. 3

We note that a similar analysis in the pionization model leads to disagreement between theory and experiment.

Further experimental verification of the predictions of the multiperipheral model are of considerable interest.

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SPIN-ORBIT INTERACTION AS A CAUSE OF THE ANISOTROPY OF THE SPONTANEOUS MAGNETIZATION OF TRANSITION METALS AT LOW TEMPERATURES

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As shown by Borovik-Romanov [1], Dzyaloshinskii [2], and later by Treves [3] and Moriya [4], spin-orbit interaction, together with indirect exchange, is the cause of the weak ferromagnetism of magnetodielectrics having a definite crystal-lattice symmetry. The spin-orbit interaction leads in this case to small deviations of the magnetic moments of the sublattices from the direction of the antiferromagnetism vector, and this causes a weak spontaneous magnetization.

Calculations performed by us have shown that the spin-orbit interaction in metals also causes small changes in the absolute value of the spontaneous-magnetization vector when the latter is rotated relative to the crystal-lattice axes, although the internal mechanism of the phenomenon is somewhat different than in the indicated ferrodielectrics. Namely, rotation of the resultant magnetic moment relative to the crystal-lattice axes, owing to the spin-orbit interaction, changes the populations of the energy bands, particularly bands with opposite spin directions, and this leads to anisotropy of the spontaneous magnetization.

The spontaneous-magnetization anisotropy was first observed experimentally by Aubert [5] and later studied by Aubert and Escudier [6]. As noted in [5], the model proposed by Callen and Callen [7] cannot explain the existence of the anisotropy of the spontaneous magnetization in nickel single crystals at low temperatures.

In the present study, the anisotropy of the spontaneous magnetization of nickel was determined on the basis of the band theory. The calculation was performed by the same method as our earlier calculation of the magnetic anisotropy of the energy (see [8, 9]). The ferromagnetic crystal was described by the approximate Hamiltonian

$$\hat{\mathcal{H}} = \frac{\hat{p}^2}{2m} + V + V_{ex} + \frac{1}{2m^2c^2}\hat{\sigma}[\nabla V \times \hat{p}] - \frac{e}{2mc}H(2\hat{\sigma} + \hat{\ell}), \tag{1}$$

where H is the magnetic field intensity and $\hat{\ell}$ the operator of the orbital momentum, while the remaining notation is the same as in formulas (1) - (3) of our article [8]. Using the method of Helborn and Sondheimer [10], we obtain for the spontaneous magnetization

$$M(\alpha_i) = \frac{N}{\Omega}\sum_n \int d^3r\, f\left\{E_n(k, \alpha_i)\right\} \langle n, k, \alpha_i \left| \frac{e}{2mc}(2\hat{\sigma} + \hat{\ell}) \right| n, k, \alpha_i \rangle, \tag{2}$$

where N is the number of unit cells of the crystal, Ω the volume of the Brillouin zone, α_i the direction cosines of the magnetization vectors relative to the axes of the cubic lattice, and f is the Fermi distribution function. The sum over n is taken over the eigenvalues $|n, k, \alpha_i\rangle$ of the operator $\hat{\mathcal{H}}$ in the absence of a magnetic field, and $E_n(k, \alpha_i)$ are the corresponding energy eigenvalues. Just as in the calculation of the anisotropy of the free energy, we must take into account here the redistribution of the free and occupied states near the Fermi levels as a function of the magnetization direction. To determine the eigenvalues and eigenfunctions of the Hamiltonian $\hat{\mathcal{H}}$, we used the method described in [11]. The numerical calculations of M were made with the same band-structure parameters as in the earlier calculation of the anisotropy constant in [8], i.e., on the basis of a band structure that agrees with the experimental data on the de Haas - van Alphen effect. The constant spin-orbit interaction was assumed to have the value $\xi_{SO} = 7.5 \times 10^{-3}$Ry determined in [12].

The value obtained for the orbital part of the magnetization of nickel is

$$M_\ell = 4{,}77 \cdot 10^{-2}\mu_B/\text{un.cell} \tag{3}$$

and agrees well with the experimental values

$$M_\ell = (5{,}07 \pm 0{,}27) \cdot 10^{-2}\mu_B/\text{un.cell} \text{ and } M_\ell = 5{,}3 \cdot 10^{-2}\mu_B/\text{un.cell}$$

obtained in [13] and [14], respectively. This shows that the orbital momentum of nickel would be completely quenched were it not for the influence of the spin-orbit interaction.

The anisotropic part of the magnetization $\Delta M_{an} = M(111) - M(100)$ receives contributions from both the spin and the orbital momentum.

For the anisotropic parts of the spin $(\Delta M_\sigma)_{an}$ and orbital $(\Delta M_\ell)_{an}$ magnetizations of nuckel, we obtained the theoretical values

$$(\Delta M_\sigma)_{an} = 1{,}59 \cdot 10^{-5} \mu_B \text{/un.cell}; \quad (\Delta M_\ell)_{an} = 4{,}19 \cdot 10^{-5} \mu_B \text{/un.cell} \tag{4}$$

and for the relative value of the anisotropic resultant magnetization we obtained

$$\Delta M_{an} / M = 0{,}82 \cdot 10^{-4} . \tag{5}$$

The obtained value $\Delta M_{an}/M$ is in satisfactory agreement with the experimental value $M_{an}/M = 1.92 \times 10^{-4}$ of Aubert and Escudier [5].

It should be noted that the agreement between the theoretical and experimental values of $\Delta M_{an}/M$ improves when the volume of the pockets of the fourth subband, with downward spins, surrounding the points X of the Brillouin zone is decreased, i.e., when our band structure comes closer to the band structure proposed by Zornberg [15] (also on the basis of experimental data). We note also that, just as in the case of the energy anisotropy, noticeable contributions are made to the spontaneous-magnetization anisotropy only by the Brillouin-zone regions in which degenerate or quasidegenerate states exist near the Fermi level when the spin-orbit interaction is turned off.

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