2) The Fierz identity (cf. footnote 1)) does not hold in the prescence of isospin structure.

3) At $d=2$ the matrices O_α can be chosen such that they coincide with the Thirring γ-matrices $O_0=\gamma_0=\sigma_x$, $O_1=\gamma_1=i\sigma_y$. For $d=2$ the Fierz identity (cf. footnote 1)) is not valid.

4) Terms of order εf^2 have been omitted, since, as can be seen from the solution $g\sim\varepsilon$, and $f\sim\varepsilon^2$.

5) Tr 1 cannot be exactly established with our method of analytic continuation.

6) Even to first approximation in ε this solution differs from the solution 22) of the system (A. 1) with $a(2)=b(2)=1$, $c(2)=0$, obtained in Sec. 4. It is natural to expect that for $\varepsilon=2$ (22) will not be an approximate solution of the system (9), since it does not reflect the symmetry of the four-dimensional problem (the Fierz identities, cf. footnote 1)).

7) Here we do not discuss the property (b). It can be investigated by means of iteration of the equations (A. 1) with the zeroth approximation in the form of the solution obtained below (Sec. 7).

8) The whole ε-dependence is included in the variables $x=\xi^{\varepsilon/2+2\Delta}$ and $y=\eta^{\varepsilon/2+2\Delta}$. For the role of Δ cf. Sec. 8.

9) This assertion remains valid also if the region of small k^2 is taken into account in (31), $(0\leqslant k^2\leqslant y)$. The quantities f_1, g_1 change insignificantly.[21]

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Verification of a possible asymmetry in the polarization of thermal neutrons after reflection from a mirror

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The neutron polarization asymetry observed previously by K. Berndofer [Z. Phys. 243, 188 (1971)] has not been confirmed by experiments with a polarizing neutron guide. In view of the spin-orbit effects currently discussed in the literature, measurements have been carried out of the polarization of neutrons, singly reflected from magnetic and nonmagnetic mirrors. It was found that the polarization asymmetry was absent to an accuracy of 10^{-4}–10^{-3}.

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When the polarization of thermal neutrons transmitted through a polarizing neutron guide was investigated,[1] a polarization asymmetry was found, depending on the direction of the magnetic field of the polarizer and the direction of the curvature of the uniformly bent neutron guide. The difference in the polarization of the neutron beam was found to be up to $\Delta P\approx 30\%$ with maximum polarization $P\approx 80\%$. This experimental result was unexpected and extremely surprising.

Subsequent theoretical work by Handel[2–4] was concerned with the explanation of the observed asymmetry in terms of the spin-orbit interaction between the neutrons and the Coulomb field due to atoms on the reflecting surface of the mirror. The potential V_i for this interaction is related to the magnetic field induced by the electric field E_i of the atom i in the coordinate frame of the moving neutron:

$$V_i = -\frac{\mu}{mc}\,\sigma\cdot(\mathbf{E}_i\times\mathbf{p}), \tag{1}$$

where μ and m are, respectively, the magnetic moment and the mass of the neutron, σ is the Pauli operator, and $\mathbf{p}$ is the momentum of the incident neutron. Averaging over all the scattering atoms shows that the field $\mathbf{E}$ is determined by the electrostatic field of a thin surface layer (1–10 Å), i.e., the dipole barrier D on the surface of the mirror, where $\mathbf{E}\parallel\mathbf{n}$ and $\mathbf{n}$ is the normal to the plane of the mirror. Because of the presence of the triple product in the potential, the sign of the potential and, consequently, the intensity of the reflected beam will depend on the mutual orientation of the vectors σ, $\mathbf{n}$, $\mathbf{p}$. This in qualitative agreement with the asymmetry observed in the Berndorfer experiment.[1] Quantitatively, however, the Handel estimate of the effect of the spin-orbit interaction on a single reflection from the mirror used in[1] turns out to be $P=1\%$. Moreover, this effect can, in principle, be increased by a garland-type multiple reflection in a sufficiently long neutron guide, since the sign of the potential V does not change in the course of these reflections and the effect itself is cumulative.

The above effect, if large enough, could lead to errors in experiments on right-left reflections of neutrons. We have therefore carried out a series of experiments with a view to obtaining a quantitative estimate for the polarization asymmetry effect. This research was stimulated by the current program of developing polarizing neutron-guide systems, because the Bendorfer effect[1] imposed definite conditions on the use of such systems in physical experiments.

According to Handel,[3] when spin-orbit effects are taken into account, the intensity of a neutron beam reflected from a mirror is

$$I = \frac{hk'}{m}e^{-2\varphi_2}(1+4A\sin\varphi_1\,\mathrm{sh}\,\varphi_2), \tag{2}$$

where k' is the wave vector of the reflected neutrons, φ_1 and φ_2 are, respectively, the real and imaginary parts of the phase ($\varphi=\varphi_1+i\varphi_2$) of the wave function of neutrons reflected from the mirror, and the expression

$$A = \frac{\mu}{c\hbar}D\frac{k}{k_3}\,\sigma\cdot(\mathbf{n}\times\mathbf{k}/k) \tag{3}$$

is the asymmetric spin-orbit term in which D is the surface dipole moment. The sign of A is determined by the sign of the triple product $\sigma\cdot[\mathbf{n}\times\mathbf{k}]$ in which $\mathbf{k}$ is the wave vector of the incident neutrons and k_3 is the normal component.

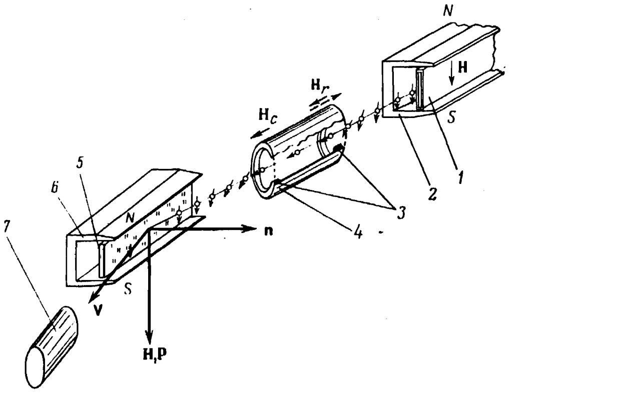

FIG. 1. Experimental arrangement: 1—polarizing neutron guide; 2, 6—permanent magnets; 3—flipper coils producing constant H_c and reversing H_r; 4—magnetic shield of the flipper; 5—mirror (specimen) under investigation; 7—$B^{10}F_3$ neutron detector.

It follows from (2) that, in experiments with nonmagnetic materials, the asymmetric term affects the polarization P_{s0} after reflection of the initially unpolarized beam. Under these conditions,

$$P_{s0} = \frac{I_+-I_-}{I_++I_-} = 4\frac{\mu}{c\hbar}D\frac{k}{k_3}\sin\varphi_1\,\mathrm{sh}\,\varphi_2, \tag{4}$$

where I_+ and I_- are the intensities of the reflected beam corresponding, respectively, to the two cases

$\sigma\cdot(\mathbf{n}\times\mathbf{k}/k)=\pm1$.

Since the experiments were performed with a polarized-neutron beam and the specimen was the analyzer, to determine P_{s0} in the case of nonmagnetic materials, it was sufficient to reverse the polarization P_0 of the beam incident on the specimen because this was equivalent to reversing the sign of σ. The polarizing properties of the analyzer were then connected only with the spin-orbit asymmetry resulting from reflection, and the measured polarization was $P_A=P_{s0}$. In the case of magnetic mirrors, the polarizing efficiency of the mirror associated with its magnetization can be eliminated by both reversing P_0 and reversing either the magnetic field $\mathbf{H}$ or the direction of reflection $\mathbf{n}$. Under these conditions,

$$P_A \equiv \Delta P = P_{+H}-P_{-H} = P_{+n}-P_{-n} \approx 2P_{s0}^{+} + 2P_{s0}^{-}/R, \tag{5}$$

where P_{s0}^+ and P_{s0}^- are the spin-orbit effects corresponding to the cases where the spin is parallel and antiparallel to the magnetizing field $\mathbf{H}$, respectively, and $R=I_+/I_-$ is the ratio of reflected-beam intensities in these two cases. In all the experiments, we determined the relative difference between I_+ and I_- when $\mathbf{P}_0$ was reversed. For nonmagnetic mirrors, this difference immediately yielded P_{s0} in accordance with (4), whereas, for magnetic materials, the difference was measured twice (for $+\mathbf{H}$ and $-\mathbf{H}$, and for $+\mathbf{n}$ and $-\mathbf{n}$) and the result was used with (5).

The experiments were carried out with a polarized-neutron system (see Fig. 1) in which the polarizer was either a single magnetized mirror or a polarizing neu-

TABLE I. Experimental values of polarization symmetry P_A.

Number of experiment	Number of specimen	Specimen	$P_A \cdot 10^4$	Vector whose sign was reversed in experiment*
1		Without specimen (constant counting channel)	-0.12 ± 1.1	P
2		Without specimen (average over counting channels)	0.8 ± 0.6	P
3		Cu	0.2 ± 1	P
4		Cd	1.6 ± 2.6	P
5	(1)	Glass	-7 ± 2	P
6	(1)	Glass	-6.5 ± 1.3	H, n
7		Ti–Gd (15% weight)	-4.6 ± 8	P
8	(1)	Fe	188 ± 45	n
9	(1)	Fe	40 ± 15	H
10	(2)	Fe	-4 ± 9	H
11	(1)	Fe^{54} (80%)	12 ± 8	H
12	(2)	Fe^{54} (80%)	10 ± 8	H
13		Fe^{54} (90%)	-2 ± 13	H
14		Fe–Co neutron guide	-42 ± 6	H

*For experiments in which the reversal of $\mathbf{P}_0$ was not the dominant influence on the determination of the polarization asymmetry effect but was merely auxiliary (to separate the polarization due to the magnetization of the mirrors in experiments 8–14 and in control measurements in experiment 6), the vector $\mathbf{P}$ is not indicated.

tron guide,[5] and the analyzer was the specimen under investigation in the form of a reflecting layer. The sign of $\mathbf{P}_0$ was altered by a flipper mounted between the polarizer and analyzer. It was also possible to reverse the sign of $\mathbf{n}$ by rotating the analyzer magnet about the vertical axis passing through the reflecting plate, and to vary the polarity of $\mathbf{H}$ in the analyzer magnet.

The specimens were prepared in the form of thin films deposited on a polished glass surface by thermal evaporation in vacuum. We investigated specimens with different ratios of real and imaginary parts of the coherent scattering amplitude, with large and small neutron cross sections, Ti–Gd specimens with the real part of the nuclear amplitude approaching zero, and polarizing mirrors with magnetized coatings consisting of Fe^{54}-enriched iron. The last specimens were introduced to vary the ratio of nuclear and magnetic coherent scattering amplitudes.

The maximum of the spectrum of the incident polarized beam corresponded to a wavelength $\lambda = 3$ Å. The glancing angle in the case of nonmagnetic specimens was about 6 minutes of arc. For magnetic mirrors, the angle was set close to the critical value. When the polarizing neutron guide became available,[5] the experiment was very close to the conditions under which Bendorfer[1] observed substantial polarization asymmetry. The neutron guide consisted of mirrors with Fe–Co coatings and a substrate of Ti–Gd, optimized for minimum reflection. The seven flat neutron-guide elements should have enhanced the resultant spin-orbit effect in the case of garland reflection. The neutron guide parameters were as follows: length 1470 mm, channel width 1.6 mm, radius of curvature 1.3×10^5 mm, mean polarization evaluated over the spectrum $\langle P \rangle = 0.97$.

Table I lists the experimental values of P_A. The system was calibrated without the specimen to determine possible systematic errors. To separate out errors connected with the detection system and with the magnetic channel, the measurements were performed both with constant counting channels for I_+ and I_- (experiment 1) and with periodic interchange of channels (experiment 2). It is clear from Table I that, in the case of single reflections, the polarization asymmetry effect was not detected to within $P_A < 10^{-4}$ in the case of nonmagnetic materials and to within $P_A < 10^{-3}$ for ferromagnetic mirrors.

Values of the asymmetry P_A exceeding the statistical measurement error were found for glass (experiments 5 and 6), iron (experiment 8), and Fe–Co neutron guides (experiment 14). However, there are no reasons to suppose that this asymmetry was entirely due to spin-orbit effects. Thus, firstly, the asymmetry P_{s0} for glass, a weakly absorbing material, should be less than for Cd and Ti–Gd [since $\varphi_2(\mathrm{Cd, Gd}) \gg \varphi_2$ (glass)] for which no asymmetry was found. Secondly, in experiment 8, an asymmetry was obtained for Fe when the sign of $\mathbf{n}$ was reversed. This asymmetry was reduced by a factor of four in experiment 9, when the sign of $\mathbf{H}$ was reversed for the same specimen, but was not found to within 10^{-3} for another specimen of Fe (experiment 10). Thirdly, the observed asymmetry for glass and for Fe–Co in the neutron guide is negative as compared with the spin-orbit effect. Among the possible reasons that could have given rise to polarization asymmetry we note the change in the adiabatic conditions for the beam transmitted by the magnetic channel between the flipper and the analyzer (experiments with reversed $\mathbf{H}$), which may have resulted in partial depolarization of the beam (which is different for $+\mathbf{H}$ and $-\mathbf{H}$), and the angular dependence of the spectral distribution of neutrons in the beam reflected from the polarizing mirror (experiment with reversed $\mathbf{n}$), since the polarizing power of the mirror is not constant over the spectrum. The asymmetry was not observed for the Fe^{54}-enriched iron mirrors either, for which the real part of the coherent-scattering amplitude was close to zero, as indicated by the high polarizing efficiency ($P \approx 1$) of these mirrors due to compensation of nuclear and magnetic scattering amplitudes.

Since it was not our aim to investigate the spin-orbit effect but merely to obtain a quantitative experimental estimate for these factors in the case of reflecting materials used in practice, we did not look for the ideal conditions under which these effects might be seen. The theoretical estimates reported by Handel[2-4] do, in fact, refer to such ideal conditions, i.e., complete compensation of the real parts of the nuclear and magnetic scattering amplitudes, sufficiently large imaginary part of the amplitude, and particular purity on the reflecting surface layer, which is quite difficult to achieve in an experiment.

On the basis of our measurements, we can find no evidence for the polarization asymmetry reported by Berndorfer[1] and consider that this effect is more likely to have been due to technological factors and not the spin-orbit contribution.

It also follows from our experiments that Handel's proposals[4] regarding the use of spin-orbit effects for measuring the potential due to the electric surface dipole layer, and for producing on this basis an electric neutron polarizer, are far from experimental realization.

In conclusion, we are indebted to G. M. Drabkin and E. F. Shender for useful discussions of the experiment and the possible spin-orbit effects, and to N. V. Borovikova for preparing the samples for the experiment.

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A bound on the proton electric dipole moment derived from atomic experiments

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The upper bound $|d/e| < 5.5\times 10^{-19}$ cm on the proton electric dipole moment (EDM) d is derived from the experimental upper bound for the EDM of the cesium atom in a state with $F=4$. Similar measurements on an $F=3$ state might improve this result by a factor of 1.5. An upper bound on the magnetic quadrupole moment of the nucleus (which might be induced, for example, by the EDM of the valence nucleon) is also derived from the same experiment. The search for the proton EDM in experiments with polar molecules is discussed.

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1. INTRODUCTION

It is well known[1] that elementary particles can have electric dipole moments (EDM) only if time-reversal invariance is violated. Up to now, T-odd interactions seem to have been observed only in the decay of K^0 mesons. From this it is clear why it is of interest to seek EDM of elementary particles. In particular, elementary-particle EDM would be of interest because of the light they might shed on the structure of the T-odd interaction.

Experiment gives the following upper bound for the neutron EDM, d_n: $|d_n/e| < 10^{-23}$ cm.[2] The difficulties in measuring the EDM of charged particles—electrons and protons—are obvious. Nevertheless, the idea of seeking the electron EDM via the EDM it induces in a neutral atom has proved to be very fruitful. At first glance the situation here would seem to be hopeless in view of Schiff's well-known theorem,[3] according to which the EDM of a system of nonrelativistic particles in equilibrium under the action of electrostatic forces will vanish provided the intrinsic EDM of each particle has the same spatial distribution as the charge of that same particle. As Sandars showed,[4] however, owing to relativistic effects the induced EDM of a heavy atom not only is not small, but on the contrary, is much enhanced as compared with the EDM of the electron inducing it. Calculations[4-7] show that the enhancement factor is ~130 for cesium and ~500 for thallium. Experiments with atomic cesium[8] and thallium[9] resulted in the following bounds for the electron EDM: $|d_e/e| < 3\times 10^{-24}$ cm and $|d_e/e| < 7\times 10^{-24}$ cm.

In the present study we derive an upper bound for the

