Polarized electrons from ferromagnets

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The review is aimed at calling attention to a new method of investigation of magnetism, photoelectron measurement of the polarization. This method, developed at a juncture of the photoeffect and of magnetism, is of interest from the point of view of studying the properties of magnets as well as developing sufficiently intense sources of polarized electrons, which are needed for a number of problems in high-energy physics. A procedure is considered for successful experiments on the measurement of the polarization of photoelectrons. Detailed descriptions are presented of the results of measurements made on polycrystalline and disordered films of transition metals, rare-earth ferromagnets, as well as films and single crystals of chalcogenides and pnyctides. The available results, which agree well with the theoretical concepts for chalcogenides and pnyctides and which indicate the need for further development of both the theory and experiment for transition metals, confirm the undisputed value of the photoelectron polarization method. An already developed pulsed source of polarized electrons based on the photoeffect from EuO is described. (The literature through September 1975 is used).

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CONTENTS

1. INTRODUCTION

Studies of the distribution of photoelectrons in energy and in emission angle are being used of late more and more extensively and with increasing success for the investigation of the electron structure of ferromagnets.[1–6] It is quite promising to measure in such experiments the predominant orientation of the photoelectron spins, i.e., to measure their polarization. If the processes that take place when photoelectrons are emitted from a substance are correctly taken into account, such experiments can yield important information on the state of the magnetic electrons. In addition, such experiments can lead to the development of an effective source of polarized electrons, which is of importance for a number of problems in atomic and nuclear physics.

The first to point out the possible existence of polarized photoelectrons from ferromagnets were Fues and Hellmann in 1930.[7] The description of the polarization of an ensemble of electrons was discussed in detail in the reviews[8,9]. In this paper we consider the present status of experiments on the measurement of the polarization of photoelectrons from ferromagnets, the results of experiments for various types of magnets, and the prospects of further utilization of this method. Some of these questions were considered briefly in[10]. An example is also given of a source of polarized electrons obtained with the aid of the photoeffect from europium oxide.

The idea of obtaining polarized electrons from ferromagnets via the photoeffect is illustrated in Fig. 1 with a hypothetical ferromagnetic d-metal as an example.[11] It is assumed that the subbands of d-electrons with opposite spins are shifted relative to one another by the exchange interaction. In the s-band, the density and polarization of the electrons are apparently small, so that they influence weakly the results of the experiment. If the photon energy exceeds $h\nu_D$, then the photoelectron polarization should be close to the ratio of the number of magnetons per atom to the total number of $3d$ and $4s$ electrons per atom ($2.2/8 = 28\%$ for Fe, $0.6/10 = 6\%$ for Ni, and $1.7/9 = 19\%$ for Co). The polarization is then negative, since the polarization vector **P** and the magnetization **M** for the magnetized ensemble of electrons are directed opposite to each other, inasmuch as the spin of the electron is antiparallel to its magnetic moment. In most published papers, the sign of the polarization is stipulated in the text, and in the figures the sign of the polarization usually coincides with the sign of the magnetic moment of the electrons. The same convention will be adhered to here. Depending on the concrete distribution of the density of states and on the employed frequency of the light, the magnitude and the sign of the polarization can vary significantly and differ noticeably from the average over the band. Thus, if the Fermi level is located at the point A, then photons with energy $h\nu_A$ produce photoelectrons with large positive polarization. If the Fermi level is located at the point B, then at a photon energy $h\nu_B$ we obtain prac-

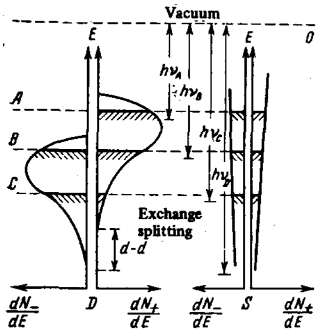


FIG. 1. Production of polarized electrons from ferromagnets by the photoeffect.

tically unpolarized photoelectrons. On the other hand, if the Fermi level is located at the point C, then the photoelectrons are negatively polarized.

The picture of the phenomenon can be altered by the scattering of the photoelectrons as they move towards the surface. The depth of the emergence of the photoelectrons ranges from several to several dozen angstroms, depending on the material and on the wavelength of the incident light,[12-14] while the emission time is close to 10^{-13} sec.[15] It is difficult to take into account beforehand the role of the collision processes in the depolarization of photoelectrons. This role can be revealed ultimately only by comparing the result of the experiments with the existing theories.

The experiment and its interpretation are made exceedingly complicated by the fact that the depth from which the photoelectrons emerge is itself small. The possible existence of surface levels, even in an ideal crystal, blurs the described experimental scheme in the same manner as the presence of oxides or adsorbed layers on the surface, the deviation of the composition of the surface from the average composition over the sample, etc. All this imposes stringent requirements on the quality of the samples and on the experimental conditions.

2. PRINCIPAL PROCESSES INFLUENCING THE POLARIZATION OF PHOTOELECTRONS

Following[16], we consider briefly the main processes that influence the polarization of photoelectrons from ferromagnets. These are: 1) transition to an excited level, 2) migration to the surface, 3) overcoming the surface potential barrier, 4) passage through external fields.

A. Transition to an excited level

Let $N(E)$ denote the density of the occupied states with energy E, and let $D(E')$ denote the density of the free states with energy E', with $E' - E = h\nu$, where $h\nu$ is the photon energy. The probability of the appearance of an exicted electron is equal to $\alpha N(E)D(E')$, where α is the matrix element of the transition. In a ferromagnet we have not only $N_\uparrow(E) \neq N_\downarrow(E)$ but also $D_\uparrow(E') \neq D_\downarrow(E')$. If α does not depend on the spin direction, then it is easily seen that the polarization of the excited electrons is

$$P=\frac{P_e+P_0}{1+P_eP_0}.$$

where

$$P_e=\frac{D_\uparrow-D_\downarrow}{D_\uparrow+D_\downarrow}.$$

$$P_0=\frac{N_\uparrow-N_\downarrow}{N_\uparrow+N_\downarrow},$$

i.e., the polarizations of the initial and final states are on a par. If $P_0 = 1$, then also $P = 1$, independently of P_e.

B. Migration to the surface

An excited electron can collide on the way to the surface with other quasiparticles. If the scattering cross sections depend on the spin, then the intensity and the polarization of the photocurrent will depend on these collisions. It is known that the most significant of these is the electron-electron collision. Nonetheless, at least in a number of cases, the picture of the density of the electronic states in the substance can be reproduced with sufficient detail from the energy distribution of the photoelectrons (see, e.g., Fig. 2). It is therefore to be hoped in this case that although the dependence of electron-electron collisions on the spin is unknown, it exerts a negligible influence on the photoelectron polarization. What is essential is the question of the possible specific spin-exchange collisions. Their possible role in the theory of such scattering, however, must be taken into account already even when it comes to the results of the observation of the polarization of the photocurrent.

C. Overcoming the surface barrier

Owing to the exchange interaction, which has opposite signs for electrons with oppositely directed spins, the overcoming of the surface barrier should depend generally speaking on the direction of the spin of the emitted electron. In the case of field emission, according to estimates, this effect can greatly distort the value of the polarization that results from polarization of the initial density of states.[17] In photoemission, the emission probability is much larger than in field emission, so that the spin direction should exert a smaller influence on the passage through the barrier on the surface. Furthermore, this effect decreases rapidly with increasing kinetic energy of the electrons.

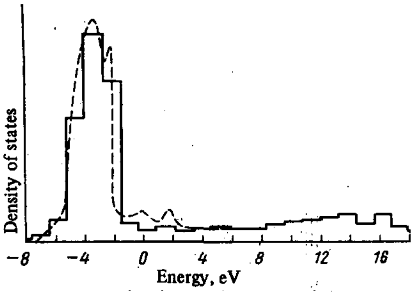


FIG. 2. Density of electronic states in Cu (from[57]). The dashed line indicates the experimental data on the photoeffect, and the solid line the calculation. The energy is reckoned from the Fermi energy.

D. Passage through external fields

The influence of macroscopic fields on the polarization of a beam of electrons was considered in detail in[8,9]. It can be observed experimentally by examining the behavior of the polarization when these fields are varied.

3. EXPERIMENTAL PROCEDURE

The first attempt to measure the polarization of photoelectrons from ferromagnets was made in[19,20]. Within 5%, there was no photoelectron polarization in these experiments.

In the next attempt to measure the photoelectron polarization, high-purity single-crystal nickel was used.[21,22] The photocurrent was emitted from the (110) face, and the magnetization reversal was along the [111] axis. The illumination source was a mercury lamp. The sample surface was purified by heating to red incandescence (800 °C). The vacuum in the experimental setup was 2×10^{-8} Torr. No polarization was observed at a measurement sensitivity 2%.

Experiments aimed at observing polarization of photoelectrons from ferromagnets were carried out also in[23,24]. The results of the first experiments, performed on bulky samples of Permendur, nickel, and the ferrite $Co_{0.02}Ni_{0.52}Zn_{0.26}Cr_{0.2}Fe_2O_4$ in a vacuum of $\sim 10^{-6}$ Torr and with illumination with a hydrogen lamp have shown that under these conditions the polarization of the photoelectrons was $\lesssim 0.2\%$. In the succeeding experiments, the samples were epitaxial iron films deposited in a separate setup on a single-crystal copper substrate. The time during which the samples were exposed to the atmosphere as they were moved to the polarization-measurement chamber was about 30 minutes. The samples were magnetized parallel to the surface and the remanent magnetization was measured. The measurements were made in a vacuum of $\sim 10^{-6}$ Torr. The measured value of the polarization was $-2.42\pm0.51\%$. The experiments on polycrystalline samples revealed no polarization even when the samples were prepared directly in the chamber used for the polarization measurements. It is obvious that the decisive condition for a successful observation of the photoelectron polarization is high quality of the surface-layer structure in the measured samples.

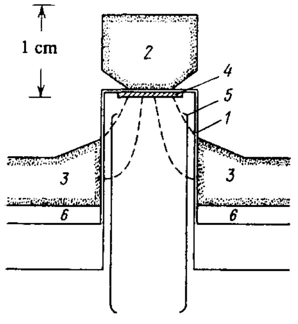


FIG. 3. Photocathode used to obtain a beam of polarized electrons. 1) Vacuum insulation, 2, 3) electromagnet poles, 4) sample, 5) electrode, 6) liquid helium.

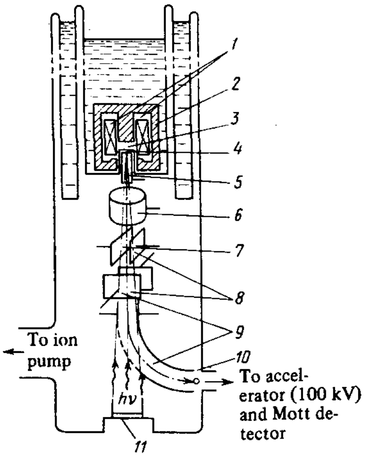


FIG. 4. Electron source and electron-optical system. 1) Superconducting solenoid, 2) magnet, 3) magnetic-field meter, 4) sample, 5) first electrode (1100 V), 6) second electrode (3700 V), 7) position of the evaporator when the sample is prepared, 8) deflecting system, 9) photoelectron beam, 10) cylindrical capacitor, 11) window.

The first and so far only successful measurements of the polarization of photoelectrons from ferromagnets were those performed in a vacuum of 10^{-10} Torr by Busch's group in Switzerland.[25] The polarization of the photoelectrons from iron reached 50% in this case. We shall describe the procedure used in these experiments.

The setup for the measurement of the polarization of photoelectrons from ferromagnets should consist of the following parts: the sample, the system for its illumination, the polarization analyzer, and the vacuum system.

Figure 3 shows the arrangement of the photocathode used to obtain the photoelectrons.[16] The magnet lies in the lower part of a Dewar with liquid helium. The Dewar is made of stainless steel. The sample is either evaporated directly in the apparatus or else it is a single crystal also cleaved directly in the apparatus for the polarization measurement. The light spot on the sample has a diameter 1–2 mm.

Figure 4 shows the photocathode together with the electron-optical system.[26] In this geometry, owing to the large demagnetizing factor, strong fields are needed to magnetize the sample. On the other hand, the electric and magnetic fields near the sample are perpendicular to its surface. The electrons move along these fields, a fact that facilitates their focusing and probably decreases the influence of the electrons from the microscopic inhomogeneities of the sample surface.[27]

The installation can be equipped with a device for evaporating several samples,[25] with a device for coating the samples with cesium,[28,29] with a device for cleaving the single crystals in a vacuum,[30] with a device for measuring the thickness of the film samples,[14,31] and with a device for evaporating samples with the aid of an electron beam.[32]

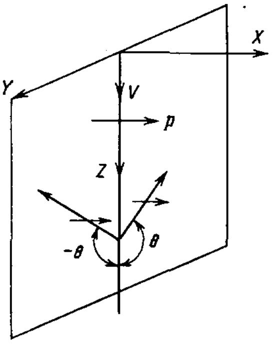


FIG. 5. Coordinate system in Mott scattering.

The analyzer used for the electron polarization is the so-called Mott detector. Its operation is based on the fact that when electrons with a spin perpendicular to the scattering plane are Coulomb-scattered from an atom, the scattering becomes asymmetric in the azimuthal direction.[33] The employed coordinate system is shown in Fig. 5. The measured quantity is in this case the asymmetry

$$A_P = |P_X|S| = \frac{J(\theta)-J(-\theta)}{J(\theta)+J(-\theta)};$$

Here P_X is the polarization of the incident beam, $|S|$ is the beam polarization produced after single scattering of the initially unpolarized beam, and $J(\pm\theta)$ is the intensity in the direction of the angle $\pm\theta$.

In the chosen coordinate system, the sign of A_p coincides with the sign of P_X. Detailed calculations of S for electron scattering by a single atom are given in[34-36]. A number of workers have performed exact measurements of S at different scattering angles and at different electron energies.[37-39] In a target of finite thickness, the multiple and repeated scatterings lead to depolarization of the incident beam.[38,40,41] This determines the maximum thickness of the employed target.

A Mott detector registers only the transverse beam polarization, i.e., the polarization perpendicular to the velocity direction. Therefore when the sample is magnetized perpendicular to the surface it becomes necessary to transform the longitudinal polarization of the beam into a transverse one with the aid of a cylindrical capacitor.[26] In addition, this capacitor is used to deflect the electron beam from the illumination direction and to divert the photoelectrons from the first electrodes of the electron-optical system. It should be noted that the use of a cylindrical capacitor complicates the installation and increases its dimensions. Its use can be obviated by magnetizing the sample along the surface; the photoelectrons are then polarized transversely at once. The whole apparatus turns out to be simpler.[24] In such a geometry it is probable that it is easier to avoid the experimental difficulties in the measurement of the polarization of photoelectrons having different energies.[10] The choice of the direction of the sample magnetization should be based on all these considerations.

The function S has a maximum at 120 keV and at a scattering angle 120°.[38] In the Mott detector used by Busch's group (Fig. 6), the electrons were accelerated to 100 keV. The beam was collimated with diaphragms and was scattered by a target in the form of a free-standing gold leaf 167 μg/cm² thick. The scattering angle was 120 ± 5°. The polarization was calculated in the following manner: In the case of a positive direction of H, the intensities J_1 and J_2 of the electrons scattered in counters 1 and 2 can be expressed in the form

$$J_1^{\uparrow} = a_1^{\uparrow}(1+PS), \quad J_2^{+} = a_2^{+}(1-PS).$$

S was assumed equal to 0.31 ± 0.01.[26] This was less than the experimental value (0.36 ± 0.01) obtained at these energies and scattering angles in[38].

To calculate the asymmetry of the Mott scattering

$$A_P = PS$$

from the measured asymmetry $A = (J_1 - J_2)/(J_1 + J_2)$, it is necessary to know the apparatus asymmetry

$$A_0 = \frac{a_1^{\uparrow} - a_2^{+}}{a_1^{+} + a_2^{+}}.$$

We obtain

$$A = \frac{A_0 + A_P}{1 + A_0 A_P}.$$

We note that A_0 depends not only on the sensitivity and on the position of the counters, but also on the position of the beam on the target and on the intensity distribution over the beam cross section. When the sign of the field H is reversed we have

$$J_1^{-} = a_1^{-}(1-PS).$$
$$J_2^{-} = a_2^{-}(1+PS).$$

If it is assumed that $a_1^{+} = a_1^{-}$ and $a_2^{+} = a_2^{-}$, then, putting $Q^{\pm} = J_1^{\pm}/J_2^{\pm}$, we obtain

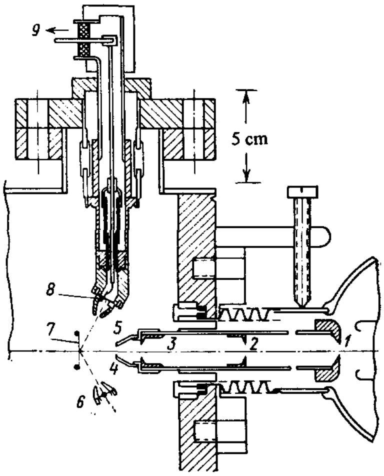


FIG. 6. Mott detector. 1–4) Incident-beam diaphragms, 5,6) cathode-beam diaphragms, 7) target, 8) solid-state detector, 9) to preamplifier.

$$A_P=\frac{1-\sqrt{Q^+/Q^-}}{1+\sqrt{Q^+Q^-}}$$

and

$$A_0=\frac{1-\sqrt{Q^+Q^-}}{1+\sqrt{Q^+Q^-}}.$$

Thus, measurement of the polarization $P=A_pS^{-1}$ reduces to measurement of Q^+ and Q^-. The value of A_0 makes it possible to monitor the reliability of the operation of the setup.

The assumption that $a^+_{1,2}=a^-_{1,2}$ is based on the fact that the focal length of the magnetic lens (see Fig. 3) does not depend on the field direction. The position of the beam on the target changed with changing sign of H, but variation of the voltage on the electrodes of the deflecting system has made it possible, by setting the maximum of the intensity of counter 1, to return the beam to the initial position. The invariance of the apparatus asymmetry to reversal of the sign of H was verified with thick targets, for which $S\approx 0$ because of multiple scatterings. In[23] we used a polarization measurement method on copper and aluminum targets instead of gold. This made it possible to take into account the possible existence of apparatus asymmetry and the change in the beam position with changing sign of the magnetic field.

A vacuum of ~ 10^{-9} Torr is sufficient to maintain the polarization constant for at least several days.[27] The vacuum was produced with ion pumps. In addition, the surface of the Dewar of the superconducting magnet served undoubtedly as a small cryogenic pump. Busch *et al.*[42,43] used special measures to prevent the surface of the sample from being the coldest part of the installation. It is stated that an increase of the pressure to 10^{-7} Torr is destructive when it comes to observing photoelectron polarization of polycrystalline nickel films.[27]

4. POLARIZED PHOTOELECTRONS FROM FERROMAGNETS OR THE IRON GROUP

The polarization of the photoelectrons emitted from ferromagnets serves as an impressive illustration of the fact that ferromagnetism is due to spontaneous spin polarization of the electrons. Particular interest attaches to measurement of the polarization of photoelectrons from ferromagnets of the iron group, owing to their special practical importance and owing to the ensuing interest in a detailed understanding of the mechanism of the ferromagnetism in these substances.

A. Polycrystalline nickel

Measurements of the polarization of photoelectrons from polycrystalline nickel are reported in[14,25,27,29].

Generally speaking, the first report of polarization of photoelectrons from nickel is contained in[16]. Its magnitude ranges from 2 to 4%. In subsequent studies, the polarization of the photoelectrons from nickel reached already 15%. The authors of[16] believe that the material used by them was not pure enough, or was not sufficiently well outgassed when the film was prepared. The vacuum conditions in these studies were identical. Thus, we see once more that the quality of the sample affects the magnitude of the polarization most significantly. For the results to be reliable, the structures of the employed films must therefore be monitored, something not yet performed in studies of the polarization of photoelectrons from ferromagnets. It would be attractive to use single crystals in such experiments, but this raises the extremely complicated question of the purification of the sample surface.

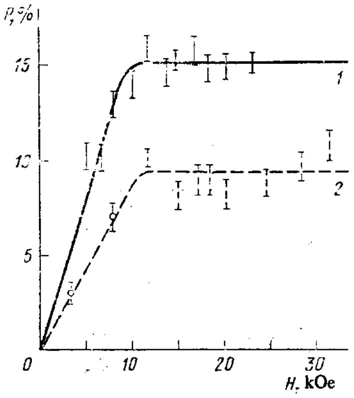


FIG. 7. Polarization of photoelectrons from nickel films. The results of curves 1 and 2 were obtained for films produced at different substrate temperatures: 383 °K (1) and 4.2 °K (2). The predominant direction of the magnetic moment of the electrons is parallel to the sample magnetization. The measurements were performed at liquid-helium temperature under illumination from a high-pressure mercury-xenon lamp.

The structure sensitivity of the polarization of the photoelectrons can be seen from the fact that films deposited on substrates with temperatures 4.2° and 383 °K, i.e., structurally disordered and ordered, had polarizations that differed by almost a factor of two (Fig. 7). For single-crystal films, the polarization was independent of the measurement temperature in the range from 4° to 300 °K.

The successful measurements of the polarization of photoelectrons from nickel provided immediate answers to certain heretofore unclear questions. First, the saturation of the polarization with increasing magnetic field indicates that similar samples do not have on their surfaces the "dead" layers whose existence on electrolytically deposited films of nickel was observed in[44]. Two such layers (~ 4 Å) on a nickel surface, at an electron-electron scattering length ~ 10 Å, would produce approximately 30% of the photocurrent. This would lead in turn to a monotonic increase of the polarization with increasing magnetic field on the sample. The absence of such an effect gives grounds for expecting a sufficiently high sample quality.

The independence of the photoelectron polarization on the measurement temperature demonstrates the possibility of neglecting the inelastic electron-magnon scattering. This question was considered theoretically in[45,46]. The argument there was as follows: At 0 °K, only magnons can be produced, i.e., the only possible spin flips of the photoelectrons moving toward the surface are those which decrease the magnetization. With increasing temperature, spin flips in both directions become possible. If this mechanism were to determine the magnitude of the polarization, then the polarization of the photoelectrons in the range from 4° to 300 °K would decrease in proportion to the Debye-Waller factor.

Cutting off the ultraviolet with a filter made it possible to measure the polarization in the region of approximately 0.4 eV near the Fermi level. It turned out that this polarization agrees within ± 2% with the polarization measured when the entire spectrum of the lamp is used for the illumination. The dependence of the polarization on the light frequency was investigated in greater detail in[29], where the work function of the nickel was decreased by coating the sample surface with cesium. The degree of coating ranged from 0 to 1 (corresponding to a single monolayer of cesium), and the work function was decreased thereby from 4.4 ± 0.1 to 2.2 ± 0.1 eV. The cesium atoms on the sample surface can influence the magnitude of the polarization for a number of reasons. For example, a noticeable photoemission of the electrons from the cesium atoms located on the nickel surface is perfectly feasible. At a photon energy close to the work function, the quantum yield from the ferromagnetic transition metals tends to zero, and the photoemission from the cesium remains the same in this case. Therefore coating with cesium can lead to the largest distortion in measurements made near the photoeffect threshold. The role of the photoeffect from cesium can be increased by elastic and inelastic collisions of the electrons from the nickel with the atoms of the coating. At low electron energies, the polarization can be significantly influenced by spin-exchange interaction between the photoelectrons and the cesium atoms. The total cross section for the spin-exchange interaction of free electrons with cesium atoms at a kinetic energy less than 0.5 kV is $\geqslant 10^{-14}$ cm^2.[47]

An increase of Θ can decrease the density of the conduction electrons in the first atomic layer of the substrate. In this case, a shift should occur in the position of the d-band in the surface layers, and this can influence the magnetization of these layers, meaning also the polarization of the photoelectrons. Whether this polarization is increased or decreased thereby is a moot question.[29]

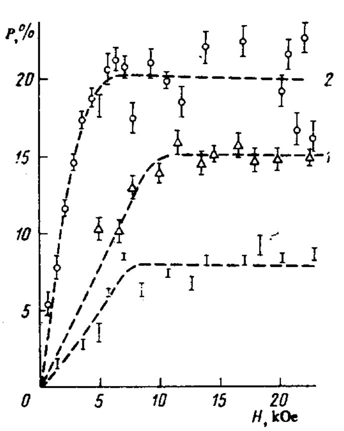


FIG. 8. Polarization of photoelectrons. 1) Pure nickel film, $e\varphi = 4.9 \pm 0.1$ eV; 2, 3)—cesium-coated films, $e\varphi$ (eV) $= 3.4 \pm 0.1$ (2) and 2.4 ± 0.1 (3). Measurement temperature 4.2 °K.

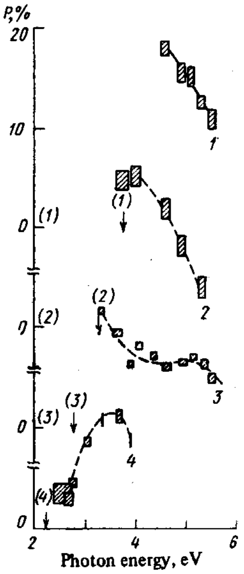


FIG. 9. Dependence of the polarization of photoelectrons from nickel films on the photon energy. Work function (±0.1 eV): 3.8 (1), 3.2 (2), 2.8 (3), and 2.2 (4).

It appears that as gross an effect as the formation of a nickel-cesium alloy in surface layers is also possible.[48] The role of all these effects can be ascertained by measuring the polarization of samples having different degrees of coatings, in different fields, and on different materials. Generally speaking, cesium coating can cause a change in the polarization of the photoelectrons simply for apparatus-related causes—the well-known "spot effect" on the photocathode.[49] This would lead to a redistribution of the intensity over the beam cross section, leading also to a change of the apparatus asymmetry. However, in the employed installation these effects could be monitored and kept under control within reasonable limits.

Figure 8 shows the dependence of the polarization of the photoelectrons from nickel films on the applied magnetic field. Curve 1 was obtained by using the entire spectrum of the Hg-Xe lamp for the illumination. The measurements represented by curves 2 and 3 were made with monochromatic illumination, $h\nu = 3.92$ eV (2) and 3.35 eV (3). All the curves of Fig. 8 have the same shape and weak saturation at $H \sim 6$–7 kOe, as expected for the case of nickel magnetized perpendicular to the surface. Figure 9 shows the dependence of the polarization on the photon energy. Their measurements were made in a field 8.4 kOe. With increasing degree of coating Θ, the polarization of the photoelectrons from the nickel decreases near the boundary of the photoeffect, and its maximum rises in a region 0.6–0.8 eV below the photoeffect threshold. It is seen from Fig. 9 that the polarization reaches a value equal to the average over the entire conductivity band (6%) when the photon energy exceeds the threshold by only 2–2.5 eV. This value is much less than the calculated width of the d-band in nickel (~ 5 eV).[50–52] Photoemission measurements yield for the band width a value ~ 3.3 eV,[3] while x-ray spectroscopy yields ~ 2.7 eV.[53] We shall return to this question later on. We note that the polarization of photoelectrons from nickel is negative at all the employed photon energies.

Measurements of the polarization of photoelectrons from polycrystalline nickel made it possible to clarify one more question of importance when it comes to understanding the photoeffect, namely, the question of the depth of emergence of the photoelectrons in the case of photoemission from transition ferromagnets.[14,31] The depth at which the photoexcited electrons are produced is determined by the depth $1/\alpha$ of penetration of the light, where α is the absorption coefficient at the corresponding frequency, and by the mean free path l of the electronic elastic scattering. Usually in metals $\alpha l \ll 1$, and the depth of the photoelectron yield is limited by the value of l. In earlier experiments they investigated the decrease of the transmitted photocurrent with increasing film thickness, or else the differences in the photocurrents from the film and from the substrate were determined from the intensity at a given photoelectron energy[54-56] (see also[12,13]). The principle underlying the experiments of [14,31] was that with increasing thickness of the film on the substrate the polarization of the photoelectrons comes closer to the polarization corresponding to the film material. It is assumed that the scattering on the path to the surface of the metal does not depend on k. The probability of emission of the photoelectron excited at a distance x from the surface and moving at an angle θ to the normal to the surface is proportional to $\exp[-x/l(E)\cos\theta]$, if the photoexcitation and emission processes are isotropic.[57] In the described experiments, the electrons are excited by photons having an energy close to the work function, and therefore $\cos\theta \sim 1$.

The polarization P of the total photocurrent I is a superposition of the polarization P_1 of the photocurrent from the substrate and of the polarization P_2 of the photocurrent from the film, and is given by the expression

$$P \cdot I(E) = P_1 I_1(E) e^{-h/l(E)} + P_2 I_2(E)\left(1 - e^{-h/l(E)}\right),$$

with $e\varphi < E < h\nu$ and

$$I(E) = I_1(E) e^{-h/l(E)} + I_2(E)\left(1 - e^{-h/l(E)}\right):$$

here h is the film thickness.

In principle, by varying P as a function of h we can determine both $I_1(E)/I_2(E)$ and $l(E)$; the value of $I_1(E)/I_2(E)$ can be obtained also by measuring the photocurrent with thick samples and by taking into account the work function, the depth of penetration of the light, and the reflection from the copper-nickel boundary. The reflection of light from the copper-nickel boundary in the range from 5.1 to 5.7 eV is less than 2%, and $1/\alpha \sim 100$ Å,[58] which is much longer than l. The described measurements have shown that $I_1/I_2 = 1.0$ with a scatter of 15% from sample to sample.

Copper was chosen to serve as the substrate for the following reasons. Its electronic structure is quite close to that of nickel, except that the density of states near E_F is lower than that for nickel. Assuming that the inelastic electron-electron collision is independent of the quasimomentum, the function $l(E)$ should be smaller in metals with larger state densities E_F.[59] This conclusion can be verified by comparing $l(E)$ for copper and for nickel. It is also of no less importance that the nickel film formed on copper becomes solid when the thickness reaches several monolayers.[60,61] This gives grounds for hoping that the results are not distorted by an island-like structure of the samples.

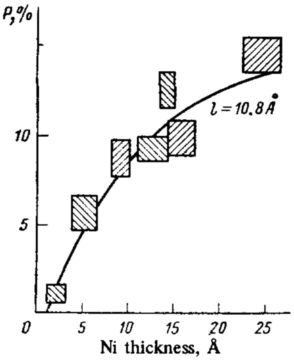


FIG. 10. Polarization of photoelectrons from Ni as a function of the sample thickness. Each experimental point is represented by a rectangle whose vertical dimension corresponds to the statistical error and the horizontal dimension to the uncertainty in the measurement of the film thickness. Rectangles hatched in the same direction represent films successively evaporated on one and the same copper substrate.

The films were produced at a substrate temperature 100 °C, or else were annealed at 100 °C. The pressure was raised in this case from 2×10^{-10} to 2×10^{-8} Torr. The evaporation was at a rate 2 Å/sec, the average film thickness was measured with a quartz radiobalance with sensitivity 25 Hz/Å. The error in the thickness measurement (0.5–1.0 Å) was determined mainly by the temperature-induced frequency shift. The work function was calculated from Fowler's curves.

The measurement results for nickel are shown in Fig. 10. The parameters l and h_0 in the formula $P = P_{\mathrm{Ni}}(1 - e^{-(h-h_0)/l}$ (solid line on Fig. 10) were chosen by least squares by taking into account of the scatter of both P and h. The polarization of the photoelectrons from the nickel, $P_{\mathrm{Ni}} = 15.15 \pm 0.3\%$, was taken from[27]. For electrons with energy 5.4 ± 0.3 eV above the Fermi level we have $l = 10.8^{+2.5}_{-1.7}$ Å. The possible existence of "dead" layers would shift the curve to the right, since it is obvious that polarization is produced in this case only when the nickel is ferromagnetic. The measurement data yield $h_0 = 1.2 \pm 1$ Å. Since the thickness of the nickel monolayer is about 2.2 Å, it is difficult to make any definite statements, on the basis of the obtained data, concerning the existence of even one "dead" layer. It is probable that the second monolayer is already ferromagnetic, and ferromagnetism definitely exists at a nickel thickness exceeding two layers. The measurements were made at 80 °K. At the same temperature, ferromagnetism was registered in electrolytically pro-

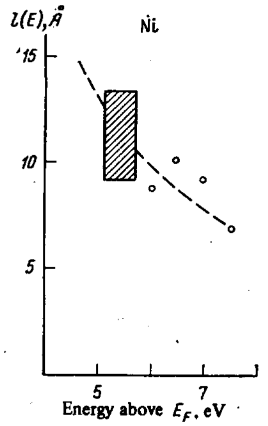


FIG. 11. Photoelectron mean free path in nickel. Rectangle—data on the photoelectron polarization, circles—results of[54]. Dashed line—calculation of $l(E)$ in the free-electron model, normalized to the measurements of the polarization.

duced nickel films only at thickness exceeding two monolayers.[44] Sputtered nickel films become ferromagnetic at room temperature only at thicknesses exceeding 7 Å.[60]

It is important that the photocurrent from one "dead" magnetic (i.e., paramagnetic) layer is only 18% of the total photocurrent ($l \approx 10.8$ Å), which cannot change the sign of the polarization. This means that the possible existence of such a layer does not determine the sign of the polarization in bulky samples.

The mean free path obtained from the measurements of the photocurrent polarization is compared in Fig. 11 with the value obtained in[54]. From the agreement between these data it can be concluded that the polarization of the nickel electrons is preserved as they advance towards the surface. But the existence of a depolarization mechanism independent of the thickness, for example spin-exchange scattering by a paramagnetic layer on the surface is still possible. This scattering can decrease the magnitude of the polarization but cannot change its sign.

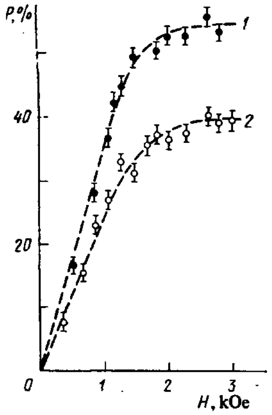


FIG. 12. Polarization of photoelectrons from Fe films at 4.2 °K. Substrate temperature in the course of sputtering: 1) 400 °K, 2) 4.2 °K. Illumination with a high-pressure mercury-xenon lamp. The predominant direction of the magnetic moment of the electrons is parallel to the sample magnetization.

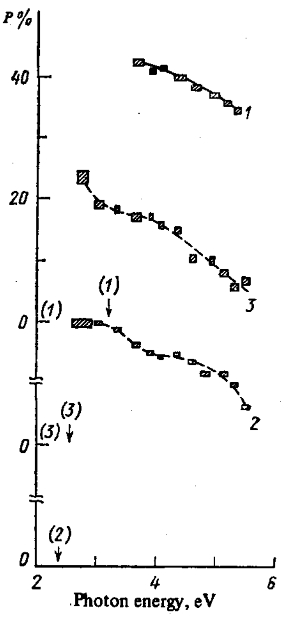


FIG. 13. Polarization of photoelectrons from iron films coated with Cs.

It was suggested in[62] that the mean free path depends on the electron spin and that this can explain the observed sign of the polarization in thick samples. However, the fact that the sign of the polarization remains unchanged even in very thick films refutes this assumption.

The photoelectron mean free path in copper was determined from measurements of the polarization with a copper film spattered on nickel. From the formula $P = P_{\mathrm{Ni}} e^{-(h-h_0)/l}$ it was found that $l = 10.0^{+2.6}_{-1.7}$ Å for electrons with energy 5.2 ± 0.5 eV over the Fermi surface and $h_0 = 3.3 \pm 1$ Å. This value of h_0 implies that the copper layer has magnetic properties due to the penetration of nickel electrons into it.

The fact that the mean free path turns out to be the same in nickel as in copper is somewhat unexpected, since experiments with silver and gold, which are similar to copper in their electron structure, yielded a value $l = 40$ Å for an energy 5.5 eV above the Fermi energy.[55]

B. Polycrystalline iron

The polarization of photoelectrons from iron was first measured in[25]. The work function of the iron polycrystalline films used in that study was 4.7 eV in the measurements. Figure 12 shows the dependence of the polarization of the photoelectrons from iron on the applied magnetic field.

Coating the sample surface with cesium makes it possible to measure the polarization of the photoelectrons from iron in the spectral interval 3 eV, by using ordinary illumination sources.[29] Just as in the case of nickel samples, when cesium coating was used the polarization reached a clearly pronounced saturation in the fields close to the saturation induction of the iron.

Figure 13 shows the dependence of the polarization

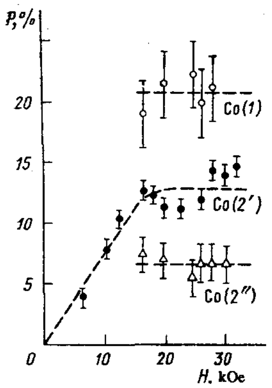


FIG. 14. Polarization of photoelectrons from Co films. The conditions are the same as in Fig. 12.

of photoelectrons from iron for films with work function 3.2 ± 0.1 eV (1) and 2.35 ± 0.1 eV (2) in a magnetic field 13.7 kOe. Curve 3 corresponds to measurement of sample 2 after storing it for four days in a vacuum of 10^{-9} Torr; the work function then increased to 2.55 ± 0.1 eV. In all these cases, the polarization decreased monotonically with increasing photon energy, and coating with cesium did not influence its magnitude strongly near the threshold of the photoeffect. As the work function changed from 3.2 to 2.35 eV, the polarization decreased from 42% to 40% for the same energy depth of the photoelectron detachment , 0.4 eV.

C. Polycrystalline cobalt

The polarization of photoelectrons from cobalt was measured in[25,28,29]. The dependence of the polarization of the photoelectrons from cobalt on the magnetic field is shown in Fig. 14; the work function of these samples is 4.9 ± 0.1 eV. Coating the cobalt films with cesium makes it possible to change the work function from 3.4 to 2.5 eV. The results of these measurements for four films with different work functions are shown in Fig. 15.

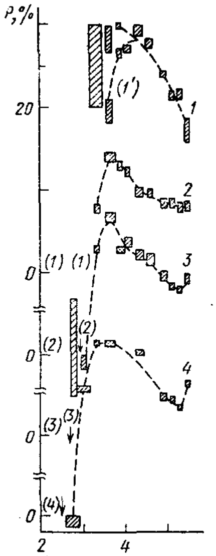


FIG. 15. Polarization of photoelectrons from cobalt films coated with Cs. Work function (eV): 3.3 (1), 2.55 (2), 2.7 (3), and 2.5 (4). Curve 1 corresponds to measurement 6.5 hours after the preparation of the film.

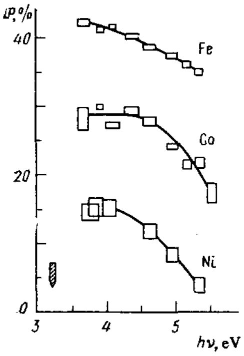


FIG. 16. Polarization of the photoelectrons from Ni, Fe, and Co films coated with cesium (work function 3.25 ± 0.1 eV) vs the photon energy.

D. Discussion of the results of experiments with polycrystalline ferromagnets of the iron group

To compare the data on the polarization of photoelectrons from transition ferromagnets, Fig. 16 shows plots of P for Fe, Co, and Ni, obtained for the same work function $e\varphi = 3.2$–3.3 eV. At the contemporary level of the study of polarization, it is meaningful to compare only the general tendency of the dependence of the photoelectron polarization on the photon energy in different materials.

To calculate the distribution of the photoelectrons with respect to their energies and their polarizations calls for a detailed knowledge of the density of states and for a calculation of the matrix elements of the electron transitions induced by the photons of corresponding energy. Figure 17 shows the contemporary data obtained for the density of states in nickel theoretically,[50] with the aid of the photoeffect,[3] and by x-ray spectroscopy.[63]

The most essential question to be answered by the described experiments is the extent to which the existing band theory predicts correctly the polarization of the photoelectrons. It is very difficult to answer this question because we still do not know clearly which of the transitions predominate in the photoeffect, direct or indirect (see, e.g., [5]). From this point of view,

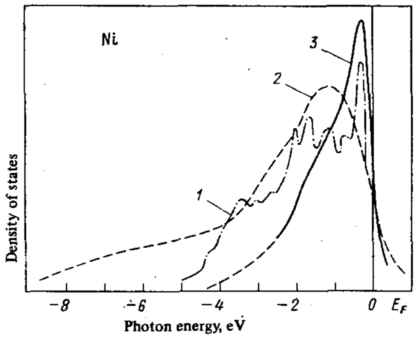


FIG. 17. Density of electronic states in Ni. 1) Calculation[50] (exchange splitting 0.41 eV), 2) data on the photoeffect in ultraviolet[3] ($h\nu=40.8$ eV), 3) data on the x-ray photoeffect[63] ($h\nu=1.25$ keV).

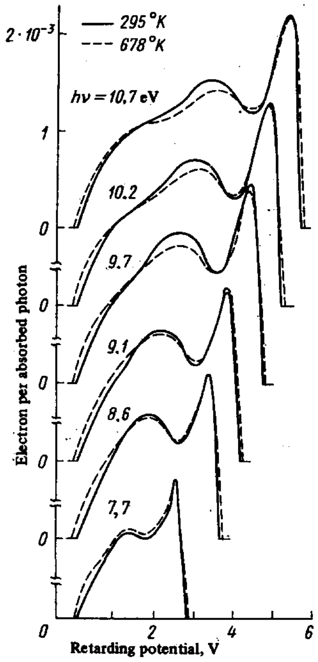


FIG. 18. Energy distribution of photoelectrons from Ni films at temperatures above (678 °K) and below (295 °K) the Curie point.

particular interest attaches to a verification, with the aid of the photoeffect, of the statement made in band theory that the exchange splitting of the subbands depends on temperature near the Curie point (see, e.g., [64]). For nickel at $T < T_c$ this splitting ranges, according to different estimates, from 0.35 to 0.50 eV.[65,66] At a temperature above the Curie point, this splitting should vanish according to the band theory. There is no doubt that this is reflected in the density of states of the electrons, meaning also in the distribution of the photoelectrons in energy. This statement was checked in[5,67,68]. In the most careful of these experiments,[5] calculations of the energy distribution curves (EDC) of the photoelectrons were made in both models of the photoeffect. The EDC were calculated by using the theoretical density of states in nickel, both paramagnetic and ferromagnetic.[51] It was assumed in the calculation that the matrix elements for different photon energies are constant, and account was taken of the finite resolution of the employed analyzer, of the spectral width of the radiation, and of the electron-electron collisions. In the comparison with experiment, principal attention was paid to the photoelectrons near the Fermi energy. According to the model of direct transitions, the shift of this peak with increasing temperature above the Curie point should amount to 0.25 eV at photon energies 7.7–10.7 eV. In the case of indirect transitions, this shift is estimated at 0.18 eV. It turned out that experiment reveals no such shift, with an accuracy better than 0.05 eV (Fig. 18). All this shows that understanding of the photoeffect from ferromagnetic metals still leaves much to be desired.

By way of illustration of the present status of the calculation of the polarization of photoelectrons from ferromagnets, we present the results of[69]. In that paper, the polarization was calculated for nickel in the direct-transition model and under the assumption that the matrix element of the transition is independent of the frequency of the light. The band structure calculated in[51] for nickel was used in the calculation. For direct transitions, the photoemission is determined by the "unified" density of states, defined as

$$D(E, h\nu) = (2\pi)^{-3} \sum_{f,i} \int_{\mathrm{B.Z}} d^3k \times \delta(E_f - E_i - h\nu)\, \delta(E_i - E);$$

here E_f and E_i are the energies of the electron in the final (f) and initial (i) states, and $h\nu$ is the photon energy.

The polarization of the photoelectrons was estimated at

$$P(h\nu) = \frac{J_\uparrow - J_\downarrow}{J_\uparrow + J_\downarrow},$$

where

$$J_{\uparrow,\downarrow} = \int_{E_l}^{E_t} T(E)\, D_{\uparrow\downarrow}(E, h\nu)\, dE:$$

here $T(E)$ denotes the work function.[57]

Figure 19 shows a typical calculation for conditions close to those in the experiment. It is seen that when $h\nu$ is within 0.1 eV of the threshold, the polarization undergoes abrupt changes that are sensitive to the choice of $e\varphi$, E_F and the details of the band structure. At larger h, calculation yields the required sign of the polarization, but the experimental values are much lower than the calculated one. It is also seen that the width of the band can be determined from the polarization measurements only by performing the latter at sufficiently large values of $h\nu$ since, generally speaking, the polarization can assume a value equal to the average over the band at several values of $h\nu$.

In the same paper they calculated the results of measurements of the polarization of energy-discriminated photoelectrons (Fig. 20). The meaning of these calculations is that if the assumptions of the band structure and of the direct-transition model are correct, then the polarization is noticeably changed in such experiments with changing E_F and hu.

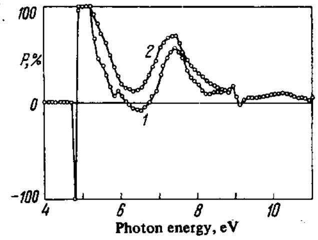


FIG. 19. Polarization of photoelectrons from nickel in the direct-transition model. $e\varphi = 4.7$ eV; $E_i = E_F$, $E_l = E_F + e\varphi - h\nu$; 1) $T(E) = \mathrm{const}$, 2) $T(E)$ is the semiclassical work function.[57]

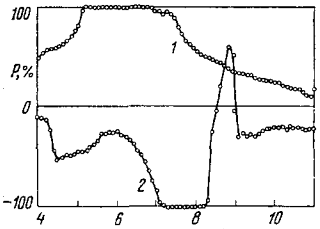


FIG. 20. Polarization of photoelectrons from nickel in the model of direct transitions with energy discrimination of the electrons. 1) $E_i = E_F$, $E_i = E_F - 0.5$ eV; 2) $E_i = E_F - 1.5$ eV, $E_i = E_F - 2.0$ eV.

We estimate now the polarization of photoelectrons from nickel under the assumption of indirect transitions, i.e., by representing the photocurrent in the form

$$J_{\uparrow,\downarrow} \sim \int_{h\nu}^{E_F - e\varphi} n_{\uparrow,\downarrow}\, dE,$$

where $n_{\uparrow,\downarrow}$ is the density of electrons with opposite spin directions, and $e\varphi$ is the work function. The results are shown in Fig. 21. Similar estimates for iron are shown in Fig. 23.

Analogous calculations were performed for cobalt in[28] (Fig. 23), where the theoretical density of states in hexagonal cobalt[75] was used. Analogously, the polarization depends on the frequency of the light also when the density of states obtained in[76] for hexagonal cobalt is used. It is known, however, that cobalt films obtained by vacuum sputtering usually are of the cubic modification of cobalt,[77] so that the presented estimates cannot demonstrate convincingly that there is a contradiction between the band theory and the measurements of the polarization of the photoelectrons from cobalt.

It can be concluded from Figs. 21 and 22 that among the existing calculations of the density of states in nickel and in iron there are also some that describe sufficiently well the results of experiments on the polarization of photoelectrons from these ferromagnets in the indirect transition model. Since the calculations used describe approximately equally the remaining properties of these substances, it is too early to speak of non-applicability of the band theory to experiments on polarization of photoelectrons. The results of these experiments can more readily help choose between these calculations. In[71] it is stated directly that the program of subsequent calculations of the density of state in nickel would include a calculation of the polarization of the photoelectrons.

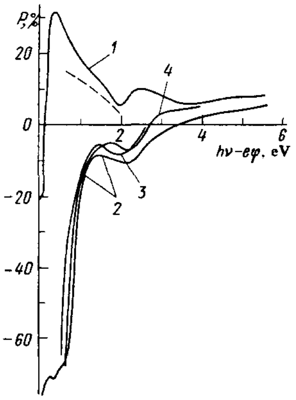


FIG. 21. Polarization of photoelectrons from nickel in the model of indirect transitions. Calculation from the data of[51] (1),[52] (2),[70] (3), and[77] (4). The dashed line indicates the experimental data.[29]

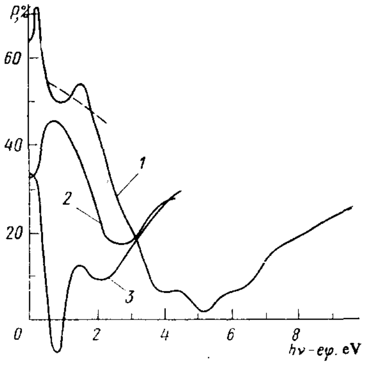


FIG. 22. Polarization of photoelectrons from iron in the model of indirect transitions. The calculation is from the data of[72] (1),[73] (2), and[74] (3). The dashed line indicates the experimental data.[29]

Measurements of the polarization of photoelectrons from transition metals have already stimulated a number of theoretical investigations devoted to a discussion of this problem. It is shown in[78] that even the ability of the simple band model to explain the results of the experiments is far from fully exploited. Modified variants of the band theory, in the opinion of the author of[79], explain quite satisfactorily both the magnitude of the polarization and its response to cesium coating.

It is shown in[80] for a simple one-dimensional model that if account is taken of the possibility of exciting electrons to surface states, i.e., to states having a wave function that decreases exponentially in the interior of the crystal and constitutes a plane wave outside the crystal, then at a polarization of definite sign, when averaged over the band, the polarization reverses sign at a certain frequency. If this mechanism operates in the three-dimensional case, then it can significantly

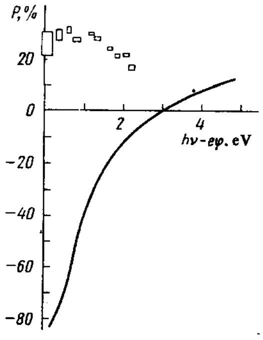


FIG. 23. Polarization of photoelectrons from Co in the indirect transition model. Calculation from the data of[75]. The experimental values were taken from[29].

TABLE I.

Method	Energy range below E_F	Sample	Maximum polarization, %			
			Ni	Fe	Co	Gd
Tunneling	10^{-3} eV	Polycrystalline films	11	44	34	4.3
Photoemission	0.4–0.8 eV	Polycrystalline films	15	54	21	5.7
Field emission	0.1 eV	Single crystal:				
		[100]	−10			
		[110]	−7.8			
		[137]	−9.5			
		[111]	7.5			
		Polycrystalline films	−13	−6		−8

influence the dependence of the polarization on the frequency of the light.

Many-particle effects that can influence the polarization of photoelectrons were considered in a number of papers.[81–83] It is proposed in[81] that a strong interaction between quasiparticles leads to a renormalization that decreases the density of states with spin downward near the Fermi boundary. At sufficiently large interactions, this phenomenon can explain the observed experimental results if the existing calculations of the density of states are correct. It is suggested in[82] that a strong correlation exists between the electrons. Therefore, it may be profitable for electron pairs to form coherent states such that the exictation of an electron with spin $\downarrow$ would require larger energies than excitation with spin $\uparrow$. This leads to the observed sign of the polarization of the photoelectrons. In the model of[83], the ground state is the same as in the Hartree-Fock model, but it does not appear in the photoemission because of the strong distortion of the orbital motion, which depends on the spin direction. This can account for the sign of the polarization near the Fermi energy and for the weak temperature dependence of the photoelectron distribution.

Other many-particle effects as applied to the polarization of photoelectrons are considered also in[84,85].

The present status of the theory does not enable us as yet to assess quantitatively the importance of many-particle interactions. It can only be stated that if the single-atom approximation plays an essential role in photoemission, then the polarization of the photoelectrons will naturally have a low sensitivity to the long-range exchange interaction postulated in the band theory of ferromagnetism.

E. Measurement of polarization of electrons from ferromagnets of the iron group by other methods

The polarization of electrons in ferromagnets are investigated also with the aid of the tunneling and field-emission phenomena.

In experiments on tunneling it is possible to determine the polarization of electrons near the Fermi energy (within ~ 1 meV).[86,87] A summary of the results of these measurements is given in Table I.[87] The table reveals a sufficiently good agreement with the data on photoelectron polarization, both in sign and magnitude of the polarization. The discrepancy between these results and the calculations of polarization from the density of states may be due to the fact that many-particle effects manifest themselves most completely near the Fermi energy.

The results of experiments on the polarization of field-emission electrons[18,88–91] are still too unreliable and call for further study (see[29] for a discussion). Questions connected with polarization of electrons by field emission are also considered in[17].

These three methods of obtaining polarized electrons differ from one another in the degree of participation of the d-electrons in the emission and this naturally must be taken into account when the results are compared.

F. Structurally disordered films of ferromagnets of the iron group

A number of measurements were made[25,27] on Ni samples evaporated on substrates at 4.2 °K or at 77 °K, or else on Co and Fe samples evaporated at 4.2 °K. All have revealed a photoelectron polarization lower than samples with substrates at room temperature or higher (see Figs. 7, 12, 14). These films turn out to be particularly sensitive to the quality of the employed material. Under pure conditions, no difference was observed between nickel samples evaporated at substrate temperatures 4.2 and 77 °K.

It is therefore difficult to attribute the lower polarization of the photoelectrons from such samples to contamination or porosity. We note that Gd films prepared at various substrate temperatures did not differ in polarization, namely, $-5.70 \pm 0.21\%$ and $-5.27 \pm 0.15\%$.[92] The assumption that the polarization is changed because of changes of the surface relief under different manufacturing conditions must therefore also be rejected, since this effect should be the same both for Ni and Gd.

We can therefore assume that the cause of this effect is the difference between the microstructures of the films in these samples. It is well known that strict periodicity is not a necessary condition for ferromagnetism.[93] When films are deposited on substrates at 4.2 °K one obtains, as a rule, strongly disordered structures, which are designated "amorphous," although there is no exact definition of this state as applied to ferromagnets. Such samples are usually investigated by electron or x-ray diffraction or else by conductivity measurements. Ferromagnetic investigations of such samples are also useful, since the exchange interaction is sensitive to the distance between the neighbors.

It is known that the ratio of the number of Bohr magnetons per atom for amorphous and polycrystalline nickel is equal to 0.6,[94] and the ratio for amorphous and polycrystalline iron is 0.7.[95,96] It is seen from Figs. 7 and 12 that the ratio of the polarizations of the photoelectrons from both types of samples corresponds approximately to these data. No decrease of n_B was observed in amorphous samples of Co.[95,96] However, the photoelectron polarization decreases for Co films evaporated on cold substrates (see Fig. 14), but the polarization values for the Co films on cold substrates were not reproducible. Figure 14 shows the extreme values of the polarization.

There is no doubt that measurement of photoelectron polarization on going to disordered samples calls for further study in conjunction with a study of the sample structure.

5. POLARIZATION OF PHOTOELECTRONS FROM RARE-EARTH FERROMAGNETS

The first successful measurements of the polarization of photoelectrons were made not with iron-group ferromagnets, but with samples of the rare-earth ferromagnet Gd.[26] Polarization of photoelectrons from Dy was subsequently also investigated.[92]

These measurements are of interest from several points of view. They provide new proof that electron polarization is preserved to a considerable degree in photoemission. Indeed, if the electron-magnon scattering mechanism is correct,[45,46] then the observed polarization P should differ from the polarization P_0 of the electronic states in the metal,[92] and furthermore at $T \ll T_c$

$$P = P_0 + P' = P_0 + c\sigma^+ x_s,$$

where $c = \text{const} \sim 1$, σ^+ is the reciprocal of the mean free path for magnon production, and x_s is the mean free path for electron-electron scattering.

The estimate obtained for σ^+ is[46,92,97]

$$\sigma^+(T=0) \approx \Omega\left(\frac{m}{\hbar^2}\right)^2 SJ^2,$$

where Ω is the atomic volume, m is the effective mass of the photoelectron, S is the number of spins per atom, and J is the exchange energy of the excited electron.

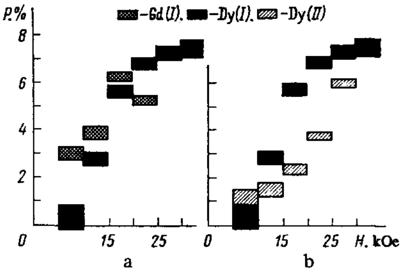


FIG. 24. Dependence of the polarization of photoelectrons from Dy and Gd on the magnetic field. Substrate temperature during sample preparation: 350 °K (a) and 4.2 °K (b). The predominant moment of the magnetic moments of the photoelectrons is parallel to the magnetization of the samples. The measurements were made at 4.2 °K using illumination from a high-pressure mercury-xenon lamp.

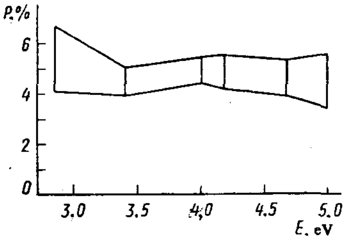


FIG. 25. Polarization of photoelectrons from Gd at different photon energies ($H = 14$ kOe).

There are at present not enough data for a reliable estimate of P'. However, measurements on Gd and Dy make it possible to show that the contribution of P' to the photoelectron polarization is apparently insignificant. Indeed, in rare-earth metals the conduction electrons are polarized via indirect exchange interaction with localized magnetic $4f$ states. The number of spins in a $4f$ state can change without a noticeable change in the states in the conduction band. It is assumed that the exchange integral J of heavy rare earths is constant. One should therefore expect

$$\frac{P'_{\text{Gd}}}{P'_{\text{Dy}}} = \frac{S_{\text{Gd}}}{S_{\text{Dy}}} = \frac{7/2}{5/2} = \frac{7}{5},$$

i.e., we should have

$$P_{\text{Gd}} > P_{\text{Dy}}.$$

The experimental values in the saturation region at 4.2 °K (Figs. 24 and 25) are.

$$P_{\text{Gd}} = 5.70 \pm 0.21\% \quad \text{for} \quad 15 < H < 25 \text{ kG},$$
$$P_{\text{Dy}} = 7.33 \pm 0.35\% \quad \text{for} \quad 30 < H < 35 \text{ kG},$$

with an approximate systematic error of 8%.

These data can be easily explained if it is assumed that $P' = 0$ and $P_{0,\text{Dy}} \neq P_{0,\text{Gd}}$. Subsequent observations confirm this assumption. For photons with energy less than 4 eV, the value of P_{Dy} increases by approximately 1%, whereas P_{Gd} remains constant within the limits of errors. This contradicts the existence of a noticeable contribution to the polarization from the electron-magnon scattering, and means that in Dy the states near the Fermi energy have a larger polarization than on the average over the conduction band, while Gd has no such states.

The existing calculations for Gd and Dy[98,99] yield only the summary density of the electronic states, but do not make it possible to calculate the polarization of the photoelectrons. We note that the calculations agree well with the photoemission experiments.[100,101]

Measurements with Gd and Dy were made both using samples evaporated on heated substrates (~350 °K) and evaporated on substrates at 4.2 °K, where the film structure should be much more disordered. However, in contrast to ferromagnets of the iron group, the polarization of the photoelectrons from Gd and Dy changes insignificantly for different types of samples. This leads to the conclusion that it is either difficult to produce a disordered structure in Gd and Dy or (possibly also simultaneously) the structure does not affect the magnetization strongly.

6. POLARIZED PHOTOELECTRONS FROM CHALCOGENIDES AND PNYCTIDES

The successful measurement of photoelectron polarization has led also to progress in the study of the magnetic properties of a new class of magnetic materials, namely chalcogenides and pnyctides.[102] The new procedure has made possible the following: 1) obtain more precisely the positions of the electron levels, 2) investigate the influence of impurities on the magnetic properties, 3) study the behavior of magnetic properties of these materials on going to the disordered state, 4) reveal new minute details concerning the scattering of photoelectrons on their path to the sample surface, 5) observe the paramagnetic behavior of the polarization of photoelectrons in a number of substances. We shall describe below the main results obtained in these fields.

A. Manifestation of band structure

Figure 26 shows schematically the band structure and the expected polarization of a ferromagnetic semiconductor.[16] Above the Curie point (Fig. 26a), subbands with opposite spin directions coincide. The Fermi level lies near the bottom of the conduction band. In the gap between the valence band and the conduction band are situated strongly localized states. In the case of europium chalcogenides, these are the $4f^7$ levels. Below the Curie point, the spins of the localized states at all the atoms have the same direction. The result is a band with 100% polarization. Owing to exchange interaction, both the valence band and the conduction band split into subbands with oppositely directed spins (Fig. 26b). Figure 26c shows the polarization of the electronic states, while the variation of the polarization with the frequency of the incident light is shown in Fig. 26d. The photoemission begins when the photon energy reaches the threshold value $h\nu_0$. The polarization should increase with increasing photon energy, when the photoelectrons begin to be emitted from the f levels.

Photoelectron polarization was measured in[103] on EuO single crystals cleaved in vacuum (Fig. 27). The dependence of the polarization on the photon energy confirms the EuO level structure obtained with the aid of photoemission measurements.[104,105] In[16], the polarization of the photoelectrons from the EuO films, depending on the method of their preparation, range from 0 to ~15%. The substrate temperature was maintained at 4.2 °K during the film preparation. The frequency dependence of the polarization from such disordered samples is also shown in Fig. 27. It is seen that the difference in the sample structure leads to differences in both the magnitude of the polarization and in the positions of the singularities in the polarized-electron spectrum.

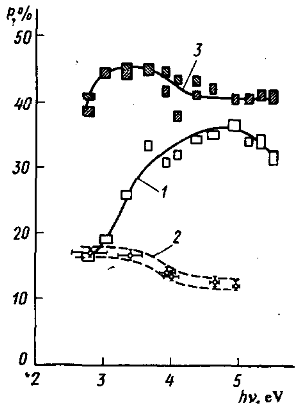


FIG. 27. Polarization of photoelectrons from different EuO samples. $T=4.2$ °K. 1)—Cleaved EuO single crystal[103], $H=6$ kOe; 2)—EuO film (sample produced on substrate with temperature 4.2 °K)[16], $H=7.5$ kOe; 3)—cleaved EuO single crystal with about 2% La, $H=6$ kOe.

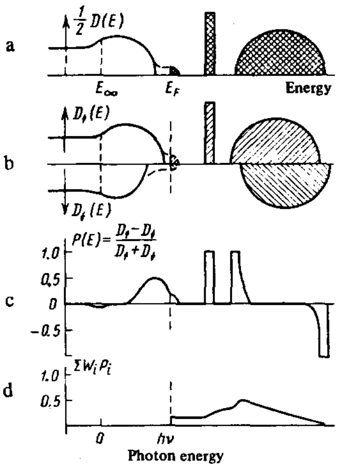


FIG. 26. Density of the electronic states and the polarization of photoelectrons for a hypothetical ferromagnetic semiconductor.

In addition to chalcogenides, an interesting new object for the study of the magnetic properties of solids are also pnyctides, i.e., compounds of rare earths with elements of the fifth group. The polarization of photoelectrons of two such compounds, Eu_3P_2 and Eu_3As_2, was investigated in[42]. The tests were made on films evaporated by electron bombardment of bulky sample on substrates heated to 390 °K. The measurements were made at 4 °K. The Curie points of Eu_3P_2 and Eu_3As_2 are 25 and 18 °K, respectively.

The measurement results for Eu_3P_2 are shown in Fig. 28. With this substance as an example, one can distinguish clearly those photon energies at which photoemission from different types of states begins. Near

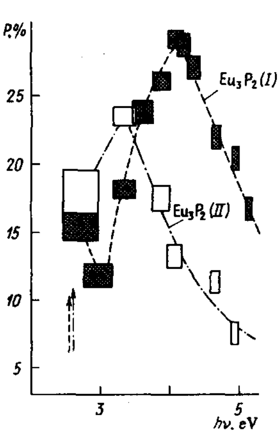


FIG. 28. Polarization of photoelectrons from ordered (I) and disordered (II) Eu_3P_2 films. $H=22.8$ kOe. The arrows mark the work functions determined from the dependence of the quantum yield on the photon energy.

TABLE II. Data on magnetic semiconductors.

	EuS	EuSe	EuTe	GdP	GdAs	GdSb
a, Å	5.96	6.19	6.60	5.72	5.86	6.22
T_0, °K	16,5	4.6	9.8*	15*	19*	28*
E_{G4f}, eV	1.65	1.85	2.00	>5	>5	>5
E_{GV}, eV	2.35	2.15	2.15	1.0	0.4	0
Φ, eV	4.0	4.4	4.8	9.8	4.8	4.8
ΔΦ, eV	0.8	0.6	0.6	0.5	0.3	0.3
ΔE_G, eV	~1.2	~0.6	~0.5	~0.2	~0	~0

Φ and ΔΦ are determined accurate to 0.1 and 0.15 eV, respectively; T_0 is the magnetic-ordering (*—antiferromagnetic ordering) temperature.

the threshold of the photoeffect, the electrons are emitted from impurity states, and then the increase of the polarization indicates the start of emission from the $4f$ levels. Electrons from the unpolarized valence band decrease the polarization. These data agree well with optical measurements.[106] By using considerations analogous to those for the experiments described above, it is possible to obtain the level diagram of Eu_3P_2. It differs from the diagram for chalcogenides in that in the pnyctides the gap between the valence band and the conduction band is smaller.

The polarization of the impurity levels is direct experimental proof of the existence of their exchange interaction with the $4f$ levels. The influence of such "magnetic impurity states" on the properties of the ferromagnetic semiconductors explains the increase of T_c in chalcogenides with impurities and the anomalous increase of the resistance near T_c.[102] Measurements[42] made on different Eu_3As_2 samples have shown that the position of the resistance peak does not depend on the carrier density, in contrast to the chalcogenides.[107,108] It is therefore possible that the character of the conducting state in chalcogenides and pnyctides is different.

B. Polarization of photoelectrons from the conduction band

Closely related to the study of the energy level diagram are investigations of the polarization of photoelectrons from the conduction-band states in rare-earth compounds.[109] These substances are of interest in that the states with localized magnetic moments are separated in energy from the conduction electrons. Depending on the magnitude of this gap, both ferromagnetic and antiferromagnetic ordering is possible. The polarization of the photoelectrons from antiferromagnets is possible only by applying a magnetic field that produces induced magnetization. In turn, the induced magnetization produces an exchange field, and it is the influence of this field on the conduction electron which manifests itself in the polarization of the photoelectrons. Table II indicates the properties of most antiferromagnets used in such measurements. These materials cover the range from the insulator EuTe to the metals GdSb and GdS.

Samples in the form of films were prepared by electron bombardment of polycrystals. The evaporation was on substrates at 400 °K. The study of the polarization of the photoelectrons from these materials has shown that it is proportional to the applied field, and its variation with the frequency of the incident light makes it possible to estimate the degree of penetration of the magnetic $4f$ levels into the valence band.

Similar measurements on GdS are of particular interest. Photoemission investigations have shown that for GdS there exists a d-type conduction band which is appreciably separated in energy from the valence band,[110,111] while the $4f$ levels lie 9 eV below E_F, at the bottom of the valence band.

The quantum yield of the employed GdS samples near the threshold is described well by the $\sqrt{Y}$ law, and the work function is 2.3 ± 0.1 eV, in accord with the result of[110,111]. Figure 29 shows a plot of $P(H)$ for three wavelengths such that only electrons from the conduction band take part in the photoeffect. It is seen that within these wavelength limits the polarization remains unchanged, and furthermore $P > P_F$. This means that the conduction electrons have an intrinsic exchange interaction that is superimposed on the interaction with the $4f$ levels.[7] Therefore the simple Ruderman-Kittel interaction cannot be regarded as the only cause of the antiferromagnetism in these compounds. If the conduction electron exhibit a ferromagnetic interaction, then the antiferromagnetism should also be governed by the even stronger antiferromagnetic interaction via the p-bands. The same result is obtained from an investigation of the $Eu_yGd_{1-y}S$ system.[112] This conclusion contradicts the earlier studies,[102,113] where everything was calculated under the assumption of non-interacting d-electrons on the basis of the Ruderman-Kittel mechanism.

C. Influence of impurities

Photoelectron polarization can be used to trace the variation of the positions of the levels in ferromagnetic semiconductors when impurities are added. This method was used in[114] to investigate the positions of the magnetic levels in $Eu_{1-x}Gd_xS$. A comparison of the dependences of the polarization of the photoelectrons on the photon energy for the cases EuS and $Eu_{1-x}Gd_xS$ yields the following: the $4f^7$ levels of Gd lie closer to the vacuum level than the $4f^7$ levels of Eu.

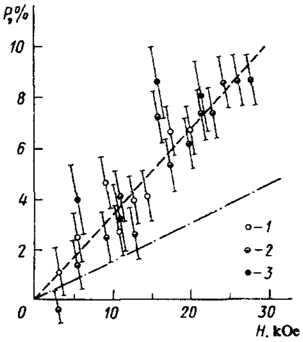


FIG. 29. Dependence of the polarization of the photoelectrons from GdS on the magnetic field at 4.2 °K for three different photon energies (eV); 4.6 (1), 3.3 (2), and 2.7 (3). The dash-dot curve shows the relative magnetization P_f of a bulky CdS sample.

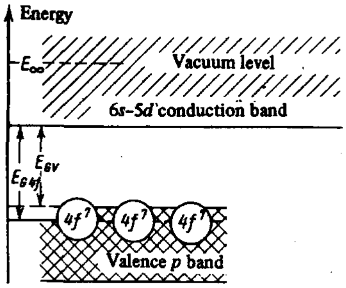


FIG. 30. Energy level scheme of magnets with NaCl structure.

The influence of La impurities on the polarization of photoelectrons from EuO was investigated in[103] (see Fig. 27). The most surprising fact is here that the polarization of the additional electrons ($h\nu < 4$ eV) introduced by the impurity turns out to be higher at $H = 6$ kOe than the polarization of the magnetic $4f^7$ electrons in EuO.

D. Disordered chalcogenide and pnyctide samples

On going from the ordered to the disordered arrangement of the atoms in a solid, one should expect changes in the electron density of states. The polarization of the photoelectrons reflects both the position of the electron levels and their magnetic properties, so that it is convenient to use this polarization to study the influence of the disorder on the magnetism.

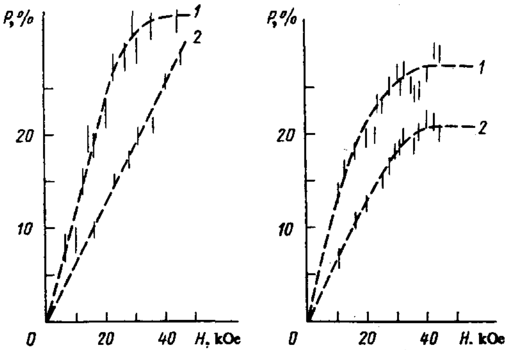
These investigations were carried out on film samples of EuS, EuSe, EuTe, GdP, GdAs, and GdSb.[43,115] All these materials have a NaCl structure, and this facilitates the interpretation of the data. The energy level scheme of these substances is shown in Fig. 30. Disordered samples were produced by evaporating films in ultrahigh vacuum on substrates at 4.2 °K.

We note that the results obtained with samples evaporated on a heated substrate coincide with the results obtained on samples evaporated on a substrate at 4.2 °K and then annealed to the substrate temperature used in the preparation of the preceding samples. The quantum yields of the photoelectrons depends strongly on the degree of order of the samples. For annealed samples, $Y^{3/2} = \text{const}(h\nu - \Phi)$, where Φ is the energy difference between the first occupied electronic state E_0 and the vacuum level E_∞. At low photon energies, the quantum yield of the disordered samples is also a straight line with a slope approximately equal to the slope of the ordered samples. It is therefore possible to determine, albeit with lower accuracy, the threshold Φ^* of the photoeffect in the disordered state. We introduce $\Delta\Phi = \Phi - \Phi^*$. For all the investigated materials we have $\Delta\Phi > 0$. In GdSb, the distance from the valence band to the conduction band is $E_{GV} = 0$, so that this material, just as a metal, has $\sqrt{Y} = \text{const} \cdot (h\nu - \Phi)$. Table II lists the obtained data on $\Delta\Phi$, which has the highest value for EuS, the compound with the largest ionic bond, and decreases with increasing E_{GV}, even though the absolute value of Φ does not experience in this case a systematic change.

We note that $\Phi = E_\infty - E_0$ and $\Delta\Phi = \Delta E_\infty + \Delta E_0$. If $E_0 = E_F$ ($T = 0$), then disorder should not shift E_0 noticeably. This holds for GdSb, and in this case $\Delta\Phi = \Delta E_\infty = 0.3$ eV. The values of $\Delta\Phi$ observed in metallic samples evaporated on cold substrates is of the same order.[116,117] We shall henceforth assume that $\Delta E_\infty = 0.3$ eV for all the investigated materials. Thus, $E_0 = \Phi - 0.3$. It can be assumed that disordering does not change, on the average, the $4f^7$ level, and its position changes only slightly from atom to atom, depending on the local environment. Much greater changes should take place with the valence band and the conduction band. Therefore the characteristic quantity is ΔE_G, which is determined as the difference between the top of the band in the ordered state and the highest filled level in the disordered state. These quantities were calculated from optical measurements[118] and $\Delta\Phi$ with allowance for the decrease of E_∞. In the Mott and Davis model of a non-crystalline semiconductor, new states should have appeared approximately at a distance $E_G/2$ above the edge of the valence band, i.e., the condiction $\Delta E_G = \text{const} \cdot E_{GV}$ should be satisfied. It is seen from Table II that this is not the case. The energies of the new states decrease more rapidly than linearly with decreasing E_{GV}.

The experiments of[43,115] have also revealed clearly the influence of the ordering of the samples on the magnetic-field dependence of the polarization.

We consider the influence of disordering with EuSe as an example (Fig. 31). The Curie temperature for polycrystalline samples is 4.6 °K. In the strong fields employed one should expect EuSe to behave like a simple ferromagnet. At $H \sim 12$ kOe ($4\pi M = 12$ kG), following illumination of the polycrystalline sample by the entire spectrum (curve 2), no singularity whatever appears on the field dependence of the polarization, nor does the polarization saturate even in a field > 50 kOe. This means that the sample is heated above T_c. If the samples are illuminated through a filter, i.e., at a lower degree of heating, saturation sets in at $H \gtrsim 40$ kOe. The polarization of disordered samples tends to saturation already in fields ~ 40 kOe, even if the entire spectrum of the lamp is used. This means that the exchange ferromagnetic interaction was increased by the disordering. It is known that introduction of impurities leads



a b

FIG. 31. Polarization of photoelectrons from EuSe. $T = 4.2$ °K. a) Ordered samples, b) disordered samples. Curve 1—illumination through a filter, 2—without a filter.

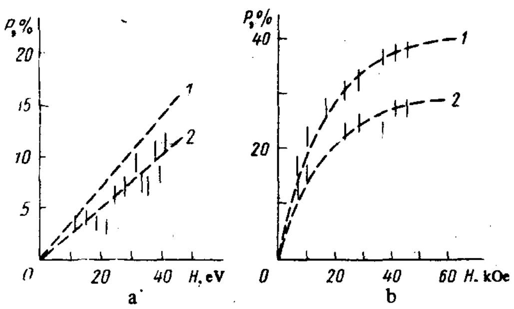


FIG. 32. Polarization of photoelectrons from GdP. The notation is the same as in Fig. 31.

to a similar effect both in EuS and in EuSe.[102] Figure 32 shows the influence of the disorder on the magnetic field dependence of the photoelectron polarization for the antiferromagnetic EdP. The magnetization of bulky samples at 4.2 °K was investigated in[121] (Fig. a).

It is obvious that the disorder intensifies the ferromagnetic interaction in this substance. The results for GdAs and GdSb indicate that disordering does not increase the ferromagnetic interaction in them.

Thus, the influence of the disorder on the exchange interaction is different for different substances in the considered theories. An increase of the ferromagnetic interaction takes place only for compounds with small lattice constant and with high degree of ionic bond (see Table II). The crystal field splits the *d* states of the cation in such a way that the center of gravity of the band is not shifted; the *s* states then remain unchanged. Since this splitting is stronger the smaller the lattice constant *a*, the lowest state turns out to be the *d* state if *a* is small and the *s* state if *a* is large. If it is assumed that disordering causes the lower state of the cation to be filled, then the tendency of the results becomes understandable, since the occupied *d* level increases the ferromagnetic interaction.

Figure 33 shows the polarization of the photoelectrons for disordered EuS and GdP samples. On the basis of these data it can be stated that actually a fraction of the level becomes singly occupied upon disordering and makes its contribution to the polarization.

The spectrum obtained from the disordered GdP (II) samples presupposes that the interatomic exchange interaction contributes to single occupation of the levels. The exchange lifts the spin degeneracy, and the splitting amounts in this case to $2J_{df}Ss \approx 0.7$ eV in Eu and Gd. The singly occupied levels can differ in this case from E_0 by 0.7 eV. It is this which explains the decrease of the polarization of the GdP (II) samples at $h\nu \sim 4.1$ eV. In EuS (II) this effect is compensated for by the increase of the polarization, owing to the fact that the 4*f* electrons begin to contribute. It is possible to compare GdP (II) samples with a different density of states near the threshold of the photoeffect and with the different values of the polarization, but the decrease of the polarization in these samples takes place invariably at a photon energy 0.7 eV above threshold. Thus, the following disorder model is possible and can explain qualitatively the results of the experiments and indicate their connection with the ionic bond. Owing to the exchange interaction, the singly occupied states are at the cations. It is assumed that they become occupied if two cations are brought closer together by the disordering. On the other hand, if the disordering brings two anions closer together, then the new states turn out to be doubly occupied, since there is no *f*-*d* exchange interaction for them. The more covalent the material, the greater the tendency of the directed covalent bonds to establish crystalline order between the nearest and next-nearest neighbors, so that the mutual approach of two anions or cations becomes less probable.

Analogous methods were used in[42] to investigate samples of Eu_3P_2 and Eu_3As_2. Since they have a structure of the Ba_3P_2 type, which is more complicated that the NaCl structure that characterizes the already mentioned chalcogenides, the influence of the disorder on the properties is particularly noticeable. It has turned out, however, that the threshold of the photoeffect remains unchanged in such samples in the disordered and in the polycrystalline states (see Fig. 28). The behavior of the polarization of photoelectrons from such samples can be explained by assuming that disorder shifts the position of the $4f^7$ levels closer to the threshold, and lengthens the "tail" of the valent states.

A number of investigations of amorphous substances revealed no singly occupied states at all, nor the appearance of occupied states in the forbidden band.[122–124] According to the predictions of the theory, the appearance of occupied states in the forbidden band is impossible in this case for systems that are in thermodynamic equilibrium.[125] Experiments on the influence of the disorder on the polarization of photoelectrons leads to the following conclusions:

1) Materials in which no new states are produced have a covalent bond and have a much higher recrystallization temperature. In the case of the investigations by the photoelectron polarization method, new states appeared only in those materials in which the bonds are ionic.

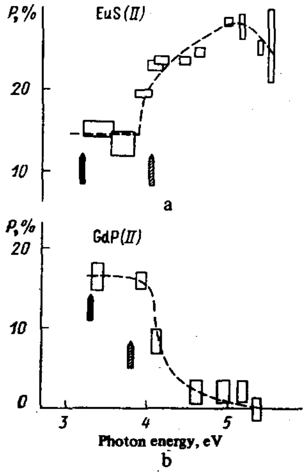


FIG. 33. Polarization of photoelectrons from EuS (II) (a) and GdP (II) (b). $T = 4.2$ °K. The shaded and dark arrows indicate the photoeffect thresholds for ordered and disordered samples, respectively.

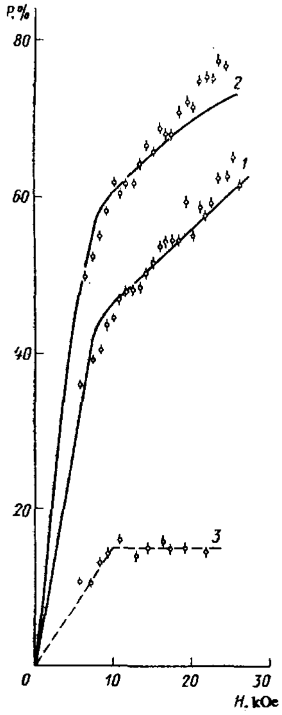


FIG. 34. Dependence of the polarization of photoelectrons on the magnetic field. 1)—Single crystal EuO, 2)—single crystal EuO with ~2% La impurity, 3)—Ni film.

2) Comparison of the results obtained with Eu_3P_2 and Eu_3As_2 and EuTe, EuS, etc. shows that an important role is played also by the NaCl type lattice.

3) Singly occupied levels observed by the paramagnetic-resonance method in disordered Si and other materials[125] were ascribed to surface states produced as a result of the tremendous increase of the surface area by the internal cracks and voids in the non-annealed amorphous substance. The internal surfaces should not influence the polarization of the photoelectrons, since the electrons must be released from the sample. To be able to attribute the presented polarization results to an increase in the interface between the vacuum and the sample, it is necessary to assume that this surface is increased for disordered samples by more than 100 times. This is not very likely in the case of the investigated samples.[127]

4) If the disordered samples were to consist of microcrystals, then the internal stresses in them would be large. This in turn could lead to a shift of the energy states, meaning also to a change in the photoeffect threshold. However, such an effect can not result in a shift of ~0.5 eV.

5) In europium chalcogenides, new states are produced at practically the same energies as in $4f^7$ states. The photoelectron polarization spectra show that new states are not displaced $4f^7$ states, as might be assumed on the basis of data on the quantum yield only.

6) Single occupation of part of the new levels is due to interatomic interaction, which is not present in other substances.

The idea of thermodynamic equilibrium[125] is undoubtedly applicable only to materials with strong covalent bond. Ionic crystals differ from them in the fact that the bond angle and the bond length are not strictly fixed in them. Therefore the random-chain model is more applicable to them. There is no doubt that the physical phenomena observed when substances with NaCl lattices are disordered are determined by the degree of the ionic character of the bond.

E. "Paramagnetic layer" on the surface

Measurement of the polarization of photoelectrons from chalcogenides of europium has revealed unexpectedly that the polarization saturation is not reached even in fields much stronger than $4\pi M$. This is most clearly manifest in the polarization of the photoelectrons from EuO single crystals (Fig. 34).[103] The effect was observed also in polycrystalline thin EuS and Eu_3P_2 film[128,129] which, as already mentioned, have different crystallographic structures.

The change in the slope of the photoelectric magnetization curve of EuO near 8–10 kOe means that, just as for a ferromagnet below the Curie point, the sample has reached magnetic saturation in value. It remains to assume that this phenomenon is due to the paramagnetic properties of the surface layer. The reason for this may be, for example, a possible increase in the interatomic distance in the surface layer, which is known to decrease the ferromagnetic exchange interaction in europium chalcogenides.[130] The depth of emergence of the photoelectrons from EuO at a photon energy near the threshold is approximately 10 lattice constants, and the thickness of the paramagnetic layer should be close to one or two lattice constants, owing to the short-range character of both the magnetic interactions and of the influence of the surface on the properties of the substance in the volume. The strong influence of such a thin layer is due to the quasielastic scattering of the photoelectrons by such a layer, as can be seen from photoemission data.[131] This turns out to be enough to cause the polarization of the photoelectrons to be determined to a considerable degree by the properties of this layer.[132]

This effect should manifest itself also in experiments in which the photoelectrons must overcome a layer with paramagnetic properties, although produced by other factors.[28,29,133]

If the paramagnetic layer on the surface is indeed about one monolayer thick, then its properties can be noticeably altered by adsorption of extraneous atoms. To this end, polarization of photoelectrons from EuO whose surface was coated with cesium was investigated in[134]. It turned out that cesium on the surface greatly decreases the relative growth of the polarization in the magnetic-field from 10 to 20 kOe, i.e., the additional electrons introduced into the europium chalcogenide increase the ferromagnetic interaction. This agrees well with the fact that T_c of very thin EuS layers (20 Å) on a tungsten substrate increases in comparison with thick samples.

7. PULSED SOURCE OF POLARIZED ELECTRONS FROM EuO

A source of polarized electrons is of undisputed interest for atomic physics and for elementary-particle physics. It is therefore exticing to use the appreciable polarization of the photoelectrons from EuO in order to produce such a source. This work was performed with the Stanford linear accelerator with an aim at using it subsequently to measure the spin dependence of the scattering amplitude in inelastic scattering of polarized electrons by polarized protons, and to study the possible parity violation in scattering of polarized electrons by unpolarized protons in a liquid-hydrogen target.[135] The source was produced with allowance for the fact that the accelator operates at a repetition frequency of 360 Hz and an approximate duration 1 msec. The planned experiment called for an intensity of not less than 10^9 electrons per pulse.

The main difficulty in the production of such a source lies in the local overheating of the crystal. To obtain approximately 4×10^{10} EuO electrons in one pulse the source must absorb a power of approximately 10 W in one microsecond. Since the exact mechanism whereby the heat is dissipated is not known, it is difficult to calculate the real temperature rise. Estimates show that a rise of 15–125 °K can be expected. Since the Curie temperature of EuO is 69 °K, only experiment can answer the question whether such a source is feasible.

An important requirement for intense photocurrent source is that the photocathode be conducting, since the charging of the insulator sample would impede its operation. It is known that a lanthanum impurity increases the conductivity of the europium oxide, and the polarization of the photoelectrons is not decreased in this case.[102,136,137] An EuO crystal with 2% La was therefore used, and the distribution of lanthanum over the sample was far from uniform. The characteristic dimension of the EuO crystals was ~ 4 mm. The crystals were cleaved directly in a setup in order to obtain an atomically pure (100) surface. For measurements in the cw regime, a mercury-xenon high-pressure lamp was used. The pulsed illumination source was a sealed xenon high-pressure lamp (5 atm) with two tungsten electrodes separated by 4 mm. At a current-pulse amplitude 2.7 kA through the lamp, the emission spectrum was approximately constant in the range 5–6.5 kV. The lamp operated at a repetition frequency 6.7 Hz and at a pulse duration on the order of 0.5–1.2 μsec. Similar lamps operate in the systems of the Stanford accelerator at a frequency of 180 pulses per second. In one pulse, a section of the sample with area 2.3 mm^2 was bombarded with approximately 10^{13} photons having an energy sufficient to knock out the $4f^7$ electrons, thus producing approximately 3×10^9 electrons per pulse.

The results of the experiments have shown that no noticeable decrease of the polarization of the photoelectrons due to the heating of the sample takes place. The polarization amounts to 58.5% in a field of 21.1 kOe in the pulsed regime.

The useful intensity of the polarized-electron beam depends on the extent to which its electron-optical characteristics match those of the accelerator. In the Stanford linear accelerator it is possible to employ a beam of 70 keV electrons in the case when the emittance of the accelerator (the angular aperture times the radius) amounts to ~ 7 mrad-cm $\times 3\times10^9$ electrons per pulse, obtained in the described source from a cathode with an effective radius 0.85 mm, corresponding to 4×10^8 electrons per pulse with an emittance ~ 7 mrad-cm and energy 70 keV.

Further increase of the beam of polarized electrons from the described source calls for an increase in the intensity of the illumination. Possible difficulties connected with overheating can be overcome to a considerable degree by using iron as the photoemitter. Cesium coating makes it possible to raise the work function of such a photocathode to 3–3.5 eV, and the quantum yield in the range 5 eV $\leqslant h\nu \leqslant$ 6.5 eV amounts to approximately 10^{-3} electrons per incident photon. In a field of approximately 20 kOe, the average polarization is expected to be 35%. A measure of the quality of the polarized-particle source is the quantity IP^2, where I is the intensity and P the polarization. Therefore a certain decrease of the polarization due to the use of an iron photoemitter can be offset by increasing the beam intensity. Improvement of the optics and the construction of a source of polarized photoelectrons using EuO will apparently make it possible to increase the intensity of sample illumination by two orders of magnitude. To decrease the undesirable overheating it is possible to filter out the photons with energy less than 4 eV, which produce approximately half the light flux of such an illumination source.

Table III, which is compiled mainly from data of[138], lists information on some of the existing sources of polarized electrons.

We note that a beam of electrons with 75% polarization and practically unlimited intensity can be obtained if the suggestion made in[146] is successfully realized.

8. CONCLUSION

The successful observation of polarization of photoelectrons has made possible extensive applications of this method. More and more publications are devoted to the very idea of the method,[147] to detailed results on the concrete material (EuO),[148,149] to information on the measurement of the polarization of photoelectrons in new classes of magnetic materials (ferrites),[150,151] and to theoretical interpretations of the performed experiments.[152] There is no doubt that with further mastery of the method an increase will take place in the number of problems in which the applications of the method are not connected directly with magnetism as such. One such example is the successful measurement of the polarization of photoelectrons from nonmagnetic semiconductors (GaAs).[153,154] The great variety of magnetic substances will undoubtedly lead to a study of the polarization of photoelectrons in numerous laboratories. The principal accomplishment of the already performed work lies precisely in the development of the procedure of a reliable measurement of the

TABLE III. Existing sources of polarized electrons.

Method	Average current, *electrons/sec*	*Operating regime*	Number of electrons in a 1.5 μsec pulse	Polarization, %	Note
Mott scattering:					
Au, 120 kev[38]		Direct current		37	
Au, 161 keV[39]	$2\cdot10^9$	" "	$3\cdot10^3$	20	Emittance 6 mrad-cm at 161 keV.
Hg, 300 eV[139]	$6\cdot10^9$	" "	$9\cdot10^3$	17	
Hg, 900 eV[140]	$6\cdot10^5$	" "	1	84	
Hg, 6.75 eV[141]	10^{11}	" "	$1.5\cdot10^5$	27	
Spin exchange:					
Polarized K atoms[142]	$2.5\cdot10^7$	Pulse	$6\cdot10^4$	10	Repetition frequency 100–2000 Hz; pulse duration 1 μsec
Field emission:					
Magnetized Ni[88]	$6\cdot10^{10}$	Direct current	$9\cdot10^4$	13	Magnetic field 10 kOe
EuS film on W[133]		Pulse		89	Magnetic field 20 kOe; pulse duration 250 μsec; repetition frequency 0.1–0.5 Hz
Optical pumping:					
Discharge in He[143]	$2.5\cdot10^{13}$	Direct current	$4\cdot10^7$	8	Magnetic field 5 Oe
Fano effect: Cs[144]	$2\cdot10^8$	" "	$3\cdot10^2$	81	
Photoionization:					
Polarized K atom[145]	10^9	Pulse	$2\cdot10^6$	55	Emittance 2 mrad-cm at 120 keV; repetition frequency 50 Hz; pulse duration 15 μsec
Polarized Li atoms[138]	$2\cdot10^9$	Pulse	$2\cdot10^8$	78	Emittance 1 mrad-cm at 100 keV; repetition frequency 10 Hz; pulse duration 1.5 μsec
Photoemission:					
Fe[25]		Direct current		54	Magnetic field 30 kOe
EuO[135]		Pulse	$3\cdot10^9$ $4\cdot10^8$	58	Magnetic field 20 kOe Emittance 7 mrad-cm at 70 keV

effect. Further development should be aimed at improving the quality of the samples and at improving their property. Most results of the performed experiments were obtained with samples in the form of films. In spite of the ultrahigh vacuum in the installations used for the measurement of the polarization, the imperfection of samples prepared by such a method should strongly influence the results. Therefore the principal qualitative conclusions, and all the more the quantitative comparisons with theory, call for assurance that the properties of the samples conform to the properties of single crystals of the corresponding substances. This is a perfectly realizable task.

The most interesting of the suggested experiments of this type, for ferromagnets of the iron group, is the measurement of the polarization and of the photoelectron energy distribution below and above the Curie point. Measurement of the polarization of photoelectrons from rare-earth magnets will undoubtedly help the study of many other subtle phenomena occurring in these interesting systems. Further development of the measurements of polarization of photoelectrons calls also for progress towards higher photon energies. This will greatly extend the capabilities of the method and will permit, in particular, measurement of the polarization of photoelectrons in the entire band, without resorting to cesium coating. The most promising in this sense is the use of synchroton radiation in such experiments, a procedure already used successfully in experiments on the photoeffect. One can also expect to obtain in the near future results of the first experiments in which a source of polarized photoelectrons is used.

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