

LONGITUDINAL POLARIZATION OF BETA ELECTRONS

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Values of the longitudinal polarization of β electrons from P^{32} , In^{144} , Sm^{153} , Lu^{177} , Ho^{166} , and Au^{198} nuclei have been measured at 300-340 keV by the method of Mott scattering (involving the transformation of longitudinal into transverse polarization). Differences up to 10% have been detected in the degree of polarization of the isotopes investigated. It has also been found that the absolute values of the polarization lie in the range $(0.86 - 0.97) v/c$. The error in the absolute measurements ($\pm 3\%$) does not include any possible inaccuracies in the theoretical calculation which relates the values of the polarization and of the scattering asymmetry.

INTRODUCTION

As is well known, the discovery of the non-conservation of parity in weak interactions^{1,2} has led to a reinvestigation of our description of β decay. In particular, it has turned out that in accordance with the two-component neutrino theory³⁻⁵ the electrons emitted in β decay of unpolarized nuclei must be longitudinally polarized. This effect was then soon discovered experimentally.⁶⁻⁸ It was shown that the magnitude of the effect agrees within an accuracy of $\pm(15 - 20)\%$ with the calculated value $\mp v/c$ for electrons and positrons respectively. During the next three years more than twenty papers have been published (cf. reference 9) in which different methods of measurement were utilized, and nuclei with different Z and with different types of transitions were studied. A considerable part of this work has been carried out with an accuracy not exceeding 15%. The majority of the results of the remaining articles (for example, references 10 - 17) which have higher accuracy happens to fall approximately in the range of values $(0.9 - 1.0) v/c$.

An opinion that has been expressed most frequently is that the observed deviations of the effect from v/c are most likely due to systematic experimental errors, and that as experiments become more refined it will be shown that the polarization of electrons emitted by different nuclei is the same, and is equal to v/c (except for special cases of which RaE can be taken as an example). However, at present several authors claim an accuracy of 3-5% for their measurements and, moreover, while the value $P = -(1.0 \pm 3\%) v/c$ has been obtained¹² in the case of P^{32} , the ratio of electron polarizations for Au^{198} and Co^{60} has turned out¹³ to be equal to $0.87 \pm 5\%$.

In the present work we have taken for our main aim the task of obtaining with the highest possible degree of precision an answer at least to the question of whether the polarization of electrons from β decay of different nuclei is different. The accuracy of the relative measurements attained by us has turned out to be sufficient to demonstrate that such differences actually do occur both in cases of allowed transitions in P^{32} and In^{144} , and also in the Coulomb transitions in Au^{198} , Lu^{177} , Sm^{153} , as well as in Ho^{166} . With respect to the deviations of the polarization from the value v/c , a discussion is given of the accuracy of the absolute measurements which have also been carried out.

1. METHOD

The method of Mott scattering has been utilized in the present investigation; with the aid of crossed electric and magnetic fields the longitudinal polarization was transformed into a transverse one, and the latter was measured by measuring the scattering asymmetry.

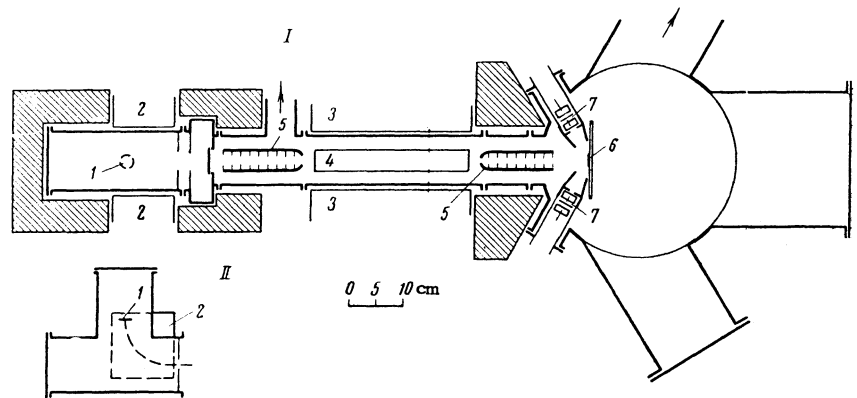
In this case the polarization P is related to the scattering asymmetry Δ by the following expression

$$\frac{P}{\beta} = \frac{\Delta}{\beta S}, \quad \Delta = \frac{I_1/I_2 - 1}{I_1/I_2 + 1},$$

where I_1 and I_2 are the "right" and "left" scattering intensities, and S is a function of angle and of energy. With an optimum choice of the energy (300 - 500 keV), of the angle of observation of the scattered electron ($110 - 140^\circ$) and of the scatterer thickness (several tenths mg/cm^2), the ratio of the scattering intensities is $I_1/I_2 \sim 1.6$.

The relatively large value of the scattering asymmetry makes this method more attractive compared to others. However, even in this case a measurement of the polarization with high pre-

FIG. 1. Schematic diagram of the apparatus: I—horizontal cross section, II—vertical cross section of the chamber containing the source. 1—source, 2—magnet poles of the preliminary analyzer, 3—magnet poles of the crossed fields system, 4—capacitor plates of the crossed fields system, 5—magnetic guides with diaphragm, 6—scatterer, 7—counters.



cision, for example, $\pm 3\%$, is a very difficult problem. Indeed, the accuracy of the results is limited primarily by systematic error: lack of precise knowledge of the asymmetry of the apparatus, of multiple scattering, of depolarization in the source, and of other factors. At the same time, in order to determine all these quantities it is necessary to carry out repeated measurements of the scattering asymmetry, the relative error in the magnitude of which is approximately equal to double the error in the ratio of the scattering intensities I_1 and I_2 for $I_1/I_2 = 1.6$.

In other known methods the required accuracy of measurement is even higher, due to the smaller difference in the readings of the indicators of polarized or unpolarized electrons.

However, relative measurements can be carried out with greater accuracy if the depolarization in the source is small, and the energy and the angular distributions of the electrons incident on the scatterer do not depend on what source is being investigated. In this case the uncertainties in the numerous corrections, which enter into the absolute measurements, become negligibly small if the ratio of the polarizations is evaluated.

2. PRINCIPAL CHARACTERISTICS OF THE EXPERIMENTAL ARRANGEMENTS AND CONTROL EXPERIMENTS

1. Description of the Apparatus. A schematic diagram of the apparatus is given in Fig. 1. The β emitters were situated at a distance of approximately 10 cm above the axis of the apparatus in the position shown in the figure. Electrons that were rotated by a transverse magnetic field through an angle $\sim 90^\circ$, passed through a collimator enclosed in an iron tube—a magnetic guide—and entered the region of the crossed fields. Then the transversely polarized electron beam again passed through the magnetic guide

containing the collimator and fell on the scatterer. The scattered electrons were recorded by counters whose axes were placed at an angle of 120° with respect to the direction of the electron beam. Each of the counters consisted of two counters placed behind one another and connected in coincidence. Between them there was a filter of thickness $\sim 25 \text{ mg/cm}^2$. The bodies of the counters were made of Plexiglas rings (10–12 mm high and 20 and 25 mm in diameter), coated with a conducting graphite layer. The working volume of the counters was separated from vacuum by a thin film of thickness $\sim 0.3 \text{ mg/cm}^2$. The sources and the scatterers were placed in an exactly specified position, and they could be changed without breaking the high vacuum.

2. Calibration of the System of Crossed Fields.

The values of the magnetic field H and of the electric field E required to rotate the spin of electrons of momentum p and of speed β through an angle φ were obtained from the following relations

$$\varphi = eHL\sqrt{1-\beta^2}/pc, \quad E = \beta H,$$

where L is the length of the region of the crossed fields ($\sim 300 \text{ mm}$). The device which determined the magnitude of the potential difference between the plates was calibrated by using known values of the magnetic field and of the energy of conversion electrons passing through the crossed fields (we utilized the 187-keV line of In^{114}). The magnitude of the applied fields corresponded to a rotation of the spin by 90° . Therefore, a relatively large error in specifying the angle of rotation of the spin which could be made as a result of an error in the determination of the effective length L of the crossed fields, should lead to no appreciable error in the measured value of the asymmetry. A control experiment in which the angle of rotation of the spin deviated from 90° by $\pm 15^\circ$ has shown that the choice of the value of the fields had indeed been made correctly: in both cases the asymmetry was reduced by $3 \pm 2\%$.

3. Sources. All the β sources were deposited on an aluminum foil 6μ thick and had a diameter of 20 mm. All the sources made of Sm, Lu, Ho, and In were prepared from unactivated low dispersion powders of the oxides of these elements with the Sm and In sources being enriched in the Sm^{152} isotope (98%) and the In^{113} (75%) isotope. The layers were deposited by evaporating suspensions of these powders in alcohol to which a small quantity of bakelite was added. The layers obtained in this manner after being dried at a temperature of approximately 200°C were sufficiently firmly attached to the backing. The Au source was obtained by sputtering in vacuum. All the sources were hermetically sealed into aluminum containers and were irradiated in a reactor. The P^{32} source was prepared by repeated application and evaporation of an active nitrate solution. The thickness of the sources varied in the range $0.6 - 1.3 \text{ mg/cm}^2$. The low aperture of the apparatus did not allow us to carry out measurements using sources of low specific activity. The most intense Sm source had an activity up to 3 C. The activity of the In source amounted to approximately 100 mC.

4. Electron Spectra. The energy spectrum of each source was carefully investigated to verify the absence within the selected range of energies of conversion lines whose appearance might be associated with an impurity due to foreign elements. Relative measurements of the polarization were carried out at an energy of 340 keV for all the sources (with the exception of gold). This energy was close to the maximum energy which we could select by crossed fields with the spin being rotated through 90° . The spectrum of electrons entering the region of crossed fields extended approximately from 240 to 440 keV. Figure 2 shows, as an example, the spectra for the In^{114} source. Due to a preliminary energy analysis the spectrum of the electrons incident on the scatterer did not depend on the shape of the source spectrum, and had a line shape standard for all the sources with a half-width of $\sim 40 \text{ keV}$ and with a relative intensity less than 1% outside the selected (340 ± 40) keV region. This enabled us to avoid corrections which would be difficult to estimate, and which would have arisen if sources having sharply different shapes of spectra were compared.

5. Elimination of Differences in Counter Efficiency. Measurements of the electron scattering asymmetry must take into account differences in counter efficiencies. The method of crossed fields enables us to eliminate easily the effect of counter

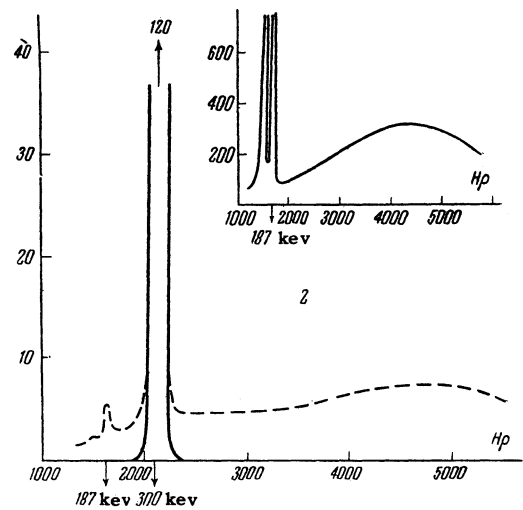


FIG. 2. Electron spectra. 1 - spectrum of electrons from In^{114} ; 2 - spectrum of electrons from In^{114} which have passed through the crossed fields system: solid curve - including preliminary analysis with respect to energy, dotted curve - without preliminary analysis.

efficiency on the results obtained. If the signs of both the electric and the magnetic fields are reversed the spin of the electrons incident on the scatterer is flipped over from the "up" (\uparrow) position into the "down" (\downarrow) position. The ratio of the scattering intensities I_1/I_2 , determined from the ratio

$$I_1/I_2 = \sqrt{(J_l/J_r)_{\uparrow} \cdot (J_l/J_r)_{\downarrow}}$$

(where J_l and J_r are the counting rates of the left and the right counters) does not contain an coefficient characteristic of counter efficiency. Effects of slow variations in counter efficiency (which in the course of the experiment might attain values of 3 - 5%) were eliminated by carrying out many series of measurements with the signs of the fields alternately reversed.

6. Counter Background. The low sensitivity of the counter to γ rays, and good screening of the source and of the counters enabled us to obtain a low background level: 60 - 70 coincidences per hour. The magnitude of the background was determined primarily by cosmic rays and by radioactive contamination, and varied little even when the most intense sources were investigated. Owing to the use of preliminary analysis of electrons by the transverse magnetic field the scatterer could not be directly "seen" from the source, and therefore γ rays from the source could not reach the scatterer. Control experiments have shown that the magnitude of the background remains the same when measured by two different methods: a) the beam enters the chamber, the scatterer is removed, b) the scatterer is placed in position,

the direction of one of the fields is reversed, and the beam is not passed through.

The low background level made possible measurements with relatively weak sources and with thin scatterers, and to a certain extent compensated for the low aperture of the apparatus.

7. The Spread in the Experimental Results. In utilizing the method of transforming the longitudinal polarization of the electrons into a transverse one by means of crossed fields it is necessary to take precautions which will guarantee that the angular spread of electrons incident on the scatterer, and consequently the magnitude of the asymmetry introduced by the apparatus, will not depend on the position of the source and on the magnitude of the fields. One of the methods by means of which this can be attained is sufficiently strong collimation of the beam, and this was in fact used in the apparatus described. A sufficient degree of collimation of the beam, and the proper adjustment of the apparatus were achieved as a result of experiments in which we measured the dependence of the magnitude of the asymmetry on the position of the source, and on the deviations in the values of the fields from the prescribed values. These experiments were carried out using the most intense Sm¹⁵³ source which enabled us to obtain the required statistical accuracy within a short time. As a result, a situation was achieved in which the magnitude of the asymmetry varied by not more than 1 – 1.5% when the current in the magnet used for the preliminary analysis was varied by $\pm 15\%$, and remained constant within 1% when the field strengths of the crossed fields were changed by an amount which exceeded by a factor of several fold the possible error in determining them.

Carefully performed experiments have shown that the magnitude of the asymmetry is practically independent of the accuracy with which the source is placed in its operating position. For a sufficiently large displacement of the source a sharp decrease in the intensity of the beam reaching the scatterer occurred due to the strong collimation. But there was no noticeable accompanying change in the scattering asymmetry. As a result of the foregoing experiments on the investigation of the constancy of the asymmetry introduced by the apparatus, and of subsequent measurements in which the asymmetry in the scattering of electrons from Sm¹⁵³ was compared with the asymmetry in the case of other sources, we could analyze approximately twenty measurements of the scattering asymmetry for β electrons from Sm¹⁵³, each of which had a statistical error of approximately 2%.

This analysis has demonstrated the presence of a spread of non-statistical character whose maximum value was estimated as $\pm 1\%$.

8. Depolarization of Electrons in Sources. A determination of the amount of depolarization in sources was carried out in several control experiments. A comparison of Sm sources of thickness 0.8 and 0.2 mg/cm² and of Au sources of the same thickness showed no difference in the magnitude of the asymmetry within the accuracy of measurement ($\pm 2\%$). In subsequent experiments layers of gold, silver and aluminum of different thicknesses up to 10 mg/cm² were placed on a Sm source of thickness 0.8 mg/cm² (both from the backing side and from the active layer side). The observed decrease in asymmetry enabled us to obtain a more accurate estimate of the amount of depolarization in the sources which has turned out to be equal to

Source	Au	Sm	In	Lu	Ho	P
Thickness, mg/cm ²	0,8	0,9 \pm 0,2	1,6 \pm 0,3	0,9 \pm 0,2	0,8 \pm 0,2	1,8 \pm 0,3
Depolarization, %	1,7 \pm 0,5	1 \pm 0,5	1,2 \pm 0,5	1,3 \pm 0,5	1 \pm 0,5	0,8 \pm 0,5

9. Role Played by Electrons Scattered from the Walls of the Apparatus. In order to reduce the scattering of electrons the walls of the chambers in which the sources and the scatterer were placed were lined with Plexiglas the surface of which was covered with graphite and grounded. A number of control experiments has shown that scattering of electrons in the chamber in which the source was placed and scattering at the edges of the first diaphragms lead to a depolarization whose magnitude was estimated as 0.5%.

Considerably greater difficulties had to be overcome in order to reduce the role played by scattering by the walls of the chamber in which the counters and the scatterer were situated. Practically all the beam electrons passing through the gold layer reach the walls, and the probability of their entering the counters (either directly or through the scatterer) on being scattered from the walls is not as small as it appeared initially. For the data on the absolute values of the polarization, published by us earlier,¹⁸ this effect had to be taken into account and a correction of $(3 \pm 1.5)\%$ had to be introduced. In the apparatus now being described the dimensions of the chamber were considerably enlarged: it was in the form of a cylinder of 350 mm diameter and approximately 400 mm high with deep traps situated opposite each of the counters in the path of the beam. In order to determine the role played by the scattering by the walls of this chamber under conditions close to those under which the

asymmetry was measured, a number of control experiments was performed. Experiments of very great sensitivity showed that as a result of the above effect corrections must be applied to the magnitude of the asymmetry: 0.4% due to the scattering from the walls of the chamber and 0.1% due to the scattering from the Plexiglas counter tips.

3. MEASUREMENTS AND RESULTS

1. Relative Measurements of Polarization.

Relative measurements of polarization were obtained by comparing the magnitude of the scattering asymmetry for each of the sources investigated with the magnitude of the scattering asymmetry for Sm^{153} . The measurements were carried out using the same scatterer, the same energy and with the spin rotated by 90° . The results of the control experiments described earlier showed that the spectra of the electrons falling on the scatterer and the value of the asymmetry introduced by the apparatus are not altered when sources are changed. This allows us to assume that the comparison of the polarizations was carried out under strictly identical conditions.

From three to five series of measurements were carried out for each source at different times in the course of several months. Each series included measurements for the source under investigation with an accuracy of 2 or 3%, and measurements for Sm^{153} which were carried out at the beginning, in the middle, and at the end of the series. Table I gives relative values of the polarization obtained from the relation $P/P_{\text{Sm}} = \Delta/\Delta_{\text{Sm}}$.

Table I

Energy	340 kev					240 kev	
	Isotope	Sm^{153}	P^{32}	In^{114}	Lu^{177}	Ho^{166}	Sm^{153}
P/P_{Sm}	1	1.05	0.96	0.95	0.94	1	0.97
Error, %		± 1.8	± 3.2	± 1.8	± 1.8		± 1.8

These ratios have been corrected for the differences in the value of the depolarization in the sources in accordance with the values given earlier. The errors in the ratios of polarizations obtained in this manner include: a) an error in the determination of Δ_{Sm} , equal to $\pm 1\%$; b) an error in the value of Δ , equal to 1.5% in the case of Lu, Ho, P, and Au, and 2.5% in the case of In; c) an error in the relative values of the depolarization in the sources, equal $\pm 0.5\%$. The quoted ratios of the polarizations do not require any cor-

rections, since the corrections for the asymmetry due to the apparatus, for the depolarization of the electrons on the way from source to the scatterer, for the finite angle of observation of the scattered electrons, etc. are completely eliminated from the ratio of two values of polarization.

2. Absolute Measurements. Absolute measurements were carried out for one source — the most intense Sm^{153} source. These measurements were carried out for an electron energy of 300 kev. They consisted of determining the role played by multiple scattering in the scatterer, and the magnitude of the asymmetry due to the apparatus.

The asymmetry due to the apparatus was determined by means of experiments in which the gold scatterer was replaced by an aluminum scatterer. Since the angular distributions in the scattering by gold and by aluminum differ from one another it was necessary to achieve such conditions that the asymmetry due to the apparatus would be close to zero (as is shown later, in the final measurements its magnitude was 0.01).

Preliminary experiments showed that thick layers of aluminum (of the order of 5 mg/cm^2) are completely unsuitable for a correct measurement of the magnitude of the asymmetry due to the apparatus. Therefore, experiments were carried out in which the asymmetry due to the apparatus was varied artificially by an amount of approximately 5%, and these changes were monitored by means of a very thin (0.5 mg/cm^2) aluminum scatterer. Simultaneously the asymmetry due to the apparatus was also measured by means of thicker scatterers (2, 3, and 5 mg/cm^2). As a result of these experiments it was shown that a scatterer of thickness 2 mg/cm^2 can still correctly reproduce the variations in the asymmetry due to the apparatus, a measurement by means of a 3 mg/cm^2 scatterer already leads to a small error, while the results obtained with the aid of 0.5 mg/cm^2 and 5 mg/cm^2 scatterers differed by an amount ~ 0.1 .

The observed effects are explained by the distortion of the angular distribution of the scattering due to multiple scattering of electrons in aluminum. This is confirmed by the fact that only for sufficiently thin layers does the intensity increase practically linearly with the thickness of the scatterer (the absolute values of the thickness were determined by weighing with an accuracy greater than 1%). For a scatterer of thickness 3 mg/cm^2 , for which the distortions of the results of measuring the asymmetry due to the apparatus are already noticeable, the deviations from a linear dependence amount to $\sim 15\%$.

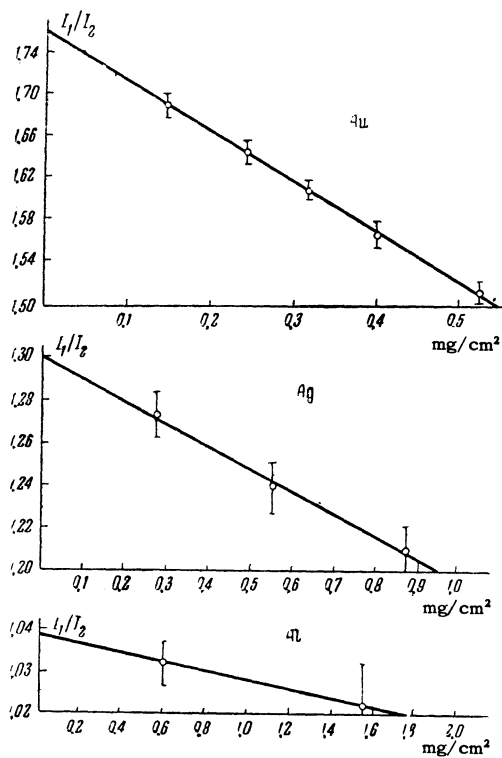


FIG. 3. Ratio of the "left-right" scattering intensities as a function of the thickness l of gold, silver, and aluminum scatterers.

In the case of gold scatterers the absolute values of the thickness could not be determined with a sufficiently high degree of accuracy by weighing. However, in order to achieve the correct extrapolation to zero it is necessary to know only the relative thickness of the layers. In order to obtain the relative thickness the intensities from different scatterers were compared with each other at the working energy (300 kev) and at a higher energy (500 kev). In the course of this those scatterers were identified for which the deviations from a linear increase in intensity are not yet very large.

In measuring the asymmetry we restricted ourselves to maximum thickness of scatterer equal to 1.6 mg/cm^2 in the case of aluminum, and to 0.5 mg/cm^2 for gold, for which the deviations described earlier do not exceed 8–10%.

Figure 3 shows the results of the measurements of the ratio of the intensities I_1/I_2 for gold, silver, and aluminum scatterers. The counting rates for the thinnest scatterers amounted to approximately 120, 60, and 30 counts per minute respectively for gold, silver, and aluminum. From the values of I_1 and I_2 we subtracted the background, the effect due to the film which was the scatterer backing, and the effect due to scattering by the walls of the chamber, which together did not exceed 2% of the

values of I for the thinnest gold layer. The extrapolated values of I_1/I_2 and the corresponding values of the asymmetry Δ are given in Table II.

Table II

Scatterers	Au	Ag	Al
I_1/I_2	$1.765 \pm 0.8\%$	$1.305 \pm 1\%$	$1.039 \pm 0.8\%$
Δ	$0.277 \pm 1.6\%$	$0.132 \pm 5\%$	$0.019 \pm 20\%$
S for $\beta = 0.776$	0.427	0.208	0.038
$\Delta_T = \beta S$	0.331	0.161	0.0295

There we have also given the values of S for $\beta = 0.776$ and the value of $\beta S = \Delta_T$ taken from Sherman's tables.¹⁹ The following corrections were applied to the values of the polarization obtained from the data of Table II.

for depolarization in the source:	$(1 \pm 0.5)\%$
for depolarization along the path from the source to the scatterer:	$(2 \pm 1)\%$
for the finite size of the scatterer, and for the spread in the angles of observation:	$(1.5 \pm 0.5)\%$
for the error in the determination of the effective value of βS :	1%

In the final result the polarization of the electrons emitted in the β decay of Sm^{153} of energy 300 kev turned out to be equal to $-0.92 \beta \pm 2.7\%$. The asymmetry due to the apparatus was not great in these measurements: -0.01 . The value of the asymmetry for a silver scatterer gives the same value of the polarization but with lower accuracy, specifically 6–7%.

Table III gives absolute values of the magnitude of the longitudinal polarization of the electrons

Table III

Isotope	Sm^{153}	P^{32}	In^{114}	Lu^{177}	Ho^{166}	Au^{198}
$-P_l(v/c)$	0.92	0.97	0.88	0.87	0.86	0.89
Error, %	± 2.7	± 3.4	± 4.2	± 3.4	± 3.4	± 3.4

for the isotopes investigated which were obtained with the aid of the results of relative measurements. We recall in this connection that the relative measurements for Au^{198} were carried out at an energy of 240 kev, while in the case of all the other isotopes they were carried out at an energy of 340 kev.

4. DISCUSSION OF RESULTS

Results of relative measurements show that the polarizations of the electrons for the isotopes investigated are not the same. It is of interest to note that the polarizations for P^{32} and In^{114} , for which the transitions are allowed and are of the Gamow-Teller type, differ from each other by

approximately 10%. The results obtained for P^{32} and Au^{198} agree within experimental error with the results of references 12 and 13.

In spite of the fact that we attempted to determine in the most careful manner all the possible causes which might lead to an underestimate of the degree of polarization, it seems to us that the absolute values obtained by us cannot yet be regarded as finally established. First of all, it is necessary to check the correctness of the theoretical calculations of the function S which gives the relation between the scattering asymmetry and the degree of polarization. Unfortunately, experiments on double scattering of unpolarized electrons still do not give for the quantity S an accuracy higher than 10%. We intend to repeat these experiments in the near future for electrons of energy 200–300 keV. In doing this we also hope to check whether we have correctly estimated the magnitude of the depolarization along the path of the beam from the source to the scatterer in the apparatus utilized in the present work.

It is impossible to predict in advance the results of these experiments. If it should turn out that the corrections to the polarization are large and amount to 10%, then in this case the spread in the values of the polarization will be shifted into the range $(0.95 - 1.05) v/c$. Then the deviations from the value of v/c would not exceed 5%, and this would apparently make it significantly easier to explain this effect by the influence of nuclear structure. However, if the true values of the polarization are close to those obtained in the present work, then it would be very interesting to carry out a measurement of the longitudinal polarization for the simplest nucleus T (for the neutron this is, apparently, practically impossible). These measurements could show whether the effect of nuclear structure is the only reason for the observed deviations, provided, of course, that it would be possible to show that in the case of T , just as in the case of the neutron,²⁰ one should expect very small deviations from v/c . We would like to express the wish that such quantitative calculations for T should be carried out.

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have carried out the irradiation of the sources over a long period.

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