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MEASUREMENT OF THE LONGITUDINAL POLARIZATION OF ELECTRONS EMITTED IN THE BETA-DECAY OF Tm^{170} , Lu^{177} , Au^{198} , Sm^{153} , Re^{186} , Sr^{90} , AND Y^{90} . * II

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The longitudinal polarization of electrons from Coulomb β -transitions is measured for various values of the electron energy. The longitudinal polarization was found to be equal to $-v/c$ for all substances investigated. It is shown that the relations $C_T = -C'_T$, $C_S = -C'_S$, $C_V = C'_V$, $C_A = C'_A$ are most probably satisfied by the β -decay coupling constants.

WITH the discovery of the violation of the conservation of parity in weak interactions,¹ the β -decay picture became more complicated. Whereas β -decay could formerly be characterized by four (more precisely, five) constants of the variants of interaction, the number of constants is now doubled, in so far as half of them reflect nonconservation of parity. And since, in general, the interaction constants can be complex, the number of parameters is increased to 16. However, new effects have come to light, through which connections between constants can be observed by physical measurements. One of these effects is, as is well known, the longitudinal polarization of electrons in the β -decay of unpolarized nuclei.²

Various combinations of the coupling constants can be obtained from the measurement of the longitudinal polarization of the electrons, depending on the type of transition of the β -active nucleus. It turns out that the maximum possible information about the coupling constants which can, in principle, be given by experiments on the measurement of the longitudinal polarization of electrons from unpolarized nuclei, is obtained by measuring very accu-

rately the longitudinal polarization of the electrons as a function of electron energy, for first forbidden transitions (the so-called Coulomb transitions) in heavy nuclei.

In the present work we attempted to measure longitudinal polarization of electrons of various energies with the greatest possible precision for just the elements with Coulomb transitions, such as Tm^{170} ($\Delta J = 1$; yes), Re^{186} ($\Delta J = 1$, yes), Sm^{153} ($\Delta J = 1, 0$; yes), Au^{198} ($\Delta J = 0$, yes) and Lu^{177} ($\Delta J = 1$, yes) or ($\Delta J = 0$, yes), containing a mixture of Gamow-Teller and Fermi interactions. For comparison, measurements were carried out in the same way for Sr^{90} and Y^{90} , which have unique transitions and pure Gamow-Teller interaction, for which there is good reason to expect the electron polarization to be equal to $-v/c$.

1. DESCRIPTION OF THE ARRANGEMENT

To measure the longitudinal polarization, we employed the method of Mott scattering, which consisted in measuring the magnitude of the azimuthal asymmetry in a single scattering of transversely polarized electrons through a large angle by a scatterer having a large Z .

To obtain a good stability and reproducibility of results of the measurements, we tried to make the construction of the apparatus as simple as pos-

*This work was reported at the Conference on Mesons and New Particles in Padua-Venice, September 27, 1957, and at the All-Soviet Conference on Nuclear Reactions at Low and Medium Energies in Moscow, November 23, 1957.

sible. We have avoided using external fields, electric or electric + magnetic, for turning the longitudinal polarization into a transverse one, because these means contain sources of errors which are difficult to control. In our case, the longitudinal polarization was turned into a transverse one by deflecting, through an angle of about 90° , the trajectory of the electron in the Coulomb field of the nucleus through multiple scattering by a relatively

thick scatterer. In the method where the polarization is transformed by using external fields, for example in a curved condenser, the upper limit on the energy of the electrons, whose polarization can be measured, is very low because it is impossible to obtain a sufficiently large voltage, owing to the possibility of sparking over in the vacuum. It is easy to see that our method does not have this limitation.

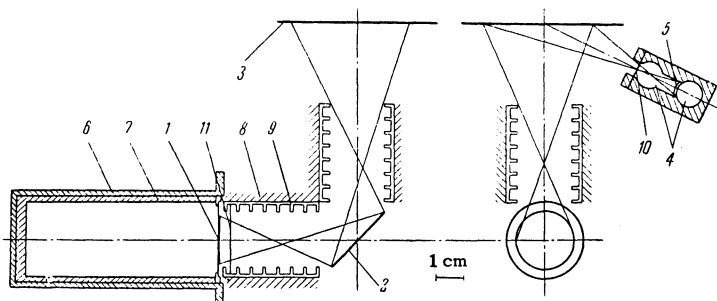


FIG. 1. Scheme of the apparatus. 1— source, 2— scatterer I (transformer), 3— scatterer II (analyzer), 4— Geiger counters, 5— aluminum filter between the counters, 6— brass container, 7— plexiglass container, 8— case of the apparatus, 9— duraluminum diaphragm, 10— polyethylene film, 11— thin collodion film.

The scheme of the apparatus is given in Fig. 1. In order to increase the intensity of the apparatus, the channels for the electron traversal were made rather large. However, in spite of the significant spread in angles of the electron trajectories, in so far as the mean angle of scattering of the electrons by the "transforming" scatterer I was near to 90° , the geometrical correction, decreasing the magnitude of the azimuthal asymmetry on account of the angular spread, was equal, in all, to $\sim 6\%$. The thin gold analyzing scatterer II was placed perpendicular to the axis of the apparatus. Such a position of the scatterer II gave the maximum symmetry for the entire apparatus. Electrons undergoing scattering in the scatterers I and II were counted by a telescope of two Geiger counters connected in coincidence. Between the counters there was placed an aluminum filter, which stopped the low energy electrons. The counters were placed at an angle of 112.5° to the axis of the apparatus, and at a very small angle with respect to the scatterer II so that a rather small solid angle of the counter telescope covered the whole area of the scatterer. Such dispositions of the counters and scatterers II gave the maximum intensity. The counters, together with the scatterer II, could be turned around the axis of the apparatus without destroying the vacuum. In order to decrease the admixture of electrons scattered from the walls of the apparatus, traps made of thin (0.5 mm) duraluminum diaphragms were placed in the canal traversed by the electrons.

The Tm, Lu, Sm, and Sr + Y sources, which were in the form of a finely dispersed active pow-

der, were coated in uniform layers on a 10μ thick aluminum foil. The Re was set electrolytically on an aluminum foil covered by a very thin layer of platinum, and the Au was sprayed on an aluminum foil in vacuum. The sources were then activated in the reactor. The foil with the source was fastened to a duraluminum ring, which was placed in a circular brass container, lined with plexiglass. A thin collodion film was placed in front of the source in several cases, to protect the apparatus against contamination by the active material.

Two analogous sets of apparatus were prepared. In the first one (1) the frame was made of brass and lead; in the second (2), of lead and tungsten.

2. MEASUREMENTS

The azimuthal asymmetry in the scattering, $\Delta = 200(I_1 - I_2)/(I_1 + I_2)$, was measured in a plane perpendicular to the plane in which the electron was turned as a result of the first scattering (I_1 is the scattered intensity in the azimuthal direction $\mathbf{v}_2 \times \mathbf{v}_1$, where \mathbf{v}_1 and \mathbf{v}_2 are the velocities of the electron before and after scattering in scatterer I, and I_2 is the intensity in the opposite direction) for several values of the mean electron energy \bar{E} . The electrons were separated by energies by placing an aluminum filter of given thickness ρ between the counters, and using a scatterer I of thickness τ . In each experiment with a definite mean energy of the electrons \bar{E} , several measurements of the azimuthal asymmetry Δ_K were carried out for different thicknesses t_K of the scatterer II.

TABLE I

ρ, τ	\bar{E}, keV	Element	$\Delta = 200 (I_1 - I_2) / (I_1 + I_2)$ for $t, \text{mg/cm}^2 \text{ Au}$				$\bar{\Delta}_0$	$\bar{\Delta}_{\text{corr}}$	$\bar{\Delta}_{\text{th}}$	$\langle \sigma \rangle / (v/c)$
			1.97	0.92	0.39	0.24				
$p_1 = 1.0 \text{ mg/cm}^2 \text{ Al};$ $\tau_1 = 3.0 \text{ mg/cm}^2 \text{ Au}$	145	Tm 0.8 mg/cm ²			22.0 ± 0.9	25.3 ± 1.2	28.0 ± 2.0	33.0 ± 1.3	36.6 ± 1.8	1.01 ± 0.05
	140	Sm 1.1 mg/cm ²			15.1 ± 1.9	23.1 ± 1.4	29.0 ± 1.6	32.0 ± 1.5	35.7 ± 1.9	1.00 ± 0.05
	130	Lu 0.3 mg/cm ²				19.0 ± 2.6	22.8 ± 2.8	26.3 ± 1.9	29.6 ± 2.3	0.97 ± 0.07
	130	Sr + Y 1.5 mg/cm ²				31.6 ± 3.7	24.8 ± 2.8	33.8 ± 3.6	37.3 ± 4.1	1.06 ± 0.12
$p_2 = 2.6 \text{ mg/cm}^2 \text{ Al};$ $\tau_2 = 6.0 \text{ mg/cm}^2 \text{ Au}$	260	Tm		22.1 ± 0.9	29.8 ± 1.2	31.5 ± 1.5	33.8 ± 2.8	37.5 ± 1.4	39.2 ± 1.5	0.93 ± 0.04
	250	Sm			30.0 ± 4.0	31.9 ± 2.5		37.6 ± 3.8	39.3 ± 3.8	0.93 ± 0.09
	200	Lu	14.0 ± 1.3	23.7 ± 2.0	38.0 ± 4.8			42.5 ± 4.4	44.4 ± 4.6	1.04 ± 0.11
	260	Re 0.1 mg/cm ²		23.3 ± 2.6	38.0 ± 4.8			43.2 ± 4.4	45.2 ± 4.6	1.06 ± 0.11
	220	Sr + Y		21.4 ± 1.7	35.7 ± 1.8	33.6 ± 4.8		41.5 ± 2.5	43.4 ± 2.7	1.03 ± 0.06
$p_3 = 5.2 \text{ Al};$ $\tau_3 = 13 \text{ Au}$	390	Tm		25.7 ± 0.9	30.4 ± 1.3	33.5 ± 2.8		37.5 ± 1.6	41.2 ± 1.9	1.01 ± 0.05
	360	Sm			30.6 ± 2.3			36.7 ± 3.0	40.4 ± 3.3	1.00 ± 0.08
	390	Au 0.2 mg/cm ²			23.8 ± 2.6	36.8 ± 4.0		33.6 ± 2.5	36.8 ± 2.9	1.00 ± 0.08
	450	Sr + Y		15.5 ± 1.2	28.0 ± 2.0			33.0 ± 3.1	36.2 ± 3.4	0.94 ± 0.09
$p_4 = 10.4 \text{ Al};$ $\tau_4 = 20.0 \text{ Au}$	520	Tm		27.4 ± 2.1	32.0 ± 2.9			35.2 ± 2.1	36.6 ± 2.2	0.99 ± 0.06
	520	Au		24.2 ± 2.6	30.0 ± 5.8			33.3 ± 2.8	34.5 ± 2.9	0.96 ± 0.08
	650	Sr + Y		23.6 ± 2.7				30.7 ± 3.1	31.8 ± 3.2	0.98 ± 0.10

*Notation: ρ - thickness of the filter between the Geiger counters, τ - thickness of the transforming scatterer I, \bar{E} - mean electron energy, t - thickness of the analyzing scatterer II, $\bar{\Delta}$ - mean of the measured values of the azimuthal asymmetry, $\bar{\Delta}_0$ - value of the azimuthal asymmetry extrapolated to zero thickness of scatterer II, $\bar{\Delta}_{\text{corr}}$ - azimuthal asymmetry with account of corrections for: 1 - instrumental asymmetry Δ_p , 2 - back scattering of electrons, δ_μ , 3 - electrons scattered from the walls of the apparatus, δ_η ; Δ_{th} is the expected value of the azimuthal asymmetry for electrons, with polarization equal to $-v/c$, $\langle \sigma \rangle / (-v/c)$ - longitudinal polarization of the electrons in units $-v/c$.

In all, three series of measurements were carried out: series I, on apparatus 1; series II, on apparatus 2; and series III, on apparatus 2, but using two counter telescopes. The azimuthal asymmetry of the scattering was defined as the mean value of the azimuthal asymmetry in each of the telescopes. These conditions excluded errors due to possible intensity changes in the electron beam during the period of measurement,

and also due to possible inhomogeneity in the thickness of the scatterer II.

Reproducibility of the Measurement Results

In order to rely on the statistical accuracy of the results of a measurement, it is necessary to ascertain that no deviations of nonstatistical character are present. This can be established by the

degree of reproducibility and by the spread of results about the mean value in repeated experiments.

In all, 80 measurements of azimuthal asymmetry in the scattering were carried out, of which 53 were repeated measurements. In spite of the fact that the measurements were carried out on different sets of apparatus, the overwhelming part of the measurements were in agreement with each other. Out of 53 repeated experiments, 40 coincided, within the limits of experimental error, with the mean values, 10 were more than one standard error away, 2 were more than 2 standard errors, and 1, more than three standard errors. The 3 final measurements were not taken into account in the calculation of the mean values in the repeated measurements. The mean values of the measured magnitude of azimuthal asymmetry are given in Table I.

Control Experiments

(a) The instrumental asymmetry was measured by scattering electrons from an aluminum foil in place of scatterer II. The instrumental asymmetry could be calculated from this, since the azimuthal asymmetry in scattering in aluminum is about 12 times smaller than that in the same thickness of gold.³ As the measurements showed, the magnitude of instrumental asymmetry Δ_n did not depend on the source material, but only on the energy of the electrons and was found to be between 0 and -2.

(b) The intensity of the electron flux reflected from the aluminum backing of the source and from the plexiglass container was measured experimentally for a point source covered on top by a small screen, which the electrons could not penetrate, so that direct radiation couldn't penetrate into the counter. The relative fraction of reflected electrons, depending on the electron energy, lay in the interval 0.5 to 1.5%. Since the reflected electrons have essentially a polarization opposite to that of the direct electrons, the corrections δ_μ in the measured values of the azimuthal asymmetry should be somewhat larger, 0.8 to 2.0%.

(c) In analogous fashion, the proportion of electrons scattered from the diaphragm and walls of the apparatus lying close to the source was measured. The corrections δ_η to the azimuthal asymmetry in this case were 3.5 to 1.9%.

(d) Measurement of the azimuthal asymmetry for various azimuthal angles showed that at all energies, the effect was maximum in the plane perpendicular to the plane of turning of the trajectory of the electron after scattering in scatterer I.

(e) K. A. Ter-Martirosian has shown that in the

multiple scattering of electrons in a light material through angle ψ , the spin of the electrons is turned through an angle*

$$\varphi = \psi [1 - \sqrt{1 - (v/c)^2}].$$

Measurements with Al and Au of equivalent thicknesses as transforming scatterers showed that the effect of azimuthal asymmetry did not depend on the material of scatterer I.

(f) In the case of measurements with Au¹⁹⁸ as a source, the Geiger counters were subjected to strong γ -radiation. Measurements of the polarization of electrons were carried out in the 300 to 700 keV energy interval where, between the counters connected in coincidence, there was placed an aluminum filter sufficiently thick so that the electrons from the γ -rays ($E_\gamma \sim 400$ keV) were practically excluded from giving coincidences in the counters.† The resolution of the counter system was sufficiently high and the background of chance coincidences did not exceed 0.5 to 1.0%. The proportion of photo- and Compton electrons produced by the γ -rays was measured in an experiment where the source was shielded by a plexiglass screen which could not be penetrated by electrons, but was transparent to γ -rays. The correction to the magnitude of azimuthal asymmetry caused by this effect constituted $\sim 2\%$.

*For an elementary act of scattering, it is easy to obtain in the Born approximation the angle of turning of the spin in the plane of the scattering. It is given by

$$\sin \varphi_i = \frac{1 - (1 - \sqrt{1 - v^2/c^2}) \sin^2(\psi_i/2)}{1 - (v^2/c^2) \sin^2(\psi_i/2)} (1 - \sqrt{1 - v^2/c^2}) \sin \frac{\psi_i}{2},$$

which for $\psi_i \ll 1$ goes into the formula $\varphi_i = (1 - \sqrt{1 - (v/c)^2}) \psi_i$, which is that for the turning of the spin in an electric capacitor.

Terms of order $(Z/137) \psi_i/2$, which correct for the use of Born approximation, are small if $\psi_i \ll 1$, even for heavy nuclei. The above formula is therefore expected to be valid for small angles (multiple scattering) even in the case of scattering from heavy nuclei. If multiple scattering takes place in one plane, then it is evident that for the resulting angles $\varphi = \sum_i \varphi_i$,

$\psi = \sum_i \psi_i$ the relation given in the text is valid.

†Note added in proof (April 17, 1958). For lower-energy electrons (145 and 260 keV) from Au¹⁹⁸, the dependence of the longitudinal polarization on the thickness of scatterer II (see below) turned out to be inconsistent with the results of measurements for the remaining elements. In view of the ambiguity in determining the magnitudes of longitudinal polarizations, the data on Au¹⁹⁸ for electrons of these energies was excluded.

Determination of the Extrapolated Values of the Azimuthal Asymmetry Corresponding to Single Scattering

In order to determine the polarization of the electrons it is necessary to know the value of the azimuthal asymmetry which corresponds to single scattering of the electrons. In the actual measurements involving electrons scattered in scatterers of finite thicknesses, a fraction of electrons is always multiply scattered, and this leads to a shift in the value of the azimuthal asymmetry. However, this correction can be obtained, experimentally.

As Artsimovich⁴ has shown, the scattering intensity of electrons of a given energy in a scatterer of thickness t is

$$I(t) = I_0 [t + \gamma(E)t^2] = I'(t) + I''(t),$$

where $I'(t) = I_0 t$ is the intensity of single scattering and $I''(t) = I_0 \gamma(t) = I_0 \gamma(E)t^2$ is the intensity of multiple scattering. In the scattering of polarized electrons, one would observe an azimuthal asymmetry:

$$\begin{aligned} \Delta(t) &= 200 \frac{I'_1(t) - I'_2(t) + I''_1(t) - I''_2(t)}{I'_1(t) + I'_2(t) + I''_1(t) + I''_2(t)} \\ &= 200 \frac{I'_1(t) - I'_2(t) + I''_1(t) - I''_2(t)}{I'(t) + I''(t)} = 200 \frac{I'_1(t) - I'_2(t)}{I'(t) [1 + (I''(t)/I'(t))]} \\ &+ 200 \frac{I''_1(t) - I''_2(t)}{I''(t) [1 + (I'(t)/I''(t))]} = \frac{\Delta_0}{1 + \gamma(E)t} + \frac{\xi(E)\Delta_0\gamma(E)t}{1 + \gamma(E)t} \\ &\approx \Delta_0 \frac{1}{1 + \gamma(E)[1 - \xi(E)]t} = \Delta_0 \frac{1}{1 + \alpha(E)t}, \end{aligned}$$

where $\Delta_0 = 200(I'_1 - I'_2)/I'$ is the azimuthal asymmetry in a single scattering and $\xi(E)\Delta_0$ is the azimuthal asymmetry in multiple scattering, with $\xi(E) \gg 1$.

Thus, we find that the inverse of Δ_k , the azimuthal asymmetry for scattering of electrons of a given energy E in scatterers II of various thicknesses t_k , is linearly connected with t_k :

$$\frac{1}{\Delta_k} = \frac{1}{\Delta_0} + \frac{\alpha(E)t_k}{\Delta_0}.$$

The value of $\overline{\alpha(E)}$ as a function of energy (Fig. 2) has been determined using all the data available for different materials and for different energies. The extrapolated values of $\overline{\Delta_0}$ for each material and each energy were found from the formula

$$\overline{\Delta_0} = \sum_k \Delta_k [1 + \overline{\alpha(E)}t_k] / k$$

subject to the condition $\overline{\alpha(E)}t_k > 1$. The extrapolated values $\overline{\Delta_{\text{Corr}}}$ with account of the corrections indicated above (Δ_n , δ_μ , δ_η) are given in

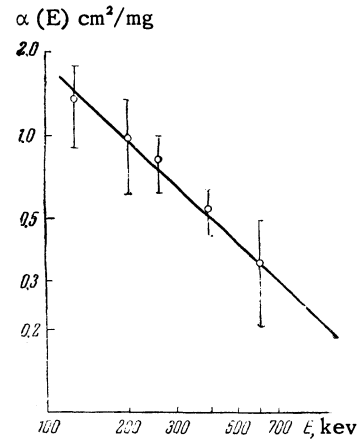


FIG. 2

Table I ($\overline{\Delta_{\text{Corr}}} = \delta_\mu \delta_\eta \sum_k (\Delta_k - \Delta_n) [1 + \overline{\alpha(E)}t_k] / k$).

From these data it can be seen that the measured values of the azimuthal asymmetry change only very slowly in a wide energy interval. This means that, in the given apparatus, a precise knowledge of the form of the electron energy spectrum is not necessary for determination of the degree of polarization of the electrons.

Energy Spectra of the Electrons

The energy spectrum of electrons undergoing double scattering and registered in the counter can be represented in the form $n = f_0 \sigma(\tau) \sigma_0 \varphi(\rho)$, where f_0 is the electron spectrum at the source, $\sigma(\tau)$ is the cross section for multiple scattering through an angle of 90° , in scatterer I of thickness τ , σ_0 is the cross section for single scattering through an angle of 112.5° , and $\varphi(\rho)$ is the proportion of electrons going through the aluminum filter of thickness ρ . The quantities σ_0 and $\varphi(\rho)$ are known.^{3,5} The energy spectra of electrons from Au^{198} (maximum energy 950 keV) and Lu^{177} (maximum energy 500 keV) undergoing double scattering through an angle of $\sim 90^\circ$ was carefully measured with a spectrometer. The measurements were carried out for Lu^{177} with scatterers I of thickness 3 mg/cm^2 and 6 mg/cm^2 Au, and for Au^{198} with 3 mg/cm^2 Au, 6 mg/cm^2 Au, 13 mg/cm^2 Au, and 20 mg/cm^2 Au. The electron spectra of Lu and Au contain conversion lines with electron energies 98 and 137 keV for Lu and 325 and ~ 400 keV for Au. In view of the fact that conversion electrons are unpolarized, their fraction in the spectrum must be taken into account in determining the expected scattered asymmetry. It turned out that this fraction could be determined, knowing the form of the β -spectrum of electrons

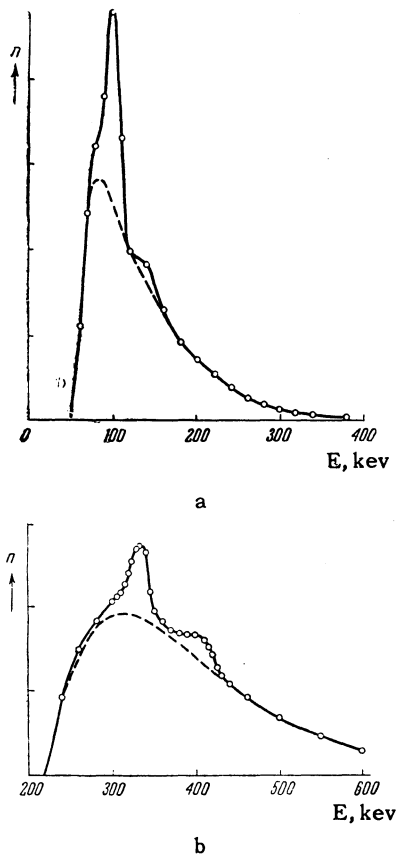


FIG. 3. Spectra of electrons undergoing double scattering and producing coincidences in the Geiger counters: a - Lu^{177} , $E_1 = 130$ keV, $\rho_1 = 1.0$ mg/cm² Al, $\tau_1 = 3.0$ mg/cm² Au; b - Au^{198} , $E_2 = 390$ keV, $\rho_2 = 5.2$ mg/cm² Al, $\tau_2 = 13$ mg/cm² Au. Solid lines and \circ - conversion electron spectra; dashed lines - spectra without conversion electrons.

undergoing multiple scattering, directly from experiment. By way of illustration, spectra of electrons from Lu^{177} ($\bar{E}_1 = 130$ keV) and Au^{198} ($\bar{E}_2 = 390$ keV), after multiple scattering through an angle of 90° and single scattering through 112.5° , are shown in Figs. 3a, b. The spectra of electrons from Re^{186} , Tm^{170} , and Sm^{153} practically coincide with the spectrum of Au^{198} without conversion electrons. The electron spectra of $\text{Sr}^{90} + \text{Y}^{90}$ were calculated.

Calculation of the Expected Value of Azimuthal Asymmetry

In order to determine the degree of longitudinal polarization of electrons in fractions of $-v/c$, it is necessary to compare the measured values with the expected values Δ_{th} of the azimuthal asymmetry in the scattering of electrons having longitudinal polarization equal to $-v/c$. Their energy spectrum n is known.

$$\bar{\Delta}_{\text{th}_i} = \frac{\sum_j \Delta_{\text{th}_j} n'_{ji}}{\sum_j n_{ji}} = 200 \frac{v}{c} \frac{\sum_j S_j \langle \sigma_{\perp} \rangle_{ji} \delta_{r_j} \delta_{Z_j} \delta_{s_j} (1 - \theta_j^2/2) n'_{ji}}{\sum_j n_{ji}},$$

where n'_{ji} is the distribution of electrons with respect to energy, excepting conversion electrons, in the i -th experiment, characterized by a filter of thickness ρ_i between counters and a thickness τ_i of the transforming scatterer I; n_{ji} is the same, but including conversion electrons; S_j is the value of the azimuthal asymmetry in the scattering of electrons of energy E_j , completely polarized in the transverse direction by mercury ($Z = 80$), taken from the table of Sherman;³ δ_{r_j} is the correction for the finite solid angle of the apparatus; δ_{Z_j} is the correction to the tabulated value S_j , connected with the fact that the scattering took place on gold ($Z = 79$); δ_{s_j} is the correction connected with the screening effect. (This correction was obtained by extrapolating the results of Mohr and Tassie⁶ to the energies of interest; the calculation of these corrections was carried out by K. A. Ter-Martirosian.) $(1 - \theta_j^2/2)$ is the depolarization in the source; θ^2 is the mean square angle for multiple scattering.⁵ The latter quantities are given in Table II as functions of the energy. $\langle \sigma_{\perp} \rangle_{ji}$ is the component of spin perpendicular to the trajectory of the electron of energy E_j , undergoing a 90° deflection as a result of multiple scattering in scatterer I of thickness τ_i . The value of this projection was calculated, using the Monte-Carlo method, by G. Adel'son-Vel'skii, A. Birzgal, and A. Kronrod on an electronic computer.* It contains a correction for depolarization of the electrons in scatterer I.

The depolarization of the electrons is due to the turning of the spin in the electric field of the nucleus. In the case where the multiple scattering of the electrons takes place in the plane formed by the initial and final trajectories of the electron in the scatterer, there is no depolarization (if only the trajectory is not a closed loop). If, in the process of scattering, the electron goes out of this plane, then there is depolarization.

Calculations showed that the turning of the spin of the electron in multiple scattering by the Coulomb field was about 5% less than the amount of turning obtained from the "condenser" formula

$$\varphi = \psi (1 - \sqrt{1 - v^2/c^2}).$$

*The authors are grateful to I. S. Bruk, director of the Laboratory of Control Machines of the Academy of Sciences, U.S.S.R., for the possibility of carrying out these calculations.

TABLE II

$E, \text{ keV}$	70	100	150	200	250	300	400	500	600	700	800	900	1000	1200	1400
v/c	0.48	0.55	0.63	0.63	0.74	0.77	0.83	0.86	0.89	0.91	0.92	0.93	0.94	0.95	0.96
S	0.38	0.39	0.40	0.41	0.40	0.39	0.37	0.35	0.33	0.31	0.29	0.28	0.25	0.22	0.17
$100 (\delta_r - 1)$	-5.2	-5.5	-6.2	-6.8	-7.3	-7.7	-8.1	-7.8	-7.1	-6.2	-5.1	-4.1	-3.0	-2.0	-1.5
$100 (\delta_z - 1)$	-2.3	-2.3	-2.2	-2.1	-2.0	-1.9	-1.8	-1.7	-1.7	-1.6	-1.5	-1.5	-1.4	-1.4	-1.4
$100 (\delta_s - 1)$	-11.0	-6.5	-1.3	0	0	0	0	0	0	0	0	0	0	0	0
$(1 - \frac{\sigma^*}{2})_{\text{Sr+Y}}$	0.89	0.94	0.97	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$(1 - \frac{\sigma^*}{2})_{\text{Tm}}$	0.93	0.97	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
$(\Delta_{\text{th}})_{\text{Sr+Y}}$	25	33	41	44	44	44	40	37	34	30	28	25	23	17	12
$(\Delta_{\text{th}})_{\text{Tm, Sm}}$	26	34	41	45	44	44	40	37	34	30	28	25	23	17	12
$(\Delta_{\text{th}})_{\text{Lu, Re}}$	28	35	42	45	44	44	40	37	34	30	28	25	23	17	12

A family of $\langle \sigma_{\perp} \rangle_{\text{ji}}$ vs. energy curves for electrons scattered by scatterers I of various thicknesses τ_i is given in Fig. 4.

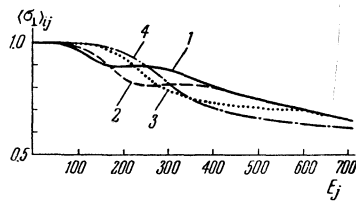


FIG. 4. Dependence of the perpendicular component of spin on the energy of the electron which is deflected by 90° from the original direction as a result of multiple scattering in scatterer I of thickness: 1 - $\tau_1 = 3.0 \text{ mg/cm}^2 \text{ Au}$; 2 - $\tau_2 = 6.0 \text{ mg/cm}^2 \text{ Au}$; 3 - $\tau_3 = 13.0 \text{ mg/cm}^2 \text{ Au}$; 4 - $\tau_4 = 20.0 \text{ mg/cm}^2 \text{ Au}$.

The details of the calculations will be published separately by their authors.

The expected values of the azimuthal asymmetry $\bar{\Delta}_{\text{th}}$ for Tm, Lu, Re, Sm, Au, and Sr+Y for various energies are given in Table I.

3. DISCUSSION OF RESULTS

The values of the longitudinal polarizations in units of $-v/c$

$$\langle \sigma \rangle_i / (-v/c) = \bar{\Delta}_{\text{corr}_i} / \bar{\Delta}_{\text{th}_i}$$

are given, as functions of energy, in Fig. 5. From these data it can be seen that the polarization of the electrons $\langle \sigma \rangle_i / (-v/c)$ for all elements studied does not depend upon energy within the limits of error. In Table III are listed the values $\langle \bar{\sigma} \rangle_i / (-v/c)$, averaged over energy, for the elements studied. In Fig. 6 are given the mean values $\langle \bar{\sigma} \rangle_i / (-v/c)$, as functions of the energy, for the Coulomb transitions in comparison with the polarization of electrons of Sr+Y.

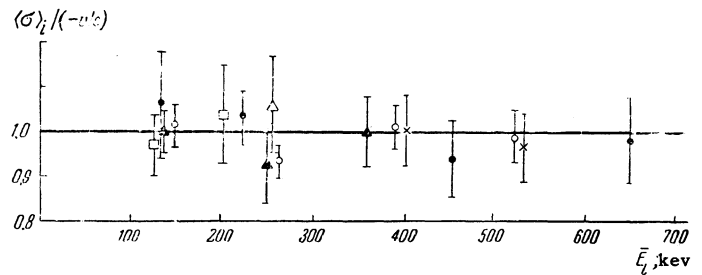


FIG. 5. Longitudinal polarization of the electrons $\langle \sigma \rangle_i / (-v/c)$ for various energies: \bullet - $\text{Sr}^{90} + \text{Y}^{90}$, \circ - Tm^{170} , \blacktriangle - Sm^{158} , \square - Lu^{177} , \times - Au^{198} , \triangle - Re^{186} .

TABLE III. Values of the longitudinal electron polarization $\langle \bar{\sigma} \rangle / (-v/c)$ averaged over energy. (Statistical errors are shown. The errors, taking into account systematic ones, are shown in parentheses.)

Element	$\langle \bar{\sigma} \rangle / (-v/c)$
$\text{Sr}^{90} + \text{Y}^{90}$	$0.99 \pm 0.037 (\pm 0.05)$
Tm^{170}	$0.98 \pm 0.015 (\pm 0.03)$
Sm^{158}	$0.98 \pm 0.037 (\pm 0.05)$
Lu^{177}	$1.00 \pm 0.058 (\pm 0.06)$
Re^{186}	$1.06 \pm 0.106 (\pm 0.11)$
Au^{198}	$0.97 \pm 0.055 (\pm 0.06)$
Average $0.98 \pm 0.01 (\pm 0.03)$	

From all of these data it is possible to draw the following conclusions.

1. The longitudinal polarization of the electrons of all measured elements is the same within an accuracy of 2 to 11%. (The errors given do not include systematic errors, which are the same for all elements.)

2. The longitudinal polarization of the electrons

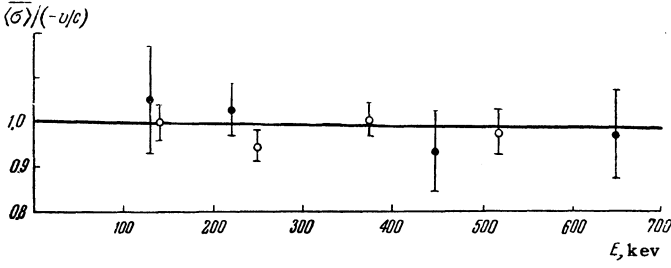


FIG. 6. Energy dependence of the longitudinal polarization of the electrons $\langle \sigma \rangle / (-v/c)$ for Coulomb transitions: ● - $Sr^{90} + Y^{90}$, ○ - Coulomb transitions.

is equal to $-v/c$ to within an accuracy of $\sim 3\%$ for the mean value over all elements.

3. The longitudinal polarization of the electrons from the Coulomb transitions does not depend on the energy in the range from 100 to 600 keV, to an accuracy of 4 to 7%.

The longitudinal polarization for first-forbidden Coulomb transitions can be given in the following form (see Ref. 7):

$$\begin{aligned} W \langle \sigma_E \rangle / (v/c) &= 2\text{Re} \{ (C_S C_S^* - C_V C_V^*) |M_F|^2 \\ &+ (C_T C_T^* - C_A C_A^*) (|M_{GT}|^2 + |M'_{GT}|^2) + \frac{Z}{137E(v/c)} [(C_T C_V^* \\ &+ C'_T C'_V) M_F^* M_{GT} - (C_S C_A^* + C'_S C'_A) M_F M_{GT}^*] \} \\ &+ 2\text{Im} \{ - (C_T C_S^* - C_A C_V^*) M_F^* M_{GT} + (C_T^* C_S - C_A^* C_V) \\ &\times M_F M_{GT}^* + \frac{Z}{137E(v/c)} [(C_S C_V^* + C'_S C'_V) |M_F|^2 \\ &+ (C_T C_A^* + C'_T C'_A) (|M_{GT}|^2 + |M'_{GT}|^2)] \}; \\ W &= (|C_T|^2 + |C'_T|^2 + |C_A|^2 + |C'_A|^2) (|M_{GT}|^2 + |M'_{GT}|^2) \\ &+ (|C_S|^2 + |C'_S|^2 + |C_V|^2 + |C'_V|^2) |M_F|^2 \\ &+ 2\text{Im} [(C_T^* C_S + C'_T C'_S + C_A^* C_V + C'_A C'_V) M_F^* M_{GT}^*] \\ &+ (2\gamma_1/E) \text{Re} [(C_S C_V^* + C'_S C'_V) |M_F|^2 + (C_T C_A^* + C'_T C'_A) \\ &\times (|M_{GT}|^2 + |M'_{GT}|^2)] + (2\gamma_1/E) \text{Im} [(C_S C_A^* + C'_S C'_A) \\ &\times M_F M_{GT}^* - (C_T C_V^* + C'_T C'_V) M_F^* M_{GT}^*], \end{aligned}$$

where E is the total electron energy in units of mc^2 ; $\gamma_1 = \sqrt{1 - (Z/137)^2}$; S, V, T, A, in the subscripts refer to the scalar, vector, tensor and axial-vector variants, respectively.

From the data of our experiment we can set the expression $\langle \sigma_E \rangle$ equal to $-v/c$, independently of energy and independently of the magnitudes of the matrix elements (in so far as the polarization of electrons for the measured elements is the same, and different elements should have different matrix elements). We then obtain 9 equations for the coupling constants

$$|C_S + C'_S|^2 + |C_V - C'_V|^2 = 0, \quad (1)$$

$$|C_T + C'_T|^2 + |C_A - C'_A|^2 = 0, \quad (2)$$

$$\text{Re}(C_S C_V^* + C'_S C'_V) = 0, \quad (3)$$

$$\text{Re}(C_T C_A^* + C'_T C'_A) = 0, \quad (4)$$

$$\text{Im}(C_S C_V^* + C'_S C'_V) = 0, \quad (5)$$

$$\text{Im}(C_T C_A^* + C'_T C'_A) = 0, \quad (6)$$

$$\begin{aligned} \text{Im}(C_T C_S^* - C_S C_T^* + C_V C_A^* - C_A C_V^* + C_T C_S^* \\ - C_T^* C_S + C_A C_V^* - C_A^* C_V) = 0, \quad (7) \end{aligned}$$

$$\text{Im}(-C_S C_A^* - C'_S C'_A + C_T C_V^* + C'_T C'_V) = 0, \quad (8)$$

$$\text{Re}(-C_S C_A^* - C'_S C'_A + C_T C_V^* + C'_T C'_V) = 0. \quad (9)$$

It is easy to see that the maximum number of relations, which can be determined from experiments with measurement of longitudinal polarization of electrons from unpolarized nuclei, have been obtained. Equations (3) and (4) were obtained earlier (absence of Fierz terms). Equations (1) and (2) were obtained in experiments measuring longitudinal polarization (accuracy of measurement 10 – 20%) in allowed and other transitions without measurement of the energy dependence of the polarization.⁸

From Eqs. (1) and (2) follow the relations

$$C_S = -C'_S, \quad C_T = -C'_T, \quad C_V = C'_V, \quad C_A = C'_A.$$

If these relations are valid, then this is the maximum information that can be obtained from the magnitude of longitudinal polarization of electrons from unpolarized nuclei. In fact, all equations are identically zero with this choice. However, the accuracy with which these relations can be obtained from Eqs. (1) and (2) is not high. In fact, let us take, for simplicity, only the tensor variant. Then we have $|C_T + C'_T|^2 = \delta (|C_T|^2 + |C'_T|^2)$, where δ is the difference of the polarization of the electrons from $-v/c$. In our case this represents an accuracy of measurement equal to 0.03.

In first approximation $C_T = -C'_T(1 + \alpha)$, $\alpha^2 = 2\delta = 0.06$; $\alpha \approx 0.25$. Thus, the relation between the constants can be determined from Eqs. (1) and (2) to an accuracy no better than 20 to 30%.

We consider another possibility. Let us assume that the absolute values of C and C' are equal:

$$|C| = |C'|$$

and $C = -C'$; this indeed occurs in the model of the two component neutrino, but $|C_V|$ and $|C_A|$ are small, for otherwise there would be a contradiction to known experiments.⁸ We assume, for simplicity, that there are only the tensor and vector variants of interaction. Then, for the allowed transitions, which lead only to Eqs. (1) and (2), we obtain

$$\frac{-|C_T|^2 |M_{GT}|^2 + |C_V|^2 |M_F|^2}{|C_T|^2 |M_{GT}|^2 + |C_V|^2 |M_F|^2} = -\frac{1 - |\epsilon|^2}{1 + |\epsilon|^2}$$

$$\approx (1 - 2|\rho|^2) = -1 + \delta,$$

$$|\rho| = \frac{|C_V||M_F|}{|C_T||M_{GT}|} \approx \sqrt{\frac{\delta^-}{2}} \approx 0.2,$$

where $\delta = 0.1$ is the best accuracy with which, at the present time, the polarization of electrons for the allowed transitions has been measured.

The energy dependence of the polarization of electrons in Coulomb transitions, as already stated, is also given by Eqs. (3) to (9). It turns out that the Eqs. (3) to (6), (8), and (9) are very sensitive to the relations between the constants. From these equations it follows that the following relations should hold between the coupling constants

$$C_T/C_T' = C_S/C_S' = -C_V/C_V' = -C_A/C_A',$$

and from the fact that the polarization of electrons, for example, from Sr^{90} (pure Gamow-Teller transition) is negative, and of the positrons from Cl^{34} (pure Fermi transition) is positive,⁹ it follows, under the assumption $|C| = |C'|$, that

$$C_T = -C_T', \quad C_S = -C_S', \quad C_V = C_V', \quad C_A = C_A',$$

with high accuracy.

In fact, in this same example, we have for the polarization of electrons in the case of a Coulomb transition

$$\frac{-|C_T|^2|M_{GT}|^2 + |C_V|^2|M_F|^2 \pm [2Z/137E(v/c)]C_T C_V^*|M_{GT}||M_F|}{|C_T|^2|M_{GT}|^2 + |C_V|^2|M_F|^2}$$

$$= -\frac{1 - |\rho|^2 \pm [2Z/137E(v/c)]\rho}{1 + |\rho|^2} \approx -1 \pm 1.5\rho = -1 + \delta.$$

from which

$$\rho = C_V^*|M_F|/C_T^*|M_{GT}| \approx 0.03, \text{ where } Z/137 \approx 0.5,$$

$$E \approx 1.2, \quad v/c \approx 0.6; \quad \delta \approx 0.05.$$

Since the polarization of electrons of all of the Coulomb transitions measured by us is the same, and it is unlikely that the ratio $|M_F|/|M_{GT}|$ is small for all of these, then it follows that the fraction of the vector variant, for which $C_V = -C_V'$ is very small. This is also valid with respect to the axial-vector variant of the interaction.

On the basis of the above, we come to the conclusion that the results of measurement of the longitudinal polarization of electrons in Coulomb transitions as a function of the energy, which we obtained in this work, indicate that most probably the following relations between the coupling constants in β -decay are satisfied

$$C_T = -C_T', \quad C_S = -C_S', \quad C_V = C_V', \quad C_A = C_A',$$

which correspond to the model of the two-component electron. If the vector and axial-vector constants or scalar and tensor constants are pair-wise

equal to zero, the present experiment agrees also with the model of the two-component neutrino.

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