Measurements on the Longitudinal Polarization of Beta Rays from P^{32}, Y^{90}, Pr^{144}, Au^{198}, and Bi^{210} (RaE)

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The polarization of the beta rays from five negatron emitters has been studied by the method of Møller scattering in a magnetized NiFe foil. The scattered incident electron and the recoil electron from the target foil are detected in coincidence by two scintillation counters. The difference between the coincidence counting rates for the two directions of foil magnetization divided by the average rate gives a quantitative measure of the longitudinal polarization of the incident beta rays. Our experimental results are as follows: P^{32}, $P=-(0.94\pm0.06)v/c$; Y^{90}, $P=-(0.86\pm0.06)v/c$; Pr^{144}, $P=-(0.90\pm0.22)v/c$; Au^{198}, $P=-(0.98\pm0.18)\times v/c$; and for RaE, $P=-(0.69\pm0.10)v/c$. The first four results may indicate a polarization magnitude slightly less than full $-v/c$. The differences are, however, within the range of possible systematic errors. The result obtained with RaE is significantly lower than the average of the other four results. This indicates a departure from $-v/c$ polarization for this nuclide.

I. INTRODUCTION

A VARIETY of experimental techniques has been used to demonstrate the longitudinal polarization of beta rays from randomly oriented nuclei. The longitudinal polarization of these beta rays is a consequence of the nonconservation of parity in beta decay. The polarization predicted theoretically depends on the nature of the beta interaction. The dominance of the vector and axial vector interactions now seems well established experimentally.[1] Assuming the two-component neutrino theory[2] the polarization is, in first approximation,[3] $P=\pm v/c$, the sign being opposite for positrons and negatrons. Experimental studies have shown that negative beta particles have a longitudinal polarization in the opposite direction to their motion, while the longitudinal polarization of positive beta particles is along their direction of motion. Although a few of the early experiments suggested a polarization of considerably less than v/c, e.g., for Au^{198} and Ga^{66},[4–6] the majority of the experimental measurements are consistent with a longitudinal polarization magnitude of v/c in both positive and negative beta decay, to within the experimental errors of 10–20%.[7]

Three methods have been used in studying the longitudinal polarization of negative beta rays. These are (a) conversion from longitudinal to transverse polarization (analyzer or nuclear scattering) followed by a Mott scattering analysis of the transverse polarization,[8–10] (b) measurement of the circular polarization of the bremsstrahlung by Compton scattering in magnetized iron,[11] and (c) scattering of beta rays from longitudinally polarized electrons in a thin magnetized foil (Møller scattering, see Frauenfelder *et al.*).[12] Method (a) requires an electrostatic analyzer to obtain quantitative results and is most readily applied to low-energy electrons. Method (b) is suitable only for a few high-energy beta emitters which do not emit energetic gamma rays. Method (c) can be used to study beta rays over a wide range of energy and can be made insensitive to accompanying gamma rays. Furthermore this method measures directly the longitudinal polarization of the beta particle.

Initially, studies were made in this laboratory of the circular polarization of the bremsstrahlung produced by negative beta particles stopping in a uranium absorber. The apparatus used was similar to that of Goldhaber, Grodzins, and Sunyar.[11] In the case of Y^{90} the effect observed is in agreement with that expected from beta particles of longitudinal polarization $-v/c$. Attempts to study the circular polarization of the bremsstrahlung produced by beta rays from Pr^{144} and K^{42} were unsuccessful. The difficulties encountered resulted from pileup of low-energy gamma-ray pulses in the electronic circuitry and the presence of weak gamma rays with energies approaching those of the beta spectrum end point: a 2180-kev γ ray (0.8%) for Pr^{144} and a 2760-kev γ ray from Na^{24} contaminant in the case of K^{42}.

This paper describes an investigation of the longitudinal polarization of the beta rays from P^{32}, Y^{90}, Pr^{144}, Au^{198}, and Bi^{210}(RaE) carried out using the Møller scattering technique, method (c). Preliminary results

[1] Herrmannsfeldt, Burman, Stähelin, Allen, and Braid, Phys. Rev. Letters, **1**, 61 (1958).
[2] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957); A. Salam, Nuovo cimento **5**, 299 (1957); L. Landau, Nuclear Phys. **3**, 127 (1957).
[3] G. E. Lee-Whiting, Can. J. Phys. **36**, 252 (1958).
[4] Frauenfelder, Bobone, von Goeler, Levine, Lewis, Peacock, Rossi, and De Pasquali, Phys. Rev. **107**, 909 (1957).
[5] H. de Waard and O. J. Poppema, Physica **23**, 597 (1957).
[6] Frauenfelder, Hanson, Levine, Rossi, and De Pasquali, Phys. Rev. **107**, 910 (1957).
[7] C. S. Wu, *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 359.
[8] Frauenfelder, Babone, von Goeler, Levine, Lewis, Peacock, Rossi, and De Pasquali, Phys. Rev. **106**, 386 (1957).
[9] Cavanagh, Turner, Coleman, Gard, and Ridley, Phil. Mag. **2**, 1105 (1957).
[10] de-Shalit, Kuperman, Lipkin, and Rothem, Phys. Rev. **107**, 1459 (1957).
[11] Goldhaber, Grodzins, and Sunyar, Phys. Rev. **106**, 826 (1957).
[12] Frauenfelder, Hanson, Levine, Rossi, and De Pasquali, Phys. Rev. **107**, 643 (1957).

were reported at the January, 1958, New York American Physical Society Meeting[13] and a brief account has been submitted to C.I.P.N. (Conférence Internationale de Physique Nucléaire, Paris, July, 1958). The beta rays from all of these negatron emitters were observed to have a negative helicity.

The magnitudes of the polarizations observed with sources of P^{32}, Y^{90}, Pr^{144}, and Au^{198} are the same within errors and are slightly less than $|v/c|$. The differences from $-v/c$ polarization are within the range of possible systematic errors and do not necessarily imply a departure from $P=-v/c$.

The RaE result is distinctly lower than the average for the other four nuclides. It is difficult to account for this discrepancy on the basis of possible systematic errors. We feel that this low result for RaE is significant and that it indicates a departure from v/c polarization for this nuclide.

II. THEORY OF THE METHOD

When an electron strikes a thin foil the two principal scattering processes are Mott (or nuclear) scattering and Møller (or electron-electron) scattering. The cross section for Mott scattering is considerably larger than that for the electron-electron scattering, and hence it is difficult to detect variations in the electron-electron scattering cross section by observing directly the individual scattered electrons. However, the target electron in the Møller scattering case is ejected from the foil. By observing both the deflected incident electron and the recoil target electron in coincidence, it is possible to distinguish scattering events of the electron-electron type.

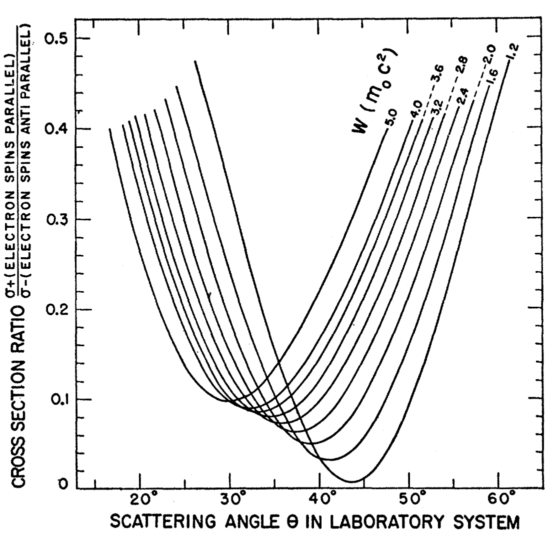

FIG. 1. Theoretical scattering cross-section ratios for longitudinally polarized electrons incident upon target electrons which are polarized parallel or anti-parallel to the direction of incidence. W is the total energy of the incident electrons in units of m_0c^2.

[13] Geiger, Ewan, Graham, and MacKenzie, Bull. Am. Phys. Soc. Ser. II, 3, 51 (1958).

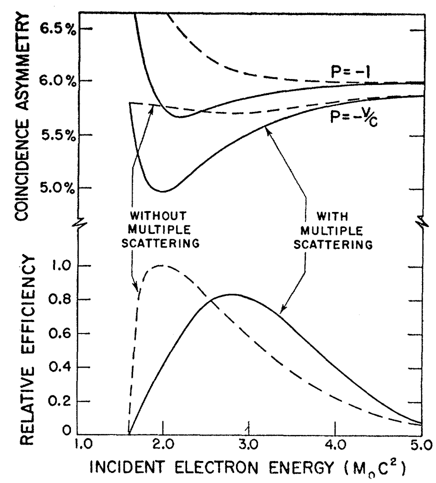

FIG. 2. Predicted effects for monoenergetic electrons in the experimental arrangement used. In the upper part coincidence asymmetries are plotted for full polarization ($P=-1$) and a $-v/c$ polarization ($P=-v/c$). The broken lines were computed without taking multiple scattering into account. The solid curves are the result of the approximate graphical analysis discussed in the text.

Electron-electron scattering of relativistic Dirac particles was studied theoretically by Møller[14] several years ago. More recently, calculations of the dependence of this cross section on the relative spin orientation of the incident and scattering electrons have been made by Bincer[15] and by Ford and Mullin.[16] The predicted variation of (σ_+/σ_-) with scattering angle in the laboratory system is shown in Fig. 1 for a series of incident electron energies. The angle corresponding to the minimum of each of these curves is that at which the electrons come off symmetrically with respect to the incident electron direction; this is the condition for the incident electron kinetic energy to be shared equally.

From a knowledge of the geometrical arrangement of the apparatus (see Figs. 3 and 4) and of the number of polarized target electrons in the scattering foil, it is possible to calculate the expected asymmetry in the true coincidence counting rate for the two directions of foil magnetization with longitudinally polarized electrons incident on the foil. Calculations have been made for monoenergetic incident electrons, taking into account (a) source size and the angular spread of the incident beam, (b) the angular range and solid angles subtended by the counters, (c) the energy selection in the counters, 150–1500 kev, (d) the variation of the Møller scattering cross section with angle, and (e) the variation of σ_+/σ_- with angle. The results of these calculations, which take no account of the multiple scattering in the Deltamax foil, are given in Fig. 2 for incident monoenergetic beta particles having a longi-

[14] C. Møller, Ann. Physik 14, 531 (1932).

[15] A. M. Bincer, Phys. Rev. 107, 1434 (1957).

[16] G. W. Ford and C. J. Mullin, Phys. Rev. 108, 477 (1957). See also K. Nagy and I. Farkas, Nuovo cimento 7, 570 (1958); J. M. C. Scott, Phil. Mag. 2, 1472 (1957).

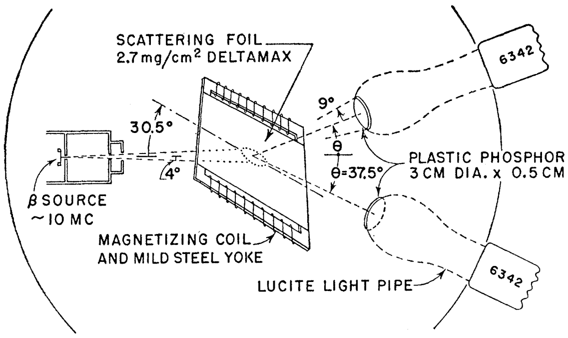

FIG. 3. Schematic diagram of Møller scattering apparatus.

tudinal polarization of $-v/c$. Appreciable multiple scattering of the electrons does occur in the 2.65-mg/cm² scattering foil used in our experiments. The total energy loss of the electrons in passing through the foil is small (5–30 kev) and has a negligible effect on the coincidence counting rate asymmetries predicted for the present experiments. The angular deflections which the electrons may undergo, in particular for those of lower energies, can be large, e.g., for 150-kev electrons the $1/e$ half-width of the Gaussian distribution is $\vartheta_\omega \sim 34°$.[17] This smearing of the electron direction reduces the asymmetries expected for incident electrons of low energy.

Graphical means were used in determining this reduction in expected coincidence counting rate asymmetry as a function of the incident electron energy. In order to simplify the computation the distribution in direction produced by multiple scattering in the foil was approximated by a rectangular distribution having an angular half-width equal to the $1/e$ half-width given by the Molière scattering theory.[17] The calculations were done by first considering the influence of the multiple scattering on the outgoing scattered electrons for a series of incident electron energies and incident electron directions. A weighted integration over the direction of incidence was then performed to take account of both the finite collimator aperture and the multiple scattering of the incident electrons in the foil. The expected asymmetries calculated in this way for monoenergetic incident electrons of polarization $-v/c$ are shown in Fig. 2. The relative detection efficiency of the apparatus as a function of incident electron energy is also given. It is evident that while the multiple scattering reduces the expected asymmetry from low-energy beta rays, it also reduces the detection efficiency of the apparatus at these energies.

An integration over incident electron energy, weighted in proportion to the product of the beta-spectrum and the detection efficiency of the apparatus, is necessary to obtain the experimental asymmetry expected for each nuclide.

[17] H. Bethe and J. Ashkin, in *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons Inc., New York, 1953), p. 289.

III. APPARATUS

A schematic diagram of the apparatus used in the present experiment is shown in Fig. 3. The electron beam from the source passed through a simple collimator giving an angular half aperture of 4° from a point source. The electrons were scattered from a 2.65-mg/cm² Deltamax foil inclined at 30.5° to the beam direction. The foil was magnetized along its length by the simple magnetic frame shown and the direction of magnetization could be reversed by reversing the current to the magnetizing coil. The two counters used to detect the electron pairs consisted of plastic phosphors cemented to Lucite light pipes which were shaped to give high light-collecting efficiency and were coupled to 6342 photomultipliers. The output pulses from the counters were fed into a fast-slow coincidence circuit[18] of resolving time $2\tau \sim 3\times10^{-8}$ sec. The two counters were placed symmetrically about the electron beam direction at plus and minus 37.5°. Each detector covered an angular range of 28.5°–46.5°. The counter pulse height windows were set to record only electrons of energy between 150 and 1500 kev for all the experiments described in this paper.

Figure 4 is a multiple-exposure photograph of the apparatus with vaccum lid removed. This shows the beam catcher which helped to minimize scattering of electrons from the vacuum chamber walls. The collimator was positioned by centering the light beam so that it passed midway between the counters. This alignment was checked using beta-ray sources and photographic film both in the position of the Deltamax foil and also at the mouth of the beam catcher. The counter angles were measured using a mirror mounted on a simple goniometer whose axis intersected the target area of the electron beam on the Deltamax foil.

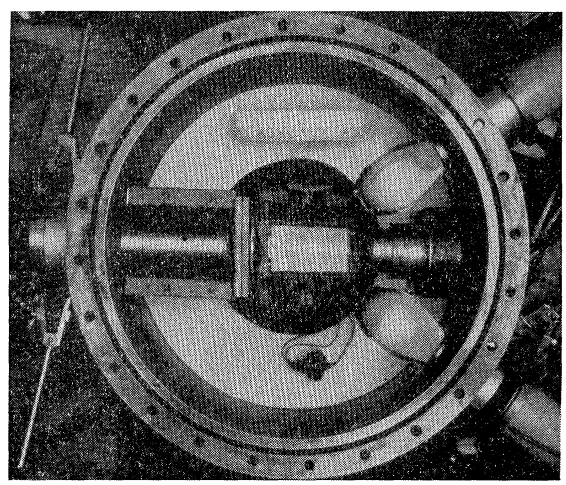

FIG. 4. Multiple exposure photograph of the apparatus with vacuum-tight lid removed. A frosted lamp placed at the source position reveals the beam direction (using smoke with foil removed) and the region of impact on the Deltamax foil (using translucent paper).

[18] Bell, Graham, and Petch, Can. J. Phys. 30, 35 (1952).

IV. SOURCE PREPARATION

Sources with strengths of several millicuries were required for these Møller scattering experiments. Circular spot sources of 3-mm diameter were used; this diameter provides a reasonable compromise between coincidence counting rate and polarization sensitivity which decreases with increasing beam aperture. In order to minimize the energy degradation and depolarization of the beta rays which results from scattering in the source material and backing these were made as thin as practicable in each case. A backing of 2.1-mg/cm^2 Al foil was used for a majority of the sources, the remainder being prepared on 800-$\mu g/cm^2$ Al leaf. Most of the sources were given a thin coat of "Quick Spray" plastic before use to prevent the spread of contamination in the apparatus. Brief descriptions of the materials and methods used in the source preparations are given in the following.

P^{32}

These sources were prepared from "carrier-free" P^{32} supplied by the Radiochemical Center, Amersham. No additional purification was attempted. The solutions as received were evaporated to dryness with excess HNO_3 to eliminate HCl. The activity was taken up in 2λ of distilled water for deposition on the aluminum backing (one $\lambda = 10^{-6}$ liters). The two sources used had strengths of ~40 mC and thicknesses of ~1.0 mg/cm^2.

Y^{90}

Carrier-free Y^{90} was prepared by separating the Y^{90} from its Sr^{90} parent with a small cation exchange column. HCl was eliminated from the carrier free material by evaporation with HNO_3 and sources were prepared by direct pipetting of the activity in 2λ of H_2O. In the carrier-free preparations, the organic residues were sufficiently great that they limited the specific activity of the sources. The strengths of the three sources used were in the range 30–100 mC and the surface densities were estimated to be ~1 mg/cm^2.

Pr^{144}

The 17-minute half-life of Pr^{144} made it impractical to use sources of the separated activity. Instead, a source of Pr^{144} in equilibrium with its 285-day Ce^{144} parent was prepared from "carrier-free" Ce-Pr^{144} obtained from the Oak Ridge National Laboratory. This material contained a disappointingly large weight of inactive cerium. After the chemical separation of iron and other impurities, spectrographic analysis revealed only traces of barium and aluminum and 0.5% calcium impurities. The source was prepared by homogeneously precipitating cerium hydroxide, slurrying the precipitate with a small volume of water and depositing it on the source mount. The source strength was ~5 mC and its estimated thickness was ~5 mg/cm^2.

Au^{198}

Two 3-mm diam disks of 3.5 mg/cm^2-gold leaf were irradiated in the N.R.X. reactor at fluxes $>10^{13}$ neutrons/cm^2/sec to give Au^{198} activities of ~20 mC. These disks were mounted on 2.1-mg/cm^2 Al foil backing. The Au^{199} activity produced in these irradiations is estimated to be $<5\%$ of the Au^{198} disintegration rate.[19]

RaE

(Bi^{210}) RaE was separated, carrier-free, from both its parent Pb^{210} and its daughter Po^{210} with a small anion exchange column in order to minimize the danger of long-lived contamination of the apparatus. The RaE, eluted in concentrated HCl, was converted to the nitrate and dissolved in 2λ of water for deposition on the source mount. The three sources had initial strengths of 10–20 mC and estimated thicknesses of ~1 mg/cm^2.

Since a low value for the polarization could result from scattering in the source material[9] the thicknesses of six deposited sources were measured. This was done by measuring the air range of a 2-mm diam beam of ThC′ (8.58 Mev) alpha rays with and without the source material in the beam. Four of the sources had surface densities of <1 mg/cm^2 as had been estimated from the source preparation techniques. One P^{32} source had a surface density of 2.6 mg/cm^2 and one RaE source 3.7 mg/cm^2. The strongest RaE source, however, was only 0.9 mg/cm^2 thick.

V. EXPERIMENTAL PROCEDURE

The data of these experiments were accumulated using automatic programming and recording. Counting intervals of both two and five minutes have been used. The program provided for measurement of both the total and the random coincidence rates for the two directions of foil magnetization. The random coincidence rates were determined by delaying by 30 mμsec the pulses from one of the counters. The detected electrons contributing to the measured coincidence rates were restricted to those of energies from 150 to 1500 kev by pulse-height selection. The channel counting rate from each counter was continuously monitored by a counting-rate meter and pen recorder.

Experiments were carried out with the Deltamax scattering foil replaced by both Cu and Al foils of comparable surface density in order to measure the asymmetry in the coincidence rates resulting from deflection of the electrons by the magnetizing field. Initially asymmetries of several percent were observed with a magnetizing field of ~5 oersteds. The asymmetry was reduced to $(0.5\pm0.5)\%$ by careful alignment of the apparatus as discussed in Sec. III. In the Deltamax scattering measurements a magnetizing field of 0.5 oersted was used and no significant portion of the observed asymmetries can be attributed to deflection

[19] Bell, Graham, and Yaffe, Can. J. Phys. 33, 457 (1956).

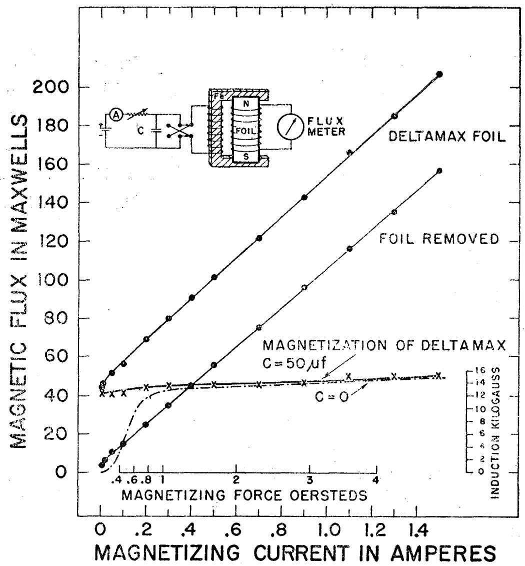

FIG. 5. Measurement of the foil magnetization using a Grassot Fluxmeter as shown in the insert. This fluxmeter was calibrated to 0.7% accuracy using a 275-turn, 2.94-in. diam flux coil, a pair of 61.3-cm diam Helmholz coils 30.7 cm apart, and a Weston Laboratory standard ammeter. The closed circles are the data taken with and without the Deltamax foil in place using a surge condenser, $C=50$ μf. The crosses are the differences and give the Deltamax contribution. The broken line shows the Deltamax magnetization without a surge condenser in the circuit.

of the electrons by the magnetizing field. The coincidence counting rates observed with the Al, Cu, and Deltamax foils were comparable. The individual counting rates, however, showed the Z dependence characteristic of the Mott scattering cross section.

Corrections to the observed coincidence counting rate asymmetries were made for coincidence counts which did not arise from Møller scattering in the Deltamax foil. In general these were due to scattering from the edge of the collimator slits and contributed 4–5% of the observed coincidence counting rate. In the case of Au^{198} and Pr^{144} an additional correction had to be applied for the observed coincidence rate between gamma-rays and Mott scattered electrons. This was measured experimentally by placing an Al absorber in front of one of the counters to remove the beta rays. The lead shielding surrounding the source was sufficient to markedly attenuate the intense 411-kev gamma ray of Au^{198} but was less effective for the higher energy gamma rays which accompany the weak beta branches ($\sim$2%) in the Pr^{144} decay and 6% of the coincidence counting rate resulted from beta-gamma coincidences for both Au^{198} and for Pr^{144}.

The surface density of the Deltamax scattering foil was determined in the following manner. The uniformity was first examined using an $\sim$7-mm diam beam of beta rays from a Ca^{45} source and a proportional counter. With this beta thickness gauge, the counting rate changed $\sim$16% per mg of absorber. The annealed foil was found to have a surface density which was uniform to $\sim$1%. The central region was carefully compared with a similar piece of unannealed foil. The counting rates were identical to $(0.1\pm0.3)\%$. A 95-cm² piece of the unannealed foil was weighed to determine its surface density. From these measurements we conclude that the annealed foil had a surface density of 2.65 ± 0.03 mg/cm².

The magnetization of the Deltamax foil was measured with the foil *in situ* in the scattering apparatus. The foil was oriented perpendicularly to the earth's magnetic field and a small steady field applied to maintain the magnetization. The momentary large field necessary to reverse the direction of foil magnetization was produced from the discharge of a condenser through the magnetizing coils. The variation of the magnetization of the foil with magnetizing current is shown in Fig. 5. The dashed curve shows the variation when the impulse condenser was disconnected. The fraction of the electrons which are polarized was deduced from the measurements of Fig. 5, and the surface density and width of the foil. At the 0.5-oersted magnetizing field used in the Møller scattering measurements, the fraction of electrons polarized, allowing 5%[20] for the orbital contribution to the magnetization, was $(4.59\pm0.14)\%$ and the induction in the foil was $B=12\,900\pm300$ gauss.

VI. RESULTS

The experimental results of the Møller scattering measurements are summarized in column 4 of Table I and plotted in Fig. 6. The experimental asymmetries listed, for each nuclide except Pr^{144}, are based on the data accumulated using several sources. The results obtained with the individual sources are in each case statistically consistent with that presented in this table. The errors given for these observed asymmetries

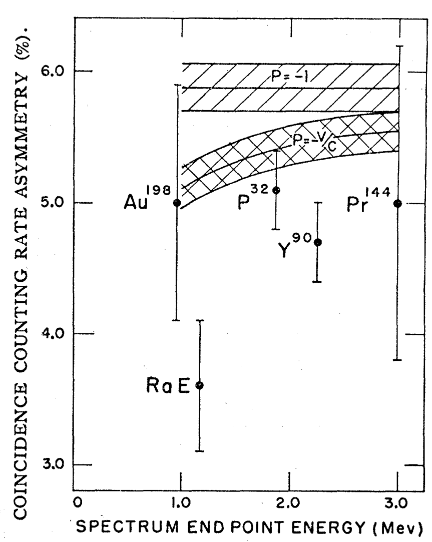

FIG. 6. Plot of the polarization results as a function of beta-spectrum end-point energy.

[20] S. J. Barnett and G. S. Kenny, Phys. Rev. 87, 723 (1952).

TABLE I. Experimental results.

Source	Transition	Spectrum end point (Mev)	Experimental asymmetry δ	Predicted asymmetry $P=-v/c$	Predicted asymmetry $P=-1$	Polarization
Au^{198}	$2-\rightarrow 2+$	0.959	5.0 ± 0.9[a]	5.1 ± 0.15[b]	5.9 ± 0.18[b]	$-(0.98\pm0.18)v/c$
RaE	$1-\rightarrow 0+$	1.17	3.6 ± 0.5	5.2 ± 0.16	5.9 ± 0.18	$-(0.69\pm0.10)v/c$
P^{32}	$1+\rightarrow 0+$	1.71	5.1 ± 0.3	5.4 ± 0.16	5.9 ± 0.18	$-(0.94\pm0.06)v/c$
Y^{90}	$2-\rightarrow 0+$	2.27	4.7 ± 0.3	5.47 ± 0.16	5.9 ± 0.18	$-(0.86\pm0.06)v/c$
Pr^{144}	$0-\rightarrow 0+$	2.99	5.0 ± 1.2	5.55 ± 0.17	5.9 ± 0.18	$-(0.90\pm0.22)v/c$

[a] These are the statistical standard deviations based on the number of counts.
[b] The 3% uncertainty associated with these predicted asymmetries allows only for the uncertainty in the fraction of the target electron spins which are polarized. Allowance has been made for a 5% orbital contribution to the magnetization (Barnett, reference 20).

are the statistical standard deviations based on the number of counts accumulated. The predicted asymmetries for both the $-v/c$ and full negative longitudinal polarization cases are given in columns 5 and 6 of Table I. These include allowance for the effects of multiple scattering in the Deltamax foil as discussed in Sec. II. The errors listed for the predicted values represent only the uncertainties in the measurement of the surface density, width, and magnetization of the Deltamax foil. In the final column of this table the observed asymmetries are compared with those expected in the case of a v/c polarization of the beta rays.

VII. DISCUSSION

With the exception of the RaE result, the observed asymmetries are consistent with the results predicted for the $-v/c$ beta polarization. The approximations made in the multiple scattering calculations, i.e., the neglect of energy loss in the foil and the rectangular angular distribution assumed, may be responsible for these measured asymmetries all falling on the low side of the predicted values. Furthermore, scattering in the sources which, in general, had surface densities of ~ 2 mg/cm^2 may have somewhat depolarized the beta rays which would reduce the measured asymmetries.[9]

In Table II the present results are compared with those of other studies of the polarization of the beta rays from these nuclides. The polarization is expressed as the ratio of the effect experimentally observed to that expected from beta rays of $+v/c$ longitudinal polarization. The assigned uncertainty in the polarization in many cases makes no allowance for systematic uncertainties and is simply the statistical error in the effect observed, based on the number of counts. It now appears that some of the early polarization values reported were low because of experimental effects whose importance was not fully realized at the time.[21,22] These include the importance of symmetrical alignment, source thickness, and unwanted effects due to accompanying gamma rays.

The measurement of the longitudinal polarization of the beta rays from Au^{198} reported in this paper supports a $-v/c$ polarization of these beta rays. This agrees with the recent result of Benczer-Koller *et al.*[23] who studied only the most energetic of these beta rays and the result of Cavanagh *et al.*[9] who examined the polarization of 128-kev beta rays from Au^{198} by the Mott scattering method.

The experimental studies to date on the polarization of beta rays from P^{32} all support $P=-v/c$ for this decay. In this case one is free from the effects of gamma rays.

The measurements of the beta polarization from a $Sr^{90}-Y^{90}$ source by Langevin-Joliot *et al.*[24] are considerably below the v/c value. These authors attribute this discrepancy to backscattering in the $Sr^{90}-Y^{90}$ source used. The result of the work presented in this paper on Y^{90} is in statistical agreement with the $-v/c$ results obtained by Alikhanov *et al.*[25] and Benczer-Koller *et al.*[23] However, it may indicate a small departure from full $-v/c$ polarization.

While the Pr^{144} measurements have rather large statistical uncertainties, the results of the present investigation are in good agreement with the earlier observations of Frauenfelder *et al.*[12] and are consistent with full $-v/c$ polarization. It has been suggested by Berestetsky *et al.*[26] that a deviation from $P=-v/c$ in the case of $0-$ to $0+$ beta decays can in principle be used to determine the pseudoscalar contribution. It should be noted, however, that pure axial vector interaction accounts for the experimentally observed spectrum shape of the dominant $0-$ to $0+$ Pr^{144} beta spectrum.[27]

The asymmetry observed for RaE beta rays is 3.1 standard deviations lower than the value predicted for

[21] de Waard, Poppema, and van Klinken, in *Proceedings of the Rehovoth Conference on Nuclear Structure, 1957*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958) p. 388.

[22] H. Frauenfelder, in *Proceedings of the Rehovoth Conference on Nuclear Structure, 1957*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 378.

[23] Benczer-Koller, Schwarzschild, Vise, and Wu, Phys. Rev. **109**, 85 (1958).

[24] Langevin-Joliot, Marty, and Sergent, Compt. rend. **244**, 3142 (1957). See also footnote, p. 393, *Proceedings of the Rehovoth Conference on Nuclear Structure, 1957*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958).

[25] Alikhanov, Eliseiev, Lubimov, and Ershler, Nuclear Phys. **5**, 588 (1958).

[26] Berestetsky, Ioffe, Rudik, and Ter-Martirosyan, Nuclear Phys. **5**, 464 (1958).

[27] Graham, Geiger, and Eastwood, Can. J. Phys. **36**, 1084 (1958).

TABLE II. Summary of polarization data.

Nuclide	Experimental method	β-energy studied (kev)	v/c	$P/(v/c)$	Reference
P^{32}	Multiple scattering, Mott scattering	>900	>0.93	∼−1[a]	de-Shalit *et al.*[d]
	Multiple scattering, Mott scattering	∼250	0.75	negative, same as Au^{198}	Lipkin *et al.*[e]
	Multiple scattering, Mott scattering			(−1.13 ±0.08)	Dulgeroff *et al.*[f]
	Electrostatic deflection, Mott scattering	168	0.66	−0.76 ±0.17	de Waard and Poppema[g]
	Electrostatic deflection, Mott scattering	170	0.66	negative, same as Au^{198}	de Waard *et al.*[h]
	Bremsstrahlung circular polarization			negative, comparable to Y^{90}	Cohen *et al.*[i]
	Møller scattering	300–1000 800–1600	(0.85)av (0.94)av	−1.00 ±0.13 −1.00 ±0.17	Frauenfelder *et al.*[j]
	Møller scattering	>300	>0.78	−0.94 ±0.06	Present work
$Sr^{90}-Y^{90}$	Bremsstrahlung circular polarization			negative[b]	Schopper and Galster[k]
	Bremsstrahlung circular polarization			negative[b]	Goldhaber *et al.*[l]
	Crossed fields, Mott scattering	300 750	0.78 0.91	−1.02 ±0.15 −1.15 ±0.4	Alikhanov *et al.*[m]
	Electrostatic deflection, Mott scattering	204 128	0.7 0.6	−0.624±0.164[c] −0.343±0.157	Langevin-Joliot[n]
Y^{90}	Bremstrahlung circular polarization			negative, comparable to P^{32}	Cohen *et al.*[i]
	Møller scattering	1200–1800	0.95–0.98	−0.93 ±0.21 −0.99 ±0.14	Benczer-Koller *et al.*[o]
	Møller scattering	>300	>0.78	−0.86 ±0.06	Present work
Pr^{144}	Møller scattering	400–1100 1200–3000	(0.86)av (0.97)av	−0.78 ±0.21 −1.08 ±0.26	Frauenfelder *et al.*[j]
	Møller scattering	>300	>0.78	−0.90 ±0.22	Present work
Au^{198}	Electrostatic deflection, Mott scattering	100 120	0.55 0.6	−0.05 ±0.06[c] −0.06 ±0.05	Frauenfelder *et al.*[p]
	Møller scattering	>0.3 0.3–0.8	>0.78 0.78–0.92	+0.05 ±0.12[c] +0.02 ±0.23	Frauenfelder *et al.*[p]
	Electrostatic deflection, Mott scattering	168	0.66	−0.24 ±0.05[c]	de Waard and Poppema[g]
	Electrostatic deflection, Mott scattering	170	0.66	negative, same as P^{32}	de Waard *et al.*[h]
	Multiple scattering, Mott scattering	∼250	∼0.75	negative, same as P^{32}	Lipkin *et al.*[e]
	Crossed fields, Mott scattering	128	0.6	−0.97 ±0.20	Cavanagh *et al.*[q]
	Møller scattering	>600	0.89–0.94	−1.02 ±0.19 −0.95 ±0.25	Benczer-Koller *et al.*[o]
	Møller scattering	>300	0.78–0.94	−0.98 ±0.18	Present work
RaE(Bi^{210})	Møller scattering	>300	>0.78	−0.69 ±0.10	Present work

[a] See analysis of F. Gürsey [Phys. Rev. **107**, 1734 (1957)].
[b] Gamma circular polarization approaches 100% as E_γ approaches the yttrium spectrum end point energy, indicating a v/c beta polarization.
[c] These low values were apparently due to technical difficulties (see references 21 and 22).
[d] See reference 10.
[e] Lipkin, Cuperman, Rothem, and de-Shalit, in *Proceedings of the Rehovoth Conference on Nuclear Structure, 1957*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958) p. 400.
[f] Dulgeroff, Lambe, and Pond, Bull. Am. Phys. Soc. Ser. II, **2**, 348 (1958).
[g] See reference 5.
[h] See reference 21.
[i] Cohen, Wiener, Wald, and Schmorak, in *Proceedings of the Rehovoth Conference on Nuclear Structure, 1957*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958) p. 404.
[j] See reference 12.
[k] H. Schopper and S. Galster, Nuclear Phys. **6**, 125 (1958).
[l] See reference 11.
[m] See reference 25.
[n] See reference 24.
[o] See reference 23.
[p] See reference 4.
[q] See reference 9.

a $-v/c$ beta polarization. This discrepancy exceeds any uncertainties suggested by the results for the other four nuclides. The difference between the RaE asymmetry and the weighted mean of the observed asymmetries for the other nuclides is (1.3±0.5)%, i.e., 2.6 standard deviations. This quantity is independent of the uncertainty in foil magnetization. Cavanagh *et al.*[9] have pointed out that scattering in the source material can lower the apparent polarization of the outgoing beta rays. Over half the RaE data was obtained from a source which was as thin as any of the sources used in our experiments (∼1 mg/cm^2). The individual asymmetries observed with the three RaE sources were (3.6±0.6)%, (3.9±1.2)%, and (3.5±0.8)%. It is difficult therefore to attribute the large RaE discrepancy to depolarization resulting from scattering in the source material. These runs were interspersed with those of other sources over a period of several months. The statistical probability of being low by 2.6 standard deviations is small. We therefore feel that there is evidence for a genuine discrepancy from full $-v/c$ polarization in the case of RaE.

The theoretical expressions for polarization of electrons in forbidden beta decay give to first order $P=\pm v/c$ if one assumes that (a) time reversal holds, (b) the two component neutrino theory holds, (c) the interaction is VA (or STP),[3] and (d) that the lepton de Broglie wavelengths are large compared to the nuclear radius. The large value of $\log ft \simeq 8$ for RaE and the forbidden shape of its spectrum are evidence for almost complete cancellation in the expressions for the spectrum shape and hence also for the polarization. If one retains higher order terms one will not necessarily predict exactly $P=-v/c$ for first-forbidden transitions.[3,28] Kotani and Ross[28] have shown for RaE that if one assumes invariance under time reversal, the expression for longitudinal polarization reduces to $P_L \cong -(p/W)(R_2/C)$, where p and W are the momentum and total energy of the electron, C is the spectrum shape factor, and R_2 is dependent only on nuclear parameters and is not a function of electron energy. Since the ratio of nuclear matrix elements cannot be determined exactly from the energy spectrum shape, the value of R_2 is uncertain. Kotani and Ross consider that a low value of R_2 may reasonably be expected for RaE but they have not made quantitative estimates as yet.[29] In a recent communication Bincer, Church, and Weneser[30] have calculated the degree of polarization expected for beta rays of RaE using Plassmann and Langer's[31] best fit to the spectrum shape. Their predictions show that the polarization is a function of the beta-ray energy for a given fit and that the absolute value depends on the choice of fit. The average value expected in our apparatus from the mean of their predicted range of values is $\sim -0.6v/c$ in agreement with our experiment. A detailed study of the polarization of RaE beta rays as a function of v/c would prove valuable in establishing the nuclear parameters for this interesting nuclide.

[28] T. Kotani and M. Ross, Progr. Theoret. Phys. Japan (to be published).
[29] T. Kotani and M. Ross (private communication).
[30] Bincer, Church, and Weneser, Phys. Rev. Letters 1, 95 (1958).
[31] E. Plassmann and L. Langer, Phys. Rev. 96, 1593 (1954).

VIII. CONCLUSION

The experiments reported here on P^{32}, Y^{90}, Pr^{144}, and Au^{198} give results which are consistent with the current view that the longitudinal polarization of negative beta rays is $-v/c$. The RaE experiments, however, indicate a polarization magnitude of less than v/c. Interference between the Fermi and Gamow-Teller contributions is believed to account for the large ft value and the nonallowed shape of the RaE beta spectrum; such interference may also give rise to low polarization.

Note added in proof.—Low values for the longitudinal polarization of RaE β rays have recently been reported by two other groups. W. Bühring and J. Heintze [Phys. Rev. Letters 1, 176 (1958)] compared the longitudinal polarization of 250–600 kev β rays from Tl^{204}, Y^{91}, and RaE using the technique of multiple followed by Mott scattering. They find that $\langle P/(-v/c)\rangle$ for RaE in this energy range is 0.83 ± 0.02. Wegener, Bienlein, and Issendorff (preprint) have measured the polarization of the RaE β rays using a spherical electrostatic analyzer and Mott scattering. For β energies of 120, 155, 209, and 290 kev their measured longitudinal polarizations are $P/(-v/c)=0.69\pm0.04$, 0.75 ± 0.04, 0.75 ± 0.03, and 0.66 ± 0.06, respectively.

IX. ACKNOWLEDGMENTS

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Excited States of V^{51} and Cr^{53}†

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The region of excitation in V^{51} up to 4.12 Mev has been investigated through studies of the inelastic scattering of protons. In this region of excitation, thirty-five excited states were found. The low-lying excited states of Cr^{53} were investigated through the $Cr^{52}(d,p)Cr^{53}$ and the $Mn^{55}(d,\alpha)Cr^{53}$ reactions. The ground-state Q values for these reactions are 5.720 ± 0.006 and 8.275 ± 0.008 Mev, respectively. The first two excited states in Cr^{53} are at 0.565 and 1.008 Mev. In these studies, the bombarding beam was provided by an electrostatic accelerator, and the reaction products were analyzed with a broad-range magnetic spectrograph.

EXCITED STATES OF V^{51}

IN a previous paper,[1] we reported on studies of the inelastic scattering of protons from vanadium and remarked that, in the region of excitation above the fourth excited state at 1.819 Mev, the level scheme was of considerable complexity. We have recently reinvestigated this reaction under somewhat better conditions than in the previous work.

A 6.51-Mev proton beam from the MIT-ONR accelerator was used, and the scattered particles were analyzed with the broad-range magnetic spectrograph at an angle of 130 degree with respect to the beam.

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[1] Buechner, Braams, and Sperduto, Phys. Rev. 100, 1387 (1955).

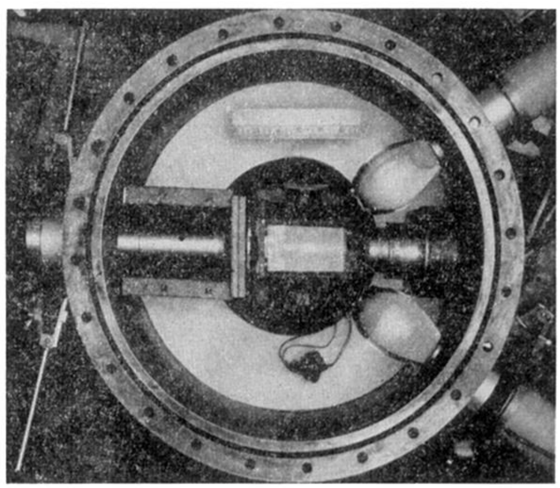

FIG. 4. Multiple exposure photograph of the apparatus with vacuum-tight lid removed. A frosted lamp placed at the source position reveals the beam direction (using smoke with foil removed) and the region of impact on the Deltamax foil (using translucent paper).