The sequence of operations is as follows. First the dc magnetic field B_0 is produced at relatively slow pace by building up the current in the dc superconducting field coil from an external power source. The capacitor C is then discharged through gap No. 1 causing the magnetic field in the HIPAC to temporarily decrease to zero as a result of currents flowing in the external ac field coil. The electron injection occurs on the second half of the ac cycle while the ac current is returning to zero and the magnetic field is returning to B_0. When the ac current has returned to zero, the capacitor C is charged in the reverse direction. At this point, spark gap No. 2 is ignited, short circuiting the ac coil and quenching the current in spark gap No. 1. The function of the ac shield is to prevent image currents from heating the dc superconducting field coil.

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Effect of Backscattering on the Helicity of β Radiation

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Experimental investigation has been carried out on the dependence on the energy of the average longitudinal polarization of β particles of ^{90}Sr+^{90}Y, backscattered by a lead target. The ratio of the polarization of backscattered to incident electrons was obtained in the energy ranges 0.3–0.8, 0.55–1.2, and 0.75–2.0 MeV with respective results of 0.657 ± 0.192, 0.503 ± 0.284, 0.650 ± 0.369. The effect of a perturbing magnetic field on helicity was also studied. The results are discussed with reference to the mechanism of the backscattering process.

1. INTRODUCTION

The main features of the β-radiation longitudinal depolarization were experimentally investigated by transmitting electrons through foils of different materials[1,2]; on the other hand the depolarization of electrons due to backscattering has not yet been carefully investigated. This paper describes our research on the effect of backscattering from lead on helicity of the β radiation from a ^{90}Sr+^{90}Y source; the average polarization of the backscattered electrons was measured by a Møller polarimeter at different energy intervals.

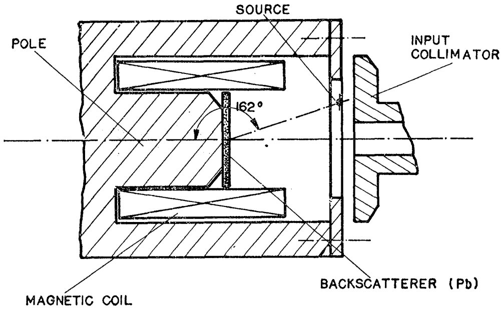

Fig. 1. Geometrical arrangement of the source, the backscatterer, and the input collimator of the polarimeter; the magnetic circuit is also shown.

The effect on the depolarization of a static magnetic field perpendicular to the backscatterer was also investigated with the aim of further clarifying the mechanism of depolarization in the backscattering process.

2. EXPERIMENTAL METHOD

A. The Apparatus

The Møller-type polarimeter, used in our measurements, was the same as described in one of our previous papers.[2] The collimators were enlarged in such a way that the electrons entering the polarimeter were received in a solid angle of about 1.4×10^{-3} sr, and the electrons scattered by the analyzer foil in the angular range between 26° and 48° were detected.

Three sources of β radiation were employed: each source consisted of 50 mCi of ^{90}Sr ($E_{\max}=0.545$ MeV), evaporated into a sintered alumina holder, covered by a layer of stainless steel 0.1 mm thick; the diameter of the active area was 10 mm. The ^{90}Sr is in equilibrium with its daughter ^{90}Y ($E_{\max}=2.26$ MeV). The depolarizer target was a disk of lead, of a thickness equal to the range of the β rays of ^{90}Y. The target was placed on the surface of the magnet pole, as may be seen in Fig. 1. The magnetic-induction value was 1740 G at the position of the target; the variation of the magnetic field was about 3 and 5% along the thickness and along the radius of the backscatterer, respectively.

The three sources were located at 60° from each other on a plane parallel to the target.

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[1] J. Van Kinklen, K. Bulthuis, and R. J. Van Duinen, Nucl. Phys. **61**, 593 (1965).

[2] L. Braicovich, B. De Michelis, and A. Fasana, Nucl. Phys. **63**, 548 (1965).

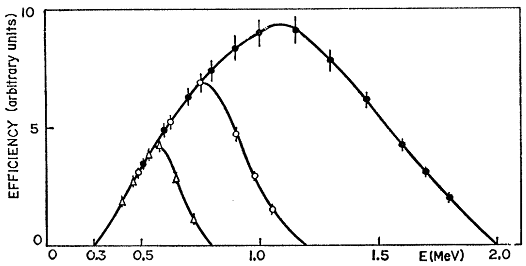

FIG. 2. The measured pair-collection efficiency of the polarimeter as a function of the energy of the electrons entering the polarimeter. The efficiencies in the energy intervals 0.3–0.8 MeV (Δ), 0.3–1.2 MeV (○), and 0.3–2.0 MeV (•) are shown.

B. Energy Requirements

The dependence of the polarization of the backscattered electrons on the energy was investigated by measuring the average counting rate asymmetries in the following energy ranges: $E_0-E_1=0.3$–0.8 MeV, $E_0-E_2=0.3$–1.2 MeV, and $E_0-E_3=0.3$–2.0 MeV. These energy ranges were chosen in order to recognize the presence of casual intrumental drifts, in spite of the prohibitively low coincidence counting rate, obtainable with β sources of reasonable intensity.

C. Experimental Procedure

The measurements of the average asymmetries were taken over several counting runs, one for each opposite magnetization direction of the analyzer foil, the runs being made alternately with and without the perturbing magnetic field. The time required to count the prompt coincidences was 810 h.

The spurious coincidences in each energy range were recorded at regular intervals over a total counting time nearly the same as that required for measuring the prompt coincidences, in order to obtain the spurious coincidence correction with a satisfactory degree of statistical accuracy ($\approx 0.15\%$). Instrumental asymmetry was measured periodically during the experiment. This asymmetry was measured in each energy range with and without the magnetic field: in no case was it larger than 3×10^{-4}.

3. COLLECTION-EFFICIENCY MEASUREMENTS

The pair collection efficiency of the polarimeter was measured by a method discussed in another paper.[3] The measured collection efficiencies are reported in Fig. 2 as a function of the energy E of the electron entering the polarimeter; the efficiences pertaining to the average asymmetry measurements in the energy intervals E_0-E_1, E_0-E_2, and E_0-E_3 are labeled with e_1, e_2, and e_3, respectively. As may be seen, the measured efficiencies are equal in a clearly defined energy range at low energies.

TABLE I. Values of 100δ. (δ = average measured backscattering asymmetry.)

Energy ranges (MeV) B (gauss)	0.3–0.8	0.3–1.2	0.3–2.0
0	$+2.16\pm 0.61$	$+1.96\pm 0.50$	$+0.51\pm 0.36$
1740	$+0.45\pm 0.58$	-0.30 ± 0.47	-0.79 ± 0.35

This feature of the curves may be explained as follows. If the small energy loss suffered by the electrons in the analyzer foil is ignored, the energies $E_{\rm I}$ and $E_{\rm II}$ of the two electrons after a Møller collision and the energy E of the electron to be analyzed satisfy the relation $E=E_{\rm I}+E_{\rm II}$. As a consequence collection efficiency is zero at the energies $2E_i$ and $2E_s$ where E_i and E_s are the lowest and highest accepted energies, corresponding to the lower and upper thresholds in the two single channels. Moreover, in the energy range $2E_i\leq E\leq E_i+E_s$, the condition $E_{\rm II}\leqslant E_s$ is certainly satisfied if $E_{\rm I}\geqslant E_i$ and the condition $E_{\rm II}\geqslant E_s$ is only verified if $E_{\rm I}\leq E_i$. The condition $E_{\rm I}\geqslant E_i$ is thus sufficient to assure that a coincident electron pair satisfies the desired energy requirements and consequently the presence of the upper threshold E_s does not influence the collection efficiency in the energy interval $2E_i\leq E\leq E_i+E_s$. The indices I and II may obviously be interchanged in these considerations.

Since the efficiencies e_1, e_2, and e_3 pertain to three cases in which the energy E_i is the same, they must be coincident at low energies; in particular the efficiencies e_1 and e_2 must be equal up to $E_1'=0.55$ MeV and the efficiencies e_2 and e_3 up to $E_2'=0.75$ MeV; the values that can be deduced from the experimental curves are consistent with those calculated.

4. RESULTS

A. Average Asymmetry Measurements

The average asymmetries which were measured in the energy ranges E_0-E_1, E_0-E_2, and E_0-E_3, respectively, are shown in Table I. The results obtained in the presence of the perturbing magnetic field do not

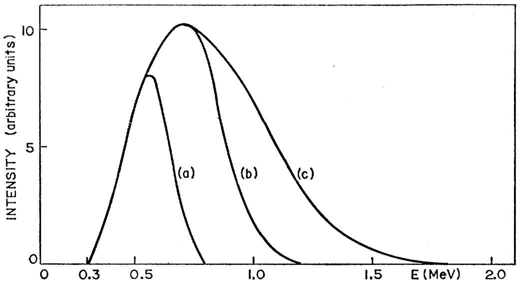

FIG. 3. The energy spectra of the electrons backscattered by lead and detected by the polarimeter in the following energy intervals: (a) 0.3–0.8 MeV, (b) 0.3–1.2 MeV, (c) 0.3–2.0 MeV.

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[3] L. Braicovich, B. De Michelis, and A. Fasana, Nucl. Phys. (to be published).

change, within the experimental errors, by reversing the direction of the field.

The energy spectra of the backscattered electrons, to which the measured asymmetries pertain, are shown in Fig. 3; these spectra were obtained by multiplying the values of spectrum $S_b(E)$ of the $^{90}\mathrm{Sr}+{}^{90}\mathrm{Y}$ radiation backscattered by the lead target with the values of the pair collection efficiencies in Fig. 2. The spectrum $S_b(E)$ was not affected within the experimental errors by the presence of the magnetic field of 1740 G perpendicular to the target.

B. Dependence of Asymmetry on the Energy

Asymmetries in the energy ranges 0.55–1.2 MeV and 0.75–2.0 MeV may be deduced from the measured asymmetries. The measured asymmetries δ_1 and δ_2 represent the average values in the energy intervals E_0-E_1 and E_0-E_2, respectively, and may be written as

$$\delta_1=\int_{E_0}^{E_1}\delta(E)e_1(E)S_b(E)dE\bigg/\int_{E_0}^{E_1}e_1(E)S_b(E)dE\,, \quad (1)$$

$$\delta_2=\int_{E_0}^{E_2}\delta(E)e_2(E)S_b(E)dE\bigg/\int_{E_0}^{E_2}e_2(E)S_b(E)dE\,, \quad (2)$$

where $S_b(E)$ indicates the energy spectrum of the $^{90}\mathrm{Sr}+{}^{90}\mathrm{Y}$ β rays backscattered by the lead target.

Since efficiencies e_1 and e_2 are equal in the energy interval E_0-E_1', the asymmetry δ_2 may be written as

$$\delta_2=\left(\delta_1\int_{E_0}^{E_1}e_1(E)S_b(E)dE+\delta_2'\int_{E_1'}^{E_2}[e_2(E)-e_1(E)]S_b(E)dE\right)\bigg/\int_{E_0}^{E_2}e_2(E)S_b(E)dE\,, \quad (3)$$

where

$$\delta_2'=\int_{E_2'}^{E_2}\delta(E)[e_2(E)-e_1(E)]S_b(E)dE\bigg/\int_{E_1'}^{E_2}[e_2(E)-e_1(E)]S_b(E)dE\,. \quad (4)$$

Since the values of δ_1 and δ_2 are known from the measurements, the value of δ_2' may be obtained from formula (3); this is the mean asymmetry in the interval $E_1'-E_2$ and pertains to the energy spectrum $[e_2(E)-e_1(E)]S_b(E)$. Obviously the same considerations may be made for asymmetries δ_2 and δ_3.

The average asymmetry values in the intervals 0.30–0.80, 0.55–1.20, and 0.75–2.00 MeV are reported in Table II. These asymmetries pertain to the backscattered electrons the spectra of which are $e_1(E)S_b(E)$, $[e_2(E)-e_1(E)]S_b(E)$, and $[e_3(E)-e_2(E)]S_b(E)$, respectively; these spectra are shown in Fig. 4.

5. ANALYSIS OF RESULTS

A. Energy Spectra of the Electrons Incident on the Backscatterer

In the discussion of our results, the energy spectra of the electrons which after backscattering have the spectra reported in Fig. 4 must be known. The spectrum $S_{\mathrm{in}}(\mathcal{E})$ pertaining to the electrons incident on the backscatterer, detected as backscattered electrons in the energy range between E_{min} and E_{max}, may be written

$$S_{\mathrm{in}}(\mathcal{E})=\int_{E_{\mathrm{min}}}^{E_{\mathrm{max}}}S(\mathcal{E})b(\mathcal{E},E)e(E)dE\,, \quad (5)$$

where the function $S(\mathcal{E})$ represents the spectrum of electrons emitted by the source, while $b(\mathcal{E},E)$ represents the density of probability that an electron incident on the backscatterer with the energy $\mathcal{E}$ is backscattered with the energy E; the backscattered electrons are collected by the polarimeter with efficiency $e(E)$.

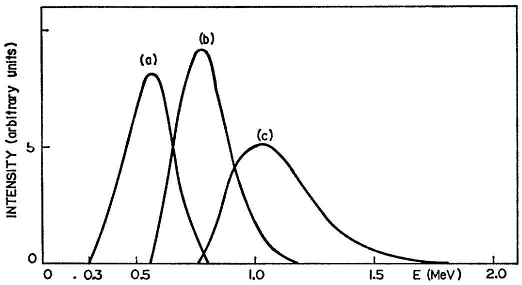

FIG. 4. The energy spectra of backscattered electrons pertaining to the energy intervals (a) 0.3–0.8 MeV, (b) 0.55–1.2 MeV, and (c) 0.75–2.0 MeV.

The function $b(\mathcal{E},E)$ has been determined from the experimental curves obtained by Bothe[4] for monoenergetic electrons (at $\mathcal{E}=680$ keV). The assumption was made that this function depends only on the variable $E/\mathcal{E}$. The departure from this type of dependence pointed out by Wright and Trump[5] was negligible, as far as the use of the calculated functions $S_{\mathrm{in}}(\mathcal{E})$ was concerned.

The formula (5) was used in calculating the energy spectra $S_{1\,\mathrm{in}}$, $S_{2\,\mathrm{in}}$, and $S_{3\,\mathrm{in}}$ of the electrons incident on the lead target, which are backscattered with energy in the intervals E_0-E_1, $E_1'-E_2$, and $E_2'-E_3$, respectively; in these cases the efficiency $e(E)$ was $e_1(E)$, $e_2(E)-e_1(E)$, and $e_3(E)-e_2(E)$, respectively. The calculated energy spectra $S_{1\,\mathrm{in}}$, $S_{2\,\mathrm{in}}$, and $S_{3\,\mathrm{in}}$ are reported in Fig. 5.

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[4] W. Bothe, Ann. Phys. (Leipzig) **6**, 44 (1949); Z. Naturforsch. **4a**, 542 (1959).

[5] K. A. Wright and J. G. Trump, J. Appl. Phys. **33**, 687 (1962).

TABLE II. Experimental data: asymmetries and helicities.

Energy ranges (MeV)		0.3–0.8	0.55–1.2	0.75–2.0
Asymmetry	$B=0$	$(+2.16\pm0.61)\times10^{-2}$	$(+1.80\pm1.01)\times10^{-2}$	$(-2.54\pm1.54)\times10^{-2}$
	$B=1740$ gauss	$(+0.45\pm0.58)\times10^{-2}$	$(-0.88\pm0.95)\times10^{-2}$	$(-1.82\pm1.47)\times10^{-2}$
$\langle v/c\rangle_{\text{in}}$		0.905	0.936	0.958
$p_{\text{in}}=\langle(v/c)(1-d)\rangle_{\text{in}}$		0.827	0.902	0.946
p_b	$B=0$	0.544 ± 0.159	0.453 ± 0.256	-0.614 ± 0.375
	$B=1740$ gauss	0.113 ± 0.146	-0.222 ± 0.240	-0.458 ± 0.371
p_b/p_{in}	$B=0$	0.657 ± 0.192	0.503 ± 0.284	-0.650 ± 0.369
	$B=1740$ gauss	0.137 ± 0.177	-0.246 ± 0.266	-0.485 ± 0.392

B. Helicity of the Electrons Incident on the Backscatterer

The average helicities of the electrons incident on the lead target and with the energy spectra shown in Fig. 5 cannot be directly measured because the polarimeter cannot be arranged so as only to detect the electrons emitted from the sources with the spectra given in Fig. 5. These average helicities may be easily calculated since the energy dependence of the helicity is experimentally well established[6] in the case of ^{90}Sr+^{90}Y; this dependence is of the v/c type. In the calculation of the average helicities allowance was also made for the degree of depolarization d in the source; using the theory of Passatore[7] discussed in our previous paper,[2] the depolarizing effect of the covering was calculated in the first Born approximation and the effect of the backing was allowed for on the basis of the measurements reported in Ref. 3. The results of these calculations are shown in Table II.

C. Comparison between the Electron Helicity after and before Backscattering

In order to compare the electron helicity after and before they are backscattered, the corresponding helicities must be obtained from the asymmetries δ_1, δ_2', and δ_3'. With this aim the average asymmetry pertaining to the β radiation emitted by the source in the interval 0.3–2.0 MeV was measured, resulting in $\delta_s=+3.60\pm0.25$ and corresponding to the helicity $p_s=0.906$, calculated as the average value of v/c allowing for the depolarization in the source. We have assumed that the ratio between each asymmetry and the corresponding helicity was a constant equal to δ_s/p_s; owing to the energy dependence of the coincidence asymmetry, a negligible error (no greater than 2.5%) is made with the previous assumption, as may be deduced by using the results of earlier calculations made by Geiger.[8] The resulting helicities with and without the magnetic perturbing field are reported in Table II. This table also gives the ratio R of the helicity of the backscattered electrons (p_b) and of the incident ones (p_{in}) with and without the magnetic field. As appears from Table II the calculated helicities of the incident electrons do not differ much one from another and thus the energy dependence of the ratio R is nearly completely determined by the dependence of the measured helicities of the backscattered electrons. For this reason a further development of the calculations of Subsecs. 5A and 5B was not considered necessary.

6. CONCLUSIONS

As appears from Table II, the longitudinal depolarization $1-R$ of the β rays which are backscattered by the lead target greatly depends on the energy; and the electrons which are backscattered in the energy range 0.75–2.00 MeV have an average polarization of a sign different from that of the incident electrons.

An interpretation of these results cannot be attempted without considering that the energy spectra of the electrons incident on the backscatterer have very different shapes in the three cases. The spectrum $S_{1\text{ in}}$ extends over a wide range of energy owing to the possibility of a high-energy electron being backscattered with an energy between 0.30 and 0.80 MeV; on the other hand, the possibility of great energy loss is greatly reduced in the case of the spectrum $S_{3\text{ in}}$, since electrons are detected which are only backscattered with an energy greater than 0.75 keV. An intermediate case is given by the spectrum $S_{2\text{ in}}$.

These considerations suggest that the backscattering mechanism may be considerably different in the three

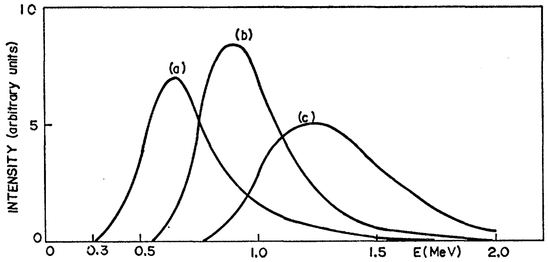

FIG. 5. The energy spectra of the electrons incident on the lead backscatterer and which enter the polarimeter after backscattering. The spectra of the corresponding backscattered electrons are shown in Fig. 4.

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[6] A. I. Alikhanov, G. P. Eliseiev, and V. A. Liubimov, Nucl. Phys. 7, 655 (1958).

[7] G. Passatore, Nuovo Cimento 6, 850 (1957); 18, 532 (1960).

[8] J. S. Geiger, G. T. Ewan, R. L. Graham, and D. R. Mackenzie, Phys. Rev. 112, 1684 (1958).

cases because the electrons have, on the average, different possibilities of energy loss in the backscattering process. Some significant information about the backscattering mechanism may be deduced from the results of a recent theoretical paper by Dashen.[9] This author calculated the backscattering coefficient assuming that, if an electron is not scattered through an angle greater than 25° in every nuclear collision, it is not scattered at all; he deduced the backscattering coefficient of monoenergetic incident electrons as a function of the energy of the backscattered electrons. On this basis, Dashen established that the contribution of the scattering at angles greater than 25° is greater for electrons backscattered with lower energy loss and is almost equal in aluminum and copper when the comparison is made with reference to the same percentage energy loss; he suggested that this fact was a general trend.

Since the electrons which are backscattered with an energy between 0.30 and 0.80 MeV have suffered an energy loss greater than that suffered by the electrons backscattered with an energy between 0.75 and 2.0 MeV, Dashen's results suggest that in this latter case scattering at angles larger than 25° is more weighted. In this case the large change in the longitudinal polarization measured agrees with this description because the longitudinal polarization changes to a larger degree at the greater scattering angles in every nuclear collision.[10] In the first case, processes of this type are present with a smaller weight and the change in polarization may be due to a greater extent to a diffusion process at small angles.

In the presence of the perturbing magnetic field, the coupling between the field and the magnetic moments of the electrons withstands the rotation of the spins of the electrons while they are scattered. Thus in every nuclear collision, helicity change is greater than that without the field. On the other hand, in the absence of the field, the helicity reverses its sign without changing its absolute value[10] when the scattering angle approaches 180°; thus the magnetic effect on the single nuclear scattering must decrease at the larger scattering angles. The results given in Table II concerning the effect of the magnetic perturbation are consistent with the previous considerations because the magnetic field increases the change in polarization due to backscattering and, within the experimental errors, the magnitude of the effect is reduced to zero at the highest energy. This latter feature may be qualitatively understood since the magnetic effect in the single nuclear collision decreases with the energy and since, according to Dashen's suggestions, at the higher energy a greater weight is given to the backscattering processes consisting of nuclear collision at larger angles.

ACKNOWLEDGMENTS

We wish to thank Professor A. Bisi and Professor E. Gatti for stimulating discussions and comments.

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[9] R. F. Dashen, Phys. Rev. **134**, A1025 (1964).

[10] J. W. Motz, H. Olsen, and H. W. Koch, Rev. Mod. Phys. **36**, 881 (1964).