PHYSICAL REVIEW VOLUME 114, NUMBER 4 MAY 15, 1959

Longitudinal Polarization of Positrons from the Decay of O^{14}†*

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(Received December 19, 1958)

The longitudinal polarization of 1.2-Mev positrons from the well-known $0+ \rightarrow 0+$ transition of 72-second O^{14} has been measured. Positrons, selected by a magnetic spectrometer, were allowed to annihilate in a plastic scintillator. Annihilation-in-flight photons were analyzed for circular polarization by Compton scattering from magnetized iron. The positrons were found to have right-handed longitudinal polarization $(+0.73\pm0.17)v/c$.

If the beta-decay interaction does not conserve parity, electrons emitted from an unpolarized radioactive source will be longitudinally polarized along their direction of motion, the amount of polarization being related to the amount of parity-nonconserving interaction present. In a pure Gamow-Teller or a pure Fermi transition, provided only a single interaction type is present, full longitudinal polarization (v/c) indicates that the beta-decay interaction can be described satisfactorily in terms of a simplified "two-component" neutrino theory.[1]

Following the experimental discovery that parity is not conserved in beta decay, numerous measurements of electron polarization in pure Gamow-Teller and mixed Fermi-(Gamow-Teller) beta transitions have been made. Similar measurements for pure Fermi transitions, more difficult because of the short lifetimes of the best known examples,[2] have been made only for Ga^{66} and Cl^{34} up to the present time.[3–5]

To obtain further information about parity in the Fermi interaction, we have measured the longitudinal polarization of the positrons from 72-second O^{14} which result predominantly[6] from the well-known $0+ \rightarrow 0+$ transition to the 2.3-Mev first excited state of N^{14}. The positron polarization was determined from a measurement of the circular polarization of the radiation of positrons annihilating in flight.

I. EXPERIMENTAL METHOD

Figure 1 is a schematic diagram of the apparatus employed in measuring the O^{14} positron polarization. 1.2-Mev positrons from the source were focused on a plastic scintillator-annihilator with a small magnetic spectrometer. Positrons which annihilated in flight were counted selectively in the plastic scintillator, and the coincident annihilation radiation, after Compton scattering from the magnetized iron cylinder, was detected by a NaI(Tl) scintillation detector. By means of a conventional fast-slow coincidence circuit, positrons which lost only a small amount of energy in the plastic scintillator before annihilating were counted in coincidence with high-energy scattered gamma rays.[7] Coincidences were recorded for each direction of magnetization, and the resulting asymmetry served as a measure of the circular polarization of the annihilation quanta. The latter is related to the initial longitudinal polarization of the positrons. Further experimental details are discussed below.

The O^{14} activity was produced by a (p,n) reaction on nitrogen gas, in a continuous flow system, by bombardment with 22-Mev H_2^+ ions in the University of Washington 60-inch cyclotron. The active gas passed from the cyclotron target through a hot CuO filter to convert unwanted C^{11} activity to CO_2, an Ascarite filter to remove the active CO_2, a hot platinum catalyst to convert oxygen to H_2O, and into the source chamber shown in Fig. 1 where the radioactive water vapor was frozen out on the end of a $\frac{1}{4}$-inch diameter copper rod the other end of which was immersed in liquid nitrogen. Finally, the remaining activity and sweeping gas were discarded through a pump to the outside atmosphere.

A small quantity of oxygen gas was added to the nitrogen flow ahead of the target chamber to act as a carrier. The interior of the aluminum target chamber was gold covered to inhibit exchange reactions with the aluminum oxide of the walls. Just ahead of the platinum catalyst hydrogen gas was added as a carrier in the conversion to water vapor. With a 100-μa beam of H_2^+ ions, 3 to 7 millicuries of O^{14} were frozen out at the spectrometer source. Not more than 9% of the total activity present under equilibrium conditions was O^{15}.

The principal purpose of the magnetic spectrometer was to separate the positrons from the coincident

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[†] This work was supported in part by the U. S. Atomic Energy Commission.

[*] A preliminary account of this work was presented at the Los Angeles Meeting of the American Physical Society, December, 1958 [Bull. Am. Phys. Soc. Ser. II, **3**, 406 (1958)].

[1] T. D. Lee and C. N. Yang, Phys. Rev. **105**, 1671 (1957).

[2] A summary of the known pure Fermi transitions has been given by J. B. Gerhart, Phys. Rev. **109**, 897 (1958).

[3] Deutsch, Gittelman, Bauer, Grodzins, and Sunyar, Phys. Rev. **107**, 1733 (1957).

[4] Frankel, Hansen, Nathan, and Temmer, Phys. Rev. **108**, 1099 (1957).

[5] S. S. Hanna and R. S. Preston, Phys. Rev. **110**, 1406 (1958).

[6] Sherr, Gerhart, Horie, and Hornyak, Phys. Rev. **100**, 945 (1955). $(0.6\pm0.1)\%$ of the O^{14} decays are to the N^{14} ground state via a Gamow-Teller transition.

[7] In addition to two-quantum annihilation radiation, single-quantum annihilation radiation and bremsstrahlung are detected with this apparatus. However, for positrons in plastics, only a few percent of the total radiation can be ascribed to these sources. For estimates of these effects see Gerhart, Carlson, and Sherr, Phys. Rev. **94**, 917 (1954).

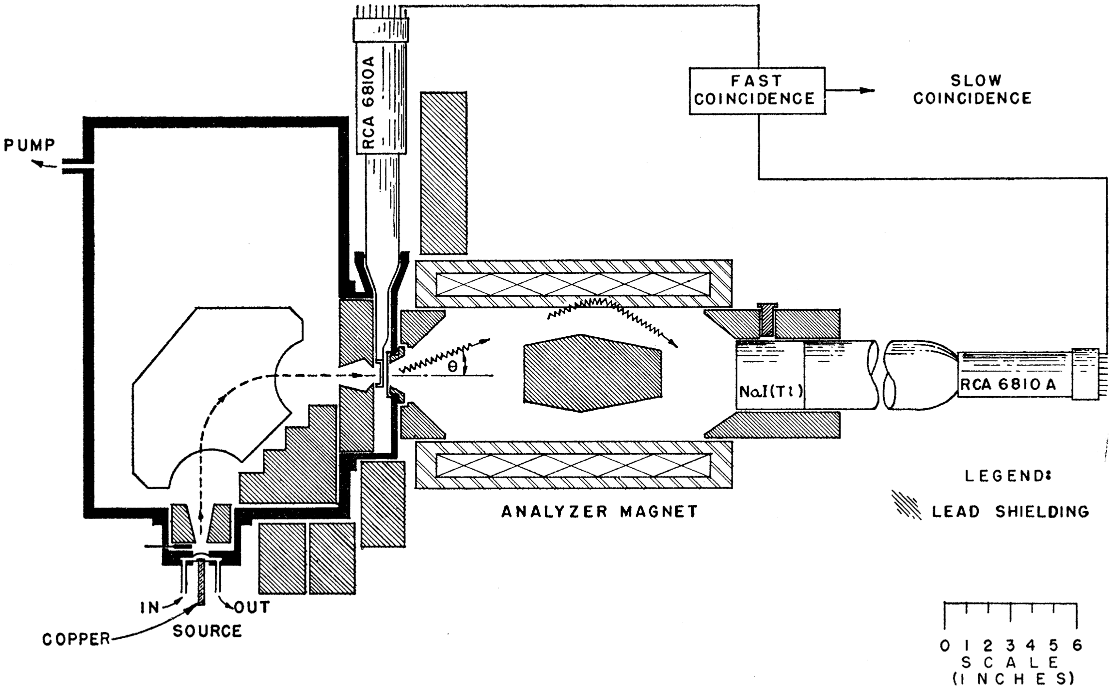

FIG. 1. Schematic diagram of apparatus.

2.3-Mev gamma radiation[8] of O^{14}. This was necessary because the cross section for Compton scattering of the 2.3-Mev photons in the plastic scintillator-annihilator is greater than the cross section for two-quantum annihilation in flight. The spectrometer is one sector of the "orange-peel" type,[9] with resolution about 17% and transmission about 0.7%. As shown in Fig. 1, the vacuum chamber was made large to minimize background from scattered gamma rays. A 0.001-inch thick aluminum foil separates the source chamber from the spectrometer vacuum. The copper rod, on which the active water vapor was deposited, projects through a hole in a 0.001-inch stainless steel foil, the latter providing thermal insulation between the source rod and the source chamber walls. A sliding shutter intercepts the positrons when desired.

The plastic scintillator-annihilator was machined in the form of a shallow open-faced box with about $\frac{1}{4}$-inch thick walls. The sides do not receive direct beta radiation, but serve to reduce spurious small pulses caused by backscattering. The scintillator is connected to an RCA 6810A photomultiplier by a Plexiglas light guide. Extensive lead shielding is provided between the source and the scintillator to reduce background pulses.

A cylindrical iron magnet analyzed the circularly polarized annihilation photons by the intensity change of radiation Compton-scattered into the NaI(Tl) detector when the magnetization was reversed.[10] A lead plug in the center intercepted direct radiation. Test coils, wound integrally into the magnet, were used to determine the magnetization. A 3×3 inch cylindrical NaI(Tl) crystal, connected through a 26-inch long Plexiglas light guide to an RCA 6810A photomultiplier was used to detect the scattered radiation. The resolution for Cs^{137} gamma rays was about 25%.

Anode pulses from the two multipliers fed to a fast coincidence circuit of resolving time 2τ about 10^{-8} second. Integrated pulses from the fourteenth dynode of the gamma counter were selected with a 20-channel pulse analyzer; pulses from the fourteenth dynode of the positron counter by a single-channel analyzer. The output of the latter was placed in "slow" coincidence with the "fast" coincidence output; the combination gated the 20-channel analyzer. The chief reason for adopting this coincidence method was that the total gamma-ray counting rate in the NaI(Tl) counter was many times the true rate. Most of these counts originated in the large background radiation accompanying cyclotron operation, and were caused, in part, by both fast and slow neutrons even though the entire apparatus was located behind heavy shielding walls some 40 feet from the cyclotron.

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[8] The beta transition to N^{14*} is followed by a prompt $E1$ gamma transition to the ground state. See F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

[9] Kofoed-Hansen, Lindhard, and Nielsen, Kgl. Danske Videnskab. Seleskab, Mat.-fys. Medd. **25**, No. 16 (1950); O. B. Nielsen and O. Kofoed-Hansen, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 6 (1955).

[10] F. Boehm and A. H. Wapstra, Phys. Rev. **106**, 1364 (1957); H. Schopper, Nuclear Instr. **3**, 158 (1958).

The sensitivities of both the gamma-ray counter and the positron detector to reversal of the analyzer magnetic field were studied in detail. For both, no changes in gain greater than 0.1% were observed.

To insure that coincidences between positrons and 2.3-Mev gamma rays were negligible, the analyzing magnet together with the center lead plug were removed, but the extensive lead shielding between the source and the gamma-ray detector was left intact. The gamma-ray coincidence spectrum was then measured, both with and without a one inch thick lead disk placed directly in the path of gamma radiation originating in the annihilator. With the former geometry only radiation scattered and degraded to energies well below the range selected for analysis produced coincidences. Without the lead disk, a gamma-ray spectrum characteristic of annihilation-in-flight plus annihilation-at-rest was observed. With the single-channel analyzer selecting positron counts set for small pulse heights, the strong 511-kev radiation was reduced by a factor of about 10 from its intensity when the entire positron pulse spectrum was used to gate the gamma-ray spectrum.

The pulse-height spectrum of 1.2-Mev positrons recorded in the plastic scintillator is shown in Fig. 2. The portion selected for gating the gamma-ray spectrum is indicated by the shaded area. For purposes of analysis it was necessary to determine from this spectrum the probability that a positron losing a particular amount of energy in the scintillator would generate a gating pulse. The dashed curve of Fig. 2 shows this probability. The maximum rate at which data could be collected was determined by limitations imposed by the electronic circuits on the integral rate in the positron counter. With a beam of 100 μa of H_2^+ ions, this rate was about 70 000 counts/sec. The differential rate was about 4000 counts/sec.

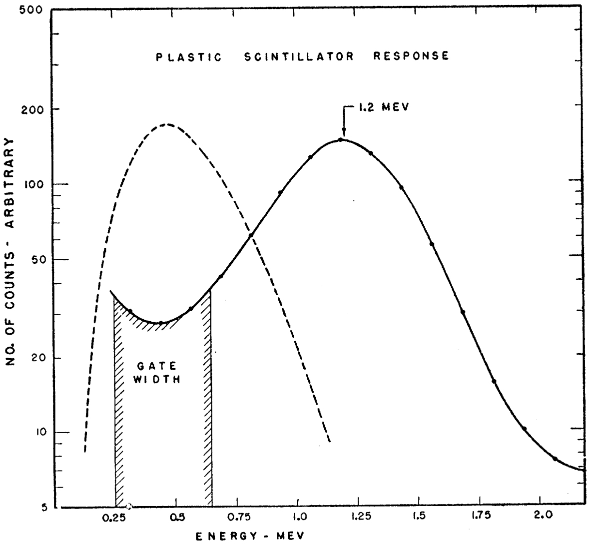

FIG. 2. Pulse-height spectrum of 1.2-Mev positrons in the plastic scintillator-annihilator. The shaded area represents the portion of this spectrum used to gate the gamma-ray spectrum. The dashed curve shows the relative probability that a positron losing a given energy will actually produce a pulse in the shaded region.

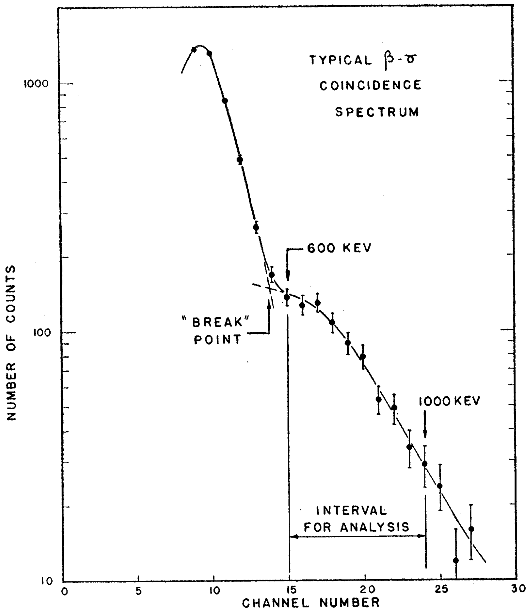

FIG. 3. Gated gamma-ray pulse spectrum. The interval from 600 kev to 1000 kev was used for determining the asymmetry in Compton scattering.

Figure 3 shows a typical gated gamma-ray pulse spectrum with the analyzer magnet and lead center plug in position. It represents the sum of four runs as described below. The sharp rise below about 550 kev is caused by Compton-scattered 511-kev radiation. The energy band from 600 kev to 1000 kev, which was chosen for analysis of the polarization, represents scattered annihilation-in-flight radiation. About 20% of the spectrum in this range is caused by accidental coincidences. These were measured, in separate runs, by inserting delay cables first in one leg of the fast-coincidence circuit and second in one leg of the slow-coincidence circuit. As was expected, the latter circuit (resolving time $2\tau \sim 4\times 10^{-6}$ sec) contributed accidental counts due mainly to 511 kev radiation.

II. ANALYSIS OF DATA

To minimize any effects of undetected, long-period instabilities of the electronic equipment, data were collected in a series of short runs in which the analyzer field was reversed from run to run. Each run was stopped when 4×10^6 positron differential counts had accumulated and ordinarily lasted 15 to 20 minutes.[11] As described in Sec. I, the portion of the gamma-ray pulse spectrum chosen for analysis ranged from 600 to 1000 kev. At the lower boundary the contamination from Compton-scattered 511-kev radiation was less

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[11] A few runs were for positron counts less than 4×10^6.

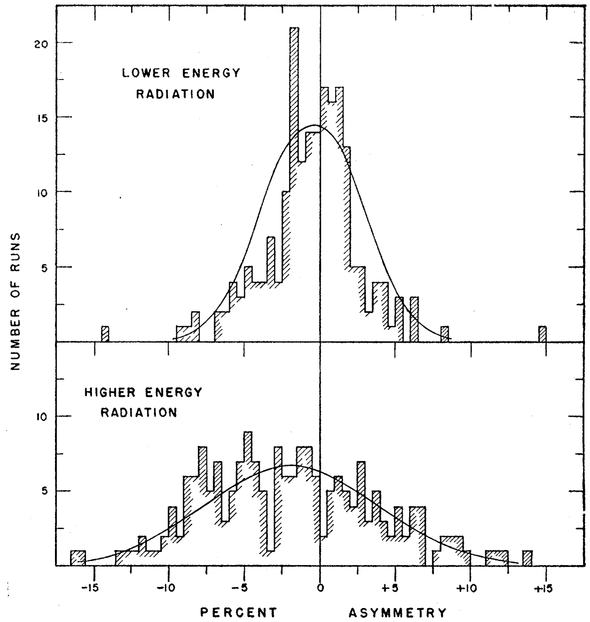

FIG. 4. The upper diagram is a histogram of the individual determinations of the asymmetry coefficient for the unpolarized annihilation-at-rest radiation. The lower diagram is a similar histogram for the high-energy annihilation-in-flight radiation. The Gaussian curves shown were fitted to these data.

than 5%. The number of true coincidences beyond the upper boundary was negligible. Each run was normalized to the number of differential positron counts. Because the time for individual runs varied with cyclotron conditions, a correction for accidental coincidences based on that time was calculated separately for each run.

An asymmetry coefficient was calculated for groups of three runs according to the prescriptions

$$A_i=\frac{\frac{1}{2}(R_i+R_{i+2})-L_{i+1}}{\frac{1}{2}(R_i+R_{i+2})+L_{i+1}},\quad A_{i+1}=\frac{R_{i+2}-\frac{1}{2}(L_{i+1}+L_{i+3})}{R_{i+2}+\frac{1}{2}(L_{i+1}+L_{i+3})}.$$

Here the normalized, corrected counts for the sequence of runs are designated by R_1, L_2, R_3, L_4, R_5, $L_6,\cdots$, where R and L refer to opposite directions of the analyzer magnetic field.[12] These prescriptions were used because they eliminate any linear instability. A histogram of the asymmetry coefficients, representing about 23 000 counts for each direction of magnetization, is shown in Fig. 4. No runs were discarded on statistical grounds. The Gaussian curve of Fig. 4 has a width very close to that expected from the statistical accuracy of a single determination. We are confident, therefore, that no serious instabilities not already eliminated by the prescriptions given above occurred during the experiment. The weighted[11] average of the asymmetry coefficients is (1.94±0.46)%. This value is unchanged if a simple sum of the normalized counts in each direction is used to calculate the asymmetry, a further check on the long-term stability of the equipment.

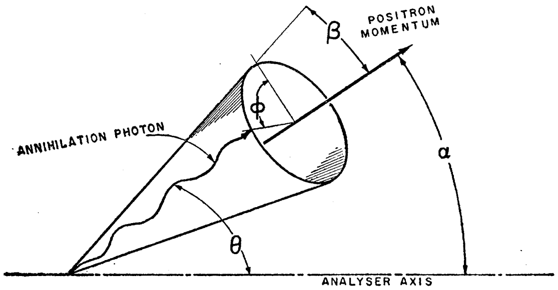

FIG. 5. Diagram showing how the angles describing the annihilation process are defined.

Also shown in Fig. 4 are the asymmetries obtained when counts from the peak of the gamma-ray spectrum (Fig. 3) are used in the analysis instead of the high-energy scattered radiation. This peak mainly represents scattered, unpolarized 511-kev radiation. We estimate that only about 20% of the counts in the peak are caused by low-energy, polarized, annihilation-in-flight quanta. The average asymmetry calculated from these data is (0.29±0.31)%. A comparison of this asymmetry with the asymmetry obtained from the higher energy pulses shows clearly that the high-energy asymmetry cannot be interpreted as being of instrumental origin.

III. CALCULATION OF POSITRON POLARIZATION

Several effects reduce the longitudinal polarization of the positrons between their origin in the O^{14} decay and their annihilation in the positron detector. Source thickness would introduce such a depolarization, but, even though a substantial ice deposit built up in the source, only the surface layer contained activity. The 72-second O^{14} half-life is small compared to the time required to deposit sufficient ice to affect the polarization appreciably.[13]

A more important source of depolarization was positron scattering in the source gas, the 0.001-inch foil separating the source and the spectrometer vacuum, and the 0.0005-inch aluminum foil which covered the plastic scintillator. Because this scattering alters the positron momentum direction without affecting its spin, a reduction of the longitudinal polarization results which is given by the cosine of the scattering angle averaged over the Molière multiple scattering distribution.[14] The combined scattering from these sources resulted in a 2% reduction in polarization of the positrons entering the annihilator.[15]

In the plastic scintillator the positrons are further scattered, are slowed down, and some of them annihilate with electrons of the plastic before stopping. At the

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[12] The asymmetry coefficient defined here is half that used by some workers.

[13] The O^{14} source was de-iced periodically between runs.

[14] H. A. Bethe, Phys. Rev. **89**, 1256 (1953).

[15] Except for the negligible effect of the anomalous magnetic moment, the spin and momentum rotate through the same angle as the positron traverses the spectrometer magnetic field.

time it annihilates, the positron has a reduced total energy E and has been multiply scattered through angle α from the analyzer axis (along which it entered the plastic). The more energetic annihilation photon is emitted in a direction, relative to the positron momentum, specified by the polar angle β and the azimuthal angle ϕ, and at angle θ with the analyzer axis (see Fig. 5). The annihilation quantum thus produced is circularly polarized if the positron was longitudinally polarized.[16]

The annihilation quantum, upon striking the iron of the analyzer, may be Compton scattered into the NaI(Tl) detector. The probability for this scattering is dependent on both the annihilation quantum polarization and the magnetization of the analyzer iron.[17] The counting rate asymmetry A observed on reversal of the analyzer magnetization, averaged over all positron energies which can produce a detected annihilation quantum, and all annihilation quantum directions which intersect the analyzer iron, is given by

$$A=\left(\frac{v}{c}\right)P\eta P_e\frac{\displaystyle\int\!\!\int\!\!\int\!\!\int(A_AA_C\cos\alpha)[F\sigma_A\sigma_C(\sin\alpha/\sin\beta)\omega N_AN_D]d\phi d\beta d\alpha dE}{\displaystyle\int\!\!\int\!\!\int\!\!\int[F\sigma_A\sigma_C(\sin\alpha/\sin\beta)\omega N_AN_D]d\phi d\beta d\alpha dE}. \qquad (1)$$

In this expression $(v/c)P$ is the initial longitudinal positron polarization; η is the depolarization of the positrons before entering the annihilator; P_e is the fraction of iron electrons which are polarized;[18] A_A is the circular polarization of the annihilation quantum[16]; A_C is the ratio of the polarization-dependent part of the Compton scattering cross section to the polarization-independent part[17]; F is the probability for multiple scattering[14] of the positron per unit solid angle in direction α; σ_A is the cross section per unit energy interval for two-quantum annihilation-in-flight[19] with the more energetic photon emitted into a unit solid angle in direction θ; σ_C is the Compton scattering cross section per steradian for unpolarized photons[20]; ω is the solid angle subtended by the NaI(Tl) detector at the site of Compton scattering; N_A is the empirically determined probability that a positron annihilating with energy E will produce a pulse in the range selected by the single-channel pulse analyzer; and N_D is the empirically determined probability that the scattered annihilation quantum will produce a pulse in the range selected in the 20-channel pulse analyzer.

In deriving this expression several approximations were made. First, the finite sizes of the incoming positron beam and the two scintillators were ignored. Second, it was assumed that the positron spins are not affected by the multiple scattering, so that at annihilation the longitudinal polarization in the direction of motion is reduced by the factor $\cos\alpha$. Finally, it was assumed that all annihilation quanta penetrate the same distance into the iron before scattering (measured along the direction of propagation), and that there are no polarization dependent effects because of absorption in the iron. Schopper[10] has shown the first of these last assumptions to be valid, and has estimated the reduction in observed asymmetry because of polarization dependent effects after scattering. However, in computing our final results we have assumed, on the basis of Schopper's work, that absorption effects reduce the observed asymmetry coefficient by a factor of 0.97.

The integrals in expression (1) must be evaluated numerically, an extremely lengthy computation. The calculation is greatly facilitated if the multiple scattering of the positrons is omitted, a procedure which introduces an error of less than 5% in our case. At first sight it is surprising that this approximation is valid; however, the reduction of longitudinal polarization of the positrons because of the scattering is counterbalanced by an increase of detection probability for the highly polarized annihilation quanta emitted at small angles with the positron momentum. The estimate of 5% accuracy is based on evaluations of the full integral for a limited number of selected positron energies and directions and photon directions. With the multiple scattering excluded, we evaluated the simplified integrals, for initial positron energy 1.2 Mev, with the aid of a digital computer. The result found, with the error taken as 5%, is $A=(0.0267\pm0.0013)P$.

IV. DISCUSSION

Combining the experimentally determined asymmetry coefficient given in Sec. II with the calculation of Sec. III, we obtain, for the initial longitudinal polarization of 1.2-Mev O^{14} positrons, $P(v/c) = (+0.73\pm0.17)v/c$. The error quoted is the *standard deviation* of the experimental data, and does not include an allowance for the uncertainty in calculation discussed in Sec. III. The sense of the experimentally observed asymmetry indicates that the positrons have right-handed polarization, that is $\boldsymbol{\sigma}\cdot\mathbf{p}$ is positive.

Although complete polarization, $P=1$, is not excluded by these results, the evidence for this conclusion is less

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[16] L. A. Page, Phys. Rev. **106**, 394 (1957).

[17] S. B. Gunst and L. A. Page, Phys. Rev. **92**, 970 (1953).

[18] P_e was taken to be 0.928 times the magnetization of the iron (in Bohr magnetons per atom), this value being based on the work of P. Argyres and C. Kittel, Acta Met. **1**, 241 (1953). The magnetic induction in this experiment was 19.0 kilogauss, corresponding to $P_e=0.0680$.

[19] H. A. Bethe, Proc. Roy. Soc. (London) **A150**, 129 (1930).

[20] O. Klein and Y. Nishina, Z. Physik **52**, 853 (1929).

substantial than might be desired. We have searched unsuccessfully for additional sources of background which could lower the observed asymmetry. In addition, as discussed in Sec. III, we have sought to take appropriate account of all effects which could lower the calculated result.

Positron polarization in two other presumed Fermi transitions has been measured. Both Ga^{66} and Cl^{34} have been studied by Deutsch *et al.*,[3] whereas Frankel *et al.*[4] and Hanna and Preston[5] have examined only Ga^{66}. The presumption that the ground-state transition from Ga^{66} is a pure Fermi transition rests on measurements of the magnetic moment[21] of Ga^{66} and on the shell-model assignment of even parity. The case of Cl^{34} is similar to O^{14}, in that S^{34}, Cl^{34}, and A^{34} should form an isotopic spin triplet. Since the *ft* value for the Cl^{34} transition is the same as the O^{14} *ft* value,[2] this view is well supported. If we consider our results on O^{14} and those of Deutsch *et al.*[3] on Cl^{34} together, then the direct experimental evidence for full polarization in pure Fermi transitions is even less conclusive.

We have attempted to make a direct comparison with a pure Gamow-Teller transition by studying positron polarization in the decay of another nuclide at the same energy (1.2 Mev) as in our O^{14} experiment. Very few suitable isotopes exist; in fact, only C^{10} seems to fulfill our experimental conditions. Unfortunately, we have been unable to produce this isotope in sufficient quantities to make practicable a study of positron polarization.

ACKNOWLEDGMENTS

We are indebted to H. Nutley for the considerable assistance he rendered during much of the experiment. A number of others helped with the tedious task of collecting data; in particular, we wish to mention I. Naqib and O. Larsen. For operation of the cyclotron, and other technical aid, we thank T. J. Morgan and the cyclotron crew. Finally, we express appreciation for valuable discussions with T. D. Lee, M. Goldhaber, and A. W. Sunyar.

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[21] Hubbs, Nierenberg, Shugart, and Worcester, Phys. Rev. **105**, 1928 (1957).