Measurement of the positron longitudinal polarization in muon decay

F. Corriveau, J. Egger,* W. Fetscher, H.-J. Gerber, K. F. Johnson, H. J. Mahler,† and M. Salzmann*
Laboratorium für Hochenergiephysik Eidgenossische Technische Hochschule Zurich, CH-5234 Villigen, Switzerland

H. Kaspar
Schweizerisches Institut für Nuklearforschung (SIN), CH-5234 Villigen, Switzerland

F. Scheck
Johannes-Gutenberg-Universität, D-6500 Mainz, Federal Republic of Germany
(Received 8 May 1981)

The longitudinal polarization of the e^+ from μ^+ decay has been measured. The spin dependence of positron-electron (Bhabha) scattering and of annihilation in flight were used as the analyzing reactions. The combined statistical and systematic error was reduced by a factor of approximately 3 below that of any previous measurement. The longitudinal polarization was found to be 1.010 ± 0.064 (statistical plus systematic error) and to be consistent with the prediction of the $V-A$ interaction.

A precise knowledge of the decay parameters in muon decay, $\mu \rightarrow e\nu\bar{\nu}$, is of fundamental importance in testing current theories of weak interactions. The existing data are not sufficient to establish the type of interaction in a precise manner.[1,2] As a first step in a program of improving the knowledge of the electron's observables in μ decay, the longitudinal polarization of the e^+ in μ^+ decay has been remeasured. In the past, several measurements have been made of the longitudinal component $\vec{P}_L$ of the polarization of the e^+ or e^- from μ decay.[3–6] The results of these measurements are consistent with the predictions of the $V-A$ interaction. However, the statistical and systematic errors are large when compared to the results of the present experiment which has improved the accuracy of $P_L = |\vec{P}_L|$ for the e^+ in μ^+ decay (see Fig. 1). This measurement is based on the spin dependence of Bhabha scattering (BHA: $e^+ + e^- \rightarrow e^+ + e^-$) and of annihilation in flight (ANN: $e^+ + e^- \rightarrow \gamma + \gamma$). Because of their comparable kinematics, the data for two independent experiments could be taken simultaneously.

The cross sections for both of these reactions[7–10] can be expressed in the form

$$\sigma_i(E_1,E_2) = \sigma_{i0}(E_1,E_2)[1 + A_i(E_1,E_2)\vec{P}_L \cdot \vec{P}_{e^-}] \quad , \quad (1)$$

where i = ANN or BHA. E_1 and E_2 are the total laboratory energies of the particles in the final state ($\gamma\gamma$ or e^+e^-) and P_{e^-} is the e^- polarization. The spin dependence as expressed by the analyzing power $A_i(E_1,E_2)$ can be accurately calculated from QED. For the two reactions, it has quite different energy behavior and, in our energy range, opposite signs (see Fig. 2).

The present experiment[11] was performed in the πE1 beam line at SIN (Schweizerisches Institut für Nuklearforschung). In Fig. 3, a schematic top view of the apparatus is shown. The 150-MeV/c π^+ beam was stopped in an oak target of density 0.63 g/cm^3 and of dimensions: height 8 cm; width 4.5 cm; thickness in beam direction 5 cm. The π^+ decay gave the

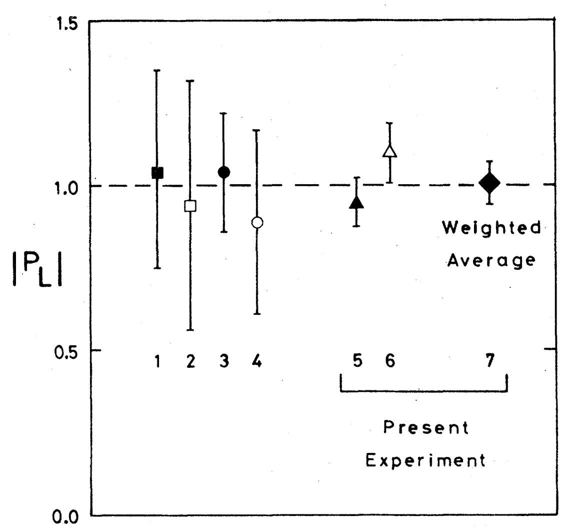

FIG. 1. Absolute value of P_L for the present and all previous experiments. The old data were obtained between 1963 and 1967 by (1) Buhler *et al.* (Ref. 3), (2) Bloom *et al.* (Ref. 4), (3) Duclos *et al.* (Ref. 5), and (4) Schwartz (Ref. 6). The data of the present experiment are indicated by (5), (6), and (7) where (5) is the result for ANN, (6) is for BHA, and (7) is the weighted average of the two. The errors include both statistical and systematic contributions. The measurement of Schwartz was made with μ^- decay and the others with μ^+ decay.

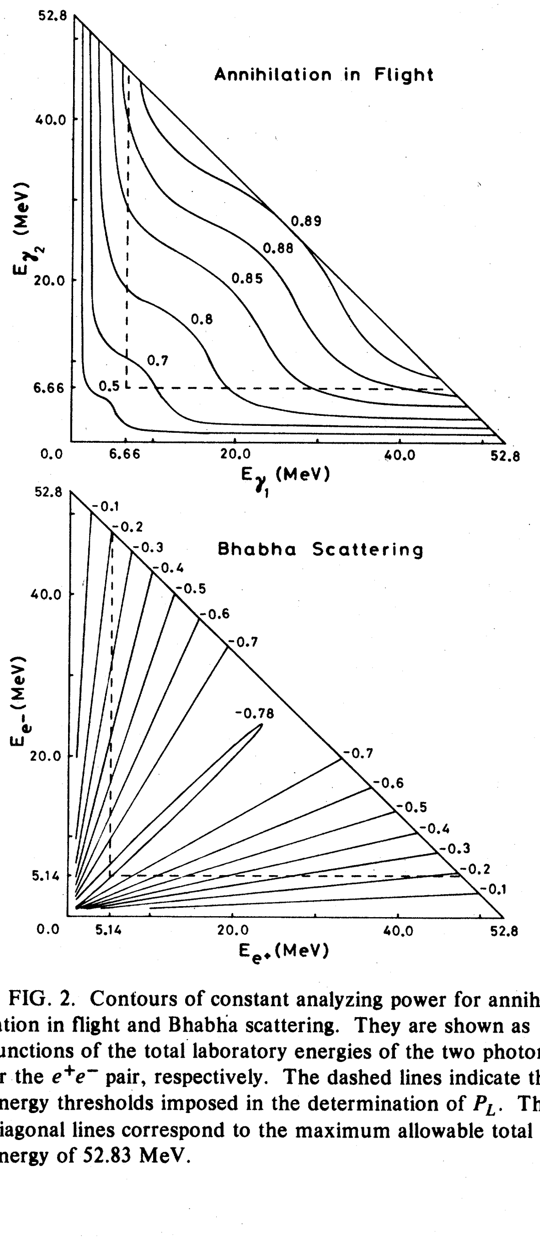

FIG. 2. Contours of constant analyzing power for annihilation in flight and Bhabha scattering. They are shown as functions of the total laboratory energies of the two photons or the e^+e^- pair, respectively. The dashed lines indicate the energy thresholds imposed in the determination of P_L. The diagonal lines correspond to the maximum allowable total energy of 52.83 MeV.

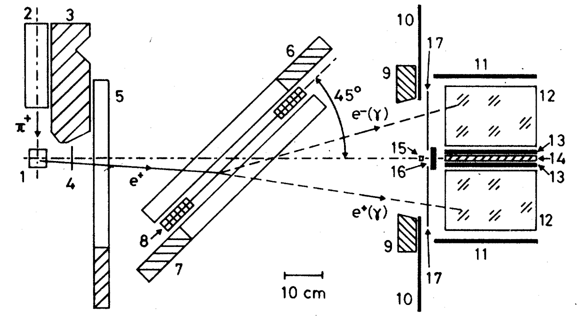

FIG. 3. Schematic top view of the apparatus. A typical event is shown for either ANN or BHA. The experimental arrangement: (1) oak stopping target; (2) Be-CH_2 moderator; (3) shielding; (4) timing counter; (5), (6), and (7) multiwire proportional chambers (labeled in the text WC_1, WC_2, and WC_3, respectively); and (8) magnet with iron foil. The total-absorption spectrometer is arranged symmetrically to the central axis. It consists of (12) four NaI detectors (only the upper pair is shown); (9) square Pb collimator; (10) square-aperture anticoincidence counter; (15) Am-Be calibration source; (17) four electron-identification counters; (16) vertical anticoincidence counter and monitor; (11) and (13) vertical anticoincidence counters; (14) vertical Fe-Pb photon converters. Not shown are the horizontal counterparts of (11), (13), (14), and (16).

$\mu^+ \rightarrow e^+$ chain.

The apparatus was designed to detect both types of particle pairs ($\gamma\gamma$ or e^+e^- produced in a magnetized iron foil which supplies the polarized electrons) with comparable acceptance. For each event, the energies of the two particles were measured in two out of four total absorption NaI detectors each of dimensions $16 \times 16 \times 24$ cm^3 (radiation length 2.6 cm). Plastic scintillators and multiwire proportional chambers (wire spacing of 2 mm) were used to select events for which the number of charged particles detected must equal one before the iron foil and equal two (for BHA) or zero (for ANN) after the foil. A typical trajectory for either type of event is shown in Fig. 3.

The magnetized foil consisted of a 0.5-mm-thick sheet of pure iron. Events were required to originate from a central region of 14×14 cm^2. The magnetic induction was in the plane of the foil and was 1.461 ± 0.015 T. This yielded a P_{e^-} of $(5.444 \pm 0.056) \times 10^{-2}$ in the foil. The magnetized iron foil, together with multiwire proportional chambers WC_2 and WC_3, was oriented at an angle of $\pm 45°$ to the symmetry axis of the apparatus (the average direction of the e^+ momentum). This was a compromise between having a large component of the e^- spin along the e^+ momentum and having a thin foil. The projection of P_{e^-} along the e^+'s momenta was determined from the incident e^+ directional distribution on the foil. This gave an effective $P_{e^-} = (3.761 \pm 0.041) \times 10^{-2}$.

During data acquisition, the foil magnetization was reversed every 15 min and the orientation of the magnetized foil was changed every 3 h between $\pm 45°$. This was done to control instrumental asymmetries and stabilities. The combination of a given orientation and foil magnetization with its mirror image leaves, to first order, the asymmetry due to polarization unchanged while it cancels instrumental asymmetries (e.g., those due to the magnetic deflection of particles in the foil). Systematic background studies were made without foil, with unmagnetized iron foils of different thicknesses (0.3, 0.5, 0.75, 1.0, and 1.5 mm), and with different foil materials (C, Al, Mo, and Pb). Furthermore, on-line calibration and stability checks of the NaI were maintained by using the 4.43-MeV γ line from an Am-Be source (see Fig. 3) and the maximum total energy (52.83 MeV) of the noninteracting positrons.

The four NaI detectors allowed for six statistically independent measurements of P_L for both ANN and BHA. These six pairs favor events for which the plane of the outgoing particles has a definite orientation: either parallel to the symmetry plane shown in Fig. 3, or perpendicular to it, or at an angle of 45°. For each pair, event type, and orientation-foil magnetization (combined with its mirror image), the data were sorted into two-dimensional energy histograms similar to Fig. 2. This sorting included considerations of geometrical acceptance, energy loss, and the NaI energy response functions. From the data with different foil magnetizations, the rate asymmetry was determined for each bin. P_L was evaluated by using Eq. (1) in a maximum-likelihood analysis for each NaI pair. For both ANN and BHA, no systematic difference was seen between pairs (within the statistical errors). The six measurements were combined to yield the results for ANN and BHA given in Table I. P_L was then studied as a function of different software threshold energies for the two final particles (the dashed lines in Fig. 2 show two threshold energies) and the results are given in Table I. The software thresholds for ANN and BHA were set individually well above a background which was dominant at low energies. The values chosen were 6.66 MeV for ANN and 5.14 MeV for BHA. Further details concerning the analysis can be found in Ref. 11.

Measurements without foil showed that events not originating in the foil (e.g., from material in WC_2 and WC_3) contributed a 13% and 28% increase in the event rate for ANN and BHA, respectively. This background was subtracted before calculation of P_L. An additional background was considered for ANN. It arises from two consecutive bremsstrahlung events in the foil or in the target and foil (if the initial e^+ is not detected in WC_3). From measurements with unmagnetized foils of different materials and thicknesses and with different targets, it was found to give a 4.4% correction to P_L. The systematic error associated with the background corrections was estimated to be $\pm 0.7\%$.

The mean depolarization of the e^+ before its point of interaction is primarily due to bremsstrahlung in the foil. This was calculated[12] giving a correction on P_L of $(2.1 \pm 1.2)\%$.

From the results of the six NaI pairs, any possible instrumental asymmetry was negligibly small compared to the statistical errors. The overall normalization (two independent monitors were used) is known to $\pm 2\%$. Possible systematic errors in the rate asymmetry and A_i due to uncertainties in the NaI energy calibration were $\pm 2\%$ and $\pm 1\%$, respectively.

As the final result, the values quoted are $P_L = 0.951 \pm 0.075 (\pm 0.068)$ for ANN and $P_L = 1.099 \pm 0.091 (\pm 0.084)$ for BHA corresponding to software energy thresholds of 6.66 and 5.14 MeV, respectively. The errors in parentheses are only statistical. The systematic errors are estimated to be $\pm 3.3\%$ for each event type. By combining the independent results of the two analyzing reactions, one obtains $P_L = 1.01 \pm 0.064 (\pm 0.053)$ (the systematic error relevant for the combined value is $\pm 3.5\%$). This is consistent with the prediction of the $V-A$ interaction ($P_L = 1$).

Under the conditions of this experiment radiative corrections to P_L are negligibly small.[13,14] Thus, the measured value can be analyzed directly in terms of the basic weak interaction. In any local gauge theory the interaction is mediated by one or several charged vector gauge bosons. The effective contact interaction responsible for muon decay is then of vector and axial-vector character only (in charge-changing order). In the framework of a more general four-fermion interaction P_L is also sensitive to possible tensor couplings.[2,15] The measured value of P_L, together with other observables in muon decay, will be used to improve the limits on such unexpected couplings.

TABLE I. Values of P_L as a function of the software threshold energy E. E is the minimum total energy of each of the outgoing particles. The statistical errors are given.

	Annihilation in flight			Bhabha scattering	
E (MeV)	$10^3 P_L$	Events	E (MeV)	$10^3 P_L$	Events
6.66	951 ± 68	238 956	5.14	1099 ± 84	266 212
7.48	967 ± 69	236 463	6.78	1135 ± 90	208 684
8.30	893 ± 74	199 157	8.42	1040 ± 101	153 749
9.15	903 ± 80	165 652	10.06	1160 ± 108	126 088
9.95	1013 ± 87	138 962	11.70	1104 ± 125	89 650
10.78	917 ± 92	122 351			

We have benefited from many discussions with various colleagues at the design stage of the experiment. We thank R. Hausammann for his participation in an earlier period. This experiment would not have been possible without the excellent contribution from several SIN groups, especially the mechanical engineering group, the electronics group, the magnet group, the computer group, and the workshop. This work was supported in part by SIN, the Schweizerischer Nationalfonds, and the German Bundesministerium für Forschung and Technologie.

---

*Present address: Schweizerisches Institut für Nuklearforschung (SIN), CH-5234 Villigen, Switzerland.

†Present address: Physics Department, University of California at Irvine, Irvine, Calif. 92717.

[1]S. E. Derenzo, Phys. Rev. 181, 1854 (1969).

[2]F. Scheck, Phys. Rep. 44, 187 (1978).

[3]A. Buhler, N. Cabibbo, M. Fidecaro, T. Massam, Th. Muller, M. Schneegans, and A. Zichichi, Phys. Lett. 7, 368 (1963).

[4]S. Bloom, L. A. Dick, L. Feuvrais, G. R. Henry, P. C. Macq, and M. Spighel, Phys. Lett. 8, 87 (1964).

[5]J. Duclos, J. Heintze, A. De Rújula, and V. Soergel, Phys. Lett. 9, 62 (1964).

[6]Daniel M. Schwartz, Phys. Rev. 162, 1306 (1967).

[7]Lorne A. Page, Phys. Rev. 106, 394 (1957).

[8]W. H. McMaster, Nuovo Cimento 17, 395 (1960).

[9]Adam M. Bincer, Phys. Rev. 107, 1434 (1957).

[10]G. W. Ford and C. J. Mullin, Phys. Rev. 108, 477 (1957).

[11]Hansjuerg Mahler, Ph.D. thesis No. 6729, Eidgenössische Technische Hochschule Zürich (ETH), 1980 (unpublished).

[12]S. M. Harris and R. J. Jabbur, Nuovo Cimento 32, 258 (1964).

[13]W. E. Fischer and F. Scheck, Nucl. Phys. B83, 25 (1974).

[14]M. T. Mehr and F. Scheck, Nucl. Phys. B149, 123 (1979).

[15]T. Kinoshita and A. Sirlin, Phys. Rev. 108, 844 (1957).