Bounds on Right-Handed Currents from Nuclear Beta Decay

V. A. Wichers, T. R. Hageman, J. van Klinken, and H. W. Wilschut
Kernfysisch Versneller Instituut, Groningen, The Netherlands

and

D. Atkinson
Instituut voor Theoretische Natuurkunde, University of Groningen, Groningen, The Netherlands
(Received 20 October 1986)

Constraints on right-handed currents are set by the precise comparison of the longitudinal polarizations P_F and P_{GT} in Fermi and Gamow-Teller β^+ decay. Measurements with a new fourfold Bhabha polarimeter gave $P_F/P_{GT} = 1.003 \pm 0.004$ with use of the matching isotopes $^{26}Al^m$ and ^{30}P. This ratio translates directly into a bound on the product of the mixing angle ζ and mass-squared ratio δ of the left- and right-handed W bosons given by $-0.49 < \delta\zeta \times 10^3 < 1.2$ at 90% confidence.

PACS numbers: 23.40.Bw, 12.15.Cc, 24.70.+s, 27.30.+t

Extension of the minimal $SU(2)_L \otimes U(1)$ electroweak theory to a left-right-symmetric theory offers an attractive mechanism whereby the parity nonconservation observed at low energies can be understood.[1] Such an extension seems the more of interest since the present lower limit on the proton lifetime[2] is hard to reconcile with the SU(5) model for grand unification. In left-right-symmetric models described by the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$, parity is spontaneously broken. The physical gauge bosons W_1 and W_2 are then linear combinations with mixing angle ζ of the weak eigenstates W_L and W_R. Deviations from the standard $V-A$ theory become manifest as a nonvanishing value of the squared mass ratio $\delta = (M_1/M_2)^2$. Bég *et al.*[3] considered limits on the admixture of right-handed currents obtained from absolute polarization measurements and muon decay. Under the instigation of their work the ratio $R = P_F/P_{GT}$, first measured in a pilot experiment,[4] was recognized as a direct probe for $V+A$ currents.[4,5] Here we report new data, which significantly reduce the region of experimentally allowed left-right parameters around the standard-model value $(\delta,\zeta) = (0,0)$. The progress in experimental bounds deduced from nuclear β decay is shown in Fig. 1. Also shown are results of measurements of the e^+ end-point energy in the decay of the muon.[7,8] These limits must be relaxed in case the masses of right-handed neutrinos cannot be neglected. A recent summary of stringent, more model-dependent bounds is presented by Jodidio *et al.*[8]

The standard model predicts $R = 1$, radiative and other corrections being ignored. However, a ratio different from unity is generally obtained in left-right-symmetric models, where $R = (1+\epsilon^2\delta)(\epsilon^2+\delta^2)(1+\epsilon^2\delta^2)^{-1} \times (\epsilon^2+\delta)^{-1}$, with $\epsilon = (1+\tan\zeta)/(1-\tan\zeta)$.[3,4] We compare the longitudinal β^+ polarization in the superallowed Fermi decay of $^{26}Al^m$, having an end point of 3211(1) keV and a half-life of 6.346 s, with that in the allowed Gamow-Teller decay of ^{30}P, with a 3205(3)-keV end point and 149.8-s half-life. The $^{26}Al^m$ and ^{30}P sources can be produced under equal conditions in (p,n) reactions on ^{26}Mg and ^{30}Si. Coulomb and radiative effects[11] cancel to better than 10^{-4} in the ratio R, because the two sources have similar atomic numbers. The dominant nuclear correction on R stems from induced weak magnetism in the ^{30}P decay. New calculations by Rood[12] show that its effect on R is less than 4×10^{-4} in magnitude, falling outside the resolving power of the present experiment. For these reasons the sources are almost identical from the experimental point of view. The influence on R of the 6 ± 3-keV difference in end-point energies is estimated to be $(-4 \pm 2) \times 10^{-4}$.

The polarizations of positrons from $^{26}Al^m$ and ^{30}P are

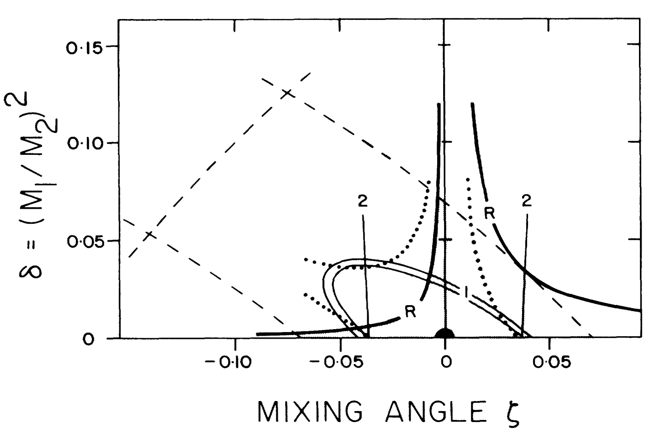

FIG. 1. Constraints at 90% confidence on the $W_{1,2}$ mass-squared ratio δ and the mixing angle ζ by R values from the present work (bold curves), and from previous β-polarization measurements (Refs. 4, 6; dashed curves). Also indicated are the bounds from measurements of the e^+ end point in muon decay (Ref. 7, outer curve; Ref. 8, inner curve 1) and from the Michel parameter (Ref. 9, curve 2). The dotted curve stems from an analysis of the decay of polarized ^{19}Ne (Ref. 10).

© 1987 The American Physical Society

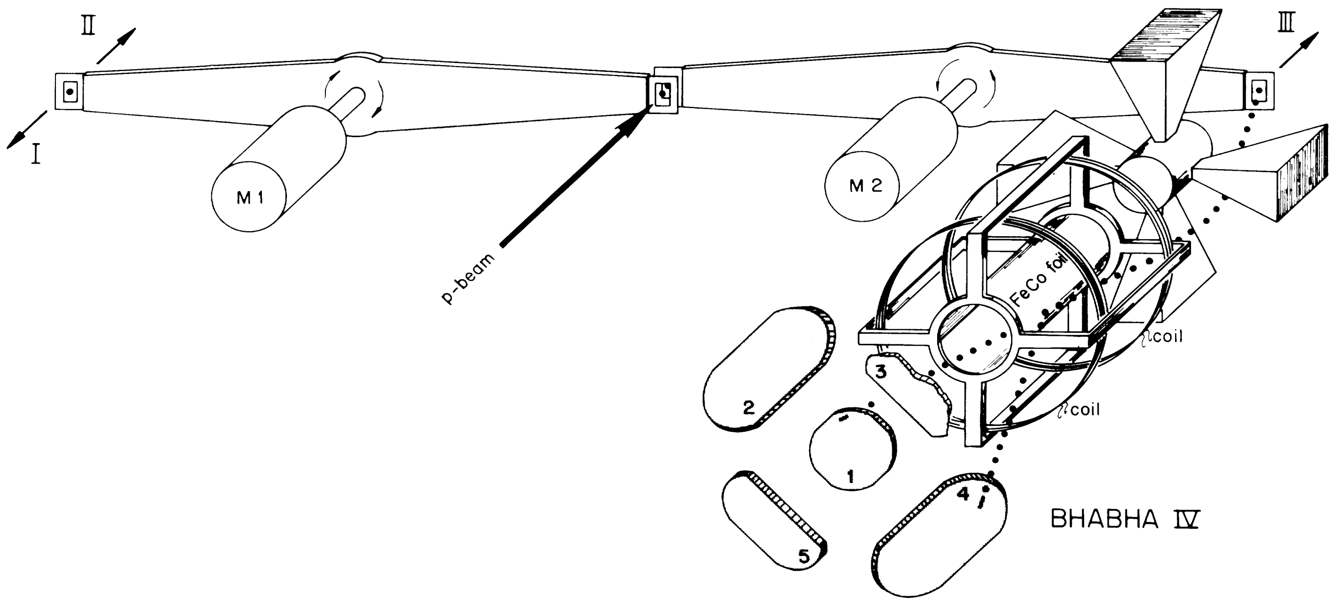

FIG. 2. Sketch of the fourfold arrangement with details on polarimeter IV. Other polarimeters (not shown) are at positions marked I, II, and III. For further details, see the text.

measured in alternating runs with the arrangement shown in Fig. 2. A ^{30}Si and a ^{26}Mg target are mounted, opposite to each other, on the tips of the rotor blades of a dual-target transport system. These double-winged target rotors, 60 cm in diameter, are made of ultralight honeycomb material and are geared by powerful stepping motors. Target activation, changing between P_F and P_{GT} runs, and adaptation of cycle periods are programmed and controlled by a microcomputer. The fourfold polarimeter is symmetrical with respect to the beam axis. On each side, two opposed polarimeters face the same activated target at right angles. During a P_F run both ^{26}Mg targets are alternately activated and measured for 2 s. Rotation between activation and measuring sites takes place in 0.25 s. To obtain equal system dead times the activation-measuring period in a P_{GT} run is changed to 47 s because of the longer lifetime of ^{30}P. During data taking and during target transport the beam is turned off, in order to avoid in-beam background and activation of the target holders, respectively.

Mini-Orange filters[13] guide the positrons from the activated targets towards cylindrical scattering foils. Each Mini-Orange consists of four wedge-shaped magnets, possessing a magnetization of 0.21 T. This configuration is tailored for an optimum transmission of about 10% at a β^+ energy of 1.85 MeV. An FeCo scatterer of 30-μm thickness is magnetized by the homogeneous, reversible magnetic field of a pair of Helmholtz coils. The foil is excited within 20 ms into saturation with a field strength of 30 A/cm. Bhabha scattering of a positron with an atomic electron can produce a twofold coincidence between any two of the five detectors. These detectors consist of Bicron plastic scintillators coupled to XP2020 photomultipliers via 150-mm-long Perspex light guides. They have a typical time resolution of 400 ps and an energy resolution of 30% at 1 MeV (FWHM). The fraction of spin-aligned electrons in the FeCo foil is 0.075. Different coincidence rates are observed when the magnetization of the foil is reversed. This is done at a frequency of 4 Hz. The energy-dependent background arises mainly from bremsstrahlung and amounts to (10–20)% of the true coincidence rate. It is independent of the foil magnetization and therefore reduces the polarization sensitivity S by 10% to 20%. The observed values of S varied from 3% to 9% for energies of incoming positrons ranging between 1.4 and 2.8 MeV. Note that the sensitivity S is identical for both P_F and P_{GT} runs and cancels in the evaluation of R. Because the strength of the holding field during measurements is only 3 A/cm, the influence of magnetic stray fields is minor, as inferred from measurements with a brass scatterer. It is 1% of the observed asymmetry and the effect on R is $\pm 1\times10^{-4}$. Data taking is inhibited during reversal and saturation of the foil magnetization.

The on-line measurements were performed with use of a proton beam of 9 MeV from the cyclotron of the Vrije Universiteit of Amsterdam. The targets were ^{30}Si pressed in tungsten gauze,[14] and ^{26}Mg foils of 6-mg/cm^2 thickness, enriched to 94% and 98%, respectively. With a beam current of 4.5 μA, the singles counting rates above the threshold of 400 keV were 250 kHz on the average, equal to within 4% for both sources. The true coincidence rate was about 0.3 kHz for each of the four polarimeters. As a result of the automated target positioning, and use of multiple diaphragms, activation of the target holders was avoided completely. The contribution of contaminants to the β^+ activity was minor and amounted to less than 10^{-3} for the $^{26}Al^m$ and $\sim 10^{-3}$ for the ^{30}P source. Furthermore, these background positrons are also longitudinally polarized, so that their effect on R is negligible.

Events were analyzed on line by dedicated hardware event processors, one for each system, in order to retain the statistical independence of the polarimeters. The data were stored in a 4k dual-port CAMAC histogramming memory. The fourteen-bit memory address contained three bits of energy information for each coincident signal, one bit distinguishing prompt and random coincidences, one bit to record the direction of foil magnetization, four bits to identify the coincident detectors, and two bits to specify the polarimeters. System dead time, the state of auxiliary controllers, and other parameters of the data acquisition system were continuously monitored and recorded by a microcomputer.

A total of 5×10^8 events was accumulated during 456 hours of beam time. Polarization data were taken in alternating P_F and P_{GT} runs of 3000-s duration. This time was sufficiently short with respect to the time scale of instrumental drifts. The polarization measurements were interrupted every 8 h for timing and energy calibrations. Values for R were calculated from maximum-likelihood analyses of pairs of P_F and P_{GT} asymmetry spectra. As a result of the symmetry of the experimental arrangement several consistency checks could be made. The ten detector pairs of one polarimeter can be considered statistically independent.[15] They were arranged into three groups, involving coincidences with the central detector (A), between two neighboring outer detectors (B), and between two opposite detectors (C). The results obtained for the individual polarimeters and for the three distinct detector geometries were statistically consistent with each other, as shown in Table I. Detector geometry C featured the highest polarization sensitivity with the lowest-event rate, whereas geometry A contributed 50% of the total event rate, but with lower sensitivity. This is reflected in the uncertainties stated in Table I. The variation in the source position along the polarimeter axes was 0.7 mm. Its influence could be investigated with long-lived β^- sources (^{106}Ru, ^{144}Ce). For this purpose, the positron (Bhabha) polarimeter was converted to an electron (Møller) polarimeter by inversion of the Mini-Orange fields. The asymmetry was found to vary linearly with a shift of the source position along the system axis. Therefore, the effect on R of a difference in the on-axis positioning of the two targets on a rotor cancels for two opposed polarimeters, but adds to the internal error of the combined result. The calculated difference in depolarization of positrons in the ^{26}Mg and ^{30}Si targets gave a correction on R of $(-8\pm4)\times10^{-4}$. The various systematic corrections are listed in Table II. The combined, uncorrected result of the four polarimeters was $R=1.004\pm0.004$. The error has been determined from the spread in the fitted R values, and was slightly larger than the uncertainty of 0.003 expected from pure counting statistics. The value of 0.004 included effects from instrumental instabilities and from small differences between polarimeters and detector combinations. After correction for the minor experimental bias of $(-9\pm6)\times10^{-4}$, introduced by the combination of all systematic effects, we obtain $R=1.003\pm0.004$.

In conclusion, our previous bounds on right-handed currents[4] could be narrowed by an order of magnitude through a fourfold realization and through basic improvements of the Bhabha polarimeter. The major progress was a doubling of the polarization sensitivity and the introduction of a new fast data-acquisition system. The running time needed for reaching a given statistical accuracy was thereby reduced by a factor of 60. For a breakthrough in accuracy beyond 10^{-3}, where nuclear recoil corrections become detectable, also polarimeters based on other concepts than Bhabha scattering have to be considered. Positron polarimeters using time-resolved positronium formation, such as presently under construction at the University of Michigan[5] and the Katholieke Universiteit van Leuven[16] may offer an elegant alterna-

TABLE I. R values per detector geometry (A, B, and C) and per polarimeter (I, II, III, and IV). Each value is the average of the fit results obtained for consecutive subsets of data, which are chosen such that they have equal counting statistics. The quoted errors are determined from the variances of the samples, formed by these subsets.

	A	B	C	Total[a]
I	0.998(0.014)	1.012(0.010)	1.009(0.012)	1.008(0.007)
II	1.010(0.011)	1.009(0.025)	1.012(0.009)	1.008(0.007)
III	0.992(0.010)	0.996(0.022)	1.027(0.010)	1.011(0.006)
IV	1.003(0.012)	0.981(0.017)	0.986(0.017)	0.994(0.008)
Total[b]	1.001(0.006)	1.000(0.010)	1.009(0.007)	1.004(0.004)

[a]Combines results per polarimeter, as weighted averages of R values from their three detector geometries.

[b]Combines results per detector geometry, with errors deduced from the variances of the samples formed by the subsets, regardless of polarimeter. The final result (underlined) is the weighted average of the R values from the three detector geometries.

TABLE II. Possible systematic effects larger than 10^{-4}.

End-point-energy difference ($^{26}Al^m - {}^{30}P$)	$(+4\pm2)\times10^{-4}$
Asymmetry in the magnetization current	$(-1\pm0.5)\times10^{-4}$
Depolarization in the sources	$(-8\pm4)\times10^{-4}$
Randoms subtraction	$(0\pm3)\times10^{-4}$
Positioning of the sources	$(0\pm1)\times10^{-4}$
Weak magnetism in ^{30}P	$(-4\pm1)\times10^{-4}$
Dead time of the electronics	$(0\pm2)\times10^{-4}$
Total	$(-9\pm6)\times10^{-4}$

tive for upscaling the present Bhabha polarimeter. We feel that the present fourfold arrangement, though perhaps not optimal in every detail, has reached the limit of feasibility.

We thank H. Wieringa of the mechanical workshop of the Laboratorium voor Algemene Natuurkunde, A. J. Hoeven, the Kernfysisch Versneller Instituut electronics department, and the cyclotron staff of the Free University for excellent help. The assistance of H. Kaper, W. Meiring, A. Stolk, and G. Wierda during the measurements is gratefully acknowledged. This work is part of the research program of the Stichting voor Fundamenteel Onderzoek der Materie with financial support from the Nederlandse Organisatie voor Zuiver Wetenschappelijk Onderzoek.

[1]J. C. Pati and A. Salam, Phys. Rev. Lett. **31**, 661 (1973), and Phys. Rev. D **10**, 275 (1974); R. N. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 566, 2588 (1975).

[2]G. Blewitt *et al.*, Phys. Rev. Lett. **55**, 2114 (1985).

[3]M. A. B. Bég *et al.*, Phys. Rev. Lett. **38**, 1252 (1977).

[4]J. van Klinken *et al.*, Phys. Rev. Lett. **50**, 94 (1983); A. Alting *et al.*, Kernfysisch Versneller Instituut Annual Report 1981, 1982 (unpublished).

[5]M. Skalsey, T. A. Girard, D. Newman, and A. Rich, Phys. Rev. Lett. **49**, 708 (1982).

[6]J. van Klinken, Nucl. Phys. **75**, 145 (1966).

[7]J. Carr *et al.*, Phys. Rev. Lett. **51**, 627 (1983); D. P. Stoker *et al.*, Phys. Rev. Lett. **54**, 1887 (1985).

[8]A. Jodidio *et al.*, Phys. Rev. D **34**, 1967 (1986).

[9]The primary input to the world average is given by J. Peoples, Nevis Cyclotron Report No. 147, 1966 (unpublished).

[10]D. Schreiber, Ph.D. thesis, Princeton University, 1983 (unpublished); B. R. Holstein and S. B. Treiman, Phys. Rev. D **16**, 2369 (1977).

[11]B. R. Holstein, Phys. Rev. C **16**, 753 (1977).

[12]H. P. C. Rood, private communication, and to be published.

[13]J. van Klinken, S. J. Feenstra, and G. Dumont, Nucl. Instrum. Methods **151**, 433 (1978).

[14]H. J. Kaper, J. van Klinken, T. Tuintjer, and V. A. Wichers, to be published.

[15]A. G. Frodesen, O. Skjeggestad, and H. Tøfte, *Probability and Statistics in Particle Physics* (Universitetsforlaget, Oslo, 1979). The correlation coefficient between R values of two detector combinations of the same polarimeter is 0.001.

[16]S. Carnoy, J. Deutsch, T. A. Girard, and R. Prieels, private communication.

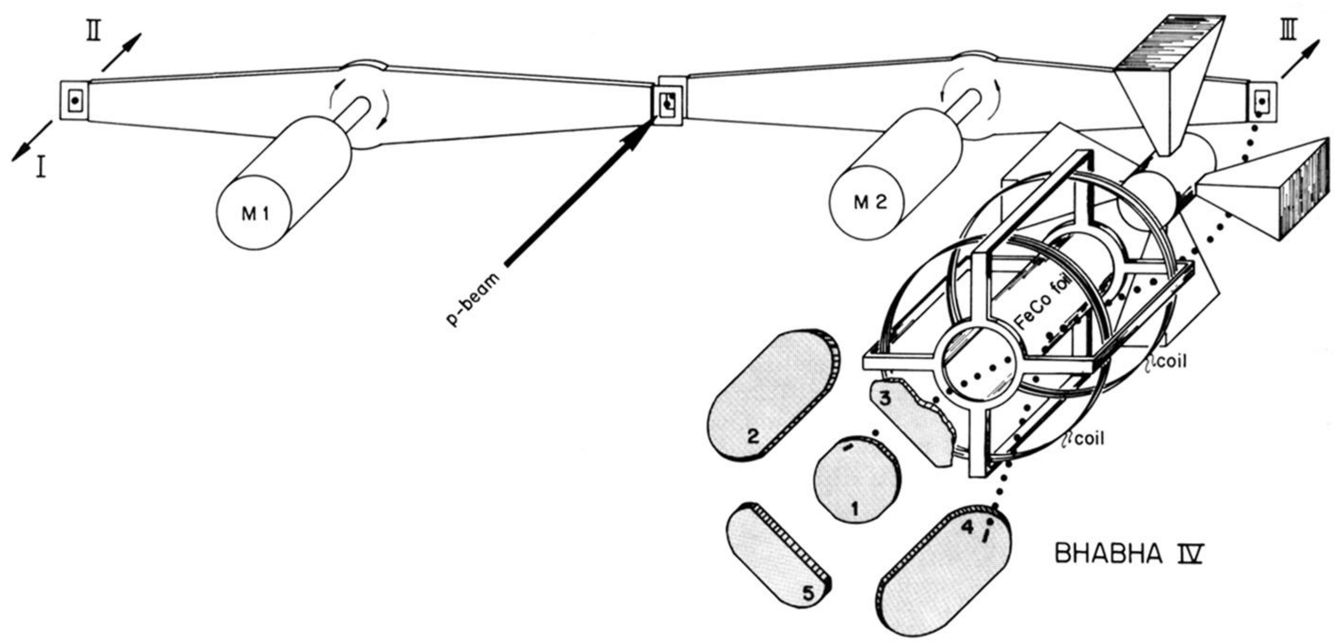

FIG. 2. Sketch of the fourfold arrangement with details on polarimeter IV. Other polarimeters (not shown) are at positions marked I, II, and III. For further details, see the text.