Limits on Right-Handed Charged Weak Currents from a Polarization-Asymmetry Correlation Experiment with ^{107}In

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A new technique, based on relative measurements of the longitudinal polarization (P) of positrons emitted in two opposite directions with respect to the nuclear polarization ($R=P^-/P^+$), is used to provide constraints on extensions of the standard model (R_0). The first result, i.e., $R/R_0=0.926\pm0.041$, was obtained with ^{107}In. Interpreted in the framework of left-right symmetric models and assuming no mixing, it provides a 90% C.L. lower limit of 225 GeV/c^2 for the mass of a possible right-handed charged W gauge boson, reducing the mass range allowed by other semileptonic experiments.

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Precision measurements of the nuclear beta decay helicity structure provide sensitive tests of the standard electroweak model (SM) and its extensions. A recent measurement of the electron asymmetry in the decay of polarized neutrons [1] has fostered speculation on the presence of right-handed currents in the semileptonic weak interaction [2,3] and new reports [4] of a possible unitarity violation in the quark-mixing matrix may also provide evidence of less than maximal parity violation. For simplicity, these deviations from the SM are interpreted in the context of the manifest left-right symmetric (MLRS) model [5], which introduces an additional, mainly right-handed charged gauge boson W_2 to restore the parity symmetry of the weak interaction at sufficiently high energies. The parameters of this model are a mixing angle ζ, and δ, which is defined as $\delta=M_1^2/M_2^2$ where M_1 and M_2 are the masses of the observed, mainly left-handed, charged gauge boson W_1 and its heavy W_2 counterpart. An analysis of the experimental data for several superallowed transitions [2] concluded that ζ must be small, in agreement with the results from the unitarity condition for the quark-mixing matrix, but that δ was 2.5 standard deviations from zero, implying that M_2 is in the range 210–320 GeV/c^2 at 90% C.L. This result is in disagreement with MLRS analyses in the purely leptonic and hadronic sectors [6] and, if real, requires invoking more complex extensions of the SM [7] which are not manifestly symmetric. New semileptonic decay experiments, preferably more sensitive to δ than the neutron and ^{19}Ne measurements used in Refs. [2] and [3], were needed to test for the presence of right-handed currents in this sector.

Here we report an experiment of this type: a ratio measurement of the longitudinal polarization of positrons emitted along (P^+) and opposite (P^-) to the direction of the nuclear polarization (the polarization-asymmetry correlation, P^-/P^+). Proposed recently by Quin and Girard [8], this novel method has the potential of high precision, and of increased sensitivity to right-handed currents compared to absolute polarization measurements. As the method is based on relative polarization measurements, a number of possible systematic effects and uncertainties are eliminated or significantly reduced. Moreover, the experiment provides constraints complementary to those obtained from measurements of the relative beta polarization $P_{\mathrm{F}}/P_{\mathrm{GT}}$ in pure Fermi and Gamow-Teller transitions [9,10]. The manifest left-right symmetric model predicts the P^-/P^+ ratio for Gamow-Teller transitions as [8]

$$R=P^-/P^+=R_0\left[1-\beta^2\frac{8\boldsymbol{\beta}\cdot\mathbf{J}A}{\beta^4-(\boldsymbol{\beta}\cdot\mathbf{J}A)^2}(\delta+\zeta)^2\right]$$
$$=R_0[1-k(\delta+\zeta)^2]\,, \tag{1}$$

where

$$R_0=\frac{(\beta^2-\boldsymbol{\beta}\cdot\mathbf{J}A)(1+\boldsymbol{\beta}\cdot\mathbf{J}A)}{(\beta^2+\boldsymbol{\beta}\cdot\mathbf{J}A)(1-\boldsymbol{\beta}\cdot\mathbf{J}A)}\,, \tag{2}$$

$\boldsymbol{\beta}=\mathbf{v}/c$, $\mathbf{J}$ is the nuclear polarization, and A is the (transition dependent) beta asymmetry parameter. The leading term, R_0, is typically on the order of unity, and can be determined from measurements of β and of the asymmetry $\boldsymbol{\beta}\cdot\mathbf{J}A$ in the decay intensity with respect to the nuclear polarization direction. The full power of the enhancement factor (k) is realized when β and $\boldsymbol{\beta}\cdot\mathbf{J}A$ are both large, i.e., close to unity. Deviations of the measured polarization ratio R from R_0 indicate a deviation from the standard model; for instance, the existence of a predominantly right-handed charged gauge boson W_2 with a mass of 250 GeV/c^2 would imply a deviation of R/R_0 from unity of about 9% for the experiment presented here. Corrections to R_0 from contributions beyond the allowed approximation will be discussed below.

The experiment presented here was carried out on the positron decay of ^{107}In which is dominated by an allowed $\frac{9}{2}^+ \to \frac{7}{2}^+$ pure Gamow-Teller transition with $\log_{10}ft = 5.7$, end-point energy $E_0 = 2.25$ MeV, half-life 32.4 m, and a maximal asymmetry parameter $A = 1$. The data were obtained with the system shown schematically in Fig. 1. The activity was produced with a 120 MeV, 4 μA ^{14}N^{4+} beam from the CYCLONE cyclotron in Louvain-la-Neuve, bombarding a Mo target placed in an ion source on the LISOL isotope separator [11]. The 50 keV, mass separated ^{107}In beam (10^5 atoms/s) was implanted continuously in an iron foil, placed inside a dilution refrigerator. The nuclei were polarized with the technique of on-line low-temperature nuclear orientation [12], at a temperature of 10 mK and in a magnetic field of 3.2 kG. Positrons were focused into the polarimeter by a spectrometer, consisting of the superconducting magnet in the refrigerator and a room temperature 0.6 kG iron-free solenoid, which selected positrons with a mean kinetic energy of 1.14 MeV (momentum resolution $\Delta p/p \simeq 27\%$) within a 1.4 sr cone oriented 35° with respect to **J**. The nuclear polarization is inverted by reversing the current in all spectrometer magnets. This was done about every 2 h. In the polarimeter the positrons crossed a Be degrader and a plastic START scintillator, before stopping in an evacuated MgO powder pellet located in a uniform magnetic field of 9.6 kG. Here, about 40% of the positrons formed positronium (Ps), the decay photons of which were detected with two BaF$_2$ STOP scintillators. Time-resolved Ps-decay spectra were obtained with a time-to-digital converter of 156 ps channel width. Timing calibration yielded a resolution of 1.4 ns FWHM. A detailed description of the polarimeter and the detection setup can be found in Ref. [10].

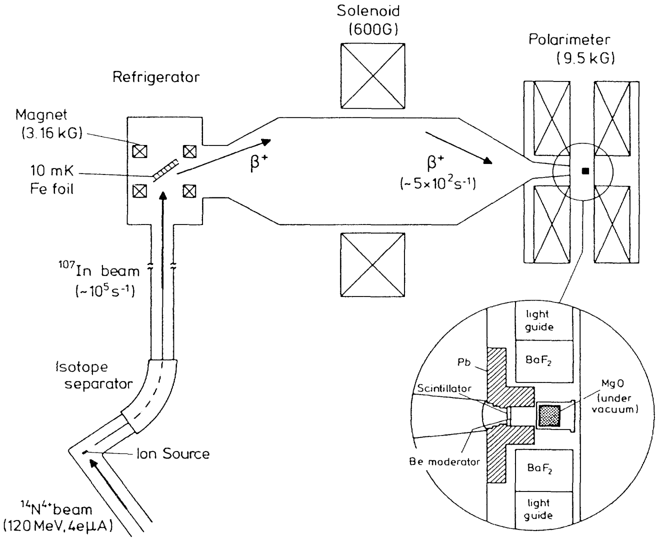

FIG. 1. Layout of the experimental setup.

The technique for measuring the positron polarization by observing the time-resolved decay spectrum of Ps hyperfine states formed in a magnetic field, has been discussed previously [13-15]. The decay spectrum can be written as

$$N^{p,a}(t) = [F(t) + T(t) + (1 \mp \epsilon P) f(t)]^{p,a}, \tag{3}$$

where N^p and N^a are the count rates for the polarimeter magnetic field parallel and antiparallel to the positron momentum, respectively, and the $-$ and $+$ signs correspond to the superscripts p and a, respectively. The polarimeter field was inverted every 4 min. Further, $F(t)$ is the contribution of direct annihilation and components with short lifetime ($\tau \le 2.5$ ns), $T(t)$ is the contribution of the unperturbed triplet state ($\tau \simeq 127$ ns), which is insensitive to the positron polarization P and used for normalization, and $f(t)$ is the contribution of the perturbed triplet state ($\tau \simeq 7.5$ ns) which depends on P and on the effective analyzing power $\epsilon \simeq 0.15$. Figure 2 shows the experimental Ps decay spectrum from one of the seven runs, together with the response function, which is obtained by replacing the MgO powder by a stack of Be foils in which all positrons annihilate directly. For time $t > 3$ ns the contribution of the "fast" component $F(t)$ is small and, normalizing to the triplet contribution $T = \sum T(t_i)$ integrated between $t_i = 80$ ns and 200 ns, we obtain the ratio of the positron polarizations for two opposite directions of the nuclear polarization ($-/+$) from

$$\frac{[N^a(t)/T^a - N^p(t)/T^p]^-}{[N^a(t)/T^a - N^p(t)/T^p]^+} = \frac{\epsilon P^- g(t)}{\epsilon P^+ g(t)} = R(t). \tag{4}$$

This ratio should be a constant, as illustrated for run No. 6 in Fig. 2(b) which shows $R(t)$ for different time bins in the polarization sensitive region of the decay spectrum. We checked the constancy of $R(t)$ also for the combination of all the runs: the χ^2 fit to a constant results in $\chi^2/\nu = 0.90$. We have used the weighted mean of the $R(t)$ values between 3 and 18 ns, as shown in the figure, to obtain the experimental value for R and R/R_0.

R_0 was calculated using the beta asymmetry $\boldsymbol{\beta}\cdot\mathbf{J}A$ determined from the intensities of the triplet component in the Ps-decay spectra, which is independent of the positron polarization, measured for opposite nuclear polarizations. To take into account variations of the source intensity, the triplet intensities were normalized to the intensity of the 205 keV γ ray in the decay of ^{107}In, taking into account the $\simeq 5\%$ anisotropy in the emission of this γ ray. The momentum calibration and the resolution of the spectrometer were obtained from a spectrometer calibration using monoenergetic conversion electrons from ^{207}Bi, which gave for ^{107}In the average value $\langle\beta\rangle = 0.9508$

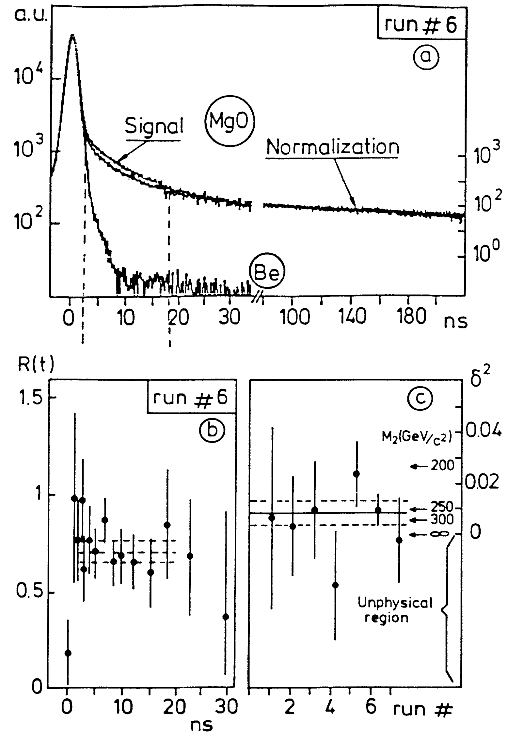

FIG. 2. (a) The experimental Ps hyperfine spectrum, showing (i) the unresolved direct annihilation and components of short lifetime (peak), (ii) the perturbed triplet (signal) and triplet (normalization) components, and (iii) the response function (Be). The difference between the two superposed spectra obtained with the MgO powder (corresponding to the two polarimeter field directions) is directly proportional to the residual polarization of the positrons forming Ps. The duration of run six was 35 h. (b) The measured polarization ratio $R(t) = P^-/P^+$ in the time interval from 0 to 30 ns. The weighted average value of 1σ errors for the polarization sensitive region between 3 and 18 ns (which is dominated by the perturbed triplet and the triplet components, as shown by the constant value of R) is indicated by the dotted lines. (c) The values of δ^2 for all seven runs (assuming $\zeta = 0$). The arrows indicate the values of δ^2 corresponding to different masses M_2 (in GeV/c^2) of a possible right-handed W gauge boson.

± 0.0030.

We checked the stability of our results for

$$\mathcal{P}^{\pm} = \frac{\epsilon P^{\pm} g(t)}{(\beta^2 \pm \boldsymbol{\beta}\cdot\mathbf{J}A)/(1 \pm \boldsymbol{\beta}\cdot\mathbf{J}A)} \tag{5}$$

in all time bins; the ratio in the denominator is the normalization characteristic of each run [see also Eqs. (1) and (2)]. For illustration sake we show also, in Table I, the values obtained for the time integral $\sum\mathcal{P}^{\pm}$ of these quantities (in the region between 3 and 18 ns), as well as χ^2/ν for their fit to a constant. Finally, the run-to-run stability of the final result is illustrated in Fig. 2(c).

The most important potential source of systematic errors is the scattering of positrons in the source foil and its backing, which can change all three measured quantities entering R/R_0, viz., $\langle\beta\rangle$, P, and $\boldsymbol{\beta}\cdot\mathbf{J}A$. From measurements carried out with a ^{68}Ga source with and without backing, the fraction of positrons scattered in the source was determined to be 5.5%. Considering the most pessimistic but unrealistic assumption that all scattered positrons had originally an energy equal to the ^{107}In end-point energy of 2.25 MeV gives $\langle\beta\rangle = 0.9508^{+0.0050}_{-0.0030}$ with negligible effect, compared to the statistical uncertainty, on R/R_0. Measurements of the positron rate as a function of the tilt angle of the source with respect to the spectrometer axis, performed with an unpolarized ^{68}Ga source, showed the dominance of small angle scattering. As a result, the correlation between the asymmetry and the polarization is preserved, implying that a correction for depolarization need not be made. This expectation is in agreement with the result obtained from a control experiment, using the ^{68}Ga source to measure the ratio of the polarizations of the scattered and unscattered positrons. The result, $P^{\text{scat}}/P^{\text{unscat}} = 0.92 \pm 0.13$, is consistent with negligible depolarization due to scattering. A possible systematic error may also arise by small time shifts of the response functions corresponding to the two nuclear polarization and polarimeter magnetic field directions. These systematic shifts, obtained from the sum of spectra p and a, were always smaller than 25 ps and were duly taken into account by shifting the corresponding time spectra. Other possible systematic errors were considered and will be discussed in more detail in Ref. [16]. They are (i) the nonvanishing contribution of $F(t)$ to our result, (ii) the effects of the difference in the positron trajectories for the various combinations of the magnetic fields, and (iii) differences in the count rates for the two directions of the nuclear polarization, i.e., about 10 and 30 counts per sec, respectively. An important check on possible systematic effects is provided by measurements performed with an unpolarized ^{107}In source, which should give $R = 1$, and we effectively obtained $R = 1.071(58)$.

The beta asymmetry $\boldsymbol{\beta}\cdot\mathbf{J}A = \beta J A\langle\cos\theta\rangle$ was typically 0.574, corresponding to a ^{107}In nuclear polarization of $\simeq 81\%$. The actual decay asymmetry allowed us to determine the standard model expectation value R_0 and the

TABLE I. The values for $\sum\mathcal{P}^{\pm}$ (defined in the text) for all seven runs, together with the χ^2/ν values for their fits to a constant.

	1	2	3	4	5	6	7	χ^2/ν
$\sum\mathcal{P}^-$	0.144(36)	0.205(24)	0.188(22)	0.218(36)	0.174(15)	0.163(14)	0.185(30)	0.82
$\sum\mathcal{P}^+$	0.129(33)	0.195(20)	0.172(17)	0.179(16)	0.191(10)	0.181(8)	0.162(18)	0.90

enhancement factor k for each run. Typical values obtained were $R_0=0.825$ and $k=8.5$. The weighted average result of all seven runs is $R/R_0=0.926\pm0.041$ ($\chi^2/\nu=0.54$).

We have evaluated the contribution to the transition rate formula of the most important form factors beyond the allowed approximation [17], i.e., that of the weak magnetism term (b), the induced tensor term (d), and the f vector form factor. Assuming for a numerical estimate the conservative values $b/Ac=d/Ac\simeq\pm20$ and $f/Ac\simeq\pm1$, where A is the mass number and c the Gamow-Teller form factor ($c\simeq0.11$), with a nuclear alignment of $\simeq38\%$, the effect of all these terms amounts to a less than 1% modification of R/R_0, which is well within our experimental accuracy.

The weighted averaged result of all seven runs for a possible contribution from right-handed currents is $(\delta+\zeta)^2=0.0087\pm0.0051$ ($\chi^2/\nu=0.61$). With the mixing angle $\zeta=0$, as obtained in Ref. [2], the sensitivity of this experimental result to the mass M_2, as reflected in the error $\sigma(\delta^2)=\pm0.0051$, is equivalent to a 1% absolute measurement of an asymmetry parameter or electron polarization [8,18]. This first result from the novel polarization-asymmetry correlation has, in fact, a better sensitivity to M_2 than the result deduced from the fourteen most precise absolute beta-polarization measurements [18], i.e., $(\delta)^2=-0.0002\pm0.0065$, where the uncertainty may moreover be optimistic due to potential systematic errors discovered later [19]. Our result is 1.7 standard deviations away from the value predicted by the standard model. Assuming $\zeta=0$, our result implies a 90% C.L. lower limit of 225 GeV/c^2 for the mass of a possible predominantly right-handed charged W_2 gauge boson [20]. This first result already reduces somewhat the region of $210<M_2<320$ GeV/c^2, allowed at 90% C.L. by all other semileptonic measurements [2,21]. We wish to stress, however, that our result is more reliable as it comes from a relative measurement and does not rely on a precise knowledge of the debated ft values of the superallowed $0^+\rightarrow0^+$ transitions. A second experiment of the same type, which is expected to yield still better precision, is at present in preparation [22].

We have limited this discussion to the manifest left-right symmetric extension of the standard model. Constraints on other types of deviations from the standard model will be discussed elsewhere [16].

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