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Left-Right Symmetry in Nuclear Beta Decay under Investigation with a New Bhabha Polarimeter

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(Received 3 August 1982)

Precise observation of the ratio P_F/P_{GT} of beta polarizations for Fermi and Gamow-Teller decays can provide stringent constraints on electroweak models. The result of a first measurement, with a Bhabha polarimeter of novel design, is $P_F/P_{GT}=0.986\pm0.038$. Resulting bounds, being comparable to those from existing muon polarization experiments, are limited by statistics. Precision of order 10^{-3} or better may be anticipated with an extended system.

PACS numbers: 23.40.Bw, 13.30.Ce, 29.75.+x

The degree of longitudinal polarization of beta rays is an important pseudoscalar quantity for studies of the electroweak interaction.[1-3] Stringent bounds on a possible left-right symmetry are set by the outcomes of two accurate experiments: the degree of longitudinal polarization P_{GT} in allowed Gamow-Teller (GT) beta decay, known[3] to 1% accuracy, and the Michel ρ parameter for muon decay, known[1] to 0.4% accuracy. In this communication, we stress the importance of the longitudinal polarization P_F in superallowed Fermi (F) beta decay and we report a first result obtained with a new positron polarimeter. To illustrate the potential of this arrangement we relate the accuracy for the parameter P_F with the accuracies reached in previous experiments: 20% for ^{14}O (Hopkins *et al.*[4]), 14% for ^{3}H (Koks and van Klinken[5]), and 4% with ^{26m}Al (present result). We shall promulgate the feasibility of arriving at progressively narrower bounds on electroweak parameters via the ratio $R=P_F/P_{GT}$.

In the standard $SU(2)_L\otimes U(1)$ model with pure $V-A$ charged currents, parity violation is maximal: $P_F=P_{GT}=1$ (in units of v/c). Any $V+A$ admixture to the weak charged current, as predicted[6] by left-right-symmetric $SU(2)_R\otimes SU(2)_L\otimes U(1)$ models with predominantly left- and right-handed W bosons of finite mass (M_1 and M_2), is reflected in a nonmaximal degree of beta polarization.[7] In terms of the ratio $\delta=(M_1/M_2)^2$ and $\epsilon=(1+\tan\zeta)/(1-\tan\zeta)$, where ζ is the mixing angle, one finds

$$P_F=2\epsilon(1+\epsilon^2)^{-1}(1-\delta)(1+\epsilon^2\delta)(1+\epsilon^2\delta^2)^{-1}, \quad (1)$$

$$P_{GT}=2\epsilon(1+\epsilon^2)^{-1}(1-\delta)(\epsilon^2+\delta)(\epsilon^2+\delta^2)^{-1}. \quad (2)$$

Clearly, a $V+A$ contribution, and thus a nonzero value of δ and ζ, has a different effect on F and GT decays, so that the ratio $R=P_F/P_{GT}$ in general differs from unity. It is this ratio that we aim to measure with high precision.

From the experimental point of view a comparative measurement is advantageous. This approach reduces the effects of various systematic errors, as noted long ago by Heintze *et al.*[8] Recently, Skalsey *et al.*[9] reported on progress with an interesting β^+ comparator based on positronium formation in a magnetic field, and made a detailed proposal for a high-precision comparison to within the 10^{-4} region. This instrument, proposed by Gerber *et al.*,[10] has now been tested to 1% accuracy with long-lived sources of GT decays. The advantages of comparative measurements led us to the construction of a polarimeter with the following design characteristics: adaptation to positrons with energies above 2 MeV, suitability for on-line operation at an activation site for short-lived radionuclides, and modest dimensions, offering perspectives for a multiple polarimeter system. A comparative measurement is the more attractive since, as also noted in Ref. 9, nature provides matching isotopes: ^{26m}Al (pure F, $E_0=3.211$ MeV, $t_{1/2}=6$ s) and ^{30}P (pure GT, $E_0=3.205$ MeV, $t_{1/2}=2.5$ min) which can be produced under the same conditions. Furthermore, corrections due to positron depolarization in source material and to radiative and Coulomb effects cancel almost completely in the ratio R; moreover, the dependence on strong form factors is small. In our case, the net effect on R can be calculated with an uncertainty less than 10^{-3}, the size of the correction itself being of order 10^{-3} (see also Ref. 11).

The polarimeter design is based on Bhabha scattering of positrons by electrons embedded in a cone-shaped foil of hyperpure iron. Figure 1 represents a sketch of the arrangement. The positrons are selected in energy by the toroidal magnetic field of a mini-orange filter,[12] the field at the same time guiding the particles towards the Bhabha scatterer. This cone-shaped foil is spanned inside a yoke, the legs being placed in the shadow of the mini-orange magnets. The spins of the scattering electrons are oriented by a magnetizing current through a coil and are inverted several times per second. This eliminates the effect of long-term variations in instrumental parameters. Scattered e^+ and e^- particles can be observed in coincidence by any pair among the five detectors. These are plastic scintillators coupled to their respective photomultipliers via 16-cm-long light guides in order to reduce interference by stray magnetic fields. A specially designed acquisition system records the energy and time information of true and accidental coincidences and sorts the data on-line. Each of the ten possible detector combinations can be considered as a separate Bhabha polarimeter. A comparison of the data from these different subunits gives information about the symmetry properties of the whole system. In the present arrangement one recognizes three detector geometries: the central plus one outer detector, two adjacent peripheral detectors, and two opposite outer detectors. Each geometry is characterized by its own polarization sensitivity function, which reflects the angular and energy dependence of the scattering process. These functions are in essence the same for the F and GT measurements, and cancel in the ratio.

The ^{26m}Al and ^{30}P sources were produced in (p,n) reactions with enriched ^{26}Mg and ^{30}Si targets of 7 mg/cm^2 thickness on 1 mg/cm^2 Ta backings, using 2 μA of 8 MeV protons at the Vrije Universiteit (Amsterdam) cyclotron. The polarization measurements were done *in situ*

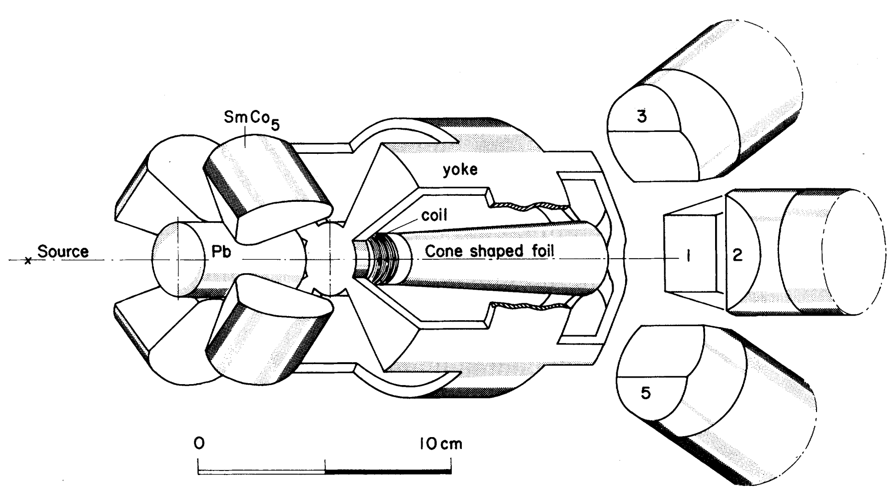

FIG. 1. Basic sketch of the new polarimeter based on Bhabha scattering in a cone-shaped foil of hyperpure iron. Only four of the five detectors are shown.

with a cycle of 0.6 s activation, 0.4 s cooling, 2.1 s data accumulation, and 0.4 s waiting. Targets were interchanged every 3000 seconds. The magnetization of the Bhabha scatterer (20 mg/cm^2 Fe) was reversed at 4 Hz. Target exchange and data collection were entirely automated and controlled by a PDP 11/03 minicomputer. The average energy of positrons effective in the Bhabha scattering was 2.2 MeV with a spread of 0.9 MeV (full width at half maximum). Events were accepted when positron and electron kinetic energies were between 0.3 and 2.2 MeV. The energy resolution of the detection channels was 19% (full width at half maximum) and the time resolution 0.8 ns. Typical counting rates were 60 kHz in the central detector and 30 kHz in the outer detectors; the true coincidence rate was 40 Hz. Differences in the yields of the two targets amounted to less than 10%. Contaminant activities could not be observed beyond a limit of 0.5% of the singles counting rates, and should actually be less than this because the 8-MeV protons open hardly any unwanted reaction channel in the targets used. Typical values for the polarization asymmetry amounted to the 4% to 5% expected for the present arrangement. An experiment with a 20 mg/cm^2 brass scatterer showed that the instrumental asymmetry is less than ~10% of the true effect. However, a residual asymmetry cancels to first order in the ratio R. In a future multiple arrangement (see below) one polarimeter can be used for precise simultaneous monitoring of instrumental effects. Other effects with their estimated influence on R are difference of depolarization in source materials ($\sim 10^{-4}$), the small (≤ 10 keV) difference in beta-ray end-point energies $[<(6\pm3)\times10^{-4}]$, and Compton scattering and beta-gamma coincidences in the decay of ^{30}P ($<2\times10^{-4}$).

The result of an experiment of eight days is $R = P_F/P_{GT} = 0.986 \pm 0.038$. The uncertainty is statistical and allows the use of P_{GT} as a calibrator with a precision of 1% (Ref. 3) This yields $P_F = 0.99 \pm 0.04$ in units v/c.

Figure 2(a) presents 90% confidence limits on δ and ζ as set by the observables P_{GT} and R. The point $(\delta, \zeta) = (0, 0)$ corresponds to the standard model and is encompassed by all experimental bounds. Previous P_{GT} values constrain δ and ζ to a valley along the line with $P_{GT} = 1$. The best previous P_F value (from measurements with tritium[5]) limits this valley far from the $V-A$ point (0, 0) but the lower R limit from the present work offers a significant reduction. The upper R limit

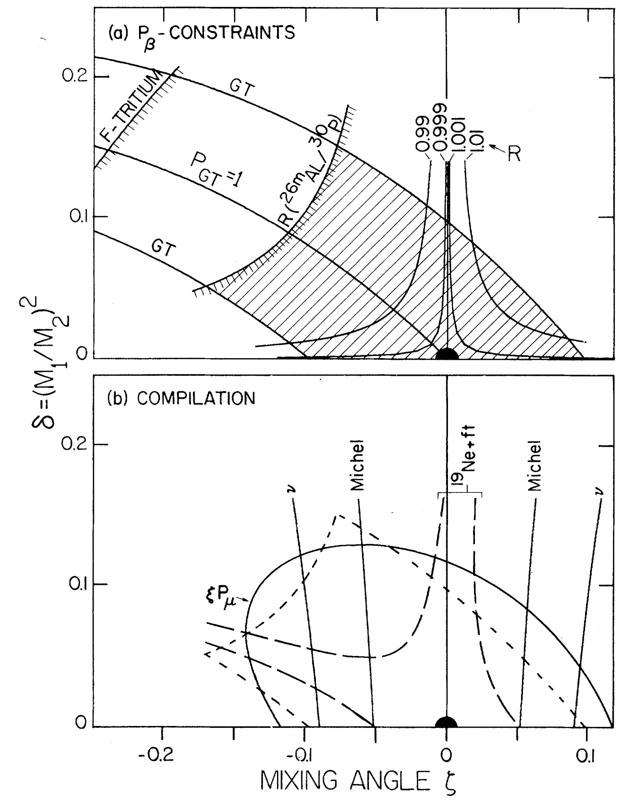

FIG. 2. Constraints in the (δ, ζ) plane (a) by P_β measurements and (b) compared with a compilation (Ref. 2) of muon (Michel ρ parameter and ξP_μ), ^{19}Ne, and ν-scattering (Ref. 13) results. The hatched region in (a) is bounded by P_{GT} and the present F/GT comparison. The set of R contours shows what progress can be expected from future ^{26m}Al/^{30}P measurements with precision 10^{-3} or better.

is less important and follows a contour (not shown) on the right-hand side of the valley. In addition to the use of nuclear β-decay observables other than P_β (and in particular other than the "clean" parameter R), $V+A$ currents are being looked for in neutrino-scattering[13] and muon-decay experiments. Present limits and projected accuracies were recently reviewed by Strovink[2] [Fig. 2(b)]. Besides providing information on the possible occurrence of a $V+A$ current, the combined results have relevance to possible neutrino masses and to universality.[2] Figure 2(b) shows that the ξP_μ and P_{GT} curves especially constrain the squared mass ratio δ, while the Michel ρ parameter and the ν results are effective in constraining the mixing angle ζ. The present P_β and R constraints are already compatible with the ξP_μ curve. The ^{19}Ne bound is derived from an ingenious combination of asymmetry in β decay of polarized ^{19}Ne and of logft values, using conservation of vector current theory.[14] Narrow, but model-dependent, bounds are derived by Beall *et al.*[15] from K^0 data.

Contours for a set of R values centered around (0, 0) are shown in Fig. 2(a). The inner curves for a hypothetical observation $R = 1$ within 0.1% accuracy would restrict the allowed (δ, ξ) region substantially, while a significant departure from the value $R = 1$ would be indicative of the presence of $V + A$ currents. Since the present limitations are purely statistical it is attractive to enlarge the number of Bhabha scattering events by orders of magnitude. We plan to improve the accuracy of the measurement of R to 0.1% or better, implying bounds on δ and ξ comparable to those promised by other groups. This improvement in the value of R will be effected by using a system of four or eight polarimeters around the same target, by using faster equipment for detection and acquisition, by data accumulation during several months, and by a number of modest steps towards improved source production and polarimeter efficiency.

The instrumentation of the Bhabha polarimeter was skillfully made by the workshops of the Laboratorium voor Algemene Natuurkunde of Groningen University. Initial tests were done with the Kernfysisch Versneller Instituut cyclotron and the ^{26m}Al/^{30}P measurements with the cyclotron of the Vrije Universiteit of Admsterdam. The 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.

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