Search for the Circular Polarization of the 1081-keV Gamma Ray in ^{18}F

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A new measurement of the circular polarization P_γ of the 1081-keV γ line in ^{18}F has been performed. The result is $P_\gamma(1081 \text{ keV}) = (2.7 \pm 5.7)\times 10^{-4}$. This result, when averaged with those of recent measurements in ^{18}F, sets an upper constraint for the absolute value of the coupling constant f_π of the weak πNN interaction of $|f_\pi| \leq 1.5\times 10^{-7}$.

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Parity nonconservation in nuclei is understood as a consequence of the weak interaction among hadrons. In the low-energy limit one expects that nuclear parity-nonconservation effects can be estimated from a parity-nonconserving potential V_{pnc}, to which there mainly contribute terms associated with the exchange of one virtual meson.[1] Among these the one arising from the exchange of one charged pion plays a peculiar role. In fact this term, which connects states with $\Delta T = 1$, determines the long-range behavior of V_{pnc} and is almost independent of the short-range part of the two-nucleon density matrix. Moreover, the value of the weak πNN coupling constant f_π comes out to be intimately related to the structure of the hadronic neutral weak currents and to the value of the quark masses.

The measurement of the circular polarization P_γ of the 1081-keV γ ray deexciting the first $J^\pi = 0^-$, $T = 0$ state in ^{18}F was recognized[2] as one of the most direct ways to determine the value of f_π. This circular polarization is induced by the parity mixing of the state at 1081 keV with the one at 1042 keV ($J^\pi = 0^+$, $T = 1$). The ratio of the lifetimes of the two states enhances by a factor 10^4 the circular polarization of the 1081-keV γ transition with respect to that of the 1042-keV one. In recent years much experimental work has been devoted to the attempt to measure the polarization of the 1081-keV γ line. The experimental value of P_γ(1081 keV) deduced as a weighted average from published measurements[3-5] is $P_\gamma = (-8 \pm 12)\times 10^{-4}$. At the same time many experimental and theoretical efforts have been made with the aim of finding a reliable and model-independent connection between P_γ and f_π; the presently accepted[6] relation is $|P_\gamma| = 4.35\times 10^3 |f_\pi|$ (with an uncertainty of $\sim 25\%$). A comprehensive summary of both experimental and theoretical results obtained up to 1983 can be found in Adelberger *et al.*[6] and Bizzeti.[7]

Till 1981 quantum-chromodynamics (QCD) calculations of f_π[8,9] set a broad range of possible values for $|P_\gamma|$, $8\times 10^{-4} \leq |P_\gamma| \leq 48\times 10^{-4}$, while quark-model estimates by Desplanques, Donoghue, and Holstein[1] (DDH) gave $0 \leq |P_\gamma| \leq 40\times 10^{-4}$, with a "best value" $|P_\gamma| = 20\times 10^{-4}$. More recently a further QCD calculation,[10] using a renormalization point and quark-mass values different from those of Ref. 8, and another one based on a rather different approach[11] taking into account the long-distance nonperturbative effects in f_π, have lowered the minimum expected value of $|P_\gamma|$ down to $\sim 4\times 10^{-4}$.

Experimentally the circular polarization P_γ(1081 keV) can be determined by measuring the asymmetry A in the counts N of the 1081-keV photopeak associated to opposite magnetization states of equal duration of a transmission-type Compton polarimeter.[3,4,5] This is done according to the relation $P_\gamma = A/S$, where S is the analyzing power of the polarimeter and A is in principle defined as $A = (N^\uparrow - N^\downarrow)/(N^\uparrow + N^\downarrow)$, where the arrows refer to the relative directions of the propagation vector of the γ-ray and the spin of the oriented electrons: Upwards arrow indicates parallel, downwards antiparallel.

Two new experiments, which reduce substantially the error in P_γ(1081 keV), have now been completed at Queen's University (Kingston, Ontario)[12] and at the University of Florence: Here we report on the experiment carried out at the 3-MV Van de Graaff accelerator of the Istituto Nazionale di Fisica Nucleare, installed in Florence. Levels in ^{18}F were populated via the reaction $^{16}O(^3He,p)$ by bombarding a water target with a $^3He^+$ beam. The beam energy was 3.4 MeV, the average current ~ 7 μA, and the total amount of charge deposited on target was 110 C. The water target was of the windowless type,[13] the advantage being that it does not require frequent maintenance and avoids carbon buildup, making the operation of the Ge detectors safer. As schematically shown in Fig. 1, the water stream passes along one diagonal of a four-prong Compton polarimeter of the transmission type, and the beam impinges on the water just in the center of the polarimeter. The polarimeter, made of Permendur 49, was placed with its prongs at 90° with respect to the beam direction. The cylindrical cores have a diameter of 52 mm and a length of 87 mm. From the measured value of the induction flux (corresponding to an internal magnetic field $B = 2.3$ T), the four prongs were verified to be equal within 0.5%, and by scaling from a previous measurement of a polarimeter made of Armco iron[14] we conservatively deduced an analyzing power (at 1081 keV) $S = (1.90 \pm 0.19)\times 10^{-2}$. The four coils are connected in series and the current loop is arranged in such a way that in the polarimeter phase

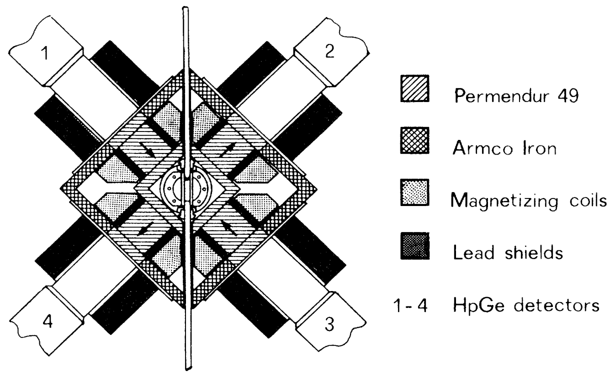

FIG. 1. Four-prong polarimeter used in this experiment. In the center of the polarimeter the water-jet target assembly is schematically shown.

denoted by "+", arms 1 and 3 are the ↓ configuration, while for arms 2 and 4 the configuration is ↑; in the current phase called "−" the situation is reversed.

Gamma rays were detected by four p-type high-purity germanium detectors. These were geometrically equal within ± 0.5 mm in both diameter and length. Efficiencies range from 28% to 30%, while summed efficiencies of faced detectors are 57.5% and 58.2%. Detectors were surrounded by 3-cm-thick lead mantles and additional shielding from scattered γ rays was provided by a 1-cm lead layer around the cores of the polarimeter. Since the counting rate in each detector could be as high as 60–80 kcps, a special linear pulse shaper was devised[15] which at 70 kcps showed a percentage of piled-up pulses of $\sim 12\%$ and a full width at half maximum (FWHM) of ~ 3 keV, referred to the 1081-keV γ line. A typical spectrum is shown in Fig. 2(a). Data acquisition was performed with four independent analyzing systems, each consisting of a 400-MHz analog-to-digital converter, equipped with analog back bias, followed by a direct memory increment circuitry acting on a 2048-channel CAMAC resident memory.[16] The memory was split into two 1024-channel subsections, which were selected, one at a time, according to the sense of the polarimeter currrent. Pulses were analyzed in the energy range 800–1580 keV. With an input rate of 60 kcps on each detector, dead time of $\sim 5\%$ and counting rates in the 1081-keV photopeak of ~ 200 cps were observed.

Data acquisition and inversion of the magnetic field in the polarimeter were controlled by a Hewlett-Packard 2108 computer. The measurement was subdivided into cycles of 320 s each; at the end of each cycle the contents of the CAMAC memory were recorded on magnetic tape as eight spectra of 1024 channels each. In the following these spectra will be referred to as "single-cycle" spectra. The pattern of polarimeter phases during one cycle was the one described in Ref. 4. At the end of the experiment a total of 46054 cycles have been accumulated. Adding up the single-cycle spectra eight "total-statistics" spectra have been obtained; in order to maintain a reasonable energy resolution each pair of single-cycle spectra belonging to the same detector, before being added, was shifted—when necessary—by an integer number of channels. The total counts of the 1081-keV photopeak are 1.22×10^{10} with a peak-to-background ratio of 2.4 (evaluated over a region 2.2 times FWHM wide).

Since the predicted asymmetry of the 1081-keV γ

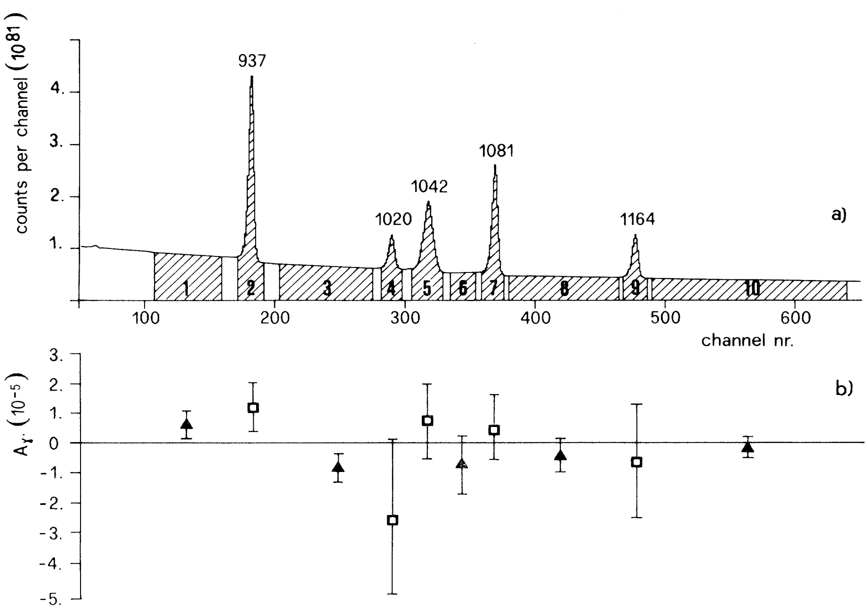

FIG. 2. (a) Typical γ spectrum; energies are in kiloelectronvolts. (b) Asymmetries of γ lines and of background regions (see Table II and Table I, column 3, respectively).

ray could be smaller than 10^{-5}, many possible sources of even tiny instrumental asymmetries must be considered.[3–5] Among the instrumental effects, those correlated with the magnetization sense, such as synchronous beam bending, are expected to introduce spurious asymmetries in the results. From magnetic field measurements the synchronous displacement of the beam spot was estimated to be less than 2 μm. In fact, displacements along the diagonals of the polarimeter were measured by the fourfold ratios $T_1^+T_2^-/T_1^-T_2^+$, $T_3^+T_4^-/T_3^-T_4^+$ (where T stands for the total contents of each total-statistics spectrum) and verified to have the expected order of magnitude. The symmetry of the apparatus makes it possible to use estimators of the asymmetry (see below) which do not depend, to first order, on either this or similar correlated effects. Other possible sources of instrumental asymmetries like those already reported[3–5] were considered (a detailed discussion will be given in a forthcoming paper[17]), but none of them was estimated to give significant contribution to final asymmetries. Since the presence of a physical asymmetry in the part of the Ge spectra due to Compton background cannot be a *a priori* excluded,[3,5] a preliminary analysis was performed with the aim of looking for possible background asymmetry to be taken into account in the subsequent calculation of the asymmetry of the γ lines. Background or background-plus-peak asymmetry has been evaluated with two procedures which, though making use of different estimators, gave identical results (in the following only the results obtained with the second procedure are reported):

$$\mathscr{A}'=\frac{1}{4}\frac{R-1}{R+1},$$

$$R=\frac{N_1^-N_2^+N_3^-N_4^+}{N_1^+N_2^-N_3^+N_4^-}=\frac{N_1^\uparrow N_2^\uparrow N_3^\uparrow N_4^\uparrow}{N_1^\downarrow N_2^\downarrow N_3^\downarrow N_4^\downarrow},$$

$$\mathscr{A}''=\tfrac{1}{4}\textstyle\sum_k A_k,\quad A_k=(N_k^\uparrow-N_k^\downarrow)/(N_k^\uparrow+N_k^\downarrow),$$

where k is the detector index and N_k is the integral over the selected energy region.

The asymmetry of five background regions and five peak zones [labeled from 1 to 10 in Fig. 2(a)] were calculated for each of the 46054 single cycles. As expected, the asymmetry values obtained from the weighted statistical average of the single-cycle values coincide with those extracted from the total-statistics spectra. These results are shown in column 3 of Table I. Standardized distributions of the single-cycle asymmetries (i.e., distributions of the single-cycle asymmetries divided by their standard deviation with only counting statistics taken into account) grouped in classes of 0.05 were fitted with a Gaussian function. As shown in Table I, column 2, the fitted widths, equal to 1 within the error, demonstrate that non-Poissonian sources of errors—like beam charge instability—give negligible contribution to the uncertainties. The next step of the analysis consisted in evaluating the asymmetries of the γ lines, taking into account the background asymmetry. A unique energy dependence of the background asymmetry was searched for by fitting with polynomials of increasing order; however, the χ^2 test on the fits did not efficiently discriminate among them. Therefore for each γ line the asymmetry A_b of its underlying background (Table I, column 4) was extracted from the asymmetries of the closest background zones reported in column 3 of Table I.

TABLE I. Column 2: fitted values of second moments of standardized distributions of the 46054 "single-cycle" asymmetries. Column 3: asymmetries of the energy regions shown in Fig. 2(a). Column 4: estimated asymmetries A_b of the background underlying the peak energy regions.

Energy region	Fitted width	Asymmetry (10^{-5})	A_b (10^{-5})
1	1.000 ± 0.003	0.55 ± 0.47	
2 (937 keV)	1.000 ± 0.003	0.46 ± 0.63	-0.05 ± 0.35
3	1.002 ± 0.004	-0.90 ± 0.52	
4 (1020 keV)	1.004 ± 0.003	-1.30 ± 1.15	-0.84 ± 0.50
5 (1042 keV)	0.999 ± 0.003	0.19 ± 0.75	-0.81 ± 0.69
6	1.000 ± 0.004	-0.78 ± 0.94	
7 (1081 keV)	1.004 ± 0.004	0.48 ± 0.77	-0.67 ± 0.67
8	0.994 ± 0.003	-0.45 ± 0.50	
9 (1164 keV)	0.996 ± 0.004	-0.69 ± 1.11	-0.20 ± 0.34
10	0.998 ± 0.004	-0.19 ± 0.41	

Procedures for calculating the asymmetry of a peak in the presence of a finite background and background asymmetry have been already reported.[3–5] Among these procedures, the ones developed in Refs. 4 and 5 exploit better the information contained in the data and render the results quite insensitive to choices of the line borders since the γ-line asymmetry—for a given detector—is obtained by weighting the information contained in each individual channel belonging to the line, with a weight proportional to the peak-to-total ratio of the channel itself.[18] We extended these procedures by calculating the asymmetry of each γ line, treating the entire set of the relevant single-channel asymmetries of the four detectors altogether. The single-channel asymmetry is defined as

$$a_{ki}=(n_{ki}^\uparrow-n_{ki}^\downarrow-2A_bB_{ki})/(n_{ki}^\uparrow+n_{ki}^\downarrow-2B_{ki}),$$

where k and i are the detector and channel indices, respectively, n_{ki} represents the channel counts, B_{ki} is the unpolarized part of the background, and A_b is the background asymmetry. B_{ki} can be determined by the background behavior in the neighboring zones. Clearly the presence of A_b and common terms in B_{ki} introduces among the single-channel asymmetries correlations which in principle cannot be disregarded. The multivariate distribution of the whole set of channel asymmetries a_{ki} is therefore introduced and the estimator of the asymmetry of the peak is obtained following the maximum-likelihood criterion (see, for instance, Brandt[19]). The present procedure, in cases where correlations are absent or negligible, coincides with the simple statistical average of the whole set of the single-channel asymmetries. Asymmetries of the five γ lines so calculated on the total-statistics spectra are reported in Table II. These results correspond to selected regions around the peak maxima 4.4-FWHM wide and show a remarkable stability with respect to different reasonable choices of the widths of the selected region. In particular for the 1081-keV γ line, in the range 2.2–4.4 times FWHM, the estimated uncertainty is stationary within 1% and the asymmetry value shows a maximum variation of only a few tenths of the uncertainty. In Fig. 2(b) the adopted asymmetries of γ lines together with those of background regions are shown. It is to be noted that none of the lines, including the one at 1042 keV, shows a sizable deviation from zero asymmetry.

Comparison of the results obtained following the adopted procedure with those obtained with procedures of Refs. 4 and 5 were also performed. With respect to the values reported in Table II, procedures of Refs. 4 and 5 gave uncertainties $\sim 1\%$ larger and asymmetry values equal within a small fraction of the estimated uncertainty, thus confirming the substantial equivalence of all these procedures. Calculations like those of Refs. 4 and 5 are less time consuming than the adopted one and therefore could be reasonably applied to each of the 46054 single-cycle spectra; the associated standardized distributions of the asymmetries have Gaussian shape and unit width. More details on all these checks will be reported elsewhere.[17]

From the measured asymmetry of the 1081-keV γ line (see Table II) and by use of the value $S = 1.9\times10^{-2}$ for the analyzing power, one obtains P_γ (1081 keV) $= (2.7\pm5.7)\times10^{-4}$. The present result, when combined with the previously published ones and with that of Evans *et al.*,[12] gives a grand average of $P_\gamma = (1.1\pm3.8)\times10^{-4}$. Neglecting contributions arising from vector-meson exchange,[6] this result leads to an upper constraint (at 1 standard-deviation confidence level) of $|f_\pi| \le 1.5\times10^{-7}$. This limit rules out a large part of DDH's reasonable range $0 < f_\pi < 11\times10^{-7}$, and is more than three times lower than the DDH "best value" $f_\pi = 4.6\times10^{-7}$. Comparison with QCD calculations shows that the present upper limit of $|f_\pi|$ is lower by a factor 1.3 with respect to the minimum value reported prior to 1981, while it is still compatible with the expected range of f_π values of Ref. 10 $[f_\pi = (0.62\text{–}3.0)\times10^{-7}]$ and Ref. 11 $[f_\pi = -(0.88\text{–}2.3)\times10^{-7}]$.

As a conclusion, one can say that although the present experimental limit reduces sizably the range of possible theoretical values of f_π, more than one theoretical interpretation is still compatible with the experimental value. Further experimental and theoretical efforts seem, therefore, necessary in order to get a deeper understanding of this subject.

TABLE II. Adopted values of the asymmetries of γ lines shown in Fig. 2(a).

γ-line energy (keV)	γ-line asymmetry (10^{-5})
937	1.16 ± 0.86
1020	-2.55 ± 2.63
1042	0.80 ± 1.25
1081	0.51 ± 1.09
1164	-0.63 ± 1.90

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[18]In Ref. 4, the final formula of the asymmetry estimator was not reported. This estimator was (symbols as in Ref. 4)

$$\mathscr{A} = \frac{\sum_i \pi_i (n_i^+ - n_i^-)}{\sum_i \pi_i (n_i^+ + n_i^-)} \frac{\sum_i \pi_i (F_i + B_i)}{\sum_i \pi_i F_i}$$

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