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ELEMENTARY PARTICLES AND FIELDS
Experiment

Experimental Value of G_A/G_V from a Measurement of Both P-Odd Correlations in Free-Neutron Decay

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Abstract—A new experimental value of the fundamental weak-interaction parameter $\lambda = G_A/G_V$ (-1.2686 ± 0.0046) is obtained for the first time by an original method that consists in measuring both P-odd correlations in free-neutron decay. © *2001 MAIK "Nauka/Interperiodica"*.

1. INTRODUCTION

The ratio of the axial-vector and vector constants of weak interaction, $\lambda = G_A/G_V$, is a fundamental parameter of the theory. Usually, it is determined from data on the neutron lifetime or on the coefficient A of correlation between the electron-emission and the neutron-spin direction. Either method requires additional data, the value of G_V from $0^+ \leftrightarrow 0^+$ transitions in the first case and the degree of neutron polarization in the second case.

In order to determine λ, we used the measurement of two P-odd correlations, $A(e, s)$ and $B(\nu, s)$, for the outgoing electron and antineutrino, respectively. The quantities λ, A, and B are related by the simple equation $\lambda = (A - B)/(A + B)$. Its form allows one to replace A and B by the actually measured products of these quantities and the neutron polarization S; that is,

$$\lambda = \frac{A - B}{A + B} \equiv \frac{SA - SB}{SA + SB}. \qquad (1)$$

Owing to this, it is not necessary to measure the beam polarization if it has the same value in both measurements.

The error in determining λ by this method is

$$\Delta\lambda = \frac{2SA \times SB}{(SA + SB)^2} \qquad (2)$$

$$\times \sqrt{\left(\frac{\Delta SA}{SA}\right)^2 + \left(\frac{\Delta SB}{SB}\right)^2}.$$

It follows that the error of $\Delta\lambda \sim \pm 0.0055$ can be achieved if $\Delta SA/SA$ and $\Delta SB/(SB)$ have been determined with the same relative error of about 1.5%. The P-odd nature of the correlations in question makes it possible to attain such an accuracy without precision spectroscopy owing to the relative character of measurement of the experimental asymmetry $X = (N^{\uparrow} - N^{\downarrow})/(N^{\uparrow} + N^{\downarrow})$ by the change in the counting rate for decay events in response to polarization reversal ($N^{\uparrow}$ versus $N^{\downarrow}$) under invariable conditions of decay-product detection.

2. EXPERIMENTAL PROCEDURE

This experiment is based on the procedure developed in measuring the correlations A [1–3] and B [4, 5]. Experience gained in combining measurements under conditions of the same experiment is summarized in [6]. This article reports on the latest technical upgrade of the setup and on the eventual result of the measurements of $\lambda = G_A/G_V$ in the PF1 beam from the reactor installed at the Laue–Langevin Institute (Grenoble, France) in 2000.

The layout of the setup is shown in the figure. The coincidence of the emergence of the decay electron and the emergence of the recoil proton was traced in the experiment. The electron energy and the time of proton delay were recorded. For this purpose, we used an electron detector (*2*) based on a plastic scintillator ($\varnothing = 75$ mm) and a proton detector (*3*) based on two microchannel plates ($\varnothing = 70$ mm).

A verification of the linearity of the scale of our electron-energy measurement and a determination of the energy of the reference source were performed

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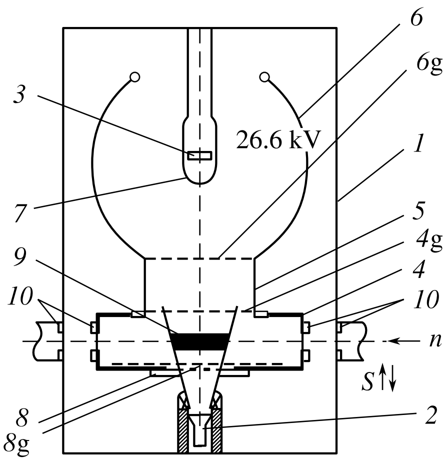

Layout of the setup used: (*1*) vacuum chamber, (*2*) electron detector, (*3*) proton detector, (*4*) electrode of the neutron-beam flight, (*4*g) grid, (*5*) time-of-flight electrode, (*6*) spherical electrode, (*6*g) grid, (*7*) spherical grid, (*8*) electron collimator, (*8*g) grid, (*9*) decay region, and (*10*) lithium collimators.

with the aid of a magnetic spectrometer by relying on the conversion lines of ^{198}Au, the relevant accuracy being about 1%. Thus, the accuracy in calibrating the energy of recorded electrons was determined completely by the electron-detector energy resolution dE/E, which was about 25% at $E = 200$ keV.

The detectors were placed opposite each other on the two sides of the neutron beam. The beam region (*9*) where decay events were recorded was separated by a collimator (*8*) arranged between the beam and the electron detector. Emphasis on decay-electron recording ensured an unaltered determination of the decay region in the measurements of SA and SB, because it was independent of the conditions of proton recording.

Protons that had passed through the time-of-flight electrode (*5*) and the grid labeled with the symbol *6*g in the figure were focused onto the detector by the electric field of a quasispherical capacitor formed by two electrodes (*6*, *7*). The diameter of the focusing-system inlet window, covered with the grid *6*g, was 260 mm. An experimental test showed that, at a voltage of 26.6 kV, all protons that had passed through this window were collected at the detector within a spot of diameter less than 50 mm.

In the requirements on the flight base, which determines the proton delay time, there is a contradiction between the measurements of SA and SB. In order to ensure optimal conditions in both measurements, the setup was designed in such a way that the focusing system, together with the proton detector, could be movable. This made it possible to change the length of the time-of-flight electrode, without breaking a vacuum, from 35 mm in measuring SA to 145 mm in measuring SB.

In measuring SA, the coincidence of the electron and the recoil proton was used only to separate the decay electron. In this case, a loss of protons would lead to a methodological error. The removal of all protons from the decay region (*9*) and their transfer to the detector *3* was ensured by a voltage of 2 kV applied between the grids *4*g and *8*g. That there were no impediments associated with the electrode *5* at the length of 35 mm was checked by consequently shutting off the paths of protons punching through the grids *6*g and *7*g. This showed that, to within fractions of a percent, there were no trajectories passing through 15% of the grid area at the grid periphery.

In measuring SB, it was impossible to determine directly the antineutrino momentum, but it could be calculated for any electron energy E_e on the basis of the recoil-proton momentum and its projection onto the electron momentum. This enabled us to measure the (ν, s) asymmetry by analyzing changes in the shape of the proton-delay spectrum in response to polarization reversal. The observed shape of this spectrum is governed by the position of the electrode *5*, its flight-base length, which was equal to 145 mm, ensuring the required accuracy of the analysis of proton delay time.

The emission of the photon accompanying neutron decay can distort such an analysis, but the degree of distortion in a particular experiment depends on the conditions under which decay events are recorded. The calculation performed in [7] showed that the role of photon emission is negligible in our case.

The vacuum chamber used was surrounded by three pairs of current loops that induced the guiding magnetic field of 4×10^{-4} T and ensured the compensation of the Earth's field to a value not higher than 3×10^{-6} T. The radio-frequency flipper was switched on and off to reverse polarization. The sign of the guiding field was changed periodically to suppress the possible uncertainty associated with the calculation of the contribution of the $a(e, \nu)$ correlation of the outgoing antineutrino and electron and the uncertainty associated with effects that could be caused by an asymmetry in flipper operation.

3. STRUCTURE OF AMPLITUDE–TIME MEASUREMENTS

Information about the recorded coincidences of signals from the electron and proton detectors was accumulated as two-dimensional $[E_i, t_k]$ matrices $[(i = 1\text{–}64) \times (t = 1\text{–}256)]$ for the electron energy E and the proton delay time t. In the run of 1998 [6], data accumulation was implemented in the CAMAC standard. A radically new measuring system with sorting performed directly by a computer was used in the latest measurements. This system employs the VME standard [8]. It has two parallel event-recording channels (the electron and the proton one) synchronized by a unified time scale. Time measurement by counting quartz-generator signals ensured, to a high degree, invariability of the scale-division unit of the time channel and enabled us to fix the proton-delay time with a precision of about 15 ns.

For each event, the system forms a single "word" that carries, in a coded form, information about the time of pulse arrival, the pulse amplitude, and the flipper state and records this word in one of the two buffers of the crate buffer memory, which are used alternately within a 0.4-s cycle. While event accumulation proceeds in one buffer, the data accumulated in the other buffer over the preceding 0.4-s cycle are transferred to the computer, processed, and summarized in its long-time memory in the form of four $[E, t]$ matrices, whereupon this buffer is cleared for a new cycle.

For the usual proton-delay time, the coincidence of events for the two flipper states were sorted in the first pair of matrices. Events accumulated there consisted of true neutron-decay events and random coincidences caused by loads of the electron and the proton channel. The second pair of matrices accumulated only random coincidences. For this, the same channel loads were sorted under the condition of an additional delay organized in the proton channel in order to remove correlated events from the coincidence range. The remaining counts were due only to random coincidences at the unchanged load of the electron and the proton channel.

The difference of the event and the background matrix separates neutron-decay events, while their sum makes it possible to determine the statistical error of the calculation. The sum of the matrices corresponding to the two flipper states yielded the matrix of the unpolarized experimental spectrum.

In measuring SA and SB, this system was adopted without any changes. The measurements of SA and SB were based on 865000 and 375000 decay events, respectively. Sixteen sets of measurements were performed for the SA–SB pair. The energy scale was calibrated by using a reference electron source for each set of measurements of SA and SB.

4. COMPUTER MODEL OF THE EXPERIMENT

In order to calculate the sought correlations, it is necessary to know the mean values of the relative electron velocity and of the cosines of the angles of emission of the neutron-decay products. They were calculated by means of a Monte Carlo code that was developed for a beta-decay simulation and which was successfully used in the experiment reported in [5]. The model took into account all necessary geometric parameters, the decay-electron spectrum in the form of the Fermi function, the response functions of the electron and the proton detector, the properties of the amplitude analyzer and of the time-to-code converter, and the calculated map of the field between the electrodes *6* and *7*. In order to process the results of the measurement of SA, a calculation of proton acceleration in the field between the grids *4*g and *8*g was included in the code.

The results of the simulation were represented in the form of four matrices in terms of the same coordinates i and k as those used in the experimental matrices. One of the matrices contained the calculated two-dimensional spectrum for an unpolarized beam, while the other three matrices contained the accumulated sums of the values of $\cos\theta_\nu$, $v/c \times \cos\theta_e$, and $v/c \times \cos\theta_{e,\nu}$. These data made it possible to obtain the required mean values for any chosen part of the matrix.

A comparison of the experimental and calculated spectra was performed with the aid of a special code that scanned all experimental spectra in order to choose the required intervals of the energy and time channels, calculated the sum of the matrices corresponding to the two flipper states in these channels, selected the same channels in the calculated two-dimensional spectrum for an unpolarized beam, compared the matched spectra in the normalized form, and calculated the SB value for them.

In processing the results of the measurements of SB, the matching of the matrices obtained from the experiment and from the simulation is the most delicate procedure, which is based on the analysis of the time-spectrum shape.

5. CALCULATIONS OF SA AND SB

Coincidences for calculating SA were selected by summing events in the interval extending from the 16th to the 56th energy channel and corresponding to events associated with an electron energy of 200 to 800 keV and in the interval from the 67th to the 88th time channel, where there was a peak of neutron-decay events. The delay of the decay proton ruled out the background of instantaneous coincidences caused by recording cascade photons and rescattered electrons. The resulting values of $(N \pm \Delta N)^\uparrow$ and $(N \pm \Delta N)^\downarrow$ were used to calculate the relative variation in the counting of decay events and its statistical error $(X \pm \Delta X)$ for each of 16 sets of measurements.

The product SA and the statistical error in it are related to $X \pm \Delta X$ by the equation

$$SA \pm \Delta SA = \frac{X \pm \Delta X}{\langle v/c \times \cos\theta_e \rangle}, \tag{3}$$

where $\langle v/c \times \cos\theta_e \rangle$ is the mean value of the product of the relative electron velocity and the cosine of its emission angle. This mean value was calculated from the lower energy threshold of electron detection on the basis of the energy-scale calibration by a reference source. The calibration accuracy was about 0.5 of a channel for the maximum of the source peak in the 46th or 47th channel.

At 200 keV, $\langle v/c \times \cos\theta_e \rangle$ was equal to 0.806 ± 0.001. The error was determined from the variation of $\langle v/c \times \cos\theta_e \rangle$ in response to the variation of the energy boundary of the 16th channel within the calibration accuracy. The precision of SA measurement by this procedure was $\pm 0.12\%$. Its sign tended to be random in some sets; therefore, the error is four times less over 16 sets.

Two corrections were introduced in calculating SA. The experimental correction took into account a 0.6% reduction of the (e, s) correlation because of recording decay electrons scattered in the chamber. It was measured to within 10% with aid of the reference source by using the number of counts for the fraction of its electrons hitting the detector as the result of scattering in the chamber. The methodological uncertainty in SA from the introduction of this correction is $\pm 0.06\%$.

The theoretical correction took into account the mimicking of (e, s) asymmetry due to the weak-magnetism effect and the G_A–G_V interference. This correction was calculated on the basis of the formulas for A from [9]; the result is 0.012. To correct SA for it, this correction should be multiplied by the degree S of neutron polarization, but the resulting correction to the correction appears to be negligible (about 0.00007) because of the smallness of the theoretical correction itself.

The weighted mean value over 16 individual measurements of SA was $SA = -0.1097 \pm 0.0016$, the distribution of their results being normal with standard deviation $\sigma = \pm 0.0014$. The total methodological uncertainty associated with the determination of the energy of the 16th channel and with taking into account electron scattering in the chamber is $\delta SA/SA \sim 0.09\%$.

In measuring SB, the relative change X in counting depends simultaneously on three correlations, SA, SB, and a:

$$X = \frac{SB\langle \cos\theta_\nu \rangle + SA\langle v/c \times \cos\theta_e \rangle}{1 \pm a\langle v/c \times \cos\theta_{e\nu} \rangle}. \tag{4}$$

We used the value of -0.1097 ± 0.0016 for SA and the value of -0.1017 ± 0.0051 for a, which were obtained in the present experiment and in [10], respectively. The error in a allows one to calculate the contribution of the correlation to a precision higher than 0.4%. The symbol $\pm$ indicates the change in the relative sign of the contributions to X from the even correlation a and the odd correlations SA and SB upon the reversal of the direction of the guiding magnetic field.

The sought asymmetry SB and the statistical error in it were found for each $[E_i, t_k]$ cell of the experimental and calculated matrices from relative variations in counting decay events, $(X \pm \Delta X)_{i,k}$:

$$(SB \pm \Delta SB)_{i,k} = \frac{(X \pm \Delta X)_{i,k} \times (1 \pm a\langle v/c \times \cos\theta_{e\nu}\rangle_{i,k}) - SA\langle v/c \times \cos\theta_e\rangle_{i,k}}{\langle \cos\theta_\nu \rangle_{i,k}}. \tag{5}$$

After that, these values were averaged over the selected intervals of the energy and time channels. The uncertainty in matching the experimental and calculated matrices determines the methodological uncertainty of this procedure. Three individual features of the experimental time-coincidence spectra made it possible to control it.

First, the peak of instantaneous correlated coincidences determined the position of the absolute time zero to a precision of 1.5 channels.

Second, the delay of the arrival of the fastest protons is virtually independent of the electron energy, since it is determined by the sum of the electron and the antineutrino momentum. The value of this delay enabled us to measure directly the length of the flight base, a basic geometric parameter that controls the shape of the time spectrum.

Finally, the width of the time-delay spectrum of decay protons is extremely sensitive to the actual value of the decay-electron energy, because it is determined by the difference of the electron and the antineutrino momentum. For example, a transition from $E = 340$ keV to $E = 511$ keV changes the width by a factor of 2, from 80 to 40 channels. This allowed one to verify the correctness of the energy-scale division chosen on the basis of the identity of matching the calculated and measured time spectra in various regions of the energy spectrum and used in the calculation.

A constant value of the asymmetry SB within

Table

	1	2	3	4	5	6	7	8
λ	−1.2959	−1.2927	−0.2731	−1.2595	−1.2396	−1.2567	−1.2969	−1.2839
$\Delta\lambda$	0.0235	0.0196	0.0189	0.0211	0.0177	0.0188	0.0171	0.0169
	9	10	11	12	13	14	15	16
λ	−1.2800	−1.2659	−0.2813	−1.2451	−1.2484	−1.2567	−1.2870	−1.2658
$\Delta\lambda$	0.0186	0.0187	0.0187	0.0163	0.0200	0.0144	0.0203	0.0181

the statistical errors as obtained by averaging $SB_{i,k}$ events over 15 intervals of $\langle\cos\theta_\nu\rangle$ was the final criterion of the correctness of matching the matrices. This criterion is especially sensitive in the region where the zero of the experimental asymmetry must coincide with the zero of the calculated cosine. The methodological uncertainty caused by the use of this criterion was found from the change in SB associated with small variations in the energy-scale division such that they did not lead to any appreciable changes in $SB_{i,k}$ in this region. The uncertainty determined by using this method did not exceed one-third of the statistical error in an individual set.

The statistical error in the measurement of SB in an individual set was $\Delta SB/SB \sim 1.7\%$. The weighted mean value over 16 individual measurements of SB was $SB = 0.9233 \pm 0.0037$, the distribution of their results being normal with standard deviation $\sigma = \pm 0.0047$. The methodological uncertainty was ± 0.0012. The difference of the statistical error and the standard deviation is in agreement with the above estimate of the methodological uncertainty.

6. CALCULATION OF $\lambda = G_A/G_V$

We used formulas (1) and (2) to calculate $\lambda = G_A/G_V$. Sixteen individual values obtained for G_A/G_V are quoted in the table.

The weighted mean value over 16 measurements is $\lambda = -1.2686 \pm 0.0046$. A statistical analysis shows that the distribution of the 16 individual values is normal with standard deviation $\sigma = \pm 0.0048$, which corresponds to the normalized χ^2 value of 1.08.

The methodological uncertainty in the resulting value of λ was found from the change in its value in response to variations in SA and SB within the methodological uncertainties in them. The result is $\delta\lambda = \pm 0.0007$.

The value of $\langle SB\rangle = 0.9233 \pm 0.0047$ determined in this study and the correlation coefficient $B = -2(\lambda - \lambda^2)/(1 + 3\lambda^2) = 0.9876 \pm 0.0004$ corresponding to the value obtained for λ make it possible to determine precisely the polarization of the neutron beam used ($S = \langle SB\rangle/B = 0.935 \pm 0.005$). A direct measurement of this polarization by the second-reflection method yielded $S = 0.940 \pm 0.010$. Good agreement of these values is an independent piece of evidence for the correctness of the procedure used.

7. CONCLUSION

For the first time, the fundamental quantity λ has been determined by using only experimental data on free-neutron decay induced by weak interaction (without recourse to data from any other measurements).

A key point of our experiment has been the use of two P-odd correlations. This has ensured an effective link between λ and the measured quantities, eliminated the need for polarization measurements, and rendered measurement of the experimental asymmetry relative.

We have obtained a new experimental value,

$$\lambda = -1.2686 \pm 0.0046 \pm 0.0007,$$

that agrees well with the world-average value recommended by the Particle Data Group and deduced from the measurements of correlations:

$$\lambda = -1.2670 \pm 0.0035\ [11].$$

Our result for λ has enabled us to calculate the corresponding values of the angular-correlation coefficients a, A, and B and the degree S of polarization of the beam used:

$$a = -0.1045 \pm 0.0014,$$
$$A = -0.1168 \pm 0.0017,$$
$$B = 0.9876 \pm 0.0004,$$
$$S = 0.935 \pm 0.005.$$

The correctness of our procedure has been verified by a direct polarization measurement that was based on the second-reflection method.

A low level of the methodological uncertainty opens the possibility for improving further the accuracy in testing the standard theory of weak interaction.

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