Phys. Rev. Lett. 30, 1346 (1973).
[2]M. Gell-Mann and F. E. Low, Phys. Rev. 95, 1300 (1954); E. C. G. Stueckelberg and A. Petermann, Helv. Phys. Acta 24, 153 (1951).
[3]C. G. Callan, Jr., Phys. Rev. D 2, 1541 (1970); K. Symanzik, Commun. Math. Phys. 18, 227 (1970), and in *Springer Tracts in Modern Physics*, edited by G. Höhler (Springer, Berlin, 1971), Vol. 57, p. 222.
[4]S. Weinberg, Phys. Rev. 118, 838 (1960).
[5]K. G. Wilson, Phys. Rev. D 3, 1818 (1971).
[6]Violations of dimensional analyses are easy to find in renormalized perturbation theory. For example, in quantum electrodynamics, for the Pauli form factor $F_2(t)$ to order α^3, we have

$$(m\partial/\partial m+\lambda\partial/\partial\lambda)\,\mathrm{Im}F_2(\lambda^2 t)=\tfrac{1}{2}m^2\pi^3(\alpha/\pi)^2\delta(\lambda^2 t-4m^2).$$

See R. Barbieri, J. A. Mignaco, and E. Remiddi, Nuovo Cimento 11A, 824, 865 (1972).
[7]By "analog of (7)" we mean the obvious:

$$(\textstyle\sum_i m_i\partial/\partial m_i+\sum_j \mu_j\partial/\partial\mu_j+\lambda\partial/\partial\lambda)\varphi=0,$$

where m_i are the fundamental masses of the theory and the μ_j represent the possible (Euclidean) renormalization points.
[8]K. G. Wilson, Phys. Rev. 179, 1499 (1969).
[9]For further references to the discussion of C_n in this connection, see the references in Ref. 1.

New Experimental Limit on T Invariance in Polarized-Neutron β Decay*

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We report an improved experimental upper limit for D, the triple-correlation coefficient in polarized-neutron decay. A nonzero value for this coefficient implies a breakdown of T invariance. We find that $D=-(1.1\pm1.7)\times10^{-3}$, consistent with T invariance.

We are reporting a new measurement of D, the triple-correlation coefficient[1] in the β decay of the polarized free neutron. This coefficient is responsible for a term in the decay rate equal to

$$D\vec{\mathrm{P}}\cdot(\vec{\mathrm{p}}_e\times\vec{\mathrm{p}}_{\bar{\nu}})/E_eE_{\bar{\nu}}, \quad (1)$$

where $\vec{\mathrm{P}}$ is the neutron polarization and $\vec{\mathrm{p}}_e$, $\vec{\mathrm{p}}_{\bar{\nu}}$, E_e, and $E_{\bar{\nu}}$ are the lepton momenta and energy, respectively. Since this quantity is odd under time reversal, a measurement of its coefficient D provides a test of T invariance, provided final-state interactions and momentum-transfer-dependent effects can be neglected. In neutron β decay the only significant final-state interaction is the Coulomb interaction, and the contribution to D from this interaction vanishes in a pure $V-A$ theory.[2] With present measured limits on possible scalar and tensor terms[3] in the effective weak Hamiltonian, this contribution is at most 10^{-3}. The principal momentum-transfer-dependent contribution to D is due to weak magnetism and has been calculated[4] using the conserved-vector-current hypothesis to be 2×10^{-5}. A measurement of D therefore provides a test of time-reversal invariance valid at least to the level of 10^{-3}.

The precision of the best previous measurement[5] of D was severely limited by counting statistics. A polarized-neutron beam intensity of 3×10^7 neutrons/sec yielded a counting rate of only 1/min, which allowed observation of 10^5 decay events. The resulting value of D was -0.01 ± 0.01.

In the present experiment, a beam intensity of 10^9 neutrons/sec was achieved. Furthermore, since the beam consisted of cold neutrons (mean velocity ≈ 1100 m/sec) rather than the previously used thermal neutrons (2200 m/sec), a further twofold increase in the effective source strength was obtained. In addition, we have improved the detection geometry, so that a counting rate of 1.5 decays/sec was observed. Based upon observation of more than 5×10^6 events, we report the value

$$D = -(1.1 \pm 1.7)\times10^{-3},$$

where the error quoted is 1 standard deviation and is dominated by counting statistics. This value is consistent with T invariance and corresponds to a phase angle φ between the coupling constants g_A and g_V given by

$$\varphi = 180.14 \pm 0.22°.$$

The experiment was performed at the high flux reactor (central flux $= 1.5\times10^{15}$ neutrons/cm^2 sec) of the Institut Laue-Langevin in Grenoble. Figure 1 shows the arrangement of the experiment. The beam was obtained from H14 (A in the figure), one of the five curved guide tubes viewing the liquid-deuterium cold-neutron moderator. The curvature of this guide tube ($\lambda_{\mathrm{cutoff}} = 2.8$ Å) allowed high transmission of cold neutrons but effectively removed nearly all fast neutrons and γ rays originating in the reactor core, which would otherwise have constituted an intense source of background. The flux of the cold-neutron beam leaving H14 was 3×10^9 neutrons/cm^2 sec. The beam was then polarized by a magnetized curved guide tube (B). This instrument has been described previously.[6] The mean polarization of the beam

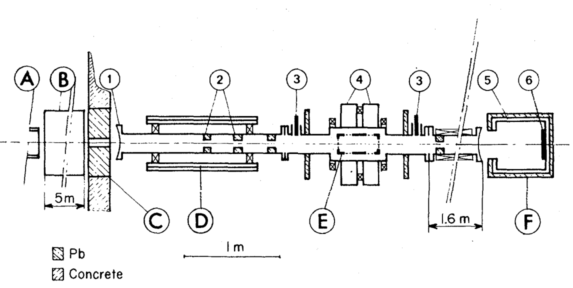

FIG. 1. Vertical section of the experimental setup: A, curved neutron-guide tube H14; B, polarizing guide tube; C, shielding; D, spin flipper; E, detection chamber; F, beam catcher; 1, Al entrance window to vacuum chamber; 2, beam collimators (Li^6F and Pb); 3, gate valves; 4, detectors; 5, LiF; 6, Li^6F.

was measured to be $(70\pm7)\%$ using a second magnetized guide tube as analyzer. The polarization measurement was performed both before and after the experiment as well as at approximately 2-week intervals during the $2\frac{1}{2}$-month period of data collection. No variations in the polarization were observed.

Upon leaving the polarizer, the beam had an intensity of 10^9 neutrons/sec and was roughly 5 cm high and 6 mm wide. The polarization direction, initially vertical, was adiabatically turned into the beam direction by means of the two coils of the spin flipper (D). For simple spin transmission, these two coils generated parallel magnetic fields, while spin flip was accomplished by reversing the current in the first coil, as suggested by Drabkin *et al.* and Hughes and Burgy.[7] With the two coils thus producing opposing magnetic fields, a region in which the combined magnetic field rapidly reversed direction was generated approximately midway between the coils. The neutron beam passed this region nonadiabatically and thereby underwent a spin flip. Depolarization of the beam in this low-field region was prevented by surrounding the entire two-coil spin flipper with a three-layer magnetic shield to exclude stray fields. The spin-flipping efficiency of this apparatus was 97%. During the experiment, the neutron polarization was reversed every second. The 3-G guide field in the decay region (E) was, of course, constant both in direction and magnitude to minimize gain shifts of the photomultiplier tubes. This guide field was maintained parallel to the beam direction within an error of 1°. After the decay region, the beam passed through a drift tube into the beam catcher (F).

A cross section of one section of the decay chamber is shown in Fig. 2. The beam direction was perpendicular to the plane of the paper. The decay chamber consisted of two such sections in series, for a total of eight detectors. Since the momentum of the neutron may be neglected, conservation of linear momentum allows the term (1) to be written

$$D\vec{\mathrm{P}}\cdot(\vec{\mathrm{p}}_p\times\vec{\mathrm{p}}_e)/E_eE_{\bar{\nu}},$$

where $\vec{\mathrm{p}}_p$ is the momentum of the recoil proton. The experimental geometry maximized the triple product by arranging the three vectors to be mutually perpendicular. At the same time the symmetrical arrangement greatly reduced systematic errors, as will be made clear below. Decay electrons originating from the beam (1) were detected by means of conventional plastic scintillation de-

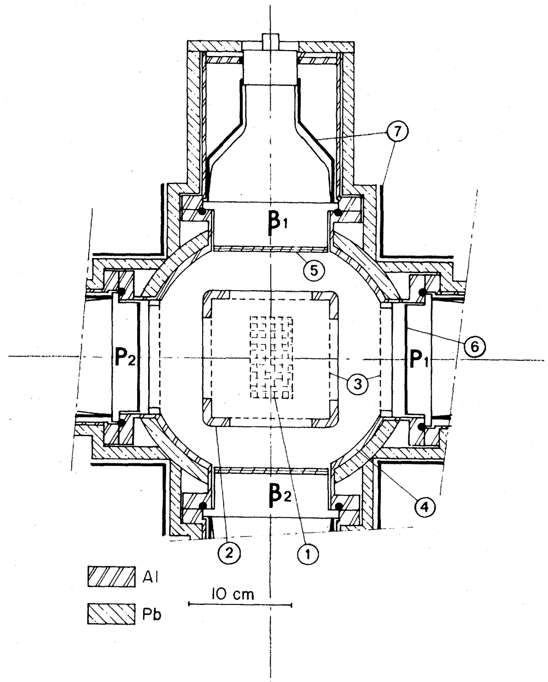

FIG. 2. Cross section of one section of decay chamber: 1, polarized neutron beam; 2, high-voltage box (20 kV); 3, proton-acceleration gap; 4, vacuum-chamber wall; 5, plastic scintillation β detector; 6, vacuum-evaporated 4000-Å layer of NaI(Tl) for proton detection; 7, magnetic shielding for photomultiplier tubes.

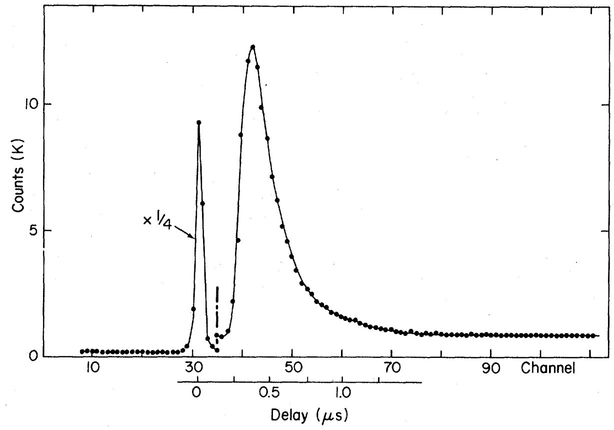

FIG. 3. Time-delay spectrum for coincidence pair $\beta 2p1$ for one of the two spin states. These data represent about two weeks of running time.

tectors (5) biased to accept electron energies between 100 and 500 keV. The recoil protons, after drifting through the field-free region inside the high-voltage box (2), were accelerated to 20 keV in the gap (3) and were counted by scintillation detectors (6) consisting of a vacuum-evaporated 4000-Å layer of NaI(Tl). The extreme thinness of these detectors allowed reduction of background while maintaining sensitivity to the protons. Special handling of the detectors was necessary because of the extremely hygroscopic character of NaI.

The electronics was based upon a single, multiplexed time-to-pulse-height converter which was started by pulses from the β detectors and stopped by pulses from the proton detectors. The sixteen resulting time spectra (four coincidence pairs for each sign of the neutron spin and for each of the two detector sections) were routed into separate regions of the memory of a 4096-channel analyzer. Figure 3 shows a time-delay spectrum for the coincidence pair $\beta 2p1$. The peak at channel 31 corresponding to $t=0$ is caused by background radiation being scattered from one detector into another. The broad peak at 0.4 μsec is due to the recoil protons, while the flat background is caused by accidental coincidences. The 0.4-μsec decay corresponds quite well with calculation of the transit time of the recoil protons from the decay volume through the field-free region and into the proton detector. The number of true coincidences was determined by simple subtraction of the flat background from the integrated recoil-proton peak.

The data are analyzed as follows. Let $\vec{N}_{\beta i p j}$ and $\overleftarrow{N}_{\beta i p j}$ be the numbers of true coincidences between β detector i and proton detector j for the two directions of the polarization vector. Thus

$$\overleftarrow{N}_{\beta 1 p 1}=c\Omega_{\beta 1}\Omega_{p1}\overleftarrow{e}_{\beta 1}\overleftarrow{e}_{p1}(1+KPD),$$

$$\vec{N}_{\beta 1 p 1}=c\Omega_{\beta 1}\Omega_{p1}\vec{e}_{\beta 1}\vec{e}_{p1}(1-KPD),$$

etc., where c is a constant proportional to the beam intensity, the Ω's are the solid angles subtended by counters $\beta 1$ and $p1$, and the e's are the detection efficiencies, where the possibility of shifts in these efficiencies as a function of the polarization direction has been allowed for. K is an instrumental coefficient, which for our apparatus has been calculated to be 0.45 ± 0.05.

Forming the combination

$$R=\frac{\overleftarrow{N}_{\beta 1 p 1}}{\vec{N}_{\beta 1 p 1}}\frac{\vec{N}_{\beta 1 p 2}}{\overleftarrow{N}_{\beta 1 p 2}}\frac{\vec{N}_{\beta 2 p 1}}{\overleftarrow{N}_{\beta 2 p 1}}\frac{\overleftarrow{N}_{\beta 2 p 2}}{\vec{N}_{\beta 2 p 2}}=\frac{(1+KPD)^4}{(1-KPD)^4},$$

it will be seen that variations in counter efficiencies, solid angles, and beam intensity are canceled. The symmetrical detector arrangement can also be shown to remove the effect of small misalignments of the polarization axis relative to the beam direction. The value of D is then determined from

$$D=\frac{1}{KP}\frac{R^{1/4}-1}{R^{1/4}+1}.$$

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[1]J. D. Jackson, S. B. Treiman, and H. W. Wyld, Jr., Phys. Rev. 106, 517 (1957).

[2]J. D. Jackson, S. B. Treiman, and H. W. Wyld, Jr., Nucl. Phys. 4, 206 (1957).

[3]H. F. Schopper, *Weak Interactions and Nuclear Beta Decay* (North Holland, Amsterdam, 1966).

[4]C. G. Callan, Jr., and S. B. Treiman, Phys. Rev. 162, 1494 (1967).

[5]B. G. Erozolimsky, L. N. Bondarenko, Yu. A. Mostovoy, B. A. Obinyakov, V. P. Zakharova, and V. A. Titov, Yad. Fiz. 11, 1049 (1970) [Sov. J. Nucl. Phys. 11, 583 (1970)].

[6]K. Berndorfer, Z. Phys. 243, 188 (1971).

[7]G. M. Drabkin, E. I. Zabidarov, Ya. A. Kasman, and A. I. Okorokov, Zh. Eksp. Teor. Fiz. 56, 478 (1969) [Sov. Phys. JETP 29, 261 (1969)]; see also D. J. Hughes and M. T. Burgy, Phys. Rev. 81, 498 (1951).

Hadron-Neutron Forward Elastic Scattering Amplitude and Hadron-Deuteron Collisions*

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Coulomb-nuclear interference in high-energy charged-hadron–deuteron collisions is treated exactly within the framework of Glauber theory. Charge-distribution effects are included. Applications are made to *pd* measurements below 70 GeV to extract ρ_n, the ratio of real to imaginary parts of the proton-neutron forward elastic scattering amplitude. An alternative and earier analysis is shown to yield comparable values for ρ_n. Both results for ρ_n differ significantly from an earlier analysis.

Among the important quantities in particle physics are the ratios of the real to imaginary parts of hadron-hadron forward elastic scattering amplitudes. At high energies this ratio ρ_n for proton-neutron collisions is generally obtained indirectly from proton-proton and proton-deuteron measurements. Extensive *pd* elastic-scattering measurements have recently been made between 10 and 70 GeV at the Serpukhov accelerator[1] and between 50 and 400 GeV at the National Accelerator Laboratory.[2] The analysis of *pd* measurements can be done by means of the Glauber approximation. Within the framework of this approximation, additional simplifications have previously been made, such as approximating the Coulomb phase-shift functions appearing in the general expression by constants and treating the incident hadron as a point charge,[3] or treating the Coulomb phase-shift functions exactly but considering both the incident hadron and the bound proton as point charges.[4]

We present here an exact solution for xd elastic scattering in the Glauber approximation, with both the incident charged hadron x and the bound proton having extended charge distributions. We then use the results to analyze recent *pd* measurements[1] in order to extract ρ_n. The values obtained are compared with those from a previous analysis of the *pd* data[5] and with values obtained from an analysis using a result derived in Ref. 3. The latter analysis involves a rather simple expression and gives values which are comparable to those obtained using the full theoretical expression.