eral parameter trends.

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Measurement of the Average and Longitudinal Recoil Polarizations in the Reaction $^{12}C(\mu^-, \nu)^{12}B$(g.s.): Magnitude of the Induced Pseudoscalar Coupling

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The polarizations, $P_{\text{av}} \equiv \langle \vec{J} \cdot \vec{\sigma}_\mu \rangle / J$ and $P_L \equiv \langle \vec{J} \cdot \hat{v} \rangle / J$, of the recoils $^{12}C(\mu^-, \nu)^{12}B$(g.s.) were measured *simultaneously* by selective recoil implantation. Their ratio R' is largely immune to the systematics of P_{av} and P_L and more dependent on the dynamics than either. Our result (normalized to unit $\vec{P}_\mu$), $R(\text{g.s.}) = -0.506(41)$, yields $g_P/g_A = 9.0(1.7)$ (impulse approximation) and $F_P/F_A(q_m^2) = -1.03(14)$ (elementary-particle treatment), to be compared to partial conservation of axial-vector current (PCAC) predictions of 7 and -0.99, respectively. Thus PCAC is quantitatively verified.

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The reaction $^{12}C(\mu^-, \nu)^{12}B$(g.s.) is for several reasons particularly useful for elucidating the nature of the hadronic axial current. On the one hand, all the observables of this transition are accessible to actual measurements; on the other hand, a sufficient number of well-determined observables (e.g., β-decay asymmetry coefficients) in related transitions in the $A = 12$ triad is available to extract the relevant form factors rather uniquely. This is particularly true for the "induced" pseudoscalar piece of the current which, as is well known, does not intervene appreciably in β decay and which constitutes the last quantitatively open question in this field. In fact, other μ-capture experiments were so far prevented either by statistical limitations and/or by theoretical difficulties in interpretation [e.g., μ capture by protons, $^{16}O(\mu^-, \nu)^{16}N(0^-)$] from providing a reliable answer of sufficient accuracy.

In a $0 \rightarrow 1$ capture there are three independent observables,[1] viz., the capture rate Γ^{cap}, the polarization P_{av} of the recoil nucleus (here ^{12}B) along the muon spin, $P_{\text{av}} \equiv \langle \vec{J} \cdot \vec{\sigma}_\mu \rangle / J$, and the longitudinal polarization of the recoil nucleus, $P_L \equiv \langle \vec{J} \cdot \hat{v} \rangle / J$ (where $\langle \vec{\sigma}_\mu \rangle = \vec{P}_\mu$ = muon polarization, $\vec{J}$ = nuclear spin, $\hat{v}$ = recoil direction).[2] These observables are functions of a single dynamical parameter X, viz.,

$$\Gamma^{\text{cap}} = C(2+X^2), \tag{1a}$$

$$P_{\text{av}} = P_\mu \tfrac{2}{3}(1+2X)/(2+X^2), \tag{1b}$$

$$P_L = 2h_\nu/(2+X^2), \tag{1c}$$

where C is a rate constant which depends[3] on essentially known quantities, P_μ is the muon polarization at capture, and h_ν is the helicity of the emitted (muon) neutrino. The dynamical significance of X emerges best in the "elementary-particle" treatment[3] where

$$X = [1 + f_P(m_\mu E_\nu/m_\pi^2) - f_E(E_\nu/2m_p)] \times [1 + f_M(E_\nu/2m_p)]^{-1}. \tag{2}$$

The f_i's are ratios of the form factors of the "induced" couplings (P, pseudoscalar; E, first-class weak electric; M, weak magnetic) to the axial form factor, taken at $q_m^2 = 0.74 m_\mu^2$; e.g., $f_P = F_P/F_A(q_m^2)$. Note that in the "allowed" limit, where only F_A is retained, $X \to 1$. With the known values of f_E and f_M[4] and the proper kinematical factors, (2) yields numerically

$$X - 1 = -0.317 + 0.417 f_P. \tag{2'}$$

Thus X depends sensitively on f_P (expected to be $\simeq -1$[5]).

P_{av} has already been measured rather accurately[6] while merely a preliminary determination of P_L exists.[7] The latter, like this work, is based on the method of selective recoil implantation. In the present experiment, P_{av} and P_L are measured *simultaneously*. Their ratio, $R' = P_{\text{av}}/P_L$, is not only more sensitive to X than either observable, but furthermore virtually immune to the systematic uncertainties associated with absolute measurements of recoil polarizations. Note that R', contrary to what Eqs. (1b) and (1c)

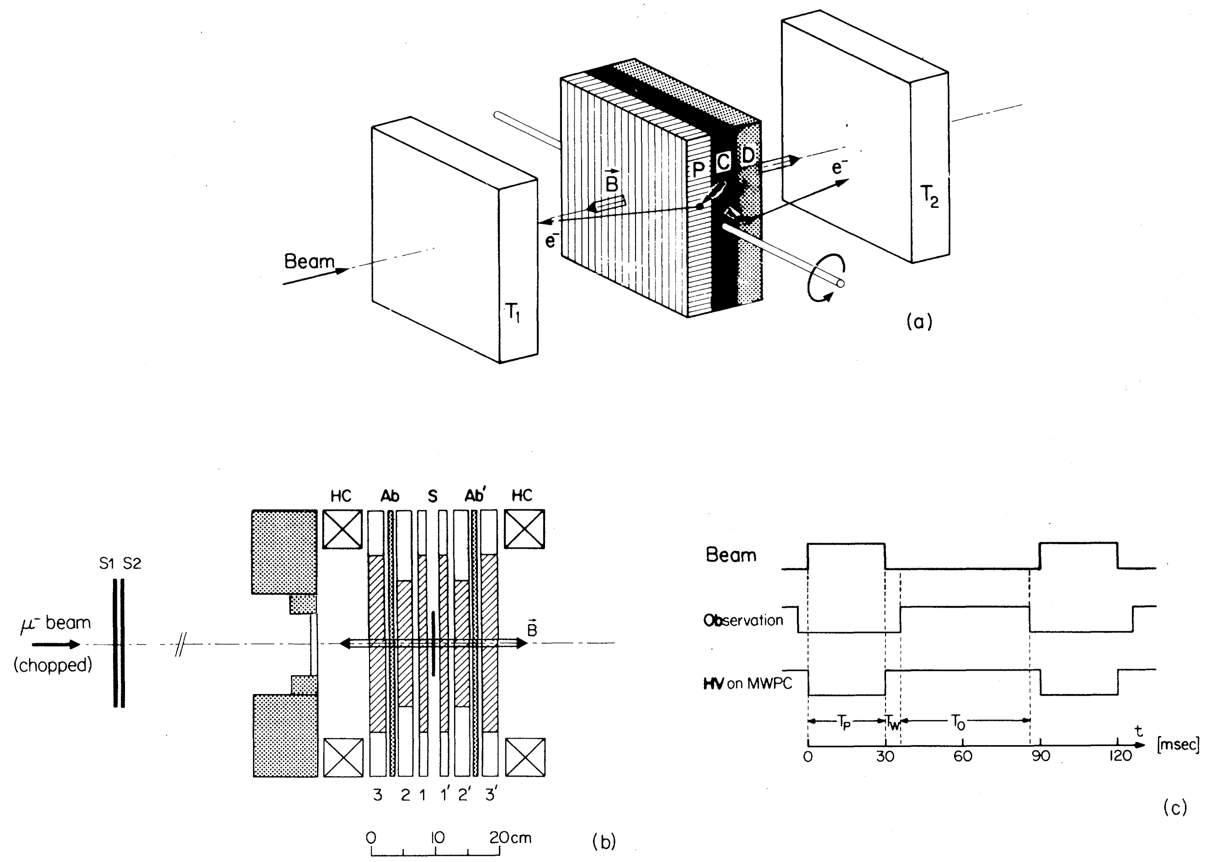

FIG. 1. (a) Principle of experiment. (b) Actual setup: S, stack target; Ab, absorber; HC, Helmholtz coils; S_1 and S_2, beam monitor; 1, 2, and 3, multiwire proportional chambers (MWPC); good events $T_1 = (\overline{S_1 \cdot S_2})(123) \cdot (\overline{1'2'3'})$ and $T_2 = (\overline{S_1 \cdot S_2})(1'2'3')(\overline{123})$. (c) Time sequence: T_p, production; T_w, waiting period; and T_0, observation period.

appear to imply, is independent of h_ν, since P_μ itself (assuming universality of the lepton current) is implicitly proportional to h_ν.

Figure 1(a) illustrates the principle of the experiment; and Fig. 1(b), the setup used. Muons are stopped in a carbon foil C sufficiently thin to let most of the ^{12}B recoils emerge, sandwiched between a polarization-retaining (P) and a polarization-destroying (D) layer. According to the neutrino direction, the recoils will be stopped either in layer P or in layer D. If a holding field $\vec{B}$ is applied along the axis of incidence of the muons, normal to foil C, polarization is retained along this axis in layer P, and is detected via the β-decay asymmetry of the short-lived (29.4 msec) ^{12}B recoils with identical telescopes T_1 and T_2. The material of layer P is such that it also becomes *depolarizing* in the absence of a magnetic field. If we assume $P_L < 0$ (and disregard P_{av}), T_1 will count more than T_2 when the sandwich is oriented as in Fig. 1(a); when it is flipped by π rad, the telescopes' roles are reversed. The asymmetry due to P_{av} will be orientation insensitive. Defining as forward orientation (F) that where recoils along $\vec{P}_\mu$ preserve their polarization, and as backward (B) the opposite, and integrating over all recoil directions, one has ideally for the total polarization (along $\vec{B}$)

$$P^F = \tfrac{1}{2}(P_{av} + \tfrac{1}{2}P_L), \quad P^B = \tfrac{1}{2}(P_{av} - \tfrac{1}{2}P_L), \tag{3}$$

so that (with $P_\mu = -h_\nu k$, where k is the muon depolarization factor[8])

$$\begin{aligned} R' &= \tfrac{1}{2}(P^F + P^B)/(P^F - P^B) \\ &= P_{av}/P_L = -\tfrac{1}{3}k(1+2X), \end{aligned} \tag{4}$$

or

$$R = R'/k = -\tfrac{1}{3}(1+2X). \tag{4'}$$

In the actual setup[9] the target S consisted of a stack of N sandwiches such as just described. Two different D-C-P stacks were used: (1) $D = 405$ μg/cm^2 Al, $C = 60$ μg/cm^2, $P = 1250$ μg/cm^2 Ag, and $N = 1000$; (2) $D = 250$ μg/cm^2 LiF, $C = 60$ μg/cm^2, $P = 800$ μg/cm^2 Ag, and $N = 1500$. Corresponding $(CH_2)_n$, "dummy" (D-P) and nondepolarizing (P-C-P) targets were also constructed for calibration purposes. Since the target S had only[10] 60 [90][10] mg/cm^2 of foil C, great care was taken to exclude foil C from other parts of the setup. The μ^- beam of 70 [88] MeV/c was produced by tuning the Swiss Institute of Nuclear Research μ-channel II to backward decays; it had a range curve of 1.0 [1.8] g/cm^2 full width at half maximum, yielding typically 3.8×10^5 [5.5×10^5] stops/sec in target S. An on/off cycle [Fig. 1(c)] of 30/60 msec was produced with a rotating chopper. After $\sim 4\times 10^7$ S_1-S_2 coincidences, $\vec{B}$ of 25 [75] G was switched on/off, and after 10 such cycles target S was flipped automatically. To ensure depolarization when the holding field $\vec{B}$ was nominally off, a transverse field $\vec{B}_T$ (3 G) was then applied. For both T_1 and T_2, time spectra and total counts were stored for all four conditions. Typically, 5.5 [8.0] counts/sec were collected with a signal/background ratio of 2.0 [1.6]. Fits yielded $\tau(^{12}\mathrm{B})$ in excellent agreement with $(CH_2)_n$ and the literature value.

The muon polarization was determined in a separate setup by the integral method,[11] great care being taken with systematics[9]; $k = 0.170(4)$ [$k = 0.156(4)$] were obtained. Corrections were applied to the raw polarizations for the following *measured* effects: (a) instrumental asymmetry [$(CH_2)_n$ target]; (b) flat, unpolarized background; (c) extraneous ^{12}B activity (D-P target); and (d) incomplete depolarization in Al. A correction was calculated for finite foil-C thickness and the partial depolarization[9] therein. The Ag-C-Al and Ag-C-Ag stacks yielded values of $P_{av} = P^F + P^B$ in good agreement. Figure 2 displays the polarizations measured with various targets. The final ratios (normalized to $P_\mu = 1$) $R = -0.506(49)$ [$R = -0.539(77)$] are in excellent accord. Their

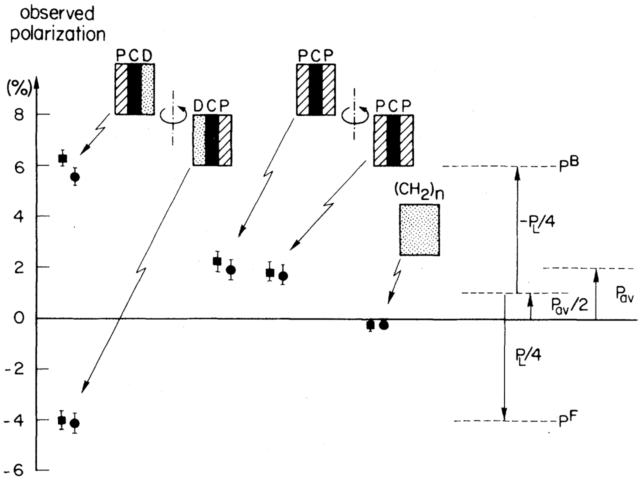

FIG. 2. Polarizations observed with various stacks and stack orientations. P = Ag; D = Al; squares, T_1; circles, T_2. On the right-hand side the quantities as defined in Eq. (3). Note that the polarization obtained with the P-C-P target, namely P_{av}, gives, as expected, twice the "offset" of the polarization of the P-C-D target.

TABLE I. X from experiment versus PCAC predictions.

X			g_p/g_A		$-F_P/F_A(q_m^2)$	
Expt.	IA[a]	EPT[b]	Expt.	Theor.	Expt.	Theor.
0.26(6)	0.32[c]	0.28[d]	9.0(1.7)	7[c]	1.03(14)	0.99[d]

[a] Impulse approximation.
[b] Elementary particle treatment.
[c] Ref. 15.
[d] Ref. 5.

weighted mean

$$R=-0.516(41) \tag{5}$$

must, however, yet be *corrected for* the contribution (~ 12%) of *excited* ^{12}B *states*. Not all their populations and none of the recoil polarizations are experimentally known; one has to rely on theoretical values. Fortunately, the predicted corrections (0.98,[12] 1.00,[13] and 1.03[14]) affect R much less than $P_{\rm av}$ or P_L, and are anyway smaller than the uncertainty in (5). Adopting the value of Ref. 12, we obtain, for the g.s.,

$$R(\text{g.s.})=-0.506(41), \text{ i.e., } X=0.26(6). \tag{5$'$}$$

This is consistent with the R calculated from separate $P_{\rm av}$ and P_L measurements,[6,7] vis., $R(\text{g.s.}) = -0.61(19)$.

Our main goal is to test the partial conservation of axial-vector current (PCAC) hypothesis. This can be done in two ways: either by comparing (5′) with impulse-approximation (IA) predictions,[15] based on the canonical *nucleon* couplings, or within the elementary-particle treatment (EPT), where PCAC is applied to the $A=12$ *nuclei* directly.[13] With EPT no model is needed in principle, but the well-supported assumption is made that F_M and F_E scale with q^2 as F_A does, i.e., that the measured[4] $q^2\approx 0$ values of F_M/F_A, F_E/F_A may be inserted into Eq. (2), valid at q_m^2, to solve for f_P; furthermore, a correction ($\delta = -0.28$) for nonpole terms[13] is required. Both comparisons are presented in Table I. Good agreement with both kinds of predictions was found; thus we verify PCAC with considerable accuracy.

After correcting the observed P_L for various losses, we obtain, with (5′), $h_\nu = -1.08(11)$. Details will be published elsewhere.[16]

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