AVERAGE POLARIZATION OF ^{12}B IN ^{12}C(μ, ν)^{12}B(g.s.) REACTION: HELICITY OF THE π-DECAY MUON AND NATURE OF THE WEAK COUPLING ★

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The helicity, h^-, of μ^- in π-decay has been determined as positive ($h^- \geqslant +0.90$) from the average polarization, $P_{av} \equiv \langle \boldsymbol{J}_B \cdot \boldsymbol{s}_\mu \rangle$, of ^{12}B produced in the $\mu^- + {}^{12}C \to \nu_\mu + {}^{12}B$ reaction We obtain also dynamical information on μ-capture (i) the weak magnetism form factor, $\mu = 4.5 \pm 1\ 1$, and (ii) the sum of the induced pseudoscalar (g_P) and the 2nd class induced tensor (g_T) couplings versus g_A, $(g_P + g_T)/g_A = 7\ 1 \pm 2\ 7$ The latter result, adopting the "canonical" value of g_P/g_A, leads to $g_T/g_A = +1 \pm 2.7$ which is compatible with zero and in strong contradiction with the value $\simeq -6$ recently advocated by Kubodera, Delorme and Rho

We present here a measurement of the average polarization, $P_{av} \equiv \langle J_B \cdot s_\mu \rangle$, of ^{12}B in the allowed ($0^+ \to 1^+$) reaction $\mu^- + {}^{12}C \to \nu_\mu + {}^{12}B$(g.s.). The result can be exploited in two ways, viz. (a) to determine the helicity of the μ^- from π-decay, following an old suggestion of Jackson et al. [1]. (This is analogous to the ν_e-helicity experiment performed in the allowed ($0^- \to 1^-$) $e^- + {}^{152}Eu^m \to \nu_e + {}^{152}Sm^*$ capture [2]. There the recoil polarization is measured with respect to the emitted ν_e, while in the present experiment the recoil polarization is determined, via its *known* β-decay asymmetry, with respect to the incoming μ direction); (b) to gain quantitative information about the induced terms in the weak coupling.

The main practical problem in such an experiment is the preservation of the polarization of ^{12}B recoils (τ = 30 ms) in the (carbon) capture target. The road to this experiment was opened by Madansky and his co-workers [3] who observed that the polarization of ^{12}B recoils (produced in the ^{11}B(d,p)^{12}B reaction) implanted in graphite can at least partly be preserved by a longitudinal magnetic field B_z Following this observation, we systematically investigated the decoupling of ^{12}B implanted in various materials and performed (at the Saclay ALS muon channel) an exploratory measurement of P_{av} using a graphite target [4]. The result, $P_{av} = 0.43 \pm 0.10$, favoured positive μ^- helicity, but could not rule out the opposite conclusion. Such an ambiguity always holds, at least if no assumptions about the nature of the μ-capture coupling are made, when $|P_{av}| \leqslant 1/3$. This fact can readily be seen as follows

In the frame z' of a (left-handed) neutrino ‡1 emitted at an angle θ with respect to the μ^- spin direction (z), the recoil nucleus is described as a superposition of $M = 1$ and $M = 0$ substates [5] as $\psi(z') = \cos(\theta/2)\sqrt{2}A|1\rangle + \sin(\theta/2)(A - B)|0\rangle$. Here $\sqrt{2}A$ and $(A - B)$ obviously represent the transverse and longi-

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‡1 Since P_{av} is a scalar, this is merely a convenient procedure.

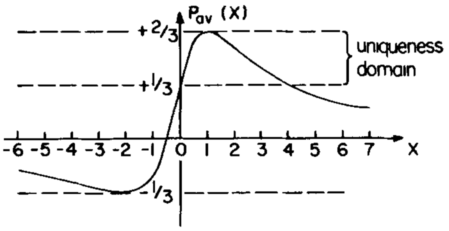

Fig. 1 P_{av}, the average polarization of ^{12}B(g.s), as a function of the parameter X defined in the text. For $0 \leqslant X \leqslant 4$, the spin of ^{12}B ($J_B$) is always along the spin of the captured $\mu^-(s_\mu)$.

tudinal amplitudes, respectively. The term B arises from "higher order" contributions, as for an allowed G–T transition there is but a single overall amplitude. Defining $X \equiv \mathrm{Re}[(A-B)/A]$, P_{av} is given in the muon frame by $P_{av} = +(2/3)(1+2X)/(2+X^2)$; for the "allowed" case ($B = 0$, i.e. $X = 1$) $P_{av} = +2/3$. The positive sign means that J_B is along s_μ. Fig. 1, a plot of $P_{av}(X)$, shows that $-1/3 \leqslant P_{av} \leqslant 2/3$. Thus the "higher order" contributions can not only induce a departure from +2/3, but even lead to a sign reversal of P_{av}. Therefore an unambiguous determination of the sign of the muon polarization from P_{av} without a priori knowledge of X is possible only if $|P_{av}| > 1/3$. Conversely, a determination of X from P_{av} can yield valuable information about the nature of the induced couplings.

The goal of the present work was to improve the precision of P_{av} with respect to ref. [4] by (1) using stronger decoupling fields, and (2) by performing careful calibration experiments with (d,p)-produced ^{12}B recoils implanted in Au and graphite. The muon beam and timing program were the same as in ref. [4] and the set up was very similar. The latter is shown schematically in the insert of fig. 2, where FC(BC) is the forward (backward) beta-ray scintillator telescope. Besides the prime graphite target ($10 \times 10 \times 1$ cm^3), we used two others of equal stopping power, viz. one of polyethylene, and one of elemental ^{10}B (98% pure). The polyethylene, a material in which the recoils get completely depolarized [4], served to check the symmetry of the detecting system, whereas the ^{10}B, in which no delayed activities were observed, served to determine the background and its asymmetry. The signal (graphite) to background (^{10}B) ratio was $\simeq 4$, and the background-corrected signal was consistent

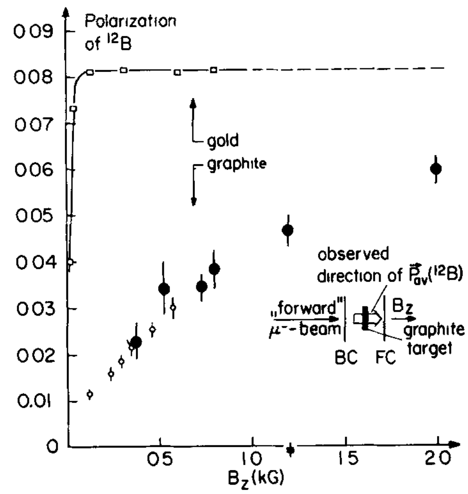

Fig. 2. Polarization of ^{12}B as a function of the uncoupling magnetic field B_z (kG). Full circles (full square): following μ-capture in graphite (polyethylene). Open circles (open circles (open squares): following the ^{11}B(d,p)^{12}B reaction and implanted in graphite (Au) The asymptotic polarization observed in Au, 8.2%, gives the polarization that would also be observed in μ-capture in the limit of perfect spin decoupling. The insert shows the direction of P_{av} observed with "forward" muons. For convenience of drawing the sign of ^{12}B polarization obtained with "backward" muons [4] has been changed.

with a single exponential with $\tau = (30 \pm 3)$ msec.

The β-decay asymmetry $A(^{12}\mathrm{B})$ was measured with "forward" muons; it is defined as $A(^{12}\mathrm{B}) = [\mathrm{BC/FC}]_{B_z}/[\mathrm{BC/FC}]_{\bar{B}_z}^{-1}$, where BC = BC (graphite) – BC(^{10}B) and similarly for FC. In actual practice, a transverse field ($B_x \simeq 10$ G) was applied when $B_z = 0$, in order to assure complete depolarization. The instrumental asymmetry was measured in the same way, using polyethylene. From $A(^{12}\mathrm{B})$ we deduce the magnitude of the effective polarization of ^{12}B and its sign relative to the incident beam direction. The present results, corrected for finite geometry and target thickness, are shown in fig. 2 together with the earlier data [4] obtained with $B_z \leqslant 0.8$ kG. The calibration data obtained with (d,p)-produced ^{12}B nuclei implanted into Au and graphite are also plotted (the Au data were corrected for relevant relaxation time $T = 125 \pm 5$ ms [6] ‡2); the

‡2 This parameter was measured in our laboratory as 120 ± 12 ms) Note that in ref. [4] $T = 200$ ms was used, so that $P_{av} = 0.43 \pm 0.10$ was somewhat ($\simeq 10\%$) underestimated.

Table 1
Correction factors applied to the detected polarization of ^{12}B in μ-capture

Origin of the correction		Factor
Geometry	(closed)	1.29 ± 0.03
	(open)	1.14 ± 0.02
Diffusion [a]	(thin target) [b]	1.08 ± 0.03
	(thick target)	1 28 ± 0.04
Timing difference in μ-capture and (d,p)-experiments		0 985 ± 0.025
^{13}C content in the target		1.05 ± 0.01
Delayed activities following particle emission in μ-capture [8]		$1.01 \pm {}^{0.01}_{0.00}$
Internal β-branch		1.015
Normalisation [c]		0.975 ± 0.025

[a] The muon polarization measured in ref [4] is corrected by 1 04, due to geometry and diffusions.
[b] Thin target (1.32 g/cm^2), thick target (1.76 g/cm^2).
[c] Considering the average of the asymptotic polarization in Au, Pd, Pt and in Cu.

Table 2
Polarization P of ^{12}B in various specific conditions, compared to the low-field average $P_{\ell f}$ (common error sources not included)

Conditions: open geometry (o) closed geometry (c)	$P/P_{\ell f}$
Backward muons (c)	−0.92 ± 0.12
Forward muons (c)	1.05 ± 0.11
Thin target (c)	0.99 ± 0.10
Thick target (c)	1.03 ± 0.12
B_z = 1.2 kG (o) thick target	0.97 ± 0.12
B_z = 2.0 kG (o) [a] thick target	⩾0.76 ± 0.05

[a] Not yet normalized.

scale is so chosen for thse points as to make the (d,p) and μ-capture graphite data coincide at low field. Thus the asymptotic polarization in Au, indicated in the figure as 0.0820 ± 0.0064 represents the polarization of the ^{12}B recoil in μ-capture in the limit of complete spin decoupling. This polarization has still to be corrected for the incomplete polarization of μ^- in ^{12}C [‡3] and for some small effects listed in table 1; the final result is P_{av} (obs.) = 0.452 ± 0.042, with J_B directed *along* the incident beam. This value of P_{av} is based on data for $B_z \leqslant 1.2$ kG. Results obtained in specific experimental conditions are given in table 2.

For the "forward" muons (for which the decay kinematics cannot reverse the polarization in the π-frame) P_{av}(obs.) = 0.452 ± 0.042 would immediately imply *positive μ-helicity*, were it not for the fact that some recoils originate from captures to excited ^{12}B states, for which the $|P_{av}| > 1/3$ uniqueness argument might be vitiated. Fortunately this is not so. The major part (88%) of recoils result from the direct (g.s to g.s.) capture and the rest from a branch feeding almost exclusively an excited 1^- state (2.62 MeV) [9]. Since $P_{av}(X)$ depends only on the spin but not on the parity of the states [5], P_{av} for this excited (1^-) state has the *same* limits as for the ground state (1^+), and thus the $|P_{av}| > 1/3$ criterion still holds. In actual practice, the P_{av} contributed by the 1^- capture is further attenuated (by $\simeq$ +0.72) through the γ-cascades leading to the ground state, and the strict limit is thus $|P_{av}(\text{obs.})| > 0.32$.

To determine the μ-helicity quantitatively one has to correct the P_{av}(obs.) for the effect of the 12% 1^- branch. A detailed calculation [10] yields for this state P_{av} = −0.24. The corrected g.s. result is thus P_{av} = +0.537 ± 0.049. The theoretical value of P_{av} predicted on the basis of the "canonical" couplings (no 2nd class, i.e. no g_T contribution!) is +0.53 [11,12] to +0.55 [13]. The ratio $P_{av}/P_{av}(\text{th})$ = +1.0 ± 0.1 corresponds thus to $h^- \geqslant +0.9$, that is the muon antineutrino is right-handed, with a left-handed component less or equal to 5% [‡4].

We discuss now the higher order contributions to

[‡3] The μ^--decay asymmetry was measured with the graphite target [4]. With the aid of this asymmetry, expressed as a fraction of the μ^+-decay asymmetry [7], we correct for the kinematical and atomic depolarization of μ^-. Hence, there is no reference to the law of μ-decay.

[‡4] The precision is fairly better than in the "classical" experiment [15] based on the scattering of muons by magnetized material, where the combination of statistical and instrumental errors gives 40% error on h. For the discussion of other "old" helicity measurements see ref. [7].

A and $A-B$. These contributions come from the gradient type couplings (q/M order effects), viz. the weak magnetism WM, the induced pseudoscalar IP and weak electricity WE (1st and 2nd class) and from forbidden matrix elements. In terms of the "effective" couplings [5, 14] G_A(axial) and G_P(pseudoscalar) one has: $A = G_A$ and $A-B = G_A - G_P$. To first order in q/M, the WM contributes only to G_A, while IP and WE contribute to $G_A - G_P$ only [14, 16]. Since the central question is now whether the 2nd class WE plays a role in the weak coupling, the prime interest is in $G_A - G_P$.

In the following calculations we use two inputs, viz. the experimental rate $\Gamma = 6100 \pm 270\ \mathrm{sec}^{-1}$ [17] and our "dynamical" parameter $X = (G_A - G_P)/G_A$ determined from P_{av} as $X = 0.36 \pm 0.11$.

Comparing Γ to the theoretical rate Γ [13, 18] = $3.53\,(10^3\ \mathrm{s}^{-1})\,|F_A(q^2)/F_A(0)|^2\, G_A^2\,(2 + X^2)$, we calculate $|G_A|$. Assuming that G_A is real, we have $G_A = 1.198 \pm 0.043$; from $G_A - 1 \simeq -(q/2Mg_A)\mu g_V$, the WM coupling is obtained (with $g_A = -1.25\, g_V$) as $\mu = 5.3 \pm 1.1$ (versus the CVC value 4.7). Next we deduce from $G_A X - 1 \equiv G_A - G_P - 1 \simeq -(q/2Mg_A)(g_P + g_T + y g_A) = -(0.57 \pm 0.13)$, the ratio $R = (g_P + g_T)/g_A$ (adopting for y the reliably calculated value, $y = 3.6$ [13, 19]) as. $R = 8.1 \pm 2.7$. The parameters g_P and g_T are the coupling constants of IP and 2nd class WE, y is a first class contribution originating from a relativistic term.

The "approximate" $\simeq$ symbols indicate the neglect of small second forbidden terms ($3 \pm 1\%$ correction to the leading matrix element [18]); with the inclusion of these, one obtains $\mu = 4.5 \pm 1.1$ and $(g_P + g_T)/g_A = 7.1 \pm 2.7$. The first of these results supports strong CVC, second agrees well with PCAC if there is no 2nd class coupling. Conversely, with the "canonical" value [13] $g_P/g_A = 6$ one gets $g_T/g_A = +1.0 \pm 2.7$. This result contradicts the recent theoretical prediction [20], $g_T/g_A \simeq -6$ [‡5,6]

[‡5] Conclusions equivalent to those have recently been drawn independently on the basis of an "Elementary Particle Approach" analysis, see ref [13]

[‡6] After the completion of this work, we were kindly informed of a calculation by M. Morita, Ohtsubo and Kobayasi which yields a *positive* sign for $P_{av}(1^-)$. In that case μ and g_T/g_A have to be considered as lower limits (however $\mu \leqslant 5.1 \pm 1.1$), and the contradiction with $g_T/g_A \simeq -6$ [20] becomes even more violent.

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