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Measurement of the Correlation between Nuclear Alignment and Electron Direction in ^{12}B Decay as a Direct Search for the Second-Class Axial-Vector Current

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The *alignment* correlation term $A\alpha_- EP_2(\cos\theta)$ has been measured in the β^- decay $^{12}\text{B} \to {}^{12}\text{C(g.s.)}$ by a novel technique. The result, $\alpha_-(E_0) = -(0.1 \pm 0.2)/\text{GeV}$, indicates that the conserved vector current weak-magnetism form factor, F_M, is essentially compensated here by the weak electricity (induced tensor) form factor F_E. Using the decomposition of $F_E = F_E^{(1)} + F_E^{(2)}$ into first- and second-class parts, as well as a reliable estimate of $F_E^{(1)}$, we conclude that $F_E^{(2)}$ is small compared to F_M, and compatible with zero.

There is currently much interest in second-class currents in β decay,[1] in particular in the possible presence of an induced tensor (or "weak electricity",[2] WE) coupling. Although arguments can be made on the basis of $(ft)_\pm$ differences, the most compelling evidence is to be obtained from correlation experiments with oriented mirror nuclei. Specifically, for a $1^+ \to 0^+$ $\beta^\mp$ decay $[{}^{12}\text{B} \to {}^{12}\text{C(g.s.)} \leftarrow {}^{12}\text{N}]$ one has the relation[3]

$$W(\theta, E)_\mp = F_\mp(E)[1 \mp P(1+\alpha_\mp E)P_1(\theta) + A\alpha_\mp EP_2(\theta)], \tag{1}$$

where P (A) is the polarization (alignment) of the 1^+ nucleus, $P_l(\theta)$ are Legendre polynomials, and E is the electron kinetic energy. The terms $\alpha_\mp E$ are contributed by *gradient* couplings (WE, and weak magnetism, WM) and recoil terms; in the "elementary particle" treatment one has[3]

$$\alpha_\mp = \pm 2(F_M - F_E^{(2)})/3F_A - 2F_E^{(1)}/3F_A, \tag{2}$$

where the F_i's are form factors (A denotes axial vector). Note the presence of a *first-class* WE term; in the impulse approximation,[4] $F_E^{(1)}/F_A = (1/2M)[1 + 2i\int \vec{r}\,\vec{\sigma}\cdot\vec{p}/\int\vec{\sigma}] \equiv y/2M$. With CVC (conservation of vector current), $F_M/F_A = 3.8/2M = 2.0/\text{GeV}$, so that $\alpha_\mp$ is typically expected to be of the order of a few times 0.1%/MeV. This smallness mades $\alpha_\mp$ determinations from the E dependence of the up-down asymmetry (with $P \neq 0$, $A \simeq 0$) particularly difficult and scale dependent.[5,6] Since the *alignment* correlation coefficient in (1) is *entirely contributed* by the quantity of interest, it is of obvious advantage to measure it *directly;* such an approach is reminiscent of direct measurements of the lepton g-factor anomaly. We present here a novel method to do this, and a determination of α_- by it. A measurement of $\alpha_\mp$ is under way.

To isolate the alignment term, we use the following (idealized) procedure: ^{12}B (^{12}N) nuclei with *vanishing* initial alignment $A^0=0$ and maximum initial polarization P^0 are implanted, in the presence of a holding field B_z, into a medium where the $\Delta m=\pm 1$ Zeeman frequencies (ν_{10}, $\nu_{\bar{1}0}$) are *not degenerate*. Thus one can choose to equalize the population p_m of either the $m=1$ and $m=0$ substates (condition 1) or of the $m=-1$ and $m=0$ substates (condition $\bar{1}$). This equalization leads (see Table I) to a reduced polarization $P(1)=P(\bar{1})=3P^0/4$, and an *induced* alignment $A(1)=-A(\bar{1})=-3P^0/4$. The isolation of the P_2 alignment term in Eq. (1) is based on this *sign change* of the *induced* A for fixed P^0. Conditions 1 and $\bar{1}$ are alternated rapidly: In one implantation cycle the nuclei are subject to 1, in the next to $\bar{1}$. Denoting the corresponding electron rates (at fixed θ) N_1 and $N_{\bar{1}}$, one can form a signal

$$S_\mp(\theta,E)\equiv 2(N_{\bar{1}}-N_1)/(N_{\bar{1}}+N_1)$$
$$=\tfrac{3}{2}P^0\alpha_\mp E P_2(\theta)/[1\mp\tfrac{3}{4}P^0P_1(\theta)]. \qquad (3)$$

In practice, the recoils are generally *not* produced with $A^0=0$, and an initial alignment leads (see Table I) to an *induced* polarization $P=A^0/2$; the signal is hence given in the general case by

$$S_\mp(\theta,E)=\frac{\tfrac{3}{2}P^0\alpha_\mp EP_2\mp(A^0/2)P_1}{1\mp\tfrac{3}{4}P^0P_1}. \qquad (4)$$

Defining the numerator of (4) as the "reduced" signal $\tilde{S}_\mp(\theta,E)$, one clearly has

$$\alpha_\mp(E)=[\tilde{S}_\mp(0,E)+\tilde{S}_\mp(\pi,E)]/3P^0E. \qquad (5)$$

In practice, we implemented the above method as follows: ^{12}B recoils were produced in the reaction[6] ^{11}B$(d,p)^{12}$B and implanted into a Mg single crystal oriented with its c axis along a holding field B_z (see Fig. 1). Mg was chosen, as it is known from the work of Haskell *et al.*[7] that the quadrupolar coupling lifts the degeneracy of the Zeeman frequencies (see inset in Fig. 1), and that the implantation occurs at a single site. The deuteron energy, $E_d\simeq 1.5$ MeV, and the recoil angle, $\theta_R\simeq 40°\pm 5°$, were so chosen as to maximize (minimize) P^0 (A^0).[8] The β's were counted with two telescopes, located respectively above (π) and below (0) the reaction plane; these telescopes consisted of six plastic scintillators interspersed with plastic absorbers (~1 g/cm^2) in order to determine the range (energy). Fast coincidence combinations from all scintillators traversed by the electrons were required. The timing sequence (TS) was 30 ms implantation, 10 ms waiting time, 25 ms counting [note that $\tau(^{12}\mathrm{B})=30$ ms].

A^0 and P^0 were determined, at the field setting used in the experiment proper ($\bar{B}_z=10.5$ G, $\nu_{10}=27.5$, $\nu_{\bar{1}0}=43.3$ kHz) by the standard technique[8] of *saturating* the two Zeeman resonances (with field modulation at 50 Hz and rf always on) and observing the changes in β-counting rates; note that the small coefficient α_- and the *induced* alignment (on which the present experiment rests) play no role in this context. The sum of the appropriately defined signals gives P^0 and their difference $|A^0|$, while the sign of A^0 is obtained from nuclear information.[9] The result was $P^0=(9.4\pm 0.2)\%$ and $A^0=(2.1\pm 0.2)\%$. We emphasize that these represent *effective* parameters which allow automatically for relaxation phenomena,[10] and that P^0 and the *induced* alignment have the *same* relaxation times since the rf is on during the entire TS.

It is essential to establish two properties of either telescope, viz., (a) the absence of spurious instrumental asymmetries and (b) constant response vs E. Property (a) was checked using a

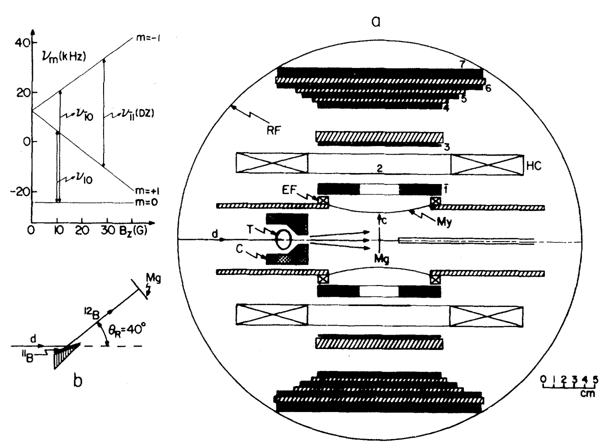

FIG. 1. Inset: Zeeman level diagram of ^{12}B recoils implanted into a Mg single crystal ($P^0\|B_z\|c$). (a) Schematic side view of apparatus. HC, Helmholtz coil(s) (B_z); RF, rf coil(s); EF, Earth field compensation coil(s); $\bar{1}$, anticounter(s); 2, 3, 4, 5, 6, 7, electron range counters (square). Coincidences: $\bar{1}$23, $\bar{1}$234, .., $\bar{1}$234567. *T*, ^{11}B target, d, deuteron beam; C, collimator, Mg, Mg single crystal (c axis indicated); My, Mylar window(s); note that d is directed at 22° out of the plane of the drawing. (b) Top view of target arrangement. ^{11}B (100 μg/cm^2) is supported on a water-cooled brass block.

fully depolarizing implantation target, polyethylene,[11] while (b) was verified by means of the so-called double-Zeeman (DZ) resonance.[12] This is an $m=1 \longleftrightarrow m=-1$ transition (normally forbidden, but made possible through off-diagonal hyperfine interactions) which obviously does not affect or induce alignment, and hence gives a signal (practically) independent of E and proportional to P^0. Once the same properties are established for both telescopes, then they may be considered *identical*, a feature which is, however, not crucial to the experiment.

The measurement of α_- and check (a) were done at $\overline{B}_z = 10.5$ G, and the rf frequency was alternated between 43.3 and 27.5 kHz for equal periods (16 TS's each). Figure 2(a) shows (heavy dots) the signals $\tilde{S}$ and (open circles) the polyethylene test data. The DZ signals (squares) were obtained by raising $\overline{B}_z$ from 10.5 to 27 G (where 43.3 kHz is resonant), all other conditions remaining unchanged. It is seen that both telescopes were free of spurious asymmetries and a constant response vs E; furthermore, the signals $\tilde{S}$ extrapolate to the expected value, $A^0/2 = (1.07 \pm 0.07)\%$.

Figure 2(b) shows $\alpha_-(E)$ as obtained from Eq. (5) combining both telescopes. The point (square) at 13.4 MeV represents the result $\alpha_-(E_0) = (0.0 \pm 0.3)$/GeV obtained by us in an earlier experiment,[13] while the dashed line indicates the WM contribution to α_-, +1.3/GeV.[14] The compensation of WM by WE in this transition is manifest. More quantitatively, we quote our result as

$$\alpha_-(E_0) = -(0.07 \pm 0.20)/\mathrm{GeV} \qquad (6)$$

since the very small second-forbidden effects[15] vanish at E_0. The quoted error allows, besides statistics, for the calibration uncertainties by the DZ method.

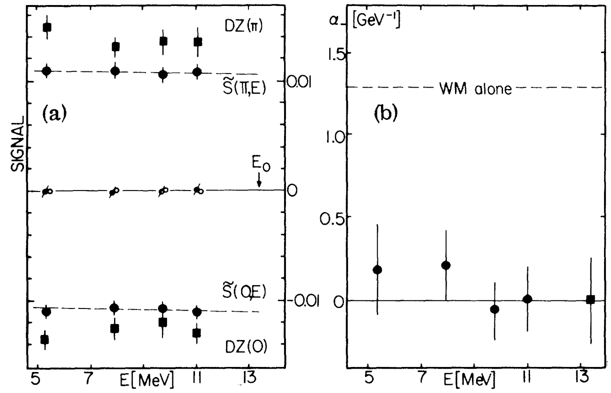

FIG. 2. (a) Open circles and barred circles (for the two telescopes), polyethylene check for spurious asymmetries; squares, "reduced" double Zeeman (DZ) signals; full circles, actual "reduced" signals $\tilde{S}$ as defined in Eq. (4); straight lines, fits by $a + bE$. All measurements were done with $\pm\overline{B}_z$, and suitably averaged. Each point has an energy uncertainty ΔE of ± 0.25 MeV. (b) Full circles, $\alpha_-(E)$, corrected for "smearing" of $P_2(\theta)$ by the finite geometry, and for the small loss of induced alignment due to modulation of B_z. Square, $\alpha_-(E_0)$ from an earlier Louvain experiment [Ref. (13)]. Dashed line, WM contribution to α_-.

In the absence of a reliable measurement of α_+, the interpretation of (6) in terms of $F_E^{(2)}$ requires a theoretical value for $F_E^{(1)}/F_A$. According to several independent calculations,[4] this quantity (y) equals +3.7 (in units of $1/2M$), just enough to cancel F_M/F_A. Adopting this input, our result (6) yields

$$F_E^{(2)}/F_A = +(0.3 \pm 0.7)/2M, \qquad (7)$$

i.e., is consistent with the *absence* of a second-class weak axial current. A similar conclusion,

TABLE I. Induction of alignment from polarization (and vice versa) by selective population equalizations ($J=1$). Polarization P and alignment A are defined as $P = p_1 - p_{-1}$, $A = p_1 + p_{-1} - 2p_0$ ($\Sigma p_m = 1$).

Initial populations p_m^0 (pure polarization)		Populations p_m after equalizations $1 \leftrightarrow 0$	$-1 \leftrightarrow 0$	Initial populations p_m^0 (pure alignment)		Populations after equalizations $1 \leftrightarrow 0$	$-1 \leftrightarrow 0$
$m = 1$	2/3	1/2	4/6	$m = 1$	1/2	1/4	1/2
0	1/3	1/2	1/6	1	0	1/4	1/4
−1	0	0	1/6	−1	1/2	1/2	1/4
	Orientations				Orientations		
	Initial	Final			Initial	Final	
P	2/3	1/2	1/2	P	0	−1/4	1/4
A	0	−1/2	1/2	A	1	1/4	1/4

$+(1.0\pm 2.7)/2M$, was drawn from a recent recoil polarization experiment[9] on $^{12}C(\mu^-, \nu)^{12}B$(g.s.).

Recently, theoretical arguments[16] have been advanced in favor of a "large" second-class contribution, $F_E^{(2)}/F_A \simeq -6/2M$. Note that with $\alpha_- \simeq 0$ this implies $\alpha_+ = -6.7$/GeV. While the currently available experimental value, $\alpha_+ = -(2.1\pm 0.7)$/GeV,[5] agrees (perhaps accidentally!) with $F_E^{(2)} = 0$ in the framework of the above analysis, it certainly does exclude such a huge slope.

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[4]See Ref. 3. This quantity has also been computed independently by H. Behrens and F. P. Calaprice (private communications).

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