Weak Magnetism and Second-Class–Current Interactions in $A = 8$

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We have measured β-α angular correlations in $A=8$ in order to extract a value for the weak-magnetism element as part of a test of conservation of vector current. Possible contributions to the angular correlation from vector second-forbidden matrix elements and a second-class induced-tensor matrix element are shown to be small on the basis of experimental evidence and wave-function calculations.

The conserved-vector-current (CVC) hypothesis directly relates a vector weak-interaction form factor with the corresponding electromagnetic form factors. Some of the consequences of CVC have been tested experimentally with the results indicating good agreement to the CVC predictions at the 10% level.[1] In nuclear β decay, one of the CVC tests involves measuring the weak-magnetism form factor. For transitions within the same isospin multiplet, the weak-magnetism form factor is related to the magnetic moments of the initial and final states (specifically for neutron β decay, the weak-magnetism form factor is proportional to the difference of the magnetic moments of the proton and the neutron). For allowed transitions between states not in the same isomultiplet, the weak-magnetism form factor is related to the isovector part of the analogous $M1$ γ transition. In this Letter we report the experimental results for β-α angular correlations from the β decays of ^{8}Li and ^{8}B as part of a test of CVC. Previous measurements in $A=8$ have been reported at β energies of 11[2] and 7 MeV.[3] We have extended the measurements to include several β energies from 5 to 13 MeV, and therefore can determine possible contributions from second-forbidden transitions. Also as we shall point out below, the results are sensitive to the presence of second-class currents.

The general form of the theoretical spectrum for β-α angular correlations was determined by Holstein on the basis of the vector–axial-vector coupling.[4] The impulse approximation is used to relate the weak-interaction form factors to single-particle nuclear matrix elements. The calculation is carried out to second order in momentum transfer and therefore includes explicitly the effects of both the induced weak currents and so-called second-forbidden transitions. The $\beta^\pm$-α angular correlation has the form

$$\omega(\theta_{\beta^\pm-\alpha}) = 1 + a_\pm \cos\theta_{\beta^\pm-\alpha} + p_\pm \cos^2\theta_{\beta^\pm-\alpha}.$$

For the appropriate spin-isospin sequence in the $A=8$ decays of

$$(J^\pi = 2^+,\ T=1) \xrightarrow{\beta} (2^+, 0) \xrightarrow{\alpha} (0^+, 0),$$

the expression for the difference of the $\cos^2\theta_{\beta^\pm-\alpha}$ coefficients is

$$\delta = p_- - p_+ = \frac{E}{m_n}\left[\frac{b}{Ac} - \frac{d_{\mathrm{II}}}{Ac} - \frac{(E_0 - E)}{m_n}\left(\frac{3}{28}\right)^{1/2}\frac{g}{A^2 c} - \frac{3}{\sqrt{14}}\frac{f}{Ac}\right], \tag{1}$$

where p_- and p_+ are the coefficients for the electron and positron decay, m_n is the mass of the nucleon, A is the nucleon number, and E and E_0 are the total β and end-point energies, respectively. The quantities b, c, f, and g are unambiguously defined by the impulse approximation in terms of the following transition matrix elements:

$$b \equiv \left[g_v \langle \Psi_f || \sum_{j=1}^{A} \tau_j^\pm \vec{1}_j || \Psi_i \rangle + (g_v + g_m) \langle \Psi_f || \sum_{j=1}^{A} \tau_j^\pm \vec{\sigma}_j || \Psi_i \rangle\right] 2M/(m_p + m_n), \quad c \simeq g_A \langle \Psi_f || \sum_{j=1}^{A} \tau_j^\pm \vec{\sigma}_j || \Psi_i \rangle,$$
$$f \equiv (\tfrac{2}{3})^{1/2} M \Delta g_v (4\pi/5)^{1/2} \langle \Psi_f || \sum_{j=1}^{A} \tau_j^\pm r_j^2 Y_2(\hat{r}_j) || \Psi_i \rangle, \quad g \equiv (-4/3) M^2 g_v (4\pi/5)^{1/2} \langle \Psi_f || \sum_{j=1}^{A} \tau_j^\pm r_j^2 Y_2(\hat{r}_j) || \Psi_i \rangle, \tag{2}$$

where the sum on j runs over all the nucleons, $g_v = 1$, $g_A \simeq 1.23$, $g_m = \kappa_p - \kappa_n = 3.7$, and M and Δ are the nuclear mass and mass difference, respectively, appropriate for $A=8$. The matrix elements defined in Eq. (2) are usually referred to as weak magnetism (b), Gamow-Teller (c), and vector second forbidden (f, g). The quantity d_{II} represents the second-class contribution to the induced-tensor form factor d and does not have an unambiguous impulse-approximation prediction. The absence of axial-vector second-forbidden matrix elements and kinematic coefficients along with the presence of a second-class induced-tensor form factor in δ is a result of the G-parity transformation properties of the vector and axial-vector currents, and the assumption of no second-class contributions to c.[5]

The measurement of the β-α angular correlation was carried out at the Brookhaven National Laboratory 3.5-MeV Van de Graaff. ^{8}Li was produced by the reaction ^{7}Li(d,p)^{8}Li with $E_d = 0.80$ MeV. The targets consisted of 50-μg/cm^2 LiF (natural Li) evaporated onto a 200-μg/cm^2 Ni backing. A ^{3}He beam of 3.45 MeV was used to produce ^{8}B via the reaction ^{6}Li(^{3}He, n)^{8}B. The ^{8}B source was made by catching recoil ions in a 280-μg/cm^2 Ni foil from a target of 250-μg/cm^2 ^{6}LiF (99.3% enriched in ^{6}Li) evaporated onto a 250-μg/cm^2 Ni backing. The incident beams and recoil ions were collimated to yield circular sources of 3.18 and 6.36 mm diam for ^{8}Li and ^{8}B, respectively. Two sources were attached to opposite ends of a 35.6-cm aluminum rod and were rotated out of the beam into the detector chamber, as shown in Fig. 1, by a Slo Syn stepping motor driven by a preset indexer. The absolute positioning accuracy was better than 0.2 mm. The experiment was operated on a 2-sec cycle by a crystal-oscillator–controlled programmer using 1.6 sec for simultaneously bombarding one source while counting the other and 0.4 sec for exchanging the positions of the sources being bombarded and counted.

Four Si surface-barrier detectors approximately 50 μm thick, and two plastic scintillators, as shown in Fig. 1, were used to detect the α and β particles, respectively. Data were taken for β-α coincidence angles of 0, 90, 180, and 270 deg with the data at 90 and 270 deg representing redundant measurements. β and α energy signals along with coincidence timing signals were event mode recorded, and the data analysis was performed off-line.

The α spectrum from the decay of the 2.90-MeV (2^+, $T=0$) state in ^{8}Be has a characteristic non–Breit-Wigner shape with a half-width of approximately 1 MeV and a tail on the high-energy side due to the effect of penetrability. The angular-correlation coefficients were determined from the coincidence data for each β detector separately by integrating over the full α spectrum resulting from the breakup of the ^{8}Be first excited state. Corrections for recoil effects and varying source thickness were applied to the α spectra in order to establish constant lower-level cutoffs. The extracted correlation coefficients were corrected for the finite solid angles of the β and α detectors and also for finite source size. The final results reported here were determined by averaging the coefficients found from the 90- and 270-deg coincidence data for each β detector and then combining the results from the two β detectors as two independent measurements. The total experimental error was found by adding the statistical and estimated systematic errors in quadrature.

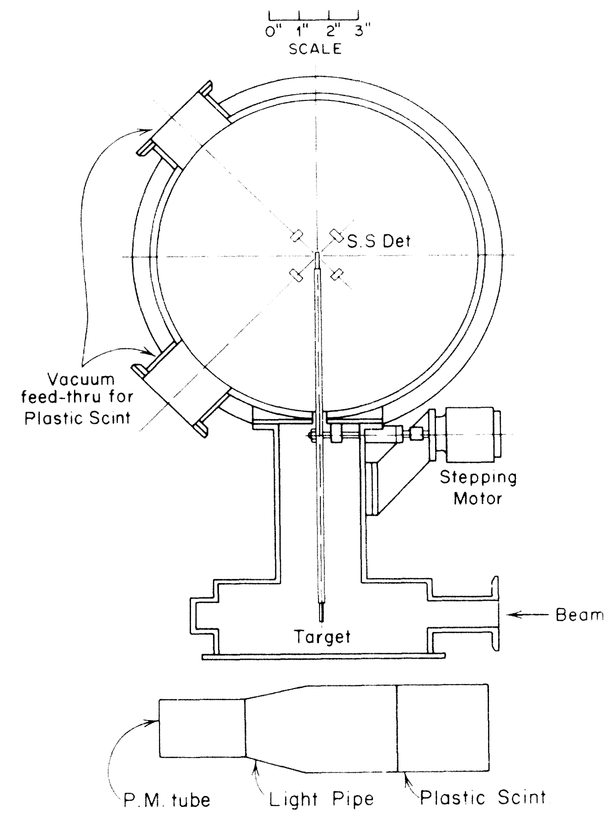

FIG. 1. Vacuum chamber and detector arrangement. Sources produced in the beam are transported, via the stepping motor, into an array of four silicon solid-state detectors and two plastic scintillators. The beam is collimated in order to fix the source location and chopped during the period of rotation.

The experimental results for $p_{\pm}$ were obtained as a function of β energy from 5 to 13 MeV in 1-MeV intervals. A linear least-squares fit to the combined data $\delta m_n / E_\beta$ gives a slope of 0.15 ± 0.2 and an intercept of 5.7 ± 1.8 with a reduced $\chi^2 = 0.66$. The small value of the slope is indicative of negligible second-order β energy dependence

TABLE I. Summary of calculations for weak-magnetism and second forbidden matrix elements. $I_1 \equiv |\sum_j \tau_j^{\pm}\vec{\sigma}_j|$, $I_2 \equiv |\sum_j \tau_j^{\pm}\vec{1}_j|$, $I_3 \equiv |\sum_j \tau_j^{\pm} r_j^2 Y_2(\hat{r}_j)|$; a_1 and a_2 parametrize δ as $\delta = (E/m_n)[b/Ac + a_1(E_0 - E) + a_2]$.

Source of wave function	$\langle\Psi_f\|I_1\|\Psi_i\rangle$	$\langle\Psi_f\|I_2\|\Psi_i\rangle$	$\langle\Psi_f\|I_3\|\Psi_i\rangle$	a_1	a_2	$\frac{b}{Ac}$	$\frac{d_{II}}{Ac}$
Ref. 6	−0.58	−1.80	0.83	+0.014	+0.04	6.5	−0.3
Ref. 7[a]	0.61	1.26	−0.84	+0.014	+0.01	5.6	−1.2
Ref. 8	−0.82	−2.94	−3.46	−0.04	−0.1	7.0	+0.2
Ref. 9	0.69	2.69	0.71	−0.01	−0.03	7.1	+0.3

[a]It is not clear to the authors how the parameters for the $A=8$ wave functions were chosen by Boyarkina. However, since the wave functions are in the literature, their predictions have been included.

in δ. Assuming only first-order energy dependence gives 6.8 ± 0.4 for the value of $\delta m_n/E_\beta$ with a reduced $\chi^2 = 1.07$. From Eq. (1) we note that the theoretical expression for δ contains terms both first and second order in β energy, with the second-order terms depending upon the size of g, the second-forbidden vector matrix element. The matrix elements b, c, f, and g were calculated with four sets of nuclear wave functions and the results are given in Table I. The theoretical predictions for δ, also indicated in Table I, typically show small values for the E_β^2 dependence, in agreement with the small slope indicated by the data.

The lack of dependence of δ on E_β^2 therefore proves that all second-forbidden contributions to δ are small compared to the induced terms such as b/Ac and possibly d_{II}/Ac. In spite of a flurry of excitement around 1970, no positive evidence has been found for second-class currents. Therefore in Fig. 2, the induced tensor contribution d_{II}/Ac was set equal to zero when calculating the predictions of the various wave functions. It is quite clear from Fig. 2 that the CVC prediction for g_m is necessary in order to get agreement between the wave-function predictions and the experimental results. We have explicitly demonstrated the effect of invoking CVC in the figure by plotting the results for Barker's wave functions with $g_m = 3.7$ and $g_m = 0$. That the nuclear wave functions agree with the data and even with one another is perhaps not too surprising since all one requires of nuclear theory in this calculation is that it yield the correct value of

$$\langle\Psi_f\|\sum_j \tau_j \vec{1}_j\|\Psi_i\rangle / \langle\Psi_f\|\sum_j \tau_j \vec{\sigma}_j\|\Psi_i\rangle.$$

Wilkinson and Alburger measured the energy dependence of $(ft)^+/(ft)^- - 1$ in $A = 8$.[10] A recent analysis of the data by Wilkinson, which gives the slope of the energy-dependent part of the asymmetry as $(-1.0 \pm 5.7) \times 10^{-4}$ MeV^{-1}, leads to $d_{II}/Ac = 0.07 \pm 0.4$.[11] In Table I we have indicated the nuclear wave-function predictions for d_{II}/Ac assuming the CVC hypothesis and the experimental result of 6.8 for $\delta m_n/E_\beta$. An average of these results corresponds to $d_{II}/Ac \approx -0.3$. Within the accuracy of the wave functions, d_{II}/Ac from this experiment is consistent with the Wilkinson-Alburger result, and not inconsistent with $d_{II}/Ac = 0$. The impulse approximation would predict $d_{II}/Ac \sim g_{II}/gA$, where g_{II} is the second-class induced-tensor coupling constant for neutron β decay.[12] The Wilkinson-Alburger result, along with our consistent result, would set a rather stringent limit on g_{II}. However, as Kubo-

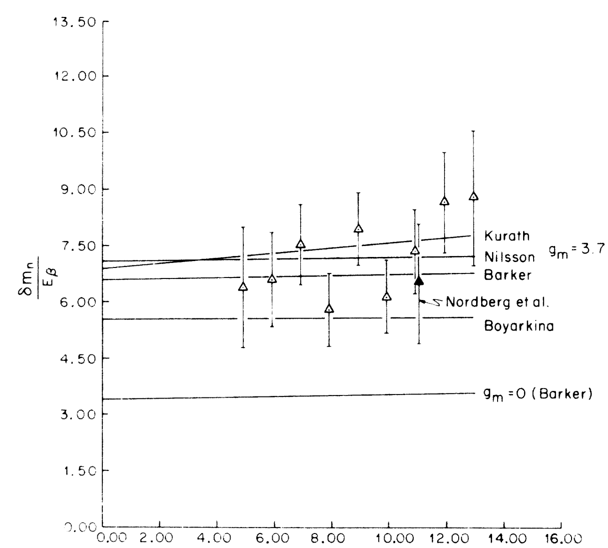

FIG. 2. Experimental results plotted with the wave-function predictions, assuming no second-class current contributions. A datum point from a previous experiment by Nordberg, Morinigo, and Barnes (Ref. 2) has been included to show the good agreement between the two experiments.

dera, Delorme, and Rho[13] have pointed out, the impulse approximation is inadequate for nonisotopic multiplets, and meson exchange effects could interfere with a nonzero g_{II} causing d_{II}/Ac to vanish fortuitously. The small contribution of d_{II}/Ac, along with evidence for negligible second-forbidden contributions to δ, makes the $A=8$ system attractive as a test of CVC. An experiment is now underway[14] to measure the $M1$ γ decay in ^{8}Be in order to remove all model dependence from the test of the CVC hypothesis.

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Evidence for a Collective $E2$ Resonance in the Reaction ^{208}Pb(p,γ)^{209}Bi†

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An $E2$ or $M1$ resonance is observed in the reaction ^{208}Pb($p, \gamma_0\gamma_1\gamma_2$)^{209}Bi at $E_p \simeq 20.0$ MeV ($E_x \simeq 23.7$ MeV) with a width $\Gamma \sim 3.5$ MeV. Present evidence supports its identification as a collective $E2$ excitation.

There is presently a great deal of interest in the study of giant-multipole resonances other than $E1$ (electric dipole) in nuclei. Recent experiments on inelastic electron, proton, and ^{3}He scattering[1] on a variety of medium and heavy nuclei show evidence for collective $E2$ or $E0$ excitations both below and above the giant-dipole resonance (GDR), at energies in agreement with theoretical expectations[2] for the centroids of the isoscalar and isovector giant-quadrupole strengths. While several measurements[1] suggest that the $E2$ assignment is the correct one for the lower excitation, the higher-energy collective resonance is seen only in inelastic electron scattering[3] and the multipole assignment is ambiguous.

In principle, radiative capture or photonuclear reactions should be a useful tool for studying the $E2$ excitations. The richness of information produced by radiative capture studies of the GDR is well known; however, to date there has been no evidence presented from these reaction studies which would corroborate the inelastic scattering studies cited above. In this Letter we present evidence for the $E2$ (isovector) excitation above