$M1$ Decay Rates and Second-Class Currents in Mass 8*

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The total isovector $M1$ γ-decay rate of the 16.6–16.9-MeV doublet in ^{8}Be to the broad first excited state has been measured with the reaction ^{4}He(^{4}He,γ). A width of 4.8 ± 0.7 eV has been found. When properly interpreted, this result seems consistent with predictions of conserved vector currect theory and with the absence of a second-class induced-tensor form factor.

The conserved vector current (CVC) hypothesis[1] relates the isovector $M1$ decay rate of the $T_z = 0$ member of an isospin triplet to the weak-magnetism form factor, b, associated with the β decay of the $T_z = \pm 1$ members of the triplet. This model-independent relationship is[2,3]

$$b = 26.95A[\Gamma_{M1}{}^{\Delta T=1}/E_\gamma{}^3]^{1/2}, \qquad (1)$$

where A is the mass number, Γ is in eV, and E_γ is in MeV. In the mass-8 system, the relevant levels are the 2^+, $T = 1$ multiplet consisting of the ground state of ^{8}Li and ^{8}B and the lowest $T = 1$ state of ^{8}Be, all of which decay to the broad 2^+ first excited state of ^{8}Be.[4] The effects of weak magnetism appear most readily in this system in the angular correlation between the emitted electron or positron and the breakup α from the daughter level. This angular correlation is of the form $f^\pm(\theta) = 1 + a^\pm \cos\theta + p^\pm \cos^2\theta$ (for $\beta^\pm$ decay). The $a^\pm$ coefficients are kinematical terms whereas the $p^\pm$ coefficients contain the information of interest. The difference between the p coefficients is given by[3]

$$\delta^- = p^- - p^+ = \frac{E_\beta}{M_n}\left[\frac{b - d_{\rm II}}{Ac}\right]. \qquad (2)$$

Here c is the allowed axial vector form factor which is related to the total decay rate by $c^2 = 6165/ft$, $d_{\rm II}$ is the second-class[5] part of the induced-tensor form factor, and M_n is the neutron mass. The contribution of second-forbidden vector terms to δ is small and is neglected in Eq. (2). The β-α angular correlation experiment has been performed by several groups, the most recent of which finds[6]

$$(M_n/E_\beta)\delta^- = (b - d_{\rm II})/Ac = 7.0 \pm 0.5. \qquad (3)$$

Although there is recent evidence for the existence of a large $d_{\rm II}$ form factor in mass 12,[7] there is as yet no compelling evidence for the existence of second-class weak interactions in mass 8. In fact, one interpretation of a recent ft-value mirror-asymmetry experiment in mass 8 results in[8] $d_{\rm II}/Ac = 0.14 \pm 0.80$. If indeed $d_{\rm II}$ is equal to zero, then a measurement of the analogous $M1$ width, when combined with the result of Eq. (3) and the ft values, constitutes a test of CVC [via Eq. (1)]. On the other hand, if CVC is assumed valid, then it is possible to determine $d_{\rm II}$ uniquely. It is from this latter point of view that we undertook an experiment to measure the $M1$-decay rate.

In trying to measure the isovector $M1$ radiative width for the lowest $T = 1$ state in ^{8}Be, one is immediately faced with the difficulty that this strength is mixed into two states. Because of an accidental degeneracy of this $T = 1$ state with a $T = 0$, 2^+ state, the resulting physical states occur at 16.63 and 16.92 MeV with α widths of $\Gamma_\alpha = 107$ and 77 keV, respectively.[9] It is straightforward, however, to show that if one sums the radiative widths of the two states, the interference term between the isovector and isoscalar amplitudes vanishes. Further we will show that the observed yield as a function of energy is just what one would expect for an isovector γ-decay mode.

The reaction ^{4}He(^{4}He,γ_1)^{8}Be was used to determine the radiative widths of the two levels. Since the total decay width of each level is essentially just the α width, the total resonant yield of γ rays (integrated over both resonances) determines the sum of the radiative widths directly. As the level widths are comparable to their spacing, the two levels interfere with each other and produce a characteristic shape which is predictable[10] if one assumes the decay to be purely isovector. The observed radiative width must be corrected for a possible $E2$-$M1$ mixing amplitude δ. Thus, the isovector $M1$ width $\Gamma_{M1}{}^1$ is directly proportional to the total resonant yield per microcurie of beam observed at 90°, $Y_T(90°)$, via

$$\Gamma_{M1}{}^1 = 4.817\times 10^{-4}(1-0.977\delta)Y_T(90°)\ \mathrm{eV}. \qquad (4)$$

The constant in Eq. (4) is independent of the isospin-mixing coefficients, the α widths, and the separations of the two levels, and assumes a value for the cross-section stopping power of 1.37×10^{-5} eV cm^2.[11]

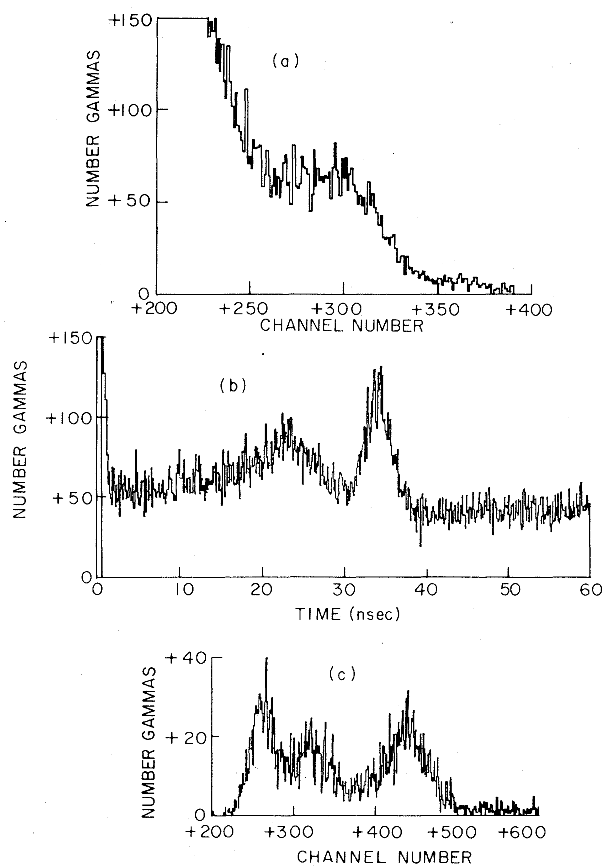

FIG. 1. (a) γ-ray spectrum for ^{4}He$(\alpha,\gamma)^8$Be taken without a pulsed beam at the 16.9-MeV resonance. (b) Time-to-amplitude converter (TAC) spectrum taken at the 16.9-MeV resonance. (c) γ-ray spectrum in coincidence with events in the prompt TAC peak in (b).

The experiment was performed in part at the Brookhaven National Laboratory MP-7 tandem Van de Graaff and at the Princeton University azimuthally varying field cyclotron. An α beam of 33–36 MeV was focused onto a 16-in. long gas cell holding 560 Torr of ^{4}He gas; 0.3-mil Kapton foils isolated the gas from the beam-line vacuum. The γ rays were viewed at 90° in a 24 cm× 24 cm NaI(Tl) detector with lead collimators defining a 3.5-in. region of the gas cell (corresponding to a 220-keV target thickness). Data were taken in 100-keV steps over a region spanning the two resonances. A typical spectrum taken at the tandem Van de Graaff is shown in Fig. 1(a). The large background shown in this figure is due to fast neutrons produced in the entrance foil and necessitated the use of a least-squares minimization fitting procedure to extract the γ-ray yield. On the other hand, the pulsed nature of the cyclotron beam and fast timing techniques[12] allowed rejection of fast-neutron–induced events in the cyclotron experiment. A typical time spectrum in Fig. 1(b) shows the prompt γ-ray peak well isolated from the fast-neutron events. The γ-ray spectrum for events falling under this prompt peak [see Fig. 1(c)] shows that the background has been virtually eliminated. These data were analyzed by summing all prompt events depositing an energy above 11 MeV in the detector, after subtracting the background uncorrelated in time with the beam.

The resulting excitation function is shown in Fig. 2 and includes all data, employing only a

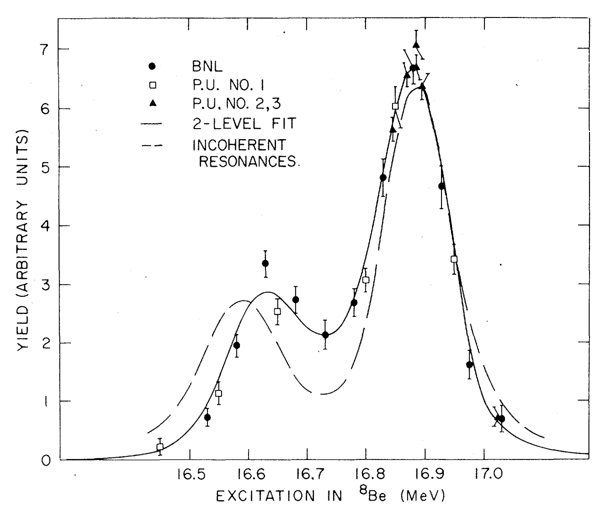

FIG. 2. ^{4}He$(\alpha,\gamma_1)^8$Be excitation function, showing runs taken at Brookhaven National Laboratory (BNL) and at Princeton University (P. U.).

single normalization of data taken at Brookhaven relative to those taken at Princeton. The solid line is a fit to the yield curve, assuming the known isospin mixing and level separation and a 1% isoscalar admixture in the total rate.[9] The good fit achieved supports our contention that the isoscalar contribution to the radiative decay is negligible. The dashed line is the expected yield curve assuming two noninterfering resonances and is included to demonstrate the pronounced effects of interference.

The total resonant radiative cross section was extracted by numerically integrating the observed excitation function, dividing by the target thickness, and applying experimentally determined values for the detector efficiency and solid angle. These latter quantities were determined to a precision of ± 7% using the resonant yield of the reaction $^{12}C(p,\gamma_0)$ at $E_p = 14.23$ MeV[13] and a $^{10}B(^3He, p)^{12}C^*(15.11)(\gamma)^{12}C$ particle-γ coincidence measurement.[14] The $E2$-$M1$ mixing amplitude was determined from an angular-distribution measurement performed with a 5× 4-in. NaI detector at the cyclotron, with the result $1 - 0.977\delta = 0.96 \pm 0.03$. Additional 5% uncertainties were assigned to the charge integration and the target thickness. The largest remaining uncertainty was in the background subtraction of the tandem data (± 6%). The analysis resulted in an $M1$ radiative width of 6.2 ± 1.0 eV for the tandem experiment and 4.5 ± 0.5 eV for the cyclotron experiment. We have taken the weighted mean as our final result; thus

$$\Gamma_{M1}{}^1 = 4.8 \pm 0.7 \text{ eV}. \tag{5}$$

This compares favorably with a calculated value of 3.8 eV using $LSJT$-coupled wave functions.[9]

In order to compare this result with Eq. (3), one must use Eq. (1) to arrive at b and the ^{8}Li-^{8}B lifetimes to arrive at c. Some special complications arise because of the breadth of the final state in ^{8}Be. In order to state the problem, one first recognizes that Eqs. (1) and (2) are model-independent relations. That is, for a specific initial state, each excitation energy E_0 in ^{8}Be has associated form factors $b(E_0)$, $c(E_0)$, and $d_{II}(E_0)$ which determine the decay rate into the energy interval near E_0. Equations (1) and (2) hold for each excitation energy E_0. In the angular correlation experiment[6] the asymmetry coefficients are averaged over the full range of energetically possible final states. Hence Eq. (3) is more properly written as

$$\frac{\delta^- M_n}{E_\beta} = \frac{\sum_{E_0}[b(E_0) - d_{II}(E_0)]c(E_0)f(E_0,E_\beta)}{A\sum_{E_0}c^2(E_0)f(E_0,E_\beta)}, \tag{6}$$

where $f(E_0,E_\beta)$ is the phase-space factor for β energy E_β and the appropriate endpoint energy associated with E_0. Note that if $b(E_0)/c(E_0)$ and $d_{II}(E_0)/c(E_0)$ are constants independent of excitation energy E_0, then Eq. (6) reduces to Eq. (3). In principle, it is possible to determine $b(E_0)$ and $c(E_0)$ from the existing γ-ray spectra and α spectra [from $^8Li(\beta^-)2\alpha$], respectively, by removing the phase-space dependence from these spectra. However, the determination of $b(E_0)$ is hampered somewhat by the necessity of unfolding the detector response from the observed γ-ray spectrum. Nevertheless, we have performed such an analysis and have discovered that $b(E_0)/c(E_0)$ is not constant over the spectrum of final states. The inset in Fig. 3 shows the measured γ-ray spec-

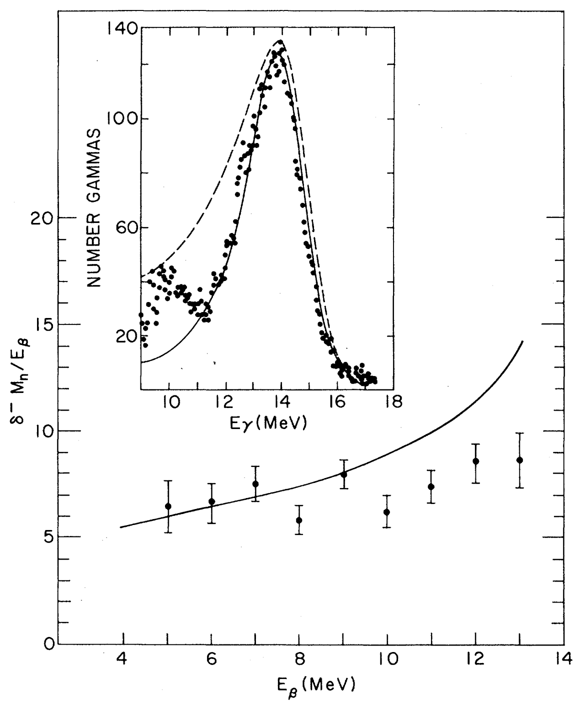

FIG. 3. The measured values of $\delta^- M_n/E_\beta$ versus E_β from Ref. 6 and the calculated values from the present experiment assuming CVC and no second-class currents. The inset shows the measured γ-ray peak shape and a calculated shape assuming a Breit-Wigner resonance for the final state with $\Gamma = 1.32$ MeV (solid line). The dashed line shows the γ-ray shape inferred from the $^8Li(\beta^-)2\alpha$ spectrum. The peak near 10 MeV does not evidence any resonant behavior and may be due to an impurity.

trum and fitted line shape found by assuming a simple Lorentzian for the final state with $\Gamma = 1.32$ MeV. Also shown is the expected line shape if the γ decay were to populate the same final states as are observed in the $^8\mathrm{Li}(\beta^-)\ 2\alpha$ spectrum. Clearly the γ decay populates a more restricted band of final states than does the β decay.[15] Thus $b(E_0)/c(E_0)$ is not a constant. Equation (6) cannot be reduced to Eq. (3).

Using our data to fix $b(E_0)$ and existing β-decay information to fix $c(E_0)$, we have computed the right-hand side of Eq. (6) as a function of E_β. In Fig. 3 the result of this calculation (which of course assumes CVC and $d_{\text{II}} = 0$) is shown with the data of Ref. 6. The difference between the calculation and the data is not large and it would be premature to ascribe the discrepancy to a nonzero value of d_{II}.

A search was conducted to obtain the best fit as a function of d_{II}/Ac.[16] A value of $d_{\text{II}}/Ac = +1.32 \pm 0.80$ is found with a reduced χ^2 of 1.40. The small nonzero value for d_{II} comes about from the difference between the calculation and the data at $E_\beta \geqslant 10$ MeV. On the basis of this analysis we conclude that there is no strong evidence for either a violation of CVC or the existence of a second-class induced-tensor form factor in $A = 8$. However more experimental information on the γ-ray peak shape would be useful to understand the anomalous behavior at high E_β and to fix a more precise limit on d_{II}/Ac.

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[16] In the impulse approximation, if the second-class axial-vector current is assumed to be divergenceless [See K. Kubodera, J. Delorme, and M. Rho, Nucl. Phys. B66, 253 (1973)], d_{II}/Ac is independent of E_0 and thus enters as an additive factor in the right-hand side of Eq. (6).

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