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Magnetic Dipole Transitions and Isospin in Be^8†

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γ transitions to the pair of $J^\pi=2^+$ states at 16.64 and 16.90 MeV in Be^8 have been observed in the reaction $Li^7(p,\gamma)Be^{8*}\to 2\alpha$. The transitions to both states are resonant at the 17.64- and 18.15-MeV states, which have $J^\pi=1^+$. The following resonant cross sections and branching ratios have been obtained: $\sigma(17.6\to 16.6)=11\pm2$ μb; $R(17.6\to 16.90/17.6\to 16.6)=(7\pm2)\%$; $\sigma(18.2\to 16.6)=1.30\pm0.32$ μb; $R(18.2\to 16.90/18.2\to 16.6)=(50\pm10)\%$. From these transitions and the reported strengths for the transitions from the $J^\pi=1^+$ states to the ground and first excited states, the amount of isospin mixing in the four highly excited states has been determined using intermediate-coupling shell-model wave functions. The squared $T=1$ components amount to 40% and 60% in the 16.6- and 16.9-MeV states, and 95% and 5% in the 17.6- and 18.2-MeV states, respectively. Using these mixing coefficients and the assumption of pure $T=0$ character for the ground and first excited states, a shell-model calculation accounts approximately for the strengths of most of the observed or reported magnetic dipole transitions from the 17.64- and 18.15-MeV states. Inclusion of a possible $J^\pi=1^+$, $T=1$ level at 19.4 MeV improves the agreement. A large nonresonant transition to the 16.6-MeV state with $\sigma\simeq2$ μb can be ascribed to direct radiative proton capture which yields a reduced proton width of $\theta_p^2=0.7$ for the final state. This transition, and the fact that the equivalent transition to the 16.9-MeV state is not observed, substantiate the predominance of a (Li^7+p) configuration for the 16.6-MeV state and agree with an assumed (Be^7+n) configuration for the 16.9-MeV level.

1. INTRODUCTION

At about the time when isospin was discovered to play a more important role in heavy nuclei than was previously believed, the first examples of large isospin impurities were discovered in light nuclei. Be^8 has become the first nucleus widely recognized to exhibit almost maximal mixing between isospins $T=1$ and $T=0$ in certain of its states. Much experimental and theoretical work has been published on this topic in the last few years. The results are summarized in three papers[1–3] to which the reader is referred for details. Specifically, the rather narrow states with $J^\pi=2^+$ near 16 MeV have provided the most convincing data for strong isospin mixing. All evidence supports the assumption that these two states have wave functions of mixed isospin character

$$\psi(16.6)=\alpha\psi(2^+,0)+\beta\psi(2^+,1)\,, \qquad (1.1)$$

$$\psi(16.9)=\beta\psi(2^+,0)-\alpha\psi(2^+,1)\,, \qquad (1.2)$$

where $\psi(2^+,0)$ and $\psi(2^+,1)$ are eigenfunctions with parity and angular momentum quantum numbers 2^+, and isospin quantum numbers 0 and 1, respectively; α^2 and β^2 are nearly equal and have a sum normalized to 1. These coefficients may be directly obtained from the observed widths of the two states if one assumes pure isospin $T=0$ for the only open channel, i.e., decay into two α particles. It was believed until recently that the widths of both states were about equal[3] but Browne *et al.*[4] in a high-resolution experiment, taking into account interference effects, obtained the more precise values $\Gamma(16.6)=108.7\pm1.3$ keV, $\Gamma(16.9)=78.2\pm1.5$ keV. This gives $\alpha^2/\beta^2=1.39$. This ratio has now been confirmed by Marion *et al.*,[5] who report $\Gamma(16.6)=113\pm3$ keV and $\Gamma(16.9)=77\pm3$ keV, leading to $\alpha^2/\beta^2=1.47$.

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[1] J. B. Marion and M. Wilson, Nucl. Phys. **77**, 129 (1966).
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[3] P. Paul, Z. Naturforsch. **21a**, 914 (1966).
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Thus it appears at present that, while the isospin mixing between the two states is still close to maximal, the state at 16.6 MeV has a somewhat larger $T=0$ component. This result is currently at variance with the $Li^7(d,n)$ stripping results[6] which indicate the lower state has a predominant $T=1$ component. However, the width measurements would appear to be irrefutable. The details of the interference effects between the 16.6- and 16.9-MeV states observed by Browne *et al.*[4] also agree with the signs of α and β as used in Eqs. (1) and (2). These signs have been obtained from an analysis of the $Li^7(d,n)$ and $Be^9(He^3,\alpha)$ reactions by Barker.[2]

The next two states at 17.64 and 18.15 MeV are above the proton threshold and have center-of-mass (c.m.) widths of 10 and 147 keV, respectively. Both states have $J^\pi=1^+$ and thus cannot decay into α particles. Shell-model calculations by Barker,[2] and Cohen and Kurath[7] predict that they should have similar wave functions but differ in their isospin. It is presently believed that they are rather pure eigenstates of isospin, in contrast to the $J^\pi=2^+$ pair, with the 17.6-MeV state having $T=1$, and the 18.15-MeV state $T=0$. The most direct experimental evidence for these assignments comes from a comparison of the $Be^9(d,T)Be^{8*}(17.6)$, and $Be^9(d,He^3)Li^{8*}(0.98)$ reactions[8] which populate the two final states with the correct ratio expected for $T=1$ analog states. A study of the $B^{10}(d,\alpha)Be^8$ reaction by Browne and Erskine[9] yields a mixing ratio of $\gamma^2/\delta^2=0.08$ for the 17.6-MeV state, where γ and δ are equivalent to α and β, respectively, of Eq. (1.1).

The radiative transition strengths between the 1^+ states and all lower states can be computed using published intermediate-coupling shell-model wave functions.[2,7] If the transitions have unique or predominant (i.e., of the order of a Weisskopf unit) magnetic dipole character, the matrix elements by virtue of Morpurgo's rule[10] are characterized by an isospin change $\Delta T=\pm1$ with an accuracy of a few percent. A comparison between computed and observed strengths of the transitions between the 1^+ and 2^+ pairs yields the isospin mixing parameters for each pair of states assuming that the unmixed wave functions provide the correct basis for the calculation. Inclusion of the magnetic dipole transitions from the 1^+ pair to the ground and first excited states into the analysis gives an overdetermined set of equations since the two lower states may reasonably be assumed to be pure $T=0$ states. This then allows a check on the unmixed wave functions of the highly excited states, which is interesting on its own merits. Few radiative widths have been available until recently in Be^8 and shell-model calculations have not been able to reproduce the energies and other characteristics of excited levels in Be^8 with the same accuracy as in other p-shell nuclei.[2,7]

The disagreement is especially obvious for the 18.15-MeV state. If it had pure isospin $T=0$, the $M1$ transition to the ground state should be forbidden. However, even if the 8% $T=1$ admixture observed in the $B^{10}(d,\alpha)$ reaction is included, the calculated strength would be only one-fourth of the observed value. The observed reduced proton width for the 18.15-MeV state is about twice as large as calculated, and as observed for the 17.6-MeV state. This discrepancy appears to destroy the symmetry of single-particle configurations which was suggested[1] at one time and is so convincingly evident in the 16.6- and 16.9-MeV states. Based on the observation that both 2^+ states have very large reduced nucleon widths, the 16.6-MeV level is assumed to have a dominant cluster configuration of the type (Li^7+p), and the 16.9-MeV state the configuration (Be^7+n), thereby generating two states maximally mixed in isospin. If this model can be extended to the 1^+ pair, the isospin mixing coefficients γ and δ predict a slightly larger proton width than neutron width for the 17.6-MeV level and the opposite for the 18.15-MeV level. The γ decay scheme between the two pairs is a severe test of this extended model, since only those transitions would be observed which connect the upper and lower proton states with each other, and again the upper and lower neutron states.

Investigation of low-energy γ transitions between the 1^+ pair and the 2^+ pair thus sheds light not only on the amount of isospin mixing in these states but also discriminates between a shell-model description and a general single-particle cluster description of highly excited states in Be^8. Partial results have been presented previously,[11,12] in particular about the low-energy transitions from the 17.64-MeV state. Experimental emphasis of this paper lies on new data concerning decay of the 18.15-MeV level. In the final sections, all known $M1$ transition strengths are compared with the predictions of the intermediate-coupling shell model.

2. EXPERIMENTAL TECHNIQUE

The present experiment measures the excitation function of low-energy γ transitions in Be^8 to the excited states at 16.64 and 16.90 MeV with $J^\pi=2^+$, specifically searching for resonances corresponding to the states with $J^\pi=1^+$ at 17.64 and 18.15 MeV. The pertinent level scheme of Be^8 is shown in Fig. 1. The 1^+ states may be populated by proton capture on Li^7 at bombarding energies[13] of 441 keV and 1.03 MeV. The range of bombarding energies used in this experiment extended

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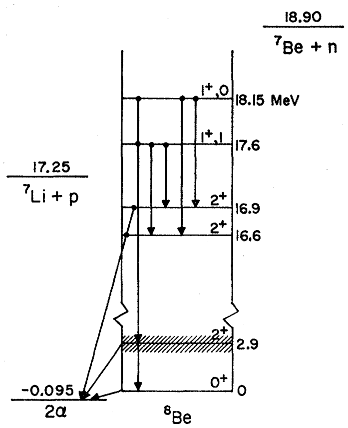

FIG. 1. Level scheme of Be^8 indicating levels and γ transitions pertinent to the present work.

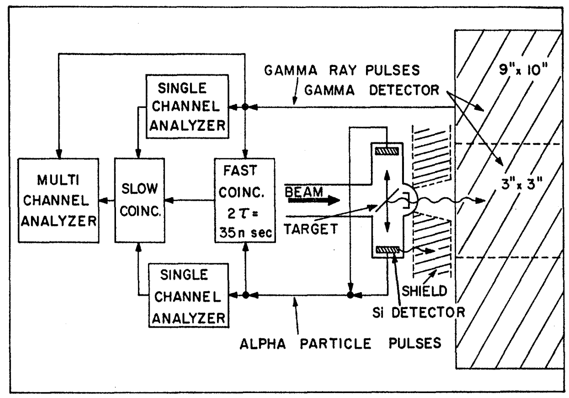

FIG. 2. Schematic of the experimental arrangement showing the relative geometries used for the particle and the γ detectors. Lead shielding was used in the indicated position during some runs. The block diagram indicates the electronic fast-slow coincidence setup.

up to 1.4 MeV. The proton beam was produced by the Stanford 3-MV Van de Graaff accelerator and its energy determined by magnetic analysis.

γ transitions from the 1^+ to the 2^+ states have energies between 0.7 and 1.5 MeV. These low-energy γ transitions compete with the strong γ transitions, of energies greater than 12 MeV, to the ground state and wide ($\Gamma \simeq 1$ MeV) first excited state of Be^8. The resulting large background in the γ spectrum down in the 1-MeV region makes direct observation of the low-energy γ transitions extremely difficult. However, use can be made of the fact that both final 2^+ states break up into two α particles. The transition to either state can thus be observed via the α-particle group from the final-state breakup, or by detecting the γ rays in coincidence with these α particles. The 180° symmetry in the c.m. system of the two 8- to 9-MeV α particles provides a unique signature for the decay of Be^8. Existence of a transition from the 17.6-MeV state to the 2^+ states was established for the first time by recording the particle spectrum using two solid-state detectors in coincidence[11] and, in another experiment,[1] using a magnetic spectrograph. Both experiments, however, are difficult because the α groups from the final-state ("delayed") breakup are positioned on the lower edge of a much more intense peak resulting from the prompt breakup of Be^8 through the tail of the wide[13] ($\Gamma = 1$ MeV) 2^+ state at 19.9 MeV. The α-γ coincidence technique eliminates this background and therefore allows a more definitive observation of the low-energy transitions. Recording the γ spectrum has the added benefit that transitions to the two final states are separated by 300 keV out of about 1 MeV total γ-ray energy. In the α spectrum this difference is only 150 keV (out of 9 MeV) due to the emission of two identical particles. For the new data presented in this work, the coincidence method was therefore employed throughout.

The target and detector geometry is sketched in Fig. 2. The target chamber was made of glass completely lined inside with Ta foil. The proton beam was stopped in a small tantalum cup 15 mm behind the thin target. Targets were prepared by evaporation *in situ* of metallic isotopically enriched (99.97%) Li^7 on various thin and thick backings. The target could then be directly inserted into the beam. In the experiment where both α particles were detected in coincidence, thin carbon or Ni foil backings were used. Otherwise the target was deposited on 1-mm Cu or 0.20-mil Ta pieces. Target thicknesses between 2 and 70 keV for 441-keV protons were used, as determined from the $Li^7(p,\gamma_0)$ excitation function over the width of the 441-keV resonance ($\Gamma_{c.m.} = 10$ keV), or from the shape of the $Li^7(p,n)$ neutron threshold at 1.88 MeV.

To detect the α particles two large (100- and 200-mm^2 area) circular Si surface-barrier detectors were mounted facing each other at 90° to the beam axis. The detector surface was at least 1.5 cm away from the target; larger distances were used for some particular checks. Due to the high α-particle energy the kinematic energy spread over the detector solid angle is considerable. For improved resolution the effective area of the small detector was reduced by a 2-mm-wide vertical aperture. This arrangement also assured, at least at low proton energies, that for each particle detected in the small detector the associated second α particle was striking, at somewhat less than 90°, the second larger counter. At higher proton energies, this solid-angle overlap ratio was slightly less than 1 and had to be determined experimentally as a function of energy. This was achieved by comparing the yield of the prompt α particles in one counter to the coincidence yield.

Both particle detectors were covered with thin Ni foils to stop the elastically scattered protons. For the measurements in the neighborhood of the 441-keV resonance a thickness of 0.15 mil was used, whereas a 0.5-mil foil was used for those near the 1.03-MeV resonance. The latter foil thickness caused an energy loss of 2 MeV for the 9-MeV α particles, decreasing the energy resolution to about 100 keV, so that the groups from the two final states were no longer clearly separated.

The γ rays were observed at 0° in a cylindrical NaI crystal. Crystal sizes of 3×3 in. and 9×10 in. were used. The latter had the advantage that the Compton peak in the spectral line shape was eliminated. This is an important advantage because the transition to the 16.9-MeV state has an energy which is 300 keV less than that of the transition to the 16.6-MeV state, and thus is just superimposed on the Compton peak of the higher line. The particle and γ detectors were put in coincidence using standard fast-slow coincidence techniques with crossover timing and conventional modular electronics, as indicated in Fig. 2. Variously, either the α or the γ spectrum was gated by the "slow" window and stored in a multichannel pulse-height analyzer. The coincidence delay curve had a half-width of typically 40 nsec and was measured using the actual reaction on the peak of the 441-keV resonance.

3. CROSS-SECTION DETERMINATIONS

The cross sections which have been reported for the observed γ transitions have been fluctuating throughout the recent publications.[1,3,11] The main source of confusion seems to stem from the fact that two α particles originate in each Be^8 breakup, and it is not always clear whether the *reaction* cross section (two α particles per reaction event) or the α-particle-*production* cross section (twice the reaction cross section) is meant by a published value. We briefly discuss this point to clarify our calibration procedure and to obtain the cross sections listed in this paper. We consider the 441-keV resonance where, as will be shown, the γ yield is largest. The relative cross sections at other energies are compatible among all authors.

Initially, a value of 11 μb/sr was reported by Paul *et al.*[11] for the dominant low-energy transition from the 17.6-MeV state. This value was obtained from the α spectrum alone and normalized to the cross section for the prompt breakup of the $Li^7(p,\alpha)$ reaction which was reported by Freeman *et al.*[14] as $d\sigma/d\Omega$ (90°) $=(0.94\pm0.08)$ mb/sr at $E_p=1.36$ MeV. That paper states specifically that this value refers to the reaction cross section. It should also be noted that this value matches the cross sections for the inverse reaction[15] $He^4(\alpha,p)Li^7$ within 20% after both cross sections are properly adjusted for the detailed balance comparison. However, more recently, Marion and Wilson[1] have obtained a value of (0.60 ± 0.050) mb/sr for the $Li^7(p,\alpha)$ reaction at 90° (which was computed from the actual value measured at 120° by use of the angular distributions of Cassagnou *et al.*[16]). This has led to the suggestion[1] that the value of Freeman *et al.*[14] refers to the α-*production* cross section rather than the *reaction* cross section.

TABLE I. Published cross sections for the reaction F^{19} (p,α_0). The original values of the second column have been transformed to the same angle and bombarding energy using the curves of Cassagnou *et al.*[a]

Reference	Reported values	$\frac{d\sigma}{d\Omega}$(90°) at $E_p=1.36$ MeV
14	$\frac{d\sigma}{d\Omega}=2.71\pm0.27$	2.71 ± 0.27
17	$\sigma=(46\pm5)$ mb	2.16 ± 0.32
18	$\sigma=(40\pm4)$ mb	1.88 ± 0.19
19		1.8 ± ?
	average	2.25 ± 0.26 mb/sr

[a] Reference 16.

A simple check on this discrepancy is offered by a comparison of the $Li^7(p,\alpha)Be^8$ yield to that of the $F^{19}(p,\alpha)O^{16}$ reaction, which can readily be obtained using a LiF target and a solid-state detector. The absolute cross section of the latter reaction has been measured by several groups[17–20] with the results collected in Table I. The average value weighted by the quoted errors is 2.25 ± 0.3 mb/sr at 90° and 1.36 MeV. We have obtained at the same bombarding energy the following ratio for the *reaction* cross sections:

$$\frac{d\sigma/d\Omega(\mathrm{Li}^7)}{d\sigma/d\Omega(\mathrm{F}^{19})}=0.42\pm0.03 \qquad (3.1)$$

between the reactions $Li^7(p,\alpha)$ and $F^{19}(p,\alpha)$. This yields for the absolute cross section $d\sigma/d\Omega$ $(Li^7)=0.95$ mb/sr ±15% in excellent agreement with Freeman's value quoted above. Relative measurements at different bombarding energies give similar agreement. We therefore feel confident that normalization of the $Li^7(p,\gamma\alpha)$ cross section to Freeman's value for the prompt breakup in $Li^7(p,\alpha)$ is valid, and that the discrepancies in the cross section quoted by different authors are indicative of the difficulties encountered in the use of lithium targets for absolute measurements.

4. 441-keV RESONANCE

In the following two sections, we will go into detail about the results obtained for the transitions from the two states at 17.64 and 18.15 MeV. It will become apparent that the experimental problems are quite different for the two states. Since the decay of the 17.6-MeV state has been reported previously in two letters,[11] these data will only be presented briefly for completeness while the main emphasis will be on the decay of the higher state.

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The 441-keV resonance corresponding to the 17.6-MeV state is observed in the transitions to both the 16.6- and 16.9-MeV states. Figure 3 shows the essential data. The dominant transition, which goes to the lower state, has a total cross section 11 ± 2 μb. This is to be compared to 6.45 ± 0.7 μb reported by Marion and Wilson[1] [and a more recent value of $(8.6\pm10\%)$ μb communicated by Marion[21]]. The proton is captured into the 17.6-MeV state in a rather pure $p_{1/2}$ configuration.[22] The angular distribution of the low-energy γ rays should therefore be very nearly isotropic, and, thus, also the α distribution (provided the γ radiation is not detected in coincidence). The transition strength to the 16.9-MeV state was measured to be $(7.8\pm2)\%$ of the transition strength to the lower state; this was recently confirmed by Marion and Wilson.[1] [However, Marion more recently[21] obtained a value of $(3.3\pm1)\%$.] A cross section of 11 μb and a 7.8% branching ratio yield the radiative widths $\Gamma_\gamma(17.6\to16.6)=3.90\times10^{-2}$ eV and $\Gamma_\gamma(17.6\to16.9)=0.3\times10^{-2}$ eV.

If one compares these values with $M1$ Weisskopf estimate[23] of $\Gamma_{\gamma w}(17.6\to16.6)=2.2\times10^{-2}$ eV, it becomes obvious that both are very strong transitions. Although this point has been debated in the literature,[24] it seems clear that this alone establishes the overwhelming $M1$ character of the transitions, the Weisskopf estimate for an $E2$ transition being only about 10^{-6} eV. Taking our experimental value for $M(M1)$ and allowing the usual Z^2 factor for coherent contributions, one expects the ratio $\delta^2=[M(E2)/M(M1)]^2$ to be smaller than 4×10^{-4}. A value of $\delta^2=(5\pm3)\times10^{-3}$ has been reported by Sweeny and Marion[24] which would indicate, relatively speaking, a surprisingly large $E2$ contribution. More recent experiments by Marion indicate, however, a smaller value.[21]

The peak due to the $17.6\to16.6$ transition in Fig. 3 has been fitted with Lorentzian curves corresponding to various widths for the final state folded into the resolution function of the detector as measured with the 1.01-MeV γ ray from Zn^{65}. Recently, two precise particle experiments[4,5] have led to new values for the total widths $\Gamma(16.6)=108.7\pm1.3$ keV and $\Gamma(16.9)=78.2\pm1.5$ keV, replacing the old values of 95 ± 20 and 85 ± 20 keV, respectively. The γ spectra, with the presently available statistical accuracy, are not able to discriminate between the old and the new values, although the quality of the fit with the larger width would not be as good at the high-energy side. Interference effects in the spectrum shape cannot be appreciable because—in contrast to the interference analysis of Browne *et al.*[4] in the $B^{10}(d,\alpha)$ reaction—essentially only one final state is populated in the (p,γ) reaction at this proton energy. This point is discussed in more detail in Sec. 7.

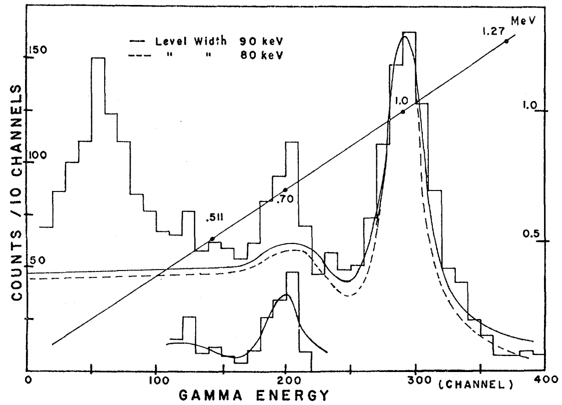

FIG. 3. γ spectrum recorded in a 3×3-in. NaI crystal at the peak of the 441-keV resonance of the $Li^7(p,\gamma)Be^8$ reaction corresponding to the $J^\pi=1^+$ state at 17.64 MeV, in coincidence with the α particles from the breakup of the two $J^\pi=2^+$ states at 16.64 and 16.90 MeV. The transitions to both final states are unfolded from the spectrum. Line shapes were obtained by folding Lorentzians with the final-state widths into the spectral response function.

5. 1.03-MeV RESONANCE

Since the main point of this paper is the verification of the existence of low-energy γ transitions from this resonance (the 18.15-MeV state), we discuss this part of the experiment in more detail.

The experimental problems are now much more severe than in the case of the 441-keV resonance for the following reasons: The particle detectors have to be covered with much thicker foils than before to eliminate the elastically scattered protons. The 9-MeV α particles lose about 2 MeV in these foils and the ensuing straggling results in the particle groups from the 16.6- and 16.9-MeV states being unresolved. In the γ-ray spectrum a very intense 480-keV background line is introduced from the inelastic scattering channel which opens at $E_p=550$ keV and is strongly resonant[13] at 1.03 MeV. While the background problems are increased, the cross section of the actual transition of interest is expected to be only about 10% of the cross section for the transition from the 17.6-MeV state, owing to the larger width of the 18.15-MeV state, and the usual energy-dependent factors.

In the geometry described in Sec. 2, γ-α coincidence spectra were taken with proton bombarding energies between 600 keV and 1.36 MeV. Targets had a thickness of between 30 and 70 keV to 441-keV protons. To establish the transition uniquely, the γ spectrum was first recorded when gated by the appropriate α particles. Figure 4 shows a typical spectrum taken at 1.03 MeV and at 0° as observed in a 3×3-in. NaI crystal. A prominent peak is centered at 1.50 MeV which corresponds rather well to the energy of a transition to the 16.64-MeV state. The spectrum was analyzed by first determining a detector response function from the shape

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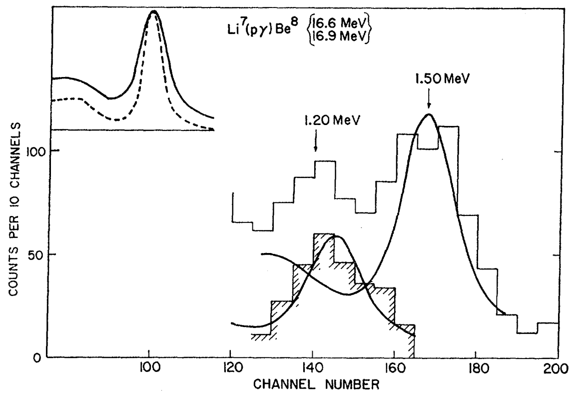

FIG. 4. Typical low-energy γ spectrum recorded in a 3×3-in. NaI crystal at $E_p=1.03$ MeV (center of the 1.03-MeV state) in coincidence with α particles from the states at 16.64 and 16.90 MeV. A sample line shape made up of the resolution function and a 90-keV-wide Lorentzian for the final state is shown in the insert. The positions of expected transitions to the two final states are indicated. The lines represent the best fits obtained with the standard line shapes.

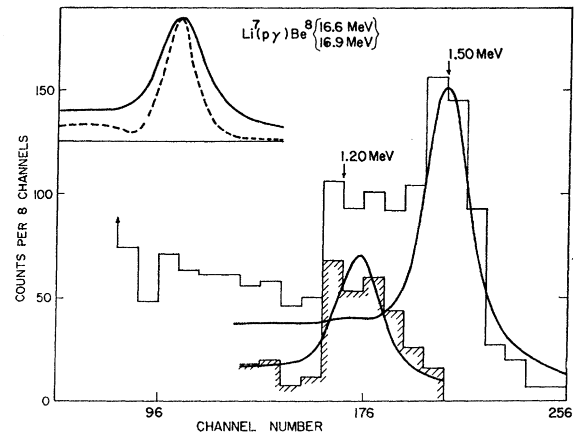

FIG. 5. γ spectrum taken under the same condition as in Fig. 4 but with a 9×10-in. NaI detector.

of the Na^{22} 1.27-MeV γ peak. A comparison with the 1.83-MeV γ-ray line shape from Y^{88} established that the change of the resolution function between 1.27 and 1.50 MeV was negligible. This line was then folded with a Lorentzian of width $\Gamma=90$ keV. This resulting curve (shown in the insert of Fig. 4) was fitted to the data in the region of the peak near 1.5 MeV. The agreement with the experimental curve is rather good in this region. The subtraction of the normalized spectrum from the data leaves a residue around 1.2 MeV. This energy is very close to the one expected for a transition to the 16.90-MeV state. A fit with the same line shape (but, of course, with a different E_γ^3 factor) generally accounts for the residual peak, i.e., all counts above 1 MeV can be explained with these two peaks. A peak around 960 keV turned out to originate from double pileup of 480-keV γ rays from inelastic scattering. Under identical conditions, a γ spectrum (with α coincidence) was taken with a 9×10-in. crystal which virtually eliminates the Compton peak. It can be seen in Fig. 5 that again two peaks at the same energies as in Fig. 4 explain the spectrum at energies above 1 MeV. The area ratio is the same as with the smaller crystal. While a nonresonant transition to the 16.6-MeV state had been reported previously at these bombarding energies by Marion *et al.*,[1] these authors did not observe a transition to the 16.9-MeV state. (A reinvestigation of their experiment by Marion *et al.*[21] now substantiates existence of the resonant transitions 18.15 → 16.9 MeV and 18.15 → 16.6 MeV.)

In both spectra the transition to the 16.9-MeV state appears to have an energy of somewhat more than 1.20 MeV. This agrees with the recent new energy determination by Marion *et al.*[5] which puts the state at 16.90 MeV and yields a γ energy of 1.25 MeV. The present γ spectra yield a transition energy $E_\gamma(18.15\rightarrow 16.9)=1.27\pm0.03$ MeV.

Before identifying the second peak with the 18.15–16.90-MeV transition, we carefully investigated several possibilities which could generate a spurious peak in the vicinity of 1.27 MeV. An α particle associated with the prompt breakup of Be^8 may scatter inelastically in the Si detector exciting the first excited state of Si^{29} at 1.28 MeV. This leaves the α particle with 7.8 MeV, which is barely distinguishable from the particles emitted from the 16.6- or 16.9-MeV states on account of the poor detector resolution. The 1.28-MeV γ ray is then detected in the NaI crystal in a true coincidence. To check for this possibility, runs were taken where the γ detection was heavily shielded from the Si detectors, then the distance between the Si detectors and the NaI detector was varied. Finally, a window was placed in the gating α spectrum eliminating all particles with an energy of less than 8 MeV (energy before passing through the absorber foil). In every case, the peak at 1.27 MeV was observed in the γ spectrum with the same strength relative to the 1.50-MeV γ ray. Inelastic scattering from the Si in the glass target-chamber wall was excluded by covering all surfaces with Ta sheet. A variety of thin and thick target backings were used to exclude inelastic α scattering in the backing leading to possible true α-γ coincidences. Since the large variety of geometric and gating configurations always gave the same result, we feel confident that the observed γ ray of 1.27 MeV (at $E_p=1.03$ MeV) is due to a transition to the 16.9-MeV state.

γ spectra in coincidence were taken over a range of bombarding energies with particular emphasis on a region covering the 1.03-MeV resonance. At all energies the spectra were very similar in character to the ones shown in Figs. 4 and 5; i.e., the transition to the 16.6-MeV state was always dominant and the one to the 16.9-MeV state clearly present in most cases. Analysis of each spectrum followed the procedure outlined above: The folded line shape was fitted to the highest peak by adjusting both amplitude and position. It was then

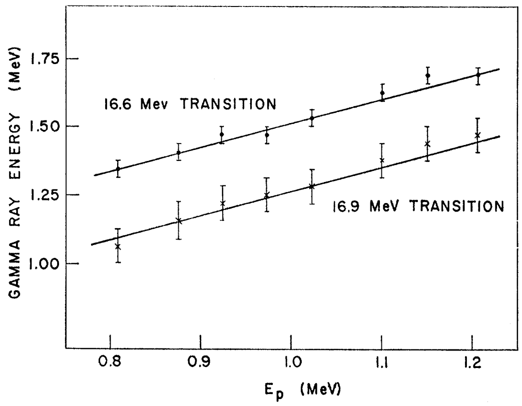

FIG. 6. Energy dependence of the observed γ peaks as a function of proton bombarding energy. The straight lines are computed from the kinematics of the $Li^7(p,\gamma)Be^8$ (16.6 and 16.9 MeV) reactions.

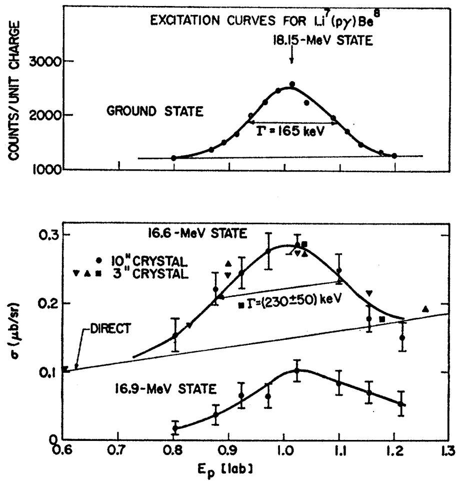

FIG. 7. Excitation functions of the low-energy γ transitions to the 16.64- and 16.90-MeV states, covering the neighborhood of the 18.15-MeV level. Different symbols represent runs taken under somewhat varied experimental conditions. The ground-state γ resonance curve is given for comparison. The nonresonant background in the transition to the 16.6-MeV state is fitted with a direct-capture calculation described in the text.

subtracted from the spectrum and a new fit made to any residual peak present. The energies of the two γ lines in each spectrum were thus determined by the experiment and not *a priori* biased toward the two transitions being sought. In Fig. 6, the experimental peak positions as a function of bombarding energy are compared to the energy dependence expected from the kinematics of the $Li^7(p,\gamma)Be^8$ reaction. The agreement is very good, although perhaps less meaningful in the case of the second peak where the position has a large uncertainty.

Each spectrum required a running time of 6–8 h and target deterioration was to be expected. The runs were therefore always normalized to the yield of prompt breakup α's. Then with a fresh target the prompt-peak excitation function was obtained with short runs. This curve is slowly and smoothly varying over the 1.03-MeV resonance and agrees with other data.[1] The absolute cross section for the $Li^7(p,\gamma\alpha)$ reaction was obtained, again, from a comparison to the prompt $Li^7(p,\alpha)$ reaction. For the latter reaction cross section at 1.03 MeV the value $d\sigma/d\Omega=0.67\pm0.06$ mb/sr was used with the same meaning as discussed in Sec. 3. If $Y(\gamma,\alpha)$ represents the yield of γ-α coincidences and $Y(\alpha)$ the prompt yield, the cross sections are related by

$$\frac{d\sigma}{d\Omega}(p,\gamma\alpha)=\frac{d\sigma}{d\Omega}(p,\alpha)\frac{Y(\gamma,\alpha)}{Y(\alpha)}\frac{4\pi}{\Omega_\gamma\epsilon_\gamma}, \qquad (5.1)$$

where Ω_γ and ϵ_γ are the solid angle and efficiency, respectively, of the γ detector. At a distance of 4.3 cm from the target the value $(\Omega_\gamma/4\pi)\epsilon_\gamma=0.058$ was used for the 1.5-MeV γ ray. With a peak to total ratio of 0.32, we obtained a cross section of $d\sigma(p,\gamma\alpha)/d\Omega=0.27$ μb/sr$\pm15\%$ at 1.03-MeV bombarding energy.

The excitation functions for the transitions to the 16.6- and 16.9-MeV states are plotted in Fig. 7. For comparison, the 1.03-MeV resonance is shown in the same figure as it is observed in the ground-state γ transition. The width of $\Gamma=165\pm8$ keV in the laboratory system observed in the latter transition agrees very well with the value of 168 keV given in the literature.[13] Manifestly, the transition to the 16.6-MeV state is resonant at about the same energy, but shows a laboratory width of $\Gamma=230\pm50$ keV. The discrepancy between these two values is somewhat outside the estimated error and we do not have any good explanation for it. The target thickness could contribute as much as 50 keV (for a rectangular profile). Some contribution may arise from angular correlation effects. Data obtained with different geometries and crystals are indicated in the curve and generally agree with the existence of the resonant contribution to the transition to the 16.6-MeV state. Note that the peak is superimposed on a rather large background. With a larger error the 1.03-MeV resonance is also observed in the transition to the 16.9-MeV state. In this case, only the more reliable results obtained with the 9×10-in crystal have been used.

By reversing the gating condition the excitation function of the α particles coincident with γ rays of energy between 600 keV and 2 MeV was obtained and is shown in Fig. 8. The poor resolution in the α-particle spectrum did not allow separation of either the two final-state groups or the prompt-breakup group. The curve does, however, offer added qualitative proof that either one or both of the low-energy transitions are resonant at the 1.03-MeV resonance. The resonance shape is similar to the one observed in the γ excitation function, with a width of $\Gamma=180\pm50$ keV which is closer to the accepted value of the resonance width than the value obtained from the γ spectra. The peak-to-background ratio is somewhat smaller than in the γ

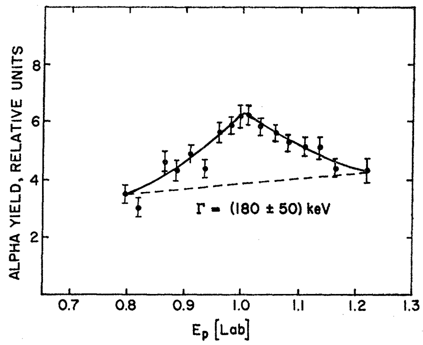

FIG. 8. Excitation function of high-energy α particles in coincidence with γ rays having energies between 0.8 and 2 MeV, observed in proton capture on Li^7 for proton bombarding energies between 0.8 and 1.25 MeV. The resonance is due to transitions to the 16.64- and/or 16.90-MeV states.

curve, while in fact, one would have expected it to be larger because of the addition of the 16.9-MeV state transition. The added values of the two transition strengths observed in the γ-ray spectrum give a peak-to-background yield ratio $Y(1.03)/Y(0.8)=2.2\pm0.4$. The α spectrum gives for the same ratio 1.8 ± 0.3. The errors are obtained from the range of possible fits to the data.

These experimental data prove that the 18.15-MeV state in Be^8 decays to both the 16.6- and 16.9-MeV states. Considering only the resonant components, the intensity ratio is $I(16.9)/I(16.6)=0.5\pm0.1$. The cross section for the 16.6-MeV transition previously reported[1] off resonance, at 850 keV, was 1 μb, which agrees reasonably well with the present result ($\sigma=1.88$ μb$\pm15\%$) provided the factor of 2, which we have discussed in Sec. 3, is applied to the former value. For the resonant transition our data give the values

$$\frac{d\sigma}{d\Omega}(18.15\rightarrow 16.6)=0.13\ \mu\text{b/sr}\pm25\%,$$

$$\frac{d\sigma}{d\Omega}(18.15\rightarrow 16.9)=0.064\ \mu\text{b/sr}\pm30\%.$$

The differential cross section refers to the geometry described in Sec. 2.

6. DIRECT-CAPTURE CALCULATIONS

In an attempt to explain the nonresonant background in the $Li^7(p,\gamma)Be^{8*}$ (16.6 MeV) reaction, we have calculated the direct-capture cross section for the emission of $E1$ radiation, for the above reaction, following the prescription of Christy and Duck.[25] Although the 16.6-MeV state is unbound with respect to α-particle emission, the breakup into Li^7+p is energetically prohibited. Hence, the straightforward application of the direct-capture theory for bound final states should be satisfactory. The cross section for electric dipole emission in the direct-capture reaction is given by Eqs. (7)–(9) of Ref. 25.

Since the final state of the proton must be a p state ($l'=1$), angular momentum and parity conservation require that, provided only $E1$ radiation is considered, the capture take place from either s- or d-wave initial states. Following Christy and Duck, we have taken all contributions to the matrix elements to be "extranuclear"; that is, we have evaluated the matrix element integrals for $r\geqq r_n=4$ F and have ignored contributions to the matrix elements from the interior where the wave functions are not explicitly known. Then the cross-section formula reduces, in our case, to

$$\sigma(p,\gamma)=(29\times10^{-6})(E_\gamma^3/k^3)[|R_s|^2+2|R_d|^2]\ \mu\text{b}, \quad (6.1)$$

where E_γ is the γ-ray energy in MeV, k is the wave number of the incident channel in F^{-1}. The quantities R_s and R_d are the s- and d-wave ($l=0$ and $l=2$) matrix elements

$$R_{s,d}=\frac{1}{k}\int_{r=r_n}^{\infty} g_f^*(r)g_{is,d}(r)r^2dr \quad (6.2)$$

with

$$g_{il}(r)=F_l(kr)+[G_l(kr)+iF_l(kr)]e^{i\delta_l}\sin\delta_l \quad (6.3)$$

and $g_f(r)=W_{\alpha l'}(kr)/r$, where $W_{\alpha l'}$ is the Whittaker function. The nuclear phase shift has been taken as $\delta_{J=l\pm1/2}=\delta_l$. The normalization of $W_{\alpha l'}(kr)$ is given by $\frac{1}{2}W_{\alpha l'}^2(kr_n)r_n=\theta_{sp}^2$, the single-particle reduced width.

For s-wave capture the integrand peaks at $r\simeq2r_n$, where the value of the integrand is about 50% greater than the value at $r=r_n$; hence the nuclear region could contribute significantly to this matrix element. We have included the contribution to the matrix element from the irregular Coulomb wave function by estimating the s-wave nuclear phase shift as that due to a hard-sphere potential of radius $r=r_n$. The introduction of $\delta_0\neq0$ decreases the s-wave contribution to the cross section by about 40% at $E_{lab}=1.0$ MeV. The s-wave–capture cross section calculated in this manner is not strongly sensitive to changes in r_n, being roughly proportional to r_n. The s-wave–capture cross section is also relatively flat over the energy range of Fig. 7.

The d-wave matrix element is completely extranuclear, with the integrand peaking at many times r_n, and with the value of the integrand at r_n negligible compared to the peak value. Here the nuclear phase shift is taken to be zero, so only the regular Coulomb wave function contributes. The d-wave–capture cross section increases by a factor of 4 over the energy interval of Fig. 7, contributing a maximum of about 50% to the total capture cross section at $E_{lab}=1.3$ MeV.

The total computed direct-capture cross section divided by 4π is fitted to the data in Fig. 7. We have ignored any anisotropic and s-d interference effects which could show up in the $(p,\gamma\alpha)$ angular correlation. The normalization gives $\theta_{sp}^2\simeq0.7$, in good agreement

[25] R. F. Christy and I. Duck, Nucl. Phys. 24, 89 (1961).

with the size of single-particle reduced widths in the nuclear p shell,[26] thus providing further confirmation of the single-particle (Li^7+p) character of the 16.6-MeV state in Be^8.

7. ANGULAR CORRELATIONS AND INTERFERENCE EFFECTS

The cross section reported[11] for the 441-keV resonance was obtained from the α yield alone and is thus independent of the $(p,\gamma\alpha)$ angular correlation. The values which we give here for the 1.03-MeV resonance, however, require correction for the angular correlation in order to obtain the total cross section. Neglecting at first all interference effects, the correlation is easily calculated with the following assumptions: The resonance capture proceeds through an isolated resonance with the proton captured into an isotropic state[2,22] which in turn decays by an $M1$ transition. The triple correlation then reduces to just the (γ,α) angular correlation and one obtains for the given spin sequence the total cross section

$$\sigma=(d\sigma/d\Omega)\times 4\pi/1.25\,, \qquad (7.1)$$

where $d\sigma/d\Omega$ is the differential cross section measured in the specific geometry of this experiment.

Interference may affect the cross sections in several ways, as described in general by Marion *et al.*[5] More specifically, in the present case, one process is interference between the direct and resonant amplitudes of each γ-ray transition. This possibility may be important for the transition to the 16.6-MeV state from the region of the 1.03-MeV resonance where the nonresonant background is comparable in size to the observed resonance magnitude (see Fig. 7). We describe the nonresonant background by the direct-capture model outlined in Sec. 6. The process is dominated by s- and d-wave capture and associated $E1$ radiation. The present geometry in which the first emitted radiation is detected in line with the beam, reduces the triple correlation to a simple formula.[27] First, the angular dependence is simply specified by the Legendre polynomials of the angle θ between the γ and the α detector. In the approximation made above, interference does not affect the total cross section but introduces terms proportional to $P_1(\cos\theta)$ and $P_3(\cos\theta)$. These terms vanish in our case, since $\theta=90°$. There remains only a small correction due to the finite solid angle of both detectors.

A second type of interference has its origin in the relatively large width (and corresponding partial overlap in energy) of the 2^+ final states. This interference between final states is the direct equivalent to the ones observed by Browne *et al.*,[4] and discussed by Barker[2,28] and by Marion *et al.*[5] It should not affect the total γ width of the 1^+ states but could, in principle, change the apparent intensity ratios of the transitions to the 16.6- and 16.9-MeV states. We assume here that the γ transitions change the isospin by 1. To the extent that both 2^+ states are isospin mixtures of the same wave functions, the corresponding transitions to these states are induced by the *same* basic matrix elements. Assuming the transitions to the 16.6- and 16.9-MeV states have the relative amplitudes A and B, the γ energy spectrum is given by

$$\frac{d\sigma}{dE_\gamma}=a\left|\frac{A}{E-E_1+\frac{1}{2}i\Gamma_1}+\frac{B}{E-E_2+\frac{1}{2}i\Gamma_2}\right|^2 E_\gamma^3\,, \qquad (7.2)$$

where $E=E_p(\text{c.m.})+Q-E_\gamma$; E_1, Γ_1 and E_2, Γ_2 refer to the 16.6- and 16.9-MeV states, respectively.

If the 1^+ states are pure isospin states, the relative sign of A and B is determined by the isospin of the 1^+ state involved in the reaction.[2] For the transitions from the $T=1$ state at 17.6 MeV, A and B are related to α and β by $A=\alpha^2\langle 2,0|M1|1,1\rangle$ and $B=\beta^2\langle 2,0|M1|1,1\rangle$ with an obvious notation. The factors α and β appear squared in the amplitudes because they enter both through the transition matrix elements and through normalization factors given by the total widths of the states. Thus we obtain destructive interference at the 441-keV resonance. In the case of the $T=0$ state at 18.15 MeV, the corresponding values for the amplitudes are $A=\alpha\beta\langle 2,1|M1|1,0\rangle$ and $B=-\alpha\beta\langle 2,1|M1|1,0\rangle$. A and B now have opposite signs and the upper resonance shows constructive interference.

The energy resolution in the γ spectra is not sufficient for a detailed shape analysis. However, the spectra of Figs. 3–5 show an indication of destructive interference at the lower (441-keV) resonance, and constructive interference at the upper (1.03-MeV) resonance as witnessed by the fact that the line shape of the transition strength to the 16.9-MeV state falls off more sharply at the high-energy side in Fig. 3, and more slowly in Figs. 4 and 5. The very fact that the 1.50- and 1.27-MeV transitions at the 1.03-MeV resonance are never clearly separated may be attributed to constructive interference filling the valley between the two peaks. We have made an estimate of the influence this interference effect may have on the analyzed ratio of the two transitions in each resonance. For constructive interference, it appears that our graphical analysis could underestimate the ratio $(18.15\rightarrow 16.9)/(18.15\rightarrow 16.6)$ by at most 10%, while for the 17.6-MeV state the corresponding correction should be much smaller.

We conclude that within the accuracy of the measure-

[26] A. M. Lane, Rev. Mod. Phys. 32, 519 (1960).

[27] S. Devons and L. J. Goldfarb, in *Handbuch der Physik*, (Springer-Verlag, Berlin, 1957), Vol. 42, pp. 362–554, Eq. 25.2.

[28] F. C. Barker, Australian J. Phys. 20, 341 (1967). It was pointed out by Barker that the treatment of the final-state interference used in Ref. 5 is different from that used in Refs. 4 and 28, and is apparently inconsistent with R-matrix theory. We have, therefore, used the form of Ref. 4.

TABLE II. Resonant cross sections for the $Li^7(p,\alpha)Be^{8*}$ (16.6 and 16.9 MeV) reactions, at $E_p=0.441$ and 1.03 MeV, corresponding to the 17.6- and 18.15-MeV states in Be^8.

Transition	Resonant cross section (μb)
17.6 MeV → 16.6 MeV	11±2
17.6 MeV → 16.9 MeV	0.8±0.25
18.15 MeV → 16.6 MeV	1.30±0.32
18.15 MeV → 16.9 MeV	0.65±0.20

ment, interference effects may be neglected. The total resonance cross sections are then obtained from Eq. (7.1) and amount to $\sigma(18.15\rightarrow16.64)=1.30$ μb±25% and $\sigma(18.15\rightarrow16.90)=0.65$ μb±30%. The set of resonance cross sections for the lower and upper resonance is listed in Table II.

8. DISCUSSION

From the total cross sections listed in Table II, radiative widths have been computed using the established total c.m. widths, i.e., $\Gamma=10$ keV at 17.6 MeV, and $\Gamma=147$ keV at 18.15 MeV. They are collected in Table III together with published[13] and some recently obtained[29] radiative widths for the transitions to the ground and first excited states. Comparison with the Weisskopf estimates underlines again the speed of the low-energy transitions, even of the weaker branches to the 16.9-MeV state. Thus all four transitions must have predominant magnetic dipole character. Comparison between the two resonances shows that relative to the Weisskopf estimates, the transition strengths to the 16.6- and 16.9-MeV states, respectively, are about the same at both resonances.

Certainly this rules out an extension of the charge-separated single-particle configuration model, which we discussed in the Introduction, from the 2^+ to the 1^+ states. Such an extension would have been an interesting possibility because it would have effectively separated the highly excited states of Be^8 into $T_z=\pm\frac{1}{2}$ subsets of core or single-particle excited states with configurations such as (Li^7+p) and/or $(Li^{7*}+p)$ at 17.6 MeV, and (Be^7+n) and/or $(Be^{7*}+n)$ at 18.15 MeV and so on.[3] Such a deviation from the shell model might not have been unexpected for Be^8 which shows such strong α-particle clustering in its lower states. Strong γ transitions would then only be expected between members within each $T_z=\pm\frac{1}{2}$ subset. The experimental results obviously disprove this model directly because the 18.15-MeV state has just as strong a matrix element to the 16.6- as to the 16.9-MeV state.

It will now be shown that the shell model can approximately account for all transition strengths with the assumption of an accidental energy degeneracy, only removed by the Coulomb force, in the 16.64- and 16.90-MeV states. It has been discussed previously[3] and shown that the shell model indeed can provide such an "initial" level degeneracy which then produces two levels which are about maximally mixed in isospin by the Coulomb force. Furthermore, Barker[2] has already shown that a shell-model calculation assuming mixed wave functions such as given by Eqs. (1.1) and (1.2) does account for the transition strengths from the 17.6-MeV state to the 16.6- and 16.9-MeV states. He obtains, in particular, 0.037 eV for the $17.64\rightarrow16.64$ transition and 0.0026 eV for the $17.64\rightarrow16.9$ decay, in excellent agreement with our experimental results (see Table III). The rather small $M1$ transition width for the ground-state decay is also well accounted for with a theoretical result of 14.2 eV. These values are obtained with only a 6% mixing of isospin $T=0$ in the 1^+ state.

We extend the calculations to include all $M1$ transitions from the 18.15-MeV state. The mixed wave functions for the 17.6- and 18.15-MeV states are defined by

$$\psi(17.6)=\gamma\psi(1,0)+\delta\psi(1,1)\,, \qquad (8.1)$$

$$\psi(18.15)=\delta\psi(1,0)-\gamma\psi(1,1)\,, \qquad (8.2)$$

where $\gamma^2+\delta^2=1$. The final states at 16.64 and 16.90 MeV are described by Eqs. (1.1) and (1.2). The wave functions $\psi(J,T)$ are taken from Barker's wave-function compilation[2] for Be^8. The reduced transition strengths Λ^2, defined in the article by Lane,[26] are then expressed in terms of the mixing parameters δ^2 and α^2, and the "pure" matrix elements $\Lambda(J_i,\ T_i\rightarrow J_f,\ T_f)$. Matrix elements with $\Delta T=0$ amount to less than 10% of the $\Delta T=1$ matrix elements but have been taken into account throughout. For the mixing parameters in the final 2^+ states, the new values which have resulted from the total-width measurements[4,5] have been

TABLE III. Radiative widths in eV for γ transitions from the excited states at 17.64 and 18.15 MeV to the final states at 0, 2.9, 16.64, and 16.90 MeV.

E_i \ E_f	0	2.9	16.64	16.90	
17.64	16.7[a]	8.2[a,b]	0.038±0.007	0.0028±0.0008	Experiment
	115	67	0.02	0.007	$M1$ Weisskopf estimate
18.15	2.1[c]	2.1[c,d]	0.15 ±0.032	0.074 ±0.02	Experiment
	126	75	0.072	0.037	$M1$ Weisskopf estimate

[a] From Ref. 13.
[b] This value is the $M1$ part only of the observed width.
[c] From Ref. 28.
[d] Sum of $M1$ and $E2$ components.

[29] G. A. Fisher, P. Paul, F. Riess, and S. S. Hanna (to be published).

used, namely, $\alpha=0.773$, $\beta=0.636$, both with positive sign. Figure 9(a) shows the computed values for $\Lambda^2(17.6\rightarrow 16.6)$ and $\Lambda^2(17.6\rightarrow 16.9)$ as a function of the mixing parameter δ^2. Comparison with the experimental values, which are shown with their errors, indicates reasonable agreement with both transition strengths for $\delta^2=0.95$. Thus the 17.6-MeV state has a 95% $T=1$ component. This is essentially the result obtained by Barker.[2] This also agrees with the various comparisons that have been made[3,8] between the first 1^+ state in Li^8 and the 17.6-MeV state which indicated that the two states are indeed relatively good analog states. Curves calculated for different values of α^2 substantiate the recent results of the width measurements, namely, that $\alpha^2>0.5$. The 16.6-MeV state thus has a slightly dominant $T=0$ character.

In Table IV, the best fits to the low-energy transition strengths and the computed strengths for the transitions to the ground and first excited states are compared with the experimental results. These latter states are assumed to have pure $T=0$. The same 17.64-MeV-state function which gives good agreement for the low-energy transitions also yields the observed $17.6\rightarrow 0$ strength. The transition $17.6\rightarrow 2.9$ involves a cancellation and is thus somewhat more sensitive to the wave functions which may explain the rather large discrepancy in this case. Barker also obtained correct values for the reduced proton width for the 17.6-MeV state. The description of this state is thus reasonably consistent with the experimental data.

The strengths for the $18.2\rightarrow 16.6$ and $18.2\rightarrow 16.9$ transitions have been computed in the same way and for the same values of α^2. Results are plotted in Fig. 9(b), versus δ^2. For $\delta^2=0.95$, agreement with the observed strength $18.2\rightarrow 16.9$ is excellent. This is remarkable because the transition involves a cancellation of terms and is therefore sensitive. However, the $18.2\rightarrow 16.6$ transition is underestimated by a factor of

TABLE IV. The squared $M1$ transition matrix elements Λ^2 for various transitions. The theoretical values are computed with Barker's shell-model wave functions for various degrees of isospin mixing in initial and final state. The mixing coefficients α and δ are defined in Eqs. (1.1), (1.2), (8.1), and (8.2) and related to final and initial state, respectively. The contribution from the $J^\pi=1^+$, $T=1$ state at 19.4 MeV is represented by ϵ. The experimental value for Λ^2 is obtained from the radiative width by $\Lambda^2=15.45\,\Gamma_\gamma/E_\gamma^3$ with Γ_γ in eV, E_γ in MeV.

Transition	Λ^2 Experiment	Λ^2, Theory $\alpha^2=0.6$, $\delta^2=0.95$	Λ^2, Theory $\alpha^2=0.6$, $\delta^2=0.90$, $\epsilon^2=0.05$
$17.64\rightarrow 0$	0.047	0.040	
$17.64\rightarrow 2.9$	0.040	0.010	
$17.64\rightarrow 16.6$	0.58 ± 0.1	0.56	
$17.64\rightarrow 16.9$	0.105 ± 0.03	0.088	
$18.2\rightarrow 0$	0.0054	0.0012	0.0021
$18.2\rightarrow 2.9$	0.0091[a]	0.00075	0.019
$18.2\rightarrow 16.6$	0.67 ± 0.18	0.18	0.28
$18.2\rightarrow 16.9$	0.58 ± 0.17	0.48	0.38

[a] This value neglects an $E2$ component of unknown size.

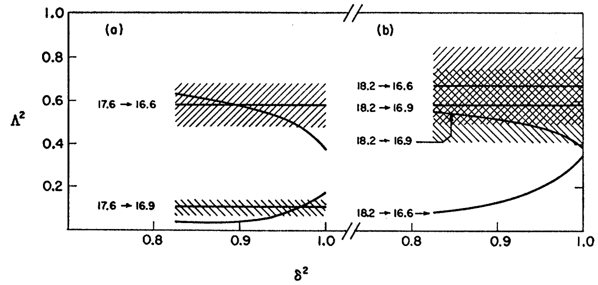

FIG. 9. Reduced transition strengths Λ^2 for the observed magnetic dipole transitions between the 17.64- and 18.15-MeV initial, and 16.64- and 16.90-MeV final states. Curves are computed from Barker's shell-model wave functions as a function of isospin mixing (δ^2) in the upper states. The experimental values and errors are also indicated.

4. Calculations using the wave functions of Cohen and Kurath[7] lead to very similar results. This discrepancy points to a series of other inadequacies apparent in previous theoretical descriptions[2] of the 18.15-MeV state. The transitions to the ground and first excited states have been underestimated by factors of 4.5 and 12, respectively. The experimentally obtained Λ^2 for the latter transition, however, may be totally in error since the radiation width may contain a large, possibly dominant $E2$ component. For the $17.6\rightarrow 2.9$ transition, the $E2$ component has been given [22] as $\Gamma_\gamma(E2)=0.15$ eV. Since the $\Delta T=0$ $E2$ transition $18.2\rightarrow 2.9$ may be collectively enhanced, it could easily have a width of 2 eV. The very large discrepancy between computed and assumed $M1$ width is thus not necessarily serious. More important is the disagreement between theory and experiment encountered in the $18.2\rightarrow 16.6$ transition for the following reasons.

The reduced proton width of the 18.2-MeV state is two times larger than that computed with Barker's wave functions. In the single-particle description of the 2^+ states, the 16.6-MeV state has the (Li^7+p) configuration. Assuming that among the 1^+ pairs the 17.6-MeV state has a larger proton than neutron reduced width, which accounts for the stronger $17.6\rightarrow 16.6$ transition, the 18.15-MeV state should then have a (Be^7+n) excess and decay primarily to the 16.9-MeV level. If the proton width is to be increased as seems to be generally indicated by experiment, this tends to enhance the 16.6-MeV-state transition in agreement with our experimental observation. However, quantitatively this description is inconsistent with the model of two states mixing their isospins, because it is not possible to simply increase the proton component of one state without reducing it in the other.

Within the shell-model framework, the discrepancies may have two explanations. One possibility is that Barker's wave functions for the unmixed states in Be^8 are wrong and the $T=1$ component of the 1^+ states carries a larger transition strength. If the three matrix elements $\Lambda(J_i, 1\rightarrow J_f, 0)$ are treated as free parameters, agreement with the ground-state and first-excited-state transitions can be improved without having to change the pure wave function significantly. In particular, one can increase the $17.6 \to 2.9$ transition to the experimental value without affecting the $17.6 \to 0$ transition much. But it does not appear possible to obtain better agreement with the $18.2 \to 16.6$ and 16.9 transitions without substantially changing the wave functions.

The other possibility is that the $T=1$ component in the 18.15-MeV state is larger. One would like to increase this component without affecting the 17.6-MeV level. This can be done by mixing components of a *second* $J=1^+$, $T=1$ state into the 18.15-MeV state. Such a state has been computed by Barker[2] to lie at 19.4 MeV. Adding a term $\pm\epsilon\psi(1,1[19.4)])$ to Eq. (8.2), new values Λ^2 for the pertinent transitions were computed and are included in Table IV. Assuming $\epsilon^2=0.05$ and $\delta^2=0.90$, i.e., an over-all 10% component of $T=1$ in the 18.15-MeV level, the agreement with all observed transitions is definitely improved. A negative sign for ϵ increases the $18.2 \to 16.6$ transition strongly, and reduces the $18.2 \to 16.9$ transition only slightly. It does not, however, seem possible to obtain agreement with the transition to the 16.6-MeV state to better than a factor of 2. There is at present no experimental evidence against such an increase in the $T=1$ component of the 18.15-MeV state.

9. CONCLUSION

The present experiment gives evidence for strong magnetic dipole transitions from the $J^\pi=1^+$ states at 17.64 and 18.15 MeV to both 2^+ states at 16.64 and 16.90 MeV. Qualitatively the observed transition strengths substantiate nearly maximal mixing of isospin $T=1$ and $T=0$ in the 2^+ pair and rather pure isospin character for the 1^+ pair. This suggests, in agreement with other experimental information, that the large isospin mixing between the 2^+ states is an accident and related to their particular wave functions rather than an indication of a general breakdown of the isospin concept in Be^8 (see Ref. 3 for a more detailed discussion).

Quantitatively the shell model predicts the magnetic dipole strengths of all four low-energy transitions from the 17.64- and 18.15-MeV states, and three of the observed transitions to ground and first excited states within a factor of 4 with only two free isospin mixing parameters. The exception is the $18.2 \to 2.9$ transition, where the large discrepancy may be attributed to a large $E2$ component. In agreement with previous observations, the analysis yields a (squared) $T=0$ component of 60%–70% in the 16.64-MeV state, and the complement in the level at 16.90 MeV, but only a 5% $T=0$ component in the 17.64-MeV state. The corresponding 5% $T=1$ admixture into the 18.15-MeV state underestimates three out of four transitions. An additional 5% $T=1$ admixture of the second state with $J^\pi=1^+$, $T=1$ predicted to be at 19.4 MeV leads to better over-all agreement.

The success of the intermediate-coupling shell model in describing the magnetic dipole transitions in Be^8 is comparable to the agreement found in other nuclei in the $1p$ shell. However, the difficulties experienced almost consistently with the 18.15-MeV state suggest that the present calculations do not describe this state completely. The underestimate of both the reduced proton width (which is twice as large as in the 17.64-MeV state where the model gives the correct value) and the γ transition to the 16.6-MeV state may stem from neglecting the fact that the 18.15-MeV state is very much unbound with respect to proton emission. The $M1$ transition matrix elements are, of course, independent of the radial wave functions. However, in terms of the qualitative cluster-model description this effect may destroy the symmetry between the two 1^+ states and increase the amplitude of the (Li^7+p) configuration present in the 18.15-MeV state even beyond the amount present in the 17.64-MeV state. A comparison with the numbers listed in Table IV shows that this effect would qualitatively improve agreement with experiment by increasing the strengths of all transitions which are sensitive to the "proton part" of the cluster wave function.

Note added in proof. A new value $d\sigma/d\Omega\ (90°)=0.42 \pm 0.06$ mb/sr has just been reported by Lerner and Marion for the $Li^7(p,\alpha)$ reaction cross section at $E_p=1.36$ MeV. This would reduce the normalization on our $Li^7(p,\gamma\alpha)$ cross sections by 0.45, and all values Λ^2 should then be multiplied by this factor. The effect that this reduction would have on the agreement between theory and experiment can be judged from Fig. 9.

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