Gamma-Ray Decay of the 6.92-, 7.12-, 8.88-, and 13.10-MeV States in O^{16}†

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The reactions $F^{19}(p,\alpha)O^{16}$ and $N^{15}(p,\gamma)O^{16}$ have been used to study the γ-ray branching of O^{16} states at 6.92, 7.12, 8.88, and 13.10 MeV. Measurements were made with two 5×6-in. and two 3×3-in. NaI(Tl) detectors in various coincidence combinations. Two-dimensional pulse-height analysis was employed in some cases. The γ-ray branches from the $J^\pi=2^+$ 6.92- and 1^- 7.12-MeV states to the $J^\pi=3^-$ 6.13-MeV level were found to be $\leq 8\times10^{-5}$ and $(7.0\pm1.4)\times10^{-4}$, respectively. For the $J^\pi=2^-$ 8.88-MeV level the branches to the 7.12-, 6.92-, 6.13-MeV, and ground states are $(12.6\pm2.0)\%$, $(4.2\pm0.8)\%$, $(76.0\pm3.0)\%$, and $(7.2\pm0.8)\%$, respectively. The $E1$ branch, $13.10\rightarrow6.06$ MeV, was observed to have an intensity of $(5.8\pm1.2)\times10^{-3}$, corresponding to a $B(E1)$ of 0.037 relative to that of the $E1$ ground-state transition. The significance of the various results in the description of states in O^{16} is discussed.

INTRODUCTION

We have recently been concerned[1] about the situation that seems to obtain in O^{16} where two sets of states of perhaps rather dissimilar configurational description completely interpenetrate. The first set consists of the states that have traditionally been thought of as "spherical," namely the ground state and the odd-parity 1-particle 1-hole states, the $J^\pi=3^-, 1^-, 2^-\cdots$ sequence at 6.13, 7.12, 8.88···MeV and the $J^\pi=0^-, 2^-, 1^-, 3^-\cdots$ $T=1$ sequence at 12.79, 12.97, 13.10, 13.26···MeV, the analogs of the ground-state quartet in N^{16}. These states received a rather convincing description[2] many years ago as 1p-1h, the success of this description being, in fact, one of the cornerstones for the building up of the independent-particle model with residual interactions that now dominates much of our thinking about nuclear structure. Even at that time, however, it was clear that such a simple description for these states was not complete, for the ground-state transition from the $J^\pi=3^-$ level at 6.13 MeV was an order of magnitude faster than predicted by the model, indicating that more complicated excitations, which we should nowadays think of as chiefly 3p-3h, 5p-5h, etc., were involved in unknown magnitude. Another strong hint came from the $J^\pi=1^-$ state at 9.58 MeV that found no place in the 1p-1h model and that therefore would be thought of as a 3p-3h, etc., state. It could presumably mix with the 1p-1h state at 7.12 MeV and displace it downwards; indeed, the model[2] had difficulty in getting the 7.12-MeV level as low in excitation as observed. The other set of states has been recognized[3] more recently as of strong permanent deformation, starting with the "rotational" sequence $J^\pi=0^+, 2^+, 4^+\cdots$ at excitations of 6.06, 6.92, 10.36···MeV. It is difficult to understand how such deformed states, presumably 2p-2h, 4p-4h···, can lie so low but it seems at present most likely that in the even-parity states, the dominant configuration is 4p-4h.[4] In that case their radiative interconnections with the "spherical" states would be weak.[5] This remark makes an interesting point of the degree to which these sequences interconnect by radiative transitions. We have already discussed[1] the problem of the mixing of the ground and first excited states and have pointed out that the branching to these two states from the $J^\pi=2^+, 1^-$ states at 6.92, 7.12 MeV are not mutually

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[1] J. Lowe, D. E. Alburger, and D. H. Wilkinson, Phys. Rev. **163**, 1060 (1967).

[2] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957).

[3] See Ref. 1 and references contained therein.

[4] D. M. Brink and E. Boeker, Nucl. Phys. **A91**, 1 (1967); E. Boeker, *ibid.* **A91**, 27 (1967).

[5] Radiative transitions are, of course, forbidden if the spherical and deformed states differ by more than one in the number of particle-hole pairs. Transitions between a 1p-1h spherical state and a 2p-2h deformed state are not forbidden for this reason; however, they tend to be weak if the configuration of the 2p-2h state is such as to produce maximum deformation. In the $SU(3)$ model, for example, $E1$ transitions between $(1p^{-(n-1)}, (2s \text{ or } 1d)^{n-1})$ and $(1p^{-n}, (2s \text{ or } 1d)^n)$ are completely forbidden if the latter state has maximum $(\lambda+\mu)$ (i.e., maximum deformation). Also, if the deformed state is a np-nh excitation *with respect to a deformed basis*, lack of overlap of the "core" particles gives a further small reduction in the transition probability.

consistent if one sticks to a 1p-1h description for the 7.12-MeV state and to a rotational relationship within the $J^\pi=0^+, 2^+, 4^+\cdots$ sequence that induces the ground-state transition of the 6.92-MeV state via a mixing of the 6.06-MeV and ground states.

In order to illuminate this problem, we have undertaken a number of measurements that bear directly on the radiative interconnections of the "spherical" and "deformed" states and that also provide material for a discussion of whether the "spherical" states are themselves adequately described as 1p-1h.

Specifically we have made the following measurements: (i) The decay of the $J^\pi=2^+$ 6.92-MeV level to the $J^\pi=3^-$ level at 6.13 MeV; this is a "deformed" $\rightarrow$ "spherical" transition. (ii) The decay of the $J^\pi=1^-$ 7.12-MeV level to the $J^\pi=3^-$ 6.13-MeV level; this $E2$ transition will have a speed close to the prediction of the independent-particle model[2] if both states are indeed 1p-1h "spherical" states but may depart significantly from this prediction if admixtures such as 3p-3h are present and build up some collective behavior. (iii) The decay of the $J^\pi=2^-$ 8.88-MeV level to the $J^\pi=1^-$, 3^- states at 7.12, 6.13 MeV; the interest here centers on the $E2$ components of these transitions to which the remarks of (ii) above apply. (iv) The decay of the $J^\pi=2^-$ 8.88-MeV level to the $J^\pi=2^+$ 6.92-MeV level: a "spherical" $\rightarrow$ "deformed" transition. (v) The decay of the $J^\pi=2^-$ 8.88-MeV level to the ground state. (vi) The decay of the $J^\pi=1^-$ 13.10-MeV level to the $J^\pi=0^+$ 6.06-MeV level; this transition, by its comparison with the ground-state transition from the same state, may be a measure of the mixing of the "spherical" ground state into the "deformed" $J^\pi=0^+$ excited state. Each of these transitions has been investigated previously; our measurements improve the accuracy of, and confidence in the earlier work. For the only transition which we failed to observe (that between the 6.92- and 6.13-MeV states) our measurements resulted in a new upper limit for the transition probability.

EXPERIMENTAL PROCEDURES

6.92- and 7.12-MeV States

Measurements on γ-ray branches from the 6.92- and 7.12-MeV states of O^{16} were made by forming these states in the $F^{19}(p,\alpha)O^{16}$ reaction, using targets of CaF_2 50 μg/cm^2 thick, evaporated onto C backings. As described previously,[1] a proton bombarding energy of 2.38 MeV was chosen to enhance the relative population of the 6.92-MeV state, while a beam energy of $E_p=2.09$ MeV was chosen for favoring the 7.12-MeV state.

Two 5×6-in. NaI(Tl) detectors were placed on opposite sides of the target each at a distance of 8.5 cm. Gains of both detectors were stabilized by means of spectrostats using a Na^{22} source as a reference. A standard coincidence setup was used, the data being stored in a 16 384-channel two-dimensional pulse-height analyzer operated in the 128×128 channel mode. Gains were adjusted such that the energy region 0–8 MeV of one detector occupied one axis while the γ-ray energy region 0–3 MeV in the other detector occupied the other axis of the analyzer. By means of a separate 400-channel pulse-height analyzer, a check on the singles γ-ray spectrum was maintained and the energy of a bias setting was established for monitoring the total high-energy γ-ray counting rate.

Since the NaI(Tl) detectors could not resolve the 6.92- and 7.12-MeV γ-ray components a Ge(Li) detector was used, as in earlier experiments,[1] to determine the relative intensities of the 6.13-, 6.92-, and 7.12-MeV γ rays. At each of the two bombarding energies, singles Ge(Li) spectra were recorded at 0°, 30°, 45°, 60°, and 90° with respect to the beam. These measurements allowed γ-ray angular distributions and the integrated relative population intensities to be derived, so that angular correlation corrections could be applied to the cascade measurements.

8.88-MeV State

γ-γ coincidence experiments on the 8.88-MeV level of O^{16} were similar to those described above. The state was excited in the $F^{19}(p,\alpha)O^{16}$ reaction at $E_p=3.3$ MeV, using a CaF_2 target of 2 mg/cm^2 thickness. A 3×3-in. NaI(Tl) detector was used for the low-energy γ rays while the high-energy γ rays were detected in a 5×6-in. NaI(Tl) crystal. The pulse-height analyzer was operated in the 64×256-channel mode with the γ-ray energy region 4–8 MeV from the 5×6-in. detector applied to the 64-channel axis and the energy region 0–3.5 MeV from the 3×3-in. detector applied to the 256-channel axis.

A singles γ-ray pulse-height spectrum covering the energy region up to 10 MeV was recorded in a 5×6-in. NaI(Tl) detector, in order to measure the intensity of the full-energy-loss peak of the ground-state γ-ray transition relative to the photopeak of the 2.75-MeV cascade transition (8.88 $\rightarrow$ 6.13). The intensity of the latter peak was measured with a 3×3-in. NaI(Tl) detector placed at angles of 0°, 30°, 45°, 60°, and 90° with respect to the beam in order to derive the angular distribution of the 2.75-MeV γ rays under the same target and beam-energy conditions as those of the coincidence experiments.

13.10-MeV State

The γ-ray branching of the $J^\pi=1^-$ 13.10-MeV $T=1$ state in O^{16} through the 6.06-MeV state was measured with an arrangement very similar to that in previous studies[1] of branching through the 0^+ first excited state, i.e., two 3×3-in. NaI(Tl) detectors were placed on opposite sides and at 5 cm from the target and a 5×6-in. detector was placed at 0° and 7 cm from the target. The procedure was to measure the pulse-height spectrum from the large crystal in triple coincidence with the two side crystals when the latter were channeled on the photopeak of 0.511-MeV γ rays. TiN^{15} was used as the target material and it was deposited in a layer of $\sim$2 mg/cm^2 thick onto a disk of 10-mil-thick steel. The target disk was then waxed onto the end of a Be target tube that was fitted with a Be absorber thick enough to stop 5-MeV positrons.

In the $N^{15}(p,\gamma)O^{16}$ resonance reaction the 13.1-MeV state is formed at $E_p=1028$ keV and the width of the state is given[6] as 140±10 keV. Excitation functions of the 13.1- and 4.43-MeV γ rays [the latter from the $N^{15}(p,\alpha)C^{12}$ reaction] were first plotted. The beam energy selected for the final "on-resonance" runs was about 150 keV above the onset of 13.1-MeV radiation but still 50 keV below the sharp rise in 4.43-MeV γ rays corresponding to the $E_p=1210$-keV resonance. "Off-resonance" data were taken at a beam energy of 900 keV, where the amount of 13.1-MeV radiation was small and easily corrected for.

RESULTS AND ANALYSIS

7.12-MeV State

Data on γ-γ coincidences were taken at $E_p=2.09$ MeV using a beam current of 0.06 μA for $\sim$24 h. The spectrum in that NaI(Tl) detector being used to cover the 0–3-MeV energy range was analyzed by summing over the channels of the pulse-height region in the other detector that encompassed the full-energy-loss and one-escape peaks of the 6.13-MeV γ rays. The result, given in Fig. 1(a), shows the 0.99-MeV γ-ray peak from the 7.12 → 6.13-MeV transition, together with the random Na^{22} peak at 1.275 MeV, the latter coming from the stabilization reference source. A normalized Na^{22} singles γ-ray spectrum was first subtracted from the data of Fig. 1(a). This produced a smooth background just above the 0.99-MeV peak which was extrapolated under the 0.99-MeV peak. From the net area under the 0.99-MeV peak the 7.12 → 6.13-MeV branching ratio was found by straightforward procedures taking into account the following: (a) the fraction of the 6.13-MeV spectrum lying within the pulse-height window used for summing, (b) the solid angle and photopeak efficiency of the 5×6-in. NaI(Tl) detector for 0.99-MeV γ rays, (c) the total number of reactions populating the 7.12-MeV state, based on the monitor count, the fraction of the total spectrum in the monitor window, and the ratio of 7.12-MeV γ rays to total high-energy γ rays, (d) absorption effects, and (e) angular correlation corrections computed from the 7.12-MeV substate populations deduced from the measurements using the Ge(Li) detector. The weighted-average result based on this run and on the run at $E_p=2.38$ MeV discussed below is as follows:

$$\Gamma(7.12\rightarrow 6.13)/\Gamma(7.12\rightarrow 0)=(7.0\pm1.4)\times10^{-4}.$$

[6] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. 11, 1 (1959).

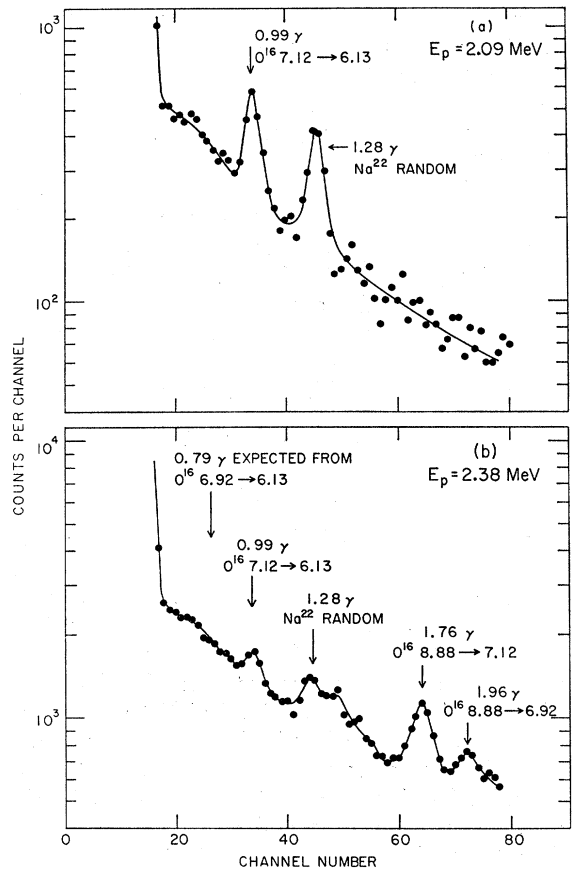

FIG. 1. Pulse-height spectra in a 5×6-in. detector, in coincidence with a 6.13-MeV γ ray in the other detector, from $F^{19}(p,\alpha)O^{16}$ at proton energies of (a) 2.09 MeV and (b) 2.38 MeV. Peaks are attributed to the indicated cascade decays of the 6.92-, 7.12-, and 8.88-MeV states, and also to random coincidences with the Na^{22} stabilization source.

6.92-MeV State

Figure 1(b) shows the result of a 77-h run with a 0.04-μA beam at $E_p=2.38$ MeV. All other experimental conditions were the same as for the 2.09-MeV run and the spectrum summing was carried out over the full-energy-loss and one-escape peaks of the 6.13-MeV radiation just as for the 2.09-MeV run. Although at this bombarding energy the population of the 7.12-MeV state is only about $\frac{1}{3}$ as great as the population of the 6.92-MeV state [whereas at $E_p=2.09$ MeV for Fig. 1(a) the corresponding population ratio is about 3], the intensity of the 0.99-MeV peak in Fig. 1(b) was sufficient to make an independent measurement of the 7.12 → 6.13 branching ratio, with somewhat less statistical accuracy. A normalized Na^{22} spectrum was first subtracted [just as in the analysis of Fig. 1(a)] before extracting the net area under the 0.99-MeV peak. As mentioned above, this calculation has been included in the weighted average of the result for the 7.12-MeV state.

It is apparent that there is additional structure in Fig. 1(b) that does not occur in the $E_p=2.09$ MeV run of Fig. 1(a). These lines are attributed to the 8.88-MeV state, which appears to have a threshold for formation at a proton energy of between 2.1 and 2.4 MeV in the $F^{19}(p,\alpha)O^{16}$ reaction.

The position of a possible 0.79-MeV peak, which would result from the $6.92\rightarrow 6.13$ transition, is indicated in Fig. 1(b). No line is observed and the upper limit on its net peak amplitude is placed at $\frac{1}{5}$ of the net amplitude of the adjacent 0.99-MeV peak. By applying all of the necessary factors, as mentioned in the above analysis of the 7.12-MeV state, the result is as follows for the branching of the 6.92-MeV level:

$$\Gamma(6.92\rightarrow 6.13)/\Gamma(6.92\rightarrow 0)\leq 8\times 10^{-5}.$$

8.88-MeV State

Experiments on the relative cascade γ-ray branchings of the 8.88-MeV level of O^{16} were similar to those described above for the 6.92- and 7.12-MeV states except for the details given in the section on procedures. In this case, the analysis of the two-dimensional pulse-height spectrum was somewhat more involved since in the summing of the 3×3-in. NaI(Tl) spectra over various pulse-height regions in the high-energy 5×6-in. detector it was necessary in the calculations to know the relative fractions of the 6.13-, 6.92-, and 7.12-MeV γ-ray spectra that were contained within the summed regions. To aid in this analysis, the high-energy spectra were first obtained when summing over the three peaks at 1.76, 1.96, and 2.75 MeV in the low-energy detector. Of the resulting three spectra, that in coincidence with the 2.75-MeV photopeak consisted of an almost pure 6.13-MeV γ-ray spectrum. In coincidence with the 1.76-MeV peak were the 7.12-MeV full-energy-loss and one-escape peaks, which were well-resolved from peaks due to 6.13-MeV γ rays, while the spectrum in coincidence with the 1.96-MeV line showed the resolved 6.92-MeV full-energy-loss peak beyond the 6.13-MeV peaks. These spectra not only established the assignments of the three γ-γ cascades with certainty but they could be used to fix the values of the high-energy channels used for summing the low-energy spectra, and thus allow the fraction of each high-energy γ-ray spectrum to be calculated.

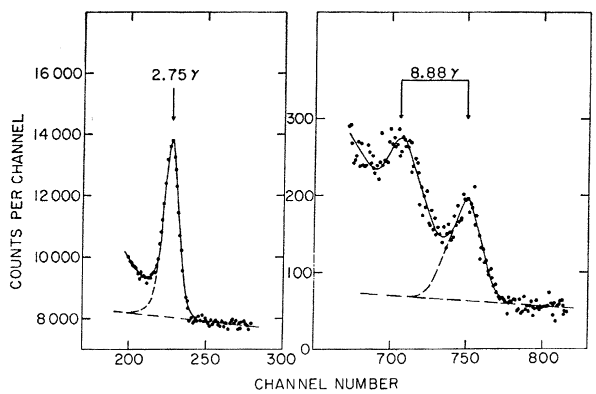

FIG. 3. Singles pulse-height spectra in the 5×6-in. detector from $F^{19}(p,\alpha)O^{16}$ at a proton energy of 3.3 MeV. Peaks are attributed to the ground-state decay of the 8.88-MeV state (8.88 γ) and to cascade decay through the 6.13-MeV state (2.75 γ).

In Fig. 2 are shown the spectra in the 3×3-in. detector when summed over the energy regions 6.28–7.26 MeV (a) and 5.43–6.34 MeV (b). The net areas were obtained by using the dashed extrapolated backgrounds and from these areas the relative intensities of the three lines were calculated making use of the various fractions of the corresponding high-energy γ-ray spectra within the summing regions as mentioned above, and the relative photopeak efficiencies of the three low-energy γ rays.

The result of a "singles" spectrum measurement using the 5×6-in. detector is shown in Fig. 3. Relative intensities of the 2.75- and 8.88-MeV γ rays were calculated in a straightforward manner based on the areas of the two photopeaks indicated in the figure.

The measured angular distribution of the 2.75-MeV γ rays was found to be isotropic to within 2%. This result was used to calculate the γ-γ angular correlation for each of the three cascades, allowing for geometrical attenuation due to the solid angles of the NaI(Tl) detectors in the coincidence experiment. Relative γ-γ intensities measured in the two detectors at 90° were then corrected in order to obtain the relative γ-ray branching ratios. By combining these results with the experimental ratio of the 2.75- and 8.88-MeV γ-ray intensities discussed above the complete branching data for the O^{16} 8.88-MeV state were found to be as follows:

$$8.88\rightarrow 7.12 \quad (12.6\pm 2.0)\%,$$
$$8.88\rightarrow 6.92 \quad (4.2\pm 0.8)\%,$$
$$8.88\rightarrow 6.13 \quad (76.0\pm 3.0)\%,$$
$$8.88\rightarrow 0 \quad (7.2\pm 0.8)\%.$$

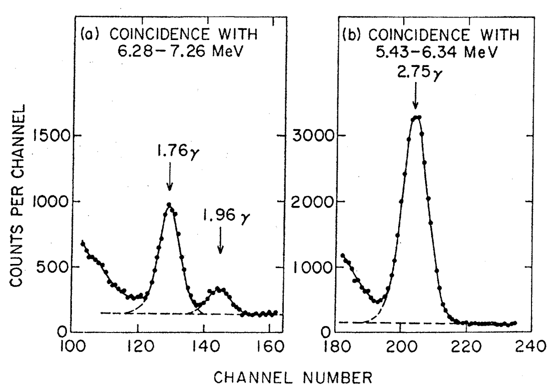

FIG. 2. Pulse-height spectra in the 3×3-in. detector of γ rays from $F^{19}(p,\alpha)O^{16}$ at a proton energy of 3.3 MeV, in coincidence with the indicated energy regions in the 5×6-in. detector. Peaks are attributed to the decay of the 8.88-MeV state to states at 7.12 MeV (1.76 γ), 6.92 (1.96 γ), and 6.13 MeV (2.75 γ).

13.10-MeV State

The γ-ray spectrum from the 5×6-in. NaI(Tl) detector in triple coincidence with the two 3×3-in. detectors, each channeled on 511-keV radiation as described in the procedures section, was taken "on" the resonance in the $N^{15}(p,\gamma)O^{16}$ and then just below the resonance, each run being for about 21 h at a beam current of 0.2 μA. By using the relative integrated beam currents, the below-resonance spectrum was normalized and subtracted from the on-resonance spectrum. The net spectrum is shown in Fig. 4. Based on an energy calibration using the 1.275-MeV γ rays of Na^{22} and the 4.44-MeV γ rays from a Pu-Be source the full-energy-loss peak of the spectrum in Fig. 4 corresponds to γ rays having an energy of 7.03±0.04 MeV. The expected energy of these γ rays, calculated by averaging over the portion of the broad resonance that is excited according to the observed excitation function for 13-MeV γ rays, and allowing for Doppler shift and finite solid angle, is 7.06 MeV.

In order to derive the cascade branching ratio, the intensity of the 7.03-MeV γ rays was obtained from Fig. 4 by subtracting the extrapolated dashed background line. The background has been drawn so as to make the net spectrum conform in shape to that of a standard spectrum in the 5×6-in. detector at this γ-ray energy. From the photopeak area the total γ-ray intensity was obtained by using the appropriate peak-to-total ratio.[7] Other information used for calculating the branching were (a) the efficiency for detecting pairs following the formation of the 6.06-MeV state, measured as described previously[1] and (b) the total number of 13.10-MeV states formed, as obtained from an analysis of the γ-ray monitor spectrum and total counts. By applying all of the necessary factors the following result is obtained for the 13.10-MeV state of O^{16}:

$$\Gamma(13.10 \rightarrow 6.06)/\Gamma(13.10 \rightarrow 0) = (5.8\pm1.2)\times10^{-3}.$$

COMPARISON WITH EARLIER MEASUREMENTS

Branching ratios measured in the present work are summarized in Fig. 5.

The decays of the 7.12- and 6.92-MeV states to the 6.13-MeV state have been investigated previously by Gorodetzky *et al.*,[8] who found branching ratios of $(8\pm2)\times10^{-4}$ and $\leq4\times10^{-4}$, respectively. For the former transition, our present result of $(7.0\pm1.4)\times10^{-4}$ is in good agreement with Gorodetzky *et al.*; apparently angular correlation corrections, which were neglected by Gorodetzky *et al.*, were not significant in their experiment. For the latter transition, our figure of $\leq8\times10^{-5}$ reduces the previous upper limit by a factor of 5.

[7] F. C.Young, H. T. Heaton, G. W. Phillips. P. D. Forsyth, and J. B. Marion, Nucl. Instr. Methods 44, 109 (1966); J. W. Olness (private communication).

[8] S. Gorodetzky, P. Mennrath, W. Benson, P. Chevallier, and F. Scheibling, J. Phys. (Paris) 24, 887 (1963).

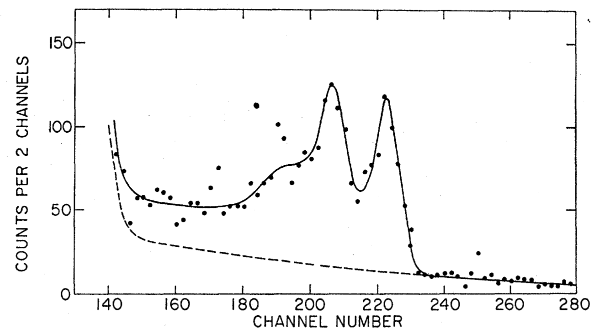

FIG. 4. Pulse-height spectrum from the $N^{15}(p,\gamma)O^{16}$ reaction at a proton energy of 1.160 MeV, in coincidence with 0.511-MeV γ rays from the decay of the 6.06-MeV state. The peaks are attributed to a 7.03-MeV γ ray from cascade decay of the 13.1-MeV state through the 6.06-MeV state.

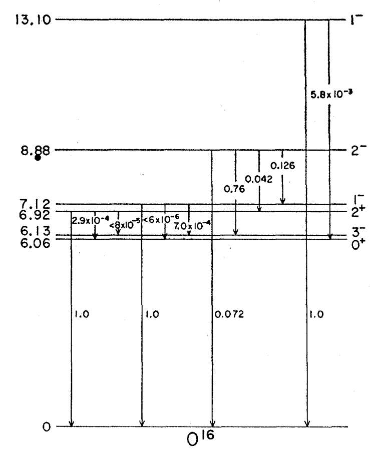

FIG. 5. Level scheme for O^{16} with level energies in MeV showing the branching ratios determined in the present experiments.

TABLE I. Branching ratios for the decay of the 8.88-MeV state.

Final state (MeV)	Branching ratio a	b	c	d	e	f
0	<0.12	0.07	0.067	0.07		0.072
6.06			<0.036		0.012	
6.13	0.75		0.71	0.77		0.76
6.92	0.03		0.048	<0.05		0.042
7.12	0.09		0.13	0.16		0.13

[a] D. H. Wilkinson, B. J. Toppel, and D. E. Alburger, Phys. Rev. **101**, 673 (1956).
[b] R. D. Bent and T. H. Kruse, Phys. Rev. **108**, 802 (1957).
[c] D. A. Bromley, H. E. Gove, J. A. Kuehner, A. E. Litherland, and E. Almqvist, Phys. Rev. **114**, 758 (1959).
[d] See Ref. 12.
[e] See Ref. 18.
[f] Present results.

Branching ratios for the decay of the 8.88-MeV state have been measured by several groups. The (concordant) results are summarized in Table I.

The 13.1- to 6.06-MeV transition was observed by Gorodetzky *et al.*[8] who found a branching ratio of $(8\pm2)\times10^{-3}$. Our present result of $(5.8\pm1.2)\times10^{-3}$ is consistent with this and excludes an earlier result[9] of $<1.3\times10^{-3}$.

[9] G. Goldring, Proc. Phys. Soc. (London) **A67**, 930 (1954).

TABLE II. Partial $E2$ radiative widths (in eV) for γ-ray transitions between $J^\pi=2^-$, 1^-, and 3^- states at 8.88, 7.12, and 6.13 MeV. Experimental values are derived from the present results as described in the text. Theoretical values for 1p-1h configurations are presented using both the independent-particle model (Ref. 2) and the $SU(3)$ model with $(\lambda,\mu)=(2,1)$. Values given for 3p-3h configurations use the $SU(3)$ model with $(\lambda,\mu)=(6,3)$. In each case, oscillator wave functions were used, with a size parameter (1.75×10^{-13} cm) deduced from electron scattering data. An effective charge of $0.5e$ has been included in all calculated values.

Transition	Experimental width	IPM 1p-1h	$SU(3)$ 1p-1h	$SU(3)$ 3p-3h
$2^-\to1^-$	$(4.0\pm0.7)\times10^{-4}$	0.94×10^{-4}	1.2×10^{-4}	7.3×10^{-4}
$2^-\to3^-$	$(2.3\pm0.4)\times10^{-3}$	1.7×10^{-3}	2.6×10^{-3}	13×10^{-3}
$1^-\to3^-$	$(4.7\pm1.7)\times10^{-5}$	1.6×10^{-5}	1.7×10^{-5}	11×10^{-5}

DISCUSSION

We will first of all discuss the $E2$ transitions among the $J^\pi=3^-$, 1^-, 2^- states at 6.13, 7.12, 8.88 MeV. The strength of that between the $J^\pi=1^-$ and 3^- states we derive from our present branching ratio for the 7.12-MeV state and from the lifetime of the 7.12-MeV state.[10] Those from the $J^\pi=2^-$ to the $J^\pi=1^-$ and 3^- states we obtain by combining the lifetime of the $J^\pi=2^-$ state[11] with our present branching ratio measurements and the $E2/M1$ measurements.[12]

The first comment is that these $E2$ transitions are very strong. In fact, that between the $J^\pi=1^-$ and 3^- states is as strong as that between the deformed and rotationally connected $J^\pi=2^+$ 6.92-MeV and $J^\pi=0^+$ 6.06-MeV states (although, of course, spin factors favor the former). This shows that it is unlikely that these states can be close to "spherical" 1p:1h states. This conclusion, already emphasized by Pixley and Benenson[11] is made quantitative in Table II, where we compare the experimental $B(E2)$ values with those deriving from a number of models. In the case of the independent-particle model[2] and $SU(3)$ predictions we have multiplied the calculated speeds by a factor of 4 in the usual way to take into account effective charges of $0.5e$ added to both neutron and proton since the computations are carried out in a spherical basis. We do not make a comparison here with a classical rotational model since that does not reproduce the spin sequence correctly, although it is clear from the numerical comparison of Table II that it is proper to speak of a high measure of collective motion being involved in these transitions. Nor do we compare these data with the predictions of the model that mixes 1p:1h excitations with 3p-3h excitations in a deformed basis[13] except to note that the relative $E2$ strengths of the three transitions appear to come out quite wrong on that model.[11]

One sure conclusion is that higher excitations such as 3p-3h are demanded, with some indication that these higher excitations are perhaps more important in the $J^\pi=1^-$ and 3^- states than in the $J^\pi=2^-$ state. This situation is consistent with expectations from the calculations of Elliott and Flowers[2] (see Introduction) and in particular with the recent calculations of Mavromatis *et al.*[14] In the latter work it was found that none of the energies of the $T=0$, $J^\pi=1^-$, 2^-, 3^- states could be accounted for, using only 1p-1h configurations with a Hamada-Johnson residual interaction; in each case substantial admixture of 3p-3h states was indicated.[13] This situation is also consistent with the picture suggested by Lowe *et al.*[1] to explain the weakness of the transition between the 7.12- and 6.06-MeV states.

Two aspects of the N^{16} β decay must be mentioned here. Firstly, the independent-particle model[2] predicts quite well the log*ft* value to the 8.88-MeV state using only 1p-1h components, which may seem to argue against strong 3p-3h admixtures in that state. Secondly, the log*ft* values[15,16] to the 7.12- and 9.58-MeV $J^\pi=1^-$ states are quite different (log*ft*=5.1 and 6.5, respectively). In the work of Brown and Green[13] and of Mavromatis *et al.*[14] these latter two states appear to be roughly equal mixtures of 1p-1h and 3p-3h components, while the experimental log*ft* values suggest a mixing of only a few percent by intensity. The trouble here may lie in the inadequate description of the N^{16} ground state as a 1p-1h state and it may seem necessary to introduce considerable 3p-3h··· components into the low-lying $T=1$ states as well as into the $T=0$ states, even though their excitation is adequately accounted for on the 1p-1h basis.[2,14] Such an introduction may seem likely to spoil the good account given[2] by the 1p-1h model of the N^{16} β decay to the $J^\pi=3^-$ state at 6.13 MeV; on the other hand it may improve the poor account[2] of the decay to the $J^\pi=1^-$ state at 7.12 MeV. The feeble $E1$ transition ($\leq10^{-3}$ Weisskopf units[17]) of the analog state in O^{16} (that at 12.97 MeV) to the $J^\pi=2^+$ 6.92-MeV state may also appear to argue *a priori* against large 3p-3h··· admixtures in the N^{16} ground state if we accept the 6.92-MeV state as largely 4p-4h.

We will not discuss the $M1$ components of the transitions since we have nothing significant to add to the remarks already made.[12,11]

We may note in passing the interesting $M2$ properties of the 8.88-MeV state. The ground-state transition is quite strong for an isotopic spin-unfavored transition, $\Delta T=0$ with $T_z=0$ (using our present branching ratio and the total width of the states[11] we find $|M|^2=0.047$ Weisskopf units, using $r_0=1.2$ fm). This strength ac-

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cords with the expectation of the 1p-1h model[2] but would be difficult to understand if the 8.88-MeV state were indeed predominantly 3p-3h and the ground state chiefly 0p-0h. It appears[18] that the $M2$ transition to the 6.06-MeV deformed $J^\pi=0^+$ state is stronger, namely of $|M|^2=0.17$ Weisskopf units, which is very strong in view of the isotopic spins. This may, in contrast to the ground-state transitions, accord well with a 3p-3h description for the 8.88-MeV state, but not with a 1p-1h description for the 8.88-MeV state, and a predominantly 4p-4h description for the 6.06-MeV state. This latter $M2$ transition in itself seems to call for substantial 3p-3h admixtures in the 8.88-MeV state; its strength is, however, surprisingly great by any standards for an isotopic-spin-unfavored transition.

We consider now the $E1$ transitions. The first of these is the 0.58% branch to the $J^\pi=0^+$ "deformed" state at 6.06 MeV from the $J^\pi=1^-$ $T=1$ "spherical" state at 13.1 MeV. If the latter were indeed[14] chiefly 1p-1h, then this branch would measure the mixing of the ground state into the $J^\pi=0^+$-excited state if the latter were entirely 4p-4h; at least we may say that if this transition was to be very weak it would be difficult to reconcile with a major mixing between the ground and excited states. Our branching ratio corresponds to

$$B(E1;\,13.1\rightarrow 6.06\text{ MeV})/B(E1;\,13.1\rightarrow 0\text{ MeV})=0.037.$$

This result is at least of the order reasonably to be expected from the wave functions of Brown and Green,[19] which suggest a 7% admixture by intensity of the spherical ground state into the 6.06-MeV level. They also suggest that the deformed component in the latter state should contain a significant 2p-2h part to which the $E1$ transition could, in principle, go; however, this contribution is expected to be small for reasons already mentioned.[1,5,20] A detailed calculation is required to determine the quantitative consistency of the branching ratio with the particle-hole prescription[19] for the 6.06-MeV state. Of course, the possibility of substantial 3p-3h admixtures into the low-lying $T=1$ states such as that at 13.10 MeV must, as we have already mentioned, be born in mind for this transition and all others. This figure, if we interpret it as a measure of the mixing of the unperturbed ground state with the unperturbed 6.06-MeV state, is also of the same order as that deduced from the branching ratio of the $J^\pi=2^+$ 6.92-MeV state to the 6.06-MeV and ground states,[1] namely 12%. This latter figure is also approximately the same as that derived from a comparison of the N^{16} β decay to the ground and 6.06-MeV states[21] and from an estimate[22] of the mutual interaction of the ground and 6.06-MeV states on the basis of the upward displacement of the latter from its unperturbed position in the $J^\pi=0^+$, 2^+, $4^+\cdots$ rotational sequence. From these several points of view it now seems very likely that the ground and 6.06-MeV states are mixed to the degree of several percent by intensity. The understanding of the very small branching ratio of the 7.12-MeV state to the 6.06-MeV state, in terms of the mixing of the 7.12- and 9.58-MeV (3p-3h$\cdots$) states and 9.58-MeV (3p-3h$\cdots$) states,[1] does not disturb this conclusion and emphasizes the considerable interest in a measurement of the transition between the 9.58- and 6.06-MeV states.

For the other two $E1$ transitions that we have investigated we find

$$|M{:}\,8.88\rightarrow 6.92\text{ MeV}|^2=4.5\times10^{-5},$$
$$|M{:}\,6.92\rightarrow 6.13\text{ MeV}|^2=<2\times10^{-5},$$

in Weisskopf units based on $r_0=1.2$ fm. Both of these are weak transitions even for isotopic-spin-inhibited radiations, although neither the measured strength of the one nor the limit on the other approaches the $|M|^2<10^{-6}$ of the 7.12- to 6.06-MeV transition.[1] (We may note that the ground-state transition from the $J^\pi=1^-$ 7.12-MeV level has $|M|^2=4\times10^{-4}$.) These weak T-forbidden $E1$ transitions may appear more appropriate to radiations linking "spherical" and "deformed" states than to radiations linking states with large 3p-3h components to states with large 4p-4h components.

SUMMARY

Our results reported here and others that we have cited do not seem to bear a simple interpretation in terms of a 1p-1h description for the traditionally "spherical" states both those of $T=0$ and those of $T=1$. It seems necessary to introduce 3p-3h$\cdots$ admixtures into the $T=0$ states and most probably into those of $T=1$ also. Certain features seem to be adequately explained without the 3p-3h admixtures and it remains to be seen whether agreement on these points can be maintained while introducing such 3p-3h$\cdots$ admixtures as may secure agreement with the data that demand them.

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