6.92- to 6.05-MeV $E2$ Transition in O^{16}†

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The branching ratio of the $J^\pi=2^+$ 6.92-MeV level of O^{16} via the $J^\pi=0^+$ 6.05–MeV level is measured to be $R=(2.3\pm0.5)\times10^{-4}$. This corresponds to an $E2$ transition strength of several single-particle units and supports the suggestion that these two states are the lowest members of a rotational band.

INTRODUCTION

It has long been known that O^{16} possesses states in the sequence $J^\pi=0^+$, 2^+, 4^+ at excitation energies of 6.05, 6.92, and 10.36 MeV, respectively.[1] Following the establishment of the familiar $J^\pi=0^+$, 2^+, 4^+, $\cdots$ pattern of rotational states in the heavy elements with excitations $1:3\frac{1}{3}:\cdots$ the possibility that such sequences might be found even in light elements and that these O^{16} states could be an unexpected example of it become an obvious speculation. The possibility is somewhat unexpected because O^{16} was traditionally thought of as a spherical nucleus, unlikely, even in its excited states that involve shell breakage, to display the strong deformations needed to generate a rotational sequence of the above spacing. But even in those early days there was made the explicit suggestion that light nuclei may have low-lying excited configurations of very different spatial character from the ground-state configuration. In particular the occurrence of very high moments of inertia such as could give rise to this type of rotational sequence was suggested.[2]

An obvious test of the hypothesized rotational relationship between the 6.05- and 6.92-MeV levels is the speed of the $E2$ transition linking them: if they are rotationally related the transition is expected to be strongly enhanced. The speed of the ground-state transition from the 6.92-MeV level is known; so to find the speed of the 0.87-MeV cascade transition in question we must measure the branching ratio:

$$R=\mathrm{rate}(6.92\to6.05)/\mathrm{rate}(6.92\to0).$$

Accordingly two of us (J.L. and D.H.W.) carried out this measurement in a way that will be briefly described shortly. We observed the low-energy transition with certainty and found $R\approx3\times10^{-4}$ which indeed corresponds to a strong enhancement as we shall see. However, two measurements conflicted with our result: One[3] gave $R<0.75\times10^{-4}$, the other[4] $R\approx0.7\times10^{-4}$. The probably-rotational character of the states has been confirmed by the discovery[5] of the $J^\pi=6^+$ member at 16.2 MeV and strengthened by the discovery[5] of a whole new rotational-like band: $J^\pi=0^+$, 2^+, 4^+, 6^+ at 11.25, 11.52, 16.8, 21.2 MeV. Interest in the measurement has been heightened by detailed theoretical work to which we refer later.

Two further measurements have appeared[6,7] giving values of R in essential agreement with our figure, confirming that the transition is strongly enhanced. We have nevertheless thought it worthwhile to repeat our experiment in essentially the same conditions and by the same method as before since the experiment is somewhat delicate, uses a different technique from the other workers, and the result is of some importance.

APPARATUS AND METHOD

Two separate experiments were carried out. In the first, the 3-MeV Van de Graaff at Brookhaven National Laboratory was used. This experiment resulted in the certain observation of the 0.87-MeV cascade γ ray but was complicated by high background; the experiment

† Work performed in part under the auspices of the U. S. Atomic Energy Commission.
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[2] H. Morinaga, Phys. Rev. **101**, 254 (1956).
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[5] E. B. Carter, G. E. Mitchell, and R. H. Davis, Phys. Rev. **133**, B1421 (1964); *ibid.* **133**, B1434 (1964).
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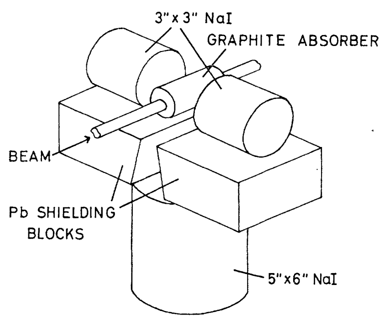

FIG. 1. Target and detector assembly.

was repeated, with more careful shielding arrangements using the 5-MeV Van de Graaff at the Atomic Energy Research Establishment, Harwell, and the 12-MeV tandem accelerator of the Nuclear Physics Laboratory, at Oxford.

The 6.92-MeV state was excited by the reaction $F^{19}(p,\alpha)O^{16}$ at a mean proton bombarding energy of 2.41 MeV. The work of Ask[8] and Swann and Metzger,[9] and measurements reported in the following section of this paper, show that, at this energy, excitation of the 6.92-MeV state is favored relative to that of the other γ-ray-emitting states at 6.13 and 7.12 MeV. No other γ-ray-emitting state is excited, and the 6.05-MeV state accounts for only 4% of the combined cross section[10] leading to excited states.

The target consisted of about 50 μg/cm^2 of CaF_2 evaporated onto a carbon backing. Tantalum backings were used in the BNL experiment, but a significant contribution to the background arose from bremsstrahlung generated in these by positron-electron pairs from the decay of the 6.05-MeV state of O^{16}.

In each experiment, cascade decay of the 6.92 MeV-state through the 6.05 MeV-state was identified by a triple coincidence between three NaI(Tl) γ-ray detectors: one large crystal (5×6 in. in the AERE-Oxford experiment which led to the more accurate result and which is the only one we shall describe in detail) to detect the 870 keV cascade γ ray, and two 3×3-in. crystals, on opposite sides of the target, to detect 511-keV radiation from annihilation of the positron coming from the pair de-excitation of the 6.05-MeV state. In the AERE-Oxford experiment, the 5×6-in. crystal was placed at 90° to the beam line, and the geometry is shown in Fig. 1. Each 3×3-in. crystal was placed with its front face 5 cm, and the 5×6-in. crystal with its front face 12.5 cm from the target. Lead shielding blocks, $2\frac{3}{4}$ in. thick, were placed to minimize scattering of γ rays between the crystals. A graphite cylinder was placed around the beam pipe to bring to rest positrons from the decay of the 6.05-MeV state.

The electronics are shown schematically in Fig. 2. All amplifiers provided double-delay-line clipped pulses and the fast-slow coincidence circuitry used zero-crossover timing with a resolving time of about 50 nsec. The spectrum of triple coincidences in the 5×6-in. detector was displayed on a multichannel analyzer. Random coincidences between the 5×6-in. detector and real doubles in the 3×3-in. detectors were simultaneously displayed in a separate subsection of the analyzer.

THE AERE-OXFORD EXPERIMENT

The triple coincidence pulse-height spectra in the 5×6-in. detector were recorded for a total of about 40 h, at a beam current of 0.2 μA. This run was divided into ten counting periods with the following measurements interspersed:

(a) The combined intensity of γ rays from the target de-exciting the 6.13-, 6.92-, and 7.12-MeV states was measured using the 5×6-in. detector. Apart from maintaining a check on the stability of the Van de Graaff and the electronics, such frequent measurement was essential because of gradual loss of CaF_2 from the carbon-backed targets during bombardment. The target was replaced before this loss amounted to about 20%.

(b) The dead-time loss arose from many sources in individual elements. Rather than estimating individual contributions, the total loss was measured directly by placing a weak ($\sim$0.1 μCi) Na^{22} source in the region of the target. Na^{22} decays by the emission of a 1.28-MeV γ ray in coincidence with a positron, and therefore gives real triple coincidences, resulting in a 1.28-MeV peak in the multichannel-analyzer spectrum. The source was weak enough so that, with the beam still on, counting rates in individual detectors were changed negligibly, and with the beam off, the counting rates due to the source alone produced a negligible dead-time loss. Hence the dead-time correction in the experiment was measured directly as the ratio of the 1.28-MeV counting rates in these two situations.

In the singles measurements of the high-energy γ rays in the 5×6-in. detector, it was not possible to resolve the γ rays from the three states excited. It was therefore necessary to determine the fraction of the total counting rate arising from 6.92-MeV γ rays. Two methods were used:

(a) Ask[8] has measured directly the ratio of γ-ray counting rates, at 90° to the beam direction, for the three states, using a three-crystal spectrometer to resolve the γ rays. From his data,

$$A=\frac{\text{Intensity of 6.92-MeV }\gamma}{\text{Total intensity of 6.13, 6.92, and 7.12-MeV }\gamma}=0.48$$

for a proton energy of 2.40 MeV.

(b) We measured, in a separate experiment, relative differential cross sections over the whole angular range

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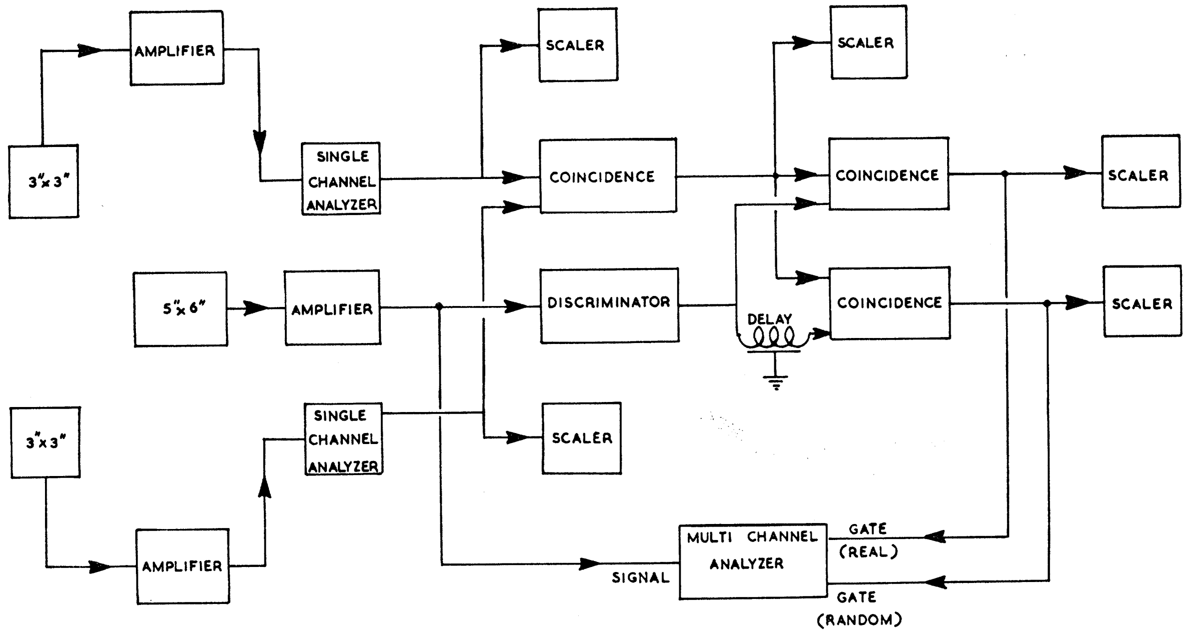

FIG. 2. Block diagram of electronics. The real and random gates address different blocks of the analyzer's memory to permit simultaneous collection of real and random coincidence spectra.

for the $F^{19}(p,\alpha)O^{16}$ reaction using a 10-μg/cm^2 CaF_2 target on a VYNS-film backing. The α particles were detected in a solid-state detector, and measurements were made at several energies in the region of interest. The results of these measurements were used initially in selecting a suitable energy for the experiment. The integrated relative total cross sections yielded the ratio

$$A'=\frac{\sigma(6.92\text{ MeV})}{\sigma(6.13\text{ MeV})+\sigma(6.92\text{ MeV})+\sigma(7.12\text{ MeV})}=0.51,$$

which was found to be essentially constant over the energy range 2.400 to 2.415 MeV.

The closeness of A and A' indicates that, as expected at this energy, the effects of the γ-ray angular distributions are not strong. The value of $A=0.48$ is taken in our subsequent analysis since, in this ratio, the γ-angular distribution functions at 90° are included. (We may note that since we measured the cascade γ ray and the ground state γ ray in the same crystal and since both final states are of $J^\pi=0^+$ any possible angular distribution effects cancel out in our determination of the branching ratio, both transitions being pure $E2$.) The results of the (p,α)-angular distributions demonstrate that slight differences in geometry, energy and target thickness between the present experiments and those of Ask have negligible effect on the relative excitation of the γ-ray emitting states.

EFFICIENCY CALIBRATION

The efficiency of the apparatus for detecting positron–γ-ray coincidences was measured by placing a Na^{22} source of known strength at the target position, giving triple coincidences in the three crystals. To compute the efficiency for detection of cascade decay of the O^{16} 6.92-MeV state from the measured efficiency for the Na^{22} source, the following corrections were necessary:

(a) The efficiency of the 5×6-in. detector is higher for 0.87-MeV γ rays from O^{16} than for 1.28-MeV γ rays from Na^{22}, because of changes both in the total efficiency and in the fraction of the spectrum in the full-energy peak. The combined correction for these effects was determined by measuring the peak efficiency for γ-ray sources of various energies in the range 0.66 to 2.62 MeV. Sources whose strengths were not known were calibrated using an unshielded 3×3-in. NaI(Tl) detector, the efficiency of which was taken from the tables of Vegors *et al.*[11] The correction was $(22\pm4)\%$.

(b) Absorption in the beam pipe, the graphite absorber and the 5×6-in. crystal can is different for 0.87 and for 1.28-MeV γ rays. This correction was computed to be 1.5% using standard absorption coefficients.

(c) The positrons from the decay of the pair state of O^{16} have kinetic energies up to 5.03 MeV, and therefore come to rest with a distribution through the graphite absorber different from that for the low-energy positrons from Na^{22}. Because the annihilation quanta are emitted at 180° to one another, the efficiency for detecting these O^{16} positrons will be less than for those from the Na^{22} source, which annihilate close to the common axis of the 3×3-in. detectors. This correction was measured by

[11] S. H. Vegors, L. L. Marsden, and R. L. Heath, Phillips Petroleum Company Report (unpublished).

comparing the double coincidence rate in the 3×3-in. detectors, due to the Na^{22} source, with that from high energy positrons from the 6.05-MeV state in O^{16}. For this purpose a resonance, at a proton bombarding energy of 1.875 MeV, for preferential excitation of the 6.05-MeV state relative to the γ-ray emitting states was used.[10] The correction measured in this way was $(36\pm4)\%$. Attempts to determine this by computation and by measuring the variation of efficiency with Na^{22} source position gave results consistent with this value, but with larger uncertainties. Finally, since the collimated 5×6-in. crystal was used for singles counting of the 6.92-MeV γ rays, its efficiency at this energy was calibrated against an uncollimated 3×3-in. detector, the efficiency of which was taken from Ref. 11.

RESULTS

The triple-coincidence pulse-height spectrum in the 5×6-in. detector, after subtraction of randoms, is shown in Fig. 3. The random spectrum accounted for about 10% of the total counting rate. The spectrum in Fig. 3 shows a peak corresponding to a transition between the 6.92 and 6.05-MeV states: There is no indication of γ rays corresponding to any other possible cascade decay in O^{16}.

The smooth background arises mainly from bremsstrahlung emitted by electrons and positrons following direct excitation of the 6.05-MeV state. Smaller contributions arise from internal bremsstrahlung in the decay of this state,[12] and from scattering of high-energy γ rays between the crystals. To provide an objective assessment of the background under the peak, a function of the form

$$y=\exp(a_0+a_1E+a_2E^2+a_3E^3+a_4E^4)$$

was fitted to the background, excluding the region of the peak, by a least-squares method. The resulting curve was then used to interpolate the background under the peak. Various background-fitting regions excluding the peak were used, and both the exponential form shown above and a simple polynomial were tried as interpolating functions. The background curve shown in Fig. 3 is the average of eight such least-squares fits. The uncertainty due to the difference between these eight fits is consistent with the statistical uncertainty on the background counts. The width and position of the peak shown at 0.87 MeV in Fig. 3 are computed from the known response of the 5×6-in. detector.

The data yield a value for the branching ratio R, defined in the Introduction, of

$$R=(2.3\pm0.5)\times10^{-4}.$$

The dominant contributions to the error are the statistical uncertainty in the count in the 0.87-MeV peak (11%), and the error (11%) in the interpolated background under the peak.

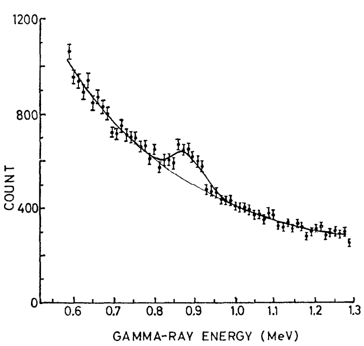

FIG. 3. Coincidence spectrum showing the 0.87-MeV cascade transition between the 6.92- and 6.05-MeV states. The background curve is computed as described in the text. The peak superposed on this is at the calculated position and with the expected width of the 0.87-MeV peak.

[12] Calculations of internal bremsstrahlung accompanying pair emission have been carried out by G. H. Burkhardt and D. Owen (private communication).

COMPARISON WITH OTHER MEASUREMENTS

Table I summarizes the measurements of the branching ratio R that are known to us. Apart from the first two results these values are concordant and we adopt the weighted average of the remainder:

$$R=(2.5\pm0.4)\times10^{-4}.$$

THE RADIATIVE WIDTH

To find the radiative width of the 6.92- to 6.05-MeV transition we need to know that of the ground-state transition. This is[9] $(5.5\pm1.4)\times10^{-2}$ eV so that for the transition now under study,

$$\Gamma_\gamma=(1.4\pm0.5)\times10^{-5}\text{ eV}.$$

The greater contribution to the error comes from the ground-state radiative width.

In order to assess the meaning of this width in as model-free a way as possible we express it in units of the single-particle width Γ_γ(s.p.) for a proton making an $E2$ jump between specified orbits in a pure potential. We have the standard result:

$$(2j_i+1)\Gamma_\gamma(\text{s.p.})=6.43\times10^{-8}E_\gamma{}^5[Z(l_ij_il_fj_f;\tfrac{1}{2}\,2)]^2\langle r^2\rangle^2,$$

where Γ_γ is in eV, E_γ in MeV, $\langle r^2\rangle$ in F^2 and the other

TABLE I. Measurements of the branching ratio: $R=\text{rate}(6.92\to6.05)/\text{rate}(6.92\to0)$.

Authors	10^4R
Goldring and Rosner[a]	<0.75
Gorodetzky *et al.*[b]	0.71 ± 0.25
Lowe and Wilkinson	$3.4_{-1.5}^{+3}$
Gorodetzky *et al.* (1963)[c]	2.9 ± 1.1
Fuchs *et al.* (1965)[d]	2.7 ± 0.7
Present experiment	2.3 ± 0.5

[a] See Ref. 3. [b] See Ref. 4. [c] See Ref. 6. [d] See Ref. 7.

symbols have their obvious meanings.

$$([Z(abcd;ef)]^2=(2a+1)(2b+1)(2c+1)(2d+1)\times[W(abcd;ef)(ac00|f0)]^2).$$

If we use wavefunctions adjusted correctly to reproduce the nuclear size and binding energies as determined by electron scattering and other methods we find values of $\langle r^2\rangle$ between 8 and 14 F^2 for the various combinations of orbitals, $1p\rightarrow 1p$, $2s\leftrightarrow 1d$, $1d\rightarrow 1d$, that can contribute to our transition; 11 F^2 is a reasonable working mean. The spin factors $[Z^2/(2j_i+1)]$ are distributed about a value of 0.6 or so (with an excursion either side by a factor of about 5)—cf. the $l+\frac{1}{2}\rightarrow\frac{1}{2}$ transition of the Weisskopf units which has a spin factor of unity. Using these figures our best *a priori* figure for the single-particle speed becomes Γ_γ(s.p.) $\approx 2.3\times 10^{-6}$ eV. Our experimental figure is therefore about 6 such single-particle units.

We may alternatively express the speed in terms of the familiar Weisskopf units, Γ_W, using a radius adjusted to fit the experimentally-determined nuclear size namely $\langle r^2\rangle\approx 7$ F^2. This gives $\Gamma_W\approx 1.6\times 10^{-6}$ eV and our experimental transition is about 9 such Weisskopf units.

These considerations show that we are indeed dealing with the strongly-enhanced transition expected if the two levels involved are the beginning of a rotational band based on a highly deformed ground state.

COMPARISON WITH ROTATIONAL MODELS

Two models which recognize the rotational interrelationship of the 6.92 and 6.05-MeV levels have yielded predictions for the $E2$ radiative transition strength between these states.[13,14] In the first of these[13] the two states are identified as belonging to the two-particle two-hole representation (42) of the $SU(3)$ group with [4444] symmetry. The prediction of this model (fitted to the experimentally determined nuclear size) is: $\Gamma_\gamma=3.4\times 10^{-6}$ eV, i.e., a factor of about 4 too low. Note that this identification in its simple form would forbid the ground state transition from the 6.92-MeV level since the ground state is taken as the fully closed $1p$ shell. This model uses a spherical basis for its two-particle two-hole states and so does not enjoy the extra $E2$ enhancements that are to be associated with nonspherical equilibrium shape. These latter effects are thought to contribute a factor of about 3–4 to the in-band $E2$ transition rates (the "effective charge factor"); this is just the factor by which the same calculation[13] fails to account for the speeds of the $E2$ transtions from the first excited states of C^{12} and Ne^{20}. If we were to apply this same factor to our present transition it would achieve agreement between theory and experiment. However, the rather considerable deformations associated with an effective charge factor of this magnitude may then imply that we should not expect the two-particle two-hole description to remain the dominant one; this indeed appears explicitly in the second calculation[14] which is performed in a deformed basis.

The second model[14] is of a more general empirical character and represents the ground state of O^{16} as a mixture of the fully closed $1p$ shell plus two-particle two-hole plus four-particle four-hole states and the 6.05-MeV state similarly. The 6.92-MeV state is a two-particle two-hole plus four-particle four-hole state (the latter component being dominant) closely related to that at 6.05 MeV. This model has the advantage that it permits the ground state transition of the 6.92-MeV state (and gets its strength about right). Its prediction for the strength of the transition that we study here is: $\Gamma_\gamma=4.7\times 10^{-5}$ eV, i.e., a factor of 3 too high. This model, unlike the first, uses a deformed basis, and so does not call for the additional application of an effective charge factor. The two theoretical models, which err equally on opposite sides of the truth, use different values for the nuclear size: Normalization to the same value increases the discrepancy between their predictions by a further factor of about 1.4. We should expect the second model, even without its use of a deformed basis, to predict stronger $E2$ transitions than the first since its chief components are four-particle four-hole whereas the first model is two-particle two-hole.

It may be a little surprising that the second model's predictions for the $E2$ radiative transition strength between the $J^\pi=4^+$ state at 10.36-MeV and the $J^\pi=2^+$ state at 6.92 MeV agree rather well with experiment [$\Gamma_\gamma(\text{expt})=0.046\pm 0.006$ eV; $\Gamma_\gamma(\text{theor})=0.060$ eV] when its success on the transition studied here is not very good. The calculation for the $4^+\rightarrow 2^+$ transition is, however, not so complete a one as for the transition studied here since it is assumed that the $J^\pi=4^+$ state is a pure four-particle–four-hole state.

The situation is probably that the 4^+–2^+ relationship is significantly closer to a rotational one than the 2^+–0^+ relationship; the 6.05-MeV $J^\pi=0^+$ state mixes with the ground state; on the other hand the $J^\pi=2^+$ and $J^\pi=4^+$ states have no such admixture to contend with. This mixing of the two $J^\pi=0^+$ states is indeed the situation hypothesized in the work of Brown and Green[14] (and also in that of Rose, Lopes, and Greiner[15]): the ideally rotational state Ψ_r mixes into the ideally spherical state Ψ_0 and vice versa. In this case the branching ratio R of this ideally rotational $J^\pi=2^+$ state uniquely determines the mixing ratio of the primitive rotational and spherical states as found in the

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[15] H. J. Rose, J. Lopes, and W. Greiner, Phys. Letters **19**, 686 (1965).

real ground and 6.05-MeV states

$$\Psi_{\text{ground}}=\alpha\Psi_0+\beta\Psi_r,$$

$$\Psi_{6.05}=\alpha\Psi_r-\beta\Psi_0,$$

where $\alpha^2+\beta^2=1$; $R=[\alpha/\beta]^2[0.87/6.92]^5$. The result reported here, $R=2.5\times10^{-4}$, then implies $\beta/\alpha=0.35$; i.e., the ground state contains 11% by intensity of the ideally rotational state.

Another handle on this situation is afforded by the pair de-excitation rate of the 6.05-MeV state to the ground state. This is known experimentally[16] but has not yet been calculated from the second model which, unlike the first, provides for it.

[16] S. Devons, G. Goldring, and G. R. Lindsey, Proc. Phys. Soc. (London) **A67**, 134 (1954).

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Properties of Excited States in C^{14}†

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The 6.59-, 6.72-, 6.89-, and 7.34-MeV levels of C^{14}, formed in the $C^{13}(d,p)C^{14}$ reaction, have been studied by means of proton-gamma and gamma-gamma coincidence techniques, magnetic-pair spectrometer measurements, and observations with a Ge(Li) gamma-ray detector. Transition branches from the 6.59-MeV level are $6.59\rightarrow6.09$ [$(99.0\pm0.4)\%$] and $6.59\rightarrow0$[$(1.0\pm0.4)\%$]. Gamma-ray branches determined for the 6.72-MeV level are $6.72\rightarrow6.09$ [$(7\pm2)\%$] and $6.72\rightarrow0$ [$(93\pm2)\%$]. For the 7.34-MeV level the gamma-ray branches are $7.34\rightarrow6.72$ [$(35\pm7)\%$], $7.34\rightarrow6.09$ [$(47\pm4)\%$], and $7.34\rightarrow0$[$(18\pm4)\%$]. Multipolarity measurements with the magnetic pair spectrometer have shown that the 6.72-MeV transition is almost certainly $E3$ and that the 7.34-MeV transition is not $E1$. Gamma rays observed with the Ge(Li) detector from the $6.72\rightarrow0$ and $6.59\rightarrow6.09$ transitions are neither Doppler-broadened nor Doppler-shifted, whereas the gamma rays from the $7.34\rightarrow0$, $7.34\rightarrow6.09$, and $6.89\rightarrow6.09$ transitions exhibit Doppler effects. Accurate gamma-ray energies were measured for some of the cascade transitions. By combining the various observations with previous work, it is concluded that the 6.72-MeV level is $J^\pi=3^-$ and the 7.34-MeV level is $J^\pi=2^-$. Theoretical calculations have been made for the various transition rates in C^{14} and are compared with the experimental results. An incidental experimental result is a value of 495.33 ± 0.10 keV for the energy of the first excited state of F^{17}.

I. INTRODUCTION

ALTHOUGH C^{14} has only six known bound nuclear excited states the spectroscopic information on these levels has been limited. Two of the states, those at 6.72 and 7.34 MeV, are both limited to spins and parities of $J^\pi=1^-$, 2^-, or 3^- by stripping analyses of $C^{13}(d,p)C^{14}$ angular distributions.[1,2] Analysis of proton-gamma angular correlations in the $C^{13}(d,p\gamma)C^{14}$ reaction by Lacambra *et al.*[2] is stated to choose from these alternatives $J^\pi=3^-$ for the 6.72-MeV level and $J^\pi=1^-$ or 2^- for the 7.34-MeV level. The exclusion of $J^\pi=1^-$ for the 6.72-MeV level and of $J^\pi=3^-$ for the 7.34-MeV

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