PHYSICAL REVIEW VOLUME 149, NUMBER 3 23 SEPTEMBER 1966

Study of the $N^{14}(p,\gamma)O^{15}$ Reaction*†

ALBERT E. EVANS AND BERNARD BROWN
U. S. Naval Ordnance Laboratory, Silver Spring, Maryland
AND
JERRY B. MARION‡
University of Maryland, College Park, Maryland

(Received 19 April 1966)

The reaction $N^{14}(p,\gamma)O^{15}$ has been studied using an anticoincidence-shielded scintillation spectrometer. Excitation functions were measured for proton energies of 0.85–1.96 MeV. Resonances were found at bombarding energies of 1.061±0.002, 1.55, 1.739±0.002, and 1800±0.004 MeV, corresponding to the well-known excited states of O^{15} at 8.283±0.003, 8.75, 8.915±0.003, and 8.972±0.005 MeV. Gamma-ray spectra show that the 8.28-MeV level decays to the ground state (54%), the 5.24-MeV level (43%), and the 6.18-MeV level (2%). In addition, coincidence spectra revealed a 1% branch through the 6.86-MeV level, which level decays to the 5.24-MeV level. No evidence was found for decay of the 8.28-MeV level to a previously reported level at 7.17 MeV. The 8.75-MeV level decays $\frac{2}{3}$ by way of the 5.19-MeV level and $\frac{1}{3}$ by way of the 6.18-MeV level. The 8.915-MeV level decays to the ground state (21%), the 5.19-MeV level (23%), the 6.18-MeV level (30%), and the 6.86-MeV level (26%). The 8.97-MeV level decays 93% to the ground state and 6% to the 5.19-MeV state. Based upon measured transition strengths and the angular distribution of the ground-state gamma rays, the spin of the 8.915-MeV level is established as $\frac{3}{2}$; the 8.972-MeV level is $\frac{3}{2}^-$ or $\frac{1}{2}^-$ and the 6.86-MeV level has a spin of either $\frac{5}{2}$ or $\frac{3}{2}$. Off-resonance spectra for E_p near 1.2 MeV indicate direct capture into the 6.79-MeV level, the ground state, and also the 7.55-MeV level. The excitation function of radiation to ground from the bound states of O^{15} indicate that the broad level of O^{15} at 9.53 MeV decays almost entirely directly to the ground state or to the ground state and to unbound levels.

I. INTRODUCTION

A. Theoretical Background

THE mirror nuclei N^{15} and O^{15} are of more than ordinary interest because they both lack only one nucleon to complete their $1p$ shells, and therefore theoretical predictions regarding these nuclei are expected to be in reasonable agreement with experiment. Comparison of experimental data on level positions, spins and parities, widths, and decay branching ratios should provide a fair test of the shell model and a measure of some of the basic parameters of the theory.

The level structure of the mass-15 nuclei was calculated by Inglis.[1] Later, Halbert[2,3] made calculations for 25 even-parity states with excitation energies between 5 and 15 MeV. The results of these calculations are shown in Fig. 1, together with the present known level structures of N^{15} and O^{15}.[4] There appears to be qualitative agreement regarding average level density as well as agreement on the distribution of spins, but there is considerable level shifting, at times causing reversal of level order. The odd-parity levels which begin to appear at excitations near 9 MeV were not considered either by Inglis or by Halbert. A detailed discussion of N^{15} and O^{15} level structure has recently been given by Warburton, Olness, and Alburger.[4]

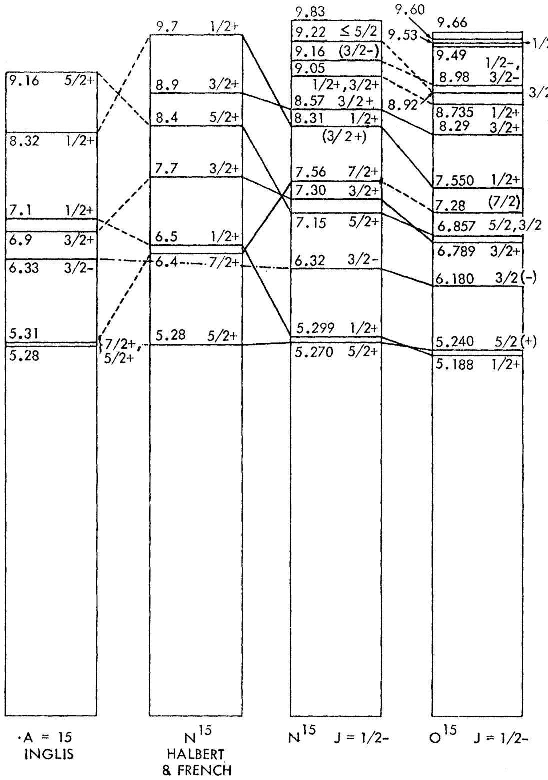


FIG. 1. Comparison of the level structures of N^{15} and O^{15} with shell-model theory. The experimental data include results given by Warburton *et al.* (Ref. 4) and in this paper.

---

* Based in part upon portions of a thesis submitted by A. E. Evans to the Department of Physics and Astronomy, the University of Maryland, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

† This paper supersedes U. S. Naval Ordnance Laboratory Technical Report No. NOLTR 65-72, 1965.

‡ Research supported in part by the U. S. Atomic Energy Commission.

[1] D. R. Inglis, Rev. Mod. Phys. **25**, 390 (1953).

[2] E. C. Halbert, Ph.D. thesis, University of Rochester, 1956 (unpublished).

[3] E. C. Halbert and J. B. French, Phys. Rev. **105**, 1563 (1957).

[4] E. K. Warburton, J. W. Olness, and D. E. Alburger, Phys. Rev. **140**, B1202 (1965).

B. Summary of Previous Experimental Data Concerning O^{15}

Present knowledge of the level structure of O^{15} below 10 MeV has come predominantly from studies of the elastic scattering of protons by N^{14} and of radiative capture of protons by N^{14}. Additional information has been obtained by using such reactions as $C^{13}(He^3,\alpha)O^{15}$ and $N^{14}(d,n)O^{15}$.

A study of the $N^{14}(p,\gamma)O^{15}$ reaction was reported by Duncan and Perry,[5] who measured the yield of positrons from the decay of the ground state of O^{15} for bombarding energies between 0.25 and 2.5 MeV. Absolute cross sections were obtained and all of the presently known levels in the region of excitation energy from 7.5 to 9.6 MeV were observed. Their results, including the partial radiation widths which were used for absolute normalization in the present work, are given in Table I.

The ground-state yield curves of Duncan and Perry, while valuable in establishing the location and radiative widths of O^{15} levels, yielded no information regarding either the mechanism of formation or the manner of decay of these levels; hence, no spin assignments could be obtained from their work. Spin assignments in this region of excitation energy have been made possible by means of gamma-ray spectroscopic and proton elastic-scattering experiments. Hagedorn *et al.*,[6] measured the absolute differential elastic-scattering cross section of nitrogen at four different angles for protons of energies between 620 and 1820 keV. Their results indicated that the 8.29-MeV level ($E_p=1.064$ MeV) is formed predominantly by *s*-wave protons, limiting the choice of spins and parity for this level to $\frac{1}{2}^+$ and $\frac{3}{2}^+$, with the $\frac{3}{2}^+$ assignment giving a better fit to their data. They further showed that the 8.75-MeV level ($E_p=1.55$ MeV) is also formed by *s*-wave protons.

Assignment of spins and parities to the levels at 8.93 and 8.98 MeV (1.74- and 1.80-MeV bombarding energies, respectively) from elastic-scattering data has presented some difficulty, because of the large "background" or off-resonance contribution to the scattering at these energies. The analysis is particularly difficult because the background appears to be other than pure *s*-wave scattering. Most of this background appears to arise from a broad level centered at a bombarding energy of 2.38 MeV. The width of this level as measured by elastic scattering[7–10] is about 500 keV, whereas Duncan and Perry[5] obtained a value of 1.2 MeV from their capture data.

TABLE I. $N^{14}(p,\gamma)O^{15}$ resonances according to Duncan and Perry.[a,b]

E_R (MeV)	Γ (keV)	$\omega\Gamma_\gamma$ (eV)	σ_R (mb)
0.277	<2	0.02	>0.15
1.064 ± 0.002	4.8 ± 1	0.63	0.37
1.55 ± 0.02	50 ± 20	0.16	0.006
1.748 ± 0.005	11 ± 3	0.21	0.03
1.815 ± 0.004	7 ± 1.5	0.52	0.11
2.356 ± 0.008	14 ± 4	2.4	0.21
2.489 ± 0.007	11 ± 3	3.3	0.35
2.60 ± 0.05	1270 ± 50	46	0.05

[a] Reference 5.

[b] A resonance reported at 0.70 MeV has been discounted as an impurity (Ref. 26).

Elastic scattering of protons by N^{14} has also been studied by Gove *et al.*,[7] Ferguson *et al.*,[8–10] Tautfest and Rubin,[11] Bolmgren *et al.*,[12] Webb *et al.*,[13] Bashkin *et al.*,[14] and Olness *et al.*[15] The measurements of Gove, Ferguson *et al.* ($1.0\leq E_p\leq 2.9$ MeV) establish the existence of a significant *p*-wave phase shift in this region, important for the analysis of off-resonance scattering. These authors did not assign spins to the 8.93- and 8.98-MeV levels, but did assign $\frac{1}{2}^+$ and a total width of 550 keV to the level at 9.47 MeV.

Tautfest and Rubin investigated the energy interval from 0.6 to 2 MeV and concluded that the 8.93- and 8.98-MeV levels both had spins of either $\frac{3}{2}^-$ or $\frac{5}{2}^-$. However, they suggested $\frac{1}{2}^+$ for the 8.29-MeV level, in disagreement with other workers.

The work of Bolmgren *et al.* covers the bombarding-energy range of 1.5–3.5 MeV and is, at lower energies, consistent with the results of Ferguson *et al.* The range of bombarding energies was extended to 4 MeV by Bashkin *et al.*, and by Olness *et al.* All of these workers are in essential agreement. However, none of them attempted to assign spin or parity to the 8.93- and 8.98-MeV levels.

Cohen-Ganouna *et al.*[16] have made a study of the shapes of the differential-elastic-scattering anomalies associated with the 8.93- and 8.98-MeV levels. They concluded that the 8.93-MeV level is formed by *d*-wave protons acting in channel spin $\frac{3}{2}$, with a most probable spin and parity for the level of $\frac{5}{2}^+$. They further concluded that the 8.98-MeV level is formed by *p*-wave protons in channel spin $\frac{3}{2}$, and that this is most probably a $\frac{5}{2}^-$ level. Their analysis, however, is quite sensitive to small changes in the *s*- and *p*-wave nonresonant phase shifts.

---

[5] D. B. Duncan and J. E. Perry, Phys. Rev. **82**, 809 (1951).

[6] F. Hagedorn, F. Mozer, T. Webb, W. Fowler, and C. Lauritsen, Phys. Rev. **105**, 219 (1957).

[7] H. E. Gove, A. J. Ferguson, and J. T. Sample, Phys. Rev. **93**, A928 (1954).

[8] A. J. Ferguson, R. L. Clarke, H. E. Gove, and J. T. Sample, Chalk River Laboratories Report No. PD-26, 1956 (unpublished).

[9] A. J. Ferguson, R. L. Clarke, and H. E. Gove, Phys. Rev. **115**, 1655 (1959).

[10] A. J. Ferguson, Phys. Rev. **115**, 1660 (1959).

[11] G. W. Tautfest and S. Rubin, Phys. Rev. **103**, 196 (1956).

[12] C. R. Bolmgren, G. D. Freier, J. G. Likeley, and F. K. Famularo, Phys. Rev. **105**, 210 (1957).

[13] T. S. Webb, Jr., Ph.D. thesis, California Institute of Technology, 1955 (unpublished).

[14] S. Bashkin, R. Carlson, and R. Douglas, Phys. Rev. **114**, 1552 (1959).

[15] J. W. Olness, J. Verona, and H. W. Lewis, Phys. Rev. **112**, 475 (1958).

[16] J. Cohen-Ganouna, M. Lambert, and J. Schmouker, J. Phys. Radium **24**, 43 (1963).

The level structure below the $N^{14}+p$ binding energy of 7.2928 MeV[17] has been deduced by gamma-ray spectroscopy and by means of the $N^{14}(d,n)O^{15}$ and $O^{16}(He^3,\alpha)O^{15}$ reactions. One previous difficulty in this area has been the existence of the "doublet" levels at 5.19–5.24 and at 6.79–6.86 MeV, which could not be easily resolved by NaI gamma-ray spectroscopy. The pair of levels at 6.79 and 6.86 MeV was found by Marion *et al.*,[18] in a study of the $N^{14}(d,n)O^{15}$ reaction. The 5.19- and 5.24-MeV levels were first resolved by means of the $O^{16}(He^3,\alpha)O^{15}$ reaction.[19,20] It is now known[4] that the 5.19- and 5.24-MeV levels have $J^\pi=\frac{1}{2}^+$ and $\frac{5}{2}^{(+)}$ (the parity of the 5.24-MeV level has not been experimentally established), respectively, so that the order is reversed from that in N^{15} (see Fig. 1). The 6.79- and 6.86-MeV pair appears also to be reversed.

Studies of spectra resulting from the decay of the 7.55- and 8.29-MeV levels have been reported. The decay of the 7.55-MeV level has been studied most recently by Tabata and Okano[21] and by Povh and Hebbard.[22] The two experiments are in essential agreement. Tabata and Okano, in determining that all gamma rays from this reaction are isotropic, support the $J=\frac{1}{2}$ assignment for this level. Both groups deduce the same decay scheme, involving transitions to the 6.79-, 6.18-, and 5.19-MeV levels. Based on angular-correlation measurements, Povh and Hebbard established the spin and parity of the 6.79- and 6.18-MeV levels as $\frac{3}{2}^+$ and $\frac{3}{2}^{(-)}$, respectively.

The decay of the 8.29-MeV level has been studied by Hebbard and Povh[23] using single-crystal and coincidence techniques. They found that this level decays to the ground state as well as through the levels at 5.2 MeV (these could not be resolved) and through the 6.18-MeV level with radiative widths of 0.54, 0.33, and 0.06 eV, respectively. They also found evidence for a transition to a new level at 7.17 MeV, with a radiative width of 0.02 eV. Finally, they found that the bulk of nonresonant production of O^{15} in the 950–1560-keV proton-energy range is by way of the 6.79-MeV level. From their spectrum of the decay of the 8.75-MeV level ($E_p=1.55$ MeV), they assert weak resonance of ground-state, 5.2-MeV, and 6.18-MeV gamma rays.

Gallmann *et al.*[24,25] have made a precision angular-distribution measurement of the 8.29-MeV ground-state gamma ray and an angular-correlation measurement of the 3.04–5.25-MeV cascade from this level. The ground-state angular-distribution measurement yielded

$$W(\theta)=1+(0.05\pm0.01)P_2(\cos\theta).$$

This distribution is consistent with a $J=\frac{3}{2}$ assignment of either parity, assuming either a mixture of s and d waves or pure p waves in formation of the level. In the even-parity case, a contribution as small as 0.25% d waves was sufficient to account for the measured angular distribution.

The off-resonance radiation from the $N^{14}(p,\gamma)O^{15}$ reaction is of considerable interest. There appears to be a mixture of resonance tails, resonance interference, and direct capture involved in the reaction between areas of resonant capture. This question has been studied for proton energies from 210 to 1070 keV by Hebbard and Bailey.[26,27] The principal finding was a nonresonant direct capture through the 6.79-MeV level. The direct-capture gamma ray leading to this level has a $\sin^2\theta$ distribution, indicating a p- to s-wave transition. These workers also indicated the possibility of small nonresonant contributions to the reaction through other levels in O^{15}.

II. EXPERIMENTAL PROCEDURES

A. Scope

The purpose of the work presented here was to examine the spectra of capture radiation from the $N^{14}(p,\gamma)O^{15}$ reaction in greater detail than had previously been practical and to extend the knowledge of the gamma spectroscopy of this reaction to higher bombarding energies. Information sought included the spins and parities of the 8.92- and 8.98-MeV levels, decay branching ratios from these levels and the 8.75-MeV level, and a close recheck of existing data for the 8.29-MeV level. Information on nonresonant radiation in the 1–2-MeV bombarding-energy range was also desired. Of special interest was any evidence which might shed further light on the 7.17-MeV level reported by Hebbard and Povh.

B. Targets

1. General

Since it proved impossible to purchase nitrogen enriched in N^{14}, targets with which most of the data were taken were prepared from natural nitrogen (99.63%N^{14}). This meant that spectra would be dominated by 4.43-MeV radiation from the prolific $N^{15}(p,\alpha\gamma)C^{12}$ reaction, placing a severe limitation upon the analysis of weak gamma radiation of lesser energy. In order to minimize the 4.43-MeV contribution to

---

[17] J. H. E. Mattauch, W. Thiele, and A. H. Wasptra, Nucl. Phys. **67**, 1 (1965).

[18] J. Marion, R. Brugger, and T. Bonner, Phys. Rev. **100**, 46 (1955).

[19] S. Hinds and R. Middleton, Proc. Phys. Soc. (London) **A73**, 727 (1959).

[20] B. Povh, Phys. Rev. **114**, 1114 (1959).

[21] T. Tabata and K. Okano, J. Phys. Soc. (Japan) **15**, 1552 (1960).

[22] B. Povh and D. Hebbard, Phys. Rev. **115**, 608 (1959).

[23] D. Hebbard and B. Povh, Nucl. Phys. **13**, 642 (1959).

[24] A. Gallmann, Ann. Phys. (Paris) **12**, 185 (1959).

[25] S. Gorodetsky, A. Gallmann, M. Croissiaux, and R. Armbruster, Nucl. Phys. **4**, 112 (1957).

[26] D. F. Hebbard and G. M. Bailey, Nucl. Phys. **49**, 666 (1963).

[27] G. M. Bailey and D. F. Hebbard, Nucl. Phys. **46**, 529 (1963).

spectra taken at $N^{14}(p,\gamma)O^{15}$ resonance energies, it was necessary to use targets with thicknesses of the same order as the natural widths of the resonances under study. Tantalum nitride targets made by heating tantalum in ammonia[23,24] were found to be of too great a thickness. Beryllium nitride targets and targets of copper with thin layers of absorbed nitrogen, such as those used by Duncan and Perry,[5] cannot be used for gamma-ray spectroscopy because of the high yield of gamma radiation from proton capture in beryllium and copper. Titanium nitride is likewise unusable for the same reason, as some of our preliminary measurements clearly indicated. Gas targets, ideal for absolute-cross-section measurements, present problems due to scattering and beam-energy straggling in the entrance window. Differentially pumped targets would have presented a formidable design problem if they were to be used in conjunction with the anticoincidence-shielded spectrometer described in Sec. IID.

2. *Sputtered Targets*

Suitable targets of tantalum nitride were prepared by sputtering tantalum onto platinum backings 0.13-mm thick in a discharge of research-grade nitrogen gas at pressures of 0.05 to 0.1 mm Hg. Durable targets of the desired thickness were produced when 1.6-cm diam backings were placed about 3.8-cm from a 3.8-cm-diam tantalum cathode, and a discharge current of 8–10 mA was maintained with a potential difference ranging from 2000 to 3000 V.

Target and backing cleanliness is vital for good adhesion of the sputtered film to its backing and in order to obtain spectra free from contaminant-induced radiation. Both the target material and the backings were degreased with trichlorethylene, soaked in CP nitric acid, and rinsed in distilled water and acetone. These components were then heated red hot in vacuum for ten minutes.

The most severe contaminant was sodium. Because of the intensity of 1.62-MeV gamma rays from the $Na^{23}(p,\alpha\gamma)Ne^{20}$ reaction, a fingerprint would, of course, ruin a target. Smaller amounts of sodium always appeared to be present, due either to its presence as a trace contaminant in the tantalum (sodium is often used in the refinement of tantalum) or to the action of the discharge on the glass of the sputtering apparatus. To reduce the possibility of sodium coming from the glass, the sputtering electrode and the target backing were shielded to the back and sides with silica. Sodium in the cathode was reduced by heating the cathode white hot in high vacuum for 30 min. These two procedures reduced the quantity of sodium present in the finished targets to levels which were acceptable at most bombarding energies.

There was evidence of considerable oxygen contamination of the sputtered targets. This at first caused some confusion in the analysis of spectra, as will be discussed later.

Slight traces of fluorine were found in some targets. This contaminant was eliminated when target backing and sputtering cathode were heated in vacuum before preparing targets. Fluorine is a particularly serious contaminant because copious quantities of 6.13-MeV radiation from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction would prevent quantitative observation of the relatively weak 6.18-MeV gamma ray in O^{15}. The possibility of fluorine contamination, frequently the case for tantalum-backed targets,[28] led to the selection of platinum for a backing material.

Platinum backings are satisfactory for proton energies below 1.7 MeV, but at higher bombarding energies Coulomb excitation in platinum becomes important. At 1.8 MeV, 350-keV radiation from this source was sufficient to cause a severe dead-time problem in the multichannel analyzer.

3. *Isotopic N^{14} Targets*

In order to obtain $N^{14}(p,\gamma)O^{15}$ spectra in which low-intensity gamma rays of energy less than 4.43 MeV could be studied quantitatively, N^{14} targets have been fabricated by bombarding 0.25-mm-thick tantalum with magnetically analyzed nitrogen ions from the Naval Ordnance Laboratory Van de Graaff accelerator. It was found that 400-keV $(N^{14})_2^+$ ions could be used to produce a target about 20–30 keV thick to 1.06-MeV protons; an accumulated charge of 0.05 coulomb of ions (in 16 h of bombardment) produced a target with an $N^{14}(p,\gamma)O^{15}$ yield approximately four times as great as that of a sputtered target of thickness 11 keV for 1.06-MeV protons. Some N^{15} was found in these targets, but the proportion of N^{15} present was reduced by factors of 10 to 100 from the natural proportion, depending upon the beam focus and defining-slit settings.

Nitrogen ions were produced in the high-voltage terminal of the Van de Graaff, using an rf ion source of standard design,[29] with research-grade nitrogen supplied to the discharge in the customary manner. The beam was found to consist of N^+ and N_2^+ ions in approximately equal amounts. The available beam was approximately 4 μA of either component for up to 8 h, after which the beam current fell off until, after about 30 h of bombarding time, there was less that 0.05 μA of beam.

Upon replacing the nitrogen-gas supply with hydrogen, it was found that the proton output of the ion source had been drastically reduced. This behavior was observed in two ion-source bottles. It appears, therefore, that the production of two N^{14} targets in this fashion is accomplished at the cost of at least reconditioning an

---

[28] S. E. Hunt, R. A. Pope, W. W. Evans, and D. A. Handcock Brit. J. Appl. Phys. **9**, 443 (1958).

[29] ORTEC Model 320 (Oak Ridge Technical Enterprises Corporation, Oak Ridge, Tennessee).

ion source.[30] For this reason, the amount of spectral data taken with targets of this type was limited.

The targets produced were found to be stable for bombardments of up to 5 μA of 1.06-MeV protons. A beam current of 7 μA of 1.82-MeV protons caused the nitrogen to spread through the target, reducing the total yield and causing the nonresonant spectral-line intensities to increase relative to the yield of resonant gamma rays. Attempts were made to produce more durable targets by increasing nitrogen-beam energy and by using the atomic N^{14+} ion, but targets so produced were too thick to permit resolution of the 1.75- and 1.80-MeV resonances in the $N^{14}(p,\gamma)O^{15}$ reaction.

The isotopic targets were found to be quite free of the contaminants which were most bothersome in the sputtered targets. In particular, there was no evidence of oxygen contamination, and very little if any sodium. Close examination of the spectra could lead one to believe that a small quantity of fluorine was present, as evidenced by a very weak indication of a 7.12-MeV gamma ray.

The principal contaminant of these targets was carbon, which was optically visible on the target and which was identified by observation of the 3.51-MeV gamma rays from the 1.70-MeV $C^{12}(p,\gamma)N^{13}$ resonance and the 9.17-MeV radiation from the 1.75-MeV $C^{13}(p,\gamma)N^{14}$ resonance. A liquid-nitrogen-cooled surface surrounding the target blank during nitrogen bombardment would probably have reduced this problem, but the necessary hardware was not readily available.

The isotopic targets suffered also from nonuniformity of thickness, making the yield from proton bombardment very sensitive to beam position. This effect was so severe that these targets were not suitable for angular-distribution studies or for the measurement of excitation functions. Future targets of this type will be made using an oscillating target holder in an attempt to provide greater uniformity.

C. Excitation Functions

In order to search for impurities and also possible new levels in O^{15}, gamma-ray excitation curves were measured with a sputtered target, which was later used for the bulk of the spectral measurements. Data were taken using a 7.6 cm×7.6 cm NaI(Tl) crystal with an integrally housed type 6363 photomultiplier, feeding two linear amplifiers with integral discriminators. Discriminators were calibrated daily using 0.511-, 1.278-, and 1.789- (sum) MeV peaks from a Na^{22} source; the ubiquitous 4.43-MeV gamma ray from the $N^{15}(p,\alpha\gamma)C^{12}$ reaction served as a further check on the gain stability.

The excitation curve was measured for proton energies between 0.8 and 1.9 MeV, obtained from the NOL Van de Graaff accelerator. The beam current for this experiment was approximately 3 μA. The proton beam was analyzed by a 90° magnet with 20-in. beam-path radius; the magnetic field was measured by a nuclear-magnetic-resonance device. Energy calibration was established from the following resonance energies[31]:

(a) $C^{13}(p,\gamma)N^{14}$ 1746.5 keV,
(b) $Al^{27}(p,\gamma)Si^{28}$ 992.0 keV,
(c) $F^{19}(p,\alpha\gamma)O^{16}$ 872.5 keV.

The energy spread of the proton beam, measured at 1.75 MeV using a "semi-thick" C^{13} target, was found to be about 500 eV. No effort was made to improve upon this value, as it was adequate for the intended work.

Two excitation curves were taken simultaneously. The first, of all gamma radiation of energy greater than 4.8 MeV, is a direct measure of all reactions leading to the ground state of O^{15} (one of the gamma rays in any cascade to the ground state must be of energy 5.19 MeV or greater). The 4.8-MeV energy bias also allowed observation of the $N^{15}(p,\gamma)O^{16}$ reaction ($Q=12.11$ MeV), the $F^{19}(p,\alpha\gamma)O^{16}$ reaction, and (p,γ) reactions from most other possible impurities except for O^{16} and C^{12}. The bulk of the radiation detected by the second integral discriminator, set at 1.2 MeV, was the 4.43-MeV gamma ray from the $N^{15}(p,\alpha\gamma)C^{12}$ reaction. This discriminator would also pass events from the $Na^{23}(p,\alpha\gamma)Ne^{20}$, $C^{12}(p,\gamma)N^{13}$, and $O^{16}(p,\gamma)F^{17}$ reactions, as well as from higher energy events.

Data were taken at 20-kc/sec intervals of NMR frequency, corresponding to energy intervals varying from 3.65 keV at 900-keV bombarding energy to 4.83 keV at an energy of 1.96 MeV. 500-μC counts required about 3 min per datum point. The resulting curves are shown in Figs. 2 (a) and (b).

No new $N^{14}(p,\gamma)O^{15}$ resonances were found. The method of high-energy gamma-ray counting that was used is inferior to the positron-counting technique of Duncan and Perry, because of the inherently high background and low efficiency of the gamma-ray measurements.

The curves do indicate a reasonable degree of target purity. Actually, a small amount of sodium was present, as was verified at the 1.35-MeV $Na^{23}(p,\alpha\gamma)$ resonance by using a detector gated for 1.2- to 1.8-MeV radiation.

By comparing the observed and known[32] widths of of the O^{15} resonance levels, it was found that the target thickness was 11 keV for 1.8-MeV protons and 18.7 keV for 1.06-MeV protons.

An interesting feature is the odd structure at 1.75 MeV. This is shown more clearly in Fig. 3, and is due to a superposition of the $C^{13}(p,\gamma)N^{14}$ 1.747-MeV resonance and the $N^{14}(p,\gamma)O^{15}$ resonance; the presence of carbon indicates that a thin layer was built up on the

---

[30] The manufacturer has suggested that replacing the aluminum exit-canal tip of the ion source with an iron or nickel tip would prolong the life of the source when nitrogen ions are being produced. D. B. Schlafke (private communication).

[31] J. B. Marion, Rev. Mod. Phys. 33, 139 (1961).

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

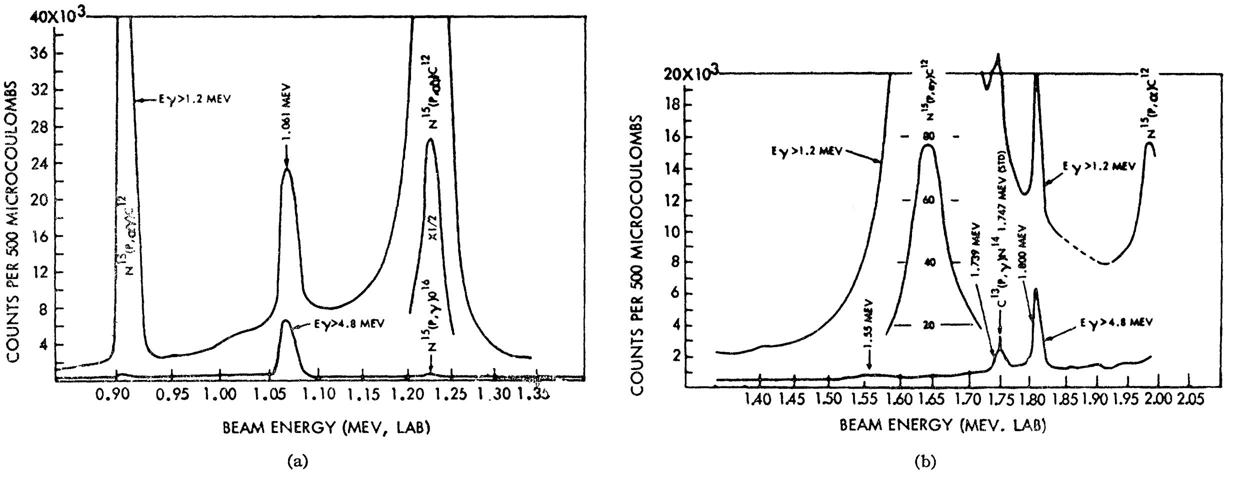


FIG. 2. Yield of gamma radiation for bombardment of tantalum nitride targets with (a) 0.85- to 1.35-MeV protons and, (b) 1.35- to 1.97-MeV protons.

surface of the target. The $C^{13}(p,\gamma)N^{14}$ resonance provides a built-in means of accurate determination of the resonance energy of the $N^{14}(p,\gamma)O^{15}$ resonance. From the data, $E_R=1.739\pm0.002$ MeV. The Q value for the $N^{14}(p,\gamma)O^{15}$ reaction is 7.2928 ± 0.0017 MeV.[17] This gives for the corresponding O^{15} level an excitation energy of 8.915 ± 0.003 MeV.

By the same method, the 1.8-MeV resonance is found to occur at 1.800 ± 0.004 MeV, giving as the excitation energy of the level 8.972 ± 0.005 MeV.

The errors ascribed to the energies of the resonances are due principally to the uncertainty imposed by the experimental shapes of the resonances. For an infinitely thin target, the resonance energy would be the energy of maximum yield. For a thick target, the resonance energy is taken as the halfway point of the leading edge of the yield "step." Since the observed resonance shapes, although several times wider than the known natural widths of the levels, do not have flat tops, one cannot be certain of the proper point to designate as the resonance energy. Comparison of the curves with those obtained using thicker sputtered targets, however, shows that the 1.8-MeV maximum resonance yield is nearly equal to the thick-target maximum yield. Therefore, the resonance energy was taken as the half-maximum yield point of the leading edge. The fact that the relatively thick target does not produce a flatter top is attributed to nonuniform distribution of nitrogen through the target film.

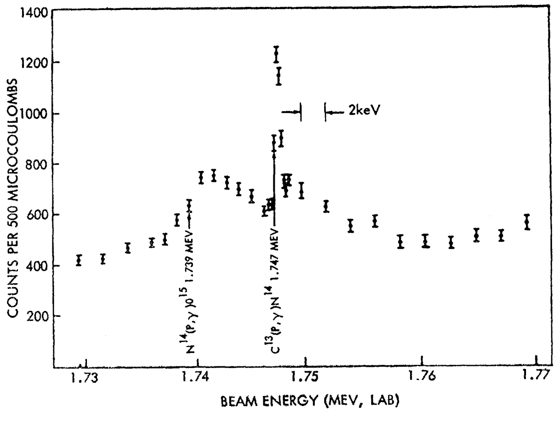


FIG. 3. Detail of the excitation curve near 1.75 MeV showing the $N^{14}(p,\gamma)O^{15}$ ($E_R=1.739$ MeV) and $C^{13}(p,\gamma)N^{14}$ ($E_R=1.747$ MeV) resonances.

Energies of $N^{14}(p,\gamma)O^{15}$ resonances determined from this experiment are compared in Table II with the measurements of other workers.

D. Spectral Measurements: Apparatus and Procedures

Gamma-ray spectra were taken using an anticoincidence-shielded spectrometer[33] consisting of a 12.7-cm diam×25.4-cm long NaI(Tl) crystal assembly surrounded by a 92-cm diam×61-cm long array of liquid-scintillator cells. The entire assembly, shown schematically in Fig. 4, is surrounded by 10 cm of lead and mounted on a modified 6-in. naval gun mount which rotates about the position of the target so that angular-distribution measurements may be made. Since the spectrometer has been described elsewhere,[33,34] no further details of its construction will be given here.

In using this instrument, instead of discarding the NaI detector pulses which are coincident with guard-cell pulses, the coincident spectrum is saved in one-half of

---

[33] A. E. Evans and J. B. Marion, Bull. Am. Phys. Soc., **9**, 47 (1964); A. E. Evans, Ph.D. thesis, University of Maryland, 1965 (unpublished); A. E. Evans, U. S. Naval Ordanance Laboratory Report No. NOLTR 65-72, 1965 (unpublished).

[34] A. E. Evans, B. Brown, and J. B. Marion, Rev. Sci. Instr. **37**, 991 (1966).

TABLE II. Resonances in the $N^{14}(p,\gamma)$ and $N^{14}(p,p)$ reactions.

Year	Author	Reaction	Resonance energy (MeV, laboratory)			
1951	Duncan and Perry[a]	(p,γ)	1.064±0.002	1.55 ±0.02	1.784±0.005	1.815±0.004
1956	Ferguson *et al.*[b]	(p,p)	1.065	1.557	1.743	1.803
1956	Tautfest and Rubin[c]	(p,p)	1.060	1.555	1.744	1.803
1957	Hagedorn *et al.*[d]	(p,p)	1.054	1.544±0.006	1.737±0.004	1.799±0.005
1957	Bolmgren *et al.*[e]	(p,p)		1.55	1.74	1.805
1958	Olness *et al.*[f]	(p,p)	1.061±0.005	1.550±0.005		1.804±0.003
1959	Bashkin *et al.*[g]	(p,p)		1.540	1.730	
1959	Val'ter *et al.*[h]	(p,p)	1.064±0.002		1.744±0.002	1.806±0.002
1963	Cohen-Ganouna *et al.*[i]	(p,p)			1.743	1.809
1964	Present work	(p,γ)	$E_R=1.061\pm0.002$ $E_x=8.283\pm0.003$[j]	1.55	1.739±0.002 8.915±0.003[j]	1.800±0.004 8.972±0.005[j]
1959	Previous E_x		8.291±0.004	8.749±0.007	8.928±0.005	8.988±0.006

[a] Reference 5.
[b] Reference. 8.
[c] Reference 11.
[d] Reference 6.
[e] Reference 12.
[f] Reference 15.
[g] Reference 14.
[h] A. Val'ter, A. Dieneko, E. Malakhov, P. Sorokin, and A. Taranov, Izv. Akad. Nauk SSR **23**, 839 (1959).
[i] Reference 16.
[j] Based on $Q=7.2928\pm0.0017$ MeV for the $N^{14}(p,\gamma)O^{15}$ reaction (Ref. 17).

the memory of a 512-channel analyzer. A fraction of this coincident spectrum is subtracted from the anticoincident spectrum in order to compensate for guard inefficiency. Prior to subtracting, the coincident spectrum is multiplied by an empirically derived function of pulse height, in order to partially correct for energy dependence of the anticoincidence shield.

The spectra obtained in the work to be described usually required exposure times of from 12 to 44 h. In order to permit *post facto* compensation for gain drift, spectra were recorded on paper tape every 4 h

For each 4-h spectrum, the position of the 0.511-MeV annihilation peak and of the 4.433-MeV line from the $N^{15}(p,\alpha\gamma)C^{12}$ reaction (which was always present in the sputtered targets, which targets were used for all precision energy measurements) were computed using a least-squares Gaussian-plus-background peak-fitting program.[35] From this information, the zero intercepts and slopes of the energy scales of the individual spectra were obtained. The energy axes of these spectra were then renormalized and the spectra added using a computer program[36] which also made the anticoincidence-guard correction described above. Background subtractions were accomplished in a similar manner. Final spectra were presented in digital form and were plotted, together with statistical uncertainties, using a magnetic-tape-controlled plotting system.

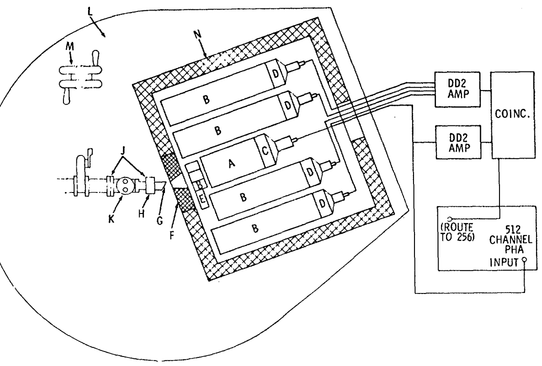


FIG. 4. Layout of the anticoincidence-shielded spectrometer and the accelerator target assembly. (A): 12.7-cm-diam×25.4-cm-long NaI(Tl) crystal; (B): liquid-scintillator guard cells; (C), (D), and (E): photomultiplier tubes; (F): tungsten-alloy collimator; (G): target holder; (H): insulator and electron-barrier electrode; (J): location of beam-defining apertures; (K): liquid-nitrogen trap (inline type); (L): rotating spectrometer table; (M): rotation mechanism; and (N): 10-cm lead-shield wall.

For coincidence studies, a 12.7-cm-diam×12.7-cm NaI(Tl) detector, located outside of the spectrometer shield, was used to gate the anticoincidence-shielded spectrometer. While this arrangement is less efficient and the gating less "clean" than the arrangement of placing both detectors inside the anticoincidence shield[37] (in terms of eliminating pulses in coincidence with Compton continua of gamma rays of energy higher than the pulse-height gate setting), it is better in terms of improved resolution and elimination of effects due to photon scattering between crystals.

For the study of the 1.06-, 1.74-, and 1.80-MeV resonances in the $N^{14}(p,\gamma)O^{15}$ reaction, spectra were taken at 0°, 45°, and 90° to the beam direction with the beam energy at the peak-yield value. Off-resonance spectra were taken and subtracted from the resonance yields.

It was found to be impractical to normalize the long spectral runs for the purpose of obtaining good angular-distribution measurements. For this reason, short runs, usually accumulating about 0.015 C of charge in a 50-

---

[35] R. W. Detenbeck (private communication).

[36] S. Madigosky and R. T. Woodham, U. S. Naval Ordnance Laboratory Technical Report No. NOLTR 64-220, 1965 (unpublished).

[37] R. W. Perkins, Nucl. Instr. Methods **33**, 71 (1965).

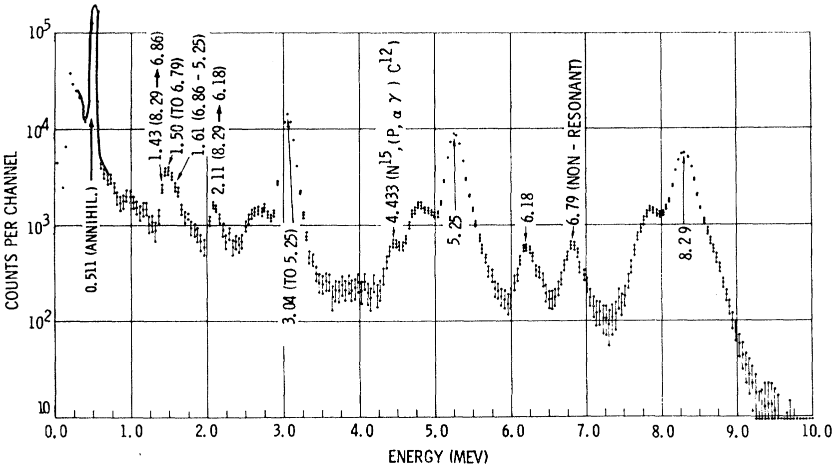


Fig. 5. Spectrum for decay of the 8.28-MeV level from an electromagnetically separated N^{14} target on tantalum backing. The proton-bombarding energy was 1.072 MeV, and the angle of observation was 15°. For this spectrum, 0.1 C of charge was accumulated on the target in $4\frac{1}{2}$ h. Time-dependent background has been subtracted, as well as an energy dependence corrected fraction of the "coincidence" spectrum from the spectrometer.

min period, were made successively at each of the three angles of observation.[38] This procedure was repeated from six to eight times. From the data so obtained, the angular distribution of one or more of the most prominent photopeaks was determined. This angular distribution could then be used to normalize the long runs in order to determine the angular distributions of some of the weaker components.

III. RESULTS

A. Decay of the 8.283-MeV Level

A typical spectrum for the decay of the 8.28-MeV level is shown in Fig. 5. Branching ratios and angular distributions determined from such spectra are given in Table III, together with derived radiative widths and transition strengths in Weisskopf units. The partial radiative widths quoted are based upon the absolute-yield measurements of Duncan and Perry.[5]

In addition to the singles spectra, several coincidence spectra were taken for this level using sputtered targets of natural nitrogen. Two of these are shown in Fig. 6. In the first, a 12.7-cm-diam×12.7-cm-long auxiliary NaI(Tl) crystal was set to detect pulses corresponding to energies from 4.8–7.75 MeV coincident with gamma rays incident upon the anticoincidence-shielded spectrometer. In the second, lower spectrum the coincidence gate covered the interval from 5 to 5.5 MeV, in order to determine the spectrum of gamma rays leading into the first and second excited levels of O^{15}. In the upper spectrum can be seen the entire low-energy portion of the decay components from the 8.28-MeV level, since all gamma radiation of energy 3.05 MeV or less leading from the 8.28-MeV level must be coincident with one gamma ray in the 5.19- to 7.55-MeV range. The absence of any 4.43-MeV radiation is proof that the coincidence spectra are free from accidentals.

The lower spectrum of the figure is of radiation coincident only with the 5.24-MeV photopeak,[39] as seen by the 12.7-cm×12.7-cm coincidence-gating detector. The presence in this spectrum of a portion of the 2.11-MeV line, leading from the 8.28- to the 6.18-MeV level, is attributed to coincidences between the 2.11-MeV gamma ray incident upon the 12.7×25.4-cm crystal and two-quantum escape or Compton-scattering events of 6.18-MeV gamma rays incident upon the 12.7×12.7-cm crystal.

In the lower spectrum, the removal of the 1.50-MeV gamma ray (leading to the 6.79-MeV level) permits observation of two gamma rays, of equal intensity, of energies 1.43 and 1.61 MeV. These indicate a cascade from the 8.28-MeV level to the 6.86-MeV level and thence to the level at 5.24 MeV. The decay of the 6.86-MeV level to the 5.24-MeV level has been seen by Warburton *et al.*[4]

These results have been checked with a pair of 12.7×12.7-cm NaI(Tl) crystals and also with 12.7×12.7-cm and 7.6×7.6-cm crystals in coincidence. The existence of the 1.43- and 1.61-MeV gamma rays was verified. It was also found that the suspected peak at 1.78 MeV coincident with 5.2-MeV radiation is in fact real. The energy of this peak is independent of incident-proton energy. It is not, however, resonant at 1.064-MeV bombarding energy, but does weaken much more rapidly with decreasing bombarding energy than does the 6.79-MeV gamma ray originating from direct capture. It is speculated that this 1.78-MeV peak may arise from the 50-keV-wide $N^{15}(p,\gamma)O^{16}$ resonance which occurs at a bombarding energy of 1.05 MeV.[32]

---

[38] It has been assumed that no captures involving $L>2$ are involved in the reaction, in which case measurements at the 3 angles are sufficient to establish the angular distribution. Such a 3-angle measurement has been shown to be statistically better than an angular-distribution measurement involving data taken at many angles, assuming a given total data-accumulation time. See, for example, C. W. Reich and J. A. Merrill, Nucl. Instr. Methods **23**, 36 (1963).

[39] It is shown in Sec. IIID that it is the 5.24- rather than the 5.19-MeV level which is involved in the decay of the 8.28-MeV level.

TABLE III. Decay properties of the 8.28-MeV level of O^{15}.

Energy (MeV)	Interpretation	% yield[a]	Angular distribution	Γ_γ (eV)[b]	Assumed multipolarity	Strength (Weisskopf units)
8.29	8.28 → 0	53.8 ±0.25	$1-(0.035\pm0.02)P_2$	0.531	$E1$	0.0017
3.04	8.28 → 5.24	42.7 ±0.5	Isotropic ±1%	0.405	$M1$	0.37
2.11	8.28 → 6.18	2.2 ±0.6		0.021	$E1$	0.04
1.43	8.28 → 6.86	1.16±0.3		0.011	$E1$, $M1$	0.0055, 0.055
1.61	6.86 → 5.24	1.37±0.3			$E1$, $M1$	
5.25	5.24 → 0	44.8 ±0.5	Isotropic ±2%		$M2$	
6.18	6.18 → 0	2.2 ±0.23			$M1$	
			Nonresonant components			
1.50	to 6.79	1.8 ±1.0[c]	$\sin^2\theta$ (d)		$M1$	
6.79	6.79 → 0	0.8 ±0.35			$E1$	
1.09	$O^{16}(p,\gamma)F^{17}$		$\sim\sin^2\theta$			

[a] % of decay of 8.28-MeV level.
[b] Based on the absolute measurements of Duncan and Perry (Ref. 5).
[c] At 45°.
[d] Reference 26.

Spectra from 7.6×7.6-cm and 12.7×12.7-cm crystals of radiation coincident with 5.6- to 7.5-MeV radiation incident upon a 12.7×12.7-cm crystal were compared for spectral-line shape with the shape of the 1.37-MeV line from Na^{24}.

For the case of the 7.6×7.6-cm crystal, the results are shown in Fig. 7. It is clear that the continuum on the low-energy side of the 1.5-MeV photopeak from the $N^{14}(p,\gamma)O^{15}$ reaction contains nothing more than the Compton shoulder to be expected from the 1.5-MeV photopeak. This is in direct disagreement with the results of Hebbard and Povh.[23]

It is now almost certain that, contrary to the finding of Hebbard and Povh,[23] there is no transition to a level at 7.17 MeV. Certainly there is no evidence for such a transition in either the singles or coincidence spectra of the present experiment. Warburton *et al.*,[4] using the $O^{16}(He^3,\alpha)O^{15}$ reaction, report a gamma ray of 2.044 MeV leading to the 5.240-MeV level, thereby indicating a new level at 7.284±0.007 MeV. This work has been confirmed by Hensley,[40] who has observed an α-particle group from the $O^{16}(He^3,\alpha)O^{15}$ reaction leading to a state at 7.276±0.004 MeV. A level at 7.285±0.010 MeV in O^{15} has also been observed by Marion, Ludemann, and Roos,[41] using the $O^{16}(p,d)O^{15}$ reaction. The angular-correlation measurements of Hensley[40] show that $J=\frac{7}{2}$ for this state, an assignment which is consistent with the $O^{16}(p,d)O^{15}$ angular distribution. It is therefore virtually certain that the new 7.28-MeV level is the analog of the $\frac{7}{2}^+$ 7.56-MeV state in N^{15}. Since the spin is $\frac{7}{2}$, a measurable transition rate from the 8.28-MeV, $J^\pi=\frac{3}{2}^+$, level would not be expected.

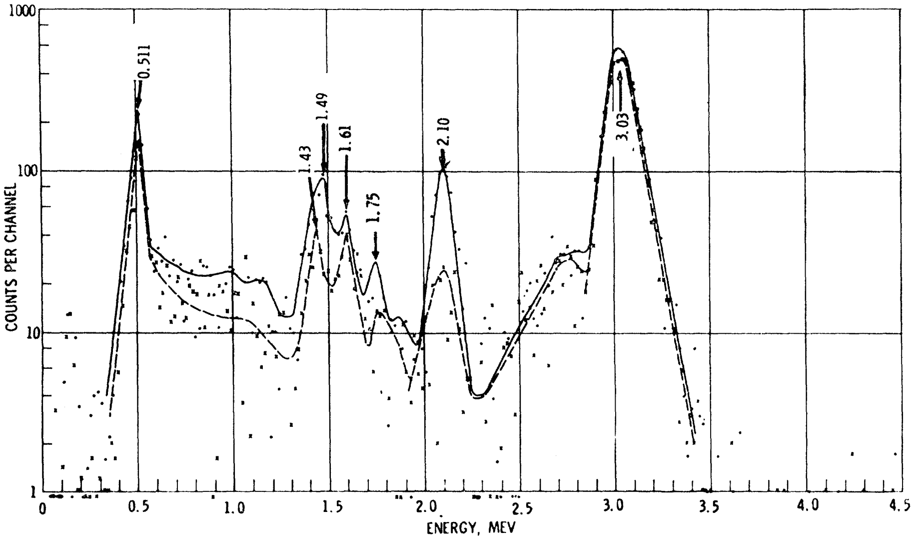


FIG. 6. Coincidence spectra for decay of the 8.28-MeV level of O^{15}. Solid curve: anticoincidence-shielded spectrometer in coincidence with 4.8- to 7.75-MeV radiation incident upon an auxiliary 12.7-cm×12.7-cm NaI(Tl) crystal. Crystals oriented at 45° to the beam direction, left and right. Dashed curve: anticoincidence-shielded spectrometer in coincidence with 5.24-MeV radiation.

---

[40] D. C. Hensley (private communication).
[41] J. B. Marion, C. A. Ludemann, and P. G. Roos, Bull. Am. Phys. Soc. **11**, 332 (1966).

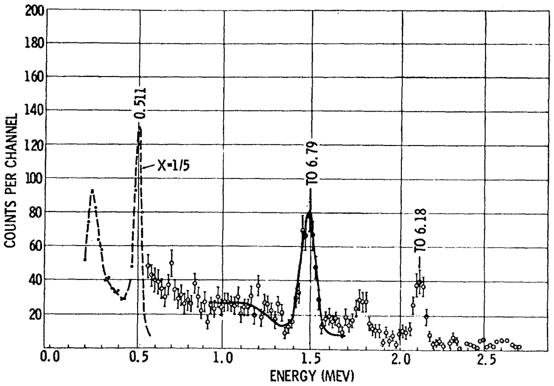


FIG. 7. Spectrum from a 7.62 cm×7.62-cm NaI(Tl) detector of pulses coincident with 5.59–7.55-MeV radiation incident upon a 12.7-cm×12.7-cm detector. Angle of observation was 105°, left and right, for the two detectors. Data were accumulated in 409 min using 5 μA of 1.07-MeV protons incident upon a natural-nitrogen sputtered target. The solid curve was derived from the 1.368-MeV gamma ray of Na^{24}, using a spectrum obtained with the identical crystal-photomultiplier combination and matched to the 1.5-MeV photopeak of this spectrum by a horizontal-scale expansion. There is no evidence for the existence of the 1.12-MeV radiation reported in Ref. 23 for a similar experiment. The peak at 1.78 MeV and the possible peak at 0.70 MeV have not been identified.

B. The 8.915-MeV Level

Spectra were taken of the decay of the 8.915-MeV level at a proton-bombarding energy (1.745 MeV) sufficiently high to excite this level but below the 1.747-MeV resonance in C^{13}. A sputtered, natural-nitrogen target was used.

Since the 5.2-MeV peak was strong and nearly isotropic, it was decided to use the angular distribution of this peak for normalization purposes. Accordingly, the angular distribution of the 5.2-MeV peak was determined in a series of short runs to provide the necessary normalization for the long-exposure spectra. For this peak, the measured angular distribution is

$$W(\theta)=1+(0.024\pm0.036)P_2(\cos\theta)$$
$$+(0.011\pm0.027)P_4(\cos I).$$

This result is consistent with an isotropic distribution for the 5.2-MeV peak in the decay of the 8.92-MeV level in O^{15}. With the assumption of strict isotropy of the 5.2-MeV line, the spectra taken at the three angles, less the below-resonance contributions to the spectra, yield the results given in Table IV.

Spectra were also taken with the 8.92-MeV level resonant, using an isotropic target. Because this target was too thick to permit resolution of the 8.92- and 8.97-MeV levels of O^{15}, the data obtained were inferior to the data from the natural tantalum nitride targets. The spectra so obtained did, however, confirm that the shoulder on the high-energy side of the 1.61-MeV peak does not originate from the $N^{14}(p,\gamma)O^{15}$ reaction. This shoulder is believed to be due to the $O^{16}(p,\gamma)F^{17}$ reaction, discussed further in Sec. IIIE.

C. The 8.972-MeV Level

Using a sputtered target, spectra were taken at 0°, 45°, and 90°, on and off the resonance which occurs at a bombarding energy of 1.800 MeV. The on-resonance spectrum at 90°, less an off-resonance contribution determined by averaging spectra taken at bombarding energies of 1.78 and 1.86 MeV, is shown in Fig. 9. The results are summarized in Table V.

The angular distribution of ground-state radiation was measured by taking five 3000-μC counts at the angles 0°, 45°, and 90°. The anticoincident output of the spectrometer was used, and integration of the spectrum was carried out over the total-absorption and first-escape peaks of the ground-state transition. The measured angular distribution is

$$W(\theta)=1+(0.053\pm0.025)P_2(\cos\theta)$$
$$+(0.034\pm0.025)P_4(\cos\theta).$$

The 8.97-MeV level decay spectrum reveals little more than the ground-state transition and the transition through the 5.19-MeV state. That it is indeed the 5.19-MeV level is shown in the following section. The indicated transitions through the 6.79- and 6.86-MeV levels and through the 6.18-MeV level must be con-

TABLE IV. Decay of the 8.915-MeV level of O^{15}.

Energy (MeV)	Interpretation	Relative yield (%)	Angular distribution	Γ_γ (eV)[b]	Assumed multipolarity	Strength (Weisskopf units)
8.92	8.92 → 0	21±2	$1+(0.31\pm0.08)P_2$	0.056	$E1$	0.0022
3.73	8.92 → 5.19	23±6		0.094	$M1$	0.038
2.74	8.92 → 6.18	30±3		0.094	$E1$	0.009
2.11	8.92 → 6.79–6.86	26±3		0.069	$E1$, $M1$	0.014, 0.14
1.61	6.86 → 5.24	23±1				
5.19	5.19 → 0	55±4	Isotropic			
	5.24 → 0					
6.18	6.18 → 0	23±4	$1-(0.26+0.2)P_2+(0.1\pm0.2)P_4$			
6.79[a]	6.79 → 0	6±4				

[a] Nonresonant.
[b] Based on the absolute total width given in Ref. 5.

TABLE V. Decay of the 8.972-MeV level of O^{15}.

Energy (MeV)	Interpretation	% yield	Angular distribution	Γ_γ (eV)	Assumed multipolarity	Strength (Weisskopf units)
8.97	8.97 → 0	93.4	$1+(0.053\pm0.03)P_2$ $+(0.0034\pm0.03)P_4$	0.74	$M1$	0.025
3.79	8.97 → 5.19	5.9		0.046	$E1$	0.0018
5.19	5.19 → 0	5.9			$E1$	
6.79	6.79 → 0	(0.50)				
6.18	6.18 → 0	(0.25)				
	(8.97 → 6.79)			(0.004)	$E1$	(0.0008)
	(8.97 → 6.18)			(0.002)	$M1$	(0.0022)

sidered uncertain because of the large amount of off-resonant 6.79-MeV radiation which had to be subtracted from this spectrum and because of the unknown amount of 6.13- and 7.12-MeV radiation which could result from the $N^{15}(p,\gamma)O^{16}$ reaction.

The 1.62-MeV line is undoubtedly from the $Na^{23}(p,\alpha\gamma)Ne^{20}$ reaction, since a resonance for the reaction exists at this energy. Using an evaporated NaCl target, it was verified that the proton energy for excitation of the Na^{23} resonance is sufficiently close to that for the 1.80-MeV $N^{14}(p,\gamma)O^{15}$ resonance that the two could not be separated. This line was not found in spectra obtained at the same bombarding energy from isotopic N^{14} targets.

The 2.1-MeV peak in the spectrum is believed to be due to an impurity reaction, possibly $Cl^{37}(p,\alpha)S^{34}$ to the first excited state of S^{34}. There is insufficient 5.2-, 6.18-, or 6.79-MeV gamma radiation in the spectrum to permit the 2.1-MeV line to be entirely due to decay of the 8.97-MeV O^{15} level or capture into the 6.79-MeV level. This peak was, however, found in the isotopic-target spectra.

The peaks at 0.85 and 0.95 MeV (and virtually all radiation of energy less than 0.51 MeV) are due to Coulomb excitation in the platinum backing. This was verified by bombarding a blank platinum disc with 1.82-MeV protons.

The 1.75-MeV peak which exists but is not resonant at this energy is probably due to the $O^{16}(p,\gamma)F^{17}$ reaction. (See Sec. IIIE.) It was not found in spectra from isotopic targets.

D. Precision Comparison of Transition Energies in the Decay of the 8.28- and 8.97-MeV Levels

In order to settle the question as to which of the two levels at 5.2 MeV is involved in the decay of the 8.97- and the 8.28-MeV levels, sets of comparison spectra were taken at 0°, 45°, and 90°, in which a spectrum for bombardment with 0.06 C of 1.81-MeV protons was followed immediately by a spectrum for bombardment with 1.07-MeV protons. In each of these spectra, peak positions of the annihilation radiation, 4.43-MeV radiation, 5.2-MeV transitions, and ground-state radiation were determined by the least-squares computer peak-fitting program mentioned previously. Uncertainty of energy measurements made in this manner was approximately 10 keV. The measured energy of the ground-

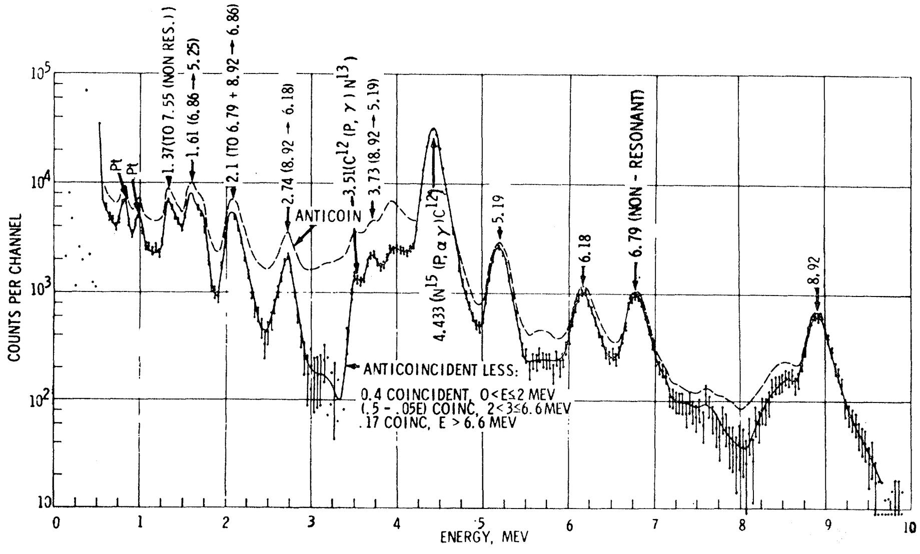


FIG. 8. Spectrum for decay of the 8.92-MeV level. A sputtered target was bombarded with 0.3 C of 1.745-MeV protons. Observation angle was 90°. Time-dependent background has been subtracted.

TABLE VI. Comparison of energies and Doppler shifts of transitions in the decay of the 8.28- and 8.97-MeV levels in O^{15}.

	$\theta=90°$ E(meas) (MeV)	$\theta=45°$ E(meas) (MeV)	δE(meas) (keV)	δE(max) (keV)	$\theta=0°$ E(meas) (MeV)	δE(meas) (keV)	δE(max) (keV)
8.97-MeV level	8.992	9.026	34	32.1	9.034	42	45.5
	5.191	5.203	12	18.6	5.207	16	26.4
8.28-MeV level	8.293	8.316	26	22.6	8.321	28	32.1
	5.242	5.246	4[a]	18.6	5.244	2[a]	26.4
	3.033	3.042	10	14.3	3.045	13	20.3

[a] Doppler shift not observed by other workers (Refs. 41 and 42).

state transition, 8.293±0.008 MeV, is in agreement with the level energy of 8.283±0.003 MeV obtained from the resonance bombarding energy and the reaction Q value obtained from Ref. 17. For the 8.97-MeV level, the measured ground-state decay energy of 8.992±0.010 MeV is in fair agreement with the value 8.972±0.005 MeV obtained for that level from the resonance energy and the Q value.

The measured values shown in Table VI clearly indicate that the 8.97-MeV level decays almost exclusively to the 5.19-MeV state, whereas the transition from the 8.28-MeV level is mainly to the 5.24-MeV state.

Although the energy of the 8.28-MeV level obtained from the resonance energy and the proton separation energy (8.283±0.003 MeV) is in agreement with the measured ground-state transition energy (8.293±0.008 MeV), the value obtained by summing the gamma-ray energies for the cascade transition through the 5.24-MeV level (3.033+5.242=8.275 MeV) is somewhat lower. The difference can be attributed to one or more of the following factors: (a) instrumental nonlinearity, (b) apparent shifting of the peak position due to weak, unresolved impurity peaks, or (c) a steep continuum background under one or more of the measured peaks. Within the limitations imposed by these effects, the values are in satisfactory agreement.

Doppler shifts for the 5.2-MeV and ground-state transitions for the 8.28- and 8.97-MeV levels in O^{15} were calculated assuming lifetimes short in comparison to the slowing-down time of the recoiling target nucleus. In Table VI, these are compared with measured transition energies and energy shifts. These Doppler-shift measurements are compatible with dipole radiation from the 5.19-MeV level and with quadrupole or higher multipolarity radiation from the 5.24-MeV level to the ground state. These conclusions are in agreement with the known spins of these levels and substantiate the (more accurate) measurements of Litherland *et al.*,[42] and of Warburton *et al.*,[43] who found no Doppler broadening of the 5.24-MeV transition.

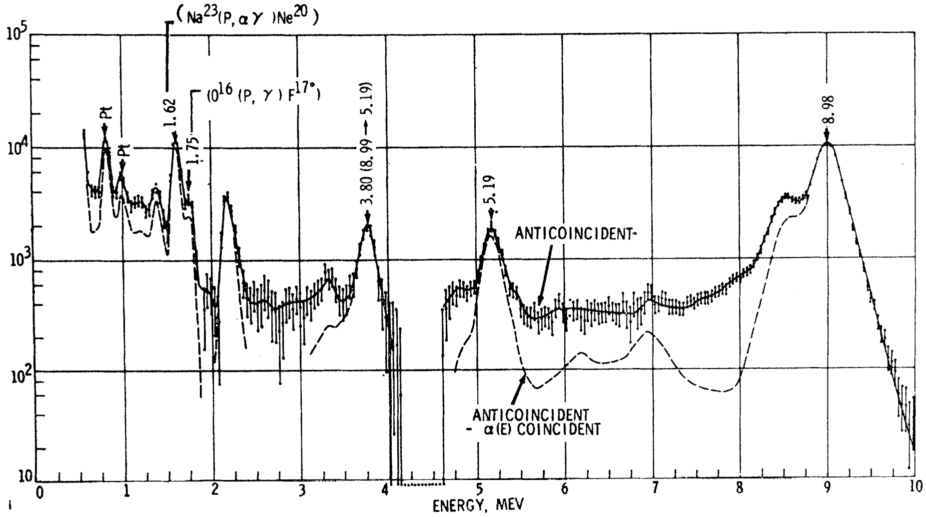
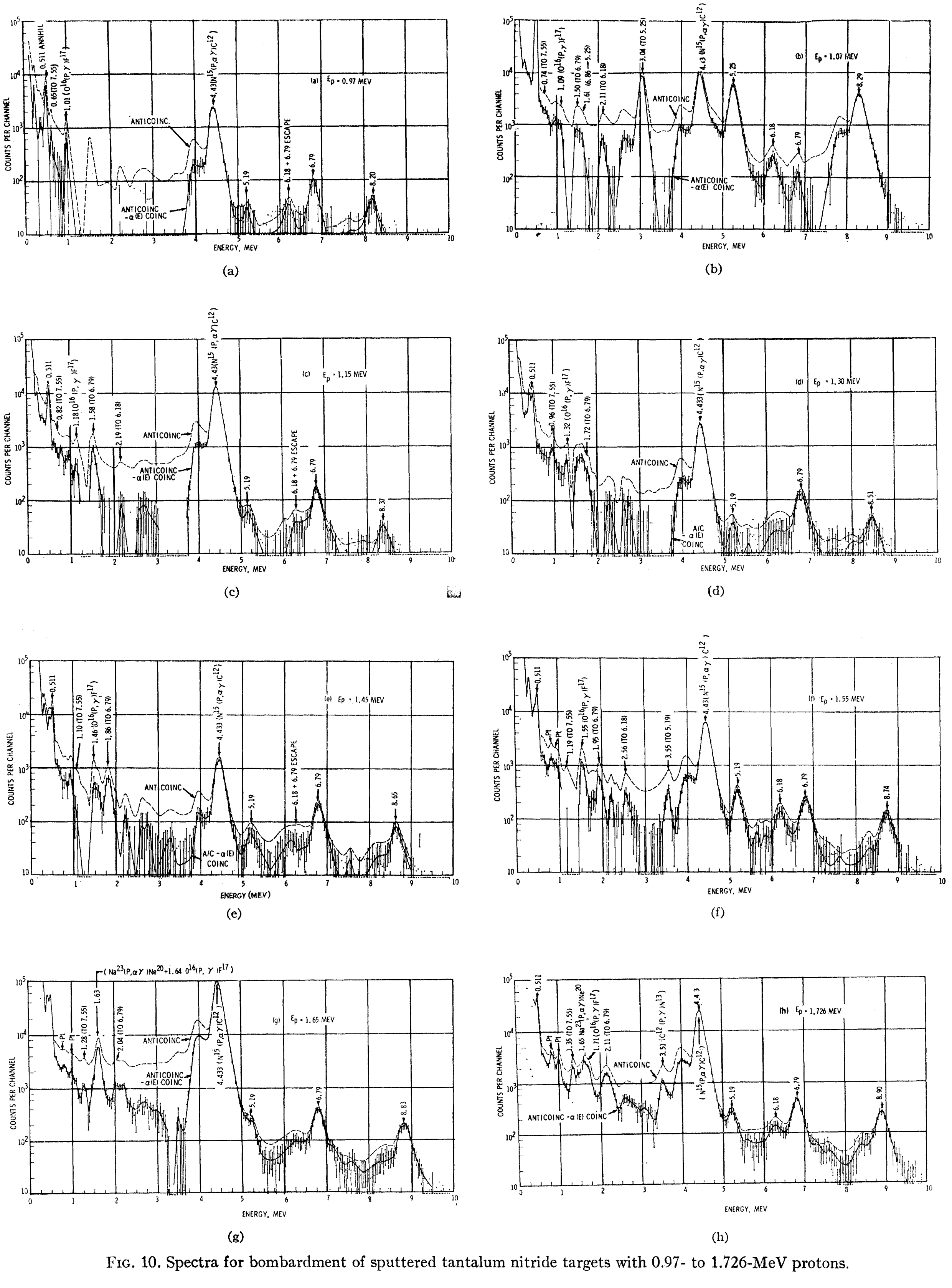


FIG. 9. Spectrum for decay of the 8.97-MeV level. Background and off-resonance spectra have been removed. A sputtered tantalum nitride target was bombarded with 0.68 C of 1.813-MeV protons. The angle of observation was 95°. The peak in the vicinity of 2.2 MeV has not been positively identified.

---

[42] A. E. Litherland, J. K. Alexander, and C. Broude, Bull. Am. Phys. Soc. **10**, 37 (1965).

[43] E. K. Warburton, K. W. Jones, D. E. Alburger, C. Chasman, and R. A. Ristinen, Phys. Rev. Letters **14**, 146 (1965).



(a) (b)

(c) (d)

(e) (f)

(g) (h)

FIG. 10. Spectra for bombardment of sputtered tantalum nitride targets with 0.97- to 1.726-MeV protons.

E. Spectra for the $N^{14}(p,\gamma)O^{15}$ Reaction for Bombarding Energies of from 0.97 to 1.96 MeV: The 8.75-MeV Level and Off-Resonance Radiation

Gamma-ray spectra for the reaction were observed at 45°, for bombardments of approximately 12 h, during each of which approximately 0.2 C of charge was collected at the target. Time-dependent background was subtracted from the spectra and all spectra normalized to 0.2 C of accumulated charge. Spectra were taken for the following 8 proton energies: (a) 0.97 MeV, (b) 1.07 MeV, (c) 1.15 MeV, (d) 1.30 MeV, (e) 1.45 MeV, (f) 1.55 MeV, (g) 1.65 MeV, and (h) 1.726 MeV. These spectra are displayed in Fig. 10.

From the areas of the observed photopeaks and the previously determined relative photopeak efficiency,[33,34] the data plotted in Figs. 11 and 12 were derived. The errors are a combination of counting statistics and uncertainties as to the continuum background under the photopeaks. The yield curves were extended to 1.96 MeV by means of the 1.80-MeV on-resonance spectra and a series of short-duration spectra taken at higher bombarding energies with the collimator and backscatter cell removed from the spectrometer and the target extended to within 2.5 cm of the 12.7×25.4-cm NaI(Tl) crystal. These latter spectra were of poorer quality, but with the increased efficiency afforded, it was possible to make a rapid survey of the yield of known spectral components.

The ability to make any quantitative measurement of transitions of energy less than 4.43 MeV is very dependent upon the strength of the $N^{15}(p,\alpha\gamma)C^{12}$ reaction. This reaction has a 64-keV-wide resonance at a proton energy of 1.65 MeV, a 21-keV-wide resonance at a 1.22 MeV, and a 38-keV-wide resonance at 0.9 MeV.[32]

Comparison of the spectra for bombardment with 1.65-, 1.55-, and 1.45-MeV protons yields the main features of the decay of the 8.75-MeV level: $\frac{2}{3}$ to the 5.19-MeV level and $\frac{1}{3}$ to the 6.18-MeV level. Hebbard and Povh[23] indicated the possibility that the 8.75-MeV level also decays to the ground state. This does not appear to be the case; the rising yield of ground-state gamma rays from the broad 2.38-MeV resonance and a probable nonresonant contribution would have led these authors to an erroneous conclusion.

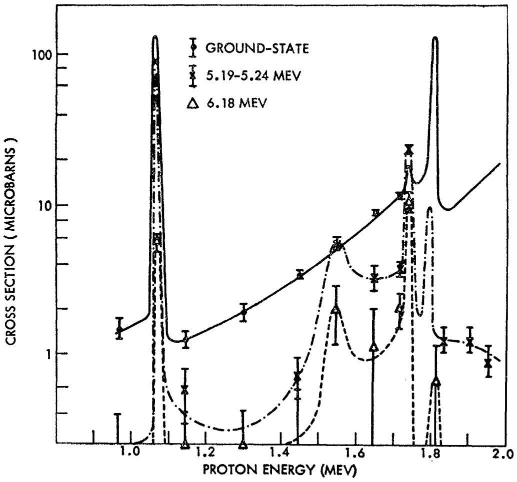


FIG. 11. Yield of ground-state, 5.2- and 6.18-MeV gamma rays as a function of bombarding energy.

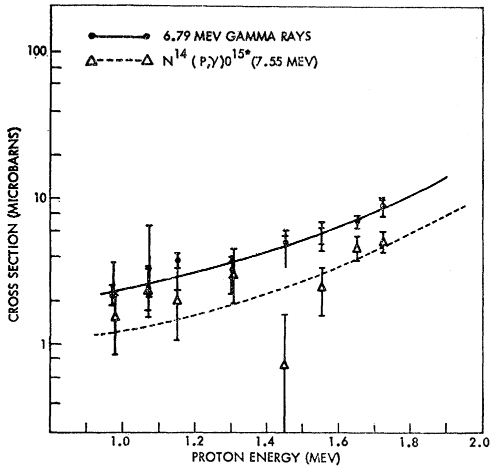


FIG. 12. Yield of 6.79-MeV gamma rays and gamma rays to the 7.55-MeV level of O^{15}.

In each of the spectra of Fig. 10, one peak has been identified as arising from the $O^{16}(p,\gamma)F^{17}$ reaction. This identification is based on angular-distribution measurements at bombarding energies of 1.07 and 1.81 MeV which indicated a vanishing yield in the forward direction, consistent with the known[44] $\sin^2\theta$ distribution for this reaction. Even more conclusive is the fact that these peaks were not found in the radiations from any of the isotopic targets. Moreover, if these peaks were due to the $N^{14}(p,\gamma)O^{15}$ reaction, the final state would be bound and the observed yield is not matched by a sufficient amount of high-energy radiation. Therefore, these gamma rays certainly do not originate in O^{15} and it is most likely that they are due to an oxygen impurity in the sputtered target. Based on the $N^{14}(p,\gamma)O^{15}$ cross-section values of Duncan and Perry[5] and the Q^{16}-$(p,\gamma)F^{17}$ cross-section value of Warren *et al.*,[44] the observed yield would indicate that the oxygen content of the sputtered target was approximately 50% of the nitrogen content. This would seem plausible if one considers that the nitriding of the tantalum in the sputtered targets is probably not complete and the sputtered layer is undoubtedly very porous, making it quite vulnerable to oxidation.

The evidence for capture into the 7.55-MeV level of O^{25} is quite weak because of the large uncertainties in the yield measurements. This level is unbound for

---

[44] J. B. Warren, K. Laurie, D. James, and K. Erdman, Can. J. Phys. 32, 563 (1964).

proton emission and one would therefore not expect an observable amount of radiation from its decay.

IV. DISCUSSION

A. Decay of the 8.283-MeV Level

The measured 8.28-MeV level decay scheme is in essential agreement with that deduced by Hebbard and Povh[23] except for the new branch through the 6.86-MeV level and the nonexistence of a transition to a level at 7.17 MeV. Comparison of the partial width for decay from the 8.28-MeV level to the 6.86-MeV level with the Weisskopf single-particle transition-strength estimate indicates that this transition is almost certainly a dipole transition, since a quadrupole transition would have a strength of approximately 500 Weisskopf units, an unreasonably large value for light nuclei.[45] Since the $\frac{3}{2}^+$ assignment for the 8.28-MeV level seems well established, it is necessary to conclude that the spin of the 6.86-MeV level is $\frac{5}{2}$ or less. Furthermore, the fact that the 6.86-MeV level decays to the $\frac{5}{2}^{(+)}$ level at 5.24 MeV rather than to the ground state or to any other level leads to the conclusion that this level has a spin of $\frac{3}{2}$ or greater. The 6.86-MeV state is almost certainly the analog of the 7.16-MeV level in N^{15} which has $J^\pi=\frac{5}{2}^+$, as has been concluded.[4]

The measured angular distribution of the ground-state transition

$$W(\theta)=1-(0.035\pm0.02)P_2(\cos\theta)$$

falls outside of the experimental limits of the previous measurement of Gallmann *et al.*,[24]

$$W(\theta)=1-(0.05\pm0.01)P_2(\cos\theta)\,.$$

The reproducibility of the present measurements was 3–4%, not large enough to account for the disagreement between the angular-distribution measurement of this work and that of Gallmann. It does not seem possible to resolve the discrepancy at this point.

The reversal of sign of the small coefficient of $P_2(\cos\theta)$ in the angular distribution does not alter the $\frac{3}{2}^+$ assignment for the 8.28-MeV level, since the sign change affects only the sign of the amplitude of the assumed *d*-wave contribution to the formation of the level with respect to the *s*-wave amplitude.

B. The 8.75-MeV Level

The decay of this level has been derived from the spectra described in Sec. IIIE above and shown in Fig. 10(f). The level decays $\frac{2}{3}$ through the 5.19-MeV level and $\frac{1}{3}$ through the 6.18-MeV level. Duncan and Perry[5] found $\omega\Gamma_\gamma=0.16$ eV for this level. The resulting partial radiative widths (assuming $J=\frac{1}{2}$) are 0.32 eV to the 5.19-MeV level and 0.16 eV to the 6.18-MeV level.

Proton-elastic scattering experiments[6–10] have established the spin and parity of the 8.75-MeV level as $\frac{1}{2}^+$. The observed strengths of transitions to the 5.19-MeV ($\frac{1}{2}^+$) and 6.18-MeV ($\frac{3}{2}^-$) levels are compatible with this assignment.

Because of the low total radiative yield of the level compared with the nonresonant processes occurring at this bombarding energy, the possibility of weak transitions to the ground state, 6.79-, 6.86-, and/or 7.55-MeV states cannot be ruled out.

C. The 8.915-MeV Level

Cohen-Ganouna *et al.*,[16] have assigned this level a most probable spin and parity of $\frac{5}{2}^+$ but with $\frac{3}{2}^+$ not ruled out. If the $\frac{5}{2}^+$ assignment is correct, the transition to the ground state is $M2$ in character and has a transition strength of 3.6 Weisskopf units. At the same time, the transition to the $\frac{1}{2}^+$ level at 5.19 MeV is $E2$ and has a strength of 60 Weisskopf units. The latter transition strength is improbably large for light nuclei.

Hagedorn *et al.*[6] indicated that the proton-elastic scattering data for this resonance were most nearly consistent with *d*-wave formation of a $\frac{3}{2}^+$ level through the $s=\frac{1}{2}$ channel, assuming interference with a primarily *s*-wave background.

The measured angular distribution of the ground-state gamma ray is

$$W(\theta)=1+(0.31\pm0.08)P_2(\cos\theta)+(0.01\pm0.10)P_4(\cos\theta)\,.$$

The term in $P_4(\cos\theta)$ is obviously of no significance. This angular distribution is incompatible with a level spin $\frac{5}{2}$, of either parity. The angular distribution is, however, compatible with an assignment of $J=\frac{3}{2}^+$ for the level with formation through channel-spin $\frac{3}{2}$ and a *d*- to *s*-wave intensity ratio of 35%. Admixtures of up to 38% channel-spin $\frac{1}{2}$ are allowed, in which case the required *d*-wave amplitude rises to 62% of the *s*-wave amplitude.

From the strength of the transition to the $\frac{1}{2}^+$ level at 5.19 MeV and from the angular distribution of the gamma ray to the ground state, it is certain that the spin of the 8.915-MeV level is $\frac{3}{2}$. The bulk of prior proton elastic-scattering data indicates probable even parity for this level.

The uncertainties in the measurement of intensities of most transitions of energy less than 4.43 MeV are too great to permit any conclusions to be drawn from the angular distributions derived therefrom.

D. The 8.972-MeV Level

The intensity of the transition from the 8.97-MeV level to the $\frac{1}{2}^+$ level at 5.19 MeV virtually eliminates the possibility that this is an $M2$ transition, as would be the case if the 8.97-MeV level had spin and parity of $\frac{5}{2}^-$, as suggested by Cohen-Ganouna *et al.*[16] Such a transition would have a strength of over 300 Weisskopf units, an unrealistically large value.

---

[45] D. H. Wilkinson, in *Nuclear Spectroscopy*, edited by F. Ajzenberg-Selove (Academic Press Inc., New York, 1960), p. 852.

E. Data from Off-Resonant Energies

1. The Ground-State Transition

The off-resonance yield of ground-state radiation from the $N^{14}(p,\gamma)O^{25}$ reaction (Fig. 11) fits to within experimental limits a Breit-Wigner single-level shape of width 1 MeV centered at $E_p=2.38$ MeV. Proton-scattering analysis has yielded values for the width of this level between 260 and 550 keV. Duncan and Perry[5] found a width of 1.2 MeV from the $N^{14}(p,\gamma)O^{15}$ yield curve. It is presumed that the reason for the difference between the width of the 2.38-MeV resonance as measured by the (p,γ) reaction, and the width as determined by proton elastic scattering is that the (p,γ) reaction yield in this bombarding-energy region is due partly to the 2.38-MeV resonance and partly to direct ground-state capture.[10] The direct-capture component would, of course, not be present in the elastic-scattering data.

There is weak evidence of interference between the 2.38-MeV resonance and the resonances at 1.061 and 1.800 MeV, as can be seen by the shift in level of the off-resonance ground-state gamma-ray yield as one passes from below to above either of these two resonances.

2. 5.19–5.24-MeV and 6.18-MeV Transitions

Measured yields of the 5.19-MeV transition at bombarding energies of 1.45 and 1.65 MeV are an order of magnitude too large to be associated with the 32-keV-wide resonance at 1.55 MeV. Because of the statistical limitations of the data, it cannot be ascertained whether this yield is due to a nonresonant contribution, to distant resonances, or to constructive interference between the 8.75-MeV level and its neighbors.

The decrease of the 5.19-MeV gamma-ray yield at bombarding energies above 1.82 MeV indicates that the 5.19- and 5.24-MeV levels are not involved to any appreciable degree in the decay of the broad 9.53-MeV level in O^{15}. This level must decay almost entirely directly to the ground state or to proton-unstable states.

The off-resonance yield of 6.18-MeV radiation was too low to permit any quantitative judgments thereon, because of overlap of its photopeak with the one-quantum escape peak of the relatively intense 6.79-MeV radiation.

3. Transitions through the 6.79-MeV and 7.55-MeV Levels

There appear to be no (p,γ) resonances in the bombarding range studied involving decay through the 6.79-MeV level in O^{15}. The excitation function for production of 6.79-MeV gamma rays is markedly different in character from the excitation function for ground-state gamma rays. The 6.79-MeV yield curve follows within experimental limits the shape of a barrier-penetration function. The data support the conclusion drawn by Hebbard and Bailey[26] and other workers[23] from data at lower bombarding energies that capture into the 6.79-MeV level is a direct process. Such an effect is expected since this level has a large proton reduced width as evidenced in the (d,n) threshold measurements.[18,46]

At a bombarding energy of 1.045 MeV, the absolute cross section for production of 6.79-MeV gamma rays was given by Hebbard and Povh[23] as approximately 4 μb. Hebbard and Povh also deduced from the work of Duncan and Perry[5] a total $N^{14}(p,\gamma)O^{15}$ cross section of 4 μb at this bombarding energy. The work of Hebbard and Bailey[26] leads to a total cross section of approximately $\frac{1}{3}$ less than that of Duncan and Perry, and indicates that approximately half of the total yield is through the 6.79-MeV level. The present work, at 1.064 MeV, yields a 3 ± 1 μb cross section for capture into this level, by comparing the ratio of 6.78- to 8.28-MeV radiation and using the resonance-cross-section value (0.37 mb) given by Duncan and Perry.

The yield of radiation apparently leading to the 7.55-MeV level is quite low, and follows the trend of the 6.79-MeV radiation. One would expect an appreciable direct capture into the 7.55-MeV level if the reduced proton width of the level were comparable to the Wigner limit. The measured width of this level in O^{15} is 1.5 ± 0.5 keV.[32] From graphs given by Gove,[47] the s-wave reduced width, γ^2, is found to be 1.2 MeV, which is an appreciable fraction of the Wigner limit of 2.7 MeV. One may conclude that it is reasonable to expect s-wave direct capture into the 7.55-MeV level.

V. CONCLUSION

The decay schemes for levels in O^{15} of excitation energies between 8.28 and 8.97 MeV are shown in Fig. 13, together with revised spin assignments.

That the spin of the 6.86-MeV level is $\frac{3}{2}$ or $\frac{5}{2}$ makes it likely that this level is the analog of the 7.16 MeV, $\frac{5}{2}^+$ level in N^{15} (see Fig. 1). The 7.28-MeV level of O^{15}, reported by Warburton *et al.*,[4] and by Hensley[40] is to be paired with the 7.56-MeV level of N^{15}, which is in turn known to have a spin and parity[4] of $\frac{7}{2}^+$. If this is indeed the case, one would expect the dominant decay of the 7.28-MeV level to be via the 5.24-MeV $(\frac{5}{2}^{(+)})$ level, as actually observed.

The 8.75-MeV level of O^{15} is tentatively paired with the 9.06-MeV level of N^{15}, known to have a spin and parity of either $\frac{1}{2}^+$ or $\frac{3}{2}^+$. This level is probably the $\frac{1}{2}^+$ level at 9.7 MeV in the model of Halbert,[2] or at 8.32 MeV in that of Inglis.[1]

The 8.97-MeV level can possibly be paired with the 9.16-MeV level in N^{15}, which is thought to have a spin of $\frac{3}{2}^-$. These odd-parity levels are not treated in either

---

[46] J. B. Marion, Nucl. Phys. **68**, 463 (1965).

[47] H. E. Gove, in *Nuclear Reactions*, edited by P. M. Endt and M. Demeur (North-Holland Publishing Co., Amsterdam, 1959), p. 259.

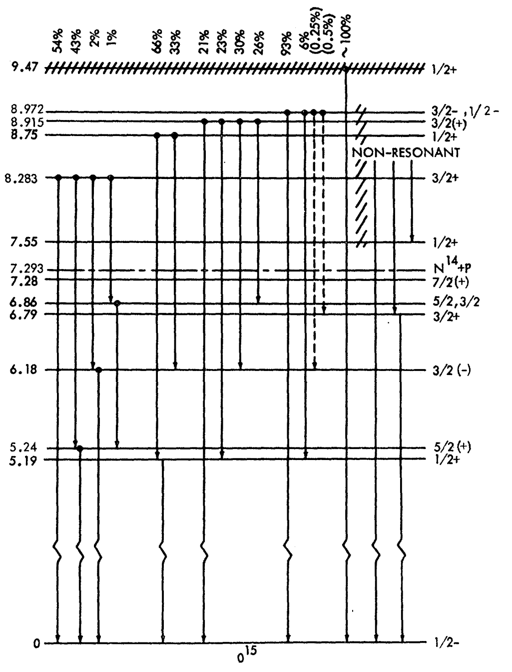


FIG. 13. Decay of excited states of O^{15}.

of the theoretical models. Hagedorn[6] suggested that the level in O^{15} is a four-particle excitation of the type discussed by Christy and Fowler.[48]

The 8.92-MeV, $\frac{3}{2}^+$ level would have to be paired with a 9.2-MeV level known to exist in N^{15}.[4,49] There is no level in either of the theoretical models, however, to account for this pair of levels in N^{15} and O^{15}.

Reconciliation of the level structure of N^{15} and O^{15} with shell-model theory appears to be complete up to an excitation energy of 8.75 MeV in O^{15} and 9.06 in N^{15}. Above these energies it is necessary to consider more complex types of excitation than have previously been taken into account. A readjustment, based upon the latest experimental data for the lower excitations of parameters used in theoretical models, is probably also necessary in order to achieve any degree of success in fitting levels of higher excitation to shell-model theory. A problem still to be resolved is the striking difference in the level shifts between various pairs of N^{15} and O^{15} levels (see Fig. 1).

ACKNOWLEDGMENTS

The authors are grateful for discussion with Dr. D. G. Simons, Dr. R. W. Detenbeck, and Dr. E. K. Warburton. The sputtered tantalum nitride targets were prepared by J. Roeder and L. Rubano. Persons aiding in accelerator operations included W. McDonald, A. Auerback, T. Crilly, K. Caudle, L. E. Nuckles, J. Anderson, and R. E. Wall.

---

[48] R. F. Christy and W. A. Fowler, Phys. Rev. **96**, A851 (1954).

[49] G. W. Phillips, F. Young, and J. B. Marion (private communication).