Nuclear Energy Levels of N^{17}, O^{18}, and O^{20}†

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The reactions $O^{18}(t,\alpha)N^{17}$, $O^{16}(t,p)O^{18}$, and $O^{18}(t,p)O^{20}$ have been studied with a 180°, double-focussing magnetic spectrometer. The measured energy levels of N^{17} up to 4.3 Mev are at 1.374, 1.851, 1.906, 2.536, 3.132, 3.212, 3.652, and 4.010 Mev. The measured energy levels of O^{18} up to 5.2 Mev are at 3.560, 3.639, 3.925, 4.457, and 5.084 Mev. The measured energy levels of O^{20} up to 4.6 Mev are at 1.682, 4.091, and 4.449 Mev. Standard deviations of 15 to 25 kev have been assigned to these excitation energies. The Q value for $O^{18}(t,\alpha)N^{17}$ was determined to be 3.872±0.015 Mev, which leads to a mass for N^{17} of 17.013 856±0.000 017 amu. The Q value for $O^{18}(t,p)O^{20}$ was determined to be 3.086±0.015 Mev, which leads to a mass for O^{20} of 20.010 430±0.000 017 amu. Reaction cross sections at 30° lab angle and 2.6-Mev triton energy are presented for each level.

INTRODUCTION

THE nuclear energy levels of N^{17}, O^{18}, and O^{20} were studied by observing the spectra of protons and alpha particles produced by the reactions $O^{18}(t,\alpha)N^{17}$, $O^{16}(t,p)O^{18}$, and $O^{18}(t,p)O^{20}$. Gas targets of normal oxygen and oxygen enriched in O^{18} were bombarded with 2.6-Mev tritons. Emerging charged particles were observed with a 16-in., 180° double-focussing magnetic spectrometer.

The mass and energy levels of N^{17} below 4.2 Mev have previously been measured by Littlejohn[1] with the reaction $B^{11}(Li^7,p)N^{17}$. There has been considerable theoretical interest in the mass-18 nuclei, shell model calculations having been carried out by several workers.[2,3] The ground state and first two excited states of O^{18} have been studied with various reactions.[4] Between an excitation energy of 3.9 and 6.8 Mev, one of us (N. J.) has previously reported[5] seven energy levels observed with the reaction $F^{19}(t,\alpha)O^{18}$.

The nucleus O^{20} is of interest since it is the lightest isobaric spin $T=2$ nucleus that has been studied and because its mass and energy levels had not been measured before the present experiment. A preliminary report of the ground-state mass and the position of one excited state of O^{20} has been made.[6]

EXPERIMENTAL PROCEDURE

Much of the equipment used in this experiment has been described previously.[7] Tritons, accelerated to a maximum energy of 2.68 Mev with a Van de Graaff accelerator, bombarded a gas target. Charged particles emerging at a laboratory angle of 30° were analyzed by means of a 16-in. radius, 180° double-focussing magnetic spectrometer.

The momentum resolution of the spectrometer, under typical conditions, was calculated to be 350. The observed full width at half maximum of the particle groups varied with particle energy. At 2 Mev, typical energy widths were 30 kev for protons and 50 kev for alphas, while at 6 Mev this figure was 48 kev for both protons and alphas. Observations of level widths were limited by experimental factors. No widths greater than the above limits were observed. The usual solid angle of acceptance of the spectrometer was 0.0024 steradian; the central angle of observation was 30° with an estimated error of $\pm\frac{1}{4}$°.

Particles passing through the spectrometer were detected at the focus with a thin (0.018 cm) CsI crystal, DuMont 6292 photomultiplier tube, conventional electronics, and an 18-channel pulse-height analyzer. The particle groups observed were identified and their energies determined by the combination of momentum analysis in the magnetic spectrometer and analysis of the pulse heights in the CsI crystal. Protons and alpha particles, which were of primary interest, had nearly the same energy at the spectrometer exit for a given spectrometer magnet current. At this same particle energy, the pulse heights in the CsI crystal were about twice as great for protons as for alphas, if both were stopped in the crystal. Therefore, proton and alpha groups were clearly differentiated by the 18-channel analyzer.

An additional test of particle identification was the observation of the decrease in pulse height for a given group when a thin aluminum foil was placed over the face of the CsI crystal. The energy loss in the foil was considerably greater for alpha particles than for protons or deuterons at a given spectrometer current. This procedure was necessary to differentiate deuterons from alphas since these particles differed only slightly in pulse height.

Background pulses in the CsI scintillation detector at the exit of the spectrometer could be traced to two main sources: (1) gamma rays from the accelerator, from various triton-induced reactions, and associated

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] C. S. Littlejohn, Phys. Rev. **114**, 250 (1959).
[2] M. G. Redlich, Phys. Rev. **99**, 1427 (1955); M. G. Redlich, Phys. Rev. **110**, 468 (1958).
[3] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. London **A229**, 536 (1955).
[4] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[5] Nelson Jarmie, Phys. Rev. **104**, 1683 (1956).
[6] Nelson Jarmie and Myron G. Silbert, Phys. Rev. Letters **3**, 50 (1959).
[7] Nelson Jarmie and Robert C. Allen, Phys. Rev. **111**, 1121 (1958).

with the copious neutron flux, and (2) low-energy, multiply scattered tritons which passed through the magnetic spectrometer. Neutrons were produced both by triton reactions in the target and by $T(t,2n)He^4$ reactions which occurred wherever the triton beam had impinged on a metal surface and built up a tritium target. Low-energy tritons were present at all spectrometer current settings. Fortunately, these background voltage pulses were considerably smaller than proton, alpha, or deuteron pulses, except at the low-energy end of the spectrum. At about 52 amp for protons and 78 amp for alphas and deuterons, the pulses of interest became nearly completely resolved from background pulses in the 18-channel analyzer. The situation improved rapidly with increasing energy, so that the background soon became negligible above these points. Considerable improvement in the background at the low-energy end of the spectra was attained by substituting a thinner CsI crystal which reduced the size of the pulses due to gamma rays.

The magnetic field in the spectrometer was measured on a relative basis with a null-type torsion fluxmeter, in which the torque of a spring was balanced by the torque of the field on a current-carrying coil.[8,5] The energy scale of the spectrometer was determined by measurements of the fluxmeter readings at the peak positions of particle groups from reactions of known Q value. Alpha particles from the reactions $C^{12}(t,\alpha)B^{11}$ (ground state) and $O^{16}(t,\alpha)N^{15}$ (g.s., 6.33-, and 7.31-Mev states) and protons from the reactions $O^{16}(t,p)O^{18}$ (g.s., and 1.98) were used in this way to calibrate the fluxmeter. Particle groups corresponding to the ground states of N^{17} and O^{20} were compared to the nearby group from the reaction $C^{12}(t,\alpha)B^{11}$ (g.s.) for which a calculated Q value of 3.857 ± 0.001 Mev was used. The atomic masses used for calculations in this paper are those derived by Everling, König, Mattauch, and Wapstra,[9] based on the O^{16} standard.

Fluxmeter readings corresponding to a given peak were dependent on the temperature of the spectrometer magnet, which increased by some 10°C during a typical run lasting 6 hours. For this reason magnet temperatures were regularly recorded and all fluxmeter readings were corrected for this effect.

The magnet current was regulated to ±4 ma by an appropriate control circuit.

During the experiment, the bombarding particle beam (T^+) was fixed in energy by focussing the diatomic (T_2^+) beam through an electrostatic analyzer and deriving a control signal from the emerging beam. The electrostatic analyzer was calibrated by observing the $Li^7(p,n)$ and $T(p,n)$ thresholds with a "long counter," using proton beams for control and target bombardment, and with appropriate solid LiF and Zr-T targets replacing the gas target. The energy spread of the triton beam incident on the target was less than 3 kev.

Thin pyrex glass windows[10] were used as the entrance and the 30° port foils in the gas target, which was normally filled to a pressure of 40 mm Hg. These glass foils were typically 25 kev thick to 1.02-Mev protons. The triton beam left the target through an aluminum foil and passed into a Faraday cup for current integration. Beam currents of 0.6 μa were commonly used.

The target gases were normal oxygen and oxygen enriched to 25% O^{18} and to 95% O^{18}.[11,12] Gas samples for mass spectrometric analysis were taken at intervals during the course of the experiment. A typical isotopic composition of the oxygen in the target gases was—normal oxygen: O^{16}—99.26%, O^{17}—0.05%, O^{18}—0.68%; oxygen enriched to 95% O^{18}: O^{16}—3.81%, O^{17}—0.89%, O^{18}—95.30%. Small amounts of hydrogen, carbon, nitrogen, and argon were present as contaminants. The percentages of hydrogen, carbon, and nitrogen could be reduced markedly by passing the gas through a liquid nitrogen cooled trap. This procedure was followed to ensure that reactions with these contaminants were not mistaken as oxygen reactions. During energy measurements, however, the presence of carbon was desired in the target gas so that the peak due to $C^{12}(t,\alpha)B^{11}$ (g.s.) could be observed. Therefore the cold trap on the gas line was not employed for these runs. As an additional precaution, background runs were made with nitrogen or methane as target gases to determine the positions of contaminant peaks in the spectra.

RESULTS AND DISCUSSION

General

Typical particle spectra observed during the triton bombardment of oxygen targets are presented in Figs. 1 and 2. Similar bombardments were made at a triton energy of 1.80 Mev; no significant differences were seen in the spectra. The peaks associated with reactions of primary interest in each spectrum are labelled by the excitation energies (in Mev) of the corresponding states of the residual nucleus. Other peaks are labelled more completely.

The beam that was directed to the target by a steering magnet at the exit of the Van de Graaff accelerator was the singly charged mass-3 beam, primarily composed of T^+ ions. Small amounts of hydrogen and deuterium in the ion source gas contributed HD^+ and H_3^+ components to this beam. Consequently, proton and deuteron peaks were observed which corresponded to the elastic scattering of these particles by the target nuclei. These scattering peaks are at 41 and 86 amp,

[8] C. C. Lauritsen and T. Lauritsen, Rev. Sci. Instr. **19**, 916 (1948).

[9] F. Everling, L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nuclear Phys. **15**, 342 (1960).

[10] A. Hemmendinger and A. P. Roensch, Rev. Sci. Instr. **26**, 562 (1955).

[11] The oxygen enriched to 25% O^{18} was kindly furnished by A. O. Nier, University of Minnesota.

[12] The oxygen enriched to 98% O^{18} was purchased from the Weizmann Institute of Science, Rehovoth, Israel.

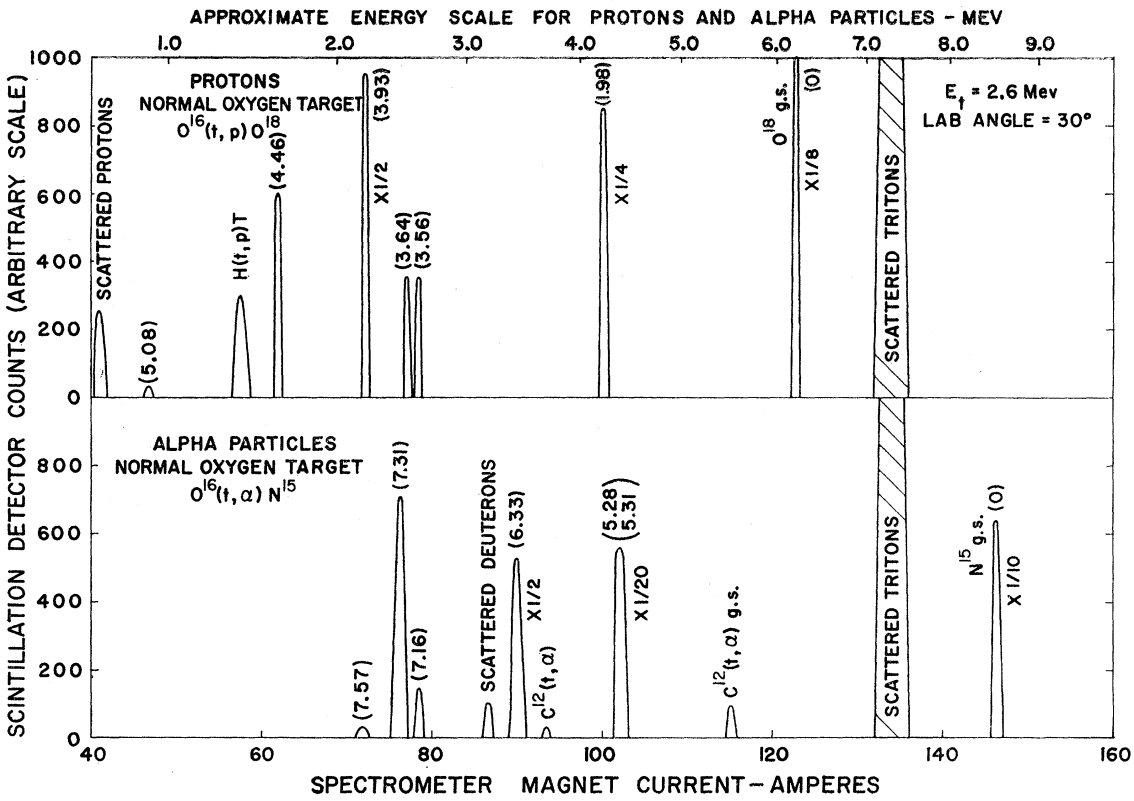

FIG. 1. Spectra of protons and alpha particles observed at 30° (lab) with 2.60-Mev tritons incident on a normal oxygen target. Peaks associated with the reactions $O^{16}(t,p)O^{18}$ and $O^{16}(t,\alpha)N^{15}$ are labelled by the excitation energies (in Mev) of the corresponding states of the residual nuclei. Other peaks are labelled more completely. The scattered proton and deuteron peaks are due to the HD^+ and H_3^+ components of the incident particle beam.

respectively. The magnitude of the scattering cross sections relative to reaction cross sections makes these peaks comparable in size to reaction peaks, although the HD^+ and H_3^+ beam components were small fractions of the total beam. The amounts of these beam contaminants relative to the T^+ component could be varied by changing the rf ion source operating conditions. This was done to ensure that none of the peaks attributed to triton-induced reactions was actually induced by protons or deuterons.

The peak due to scattered tritons is indicated at 134 amp. This peak was so large that it jammed the counting equipment over approximately the energy range indicated. This region was investigated by decreasing the incident triton energy, which changed the position of the scattered triton peak more than that of the reaction peaks. It should be noted that the indicated energy scale applies only to protons and alpha particles.

Another component originally present in the beam was $(He^3)^+$. He^3 was formed by β decay of the tritium ion source gas. This beam contaminant was eliminated by passing the ion source gas through palladium.

The proton peak at 57 amp corresponds to the elastic scattering of tritons by hydrogen present in the target gases, the ejected protons emerging at 30°. This peak, as well as those indicated as $C^{12}(t,\alpha)$ reactions, could be considerably reduced by passing the target gas through a liquid nitrogen-cooled trap.

The spectra were effectively searched for particle groups corresponding to reaction peaks down to 44 amp for protons (0.87 Mev at the center of the target) and 62 amp for alpha particles (2.04 Mev at the center of the target).

N^{17}

A typical alpha-particle spectrum observed with the O^{18}-enriched target is presented in Fig. 2. The energy levels of N^{17} up to an excitation of 4.3 Mev, as determined by the present experiment, are given in Table I together with the results of Littlejohn.[1] Approximate cross sections for the various groups are included. Indicated errors in the present work are standard deviations.

The Q value for the reaction $O^{18}(t,\alpha)N^{17}$ (g.s.) is 3.872 ± 0.015 Mev, by comparison to the nearby peak due to $C^{12}(t,\alpha)B^{11}$ (g.s.). It was necessary to use a triton energy of 2.0 Mev rather than 2.6 Mev in order to distinguish the alphas due to $C^{12}(t,\alpha)B^{11}$ (g.s.) from the protons due to $O^{18}(t,p)O^{20}$ (g.s.). The pulse heights in the CsI detector were the same at the reaction energies

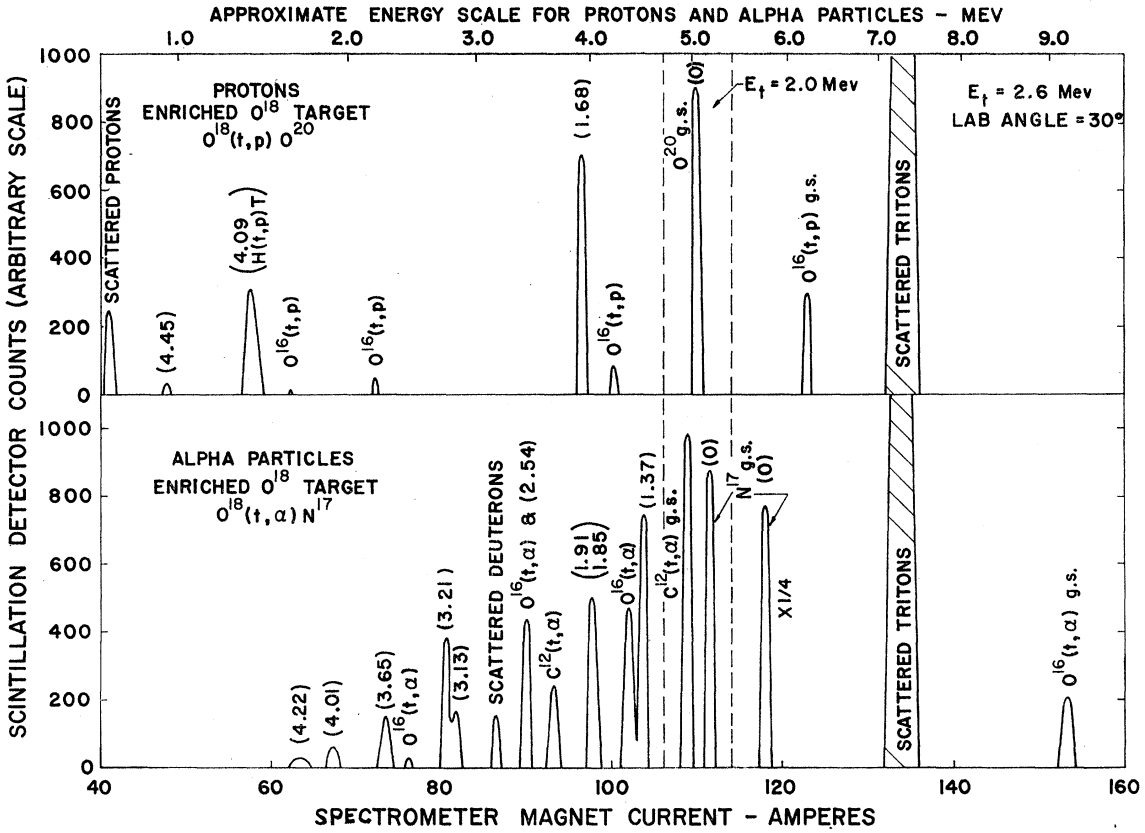

FIG. 2. Spectra of protons and alpha particles observed at 30° (lab) with 2.60-Mev tritons incident on an O^{18} (95% enriched) target. Peaks associated with the reactions $O^{18}(t,p)O^{20}$ and $O^{18}(t,\alpha)N^{17}$ are labelled by the excitation energies (in Mev) of the corresponding states of the residual nuclei. Other peaks are labelled more completely.

produced by 2.6-Mev tritons since protons of this energy passed completely through the CsI, with a subsequent decrease in pulse height. This ambiguity existed only in a narrow region around 116 amp. The measured Q value leads to a mass for N^{17} of 17.013 856±0.000 017 amu and a mass excess (M-A) of 12.902±0.016 Mev.

The values determined by Littlejohn were 17.013 88± 0.000 06 amu and 12.92±0.06 Mev, respectively. The report by Littlejohn includes a discussion of previous determinations of the mass of N^{17} and shell model predictions of N^{17} levels.

The levels observed by Littlejohn at 1.89±0.08 and 3.27±0.09 Mev excitation were each shown by the present experiment to be a doublet, of 55- and 80-kev separation, respectively. These peaks, marked 1.85 and 1.91, and 3.13 and 3.21 in Fig. 2, were not completely resolved. The alpha groups are shown on an expanded scale in Fig. 3. The 1.89-Mev level was expected to be a doublet of about 230-kev separation on the basis of shell-model predictions[1] and Littlejohn could not rule out the possibility of it being a somewhat closer doublet.

The peak at 90 amp consists of two groups of alpha particles, from $O^{18}(t,\alpha)N^{17}$ (2.54 Mev) and from $O^{16}(t,\alpha)N^{15}$ (6.33 Mev). The energies of the two groups were so close that no deviation from normal peak shape could be noticed. Based on the relative size of alpha peaks with the normal oxygen target and on the size of other alpha groups from $O^{16}(t,\alpha)$ with this target, a peak 60 counts high would be expected for $O^{16}(t,\alpha)N^{15}$ (6.33 Mev). The observed peak, including both groups, was 430 counts high, so that little error in energy deter-

TABLE I. Energy levels of N^{17} and cross sections for $O^{18}(t,\alpha)N^{17}$ at 30° (lab) and 2.6-Mev triton energy. Absolute standard deviations in the cross sections are ±30%.

Present experiment		Littlejohn[a]
Excitation energy (Mev)	Cross section (mb/sr)	Excitation energy (Mev)
0	3.6	0
1.374±0.018	1.0	1.32±0.08
1.851±0.018	0.32	1.89±0.08
1.906±0.018	0.66	
2.536±0.018	0.61	2.50±0.08
b	<0.012	2.82±0.08
3.132±0.018	0.33	3.27±0.09
3.212±0.018	0.83	
3.652±0.025	0.24	3.57±0.09
4.010±0.025	0.17	3.86±0.09
(4.215±0.025)	(~0.06)	4.18±0.09

[a] C. S. Littlejohn, Phys. Rev. 114, 250 (1959).
[b] Not observed.

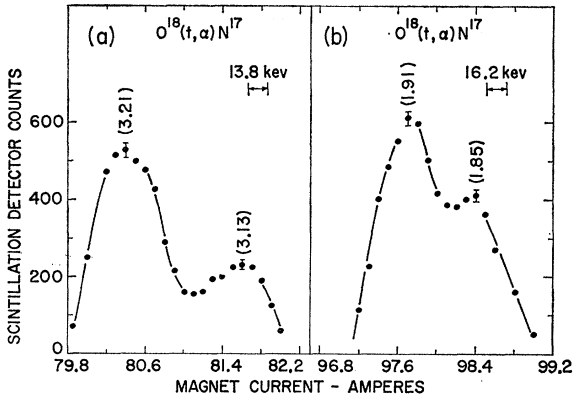

FIG. 3. Unresolved levels in N^{17}—expanded scale. Error bars indicate statistical counting errors. (a) 3.13- and 3.21-Mev levels. (b) 1.85- and 1.91-Mev levels.

mination of $O^{18}(t,\alpha)N^{17}$ (2.54 Mev) would be expected from the presence of the smaller group from $O^{16}(t,\alpha)N^{15}$ (6.33 Mev).

The level reported by Littlejohn at (2.82±0.08)-Mev excitation corresponds to the position in which we observed the peak due to scattered deuterons. This group was definitely identified as deuterons in our case, by measuring the decrease in pulse height when a thin aluminum foil was placed over the CsI detector. This was confirmed by virtually eliminating the HD^+ beam component by using appropriate rf ion source operating conditions, and noting the disappearance of the peak. The yield of alpha particles (at 30° lab angle and 2.6-Mev triton energy) from an $O^{18}(t,\alpha)N^{17}$ reaction corresponding to a level at 2.82 Mev is less than 2% of the yield corresponding to the 2.536-Mev level.

The peak at 63 amp (4.215-Mev excitation) was small, not well defined, and rather broad. It may represent a doublet of about 35-kev separation.

O^{18}

A typical proton spectrum observed with a normal oxygen target is shown in Fig. 1. The energy levels of O^{18} up to an excitation of 5.2 Mev, as determined by the present experiment, are given in Table II together with the results of Jarmie, obtained with the reaction $F^{19}(t,\alpha)O^{18}$.[5] Approximate cross sections for the various groups are included. The energies of the levels were compared to that of the first excited state, for which an excitation energy of 1.982±0.004 Mev[4] was used.

The first excited state at 1.98 Mev has been observed by several investigators.[4] That at 3.55 Mev was reported by Bach and Hough[13] and by Jarmie.[5] The former did not search above 3.55-Mev excitation; the latter reported levels up to 6.8 Mev. Ahnlund[14] searched to an excitation of 4.8 Mev, but observed only the ground-state and 1.98-Mev peaks. Ribe[15] reported groups corresponding to the ground and 1.98-Mev states, and also a broad, unresolved group between 3- and 4-Mev excitation.

The peaks marked 3.64 and 4.46 in Fig. 1 correspond to previously unreported levels in O^{18}. The level at 3.639 Mev was not observed by Jarmie with the reaction $F^{19}(t,\alpha)O^{18}$. Possibly a minimum in the differential cross section as a function of angle for this level coincided with the angle of observation (90°) in that experiment. The level at 4.457 Mev is in the energy interval which was obscured by the $O^{16}(t,\alpha)N^{15}$ (g.s.) peak in the F^{19} experiment. In the range of excitation energy 2 to 3.5 Mev, no proton group was observed in the present experiment with an intensity greater than 3% of the groups corresponding to the 3.560- and 3.639-Mev levels.

The nucleus O^{18} is of considerable theoretical interest. Shell model calculations of the energy levels of mass-18 nuclei have been carried out by Redlich[2] and by Elliott and Flowers.[3] A review of the theoretical situation for O^{18} can be found in the study of this nucleus by Gove and Litherland.[16]

The possibility of a state at 4.4 Mev was noted by Gove and Litherland[16] in their discussion of gamma rays observed with $C^{14}(\alpha,\gamma)O^{18}$. They also reported a prediction of Elliott, in a private communication, of a level at 4.3 Mev.

O^{20}

A typical proton spectrum obtained with an enriched O^{18} target is presented in Fig. 2. Four groups have been attributed to the reaction $O^{18}(t,p)O^{20}$, corresponding to the ground state and three excited states of O^{20}. No other O^{20} levels were seen up to an excitation energy of 4.6 Mev. The Q value for $O^{18}(t,p)O^{20}$ (g.s.), by comparison to the $C^{12}(t,\alpha)B^{11}$ (g.s.) peak, is 3.086±0.015 Mev. This leads to a ground-state mass for O^{20} of 20.010 430± 0.000 017 amu and an $(M\text{-}A)$ value of 9.712±0.016 Mev. The levels observed in O^{20} are presented in Table III, together with approximate cross sections.

TABLE II. Energy levels of O^{18} and cross sections for $O^{16}(t,p)O^{18}$ at 30° (lab) and 2.6-Mev triton energy. Absolute standard deviations in the cross sections are ±30%.

Present experiment		Jarmie (1956)[a]
Excitation energy (Mev)	Cross section (mb/sr)	Excitation energy (Mev)
0	5.1	0
b	1.7	1.989±0.024
3.560±0.015	0.27	3.504±0.034
3.639±0.015	0.29	c
3.925±0.015	1.8	3.929±0.040
4.457±0.015	0.76	c
5.084±0.018	0.057	5.007±0.040

[a] N. Jarmie, Phys. Rev. **104**, 1683 (1956).
[b] Observed, but not measured.
[c] Not observed.

[13] D. R. Bach and P. V. C. Hough, Phys. Rev. **102**, 1341 (1956).
[14] K. Ahnlund, Phys. Rev. **96**, 999 (1954).
[15] F. L. Ribe, Phys. Rev. **106**, 767 (1957).
[16] H. E. Gove and A. E. Litherland, Phys. Rev. **113**, 1078 (1959).

At $E_t=2.60$ Mev the proton peak corresponding to the level at 4.091-Mev excitation was obscured by the proton peak due to $H(t,p)T$. This region of excitation was searched by decreasing the triton bombarding energy by 200 kev, which decreased the $H(t,p)$ proton energy by about 110 kev and decreased the $O^{18}(t,p)O^{20}$ (4.091 Mev) proton energy by about 190 kev, thus clearly separating the two peaks. The enriched target gas contained nearly 4% of O^{16}; four proton groups were identified as being due to $O^{16}(t,p)O^{18}$ by comparing them with the spectrum obtained with the normal oxygen target.

O^{20}, with 8 protons and 12 neutrons, is the lightest $T=2$ nucleus which has been studied. Previous attempts[17] to identify O^{20}, by observing its decay, were unsuccessful. After the present experiment had indicated that the reaction $O^{18}(t,p)O^{20}$ had an appreciable cross section at $E_t=2.6$ Mev, the decay of O^{20} was studied at this laboratory with a scintillation spectrometer.[18]

Talmi and Thieberger[19] calculated a binding energy for O^{20} which corresponds to an $(M\text{-}A)$ value of 11.37 Mev, by assuming shell model wave functions with jj coupling and charge-independent two-body interactions. More recently,[20] they have carried out calculations for the $d_{5/2}$ shell in a more refined way and obtain $(M\text{-}A)$ values of 9.67 ± 0.42 or 9.80 ± 0.55 for O^{20}. Kerman and Brink[21] have considered deformed-well wave functions and two-body forces to obtain a binding energy for O^{20} corresponding to $(M\text{-}A)$ of 9.74 Mev. These recent theoretical predictions are in excellent agreement with the experimental value of 9.71 Mev.

TABLE III. Energy levels of O^{20} and cross sections for $O^{18}(t,p)O^{20}$ at 30° (lab) and the indicated triton energy. Absolute standard deviations in the cross sections are ±30%.

Excitation energy (Mev)	Cross section (mb/sr)	E_t (Mev)
0	0.85	2.0
1.682±0.020	0.39	2.0
4.091±0.025	0.061	2.4
4.449±0.025	0.070	2.6

Inspection of the positions of the first two excited states in neighboring even-even nuclei such as O^{18}, Ne^{20}, and Ne^{22} leads to the expectation that the first excited state in O^{20} should lie about 1.6 Mev above the ground state and the second excited state a comparable distance above the first. The observed level at 1.68 Mev is in good agreement with this expectation. The second level is observed at 4.09 Mev.

ACKNOWLEDGMENTS

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[17] S. Katcoff and J. Hudis, J. Inorg. & Nuclear Chem. **3**, 253 (1956); S. Amiel and R. E. Segel, J. Inorg. & Nuclear Chem. **10**, 4 (1959).
[18] G. Scharff-Goldhaber, A. Goodman, and M. G. Silbert, Phys. Rev. Letters **4**, 25 (1960).
[19] I. Talmi and R. Thieberger, Phys .Rev. **103**, 718 (1956).
[20] R. Thieberger (private communication, 1959).
[21] A. K. Kerman, in *Nuclear Reactions*, edited by P. M. Endt and M. Demeur (North-Holland Publishing Company, Amsterdam, 1959), Vol. I; D. M. Brink and A. K. Kerman, Nuclear Phys. **12**, 314 (1959).