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Positions and Widths of O^{16} Levels up to 15-MeV Excitation*

C. P. BROWNE AND I. MICHAEL†
University of Notre Dame, Notre Dame, Indiana

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Protons from the $N^{14}(He^3,p)O^{16}$ reaction were analyzed with a broad-range spectrograph. Results from 10 runs were averaged to give positions of 23 levels and the widths of 11 of these which are more than 12 keV wide. Two levels were found near 11 MeV with a spacing of 16.0±0.5 keV. Excitation energies (in MeV) follow with measured widths (in keV) in parentheses. 6.052±0.005, 6.131±0.004, 6.916±0.003, 7.115±0.003, 8.870±0.003, 9.614±0.030(510±60), 9.847±0.003, 10.353±0.004(27±8), 10.952±0.003, 11.080±0.003, 11.096±0.003, 11.521±0.004(78±8), 12.053±0.003, 12.437±0.007(94±15), 12.528±0.003, 12.798±0.006(41±10), 12.964±0.003, 13.105±0.015(160±30), 13.253±0.005(25±8), 13.665±0.006 (65±8), 13.869±0.010(85±20), 13.975±0.004(27±8), 14.922±0.006(60±10). A new level in O^{16} is thus found, precise excitation energies are given, and width measurements are confirmed for levels broader than 10 keV.

INTRODUCTION

THE nuclear energy levels of O^{16} are especially interesting because one may attempt to describe the structure with an alpha-particle model or with a shell model in which there are double closed shells. Much theoretical and experimental work has been done on this nucleus, and a glance at a compilation of nuclear data suggests that the level structure is well known. Closer examination, however, raises some questions. Table I illustrates the situation. Here, excitation energies of O^{16} up to 15 MeV, are listed in the second column, and reactions through which levels have been seen are shown by letters in the remaining columns. Reactions represented by the letters are shown in the table footnotes. An asterisk on a letter indicates that the level position was measured to within ±20 keV or better. Brackets between two excitation energies indicate that the levels were not resolved. The table shows that most reactions were used to cover only limited regions of excitation, and in most cases some of the levels in the explored region were missed. Certain levels cannot be seen with some reactions; for example, alpha particles scattered from C^{12} should not excite "unnatural parity" states or $T=1$ states. In the one experiment[1] covering a wide range of excitation, i.e., $O^{16}(p,p')O^{16*}$, low resolution and low precision were available.

Work done on other reactions will be discussed in the order in which the reactions appear in Table I. Two groups[2,3] used magnetic analysis of the alpha particles from the $F^{19}(p,\alpha)O^{16*}$ reaction to measure excitation energies with precisions between 10 and 17 keV. In the first work[2] the five lowest levels and the seventh, eighth, and tenth levels were measured. The broad sixth excited state may have contributed alpha particles which could not be distinguished from background. Two unknown groups were reported, one of which appears to correspond with the now known ninth level. The second experiment[3] gave precise excitation energies for the first five states only.

Resonances in the elastic scattering of alpha particles from C^{12} were used in three measurements[4–6] giving excitation energies of the levels marked in column 5 of Table I. The evidence[5] for a weakly excited level near 11.1 MeV was somewhat doubtful. The level at 10.95 MeV was not seen, nor was a level at 12.05 MeV. These results[5] are still the only evidence for broad levels at 11.26 and 11.63 MeV.

The existence of two states near 11 MeV was suggested by measurements of γ-ray transitions between O^{16} levels excited with the $F^{19}(p,\alpha)O^{16*}$ and $N^{15}(d,n)O^{16*}$ reactions.[7] Excitation energies of 10.935 and 11.061 MeV were precisely measured by observing[8] thresholds in the $N^{15}(d,n)O^{16}$ reaction. A suggestion that there might be a "doublet" near 11 MeV was made earlier[9] on the basis of γ-ray transitions induced by $N^{14}(He^3,p)O^{16*}$. A very extensive study of these γ rays and the coincident protons was made[10] with the object of assigning spins and parities to the levels. Levels seen by these authors are indicated in column 8 of Table I. Many other observations of γ-ray transitions between O^{16}

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† Present address: Northrop Space Laboratories, Hawthorne, California.

[1] W. F. Hornyak and R. Sherr, Phys. Rev. **100**, 1409 (1955).

[2] G. L. Squires, C. K. Bockelman, and W. W. Buechner, Phys. Rev. **104**, 413 (1956).

[3] T. E. Young, G. C. Phillips, and R. R. Spencer, Phys. Rev. **108**, 72 (1957).

[4] R. W. Hill, Phys. Rev. **90**, 845 (1953).

[5] J. W. Bittner and R. D. Moffat, Phys. Rev. **96**, 374 (1954).

[6] C. Miller Jones, G. C. Phillips, R. W. Harris, and E. H. Beckner, Nucl. Phys. **37**, 1 (1962).

[7] R. D. Bent and T. H. Kruse, Phys. Rev. **108**, 802 (1957).

[8] J. L. Weil, K. W. Jones, and L. J. Lidofsky, Phys. Rev. **108**, 800 (1957).

[9] D. A. Bromley, A. J. Ferguson, H. E. Gove, A. E. Litherland, and E. Almqvist, Bull. Am. Phys. Soc. **2**, 51 (1957); A. E. Litherland, E. Almqvist, D. A. Bromley, H. E. Gove, and A. J. Ferguson, *ibid.* **2**, 51 (1957).

[10] D. A. Bromley, H. E. Gove, J. A. Kuehner, A. E. Litherland and E. Almqvist, Phys. Rev. **114**, 759 (1959); J. A. Kuehner, A. E. Litherland, E. Almqvist, D. A. Bromley, and H. E. Gove, *ibid.* **114**, 775 (1959).

Table I. Reactions used to excite O^{16} levels. Each letter in the body of the table designates the reaction shown in the footnotes. An asterisk shows that the excitation energy was measured to ±20 keV or better. Brackets show unresolved levels. See text for references.

Group no. this work	Excitation energy (MeV)	Reactions used to observe												
1	6.052	{A*	B*				F		{H		{J			
2	6.131		B*		D		F	G						
3	6.917	{A	B*		{D		F		{H		{J			
4	7.116		B*				F	G						
5	8.870	A	B*		D		F	G*			J			
6	9.62			C*						I				
7	9.848	A	B*	C*						I				
8	10.353	A	B*	C*			F							
9	10.953				D	E*	F							
10	11.080	{A	{B*	{C*		{E*	{F							
11	11.095													
	11.26			C*										
12	11.521	A		C*						I				
	11.63	[illegible]		C*										
13	12.052	A												
14	12.437			C*								K*		M*
15	12.528	A										K*		M*
16	12.798											K*	L*	
17	12.964												L*	M*
18	13.101	A										K*	L*	M*
19	13.252												L*	M*
20	13.666												L*	M*
21	13.870													M*
22	13.975												L*	M*
23	14.921												L*	M*

A. $O^{16}(p,p')O^{16}$
B. $F^{19}(p,\alpha)O^{16}$
C. $C^{12}(\alpha,\alpha)C^{12}$
D. $N^{15}(d,n\gamma)O^{16}$, $F^{19}(p,\alpha\gamma)O^{16}$
E. $N^{15}(d,n)O^{16}$
F. $N^{14}(He^3,p)O^{16}$, $N^{14}(He^3,p\gamma)O^{16}$
G. $N^{16}(\beta^-)O^{16}$
H. $O^{16}(n,n'\gamma)O^{16}$
I. $C^{12}(\alpha,\gamma)O^{16}$
J. $O^{16}(\alpha,\alpha')O^{16}$
K. $N^{15}(p,\gamma)O^{16}$
L. $N^{15}(p,p)N^{15}$
M. $N^{15}(p,\alpha)C^{12}$

levels at less than 12-MeV excitation are recorded in the literature.[11]

Column 11 in the table marks the levels seen thorugh inelastic alpha scattering.[12]

For the region of excitation above 12 MeV, information on O^{16} levels comes almost entirely from resonances in various reactions of protons with N^{15}. Capture γ rays disclose[13–15] the levels marked in column 13; resonance scattering of protons from N^{15} shows [14,16] levels marked in column 14; and resonances in the $N^{15}(p,\alpha)C^{12}$ reaction show[15–20] levels marked in column 15.

This summary of experimental data covers most of the earlier work on O^{16} levels up to 15-MeV excitation that is relevant to the present measurement of positions and widths. Much theoretical work has been done on this nucleus. Summaries of the comparison with experimental work appear in some of the references given.[6,10]

It is to be noted that the results summarized in Table I indicate a level at 10.95 MeV and a second nearby level at about 11.1 MeV. A suggestion that the α-emitting state seen[5] with $C^{12}(\alpha,\alpha)C^{12}$, and the γ-emitting state seen[1,10] with $O^{16}(p,p'\gamma)O^{16}$ and $N^{14}(He^3,p\gamma)O^{16}$ were not the same, and thus that there might actually be three levels near 11 MeV was made by Weil *et al.*[8] and by Bromley *et al.*[10]

There appeared to be enough uncertainties in the O^{16}-level structure to warrant a measurement with the high resolution and precision of the broadrange spectrograph, using the $N^{14}(He^3,p)O^{16}$ reaction. This reaction allows a large range of excitation to be covered with the modest bombarding energy of 4 MeV and there should be no restrictions on exciting any levels in the region covered. It will be shown that the work was useful in finding a new level in O^{16}, giving considerably more precise excitation energies than heretofore, and confirming width measurements of levels broader than 10 keV.

MEASUREMENTS

The major problem in this work was posed by the targets. High resolution demanded a thin uniform

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[11] See for example: R. B. Day, Phys. Rev. **102**, 767 (1956); L. C. Thompson and J. R. Risser, *ibid.* **94**, 941 (1954); L. E. Beghian, D. Hicks, and B. Milman, Phil. Mag. **46**, 924 (1955); D. H. Wilkinson, B. J. Toppel, and D. E. Alburger, Phys. Rev. **101**, 673 (1956); D. E. Alburger, *ibid.* **111**, 1586 (1958); Von. B Duelli and L. Hoffman, Z. Naturforsch. **13a**, 204 (1958); R. E. Meads and J. E. G. McIldowie, Proc. Phys. Soc. (London) **75**, 257 (1960); S. D. Bloom, B. J. Toppel, and D. H. Wilkinson, Phil. Mag. **2**, 57 (1957); T. Wakatsuki, Y. Hirao, E. Odaka, and I. Miura, J. Phys. Soc. Japan **12**, 1178 (1957).

[12] J. C. Correlli, E. Bleuler, and D. J. Tendam, Bull. Am. Phys. Soc. **2**, 34 (1957); J. C. Correlli, E. Bleuler, and D. J. Tendam, *ibid.* **3**, 200 (1958).

[13] A. Schardt, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **86**, 527 (1952).

[14] F. B. Hagedorn, Phys. Rev. **108**, 735 (1957).

[15] D. F. Hebbard, Nucl. Phys. **15**, 289 (1960).

[16] S. Bashkin, R. R. Carlson, and R. A. Douglas, Phys. Rev. **114**, 1543 (1959).

[17] F. B. Hagedorn and J. B. Marion, Phys. Rev. **108**, 1015 (1957).

[18] S. Bashkin and R. R. Carlson, Phys. Rev. **106**, 261 (1957).

[19] A. Schardt, Phys. Rev. **80**, 136A (1950).

[20] L. Lidofsky, K. Jones, R. Bent, J. Weil, T. Kruse, M. Bardon, and W. W. Havens, Bull. Am. Phys. Soc. **1**, 212 (1956).

target, and the relatively low yields required a high nitrogen content. Attempts to use a gas target failed because the foils required to contain the necessary nitrogen pressure introduced too much straggle in the input-beam energy. Nitrogen compounds in which the nitrogen gives a reasonable amount of the total stopping are generally rather unstable and so decompose under bombardment. Targets were made by nitriding thick titanium or tantalum backings, but there was sufficient oxygen distributed through the backing to give a large background from the $O^{16}(He^3,p)F^{18}$ reaction. These targets were useless for observing proton groups of energies less than that from the oxygen reaction. Thin layers of titanium were evaporated onto Formvar backings and exposed to nitrogen. The amount of nitrogen for a usable total target stopping was too low. Adenine ($C_5N_5H_5$) proved to be the best target material. When this was evaporated onto the standard Formvar backings or onto thick tantalum backings it was found that He^3 beams of more than a few hundreths of a microampere quickly decomposed the adenine. The best results were obtained with a rotating target consisting of adenine evaporated onto a circular Formvar backing one inch in diameter. A thin layer of gold was evaporated onto the back of the Formvar. This layer was thick enough to appear bluish-green by transmitted light but not so thick as to show gold color with reflected light. The beam, which was 0.5×3 mm in size, struck this target near the periphery and the target rotated about twice a second. Beam currents up to 0.15 μA were run for several hours without serious target decomposition under these conditions.

A technique for producing adenine targets of desired thickness was developed. A pellet was made from the powdered adenine and placed in a tantalum boat in the evaporator. These pellets did not tend to jump out of the boat when gently heated the way the powder did. By completely evaporating a pellet of a given size onto backings placed a fixed distance (20 cm) away, target thicknesses could be predicted and reproduced. The pellets were made in a pill press consisting of a $\frac{1}{4}$-in. steel rod moving in a steel plate. A removable plug closed the bottom of the hole. Pressure was applied with a drill press. A drop of alcohol helped to compact the powder.

In the later stages of the measurements the target was monitored by a solid-state detector mounted in the target chamber. He^3 groups elastically scattered from gold, nitrogen, and carbon were recorded by a pulse-height analyzer. The relative heights of the groups from nitrogen gave a measure of target condition. When noticeable deterioration occurred a fresh target spot was used or the exposure discontinued. This monitor was very useful in detecting tears or cracks that often formed in the rotating targets under long bombardment.

Other experimental details were the same as reported before.[21,22] Most runs were made at a He^3-bombarding energy of 3.74 MeV with a beam analyzer resolving power of 1200. A bombarding energy of 3.99 MeV was also used. Various angles of observation from 20 to 130° were used to give positive identification with the correct reaction for all particle groups. Protons leaving O^{16} in the lower excited states have high energy and hence leave low-density tracks in the nuclear emulsion. To make these tracks more easily counted a layer of aluminum foil was placed over the emulsion. An emulsion thickness of 100 μ was used to stop deuterons of about the same magnetic rigidity and hence allow discrimination from protons.

As widths of levels observed in this work varied from minute fractions of an eV to about 0.5 MeV, it was necessary to use targets varying in stopping from the order of the beam-energy spread up to 200 keV. Peak heights of groups from levels of natural width greater than target stopping are increased, with no appreciable change in group width, by using a thicker target. For levels of natural width less than target stopping the peak height is unchanged while group width increases. Methods of extracting Q values and widths from wide groups observed with thick targets were discussed before.[22] Because of the many wide and overlapping groups of low intensity, this proved to be a difficult spectrum to analyze. In several cases, groups from narrow levels are superimposed on groups from broad levels. The presence of strong groups from oxygen contamination added to the difficulties, and many runs were needed to obtain good energy values for all the levels.

The work extended over a period of some three years and a complete recalibration and realignment of the spectrograph was made in this period. Reaction Q values measured with the old and with the new calibration are in complete agreement. This fact, coupled with the large number of runs, allows quite small uncertainties to be placed on the excitation energies.

A typical proton spectrum covering excitation energies up to 11 MeV is shown in Fig. 1. Here, the bombarding energy was 3.973 MeV, the observation angle 90°, and the target stopping 60 keV for the incident beam. The group widths shown in the figure correspond to the target thickness or the natural level width, whichever is greater. The resolution width is considerably smaller than any of the observed group widths. The very wide group 6 gives a barely discernible rise above background. A very intense group from the $C^{12}(He^3,p)N^{14}$ reaction appears at about 35.8-cm trajectory radius. A deuteron group from the $N^{14}(He^3,d)O^{15}$ reaction is shown at about 39-cm trajectory radius. Foil was not used over the plate in this particular run so deuterons and protons were not distinguished.

To bring up the wide group 6, a run was made with

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[21] C. P. Browne, J. A. Galey, J. R. Erskine, and K. L. Warsh, Phys. Rev. **120**, 905 (1960).

[22] J. R. Erskine and C. P. Browne, Phys. Rev. **123**, 958 (1961).

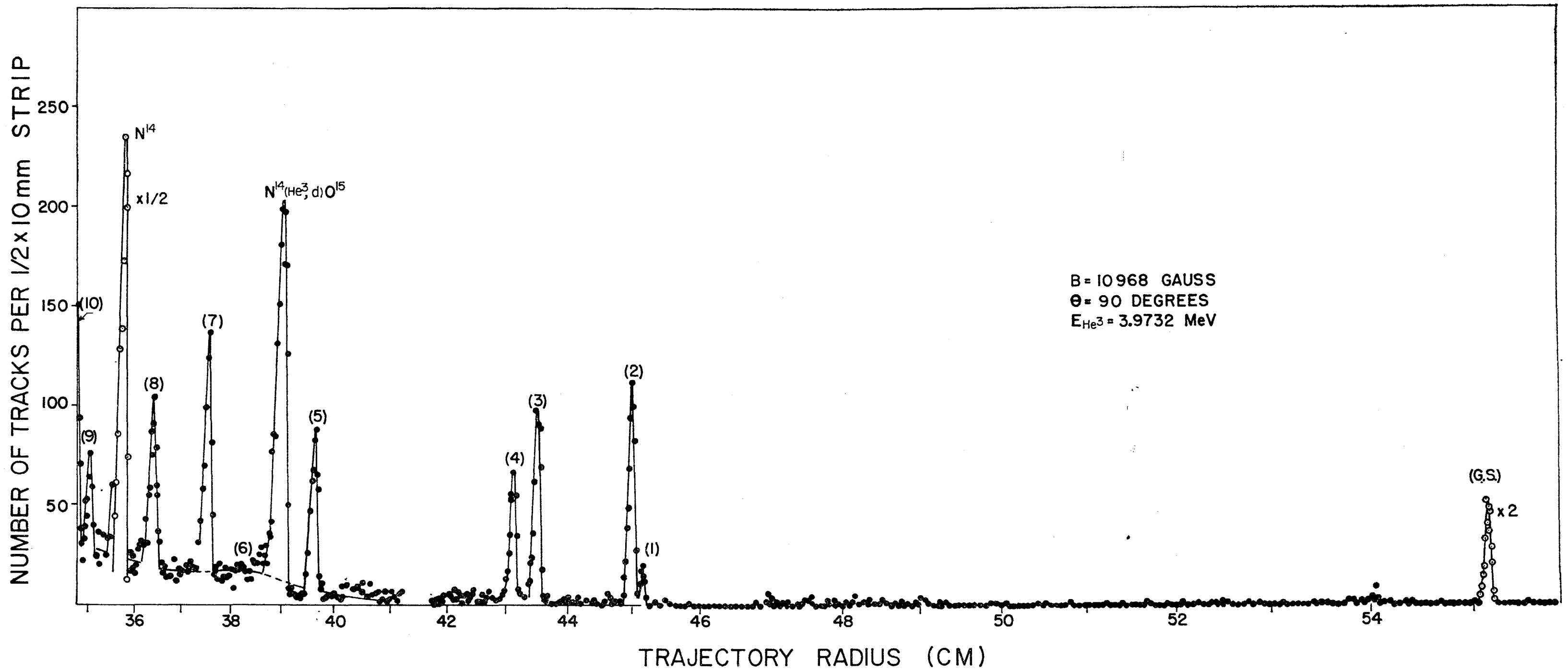

FIG. 1. Spectrum of particles from adenine target bombarded with a 3.9732-MeV He^3 beam. Groups from the $N^{14}(He^3,p)O^{16}$ reaction are numbered in order of excitation energy in O^{16}. The ground-state group is marked (G.S.). A group from the $C^{12}(He^3,p)N^{14}$ reaction is labeled N^{14}. A deuteron group from the $N^{14}(He^3,d)O^{15}$ reaction is so labeled. Open circles denote a change in ordinate scale.

a 210-keV-thick target. A section of the spectrum is shown in Fig. 2. In this run, foil was used so deuterons were excluded in counting. The curve is a Breit-Wigner curve added to the sloping background shown. The fact that the group from the narrow level 7 is superimposed on the low-energy side of group 6 makes the measurement of position and width of the later very difficult. A thicker target results in more overlapping of groups and a thinner target gives very large statistical uncertainties in the data points for the wide groups. The presence of level 6 is indisputable but large uncertainties must be attached to its position and width.

Levels below 7.15-MeV excitation can decay only by γ emission and hence have widths[11] much less than those measureable by the present technique. Level 5 is a 2^- level and α decay is forbidden so only γ-decay can occur. The width of level 7 has been measured twice[4,6] and found to be 0.75 keV (c.m.), again too small to be measured in this work. For this reason no effort was made to measure widths of narrow levels below 10-MeV excitation and the thinnest target used for this region had a stopping of 20 keV.

In the excitation region above 11 MeV, the spectrum becomes much more complicated. Two representative spectra are shown in Fig. 3. The upper spectrum came from a target with 34-keV stopping and the lower spectrum from a target with 15-keV stopping. The enhancement, with increased target thickness, of the groups from broad levels is seen. It is interesting to note the narrow group 17 superimposed on the overlapping broad groups 16 and 18. In this figure groups from reactions with carbon and oxygen are labeled with the symbol of the residual nucleus. The region between 14 and 15 MeV is partially obscured, especially with thicker targets, by a smear of protons from the $O^{16}(He^3,p)F^{18*}$ reaction leading to the four F^{18} states near 1-MeV excitation. The relatively high yield from this reaction and the distribution of oxygen contamination through the target backing made it very difficult to observe this region. A range of observation angles and bombarding energies was used and it is felt that any level of less than 30-keV width, giving a group of 20% the intensity of group 22, would have been found. A broad weak group could well be submerged in the background and the smear from $O^{16}(He^3,p)F^{18}$. The levels reported[5] at 11.26 MeV with a width of 2500 keV (c.m.) and at 11.62 with a width of 1200 keV (c.m.) are too broad to be seen in the proton spectrum. Protons leading to these levels would simply add a small amount to the background. Another contribution to a continuous background, above an excitation of 7.15 MeV, presumably comes from the three-particle reaction $N^{14}(He^3,p\alpha)C^{12}$.

One of the most interesting features of Fig. 3 is the close-spaced pair labeled groups 10 and 11. Evidence for assigning both groups to $N^{14}(He^3,p)O^{16}$ is shown in Fig. 4. As the observation angle is changed from 20 to 120°, the group spacing remains constant. The Q values for both groups remain constant. If one of the groups came from a target one mass unit less than N^{14}, the level spacing would change by 98 keV with this change of angle. The double group was observed 14 times under varying conditions. In 9 cases, the target was thin enough to make it clear that there were two groups, and in 7 cases, the energy of the lower particle group could be accurately measured. For comparison of group shape, group 9 was included in Fig. 4. Level 9 and the unresolved pair of levels, 10 and 11, are often referred to in the literature as a "doublet." The present data clearly shows that there are actually three levels here.

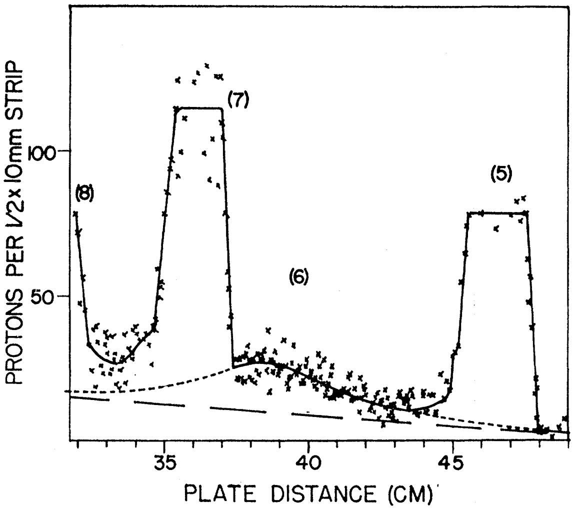

Fig. 2. Partial spectrum of protons from a 210-keV thick target. Groups (5) and (7) correspond to narrow energy levels in O^{16}, so the observed width comes only from target stopping. Group (6) corresponds to a level 510±60 keV wide. The curve drawn through this group is calculated from a Breit-Wigner formula.

EXCITATION ENERGIES

It is evident from Fig. 1 that it was not possible to measure the energy of the ground-state group at the same magnetic field setting required for groups above 11-MeV excitation. Also the field required to record the ground-state group was above that for which the calibration of the spectrograph was known to be constant. Finally, a considerably more accurate measurement may be made by finding the input energy from a particle group on the same exposure as the unknown group rather than from an elastically scattered group recorded at a different field setting. Differential hysteresis effects are thus avoided.

For the above reasons the quantity actually measured in the range of excitation from 11 to 15 MeV was the Q value. The input energy was in most cases determined from a particle group arising from the $C^{12}(He^3,p)N^{14}$ reaction leading to the ground or first excited state. Q values for this reaction were recently determined

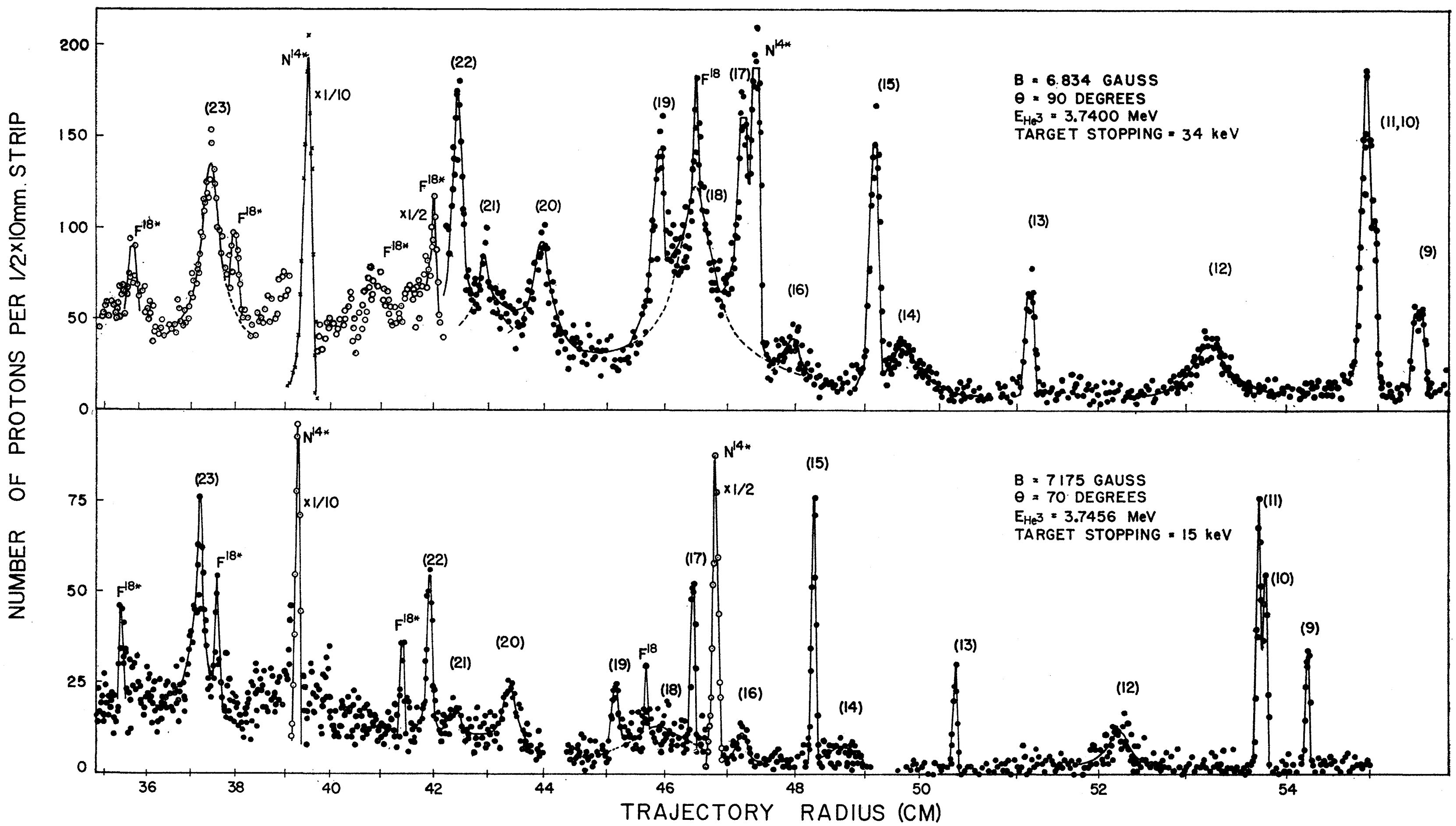

FIG. 3. Spectra of protons from adenine targets bombarded with 3.74-MeV He^3 particles. The excitation region in O^{16} is above that shown in Fig. 1. Labeling of groups is the same as in Fig. 1. The lower spectrum came from a target with 15-keV stopping and the upper spectrum from a target with 34-keV stopping. Note enhancement of groups from wide levels with the thicker target. Excitation region covered is from 10.9 to 15 MeV. Open circles denote change in ordinate scale.

TABLE II. Positions and widths of O^{16} levels measured in this work.

Particle group No.	Times observed	Measurements in average	Mean from excitations (MeV)	Mean from[a] Q values (MeV)	Final value[b] (MeV)	Width (keV)
1	7	6	6.055	6.048	6.052±0.005	<20
2	8	7	6.133	6.130	6.131±0.004	<20
3	8	7	6.914	6.917	6.916±0.003	<20
4	9	7	7.114	7.116	7.115±0.003	<20
5	11	8	8.870	8.870	8.870±0.003	<20
6	4	4	9.62	9.613	9.614±0.030	510±60
7	11	9	9.846	9.848	9.847±0.003	<20
8	12	9	10.354	10.353	10.353±0.004	27±8
9	12	9	10.952	10.952	10.952±0.003	<12
10	14	10		11.080	11.080±0.003[c]	<12
11	9	7		11.096	11.096±0.003[c]	<12
12	6	6		11.521	11.521±0.004	78±8
13	6	5		12.053	12.053±0.003	<12
14	7	6		12.437	12.437±0.007	94±15
15	11	10		12.528	12.528±0.003	<12
16	5	5		12.798	12.798±0.006	41±10
17	7	6		12.964	12.964±0.003	<12
18	5	4		13.105	13.105±0.015	160±30
19	8	8		13.253	13.253±0.005	25±8
20	8	8		13.665	13.665±0.006	65±8
21	6	6		13.869	13.869±0.010	85±20
22	8	8		13.975	13.975±0.004	24±8
23	6	6		14.922	14.922±0.006	60±10

[a] A ground-state Q value of 15.242 MeV was used in calculating excitation energies in this column.
[b] Errors, which may be considered as standard deviations, do not include the error in the ground-state Q value. The energy of alpha particles from Po^{210} was taken as 5.3045 MeV.
[c] The spacing between these two levels is 16.0±0.5 keV.

with high precision.[23] For the region of excitation from 6 to 11 MeV, measurements of two types were made. One was the same as for the higher excitation region, whereas the other was a direct measurement of excitation energy as a difference between the measured excited-state Q value and the measured ground-state Q value. In order to compare results of the two methods, a ground-state Q value must be assumed for calculating excitation energies from the Q values measured in the first method. Although the procedure is questionable. it was decided to use the average-mass values[24] to get a ground-state Q value. It was gratifying to find the measured Q value agreed with the one thus calculated but, because of the stated uncertainty in the high-field calibration, conclusions must be reserved. Work is in progress on an accurate measurement of the ground-state Q value and a preliminary result agrees with the mass differences.

Results of the measurements are summarized in Table II. The particle group number, number of times observed, and number of these observations used for energy measurements, are given in the first three columns, respectively. Agreement of the values in columns 4 and 5 reflects the agreement of the measured ground-state Q value used for column 4 and the Q value calculated from mass differences used for column 5, and indicates, moreover, that the calibration at high field

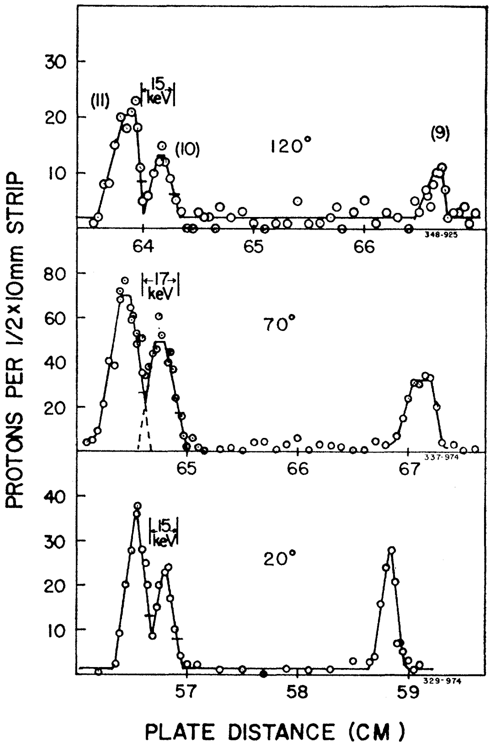

FIG. 4. Evidence for a pair of close-spaced levels in O^{16} at 11-MeV excitation. The three proton spectra were taken at 20, 70, and 120 degrees, respectively. Groups (10) and (11) correspond to levels in O^{16} at 11.080±0.003 MeV and 11.096±0.003 MeV with a spacing of 16.0±0.5 keV. Group (9) is included in the plot to show the effect of target stopping on the group shape for each run. The corresponding O^{16} level is at 10.952±0 003 MeV.

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[23] R. K. Bardin, C. A. Barnes, W. A. Fowler, and P. A. Seeger, Phys. Rev. Letters 5, 323 (1960).

[24] F. Everling, L. A. König, J. H. E. Mattauch, and H. A. Wapstra, Nucl. Phys. 18, 529 (1960).

Table III. Summary of precision determinations of O^{16}-level positions. Excitation energies are given in MeV. Footnotes give the reactions used in previous measurements and the adjustments made to the values given in the references.

Group no. this work	Excitation energy					
	This work	Previous values				J^π
1	6.052±0.005	6.057±0.010[b]	6.053[c]			0^+
2	6.131±0.004	6.14 ±0.02[a]	6.137±0.010[b]	6.133[c]		3^-
3	6.916±0.003	7.02 ±0.02[a]	6.927±0.010[b]	6.921[c]		2^+
4	7.115±0.003	7.127±0.010[b]	7.117[c]			1^-
5	8.870±0.003	8.87 ±0.03[a]	8.883±0.012[b]	8.877[c]	8.87 ±0.02[h]	2^-
6	9.614±0.030	9.59 ±0.010[d]	9.552±0.030[f]			1^-
7	9.847±0.003	9.85 ±0.03[a]	9.862±0.012[b]	9.847±0.010[d]	9.812±0.020[f]	2^+
8	10.353±0.004	10.34 ±0.03[a]	10.374±0.014[b]	10.37 ±0.02[e]	10.329±0.025[f]	4^+
9	10.952±0.003	10.954±0.010[g]				0^-
10	11.080±0.003	11.08 ±0.03[a]	11.11(?)[e]	11.080±0.015[g]	11.096±0.014[b]	
11	11.096±0.003					3^+
		11.26 ±0.020[e]				0^+
12	11.521±0.004	11.51 ±0.03[a]	11.52 ±0.020[e]			2^+
		11.63 ±0.02[e]				3^-
13	12.053±0.003	12.02 ±0.03[a]				
14	12.437±0.007	12.44 ±0.020[e]	12.442[i]			1^-
15	12.528±0.003	12.53 ±0.03[a]	12.527±0.001[i]			2^-
16	12.798±0.006	12.790±0.007[j]				0^-
17	12.964±0.003	12.966±0.001[i]	12.966±0.001[j]			2^-
18	13.105±0.015	13.06 ±0.03[a]	13.11[i]	13.088±0.010[j]		1^-
19	13.253±0.005	13.259±0.003[i]	13.259±0.003[j]	13.259±0.010[l]		3^-
20	13.665±0.006	13.662±0.003[j]	13.662±0.003[k]	13.67 ±0.015[l]		1^+
21	13.869±0.010	(13.88)[k]	13.89 ±0.020[l]			
22	13.975±0.004	13.979±0.003[k]	13.98 ±0.020[l]			2^-
23	14.922±0.006	14.93 ±0.030[l]				4^+

[a] $O^{16}(p,p')O^{16}$, see text Ref. 1.
[b] $F^{19}(p,\alpha)O^{16}$, see text Ref. 2. Values raised 0.01% for change in Po^{210} alpha energy.
[c] $F^{19}(p,\alpha)O^{16}$, see text Ref. 3. Values lowered 10 keV for change in g.s. Q value.
[d] $C^{12}(\alpha,\alpha)C^{12}$, see text Ref. 4. Values raised 12 keV for change in masses and in $Li^7(p,n)Be^7$ threshold energy.
[e] $C^{12}(\alpha,\alpha)C^{12}$, see text Ref. 5. Values raised 12 keV for change in masses and in $Li^7(p,n)Be^7$ threshold energy.
[f] $C^{12}(\alpha,\alpha)C^{12}$, see text Ref. 6.
[g] $N^{15}(d,n)O^{16}$, see text Ref. 8. Values raised 19 keV for change in masses.
[h] $F^{19}(p,\alpha\gamma)O^{16}$ and $N^{16}(\beta^-)O^{16}$, see text Ref. 11.
[i] $(N^{15}+p)$ resonances, see text Ref. 13. Values calculated from resonance energies given in reference.
[j] $(N^{15}+p)$ resonances, see text Ref. 14. Values calculated from resonance energies given in reference.
[k] $(N^{15}+p)$ resonances, see text Ref. 17. Values calculated from resonance energies given in reference.
[l] $(N^{15}+p)$ resonances, see text Refs. 16 and 18. Values adjusted for change in masses.

is the same as at low field. Because of this agreement, values from both types of measurement were averaged together in getting the final weighted averages shown in column 6. Groups with low numbers of tracks, and runs where protons passed through the target backing and stopping corrections were applied, were given lower weight in averaging. The spectrograph was calibrated using a value of 5.3045 MeV[25] for the energy of alpha particles from Po^{210}. The separation between the 11.080- and 11.096-MeV levels is 16.0±0.5 keV. Measured level widths are given in the last column of Table II.

Uncertainties attached to values in column 6 of Table II are generally two or three times the standard deviations calculated from the spread in values from the various runs. With so many runs one might expect that counting and plotting errors and small local deviations from the calibration curve could be considered random. As two independent calibrations and alignments were used for different parts of the data, a systematic error in calibration is less likely. Uncertainties in reaction angle give negligible errors. The same exposure gave input and output energies so field drift is not significant. There is an uncertainty in the actual field, that is an uncertainty in the calibration for a given run. Again the large number of runs used in the mean should tend to average out this uncertainty. Fresh targets were used for each run in an attempt to minimize surface layers. Uncertainties in positions of broad levels are greater because of the difficulty of locating the center of the wide particle groups and the corrections that must be applied for target thickness.

COMPARISONS WITH OTHER WORK

In Table III the excitation energies measured in this work are compared with those measured by others. Published values were adjusted to the current values of calibration standards and mass differences. Squires *et al.*[2] used 5.299 MeV for the Po^{210} alpha energy, so their values were raised by 0.1%. The increasing deviation, with increasing excitation, of their numbers from the present values, suggests a surface layer slowing the outgoing alphas from their $F^{19}(p,\alpha)O^{16}$ reaction. In the case of Young *et al.*,[3] the values were lowered 10 keV to adjust their ground-state Q value to that calculated from the mass table.[24] Hill's values[4] were raised 12 keV to adjust for mass differences and to lower the $Li^7(p,n)$ Be^7 threshold to 1.8807 MeV. The same adjustment

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[25] C. P. Browne, Phys. Rev. **126**, 1139 (1962); Proceedings of the Second International Conference on Nuclidic Masses, 1963 (to be published).

TABLE IV. Comparison of O^{16} level widths between this and previous work. Widths given in keV. All values converted to center-of-mass system.

Excitation energy (MeV)	Level width (keV)			
	This work	Previous work		
9.61	510±60	645[c]	594[d]	
9.85	<20	0.75[c]	0.75[d]	
10.35	28±8	27±2[a]	27 ±3[b]	25[d]
11.26		2500[b]		
11.52	78±8	80±8[b]		
11.62		1200±120[b]		
12.44	94±15	170±17[b]	88[e]	
12.53	<12	0.8[e]		
12.80	41±10	39±4[f]		
12.96	<12	2.1[e]	2.1±0.2[f]	
13.11	160±30	140[e]	130 ±10[f]	
13.25	25±8	21.0[e]	21.0±1[f]	23±5[h]
13.66	65±8	64±3[f]	64 ±3[g]	61±10[h]
13.87	85±20	85±20[j]		
13.97	24±8	22±2[g]	23±5[h]	23±5[j]
14.92	60±10	42±10[h]	56[i]	42±10[j]

[a] $F^{19}(p,\alpha)O^{16}$, see text Ref. 1.
[b] $C^{12}(\alpha,\alpha)C^{12}$, see text Ref. 5.
[c] $C^{12}(\alpha,\alpha)C^{12}$, see text Ref. 4.
[d] $C^{12}(\alpha,\alpha)C^{12}$, see text Ref. 6.
[e] $(N^{15}+p)$ resonance, see text Ref. 13.
[f] $(N^{15}+p)$ resonance, see text Ref. 14.
[g] $(N^{15}+p)$ resonance, see text Ref. 17.
[h] $(N^{15}+p)$ resonance, see text Ref. 18.
[i] $(N^{15}+p)$ resonance, see text Ref. 20.
[j] $(N^{15}+p)$ resonance, see text Ref. 16.

was made in the Bittner and Moffat[5] data. A 19-keV adjustment was made in the data of Wiel *et al.*[8] for masses. Schardt *et al.*,[19] Hagedorn,[14] and Hagedorn and Marion[17] give proton resonance energies only. The excitation energies in Table III were calculated from these data by converting to center of mass energy and using mass differences. Values of Bashkin *et al.*[16] and Bashkin and Carlson[15] were adjusted by 10 keV to account for changes in mass values. When one compares the numbers in Table III, these adjustments should be borne in mind. Listed errors are those of the authors and do not include uncertainties in masses or calibration energies.

The agreement of the various measurements is very good. The excitations of the lowest two levels, as determined in the present work and the work of Young *et al.*,[3] agree within 1 and 2 keV, respectively, while the value for the excitation of the 13.975-MeV state agrees within 4 keV with that given by Hagedorn and Marion.[17] Such close agreement over so wide a range of energies indicates consistency in mass values and suggests that any systematic errors in the present work are small. Spins and parities of many of the levels are listed for reference in the last column of Table III. These were taken from the literature.

Table IV compares measurements of level widths. Again, agreement is excellent in most cases. The present value for the width of the 9.16-MeV level is somewhat low but, as explained above, this group was partially obscured and the present value has a large uncertainty. Bittner and Moffat[5] find a larger width for the 12.44-MeV level than the present value, which agrees with that of Schardt *et al.*[19] The present data give no indication of a second wider level under the 94-keV wide level at 12.437-MeV excitation.

The question arises as to how to identify the two states at 11.080 and 11.096 MeV with previous work. Both levels probably contributed to inelastic proton scattering[1] and were unresolved. Target thickness was too great to resolve the levels in the $F^{19}(p,\alpha)O^{16}$ reaction,[2] although in the published data, the group corresponding to these levels does look somewhat wider than that for a single group at that position on the track plate. Bromley *et al.*[10] give a separation of 146±10 keV between the 10.952-MeV level and a level near 11 MeV. This compares with 142±4 keV between the 10.952- and 11.096-MeV states and suggests that the state at 11.096 MeV is the 3^+ level of Bromley *et al.* The indication of a level seen by Bittner and Moffat[5] may then have been the 11.080-MeV level. Wiel *et al.*[8] find a spacing of 126±18 keV in their neutron thresholds which agrees with 128±4 keV between the 10.952- and 11.080-MeV levels. If this surmise is correct, the spin and parity of the 11.080-MeV level is still to be determined.

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