clear that the broad structure below A, which was attributed above to an alpha continuum, could not alternatively be a triton group indicative of a broad state in Be^8, since it does not move correctly with a change in the bombarding energy. As has been pointed out[1,7] this structure is properly assigned to the processes $Be^9(d,t)Be^{8*}(\alpha)He^4$ (cutoff labeled A) and $Be^9(d,\alpha)Li^{7*}(\alpha)H^3$ (cutoff labeled B). The superposition of these continua leads to the characteristic shape displayed by the curves: the former reaction involving a broad intermediate state produces a rise of moderate slope; the latter process involving a narrow state leads to a sharp high-energy cutoff.

It is interesting to compare the three-particle continua observed here with those obtained recently in several different reactions by workers[5,6] investigating states in Be^9. They have found relatively sharp structure at the high-energy end of the many-body continuum. This structure has been interpreted by some[5] to indicate the existence of a state in Be^9 and by others[6] as being due to the presence of a very strong directional correlation among the disintegrating particles. No such sharp structure is observed in any of the Be^9+d continua.

Figure 4 shows the data obtained in the search for a 5.5-Mev state in Li^7. The expected position of an alpha group at $E_{ex}=5.5$ is labeled with the letter J. There is no evidence for a peak in this region of the spectrum. We estimate that a transition having an intensity greater than 5% of the ground-state intensity would have been detected.

We should like to thank Mr. James Lambert for assistance in processing the plates and operating the spectrograph.

[7] P. Cüer and J. J. Jung, Compt. rend. **234**, 204 (1952).

PHYSICAL REVIEW VOLUME 104, NUMBER 6 DECEMBER 15, 1956

Energy Levels of O^{18} and F^{21}†

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(Received August 29, 1956)

The reactions $F^{19}(t,\alpha)O^{18}$ and $F^{19}(t,p)F^{21}$ have been studied, yielding the following results: the energy levels of O^{18} up to 6.8 Mev are 1.989, 3.504, 3.929, 5.007, 5.170, 5.311, 5.456, 6.190, and 6.328 Mev. The energy levels of F^{21} up to 2.14 Mev are 0.269, 1.087, 1.694, and 2.036 Mev. The mass defect of F^{21} is measured to be 6.195 Mev, giving a mass of 21.006653 atomic mass units. The yields and cross sections of the levels are studied. These results are compared with data obtained elsewhere and the isobaric systems of mass 18 and 21 are discussed.

INTRODUCTION

INTEREST has been growing in the nuclei whose protons and neutrons number one or two more or less than the closed p shell (O^{16}). A nucleus with just one odd proton or neutron can be described, in part, by shell theory. When one considers a nucleus with two nucleons above the closed shell (as in O^{18} with two extra neutrons), the additional effect of the coupling between these nucleons must be considered. A study of such nuclei, assuming predictable behavior of the core, may give information on the interaction of two nucleons in such a situation. It is with this in mind that the results of an experiment to measure the energy levels of O^{18} are given, with the data on F^{21} coming out more or less as a by-product. The results of these experiments are of interest, also, in the study of reactions with three-particle projectiles.

The levels of O^{18} are obtained from the experimental energies of α particle groups in the reaction $F^{19}(t,\alpha)O^{18}$, using a precision double-focusing magnetic spectrometer. The F^{21} levels are obtained in a similar way from the $F^{19}(t,p)F^{21}$ reaction.

The F^{21} data given here supersede the preliminary information published in 1955.[1] A preliminary report of the O^{18} work has also been published.[2]

EXPERIMENTAL APPARATUS

The apparatus used is shown in Fig. 1. Tritons are accelerated in one of the 2.5-Mev electrostatic generators of the Los Alamos Scientific Laboratory. The energy of the beam is determined to 1 or 2 kev by sending the diatomic (T_2^+) beam through an electrostatic analyzer. The apertures and target are part of an elaborate 22-inch diameter reaction chamber. Fragments from the reaction on the target leave the chamber through a port at 90° to the beam. The fragments then enter a 16-inch radius, double-focusing magnetic spectrometer and are detected at the focus by a scintillation detector employing a thin CsI(Tl) crystal and a 6292 DuMont photomultiplier tube. The

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Nelson Jarmie, Phys. Rev. **99**, 1043 (1955).
[2] Nelson Jarmie, Bull. Am. Phys. Soc. Ser. II, **1**, 28 (1956).

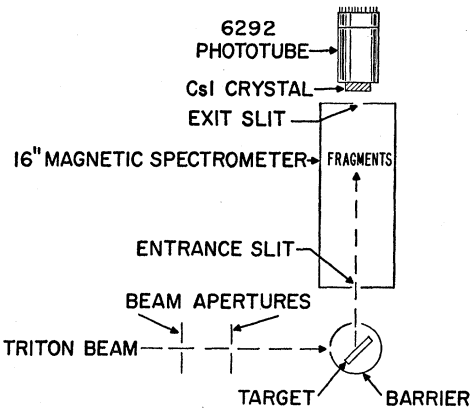

FIG. 1. Simplified diagram of the experimental apparatus to show the essential features. Not to scale.

spectrometer is very similar to one designed and built at the California Institute of Technology, the major improvements being the use of water-cooled hollow copper magnet windings and a strong, thin, welded stainless-steel vacuum box. Pulses from the phototube are amplified and sent to an 18-channel pulse-height analyzer in a straightforward manner without too much worry about resolution since the critical energy measurements are made with the magnetic spectrometer.

The targets of CaF_2 and PbF_2 are made by evaporating thin films of the substances onto gold disks. Gold is used, in most cases, for target backings as it was found that there was much less oxygen in it or on it to produce contaminating particles from the $O^{16}(t,\alpha)$ reaction than other high-Z materials like tantalum. Calcium and other subsidiary targets are also made by evaporation. The target disks are polished to less than a few microinches roughness, thoroughly cleaned, and then used in a high-vacuum evaporation chamber in the usual way with no special difficulties.

A simple null-type torsion fluxmeter was built to make the accurate field measurements in the spectrometer. This fluxmeter is identical in principle and similar in design with that described by Lauritsen and Lauritsen,[3] and will not be described in any detail here. For intermittent and relative measurements, such as in this experiment, the accuracy of the fluxmeter was shown to be surprisingly good, well within the resolution of the spectrometer. However, for long-range, continuous, or absolute measurements, a nuclear-moment device would probably be desirable.

TABLE I. Energy levels of O^{18} and F^{21} with standard deviations.

O^{18} levels (Mev)	F^{21} levels (Mev)
1.989±0.024	0.269±0.040
3.504±0.034	1.087±0.040
3.929±0.040	1.694±0.040
5.007±0.040	2.036±0.040
5.170±0.040	
5.311±0.040	
5.456±0.040	
6.190±0.040	
6.328±0.040	

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

The spectrometer resolution for this experiment is indicated by several numbers. The "half-edge" at half-maximum for scattered 1.8-Mev tritons (off a thick gold target with a 100-mil beam and a $\frac{1}{16}$-inch slit at the spectrometer focus, which were the parameters used in the experiment) was 0.33% (6 kev) in energy. The full width at half-maximum for protons scattered off a very thin gold evaporated layer (beryllium backing) for the same conditions but with a 6-mil slit at the focus is 0.18%. No real attempt was made to attain the ultimate resolution because the accuracy of the energy levels was limited to a larger value for other reasons. The solid angle of the spectrometer used was about 0.0024 steradian and the angular error of the 90° observation was not more than 1°. The temperature of the magnet was observed and kept to reasonable levels.

EXPERIMENTAL PROCEDURE

A fresh target (say, CaF_2) was placed in the chamber for each run and a high vacuum produced. The average target was about 10 to 40 kev thick to 1.8-Mev tritons. Liquid-nitrogen traps on the side of the chamber suppressed deposition of a carbon layer from residual organic vapors. Beams of about 1 μa were used. The scattered triton beam was used to measure the energy thickness of the target by comparing the energy of the tritons with those scattered off a blank gold disk. These measurements were used in the target-thickness corrections of the data. Since protons and alpha particles have about the same energy for a given magnetic field, some method was necessary for separate detection. This was found to be easy since the CsI crystal was determined to be 1.7 times more efficient for protons than for alpha particles of the same energy, and the particle groups were well separated in the pulse-height analyzer. Proof of the identity of these groups was obtained by placing thin metal foils over the crystal and observing the proper energy attenuation or stopping of the particles.

Alpha and proton groups were found at various settings of the magnetic field, and precise measurements of the position of these peaks were taken with the fluxmeter. Only particle groups above a certain energy could be detected because of the flood of scattered tritons from the thick gold backing. More low-energy groups could be measured by using a very thin backing, but additional problems would arise of background and a wealth of contaminant levels. Because a large number of levels could already be observed, thin backings were not tried.

Targets of PbF_2, Ca, and substances containing

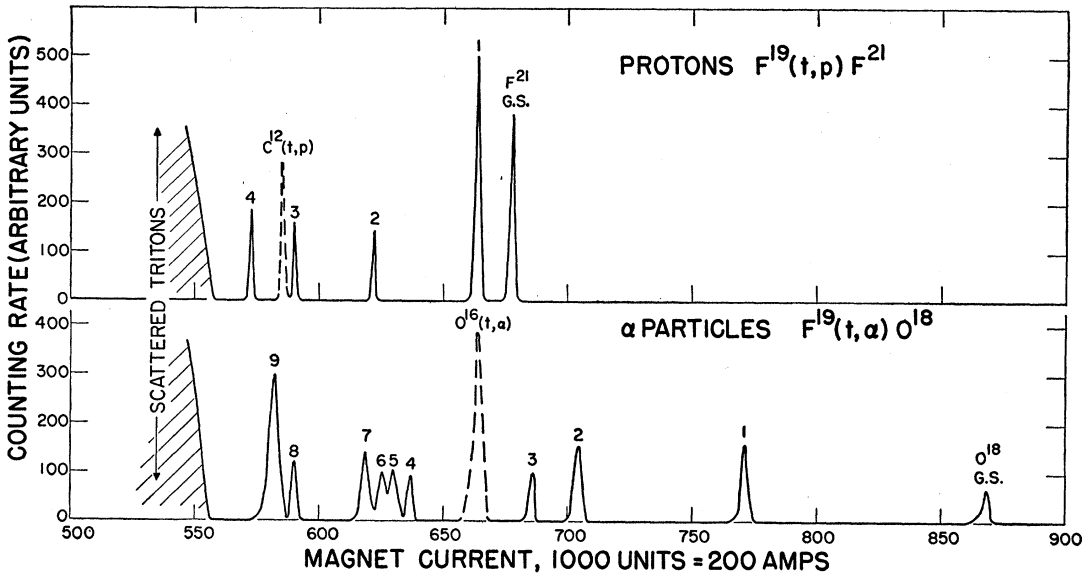

FIG. 2. Typical experimental yield curve for protons and alpha particles. The magnet begins to saturate at large currents so that the horizontal scale is not exactly linear with momentum.

carbon, nitrogen, and oxygen were used with both gold and tantalum backings to cross-check and positively identify all particle groups observed. Measurements using alphas from the $F^{19}(p,\alpha)O^{16}$ reaction and from Pu^{239} disintegrations were made to check out the general behavior of the spectrometer.

The levels found were very distinct and isolated due, in part, to the high Q of the reactions [11.847 Mev for $F^{19}(t,\alpha)O^{18}$], giving very positive and unambiguous identification to the observed data. Alphas from the $O^{16}(t,\alpha)N^{15}$ reaction were used as an absolute calibration to determine the energy of the nearby proton peak of the ground state of the $F^{19}(t,p)F^{21}$ reaction and subsequently the mass of F^{21}.

An attempt to measure the absolute cross section of the $F^{19}(t,\alpha)O^{18}$ reaction was considered worthwhile. This turned out to be difficult and not very accurate with the equipment used, but a measurement was made for one of the stronger peaks (first excited state of O^{18}) with some modifications in the apparatus. A triatomic hydrogen beam (H_3^+) is accelerated along with the triton beam and must be eliminated from the beam current measurement. This was done by using a target on a thin gold backing just thick enough to stop the H_3^+ but allow the triton beam to pass through into a Faraday cup. There were 1.62×10^{18} fluorine atoms per cm^2 in the target. The focus slit on the spectrometer was opened so that the detector would count the entire particle group at one time.

Background counts in the crystal were due mostly to neutrons (and the resultant gamma rays) which were generated by the triton beam striking parts of the accelerating tube and other apparatus. The neutrons presumably come from triton breakup and the $t+t$ reaction with absorbed and impacted tritium. However, these neutrons mostly produced small pulses and did not interfere with the high-energy alphas being observed (5 to 10 Mev). Very little background came from the target or other sources.

RESULTS

A typical yield curve of the alpha and proton groups is shown in Fig. 2. The energy levels of O^{18} calculated from the experimental results are given in Table I and Fig. 3. These are the levels found in this nucleus up to an excitation of 6.79 Mev. The error given is the standard deviation and to a large extent arises from the subtraction of two large, similar, particle energies to arrive at an energy level. The measurements were made with a 1.802-Mev triton beam. The spectrum was also inspected with a beam of 1.5-Mev tritons but no difference was found. A measure of the relative

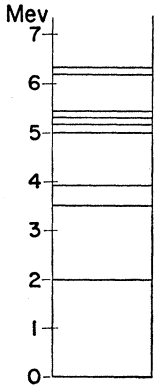

FIG. 3. Energy level diagram of O^{18} as determined in this experiment.

intensity of the levels can be gotten from the yield curve of Fig. 2.

Only one contaminant peak was found in the alpha spectrum. This is due to the ground state of the $O^{16}(t,\alpha)N^{15}$ reaction and produces an occluded region in the O^{18} energy level scheme between 4.423 and 4.471 Mev where a small level might have been missed. The differential cross section (lab system) of $F^{19}(t,\alpha)O^{18*}$ for the first excited state of O^{18} at an angle of 90° (lab system) and a triton energy of 1.802 Mev was determined to be 0.072 millibarn per steradian (±30%). Rough excitation functions of the ground state and first excited state are shown in Figs. 4 and 5. The graph for the first excited state can be normalized to the above value for the cross section, but not too much reliance should be placed on the exact structure of the curves because of difficulty in the analysis of the data. They are to be considered only as an indication of the trend of the cross sections. This region corresponds to an excitation of the intermediate nucleus, Ne^{22}, of about 21 Mev.

The energy levels of F^{21} are given in Table I and Fig. 6. The error is again the standard deviation. The levels were determined up to an excitation of 2.14 Mev of the F^{21} nucleus. The occluded region where a small level might have been missed is from 1.800 to 1.870 Mev. This is due to the only contaminant group in the proton spectrum: the ground state of the $C^{12}(t,p)C^{14}$ reaction. The mass defect of F^{21} is calculated to be 6.195±0.030 Mev, or in other units the mass is 21.006653±0.000032 amu. The Q of the $F^{19}(t,p)F^{21}$ reaction is 6.200±0.025 Mev. Note that the mass value in amu differs considerably from that quoted in the preliminary report[1] because of a computation mistake in the early value.

Any level in between those found would have a cross section at least 100 times smaller than that of an average level and in most cases much smaller. An upper bound for the cross section of levels not seen calculates to be about 1 microbarn per steradian or smaller if one uses the cross section quoted for the first excited state of O^{18}. No levels appeared which were due to calcium, lead, tantalum, or gold. The widths of the particle groups were estimated to be caused by the apparatus so that it was impossible to observe any inherent widths of the levels. Masses used in the calculations were taken from Ajzenberg and Lauritsen.[4]

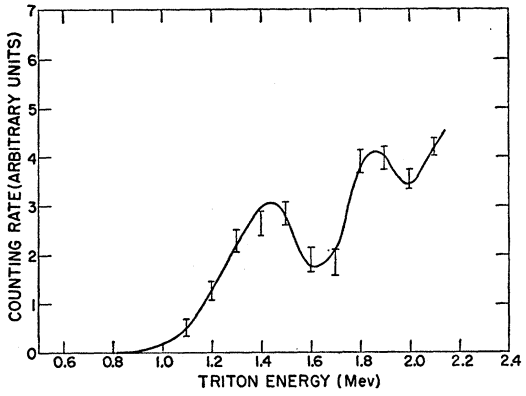

FIG. 4. Excitation function at 90°of the ground state of $F^{19}(t,\alpha)O^{18}$.

DISCUSSION

O^{18}

The region up to 3 or 4 Mev excitation in the O^{18} nucleus has now been inspected by a number of experimenters using several reactions. The first excited state near 2 Mev has been seen by all observers[5–9] and is well established. The situation at higher energies is not so clear. A preliminary observation[8] of a level at 2.45 Mev, counterindicated by the present work and several previous experiments,[5–7,9] is probably spurious. Hough and Bach[7] observed a level at 3.555±0.013 Mev in agreement with our value of 3.504±0.034 Mev; however, Ahnlund[6] searched up to 4.5 Mev and found nothing other than the 2-Mev state. At the time of writing, the levels included in this report are the only ones observed above 3.5 Mev.

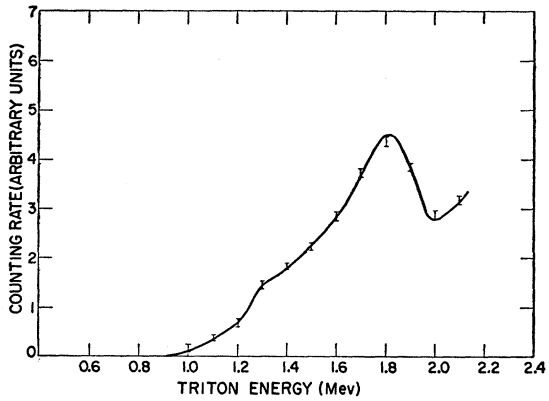

FIG. 5. Excitation function at 90° for the first excited state of $F^{19}(t,\alpha)O^{18*}$.

Theoretical work predicting the structure of nuclei of mass 18 is being done by Elliot and Flowers,[10] and Redlich.[11] For O^{18} Elliot and Flowers calculate even parity states and can predict the 2-Mev level, but do not give any correspondence to other observed levels. Information on the levels of F^{18} that is useful for

[4] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 157 (1955).
[5] F. L. Ribe, Phys. Rev. **100**, 1254(A) (1955), and private communication.
[6] K. Ahnlund, Phys. Rev. **96**, 999 (1954).
[7] P. V. C. Hough and D. R. Bach, Phys. Rev. **102**, 1341 (1956), and private communication.
[8] Holmgren, Hanscome, and Willet, Phys. Rev. **98**, 241(A) (1955).
[9] Spencer, Phillips, Schiffer, and Young, Bull. Am. Phys. Soc. Ser. II, **1**, 95 (1956).
[10] J. P. Elliot and B. H. Flowers, Proc. Roy. Soc. (London) **A229**, 536 (1955), and private communication.
[11] M. G. Redlich, Phys. Rev. **99**, 1427 (1955); **95**, 448 (1954).

comparison with the O^{18} levels is limited. Almost all investigations of F^{18} states have been made with reactions that should not lead to $T=1$ states, if isobaric spin conservation holds. The only work noticed for $T=1$, is that of Butler, Holmgren, and Kunz,[12] which explains only the level in F^{18} corresponding to the ground state of O^{18}. We are considering an attempt to measure the energy levels of O^{18} and F^{18} by very similar experiments in order to get a comparison between the members of an isobaric triplet as completely devoid of systematic error as possible. It is planned to use the reaction $F^{19}(t,\alpha)O^{18}$ and the mirror reaction $F^{19}(He^3,\alpha)F^{18}$ with the same target, detection system, accelerating system, and so on.

Ne^{18}, the other member of the mass 18 isobaric triplet, has been observed[4] with a mass defect of 10.4 Mev. If one calculates the "excitation" of the $T=1$ state (ground state of F^{18}) one gets about 1.0 Mev, which is in close agreement with the same calculation for the $O^{18}-F^{18}$ pair, as would be expected from the isobaric spin hypothesis. This calculation is the usual one[13] that eliminates the effect of the Coulomb energy and neutron-proton mass difference and uses the mass difference of the nearest set of mirror nuclei (in this case, $Ne^{19}-F^{19}$). Also, the calculation assumes nuclear force symmetry (n-n=p-p) and assumes the Coulomb energy difference is not affected much by the addition of a neutron each to a pair of nuclei.

F^{21}

Our value for the mass defect of F^{21} predicts a maximum energy for beta emission of 5.73 Mev. From the known data on nearby nuclei, the value indicates that F^{21} is not a "delayed neutron" emitter as one might suspect from the fact that it is a N^{17} nucleus plus an alpha particle. The half-life of F^{21} has been reported by other sources to be around 5 seconds.[14,15]

Besides the preliminary report of this experiment,[1] the detection of F^{21} by the $F^{19}(t,p)F^{21}$ process has been reported by Bigham, Allen, and Almqvist.[16] They give a mass defect of 6.37 ± 0.1 Mev and energy levels at 0.89, 3.34, and 4.01 Mev. Their mass defect is in rough agreement with ours but the values of the excited states do not agree well at all.

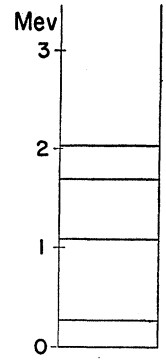

FIG. 6. Energy level diagram of F^{21} as determined in this experiment.

Assuming the validity of the isobaric spin concepts, the F^{21} ground state should be a member of an isobaric spin $T=\frac{3}{2}$ quartet. The other members of this quartet are Ne^{21}, Na^{21}, and the unobserved Mg^{21}. A slight variation on the usual method of calculating the "excitation" of the $T=\frac{3}{2}$ state over the $T=\frac{1}{2}$ ground state indicates that the first $T=\frac{3}{2}$ state in the Na^{21} and Ne^{21} nuclei should be observed at about 9.25 Mev above their ground states. Levels in Ne^{21} have been observed at and clustering about this value so there is no contradiction, but no real information can be deduced from this comparison except that it shows that there nuclei are a little too heavy and the energy levels are too dense for comparison, at least for $T=\frac{1}{2}, \frac{3}{2}$ systems. Even if the energies were measured accurately enough, the validity of any conclusions might well be obscured by mixing of these nearby states.

It is interesting to note an early prediction of the F^{21} mass by Barkas of 21.0059 amu.[17]

ACKNOWLEDGMENTS

I wish to express my appreciation to the other members of the 2.5-Mev electrostatic generator group at Los Alamos for their advice and help and also because they were responsible for the development of much of the major equipment.

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[14] E. C. Campbell and J. E. Strain, Oak Ridge Quarterly Report, ORNL-1496, December, 1952 (unpublished), p. 9.
[15] H. Morinaga and R. W. King, Purdue University Progress Report, COO-173, June, 1956 (unpublished).
[16] Bigham, Allen, and Almqvist, Phys. Rev. 99, 631(A) (1955).
[17] W. Barkas, Phys. Rev. 55, 691 (1939).