The Neutron Spectrum from the $O^{18}(d,n)F^{19}$ Reaction*†

ROBERT L. SEALE‡
Physics Department, University of Texas, Austin, Texas
(Received July 1, 1953)

The neutron spectrum from the $O^{18}(d,n)F^{19}$ reaction has been investigated. $BaCO_3$ targets enriched in O^{18} were bombarded with 2-Mev deuterons and the emitted neutrons were detected using 100- and 200-micron Ilford nuclear plates. The method of analyzing the data is discussed in detail. The results of the experiment indicates the presence of 4 excited levels in the F^{19} which had not been previously reported. These levels are at 0.9 Mev, 2.2 Mev, 5.2 Mev, and 5.5 Mev.

INTRODUCTION

An investigation of the excited states in the F^{19} nucleus has been made using the $O^{18}(d,n)F^{19}$ reaction. The Q value for the reaction as calculated from the atomic mass values is 5.73 ± 0.05 Mev.

Several investigations of excited levels in F^{19} have been made; none, however, with this reaction. A summary of these previous studies is given by Ajzenberg and Lauritsen.[1]

EXPERIMENTAL TECHNIQUE

O^{18} is a relatively rare isotope (0.20 percent) of oxygen, making the investigation of this reaction quite difficult under ordinary conditions. However, a sample of CO_2 enriched in O^{18} to 14 atom percent was obtained from the Temple University Research Foundation, Philadelphia, Pennsylvania. $BaCO_3$ was prepared using the O^{18} enriched CO_2. The concentration of O^{18} in the $BaCO_3$ produced was 9.3 atom percent.

It was decided that a solid target be used. Targets were prepared by painting a suspension of the $BaCO_3$ in distilled water on silver disks and allowing the water to evaporate. Uniform targets 100 kev thick could be prepared using this method.

A preliminary exposure of an O^{18}-enriched target was made on the Carnegie Institution of Washington Van de Graaff machine. The target used was 300 kev thick. The thickness of the target was estimated by extrapolating the data in Livingston and Bethe.[2] An exposure of 280 000 microcoulombs of atomic deuterons of 2-Mev energy was made with packs of nuclear plates placed at 0° and 90° with respect to the incident deuteron beam. These plates were processed and scanned in the conventional manner. An analysis of the results showed that the neutron spectrum was quite complex and that the neutron groups due to the different levels in the F^{19} nucleus overlapped considerably. There were on the average five usable tracks in each field of view suggesting that the bombardment could be readily decreased.

With these results in mind a second exposure was made on the University of Texas Van de Graaff machine as soon as it was in operation. In this exposure the bombardment was reduced to 108 000 microcoulombs of (2 ± 0.04) Mev deuterons and the target used was only 100 kev thick. Nuclear plates were placed in several positions about the target relative to the incident beam. Plates exposed at 0° and 20° were scanned.

ANALYSIS OF DATA

The results were thus obtained in the form of a plot of number of recoil protons *versus* range. However, the distribution of neutrons emitted from the target *versus* neutron energy was desired. A neutron energy interval of 100 kev was selected for the energy distribution plot. To express these energy increments in terms of observed recoil proton lengths the following conversion was made:

(1) The recoil proton energy corresponding to a given neutron energy is given by

$$E_p=E_n\langle\cos^2\theta\rangle_{\text{Av}},$$

where θ is the angle between the path of the incident neutron and the path of the recoil proton. The value of θ for tracks read is a function of the size of the source and the acceptance criteria for recoil tracks. The average value of $\cos^2\theta$ was calculated for the geometry of the system used.[3]

(2) Using the range-energy curve for protons in Ilford C-2 emulsion[4] the proton energies calculated above were converted to track lengths.

(3) The track lengths read in the procedure used were the projections of the track lengths on the long axis of the plate. The plates were arranged in the exposure so that their long axes were coplanar with the incident deuteron beam. The observed track lengths are given by

$$L_{\text{obs}}=L_{\text{true}}\langle\cos\theta'\rangle_{\text{Av}},$$

* Part of a dissertation presented to the Faculty of the Graduate School of the University of Texas as a partial fulfillment of the requirements for the degree of Doctor of Philosophy.

† Assisted by the U. S. Atomic Energy Commission.

‡ Now at Consolidated Vultee Aircraft Corporation, Fort Worth, Texas.

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. 24, 321 (1952).

[2] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. 9, 261–286 (1951).

[3] J. C. Allred and A. H. Armstrong, *Laboratory Handbook of Nuclear Spectroscopy* (Los Alamos Scientific Laboratory of the University of California, 1951) (unpublished).

[4] Lattes, Fowler, and Cuer, Proc. Phys. Soc. (London) 59, 883 (1947).

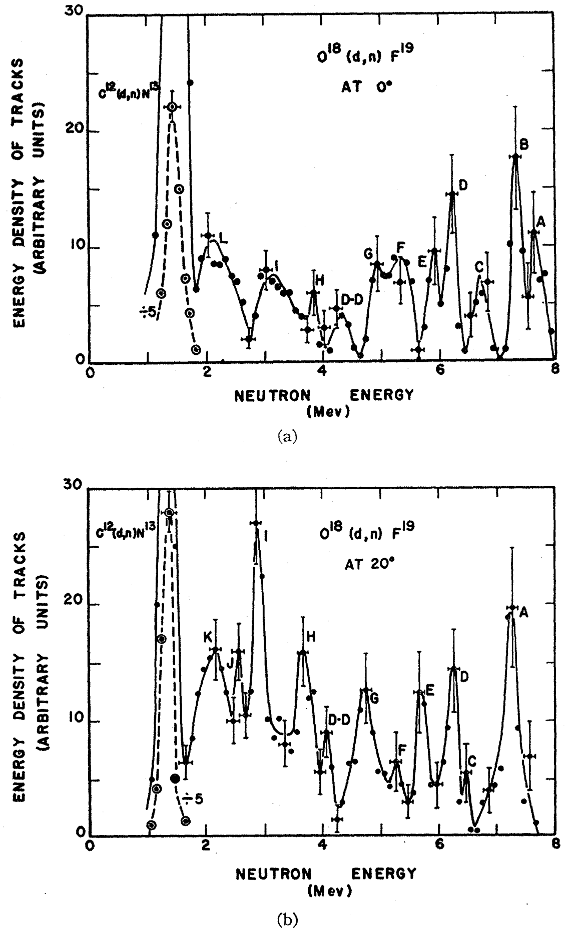

FIG. 1. The energy density of tracks *versus* neutron energy is shown (a) at 0° and (b) at 20° for the bombardment of O^{18} with 2-Mev deuterons.

where $\langle\cos\theta'\rangle_{Av}$ is the average value $\cos\theta'$, θ' being a function of the track acceptance criteria.

By using the scheme outlined, neutron energy increments could be converted to the corresponding observed track lengths. The neutron energy increments were then marked off on the number of recoil proton *versus* observed track length histogram. The tracks falling within a given 100-kev energy interval were counted and plotted as an ordinate at the center of the interval, the abscissas still linear in track length. A smooth curve was then drawn through these points. The area under this curve within each energy interval was taken as a measure of the energy density of tracks in that interval. The energy densities of tracks thus obtained were then plotted as ordinates against a linear energy scale after the corrections for the variations of the *n-p* cross section with energy and for the thickness of the emulsion were applied.

The results of a plot of energy density of tracks *versus* energy at 0° and 20° are shown in Fig. 1.

The probable error in the energy density of tracks was taken as the normalized square root of the energy density of track. Again the *n-p* cross section and emulsion thickness corrections were applied.

The energies assigned to the groups shown in Fig. 1 were obtained by making an integral plot of track density *versus* energy of each group and "extrapolating" the steepest tangent on the curve after the method of Livingston and Bethe.[2]

A neutron group from the dueteron on deuteron reaction was observed. This group is probably due to the surface absorption of deuterons from the gas in the vacuum system by the target.

The energies of neutron groups from the transitions to the ground state of the $O^{18}(d,n)F^{19}$, the $C^{12}(d,n)N^{13}$, and the $H^2(d,n)He^3$ reactions as determined from the data shown and from the calculated Q values check with one another within the limits of experimental error. This serves as a check on the absolute energy of each of the groups.

TABLE I. Experimental determination of energy levels of F^{19}.

Group	Extrapolated group energy[a] (Mev)		Q-value of group[a] (Mev)		Energy of excited levels[a] (Mev)			Known levels[b]
	At 0°	At 20°	At 0°	At 20°	At 0°	At 20°	Av	
A	7.7	7.6	5.7	5.7	0.0	0.0	0.0	0.0
B	7.5	···	5.5	···	0.2	···	0.2	0.19
C	6.9	6.6	4.9	4.7	0.8	1.0	0.9	···
D	6.3	6.1	4.3	4.3	1.4	1.4	1.4	1.37
E	6.0	5.9	4.0	4.0	1.6	1.6	1.6	1.59
F	5.5	5.4	3.5	3.5	2.2	2.2	2.2	···
G	4.9	4.9	2.9	3.0	2.8	2.7	2.75	2.82
H	3.8	3.8	1.8	1.9	3.9	3.8	3.85	3.94
I	3.2	3.1	1.2	1.2	4.5	4.5	4.5	4.48
J	···	2.9	···	0.9	···	4.8	4.8	4.76
K	···	2.5	···	0.5	···	5.2	5.2	···
L	2.2	···	0.2	···	5.5	···	5.5	···

[a] All values ±0.1 Mev.
[b] See reference 1.

The energies assigned to the excited levels of F^{19} as well as the excitation energies for known levels in F^{19} are summarized in Table I.

At excitation energies above 4 Mev the levels become closely spaced and resolution of the individual groups becomes very difficult. However, there are a few definite peaks which appear superimposed on a rather heavy background.

Four additional levels in F^{19} are indicated. These are at 0.9±0.1 Mev, 2.2±0.1 Mev, 5.2±0.1 Mev, and 5.5±0.1 Mev.

A normal $BaCO_3$ target was also bombarded and scanned as a check against the possibility of assigning a spurious group to the F^{19} spectrum.

The author wishes to express his appreciation to Dr. E. L. Hudspeth for many helpful suggestions throughout the course of this work, to Dr. N. P. Heydenberg of the Carnegie Institution, Department of Terrestrial Magnetism, Washington, D. C., for making the preliminary exposures, and to acknowledge the assistance of the entire Van de Graaff group of the University of Texas.