Measurement of Energy Levels in F^{19} and O^{16}†

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(Received July 5, 1956)

The broad-range magnetic spectrograph of the Massachusetts Institute of Technology High Voltage Laboratory has been used to study the proton groups from the reaction $F^{19}(p,p')F^{19*}$ and the alpha-particle groups from the reaction $F^{19}(p,\alpha)O^{16*}$. The incident protons had an energy of 7 Mev and were produced by the MIT-ONR Van de Graaff generator. The ground-state Q value for the $F^{19}(p,\alpha)O^{16}$ reaction was found to be 8.110±0.010 Mev. Values of the energy levels of F^{19} and O^{16} are given up to 4.05 and 11.3 Mev, respectively.

I. INTRODUCTION

ENERGY levels of F^{19} have been measured by Arthur *et al.*[1] by the magnetic analysis of protons inelastically scattered by F^{19}. In the region up to 4.1 Mev, they found levels at 1.37, 1.59, 2.82, 3.94, and 4.06 Mev. Since their work, additional levels have been found at 0.110, 0.197, and 1.452 Mev by several methods,[2,3] chiefly by the measurement of the energies of the gamma rays that follow inelastic proton or alpha-particle scattering from F^{19}. In addition, two further levels at 0.9 and 2.2 Mev have been reported by Seale,[4] who measured the energies of the neutron groups from the reaction $O^{18}(d,n)F^{19*}$.

The energy levels of F^{19} are of considerable theoretical interest.[3,5] Therefore, to check the previously reported values and to search for further levels, the levels up to 4.05 Mev have been measured once more, by the magnetic analysis of the proton groups inelastically scattered by F^{19}.

At the same time, the alpha particles from the reaction $F^{19}(p,\alpha)O^{16*}$ were analyzed. From these measurements, values for the energy levels of O^{16} up to 11.3 Mev were obtained.

II. DESCRIPTION OF EXPERIMENT

The MIT-ONR generator and the analyzing spectrograph have been described previously.[6,7]

In the present experiment, the target was a thin layer of barium fluoride evaporated onto a thin gold film stiffened by Formvar. The energy of the incident protons had various values between 7.0 and 7.3 Mev and was determined by measuring the energy of the protons elastically scattered by F^{19}. The beam current was about 0.1 microampere. The majority of the bombardments corresponded to 600 microcoulombs of incident protons. However, the elastically scattered proton group obtained from such an exposure was too intense to be countable. To locate this group, a separate bombardment of 40 microcoulombs was made.

Measurements were made at scattering angles of 60, 90, and 130 degrees in the laboratory system. The target was set up at 45 degrees to the incident proton beam in each case. For the measurements at 60 degrees, the incident protons passed through the gold before striking the barium fluoride; for the measurements at 90 and 130 degrees, the protons struck the barium fluoride before the gold. At each of the scattering angles, plates were exposed at three values of the spectrograph magnetic field. In this way, protons were recorded over a range of energy from 1.5 to 7 Mev, and alpha particles, over a range from 2.7 to 13 Mev. The target contained several impurities. Apart from barium and gold, the chief of these were C^{12}, C^{13}, O^{16}, and S^{32}. The mass of the target nucleus corresponding to a particular group of scattered particles can be calculated from the variation of the energy of the group with the scattering angle. The proton and alpha-particle groups from impurities in the target were thus readily separated from those that were due to F^{19}.

III. RESULTS

A typical set of results for the proton groups is shown in Fig. 1. The energy levels of F^{19} are listed in Table I, together with values from previous experiments.[1,3,8] Each value in the left-hand column of the table is the mean of the three values obtained at the three scattering angles. The spread in the individual values indicates that they are reproducible to 1 kev.

A typical set of results for the alpha-particle groups is shown in Fig. 2. The groups labeled A and B have not been identified. Group A may correspond to the reaction $Na^{23}(p,\alpha)Ne^{20*}$, with the Ne^{20} in an excited

† This work has been supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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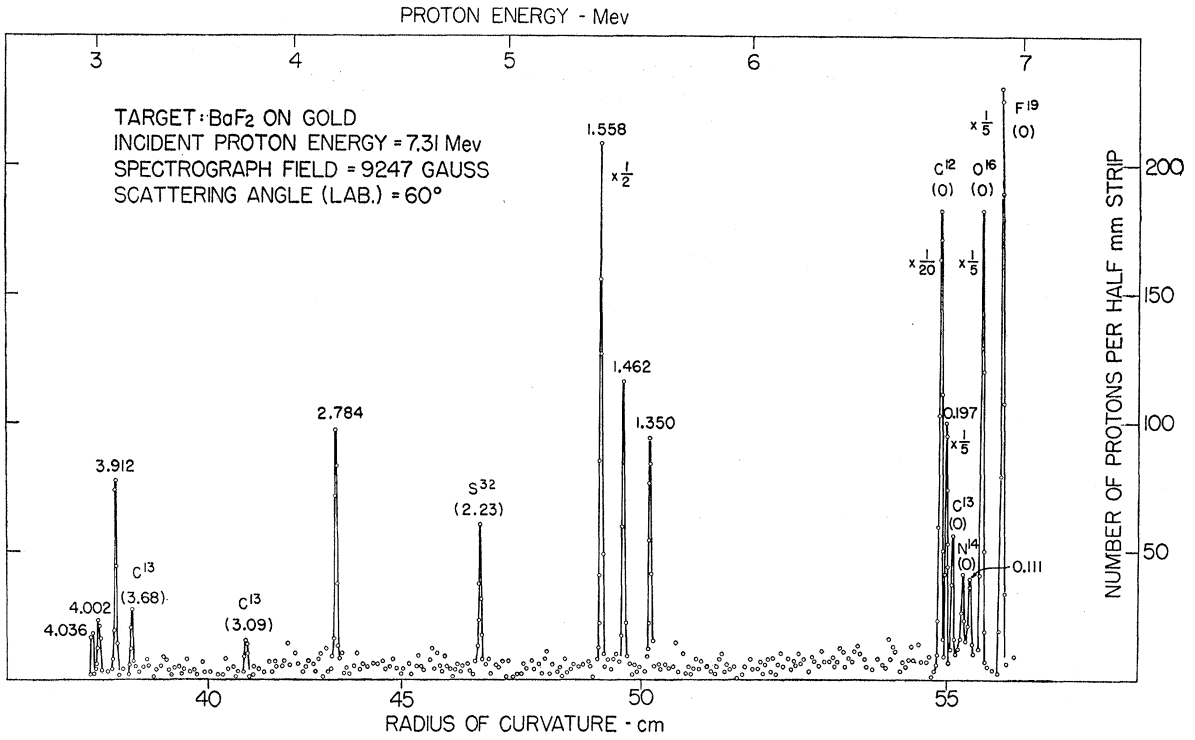

FIG. 1. Spectrum of protons scattered from a barium-fluoride target. The excitation energies of the recoil nuclei are given in Mev. Peaks not attributed to F^{19} are labeled.

state at 5.4 Mev. However, the corresponding alpha-particle group does not appear at the other scattering angles.

The ground-state Q value for the reaction $F^{19}(p,\alpha)O^{16}$ was found to be 8.110 ± 0.010 Mev. The energy levels of O^{16} are listed in Table II, together with values from previous experiments.[2,9–12] The values given in the left-hand column of Table II were obtained by subtracting the measured Q values from 8.110 Mev. The values of the O^{16} energy levels are again the mean of three values, one from each scattering angle. The spread in the individual values indicates that they are reproducible to 4 kev.

In addition to random errors, there are several sources of systematic errors in the measurements. These have been discussed in a previous paper.[13] The two most important are (1) the effect of surface contamination on the energies of the incident and emitted particles and (2) uncertainties in the calibration of the spectrograph. The errors in our energy-level values given in Tables I and II represent a combination of the random and estimated systematic errors.

The F^{19} levels given in the left-hand column of Table I are all that have been found. The measurements indicate that, in the region up to 4.05 Mev, there are no other levels that give rise to proton groups with heights greater than 2% of the height of the group corresponding to the 1.558-Mev level. It can be seen that we do not observe the levels at 0.9 and 2.2 Mev reported by Seale. Apart from this, our results are consistent with those obtained in previous experiments. As far as we are aware, the level at 4.002 Mev has not been previously reported.

The values of the O^{16} energy levels are also consistent with previous values. Hill[10] has found a broad level at 9.58 Mev. At 130 degrees, we observed a weak broad

TABLE I. Energy levels of F^{19} (in Mev).

Value from present experiment	Value from previous experiments	Reference
0.111 ± 0.002	0.110 ± 0.001[a]	b,c
0.197 ± 0.002	0.197 ± 0.001[a]	b,c
1.350 ± 0.005	1.342 ± 0.010	d
1.462 ± 0.005	1.452 ± 0.010	d
1.558 ± 0.005	1.551 ± 0.010	d
2.784 ± 0.008	$2.82\ \pm0.03$	e
3.912 ± 0.010	$3.94\ \pm0.03$	e
4.002 ± 0.010		
4.036 ± 0.010	$4.06\ \pm0.03$	e

[a] These values are the weighted means of the values given in references 2 and 8.
[b] See reference 2.
[c] See reference 8.
[d] See reference 3.
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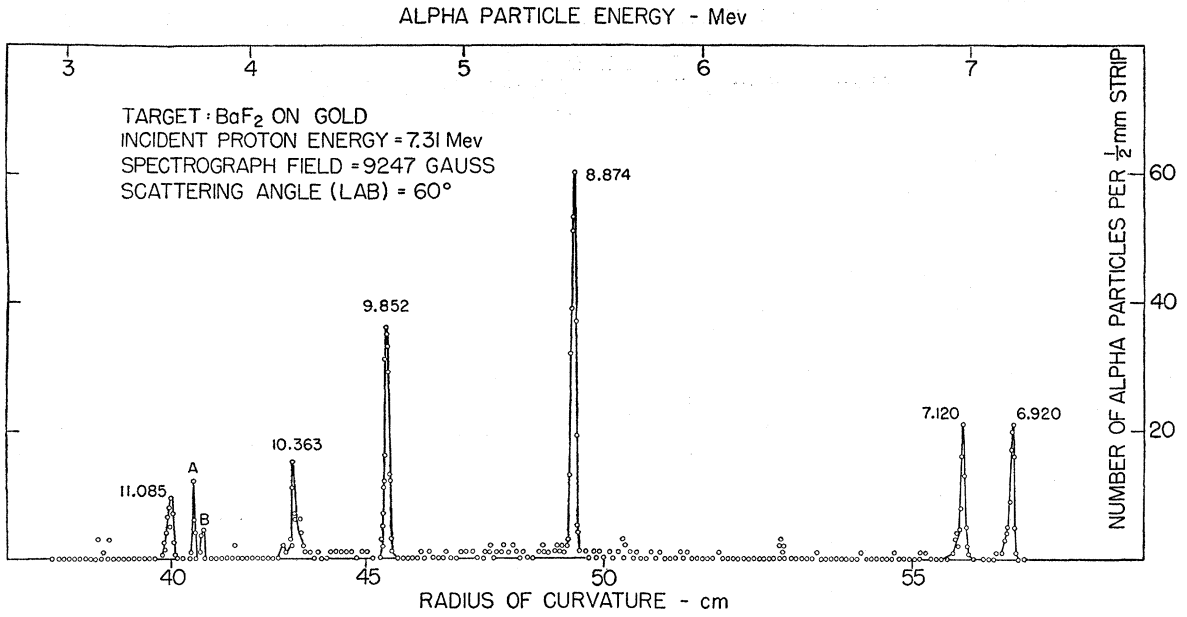

FIG. 2. Spectrum of alpha particles obtained from the proton bombardment of a barium-fluoride target. The excitation energies of the O^{16} recoil nuclei are given in Mev. The peaks labeled *A* and *B* are discussed in the text.

TABLE II. Energy levels of O^{16} (in Mev).

Value from present experiment	Value from previous experiments	Reference
6.051±0.010	6.06	a
6.131±0.010	6.14	a
6.920±0.010	6.91	a
7.120±0.010	7.12	a
8.874±0.012	8.87 ±0.02	b
9.852±0.012	9.835±0.010	c
10.363±0.014	10.35 ±0.02	d,e
11.085±0.014	11.10 ±0.02	d

[a] See reference 2.
[b] See reference 9.
[c] See reference 10.
[d] See reference 11.
[e] See reference 12.

group of alpha particles corresponding to this level, but at 60 and 90 degrees, the group was so weak as to manifest itself only as an apparent increase in the background. Apart from this, all the O^{16} levels that we found are given in Table II. There are no other levels, in the region of investigation, giving rise to alpha-particle groups with heights greater than 5% of the height of the group corresponding to the 8.874-Mev level.

The width at half-height of the alpha-particle group corresponding to the ground state of O^{16} was about 20 kev. This broadening is due partly to the apparatus itself and partly to the thickness of the target. The levels in Table II from 6.051 through 9.852 Mev gave rise to groups whose widths were also about 20 kev, which indicated that these levels are narrow. The widths of the groups corresponding to the 10.363- and 11.085-Mev levels were about 25–30 kev. Bittner and Moffat[11] have reported a tentative level at 11.10 Mev with a Γ_{lab} value of 10 kev. Hornyak and Sherr,[12] observing proton-gamma coincidences from the inelastic scattering of protons by O^{16}, have found a level at 11.08 Mev. However, they deduce from the coincidence rate that the width is considerably greater than 10 kev. Therefore, the width of our 11.085-Mev level indicates that it corresponds to the level found by Bittner and Moffat.

ACKNOWLEDGMENTS

We wish to thank Dr. R. Sharp and Mr. A. Sperduto for their cooperation during the experiment, and also the members of the counting group for their careful scanning of the plates. One of us (GLS) is indebted to the International Cooperation Administration of the United States Government for a Fellowship.