Nuclear Energy Levels in O^{16}, O^{18}, and F^{19}†

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Thin targets of F^{19} and O^{18} have been bombarded with protons of approximately 5 Mev from the Rice Institute Van de Graaff accelerator. Excited states were observed at 1.344±0.005, 1.458±0.005, and 1.554 ±0.005 Mev in F^{19}, and at 1.981±0.004 Mev in O^{18}. Q values for the $F^{19}(p,\alpha)O^{16}$ reaction were determined to be 2.061±0.015, 1.981±0.008, 1.193±0.008, 0.997±0.008, and −0.763±0.008 Mev.

INTRODUCTION

THE experiments discussed in this paper were performed to seek confirmation, by independent methods, of nuclear energy levels which had been reported mainly from studies of gamma radiation. Of interest were states observed at 8.86 Mev in O^{16} by Sherr and Hornyak[1] and by Wilkinson *et al.*[2]; at 1.98 Mev in O^{18} by Ahnlund[3] and by Holmgren *et al.*[4]; and at 1.45 Mev in F^{19} by Toppel *et al.*[5] The α-particle model, which successfully describes many excited states in O^{16}, has not been found capable of explaining a state at 8.86 Mev of excitation.[6] It is therefore of particular interest that the existence of this level be well substantiated. It was also hoped that the isotopic spin of the 1.98-Mev state in O^{18} could be determined by observation of inelastically scattered deuterons.

EXPERIMENTAL PROCEDURE

Thin targets of F^{19} and O^{18} were bombarded with protons of approximately 5 Mev from the Rice Institute 5.5-Mev Van de Graaff accelerator. Fluorine targets were prepared by evaporating CaF onto thin carbon and nickel foils. Four and ten micro-inch nickel foils were heated in approximately 25 mm of Hg absolute pressure of oxygen enriched to 37% in O^{18} to produce targets of NiO.[7] The various targets used were from 3 to 15 kev thick to the incident beam.

Reaction products emitted at 180° to the incident beam were studied using the Rice Institute annular magnetic spectrometer, which has been described previously.[8] A modification of the target assembly has reduced the background in inelastic-scattering experiments to less than 20 microbarns/sterad. Ilford $E1$ nuclear track plates were used to detect the reaction products.

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[1] R. Sherr and W. F. Hornyak, Phys. Rev. **99**, 632 (1955).
[2] Wilkinson, Toppel, and Alburger, Phys. Rev. **101**, 673 (1956).
[3] K. Ahnlund, Phys. Rev. **96**, 999 (1954).
[4] Holmgren, Hanscome, and Willett, Phys. Rev. **98**, 241(A) (1955).
[5] Toppel, Wilkinson, and Alburger, Phys. Rev. **101**, 1485 (1956).
[6] D. M. Dennison, Phys. Rev. **96**, 378 (1954); S. L. Kameny, Phys. Rev. **101**, 358 (1956).
[7] O_2 enriched in O^{18} was supplied by Professor A. O. C. Nier of the University of Minnesota.
[8] Gossett, Phillips, and Eisinger, Phys. Rev. **98**, 724 (1955).

RESULTS

1. $F^{19}(p,\alpha)O^{16}$ Reaction

Shown in Fig. 1 is the α-particle spectrum obtained at 5.21-Mev bombarding energy and corresponding to excitation of between 6 and 9 Mev in O^{16}. Q values, levels of excitation, and approximate cross sections are given in Table I. The values given are the averages of values obtained at 5.21- and 5.08-Mev incident proton energies. The low intensity of α particles from the pair-emitting state at 6.06 Mev requires the relatively large error assigned to the energy of that state. Errors quoted for the energies of excited states are based on the assumption of a ground-state Q value of 8.124±0.007

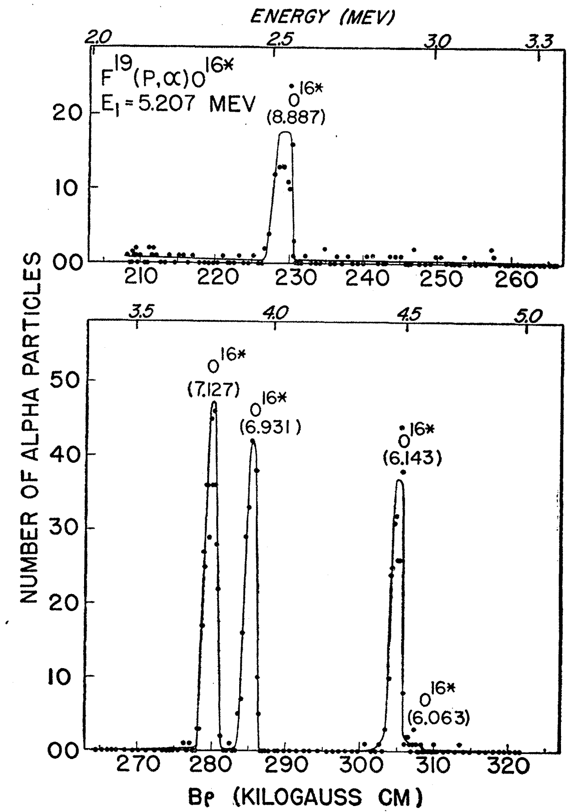

FIG. 1. Alpha-particle spectrum observed from F^{19} target at an incident proton energy of 5.207 Mev. Numbers by α-particle groups indicate, in Mev, the energy of excitation in the residual O^{16} nucleus.

Mev.[9] The results are in good agreement with the values reported from the study of γ radiation.[1,2] Any additional α-particle groups, corresponding to excitations of from 6 to 9 Mev, which originated from reactions having cross sections of as much as 0.4 mb/sterad would have been observed.

2. $O^{18}(p,p')O^{18}$ Reaction

Spectra at three incident proton energies were taken covering the region of excitation in O^{18} below 2.6 Mev. The spectrum observed at 4.58 Mev is shown in Fig. 2. The bombarding energies were determined from the extrapolated leading edges of the O^{16} and O^{18} peaks. A group of protons corresponding to the 1.98-Mev state in O^{18} was observed at each bombarding energy. Table I gives the mean value of the three determinations of the excitation energy and cross section of this state. There was no evidence for a state in O^{18} near 2.45 Mev[4] with an intensity greater than 10% that of the 1.98-Mev state.

TABLE I. Average values of experimental determinations. The energies of excitation in the O^{16} nucleus have been computed by using a ground-state Q value of 8.124±0.007 Mev. Cross sections are expected to be correct only to within a factor of two or three.

Element	Q value (Mev)	Energy of state (Mev)	Cross section (mb/sterad)
O^{16}	2.061±0.015	6.063±0.017	0.1
	1.981±0.008	6.143±0.011	0.8
	1.193±0.008	6.931±0.011	1
	0.997±0.008	7.127±0.011	2
	−0.763±0.008	8.887±0.011	0.6
O^{18}	−1.981±0.004	1.981±0.004	3
F^{19}	−1.344±0.005	1.344±0.005	6
	−1.458±0.005	1.458±0.005	3
	−1.554±0.005	1.554±0.005	6

3. $O^{18}(d,d')O^{18}$ Reaction

A partial spectrum covering the region of excitation of the 1.98-Mev state was taken at an incident deuteron energy of 4.98 Mev. No inelastic deuteron peak was observed with an intensity greater than 3% that of the deuteron elastic peak from O^{18}. A recent report[10] indicates that this state has been observed by inelastic scattering of 7.7-Mev deuterons.

4. $F^{19}(p,p')F^{19}$ Reaction

Shown in Fig. 3 is the proton spectrum obtained at 5.21-Mev bombarding energy. Information concerning states in F^{19} at 1.34, 1.46, and 1.55 Mev is presented in Table I. No proton groups were observed which could be assigned to states in F^{19} in the region of excitation between 1.55 and 2.35 Mev. In Fig. 3 the weak groups (A) and (B) would correspond to excitations of 2.22

[9] Li, Whaling, Fowler, and Lauritsen, Phys. Rev. **83**, 512 (1951).
[10] D. R. Bach and P. V. C. Hough, Phys. Rev. **102**, 1341 (1956).

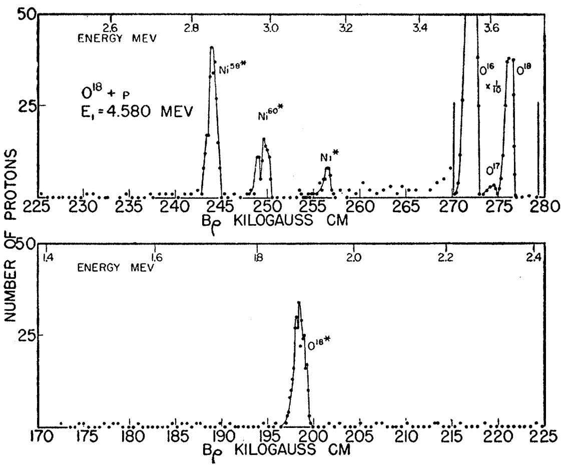

FIG. 2. Proton spectrum observed from O^{18} target at an incident proton energy of 4.58 Mev, showing the proton group corresponding to an excitation of 1.981±0.004 Mev in O^{18}.

Mev[11] and 2.34 Mev, respectively in F^{19}. These groups have widths which indicate that they could be assigned to calcium, nickel, or fluorine. Such assignment was not possible since they appeared at only one bombarding energy. Proton groups which have not been identified in Fig. 3 have been assigned to reactions in the nickel backing. The specific isotopes responsible for the various peaks have been determined by use of enriched targets. This experiment is discussed in the preceding paper.

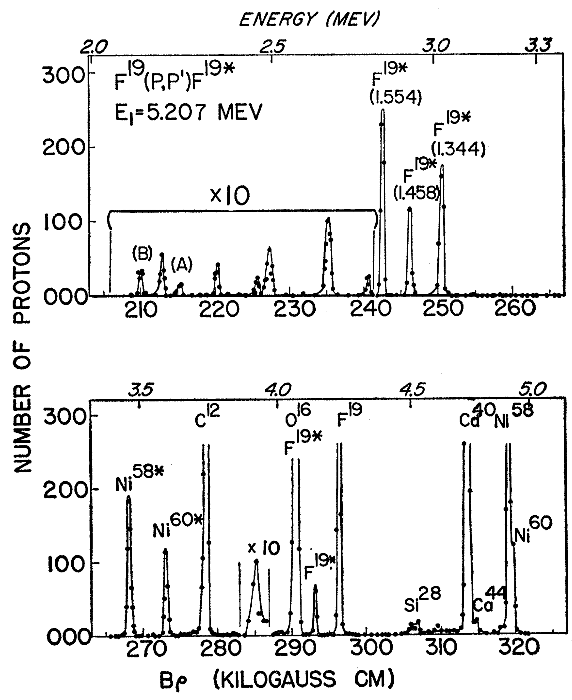

FIG. 3. Proton spectrum observed from F^{19} target at an incident proton energy of 5.207 Mev. Numbers by inelastic proton groups show, in Mev, the energy of excitation in the residual nucleus.

[11] R. L. Seale, Phys. Rev. **92**, 389 (1953).

The energies of levels at 1.34, 1.46, and 1.55 Mev are in excellent agreement with the values recently reported from measurement of γ radiation.[5] If proton groups (A) and (B) do not correspond to states in fluorine, the upper limit of the cross section for excitation of other possible states is 0.1 mb/sterad.

DISCUSSION

Confirmation has been obtained for states at 6.06, 6.14, 6.93, 7.13, and 8.88 Mev of excitation in O^{16}. These include three of the four states usually used to set up the α-particle model. An extensive discussion of the 8.88-Mev state and its implications in relation to the α-particle model has been given by Wilkinson *et al.*[2] Excited states at 1.34, 1.46, and 1.55 Mev in F^{19} have been confirmed by inelastic proton scattering. No conclusive results were obtained regarding a state in F^{19} at 2.22 Mev, and no evidence was seen for a state at 0.9 Mev.[11] The results presented here are in good agreement with those obtained for O^{16} and F^{19} by Squires *et al.*[12] The state at 1.98 Mev in O^{18} has been observed by inelastic proton scattering, but no evidence was seen for a state at 2.45 Mev. These results might be interpreted as meaning the isotopic spin of this state is not the same as that of the ground state. However, the contradictory results of this and the other recent experiment[10] of $O^{18}+d$ scattering leave the isotopic spin of the 1.98-Mev state in O^{18} in question.

[12] Squires, Bockelman, and Buechner, Phys. Rev. **104**, 413 (1956).

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Impulse Approximation for Stripping Reactions*

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The impulse approximation expansion is applied to stripping processes. We find that the first term of the impulse expansion for the stripping problem is identical with the first term of the Born expansion. It is suggested that the impulse approximation argument may provide a better justification for the usual treatment of stripping and pickup reactions than does the Born approximation argument.

I. INTRODUCTION

THEORETICAL analyses developed to describe deuteron stripping and pickup reactions[1] have had a large measure of success. These treatments all contain two central assumptions. It is first of all assumed that the interactions giving rise to the stripping and pickup reactions all take place in the surface or outside region of the target nucleus. This is called the cutoff assumption. Secondly, it is assumed that these interactions can be treated by Born approximation. It is the second of these two assumptions which we wish to discuss.

It is, at first sight, surprising that the kind of interactions involved in stripping reactions can be satisfactorily treated by Born approximation. It is well known that when these same interactions are involved in elastic scattering processes they cannot be treated by Born approximation. We shall show that the Born approximation expression for the transition amplitude can be derived by means of an impulse approximation.[2] The impulse approximation would appear to be better justified for the stripping problem than the Born approximation, but for neither case has any quantitative estimate been made.

II. BORN APPROXIMATION TO STRIPPING

Consider a system consisting of three particles which we denote by n (a neutron), p (a proton), and N (a nucleus). Let n interact with p by means of potential V_{np}, and let V_{Np} represent the interaction between N and p. For simplicity assume there is no interaction between N and n. Let $T=T_n+T_p+T_N$ be the kinetic energy operator. The Schrödinger equation for this system is then

$$(E_0-T-V_{Np}-V_{np})\psi_0=0. \qquad (1)$$

To discuss the solutions of the above equation we introduce the solutions of the Schrödinger equations for

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