pound-nucleus formation,[27] then the characteristic width must be $\gtrsim$250 keV, since the measurement involved an average over this interval. In fact, the similarities in the angular distributions of $P(\theta)$ at 2.5 and 2.8 MeV suggest that the characteristic width is $\gtrsim$500 keV. Schiffer *et al.*[4] suggested that two widely separated resonances at 2.0 MeV (Γ=0.5 MeV) and 3.7 MeV (Γ=0.7 MeV) dominate the reaction in this energy region.

The smooth energy variations are, of course, consistent with a direct-reaction mechanism. Even spin-independent distorted-wave-Born-approximation theories predict the possibility of large polarizations for this particular direct reaction.[28] In (d,p) reactions it has been shown that spin-orbit terms in the distorting potentials are important,[29,30] and they would probably be required here as well.

The large size of the polarization contradicts the hypothesis that the reaction involves many overlapping levels in a statistical compound nucleus. The smooth energy variation rules out contributions to the polarization from levels with widths appreciably less than 250 keV.

ACKNOWLEDGMENTS

We would like to express our appreciation to Dr. H. L. Fann for his valuable assistance and for his loan of the He^3 target for the calibration measurements. We would also like to thank Dr. Margaret Waggoner for her helpful discussions during the early stages of measurement and to T. S. Bhatia for his assistance in making the measurements.

[27] T. Ericson, *Advances in Physics* (Francis & Taylor, Ltd., London, 1960), Vol. 9, p. 425.
[28] L. J. B. Goldfarb and R. C. Johnson, Nucl. Phys. **18**, 353 (1960).
[29] D. Robson, Nucl. Phys. **22**, 47 (1961).
[30] N. K. Glendenning, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Palo Alto, California, 1963), Vol. 13.

PHYSICAL REVIEW VOLUME 137, NUMBER 6B 22 MARCH 1965

$N^{14}(He^3,n)F^{16}$ Reaction*

C. D. ZAFIRATOS†
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

AND

F. AJZENBERG-SELOVE
Haverford College, Haverford, Pennsylvania

AND

F. S. DIETRICH‡
California Institute of Technology, Pasadena, California

(Received 5 November 1964)

Time-of-flight neutron spectra from the bombardment of a chromium nitride target by 3.5- and 6.2-MeV He^3 particles indicate five neutron groups corresponding to the ground state of F^{16} and to excited states at 0.20±0.05, 0.436±0.030, 0.736±0.040, and 3.78±0.06 MeV, with widths of 50±30, <40, 40±30, <15 and <40 keV, respectively. The ground state Q value is −0.963±0.040 MeV, corresponding to a F^{16} atomic mass excess of 10.686±0.040 MeV. The results are discussed in terms of the known information on the $T=1$ states in the $A=16$ isobaric triad.

INTRODUCTION

FLUORINE[16] can be investigated by means of three reactions: $N^{14}(He^3,n)F^{16}$, $O^{16}(p,n)F^{16}$ and $O^{16}(He^3,t)F^{16}$. From charge-independence arguments and knowledge[1] of the excitation energy of the first $T=1$ state in O^{16}, one calculates Q values of approximately −1 MeV for the (He^3,n) reaction and approximately −16 MeV for the (p,n) and (He^3,t) reactions. The energy-level structure of F^{16} can be roughly predicted from the known information on the levels of N^{16} and on the $T=1$ states in O^{16}: There should be a cluster of four odd-parity states [in N^{16} these occur at 0, 0.120, 0.296, 0.396 MeV with $J^\pi=2^-$, 0^-, 3^-, 1^-; in O^{16} at 12.79, 12.97, 13.10, 13.26 MeV with $J^\pi=0^-$, 2^-, 1^-, 3^-] followed by a sizable energy gap devoid of levels [in N^{16}, 3 MeV; in O^{16}, not known]. F^{16} should be proton-unstable.

The difficulties in investigating F^{16} can be summarized as follows: (a) the close spacing of the first four states of F^{16} require both a well-defined incident-

* Experimental work performed at Los Alamos Scientific Laboratory under sponsorship of the U. S. Atomic Energy Commission, and otherwise supported by the National Science Foundation and the U. S. Office of Naval Research.
† Now at Oregon State University, Corvallis, Oregon.
‡ Now at Stanford University, Stanford, California.
[1] F. Ajzenberg-Selove and T. Lauritsen, Nucl. Phys. **11**, 1 (1959); T. Lauritsen and F. Ajzenberg-Selove, Nucl. Phys. (to be published).

particle energy and a high-resolution detecting system for the outgoing particles; (b) the requirement for a well-defined incident particle energy suggests study of the $N^{14}(He^3,n)F^{16}$ reaction ($Q\sim-1$ MeV) which is easily in the range of present Van de Graaff accelerators, but the Q of the $C^{12}(He^3,n)O^{14}$ reaction is -1.148 MeV and the ubiquitous carbon contamination of targets would provide an intense source of neutrons of closely the same energy as those of the $N^{14}(He^3,n)F^{16}$ reaction; (c) all states of F^{16} are unbound and may have large intrinsic widths.

There have been several attempts[1-4] made to observe the first four states of F^{16} in the $N^{14}(He^3,n)F^{16}$ reaction. None was successful, although the work of Bryant *et al.*[4] does indicate unresolved structures near the predicted energy of the ground state and at excitation energies $\gtrsim 3$ MeV. Recently, Griffith *et al.*[5] have investigated the $O^{16}(p,n)F^{16}$ reaction using 30- and 50-MeV protons from the Rutherford linear accelerator. A time-of-flight spectrometer analysis of the neutron spectra showed groups attributed to the ground state of F^{16} and to excited states at 4.20 ± 0.05, 6.16 ± 0.05, 7.3 ± 0.3, 9.26 ± 0.05, 11.1 ± 0.1, and 11.7 ± 0.1 MeV, based on a ground state Q value of -16.40 ± 0.11 MeV. The "ground-state" neutron group had an observed width equal to the instrumental width, and the other three neutron groups expected within 1-MeV excitation of the ground state were not observed. From the Q value given above, the atomic mass excess of F^{16} (relative to the C^{12} standard) would be 10.88 ± 0.11 MeV and the Q of the $N^{14}(He^3,n)F^{16}$ reaction would be -1.16 MeV.

In view of the continuing lack of information about the low-lying states of F^{16}, we decided to study the $N^{14}(He^3,n)F^{16}$ reaction using a monoenergetic beam of He^3 particles and a high-resolution time-of-flight system.

EXPERIMENTAL PROCEDURES

The experimental setup consisted of the large Los Alamos electrostatic generator and the time-of-flight equipment and Mobley magnet bunching system described elsewhere.[6-8]

The neutron detector was a 1 in.$\times$5 in. piece of NE-102 plastic scintillator viewed by a 58AVP photomultiplier. The detector was mounted inside a collimator.[8] This assembly could be rotated so as to view neutrons coming at angles of 0 to 156°. The flight path was varied between 2.5 and 4.0 m.

The sensitivity of the detector was obtained by scattering neutrons of known energy from the hydrogen in a polyethylene scatterer.[8] The over-all gain and effective bias of the detection system were adjusted daily on the basis of pulses produced by the 60-keV γ ray from an Am^{241} source, thereby duplicating the conditions under which the detector sensitivity had been determined.

The calibration of the output of the pulse-height analyzer in terms of time was determined by looking at the ground state neutrons from the $C^{12}(He^3,n)O^{14}$ reaction whose Q value (-1.148 MeV) is known to ±0.5 keV.[9,10] On each of the days during which the $N^{14}(He^3,n)F^{16}$ reaction was studied, several runs were made with a carbon target of known thickness.[11] The time per channel was found to be 0.877 ± 0.003 nsec.

An initial attempt[12] to use a nitrogen-gas target gave some indication of four neutron groups in the region of the ground state. However, the 0.05-mil nickel foil which served as the gas-cell window produced sufficient straggling in the He^3 energy that good results could not be obtained. Two types of solid nitrogen targets were used: titanium nitride and chromium nitride. The most satisfactory target proved to be the latter.

The chromium nitride target was prepared[13] at Rice University. It was then spot welded onto a 40-mil-thick Ta cup. This cup was mounted off center with respect to the incident beam, and could be rotated so that the beam either struck the target or the bare cup. An electron barrier, biased 300-V negative with respect to the target, prevented the loss of secondary electrons. The target was air cooled and connected to a current integrator. A background run on the bare Ta cup was made following (or preceding) each of the nitrogen runs. The buildup of carbon on the target was reduced by a large liquid nitrogen cold trap in the vacuum system near the target. The raw data were processed by the IBM 7094 computer at Los Alamos which subtracted the background runs (suitably corrected for any difference in incident-beam charge and analyzer

[2] J. W. Butler, Bull. Am. Phys. Soc. **1**, 94 (1956).
[3] T. W. Bonner, E. A. David, G. U. Din, and H. M. Kuan, in *Proceedings of the International Conference on Nuclear Structure, Kingston*, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960). These preliminary results were later reported by Dr. Bonner to be in error.
[4] H. C. Bryant, J. G. Beery, E. R. Flynn, and W. T. Leland, Nucl. Phys. **53**, 97 (1964).
[5] J. A. R. Griffith, C. J. Batty, R. Gilmore, and G. H. Stafford, in Proceedings of the Low and Medium Energy Nuclear Physics Conference, University of Manchester, 1963 (unpublished); National Institute for Research in Nuclear Science Report NIRL/R/60, 1963 (unpublished); and J. A. R. Griffith (private communication). We are indebted to Dr. Griffith for his kindness in sending us his results prior to publication.
[6] L. Cranberg, R. A. Fernald, F. S. Hahn, and E. F. Shrader, Nucl. Instr. Methods **12**, 335 (1961).
[7] L. Cranberg, J. S. Levin, and C. D. Zafiratos, Bull. Am. Phys. Soc. **8**, 82 (1963).
[8] L. Cranberg, C. D. Zafiratos, J. S. Levin, and T. A. Oliphant, Phys. Rev. Letters **11**, 341 (1963); further details of the experimental set-up will be published shortly.
[9] J. W. Butler and R. O. Bondelid, Phys. Rev. **121**, 1770 (1961).
[10] R. K. Bardin, C. A. Barnes, W. A. Fowler, and P. A. Seeger, Phys. Rev. **127**, 583 (1962).
[11] The target had a thickness of 25 μg/cm^2. It was prepared by Mrs. Judith Gursky by carbon-rod discharge evaporation directly onto a Ta cup which fitted the end of the beam tube. We are indebted to Mrs. Gursky for preparing this target.
[12] L. Cranberg, F. Ajzenberg-Selove, and F. S. Dietrich, (unpublished).
[13] We are indebted to the late T. W. Bonner for this target. The tungsten blank was first heated in vacuum and degassed. Chromium nitride powder was evaporated onto the blank from a tungsten boat. The target was then heated in an induction heater in 11 in. of nitrogen gas pressure for 17 min. This information was kindly supplied to us by Dr. G. U. Din.

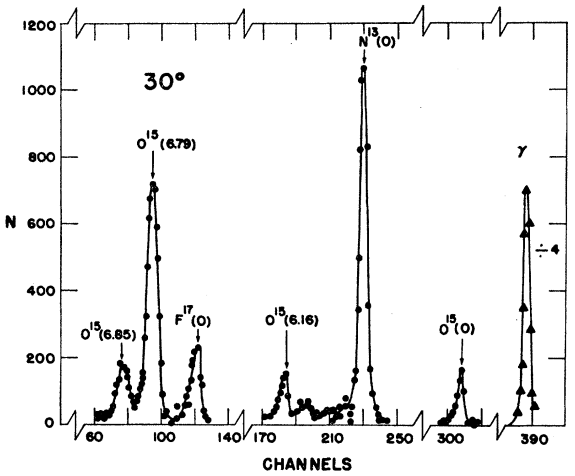

FIG. 1. Spectrum of neutrons from $N^{14}(d,n)O^{15}$ at $E_d=2.58$ MeV ($\theta=30°$; flight path=3.00 m). The group labeled O^{15} (0) is the ground-state group. Groups N^{13} (0) and F^{17} (0) are from the $C^{12}(d,n)N^{13}$ and $O^{16}(d,n)F^{17}$ ground-state reactions. N is the number of counts per channel.

dead time) from the foreground runs, and integrated the resultant spectrum.

In order to determine the mean He^3 energy in the nitrogen target, and thus accurate Q values, and in order to be able to calculate cross sections one needs to know the target thickness. Unfortunately, it had not been determined at the time it was prepared. We were, however, able to determine it indirectly by using the known cross section of the $N^{14}(d,n)O^{15}$ reaction. Excitation curves for the ground-state groups have been measured[14] at several angles for $E_d=0.66$ to 5.62 MeV and complete angular distributions have been determined at 10 energies in this range. The differential cross sections are quoted to $\pm 6\%$. We bombarded the chromium nitride target with 2.58-MeV deuterons, for which a complete angular distribution was available, and observed the neutron spectra at 0, 30, and 110° to the incident beam. Figure 1 shows the 30° spectrum. The number of ground-state neutrons at the three angles was calculated from the total number of counts in each of the three peaks by applying the detector sensitivity correction. Each of the runs was monitored with a charge integrator preset to stop the run at a known charge (178.8 μC).

The differential cross sections[14] at $E_d=2.58$ MeV are 4.4, 4.8, and 1.19 mb/sr at 0, 30, and 110°, respectively. From these values the target was calculated to contain $1.2\times10^{18}N^{14}$ nuclei/cm^2 or 28 μg/cm^2 with an uncertainty of $\pm 12\%$. From range-energy relations[15] this corresponds to a 22 ± 4 keV full width loss in the nitrogen at $E(He^3)=3.5$ MeV and to a 15 ± 3 keV loss at $E(He^3)=6.2$ MeV. Of course, there is also an energy loss in the chromium. The compound CrN involves equal numbers of nitrogen and chromium atoms. The chromium then corresponds to 104 μg/cm^2 and leads to a full energy loss of 60 ± 10 keV and 40 ± 7 keV, respectively, for 3.5 and 6.2-MeV He^3 particles. By comparing the intensity of the carbon contamination group when 3.5-MeV He^3 particles hit the CrN target with the intensity obtained with a carbon target of known weight (25 μg/cm^2), we estimate that the carbon layer on the CrN target was ~ 10 μg/cm^2 thick. The total target thickness (CrN+carbon) is therefore 92 ± 20 keV and 62 ± 20 keV for 3.5- and 6.2-MeV He^3 particles.[16] The mean He^3 energies in the center of the CrN target are then 3.450 ± 0.020 MeV and 6.165 ±0.020 MeV, respectively.[17] These were the input energies which were used to calculate the Q values in the next section. The uncertainty in beam energy and the energy spread introduced by the rf deflection system of the buncher contribute a relatively negligible uncertainty to these energy values.

EXPERIMENTAL RESULTS

Figures 2 and 3 show typical $N^{14}(He^3,n)F^{16}$ time-of-flight spectra at $E(He^3)=3.50$ MeV. The groups labeled 0, 2, and 3, correspond to the ground state and to the second and third excited states of F^{16}. The group labeled C+1 (Fig. 2) is the unresolved composite of the neutron groups to the ground state of O^{14} (from carbon contamination of the CrN target) and to the first excited state of F^{16}. At 156° (Fig. 3), these two groups are partially resolved.

Figure 4 provides additional evidence for the first excited state: The angular distribution of the neutrons from the He^3 bombardment of the 25 μg/cm^2 C^{12} target is compared with the distribution of the neutrons in

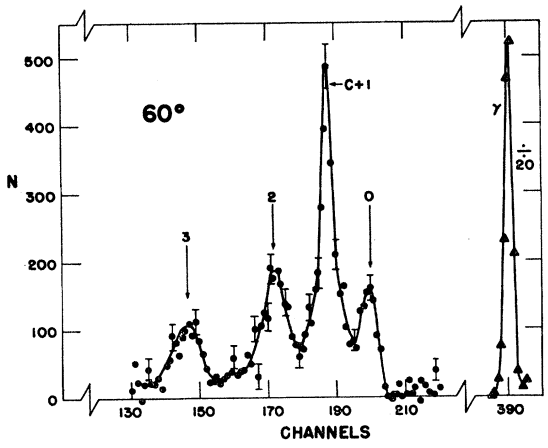

FIG. 2. Spectrum of neutrons from $N^{14}(He^3,n)F^{16}$ at $E(He^3)=3.50$ MeV ($\theta=60°$; flight path=3.00 m). The groups labeled 0, 2, and 3 correspond, respectively, to the ground, second, and third excited states of F^{16}. The group C+1 corresponds to the unresolved groups from $C^{12}(He^3,n)O^{14}$ (0) and the first excited state of F^{16}.

[14] T. Retz-Schmidt and J. L. Weil, Phys. Rev. **119**, 1079 (1960); J. L. Weil, 1964 (private communication). We are much indebted to Professor Weil for sending us corrected values of the differential cross sections.

[15] M. Rich and R. Madey, UCRL-2301, 1954, and D. Demirlioglu and W. Whaling, (unpublished).

[16] These values assume that the target was of uniform thickness.

[17] The errors include contributions from the Van de Graaff and buncher system.

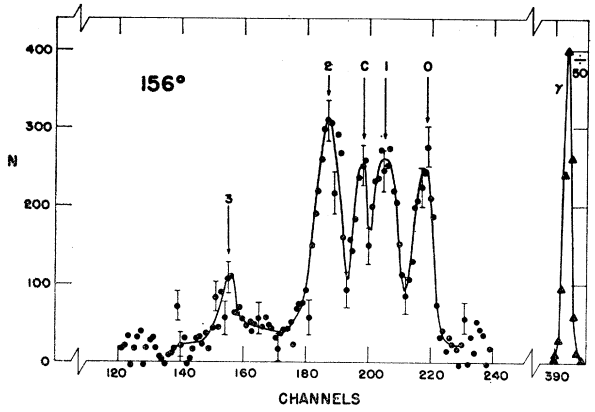

FIG. 3. Spectrum of neutrons from $N^{14}(He^3,n)F^{16}$ at $E(He^3)=3.50$ MeV ($\theta=156°$; flight path=2.60 m). See also caption of Fig. 2.

the composite (C+1) groups from the CrN target. Both distributions were obtained at $E(He^3)=3.50$ MeV. The two curves were normalized at 0°. The "surplus" of neutrons from the composite group, particularly striking at 120 and 156°, is supporting evidence for the first excited state.

The $C^{12}(He^3,n)O^{14}$ angular distribution shown in Fig. 4 is in excellent agreement with the previous work of Towle and Macefield,[18] both as to shape and as to cross section. We find $\sigma(\theta)=2.4$ mb/sr at 0° as compared to their value[19] of 2.2 mb/sr.

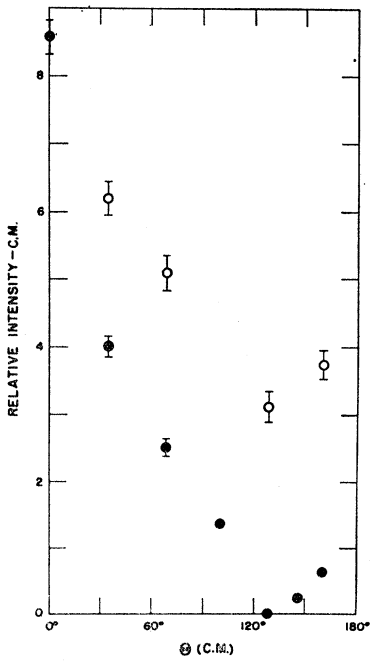

FIG. 4. Angular distribution of neutrons in the center-of-mass system at $E(He^3)=3.50$ MeV. The full points represent the data for $C^{12}(He^3,n)O^{14}$ (0); the circles those for the composite C+1 groups (see Fig. 2 caption). The data were normalized at 0°. See the text for further discussion.

[18] J. H. Towle and B. E. F. Macefield, Proc. Phys. Soc. (London) 77, 399 (1961).

[19] These are approximate values. The value of 2.2 mb/sr is estimated from Fig. 6 of Ref. 18. These are laboratory coordinate system values. Fig. 4 of this paper is plotted in the c.m. system. One unit on the ordinate axis corresponds to 0.20 mb/sr.

TABLE I. States of F^{16}.

Q value[a] (MeV)	E_x (MeV)	Γ (keV)
−0.963±0.040[b]	0	50±30
−1.160±0.060[c]	0.20 ±0.05	<40[d,e]
−1.399±0.040[b]	0.436±0.030	40±30
−1.699±0.050[b]	0.736±0.040	<15[e]
−4.742±0.060[c]	3.78 ±0.06	<40[d,e]

[a] Q value of observed neutron groups in the $N^{14}(He^3,n)F^{16}$ reaction.
[b] Weighted average from data at eight angles; rms deviation <15 keV.
[c] Weighted average from data at two angles; rms deviation <15 keV.
[d] Width derived from results at one angle.
[e] The data are consistent with the state being sharp.

Figure 5 shows the neutron spectrum at $E(He^3)=6.20$ MeV, $\theta=0°$. The groups labeled C and O are due to the $C^{12}(He^3,n)O^{14}$ and $O^{16}(He^3,n)Ne^{18}$ ground state reactions. The intensities of these groups are such that the first four states of F^{16} cannot be observed at this energy. However, the group labeled 4 is due to an excited state of F^{16}~3 MeV above the low-lying quartet of states.

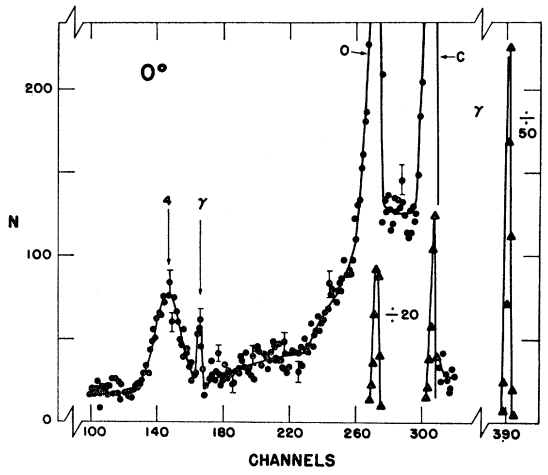

FIG. 5. Spectrum of neutrons from $N^{14}(He^3,n)F^{16}$ at $E(He^3)=6.20$ MeV ($\theta=0°$; flight path=2.50 m). The group labeled 4 corresponds to the $E_x=3.78$-MeV state of F^{16}. The groups C and O are due to carbon and oxygen contamination.

Table I summarizes the Q values of the observed F^{16} groups, the excitation energies of the levels, and their intrinsic widths.

The Q values were obtained by standard calculations using a time per channel, τ_c (as discussed in the preceding section), of 0.877±0.003 nsec/channel. The mean He^3 energy was taken to be 3.45 and 6.16(5) MeV (±20 keV). The errors quoted take account of the rms deviations of the values obtained at the various angles, and the errors in $\bar{E}(He^3)$ and in τ_c.

The widths were obtained as follows: (1) First, preliminary values for the widths of the states were obtained from the observed widths of the neutron groups by converting the observed widths to excitation energy

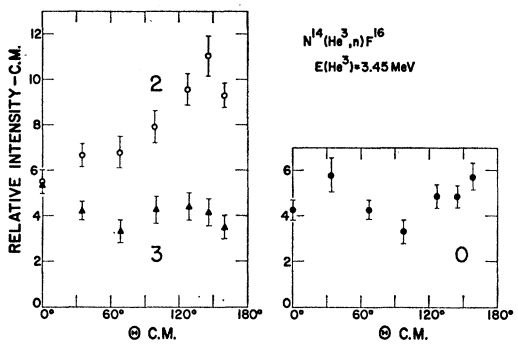

FIG. 6. Angular distribution of neutrons from $N^{14}(He^3,n)F^{16}$ at $\bar{E}(He^3)=3.45$ MeV. The full points depict the ground state data, the circles those due to the 0.44-MeV state, and the triangles show the 0.74-MeV state data.

widths according to the formula

$$\delta E_x=\tfrac{1}{2}\delta E_n\left\{\left(1+\frac{M_3}{M_4}\right)+\frac{1}{E_n}\left[Q+E_1\left(1-\frac{M_1}{M_4}\right)\right]\right\},$$

where δE_n is the full energy width at half-maximum height of the neutron group, E_n is the energy of the center of the neutron group, E_1 is the incident He^3 energy and M_1, M_3, and M_4 are, respectively, the masses of the incident particle, the outgoing particle, and the residual nucleus (He^3, n, and F^{16} in this case). (2) The widths δE_x thus calculated include contributions from the intrinsic resolution of the spectrometer and from target thickness. The true level widths Γ are obtained from δE_x by subtracting these contributions according to the usual rms procedure.

The widths obtained for the first four states of F^{16} are 50 ± 30, <40, 40 ± 30, <15, and <40 keV. These results may be compared with the known widths for proton emission of the first four $T=1$ states in O^{16}. These are[1] 40, 1.2, 110, and 4.1 keV for the 0^-, 2^-, 1^-, and 3^- states, respectively.

While our results do not show any states of F^{16} between $E_x=0.74$ and 3.78 MeV, and while this is consistent with present evidence in the mirror nucleus N^{16}, such states could have been missed if the corresponding neutron groups were broad and/or weak.

Figure 6 shows the angular distributions of the neutrons to the ground state of F^{16} and to the states at 0.44 and 0.74 MeV. The error bars represent the statistical errors as well as estimates of the uncertainties involved in determining the intensities of incompletely resolved groups. Since these are unbound states, reliable direct-interaction analysis of the distributions is not presently possible. The cross section corresponding to one unit on the ordinate axis of Fig. 6 is 0.038 mb/sr ($\pm25\%$).

DISCUSSION

From the $N^{14}(He^3,n)F^{16}$ ground-state Q value, -0.963 ± 0.040 MeV, one can calculate the atomic mass excess of F^{16}:

$$(M-A)=10.686\pm0.040 \text{ MeV}.$$

This corresponds to a F^{16} mass of 16.011473 ± 0.00004 amu. The F^{16}-O^{16} mass difference is 15.43 MeV, and F^{16} is unstable with respect to decay into $O^{15}+p$ by 0.536 MeV.

Figure 7 shows the isobaric diagram for the $A=16$ triad. The usual[20] isobaric correction has been made to the $N^{16}-O^{16}$ and $F^{16}-O^{16}$ mass differences. In calculating the Coulomb-energy difference, the crude assumption of uniform distribution of charge has been made. The isobaric mass differences $N^{16}-O^{16}$ and $F^{16}-O^{16}$ are then 13.0 and 12.4 MeV, respectively, which may be compared with 12.79 MeV, the excitation energy of the first $T=1$ state in O^{16}.

The single-particle shell model predicts that the low-lying structure of N^{16} and F^{16} consists of a cluster of four closely spaced levels, followed by a large energy gap. Two of the levels should have spin and parity 0^- and 1^-, corresponding to the coupling of a $1p_{1/2}$ hole with a $2s_{1/2}$ particle. The other two levels should be 2^- and 3^-, corresponding to the coupling of the $1p_{1/2}$ hole with a $1d_{5/2}$ particle. If the couplings are weak, and since the $2s_{1/2}$ and $1d_{5/2}$ single-particle levels are very close in energy, we may expect the four states to be nearly degenerate. In order to produce other configurations, particles must be elevated through sizeable energy differences between single-particle levels, and therefore an energy gap is expected just above the four lowest lying states. The above arguments apply to the lowest lying $T=1$ states of O^{16} as well as to the N^{16} and F^{16} levels.

In N^{16} and O^{16} the J^π of the first four $T=1$ states

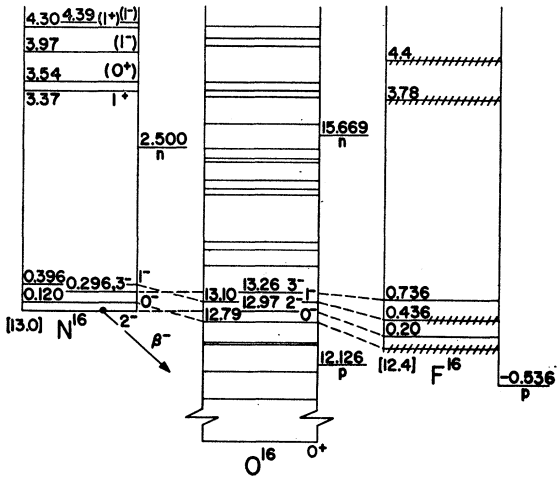

FIG. 7. The mass 16 isobaric triad. The levels whose energies are indicated are $T=1$ states. Corrections have been made for coulomb energy differences and the n-p mass difference. See text for further details.

[20] T. Lauritsen, Ann. Rev. Nucl. Sci. 1, 67 (1952); T. Lauritsen and F. Ajzenberg-Selove, in *American Institute of Physics Handbook* (McGraw-Hill Book Company, Inc., New York, 1957).

are known, and one can compare analogous states. The J^π of the first four states in F^{16} has not been determined, although one can argue that the expected 0^- and 1^- states should be broader than the 2^- and 3^- states. The decay of 0^- and 1^- states to $O^{15}+p$ is by s-wave proton emission while the decay of 2^- and 3^- states involves d-wave protons. This qualitative argument suggests that the 0^- and 1^- states in F^{16} are the ground state and the 0.44-MeV state. The order cannot be determined uniquely but it is suggested by the ordering of the O^{16} states. Similarly, the sharper excited states at 0.20 and 0.74 MeV are presumably the 2^- and 3^- states, respectively. These ambiguities may be resolved when direct interaction theories are applied to unbound states. In the meantime, the angular distributions shown in Fig. 6 cannot be analyzed to furnish information on the J^π of the corresponding states.

One may note that there is a downward shift in the location of the 0^- and 1^-, $T=1$ states in O^{16}, relative to their positions in N^{16}. Such a shift occurs in other isobaric multiplets.[20–22] On the other hand, the 2^- and 3^- states in O^{16} are virtually unshifted from their N^{16} energies (see Fig. 7). The first four states in N^{16} are bound, while the corresponding states in both O^{16} and F^{16} are unbound. The high orbital angular momentum of the decay of the 2^- and 3^- states, which involves emission of the $1d_{5/2}$ nucleon, inhibits the downward energy shift which is characteristic of unbound single-particle levels.[21] If the unbound channel in O^{16} accounts for the difference in level ordering in N^{16} and O^{16}, then we may expect that the ordering in F^{16} should be the same as in O^{16}, since F^{16} and the $T=1$ O^{16} levels are unbound by nearly the same amount. This result is consistent with our suggestions for the level ordering.

If the ground state of F^{16} is O^-, as seems probable, the mirror nuclei N^{16} and F^{16} have different ground state angular momenta. This is unusual, but not, of course, very significant.

The 3.78-MeV excited state of F^{16} reported in this work has a width of <40 keV. In N^{16}, five states have recently been reported[23] at 3.37-, 3.54-, 3.97-, 4.30-, and 4.39-MeV excitation, from the observation of resonances in the total neutron cross section of N^{15}. These states have $J^\pi=1^+$, (0^+), (1^-), (1^+), and 1^-, and their widths are 30, 20, ≤ 10, ≤ 15, and 55 keV. We are not able to identify which of these states is the analog of the F^{16} state at 3.78 MeV.

ACKNOWLEDGMENTS

We are much indebted to the staff of the P-9 group, and in particular to Dr. J. L. McKibben, R. Woods, H. J. Lang, Marie Murphy, and R. Luders for their generous assistance. The encouragement and guidance of Professor L. Cranberg and Dr. McKibben are deeply appreciated. This experiment could not have been performed without the excellent chromium nitride target which was given to Dr. Cranberg by the late T. W. Bonner, and which Dr. Cranberg generously made available to us.

[21] R. G. Thomas, Phys. Rev. **88**, 1109 (1952); J. B. Ehrmann, *ibid.* **81**, 412 (1951).

[22] J. P. Elliott and B. H. Flowers, Proc. Roy. Soc. (London) **A242**, 57 (1957); see, in particular, Sec. 9.

[23] D. B. Fossan, R. A. Chalmers, L. F. Chase, Jr., and S. R. Salisbury, Phys. Rev. **135**, B1347 (1964).

PHYSICAL REVIEW VOLUME 137, NUMBER 6B 22 MARCH 1965

Determination of Spins of Neutron Resonances and the Hyperfine Coupling Constant in Ho^{165}†

G. BRUNHART, H. POSTMA,* AND V. L. SAILOR
Brookhaven National Laboratory, Upton, New York
(Received 11 November 1964)

Neutron transmission measurements on targets of polarized holmium nuclei were extended using a holmium single crystal. Owing to the large hyperfine coupling in holmium and the complete magnetization of the single-crystal sample, it was possible to make spin determinations for the compound states corresponding to the neutron resonances at 18.2 eV and 21.3 eV. The spins were both found to be $I-\frac{1}{2}=3$. The nuclear polarization of the sample was obtained as a function of temperature at the 3.924-eV resonance and the data were fitted to a theoretical curve with the magnetic and electric hyperfine splitting constants as fitting parameters. The results for the magnetic and electric hfs constants are, respectively, $A/k=0.610\pm0.005$°K and $P/k=0.002\pm0.001$°K. This corresponds to an effective magnetic field at the nucleus of 8.8×10^6 Oe.

I. INTRODUCTION

THE usefulness of the method to determine the spin of low-energy neutron resonances by the transmission of polarized neutrons through samples of completely or partially polarized nuclei has been demon-

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

* Permanent address: Kamerlingh Onnes Laboratory, Leiden, The Netherlands.