$T = 3/2$ levels in ^{15}F and ^{15}O

W. Benenson, E. Kashy, A. G. Ledebuhr, R. C. Pardo, R. G. H. Robertson, and L. W. Robinson
Cyclotron Laboratory and Physics Department, Michigan State University, East Lansing, Michigan 48824
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The ^{20}Ne(^{3}He,^{8}Li) reaction has been used to study the particle-unstable nucleus ^{15}F. The ground state of ^{15}F is observed as a broad peak at a mass excess of 16.9 ± 0.2 MeV with a width greater than 900 keV. A well defined narrower peak is observed at a mass excess of 18.088 ± 0.025 MeV and with a width of 240 ± 30 keV. It is shown to be the mirror of the $5/2^+$ first excited state of ^{15}C. The analog of the $5/2^+$ state was observed in ^{15}O at $E_x = 12.255 \pm 0.013$ MeV. This state is shown to proton decay to the $T = 1$ first excited state of ^{14}N and to have a width of 135 ± 15 keV.

[NUCLEAR REACTIONS ^{20}Ne(^{3}He, ^{8}Li)^{15}F^{17}O$(p,t)^{15}$O ($T=\frac{3}{2}$) measured reaction Q values, $\Gamma_{c.m.}$; deduced mass excesses, excitation energies. Deduced coefficients IMME.]

I. INTRODUCTION

Because it would be the mirror of ^{15}C, which has a $1/2^+$ ground state, and because it is predicted to be approximately 2 MeV unbound to proton decay, one would expect ^{15}F to have a very broad ground state. The situation is in fact very similar to ^{11}N, the ground state of which would also be $1/2^+$ and has proven to be unobservable in multinucleon transfer reactions.[1] The first excited state of ^{11}N, however, was observed as a broad, asymmetric peak in the ^{14}N(^{3}He,^{6}He) reaction.[1] The present experiment is one of the first attempts to measure the mass and energy levels of ^{15}F. The reaction used was ^{20}Ne(^{3}He,^{8}Li) at 75 MeV, and the resulting spectra show clear evidence for the $5/2^+$ first excited state and somewhat weaker evidence for the ground state.

To support the above identifications of ^{15}F states, the ^{17}O(p,t)^{15}O reaction was used to search for the unknown analogs of the ^{15}F levels in ^{15}O. The first excited state analog was located and identified both by its spin and isospin. The resulting completed mass quartet agrees well with the isobaric multiplet mass equation.[2]

II. EXPERIMENTAL METHOD AND RESULTS

In the present paper three separate experiments will be discussed. The first is the study of ^{15}F by the ^{20}Ne(^{3}He,^{8}Li) reaction, and the other two are investigations of T = 3/2 states in ^{15}O. Details and results of these experiments are described below.

A. ^{20}Ne(^{3}He,^{8}Li) Reaction

Spectra from the ^{20}Ne(^{3}He,^{8}Li) reaction were taken at 9°, 10°, 11°, and 13° utilizing two different gas target systems. About 1 μA of 74.5 MeV ^{3}He particles from the Michigan State University Cyclotron bombarded the target, and the ^{8}Li-particles were detected on the focal plane of an Enge split-pole spectrograph using a method identical to that described previously.[3] The 10° data were taken in the same fixed-angle gas cell which was used in other mass measurements.[4] The 9°, 11°, and 13° data were taken in a new cell which has variable angle capability by means of the conventional extended exit foil and movable collimator. The exit foil thickness which was required, 2.2 mg/cm^2 of Ni, led to greater energy loss corrections than were made for the fixed cell, which used a 0.45 mg/cm^2 Mylar foil. Both cells held a gas pressure of 150 to 200 torr of isotopically enriched (99.95%) ^{20}Ne. A previous run with a non-enriched Ne at 10° was not included in the present analysis since the 9.5% of ^{21}Ne and ^{22}Ne seem to produce a non-negligible background.

A sum of all the 10° data (Q = 75 000 μC) is shown in Fig. 1. The peak labelled A is due mainly to the ground state of ^{15}F which is apparently very broad since it can decay with an L = 0 proton of an energy right at the top of the Coulomb barrier. Some of the yield may be attributable to the ^{20}Ne(^{3}He,^{8}Li)^{14}O + p reaction, but is is impossible to ascertain how much. In addition, the upper edge of peak A is obscured by the peak labelled B which is the mirror of the $5/2^+$, 740 keV state of ^{15}C as will be shown below. The cross section for producing this state at 10° is quite large, 0.25 ± 0.02 μb/sr, as would be expected from simple shell model considerations. The data taken at 9°, 11°, and 13° have somewhat poorer statistics but show that the peak labelled B has the correct kinematics for the ^{15}F state. All the data were used in determining the mass excess and width of the peak as described below. The peak labelled C corresponds to both ^{8}Li and ^{15}F being left in their first excited states, and its shape shows the effect of the decay in flight of ^{8}Li. A small peak just to the left of C is the ^{14}N(^{3}He,^{8}Li) reaction from a slight air contamination of the gas.

The energy scale was calibrated by means of the

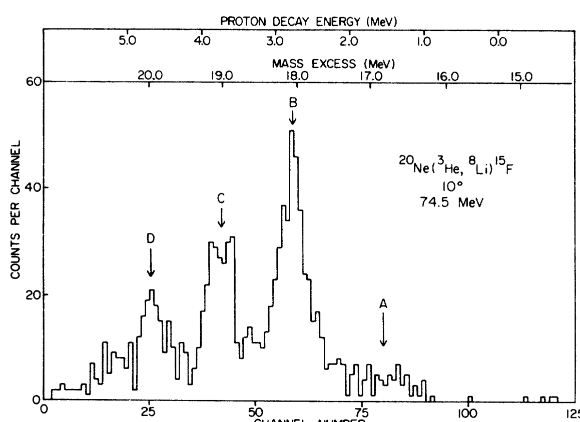

FIG. 1. Spectrum from the ^{20}Ne(^{3}He,^{8}Li) reaction at 10° and 74.5 MeV.

TABLE I. T = 3/2 Levels in A = 15.

Nucleus	T_z	Spin	M.E. (MeV)	E_x (MeV)	Γ (keV)	Ref.
^{15}F	-3/2	$1/2^+$	16.9 ± 0.2	0.0	> 900	Present
^{15}O	-1/2	$1/2^+$	unknown			
^{15}N	1/2	$1/2^+$	11.717 ± 0.004	11.615 ± 0.004	405 ± 6	Ref. 9
^{15}C	3/2	$1/2^+$	9.873 ± 0.0008	0.0	bound	Ref. 9
^{15}F	-3/2	$5/2^+$	18.088 ± 0.025	1.19 ± 0.2	240 ± 30	Present
^{15}O	-1/2	$5/2^+$	15.118 ± 0.017	12.255 ± 0.013	135 ± 15	Present
^{15}N	1/2	$5/2^+$	12.624 ± 0.008	12.522 ± 0.008	58 ± 4	Ref. 9
^{15}C	3/2	$5/2^+$	10.613 ± 0.0015	0.740 ± 0.0015	bound	Ref. 9

$^{20}Ne(^3He,^7Be)$ and $^{14}N(^3He,^8Li)$ reactions. In addition, the energy loss corrections were checked by means of $^{14}N(^3He,^6Li)$, $^{14}N(^3He,^7Li)$ and $^{20}Ne(^3He,^6Li)$. These corrections, which were as large as 1.2 MeV, led to discrepancies of at most 50 keV between the reactions. Fortunately the two calibration reactions had calculated energy losses within 70 keV of the primary reaction, and therefore the uncertainty in the difference between these corrections was only about 10 keV. The internal error of the measurements was 25 keV which reflects quite well the uncertainties associated with the experiment such as those in the energy loss corrections, and beam energy, angle and centroid determination. The final value for the Q value is −31.146 ± 0.025 MeV and the corresponding mass excess of the $5/2^+$ state is 18.088 ± 0.025 MeV.

The width of the $5/2^+$ peak was determined by fitting a Gaussian to it with a small linear background. The resulting width in ^{15}F is 240 ± 30 keV. A large part of the uncertainty comes from determining the width of the resolution function which was both calculated and measured in the $^{14}N(^3He,^8Li)$ run and found to be 210 ± 20 keV. The ground state peak was investigated by subtracting from the spectrum the Gaussian peak fitted to the $5/2^+$ state. The resulting peak was then fitted by a Gaussian, and a width of 1.2 ± 0.3 MeV was obtained. If the width had been much less than 0.9 MeV, the two peaks would have been resolvable and the error would be considerably lower. The lack of a minimum between the ground and first excited state peaks makes a mass excess determination for the ground state difficult. Using the decomposition described above, the mass excess of the ground state is found to be 16.9 ± 0.2 MeV. This value is consistent with the A = 15, T = 3/2 level systematics given in Table I. These data on ^{15}F are in good agreement with the results of Kekelis et al.,[5] who studied the same reaction at 75 and 88 MeV, except for the width of the first excited state which is much narrower in the present work.

It is possible to estimate whether the widths found for the ground and first excited states of ^{15}F are consistent with what one would expect on theoretical grounds. A real Woods-Saxon well with the parameters $V = -47.0$ MeV, $r = 1.25$ fm, $a = 0.65$ fm, $V_{SO} = 8.0$ MeV, $r_{SO} = 1.12$ fm, $a_{SO} = 0.65$ fm was used to study quasibound states with spins $1/2^+$ and $5/2^+$. These parameters are very close to standard ones except that they were slightly adjusted to put the $5/2^+$ state at the correct binding energy. The wavefunction amplitude inside the nucleus for a normalized external incident proton wave was then calculated as a function of proton energy. The resulting $|\psi|^2$ from the calculations, which is shown in Fig. 2, bears a striking resemblance to the data because the states in question are of almost perfect single particle character. The spectroscopic factor obtained by comparing the experimental width to that calculated for the $5/2^+$ state is 0.92 ± 0.12 in excellent agreement with the shell model calculations of Reehal and Wildenthal[6] (0.94) and the measurements of the spectroscopic factor for the mirror level in ^{15}C which range from 0.76 to 1.03 depending on the details of the DWBA calculations.[7] The calculations in Fig. 2 also show that it is somewhat meaningless to discuss the width of the ground state of ^{15}F and that the lack of a minimum between the two states in the $(^3He,^8Li)$ spectrum is a consequence of the absence of a centrifugal barrier for the proton decay of the $1/2^+$ state and its essentially unit spectroscopic factor.

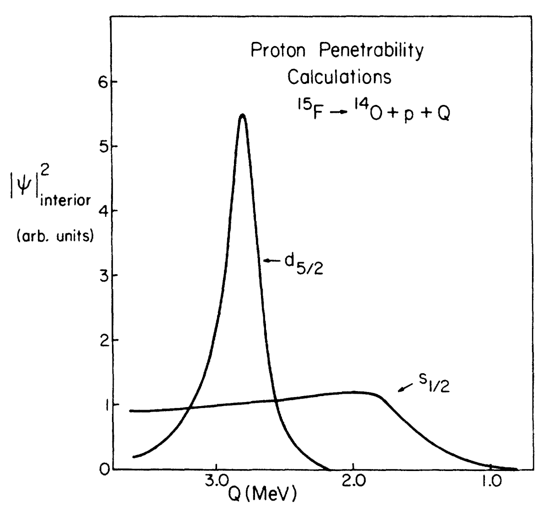

FIG. 2. Result of calculations to estimate the width of unbound single particle states in ^{15}F. The method is described in the text.

B. The $^{17}O(p,t)$ singles experiment

To help identify the ^{15}F states, their analogs were searched for in ^{15}O by means of the $^{17}O(p,t)$ reaction at 45 MeV. A 50 cm long slanted-cathode delay-line counter was used on the focal plane. The target was 70 μg/cm^2 of WO_3 enriched to 70% ^{17}O on a gold backing. The isobaric multiplet mass equation was used to predict the excitation energy of the states using b and c coefficients from systematics and the known energies of ^{15}C and ^{15}N, T = 3/2 states . The $5/2^+$ state is predicted to lie directly under $^{12}C(p,t)^{10}C$ g.s. and to have a width much greater than the experimental resolution, 15 keV. As can be seen in Fig. 3, there is a broad peak in the region of interest, and it is possible to extract an angular distribution as is shown in Fig. 4. The shape is very similar to $^{16}O(p,t)^{14}O$ (g.s.) taken at the same energy. The L = 0 shape shows the state to be $5/2^+$ but does not prove it to be T = 3/2. The excitation energy found by fitting a Gaussian to the data at all angles is $E_x = 12.244 \pm 0.020$ MeV, and the width was found to be 130 ± 20 keV. No indication of the $1/2^+$ ground state analog was observed in the data, probably because the $^{17}O(p,t)$ reaction did not populate the level strongly.

C. Proton-decay of the T = 3/2 states in ^{15}O

The state which was observed in the $^{17}O(p,t)^{15}O$ reaction at 12.244 MeV is broad because its proton decay is allowed by energy and isospin conservation to the T = 1, 2.31 MeV state of ^{14}N. In fact, the signature of the state as compared with the T = 1/2 background levels would be its decay to the 2.31 MeV state and not the ground state of ^{14}N. Therefore the proton decay of this region of excitation in ^{15}O was studied in a coincidence experiment. A 200 mm^2, 700 μm thick silicon surface-barrier detector was placed at 90° to the beam and 5 cm from the beam spot on target. A conventional fast-slow coincidence arrangement was used. Along with the six signals from the focal plane detector, which was the same double wire charge-division counter used in the ^{15}F experiment, the energy signal from the silicon detector and the time relative to the wire counter were recorded in the computer. The data were taken at 42 MeV and 28°. The raw data without any corrections for chance coincidences are shown in Fig. 5. A broad peak decaying to the T = 1 state is clearly visible. By comparison to the singles spectrum shown on the top of Fig. 4, its excitation energy was established to be 12.263 ± 0.017 MeV. The uncertainty is almost entirely statistical because of the small number of counts in the peak. The other peaks marked with energies are known, narrow ^{15}O states. The width of the state is 140 ± 40 keV which includes a correction for the 20 keV resolution of the system. Unfortunately no indication of the $1/2^+$, T = 3/2 state was obtained. The excitation energy and mass excess of the $5/2^+$, T = 3/2 state in ^{15}O given in Table I is a weighted average of the two measurements, ($E_x = 12.255 \pm 0.013$ and $\Gamma_{c.m.} = 135 \pm 15$ keV).

III. DISCUSSION

The results of the present experiment are summarized in Table I along with all the other information known on T = 3/2 states in the A = 15 system. The coefficients of the isobaric multiplet equation which fit the A = 15 data are given in Table II. The ground state quartet is lacking

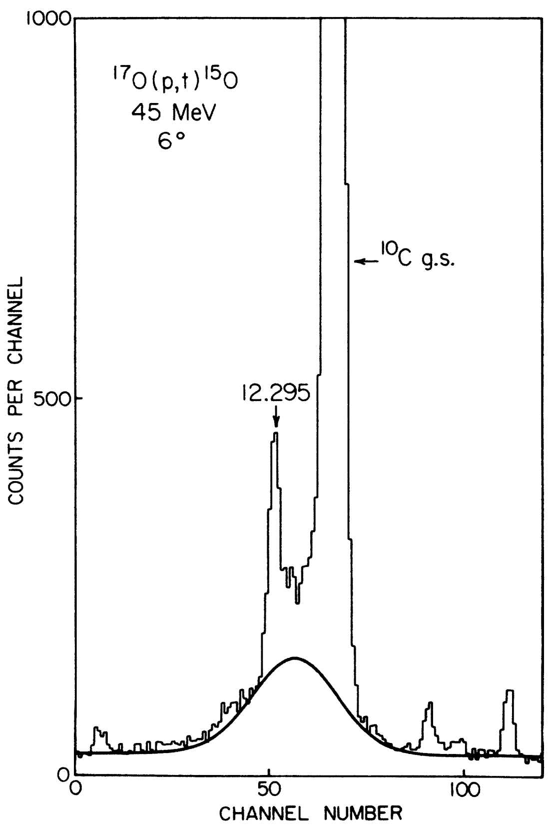

FIG. 3. A portion of the high resolution spectrum of $^{17}O(p,t)$ at 45 MeV and 6°. The curve is the background plus broad Gaussian component of a fit made to the data.

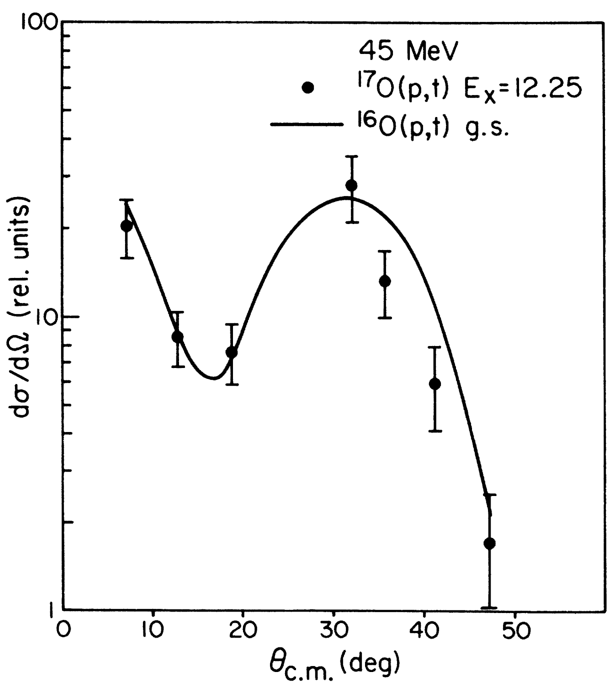

FIG. 4. Angular distribution of the broad Gaussian peak unfolded from the $^{17}O(p,t)$ spectra. The solid curve is a smooth line drawn through $^{16}O(p,t)^{14}O$ g.s. data taken at the same energy.

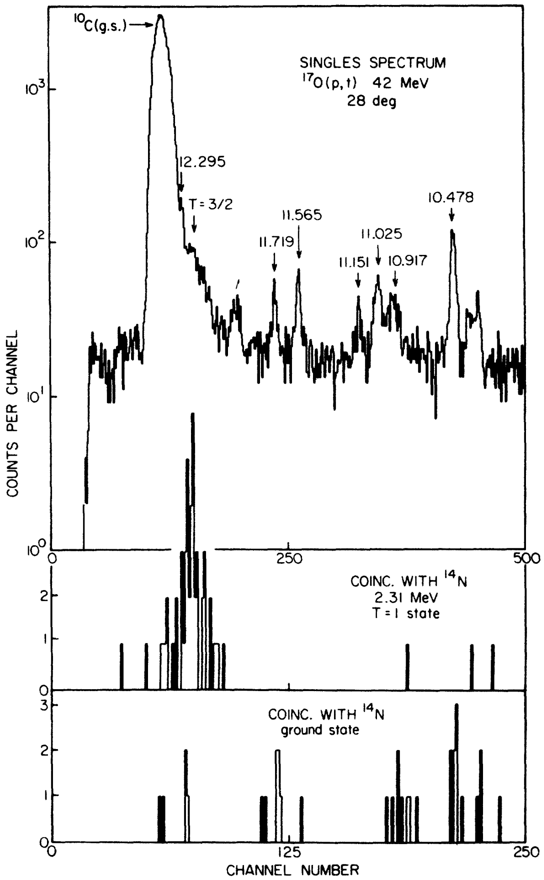

FIG. 5. Spectra taken in singles and in coincidence with proton decays to the ^{14}N ground and T = 1 first excited state.

one member, but the coefficients are given anyway to compare to the complete $5/2^+$, first excited state quartet. The b coefficient, which is essentially a Coulomb displacement energy, shows clearly the effect of the

TABLE II. Coefficients of the isobaric multiplet mass equation for mass excesses of the ground and first excited states of the A=15 system (keV).

J	a	b	c	d	χ^2
$1/2^+$	12826±25	-2342±66	249±33	----	---
$5/2^+$	13807± 9	-2485±17	242± 7	-3±9	---
$5/2^+$	13808± 8	-2490± 7	240± 6	----	0.3

absence of the centrifugal barrier for the $1/2^+$ state.

The ground state quartet of the A = 15 system would make a very interesting case since in ^{15}F the state lies at the top of the Coulomb barrier, and there is no centrifugal barrier for the proton decay. The ^{20}Ne(^{3}He,^{8}Li) reaction makes ^{15}F preferentially in its $5/2^+$ state, but it is conceivable that the ^{19}F(^{4}He,^{8}He) reaction would populate the ground state more favorably and lead to a more unambiguous identification. It is possible that the analog of the ground state in ^{15}O could be observed in a coincidence experiment like the one described above but with larger solid angles and a much longer counting time. In any case the 5/2 quartet is one of the most unbound complete quartets containing three quite broad levels, and it therefore provides additional proof that the quadratic form of the isobaric multiplet mass equation works as well for unbound levels as it does for bound or quasibound levels.

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[1] W. Benenson, E. Kashy, D.H. Kong-A-Siou, A. Moalem, and H. Nann, Phys. Rev. C 9, 2130(1974).
[2] E.P. Wigner, in Proceedings of the Robert A. Welch Foundation Conferences on Chemical Research, Houston, Texas, 1957, Edited by A. Milligan (Robert A. Welch Foundation, Houston, Texas, 1957). The Structure of the Nucleus, p. 67.
[3] W. Benenson, E. Kashy, I.D. Proctor, and B.M. Preedom, Phys. Lett. 43B, 117(1973).
[4] H. Nann, W. Benenson, E. Kashy, and P. Turek, Phys. Rev. C 9, 1848(1974).
[5] G.J. Kekelis, M.S. Zisman, D.K. Scott, R. Jahn, D.J. Vieira, Joseph Cerny, and F. Ajzenberg-Selove Phys. Rev. (preceding paper).
[6] B.S. Reehal and B.H. Wildenthal, Particles and Nuclei 6, 137(1973).
[7] F.E. Cecil, J.R. Shephard, R.E. Anderson, R.S. Peterson, and P. Kaczkowski, Nucl. Phys. A255, 243(1975).
[8] R.G. Markham and R.G.H. Robertson, Nucl. Instr. and Methods 129, 131(1975).
[9] F. Ajzenberg-Selove, Nucl. Phys. A268, 1(1976).