PHYSICAL REVIEW C VOLUME 8, NUMBER 2 AUGUST 1973

^{15}C States via the ^{14}C(d, p)^{15}C Reactions*

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(Received 21 May 1973)

Protons from the ^{14}C(d, p)^{15}C reaction were analyzed with a magnetic spectrograph. Data were taken at the bombarding energies of 12.0, 13.0, and 14.0 MeV at the observation angles of 60, 90, and 120°. Nine states were found in ^{15}C between the ground state and the 7.35-MeV region of excitation. Excitation energies and uncertainties in keV are 744.1 ± 2, 3105.3 ± 5, 4221.1 ± 3, 6428.1 ± 7, 6539.8 ± 5, 6844.9 ± 5, 6882.4 ± 5, 7097.2 ± 6, and 7351.3 ± 6. Widths of approximately 42 and 61 keV were measured for the levels at 3105.3 and 6428.1 keV, respectively. Uncertainties in excitation energies are reduced by almost an order of magnitude from previous work.

INTRODUCTION

Recent attempts[1,2] to identify the $T=\frac{3}{2}$ states in ^{15}N have pointed out the need for accurate information concerning the energy-level spectrum of ^{15}C. The level structure of ^{15}C is very poorly known and many of the levels are indicated in the latest compilation[3] as being doubtful. The large neutron excess of ^{15}C limits the number of reactions which are feasible and the low binding energy (1.218 MeV) means that the excited states soon become unbound and lie in a continuum background. The two charged-particle reactions which can most easily be studied are ^{9}Be(^{7}Li, p)^{15}C and ^{14}C(d, p)^{15}C, but little information about these reactions, especially concerning excitation energies, has been published. In the present work the ^{14}C(d, p)^{15}C reaction was studied with our 100-cm modified broad-range magnetic spectrograph[4] and the results of these measurements are reported below.

EXPERIMENTAL

The target was 60% enriched ^{14}C deposited on a thin (0.12-μm) Ni foil and was approximately 14 keV thick to 13-MeV deuterons. The deuteron beams were produced with the University of Notre Dame F. N. tandem Van de Graaff accelerator and the nominal input energy was determined by magnetic analysis. The reaction products were momentum analyzed with the spectrograph and nuclear track plates were used as particle detectors. The track length and intensity gave conclusive particle identification.

A total of six runs was made. Data were taken at the nominal input energies of 12.0, 13.0, and 14.0 MeV and at the observation angles of 60, 90, and 120°. The target was placed in reflection geometry in all runs to minimize the effect of target thickness on the measurement of the excitation energies. Excitation energies were measured with respect to the ground state. A proton spectrum taken at 60° with a bombarding energy of 14.012 MeV is shown in Fig. 1. The large continuum background clearly dominates the spectrum. Proton groups leading to states in ^{15}C are labeled with the excitation energy. The contaminant groups are labeled with the symbol for the residual nucleus and its excitation energy. The small peak on the low-energy side of each group arises from a small amount of target material on the back side of the Ni foil. The ^{13}C groups which are also indicated on the figure allow a convenient check of the calibration.

RESULTS AND DISCUSSION

The results of the present work are given in Table I. The number of times a level was observed is given in column 1 and the standard deviation of the mean is listed in column 4. The uncertainties given for our excitation energies are the internal errors calculated according to standard procedures described in Ref. 5. These include estimates of uncertainties in the following quantities: the position of a group on the plate, beam-spot position, reaction angle, input energy, spectrograph field, and spectrograph calibration curve. We found two of the levels to be significantly wider than our experimental resolution of approximately 14 keV. These groups were fitted by computer using an incoherent sum of a simple Breit-Wigner resonance term and a quadratic background term. The widths obtained were corrected for finite-target thickness and kinematic broadening. Because of the large continuum background and the sensitivity of width measurements to an accurate description of the background, only estimates for the widths are given. A comparison with other work is given in the remaining columns of the table.

Little work on the ^{14}C$(d,p)^{15}$C reaction has previously been reported. The ^{14}C$(d,p)^{15}$C results of Moore and McGruer[6] tabulated in Table I, are taken from the latest compilation of Ajzenberg-Selove.[3] The excitation energies given there are not precisely those given in Ref. 6 and the level at 4.21 MeV and the uncertainties in the excitation energies were not mentioned in the reference. For those levels which were observed in both experiments, agreement within stated uncertainties is good. Though we observe more levels above 6.4 MeV than Moore and McGruer, the levels at 5.94 and 6.38 MeV seen by them are not observed in the present work. Their measurements were made at observation angles ranging from 2 to 90° whereas our most forward angle was 60°. At 60° a group corresponding to 6.370 MeV in ^{15}C is observed (see Fig. 1), but as it was not seen in the other runs, it was not possible to positively identify it as a ^{15}C group. The difference in angular ranges in the two experiments might explain the apparent discrepancy in the number of levels seen.

Our work generally agrees well with previous studies of the ^{9}Be(^{7}Li$,p)^{15}$C reaction; however there are some differences. The level observed by Murphy[7] at 2.48 MeV is not observed in the present work nor was it seen in other ^{9}Be(^{7}Li$,p$)-^{15}C studies.[8-10] If such a level, however, had a width greater than 100 keV and were weakly populated (i.e., less than 30 counts above background), it would not be observable in our data.

Measurements with the ^{9}Be(^{7}Li$,p)^{15}$C reaction were very recently reported by Ajzenberg-Selove, Bingham, and Garrett.[10] The levels they see at

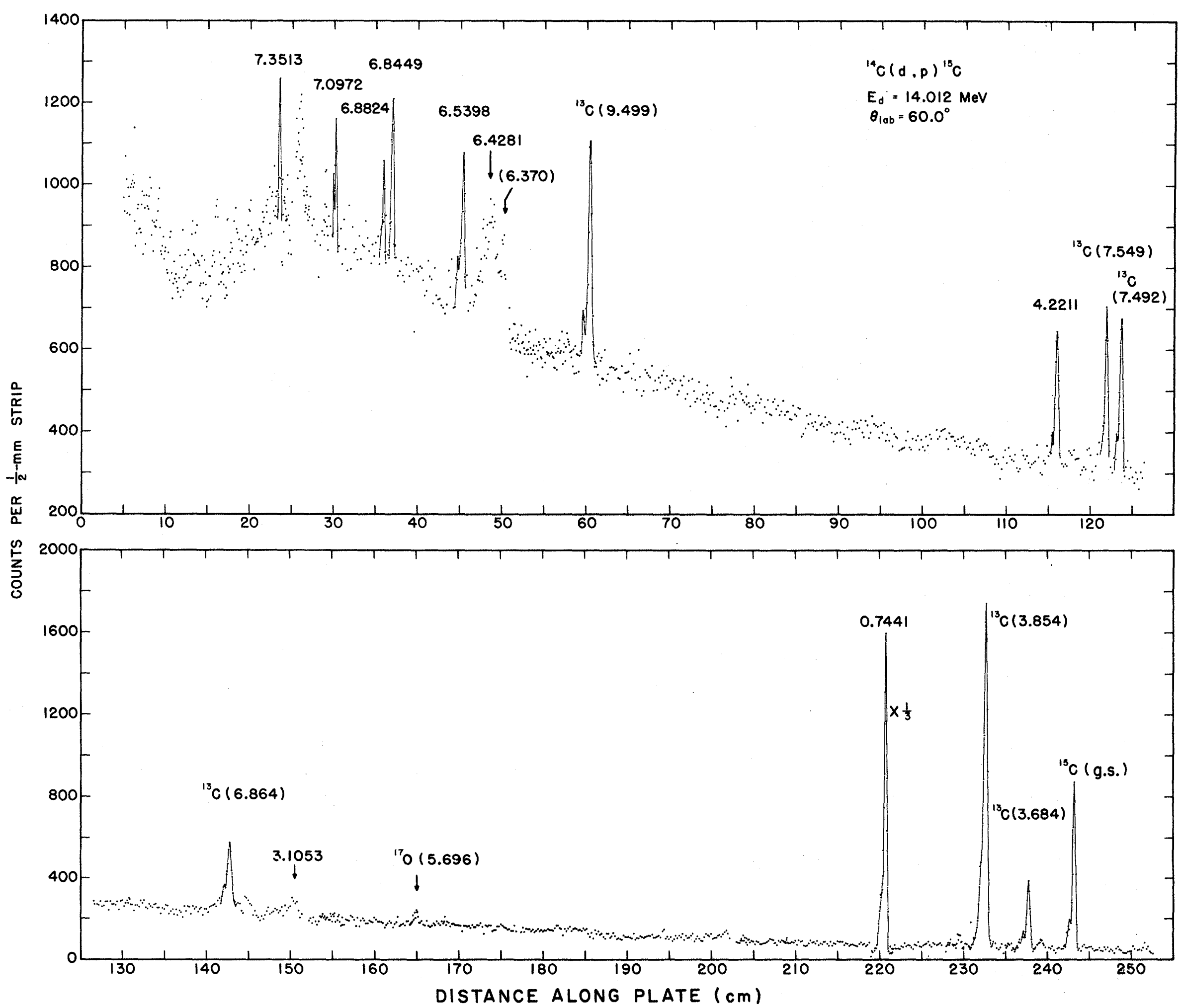

Fig. 1. Proton spectrum from the ^{14}C$(d,p)^{15}$C reaction measured at 60° and 14.012-MeV bombarding energy. Proton groups leading to states in ^{15}C are labeled with the excitation energy. The contaminant groups are labeled with the symbol for the residual nucleus and its excitation energy.

TABLE I. Levels in ^{15}C.

No. of Runs	Present work Excitation energy (MeV ± keV)	σ_m (keV)	Γ_m (keV)	Excitation energies (MeV ± keV) ^{14}C$(d,p)^{15}$C (Ref. 6)	^{9}Be$(^{7}$Li$,p)^{15}$C (Ref. 7)	^{9}Be$(^{7}$Li$,p)^{15}$C (Ref. 8)	^{9}Be$(^{7}$Li$,p)^{15}$C (Ref. 10)
6	g.s.			g.s.	g.s.	g.s.	g.s.
6	0.7441 ± 2.0	0.2		0.75 ± 30	0.62 ± 60	0.74 ± 30 [a]	0.75 [b]
					2.48 ± 50		
4	3.1053 ± 5.0	1.4	≈42	3.09 ± 30	3.08 ± 40	3.08 ± 30	3.10
6	4.2211 ± 3.0	1.1		4.21 ± 30	4.26 ± 40	4.16 ± 30	4.23
						4.60 ± 30	(4.55)
						5.81 ± 30	5.84
				5.94 ± 30	5.93 ± 40		5.87
				6.38 ± 30		6.39 ± 30	6.38
4	6.4281 ± 7.0 [c]	4.0	≈61				6.44
							6.47
3(4)	6.5398 ± 5.0	1.3			6.58 ± 40	6.58 ± 30	6.55
							6.65
5	6.8449 ± 5.0	1.3				6.84 ± 30	6.85
4	6.8824 ± 5.0	1.2					6.90
3	7.0972 ± 6.0	1.0				7.06 ± 30	7.11
3	7.3513 ± 6.0	1.7		7.32 ± 30		7.31 ± 30	7.36

[a] Uncertainty given in Ref. 3.
[b] Preliminary values, uncertainties ± 15 to 30 keV, see Ref. 9.
[c] Possibility that this level is a doublet is discussed in the text.

5.84, 5.87, 6.38, and 6.65 MeV and the possible level at 4.55 MeV are also not observed in the present work. The authors do not indicate that these levels are broad, so it is unclear why they were not seen in our work. Possibly some of the levels have high spin and are not populated by the ^{14}C$(d,p)^{15}$C reaction. As mentioned above, states have been seen with the ^{14}C$(d,p)^{15}$C reaction by Moore and McGruer[6] at 5.94 and 6.38 MeV which we did not observe, so that reaction conditions may have determined which levels were populated in our work.

We measured the levels at 3.1053 and 6.4281 MeV to have natural widths of approximately 42 and 61 keV, respectively. The relatively large standard deviation of the mean (4 keV) for the 6.4281-MeV state suggests that there may be more than one state here. Two close-lying levels are observed at 6.44 and 6.47 MeV by Ajzenberg-Selove, Bingham, and Garrett.[10] Our data are insufficient to do more than suggest the possibility of a doublet here, but the width we obtain would indicate that if there are two levels, at least one of them has a natural width of about 50 keV.

SUMMARY

Accurate excitation energies of levels in ^{15}C up to 7.35 MeV have been measured with the ^{14}C(d,p)-^{15}C reaction. Uncertainties in excitation energies are as much as a factor of 8 lower than those in previous work. Approximate widths for two of the levels have been given and the possibility that the level at 6.4281 MeV is a doublet has been discussed. Agreement with other work where comparisons can be made is in general quite good. In the region of excitation above 6.4 MeV the agreement of excitation energies and the number of levels observed in the ^{14}C$(d,p)^{15}$C and the most recent study[10] of the ^{9}Be$(^{7}$Li$,p)^{15}$C reaction is excellent. In the region between 4.55 and 6.4 MeV, three or possibly four levels are observed in other work which are not seen by us. Possible explanations for this are given in the text. Because of the large background, broad states, i.e., $\Gamma > 100$ keV would probably be missed in the present work.

ACKNOWLEDGMENTS

The authors would like to thank G. L. Marolt for help with the fitting of the broad groups and the plate counters: Patricia Huston, Linda Thorpe, Debbie Smith, and Ildiko Molnar for the counting of several million proton tracks.

*Research supported by the National Science Foundation under Grant No. GP-27456.

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