HIGH-LYING NEUTRON-HOLE STATES POPULATED IN THE REACTION

$^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ at 62 MeV.*

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ABSTRACT

The single-nucleon pick-up reaction $^{13}\text{C}(p,d)^{12}\text{C}$ at 62 MeV has been employed to study high-lying states in ^{12}C . States are seen at excitation energies $E_x = 17.79, 18.84, 21.5$ and 22.5 MeV in ^{12}C , and the lp neutron-hole strength found is in qualitative agreement with theoretical predictions. However, the lp neutron-hole strength at high excitation is distributed over more states than predicted by intermediate coupling shell model calculations.

I. INTRODUCTION

The experimental and theoretical study of the structure of the high lying states in ^{12}C (states at excitation energies $E_X > 15$ MeV) has achieved considerable success. This is evident in the most recent compilation of experimental results¹ on ^{12}C as well as in various theoretical calculations.^{1,2} In this energy region the cross sections from the photonuclear reactions are dominated by the broad envelope of the giant dipole resonance corresponding to E1 capture into negative parity, isospin $T=1$ states. Structure calculations employing the particle-hole model³⁻⁵ reproduce the main features observed experimentally, as well as do collective model type calculations⁶⁻⁸ including deformations. There is, however, also some evidence of fine structure present in the photonuclear cross section. To shed some light on the origin of this fine structure and to study expected states other than the dipole excitations in this energy region, several reactions less selective than the photonuclear reactions have been performed. Two of these reactions, namely the resonance reaction $^{11}\text{B}(p, \alpha)^8\text{Be}$ (Refs. 9,10) and the reaction $^{12}\text{C}(p, p\alpha)^8\text{Be}$ (Ref. 11), where the α -decay of the inelastically excited states is observed, are partially selective since, assuming isospin conservation, they should allow only the excitation of $T=0$ states with natural parity. Resonance reactions like $^{11}\text{B}(p, n)^{11}\text{C}$ (Ref. 12) and $^{11}\text{B}(p, p)^{11}\text{B}$ (Refs. 13-15) favour equally $T=0$ and $T=1$ states of either natural or unnatural parity. In addition there are certain reactions like $^{10}\text{B}(^3\text{He}, p)^{12}\text{C}$ (Refs. 16 and 17) and $^{14}\text{C}(p, t)^{12}\text{C}$ (Ref. 13) in which high lying states in

^{12}C were produced as final states. Both of these two-nucleon transfer reactions have useful selective properties: while the former reaction may populate preferentially $T=1$, two-particle two-hole configurations, the latter is restricted to exciting states resulting almost from pure p-shell pick up. The $^{11}\text{B}(^3\text{He},d)^{12}\text{C}$ reaction has also been studied.^{19,20} Both positive and negative parity states in ^{12}C are excited by this reaction.

We present here the results of the $^{13}\text{C}(p,d)^{12}\text{C}$ reaction performed at $E_p = 62$ MeV to study the structure of the states in ^{12}C with excitation energies greater than 15 MeV. A brief account of this work has been presented already.²¹ This reaction is ideally suited for exciting states resulting from pure p-shell pick up. The distribution of the neutron hole strength and the energy of the relevant states are predicted by Cohen and Kurath²² from an extensive intermediate-coupling calculation. Two recent experiments utilizing the $^{13}\text{C}(p,d)^{12}\text{C}$ reaction at slightly lower energies were concerned with the distribution of the neutron hole strength among the states below 16 MeV excitation.^{23,24,25}

Section II contains a brief description of the experimental procedure and an outline of the data analysis and final results. In Section III the results are discussed in conjunction with the variety of the available experimental information concerning the formation and the decay of the high-lying states in ^{12}C , such as energy and configurations, and are compared with existing theoretical models.

II. EXPERIMENT

In order to explore states of high excitation energy (>15 MeV) and in order to resolve those states in the final spectrum, the 62 MeV proton beam of the Oak Ridge Isochronous Cyclotron (ORIC) was used in conjunction with the associated broad range spectrograph.²⁶ The beam-energy resolution, the 2.5 mm width of the beam spot on target, and the particular spectrograph entrance aperture gave rise to an energy resolution of about 80 keV in the experimental spectra. The beam intensity was monitored by a Faraday cup inside the scattering chamber as well as by a 1" x 3/4" NaI(Tl) crystal placed at 31° to the beam direction. The target used was about 100 g/cm^2 thick and consisted of 44.6% ^{12}C and 55.4% ^{13}C . The target was prepared by cracking enriched methyl iodide onto a thin Ni foil and etching the foil away.²⁷ The deuterons were detected on Kodak NTB 50 micron plates placed in the focal plane of the magnetic spectrometer. Aluminum absorbers in front of the plates stopped those heavier particles produced from proton induced reactions on C which have the same rigidity in the magnetic field as the deuterons of interest.

The run time available for the experiment and the low cross sections expected allowed the exposure of plates only at the scattering angles $\theta_{\text{LAB}} = 6^\circ, 12^\circ, 18^\circ, \text{ and } 25^\circ$. The plates were scanned in 1/2 mm strips and the number of proton tracks were corrected for the effect of changing solid angle along the focal plane. In a very careful study, Freedom *et al.*²⁸ determined absolute cross sections in the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction at the same bombarding energy as used in the present experiment. Those

cross sections associated with the strong ^{11}C states seen in our experiment from the 44.6% ^{12}C impurity in the target were utilized to determine the normalization of the cross sections.

The present experiment covered an excitation energy range from 12 to 25 MeV in ^{12}C and there is good agreement with the results of Refs. 23 and 24 in the common region of excitation energy, i.e. below $E_x = 16.11$ MeV. In particular we confirm absence of a measureable transition to the state at 14.08 MeV in ^{12}C which Scott et al.²⁴ have assigned a spin of 4^+ . (See, however Ref. 25) A differential cross section of more than 10 μb to the 14.08 state would have been measureable in the present experiment. Our main concern is with states above these energies, and Fig. 1 displays the region between about 15 MeV and 23 MeV excitation in ^{12}C from the four spectra. The number of counts in each spectrum is given in the laboratory system and has been normalized to unit charge and solid angle. The choice of scale is such that the area under a given peak is the laboratory cross section in $\mu\text{b}/\text{steradian}$. It is therefore possible to read off easily the intensity variation of one line as a function of scattering angle. Furthermore, the spectra are plotted such that the states with the same Q value lie on a vertical line. The only impurity peaks detected in the region of interest were the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction ($Q=-16.5$ MeV) for which the energy levels are precisely known. The points resulting from the $^{12}\text{C}(p,d)^{11}\text{C}$ reaction have been deleted and the resulting empty spaces are marked in the 6° spectrum by numbers in parentheses which indicate the appropriate excited state in

^{11}C , e.g. (1) indicates the first excited state ($E_X = 1.995$ MeV). Also indicated in the 6° spectrum are the strong peaks corresponding to states in ^{12}C at 15.11 and 16.11 MeV and weaker structure correlated between all four spectra is observed at 17.79, 18.84, 19.82, 20.55, 20.95, 21.50, 22.50, and possibly 22.80 MeV excitation. Furthermore, there is a clustering of strength around 20 MeV of excitation in ^{12}C .

III. DISCUSSION

In the recent $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ experiments of Taketani et al.²³ and Scott et al.²⁴, the lp neutron pick-up strength observed is in good agreement with the predictions of Cohen and Kurath²² based upon intermediate coupling wave functions. The five strongest transitions predicted by Cohen and Kurath were observed at $E_X=0.0, 4.43, 12.71, 15.11$, and 16.11 MeV with spectroscopic strengths close to the theoretical values. These five states comprise 80% of the predicted lp-shell neutron pick-up strength. Of the remaining 20% of the lp neutron pick-up strength, 12% is expected to be concentrated in three states of $(J^\pi, T) = (0^+, 0), (2^+, 0)$, and $(1^+, 1)$. The two strong peaks in the spectrum of Fig. 1 correspond to the 15.11 and 16.11 MeV states of ^{12}C and have maximum c.m. cross sections of 2.5 mb/sr and 3.5 mb/sr, respectively. Because of their low cross sections (e.g. about 140 $\mu\text{b/sr}$ for the 17.79 MeV state and 35 $\mu\text{b/sr}$ for the 18.84 MeV state at 12°) any other state must have spectroscopic strength at least an order of magnitude smaller than that for the 15.11 and 16.11 MeV states. Hence at high excitation energies the lp-neutron pick-up strength is distributed over a larger range of excitation energies than predicted by the intermediate-coupling shell model.

The only information concerning the states that are seen in the present experiment results from cross sections measured at the four angles displayed in Fig. 1 and such "four-point angular distributions" really do not warrant extensive distorted-wave Bonn approximation (DWBA) calculations. However, on the

basis of some exploratory DWBA calculations performed entirely in the spirit of the calculations of Ref. 29, which deals with the problem of obtaining reliable spectroscopic information from high-energy (p,d) reactions in the lp shell, and on the basis of comparing the experimental cross sections to other lp shell states, a few speculations concerning the possible structure of the high lying states detected can be made. The approximate selectivity of a single lp neutron pick-up reaction is of some help since only final states of positive parity with spins less than or equal to 2^+ are populated via a simple one-step process.

The state at 17.79 MeV is presumably the 17.77 MeV state quoted in Ref. 1 and has $(J^\pi, T) = (0^+, 1)$. It is the analogue of the 2.72 MeV state in ^{12}B (Ref. 30). In the intermediate coupling model²² there are only two $(0^+, 1)$ states in ^{12}C with appreciable spectroscopic factors for neutron pick up from ^{13}C . The $(0^+, 1)$ state predicted at 19.6 MeV with $C^2S = 0.086$ probably corresponds to the state observed experimentally at 17.79 MeV. However, by taking the ratio³⁰ of the peak cross section to that for the 15.11 MeV state, the neutron pick up strength is approximately $C^2S_{\text{exp}} = 0.04$. The shape of the angular distribution of this state is the same as that for the state at 15.11 MeV.

The level seen at 18.84 MeV has been assigned¹ $(J^\pi, T) = (2^+, 1)$. A weak fraction of the lp neutron pick up strength is expected to lie around 20.0 MeV ($C^2S = 0.006$) and the ratio of the experimental peak cross section for the state at 18.84 to that for the 15.11 MeV state suggests $C^2S_{\text{exp}} = 0.008$ for the 18.84

MeV state. As in the case of the state at $E_x = 17.79$ MeV, the shape of the angular distribution of this state is also identical to the one at 15.11 MeV.

The next clustering of states observed is around 20 MeV excitation. In this region ^{12}C is unbound with respect to neutron emission. There are weak transitions to at least three broad states in this region. There is a definite peak at 20.55 MeV and the excitation energies 19.82 and 20.95 are assigned with a somewhat lower accuracy to weaker structure in the broad rise near 20 MeV excitation. Unfortunately the presence of peaks from $^{12}\text{C}(p,d)^{11}\text{C}$ (6.34 and 6.48 MeV) obscures the picture some. In a study of the reaction $^{10}\text{B}(^3\text{He}, p)^{12}\text{C}$, Comfort and Baglin¹⁶ detected a strong and broad state at 20.6 MeV of presumably positive parity. This was determined on the basis of a sizeable $L = 0$ component in the angular distributions, which would also restrict the spin to be 2, 3, or 4. Within the assumption of lp neutron pick-up a spin assignment of 2^+ would be indicated. An isolated level has been observed^{9,10} in the reaction $^{11}\text{B}(p, \alpha_0)^8\text{B}$ at 20.64 MeV excitation in the ^{12}C compound system, and from a sizeable A_4 term in its angular distribution a spin and parity of either 2^+ or 3^- was suggested. Since this state is also present in $^{11}\text{B}(p, \gamma_1)^{12}\text{C}$ it was suggested that it has $(J^\pi, T) = (3^-, 1)$. It is felt that the 20.55 MeV state seen in the $^{13}\text{C}(p,d)^{12}\text{C}$ and $^{10}\text{B}(^3\text{He}, p)^{12}\text{C}$ experiments is very likely a positive parity state near the 20.6 MeV state and is at most weakly excited in the (p, α_0) and (p, γ_1) reactions on ^{11}B .

Of the remaining two states, the state at 21.50 MeV has an angular distribution typical of an $L = 1$ shape, is clearly located right at the main strength of the ground dipole resonance, and is close to anomalies detected in the cross sections of the reactions $^{11}\text{B}(p,n)^{11}\text{C}$ (Ref. 12), $^{11}\text{B}(p,p)^{11}\text{B}$ (Ref. 13) and of $^{11}\text{B}(p,\gamma_0)^{12}\text{C}$ (Ref. 31). The radiative capture work suggests $(J^\pi, T) = (1^-, 1)$. However, on the basis of its angular distribution, the sufficiently high level density of levels with both parities in ^{12}C at this excitation energy, and the uncertainty in the energy calibration of the different experiences it is probably not a state of the particle-hole giant-dipole character.

The angular distribution of the 22.5 MeV state peaks further out as that from a p-shell state and the excitation energy is correlated with a state observed in the reaction $^{10}\text{B}(^3\text{He}, p)^{12}\text{C}$. Again, this state lies right in the region of the main giant resonance.

In fact if some of the negative parity states from the photonuclear work and the other reactions are seen weakly in the $^{13}\text{C}(p,d)^{12}\text{C}$ reaction also, then mechanisms other than the simple one-step lp-shell pick-up have to be invoked. Negative parity, $T=1$ states could be formed by pick-up of a 1s particle, a process which is highly unlikely at the bombarding energies of the present (p,d) reaction. Radvanyi et al.³² concluded from the reaction $^{12}\text{C}(p,d)^{11}\text{C}$ at $E_p = 154.5$ MeV, that the probability of finding a lp neutron in ^{12}C with the correct momentum for forming a deuteron at 20° is about six times

larger than the probability of finding a 1s neutron of the same momentum. Consequently, configurations with a hole in the 1p-shell are favoured. The possibility of two-step processes involving inelastic excitations³³ before the pick-up occurs may also be important. Such two-step processes do seem to be important for the impurity reaction $^{12}\text{C}(p,d)^{11}\text{C}$. The spectra including the impurity peaks are shown in Fig. 2. If the intermediate coupling model were valid for the ground state of ^{12}C and if the (p,d) mechanism were one-step neutron pick-up, then only three states in ^{11}C would be excited, i.e. $3/2^-$ (0.00), $1/2^-$ (1.995), and $3/2^-$ (4.794). Hinterberger *et al.*³⁴ have suggested that in the analogous reaction $^{12}\text{C}(d,^3\text{He})^{11}\text{B}$ the $5/2^-$ and $7/2^-$ states are formed by a two-step process with p-shell neutron pick-up following inelastic excitation of the 2^+ excited state of ^{12}C . However, because of the single-particle character of the ^{13}C target nucleus, one would expect two-step processes in the $^{13}\text{C}(p,d)^{12}\text{C}$ reaction to be relatively less important.

If configurations with two particles in the 2s-1d shell and one hole in the 1p shell are included in the ground state of ^{13}C , then negative parity states in ^{12}C may be excited by the pick-up of a neutron from the 2s-1d shell. The cross section for such pick-up reactions to negative parity states in ^{12}C may be estimated using the Tamm-Dancoff approximation wave functions of Gillet and Vinh Mau⁴ for ^{12}C . For example, without such admixtures in the ground state of ^{13}C , the (p,d) transition to the 10.84 MeV ($1^-, 0$) state in ^{12}C would proceed by

$1s_{1/2}$ pick-up with a cross section near 20° of the order of 100 $\mu\text{b}/\text{sr}$. The admission of greater than a 1% admixture of $(2s_{1/2}^2, 1p^{-1})$ results in a cross section of more than 250 $\mu\text{b}/\text{sr}$ which would have been detectable in the experiment of Taketani et al.²³ For smaller admixtures there may be some cancellation between $1s_{1/2}$ and $2s_{1/2}$ pick-up depending on the phase of the spectroscopic amplitudes. Since no transition to this state in ^{12}C was detected in the experiments Taketani et al.²³ and Scott et al.,²⁴ the admixture of $(2s_{1/2}^2, 1p^{-1})$ in ^{13}C is probably less than 5%. Similar arguments cannot be constructed regarding the possibility of $2d$ particles in the ground state of ^{13}C since $d_{5/2}$ pick-up to the $(1^-, 0)$ at 10.84 MeV state in ^{12}C is not allowed for first order processes, and the fraction of $d_{3/2}$ strength in the $(1^-, 0)$ state is sufficiently small that cross-section for $d_{3/2}$ pick-up to this state would be difficult to detect. Additional evidence that processes other than p-shell neutron pick-up may be negligible comes from the $^{14}\text{C}(p, t)^{12}\text{C}$ reaction (Ref. 18), where all the strong states seen are low lying p-shell states.

The spectroscopic information (excitation energies, strengths and tentatively proposal configuration assignments) are given in Table I.

IV. CONCLUSION

The results of the $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ study indicate that the distribution of neutron pick-up strength is in good qualitative agreement with the results of the intermediate coupling calculations of Cohen and Kurath²² up to 23 MeV excitation in ^{12}C . In particular the electric dipole and octupole states in ^{12}C are only very weakly excited, if excited at all. Neutron pick-up transitions to states at 17.77 MeV and 18.84 have been observed with estimated spectroscopic strengths of $C^2S_{\text{exp}} = 0.04$ and 0.008 respectively. There is also a clustering of very weak strength near 20 MeV excitation. Several suggestions regarding the structure of these states have been offered. However, using the spectroscopic values given by Taketani *et al.*²³ for those transitions observed up to 16.11 MeV and our estimates for excitations from 17 to 23 MeV, the spectroscopic sum rule implies the average number of lp-shell nucleons in $^{13}\text{C}(\text{g.s.})$ is about 7. This would suggest that either $^{13}\text{C}(\text{g.s.})$ has some admixtures of more complex configurations, or the remaining lp-shell pick-up strength is thinly distributed over higher excitation energies. The experimental evidence, as discussed in Section III is, that the admixture in the ^{13}C ground state of configurations involving particles above the lp shell is too small to account for the missing strength. Consequently the remaining 10% to 15% of the lp-shell pick-up strength must be distributed over excitation energies greater than 23 MeV in ^{12}C . Of course, the spectroscopic factors themselves may also be underestimated in the work of Taketani *et al.*²³ with cor-

respondingly less lp-shell strength above 23 MeV excitation.

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FIGURE CAPTIONS

Fig. 1 Spectra of the $^{13}\text{C}(p,d)^{12}\text{C}$ reaction at $E_p = 63$ MeV. The spectra are mounted such that the states with the same Q -value line up under different angles. The yield is normalized per unit solid angle and charge and the normalization is such that the area under a given peak is the laboratory cross section in $\mu\text{b}/\text{sr}$. Statistical errors are indicated on some of the points. Those peaks from the reaction $^{12}\text{C}(p,d)^{11}\text{C}$ have been deleted (see text).

Fig. 2 Spectra of the (p,d) reaction without the $^{12}\text{C}(p,d)^{11}\text{C}$ impurity peaks deleted. The yield is normalized as in Fig. 1 and the strong peaks from $^{13}\text{C}(p,d)^{12}\text{C}$ have been left out to emphasize the $^{12}\text{C}(p,d)^{11}\text{C}$ impurity reaction.

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The validity for obtaining the spectroscopic strength C^2S_{exp} by taking the ratio of the peak cross section of a state with known spectroscopic strength to that of a state with unknown strength has been tested with several DWBA calculations. The Q-value dependence of the calculated cross sections was almost linear for states in ^{12}C between 15.11 and 21.5 MeV excitation energy, the cross section being different at those two energies by only a factor of about 1.2. Hence the procedure of taking ratios of experimental cross sections was adopted for all states detected at $E_x > 16.11$ MeV.

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TABLE I
Spectroscopic information on levels observed above 15 MeV
excitation in the $^{13}\text{C}(\text{p},\text{d})^{12}\text{C}$ reaction.

E_X	(J^π, T)	ℓ_n	$c^2S_{\text{exp}}/c^2S_{\text{exp}}(15.11)^a$	c^2S_{exp}	$c^2S_{\text{theory}}^b$
15.11	$(1^+, 1)$	1	1.0	0.56	0.60
16.11	$(2^+, 1)$	1	1.84	1.03	1.02
17.79	$(0^+, 1)$	1	.072	0.04	.086
18.84	$(2^+, 1)$	1	.014	0.008	.006
19.82					
20.55					
20.95					
21.50	$\pi = +$	1			
22.50		>1			

a) $c^2S_{\text{exp}}(15.11)$ value from ref. 23.

b) ref. 22.

Fig. 1