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High-lying neutron-hole states populated in the reaction $^{13}C(p, d)^{12}C$ at 62 MeV

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The single-nucleon pickup reaction $^{13}C(p,d)^{12}C$ at 62 MeV has been employed to study high-lying states in ^{12}C. States are seen at excitation energies $E_x = 17.76$, 18.80, 21.5, and 22.5 MeV in ^{12}C and the $1p$ neutron-hole strength found is in qualitative agreement with theoretical predictions. However, the $1p$ 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 results[1] 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 states with negative parity and isospin $T = 1$. Structure calculations employing the particle-hole model[3-5] reproduce the main features observed experimentally as well as do collective-model calculations[6-8] including deformations. However, the photonuclear cross section shows some evidence of fine structure. 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 used. Two of these reactions, namely the resonance reaction[9,10] $^{11}B(p, \alpha)^8Be$ and the reaction[11] $^{12}C(p, p\alpha)^8Be$ in which the α decay of the inelastically excited states is observed, are partially selective since, if isospin is conserved, they should allow only the excitation of $T = 0$ states with natural parity. The excitation of states with either $T = 0$ or $T = 1$ and with either natural or unnatural parity are equally favored by resonance processes such as the $^{11}B(p, n)^{11}C$ reaction[12] and $^{11}B(p, p)^{11}B$ inelastic scattering.[13-15] In addition, high-lying states in ^{12}C are produced as final states in certain reactions such as $^{10}B(^3He, p)^{12}C$ stripping[16,17] and $^{14}C(p, t)^{12}C$ pickup.[18] Each of these two-nucleon transfer reactions has useful selective properties: While the former reaction may preferentially populate $T = 1$ two-particle–two-hole configurations, the latter is restricted to exciting states resulting from almost pure p-shell pickup. The $^{11}B(^3He, d)^{12}C$ 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 $^{13}C(p, d)^{12}C$ reaction 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 pickup. The distribution of the neutron-hole strength and the energy of the relevant states are predicted by Cohen and Kurath[22] from an extensive intermediate-coupling calculation. Two recent experiments utilizing the $^{13}C(p, d)^{12}C$ reaction at slightly lower energies were concerned with the distribution of the neutron-hole strength among the states below 16 MeV excitation.[23,24] The pickup reaction $^{14}N(d, \alpha)^{12}C$ has also been reported.[25]

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

II. EXPERIMENT

In order to explore states of high excitation energy (>15 MeV) and 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 energy spread of the beam, the 2.5-mm width of the beam spot on target, and the particular spectrograph entrance aperture resulted in an energy resolution width of about 45 keV in the experimental spectra. The beam intensity was monitored by a Faraday cup inside the scattering chamber as well as by a 2.5×1.9-cm NaI(Tl) crystal placed at 31° to the beam direction. The target used was about 100 $\mu g/cm^2$ thick and consisted of 44.6% ^{12}C and 55.4% ^{13}C. It 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-μm plates placed in the focal plane of the magnetic spectrometer. Aluminum absorbers in front of the plates stopped the heavier particles produced from proton-induced reactions on carbon and having the same magnetic rigidity as the deuterons of interest.

The limited running time available for the experiment and the low cross sections expected allowed the exposure of plates only at the scattering angles θ_{lab} = 6, 12, 18, and 25°. The plates were scanned in $\frac{1}{2}$-mm strips and the number of deuteron tracks was corrected for the effect of changing solid angle along the focal plane. In a very careful study, Preedom *et al.*[28] determined absolute cross sections in the $^{12}C(p,d)^{11}C$ reaction at the same bombarding energy as was 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.

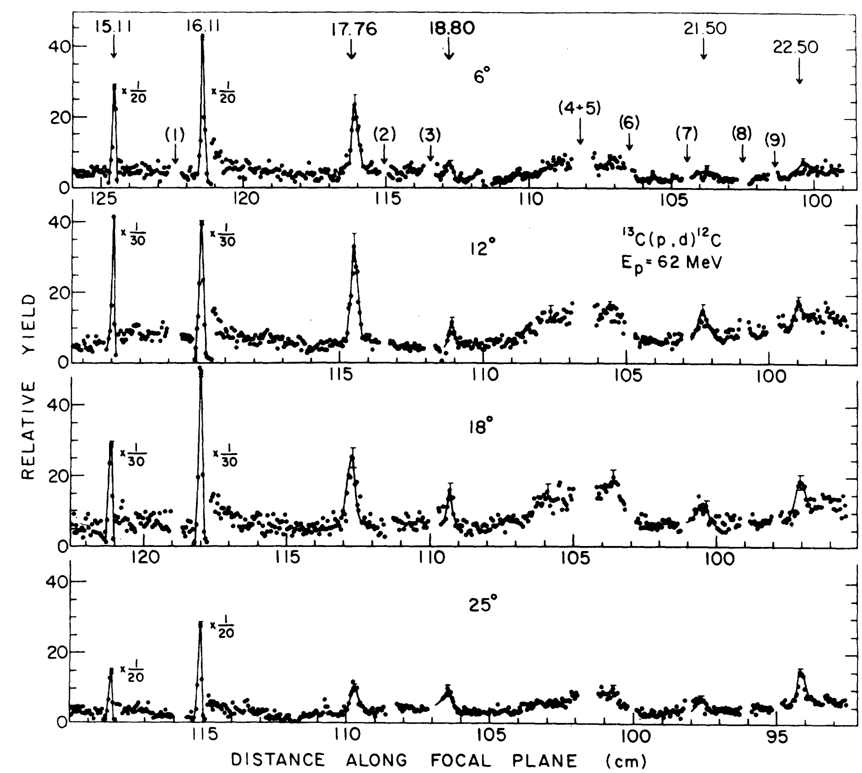

FIG. 1. Spectra of the $^{13}C(p,d)^{12}C$ reaction at E_p = 62 MeV. The spectra taken at different angles are placed so that the state with a given Q value is at the same horizontal position in all four. The yield is normalized per unit solid angle and charge and the scale is such that the area under a given peak is the laboratory cross section μb/sr. Statistical errors are indicated on some of the points. Peaks from the reactions $^{12}C(p,d)^{11}C$ have been deleted and the parenthetic number labeling each gap is the number of the appropriate excited state in ^{11}C.

The present experiment covered excitation energies ranging 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 the absence of a measurable transition to the state at 14.08 MeV in ^{12}C, to which Scott *et al.*[24] have assigned a spin of 4^+. (However, see Ref. 25.) A differential cross section of more than 10 μb/sr for the transition to the 14.08-MeV state would have been measurable in the present experiment. Our main concern is with states above the range of overlap. In Fig. 1, which covers the region between about 15 and 23 MeV excitation in ^{12}C, the number of counts in the spectrum at each angle is normalized to unit charge and solid angle and the scale is chosen such that the area under any given peak is the laboratory cross section in μb/sr. The intensity variation of one line as a function of scattering angle can therefore be read off easily. Furthermore, the spectra are plotted such that the states with the same Q value lie on a vertical line. The error bars in the figure indicate statistical error. The only impurity peaks detected in the region of interest were due to the $^{12}C(p,d)^{11}C$ reaction ($Q = -16.5$ MeV) for which the energy levels are precisely known. The points resulting from the $^{12}C(p,d)^{11}C$ reaction have been deleted from all four spectra, and in the 6° spectrum each resulting empty space is labeled with the number of the appropriate excited state in ^{11}C; e.g., (1) indicates the first excited state ($E_x = 1.995$ MeV). The arrows in the 6° spectrum associate excitation energies in ^{12}C with structures observed in the deuteron spectra. States at 15.112 ± 0.005, 16.110 ± 0.005, and 17.76 ± 0.02 MeV in ^{12}C are excited quite strongly. Weaker structure is evident at all four angles for excitation energies of 18.80 ± 0.04, 21.5 ± 0.1, and 22.55 ± 0.05 MeV. The angular dependence of the cross sections for these six transitions is presented in Fig. 2. The error bars in this figure indicate both statistical error and an estimate of the error in background subtraction. For the weaker transitions at 18.80, 21.5, and 22.5 MeV, the latter error is substantial and we regard the cross sections as upper limits which are suggestive of the angular dependence of these transitions. Spectroscopic information including l transfer and level widths for these five transitions are displayed in Table I. Finally, we note that there is a clustering of pickup strength near 20 MeV excitation in ^{12}C.

III. DISCUSSION

In the recent $^{13}C(p,d)^{12}C$ experiments of Taketani *et al.*[23] and Scott *et al.*[24] the $1p$ neutron-pickup strength observed is in good agreement with the predictions of Cohen and Kurath,[22] whose calculations were 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, and the spectroscopic strengths were close to the theoretical values. These five states exhaust 80% of the predicted $1p$-shell neutron-pickup strength. Of the remaining 20% of the $1p$ neutron-pickup strength, 12% is expected to be concentrated in three states with $(J^\pi, T) = (0^+, 0)$, $(2^+, 0)$, 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 center-of-mass cross sections (e.g., about 140 μb/sr for the 17.76-MeV state and 35 μb/sr for the 18.80-MeV state at 12°), the spectroscopic strength of any other state must be at least an order of magnitude smaller than that for

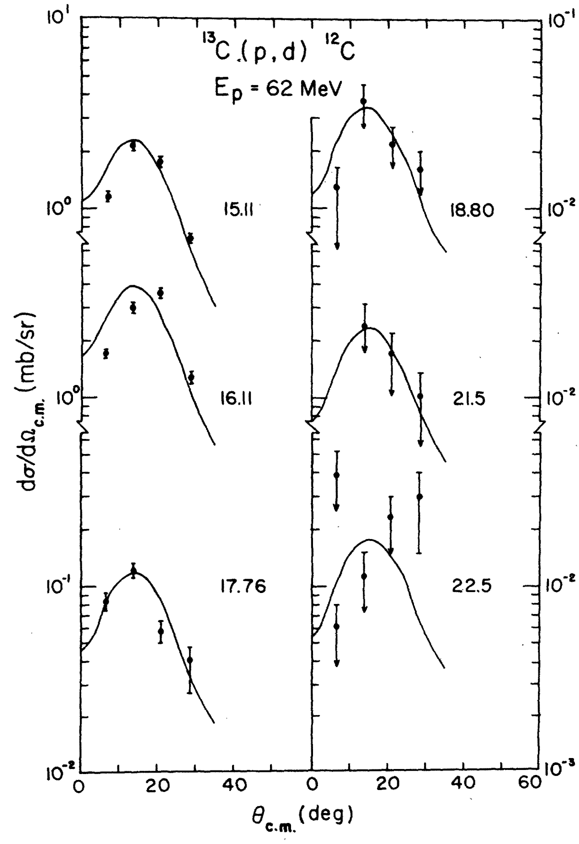

FIG. 2. The angular dependence of the observed transitions in the $^{13}C(p,d)^{12}C$ reaction. The error bars represent statistical error and an estimate of the error due to background subtraction. The solid curves are DWBA calculations for pickup of a $1p$-shell neutron. The calculated curves are renormalized to fit the data. The DWBA parameters are presented in the Appendix.

the 15.11- and 16.11-MeV states. Hence at high excitation energies the $1p$ neutron-pickup strength is distributed over a larger range of excitation energies than is predicted by the intermediate-coupling shell model.

The only information concerning the states seen in the present experiment comes from cross sections measured at the four angles displayed in Figs. 1 and 2 and such "four-point angular distributions" really do not warrant extensive distorted-wave Born-approximation (DWBA) calculations. However, some exploratory DWBA calculations were performed for $1p$-shell neutron pickup to excitation energies $E_x = 15.11$, 16.11, 17.76, 18.80, 21.5, and 22.5 MeV using the radial cutoff prescription described by Snelgrove and Kashy.[29] The results are displayed in Fig. 2. Although no attempt was made to "fit" the angular dependence of these cross sections, this analysis and a comparison with transitions to known $1p$-shell states suggest a few speculations concerning the possible structure of the high-lying states detected. The approximate selectivity of a reaction involving the pickup of a single $1p$ neutron is of some help since only final states of positive parity with spins $\leq 2^+$ are populated via a simple one-step process.

The state at 17.76 MeV is presumably the 17.77-MeV state quoted in Ref. 1 and has $(J^\pi, T) = (0^+, 1)$. It is the analog of the 2.72-MeV state in ^{12}B.[30] In the intermediate-coupling model,[22] only two $(0^+, 1)$ states in ^{12}C have appreciable spectroscopic factors for neutron pickup 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 17.76 MeV. However, by taking the ratio[31] of the peak cross section to that for the 15.11-MeV state, the neutron-pickup strength is found to be approximately $C^2S_{exp} = 0.04$. The shape of the angular distribution of this state is the same as that for the state at 15.11 MeV.

We associate the level seen at 18.80 MeV with the 18.84-MeV level which has been assigned[1] $(J^\pi, T) = (2^+, 1)$. A small fraction ($C^2S = 0.006$ of the $1p$ neutron-pickup strength is expected to lie around 20.0 MeV, and the ratio of the experimental peak cross section for the 18.80-MeV state to that for the 15.11-MeV state suggests $C^2S_{exp} = 0.008$ for the 18.80-MeV state. As in the case of the state at $E_x = 17.76$ MeV, the shape of the angular distribution of this state is also identical to that of the one at 15.11 MeV.

The next clustering of strength observed is around 20 MeV excitation. In this region, ^{12}C is unbound with respect to neutron emission. Individual weak transitions in this region are difficult to assign, in contrast to the reactions $^{10}B(^3He, p)^{12}C$ (Ref. 16) and $^{11}B(p, \alpha)^8Be$ (Refs. 9 and 10). The angular dependence of this pickup strength has a maximum near 15°, which is characteristic of $l = 1$ pickup at this energy. This would suggest the excitation of positive-parity $1p$-shell particle-hole strength. It is interesting to note that this excitation energy corresponds to the energy expected for the isoscalar component of the giant quadrupole vibration.[32,33] If this excitation strength is related to the giant quadrupole excitation, then it would be evidence for a weak coupling of the $0\hbar\omega(p_{3/2}{}^{-1}p_{1/2})2^+$ strength to the dominant $2\hbar\omega$ component of the giant quadrupole resonance.

Of the remaining two states, the one at 21.50 MeV has an angular distribution typical of an $l = 1$ shape, is clearly located right at the main strength of the giant dipole resonance, and is close to anomalies detected in the cross sections of the reactions $^{11}B(p, n)^{11}C$ (Ref. 12) and $^{11}B(p, p)^{11}B$ (Ref. 13) and of the $^{11}B(p, \gamma_0)^{12}C$ decay.[34] The radiative-capture work suggests $(J^\pi, T) = (1^-, 1)$. However, on the basis of its angular distribution, one concludes

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

E_x (MeV)	(J^π, T)	l_n	Relative C^2S_{exp} [a]	C^2S_{exp}	C^2S_{theory} [b]	Experimental [c] width (keV)
15.112 ± 0.005	$(1^+, 1)$	1	1.0	0.56	0.60	45 ± 5 [d]
16.110 ± 0.005	$(2^+, 1)$	1	1.84	1.03	1.02	48 ± 5
17.76 ± 0.02	$(0^+, 1)$	1	0.072	0.04	0.086	90 ± 15
18.80 ± 0.04	$(2^+, 1)$	1	≤0.014	≤0.008	0.006	90 ± 30
21.50 ± 0.10	+ parity	(1)				<200
22.55 ± 0.05		≠1				<200

[a] Relative to C^2S_{exp} (15.11) as taken from Ref. 23.
[b] Reference 22.
[c] FWHM including experimental resolution.
[d] The width of this line is a measure of the experimental resolution.

that this is a positive-parity state.

The angular dependence of the 22.5-MeV structure peaks farther out than does that from the pickup of a $1p$-shell neutron, so that a mechanism other than the simple one-step $1p$-shell pickup must be invoked. One alternative is the pickup of a $1s$-shell neutron, a process that should be quite weak at the bombarding energies of the present (p,d) reaction. Radvanyi, Gemin, and Detraz[35] concluded from the reaction $^{12}C(p,d)^{11}C$ at $E_p = 154.5$ MeV, that the probability of finding a $1p$ neutron in ^{12}C with the correct momentum for forming a deuteron at 20° is about 6 times the probability of finding a $1s$ neutron of the same momentum. The possibility of two-step processes involving inelastic excitations[36] before the pickup occurs may also be important. Such two-step processes do seem to be important for the impurity reaction $^{12}C(p,d)$-^{11}C. The spectra including the impurity peaks are shown in Fig. 3. If the intermediate-coupling model were valid for the ground state of ^{12}C and if the (p,d) mechanism were one-step neutron pickup, then only three states in ^{11}C would be excited, namely the $\frac{3}{2}^-$ ground state and the $\frac{1}{2}^-$ ($E_x = 1.995$-MeV) and $\frac{3}{2}^-$ (4.794-MeV) excited states. Hinterberger *et al.*[37] have suggested that in the analogous reaction $^{12}C(d,{}^3He)^{11}B$ the $\frac{5}{2}^-$ and $\frac{7}{2}^-$ states are

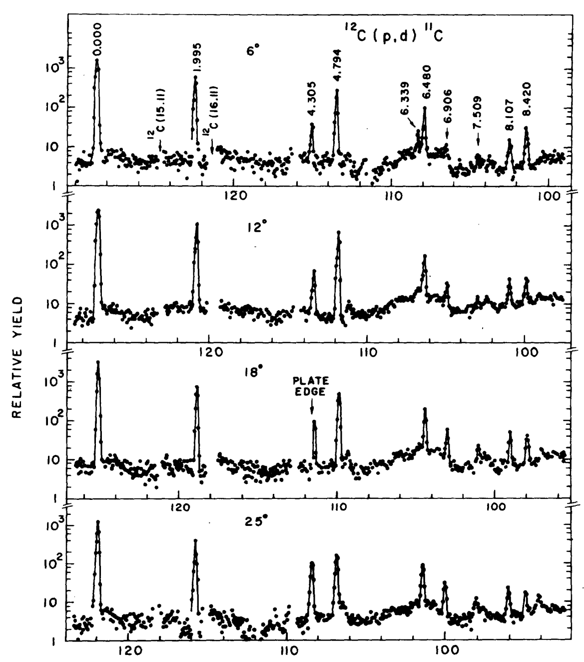

FIG. 3. Spectra of the (p,d) reaction without the $^{12}C(p,d)^{11}C$ impurity peaks deleted. The yield is normalized as in Fig. 1, and the strong peaks from $^{13}C(p,d)^{12}C$ have been left out to emphasize the $^{12}C(p,d)^{11}C$ impurity reaction.

formed by a two-step process consisting of p-shell neutron pickup following inelastic excitation of the 2^+ excited state of ^{12}C. A measure of the significance of such two-step processes in the $^{13}C(p,d)$-^{12}C reaction is the excitation of the 9.64-MeV 3^- state in ^{12}C. This state was observed as a very weak transition by Scott *et al.*[24] Hence the two-step process may occur in the $^{13}C(p,d)^{12}C$ reaction, but only as a very weak mechanism. Thus, while the structures observed at 15.11, 16.11, 17.76, 18.80, and 21.5 MeV do seem to be $1p$-shell pickup transitions, more detailed data are required to determine the nature of the transition to the 22.5-MeV structure.

IV. CONCLUSION

The results of the $^{13}C(p,d)^{12}C$ study indicate that the distribution of neutron-pickup strength is in good qualitative agreement with the results of the intermediate-coupling calculations of Cohen and Kurath[22] up to 23 MeV excitation in ^{12}C. In particular, the electric dipole and octopole states in ^{12}C are only very weakly excited, if excited at all. Neutron-pickup transitions to states at 17.76 and 18.80 MeV have been observed with estimated spectroscopic strengths of $C^2S_{exp} = 0.04$ 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, when 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 are substituted in the spectroscopic sum rules, the result implies that the average number of $1p$-shell nucleons in ^{13}C(g.s.) is about seven. This would suggest either that ^{13}C(g.s.) has some admixtures of more complex configurations or that the remaining $1p$-shell pickup strength is thinly distributed over higher excitation energies. As discussed in Sec. III, the experimental evidence is that contributions to the ground state from configurations involving particles above the $1p$ shell constitute too small an admixture to account for the missing strength. Consequently the remaining 10–15% of the $1p$-shell pickup 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] and this would imply correspondingly less $1p$-shell strength above 23 MeV excitation.

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TABLE II. DWBA parameters.

	V (MeV)	W_V (MeV)	W_s (MeV)	V_{so} (MeV)	r_R (fm)	a_R (fm)	r_I (fm)	a_I (fm)
p [a]	44.5	7.5	5.88	5.5	1.09	0.57	1.09	0.50
d [b]	$106.5-0.5E_d$		9.58	3.0	1.05	0.80	1.28	0.76
n	Adjusted [c]				1.25	0.65		

[a] F. Hinterberger, G. Mairle, U. Schmidt-Rohr, G. J. Wagner, and P. Turek, Nucl. Phys. A111, 265 (1968), Set 2.
[b] B. A. Watson, P. P. Singh, and R. E. Segel, Phys. Rev. 182, 977 (1969).
[c] V adjusted to fit neutron binding energies.

were in Oak Ridge. We also thank Art Pugh for his help in running the experiment. We are grateful to Dr. D. Robson and Dr. D. Kurath for our profitable discussions with them and to Dr. F. E. Throw for his help with the manuscript.

APPENDIX

The potentials used in the DWBA calculations have the following forms:
Proton elastic scattering:

$$V(r)=-Vf(x_R)+iW_v f(x_I)+4iW_s\frac{d}{dx_I}f(x_I)+V_{so}(\hbar/m_\pi c)^2 R_R^{-1}\frac{d}{dr}f(x_R)\vec{1}\cdot\vec{\sigma}+V_{\rm Coul}\,.$$

Deuteron elastic scattering:

$$V(r)=-Vf(x_R)+4iW_s\frac{d}{dx_I}f(x_I)+V_{so}(\hbar/m_\pi c)^2 r^{-1}\frac{d}{dr}\times f(x_R)\vec{1}\cdot\vec{\sigma}+V_{\rm Coul}\,.$$

Neutron bound state:

$$V(r)=-Vf(x_R)+V\lambda(90.4r)^{-1}\frac{d}{dr}f(x_R)\vec{1}\cdot\vec{\sigma}\,,$$

where

$$f(x)=(1+e^x)^{-1}\,,$$
$$x_i=(r-R_i)/a_i\,,$$
$$R_i=r_iA^{1/3}\,,$$
$$V_{\rm Coul}=ZZ'e^2/r\,,\quad r>R_R$$
$$=ZZ'e^2[3-(r/R_R)^2]/2R_R\,,\quad r\le R_R\,,$$

and $\lambda=25$. The specific values of the parameters are given in Table II. In agreement with Snelgrove and Kashy[29] we find that a lower cutoff of 3 fm in the radial integration is most consistent with the data. The DWBA calculations employed the October 26, 1967 version of computer code DWUCK.

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[1]F. Ajzenberg-Selove and T. Lauritzen, Nucl. Phys. A114, 1 (1968).
[2]For an excellent review of the experimental information and the various theoretical models concerning ^{12}C, see S. S. Hanna, Brookhaven National Laboratory Report No. C-46, 1965 (unpublished), Vol. II, p. 763.
[3]N. Vinh-Mau and G. E. Brown, Nucl. Phys. 29, 89 (1962).
[4]V. Gillet and N. Vinh-Mau, Nucl. Phys. 54, 321 (1964).
[5]F. H. Lewis, Jr., and J. D. Walecka, Phys. Rev. 133, B849 (1964).
[6]M. Kamimura, K. Ikeda, and A. Arima, Nucl. Phys. A95, 129 (1967).
[7]S. G. Nilsson, J. Sawicki, and N. K. Glendenning, Nucl. Phys. 33, 239 (1962).
[8]D. Drechsel, J. B. Seaborn, and W. Greiner, Phys. Rev. Lett. 17, 488 (1966).
[9]G. D. Symons and P. B. Treacy, Nucl. Phys. 46, 93 (1963).
[10]H. R. Blieden, report (to be published); and private communication.
[11]M. Epstein, H. D. Holmgren, M. Jain, H. G. Pugh, P. G. Roos, N. S. Wall, C. D. Goodman, and C. A. Ludemann, Phys. Rev. 178, 1698 (1969).
[12]J. C. Overley and R. R. Borchers, Nucl. Phys. 65, 156 (1965).
[13]A. Richter, L. J. Parish, and J. D. Fox, Bull. Am. Phys. Soc. 13, 84 (1968).
[14]E. Salzborn and G. Clausnitzer, Annual Report, Physikalisches Institut der Universität Erlangen-Nürnberg, Germany, 1967 (unpublished).
[15]W. B. Thompson and P. D. Parker, in Contributions to the International Conference on Properties of Nu-

clear States, Montreal, Canada, August 25–30, 1969, contribution 4.67.

[16]J. R. Comfort and J. E. E. Baglin, Bull. Am. Phys. Soc. 12, 34 (1967); private communication.

[17]W. Bohne, M. Hagen, H. Homeyer, K. H. Maier, H. Lettau, H. Morgenstern, and J. Scheer, Phys. Rev. C 2, 2072 (1970).

[18]G. T. Garvey and J. Cerny, private communication.

[19]W. Bohne, H. Homeyer, H. Morgenstern, and J. Scheer, Nucl. Phys. A115, 457 (1968).

[20]G. M. Reynolds, D. E. Rundquist, and R. M. Polichar, Phys. Rev. C 3, 442 (1971).

[21]L. J. Parish, R. A. Brown, K. A. Eberhard, A. Richter, and W. von Witsch, Bull. Am. Phys. Soc. 15, 520 (1970).

[22]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[23]H. Taketani, J. Muto, H. Yamaguchi, and J. Kokame, Phys. Lett. 27B, 625 (1968).

[24]D. K. Scott, P. M. Portner, J. M. Nelson, A. C. Shotten, A. J. Mitchell, N. S. Chant, D. G. Montague, and K. Ramavataram, Nucl. Phys. A141, 497 (1970).

[25]M. A. Fawzi, Z. Phys. 250, 120 (1972).

[26]J. B. Ball, IEEE Trans. Nucl. Sci. NSB(4), 340 (1966).

[27]G. C. Phillips and J. E. Richardson, Rev. Sci. Instrum. 21, 885 (1950).

[28]B. M. Preedom, R. W. Peele, T. A. Love, N. W. Hill, and W. R. Burrus, Oak Ridge National Laboratory Report No. ORNL-4274, 1968 (unpublished).

[29]J. L. Snelgrove and E. Kashy, Phys. Rev. 187, 1246 (1969).

[30]J. E. Monahan, H. T. Fortune, C. M. Vincent, and R. E. Segel, Phys. Rev. C 3, 2192 (1972).

[31]The validity of the spectroscopic strength C^2S_{exp} obtained 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 for states in ^{12}C was almost linear 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.

[32]G. R. Satchler, Nucl. Phys. A195, 1 (1972).

[33]M. B. Lewis and F. E. Bertrand, Nucl. Phys. A196, 337 (1972).

[34]R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. 58, 122 (1964).

[35]P. Radvanyi, J. Gemin, and C. Detraz, Phys. Rev. 125, 295 (1962).

[36]H. G. Pugh, D. L. Hendrie, M. Chabre, and E. Boschitz, Phys. Rev. Lett. 14, 434 (1965).

[37]F. Hinterberger, G. Mairle, U. Schmidt-Rohr, P. Turek, and G. J. Wagner, Nucl. Phys. A106, 161 (1967).