The $^{12}C(p,d)^{11}C$ Reaction at E = 121.2 MeV

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The Indiana University Cyclotron Facility was used to measure $^{12}C(p,d)^{11}C$ angular distributions for all known levels in ^{11}C up to 8.67 MeV. The 6.34 MeV $1/2^+$ level was very weakly excited and seen at one angle; the states at 8.66 and 8.70 MeV were not resolved.

Interpretation of the results began with straightforward distorted wave Born approximation analysis of the $3/2^-$ ground state transition using DWUCK4.[1] The standard techniques worked well when finite range and non-locality corrections were used, as seen in Fig. 1. Sensitivity to optical model and neutron bound state potentials was not great. Potentials used appear in Table 1.

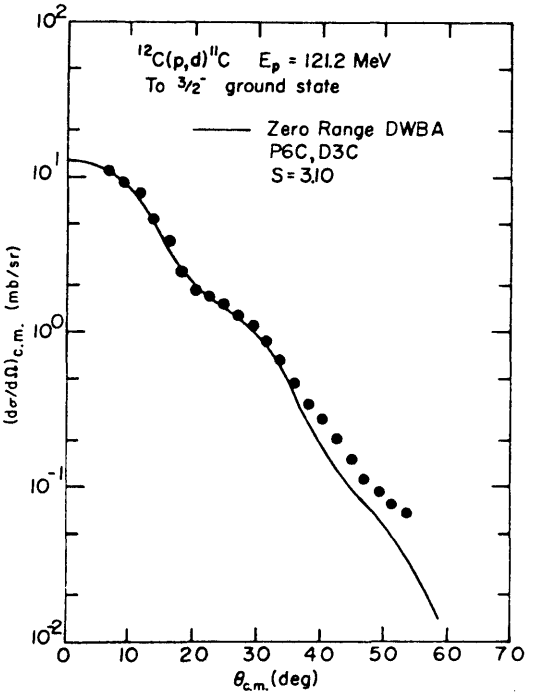

Figure 1. DWBA result compared with $3/2^-$ ground state angular distribution. Deuteron spin orbit potential included.

Table 1. Optical Model and Bound State Potentials

	Proton P6C	Deuteron D3C	Neutron
U	-22.07	-69.03	*
r	1.13	1.15	1.44
a	0.605	0.79	0.38
W	- 5.21	- 4.61	
W_V	- 4.26	- 9.275	
r'	1.31	1.33	
a'	0.65	0.591	
V_{so}	- 3.52	- 6.7	
r_{so}	0.93	0.98	
a_{so}	0.50	1.0	
r_c	1.33	1.30	

*Central depth adjusted to give correct binding energy. Spin orbit potential for binding well given by:

$$-U*0.588* \frac{1}{r} \frac{d}{dr} f(r),$$

where f(r) is the usual Woods-Saxon shape function.

Exact finite range calculations done with the program DWUCK5[1] showed finite range effects to be well accounted for in the zero-range DWBA by the Local Energy Approximation (LEA) method, provided that a somewhat reduced s-state normalization parameter, D_o, was used. The value obtained for D was 105 MeV $fm^{3/2}$ compared to the standard low energy value of $\sim$ 125 MeV $fm^{3/2}$. Contributions from the D-state of the deuteron were found to be less than 10% for all scattering angles less than 35°.

Several previous studies[2] of single nucleon pickup reactions on ^{12}C have stressed the importance of two-step processes which proceed through an

intermediate channel via inelastic scattering. Such a mechanism must be invoked to explain the strong excitation of, e.g., the 6.48 MeV $7/2^-$ and the 4.32 MeV $5/2^-$ levels since single-step DWBA explanations require $f_{7/2}$ and $f_{5/2}$ components of the ^{12}C ground state which are unreasonably large. Consequently, the analysis must proceed using the coupled channels Born approximation (CCBA). Calculations were carried out with the program CHUCK.[1)]

The coupling scheme appearing in Fig. 2 was assumed in these calculations. For a given ^{11}C excited state only inelastic quadrupole coupling to the g.s. was considered. This restriction was imposed by computational limitations but there is physical justification as well. Since the $3/2^-$ g.s. is by far the most strongly excited ^{11}C level it seems reasonable that the most important inelastic coupling for the excited levels is that to the ground state. Because structure calculations for the A = 11 systems (to be discussed next) do not reproduce observed ^{11}B inelastic scattering cross sections,[3)] empirical deformation parameters tied to experiment were used in the present CCBA calculations for both the A = 11 and 12 systems. The value $\beta_2 = -0.6$ was used for ^{12}C.

Since only the magnitude of nuclear deformation can readily be determined from inelastic scattering measurements, the signs of the deformation parameters connecting excited states with the ^{11}C ground state are unknown. Consequences of these ambiguities will be discussed below. It should also be noted that the

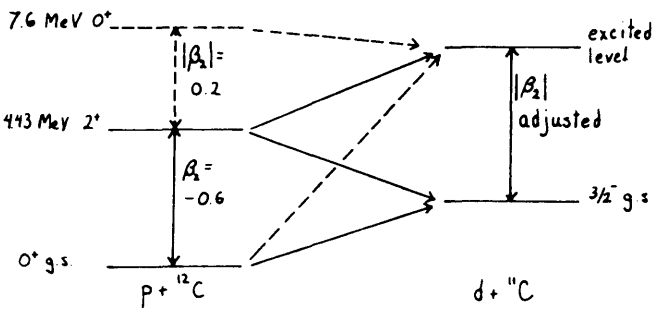

Fig. 2. Coupling scheme used in CCBA calculations. Excited levels of ^{11}C are treated one at a time. Solid lines represent levels and couplings included in all calculations. Dashed lines indicate those considered only in special cases. Magnitudes of β_2 in ^{11}C are adjusted to reproduce experimental inelastic cross sections to mirror levels in ^{11}B.

β's quoted in the figures for the A = 11 system were multiplied by the strong coupling Clebsch-Gordan coefficient $(3/2\ 2\ 1/2\ 0 \mid J_f\ 1/2)$ where J_f is the angular momentum of the excited ^{11}C state. This Clebsch-Gordan coefficient is included in the CCBA calculation by the code CHUCK.

The single nucleon transfer amplitudes depend on the details of the ^{12}C and ^{11}C wave functions. Wave functions resulting from three different calculations of structure in the nuclear 1p shell have been used in the present study. The Coriolis band mixing model of Clegg[4)] is very straightforward and gives a reasonable account of the level spacing of the first five negative parity states. Of course other levels are not accounted for in this scheme. The intermediate coupling model of Cohen and Kurath[5)] has been shown to reproduce well many of the features of the entire 1p shell. Recent calculations have

been extended to include positive parity levels in A = 11 nuclei.[6] The shell model calculations of Norton and Goldhammer,[7] while limited to negative parity levels, are of interest since they alone predict the presence of the 8.10 MeV $3/2^-$ and 8.43 MeV $5/2^-$ levels which are appreciably excited here.

The magnitudes and relative phases of the three sets of spectroscopic amplitudes are in remarkable agreement, except that some sets are more extensive than others. All calculations discussed below employ the Norton and Goldhammer amplitudes unless otherwise stated.

Presentation of Results:

The 2.0 MeV $1/2^-$ level

Curiously, agreement with experiment is best if two-step amplitudes are ignored. Fig. 3 shows this quite clearly. Full CCBA agreement is somewhat better if the Clegg amplitudes are used, but the single-step calculation is still superior. Overall agreement is thus only fair.

The $3/2^-$ levels

The predicted g.s. angular distribution is unaffected by inclusion of the two-step process due to the small amplitude for the 2^+ coupled term compared to the very large direct term. Hence agreement remains excellent.

Agreement with the 4.80 MeV $3/2^-$ data is quite good as shown in Fig. 4. This calculation uses $\beta_2 = +0.35$; as shown in the figure, results using the negative sign compare much less favorably. The two-step calculation is in better agreement

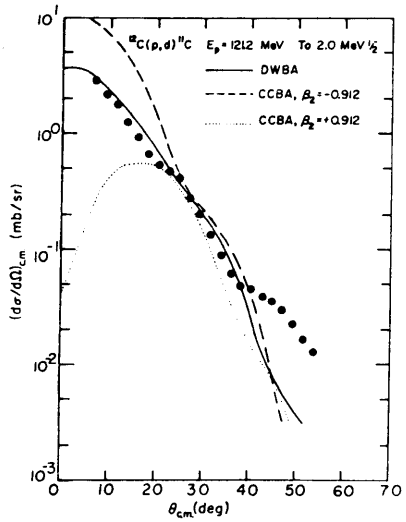

Fig. 3. One- and two-step calculations compared to 2 MeV $1/2^-$ angular distribution. As in all CCBA calculations, no deuteron spin orbit potential was used. The β_2 referred to in the figure is that for connecting the $3/2^-$ g.s. and the $1/2^-$ excited state.

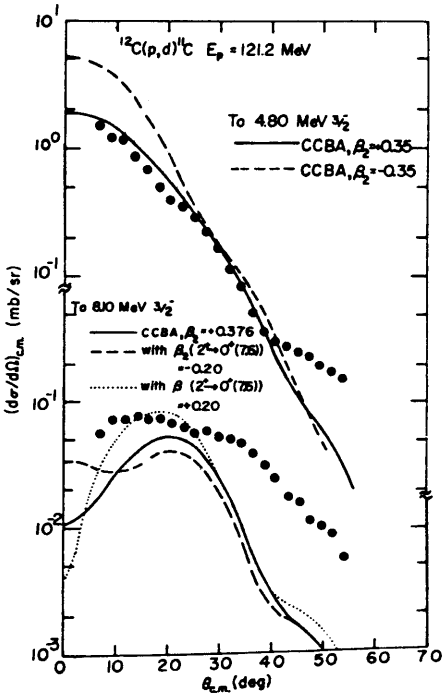

Fig. 4. CCBA results are compared with $3/2^-$ angular distributions. For the 8.10 MeV level, the effect of coupling to the 7.6 MeV 0^+ level of ^{12}C is indicated.

with the data than the single-step result.

The angular distribution for the 8.10 MeV $3/2^-$ state is of interest because neither the Clegg nor the Cohen and Kurath calculations predict this level. Furthermore, the shape is much different from that of the other two $3/2^-$ transitions. It is remarkable that calculations using the Norton and Goldhammer amplitudes reproduce this unusual shape quite well, providing that the positive sign is chosen for the inelastic coupling to the ground state. Also shown in Fig. 4 are CCBA results in which couplings through the 7.67 0^+ level are included. Choice of negative sign for β_2 $(2_1^+ \rightarrow 0_2^+)$ results in somewhat improved agreement.

The 6.48 MeV $7/2^-$ level

As discussed previously, excitation of this state is expected to proceed primarily through two-step mechanisms. Calculations involving only the two-step mechanism appear in Fig. 5 and do not reflect the shape of the data. When a small admixture of single-step $1f_{7/2}$ pickup is included, with a phase giving destructive interference between one-step and two-step mechanisms, agreement becomes reasonable. No other choice of single-step or inelastic phases can reproduce the shape of this angular distribution. The necessity for single-step admixture in the (p,d) excitation of the 7.2^- level has been noted previously[2] and the amplitude required in the present calculation, corresponding to $S \sim 0.01$, is consistent with the previous findings. This analysis is a very powerful method for determining the

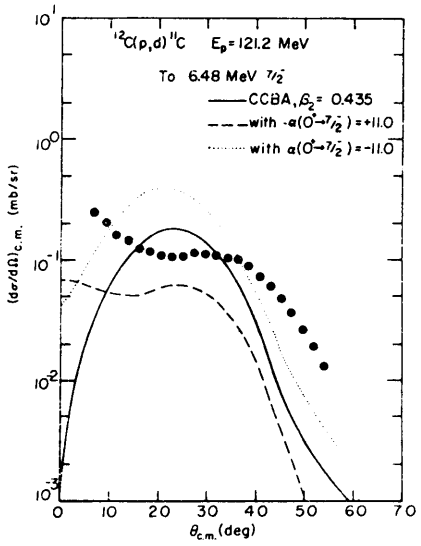

Fig. 5. CCBA results are compared with 6.48 MeV $7/2^-$ angular distribution. The effect of small one-step amplitudes is shown. The coupling strength α is the product of the spectroscopic amplitude and D_o (105 MeV $fm^{3/2}$).

amplitude and relative phase of a very small component of the ^{12}C ground state wave function.

The $5/2^-$ levels

The angular distributions for the 8.43 and 4.32 MeV $5/2^-$ levels are dramatically different in shape. The bell shaped angular distribution for the lower level looks like a classical two-step transition such as was calculated for the $7/2^-$ level without single-step admixture. Indeed, Fig. 6 shows that a simple two-step calculation using β_2 = +1.27 reproduces the experimental shape and magnitude quite well. However, Fig. 5 also shows that two-step calculations fail to describe the angular distribution for the 8.43 MeV level in a manner reminiscent of the $7/2^-$ level discussed above. Indeed, when a small ($S \sim 0.009$) admixture of $1f_{5/2}$ pickup is included,

again phased to result in destructive interference with the two-step amplitude, the substantially improved agreement shown in Fig. 6 is achieved. What implication does this have for the analysis of the lower $5/2^-$ level? It seems unlikely that single-step contributions can be ruled out for this level while they are required for the nearby $5/2^-$ state. In fact, using a one-step amplitude equal in magnitude to that used for the upper $5/2^-$ level and out of phase with the two-step component reproduces the experimental data excellently as is shown in Fig. 6.

Positive Parity Levels

The first five positive parity levels are observed in ^{11}C, although the last two appear as an unresolved doublet. Transitions to these levels are generally comparable in intensity to or a bit smaller than those to the negative parity levels, except for the 6.34 MeV $1/2^+$ level which is very weakly excited. It seems likely that these states are excited through two-step processes predominantly, since single-step explanations would again require unreasonably large sd shell admixtures in the ^{12}C ground state. There are several indirect indications of the presence of two-step processes. The shapes of the lower $3/2^+$ and $5/2^+$ angular distributions show a forward peaked shape similar to the 6.48 MeV $7/2^-$ and the 8.42 MeV $5/2^-$ levels, suggesting that perhaps small one-step components are interfering destructively with two-step mechanisms. Conversely, the $5/2^+$, $7/2^+$ 8.7 MeV doublet has the bell shape of the 4.32 MeV $5/2^-$ level which reflects either pure two-step or constructively interfering one- and two-step mechanisms. If it is assumed that the predominant two-step pathway is via excitation of the 9.6 MeV 3^- level in ^{12}C followed by $1p_{3/2}$ or $1p_{1/2}$ pickup, then, of course, the $1/2^+$ level should not be excited. Indeed, this level is very weakly excited, and can be seen only at the most forward angle with an intensity which gives, assuming $2s_{1/2}$ pickup, $S \sim 6 \times 10^{-4}$, or assuming $1s_{1/2}$ pickup, $S \sim 8 \times 10^{-3}$.

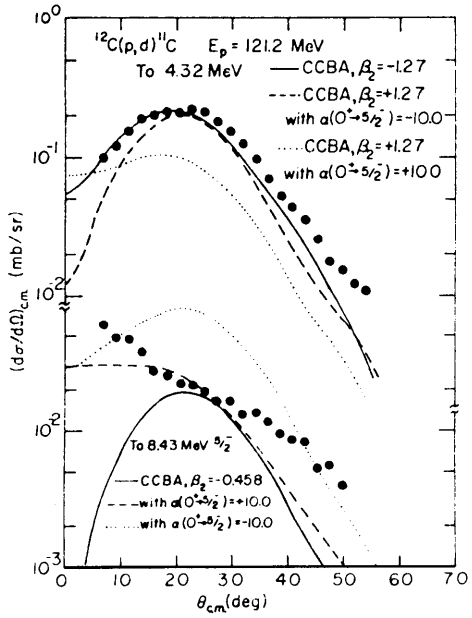

Fig. 6. CCBA results are compared with 6.48 MeV $5/2^-$ angular distributions. The effect of small one-step amplitudes is shown. The coupling strength α is the product of the spectroscopic amplitude and D_o (105 MeV $fm^{3/2}$).

More generally, it is worth noting that states strongly excited in stripping reactions on ^{10}B, the $7/2^+$ and upper $5/2^+$, are weakly excited in this work. The converse is true for the $3/2^+$ and lower $5/2^+$,

while the $1/2^+$ is weak in both instances. This suggests that the parentage of the $3/2^+$ and lower $5/2^+$ may be much more strongly based on the 3^- level of ^{12}C than that of the $7/2^+$ and upper $5/2^+$.

Nuclear structure calculations for the positive parity levels of A = 11 are limited to a single recent paper.[6] Reproduction of observed level spacings is only fair, but the first five levels can be identified with little ambiguity. The spectroscopic amplitudes necessary for CCBA analysis are not available and no such analysis has been attempted. However, one quantitative comparison with the results of Ref. 6 is possible. The extracted spectroscopic factor for the $1/2^+$ level, assuming $1s_{1/2}$ pickup, does not compare favorably with their value, being about an order of magnitude smaller than the prediction.

Conclusions

On the basis of the excellent agreement between a zero range DWBA calculation and the measured $3/2^-$ ground state angular distribution, one may conclude that the DWBA can successfully be applied at the present energy in a very straightforward manner. Comparison with exact finite range calculations show that the zero-range approximation is adequate provided finite-range corrections are used. Excited states are populated by both one- and two-step mechanisms and must be treated in a coupled channels formalism. Spectroscopic amplitudes from several different models are enough alike that no clear preference is evident from comparison with the data. In several cases, where one- and two-step amplitudes appear to interfere destructively, detailed information about small admixtures in the ^{12}C ground state wave function can be extracted. In general, angular distributions for the first seven negative parity levels are adequately explained using the wave functions of Norton and Goldhammer.[7] While no CCBA calculations were performed for transitions to positive parity levels, there is some indirect evidence that these, too, are populated by mixtures of single-step and two-step processes, probably proceeding through the 9.6 MeV 3^- level in ^{12}C. The spectroscopic strength for the 6.34 MeV $1/2^+$ transitions is seen to be much smaller than the predictions of Teeters and Kurath.[6]

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