Role of pion absorption on quasi-deuterons in $^{12}C(\pi^+,2p)$

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Data by Altman *et al.* for exclusive pion absorption on ^{12}C are reexamined using an impulse approximation formalism which treats pion absorption as proceeding only through absorption on a deuteronlike structure within the target nucleus. The results indicate that previous estimates of the strength of this quasi-deuteron absorption component of the reaction mechanism by Altman *et al.* are probably too low. Reasonable agreement with the shape and magnitude of the observed angular distribution is achieved by ignoring distortions for both the incoming pion and outgoing nucleons, with somewhat poorer agreement with inclusion of distortions.

I. INTRODUCTION

The absorption of pions by atomic nuclei is a topic of considerable experimental and theoretical interest for several reasons. Most notably, pion absorption by the nucleus dominates the pion-nucleus reaction cross section at low energies, and remains a sizable component at energies throughout the resonance region. Thus, an understanding of the absorption process can be expected to be important for a complete description of most phenomena observed in pion-nucleus reactions.

Several studies of pion absorption on nuclei heavier than the deuteron have reported correlations between the outgoing protons indicative of absorption on a deuteronlike structure within the absorbing nucleus (e.g., Refs. 1–3). Specifically, the observed correlations show enhancements close to the opening angles given by the kinematics of the $\pi^+ + d \rightarrow p + p$ reaction. Integrals of these distributions, with an approximation for background processes subtracted, have been used to estimate a "two-body" or quasi-deuteron absorption cross section. The results[1] ($\sim 10\%$ of the total absorption cross section in ^{12}C) have tended to support the conclusion that much of the absorption cross section cannot be explained by the two-body strength alone.

In this paper, the role of the quasi-deuteron component in pion absorption is examined using a distorted wave impulse approximation formalism. As sample data for description, we have chosen the results of Altman *et al.*[1] for "exclusive" pion absorption on ^{12}C at 165 MeV in which two coincident protons are detected at specific angles but the data are integrated over energy. The results described in the following, wherein the only component of the absorption process is assumed to be that due to quasi-deuterons, are consistent with the observed cross sections. Though the calculations do not unambiguously predict the absolute strength of the quasi-deuteron component, they do call into question the previous experimental analyses in which significant backgrounds were removed from the quasi-deuteron peak, and thus indicate that the two-body component is more important than previously suggested.

II. FORMALISM

The formalism used for this investigation was the distorted wave impulse approximation (DWIA) description of cluster knockout reactions described in Ref. 4, which was extended to the $(\pi^+,2p)$ process in Ref. 5. This method employs a factorized distorted wave impulse approximation in which the pion is assumed to capture on a quasi-deuteron bound in the target nucleus. Schematically, the cross section for the $^{12}C(\pi^+,2p)^{10}B$ reaction leading to a specific final state is, using the notation of Ref. 3 for $A(\pi^+,2p)B$,

$$\frac{d^3\sigma}{d\Omega_1 d\Omega_2 dE} = KC^2S\frac{d\sigma}{d\Omega}\bigg|_{\pi d\rightarrow pp}\sum_{\Lambda}|T_{BA}^{\alpha L\Lambda}|^2, \qquad (1)$$

where

$$T_{BA}^{\alpha L\Lambda} = (2L+1)^{-1/2}\int \chi_{p_1B}^{(-)*}(\vec{k}_{p_1B},\vec{r})\chi_{p_2B}^{(-)*}(\vec{k}_{p_2B},\vec{r}) \times \chi_{\pi A}^{(+)}(\vec{k}_{\pi A},\gamma\vec{r})\phi_{L\Lambda}^{\alpha}(\vec{r})d^3r$$

and $\gamma = B/A$ is a recoil correction. The quantity K is a kinematic factor, $d\sigma/d\Omega$ is the free two-body $\pi d \rightarrow 2p$ cross section, and the χ's represent the incoming pion and outgoing proton scattering wave functions. The wave function $\phi_{L\Lambda}^{\alpha}$ represents the center-of-mass motion of a deuteron cluster resulting from the projection of the target wave function onto the residual nucleus and a deuteron in its ground state. The quantity C^2S is the spectroscopic factor for a nucleon pair with quantum numbers $T=0$, $S=1$ and $1s$ relative motion.

While the formalism developed in Ref. 3 was specifically for calculations of the $(\pi^+,2p)$ reaction to discrete states in the final nucleus, the data of Ref. 1 place no restrictions on the missing mass. In addition, angular distributions were obtained by integrating over the detected nucleon energy spectrum. Thus, the calculated predictions were integrated over an appropriate kinematic range to permit comparison with the exclusive data under discussion. In approximating the integral over missing mass, we have assumed that pion absorption occurs only on a $1p$ shell nucleon pair having either $L=0$ or $L=2$ c.m. orbi-

tal angular momentum with respect to the ^{10}B core. Spectroscopic factors for these two transferred angular momenta were taken to be the sum of values for states below 7.7 MeV excitation in ^{10}B calculated by Cohen and Kurath.[6] The motion of the center-of-mass of the nucleon pair represented by the wave function $\phi^{\alpha}_{L\Lambda}$ was approximated by an eigenfunction of a Woods-Saxon potential with an average energy eigenvalue corresponding to about 1 MeV excitation in ^{10}B.

The differential cross section for the πd$\rightarrow$pp process was taken from a parametrization of the free absorption cross section. The Niskanen convention[9] for expressing the differential cross section was found to be convenient:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{c.m.}} = \frac{1}{2\pi}\sum_{n=0,2,4}\alpha_n P_n(\cos\theta_{\text{c.m.}}) .$$

With the differential cross section expressed in this form, α_0 represents the total absorption cross section. Since the incident energy of the pion on the quasi-deuteron could vary somewhat due to the relative motion of the quasi-deuteron and residual nucleus, an expression for the energy dependence of the differential cross section was required. For these calculations, α_0 was taken from Eq. (3) of Ref. 10, in which a parametrization of recent total cross section data for πd$\rightarrow$pp was presented. Specifically,

$$\alpha_0=\sigma=a+\frac{b}{\sqrt{T_\pi}}+\frac{c\times 10^4}{(E-E_R)^2+d} ,$$

where E is the invariant energy, T_π is the laboratory pion kinetic energy, and the remaining parameters (a, b, c, d, and E_R) are (-1.2 mb, 3.5 mb MeV$^{1/2}$, 7.4 mb MeV^2, 5600 MeV^2, and 2136 MeV), respectively.[10] The α_2 coefficient was parametrized by omitting the second term of this expression and substituting $a=-1.7$ mb, $c=8.1$ mb MeV^2, and $E_R=2131$ MeV. The coefficient α_4 was given by

$$\begin{aligned}\alpha_4 &= 0 && : T_\pi < 100 \text{ MeV}\\ &= (T_\pi - 100 \text{ MeV})\times 0.026 \text{ mb MeV}^{-1} && : 100 \text{ MeV} \le T_\pi \le 170 \text{ MeV} .\end{aligned}$$

The predicted πd$\rightarrow$pp differential cross sections were observed to be in excellent agreement with measured results.

In calculations for truly exclusive reactions, the scattering wave functions $\chi^{(\pm)}$ are typically generated using optical potentials which reproduce appropriate elastic scattering data. In the present case the situation is more complicated. Firstly, since the experiment does not select specific residual states, some of the outgoing protons have lost energy due to multiple scattering before detection. However, describing the emitted proton wave functions with a complex optical potential determined from elastic scattering of the protons on the residual nucleus, will, in principle, exclude this component of the outgoing flux, which nonetheless is detected. To estimate the significance of this possibility, we have carried out calculations both with the imaginary part of the proton optical potential set equal to zero, and, as an alternative, with plane waves representing the outgoing protons. In either case, we have thus assumed that each of the two protons resulting from pion absorption on the valence $1p$ nucleon pair gives rise to one, and only one, proton above the approximately 40 MeV threshold of the detection system of Ref. 1. Any additional protons ejected due to the multiple scattering are assumed to lie below the detection system energy threshold, and loss of the initial proton due to energy sharing is ignored.

Secondly, the choice of optical potential to describe the incident pion is also somewhat open to question. Since inelastically scattered pions may also be absorbed, the use of an optical potential obtained by fitting elastic pion scattering data may possibly exclude pions from the absorption process which do, in fact, participate. Thus, it has been suggested[7] that a plane wave approximation for the incoming channel may be more appropriate. Clearly this might be appropriate if, for example, inelastic scattering to states having significant deuteron components were to dominate the absorptive component of the optical potential, and nuclear structure ingredients such as C^2S and $\phi^{\alpha}_{L\Lambda}$ were similar for deuteron components in the ground and excited states of the target. In practice, these assumptions are not correct. Rather, nucleon knockout and true absorption itself represent more than half of the total inelastic cross section at the energy studied here;[8] thus, depending on the role of these processes, a plane wave calculation can be expected to overestimate the cross section. It may, however, be worth noting that sensitivity to absorption on quasi-deuteron structures in an excited target will be enhanced owing to the corresponding reduction in deuteron-core binding energy. In the absence of a rigorous treatment of multistep contributions, which properly includes excited state structure factors and binding energies, we have, for completeness, treated the entrance and exit channels with and without distortions, and present all results in the following section.

III. RESULTS AND DISCUSSION

DWIA calculations of the triple differential cross sections of Eq. (1) were carried out using the code THREEDEE.[11] The calculations were averaged over the finite solid angles described in Ref. 1. Integrations were made over the energy sharing distributions, with the finite solid angle folded in, for comparison with the experimental results.

The results of the calculations assuming plane waves for the incident and emitted particles in the entrance and exit channels are shown in Fig. 1, compared with the data of Ref. 1. The deuteron-^{10}B potential was taken to be a Woods-Saxon shape, with $r_0=1.0$ fm, $a=0.65$ fm, which yields a wave function having an rms radius of 3.00 fm,

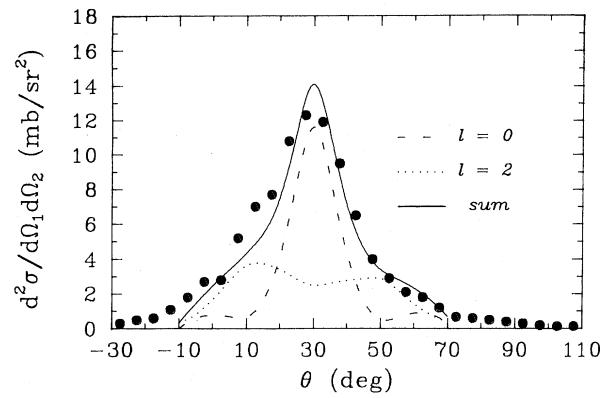

FIG. 1. Results of PWIA calculations as described in the text. The dotted, dashed, and full curves represent $L=0$, $L=2$, and summed (with spectroscopic factors 1.63 and 2.64, respectively) differential cross sections.

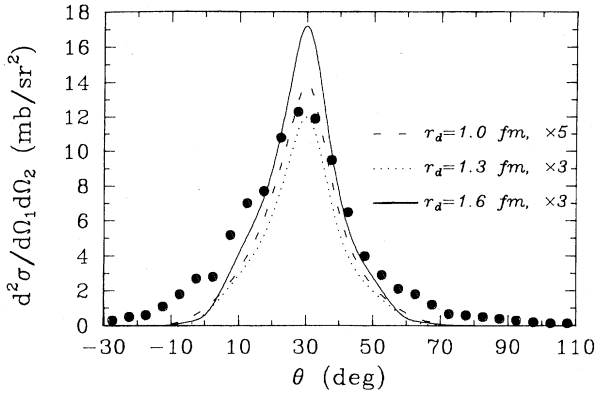

FIG. 3. Effect of varying the deuteron-core relative wave function radius parameter with distortions as in Fig. 2.

somewhat larger than the electron scattering value[12] of 2.45 fm for the charge radius of ^{12}C. Several observations are worth noting. First, the magnitude of the predicted peak in the angular distribution is in surprisingly good agreement with the data. While our approximate treatment of the $^{12}C \rightarrow {}^{10}B + d$ nuclear structure certainly oversimplifies the true situation, the agreement is encouraging and lends some support to the arguments already outlined that plane waves should be used in order to describe such exclusive data. Second, the predicted shape of the distribution is also in very good agreement with the observed distribution, showing essentially the same asymmetry about the central kinematic angle. Finally, it appears that the background subtracted in Ref. 1 excludes strength that actually represents quasi-deuteron absorption primarily on $L=2$ clusters, and may not be attributable solely to final state interactions or more complex processes, as suggested by the authors of Ref. 1.

To explore the effect of incident pion distortions, particularly absorption, on the predictions, a pion-nucleus optical potential was employed, using the Cottingame-Holtkamp prescription.[13] The hadronic density assumed for ^{12}C was a harmonic oscillator, with a size parameter of 1.65 fm. The outgoing proton waves were calculated using a purely real potential with no absorption. The proton potential was taken from Nadasen *et al.*[14] who report a global fit to proton scattering data from 40 to 180 MeV for nuclei from ^{28}Si to ^{208}Pb. The results are shown in Fig. 2. The predictions are seen to fall below the data by a considerable amount, and the predicted shape disagrees with experiment more seriously than is the case when distortions are completely omitted. As noted above, the simple treatment of the target nucleus structure used here may possibly lead to some disagreement in absolute cross section, particularly in view of difficulties in correctly predicting the absolute magnitude of differential cross sections for related reactions, such as (p,t) and (p,^{3}He), even in exact full finite-range treatments.[15] Since the parameters of the Woods-Saxon well used to generate the deuteron-core relative wave function are not independently well determined, we also carried out calculations with the radius parameter r_0 increased to 1.3 and 1.6 fm. This produced rms radii of 3.17 and 3.36 fm, respectively, which are larger than the aforementioned electron scattering value of 2.45 fm. However, the magnitude of the

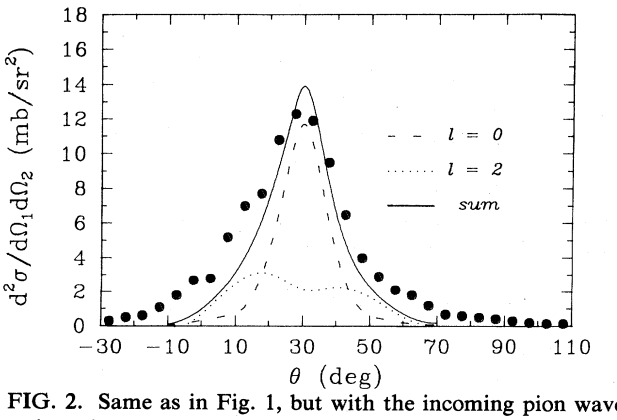

FIG. 2. Same as in Fig. 1, but with the incoming pion wave function distorted by a complex pion-nucleus optical potential and the outgoing protons distorted by the real part of a proton-nucleus optical model potential (see the text). The results have been multiplied by a factor of 5.

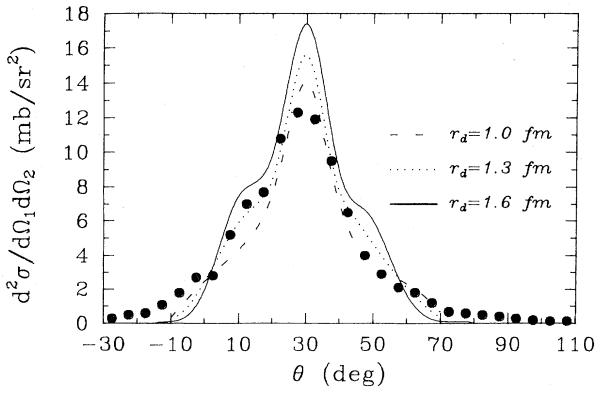

FIG. 4. Same as Fig. 3 for PWIA treatment of incoming pions and outgoing nucleons.

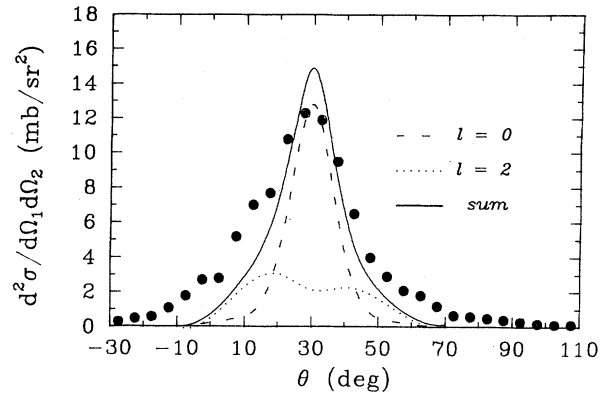

FIG. 5. Results of full DWIA calculations which include absorption for outgoing proton wave functions. The calculations have been multiplied by a factor of 10.

predicted cross sections, as seen in Fig. 3, improved in agreement with experiment only slightly, and resulted in a narrower peak in poorer agreement with the observed shape. The results of a similar variation of r_0 for the plane-wave impulse approximation (PWIA) case are shown in Fig. 4.

For completeness Fig. 5 shows the results for a full distorted wave calculation where the incoming pion distortions are treated as in Fig. 2, and the full complex proton-nucleus potential of Ref. 14 is used in the exit channel. It is seen that these predictions lead to even smaller cross sections due to the attenuation of the proton waves, and that agreement with the observed shape of the quasi-deuteron peak is again poorer than for the calculations of Fig. 2. Variation of the deuteron well radius again improves the agreement only slightly. This lack of agreement is not surprising, since such calculations are expected to be appropriate for transitions to low-lying states in which both the energies and angles of the detected protons are measured.

Of these various calculations, it is interesting to note that the simplest does remarkably well in fitting the magnitude and shape of the measured angular distribution. The only additional detailed data published by Altman *et al.* are the proton energy spectrum measured for one pair of angles. Unfortunately, the present calculations, either plane wave or distorted wave, cannot be directly compared to such data, since they make no predictions concerning the effect of multiple scattering on the energy spectrum. All calculations predict a width for transitions to low-lying states approximately a factor of 2 smaller than the experimental data, which one may interpret as evidence for multiple scattering, in which many events lie in the region of four-body breakup.

IV. CONCLUSION

The present work suggests that the role of the quasi-deuteron component in the reaction $^{12}C(\pi^+,2p)$ could be considerably larger than the value of $\sim 10\%$ reported in Ref. 1. Calculations which treat the absorption as primarily proceeding through deuteron clusters in the target nucleus predict the observed cross section shape reasonably well. This feature holds true regardless of how the distortions are treated, but best agreement was obtained with all distorting potentials set to zero. Furthermore, this calculation produced very good agreement with the magnitude of the observed cross section, whereas the calculations which included distortions in one channel or both underestimated the cross section by as much as an order of magnitude.

In summary, while our analysis is subject to many uncertainties, we find no evidence that significant "background" processes are needed to explain the experimental data. Clearly, additional comparisons at other energies and to other nuclei are desirable in order to clarify the situation. It would be most useful if such data had good missing mass resolution.

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