Observation of a Quasideuteron Component in the Reaction $^{12}C(\pi^+, 2p)$

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The reaction $^{12}C(\pi^+, 2p)$ was studied at 165 and 245 MeV over a broad kinematic range by coincidence measurement of the outgoing protons. The p-p angular correlations and proton energy spectra allow an identification of the "quasideuteron" component of the reaction. The angular distribution of this component has a shape similar to that of the $\pi^+ d \to pp$ reaction. It is found that one-step quasideuteron absorption accounts for at most 25% of the total absorption cross section.

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Pion absorption on a nucleon pair is the simplest mode of pion absorption in nuclei. The question of whether this is also the dominant mode has created much controversy in recent years. Single-arm measurements of proton spectra following pion interaction with nuclei show a high-energy peak, characteristic of an absorption on a nucleon pair,[1] only for very light nuclei at forward angles, and it was suggested that more complicated processes play an important role in pion absorption. On the other hand, theoretical calculations[2,3] were able to reproduce experimental data reasonably well under the assumption of only absorption on nucleon pairs, followed by final-state interaction of the outgoing nucleons. The first step of pion-nucleus interaction at energies near the (3, 3) resonance is described by formation of a Δ. The resonance may subsequently decay with the emission of a pion, or undergo further interactions, one of which is the two-nucleon absorption mode, $N\Delta \to NN$. Studies of inclusive pion inelastic scattering show[4,5] that it is dominated by quasifree scattering at backward angles. This process may be interpreted as direct decay of the Δ, which was formed in the first step of the interaction. The main purpose of the present work is to study the strength of the $N\Delta \to NN$ interaction of this Δ and its contribution to the total absorption cross section. This is done by studying the $(\pi^+, 2p)$ reaction and identifying the component of this process which has characteristics similar to those of the $\pi^+ d \to pp$ reaction. Previous studies of the $(\pi^+, 2p)$ reaction on nuclei[6] were confined to a small part of the available phase space, and therefore could not yield the total cross section for this process.

We studied the $(\pi^+, 2p)$ reaction on ^{12}C at 165 and 245 MeV at the πM3 channel of the Swiss Institute for Nuclear Research accelerator. The two outgoing protons were detected in coincidence and the corresponding cross sections were measured. One arm of the experimental system consisted of three telescopes, each made of two $5 \times 5 \times 5\text{-cm}^3$ cubes of plastic scintillators, where energy-loss measurements were used to identify protons. The coincident protons were detected with a 1-m^2 array of twenty scintillators. A 1-mm-thick scintillator was placed in front of the array for proton/neutron identification. Pulse-height and time-of-flight (TOF) information were recorded for each scintillator. This information was used for separating protons from pions. The TOF information was used to obtain the proton energies. The pion beam was monitored by two thin plastic scintillators mounted on the beam axis, and a collimating scintillator with a $5 \times 5\text{-cm}^2$ hole, in which the target was placed. The $\pi^+p \to \pi^+p$ and $\pi^+d \to pp$ reactions were used for energy and absolute normalization calibrations: CH_2 and D_2O targets were used, and the results of π-p or p-p coincidence measurements were compared with previous data.[7] The overall energy resolution was 32 MeV for 200-MeV protons. The angular resolution for the protons detected in the array was 5° in the horizontal (reaction) plane and 4° in the vertical plane. The protons in the telescopes were detected in the angular range of 50°–140° in steps of 10°. For each such detection angle, protons in the array were detected over an angular range of about 100°, centered around the angle of the $\pi^+d \to pp$ kinematics, and covering simultaneously a vertical angular range $-20° < \varphi < +20°$. The full details of the experimental setup are given elsewhere.[8]

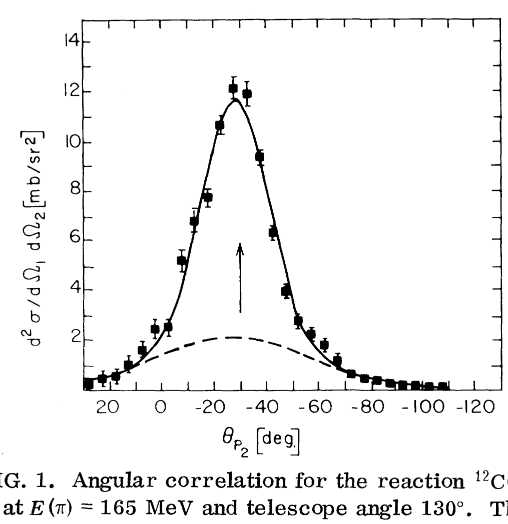

FIG. 1. Angular correlation for the reaction $^{12}C(\pi^+, 2p)$ at $E(\pi) = 165$ MeV and telescope angle 130°. The arrow marks the angle for the $\pi^+d \to pp$ reaction. The curves are Gaussian fits to the data (see text).

Figure 1 shows the angular correlation between protons in the telescopes (set at $\theta_{p_1} = 130°$) and protons in the array for incident pions of 165 MeV. The data are presented for the horizontal plane ($\Delta\varphi \pm 6°$) and integrated over the outgoing proton energies above a cutoff set at least 80–100 MeV below the peak of their energy spectrum (Fig. 2). The angular correlation in the vertical plane was found to have a similar shape. The errors shown contain statistical and angle-dependent systematic uncertainties. There is an additional overall normalization uncertainty of 9%. All the angular correlation curves show a strong peak centered near the angle for the $\pi^+d \to pp$ kinematics, superimposed on a "background." Figure 2 shows a proton energy spectrum measured at the peak of the angular correlation for $T_\pi = 165$ MeV. Here, too, a peak centered near the energy corresponding to the $\pi^+d \to pp$ kinematics is observed.

Each p-p angular correlation, including the data outside the reaction plane, was fitted by a least-squares method with a sum of two two-dimensional Gaussian functions (the solid curve in Fig. 1). The peak positions, amplitudes, and widths of these functions were treated as free

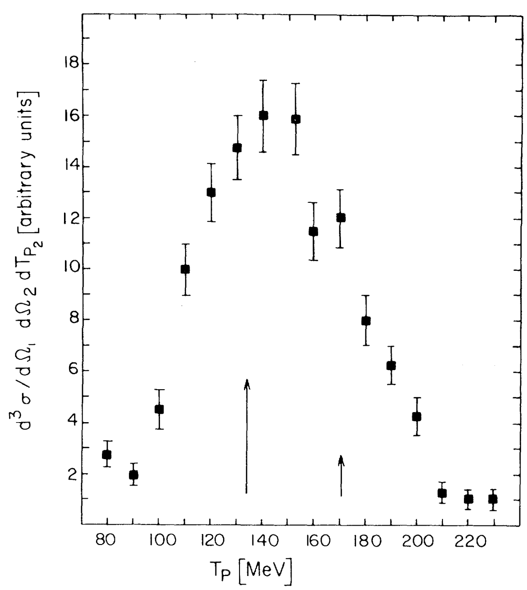

FIG. 2. Proton energy spectrum from the reaction $^{12}C(\pi^+, 2p)$ measured at $-82.5°$ in coincidence with protons detected at 70°. The bombarding energy is 165 MeV. The long arrow marks the proton energy for $\pi^+ {}^{12}C \to 2p + {}^{10}B$. The short arrow marks the proton energy for $\pi^+ {}^{12}C \to p + (pn) + {}^9B$. In both cases the residual nucleus is assumed at rest.

parameters. We obtained, for all cases, one narrow and one broad Gaussian. The peak of the narrow Gaussian was always found to be very near the angle corresponding to the $\pi^+d \rightarrow pp$ kinematics. These results suggest the identification of the narrow Gaussian component in the angular correlation with a direct absorption on a p-n pair, representing a "quasideuteron" absorption process. The broad Gaussian (the dashed curve in Fig. 1) is attributed to a background generated by a final-state interaction of the outgoing protons and by more complex absorption mechanisms.

We examined our results to determine whether a p-(pn) component[9] could be included in our p-p quasideuteron results (a p-d coincidence is excluded by particle identification). Such a component yields proton energies 40 MeV higher than those from quasideuteron absorption and should be seen as a peak at the higher part of the proton spectrum (e.g., Fig. 2). No such peak is observed but the data cannot rule out a small contribution from this process.

In order to determine the contribution to the total absorption cross section[10] from the quasideuteron absorption mechanism, we integrated the area under the two-dimensional narrow Gaussian in the angular correlation. Figure 3 shows the resulting angular distributions as a function of $\cos^2\theta_{p_1}$, where θ_{p_1} is the telescope's angle transformed to the center-of-mass system of the $\pi^+d \rightarrow pp$ reaction. This transformation reflects the underlying assumption of absorption on a p-n pair, with the rest of the nucleus acting as a spectator. The curves are the angular distributions of the $\pi^+d \rightarrow pp$ reaction normalized to our data. [Note that the present data and those of Ref. 7 are normalized in such a way that $\sigma = \pi\int(d\sigma/d\Omega)d\cos\theta$.] The similarity of the angular distributions at the two energies further supports the identification of the quasideuteron process. The normalization factor D_{eff}, which is the ratio between the quasideuteron cross section and that of the free $\pi^+d \rightarrow pp$ reaction, may be regarded as the effective number of quasideuterons participating in the process. These values are listed in Table I. Also listed in Table I is another normalization factor, N_{eff}, representing the effective number of nucleons participating in pion quasifree scattering.[10] Although the definition of D_{eff} may not be entirely analogous to that of N_{eff}, and their similar values may be fortuitous, it is interesting to note that both factors vary with bombarding energy in a very similar way. This suggests a probable common origin, namely the formation of a Δ at the nuclear surface. The lower value at 165 MeV reflects the shorter mean free path for the pion at the peak of the (3, 3) resonance.

By integrating the angular distributions of Fig. 3, we obtain the total cross section for quasideuteron absorption. The results are listed in Table I together with the total absorption cross sections on carbon at these energies. The measured contribution of the quasideuteron process to the total absorption cross section, before accounting for losses, is (9 ± 2)% and (11 ± 2)% for 165 and 245 MeV, respectively, not including errors in the total absorption cross sections. These values are similar to the 9.5% contribution observed in bubble-chamber experiments[11] at 130 MeV. Loss-

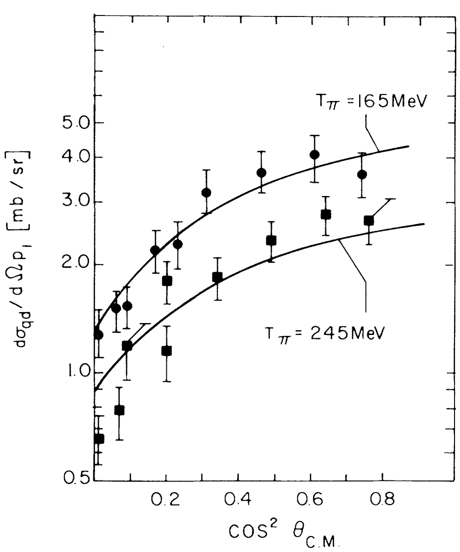

FIG. 3. Angular distribution of the quasideuteron component of the reaction $^{12}C(\pi^+, 2p)$ represented in the c.m. system of the $\pi^+d \rightarrow pp$ reaction. The curves are the results for the latter reaction normalized to the data.

TABLE I. Normalization factors for inelastic scattering (N_{eff}), normalization factors (D_{eff}) and cross sections (σ_{qd}) for the quasideuteron absorption, and total absorption cross sections (σ_{abs}) (see text).

T_π (MeV)	σ_{qd} (mb)	σ_{abs} (mb)[a]	D_{eff}	N_{eff}[a]
165	17.8 ± 2.7	194 ± 36	1.47 ± 0.1	1.41
245	11.4 ± 2.0	95 ± 32	2.70 ± 0.2	2.78

[a] From Ref. 10.

es due to final-state interaction of the outgoing protons should be smaller than the losses in the similarly measured $(\pi^+, \pi^+ p)$ reaction,[8] since in our case we are dealing with higher-energy protons that have longer mean free paths. In the $(\pi^+, \pi^+ p)$ case the correction for this effect was estimated to be not more than a factor of 2. We therefore estimate that the quasideuteron contribution to the total absorption cross section should not exceed 18% and 22% for 165 and 245 MeV, respectively.

Unlike the situation in total inelastic scattering, where a large fraction of the process originates from one-step Δ formation and decay, we find that the one-step Δ formation followed by $N\Delta \to NN$ interaction is only a small part ($\lesssim 25\%$) of the total absorption cross section. The bulk of the absorption cross section is, therefore, in other processes such as multiple pion scattering followed by a final two-nucleon absorption, absorption on clusters, or double-Δ formation.[12] These results are in qualitative agreement with recent calculations by Masutani and Yazaki[13] and by Fraenkel, Piasetzky,[14] and Kalbermann.

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[1]R. D. McKeown *et al.*, Phys. Rev. C 24, 211 (1981).

[2]J. Ginocchio, Phys. Rev. C 17, 195 (1978).

[3]H. C. Chiang and J. Hufner, Nucl. Phys. A2352, 442 (1981).

[4]D. Ashery *et al.*, Phys. Rev. C 23, 2173 (1981).

[5]S. Levenson *et al.*, Phys. Rev. Lett. 47, 479 (1981).

[6]J. Favier *et al.*, Nucl. Phys. A169, 540 (1971); E. D. Arthur *et al.*, Phys. Rev. C 11, 332 (1975).

[7]C. Richard-Serre *et al.*, Nucl. Phys. B20, 413 (1970).

[8]E. Piasetzky *et al.*, Phys. Rev. Lett. 46, 1271 (1981), and Phys. Rev. C 25, 2687 (1982).

[9]D. Gotta *et al.*, Phys. Lett. 112B, 129 (1982).

[10]I. Navon *et al.*, Phys. Rev. C 22, 717 (1980).

[11]E. Bellotti *et al.*, Nuovo Cimento 18, 75 (1973).

[12]G. E. Brown *et al.*, Phys. Lett. 118B, 39 (1982).

[13]K. Masutani and K. Yazaki, Phys. Lett. 104B, 1 (1981).

[14]Z. Fraenkel, E. Piasetzky, and G. Kalberman, Phys. Rev. C 26, 1618 (1982).