Quasifree subthreshold pion production in the reaction $^{12}C(p,d\pi^+)^{11}B$

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Nuclear pion production has been studied by means of the reaction $^{12}C(p,d\pi^+)^{11}B$ at an incident energy of 223 MeV, which is considerably below the threshold for a free N-N process. The shape and absolute cross section of the experimental energy-sharing distribution are in remarkable agreement with the prediction of a distorted-wave impulse approximation theory. This shows that the reaction mechanism is quasifree pion production, which is related to the elementary reaction $p+p\rightarrow\pi^+ +d$.

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Although exclusive $(p,\pi^\pm)$ reactions have been studied extensively for many years, pion production in nucleon-nucleus collisions far below the threshold for a free $N-N$ process is still poorly understood. In view of the general success of the traditional model of the atomic nucleus, which conceptualizes nuclear matter as consisting of nucleons and isobars with meson-exchange currents accounting for the strong interaction, this situation is somewhat disconcerting. Furthermore, the desire to exploit the high-momentum transfers intrinsic to pion-production reactions to reveal, for example, effects due to quark structure is frustrated in the absence of a sound description of the process in terms of a conventional nuclear model.

One problem which is often encountered in exclusive pion-production studies is that it is not possible to disentangle [1] the underlying reaction mechanism from complicated nuclear-structure effects. Nevertheless, evidence has recently been presented for the dominance of a quasifree two-nucleon mechanism in nuclear subthreshold pion production [2], as opposed to a one-nucleon pionic stripping process [3]. Therefore, direct observation of quasifree knockout pion production, which can more readily be related to an elementary $NN\rightarrow NN\pi$ intranuclear process than can exclusive (p,π) production, now becomes crucial to a better understanding of the mechanism of pion production at subthreshold bombarding energies.

Of the various fundamental two-nucleon processes which are in principle possible in proton-induced pion-production reactions, $pp\rightarrow d\pi^+$ is likely [2] to be dominant. Furthermore, the pion-absorption reaction $(\pi^+,2p)$, which may be viewed as roughly related to the time-reversed $(p,d\pi^+)$ reaction, has been shown [4] to be understood reasonably well at $E_\pi=165$ MeV in terms of a distorted-wave impulse-approximation (DWIA) theory. Consequently, the DWIA theory is expected to be a useful tool for the interpretation of the pion-production knockout reaction $^{12}C(p,d\pi^+)^{11}B$, which was studied at $E_p=233$ MeV in this work.

In this paper we report the first direct experimental observation of quasifree two-nucleon pion production well below the threshold energy needed for a free N-N process. The energy-sharing distribution for the reaction $^{12}C(p,d\pi^+)^{11}B$ is found to be in very good agreement with predictions of a simple DWIA model.

The experiment was performed at the cyclotron facility of the National Accelerator Centre with a proton beam of 223 ± 0.5 MeV. The target was a self-supporting natural carbon foil of thickness 4.5 ± 0.4 mg/cm^2. Plastic scintillator (NE102) telescopes were used for the detection of pions and deuterons. The telescope for pions consisted of an 8-mm-thick transmission detector (ΔE), followed by a 150-mm-thick pion-stopping ($E_\pi<70$ MeV) detector (E). A veto detector (8 mm thick) to discriminate against high-energy reaction products which penetrate the E detector was placed behind the telescope. The telescope for the detection of deuterons up to 65 MeV consisted of a 1.5-mm-thick ΔE and 20-mm-thick E scintillator, followed by a 20-mm-thick veto detector. Each telescope subtended a solid angle of 8 msr and had an angular acceptance of 6°. The telescopes were positioned in a 1.5-m-diam scattering chamber at coplanar symmetric angles of 20° with respect to the incident beam direction.

Conventional techniques were used to establish coincidence requirements and to gate charge-sensitive analog-to-digital convertors, which converted the energy signals for further computer processing. Identification of deuterons was based on the usual ΔE-E technique, but for pions the decay muons from $\pi^+\rightarrow\mu^+ +\nu$ served as an additional signature [5] in order to separate pions from the reaction tail of protons in the detectors. As described in Ref. [5], the signals of the pion telescope were clipped to ~ 8 ns and an inspection period of 90 ns was allowed for the appearance of a 4.1-MeV muon signal from the decay of a pion at rest.

Figure 1 shows the ΔE-vs-E spectrum of pions gated on a muon signal, overlaid with an ungated spectrum for protons and deuterons, which were scaled down for display.

The pions are concentrated on a well-defined locus, and the background is negligible. The efficiency for the detection of pions ($\sim 50\%$) was determined from the pion-muon relative time shown in Fig. 2. A fit to these data is consistent with the known mean lifetime. To obtain the total number of pions, a lifetime of 26 ns was assumed and the resultant decay curve normalized to the data in Fig. 2 for times greater than 20 ns. This normalized curve was then integrated to obtain the total number of detected pions.

These data were further corrected for losses due to pion decay between the target and stop position in the detector (6%–8%), for the losses due to stopped-pion decay followed by muon decay (4%), as well as for losses due to reactions of pions and deuterons in the detector material ($<6\%$ for both pions [5] and deuterons [6]). Beam currents were limited to ~ 4 nA in order to have negligible ($<5\%$) random coincidences, as the very low π-d true coincidence rate made a statistically reliable background subtraction impossible.

A clear kinematic locus due to ^{12}C $(p,d\pi^+)$ ^{11}B was observed in the E_d-vs-E_π spectrum, which is plotted as a binding-energy spectrum in Fig. 3. This shows a prominent broad peak from knockout pion production to the ground and low-lying states of ^{11}B, which we identify with $1p$-proton shell removal. The energy-sharing distribution of the "ground-state" peak, which is the cross section plotted as a function of the deuteron kinetic energy, is displayed in Fig. 4.

The experimental results are interpreted in terms of DWIA theory for a reaction $A(p,d\pi^+)B$, which, in the absence of spin-orbit interactions, simplifies [7] to

$$\frac{d^3\sigma}{d\Omega_d d\Omega_\pi dE_d} = S_p F_k \frac{d\sigma}{d\Omega_{\pi d}} \sum_\Lambda |T_L^\Lambda|^2 ,$$

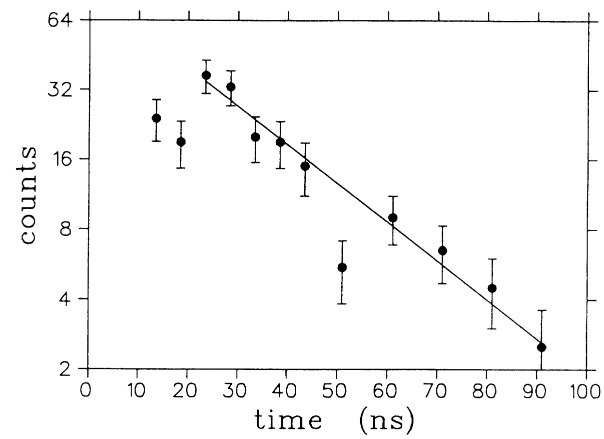

FIG. 2. Pion-muon decay distribution. The curve indicates a mean lifetime of 26 ns.

where S_p is the spectroscopic factor for a proton p_b bound in the target nucleus, F_k is a kinematic factor, and $d\sigma/d\Omega_{\pi d}$ is a half-shell two-body cross section for the elementary reaction $p+p_b \to d+\pi^+$. The quantity $\sum_\Lambda |T_L^\Lambda|^2$ is a distorted momentum distribution expressed as

$$T_L^\Lambda = (2L+1)^{-1/2} \times \int \chi_d^{(-)*}(\mathbf{r}) \chi_\pi^{(-)*} \phi_L^\Lambda(\mathbf{r}) \chi_p^{(+)} \left[\frac{B}{A}\mathbf{r}\right] d\mathbf{r} ,$$

where the χ's are distorted waves for the incident and emitted particles and $\phi_L^\Lambda(\mathbf{r})$ is the relative-motion wave function for p_b and B in the target A, with relative angular momentum L and projection Λ.

For ^{12}C $(p,d\pi^+)^{11}$B we treat the target as a closed $1p_{3/2}$-proton shell nucleus, and we exclude spin-orbit terms in the optical potentials which are used to generate distorted waves in order to retain the factorized expres-

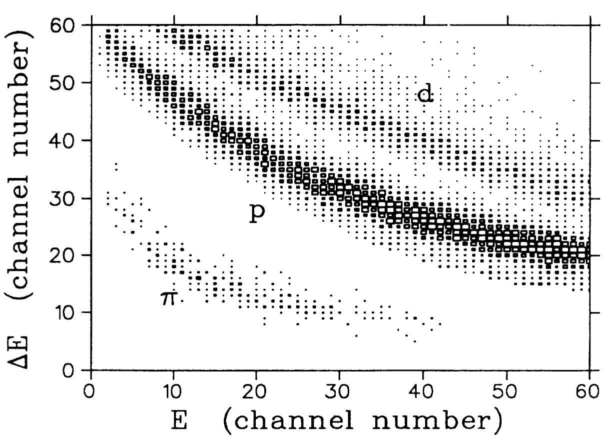

FIG. 1. Particle-identification spectra of ΔE vs E. Stopped pions π were gated on muon-decay signals, and ungated protons p and deuterons d have been prescaled for convenient display.

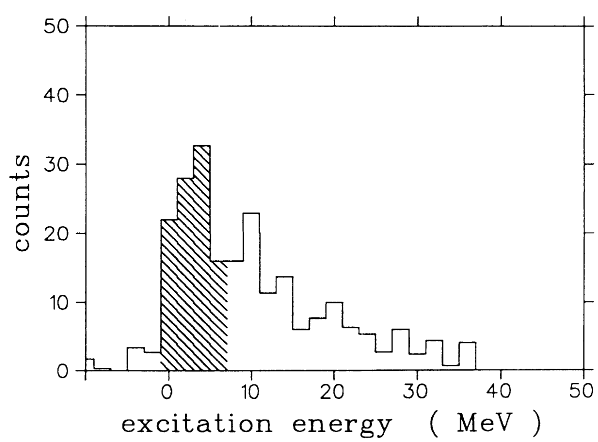

FIG. 3. Binding-energy spectrum measured for the reaction ^{12}C$(p,d\pi^+)^{11}$B, with the crosshatched area indicating the assumed extent of the ground-state peak.

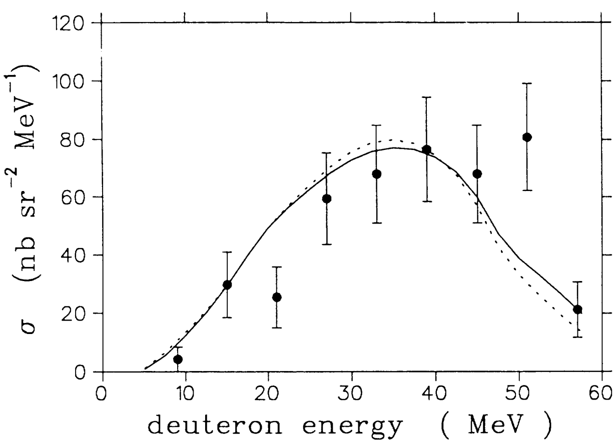

FIG. 4. Energy-sharing distribution for ^{12}C $(p,d\pi^+)^{11}B$ corresponding to the ground-state peak in the binding-energy spectrum (Fig. 3). Error bars are statistical only. The curves are distorted-wave impulse-approximation calculations for the two on-shell energy prescriptions (solid curve, IEP; dashed curve, FEP), as discussed in the text.

sion for the cross section. Otherwise, the two-body t matrix would remain embedded in the sum over spin projections [8,9] and the calculation would become more complicated. Optical potentials for the incident proton were taken from the global analysis of Nadasen *et al.* [10] and those for emitted deuterons from Bojowald *et al.* [11]. Kisslinger-type optical potentials for emitted pions were taken from the study of Amann *et al.* [12]. The single-particle bound-state wave function was generated with the Woods-Saxon potential parameters of Elton and Swift [13], and the half-shell two-body cross section was approximated by on-shell values interpolated from empirical cross sections [14] appropriate for $p+p\rightarrow d+\pi$. DWIA calculations were performed with the code THREEDEE [15] for the initial energy as well as the final energy prescription (IEP and FEP), which correspond to using the relative energy of the incident $p+p$ system, or the final $d+\pi$ system, to evaluate the two-body cross section.

As shown in Fig. 4, DWIA theory reproduces the shape of the experimental energy-sharing distribution remarkably well for both the IEP and FEP. We note that the shape primarily reflects the distorted momentum distribution $|\sum_\Lambda T_L^\Lambda|^2$, which is strongly peaked, in agreement with the data. By contrast, three-body phase space, which might be expected to describe the shape for more complicated multistep processes, is quite flat, varying by less than 10% from 10 to 45 MeV deuteron energy before falling by about 30% from 45 to 55 MeV. This is in obvious disagreement with the data. The absolute magnitude for the IEP is predicted with a spectroscopic factor of 1.0, and for the FEP a value of 4.7 is obtained. If it is assumed that the two prescriptions represent the extremes of a proper half-shell treatment, these spectroscopic values are reasonable. For example, the spectroscopic $1p$ strength measured [16] in $^{12}C(e,e'p)^{11}B$ is 2.2. Thus the results of the factorized DWIA are in excellent agreement with the experimental data for the reaction $^{12}C(p,d\pi^+)$ ^{11}B. It should be noted that these data represent recoil momenta in the range 240–340 meV/c, which implies relatively high-momentum components of the single-particle wave function in a plane-wave impulse approximation.

To summarize, we find that a large proportion of the yield in the reaction ^{12}C $(p,d\pi^+)^{11}B$ at 223 MeV is concentrated close to the kinematic locus for quasifree pion production. A simple DWIA theory for such a process correctly predicts the shape of the resultant energy-sharing distribution, as well as the absolute cross section. This strongly identifies subthreshold pion production in $^{12}C(p,d\pi^+)^{11}B$ with a quasifree mechanism traceable to the elementary $pp\rightarrow d\pi^+$ process in the nuclear medium. The measured data should provide a stringent test for the various existing theoretical ideas about nuclear pion production at these relatively low energies. Clearly, further theoretical and experimental work is desirable.

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