PHYSICAL REVIEW C VOLUME 22, NUMBER 2 AUGUST 1980

Communications

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Quasi-elastic scattering of pions on carbon

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(Received 26 November 1979)

We have measured the cross sections of the reaction ^{12}C(π^+,π^+p)^{11}B in a coincidence experiment at 100 and 130 MeV and compare our results with the cross sections calculated in the plane-wave impulse approximation.

[NUCLEAR REACTIONS ^{12}C(π^+, $\pi^+ p$)^{11}B, $e = 100$ and 130 MeV; measured $\sigma(E, E_\pi, E_p, \theta_\pi, \theta_p)$ in coincidence; compared with plane wave impulse approximation.]

Experimental studies of the ($\pi,\pi N$) reaction in nuclei have used the activation method[1] and nuclear emulsions.[2] An inclusive counter experiment measuring only the protons[3] was inconclusive because of background problems. In the same experiment some data were taken in a coincidence mode and used to obtain ratios for the cross sections σ^+ and σ^- on ^{12}C, ^{27}Al, and ^{208}Pb.

Other experiments have been concerned with particular aspects of the ($\pi,\pi N$) interaction such as the excitation of certain final states as evidenced by the γ emission of the residual nuclei.[4] Theoretical[5] and experimental[6] studies have been made of the ratio of the cross sections for positive and negative pions. In a recent paper[7] we reported the observation of the reaction ^{12}C(π^+, π^+p)^{11}B in the course of an experiment designed to study cluster effects in nuclear pion capture. We have now studied this reaction in more detail and present here our experimental results and a comparison with the plane wave impulse approximation (PWIA).

The experiment was performed at the low energy pion channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). In the pion arm we used a 10 cm thick NaI(Tl) detector preceded by two Si surface barrier detectors of 800 mm^2 area and 1 mm thickness. This system allowed us to stop and identify pions with $T \leq 95$ MeV. In the proton arm we used an intrinsic Ge detector of 12 mm thickness and 35 mm diameter preceded by a 1 mm thick Si(Li) detector. This array was able to stop and identify protons of $T \leq 70$ MeV.

The thickness of the graphite target was 169 mg/cm^2 and the energy spread of the incident pion beam was ±1 MeV. The cross section depends strongly on the kinematic conditions.[8] We therefore discuss here briefly the kinematics of the (π^+,p,^{11}B) system: In a scatterplot of T_3 vs T_2 [Fig. 1(a)] the events are clustered along a line that corresponds to the ground state of ^{11}B. Because the pion and the proton are so much lighter than the ^{11}B, they share most of the available energy and this ground-state line is nearly straight. There is lateral structure in this line due to the—here barely resolved—excited states of ^{11}B at 2.02 and 5.2 MeV [see also Fig. 2(a)]. The continuum below the line is due to the excitation of ^{11}B into the particle unstable region. The background events in the unphysical region above the line are largely due to μ-e decays in our pion detector.

The events are kinematically determined by the energy of the incident pion T_1, the pion and proton angles [130 MeV, −120°, 40° in the example of Fig. 1(a)], the mass of the residual nucleus, and the energy of the scattered pion T_2. For a given state of the residual nucleus one can thus calculate T_3 as well as the recoil momentum p_4 as a function of T_2: Curve (a), Fig. 1(b) shows p_4 for the ground state of ^{11}B. The regions of large recoil momenta correspond to large momentum components in the nuclear wave function. For such momenta one would expect the cross section to be small, in qualitative agreement with the distribu-

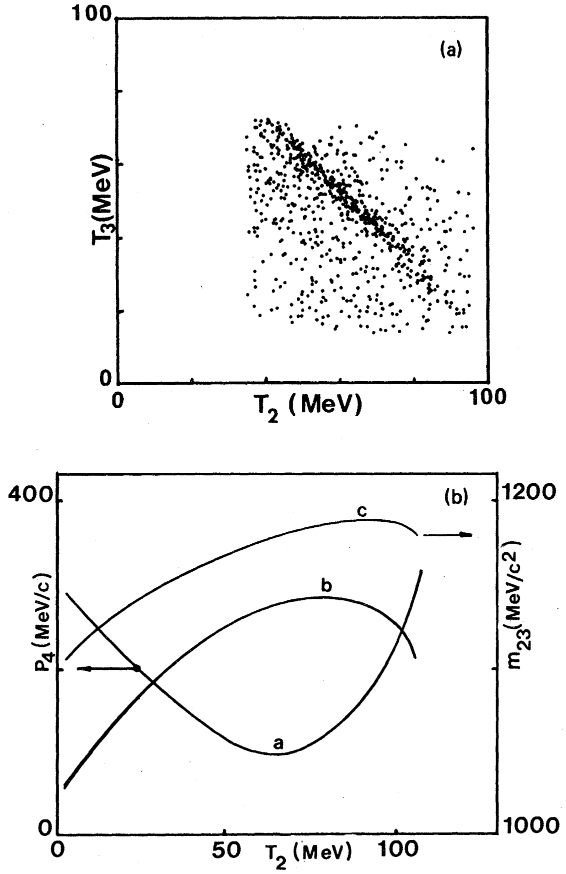

FIG. 1. (a) Scatter plot of proton energy T_3 vs pion energy T_2. The band corresponds to particle stable states of ^{11}B. Events above are background, below are background plus particle unstable states. The cutoffs at $T_2 \sim 95$ MeV and $T_3 \sim 70$ MeV are due to the finite thickness of our detectors. The low energy cutoffs were introduced by us. (b) (*a*): p_4 (left scale), (*b*): kinematic factor K (arbitrary units), (*c*): m_{23} (right scale) as functions of T_2.

tion of the events in Fig. 1(a). Also shown are the phase space, curve (*b*), and the invariant mass m_{23}, curve (*c*). It should be noted that m_{23} varies considerably with T_2 even though T_1 remains unchanged; i.e., our experiment probes a region of the $(\frac{3}{2}, \frac{3}{2})$ resonance for each choice of the incident energy T_1.

When one uses a scintillation detector for pion detection, muons, from π-μ decays inside the detector, may decay during the acceptance period of the linear gates (~1 μsec) depositing an unknown amount of energy. Also, some pions may interact in the detector causing the emission of neutrons whose energy remains unobserved.

If, as in our experiment, the energy spectra of the scattered pions are similar for the various measurements, these effects will have little influence on the relative cross sections. In order to further reduce uncertainties we have restricted the following comparison with the PWIA to the easily identifiable contributions from the particle stable states of ^{11}B, considering all events with an

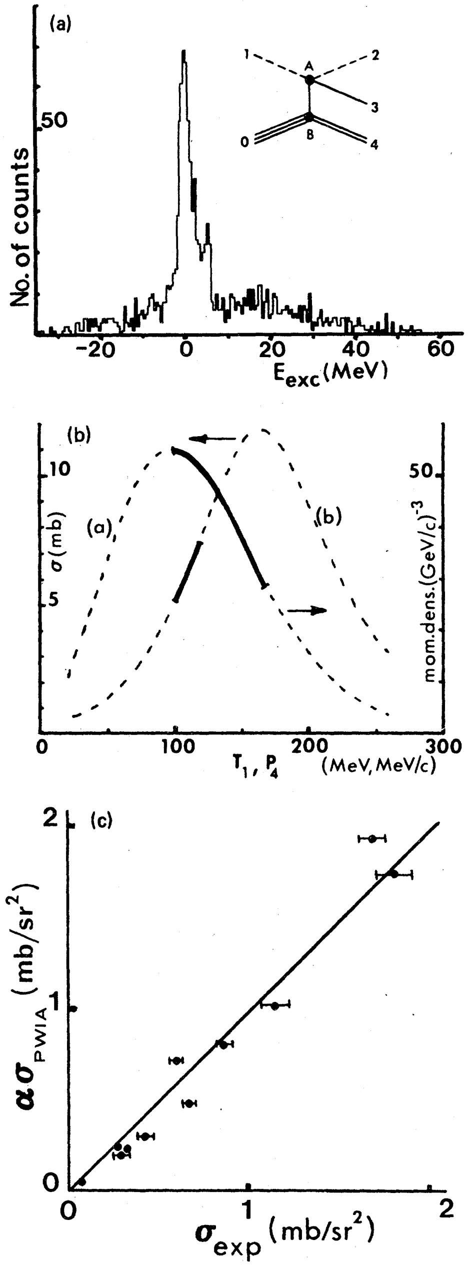

FIG. 2. (a) Cross section (rel.) as a function of the ^{11}B excitation energy. Insert: proton pole diagram used in the PWIA. (b) (*a*): single proton density in momentum space according to Mougey *et al.* (Ref. 9), (*b*) free (π, p) cross section. The regions covered by our experiment for $T_1 = 130$ MeV, $\theta_\pi = -120°$, $\theta_p = 40°$ are emphasized. (c) Comparison of normalized PWIA and measured cross sections.

TABLE I. Cross sections in mb/sr^2 for the reaction $^{12}C(\pi^+,\pi^+p)^{11}B$ for all final states/particle stable states only. The relative values should be within the stated error limits. The errors of the absolute values could be twice as large.

θ_p / θ_π	$T_1 = 100$ MeV		$T_1 = 130$ MeV		
	40°	60°	80°	40°	60°
−82°		0.44 ± 0.03 0.27 ± 0.02			
−85°				1.46 ± 0.07 0.65 ± 0.04	
−86.5°	0.45 ± 0.04 0.29 ± 0.03				
−90°					1.6 ± 0.07 0.83 ± 0.05
−98°	0.69 ± 0.13 0.43 ± 0.03				
−100°				2.2 ± 0.11 1.16 ± 0.08	
−120°	0.98 ± 0.04 0.59 ± 0.03		0.17 ± 0.14 0.07 ± 0.01	3.4 ± 0.09 1.6 ± 0.07	
−135°				3.2 ± 0.13 1.7 ± 0.1	0.86 ± 0.06 0.33 ± 0.04

excitation energy of more than 9.75 MeV as coming from particle unstable states. [See Fig. 2(a).]

We have measured the cross sections at the combinations of the experimental parameters, given in Table I, have ordered them according to size, regardless of the kinematic conditions under which they were taken, and have calculated for each set of conditions the cross section in the PWIA.

This approximation, symbolized by the graph shown in Fig. 2(a) (insert), assumes that the incident pion (1) scatters off one of the nuclear protons knocking it out of the nucleus (0) to become a free proton (3), while the residual nucleus (4) recoils.

The PWIA cross section is the product of the phase space factor K, the probability $\tilde{n}_{sp}(p_4)$ of having a proton of momentum p_4, as given by the proton momentum density at the lower vertex B, and the (π,p) cross section for scattering on a free proton of such a momentum at the upper vertex A:

$$\frac{d^4\sigma}{d(m_5{}^2)d(m_{23}{}^2)dt\,d\phi_{TY}} = K\tilde{n}_{sp}(p_4)\frac{d\sigma(m_{23},t)}{dt}\,, \quad (1)$$

where $t=(P_2-P_1)^2$ is the invariant momentum transfer and ϕ_{TY} the Treiman-Yang angle. $m_{23} =[(P_2+P_3)^2]^{1/2}$ is the invariant mass of the outgoing $(\pi' p)$ pair, and m_5 that of the exchange proton.

For the actual calculation we have used the ^{12}C p-state proton momentum distribution from the $(e,e'p)$ experiment of Mougey *et al.*[9] and the tabulated cross sections for free (π^+,p) scattering, selected at those incident pion energies which gave the values of m_{23} observed in our experiment.

Figure 2(b) shows the proton momentum distribution in ^{12}C and the free (π,p) cross section; the regions probed with one particular choice of parameters in our experiment are emphasized.

The PWIA does not take into account the existence of other reaction mechanisms e.g., pion absorption. The calculated cross sections must therefore be normalized to the experimental ones.

We have determined a common normalization factor α by minimizing

$$S=\sum_k(\sigma_k^{\text{exper}}-\alpha\sigma_k^{\text{PWIA}})^2 \quad (2)$$

and find it to be $\frac{1}{28}$ for the ground state events or $\frac{1}{14}$ for all events. Figure 2(c) shows that after this normalization the agreement between theory and experiment is quite satisfactory. The absolute cross sections, corrected for detector effects, integrated over *all* final states of ^{11}B, and the cross sections for the particle stable states only, are given in Table I.

We conclude: While other reaction mechanisms dominate the pion nucleus cross section, certain clearly identifiable events constituting about $\frac{1}{14}$ of the maximum possible are reasonably well described by the PWIA. Of these events about 50% leave the residual nucleus in the ground state or one of the lower particle stable excited states.

We wish to acknowledge stimulating discussions with J. Noble and R. Silbar and the assistance of J. C. Comiso and J. Boswell. We thank M. Moinester for the loan of the Si detectors. This work was supported by the D.O.E. and the N.S.F.

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