Measurement of the Ratio $\sigma(^{12}C(\pi^+, \pi^+ p)^{11}B)/\sigma(^{12}C(\pi^-, \pi^- p)^{11}B)$

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The cross section of the pion-induced proton-knockout reaction $^{12}C \to {}^{11}B$ has been measured with positive and negative pions. The ratio of the cross sections is compared with the ratio calculated in the plane-wave impulse approximation and agreement is found for those events that lead to particle-stable final states.

The finding[1-3] that at the $(\frac{3}{2}, \frac{3}{2})$ resonance the ratio

$$R = \frac{\sigma(^{12}C(\pi^-; \pi^- n)^{11}C)}{\sigma(^{12}C(\pi^+; \pi^+ n, \pi^0 p)^{11}C)} = 1.56 \pm 0.06 \qquad (1)$$

differs significantly from the value $R = 3$, that was expected from isospin conservation in the impulse approximation, has attracted considerable interest.[4,5] Hewson[4] has tried to explain the discrepancy between theory and experiment in terms of coherent charge exchange between the outgoing nucleon and the isobaric analog states of ^{11}B and ^{11}C, respectively, and others have considerably refined and extended this idea.[5] Tha activation experiments conducted so far[1-3] integrate all experimental parameters over the entire range allowed by kinematics and are not well suited to decide between different theoretical models. In a recent experiment at Schweizerisches Institut für Nuklearforschung (SIN), we have therefore determined the ratio of the cross sections for the reactions $(\pi^\pm, \pi^\pm p)$,

$$R' = \sigma(^{12}C(\pi^+, \pi^+ p)^{11}B)/\sigma(^{12}C(\pi^-, \pi^- p)^{11}B), \qquad (2)$$

in a kinematically well-determined situation.

We have measured the outgoing pions and protons in coincidence, using the "SUSI" magnetic spectrometer of SIN for the measurement of the pion energy. We have identified the protons and measured their energy with a four-element Si-Ge spectrometer of high resolution. The Si-Ge spectrometer contained three intrinsic Ge detectors of ~12 mm thickness and ~35 mm diameter, mounted one behind the other. The Ge detectors were preceded by a 1-mm-thick Si(Li) detector which facilitated $\Delta E, E$ particle identification. We used a graphite target of 202 mg/cm^2 mounted at 60° to the beam direction. The observation angle for the protons was $\theta_p = 30°$, the pion arm ("SUSI") was set to $\theta_\pi = -100°$ and $\theta_\pi = -110°$. The incident pion energy was 180 ± 3.6 MeV. The energy of each incident pion was measured to $\pm 0.04\%$ with a 48-element hodoscope at the intermediate focus of the pion channel. The intensity of the incident beam was monitored in a scintillation counter that preceded the target by ~30 cm. The incident pions were identified by time of flight with respect to a signal derived from the cyclotron rf voltage. During the π^+ run a particle separator was employed to eliminate protons. The microstructure of the SIN beam consists of 1-nsec-wide pulses spaced 20 nsec apart. Events that had more than one incident particle in a micropulse were identified with the hodoscope and rejected.

The kinematic range of the scattered pions extended from 0 to 154 MeV. The magnetic spectrometer was set to accept the energy range from 59 to 109 MeV. These pion energies correspond to proton energies from 104 to 55 MeV for those events that lead to the ^{11}B ground state.

Figure 1 shows the measured excitation spectra for both the π^+- and the π^--induced reactions. The qualitative difference between the two spec-

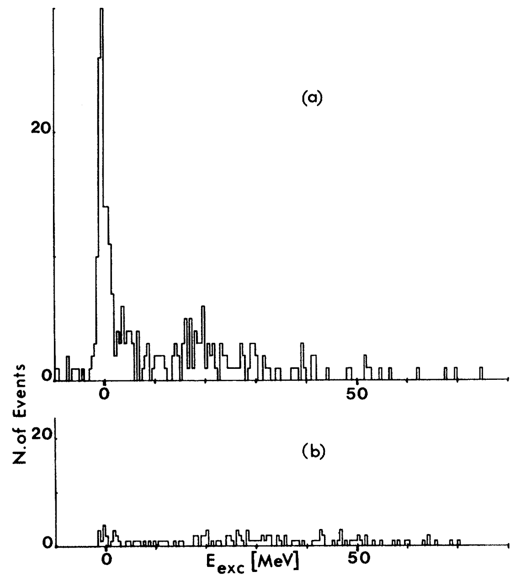

FIG. 1. (a) Excitation spectrum of the reaction $^{12}C(\pi^+,\pi^+p)^{11}B$. Incident pion energy $T_{inc}=180$ MeV, $\theta_\pi=-110°$, $\theta_p=30°$. (b) Excitation spectrum for the reaction $^{12}C(\pi^-,\pi^-p)^{11}B$ for the same experimental parameters. The figures are scaled so that equal distances on the ordinate represent equal cross sections.

tra is quite striking. Whereas σ^+ shows a pronounced peak in the vicinity of $E_{exc}=0$ indicating that a large number of events lead to the ground state of ^{11}B or to one of its particle-stable excited states, the corresponding peak in σ^- is reduced by approximately the ratio $\sigma(\pi^+p)/\sigma(\pi^-p)$ of the free cross sections under the kinematic conditions of our experiment. The "isospin ratio" $\sigma^+/\sigma^- = \frac{9}{1}$ applies only to the total cross section. The ratio of the differential cross sections varies from 18:1 to 1:1 as a function of angle and energy; see, e.g., Sternheim and Silbar.[5]

The numerical results are listed in Table I together with a calculation of the ratio R' [Eq. (2)] in the plane-wave impulse approximation (PWIA). The PWIA calculation is based on the momentum distribution of p-shell protons as measured by Mougey *et al.*[6] and on the phase shifts for free π,p scattering.[7] Because we compared pairs of cross sections measured with positive and negative pions under otherwise identical conditions the kinematic factor and the proton momentum distribution enter the calculation only in second order. In determining the cross section of this half-on-, half-off-shell interaction in the PWIA there is some ambiguity as to the energy at which the free πp cross section, used in the calculation, should be evaluated. Two possible choices are (a) the incident pion energy in free πp scattering that equals the energy of the incident pion in the rest frame of the "exchange proton" in our experiment; or (b) the incident pion energy in free πp scattering that produces an invariant mass in the outgoing πp system that equals the one we observe in our experiment. Of these two choices the latter was used because it gave a slightly higher value for R' and thus better agreement with the measured value. Further experiments and more refined calculations will have to be made before any statements on the off-shell behavior of the $(\pi,\pi p)$ cross section can be made.

The PWIA calculation agrees best with the values measured for $E_{exc}< 9.75$ MeV as one would expect: The events with a small excitation energy of the residual nucleus are the ones that most nearly satisfy the assumption underlying the PWIA that the residual nucleus remain in the role of a spectator.

In contrast to this the events leading to highly excited states are more likely to arise from final-state interactions. It should be pointed out that the final-state interaction need not be very strong to change the +/− ratio substantially for the continuum states: If 10% of the primary (π^-,π^-n) events are thrown into the $E_{exc}\geq 9.75$ MeV region of the (π^-,π^-n) reaction and vice versa, the ratio R' will remain unchanged for the events with $E_{exc}<9.75$ MeV but will be reduced from 13.7 to 3.4 for those with $E_{exc}\geq 9.75$ MeV. Comiso *et al.*[8] have derived the ratio R' [Eq. (2)] from the value of R [Eq. (1)] assuming coherent charge exchange. They obtained $R'=2.6$. The activation experiments[2,3] are sensitive to

TABLE I. Ratio R' of the cross sections for π^+- and π^--induced proton knockout in ^{12}C. $\theta_p=30°$, $T_{inc}=180$ MeV, $59<T_{\pi'}<109$ MeV.

θ_π	PWIA	$E_{exc}<9.75$ MeV	$E_{exc}\geq 9.75$ MeV	All events
100°	13.7	14 ± 5	3.2 ± 0.7	5.5 ± 1
110°	12.7	14 ± 3	2.6 ± 0.4	5.2 ± 0.5
Ref. 5		7.1	4.8	6.0

those events that leave the residual ^{11}C nucleus in a particle-stable state. In comparing R and R' one must therefore take into account only those events that lead to a particle-stable state of ^{11}B. We have, somewhat arbitrarily, chosen an excitation energy of $E_{exc}=9.75$ MeV as the dividing line (Fig. 1). This value is based on the fact that the region of particle instability begins at 8.7 MeV and makes some allowance for the small phase space available for nuclear breakup directly above threshold and for the finite resolution of our experiment. Our measured value $R'=14\pm 3$ (5) (Table I) disagrees quite flagrantly with the value of Comiso *et al.* This and the good agreement with the PWIA (Table I) shows that, at least under the conditions of our experiment, *coherent* charge exchange plays no significant role. Sternheim and Silbar[5] suggest a plausible way to reconcile our result with that of the activation experiments: Our experiment probes a region where the nucleons are quite energetic ($\langle T_p \rangle \sim 68$ MeV) and will not undergo charge exchange, whereas the activation experiments average over all angles and give full weight to low-energy nucleons that have a large charge-exchange cross section. While this would explain the observed tendencies there remain substantial quantitative discrepancies (see Table I) and the agreement for the ratio averaged over all excitation energies (last column) may be fortuitious.

To sum up, we have compared pairs of cross sections measured under identical conditions with positive and negative pions. The ratio of the cross sections for events with $E_{exc}<9.75$ MeV agrees with the value calculated in the PWIA assuming the absence of final-state interactions. For events leading to particle-unstable final states ($E_{exc}\geq 9.75$ MeV) there is disagreement with the PWIA calculation. This disagreement could easily be due to a weak final-state interaction of the neutrons in the $(\pi^-, \pi^- n)$ reaction, which dominates the cross section for negative incident pions.

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