1433 (1974).

[17] R. E. Schlier and H. E. Farnsworth, in *Semiconductor Surface Physics*, edited by R. H. Kingston (Univ. of Pennsylvania Press, Philadelphia, 1957), p. 3.

[18] R. Seiwatz, Surface Sci. 2, 473 (1964).

[19] G. W. Gobeli and F. G. Allen, in *Semiconductors and Semimetals*, edited by R. K. Willardson and A. C. Beer (Academic, New York, 1966), Vol. 2, p. 279.

[20] M. Henzler, Surface Sci. 24, 209 (1971).

[21] M. Henzler, Surface Sci. 19, 159 (1970).

Excitation Functions for the Reactions $^{12}C(\pi^{\pm}, \pi N)^{11}C$ over the Region of the (3,3) Resonance*

B. J. Dropesky, G. W. Butler, C. J. Orth, and R. A. Williams
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

and

G. Friedlander
Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973

and

M. A. Yates
Chemistry Department, Carnegie-Mellon University, Pittsburgh, Pennsylvania 15213

and

S. B. Kaufman
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439

(Received 6 February 1975)

The excitation functions for the reactions $^{12}C(\pi^{\pm}, \pi N)^{11}C$ have been measured by activation over the energy ranges 50 to 470 MeV for π^+ and 40 to 550 MeV for π^-. These excitation functions, clearly reflecting the (3,3) pion-nucleon resonance, show an upward energy shift in the resonance peak for π^- and a downward shift for π^+. The $\sigma_{\pi^-}/\sigma_{\pi^+}$ ratio at 180 MeV is 1.55 ± 0.10.

The observation by Chivers *et al.*[1,2] in 1968 that the cross sections for the formation of ^{11}C from ^{12}C by π^+ and π^- near the (3,3) resonance energy (180 MeV) are the same within ± 10% aroused considerable theoretical interest because, on the basis of the free-particle pion-nucleon cross sections and a simple nucleon knockout model, a $\sigma_{\pi^-}/\sigma_{\pi^+}$ ratio near 3 was expected. This apparent puzzle together with the serious discrepancies among the several reported measurements[2-6] of the cross sections for the π^+-induced reaction (see Fig. 1) provided the incentive for remeasuring these cross sections. Also, the need to establish the reaction $^{12}C(\pi^{\pm}, \pi N)^{11}C$ as a foil-activation flux monitor for pion beams, in analogy with the widely used reaction $^{12}C(p, pn)^{11}C$ for proton beams, called for a careful remeasurement of the excitation functions for the formation of ^{11}C by π^+ and π^- over the energy range available at the Clinton P. Anderson Meson Physics Facility (LAMPF).

Since the present results for the π^+ cross sections above ~ 120 MeV differ considerably from earlier measurements, we will describe the experimental techniques in some detail.

The method used to determine the cross sections consisted of a direct measurement of the total number of pions passing through a three-element scintillation-counter telescope during the irradiation of a plastic scintillator target placed directly in front of, and of the same size as, the first element of the telescope. The ^{11}C activity induced in the target was determined after the irradiation by β^+-γ coincidence counting.

The irradiations were carried out at the low-energy pion channel (LEP), 15 m long, and at the high-energy pion channel (P^3), 20 m long, of LAMPF, the former being used for pion energies between 50 and 220 MeV, the latter for energies between 100 and 550 MeV. At least duplicate determinations were made at each reported pion energy, usually at beam intensities that differed

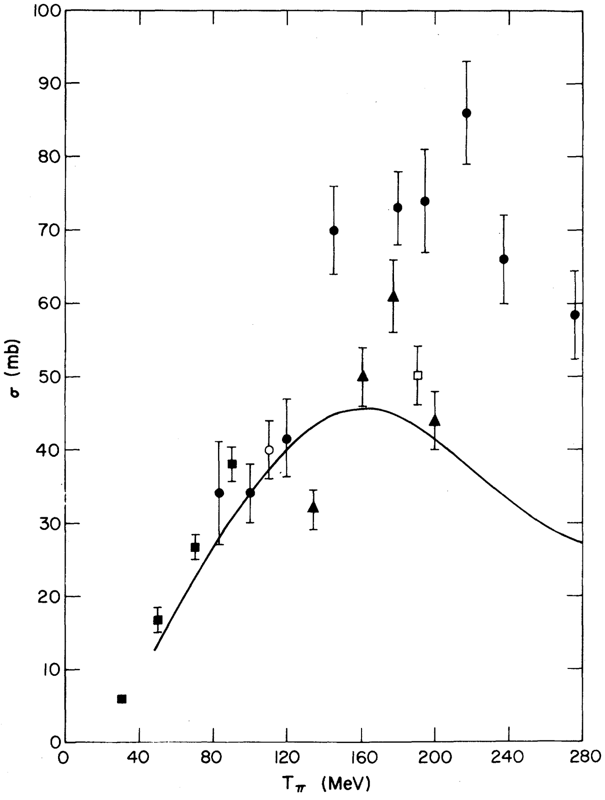

FIG. 1. Previously measured cross-section values for the reaction $^{12}C(\pi^+,\pi N)^{11}C$: ● Chivers *et al.* (Ref. 2); ○ Reeder (Ref. 3); ▲ Hogstrom *et al.* (Ref. 4); □ Yester *et al.* (Ref. 5); and ■ Moinester *et al.* (Ref. 6). The smooth curve represents the excitation function measured in the present work.

by a factor of 2 or more. Pion fluxes ranged from 2×10^4 to 3×10^5 per sec and the length of each irradiation was from 10 to 30 min. The position and size of the beam spot both in front of and behind the telescope were measured with Polaroid-film exposures to optimize the beam at each energy setting. The observed beam spot was always within the area of the target and the telescope elements.

The counter telescope consisted of three Pilot U plastic scintillators[7] 3.2 mm thick and spaced about 5 mm apart. The three circular scintillators had diameters of 38, 46, and 46 mm, respectively, and were coupled via Lucite light guides to RCA-31016F phototubes. The electronics consisted of fast MECL III[8] discriminators, majority logic, and prescalers followed by conventional modules. The singles rate in the first scintillator as well as triple coincidences and delayed coincidences between the first and second counters were recorded in each run. The triple coincidence rates were used to determine the particle fluxes. Appropriate corrections for counting losses[9] were calculated based on the delayed coincidence rate, the 6.5-nsec (full width at half-maximum) system resolving time, and the 5-nsec spacing of the accelerator micropulses. These corrections to the measured rates were at most 10%.

The beam intensity was monitored continuously during each irradiation by recording the triple coincidence counts in each 10- or 20-sec interval with a pulse-height analyzer operating in the multiscaler mode. In most runs the beam intensity was very steady, while for some the measured intensity fluctuations required small corrections ($\leq 3\%$) to be made to the saturation values of the ^{11}C activities.

The targets consisted of 3.2-mm-thick by 38-mm-diam disks of Pilot B plastic[7] containing 91.6% carbon by weight. (The cross sections reported in this paper are calculated as if the carbon were 100% ^{12}C, since the small contribution to ^{11}C production from the 1% ^{13}C content is not known.) Within a few minutes after the end of each irradiation the target scintillator was mounted on a Dumont 6292 photomultiplier tube, covered with an aluminum foil and a positron-absorber cap, and placed against a 75 mm× 75 mm NaI(Tl) detector. The ^{11}C β^+ particles were detected in the plastic scintillator, the annihilation quanta were detected in the NaI(Tl) unit, and β^+, γ, and β^+-γ coincidence events were recorded as a function of time for at least two 20.4-min ^{11}C half-lives. The efficiency of internal scintillation counting of the ^{11}C positrons was usually between 0.93 and 0.97. End-of-bombardment (EOB) ^{11}C disintegration rates were obtained from analysis of the decay curves. No components other than 20.4-min ^{11}C and a small constant background were ever detected. The EOB activity levels were in the range 2×10^2 to 8×10^3 disintegrations per min.

Determination of the contamination of the pion beam with other particles was a major concern. In the majority of the runs in the P^3 beam, time-of-flight measurements over a 10-m flight path between an upstream scintillator (in mid-channel) and the counter telescope were used to determine the beam composition. On the LEP channel, time-of-flight measurements were not feasible at the time of these experiments; dE/dx measurements with a 2.5-cm-thick plastic scintillator were made for energies $\leq$ 100 MeV. In the π^- beam of P^3 the $e^- + \mu^-$ contamination ranged from ~ 5% at 430 MeV to ~ 60% at 100 MeV; in the π^+ beams, the lepton contributions were somewhat smaller. The shorter LEP channel provides a beam with considerably less $e^\pm$ contamination at a given energy. The agreement between cross-section values measured over the same energy range at the two-pion channels lends confidence in our beam-composition measurements. While the electrons and muons contribute to the measured beam intensity, it is assumed that they contribute negligibly to ^{11}C production. The situation is different with regard to proton contamination in the π^+ beams, especially at energies above about 300 MeV where the removal of the rapidly increasing number of protons from the π^+ beam by momentum degradation becomes less effective. In the time-of-flight and dE/dx spectra, protons were clearly resolved from π^+, but since the reaction $^{12}C(p,pn)^{11}C$ has sizable cross sections over the energy range of interest, experiments in which the proton contribution to the beam intensity exceeded ~ 20% were excluded. For this reason the π^+ excitation function was not extended beyond 470 MeV. Corrections for the ^{11}C activation by protons were made according to the adopted cross-section values from the review paper by Cumming.[10] A number of checks on possible contribution to the ^{11}C activation by background neutrons in the target-telescope region were made with scintillator targets placed 5 to 10 cm outside the beam-spot area; no significant neutron effects were found.

The effect of target thickness on the possible enhancement of ^{11}C production due to secondary particles was examined by carrying out two comparative measurements with 150-MeV π^+ and 230-MeV π^- on 3-mm- and 20-mm-thick scintillator targets. Since the measured ^{11}C activity per unit thickness per unit pion flux showed less than 5% variation for the two thicknesses, we conclude that the target-thickness effect is negligible for our 3-mm targets.

The results of the present measurements are shown in Fig. 2. The error bars shown are based on an rms combination of conservatively estimated uncertainties in beam intensity, beam contamination, ^{11}C disintegration rate, and the number of target atoms in the beam. Our π^- cross section values are in reasonably good agreement with previous measurements, especially those of Reeder and Markowitz.[11] In contrast, poor agreement with most previous measurements of π^+ cross sections above ~ 120 MeV is apparent in Fig. 1. This may be attributed to difficulties in earlier work in measuring beam composition and in determining absolute disintegration rates of the induced activity in large targets.

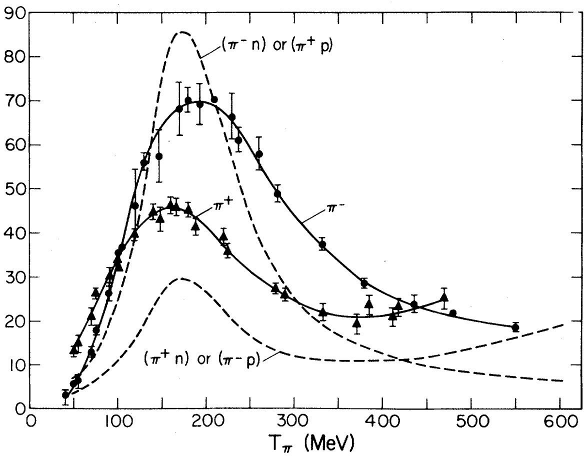

FIG. 2. Excitation functions: reactions $^{12}C(\pi^\pm,\pi N)^{11}C$ (solid curves join data points); and free-particle pion-nucleon reactions [dashed curves from Carter *et al.* (Ref. 12) and others, reduced by a factor of 2.4].

The most striking features of our excitation functions are the following: (a) The ratio $\sigma_{\pi^-}/\sigma_{\pi^+}$ at 180 MeV is 1.55 ± 0.10, in contrast to the previously measured[2] value of 1.0 ± 0.1 and the experimental free-particle ratio of 3.0.[12] (b) The peak in the (3, 3) resonance for π^+ on carbon is shifted upward and for π^+ it is shifted downward, relative to the free-particle resonance at about 180 MeV. These shifts in the resonance for carbon obviously result in the $\sigma_{\pi^-}/\sigma_{\pi^+}$ ratio varying with pion energy. (c) The widths of the resonances for carbon are noticeably greater than the free-particle resonances, presumably as a result of the Fermi motion of the ^{12}C nucleons. (d) The π^+ cross section above about 350 MeV rises, apparently as a result of the onset of the large $T = \frac{1}{2}$ free-nucleon resonances at 600 and 900 MeV.

A theoretical treatment accounting for the observed shifts in energy of the (3, 3) resonance in carbon and the consequent variations in the $\sigma_{\pi^-}/\sigma_{\pi^+}$ ratio with energy is presented in the following Letter by Sternheim and Silbar.[13]

A detailed report on the study presented here will be prepared for publication at a later date.

The authors are indebted to R. J. Macek, R. L. Burman, and R. D. Werbeck for their advice and assistance with regard to the pion channels.

---

*Work performed under the auspices of the U. S.

Atomic Energy Commission.

[1] D. T. Chivers, J. J. Domingo, E. M. Rimmer, R. C. Witcomb, B. W. Allardyce, and N. W. Tanner, Phys. Lett. 26B, 573 (1968).

[2] D. T. Chivers, E. M. Rimmer, B. W. Allardyce, R. C. Witcomb, J. J. Domingo, and N. W. Tanner, Nucl. Phys. A126, 129 (1969).

[3] P. L. Reeder, doctoral thesis, University of California Report No. UCRL-10531, 1962 (unpublished).

[4] K. R. Hogstrom, B. W. Mayes, L. Y. Lee, J. C. Allred, C. Goodman, G. S. Mutchler, C. R. Fletcher, and G. C. Phillips, Nucl. Phys. A215, 598 (1973).

[5] M. V. Yester, A. A. Caretto, M. Kaplan, P. J. Karol, and R. L. Klobuchar, Phys. Lett. 45B, 327 (1973).

[6] M. A. Moinester, M. Zaider, J. Alster, D. Ashery, S. Cochavi, and A. I. Yavin, Phys. Rev. C 8, 2039 (1973).

[7] Pilot Chemicals Division, New England Nuclear Corp., Watertown, Ma.

[8] MECL is Motorola Emitter Coupled Logic; the NIM units were fabricated by the Physics Division, Lawrence Berkeley Laboratory.

[9] Formulas developed by K. McFarlane (private communication) were used.

[10] J. B. Cumming, Annu. Rev. Nucl. Sci. 13, 261 (1963).

[11] P. L. Reeder and S. S. Markowitz, Phys. Rev. 133, B639 (1964).

[12] A. A. Carter, J. R. Williams, D. V. Bugg, P. J. Bussey, and D. R. Dance, Nucl. Phys. B26, 445 (1971).

[13] M. M. Sternheim and R. R. Silbar, following Letter [Phys. Rev. Lett. 34, 824 (1975)].

Effects of Nucleon Charge Exchange on the $(\pi, \pi N)$ Puzzle

Morton M. Sternheim*
Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01002

and

Richard R. Silbar†
Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544

(Received 6 February 1975)

Charge-exchange interactions of the nucleons within the nucleus are shown to account for the observed differences in the ratios of neutron-knockout cross sections for $\pi^\pm$ from the impulse-approximation predictions. Also, the energy dependence of the knockout cross sections is obtained from the measured total pion reaction cross sections with a simple model for the threshold behavior.

New measurements[1] of the cross sections $\sigma^\pm$ for the removal by $\pi^\pm$ of a neutron from a light nucleus have provided information relative to one of the most interesting puzzles in medium-energy nuclear physics. In this Letter we will show that many features of these experiments can be attributed to the final-state charge-exchange interactions of the outgoing nucleons.

For a $Z=N$ nucleus, the impulse approximation implies that the ratio $\mathcal{R}=\sigma^-/\sigma^+$ equals the ratio of free $\pi^\mp$ cross sections, which is about 3 in the (3, 3) resonance region from 100 to 300 MeV. However, earlier measurements[2] on ^{12}C, ^{14}N, and ^{16}O all gave $\mathcal{R}\approx 1$ at 180 MeV. In addition to nucleon charge exchange,[3,4] several other mechanisms were proposed to explain the large discrepancy: "quasi-α particles,"[5] excitation of intermediate states of definite isospin,[2,6] Fermi averaging,[7] compound-nucleus effects,[4] formation of nucleon isobars with particular nuclear interactions, etc. The relatively limited data made it difficult to test these suggestions.

Nucleon charge exchange has a large effect on $\mathcal{R}$ because it both increases σ^+ and decreases σ^-. A π^+ has a large cross section for scattering by a proton. If a struck proton charge exchanges before it leaves the nucleus, the net result is a neutron knockout. Similarly, when a π^- strikes a neutron which charge exchanges, the net result is a proton knockout.

The new carbon data (Figs. 1 and 2) show that $\mathcal{R}$ rises steadily with the pion energy T_π in the resonance region, increasing from *less than 1* at 50 MeV to about 1.8 at 290 MeV; at 180 MeV it is about 1.6, considerably more than the old value of 1.0. This gradual approach toward the impulse-approximation prediction for $\mathcal{R}$ is consistent with the fact that the nucleon charge-exchange cross section decreases as the average nucleon energy T_N increases.

To illustrate the nucleon charge-exchange effects, we suppose that the probability for a nu-