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$^{12}C(\bar{p}, \bar{p}n)^{11}C$, $^{12}C(\pi^-, \pi^-n)^{11}C$, and $^{19}F(\pi^-, \pi^-n)^{18}F$ Cross Sections at 2.5 GeV/*c**

S. O. Thompson, L. Husain,† and S. Katcoff
Chemistry Department, Brookhaven National Laboratory, Upton, New York 11973

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The cross section for the $^{12}C(\bar{p},\bar{p}n)^{11}C$ reaction measured at 1.73 GeV is 28.2 ±3.6 mb, a value virtually identical with that of the corresponding proton-induced reaction (27.5 ± 0.6 mb). The $^{12}C(\pi^-,\pi^-n)^{11}C$ and $^{19}F(\pi^-,\pi^-n)^{18}F$ cross sections at 2.36 GeV are 19.4 ±1.5 and 16.0 ±2.0 mb, respectively. Each is about 25% lower than the corresponding reaction induced by 2.4-GeV protons. These results are discussed in terms of the free-particle cross sections.

I. INTRODUCTION

High-energy nuclear reactions have been studied mainly with protons as projectiles. Experiments with a variety of incident particles should contribute to our understanding of the mechanisms involved. Differences in the free-particle cross sections are expected to affect the cross sections of specific nuclei produced from corresponding high-energy nuclear reactions. Table I shows a comparison of p-n, $\bar{p}$-n and π^--n total and partial free-particle cross sections[1-4] at 2.0 GeV. The large $\bar{p}$-n annihilation cross section σ_{anh} leads to production of about five pions.[2] When these are formed in a complex nucleus some may be reabsorbed and thus deposit a large amount of excitation energy.[5]

In this paper we report on a few simple reactions induced by 2.5-GeV/*c* antiprotons and negative pions. The antiproton beam was of high purity but the low intensity of about 150/sec necessitated the use of large targets and low-level counting. The accuracy of these results is much better than that of previous measurements.[6,7]

II. EXPERIMENTAL PROCEDURE

The irradiations were performed in the medium-energy separated beam at the Brookhaven alternating-gradiant synchrotron (AGS), slightly upstream from the 31-in. bubble chamber.[8] There were two stages of separation so that the purity of the antiprotons was about 99%. The muon and electron contamination in the pion beam was estimated as ≤2%. The beams had a spread of about 1 cm vertically (full width at half maximum) and 4.5 cm horizontally. A counter telescope consisting of two thin plastic detectors was used to monitor the intensity of every pulse. The counters were calibrated with 100-μ-thick Ilford G-5 pellicle emulsions[9,10] which were placed directly upstream from some of the targets. The incident particles entered normal to the emulsion surface and registered plunging tracks. Careful scanning yielded the absolute beam density distribution in an area somewhat greater than that of the targets. Numerical integration over the target area gave the total number of incident projectiles. About $\frac{1}{3}$ of the irradiations were monitored directly with an emulsion. The others were monitored with the counters, which were calibrated relative to the emulsions.

The carbon targets were in the form of NE 102 plastic cylinders 3.8 cm in diameter and having thicknesses of 0.32, 0.95, and 1.91 cm. After irradiations of 4 to 60 min the cylinders were mounted on RCA 6342A photomultiplier tubes, and the induced ^{11}C activity was measured by internal scintillation counting.[7,9,10] The discriminator was set at 59 keV with a source of ^{241}Am. Background was reduced by a ring of anticoincidence counters plus mercury and iron shielding. With the 0.95-cm scintillators the background was 7 counts/min. The targets were counted continuously for several hours and the decay curves were analyzed by a least-squares program (CLSQ). When the saturation activities were calculated account was taken of the time variation of the beam intensity during each run. These corrections amounted to no more than 2%. Counting efficiencies[10,11] were taken as 93.3–96.0% (Table II).

Secondary particles (nucleons and pions) produced in the targets by the primary beam can also contribute to the formation of ^{11}C. An attempt was made, by irradiating target disks of different thicknesses, to determine the magnitude of this effect. However the precision of these experiments was not sufficiently high. Therefore the secondary corrections were estimated from earlier experiments[9,12-14] performed at other energies with various projectiles. The values used are shown in Table II. The effect of neutral particles which may have been present in the vicinity of the beam was tested by placing the larger plastic targets 7.6 cm above and below the beam line. No detectable activity was found, which shows that the effect of neutrals is ≤3%.

The fluorine target, consisting of Teflon in the form of a plate 2.5 × 1.3 × 0.34 cm, was irradiated

TABLE I. Comparison of (p-n), ($\bar{p}$-n), and (π^--n) cross sections at 2.0 GeV (lab): total cross section σ_t, elastic scattering σ_{el}, inelastic scattering excluding annihilation σ_{inel}, cross section for annihilation σ_{anh}. Values are given in mb.

	p-n	$\bar{p}$-n	π^--n
σ_t	41	80	31
σ_{el}	24	28	10
σ_{inel}	17	12	21
σ_{anh}	···	38	···

in the antiproton and pion beams. The counting was done with a pair of NaI detectors. 7.6-cm diam, which recorded the coincident 511-keV photons. Narrow channels were set around 511 keV, and the background was 0.27 counts/min. The system was cross calibrated with a NaI well crystal whose absolute efficiency for annihilation radiation was well known from previous measurements.[15] For this calibration a strong source of ^{18}F was prepared by an (n, 2n) reaction in a similar Teflon target; the efficiency was found to be 6.85%. The antiproton irradiations yielded insufficient ^{18}F activity (~0.2 counts/min) for significant cross-section measurements. In one 60-min pion irradiation the ^{18}F activity was 2.93 ± 0.22 counts/min, corrected to the end of bombardment.

III. RESULTS AND DISCUSSION

The data obtained in each experiment are shown in Tables III and IV. Chemical analyses of the targets showed that the plastic target was 90.7% carbon and the Teflon target was 75.8% fluorine. The final cross-section results are compared with previous work[7,12,16,17] in Table V.

Antiproton runs were also made with thinner targets (0.32 cm) but low beam intensity led to large statistical errors in the ^{11}C counting. For the targets listed in Table III these errors were about ±10%. In the pion runs, beam intensities were much higher and statistical errors were about ±2% (Table IV). The estimated uncertainty in beam intensity is ±8%; this takes into account emulsion scanning errors, fluctuations of counter telescope efficiency, and small shifts of beam position during irradiation. In estimating the over-all errors of the means (Tables III and IV), account was also taken of uncertainties in the secondary corrections and counting efficiencies.

TABLE II. Counting efficiencies and secondary-particle corrections for the plastic scintillators.

Target thickness (cm)	Counting efficiency	Correction for secondaries
1.91	0.960	0.904
0.95	0.950	0.952
0.32	0.933	0.984

TABLE III. Cross section of $^{12}C(\bar{p},\bar{p}n)^{11}C$ at 1.73 GeV.

Target thickness (cm)	Irradiation time (min)	$\bar{p}/cm^2$ ($\times 10^5$)	Counts/min at EOB [a]	Cross section (mb)
1.91	30	1.25	72.2 ± 2.5	24.4
1.91	17	0.40	26.4 ± 2.4	22.9
1.91	60	0.55	27.2 ± 3.7	30.7
0.95	40	0.85	20.5 ± 3.0	26.3
0.95	40	0.60	19.2 ± 1.2	33.6
0.95	40	0.60	17.1 ± 0.9	30.4
0.95	40	0.57	15.9 ± 1.4	29.3
			Mean	28.2 ± 3.6

[a] End of bombardment.

The present results are compared with earlier work in Table V. Although the beam energies are somewhat different, they are in a region where the relevant cross sections[12,16] appear to be nearly constant with beam energy (1.6–2.4 GeV). The only previous determination[7] of the $^{12}C(\bar{p},\bar{p}n)^{11}C$ cross section was at 2.8 GeV, and it was based on a single measurement at very low counting rate. With these qualifications, it is seen that the new results are quite consistent with previously reported values.

The (π^-, π^-n) cross sections of ^{12}C and of ^{19}F are both about 25% lower than the corresponding (p,pn) cross sections. This has been related to the relative free-particle (π^--n) and (p-n) cross sections[7,12,18] (Table I), since the production of ^{11}C and ^{18}F is thought to be mainly by the "clean-knock-out" mechanism[19] (in which the incident particle interacts with a single nucleon and both escape from the nucleus without further interaction). The previous data[18] tend to support this idea. Interaction of the incident particle with protons in the nucleus (or with neutrons in certain inelastic collisions) would not lead to formation of ^{11}C, or

TABLE IV. Cross section of $^{12}C(\pi^-,\pi^-n)^{11}C$ at 2.36 GeV.

Target thickness (cm)	Irradiation time (min)	π^-/cm^2 ($\times 10^5$)	Counts/min at EOB [a]	Cross section (mb)
0.95	4.0	3.53	109.6 ± 2.5	19.4
0.95	10.0	15.4	429 ± 6	19.3
0.32	20.0	17.9	147.4 ± 3.2	19.7
0.32	20.0	16.5	134.7 ± 2.6	19.6
0.32	20.0	24.6	200.4 ± 4.1	19.1
			Mean	19.4 ± 1.5

[a] End of bombardment.

TABLE V. Summary of results and comparison with previous work.

Reaction	GeV	Cross section (mb)	Reference
^{12}C($\bar{p}$,$\bar{p}n$)^{11}C	2.8	30 ± 9	7
	1.73	28.2 ± 3.6	Present work
^{12}C(p,pn)^{11}C	2.4	27.2 ± 0.6	16
	1.7	27.5 ± 0.6	16
^{12}C(π^-,$\pi^- n$)^{11}C	2.36	19.4 ± 1.5	Present work
	1.8	20.9 ± 1.5	7
	1.6	20.5 ± 0.8	12
^{19}F(π^-,$\pi^- n$)^{18}F	2.36	16.0 ± 2.0	Present work
	1.8	16.6 ± 0.9	12
^{19}F(p,pn)^{18}F	2.4	23.5 ± 2.4	17
	1.8	22.7 ± 2.3	17

^{18}F, but would cause an attenuation of the cross section. The magnitude of this effect should depend on the nature of the incident particles, since the free-particle cross sections are different. Attempts to demonstrate this attenuation effect have been only partially successful.[7,12]

The antiproton-nucleon total cross sections are much larger than the corresponding proton-nucleon cross sections (Table I). Therefore one might expect the attenuation effect to be substantially greater for incident antiprotons (smaller ^{11}C cross section). Yet the production of ^{11}C at 1.7 GeV is about the same for antiprotons as for protons (Table V). This fact suggests two alternative interpretations. Either attenuation is not important for light nuclei such as ^{12}C, or the effect of attenuation is cancelled by another process which tends to increase production of ^{11}C. Such a process may be $\bar{p}$-n annihilation with escape of all pions from the residual ^{11}C nucleus. Extension of this work to measurements at lower energies will help to decide among these alternatives, since the differences in free-particle cross sections are even greater at lower energies. Extension of the studies to other targets and more complex reactions is difficult because of the low beam intensities presently available.

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†Present address: Department of Earth and Space Sciences, State University of New York, Stony Brook, New York 11790.

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