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$C^{12}(\pi^-,\pi^-n)C^{11}$ Excitation Function*

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The $C^{12}(\pi^-,\pi^-n)C^{11}$ excitation function was measured with incident pions of energies from 0.45 to 1.9 GeV. The present work supplements the lower energy measurements of Reeder and Markowitz. The excitation function of this simple nuclear reaction shows effects of the elementary pion-nucleon resonances. The $\pi^- - n$ resonances tend to be reproduced in the excitation function, while the $\pi^- - p$ resonances tend to cause a reduction in the cross sections. The production of C^{11} and F^{18} by π^- interactions with Al targets was also studied over the same energy range. These excitation functions do not exhibit any structure.

INTRODUCTION

THE study of nuclear reactions induced by high-energy pions is useful both for exploring the interactions of pions in nuclei and for investigating the mechanism of high-energy nuclear reactions in general. The pion-nucleon total cross sections exhibit pronounced resonances in contrast with the relatively structureless nucleon-nucleon cross sections. Observation of the effects, if any, of these resonances on a high-energy nuclear reaction would help to elucidate the mechanism of the reaction. In particular, on the basis of the impulse approximation, the effects would indicate the relative importance of the initial interaction between the projectile and a nucleon in the nucleus in forming the product of interest. At high energies the (p,pn) reaction is thought to take place predominantly by a direct knock-out mechanism, and this same mechanism would be expected for high-energy $(\pi,\pi n)$ reactions. A comparison of (p,pn) and $(\pi,\pi n)$ cross sections would thus bear directly on the interaction of the incident particles with a neutron bound in the nucleus.

Reeder and Markowitz[1] have measured the excitation function of the $C^{12}(\pi^-,\pi^-n)C^{11}$ reaction from 53 to 423 MeV. This spans the region of the large $(\frac{3}{2},\frac{3}{2})$ pion-nucleon resonance and they observe a large peak in the (π^-,π^-n) excitation function at the energy of this resonance. The present paper reports on the $C^{12}(\pi^-,\pi^-n)C^{11}$ excitation function from 0.45 to 1.9 GeV. A simple qualitative interpretation of the higher energy data in terms of the elementary particle cross sections will be presented. The $C^{12}(\pi^-,\pi^-n)C^{11}$ cross sections will also be useful for monitoring high-intensity pion beams.

Cross sections for the production of C^{11} and F^{18} from Al were also obtained from 0.45 to 1.8 GeV in order to look for effects of the pion-nucleon resonances on more complex spallation reactions.

EXPERIMENTAL

The C^{11} activity produced in plastic scintillator targets was measured by internal scintillation counting. For most of the measurements the pion flux was monitored by means of nuclear emulsions and the technique was the same as that used for the second series of measurements described by Poskanzer *et al.*[2] The irradiations were performed in beam I of the Cosmotron,[3] and an image-intensifying camera[4] was used to help locate the beam position. The targets were plastic scintillators $\frac{3}{8}$-in. thick by $\frac{3}{4}$-in. in diameter with nuclear emulsion pellicles mounted on the upstream side. The momentum spread of the Cosmotron pion beams was generally 7 to 10% expressed as full widths at half maximum, although the spread across the small targets used in this experiment was probably less. The irradiations varied from 2 to 40 min in length. Variations of beam intensity with time were monitored with a detector placed downstream from the target, and proper corrections were made to the C^{11} saturation factors. The initial C^{11} activities were about 100 counts/min. By means of a mercury and iron shield with a ring of anticoincidence proportional counters, the background activity was reduced to about 3 cpm. It was found that RCA 6342A photomultiplier tubes have good noise characteristics, and also that an $\frac{1}{8}$-in.-thick light pipe on the phototube helps to reduce the background. With the discriminator set at 59 keV as described previously,[2] the counting efficiency was taken to be[2,5] $(95\pm2)\%$. Scintillators outside of the beam indicated that the activation of C^{11} by stray secondary radiation varied from zero at the lower energies to 2% at the higher energies. The production of C^{11} by secondary particles produced in the target stack was conservatively estimated[6] to be $(1\pm1)\%$ at all energies. For the nuclear emulsions the scanning efficiency was estimated to be $(99\pm2)\%$, and the microscope reticle area was known to $\pm2\%$.

The calculated cross sections are listed in Table I, column three, and the indicated errors are the standard errors, based on the statistical errors of C^{11} counting and track counting. When two irradiation numbers are indicated, duplicate determinations were performed.

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

[2] A. M. Poskanzer, L. P. Remsberg, S. Katcoff, and J. B. Cumming, Phys. Rev. **133**, B1507 (1964).

[3] L. Marshall, Rev. Sci. Instr. **33**, 919 (1962).

[4] L. Marshall and A. Wattenberg, Rev. Sci. Instr. **32**, 1258 (1961).

[5] J. B. Cumming and R. Hoffmann, Rev. Sci. Instr. **29**, 1104 (1958).

[6] J. B. Cumming, G. Friedlander, and C. E. Swartz, Phys. Rev. **111**, 1386 (1958).

TABLE I. Cross sections in mb for production of C^{11} from carbon, and C^{11} and F^{18} from aluminum with high-energy pions.

	$C^{12}(\pi^-,\pi^-n)C^{11}$				Al target		
Pion energy (GeV)	Irradiation No.	Cross section[c]	$\mu+e$ corr. (%)	Corr. cross section[d]	Irradiation No.	$\sigma_{Al}(C^{11})$	$\sigma_{Al}(F^{18})$
0.45	40,41	16.8±0.7	12	19.1±2.4	42,43	2.2±0.3	6.2±0.8
0.70	38,39	13.5±0.6	7	14.5±1.3	37	3.8±0.4	6.2±0.6
0.90	31,32	14.4±0.6	2	14.7±0.8	30	4.2±0.4	6.8±0.5
0.98	11[b]	18.2	5	19±2	...	...	...
1.37	26,27	23.3±0.8	2	23.8±1.3	29	5.1±0.8	6.8±1.0
1.46	17[b]	24.5	5	26±3	15,16	5.8±0.9	6.0±1.0
1.76	33,34	20.1±1.0	2	20.5±1.3	35,36	4.9±1.0	6.6±1.0
1.86	20,21[a]	21.3±1.5	0	21.3±1.7			

[a] AGS irradiations.
[b] Early indirect measurements. Errors are almost entirely systematic.
[c] Only statistical error is indicated.
[d] Corrected for μ^- and e^- beam contamination. Systematic error included.

In general the agreement of duplicates was accidently better than the random errors would indicate. However, corrections are necessary for the μ^- and e^- contamination in the pion beam. The muons arise from pion decay in flight, largely before the first bending magnet and after the last bending magnet. The electrons come from conversion of the π^0-decay gamma rays in the pion-producing target. The contaminating leptons presumably do not produce C^{11}, but leave tracks in the nuclear emulsion which are indistinguishable from pions. It was calculated that the μ^- contamination in the beam passing within the $\frac{3}{4}$-in.-diam target was 2% or less.[6a] The e^- contamination increases with decreasing pion energy and rough estimates gave values ranging up to 10% at the lowest pion energy. The total corrections used for beam contamination are listed in column 4 of Table I. It is assumed that these corrections introduce a systematic error equal to the size of the corrections. The root-mean-square combination of the other systematic errors which have been mentioned is 3.6%. The corrected cross sections with their total errors are listed in column 5.

At the highest pion energy the irradiations (Nos. 20 and 21) were performed at the Alternate Gradient Synchrotron. Here the pion beam was focused to a narrow slit and was entirely contained within the $1\frac{1}{2}$-in.-diam scintillators used. The C^{11} counting efficiency of these scintillators, also $\frac{3}{8}$ in. thick, was taken to be (96±2)%. Because of their larger size, the contribution to C^{11} activity from internally produced secondaries was estimated to be (3±1)%. The place of irradiation was close to the accelerator shield and consequently the stray radiation level (mostly neutrons) was higher than at the Cosmotron. Scintillators at several positions outside of the beam indicated that (30±10)% of the C^{11} activity was due to this effect. In scanning the emulsions the total flux in the focussed beam was determined. The tracks which were uniformly distributed over the emulsion were considered as background tracks due to stray charged particle radiation and muons. Since most of the μ^- contamination in a pion beam is less well focused than the primary beam, subtracting the background tracks eliminated most of the μ^- correction for these irradiations.

Preliminary measurements[7] of the cross sections at 1.0 and 1.5 GeV (irradiations Nos. 11 and 17) were obtained in an indirect manner. The production rate of C^{11} in plastic scintillators was measured both in the pion beams and a 3-GeV proton beam. During the irradiations, the light output of a second plastic scintillator which intercepted the same flux of beam particles was monitored. By assuming that the relative amount of light produced by the pions and protons is proportional to the relative energy losses of the particles in the second scintillator, the (π^-,π^-n) cross sections could be calculated from a knowledge of the (p,pn) cross section. The second scintillator was mounted on a long light pipe containing a variable diaphragm. At the end of the light pipe was a phototube from which the anode current was integrated.[8] Both scintillators were $2\frac{1}{2}\times4\times\frac{1}{2}$ in. thick. Measurements were made concerning the effects of secondary particles on the production of C^{11} in the first scintillator and light in the second scintillator. It was concluded that the ratio of these effects was 2% in the pion beams and 4% in the proton beam, necessitating a net 2% reduction of the pion cross sections. To evaluate the effect of e^- contamination in the pion beam, separate irradiations were performed with pion-producing targets consisting of 2 in. of Be and 6 in. of brass, and no difference was observed. Irradiations were also performed in beams differing by a factor of 30 in intensity, and no effect was observed. The relative energy losses in the second scintillator of 1.0- and 1.5-GeV pions to 3-GeV protons were taken to be 1.07 and 1.12, respectively,[9] and the 3-GeV proton cross section used was

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[6a] The pion focus was two to three times the size of the target, and the muons were presumably spread out over a much larger area. The smallness of the contamination was due to the small size of the target.

[7] A. M. Poskanzer, J. B. Cumming, G. Friedlander, J. Hudis, and S. Kaufman, Bull. Am. Phys. Soc. 6, 38 (1961).

[8] The current integrator circuit was kindly designed by R. L. Chase.

[9] M. Rich and R. Madey, University of California Radiation Laboratory Report, UCRL-2301, 1954 (unpublished).

26.6 mb.[6] However, because of systematic uncertainties in the method, large errors have been placed on these cross sections which are shown in Table I.

Cross sections for C^{11} and F^{18} production from Al were also measured. The targets were Al disks (99% pure) 1 cm thick by $1\frac{1}{2}$ in. in diameter. On the upstream side were mounted $\frac{1}{8}$-in.-thick plastic scintillators of the same diameter. These were assayed by internal scintillation counting to determine the pion flux. The irradiations were usually 40 min in length, and the time variation of beam intensity was monitored as usual by a detector downstream. The Al was assayed without chemical separations by means of coincidence counting of the C^{11} and F^{18} positron-annihilation radiation. The Al disks were wrapped in a 0.015-in. Cu jacket and supported between two 3-×3-in. NaI crystals placed as close together as the Al and Cu would allow. Energy channels were placed on the 511-keV peaks, making the background rate only one cpm. The initial counting rates ranged from 2 to 40 cpm. The counting efficiency of this system was determined by making a mock-up of the target with Cu and a C^{11}-containing plastic scintillator irradiated with the same beam distribution. The scintillator was then assayed absolutely by internal scintillation counting. The counting efficiencies determined in this manner each time the system was used were between $5\frac{1}{2}\%$ and 8%. The F^{18} cross sections were calculated using a 97% positron abundance. These cross sections are also listed in Table I. They are based on the corrected $C^{12}(\pi^-,\pi^-n)C^{11}$ cross sections listed in column 5, and their errors include the errors of column 5. No corrections have been made for the effects of secondary particles on the production of C^{11} in the $\frac{1}{8}$-in. monitor scintillator, or on the production of C^{11} and F^{18} in the aluminum. The effect in the plastic is probably less than 1–2% and would tend to be cancelled by the effect in the aluminum.

DISCUSSION

The mechanism[10,11] of the $C^{12}(p,pn)C^{11}$ reaction at high energies is thought to be predominantly "clean knock out." That is, the high-energy incident proton makes one collision with a neutron inside the nucleus and both particles escape without further interaction. In the impulse approximation the cross section should be proportional to the elementary p-n cross section. When additional nucleons are struck, it is unlikely that particle-stable states of C^{11} will be formed. Thus, other collisions effectively produce an attenuation of the cross section for the production of C^{11}. If this same knock-out mechanism is important for the (π^-,π^-n) reaction under consideration here, then the π^--n resonances shown in Fig. 1(A) should be reflected in the nuclear excitation function. The $C^{12}(\pi^-,\pi^-n)C^{11}$ excitation function, including the data of Reeder and Markowitz, is shown in Fig. 1(b). The similarity of the (π^-,π^-n) nuclear excitation function to the π^--n elementary particle cross sections is striking.

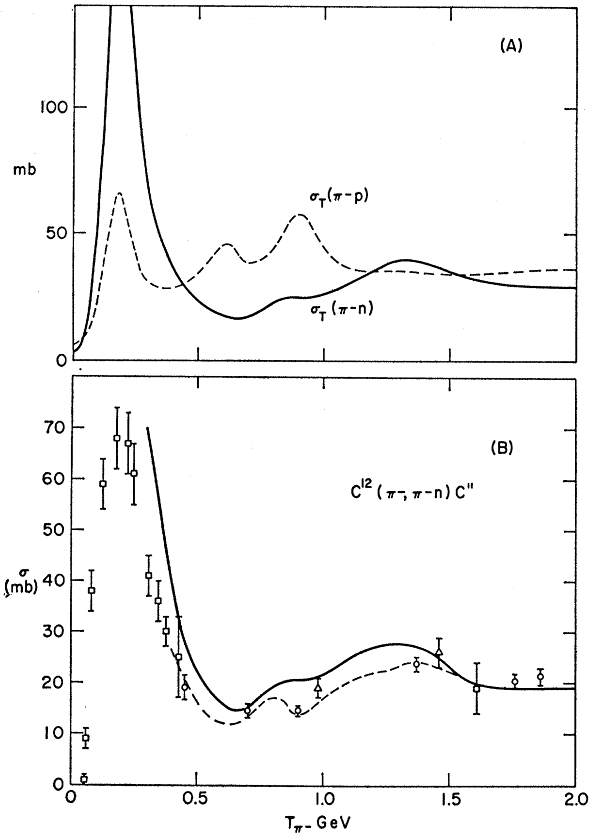

FIG. 1. (A) Total cross sections for the interaction of negative pions with neutrons (solid line) and protons (dashed line). (B) Excitation function for the reaction $C^{12}(\pi^-,\pi^-n)C^{11}$. Squares: Reeder and Markowitz, Ref. 1. Circles: This work. Triangles: Earlier measurements, Ref. 7. Solid curve calculated by the following equation: $\sigma(\pi^-,\pi^-n)=\sigma(p,pn)\sigma_T(\pi^-n)/\sigma_T(pn)$. Dashed curve includes approximate ratios of the π^- and p attenuation factors.

Next, let us consider the ratio of the nuclear cross sections of the (π^-,π^-n) to the (p,pn) reactions above 0.5 GeV. Because the initial and final nuclei are the same, one would expect that many of the nuclear structure effects, such as the number of target neutrons available to participate, would cancel out of the ratio. The attenuation effects would also tend to cancel because the average pion-nucleon cross sections are not very different from the average nucleon-nucleon cross sections at high energies. Thus, for the simplest idea, the ratio of the (π^-,π^-n) to (p,pn) nuclear cross sections should be equal to the ratio of the π^--n to p-n elementary-particle cross sections. The solid curve in Fig. 1(B) for the (π^-,π^-n) cross sections is constructed on this basis, taking the ratios at equal bombarding energy. Because both the (p,pn) and p-n excitation functions are relatively structureless, the solid curve reflects the resonances in the π^--n interaction. In fact, the general magnitude of the curve obtained using this simple idea

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[10] S. Singh and J. M. Alexander, Phys. Rev. **128**, 711 (1962).

[11] J. R. Grover and A. A. Caretto, Jr., Ann. Rev. Nucl. Sci. **14**, to be published.

agrees well with the experimental data. The most significant deviation occurs at 0.9 GeV, the energy shown in Fig. 1(A) for a π^--p resonance. This is probably a result of the attenuation of the incident beam by the protons of the nucleus. A crude calculation of the ratio of the attenuation factor for π^- to that for protons was performed using straight-line trajectories and assuming most of the reaction sites occurred on the downstream side of the nucleus. The resulting excitation function is shown in Fig. 1(B) as a broken curve normalized to the solid curve at high energies. The better fit qualitatively suggests that the π^--p resonances reduce the cross section even in a nucleus as small as carbon.

Below about 0.5 GeV the above simple ideas are less likely to apply for several reasons. The momentum of the incident pion becomes comparable to the Fermi momentum of the struck nucleons. This affects the reaction rate both through the change in relative velocity of the colliding particles and also the change in available center-of-mass energy. The binding energy of the least-bound neutron in C^{12} is very large, 18 MeV. The necessity to transfer this much kinetic energy to the struck neutron restricts the reaction not only at very low incident-pion energies, but also just above the $(\frac{3}{2},\frac{3}{2})$ resonance where the pion angular distributions are strongly peaked forward. Finally, the lower the irradiating energy, the less probable it is that the knock-out mechanism predominates.[1]

A more detailed calculation of the $C^{12}(\pi^-,\pi^-n)C^{11}$ excitation function has not been performed, even at the higher energies, because Monte-Carlo calculations in progress by other workers make it possible to treat quantitatively the classical, impulse-approximation model used in the present discussion. The present paper simply attempts to point out the qualitative effects of the elementary particle resonances on the excitation function of this simple nuclear reaction. It is suggested that it would be interesting to study the $C^{12}(\pi^+,\pi^+n)C^{11}$ reaction,[12] especially in the region of the 900-MeV resonance. Here, one could determine the width of an elementary particle resonance in nuclear matter, only slightly affected by the complications mentioned that occur at lower bombarding energies. Also, since the attenuation factors for π^+ and π^- are equal in nuclei with equal numbers of protons and neutrons, the simple idea, that the ratio of the cross sections for the nuclear reactions should equal the ratio of the elementary particle cross sections, should be accurate for the clean knock-out mechanism, and provide a stringent test of this mechanism.[13]

For the more complex spallation reactions, the production of C^{11} and F^{18} from Al^{27}, the cross sections shown in Table I exhibit no structure within experimental error. The C^{11} cross sections are the same as those for protons[14] of the same incident energy, while the F^{18} cross sections are perhaps 15% lower than those for the corresponding proton-induced reaction. One might expect that the elementary particle resonances would affect the transparency of the nucleus to the pion and thus the total reaction cross sections. This, in turn, might affect the individual cross sections. However, the effect is evidently small in the region of the higher resonances where the present measurements were performed.

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[12] This idea of studying the same nuclear reaction with various incident particles could be pursued even further. A preliminary measurement of the $C^{12}(\bar{p},\bar{p}n)C^{11}$ cross section for 2.8-GeV antiprotons gave a result of 30±9 mb.

[13] P. Reeder, University of California Radiation Laboratory Report UCRL-10531, 1962 (unpublished).

[14] J. B. Cumming, J. Hudis, A. M. Poskanzer, and S. Kaufman, Phys. Rev. **128**, 2392 (1962).