measurements of this channel could be extended farther away from the analog resonance in order to verify the expected gradual falloff in both directions of the strength function (according to the Breit-Wigner formula, with the spreading width from Σ included with Γ in the total doorway width). In other cases, the strength function will decrease monotonically in one direction away from the analog resonance while in the other it will increase as the $T_<$ doorway center is approached. Following the Breit-Wigner formula, the strength function will reach a maximum, and then decrease as the doorway state is passed by.

In summary, an analog resonance can be regarded as a simple tool for the study of the much richer spectrum of $T_<$ states of the compound nucleus. Although we have referred to the $T_>$ analog states as doorways, they are much simpler than the $T_<$ doorways, for there are no hallways connected with them. In other words, the $T_>$ doorways do not actually provide an entrance into the nucleus (in terms of Hilbert space, rather than configuration space, of course). The case of a single $T_<$ doorway, when probed by an analog resonance, yields a characteristic modulation of the fine structure with a complete suppression at some point in the spectrum.[15] In each such case, much more experimental information on this nearby doorway would be desirable.

[15] This is also true when the $T_<$ doorway is coupled to additional open channels. Equations (10–13) can be extended to this case by including a negative imaginary damping term in E_D. Equation (13) then describes the fluctuations in the *total* cross section.

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Excitation Functions for the $(\pi^-,\pi^- n)$ Reaction on C^{12} and F^{19} †

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Cross sections for the reactions $C^{12}(\pi^-,\pi^- n)C^{11}$ and $F^{19}(\pi^-,\pi^- n)F^{18}$ were measured with incident pions of kinetic energy between 0.70 and 1.80 GeV. The results, together with earlier measurements of the former reaction, are compared with a simple model of (X,XN) reactions, assuming a clean knockout of a nucleon N by an incident particle X. It is shown that the model does not correctly predict the magnitude of the $(\pi^-,\pi^- n)$ cross sections, although it is successful in predicting the general trend of cross section with energy.

I. INTRODUCTION

SIMPLE nuclear reactions (those in which the final nucleus differs from the initial one by less than a few units of Z and A) have been extensively studied at high energy. The class of reactions which result in a nucleus of mass number one less than the target have been the most popular. The picture which has emerged[1] of the mechanism for these reactions is that near 400 MeV the clean knockout mechanism, in which the incident particle interacts with a single nucleon and both escape from the nucleus without further interaction, predominates. Below this energy the contribution from processes which proceed through evaporation of a nucleon increases. For example, Grover and Caretto[1] estimate that the contribution of the clean knockout mechanism is about 80% of the total (p,pn) cross section at 400 MeV for C^{12}, falling to about 60% at 200 MeV and to about 45% at 100 MeV. Above this energy inelastic events, in which one or more mesons are created, become more probable, and should act to reduce the clean-knockout contribution, because of the higher probability that the outgoing particles will interact with the rest of the nucleus. However, the nearly energy-independent behavior of (p,pn) cross sections above 400 MeV[1] suggests that inelastic events can lead to a clean knockout to the same extent as elastic events.

The predominance of the clean-knockout mechanism for (X,XN) reactions (where X is an incident particle and N is a nucleon) at high energy should result in an approximate proportionality of the cross section to the X–N free-particle cross section. Any prominent structure in the free-particle cross section should thus appear in the (X,XN) reaction cross section. This has been found by Reeder and Markowitz[2] in the $C^{12}(\pi^-,\pi^- n)$ reaction as a prominent peak near 200 MeV, corresponding to the $T=\frac{3}{2}$ resonance in scattering. The authors showed that the ISE mechanism (inelastic scattering followed by evaporation) would result in a minimum in the $(\pi^-,\pi^- n)$ cross section at the resonance, because of the attenuation of the scattered pion by the nucleus. Thus even at the relatively low energy of 200 MeV it

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

appears that the clean-knockout mechanism predominates for this reaction.

The two $T=\frac{1}{2}$ resonances at 600 and 900 MeV in $\pi^- - p$ scattering are less prominent than the 200-MeV resonance, but evidence for their presence has been found in the $Ar^{40}(\pi^-, \pi^- p)Cl^{39}$ reaction.[3] The spreading out of these peaks was used to estimate the momentum distribution of the struck proton. Measurements of the $Ce^{142}(p,2p)La^{141}$ cross section[4] showed a significant rise between 0.4 and 1.0 GeV, correlated with the rise in the $p-p$ cross section, but smaller in magnitude. In all three reactions, the effect of the nucleus was to reduce and to spread out the elementary-particle structure. These changes offer the possibility of obtaining information about the nucleus and its interaction with the bombarding particle.

An opposite effect of a resonance in an elementary cross section was noted by Poskanzer and Remsberg.[5] The 900-MeV peak in $\pi^- - p$ scattering should reduce the $(\pi^-, \pi^- n)$ cross section because of the increased attenuation of the incident pion. Their datum point at 900 MeV seemed low, and they attributed it to this effect.

In order to investigate these effects further we have measured the cross sections for the reactions $C^{12}(\pi^-, \pi^- n)C^{11}$ and $F^{19}(\pi^-, \pi^- n)F^{18}$ at a number of pion kinetic energies between 0.70 and 1.80 GeV. Particular attention was given to the 0.70–1.00 GeV region, in order to see if the reduction of the cross section by attenuation was observable.

II. EXPERIMENTAL PROCEDURE AND RESULTS

Irradiations were done in the 13° secondary beam of the Princeton-Pennsylvania Accelerator (PPA). The procedure was similar to that described previously.[3] The targets were solid disks, 2 in. diam×0.25 in. thick, and were taped to the front of a 2-in.-diam plastic scintillator, which was the first element of a counter telescope. The second counter was about 6 in. behind the first and was larger, ensuring that all particles in the beam which went through the first counter would also go through the second. The beam intensity was measured as a function of time during the irradiation so that saturation corrections could be made. Irradiations lasted from 10 to 40 min for the carbon targets, and from $1\frac{1}{2}$ to 2 h for fluorine.

The fractions of π^-, μ^-, and e^- in the beam were obtained as a function of momentum from the data of other experimenters,[6] as were the proper magnet currents. The beam intensity was corrected for coincidence loss as previously described.[3] The momentum spread of the beam was 2% full width at half-maximum (FWHM) for irradiations in the range 0.70–0.94 GeV, and was 5% FWHM for higher energies. This was in order to detect possible fine structure in the lower energy range.

The targets used for measuring the carbon cross section were plastic scintillator,[7] which was assumed to have the composition $CH_{1.10}$; cross sections were calculated on the basis of 100% C^{12}, ignoring the C^{13} contribution. After the irradiation, the scintillator was optically coupled to a 3-in.-diam RCA 8054 photomultiplier tube and counted inside a lead shield. The threshold was set to give a relatively low background but still have a high efficiency for C^{11} β particles. The efficiency as a function of discriminator setting was measured by the β-annihilation-radiation coincidence technique.[8] For the usual discriminator setting, the efficiency was 85% and the background was 35 counts/min.

For the fluorine cross sections, the targets were Teflon, assumed to have the composition CF_2. Counting was done by wrapping the target in a 0.010-in. Cu jacket and placing the jacketed target between two 3×3-in. NaI crystals, with the Cu in contact with the crystal jackets. Narrow energy channels were set on the 511-keV peaks and coincidences were counted. The background was 2–3 counts/min. The efficiency of this arrangement was measured by counting the disintegrations of a plastic scintillator whose disintegration rate had been determined as above. This efficiency was lowered by a factor of 0.915 to take into account the greater absorption of 511-keV γ rays by Teflon, due to its higher density and atomic number. The efficiency was corrected for slight differences in window widths by counting a standard Na^{22} source. The counting efficiency for Teflon was about 9%. The branching ratio for β^+ decay of F^{18} was taken as 0.97.

By exposing thick plastic scintillators just outside the beam and counting them, the vicinity of the beam was checked for stray radiation, such as neutrons, which could cause nuclear reactions. Negligible activity was found.

The effect of secondary particles, which are produced in the target and interact before escaping, in producing the activity of interest was measured by irradiating a "sandwich" of the usual target between two 0.5-in.-thick disks of the same material. The results are given in Table I, at two energies for each target. The effect is larger at the higher energy, as is expected. The secondary effect for C^{11} is in qualitative agreement with the results for 2–3 GeV protons.[9] The effects for F^{18} and C^{11} are equal, which is surprising, because one would expect a larger effect for F^{18}, due to the lower energetic threshold of the reaction (18.71 MeV for C^{11} and 10.41 MeV for F^{18}) and the higher density of the target.

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[6] The names of these experimenters are given in the Acknowledgments.
[7] Pilot-B scintillator, manufactured by Pilot Chemicals, Inc., Waltham, Massachusetts.
[8] J. B. Cumming and R. Hoffman, Rev. Sci. Instr. **29**, 1104 (1958).
[9] J. B. Cumming, G. Friedlander, and C. E. Swartz, Phys. Rev. **111**, 1386 (1958).

TABLE I. Effect of target thickness on cross section.

Pion KE (GeV)	Target	Cross section (mb) 0.25 in.	1.25 in.	$\Delta\sigma$ (mb/in.)
0.92	plastic	17.3±0.4	19.8±0.4	2.5±0.6
1.60	plastic	21.9±0.7	24.7±0.6	2.8±0.9
0.92	Teflon	14.1±0.4	16.3±0.4	2.2±0.6
1.80	Teflon	17.6±0.7	20.7±0.8	2.9±1.1

In order to correct the data for the secondary effect, the following procedure was used. The correction was expressed as mb/g cm^{-2} of thickness, and the thickness of the beam monitor counter on which the targets were mounted was included in the target thickness. The correction was assumed to vary linearly with energy.

The experimental thick-target cross sections and the corrected cross sections are given in Table II. The last line in that table refers to irradiations made in a positive beam, which at a momentum of 1.7 GeV/c contains 95% protons, 5% pions, and negligible muons and electrons. The errors assigned to a measurement are made up of the standard deviation of the counting rate, as given by a least-squares decay curve program,[10] the uncertainty in the fraction of pions in the beam, and an estimated 1% error in aligning the target with the counter telescope. The uncertainty in counting efficiencies is estimated to be 2% for the plastic scintillator counting and 5% for the coincidence counting of the Teflon disks. This factor has not been included in the assigned error because it does not affect the relative cross sections at different energies. The secondary (thickness) correction may introduce a systematic error; the correction was 6–7% for all the points.

TABLE II. Experimental and corrected cross sections.

Pion KE (GeV)	$C^{12}(\pi^-, \pi^-n)C^{11}$ Experimental cross section (mb)	Cross section[a] corrected for thickness (mb)	$F^{19}(\pi^-, \pi^-n)F^{18}$ Experimental cross section (mb)	Cross section[b] corrected for thickness (mb)
0.70	16.5±0.8	15.5±0.9		
0.75	15.0±0.8	14.0±0.9		
0.80	17.2±0.9	16.1±1.0	12.7±0.7	11.9±0.8
0.80	16.4±0.6	15.3±0.7		
0.85	16.0±0.5	14.9±0.6		
0.92	17.3±0.4	16.2±0.6	14.1±0.4	13.3±0.5
0.94	17.2±0.7	16.1±0.8		
1.00			13.2±0.5	12.4±0.6
1.10	19.8±0.4	18.6±0.6		
1.20	21.7±0.6	20.5±0.7	14.9±0.5	14.0±0.6
1.40	23.2±0.6	21.9±0.7	18.0±0.7	17.0±0.8
1.50	23.5±0.7	22.1±0.8	18.0±0.7	17.0±0.8
1.60	21.9±0.7	20.5±0.8	19.1±1.0	18.1±1.2
1.80			17.6±0.7	16.6±0.9
1.00[c]	30.6±0.7	29.5±0.8	23.3±0.9	22.5±1.0

[a] Estimated error of 2% in counting efficiency not included.
[b] Estimated error of 5% in counting efficiency not included.
[c] Proton kinetic energy. The beam contained 5% π^+ mesons of kinetic energy 1.56 GeV.

[10] J. B. Cumming, U. S. At. Energy Comm. Report No. NAS-NS 3107, (1963).

The two measurements with 1.00-GeV protons are useful because the reliability of the experimental method can be judged by comparing these measurements with previous ones. The $C^{12}(p,pn)C^{11}$ cross section was measured at 1.0 GeV[11] with a result of 29.0±1.3 mb; the "adopted value" of Cumming[12] at 1.0 GeV is 28.5±1.4 mb. Thus our value of 29.5±1.0 mb for a beam containing 5% π^+ mesons is in agreement with these. (The 2% uncertainty in counting efficiency is included here.) The $F^{19}(p,pn)F^{18}$ reaction is less reliably known. Averaging the results of Markowitz *et al.*[13] at 0.8, 1.0, and 1.2 GeV yields 23.0±1.7 mb; the measurement of Symonds *et al.*[14] at 0.98 GeV, when corrected for the low monitor cross section they used, is 24.2 mb. Our result of 22.5±1.5 mb (including counting efficiency uncertainty) is in agreement with these measurements.

III. DISCUSSION

Under the assumption that the clean-knockout mechanism predominates for these reactions, we wish to compare the (π^-, π^-n) cross sections with the $\pi^- - n$ free-particle cross section. As pointed out by Poskanzer and Remsberg,[5] the ratio of (π^-, π^-n) to (p,pn) cross sections for the same nucleus should equal the ratio of π^-n to pn free-particle cross sections taken at the same incident kinetic energy, as a first approximation. This is so because many of the nuclear-structure effects tend to cancel. The main difference between the pion- and proton-induced reactions lies in the different attenuation of the incident particles by the nucleus. Therefore we can write as a second approximation

$$\sigma(\pi^-, \pi^-n) = \sigma(p,pn)\frac{\sigma_{\pi^-n}}{\sigma_{pn}}\frac{F_{\pi^-}}{F_p}. \quad (1)$$

In Eq. (1), F_{π^-} and F_p are the attenuation factors for pions and protons in a given nucleus. These were estimated in Ref. 5, assuming straight-line trajectories and localization of the reaction site at the downstream side of the nucleus.

In Fig. 1(a) we show the experimental points for the $C^{12}(\pi^-, \pi^-n)C^{11}$ reaction above 0.6 GeV, including the earlier data,[2,5] and also the curves calculated in the manner described above. The solid curve is the ratio $\sigma_{\pi^-n}/\sigma_{pn}$ times the $C^{12}(p,pn)C^{11}$ cross section, and the dashed curve shows the effect of the different π^- and p attenuation factors, taken from Ref. 5. The dashed curve has been normalized to the solid curve at high energies; without this normalization the dashed curve would be above the solid curve at most energies, because the mean pion-nucleon cross section is less than the

[11] A. Poskanzer, L. Remsberg, S. Katcoff, and J. B. Cumming, Phys. Rev. 133, B1507 (1964).
[12] J. B. Cumming, Ann. Rev. Nucl. Sci. 13, 261 (1963).
[13] S. Markowitz, F. Rowland, and G. Friedlander, Phys. Rev. 112, 1295 (1958).
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mean proton-nucleon cross section except near 900 MeV. Thus the simple approximation that the attenuation factor is $\exp(-x/\lambda)$, where x is the mean distance traveled and λ is the mean free path, predicts too large a $(\pi^-, \pi^- n)$ cross section. However, the shape of the dashed curve seems to be in good agreement with the experimental points.

Figure 1(b) shows the experimental points for the $F^{19}(\pi^-, \pi^- n)F^{18}$ reaction, and the solid curve is analogous to the solid curve in Fig. 1(a), using here the experimental $F^{19}(p,pn)$ cross section.[15] For both reactions the

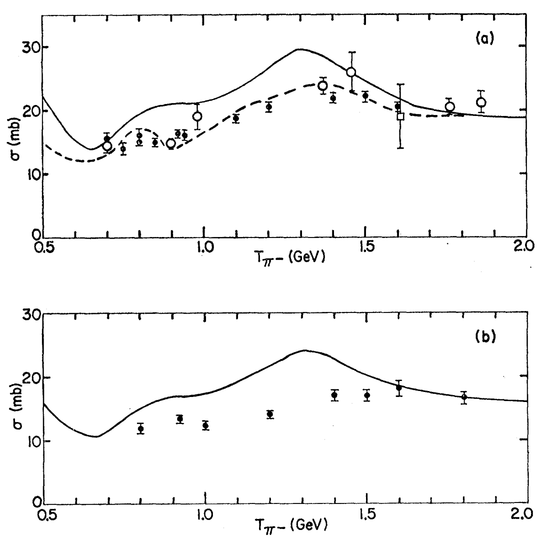

FIG. 1. (a) Experimental cross sections for $C^{12}(\pi^-, \pi^- n)C^{11}$ above 0.6 GeV. Solid circles: this work; open circles: Poskanzer and Remsberg, Ref. 5; square: Reeder and Markowitz, Ref. 2. Solid line is $\sigma(p,pn) \times (\sigma_{\pi^- n}/\sigma_{pn})$; dashed line includes π^- and p attenuations. (b) Experimental cross sections for $F^{19}(\pi^-, \pi^- n)F^{18}$. Solid line is $\sigma(p,pn) \times (\sigma_{\pi^- n}/\sigma_{pn})$.

points fall below the solid curve between 0.75 and 1.50 GeV, indicating a stronger attenuation of pions than protons in this energy range. This can be shown as a function of energy by taking the ratio of each experimental point to the solid curve at the same energy. This ratio is F_{π^-}/F_p, from Eq. (1), and is shown in Fig. 2.

[15] The measurements of Ref. 14 for $F^{19}(p,pn)$ at 0.65 and 0.73 GeV are much higher than those at other energies. These were ignored, and a constant cross section of 23.0 ± 1.5 mb was used. The "adopted values" from Ref. 12 were used for the $C^{12}(p,pn)$ cross sections.

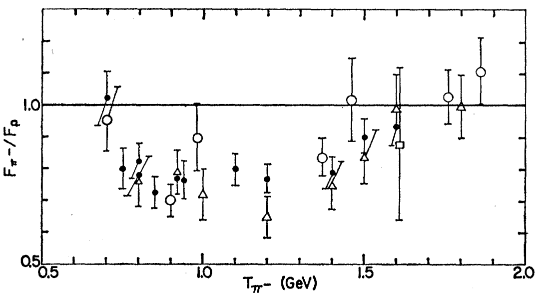

FIG. 2. Ratio of π^- and proton attenuation factors, F_{π^-}/F_p. Solid circles: this work, C^{12}; open circles: Poskanzer and Remsberg, Ref. 5, C^{12}; square: Reeder and Markowitz, Ref. 2, C^{12}; triangles: this work, F^{19}.

For both carbon and fluorine the attenuation of pions is greater (smaller F_{π^-}) than that of protons between 0.75 and 1.4 GeV. There is no indication of structure in the ratio which could be due to resonances in the pion-nucleon cross sections. In particular, the predicted structure near 0.9 GeV, although consistent with the data, is not definitely indicated. The experimental errors and the fluctuations of the data are of the same order of magnitude as the predicted structure.

As stated above, the simple estimate of the pion and proton attenuations predicts an attenuation ratio greater than unity, except near 0.90 GeV. It is clear that arguments based on such simple considerations must be used with caution until more is learned about the reason for this discrepancy. It may be due to details of the scattering process, especially the angular and energy distributions of inelastic reactions. Or it may mean that the (p,pn) and the $(\pi^-, \pi^- n)$ reactions are localized differently in the nucleus, so that the pion travels a longer distance through denser parts of the nucleus. Further measurements may help to clarify the picture. In particular, reactions induced by π^+ mesons should be studied, in order to introduce different resonances.

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