($\pi^{\pm}$,πN) reactions on ^{14}N, ^{19}F, ^{23}Na, ^{27}Al, and ^{31}P near the Δ(1232) resonance

B. Joseph Lieb
George Mason University, Fairfax, Virginia 22030

Hans S. Plendl
Florida State University, Tallahassee, Florida 32306

Carey E. Stronach
Virginia State University, Petersburg, Virginia 23803

Herbert O. Funsten
College of William and Mary, Williamsburg, Virginia 23186

V. Gordon Lind
Utah State University, Logan, Utah 84322
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The validity of the nucleon charge exchange model for ($\pi^{\pm}$,πN) reactions is tested by comparing cross sections for ($\pi^{\pm}$,πN) reactions near the Δ(1232) resonance on the odd-Z nuclei ^{14}N, ^{19}F, ^{23}Na ^{27}Al, and ^{31}P that were measured by observing the γ decays of the residual nuclei with cross sections calculated from the model. The model reproduces the general trend of the data, but not the detailed features. Comparison of experimental and calculated cross sections indicates that the reactions are largely quasifree, in agreement with our earlier results for self-conjugate nuclei.

[NUCLEAR REACTIONS ^{14}N, ^{19}F, ^{23}Na, ^{27}Al, ^{31}P, ($\pi^{\pm}$,πN), $E\simeq200$ MeV; detected γ's, Ge(Li); measured 90°σ for residual levels; deduced σ ratios, reaction mechanism; compared results with N-CEX model.]

I. INTRODUCTION

Several years ago Sternheim and Silbar proposed that final-state nucleon charge exchange (N-CEX) could account for some of the previously unexplained features of ($\pi^{\pm}$,πN) experiments in the Δ(1232) reasonance region.[1] (N refers to the ejected nucleon, π to the outgoing pion with either the same charge as the incident pion or with zero charge in case of charge exchange.) In another paper[2] they explored the effects of nuclear structure on the ratios of ($\pi^{\pm}$,πN) cross sections. They assumed that the final-state nucleon charge exchange was dominated by charge exchange to analog states. This refined N-CEX model produced predictions that depended dramatically on the structure of the individual nucleus. In a later paper,[3] they reexamined the extent of analog dominance of the final-state charge exchange, concluding that the assumption of complete analog dominance may not be justified.

Several recent papers have reawakened interest in the charge exchange model. In one of these papers Sternheim and Silbar[4] extended their N-CEX model to energies above the Δ(1232) resonance by including the effects of π production, the Pauli principle, and Fermi motion. In another paper Karol[5] questioned the validity of the charge exchange model. Using different assumptions, he calculated that P, the probability for a charge exchange to happen in a (π,πN) reaction, is $<10\%$, which is somewhat less than the $\sim25\%$ assumed by Sternheim and Silbar. More recently, Ohkubo and Porile[6] performed a Benioff-type calculation[7] of the (π,πN) reaction on ^{12}C, ^{25}Mg, ^{127}I, and ^{197}Au in which P was an adjustable parameter. They concluded that nucleon charge exchange was important only for the light nuclei they examined.

In this paper, we present γ-ray data from (π,πN) reactions on the odd-Z nuclei ^{14}N, ^{19}F, ^{23}Na, ^{27}Al, and ^{31}P. These cross sections were originally recorded as part of a study of $\pi^{\pm}$ induced multinu-

TABLE I. Cross sections for $(\pi^{\pm},\pi N)$ reactions on ^{14}N, ^{19}F, ^{23}Na, ^{27}Al, and ^{31}P.

Target nucleus	Residual nucleus state E_x (MeV)	$J^{\pi};T$	Transition	$\sigma_{\rm tot}^{-}$ [a] (mb)	$\sigma_{\rm tot}^{+}$ [a] (mb)	$\left(\frac{\sigma_{\rm tot}^{-}}{\sigma_{\rm tot}^{+}}\right)_{\rm expt}$	$\left(\frac{\sigma_{\rm tot}^{-}}{\sigma_{\rm tot}^{+}}\right)_{\rm theor}$ [b]
^{14}N	^{13}C 3.684	$\frac{3}{2}^{-};\frac{1}{2}$	II → 0	3.1±1.0	9.2±1.7	0.34+0.15	0.56
	3.854	$\frac{5}{2}^{+};\frac{1}{2}$	III → 0	1.6±0.4	1.7±0.7	0.9 +0.5	
^{19}F	^{18}F 0.937	$3^{+};0$	I → 0	22 ±2.2	8.6±0.9	2.6 ±0.7	2.6
	1.042	$0^{+};1$	II → 0	12 ±0.8	3.7±0.6	3.2 ±0.9	1.7
	1.081	$0^{-};0$	III → 0	4.6±0.7	0.9±0.2	5.1 ±1.8	3.0
	1.701	$1^{+};0$	V → II	4.1±1	0.9±0.4	4.6 ±2.5	3.0
	2.101	$2^{-};0$	VI → I	7.7±2.6	c		
	2.523	$2^{+};0$	VII → 0	1.6±0.3	<3.0		3.0
	3.062	$2^{+};1$	VIII → I	<6.5	3.2±1.6		1.1
	3.134	$1^{-};0$	IX → III	<5.1	<3.6		3.0
	^{18}O 1.982	$2^{+};1$	I → 0	24 ±1.7	21 ±2.4	1.1 ±0.3	0.56
	3.555	$4^{+};1$	II → I	1.9±0.5	0.6±0.1	3.2 ±1.2	
	3.635	$0^{+};1$	III → I	8.3±1	9.4±0.9	0.88±0.23	0.56
	3.921	$2^{+};1$	IV → I	<1.2	<3.4		
	4.456	$1^{-};1$	V → I	7.5±2.8	3 ±1.2	2.5 ±1.5	0.56
	5.098	$3^{-};1$	VI → I	c	<4.0		
^{23}Na	^{22}Na 0.583	$1^{+};0$	I → 0	30 ±9	26 ±8	1.2 ±0.7	2.1
	0.891	$4^{+};0$	III → 0	7.1±0.3	5.7±0.6	1.2 ±0.5	3.0
	1.952	$2^{+};1$	VI → I	<11	<8.0		1.8
	1.984	$3^{+};0$	VII → I	<17	<14		2.0
	2.212	$1^{-};0$	VIII → II	2.0±0.5	1.7±0.4	1.2 ±0.6	3.0
	^{22}Ne 1.275	$2^{+};1$	I → 0	25 ±0.4	36 ±0.6	0.69±0.29	0.56
	3.357	$4^{+};1$	II → I	6.7±0.6	8.6±0.5	0.78±0.34	0.56
	4.457	$2^{+};1$	III → I	4.7±0.8	13 ±1	0.36±0.17	0.56
	5.148	$2^{-};1$	IV → III	4.0±0.4	6.6±0.9	0.61±0.28	0.56
^{27}Al	^{26}Al 0.417	$3^{+};0$	II → 0	10 ±1.3	12 ±0.9	0.83±0.21	1.8
	1.058	$1^{+};0$	III → I	19 ±0.9	11 ±2.5	1.7 ±0.5	1.6
	1.759	$2^{+};0$	IV → II	<2.4	2.2±1		2.2
	2.069	$4^{+};0$	VI → II	5.1±1.9	4.3±1	1.2 ±0.6	3.3
	2.070	$2^{+};1$	VII → III	<5.9	c		1.4
	2.072	$1^{+};0$	VIII → I	<1.7	c		1.1
	2.365	$3^{+};0$	IX → II	<3.3	c		1.7
	2.545	$3^{+};0$	X → VI	4.3±0.7	2.8±0.5	1.5 ±0.5	2.0
	^{26}Mg 1.809	$2^{+};1$	I → 0	44 ±5	48 ±5	0.92±0.24	0.56
	2.938	$2^{+};1$	II → I	12 ±0.8	15 ±2	0.8 ±0.2	0.56
	3.588	$0^{+};1$	III → I	<3.4	2.5±1		0.56
	3.941	$3^{+};1$	IV → II	<8.8	4.7±1.6		0.56
	4.318	$4^{+};1$	V → I	c	14 ±2.1		0.56
^{31}P	^{30}P 0.677	$0^{+};1$	I → 0	2.5±0.3	2.6±0.6	1.0 ±0.5	1.5
	0.709	$1^{+};0$	II → 0	7.8±1.6	4.9±1.5	1.6 ±0.9	2.3
	1.454	$2^{+};0$	III → 0	1.8±0.6	1.8±0.8	1.0 ±0.7	1.9
	2.839	$3^{+};0$	VII → II	c	4.5±1.8		
	2.938	$2^{+};1$	VIII → III	c	4.5±1.9		1.3

[a] $\sigma_{\rm tot}$ is the cross section for production of a particular state by direct excitation and/or by γ-ray feeding from higher states.

[b] N-CEX prediction with $P=0.25$ including direct excitation, outgoing nucleon charge exchange to analog states, and γ-ray feeding from higher states.

[c] Cross section or upper limit could not be determined.

cleon removal, and some of the data presented have already been published without comparison with $(\pi,\pi N)$ theoretical work ($\pi^- + {}^{19}$F, ^{17}Al: Ref. 8; $\pi^\pm + {}^{23}$Na, ^{31}P: Ref. 9. The present data thus represent a fairly complete survey of $(\pi,\pi N)$ reactions on light odd-Z nuclei. We also present a comparison of our data with the refined N-CEX model of Sternheim and Silbar.[2] Since that model was developed to interpret activation data, we adapted it so that its predictions could be compared with γ-ray data.

II. EXPERIMENT AND RESULTS

Since the experimental technique has been described previously,[8] we will give only a few details. The γ rays were detected with a Ge(Li) detector in coincidence with incident 190 MeV π^+ and 220 MeV π^- from the Space Radiation Effects Laboratory (SREL) synchrocyclotron. The energy difference in the beams is not significant because of the width of the $\Delta(1232)$ resonance and the fact that the π^+ resonance occurs at a lower energy than the π^- resonance.[10] The targets were isotopically unseparated $LiNH_2$ (0.89 g/cm^2), LiF (1.4 g/cm^2 for π^+ and 2.75 g/cm^2 for π^-), metallic sodium (9.6 g/cm^2), aluminum (6.9 g/cm^2 for π^+ and 13.5 g/cm^2 for π^-), and phosphorus powder (2.9 g/cm^2).

The peaks were fitted to a Gaussian line shape and an exponential background using a least-squares method. Cross sections were computed from the area of the peak, the absolute detector efficiency, the target parameters, and the number of incident pions. A correction for γ-ray absorption was applied. Isotropic emission of the γ rays was assumed. Sample spectra for ^{19}F$(\pi^-,\pi N)$ and ^{27}Al$(\pi^-,\pi N)$ have been published previously.[8]

The γ-ray lines were identified and corrected for branching using the known γ-decay schemes.[11,12] The cross sections σ_{tot} for excitation of a particular state, without correction for feeding from higher states, are presented in Table I. The quoted uncertainties, which are due to statistics and uncertainties in the detector efficiency, are the relative uncertainties in data from a particular spectrum. The uncertainties in the absolute nomalization, due to geometry and other factors, are large (30% for ^{23}Na and ^{31}P, and 15% for the other targets).

Also shown in Table I are the cross section ratios

$$\frac{\sigma_{\text{tot}}^-}{\sigma_{\text{tot}}^+}$$

for states detected in both the π^- and π^+ spectrum. The large uncertainties quoted are due to the large uncertainty in absolute cross sections.

III. ADAPTATION OF THE REFINED N-CEX MODEL TO γ-RAY DATA

In the remainder of the paper, we will compare the experimental cross sections with the predictions of the refined N-CEX model. We will examine the questions raised by the authors of the model[3] concerning the extent of analog dominance of the final state charge exchange. Furthermore, we will test the ability of a γ-ray experiment to resolve questions of this nature. Such experiments provide a wealth of information about the excitation of specific residual states, but the interpretation of such results is complex for all but the simplest nuclei. It is usually impossible to detect all residual excited states, and it is difficult to correct for the effects of γ-ray feeding from higher energy states. If, however, a model can make specific predictions about the excitation of all states of the residual nucleus, it should be possible to use the known γ-ray decay scheme to make predictions about the excitation of the states that are actually detected.

Because it was developed to explain activation results, the refined N-CEX model makes predictions that are a sum over all possible bound final states. We modified the model to predict cross sections for excitation of particular residual states either directly, by nuclear charge exchange, or by γ-ray feeding from higher energy states. This modification begins with Eq. (2a) of Ref. 2 which gives the cross section for π^- to remove a neutron as

$$\sigma_n^- = \tfrac{1}{9}\sigma_{(3,3)}[9N_{\text{eff}}(1-P_1^d)+ZP_2^e] ,$$

where N_{eff} is the effective number of neutrons participating in the reaction and Z is the number of protons. P_1^d is the probability for a final state reaction which depletes the desired product nucleus, hence $(1-P_1^d)$ is the probability for no such charge exchange. The second term expresses the possibility that a struck proton may charge exchange (with probability P_2^e), thus producing the desired product nucleus. The factor-of-9 difference between these two terms results from the isospin dependence of the free π-N cross sections for π^- on neutrons and protons, respectively.

Similar equations are written for the cross sections of all possible reactions: σ_n^-, σ_n^+, σ_p^-, σ_p^+, σ_{up}, and σ_{down}. The authors of Ref. 2 characterize the last two reactions as "knight's moves on the Chart of Nuclides chessboard": $(Z,N)\rightarrow(Z+1,\ N-2)$ and $(Z,N)\rightarrow(Z-2,N+1)$, respectively.

The P_1^d and P_2^e terms are defined by setting

$$P_1^d = f_1^d P \ ,$$

$$P_2^e = f_2^2 P \ ,$$

where P is the probability of a nucleon charge exchange; f_1^d and f_2^e are written as sums of spectroscopic factors under the assumption of analog dominance of the nucleon charge exchange. N_{eff} (and Z_{eff}) are also written as sums of spectroscopic factors.

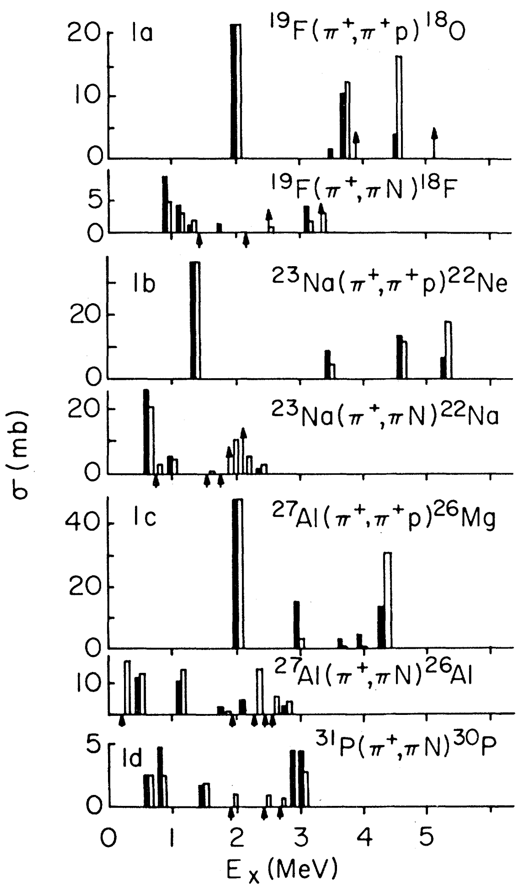

FIG. 1. Histograms comparing the experimental cross sections (dark bars) with the predictions of the refined N-CEX model (open bars), with $P=0.25$, for (a) $\pi^+ + ^{19}$F, (b) $\pi^+ + ^{23}$Na, (c) $\pi^+ + ^{27}$Al, and (d) $\pi^+ + ^{31}$P. Arrows indicate states that were not detected experimentally: Below-axis arrows indicate states that could not be detected because of experimental difficulties, and above-axis arrows are upper limits. The model predictions are normalized to the first excited state of the $(Z-1)$ residual nucleus for each target except for the ^{31}P target which uses the first excited states of ^{30}P.

These spectroscopic factor sums derive from the fact that the refined N-CEX model was developed to explain activation experiments, which detect the sum of all bound states. Since we wish to modify the theory to account for γ-ray spectra, these sums are not completed. Instead each term in the sum becomes the predicted strength for excitation of its respective state, either directly or by nucleon charge exchange. We then use the known γ-decay schemes to compute the feeding of lower states. The result of this calculation is a predicted relative cross section σ_{tot} for every bound state that includes direct excitation, outgoing nucleon charge exchange, and γ-ray feeding from all higher states.

The results of these calculations are compared with the experimental results in two ways: as

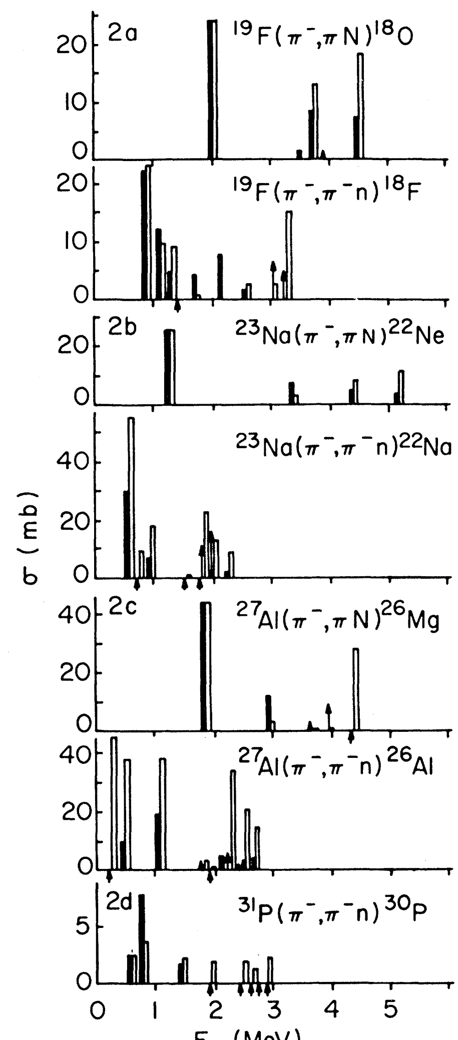

FIG. 2. Same histograms as Fig. 1, for the corresponding π^- induced reactions.

$$\frac{\sigma_{\rm tot}^-}{\sigma_{\rm tot}^+}$$

ratios in Table I and as histograms in Figs. 1 and 2. Since there is no absolute normalization in the theory, the cross sections for the histograms are normalized to the first excited state of the $Z-1$ residual nucleus, except for the ^{31}P target where the $N-1$ nucleus first excited state was used because the $Z-1$ nucleus was not detected. No such normalization is required for the

$$\frac{\sigma_{\rm tot}^-}{\sigma_{\rm tot}^+}$$

ratios.

The comparison with theory is presented in two ways because of limitations in the theory and in the experiments. The theory unambiguously predicts

$$\frac{\sigma_{\rm tot}^-}{\sigma_{\rm tot}^+}$$

ratios, but the experimental values of these ratios suffer from the large uncertainty in the absolute normalization. Since the relative errors in the experimental ratios are smaller, we looked for a common factor for each spectrum which would bring the experimental ratios into agreement with theory. The fact that such factors do not exist suggests that the disagreement between theory and experiments is not due to absolute normalization problems.

The histograms emphasize the selectivity of the reaction for certain final states and take advantage of the low relative uncertainty in data from the same spectrum. However, such a comparison introduces uncertainties associated with differences in the relative fragility of the two nonmirror residual nuclei that are not included in the theory. (The concept of relative fragility was introduced by Sternheim and Silbar[13] to express the fact that odd Z-odd N residual nuclei are much less stable than even Z-even N residual nuclei.)

The arrows in Figs. 1 and 2 indicate states that were not detected experimentally. Arrows above the axis represent upper limits, and arrows below the axis indicate states that could not be detected because of experimental difficulties. With a few exceptions that will be noted later, these below-axis arrows probably indicate states that are not strongly excited in our experiments.

The theoretical results presented in Table I and Figs. 1 and 2 assume $P=0.25$ and analog dominance of the charge exchange cross sections. We used the theoretical spectroscopic factors of McGrory and Wildenthal[14] for ^{19}F and experimental spectroscopic factors[12] for ^{23}Na, ^{27}Al, and ^{31}P. It is likely that the spectroscopic factors have an uncertainty of up to 25%.

In several additional calculations (not presented) we attempted to improve the agreement between theory and experiment by varying the P parameter from 0 to 1. In order to test the assumption of analog dominance of the charge exchange cross sections, we also modified the N-CEX model by distributing the charge exchange strength equally among all states. These changes resulted in improvements for individual spectra, but no single set of conditions improved all of the spectra.

IV. DISCUSSION

We will now consider the experimental and theoretical results for each target. The interpretation of the $\pi^\pm + {}^{14}N$ results is unambiguous because there are only three bound excited states in the residual nucleus ^{13}C and none in its mirror nucleus ^{13}N. Cohen and Kurath[15] have calculated that the spectroscopic factor of the $\frac{3}{2}^-$, second excited state at 3.684 MeV in ^{13}C should be $\sim$25% of the spectroscopic factor for the $\frac{1}{2}^-$ ground state. The other two excited states of ^{13}C have positive parity; their spectroscopic strength is unknown, but probably small.

The largest measured cross section is for the $\frac{3}{2}^-$ second excited state. The only other state observed was the $\frac{5}{2}^+$ third excited state, which accounts for 17% of the total π^+ cross section and 40% of the total π^- cross section. These percentages are larger than would be expected from the expected relative spectroscopic strength of the two states.

Since a spectroscopic factor was available for only one of the two observed states, a comparison with theory is made only for the cross section ratio for this state (Table I). The agreement is reasonably good.

In an activation study[16] of the $^{14}N(\pi^\pm,\pi N)^{13}N$ reaction, cross sections of 15 mb for π^- and 9 mb for π^+ were measured for production of the $\frac{1}{2}^-$ ground state of ^{13}N (the only bound state of ^{13}N) at the present energies. The ratio σ^-/σ^+ for production of the ground state of ^{13}N is thus ~ 1.7. This ratio is, within error limits, reciprocal to the value of the ratio for production of all states of ^{13}C measured by us, and the relative size of the cross sections is in agreement with the spectroscopic factors. We have observed a similar reciprocity of $(\pi,\pi N)$ cross section ratios in earlier experiments on all even-even targets that can be studied by this method: ^{12}C, ^{16}O, ^{24}Mg, ^{32}S, and ^{40}Ca.[17,18] The residual nuclei formed in the $(\pi,\pi N)$ reactions on these targets are also mirror nuclei.

Despite the complexity of the mass 18 level schemes, the refined N-CEX model is successful in reproducing the $\pi^{\pm}+^{19}F$ results [Figs. 1(a) and 2(a)]. It should be noted that the cross sections for both ^{18}O and ^{18}F are normalized to the first excited state of ^{18}O for π^+ and π^-. For ^{18}O the agreement is good except that the calculated value for the fifth excited state is considerably higher than the experimental one.

The model reproduces successfully both the absolute magnitude of the ^{18}F cross sections and the selectivity of the states produced. The only disagreement is in the π^- predictions, in which the fifth and sixth excited states are too low and the sixth excited state is too high.

In an activation study of the $^{19}F(\pi^{\pm},\pi N)^{18}F$ reaction by Jacob and Markowitz,[16] cross sections of 47 mb were measured for π^- and 28 mb for π^+ at the present energies. The summed cross sections in the present results represent 90% and 50%, respectively, of these activation results which sum over all bound states. The ratio of the present cross sections for the first excited state of ^{18}F to the total ^{18}F cross section (from the activation experiment) is in good agreement with the predictions of the refined N-CEX model for both π^- and π^+.

For the $\pi^{\pm}+^{23}Na$ reactions, there is reasonably good agreement between the experimental and calculated results for incident π^+ [Fig. 1(b)]. In the case of incident π^- [Fig. 2(b)], the agreement is also good for ^{22}Ne, but for ^{22}Na, the calculated results are a factor of ~ 2 higher than the experimental results. For both incident π^+ and π^-, there are several states just below 2 MeV in ^{22}Na with considerable theoretical strength that were not detected, but the experimental upper limits are comparable in size.

The agreement between the experimental and calculated $\pi^+ + ^{27}Al$ cross sections [Fig. 1(c)] is good. In these results there are several exceptions to the earlier statement that the cross sections for states that could not be detected are probably small. In particular, the lifetime of the first excited state of ^{26}Al is too long for the state to be seen in our experiment, and the seventh excited state was overlapped by the second excited state of ^{27}Al. Hence, the prediction of large cross sections for these nondetected states should not be treated as evidence against the model.

For $\pi^- + ^{27}Al$ [Fig. 2(c)], the refined N-CEX model does well in reproducing the measured ^{26}Mg cross sections and the relative strengths of the ^{26}Al cross sections, but the calculated values for ^{26}Al are a factor of ~ 2.5 too high. This behavior is quite similar to that which was observed for the ^{23}Na target.

For $\pi^{\pm}+^{31}P$, there are no detected proton removal states (the first and second excited states of ^{30}Si are overlapped by other peaks in our spectra, and we did not observe the third and fourth excited states). Hence the calculated results in Figs. 1(d) and 2(d) are normalized to the first excited state of ^{30}P. The agreement with the experimental results is reasonably good but not very conclusive because of the limited number of states involved.

An activation study of the $^{31}P(\pi^-,\pi^- n)^{30}P$ reaction resulted in a cross section of ~ 45 mb at the present energy.[19] The sum of the present $^{31}P(\pi^-,\pi^- n)^{30}P$ cross sections is $\sim 25\%$ of this value. This small percentage can be understood, because the theoretical calculation resulted in considerable strength for higher energy states that do not feed the first few excited states which were detected in the present results.

V. SUMMARY

From an examination of our data, it is evident that the reaction mechanism selects only certain final states and produces considerable variation in the cross sections and cross section ratios for these states. An examination of the decay schemes of the residual nuclei indicates that these cross section results could not be produced by a mechanism in which the lower excited states are fed by γ decay from statistically populated levels.

The refined N-CEX model is generally successful in reproducing the states selected by the reaction mechanism. In particular, a number of states that were predicted to have a low cross section by the model were, in fact, not detected in the present results.

The refined N-CEX model is also reasonably successful in reproducing the relative size of the cross sections. In evaluating this result, one should consider not only the experimental uncertainties but also the uncertainties in the spectroscopic factors, which may be as high as 25%.

For two of the targets (^{23}Na and ^{27}Al), the theoretical predictions for π^- induced neutron removal were a factor of ~ 2 high. (The normalization technique guarantees good agreement for proton removal.) Since the model does not include corrections for differences in the relative fragility[13] of the two nonmirror residual nuclei, this discrepancy is not unexpected.

There is considerable variation in the experimental

$$\frac{\sigma_{\rm tot}^{-}}{\sigma_{\rm tot}^{+}}$$

ratios that is not reproduced by the model. The lack of a common factor (except for the ^{31}P results) that could bring the experimental results into closer agreement with the calculated results suggests that the problem is not due to errors in the absolute normalization of the cross sections.

It should be noted that the predictions of the refined N-CEX model are proportional to spectroscopic factors, so that any model based on a mechanism with a large quasifree component is likely to give similar agreement with the data. Variation of P from $0\rightarrow 1$ and relaxation of the assumption of analog dominance of nucleon charge exchange did not result in significant changes in the model predictions.

The observed general agreement between our experimental cross sections and the corresponding spectroscopic factors is indicative of a large quasifree component in the reaction mechanism. Similar results have been obtained in previous $(\pi,\pi N\gamma)$ experiments on self-conjugate target nuclei.[17,18]

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