$(\pi,\pi N)$ reactions on ^{25}Mg and ^{197}Au

S. B. Kaufman and E. P. Steinberg
Chemistry Division, Argonne National Laboratory, Argonne, Illinois 60439

G. W. Butler
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87544
(Received 25 September 1978)

Activation cross sections have been measured for the reactions ^{25}Mg$(\pi^{\pm},\pi^{\pm}N)^{24}$Na and ^{197}Au$(\pi^{\pm},\pi^{\pm}N)^{196}$Au between 100 and 300 MeV. The cross section ratios $R_p = \sigma(\pi^+)/\sigma(\pi^-)$ and $R_n = \sigma(\pi^-)/\sigma(\pi^+)$ are smaller than the corresponding free-particle ratios in all cases. Comparisons with the predictions of intranuclear cascade calculations and the nucleon charge-exchange model indicate that the former gives good agreement for a heavy nucleus but not for light nuclei, while the inverse is true for the latter model.

[NUCLEAR REACTIONS ^{25}Mg$(\pi^{\pm}, \pi^{\pm}N)$ ^{24}Na, ^{197}Au$(\pi^{\pm}, \pi^{\pm}N)$ ^{196}Au, E=100–300 MeV; measured σ (activation). Compared with intranuclear cascade calculation, nucleon charge-exchange model.]

I. INTRODUCTION

There has been considerable interest in the $(\pi,\pi N)$ reactions in the (3,3) resonance region because they provide a unique probe of the nuclear surface and insight into the pion-nucleon interaction in the nuclear environment. In particular, deviations from the expectations of the impulse approximation have been observed in the cross section ratio

$$R_n = \sigma(\pi^-, \pi^- n)/[\sigma(\pi^+, \pi^+ n) + \sigma(\pi^+, \pi^0 p)].$$

Both activation[1–4] and prompt γ-ray measurements[5–9] give a ratio which is considerably reduced from the free-particle ratio ($R_n = 3$) for all targets studied. In the reaction for which the most data are available,[2,3] ^{12}C$(\pi^{\pm},\pi n)^{11}$C, a value of $R_n = 1.55$ was found at an incident pion energy of 180 MeV. Furthermore, the shapes of the excitation functions for the π^+- and π^--induced reactions were quite different, so that R_n varied from 0.5 at 50 MeV to 1.7 at 300 MeV. Similar results were obtained[4] for the analogous reactions with targets of ^{14}N, ^{16}O, and ^{19}F, with $R_n = 1.68$ for all targets near $T_\pi = 180$ MeV.

The activation measurements sum over all particle-stable states of the final nucleus, while the prompt γ-ray measurements detect transitions from individual levels. In the case of even-even nuclei, most particle-stable levels are expected to decay by cascades leading eventually to the first-excited state, so that the yield of γ rays from that state is a good measure of the total yield. This is not true in general for odd-A and odd-odd nuclides, where much of the total yield may not pass through a single strong transition.

Prompt γ-ray measurements of R_n for pion energies near 180 MeV have been made for targets of ^{7}Li,[6,8] ^{13}C,[7,8] ^{58}Ni,[9] and ^{60}Ni,[9] with results in the range $R_n = 1.9$–2.0. The corresponding ratio for single proton removal, R_p, has been measured for only one target, ^{9}Be,[8] with the result of $R_p = 0.85 \pm 0.10$ at 180 MeV. In addition, prompt γ-ray measurements at 70 MeV have been made on a number of targets,[5,10] at which energy the ratios are all less than unity.

The deviations of these ratios from the impulse approximation prediction have aroused much theoretical interest.[11–16] The most successful approach has been the nucleon charge-exchange model of Sternheim and Silbar.[15,16] In this model the final-state charge-exchange interactions of the outgoing nucleon are taken into account, using a semiclassical transport model. It was shown that this can enhance the cross section for neutron emission in a π^+ interaction and deplete that for a π^- interaction, thus lowering the value of R_n. Using this model good agreement with the activation measurements[2,4] on light nuclei was obtained, and also the energy shift of the resonance peak in the ^{12}C reaction was accounted for. The theory could also account for the observed ^{58,60}Ni nucleon removal ratios.[17]

A modification of this model,[16] in which the nucleon charge-exchange process was assumed to proceed predominantly through the isobaric analog state, was later described in detail, and was shown[18] to result in reasonable charge-exchange probabilities when applied to the experimental data[6,8] for ^{7}Li. However, doubts have been cast on the assumption of analog-state dominance by an experiment[7,8] in which R_n was measured for the $^{13}C \rightarrow ^{12}C$ reaction separately for transitions to the 4.44-MeV $T=0$ state and the 15.11-MeV $T=1$ state. Since analog charge exchange is forbidden for the former state and allowed for the latter, one would expect the value of R_n to be close to the free pion-nucleon ratio for the $T=0$ state, and be lowered in the typical way for the $T=1$ state. Instead, very similar ratios were found for both reactions,[8] namely $R_n(T=0)=1.7\pm 0.2$ and $R_n(T=1)=2.0\pm 0.2$ at 180 MeV.

The interactions of pions with nuclei have also been modeled by means of intranuclear cascade (INC) calculations.[19-22] In these models the pion-nucleus interaction is described by sequential two-body scatterings of pions and nucleons inside the nucleus. Free-particle cross sections are used to describe these scatterings, and the nuclear density distribution is approximated by a number of concentric shells of different density. Several comparisons of the results of these calculations with experimental values of R_n and R_p have been made,[4,22] and poor agreement was found.

The previous activation measurements[1-4] have all measured neutron removal from light targets. It is desirable to extend these measurements to heavier targets and to proton removal reactions. In this work we report cross section measurements for proton removal from ^{25}Mg to form ^{24}Na and neutron removal from ^{197}Au to form ^{196}Au, for π^+ and π^- mesons in the energy range 100–300 MeV.

II. EXPERIMENTAL PROCEDURE AND RESULTS

The experiments were performed using the beams of the P^3 channel of the Clinton P. Anderson Meson Physics Facility (LAMPF). The ^{25}Mg targets were 2×2 cm metallic foils, of thickness 24 mg/cm^2, with isotopic composition 91.5% ^{25}Mg, 8.3% ^{24}Mg, and 0.2% ^{26}Mg. In calculating the ^{24}Na production cross section we assumed that ^{24}Na was formed only from the ^{25}Mg present. The production of ^{24}Na from the ^{24}Mg in the target is expected to be small (approximately 1 mb), in analogy with other $(\pi^\pm, \pi^0)$ elastic charge-exchange cross sections.[23] The ^{197}Au targets were 4×4 cm metallic foils, with thickness varying from 48 to 190 mg/cm^2. No effect of target thickness on cross section was observed.

Beam intensities through the targets varied from ~10^7/s (100 MeV π^-) to ~2×10^8/s (300 MeV π^+), and were determined by foil activation, using the $^{27}Al \rightarrow ^{24}Na$ reaction.[24] The monitor foil was the same area as the target foil, was typically 25–50 mg/cm^2 thick, and was separated from the target by Mylar guard foils.

The irradiations varied in length from 2 to 8 h; variations of the pion beam intensity during the irradiation were measured with a plastic scintillator placed near the target and recorded as a function of time. Following each irradiation the monitor and target foils were removed and their radioactive γ rays assayed with calibrated Ge(Li) spectrometers. The 1368.5-keV γ ray of 15.0-h ^{24}Na in both the monitors and the ^{25}Mg targets, and the 355.7-keV γ ray of 6.18-day ^{196}Au in the gold targets were measured. The efficiency of the spectrometers as a function of γ-ray energy was determined with standard sources; corrections for summing of coincident γ rays were made when necessary. The disintegration rates thus determined were corrected for the finite irradiation length and for intensity variations by the usual methods.[25]

The cross sections[24] for the monitor reaction at the pion energies used are given in Table I. These cross sections were measured relative to the $^{12}C \rightarrow ^{11}C$ reaction[2] and are estimated to have uncertainties of 10%. Because the ^{25}Mg and ^{197}Au cross sections are based on the values given in Table I, they should be changed appropriately if in the future different values from those used here are adopted.

The results are given in Table I, which lists the one-nucleon out cross sections for ^{25}Mg and ^{197}Au for incident π^+ and π^- beams at each energy for which they were measured. The ratios R_p

TABLE I. Cross sections in mb for the monitor reaction, $^{27}Al \xrightarrow{\pi^\pm} ^{24}Na$, and for the one-nucleon removal reactions, $^{25}Mg \xrightarrow{\pi^\pm} ^{24}Na$ and $^{197}Au \xrightarrow{\pi^\pm} ^{196}Au$. The latter two sets of cross sections are normalized to the listed values for the ^{27}Al monitor reaction (Ref. 24).

Pion energy	$^{27}Al \rightarrow ^{24}Na$		$^{25}Mg \rightarrow ^{24}Na$			$^{197}Au \rightarrow ^{196}Au$		
(MeV)	$\sigma(\pi^+)$	$\sigma(\pi^-)$	$\sigma(\pi^+)$	$\sigma(\pi^-)$	R_p	$\sigma(\pi^+)$	$\sigma(\pi^-)$	R_n
100	12.3	22.0	35.3	36.0	0.98	68	130	1.91
140	18.5	26.0	63.2	39.4	1.60			
180	21.2	24.0	70.6	40.4	1.75	79	181	2.29
240	18.3	18.3	63.0	31.4	2.01			
300	14.3	15.9	43.1	28.0	1.54	61	107	1.75

$=\sigma(\pi^+)/\sigma(\pi^-)$ and $R_n=\sigma(\pi^-)/\sigma(\pi^+)$ for the reactions $^{25}Mg \rightarrow {}^{24}Na$ and $^{197}Au \rightarrow {}^{196}Au$, respectively, are also given in Table I. The main uncertainty arises from the 10% uncertainty in monitor cross sections, since the errors in count-rate determinations were ~1% and the estimated uncertainty in detector calibration is <3%.

III. DISCUSSION

The results in Table I are shown in Figs. 1 and 2, where they are compared with the theoretical predictions of both the nucleon charge-exchange (N-CEX) model[15,16] and the INC model.[20,21] The experimental cross sections for the reaction $^{25}Mg(\pi^+, \pi^+p)\,^{24}Na$ are shown in Fig. 1(a) as the solid points, and those for the reaction $^{25}Mg[(\pi^-, \pi^-p) + (\pi^-, \pi^0 n)]^{24}Na$ are shown in Fig. 1(b). For comparison, the open points are the theoretical results using the INC model and an evaporation calculation.[26] With the exception of 100 MeV π^+, the calculated cross sections are smaller than the experimental ones, by about a factor of 2 for incident π^-, and by somewhat less for incident π^+.

The ratio R_p is shown in Fig. 1(c) for ^{25}Mg, with the solid points again representing the experimental ratios and the open points the INC calculation. The disagreement between theory and experiment is evident, with the former only approaching the latter at the highest energy measured. The INC calculation is close to the free-particle ratio, shown by the solid curve, while the experimental ratio is consistently smaller.

The dahsed curves in Fig. 1(c) show the predictions of the N-CEX model in its two versions,

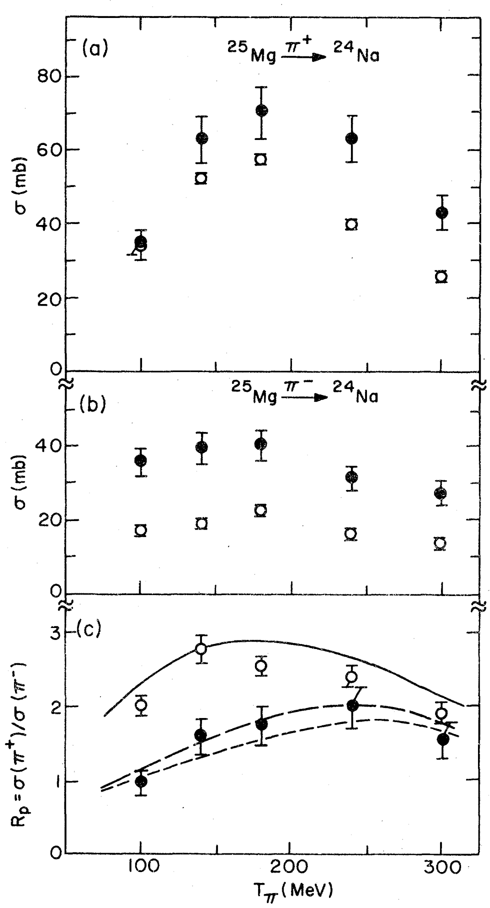

FIG. 1. Cross sections for formation of ^{24}Na by $\pi^\pm$ incident on ^{25}Mg. Solid points: expt.; open points: INC calculation; short-dashed curve: R_p calculated by simple charge-exchange model (Ref. 15); long-dashed curve: analog-dominance model (Ref. 16); solid curve: free-particle ratio.

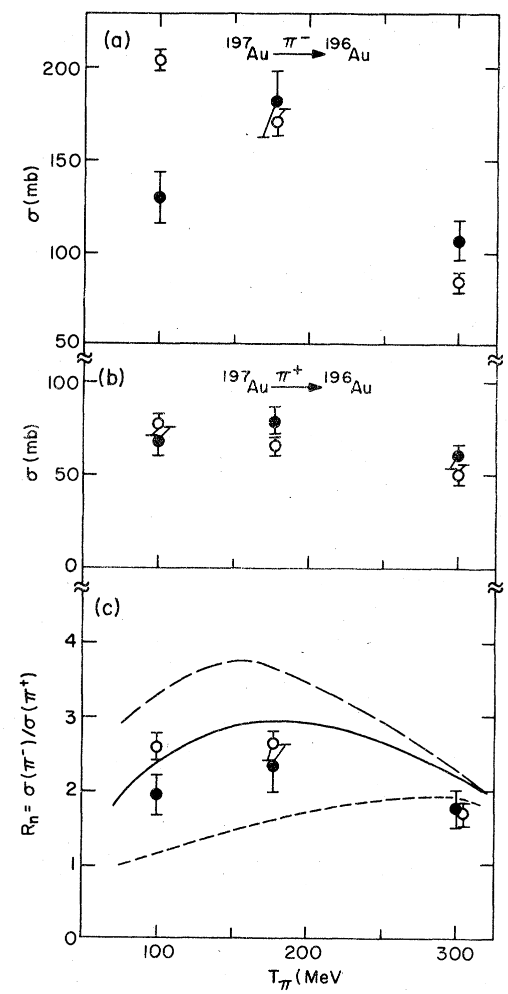

FIG. 2. Cross sections for formation of ^{196}Au by $\pi^\pm$ incident on ^{197}Au. See Fig. 1 caption for significance of symbols and curves.

the original one[15] by the short-dashed curve and the analog-dominance one[16] by the long-dashed curve. There are no free parameters in these calculations; the charge-exchange probability P was calculated at each energy by the scaling method outlined in the Appendix of Ref. 16, scaling from ^{12}C to ^{25}Mg. The two versions of the model yield similar curves, which are both in good agreement with the experimental ratios, the analog-dominance curve being in somewhat better agreement than the other.

The same comparisons are shown for the $^{197}Au \rightarrow {}^{196}Au$ reactions in Fig. 2. Figure 2(a) shows the experimental and INC calculations for the $^{197}Au(\pi^-, \pi^- n)^{196}Au$ cross sections and Fig. 2(b) those for the $^{197}Au[(\pi^+, \pi^+ n) + (\pi^+, \pi^0 p)]^{196}Au$ cross sections. In contrast to ^{25}Mg, the INC calculation is in fairly good agreement with experiment, except for 100 MeV π^-. The ratio R_n is shown in Fig. 2(c), which illustrates the extent of agreement between theory and experiment. Also in Fig. 2(c) are shown the predictions of the N-CEX model in its simple form (short-dashed curve) and analog-dominance form (long-dashed curve), as well as the free-particle ratio (solid curve). The two versions of the model are quite different and neither one agrees well with experiment, except at 300 MeV. At 180 MeV, for example, the simple N-CEX model predicts $R_n = 1.6$, the analog model $R_n = 3.6$, and the experimental value is $R_n = 2.3$.

Thus, there appears to be a contrast in the application of the INC and N-CEX models to these $(\pi, \pi N)$ reactions. The INC model is unsuccessful in predicting both the magnitude of the cross sections and the ratio R_p for ^{25}Mg. A similar failure has been noted[4] for other light nuclei. On the other hand, the INC model results for ^{197}Au are in fairly good agreement with experiment. The situation is reversed for the N-CEX model, which can account for the R_p ratios for ^{25}Mg, but not the R_n ratios for ^{197}Au.

One possible explanation for the failure of the INC model for light nuclei is that the representation of the nuclear surface as a series of steps in density may be inadequate for light nuclei, in which the surface-to-volume ratio is large. Since the simple $(\pi, \pi N)$ reactions are localized mainly in the surface region, the calculation may be sensitive to the details of the model there. One way to test this possibility is to compare calculation with experiment for the analogous reactions with incident protons. This has already been done for the $^{197}Au(p, pn)^{196}Au$ reaction[19] between 100 and 400 MeV, for which satisfactory agreement was found. We have performed the calculation for 200-MeV protons incident on ^{25}Mg, and found a $^{25}Mg(p, 2p)$-^{24}Na cross section of 17.5 mb, in good agreement with experiment.[27] Thus there does not appear to be any problem with the representation of the nuclear surface in the model.

TABLE II. Percent of quasi-free scattering (QFS) as given by INC calculation.

Pion energy (MeV)	^{25}Mg π^+	^{25}Mg π^-	^{197}Au π^+	^{197}Au π^-
100	90	69	40	69
140	98	84		
180	98	89	70	88
240	98	85		
300	97	86	59	76

The failure of the N-CEX model for ^{197}Au may be due to the possibility that reaction mechanisms other than quasi-free scattering (QFS) contribute, especially at the lower energies. The N-CEX model assumes that the only mechanism for the single-nucleon removal reactions is QFS, with final state interactions (nucleon charge exchange). There is another possible mechanism, namely pion inelastic scattering which leaves the nucleus in an excited state from which nucleon evaporation occurs. The INC calculation provides estimates of the proportion of these two processes, and the results are given in Table II, as percent of QFS reaction. Except for 100 MeV π^- the QFS mechanism dominates for ^{25}Mg, because proton evaporation is unlikely and thus only the charge exchange (π^-, π^0) followed by neutron evaporation contributes appreciably. For ^{197}Au, however, neutron evaporation is important at all energies, especially for incident π^+.

The few cases so far investigated do not warrant any broad generalizations at this time, but an interesting dichotomy seems apparent. In spite of its simplicity the N-CEX model is surprisingly successful in accounting for the results with light nuclei. It is unsuccessful, however, in the case of a heavy nucleus. On the other hand, the INC calculation is quite successful for a heavy nucleus but not for light nuclei. The present data on these reactions confirm the general reduction of cross section ratios below that expected from free-particle properties.

We wish to thank D. G. Perry for his assistance in the early phase of these experiments and J. N. Ginocchio for supplying the FORTRAN program for the most recent version of the INC calculation. The hospitality of B. Dropesky and the LAMPF Nuclear Chemistry Group is gratefully acknowledged. This research was supported by the Division of Nuclear Physics of the U. S. Department of Energy.

[1]D. T. Chivers, E. M. Rimmer, B. W. Allardyce, R. C. Witcomb, J. J. Domingo, and N. W. Tanner, Nucl. Phys. A126, 129 (1969).
[2]B. J. Dropesky, G. W. Butler, C. J. Orth, R. A. Williams, G. Friedlander, M. A. Yates, and S. B. Kaufman, Phys. Rev. Lett. 34, 821 (1975).
[3]L. H. Batist, V. D. Vitman, V. P. Koptev, M. M. Makarov, A. A. Naberezhnov, V. V. Nelyubin, G. Z. Obrant, V. V. Sarantsev, and G. V. Scherbakov, Nucl. Phys. A254, 480 (1975).
[4]N. P. Jacob and S. S. Markowitz, Phys. Rev. C 13, 754 (1976).
[5]D. Ashery, M. Zaider, Y. Shamai, S. Cochavi, M. A. Moinester, A. I. Yavin, and J. Alster, Phys. Rev. Lett. 32, 943 (1974).
[6]J. E. Bolger, W. J. Braithwaite, J. J. Kraushaar, J. McGill, C. F. Moore, C. L. Morris, R. J. Peterson, R. A. Ristinen, G. Smith, L. E. Smith, H. A. Thiessen, and J. Whitenton, Phys. Rev. Lett. 37, 1206 (1976).
[7]C. L. Morris, H. A. Thiessen, W. J. Braithwaite, C. F. Moore, J. E. Bolger, L. E. Smith, R. J. Peterson, R. L. Boudrie, J. J. Kraushaar, R. A. Ristinen, and G. R. Smith, Phys. Rev. Lett. 39, 1455 (1977).
[8]C. L. Morris, R. L. Boudrie, J. J. Kraushaar, R. J. Peterson, R. A. Ristinen, G. R. Smith, J. E. Bolger, W. J. Braithwaite, C. F. Moore, and L. E. Smith, Phys. Rev. C 17, 227 (1978).
[9]H. E. Jackson, D. G. Kovar, L. Meyer-Schützmeister, R. E. Segel, J. P. Schiffer, S. Vigdor, T. P. Wangler, R. L. Burman, D. M. Drake, P. A. M. Gram, R. P. Redwine, V. G. Lind, E. N. Hatch, O. H. Otteson, R. E. McAdams, B. C. Cook, and R. B. Clark, Phys. Rev. Lett. 35, 641 (1975).
[10]M. Zaider, D. Ashery, S. Cochavi, S. Gilad, M. A. Moinester, Y. Shamai, and A. I. Yavin, Phys. Rev. C 16, 2313 (1977).
[11]P. W. Hewson, Nucl. Phys. A133, 659 (1969).
[12]D. Robson, Ann. Phys. (N.Y.) 71, 277 (1972).
[13]R. Seki, Nuovo Cimento 9A, 235 (1972).
[14]V. M. Kolybasov, Phys. Lett. 27B, 3 (1968); V. M. Kolybasov and N. Ya. Smorodinskaya, *ibid.* 30B, 11 (1969).
[15]M. M. Sternheim and R. R. Silbar, Phys. Rev. Lett. 34, 824 (1975).
[16]R. R. Silbar, J. N. Ginocchio, and M. M. Sternheim, Phys. Rev. C 15, 371 (1977).
[17]J. E. Monahan and F. J. D. Serduke, Phys. Rev. Lett. 36, 224 (1976).
[18]R. R. Silbar, Phys. Rev. C 15, 1158 (1977).
[19]K. Chen, Z. Fraenkel, G. Friedlander, J. R. Grover, J. M. Miller, and Y. Shimamoto, Phys. Rev. 166, 949 (1968).
[20]G. D. Harp, Phys. Rev. C 10, 2387 (1974).
[21]J. N. Ginocchio, Phys. Rev. C 17, 195 (1978).
[22]H. W. Bertini, Phys. Rev. C 6, 631 (1972).
[23]Y. Shamai, J. Alster, D. Ashery, S. Cochavi, M. A. Moinester, A. I. Yavin, E. D. Arthur, and D. M. Drake, Phys. Rev. Lett. 36, 82 (1976).
[24]R. A. Williams, C. J. Orth, G. W. Butler, G. C. Giesler, M. A. Yates-Williams, and B. J. Dropesky (unpublished).
[25]G. Friedlander, J. W. Kennedy, and J. M. Miller, *Nuclear and Radiochemistry* (Wiley, New York, 1964), p. 78.
[26]I. Dostrovsky, Z. Fraenkel, and G. Friedlander, Phys. Rev. 116, 1683 (1959).
[27]P. L. Reeder, Phys. Rev. 178, 1795 (1969).