(π,πN) reactions in ^{48}Ca

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Excitation functions for the formation of ^{47}Ca and ^{47}K from ^{48}Ca with 100-, 180-, and 300-MeV $\pi^{\pm}$ have been determined by activation methods. The contributions of both quasifree and nonquasifree processes are observed in the excitation functions. Unlike (π,πN) reactions on ^{12}C, final-state nucleon charge exchange is found to play only a minor role in ^{48}Ca. This decreasing importance of nucleon charge exchange with increasing nuclear mass is explained by a newly-developed (π,πN) theory. In order to establish the magnitude of nucleon charge exchange in medium-mass nuclei, we have measured the cross section for the reaction ^{45}Sc(π^-,πN)^{44}K at 180 MeV. An upper limit of 0.25 mb has been determined.

I. INTRODUCTION

Pion-induced single nucleon removal reactions have been extensively studied at the Clinton P. Anderson Meson Physics Facility (LAMPF) and other meson facilities. First experimental evidence indicating the presence of important reaction processes other than quasifree knockout was obtained in radiochemical measurements of ratios of the integrated (π^-,πN) to (π^+,πN) cross sections for residual nuclear products. For example, the value of the ratio

$$R_n=\sigma[^{12}\mathrm{C}(\pi^-,\pi^-\mathrm{n})^{11}\mathrm{C}]/\sigma[^{12}\mathrm{C}(\pi^+,\pi\mathrm{N})^{11}\mathrm{C}]$$

at 180 MeV is 1.59±0.07 (Refs. 1 and 2), which is much lower than the plane wave impulse approximation (PWIA) ratio of 2.9 (Ref. 3) and the distorted wave impulse approximation (DWIA) ratio of 2.5 (Ref. 4) obtained in the framework of the quasifree scattering mechanism.

To account for the discrepancy between the measured ratio and the PWIA ratio for the ^{12}C($\pi^{\pm},\pi$N)^{11}C reactions, Hewson[5] included final-state nucleon charge exchange (NCX): $\pi^{\pm}+{}^{12}\mathrm{C}\rightarrow\pi^{\pm}+({}^{11}\mathrm{B}+\mathrm{p})\rightarrow\pi^{\pm}+{}^{11}\mathrm{C}+\mathrm{n}$. If we use a, b, and c to denote, respectively, the amplitudes for the processes ${}^{11}\mathrm{C}+\mathrm{n}\rightarrow{}^{11}\mathrm{C}+\mathrm{n}$, ${}^{11}\mathrm{B}+\mathrm{p}\rightarrow{}^{11}\mathrm{C}+\mathrm{n}$, and ${}^{11}\mathrm{C}+\mathrm{p}\rightarrow{}^{11}\mathrm{C}+\mathrm{p}$, then the cross-section ratio can be expressed as

$$R_n=\frac{9|a|^2+3\times 2\,\mathrm{Re}(a^*b)+|b|^2}{|a|^2+3\times 2\,\mathrm{Re}(a^*b)+9|b|^2+2|c|^2}=\frac{|3a+b|^2}{|a+3b|^2+|\sqrt{2}c|^2}\,.$$

Here, the symbols Re and * stand for the real part and complex conjugate. The factors in the last expression for R_n are due to the isospin ratio of free πN scattering amplitudes. If we do not take into account NCX (i.e., $b=0$) and assume the distortions for the outgoing proton and neutron are the same (i.e., $a=c$), then R_n equals 3, which is the PWIA ratio for the $J=\frac{3}{2}$ and $I=\frac{3}{2}$ channel. The quantities $|b|^2$ and Re(a^*b) represent pure NCX and quantum mechanical (QM) interference between the quasifree scattering and NCX processes, respectively. From his calculation, Hewson concluded that the inclusion of NCX was important at 180 MeV: about 5% of the quasifree scattering contribution for ^{12}C(π^-,π^-n)^{11}C and about 50% for ^{12}C(π^+,πN)^{11}C. However, Hewson used only the p_{33} πN interaction. Furthermore, distortions for the incident and outgoing pion waves were not included in his calculation. Therefore, neither the absolute magnitude nor the energy dependence of the cross sections for the ^{12}C(π^-,π^-n)^{11}C and ^{12}C(π^+,πN)^{11}C reactions could be calculated. Several researchers[6–8] have since proposed other NCX models in which the quantum mechanical interference term is not present, but an adjustable parameter is introduced to simulate NCX contributions. The quantitative conclusions concerning NCX, drawn from these latter analyses, are therefore incorrect[4] (see also Sec. III).

Recently, Ohkubo and Liu[4] have developed a microscopic theory which extends the conventional distorted-wave theory of single nucleon removal to treat simultaneously quasifree knockout, NCX, final-state pion charge exchange, and the interference effects among all these processes. They have calculated the cross sections and ratio (R_n) for the ^{12}C($\pi^{\pm},\pi$N)^{11}C reactions across the (3,3) resonance region and have found that both pure NCX and the quantum mechanical interference between quasifree scattering and NCX contribute significantly to the ^{12}C($\pi^{\pm},\pi$N)^{11}C reactions.

The present work was intended to investigate the nature of nonquasifree mechanisms in a medium-mass nucleus and to determine the relative importance of the NCX contribution to single nucleon removal reactions. We chose ^{48}Ca because of the large difference in the neutron- and proton-separation energies. Therefore, by measuring the excitation functions of both single-neutron and single-proton removal and by using the Ohkubo-Liu formalism to evaluate the NCX contributions, we can extract information about the importance of processes sensitive to separation energies. Results and discussion are presented in Sec. III.

We have also measured the cross section for the ^{45}Sc(π^-,πN)^{44}K reaction at 180 MeV to test the Ohkubo-Liu formalism. This reaction cannot proceed

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through a one-step quasifree mechanism, but proceeds through two-step processes. As discussed in Sec. III, the dominant two-step process is NCX. Consequently, with the absence of large one-step quasifree contributions, a comparison between data and theoretical prediction should provide a stringent test of the reliability of the theory in calculating quantitatively the NCX contributions.

II. EXPERIMENTAL

The irradiations were performed in the P^3 and low energy pion (LEP) channels of the Clinton P. Anderson Meson Physics Facility (LAMPF) with 100-, 180-, and 300-MeV π^+ and π^-. The pion channels were tuned for a momentum bite of $\pm 4\%$. Cross sections for the residual products from single neutron and proton removal reactions were measured by activation methods.

The targets were 101-mg/cm^2 thick, 95% enriched ^{48}Ca metal foils. They were irradiated in Ar-filled aluminum containers with a 0.12-mm thick Kapton entrance window and a 0.25-mm thick aluminum exit window. The pion beam intensity was monitored with 34-mg/cm^2 thick aluminum foils using the ^{27}Al(π,X)^{24}Na monitor reactions,[9] and in some cases also with 230-mg/cm^2 thick silicon disks using the Si(π,X)^{24}Na monitor reactions.[9] The fluctuations in pion beam intensity during irradiation were monitored with a plastic scintillation counter located near the target, and appropriate corrections were made for beam-off periods. To measure the short-lived proton-out product (17.6-s ^{47}K), a 0.9-m long pneumatic piston assembly was used to transport the target back and forth between the pion beam and a shielded γ-ray counter.

The ^{48}Ca and monitor foils were assayed separately with Ge(Li) γ-ray spectrometers. The 4.54-d ^{47}Ca n-out product was identified in the spectra by means of its half-life and deexcitation γ ray at 1297 keV (77%) (Ref. 10), and the 17.6-s ^{47}K p-out product was identified by its half-life and characteristic γ rays at 586 keV (85%) and 2013 keV (100%) (Ref. 10). The γ-ray spectra were analyzed by means of the GAMANAL (Ref. 11) code, with the end-of-bombardment activities determined through use of the code CLSQ.[12] From similar single nucleon removal measurements[1,13] on lighter and heavier mass targets, we conclude that the contribution of secondary reactions to either the ^{48}Ca(π,πN) or the monitor reaction cross sections is less than a few percent.

A thick (750 mg/cm^2)^{45}Sc metal foil was irradiated with 180-MeV π^- to study NCX in the ^{45}Sc(π^-,π^0n$\rightarrow$p)^{44}K reaction. The disintegration rate of ^{44}K was determined from the ^{44}K half-life (22.2 min) and the intensity of the characteristic γ ray at 1157 keV (100%) (Ref. 10). In this measurement, the pion beam intensity was determined by activation of a Pilot B plastic scintillator and the reported cross section for the ^{12}C(π^-,π^-n)^{11}C reaction.[1]

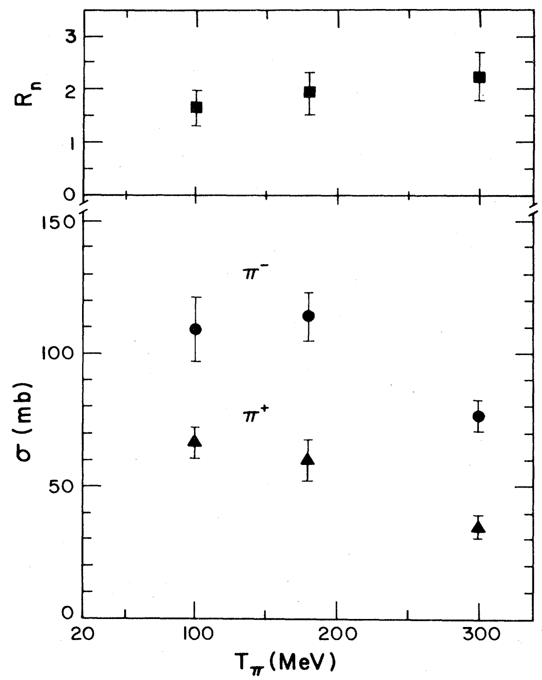

FIG. 1. Excitation functions and cross-section ratios $R_n = \sigma(\pi^-)/\sigma(\pi^+)$ for ^{48}Ca($\pi^\pm$,πN)^{47}Ca. Circles, triangles, and squares represent, respectively, the measured cross sections for π^-, π^+, and their ratios.

III. RESULTS AND DISCUSSION

The results of these measurements are presented in Table I. The uncertainty given for each cross section represents the statistical counting errors for the ^{48}Ca target and the monitor plus the uncertainty in the monitor cross section.[9] From duplicate runs, the systematic errors were estimated to be about $\pm 5\%$, which were not included in the quoted uncertainty. Figures 1 and 2 show the measured excitation functions for the ^{48}Ca($\pi^\pm$,πN)^{47}Ca and ^{48}Ca($\pi^\pm$,πN)^{47}K reactions, respectively. An apparent feature of the results is that the ^{48}Ca(π^+,π^+p)^{47}K excitation function (▲ in Fig. 2) shows a clear maximum in the (3,3) resonance region, while the other excitation functions do not exhibit this resonance structure. The absence of clear resonance structure in the latter three excitation

TABLE I. Cross sections (mb) for single nucleon removal from ^{48}Ca.

Energy (MeV)	^{48}Ca(π,πN)^{47}Ca π^-	^{48}Ca(π,πN)^{47}Ca π^+	^{48}Ca(π,πN)^{47}K π^-	^{48}Ca(π,πN)^{47}K π^+	^{45}Sc(π,πN)^{44}K π^-
100	109 ±12	66.6±6.1	23.6±2.3	12.8±1.5	
180	114 ± 9	59.7±7.7	19.8±1.1	33.7±1.7	<0.25
300	76.7± 5.9	34.7±4.4	12.7±1.1	21.4±1.5	

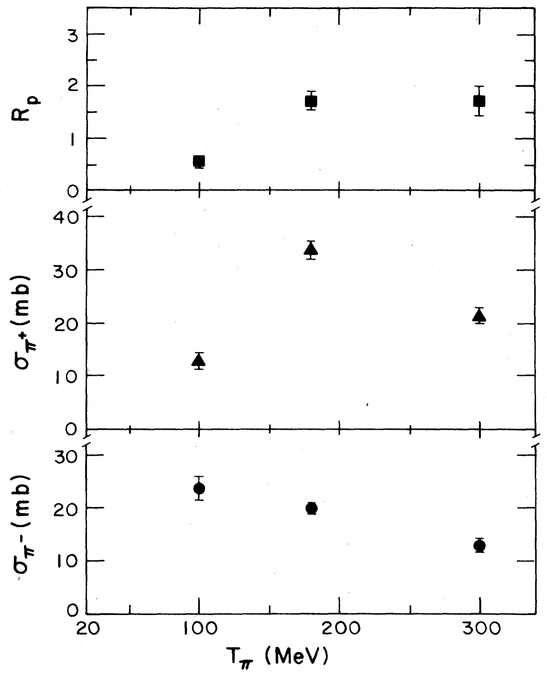

FIG. 2. Excitation functions and cross-section ratios $R_p=\sigma(\pi^+)/\sigma(\pi^-)$ for $^{48}Ca(\pi^{\pm},\pi N)^{47}K$. Symbols have the same meaning as for Fig. 1.

functions led us to examine in detail nonquasifree knockout processes.

We have calculated the contribution of pion absorption to single nucleon removal by applying the principle of detailed balance to the published data[14] on the $^{48}Ca(p,\pi^-)$ reaction to low-lying 2p-1h states. We found that the corresponding cross sections are at most 100 μb. Consequently, this process will not be discussed further.

The competition between the quasifree and NCX mechanisms was calculated with the formalism of Ref. 4. In these calculations, we included the distortions of the pions and the outgoing nucleon. The nucleon-nucleus charge-exchange potential V_{NCX} was taken to be the isovector part, $(\mathbf{t}\cdot\mathbf{T})/A$, of the nucleon-nucleus optical potential of Becchetti and Greenlees.[15] Our calculations show that the NCX contributions are strongest at resonance energies. However, as a whole, NCX contribution to single nucleon removal in ^{48}Ca is small. We have found for the $^{48}Ca(\pi^-,\pi^- n)^{47}Ca$ and $^{48}Ca(\pi^+,\pi N)^{47}Ca$ reactions at $T_\pi=180$ MeV that the combined contributions from pure NCX and QM interference are only 3.4 and 2.2 mb, respectively, about 3% and 6% of the total single nucleon removal cross section. We conclude, therefore, that NCX cannot account for the nonquasifree feature of the observed excitation functions.

The cross section ratios $R_n\equiv\sigma(\pi^-)/\sigma(\pi^+)$ for $^{48}Ca(\pi^{\pm},\pi N)^{47}Ca$, and $R_p\equiv\sigma(\pi^+)/\sigma(\pi^-)$ for $^{48}Ca(\pi^{\pm},\pi N)^{47}K$, obtained in our nuclear chemistry experiments, cannot be accounted for by the recently proposed delta-induced nonquasifree knockout mechanism.[16] This is because the mechanism will lead to values for R_n and R_p much greater than the free π^-n/π^+n and π^+p/π^-p ratios, respectively. Our measured ratios (Figs. 1 and 2) indicate otherwise. We believe that this apparent disagreement is due to the fact that the coincidence experiment of Ref. 16 addressed the ground-state reaction in which only the least bound nucleon was removed, leaving the residual nucleus in its ground state. In our experiments we did not measure the outgoing pion and nucleon, but instead we measured the angle-integrated cross sections for the formation of the residual nucleus. Therefore, inelastic pion scattering followed by evaporation can be a predominant contributor to our measurements, making the contributions from the ground-state reaction insignificant.

It remains for us to examine in detail the evaporation process whose contributions to activation measurements of a residual product are known to be generally important. In the evaporation process the nucleon separation energies and Coulomb barrier play an important role. The separation energies[17] of the least-bound neutron and proton in ^{48}Ca are 10 and 16 MeV, respectively. The Coulomb barrier for a proton is about 6 MeV and, therefore, the minimum energy required to evaporate a proton is about 22 MeV, which is higher than the separation energy of the least-bound two neutrons (17 MeV). Consequently, neutron evaporation contributes to single nucleon removal in ^{48}Ca, whereas proton evaporation is less probable. The lack of a significant contribution from evaporation in the $^{48}Ca(\pi^+,\pi N)^{47}K$ reaction is thus responsible for the observation of clear resonance structure in its excitation function. For incident π^- the resonance structure in the excitation function for ^{47}K is largely hidden by the following inelastic scattering-evaporation process: the incident π^- charge exchanges to produce π^0 and $^{48}K^*$, and this excited nucleus evaporates one neutron $[S(n)=5$ MeV] to become ^{47}K. We thus conclude that the observed nonquasifree feature of the excitation functions is consistent with the characteristics of evaporation processes.

A comment on the relative importance of NCX, evaporation, and quasifree knockout in different nuclei is in order. The calculations of Ref. 4 show that for the $^{12}C(\pi^-,\pi^- n)^{11}C$ and $^{12}C(\pi^+,\pi N)^{11}C$ reactions at $T_\pi=180$ MeV, the contribution of the QM interference term amounts to 8.4 and 4.3 mb, respectively, whereas for the $^{48}Ca(\pi^-,\pi^- n)^{47}Ca$ and $^{48}Ca(\pi^+,\pi N)^{47}Ca$ reactions at the same energy, the QM interference term contributes only 3.3 and 1.4 mb. In order to understand the reduction of about a factor of 3 in the magnitude of this QM interference term with increasing nuclear mass, we note that the A^{-1} dependence of the V_{NCX} predicts a reduction of the QM interference contribution by a factor of 4 from $A=12$ to 48. This simple factor is, however, modified by two other competing factors. First, there are more isobaric NCX possibilities in ^{48}Ca than in ^{12}C. This would increase NCX contributions in ^{48}Ca. But the pion and nucleon distortions associated with the removal of inner shell nucleons are stronger. Thus, the effective NCX contributions are much smaller than what one would expect from a simple counting of the number of transitions available. These two competing factors, when combined with the A^{-1} dependence, lead to an actual reduction in the importance in QM interference contributions by a factor of only 3. We note that for the pure NCX, the reduction is even greater, because the cross section due to pure NCX is proportional to $|V_{\rm NCX}|^2$ or A^{-2}. We conclude from the general A^{-1} dependence of NCX that the contribution of NCX to single nucleon removal reactions is small ($\lesssim 1\%$) for heavy nuclei such as ^{127}I and ^{197}Au, lending support to the earlier statement of Ohkubo and Porile.[8,13] In brief, not only does the general A dependence make NCX more important in ^{12}C, but also evaporation is suppressed because of large separation energies. Therefore, NCX is the dominant nonquasifree process in ^{12}C but not in ^{48}Ca.

Finally, as a quantitative test of the theory of Ref. 4 for calculating the NCX contributions, we have measured the cross section for the production of ^{44}K from 180 MeV π^- on ^{45}Sc, the $^{45}{\rm Sc}(\pi^-,\pi N)^{44}{\rm K}$ reaction. This reaction was chosen because it cannot proceed through a one-step quasifree process and is thus particularly suitable for testing reaction models for two-step processes. The ^{44}K can be produced via one or several of the following mechanisms: (a) a two-step quasifree double-charge-exchange (DCX) scattering $^{45}{\rm Sc}(\pi^-,\pi^+ n)^{44}{\rm K}$; (b) the evaporation process

$$\pi^- + {}^{45}{\rm Sc} \to \pi^0 + {}^{45}{\rm Ca}^* \to \pi^0 + {}^{44}{\rm K} + p \ ;$$

(c) the secondary reaction contribution $^{45}{\rm Sc}(n,2p)^{44}{\rm K}$; and finally (d) the NCX process

$$\pi^- + {}^{45}{\rm Sc} \to \pi^0 + (n + {}^{44}{\rm Ca}) \to \pi^0 + p + {}^{44}{\rm K} \ .$$

The measured upper limit for the cross section is 0.25 mb. Since double-charge-exchange scattering follows a $(N-Z)(N-Z-1)A^{-4/3}$ dependence,[18] we have estimated the contribution for (a) by scaling the integrated cross sections for the reaction $^{209}{\rm Bi}(\pi^+,\pi^- n)^{208}{\rm At}$ ($\sigma_{\rm DCX} \sim 10$ μb, Ref. 19), giving ~ 0.3 μb for the cross section of $^{45}{\rm Sc}(\pi^-,\pi^+ n)^{44}{\rm K}$. Process (b) is suppressed because the sum of the proton separation energy [S(p) = 12 MeV] and Coulomb barrier for proton evaporation ($E_{\rm Coul} \simeq 6$ MeV) in ^{45}Ca is much larger than the neutron separation energy [S(n) = 7.4 MeV]. The secondary contribution (c) has been estimated from a Monte Carlo calculation to be <0.2 mb. The calculation for NCX (d) in ^{45}Sc based on Ref. 4 gives 0.12 mb, which is consistent with the measured cross section.

In the case of the $^{48}{\rm Ca}(\pi^-,\pi^- n)^{47}{\rm Ca}$ reaction, the same theory[4] predicts about 0.10 mb for pure NCX and 3.3 mb for the QM interference between quasifree scattering and NCX. It is worth emphasizing that in previous NCX models,[6–8] the QM interference is erroneously omitted from the theory. Consequently, effects arising from the pure NCX and QM interference are indistinguishable in these models and are combined into a single term identified with "pure" NCX. If these models were used in our calculations of the $^{48}{\rm Ca}(\pi^-,\pi^- n)^{47}{\rm Ca}$ reaction, the pure NCX would be assigned ~ 3.4 mb, 34 times greater than its calculated value of 0.10 mb. Accordingly, the NCX contributions to the $^{45}{\rm Sc}(\pi^-,\pi N)^{44}{\rm K}$ reaction, when calculated with those models, would also be increased by a similar ratio to become ~ 4 mb, a factor of 16 greater than the experimentally determined upper limit. This illustrates the importance of including the QM interference between quasifree scattering and NCX in the theory for $(\pi,\pi N)$ reactions.

IV. SUMMARY AND CONCLUSIONS

We have found that, unlike in ^{12}C, in the mass region $A = 45$–48, the most important nonquasifree component of the $(\pi,\pi N)$ reaction is not NCX, but most likely evaporation. The large nonquasifree contribution is mainly responsible for the absence of clear resonance structure in the measured excitation functions for the $^{48}{\rm Ca}(\pi^\pm,\pi N)^{47}{\rm Ca}$ and $^{48}{\rm Ca}(\pi^-,\pi N)^{47}{\rm K}$ reactions.

The systematics for NCX indicates that the pure NCX and the QM interference contributions to $(\pi,\pi N)$ reactions decrease with increasing target mass. For the $^{48}{\rm Ca}(\pi^-,\pi^- n)^{47}{\rm Ca}$ and $^{48}{\rm Ca}(\pi^+,\pi N)^{47}{\rm Ca}$ reactions at $T_\pi = 180$ MeV, calculations indicate that the combined pure NCX and QM interference contribute only 3% and 6%, respectively, to the total single nucleon removal cross section.

We have experimentally determined an upper limit for the $^{45}{\rm Sc}(\pi^-,\pi N)^{44}{\rm K}$ reaction cross section at 180 MeV. The calculation for pure NCX based on Ref. 4 is consistent with this limit. Because of the incorrect treatment of NCX in previous models, they would predict a cross section greater than the experimentally determined upper limit by an order of magnitude.

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