Total cross sections for the $A(\pi^+,\pi^+\pi^-)$ reaction at T_{π^+} =280 MeV

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The $(\pi^+,\pi^+\pi^-)$ reaction on ^{2}H, ^{4}He, ^{16}O, and ^{208}Pb has been measured in the reaction plane at T_{π^+}=280 MeV and the cross sections determined. The out of plane behavior of the reaction has been accounted for by phase space and, by integration over it, total cross sections have been deduced. Data are compared with the results of model calculations that, based on different approaches and approximations, predict total cross sections largely discordant. Finally, the analogy between the processes of pion production and double charge exchange is discussed in terms of total cross sections.

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When a nucleus is probed with pions of energy above the pion production threshold, the detection of two pions in coincidence identifies the occurrence of a pion production reaction or $(\pi,2\pi)$. For some of the charged channels this is defined by the $\pi^\pm \to \pi^\pm\pi^\mp$ reaction. Detecting only the opposite charged pion, the $\pi^\mp$ in the above reaction, customarily identifies a double charge exchange (DCX) transition, $\pi^\pm \to \pi^\mp$. Detecting only a single pion usually does not unambiguously establish the nature of the process, whether $(\pi,2\pi)$ or just DCX, unless the measurement regards exclusive DCX transitions [like double isobaric analog transition or $A(\pi^\pm,\pi^\mp)A'_{\rm g.s.}$], or the scattered pion energy is above the end point of the $(\pi,2\pi)$ reaction or the cross section of the $A(\pi,2\pi)A'$ reaction is suppressed (for instance, when the pion production process is examined at energies close to threshold). In the case of deuterium, however, the identification of a $(\pi,2\pi)$ event may simply involve the detection of a single pion of opposite charge because the competing reaction of DCX cannot take place.

The $(\pi,2\pi)$ yield in complex nuclei has been believed to be suppressed at energies of the Δ resonance, hence neglected when inclusive $A(\pi^\pm,\pi^\mp)X$ measurements have been presented (references are quoted below when explicitly discussing ^{4}He, ^{16}O, and ^{208}Pb). However, the diagrams underlying the $(\pi^\pm,\pi^\pm\pi^\mp)$ process in nuclei may contribute to an appreciable fraction of the DCX strength through meson exchange currents (MEC) [1–5]. According to the MEC mechanism one of the final pions, $\pi^\pm$, may be absorbed by a nucleon so that the original $(\pi,2\pi)$ process appears as a DCX process, Figs. 1(a) and 1(b). However, there is a mechanism contributing to the DCX dynamics that is not shared with the pion production process, the double sequential (DS) mechanism where the incident pion scatters with a pair of nucleons exchanging a unit of charge with each nucleon, Fig. 1(c). The MEC and DS mechanisms have been found to compete in DCX above the Δ region [1–4], hence suggesting that the cross section for the $(\pi,2\pi)$ and DCX reactions may have comparable values.

Total cross sections for the $(\pi^+,\pi^+\pi^-)$ reaction on ^{4}He and ^{16}O were determined by the methods described in [6–8]. The methods used for the previously unpublished ^{208}Pb data were identical. The cross section values are listed in Table I under the label P. Total cross sections for the *inclusive* $A(\pi^+,\pi^-)X$ reaction are tabulated in the column labeled I, namely, cross sections determined by detecting solely the opposite charged pion, the π^- in the (π^+,π^-) and $(\pi^+,\pi^+\pi^-)$ channels. Finally, total cross sections for the *genuine* $A(\pi^+,\pi^-)A'$ reaction appear under the label X. The latter is evaluated by subtracting the second from the first cross section. Total cross sections for the inclusive DCX reaction are available in the literature at energies in the region of the Δ resonance although not at 280 MeV. For the sake of com-

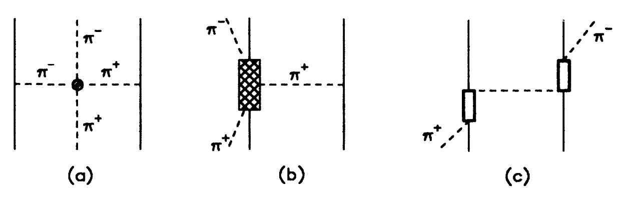

FIG. 1. Diagrammatic representation of the mechanisms contributing to DCX; pions, nucleons, and deltas are drawn with dashed, thin, and thick lines, respectively. (a) and (b) Meson exchange currents (MEC); the filled box in (b) represents the transitions contributing to the $\pi N \to \pi\pi N$ reaction. (c) Double sequential (DS) mechanism.

TABLE I. Total cross sections for the inclusive double charge exchange reaction, I: $[(\pi^+,\pi^+\pi^-) + (\pi^+,\pi^-)]$, for the pion production reaction, P: $(\pi^+,\pi^+\pi^-)$, and for the genuine double charge exchange reaction, X: (π^+,π^-). Their values, either measured or scaled, are at T_{π^+}=280 MeV.

Nucleus	σ (mb)		
	I^a: $[(\pi^+,\pi^+\pi^-)+(\pi^+,\pi^-)]$	P: $(\pi^+,\pi^+\pi^-)$	X: (π^+,π^-)
^{4}He	1.17	0.433±0.091 [6]	0.73
^{16}O	6.13	2.25±0.35 [8]	3.88
^{208}Pb	92	8.7±2.2[b]	83.3

[a]See text for the method used to obtain these values.
[b]Present work. The experimental equipment and the data analysis have been described in [6–8].

parison, the σ_I have been scaled to 280 MeV. The scaling method employed is described below as well as the σ_P scaling to lower energies.

^{4}He: In order to obtain the cross section value for the inclusive DCX reaction at 280 MeV a polynomial expansion has been fitted to the available data above the $(\pi,2\pi)$ energy threshold ($T^{\rm thr}_{\pi 2\pi}$) [2, 9, 10]. With this procedure, $\sigma_I = 1.17 \pm 0.07$ mb at $T_{\pi^+} = 280$ MeV. The uncertainty quoted reflects the range of values of σ_I obtained when different forms of polynomial expansions are used to fit the data above $T^{\rm thr}_{\pi 2\pi}$ ~159 MeV. The relative yield of the $(\pi^+,\pi^+\pi^-)$ reaction channel, Y_P, accounts for 37% of the inclusive DCX yield.

^{16}O: The same procedure as for the helium case has been employed for energies above $T^{\rm thr}_{\pi 2\pi}$ ~154 MeV with data from [10–13], resulting in σ_I=6.13±0.07 mb and Y_P=37%. Furthermore, to assess σ_P at T_{π^+} =270, 240, and 210 MeV, and ultimately Y_P, the measured datum at T_{π^+}=280 MeV has been scaled with the ratio of the total cross sections predicted by the model calculations of [14] for the ^{16}O$(\pi^+,\pi^+\pi^-)$ reaction. With this approach Y_P=28, 8, and 1 % for T_{π^+} =270, 240, and 210 MeV, respectively.

^{208}Pb: By applying the same method as for helium for energies above $T^{\rm thr}_{\pi 2\pi}$ ~146 MeV with data from [10], σ_I=92±1 mb and Y_P=9.5%.

Furthermore, a correct interpretation of the differential cross sections of inclusive DCX data crucially depends on the contribution of the $(\pi,2\pi)$ reaction, which has been accounted for by relying on phase space behavior [11, 13] or on a microscopical model prediction [15]. In fact, differential cross sections of the $A(\pi^+,\pi^+\pi^-)$ reaction have been observed to concentrate most of their strength at low pion energies (T_π <70 MeV) [6–8, 16].

The pion induced pion production reaction in nuclei, $A(\pi^+,\pi^+\pi^-)$, has been investigated with various models [14, 17–21] that commonly use the one-body $\pi N \to \pi\pi N$ reaction for pion production. The diagrams underlying the $\pi N \to \pi\pi N$ reaction are customarily derived from the Weinberg Lagrangians. However, the approximations used to calculate the elementary amplitude [22], and different approaches about the effects of the nuclear matter, have led to discordant theoretical results. The experimental total cross sections, $\sigma^{\rm exp}$ listed in Table II, although bearing uncertainties as large as 25%, are sufficiently accurate to set a scale of validity among the available model calculations. The predictions of $A(\pi^+,\pi^+\pi^-)$ models and their comparison with experimental results are summarized in the following.

Mod1. The model developed by Oset and Vicente-Vacas offers the option either to use a set of parametrized amplitudes for the $\pi N \to \pi\pi N$ reaction [14], or calculated amplitudes [23]. In the latter case, the amplitudes depend on four phenomenological parameters: the chiral symmetry breaking parameter ξ arising from the $\mathcal{L}_{\pi\pi}$ Weinberg Lagrangian, the $\Delta\Delta\pi$ coupling constant, f_Δ, the parameter arising from the Lagrangian describing the $N^*N(\pi\pi)_{s\ \rm wave}$ vertex, C, and $g_{N^*\Delta\pi}$, the $N^*\Delta\pi$ coupling constant. The model accounts for the distortions of initial and final pions, and evaluates both differential and total cross sections for a Fermi sea of nucleons then reducing the results to finite nuclei. Furthermore, cross sections are calculated with a Monte Carlo method that widely frees them from computation approximations. Oset and Vicente-Vacas have found that a valuable contribution (a factor of 2.5 to 3) to the cross sections derives from the renormalization of the final pions, namely, from the modification of the dispersion relation of pions propagating inside the nuclear medium, while the renor-

TABLE II. Comparison of experimental and theoretical total cross sections. The meanings of Mod1 and Mod2 are explained in the text.

Nucleus	$\sigma^{\rm exp}$ (mb)	$\sigma^{\rm th}$ (mb)	
		Mod1[c]	Mod2
^{12}C	0.7±0.1[a]	2.4	
^{16}O	2.25±0.35 [8]	2.7	3.8, 4.5, 6.0[d]
^{208}Pb	8.7±2.2[b]	11.9	7.5[e]; 20[f], 43[f], 179[f]

[a]$\sigma^{\rm exp}$ has been determined at T_{π^+} =292 MeV [24] and scaled at T_{π^+}=280 MeV for comparison.
[b]Present work.
[c]In Mod1 the precritical behavior enhances σ by about 20%. The Migdal parameter, g', is 0.6.
[d]Model predictions are from [18]; the three values are calculated for g'=0.7, 0.55, and 0.40, respectively.
[e]Model prediction is from [17] with no precursor enhancement.
[f]Model predictions are from [17] for g'=0.6, 0.5, and 0.42, respectively.

malization of the virtual pion in the pion pole diagram [pictorially represented by the pion line attached to the nucleon line in Fig. 1(a)] leads to an increase of the cross sections of only ~20%.

In the case of ^{16}O and ^{208}Pb the model predictions reproduce the overall strength of the data when using parametrized amplitudes, as shown in Table II. The model, however, does not embody the effects of Coulomb interaction of the initial pion with the nucleus. For lead, the Coulomb energy may exceed 10 MeV, and for T_{π^+}=280 MeV an energy drop of 10 MeV results in a decrease of the calculated cross section by $\sim$ 30%. Hence, by accounting for Coulomb corrections, the model is able to closely reproduce the measured $(\pi^+,\pi^+\pi^-)$ yields. The parametrized model overestimates the ^{12}C total cross section [24]. Finally, the option that calculates the elementary amplitudes predicts $\sigma^{\rm th} \sim \frac{1}{2}\sigma^{\rm exp}$ for $\xi = -0.2$, f_Δ=$0.5(\frac{4}{5}f_{NN\pi})$, $C = -2.24m_\pi^{-1}$, and $g_{N^*\Delta\pi} = 1.0m_\pi^{-1}$.

Mod2. Eisenberg and Cohen have suggested studying the $(\pi,2\pi)$ reaction near threshold to probe spin-isospin strength distributions in nuclei, or pion condensation precursor phenomena. In accordance with their approach, the precursor features may become evident in an enhancement of the reaction cross section at a momentum transfer to the nucleus of 2–3m_π; the experiments in this Brief Report have been designed to respond to the above requirements. The model calculation [18, 19] overestimates the cross section of the $^{16}{\rm O}(\pi^+,\pi^+\pi^-)$ reaction (Table II) with the Migdal parameter, g', ranging from 0.7 to 0.4. This occurs even though the amplitude used to evaluate the cross section for the elementary $\pi^-p \rightarrow \pi^+\pi^-n$ reaction underestimates the experimental $\pi^-p \rightarrow \pi^+\pi^-n$ cross section by an order of magnitude at T_{π^+}=280 MeV [22]. For lead [17], the only theoretical result consistent with the experimental cross sections is obtained when the precursor features are omitted. When included, the predicted cross sections largely overestimate the experimental one for g' ranging in the interval 0.6–0.42.

Mod3. The model of Rockmore [20, 21] calculates σ vs T_π for a variety of light nuclei for both the $(\pi^\pm,\pi^\pm\pi^\mp)$ and $(\pi^\pm,\pi^\pm\pi^\pm)$ channels. The $\pi N \rightarrow \pi\pi N$ amplitude is calculated in the neighborhood of the $(\pi,2\pi)$ threshold (T_π < 250 MeV): for the $(\pi^\pm,\pi^\pm\pi^\pm)$ channel, calculations closely reproduce the experimental data, while the approach used to calculate the $(\pi^\pm,\pi^\pm\pi^\mp)$ amplitudes underestimates the experimental results, as discussed in [22]. However, the method developed to calculate total cross sections in nuclei appears inadequate since the model predicts values for $\sigma^{\rm th} < \frac{1}{10}\sigma^{\rm exp}$, hence rendering ineffectual any conclusion arising from the comparison between predicted and measured total cross sections.

In conclusion, the significance of our experimental results are summarized in the following.

(1) In *inclusive* DCX measurements, namely, when the measurement involves solely the detection of the opposite charge pion, a sizable fraction of the reaction cross section is due to the $(\pi,2\pi)$ channel, even at energies below 280 MeV. The $(\pi,2\pi)$ channel especially influences the spectral shape of the differential energy cross sections since $(\pi,2\pi)$ events are mostly confined at low energies, a feature also supported by the calculations of [15]. For ^{208}Pb, the ratio of $(\pi,2\pi)$ to DCX is $\sim \frac{1}{10}$ at T_{π^+} = 280 MeV. Such a low contribution is understandable by realizing that lead is a neutron rich nucleus and its larger neutron radius with respect to the proton radius may favor the $\pi^+nn \rightarrow \pi^-pp$ reaction channel over the $\pi^+n \rightarrow \pi^+\pi^-p$ channel [25].

(2) The $A(\pi^+,\pi^+\pi^-)$ model of Oset and Vicente-Vacas predicts the correct strength for the pion production process on both complex nuclei and deuterium [7]. A conspicuous contribution to the $(\pi,2\pi)$ process derives from the renormalization of the real pions. The renormalization of the virtual pion lines does not appreciably contribute to the $(\pi,2\pi)$ strength. The $A(\pi^+,\pi^+\pi^-)$ reaction has been suggested to probe the existence of pion condensation precursor phenomena; however, models based on this hypothesis consistently overestimate the experimental total cross sections. In addition, the model of Eisenberg [17] predicts for lead the correct cross section in absence of precursor effects, namely, with a conventional distorted wave impulse approximation calculation. The above features contradict the existence of such precursor phenomena, at least for the $A(\pi^+,\pi^+\pi^-)$ reaction.

(3) The data presented in this Brief Report constitute the bulk of the $A(\pi^+,\pi^+\pi^-)$ data [26]. Clearly, to understand the role played by the nuclear matter on the dynamics of both pion production and propagation, a wider $A(\pi^+,\pi^+\pi^-)$ database is needed. In this regard, the $(\pi^\pm,\pi^\pm\pi^\mp)$ and $(\pi^\pm,\pi^\pm\pi^\pm)$ reactions will be studied at TRIUMF for a variety of nuclei and in the energy range 220–350 MeV with the large acceptance spectrometer CHAOS, which is presently being built at TRIUMF [27].

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