$\pi\pi$ pairs in nuclei and the σ meson

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In-medium pion-pion correlations were studied via their effect on experimental observables measured for the $\pi^+ \to \pi^+ \pi^\pm$ reaction in nuclei (A: ^{12}C, ^{40}Ca, and ^{208}Pb) and in deuterium, from which it is inferred the observables for the nucleon (N: n and p). The measurements were performed at TRIUMF using a positive-pion flux with a bombarding energy of 283 MeV. The $\pi\pi$ invariant mass distributions $M_{\pi\pi}$ were measured from the $2m_\pi$ threshold up to the kinematic maximum, and total cross sections σ_T deduced. The $\pi\pi$ medium modifications were investigated by forming the composite ratio $C^A_{\pi\pi} = (M^A_{\pi\pi}/\sigma^A_T)/(M^N_{\pi\pi}/\sigma^N_T)$ which proved to be only weakly affected by the (π,2π) reaction mechanism. In the $I=J=0$ channel the $C^A_{\pi\pi}$ distributions are peaked at the $2m_\pi$ threshold and increases with A. For pion pairs in the $I=2$, $J=0$ channel the $C^A_{\pi\pi}$ distributions are nearly independent of A. The distinctive behavior of $C^A_{\pi\pi}$ may be related to the appearance of the σ meson. [S0556-2813(99)00707-4]

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The $\pi\pi$ interaction in nuclei was studied at TRIUMF by means of the $\pi^+ A \to \pi^+ \pi^\pm A'$ (π,2π) reactions, which were measured simultaneously. Although the measured $\pi^+\pi^+$ invariant mass distributions $M_{\pi^+\pi^+}$ exhibited little A dependence, the same distributions in the $J=I=0$ channel $M_{\pi^+\pi^-}$ increased in strength near the $2m_\pi$ threshold with increasing nuclear mass number A [1]. It was further realized that this increase was not due to the reaction mechanism since the quasifree nature of the interaction mechanism is independent of A [2], and the elementary $\pi^+ n \to \pi^+ \pi^- p$ reaction has a $\pi^+\pi^-$ invariant mass distribution of negligible intensity near threshold [3]. A similar behavior was presented in an earlier article describing the $M_{\pi^+\pi^-}$ distribution as a function of A [4], although in that experiment the apparatus was only able to detect $\pi\pi$ pairs with $M_{\pi^+\pi^-} > 300$ MeV.

These experimental results inspired a number of theoretical works [5–7] which addressed the issue of the influence of the nuclear medium on the $(\pi\pi)_{I=J=0}$ properties, a topic extensively studied for vector mesons. All the models satisfy chiral constraints, and predict some common features, which for convenience of discussion are labeled Ti.

$T1$: The mass distribution of the $\pi\pi$ system at $\rho=0$ (i.e., in the vacuum) appears as a broad peak with a width $\Gamma \approx 500$ MeV [5–8] while for $0<\rho\leqslant\rho_n$, where $\rho_n = 0.17$ fm^{-3} (the saturation density), the mass distribution splits into two branches [5–7]. The low energy branch peaks at, or even below, the $2m_\pi$ threshold.

$T2$: The intensity of the $\pi\pi$ mass distribution around the $2m_\pi$ threshold depends markedly on ρ. The intensity increases as the average nuclear density increases.

$T3$: The enhancement of the $M_{\pi^+\pi^-}$ distribution around $2m_\pi$ is obtained for $\rho\leqslant\rho_n$, that is, for nuclear densities of stable nuclei.

$T4$: In spite of the fact that all the models use quite different approaches, they all find that the accumulation of strength around the $2m_\pi$ threshold is due to the $(\pi\pi)_{I=J=0}$ interacting system.

The broad mass distribution predicted by various models for the σ meson, $\Gamma_\sigma \approx 500$ MeV, indicates that it is a short-lived resonance with a lifetime $\tau \approx 10^{-24}$ s, which is on the time scale of strong interactions. This large width of the σ prevents a direct measurement of its invariant mass distribution over a nonresonant background. Thus, the σ, which is responsible for the midrange nucleon-nucleon attraction, is commonly treated as an *effective* meson. That is, as a system of two pions coupled to the $I=J=0$ channel but not necessarily bound. This can be contrasted with the case of the strongly decaying ρ meson, which has a width of $\Gamma_\rho = 150.7$ MeV ($\Gamma_\sigma \approx 3\Gamma_\rho$), and is usually regarded as a real particle. For the (π,2π) reaction, the observation of two pions in the $J=I=0$ channel does not necessarily infer the existence of a scalar-isoscalar resonance (the σ meson), since it is not possible to exclude a direct, nonresonant, contribution to the $\pi^+ n \to \pi^+ \pi^- p$ reaction. Therefore, only the detection of a peak in the $\pi\pi$ invariant mass distribution (or in a quantity related to it) over a continuous background would indicate the presence of a resonance particle.

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TABLE I. Measured total cross sections for the pion-production reaction at an incident pion energy of 283 MeV, and their comparison with other available experimental data. The notations σ_T^{+-} and σ_T^{++} refer to the measured cross sections for the $\pi^+\rightarrow\pi^+\pi^-$ and $\pi^+\rightarrow\pi^+\pi^+$ channels, respectively. The quantity $f_A^{\rm abs}$ accounts for the depletion of the outgoing $\pi^+\pi^\pm$ flux due to nuclear absorption.

Nucleus	σ_T^{+-}(mb)	σ_T^{++}(μb)	T_π(MeV)	$\sigma_T^{+-}/\sigma_T^{++}$	$f_A^{\rm abs}$
^{2}H	0.360±0.036 [3]	41.4±4.3 [3]	283	8.7±0.9	1.00
^{12}C	1.69±0.20	196±24	283	8.6 ±1.0	1.33
^{16}O	2.25±0.35 [17]		280		1.41
^{40}Ca	4.19±0.59	436±61	283	9.6±1.1	1.88
^{208}Pb [a]	6.48±0.91	501±70	283	9.7±1.6	3.37
	8.7±2.2 [11]		280		3.37

[a]For this nucleus the ratio $\sigma_T^{+-}/\sigma_T^{++}$ is divided for the quantity $(N/Z)^{2/3}$ since ^{208}Pb is a $N\neq Z$ nucleus.

The new results that will be presented in this article along with those of the $M_{\pi^+\pi^\pm}$ distributions in nuclei [1,4], previous results of the $(\pi,2\pi)$ reaction in nuclei [2] and a recent study of the ^{2}H$(\pi^+,\pi^+\pi^\pm)NN$ reaction at $T_{\pi^+}=283$ MeV [3] should yield significant experimental guidance toward the understanding of the $\pi\pi$ dynamics in nuclear matter and, ultimately, on the nature of the σ meson.

The data were collected on the M11 channel at TRIUMF using the CHAOS spectrometer [9]. CHAOS is composed of four cylindrical wire chambers surrounded by a ring of 20 telescopes which are employed to mass-identify charged particles (e,π,p,d) and to deliver the first level trigger. Each telescope consists of two layers of plastic scintillators followed by one layer of lead-glass for Cerenkov light detection. Particle detection with CHAOS is limited to $\pm 7°$ from the horizontal plane but allows for a solid angle coverage of up to $\sim$1 sr. Particle kinetic energies were measured with an uncertainty of 1–2 % [full width at half maximum (FWHM)]. The 283 MeV incident positive pions were selected with a kinetic energy spread of $\Delta T/T\sim 3\%$ (FWHM). The targets employed were solid self-supporting foils for ^{12}C(0.332 g/cm^2), ^{40}Ca(0.180 g/cm^2), and ^{208}Pb(0.604 g/cm^2), and liquid for ^{2}H which was contained in a cylindrical vessel of 5 cm in diameter by 5 cm in height. The targets were accommodated in the central vertical axis of the magnet. The number of events analyzed for each of the solid targets was about 3000 for the $\pi^+\rightarrow\pi^+\pi^-$ channel and about 400 for the $\pi^+\rightarrow\pi^+\pi^+$ channel, while for the deuterium the number of events was about 12 000 and 1500, respectively. A comprehensive discussion of the experimental apparatus and data analysis are given in Refs. [9,10].

Comprehensive discussions of the features of the $\pi^+A\rightarrow\pi^+\pi^\pm A'$ reaction at an incident pion energy of 283 MeV were highlighted in previous articles [1–4,11]. Those features which are most useful for the present discussion are labeled as Ei in the following summary.

$E1$: The $(\pi,2\pi)$ reaction on nuclei is a quasifree process. From the deuterium data it was learned the dynamics of the pion-production on a neutron and on a proton, $\pi^+n\rightarrow\pi^+\pi^-p$, and $\pi^+p\rightarrow\pi^+\pi^+n$.

$E2$: The $(\pi,2\pi)$ reaction occurs primarily at the nuclear surface.

$E3$: The kinetic energy of the detected pion pairs is rather unaffected by final-state interactions with the residual nucleus.

$E4$: Near the $2m_\pi$ threshold $\pi^+\pi^-$ and $\pi^+\pi^+$ pion pairs have $I=J=0$ and $I=2,J=0$ quantum numbers, respectively.

The total cross sections (σ_T) of the $\pi^+A\rightarrow\pi^+\pi^\pm A'$ reactions which were measured in the present experiment are listed in Table I, along with some total cross sections measured in earlier experiments. Also given in Table I are the ratios of the measured total cross sections $(\sigma_T^{+-}/\sigma_T^{++})$, and the quantity $f_A^{\rm abs}$, which predicts the decrease in the measured $(\pi,2\pi)$ cross sections due to nuclear absorption of the produced pions during their passage through the residual nucleus. $f_A^{\rm abs}=\sigma_A/\sigma_A^{\rm abs}$, where σ_A is the intrinsic total cross section of the $\pi A\rightarrow\pi\pi A'$ reaction, and $\sigma_A^{\rm abs}$ is the total cross section after pion absorption. Both σ_A and $\sigma_A^{\rm abs}$ are calculated with the model described in Ref. [12]. Note that the σ_T's and $\sigma_T^{+-}/\sigma_T^{++}$ are not corrected for $f_A^{\rm abs}$. The results listed in Table I lead to the following experimental points.

$E5$: The value of the ratio $\sigma_T^{+-}/\sigma_T^{++}$ is fairly constant with A and its mean value is 9.1 ± 0.6. For the elementary $\pi N\rightarrow\pi\pi N$ reaction the ratio is 7.9 ± 0.8. This was calculated by averaging the total cross-section values listed in the database of Ref. [13] and the results of a recent measurement [14]. The cross sections considered were those included in the energy interval $\Delta T/T\sim 3\%$ (FWHM) with $T=283$ MeV. The values of the two ratios are the same within the error bars thus implying that a common reaction mechanism underlies the $(\pi,2\pi)$ process whether it occurs on a nucleon or a nucleus.

$E6$: A significant fraction of the $(\pi,2\pi)$ reaction strength is lost because of pion nuclear absorption. The loss of flux can be expressed in terms of a mean free path $\lambda^{\rm abs}$ via the relation $f_A^{\rm abs}=\exp(l_A/\lambda^{\rm abs})$, where l_A is the overall $\pi\pi$ propagation length before pion absorption. In the case of ^{208}Pb outgoing pions have an average kinetic energy of about 35 MeV [4] which corresponds to a $\lambda^{\rm abs}\approx 6$ fm [8,15]. Pion pairs can thus propagate a distance of $l_A\approx 7$ fm in the nuclear interior before being absorbed. It should be pointed out that pion absorption does not affect the shapes of the measured $\pi\pi$ invariant mass distributions since it only re-

TABLE II. Corrected total cross sections for the $\pi^+ \to \pi^+\pi^-$ channel and ratios between total cross sections. See text for more details.

Nucleus	$\tilde{\sigma}_T^{+-}$(mb)	$R_{\tilde{\sigma}}^{+-}$	$(A-Z)^{2/3}$	R_A^{+-}
^{2}H	0.36±0.04	1.0	1.0	1.0
^{12}C	2.3±0.3	6.4±1.0	3.30	1.9±0.3
^{16}O	3.2±0.5	8.9±1.7	4.00	2.2±0.4
^{40}Ca	7.9±1.1	21.9±3.8	7.37	3.0±0.5
^{208}Pb	22.1±3.0	61.4±10.1	25.14	2.4±0.4

moves pion pairs from the outgoing flux, and the removal rate is fairly flat at pion kinetic energies below 80 MeV [15]. Similarly, the mean free path for pion inelastic scattering (i.e., $\pi A \to \pi' A$) exceeds 10 fm at pion energies around 35 MeV [15], and can thus safely be neglected. Other πA reaction channels have a negligible impact on the $M_{\pi\pi}$ shapes. As a result, the $\pi\pi$ invariant mass distributions are likely to retain their intrinsic shapes. Such a medium transparency to $\pi\pi$ pairs is also supported by the experimental findings summarized in $E3$.

The measured total cross sections corrected for nuclear absorption, $\tilde{\sigma}_T = f_A^{\rm abs} \times \sigma_T$, are given for the $\pi^+ \to \pi^+\pi^-$ and $\pi^+ \to \pi^+\pi^+$ reaction channels in Tables II and III, respectively. These tables also list the ratios $R_{\tilde{\sigma}}$, which are the values of the $\tilde{\sigma}_T$'s measured for nuclei divided by $\tilde{\sigma}_T$ measured for deuterium. It was expected ($E2$ and Ref. [16]) that $R_{\tilde{\sigma}}^{+-}$ would increase as $(A-Z)^{2/3}$, and $R_{\tilde{\sigma}}^{++}$ as $Z^{2/3}$. As can be seen in Tables II and III, this is not the case. The last column in Table II gives the ratio R_A^{+-} between $R_{\tilde{\sigma}}^{+-}$ and $(A-Z)^{2/3}$. Similarly, the last column in Table III lists the ratio R_A^{++} between $R_{\tilde{\sigma}}^{++}$ and $Z^{2/3}$. The uncertainties in the cross sections and the relative ratios were evaluated by assuming the (model dependent) parameter $f_A^{\rm abs}$ to be error free. The ratios $R_A^{+-} = R_{\tilde{\sigma}}^{+-}/(A-Z)^{2/3}$ and $R_A^{++} = R_{\tilde{\sigma}}^{++}/Z^{2/3}$ vary between 2 and 3 for all nuclei studied. This point is in quantitative agreement with the prediction of a theoretical work [12], which calculates total cross sections for the $\pi^+ A \to \pi^+\pi^\pm A'$ reactions at intermediate energies. In this work the pion propagator in nuclear matter is dressed with an additional term with respect to the free pion propagator, the pion self-energy. The modified propagator for the outgoing pions has the effect of enhancing the $(\pi,2\pi)$ cross sections. This enhancement varies from 2.0 to 2.5 for pions with incident energies between 230 and about 300 MeV [12]. The size of this effect was lately confirmed by a measurement of the $(\pi,2\pi)$ reaction on^{16}O at $T_{\pi^+} = 280$ MeV [17], and the effect is known as the *binding* of the pions.

TABLE III. Corrected total cross sections for the $\pi^+ \to \pi^+\pi^+$ channel and ratios between total cross sections. See text for more details.

Nucleus	$\tilde{\sigma}_T^{++}$(μb)	$R_{\tilde{\sigma}}^{++}$	$Z^{2/3}$	R_A^{++}
^{2}H	41.4±4.3	1.0	1.0	1.0
^{12}C	261±32	6.3±1.0	3.30	1.9±0.3
^{40}Ca	820±115	19.8±3.4	7.37	2.7±0.5
^{208}Pb	1688±236	40.8±6.7	18.87	2.2±0.4

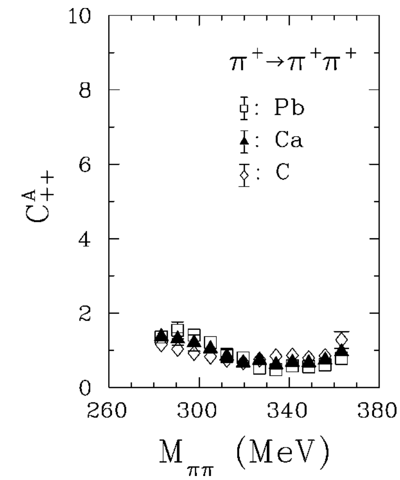

FIG. 1. $C^A_{\pi\pi} = \mathcal{M}^A_{\pi\pi}/\mathcal{M}^p_{\pi\pi}$, the bin-by-bin ratio of $\pi\pi$ invariant mass distributions for the two reactions $\pi^+ A \to \pi^+\pi^+ A'$ and $\pi^+ p \to \pi^+\pi^+ n$, as a function of the $M_{\pi\pi}$ energy. The nuclei (A) examined are ^{2}H (which plays the role of a proton, p), ^{12}C (open diamonds), ^{40}Ca (full triangles), and ^{208}Pb (open squares).

In order to focus on the medium modifications of $\pi\pi$ properties, the behavior of the observable $C^A_{\pi\pi}$ was examined, where $C^A_{\pi\pi}$ is defined as the bin-by-bin ratio between $\mathcal{M}^A_{\pi\pi}$ and $\mathcal{M}^N_{\pi\pi}$, $\mathcal{M}^{A(N)}_{\pi\pi} = M^{A(N)}_{\pi\pi}/\sigma_T^{A(N)}$ and $\sigma_T^{A(N)}$ is the measured total cross section for the $(\pi,2\pi)$ process in nuclei (nucleon). The deuterium data for both $M^N_{\pi\pi}$ and σ^N_T was used, which is justified by the experimental finding $E1$. The composite ratio $C^A_{\pi\pi}$ is calculated for the range from the $2m_\pi$ threshold to about 370 MeV, the upper limit being imposed by the kinematics of the $\pi N \to \pi\pi N$ reaction [3]. The feature $E5$ ensures that $C^A_{\pi\pi}$ is fairly unconstrained by the $(\pi,2\pi)$ reaction mechanism. Furthermore, $\mathcal{M}^{A(N)}_{\pi\pi}$'s are normalized to $\sigma_T^{A(N)}$'s thus the observable $C^A_{\pi\pi}$ is independent of the varying number of scattering centers available in nuclei. Nuclear pion absorption, which depends on A, does not affect $\mathcal{M}^A_{\pi\pi} = M^A_{\pi\pi}/\sigma^A_T$ (thus $C^A_{\pi\pi}$) since the same rate of absorption is embedded in both terms of the ratio. The same consideration applies to the binding of the pions. Finally, $\mathcal{M}^N_{\pi\pi}$ was found to display no evidence for a light isoscalar $\pi\pi$ resonance [3]; therefore, the $C^A_{\pi\pi}$ distributions (Figs. 1 and 2) yield the *net effect* of nuclear matter on the $\pi\pi$-interacting system regardless of the reaction mechanism used to produce a pion pair.

In the case of the $\pi^+ \to \pi^+\pi^+$ channel (Fig. 1) C^A_{++} shows almost no A dependence. Its mean value and the 2σ spread around it, $C^A_{++} \approx 1 \pm 0.5$, indicate the following.

$E7$: The $\pi^+\pi^+$ interaction, which couples to the $I=2$, $J=0$ quantum numbers ($E4$), is unaffected by the presence of nuclear matter.

In the $\pi^+ \to \pi^+\pi^-$ channel (Fig. 2) the data points display a distinctive A dependence: the increase of A is followed by an increase of the C^A_{+-} yield for $M_{\pi\pi}$ approaching

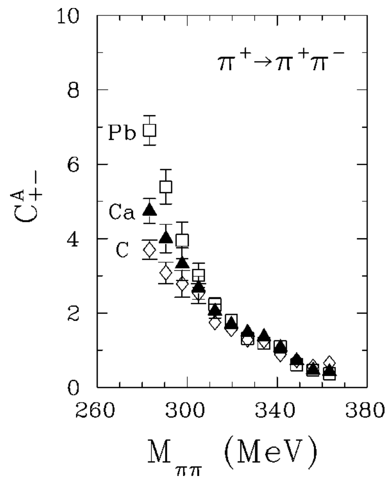

FIG. 2. Same caption as in Fig. 1 but for the $\pi^+ \rightarrow \pi^+\pi^-$ reaction channel.

the $2m_\pi$ threshold. The condition $C^A_{+-} \approx 1 \pm 0.5$ sets a limit on $M_{\pi\pi}$ at about 330 MeV. Below 330 MeV, the C^A_{+-} distributions progressively depart from unity to reach their maxima at the $2m_\pi$ threshold. This behavior suggests that the $\pi^+\pi^-$ system, when embedded in nuclear matter, may develop strength below the $2m_\pi$ threshold. Therefore, we have the following.

$E8$: A $\pi\pi$ system is strongly modified by nuclear matter only when it interacts in the $I=J=0$ channel, that is, when the pion pair has the same quantum numbers as the σ meson. A trait of in-medium modifications is the capability of the $\pi^+\pi^-$ pairs to build up strength at energies below $2m_\pi$.

The understanding of $\pi\pi$ dynamics in nuclei would likely not improve if experiments were performed with more energetic pions, i.e., $T_\pi > 350$ MeV. At these energies the (average) kinetic energy of pions from the $(\pi,2\pi)$ reaction is ≈ 100 MeV and their mean free path in nuclear matter is only ≈ 2 fm [15]. Such pions have little chance of escaping from nuclear matter, unless they are produced on the external rim of a nucleus where $\rho \ll \rho_n$. Such a selective nuclear filtering may distort measured invariant mass spectra, and the observation of a $M^A_{\pi\pi}$ enhancement at $2m_\pi$ may then be due to effects other than in-medium $(\pi\pi)_{I=J=0}$ dynamics [18]. The useful energy interval for observing the on-shell span of the σ is $2m_\pi \leqslant M^A_{\pi\pi} \leqslant 330$ MeV. This interval may seem quite narrow for tests of in-medium $\pi\pi$ models, considering the broad width of the σ. However, the A dependence of variables such as $C^A_{\pi\pi}$ provides additional information on which to base model calculations of the σ mass distribution. As already mentioned, theoretical models predict a wider energy span for an off-shell σ, i.e., $0 < M^A_{\pi\pi} \leqslant 2m_\pi$. However, it is not a trivial task to conceive of a process in which such a virtual σ excitation would lead to detectable decay products which could be experimentally observed.

The experimental findings $E1$–$E8$ should provide guidance for $(\pi,2\pi)$ models aimed at studying in-medium $(\pi\pi)_{I=J=0}$ dynamics. Observables such as $C^A_{\pi\pi}$ should be especially useful for comparison since they are sensitive to $\pi\pi$ in-medium modifications, fairly independent of the reaction mechanism, and free from well-known nuclear effects. Conclusions from recent calculations, $T1$–$T4$, are in substantial agreement with the experimental results discussed in the present article, although the calculations are still too incomplete for a direct comparison with the data.

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