A Dependence of the $(\pi^+, \pi^+\pi^\pm)$ Reaction near the $2m_\pi$ Threshold

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The ^{2}H, ^{12}C, ^{40}Ca, ^{208}Pb$(\pi^+, \pi^+\pi^\pm)$ reactions have been studied at $T_{\pi^+} = 282.7$ MeV, and the $\pi^+\pi^\pm$ invariant mass distributions $M^A_{\pi^+\pi^\pm}$ measured down to the $2m_\pi$ threshold. The $M^A_{\pi^+\pi^-}$ yield near threshold is close to zero for $A = 2$, and increases dramatically with increasing A (from 12 to 40 to 208). A phase analysis indicates that the $\pi^+\pi^-$ pairs in this range of $M^A_{\pi^+\pi^-}$ have $J = I = 0$. In the case of $M^A_{\pi^+\pi^+}$, there is some strength near threshold regardless of A, and the $\pi^+\pi^+$ pairs have $J = 0, I = 2$. The experimental results indicate that nuclear matter strongly modifies the $\pi\pi$ interaction in the $J = I = 0$ channel. [S0031-9007(96)00657-6]

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In the experiment described in this Letter, the pion production reaction $\pi A \rightarrow \pi\pi A'$ was studied in order to probe modifications of the $\pi\pi$ interaction due to nuclear matter. The $\pi \rightarrow \pi\pi$ reaction was first examined on deuterium, where incident positive pions colliding with the proton or neutron open two elementary pion production channels [1,2]: $\pi^+ p \rightarrow \pi^+\pi^+ n$ and $\pi^+ n \rightarrow \pi^+\pi^- p$, which were detected simultaneously. The same reaction channels were then also studied with ^{12}C, ^{40}Ca, and ^{208}Pb targets.

A valuable summary of previously measured differential cross sections for the (π^+, π^+, π^-) reaction on ^{2}H^4, He^{16}, O, and ^{208}Pb can be found in Ref. [3], where it was noted that the maximum in the $\pi^+\pi^-$ invariant mass distributions $M_{\pi^+\pi^-}$ shifts noticeably toward the $2m_\pi$ threshold with increasing mass number. However, $M_{\pi^+\pi^-}$ yields were only measured above 300 MeV, hence missing the critical behavior near the 280 MeV threshold. Consequently, the authors were only able to provide qualitative interpretations of the data.

On the theoretical side, there are models that describe the pion production reaction on deuterium [4] and more complex nuclei [5], as well as those that describe the influence of nuclear matter on $J = I = 0, 1$ correlated pion pairs [6]. These models will be used to understand the present results, although none of them is able to completely describe the data. Furthermore, the data will be discussed in the context of the σ meson.

The study of the nuclear medium influence on the meson properties are of general interest to understand meson interactions with a nuclear many-body environment [7]. Such an environment is often characterized by densities (ρ) which exceed the nuclear saturation density (i.e., a neutron star medium), hence hardly reproducible in a laboratory. A common meson observable is the mass distribution; for interaction pion pairs of given quantum numbers, it is speculated [6] that their mass distributions are modified by the density of nuclear environment. For $\pi\pi$ pairs interacting in the $J = I = 0$ channel, the modification of the mass distribution may experimentally be observed, even at densities below the nuclear saturation density (0.16 fm^{-3}). While in the ρ channel ($J = I = 1$), the mass distribution modifies at $\rho \approx 1.5$ times the nuclear saturation density.

The experiment was performed at the CHAOS spectrometer facility [8], at TRIUMF, using the medium energy pion beam line M11. Incident pions were monitored by a segmented plastic scintillator counter, which consisted of four independent and adjacent strips, each viewed by a fast photomultiplier to minimize pileup effects at the intense pion fluxes used (typically 5×10^6 particles/s). The strip size was optimized for timing purposes; in fact, this counter started the time measurements for the CHAOS drift chambers and counter telescopes. Outgoing charged particles were tracked by four rings of cylindrical wire chambers. The inner two are fast proportional wire chambers capable of withstanding intense fluxes in order to track the incident pion beam, while the outer two are drift chambers. The three inner chambers operated in the dipole field of 0.5 T used for the present measurement. The two narrow sections of each drift chamber directly traversed by the beam were switched off during the data taking phase. The particle identification (PID) system consists of 20 telescopes which closely surrounded the outer drift chamber, two of which were removed to accommodate the incident and outgoing beam. Each telescope consists of three layered elements: two NE110 plastic scintillators, followed by a thick block ($5\chi_0$) of SF_5 lead glass. The front face of the first scintillator is 71 cm from the target. A particle was identified by combining the energy released in the three elements of a telescope with its momentum. The PID efficiency for $e^{\pm}$, $\pi^{\pm}$, and p was $\sim$98%. The overall chamber mass and the thickness of the first scintillator (3.2 mm) established the lower momentum threshold of CHAOS, which was only 55 MeV$/c$ for pions and electrons and 185 MeV$/c$ for protons, emerging from the target. The first level trigger was a coincidence between the in-beam counter and any two of the PID telescopes. A hardware second level trigger was used to improve the live time of the data acquisition system. It rejected events with missing wire chamber hits, events not originating from the target region, and background events from other reactions based on the momentum sum of the identified tracks. With these constraints about 97% of the events passed by the first level trigger were rejected. A sample of rejected events was recorded for diagnostic purposes. With CHAOS we could measure two or more charged particles over 360° in the reaction plane, except for an angular range of ±9° around the incoming and outgoing beam directions. The out-of-the-reaction-plane acceptance was ±7°. The momentum resolution was about 2% $\Delta p/p$ with an overall detection efficiency of 92% per track.

The nominal energy (momentum) of the incoming pion beam was 282.7 MeV (398.6 MeV$/c$) at the target. At this energy the beam composition was 90% pions and 10% protons. The electron and muon fractions were negligible. Furthermore, pions were fully discriminated from protons by time of flight and energy loss in the timing counter.

The targets used were ^{2}H, ^{12}C, ^{40}Ca, and ^{208}Pb. The ^{2}H target consisted of a cylindrical cell of 5 cm in diameter by 5 cm in height filled with liquid deuterium. The remaining targets were self-supporting slabs of areal densities 0.332 g/cm^2 ^{12}C, 1.180 g/cm^2 ^{40}Ca, and 0.604 g/cm^2 ^{208}Pb.

All the results reported here are in relative units. The data are corrected for the irregular in-plane CHAOS acceptance with the GEANT Monte Carlo code: each detected $\pi\pi$ event was weighted to reproduce a uniform detector acceptance. The error bars in the figures presented below thus include the statistical uncertainty of the GEANT weight and the bin content. No corrections have been made to account for the limited out-of-plane acceptance of CHAOS. The data for the $(\pi^+, \pi^+\pi^-)$ and $(\pi^+, \pi^+\pi^+)$ reaction channels were acquired simultaneously. After the GEANT corrections, the in-plane CHAOS acceptance was identical for both these reactions, and thus does not contribute to the measured differences between $M^A_{\pi^+\pi^-}$ and $M^A_{\pi^+\pi^+}$. The interpretation of the results also relies on a direct comparison of the $M^A_{\pi^+\pi^\pm}$ distributions for the four nuclear targets studied. Hence, changes in the experimental apparatus were minimal: only the targets were changed throughout the measurement, while the beam and spectrometer settings were kept constant.

Figures 1 and 2 show the invariant mass distributions for the $(\pi^+, \pi^+\pi^-)$ and $(\pi^+, \pi^+\pi^+)$ reactions, respectively. The $M_{\pi^+\pi^\pm}$ distributions for ^{2}H are compared with predictions normalized to our data. The curves are the result of an extended version of Oset's model [4] which includes both the Fermi motion and the $N^\star \rightarrow N(\pi\pi)_{p\text{-wave}}$ reaction channel [2], and incorporates the kinematical limits of CHAOS [9]. Near threshold, the $M_{\pi^+\pi^-}$ yield is close to zero for deuterium, but increases dramatically from ^{12}C to ^{40}Ca to ^{208}Pb. In contrast, the $M_{\pi^+\pi^+}$ yield near threshold barely changes with A. Note that $M_{\pi^+\pi^\pm}$ broadens with increasing mass number because the phase-space volume available to the final pions becomes larger. In addition, $M_{\pi^+\pi^+}$ broadens because of the larger Coulomb boost undergone by the positive pions while leaving the nucleus.

Figure 3 shows the angular distributions for the $(\pi^+, \pi^+\pi^\pm)$ reaction channels. These are presented in the $\pi^+\pi^\pm$ center-of-mass frame in order to determine the $\pi\pi$ relative orbital angular momentum (l). The flatness of the distributions indicates an $l = 0$ dominance for both the $(\pi^+, \pi^+\pi^-)$ and $(\pi^+, \pi^+\pi^+)$ channels in the range $2m_\pi \leq M^A_{\pi^+\pi^\pm} \leq 315$ MeV. The S-wave nature of the $\pi^+\pi^\pm$ interaction is common to all the nuclei, although

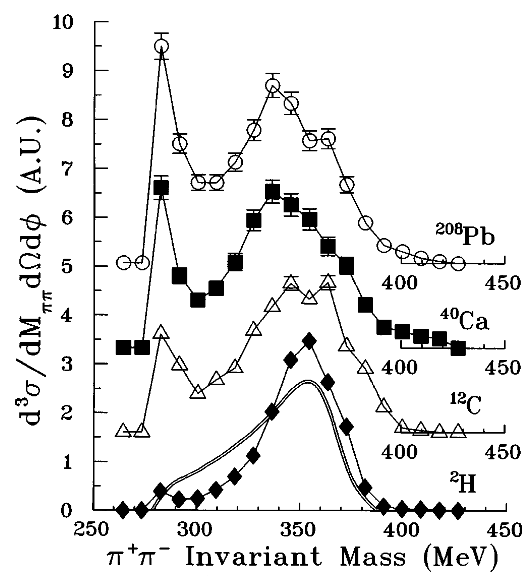

FIG. 1. Invariant mass distributions for the $(\pi^+, \pi^+\pi^-)$ reaction channel. The vertical scale is in arbitrary units. The curve is the prediction of an extended version of Oset's model for ^{2}H [2,9] normalized to the data. The thin lines drawn through the data points are to guide the eye.

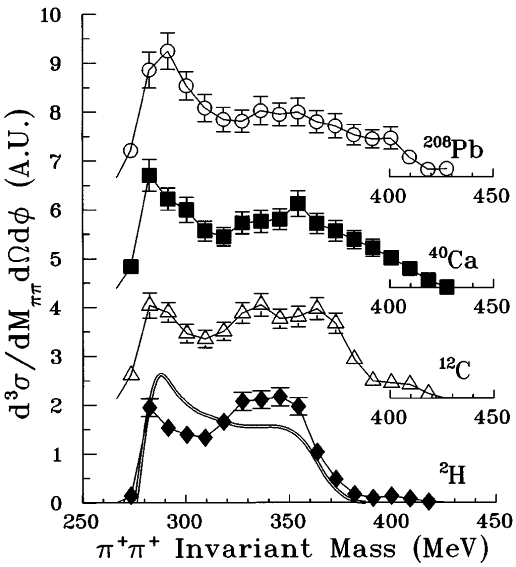

FIG. 2. Invariant mass distributions for the $(\pi^+, \pi^+\pi^+)$ reaction channel. The vertical scale is in arbitrary units. The curve is taken from Ref. [9].

only two angular distributions are shown. The $\pi\pi$ symmetric wave function restricts the quantum numbers of the $\pi^+\pi^\pm$ pairs to $J = 0, I = 0$ for $\pi^+\pi^-$ and $J = 0, I = 2$ for $\pi^+\pi^+$. Note that the $\pi^+\pi^-$ system can also carry $J = 0, I = 2$ quantum numbers. However, the contribution to the $\pi^+\pi^-$ pairs from this channel is negligible at the energy of this experiment [10].

From the above experimental results the following becomes apparent: (a) The $M^A_{\pi^+\pi^-}$ distributions increase remarkably in strength near the $2m_\pi$ threshold for A ranging from ^{12}C to ^{40}Ca to ^{208}Pb. For the $\pi^+\,{}^2\mathrm{H} \to \pi^+\pi^- pp$ reaction, the $M^A_{\pi^+\pi^-}$ strength is negligible near threshold, and its behavior is reasonably well described by an extended version of Oset's model. (b) The $(\pi^+\pi^-)_{J=I=0}$ system accounts for a large fraction of the invariant mass

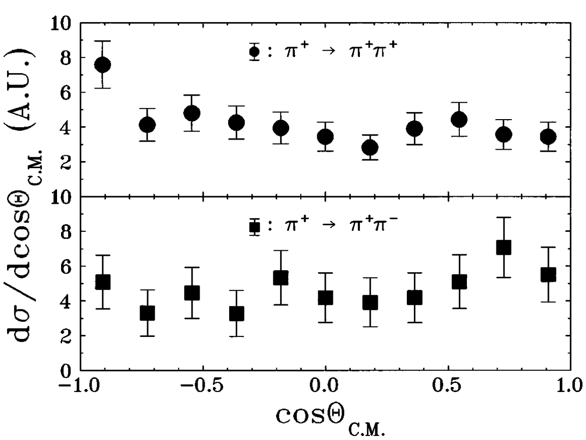

FIG. 3. Angular distributions for the $(\pi^+, \pi^+\pi^\pm)$ reaction channels on ^{40}Ca. The vertical scale is in arbitrary units. The invariant mass is limited to $2m_\pi \leq M_{\pi^+\pi^\pm} \leq 315$ MeV.

strength near the $2m_\pi$ threshold, i.e., $2m_\pi \leq M^A_{\pi^+\pi^-} \leq 315$ MeV. (c) For the $(\pi^+\pi^+)_{J=0;I=2}$ system, the $M^A_{\pi^+\pi^+}$ distributions near threshold for ^{2}H, ^{12}C, ^{40}Ca, and ^{208}Pb show little A dependence. For ^{2}H, the overall strength is predicted by an extended version of Oset's model. These findings permit a more quantitative description of the influence of the nuclear medium on the $\pi\pi$ interaction than was possible previously. The interaction is either strongly or weakly modified depending on whether the di-pion system is in the $J = I = 0$ or $J = 0, I = 2$ channel, respectively. At this stage an interesting question arises: Does the nuclear matter mediate a clustering effect $[(\pi\pi)_{J=I=0} \to 2\pi$ cluster], a quark effect $[(\pi\pi)_{J=I=0} \to \sigma \equiv q\bar{q}$ state], or other effects that, nevertheless, require a strongly correlated $\pi\pi$ system in the $I = J = 0$ channel? The present results and analysis do not allow one to distinguish between these hypotheses. Comparisons with model calculations do not improve the picture either, since none of the models available at the present time incorporate all the essential features of the reaction in one consistent theoretical framework.

In the region below 1 GeV a scalar meson decaying mainly into two pions has yet to be observed, despite the fact that its *presence* has been envisaged to explain fundamental hadronic processes [11], or to characterize light meson properties [12]. In the approach of [11], the $\pi\pi$ exchange interaction explains the dynamical origin of the σ meson: It is introduced as an *effective* boson with a mass between 500 and 900 MeV and a width of $\approx$400 MeV, i.e., as a conventional resonant state. In a second, more microscopic approach [12], effective Lagrangians, incorporating important QCD features, are used to describe the mass spectra, decay widths, etc., of light mesons, of which the σ is one. However, none of these models embodies the effects of nuclear matter below the saturation density ($\rho_n = 0.16$ fm^{-3}) in the $\pi\pi$ system.

There exists a rather complete model of pion production in nuclei, Oset's in Ref. [5], which is able to correctly predict total cross sections [13] as well as some differential cross sections [14]. In this model the pion propagator is renormalized (or *dressed*) to account for the nuclear medium. However, the model does not take into account $\pi\pi$ correlations, and the model fails to predict the shift of the $M^A_{\pi^+\pi^-}$ maximum for oxygen and lead [3]. The present data confirm the discrepancy: The model calculations are unable to explain the $M^A_{\pi^+\pi^-}$ strength near the $2m_\pi$ threshold for ^{12}C, ^{40}Ca, ^{208}Pb. For these nuclei, the $M^A_{\pi^+\pi^-}$ distributions look like the ^{2}H $M^A_{\pi^+\pi^-}$ distribution but broaden out as A increases, in accordance with increasing Fermi momentum and phase-space volume [15]. The model, however, does predict the overall shape of the ^{2}H $M^A_{\pi^+\pi^+}$ distribution, which is similar for all the nuclei studied.

The models of Chanfray and co-workers [6] aim at studying the modification of $\pi\pi$ correlations in nuclear matter. For the two-pion system, with the $J = I = 0$ quantum numbers, both models predict a mass distribution that increasingly peaks at (and below) the $2m_\pi$ threshold for $0 \leq \rho \leq \rho_n$, as observed in the present data. The models are not, however, sensitive to the exact nature of the $(\pi\pi)_{J=I=0}$ system [2π cluster or $\sigma(\equiv q\overline{q})$ meson]. Chiral symmetric constraints were added to Chanfray's model by Aouissat *et al.* [6]. An immediate consequence is the noticeable reduction of the $\pi\pi$ scalar channel mass distribution strength around the $2m_\pi$ threshold, for $\rho \leq \rho_n$. Since the present data show a substantial increase instead, within the context of this model, this seems to imply that the nature of the chiral symmetry breaking of QCD is different in nuclear matter.

In summary, the present results indicate that the nuclear medium modifies the $\pi\pi$ interaction favoring the formation of a di-pion system bearing the $J = I = 0$ quantum numbers. The present theoretical framework does not help to clarify its nature.

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