The $\pi \rightarrow \pi \pi$ process in nuclei and the restoration of chiral symmetry

CHAOS Collaboration

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Abstract: The results of an extensive campaign of measurements of the $\pi \rightarrow \pi \pi$ process in the nucleon and nuclei at intermediate energies are presented. The measurements were motivated by the study of strong $\pi \pi$ correlations in nuclei. The analysis relies on the composite ratio $C_{\pi \pi}^{A}$, which accounts for the clear effect of the nuclear medium on the $\pi \pi$ system. The comparison of the $C_{\pi \pi}^{A}$ distributions for the $(\pi\pi)_{I=J=0}$ and $(\pi\pi)_{I=0,J=2}$ systems to the model predictions indicates that the $C_{\pi \pi}^{A}$ behavior in proximity of the $2m_{\pi}$ threshold is explainable through the partial restoration of chiral symmetry in nuclei.

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I. INTRODUCTION

Spectral properties of pion pairs interacting in the $I=J=0$ channel (the $\sigma$-channel) are predicted to vary significantly from the vacuum to nuclear matter as a consequence of the partial restoration of chiral symmetry. As an example, the vacuum spectral function of $\sigma$, a broad ($\Gamma \sim 500$ MeV) resonance centered at $\sim 500$ MeV, substantially reshapes in nuclear matter by forming a peak-like structure at around $2m_{\pi}$ [1, 2, 3]. The underlying theory regards the $\sigma$ meson as a $\bar{q}q$ excitation of the QCD vacuum, in which the spontaneous breaking of the chiral symmetry leads to the $\sigma$-$\pi$ mass difference. The sigma ($J^P = 0^+$) is

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also the chiral partner of the pion \( (J^P = 0^-) \). When the properties of the \( \sigma \) meson are studied in nuclear matter, the theory predicts a substantial change of the \( \sigma \) spectral function, which strongly reduces the \( \sigma - \pi \) mass difference. This occurrence indicates that nuclear matter partially restores the chiral symmetry. The \( I=0 \) \( \pi\pi \) interaction in nuclear matter is also studied in Ref.\[4\], which reflects the current theoretical understanding on this topic.

An additional source of reshaping of the \( \sigma \) spectral function at around threshold is yielded by standard many-body correlations; i. e., the \( P-\)wave coupling of pions to particle - hole and \( \Delta - \)hole states \[2, 3, 5\]. The combined effect of partial restoration and collective \( P \)-wave pionic modes produces a conspicuous enhancement of the \( \sigma \) spectral function at around the \( 2m_\pi \) threshold \[2, 3\]. This letter presents further analysis of experimental results on the \( \pi \rightarrow \pi\pi \) process near the \( 2m_\pi \) threshold, which are then related to the direct observation of \( \pi\pi \) in-medium correlations. In this regard, final pion pairs are studied in the vacuum and in the nuclear medium, and are further examined in the isospin 0 and 2 channels. The comparison of different isospin channels conveys additional information on the spectral changes of the \( \sigma \)-channel (\( I=0 \)) with respect to the non-resonant \( I=2 \) channel. Finally, the data from the present measurements will directly probe the \( \sigma \)-spectral predictions around threshold and accordingly the underlying physics of chiral symmetry restoration.

The \( \sigma \) (or \( f_0(600) \)) meson is understood to be a broad resonant state \( \Gamma_\sigma \sim m_\sigma \sim 500 \) MeV which predominantly decays into two S-wave pions \( \sigma \rightarrow \pi\pi \) \[6\]. The \( \sigma \) broad structure makes this meson difficult to directly observe via the \( \pi N \rightarrow \pi\pi N \) elementary reaction \[7\], or heavy meson decays \[8\]. A systematic analysis of a broad sample of data involving pion pairs in the \( I=J=0 \) channel however provides firm evidence of \( \sigma \) \[9\]. A clear signature of \( \sigma \) in the vacuum appears controversial. Conversely, the nuclear medium may condensate \( I=0 \) pion pairs by changing the structure of the QCD vacuum; therefore, the study of \( \sigma \) by means of two coincident \( I=0 \) pions via the \( \pi \rightarrow \pi\pi \) process appears appropriate.

The \( \sigma \) spectral properties are studied by means of the \( \pi\pi \) invariant mass and the composite observable \( C^A_{\pi\pi} \), which is described in Sec. 3. In order to normalize this observable to pion production on the nucleon and explicitly consider the ratio for nuclei from \( ^2H \) to \(^{208}Pb \), a new analysis of our previously published \[10\] pion production data on the nucleon was completed as a function of the same kinematic quantities as were used for the nuclear data. \( C^A_{\pi\pi} \) appears slightly different from the previously published one, which was normalized to deuterium \[11\]. In addition, new results for the composite observable are presented for Sc as a function of incident energy. The final pions have an energy distribution which is broadly centered between 20-50 MeV, depending on the energy of the projectile \[11, 12\]. In this energy range, an earlier \( \pi 2\pi \) measurement reported that the shape of spectra was only slightly altered by final state interactions \[13\]. This result finds a qualitative explanation in the long mean-free path of low-energy pions in nuclear matter. The mean-free path of pions exceeds 10 fm for \( \rho = \rho_0/2 \) at \( T_\pi=50 \) MeV \[14\], which highly reduces the pion distortions due to \( \pi N \) final-state interactions. Furthermore, pion absorption has only the effect of removing final
pions and the removal is mildly dependent on the pion energy in the interval 50±30 MeV [15] thus causing little reshaping of pion spectra. Finally, pion distortions due to other $\pi A$ reactions can safely be neglected [15]. Previous studies of the $\pi A \rightarrow \pi \pi A'$ reaction showed that at intermediate energies the pion production process takes place at the nucleus skin $\rho \sim \frac{1}{3}\rho_0$, where $\rho_0$ is the nuclear density at saturation [12]. This occurrence further increases the nuclear transparency to final pion pairs. The moderate fraction of $\rho_0$ inspected by pions however limits the $\sigma$ spectral changes. These can only be augmented by probing higher nuclear densities, which can be obtained with the use of electromagnetic beams. This in fact was the approach used by the authors of Ref. [16], who were able to probe nuclear densities up to $\rho \sim \frac{2}{3}\rho_0$ for $^{208}\text{Pb}$ by employing $\gamma$’s of energies in the range 400-460 MeV.

II. THE MEASUREMENT

The data were taken at the M11 pion channel of TRIUMF with the CHAOS spectrometer [17]. Both positive and negative pions were used to study the pion-production reaction ($\pi 2\pi$) as a function of the atomic mass number (A) and the projectile incident energy (T):

$$\pi^\pm p \rightarrow \pi^+\pi^\pm n \text{ at } T = 243, 264, 284 \text{ and } 305 \text{ MeV} \quad (1)$$

$$\pi^+ A \rightarrow \pi^+\pi^\pm X \text{ with } A: ^2\text{H}, ^{12}\text{C}, ^{40}\text{Ca} \text{ and } ^{208}\text{Pb} \text{ at } T = 283 \text{ MeV} \quad (2)$$

$$\pi^+ \text{Sc} \rightarrow \pi^+\pi^\pm X \text{ at } T = 243, 264, 284 \text{ and } 305 \text{ MeV} \quad (3)$$

The measurements from (1) to (3) were performed under the same kinematic conditions to ensure a direct comparison among the $\pi 2\pi$ data. In addition, final pion pairs were detected in coincidence to avoid the overwhelming background from the reaction of pion scattering. The results of the measurements (1), (2) and (3) were previously published in Refs. [10], [11] and [12], respectively.

The CHAOS spectrometer consists of a dipole magnet, four rings of cylindrical wire chambers and a multilayer mass-identification system (CFT). The events were analyzed in the plane of the reaction due to the geometry of the dipole; that is, for azimuth angles $\Theta$ ranging from 0° to 360° and for zenith angles $\Phi$ from -7° to +7°. Final pions (from (1) to (3)) were detected with an energy resolution of $\delta T/T=4-7\%$ ($\sigma$), for the CHAOS field set at 0.5-0.6 T. Such a field also established the pion detection threshold, which was 11 MeV. The CFT system was designed to deliver the first level trigger and mass identify charged particles; i.e., $e$’s, $\pi$’s, $p$’s and $d$’s. The particle mass identification (PID) relies on the observed correlation between the trace momentum and the pulse heights in the CFT layers. Reconstructed events with a valid PID were further restricted to the $\pi 2\pi$ phase-space volume before being finally saved. The prime PID capability of CHAOS is illustrated in Fig. 1, which shows the missing mass distribution of reactions (1) at $T=264$ MeV. The missing mass expected is the neutron mass irrespective of the projectile charge and energy. In fact,
a distinct peak centered around 940 MeV with a \( \sigma \) of about 3 MeV is observed in each channel. By averaging the peak-value over the four energies and the two reaction channels, the missing mass distribution yields a mean value of 941.2\( \pm \)3.0 MeV which is consistent with the neutron mass.

### III. THE OBSERVABLE

The \( \pi 2\pi \) experimental results will be compared to the theoretical predictions via the composite observable

\[
C_{\pi\pi}^A = \frac{\sigma(M_{\pi\pi}^A)/\sigma_T^A}{\sigma(M_{\pi\pi}^N)/\sigma_T^N}
\]

(4)

where \( \sigma(M_{\pi\pi}^A) \) (\( \sigma(M_{\pi\pi}^N) \)) is the triple differential cross section \( d^3\sigma/dM_{\pi\pi}d\Omega_\pi d\Omega_\pi \) for nuclei (nucleon), \( M_{\pi\pi} \) represents the \( \pi\pi \) invariant mass, \( \Omega_\pi \) denotes the solid angle into which a charged pion is scattered, and \( \sigma_T^A \) (\( \sigma_T^N \)) is the total cross section in nuclei (nucleon). Differential as well as total cross sections were determined by means of the CHAOS measurements, details of the experimental method used are reported in [11, 12]. The extrapolation of the raw data to the full solid angle is model-dependent because of the limited \( \Phi \)-acceptance of the magnetic spectrometer. A detailed discussion is reported in Ref. [12]. The effects of such an extrapolation must be accounted for when comparing the CHAOS cross sections to model predictions. However, these effects cancel to a large extent in the composite ratio \( C_{\pi\pi}^A \),
Figure 2: Simulated behavior of $C^\text{Sc}_{\pi\pi}$ for CHAOS (filled histogram) and for an ideal $4\pi$ detector (open histogram) as a function of the $\pi\pi$ invariant mass ($M_{\pi\pi}$). The reactions simulated are $\pi^+\, ^{45}\text{Sc} \to \pi^+\pi^-p\, ^{44}\text{Sc}$ (upper panel) and $\pi^+\, ^{45}\text{Sc} \to \pi^+\pi^+n\, ^{44}\text{Ca}$ (lower panel) at an incident projectile energy of 284 MeV.

which therefore is better suited for the discussion of the observed effects than the invariant mass distributions themselves.

Such an observable is useful to focus on the medium modification of meson properties. $C^A_{\pi\pi}$ in fact describes the clear effects of the nuclear medium on the $\pi\pi$ interacting system. The pion-production reaction in nuclei is a quasi-free process, which requires a single nucleon $\pi N \to \pi\pi N$ \cite{13}; therefore, the ratio of $\sigma(M_{\pi\pi}^A)$ to $\sigma(M_{\pi\pi}^N)$ is loosened from the reaction mechanism, and accordingly is $C^A_{\pi\pi}$. The normalization of $\sigma(M_{\pi\pi}^A)$ to $\sigma_T^A$ removes the dependence of $C^A_{\pi\pi}$ from the number of scattering centers in nuclei, since both terms depend equally on $A$. Furthermore, the limited acceptance of CHAOS should slightly affect $C^A_{\pi\pi}$ since the detector acceptance is the same for N and A. In order to verify such an assumption, the behavior of $C^A_{\pi\pi}$ was simulated for CHAOS (open histogram) and an ideal $4\pi$ detector (filled histogram), and the results of the simulations are shown in Fig. 2 for the $\pi^+\, ^{45}\text{Sc} \to \pi^+\pi^-p\, ^{44}\text{Sc}$ (upper panel) and $\pi^+\, ^{45}\text{Sc} \to \pi^+\pi^+n\, ^{44}\text{Ca}$ (lower panel) reactions at 284 MeV. The histograms were plotted without requiring any normalization, but the observables forming the nominator (denominator) of $C^A_{\pi\pi}$ were generated by feeding the Monte Carlo code with the same number of input events. The out-of-plane behavior of the $\pi N(A) \to \pi\pi N(A')$ reactions was accounted for by the model described in Ref.\cite{5} (and references therein quoted). The histograms display a monotonic decrease and nearly the same intensities at the varying of $M_{\pi\pi}$, with the exception of a shallow dip at $M_{\pi\pi} \sim 350$ MeV for the CHAOS distribution.
This convincingly demonstrates that $C_{\pi\pi}^A$ is both weakly related to the detector acceptance and nearly independent of the reaction channel.

Some models which describe the $\pi\pi$ dynamics in nuclear matter do not deal with the $\pi2\pi$ reaction mechanism nor account for the nuclear structure [11, 2, 3]. These models focus on understanding how nuclear matter alters the vacuum structure of QCD and the repercussions on the spectral properties of mesons and hadrons. Mesons are of prime interest because they are considered as the elementary $\bar{q}q$ excitation of the vacuum. In this framework, the observable $C_{\pi\pi}^A$ can be quantitatively compared to the model predictions. At the variance, the model quoted in Ref. [5], provides a comprehensive study of the $\pi A \rightarrow \pi\pi X$ reaction: it accounts for the elementary process of pion production $\pi N \rightarrow \pi\pi N$ as well as standard nuclear effects (Pauli blocking, Fermi motion, etc.). It also examines the effects of the nuclear environment on $J=I=0$ interacting pion pairs via the $P-$wave coupling of pions to particle − hole and $\Delta-$hole configurations [18]. The model, which embeds the CHAOS acceptance, predicts $\sigma(M_{\pi\pi}^{A(N)})$ and $\sigma_T^{A(N)}$ therefore $C_{\pi\pi}^A$ for the $\pi^+ \rightarrow \pi^+\pi^\pm$ reaction channels.

IV. THE A- AND T-DEPENDENCE OF $C_{\pi\pi}^A$

The error bars of the $C_{\pi\pi}^A$ data points plotted in figures from 3 to 5 account solely for statistical uncertainties, which primarily reflect those of measurements (2) and (3). The systematic uncertainties associated to $C_{\pi\pi}^A$ range from 15.0% (A-dependence, measurement (2)) to 16.7% (T-dependence, measurement (3)), which must be summed in quadrature with the statistical ones to obtain the overall uncertainties. The A-dependence of the composite ratio is reported in Fig. 3 for a projectile kinetic energy of 284 MeV. In the $\pi^+\pi^-$ channel, pion pairs largely ($\sim 95\%$) couple to $I=J=0$ quantum numbers [11, 19]; however, the fraction of $I=J=0$ pion pairs which couple to the $\sigma$-meson cannot be established by the present measurement. The pure isospin $I=2$ is instead always reached by $\pi^+\pi^+$ pairs. In this isospin channel, $C_{\pi\pi}^A$ barely depends on $A$: data overlap from $^2H$ to $^{208}Pb$ and the weak threshold enhancement is primarily due to phase space as denoted by the $C_{\pi\pi}^{Sc}$ behavior in Fig. 2 (see also discussion of Fig. 5). The $\sigma$-channel is characterized by a substantial dependence on $A$ but only for $A > 2$, when nuclear matter is realized. The $C_{\pi\pi}^A$ observable is compared with the model predictions of Ref. [5] for $A=^{40}Ca$ (continuous line). The agreement is good for the $\pi^+\pi^+$ channel, except for the low-energy part of the spectrum where the model calculations underestimate the data by nearly a factor of two. The model fails also to reproduce the threshold enhancement of $C_{\pi\pi}^A$ for the $\pi^+\pi^-$ channel, which indicates that the model fails to account for medium modification on pion pairs interacting in the $\sigma$-channel. In the framework of this model, an explanation of the threshold enhancement of $C_{\pi\pi}^A$ may be related to the modifications of the $\pi \rightarrow \pi\pi$ elementary amplitude inside nuclear matter. In fact, a modification of some pieces of this amplitude may modify the strong interferences present at threshold, thus causing a significant reshaping of $C_{\pi\pi}^A$. Studies are in progress.
The $T$-dependence study of $C_{\pi\pi}$ done for $A=^{45}\text{Sc}$ delivers the same general picture as the $A$-dependence, Fig. 4. A strong enhancement is observed for $C_{\pi\pi}$ in proximity of the $2m_{\pi}$ threshold for the isospin 0 channel (left panel), while $C_{\pi\pi}$ is flat over the $\pi\pi$ invariant mass range for $I=2$ (right panel). For a selected isospin channel, $C_{\pi\pi}$ depicts a behavior weakly varying with $T$. This is consistent with a previous study on the properties of the pion production reaction, which were based on the model calculation of Ref. [5]. The study shows that the average nuclear density ($\rho$) probed by incident pions barely changes from 240 to 320 MeV. In fact, $\rho \sim 0.36\rho_0$, which localizes the reaction to occur at the nucleus surface.

In order to compare the $C_{\pi\pi}$ distributions with similar results from other available theories [1, 2, 8], the $\pi 2\pi$ data must be normalized to their phase space. This is because such theories deal only with pion pairs in nuclear matter taking no regard to the reaction of pion production; therefore, to its phase space. Fig 5 depicts the $C_{\pi\pi}$ distributions divided by the reaction phase space, which also accounts for the CHAOS acceptance. In the $\pi^+\pi^+$ channel, $C_{\pi\pi}$'s are flatly distributed at around 1, and the distributions cannot factually be distinguished from $A=2$ to $A=208$. This clearly shows that the nuclear medium leaves the isospin 2 $\pi\pi$ interaction substantially unaltered. Strong medium modifications of the elementary $\pi\pi$ interaction are observed in the isospin 0 channel but only for $A > 2$; in fact, the $C_{\pi\pi}$ intensities display a sharp increase at around $2m_{\pi}$ solely for $^{12}\text{C}$, $^{40}\text{Ca}$ and $^{208}\text{Pb}$.
Figure 4: T-dependence of $C_{\pi\pi}^A$ as a function of the $\pi\pi$ invariant mass.

For $^2H$, $C_{\pi\pi}^A$ is a relatively flat distribution in $M_{\pi\pi}$, without any indication of a threshold enhancement.

For the examined nuclei, the composite ratio $C_{\pi\pi}^A$ is compared to the model predictions [1, 2, 3], which are normalized to the data at $M_{\pi\pi}>340$ MeV. The open diagram represents the results of Ref. [3] Fig. 7(a), for $\rho = 0.5\rho_0$. In this model, the threshold enhancement is due to collective P-wave pionic modes as well as S-wave pionic modes, which largely contributes to the intensity at around the $2m_\pi$ threshold. The P-wave modes are described by the standard phenomenology of nuclear physics; that is, the $P$-wave coupling of pions to particle–hole and $\Delta$–hole configurations. The collective S-wave modes are studied via the Linear $\sigma$ Model developed to account for finite nuclear densities; in this study, the parameter $\rho$ can vary from 0 to $2\rho_0$. The theory relates the $\pi\pi$ interaction in the scalar-isoscalar channel to the appearance of the $\sigma$-meson and, finally, to the partial restoration of chiral symmetry in the nuclear medium. The filled diagram in Fig. 5 is an earlier theoretical result [4], which is based on the existence of the $\sigma$-meson in nuclear matter ($\rho = \rho_0$), $\sigma$ being generated by the fluctuation of the $<\bar{q}q>$ chiral order parameter of QCD. The calculations depend on a complex parameter $\Phi(\rho)$, which for $\rho = \rho_0$ can vary from 0.7 to 0.9. In Fig. 5, $\Phi(\rho = \rho_0)=0.8$. In the theory, the $\sigma$-meson reflects its existence by means of a marked enhancement of the spectral function at $\sim 2m_\pi$, which is a phenomenon commonly associated to the (partial)
The above comparison between experimental results and theoretical predictions clearly indicates that the $\pi\pi$ interaction is strongly modified by the presence of nuclei solely for $I=J=0$ pion pairs. Furthermore, collective P-wave pion modes are far from explaining the strength at $\sim 2m_\pi$; i.e., predictions of $[5]$ reported in Fig. 3. On the other hand, the inclusion in the models of collective S-wave pionic modes is able to yield the requested threshold intensity even at $\rho < \rho_0$; i.e., calculations of Refs. $[1, 2, 3]$ reported in Fig. 5.

V. CONCLUSIONS

The data discussed in the present letter are the results of an extended campaign of measurements of the $\pi N(A) \rightarrow \pi\pi N(A')$ reactions at several intermediate energies, which involved the CHAOS collaboration at TRIUMF. Only charged pions were detected, which allowed the $\pi\pi$ system to be studied in the isospin 0 and 2 channels. The simultaneous study

Figure 5: A-dependence of $C^A_{\pi\pi}$ normalized to the $\pi A \rightarrow \pi\pi N[A - 1]$ phase space (PS) at an incident projectile energy of 284 MeV. The phase-space simulations embody the CHAOS acceptance. The open and filled diagrams are the result of the model predictions of $[3]$ and $[1]$, respectively, which are normalized to the data above 340 MeV.
of the two isospin channels was essential to establish the correct size of the \( \sigma \)-strength. The only observable employed to reduce the data was the composite ratio \( C^A_{\pi\pi} \), which accounts for the clear effect of the nuclear medium on final pion pairs. Such an observable is nearly independent of the detector acceptance.

In general, the nuclear medium has a negligible effect on the \((\pi\pi)^{I=2,J=0}\) system: the strength of the \( \pi\pi \) interaction appears nearly the same in the vacuum as well as in the nuclear medium. In fact, the \( C^A_{\pi\pi} \) distributions are planar at the varying of \( M_{\pi\pi} \) regardless of \( A \). In the \( \pi^+\pi^- \) channel, the \((\pi\pi)^{I=J=0}\) interaction is strongly modified by the medium even at moderate densities (i.e., \( \rho \sim \frac{1}{3}\rho_0 \)), except for \( A=2 \) when nuclear matter is not realized. The distinctive signature of medium modification is the \( C^A_{\pi\pi} \) threshold enhancement. These conclusions are common to all the examined energies, from 243 to 305 MeV. The \( C^A_{\pi\pi} \) distributions are finally compared to the theoretical predictions, which denote that the \( C^A_{\pi\pi} \) behavior is consistent with the effects of partial restoration of chiral symmetry in nuclear matter. Standard nuclear effects (such as Pauli blocking, Fermi motion, \( \pi N \) final-state interactions, etc.), or collective P-wave pionic modes are far from being able to explain the threshold enhancement.

The threshold enhancement found for \( C^A_{\pi^+\pi^-} \) in the \( \pi \to \pi\pi \) reaction \cite{11, 12} was also found in the \( \gamma \to \pi\pi \) reaction by the TAPS collaboration \cite{16}. In the latter case, gammas penetrate deeper into the nucleus thus being able to probe a nuclear density \( \rho \sim \frac{2}{5}\rho_0 \) for \(^{208}\text{Pb} \), which nearly doubles the density probed by the CHAOS measurements. Fig. 2 of Ref.\cite{16} shows the TAPS \( C_{\pi\pi} \) ratio in comparison with the CHAOS ratio; in this case, the lead data are scaled to the carbon data. At the 2m, threshold, the TAPS ratio exceeds by \( \sim 1.2 \) times the CHAOS ratio, which only partially reflects the higher density inspected by the TAPS measurements. On the other hand, Fig. 5 (left panel) yields \( C^A_{\pi\pi} \sim 8 \) at threshold for C or Ca, which tends to favor the picture of a rapidly raising \( \sigma \) formation as soon as an isospin 0 \( \pi\pi \) system establishes into the nuclear medium even of moderate density.

It is finally worthwhile commenting the results of a recent theoretical work on the \( \gamma \to \pi\pi \) reaction in nuclei\cite{21}. The model examines the production and propagation of pion pairs in nuclear matter by using a semi-classical approximation and by fully accounting for the final state interactions of pions with the nuclear medium. The latter are found to distort considerably the \( \pi\pi \) invariant mass distributions, which are then used for comparison to the TAPS data (i.e., Fig. 4 of Ref.\cite{21}). The model predictions are capable of describing the threshold behavior of the \( I=0 \) \( \gamma \to \pi^0\pi^0 \) reaction channel for both \(^{12}\text{C} \) and \(^{208}\text{Pb} \). The predictions from the same model however fail to reproduce the invariant mass distributions of the \( I=1 \) \( \gamma \to \pi^0\pi^+\pi^- \) channel. In fact, the curves show intensities 2-3 times higher than the data, and are 20-30 MeV downward peaked with respect to the experimental distributions. Regardless of the \( \pi\pi \) reaction channel, the mass distributions of Ref.\cite{21} depict nearly the same threshold behavior, exactly where the effects of medium modification are experimentally observed. In order to account for such effects on \( \pi\pi \) data, a model calculation must
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