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The $\pi \to \pi\pi$ 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 $\pi \to \pi\pi$ 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 $\mathcal{C}^A_{\pi\pi}$, which accounts for the clear effect of the nuclear medium on the $\pi\pi$ system. The comparison of the $\mathcal{C}^A_{\pi\pi}$ distributions for the $(\pi\pi)_{I=J=0}$ and $(\pi\pi)_{I=0,J=2}$ systems to the model predictions indicates that the $\mathcal{C}^A_{\pi\pi}$ behavior in proximity of the $2m_\pi$ threshold is explainable through the partial restoration of chiral symmetry in nuclei.

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measured invariant mass distributions, $C^A_{\pi\pi}$ composite ratio determined; deduced partial chiral symmetry restoration.

1. Introduction

Spectral properties of pion pairs interacting in the $I = J = 0$ channel (the σ-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 σ, a broad ($\Gamma \sim 500$ MeV) resonance centered at ~ 500 MeV, substantially reshapes in nuclear matter by forming a peak-like structure at around $2m_\pi$ [1–3]. The underlying theory regards the σ meson as a $\bar{q}q$ excitation of the QCD vacuum, in which the spontaneous breaking of the chiral symmetry leads to the σ–π mass difference. The sigma ($J^P = 0^+$) is also the chiral partner of the pion ($J^P = 0^-$). When the properties of the σ meson are studied in nuclear matter, the theory predicts a substantial change of the σ spectral function, which strongly reduces the σ–π 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 σ spectral function at around threshold is yielded by standard many-body correlations; i.e., the P-wave coupling of pions to *particle–hole* and *Δ–hole* states [2,3,5]. The combined effect of partial restoration and collective P-wave pionic modes produces a conspicuous enhancement of the σ spectral function at around the $2m_\pi$ threshold [2,3]. This letter presents further analysis of experimental results on the $\pi \to \pi\pi$ 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 σ-channel ($I = 0$) with respect to the non-resonant $I = 2$ channel. Finally, the data from the present measurements will directly probe the σ-spectral predictions around threshold and accordingly the underlying physics of chiral symmetry restoration.

The σ (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 $\sigma \to \pi\pi$ [6]. The σ broad structure makes this meson difficult to directly observe via the $\pi N \to \pi\pi N$ 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 σ [9]. A clear signature of σ 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 σ by means of two coincident $I = 0$ pions via the $\pi \to \pi\pi$ process appears appropriate.

The σ spectral properties are studied by means of the $\pi\pi$ invariant mass and the composite observable $\mathcal{C}^A_{\pi\pi}$, which is described in Section 3. In order to normalize this observable to pion production on the nucleon and explicitly consider the ratio for nuclei from ^{2}H 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. $\mathcal{C}^A_{\pi\pi}$ 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 ear-