In medium $\sigma$ meson effects in two pion photoproduction in nuclei.

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We show theoretical results for $(\gamma, \pi^0\pi^0)$ production on nucleons and nuclei in the kinematical region where the scalar isoscalar $\pi\pi$ amplitude is influenced by the $\sigma$ pole. The final state interaction of the pions modified by the nuclear medium produces a spectacular shift of strength of the two pion invariant mass distribution induced by the moving of the $\sigma$ pole to lower masses and widths as the nuclear density increases.

1. INTRODUCTION

In the last years there has been an intense theoretical and experimental debate about the nature of the $\sigma$ meson, mostly centered on the discussion about its interpretation as an ordinary $q\bar{q}$ meson or a $\pi\pi$ resonance. The advent of $\chi PT$ showed up that the $\pi\pi$ interaction in s-wave in the isoscalar sector is strong enough to generate a resonance through multiple scattering of the pions. This seems to be the case, and even in models starting with a seed of $q\bar{q}$ states, the incorporation of the $\pi\pi$ channels in a unitary approach leads to a large dressing by a pion cloud which makes negligible the effects of the original $q\bar{q}$ seed. This idea has been made more quantitative through the introduction of the unitary extensions of $\chi PT$ ($U\chi PT$). Even more challenging is the modification of the properties of the $\sigma$ meson at finite nuclear density. Since present theoretical calculations agree on a sizeable modification in the nuclear medium of the $\pi\pi$ scattering in the $\sigma$ region our purpose here is to find out its possible experimental signature in a very suited process like the $(\gamma, \pi^0\pi^0)$ reaction in nuclei. (This contribution is a summary of the more extended work [1].) This reaction is much better suited than the $(\pi, \pi\pi)$ one to investigate the modification of the $\pi\pi$ in nuclear matter because the photons are not distorted by the nucleus and the reaction can test higher densities.

2. MODEL

For the model of the elementary $(\gamma, \pi\pi)$ reaction we follow [3] which considers the coupling of the photons to mesons, nucleons, and the resonances $\Delta(1232)$, $N^*(1440)$, $N^*(1520)$ and $\Delta(1700)$. This model relies upon tree level diagrams. Final state interaction of the $\pi N$ system is accounted for by means of the explicit use of resonances with their...
widths. However, since we do not include explicitly the $\sigma$ resonance, the final state interaction of the two pions has to be implemented to generate it.

The $\gamma N \rightarrow N\pi^0\pi^0$ amplitude can be decomposed in a part which has in the final state the combination of pions in isospin $I=0$ and another part where the pions are in $I=2$.

$$|\pi_1^0\pi_2^0\rangle = \frac{1}{3}|\pi_1^0\pi_2^0 + \pi_1^+\pi_2^- + \pi_1^-\pi_2^+\rangle_{I=0 \text{ part}} - \frac{1}{3}|\pi_1^0\pi_2^0 + \pi_1^+\pi_2^- + \pi_1^-\pi_2^+\rangle_{I=2 \text{ part}} + |\pi_1^0\pi_2^0\rangle \\ (1)$$

The renormalization of the $I = 0 (\gamma, \pi\pi)$ amplitude is done by factorizing the on shell tree level $\gamma N \rightarrow \pi\pi N$ and $\pi\pi \rightarrow \pi\pi$ amplitudes in the loop functions.

$$T_{(\gamma,\pi^0\pi^0)}^{I=0} \rightarrow T_{(\gamma,\pi^0\pi^0)}^{I=0} \left(1 + G_{\pi\pi}t_{\pi\pi}^{I=0}(M_f)\right) \quad (2)$$

where $G_{\pi\pi}$ is the loop function of the two pion propagators, which appears in the Bethe-Salpeter equation, and $t_{\pi\pi}^{I=0}$ is the $\pi\pi$ scattering matrix in isospin $I=0$, taken from \[3\].

The multiple scattering of the two final pions can be accounted for by means of the Bethe-Salpeter equation,

$$t = V + VG_{\pi\pi}t$$

where $V$ is given by the lowest order chiral amplitude for $\pi\pi \rightarrow \pi\pi$ in $I = 0$ and $G_{\pi\pi}$, the loop function of the two pion propagators can be regularized by means of a cut off or with dimensional regularization. In both approaches it has been shown that $V$ factorizes with its on shell value in the Bethe-Salpeter equation. Hence, in the Bethe-Salpeter equation the integral involving $Vt$ and the product of the two pion propagators affects only these latter two, since $V$ and $t$ factorize outside the integral, thus leading to Eq. (3) where $VG_{\pi\pi}t$ is the algebraic product of $V$, the loop function of the two propagators, $G_{\pi\pi}$, and the $t$ matrix.

When we renormalize the $I=0$ amplitude in nuclei to account for the pion final state interaction, we change $G$ and $t_{I=0}^{I=0}$ by their corresponding results in nuclear matter \[4\] evaluated at the local density. In the model of \[3\], the $\pi\pi$ rescattering in nuclear matter was done renormalizing the pion propagators in the medium and introducing vertex corrections for consistency.

In the model for $(\gamma, 2\pi)$ of \[2\] there are indeed contact terms as implied before, as well as other terms involving intermediate nucleon states or resonances. In this latter case the loop function involves three propagators but the intermediate baryon is far off shell an the factorization of Eq. (2) still holds. There is, however, an exception in the $\Delta$ Kroll Ruderman term, since as we increase the photon energy we get closer to the $\Delta$ pole. For this reason this term has been dealt separately making the explicit calculation of the loop with one $\Delta$ and two pion propagators.

The cross section for the process in nuclei is calculated using many body techniques. From the imaginary part of the photon selfenergy diagram with a particle-hole excitation and two pion lines as intermediate states, the cross section can be expressed as
\[ \sigma = \frac{\pi}{k} \int d^3 \vec{r} \int \frac{d^3 \vec{q}_1}{(2\pi)^3} \int \frac{d^3 \vec{q}_2}{(2\pi)^3} F_1(\vec{r}, \vec{q}_1) F_2(\vec{r}, \vec{q}_2) \frac{1}{2\omega(\vec{q}_1)} \frac{1}{2\omega(\vec{q}_2)} \]

\[ \cdot \sum_{s_i, s_f pol} |T|^2 n(\vec{p})[1 - n(\vec{k} + \vec{p} - \vec{q}_1 - \vec{q}_2)] \]

\[ \cdot \delta(k^0 + E(\vec{p}) - \omega(\vec{q}_1) - \omega(\vec{q}_2) - E(\vec{k} + \vec{p} - \vec{q}_1 - \vec{q}_2)) \]

where the factors \( F_i(\vec{r}, \vec{q}_i) \) take into account the distortion of the final pions in their way out through the nucleus and are given by

\[ F_i(\vec{r}, \vec{q}_i) = \exp \left[ \int_{\vec{r}_i}^{\infty} dl_i \frac{1}{|\vec{q}_i|} Im \Pi(\vec{r}_i) \right] \]

\[ \vec{r}_i = \vec{r} + l_i \frac{\vec{q}_i}{|\vec{q}_i|} \]

where \( \Pi \) is the pion selfenergy, taken from a model based on an extrapolation for low energy pions of a pion-nucleus optical potential developed for pionic atoms using many body techniques. The imaginary part of the potential is split into a part that accounts for the probability of quasielastic collisions and another one which accounts for the pion absorption. With this approximation the pions which undergo absorptions are removed from the flux but we do not remove those which undergo quasielastic collisions since they do not change in average the shape or the strength of the \( \pi \pi \) invariant mass distribution.

3. RESULTS

In the figure we can see the results for the two pion invariant mass distributions in the \((\gamma, \pi^0\pi^0)\) and \((\gamma, \pi^+\pi^0)\) reactions on \(^1H\), \(^{12}C\) and \(^{208}Pb\). The difference between the solid and dashed curves is the use of the in medium \( \pi\pi \) scattering and \( G \) function instead of the free ones, which we take from [3]. As one can see in the figure, there is an appreciable shift of strength to the low invariant mass region due to the in medium \( \pi\pi \) interaction. This shift is remarkably similar to the one found in the preliminary measurements of [4]. This shift is not seen in the \((\gamma, \pi^+\pi^0)\) channel because the \( \pi^\pm\pi^0 \) are not allowed to be in isospin \( I=0 \).

These results show a clear signature of the modified \( \pi\pi \) interaction in the medium. The fact that the photons are not distorted has certainly an advantage over the pion induced reactions and allows one to see inner parts of the nucleus.

Although we have been discussing the \( \pi\pi \) interaction in the nuclear medium it is clear that we can relate it to the modification of the \( \sigma \) in the medium. We have mentioned that the reason for the shift of strength to lower invariant masses in the mass distribution is due to the accumulated strength in the scalar isocalar \( \pi\pi \) amplitude in the medium. Yet, this strength is mostly governed by the presence of the \( \sigma \) pole and there have been works suggesting that the sigma should move to smaller masses and widths when embedded in the nucleus. The present results represent an evidence of the move of pole position of the \( \sigma \) moves to smaller energies as the nuclear density increases, a phenomenon which would come to strengthen once more the nature of the \( \sigma \) meson as dynamically generated by the multiple scattering of the pions through the underlying chiral dynamics.
Figure 1. Two pion invariant mass distribution for $\pi^0\pi^0$ and $\pi^+\pi^-\pi^0$ photoproduction in $^{12}C$ and $^{208}Pb$. Continuous lines: using the in medium final $\pi\pi$ interaction. Dashed lines: using the final $\pi\pi$ interaction at zero density. Exp. data from [4].

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