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Investigation of in-medium ω photoproduction

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Abstract. Recent experimental results on the in-medium modification of the ω meson are discussed. The experiment described was performed at the ELSA accelerator facility in Bonn using the combined detector system of Crystal Barrel and TAPS. The ω-meson was identified via the reaction $\gamma + A \rightarrow \omega + X \rightarrow \pi^0\gamma + X$.

Keywords. Photoproduction reactions; properties of mesons.

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1. Introduction

The measured dilepton enhancement below the ρ-meson mass in heavy-ion collisions relative to the expected yield from the known *pp* sources has motivated widespread activities in understanding the modification of hadronic properties in hot and/or dense matter, both on the experimental and theoretical sides. In fact, a variety of theoretical models are currently being discussed. However, the discussion in the literature is very controversial. The predictions for a downward shift of the ω-meson mass at normal nuclear matter density ρ_0, for example, vary within the range of 640 to 765 MeV [1–4] (compared to the vacuum mass of 782 MeV). But even upward shifts of the mass [5] as well as the appearence of additional peaks [6] or no mass shift and only a broadening of the width [7] are currently under debate. This emphasizes the need of experimental data for clarification.

In fact, during the past decade several experiments studying the in-medium behaviour of vector mesons in hot and dense matter have been performed. The CERES experiment at CERN, for example, has found a considerable excess of dilepton pairs in the mass range of $0.3 \leq m_{e^+e^-} \leq 0.7$ GeV in heavy-ion collisions relative to the known sources (hadronic cocktail) in *pp* collisions [8,9]. The KEK-PS E325 Collaboration in Japan investigated $p + A$ reactions at 12 GeV and reported an enhancement in the e^+e^- invariant mass spectra in the region of $0.55 \leq m_{e^+e^-} \leq 0.77$ GeV [10]. Presently an experiment performed at JLAB using a photon beam and different nuclear targets is being analyzed [11]. At GSI, it has been proposed [12] to perform pion-induced experiments with the HADES [13] detector system.

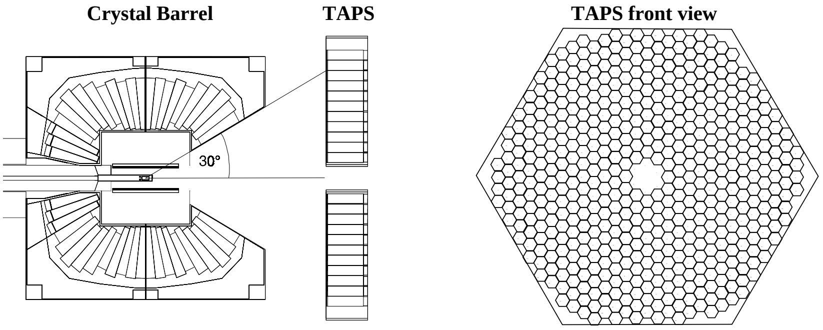

Figure 1. Experimental set-up: the Crystal Barrel detector consisting of 1290 CsI(Tl) scintillators was combined with the photon spectrometer TAPS, providing an almost 4π solid angle coverage.

1.1 *The* $\omega \to \pi^0\gamma$ *decay mode*

All experiments mentioned above investigate the in-medium behaviour of vector mesons via the dileptonic decay mode. This approach is ideal and clean in a sense that the leptonic decay products do not feel the strong force. Hence the invariant mass of the mesons can be reconstructed from the measured and undistorted 4-momentum vectors of the leptons (no strong final-state interaction). However, all e^+e^- experiments suffer from the small branching ratios (BR) of vector mesons (ρ, ω) into dileptons which is in the order of $10^{-5} - 10^{-4}$. The comparable decay rates of the ρ- and ω-mesons imply a superposition of the ω in-medium signal with the theoretically predicted broad and smeared out ρ-meson distribution (i.e. [1]). The extraction of an isolated ω in-medium signal is hence rather difficult.

An alternative and promising approach to study in-medium modifications of the ω-meson is the $\omega \to \pi^0 + \gamma$ decay mode, as pointed out in [14–16]. One essential advantage of this decay channel is the large BR of almost 9%. This is three orders of magnitude larger than the BR in the dilepton (e^+e^-) final state. Furthermore, this mode is a clean and exclusive way to study ω in-medium properties since the $\rho \to \pi^0\gamma$ BR is only $6.8 \cdot 10^{-4}$ (suppression by two orders of magnitude relative to the ω BR). The drawback, however, is a possible rescattering of π^0 within the nuclear medium, thereby changing the pion momentum and thus distorting the deduced ω invariant mass (final-state interactions). This effect has been investigated in detail [14]. Fortunately, the fraction of distorted events in the range of $0.6 < M_{\pi^0\gamma} < 0.85$ GeV is only a few per cent. This is mainly due to the kinematics of the decay of Δ resonance. Pions rescatter in nuclei predominately via the formation of an intermediate Δ resonance. The subsequent decay of Δ emits pions with low momenta. Thus the reconstructed $\pi^0\gamma$ invariant mass is small, centered approximately around 400 MeV. This result has recently been confirmed by an independent calculation [15], also claiming the feasibility of the proposed experiment.

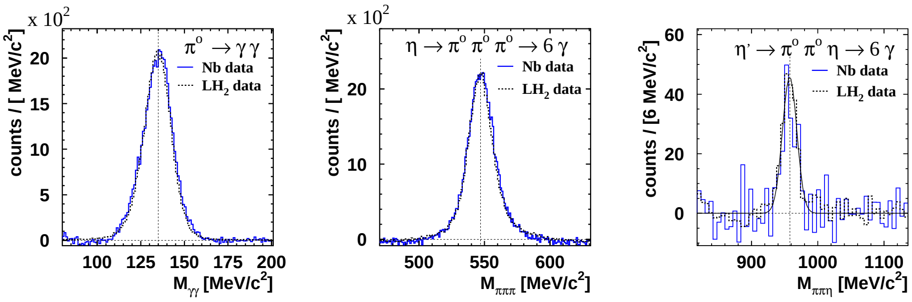

Figure 2. Background subtracted invariant mass distributions for the long-lived mesons π^0, η and η' which are used as a calibration check. The solid blue and dashed black histograms correspond to data taken with a Nb and LH_2 target, respectively (in addition, the Monte Carlo line shape for the η'-meson is shown as a solid curve). Further details are given in the text.

2. The CBELSA/TAPS experiment

Motivated by the predicted results reported in [14] the experiment was carried out at the ELectron Stretcher Accelerator (ELSA) in Bonn. Bremsstrahlung photons in the tagged range of 640 to 2530 MeV have been produced by the continuous 2.8 GeV electron beam from ELSA impinging on a radiator foil. The photon energy $E_\gamma = E_\mathrm{e} - E'_\mathrm{e}$ was determined event-by-event from the incident electron beam energy E_e and the energy E'_e of the scattered electron measured with a magnetic spectrometer (tagger). The detector system is shown in figure 1. The Crystal Barrel detector (CB) is a photon calorimeter consisting of 1290 CsI(Tl) crystals ($\sim$16 radiation lengths X_0). In this set-up the CB covered 30° up to 168° in the polar angle and the complete azimuthal angle. Between CB and the target a three-layer scintillating fiber detector (513 fibers of 2 mm thickness) was installed for charged particle identification. Reaction products emitted in forward direction were detected in TAPS, a detector consisting of 528 hexagonally shaped BaF_2 detectors ($\sim 12X_0$) covering polar angles between 4° and 30° and the complete azimuthal angle. In front of each BaF_2 module a 5 mm thick plastic scintillator was mounted for the identification of charged particles. The resulting geometrical solid angle coverage of the combined system was 99% of 4π. The Nb target had 1 mm thickness. The LH_2 target, used as a reference measurement, had a thickness of 53 mm. Both had 30 mm diameter. For further details, see [17–19].

3. Results

The invariant masses of the mesons were calculated from the measured 4-momenta of the decay photons. Clearly, only mesons decaying inside the nuclear medium may be in-medium modified. Hence a criterion for observing in-medium properties is that the decay length ($\gamma\beta c\tau$) should be in the order of the nuclear radius (some fm). The long-lived mesons π^0 ($c\tau = 25.1$ nm), η ($c\tau = 0.15$ nm), and η' ($c\tau = 0.001$ nm)

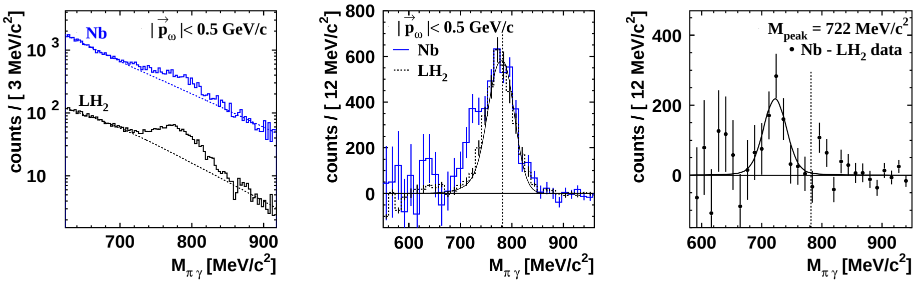

Figure 3. Left panel: Inclusive $\pi^0\gamma$ invariant mass spectra for ω-momenta less than 500 MeV. Upper histogram: Nb data, lower histogram: LH$_2$ target reference measurement. The dashed lines indicate fits to the respective background. Center panel: $\pi^0\gamma$ invariant mass for the Nb data (solid blue histogram) and LH$_2$ data (dashed black histogram) after background subtraction. The error bars show statistical uncertainties only. The solid curve represents the simulated lineshape for the LH$_2$ target. Right panel: In-medium decays of ω-mesons along with a Voigt fit to the data (see text). The vertical line indicates the vacuum ω mass of 782 MeV.

do not decay inside the nucleus. Consequently, they are ideal candidates to carefully cross-check the calibrations for the two data samples: the Nb data, and the reference LH$_2$ measurement. Figure 2 shows the comparison of the background subtracted invariant mass distributions for $\pi^0 \to \gamma\gamma$, $\eta \to \pi^0\pi^0\pi^0 \to 6\gamma$ and $\eta' \to \pi^0\pi^0\eta \to 6\gamma$. Indeed, no difference in the line shapes is observed. In addition, the meson line shapes are reproduced by Monte Carlo simulations. This is demonstrated in figure 2 only for the η'-meson, since due to the abundant statistics of the π^0- and η-mesons the difference in the line shape is not visible. Thus, in figure 2 an additional curve can be seen only for the η'-meson.

The ω-meson, on the other hand, has a finite decay probability inside the nuclear medium, which can be further increased by gating on mesons with low momentum. When investigating the $\omega \to \pi^0\gamma$ invariant mass distribution, we find a significant change in the line shape for the two data samples. The left panel of figure 3 shows the $\pi^0\gamma$ invariant mass with no further cuts applied except a three-momentum cut-off of $|\vec{p}_\omega| < 500$ MeV. The central panel of figure 3 shows the invariant mass distribution obtained after background subtraction (indicated as dashed lines in the left panel). We observe the expected superposition of decays outside the nucleus at the nominal vacuum mass with decays occurring inside the nucleus, responsible for the shoulder towards lower invariant masses. Again, at least for the LH$_2$ data, the background subtraction is supported via Monte Carlo simulation (solid curve). The enhancement toward lower invariant masses is attributed to an in-medium modification of the ω-meson in dense matter. The high mass part of the ω-mass signal appear identical for the Nb and LH$_2$ targets, indicating that this part is dominated by ω-meson decays in vacuum. These decays are eliminated by matching the right-hand part of the Nb invariant mass spectrum to the LH$_2$ data and then subtracting the two spectra from each other. For this normalization the integral of the undistorted spectrum corresponds to 75% of the counts in the Nb spectrum,

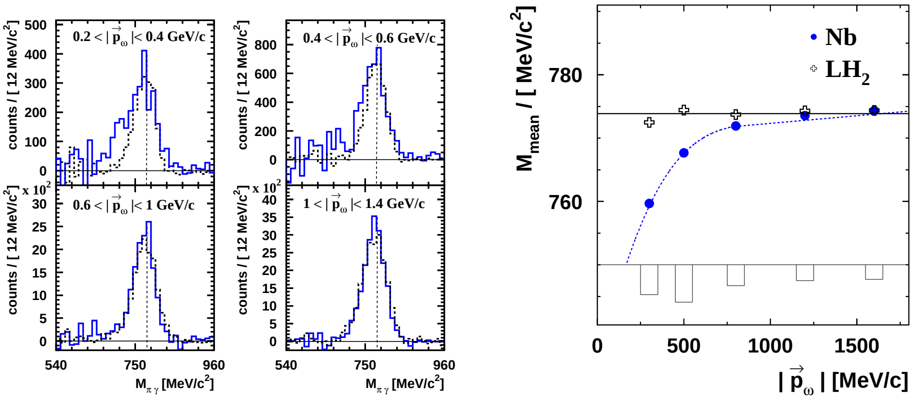

Figure 4. Left: $\pi^0\gamma$ mass spectrum after background subtraction and FSI suppression ($T_{\pi^0} > 150$ MeV) for different ω-momentum bins. Solid blue histogram: Nb data, dashed black histogram: LH$_2$ data. Right: Mean value of the $\pi^0\gamma$ invariant mass as a function of the ω-momentum at an estimated average density of $0.6\rho_0$ for the Nb data (circles) and the LH$_2$ data (crosses) along with a fit.

in line with a theoretical prediction obtained from a transport code calculation [15,20]. The resulting in-medium signal is shown in the right panel of figure 3. A Voigt fit (Breit–Wigner folded with Gaussian) to the data within this scenario yields a change of the ω in-medium mass to $M_{\text{medium}} = [722^{+4}_{-4}(\text{stat.})^{+35}_{-5}(\text{syst.})]$ MeV. The in-medium width is governed by the experimental resolution of $\Gamma = 55$ MeV (FWHM). This result corresponds to a lowering of the ω-mass by 8% with respect to the vacuum value at an estimated average nuclear density of $0.6\rho_0$ [14]. Consistency with a scaling of the ω-mass by $m = m_0(1 - 0.14\frac{\rho}{\rho_0})$ is found [21]. The systematic uncertainty mainly reflects different assumptions for the subtraction of decays of the ω-mesons in vacuum. The fraction of these decays was varied within a broad range from 80 to 45% (the central and right panel of figure 3 correspond to 75%). The case with 45% corresponds to the upper bound of the systematic uncertainty (+35 MeV). This extreme scenario would, however, require an increase of the in-medium width of ω by almost an order of magnitude.

Furthermore, the dependence of the signal on the ω-momentum has been studied. It is expected that only low-momentum ω-mesons (with a corresponding low velocity) decay inside the nucleus and carry information on the in-medium properties of the ω-meson. The left panel of figure 4 shows the $\pi^0\gamma$ invariant mass distribution after background subtraction and FSI suppression ($T_{\pi^0} > 150$ MeV) for different ω-momentum bins. A pronounced modification of the line shape is only observed for ω-momenta in the range of 200 MeV $< |\vec{p}_\omega| <$ 400 MeV. The right panel of figure 4 shows the mean value of the mass distribution vs. the 3-momentum of the ω-meson for the LH$_2$ and the Nb data, indicating a momentum dependence of the extracted ω-meson signal for the Nb data and a flat distribution, as expected, for the LH$_2$ measurement. This result might allow one to extract the momentum dependence of the ω-nucleus potential [15,20].

4. Conclusions

We have investigated the in-medium modifications of ω-mesons in photoproduction experiments using the Crystal Barrel/TAPS detector at the ELSA accelerator facility in Bonn. While for the long-lived π^0-, η- and η'-mesons no difference in the line shape is observed when comparing data from a LH_2 and Nb target, respectively, we find a pronounced modification of the ω-meson mass. This mass shift is observed for ω-mesons with momenta less than 500 MeV. The in-medium mass is determined to be $M_{\text{medium}} = [722^{+4}_{-4}(\text{stat.})^{+35}_{-5}(\text{syst.})]$ MeV at an estimated average nuclear density of $0.6 \cdot \rho_0$. The width is found to be within the experimental resolution of $\Gamma = 55$ MeV. The momentum dependence of ω-meson has also been studied. As expected, only low-momentum ω-mesons contribute to the downward mass shift. In contrast, ω-mesons with high momenta decay outside the nucleus. First evidence for a lowering of the ω-mass in the nuclear medium has been observed.

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