First observation of in-medium modifications of the ω meson

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The photoproduction of ω mesons on nuclei has been investigated using the Crystal Barrel/TAPS experiment at the ELSA tagged photon facility in Bonn. The aim is to study possible in-medium modifications of the ω meson via the reaction $\gamma + A \rightarrow \omega + X \rightarrow \pi^0\gamma + X'$. Results obtained for Nb are compared to a reference measurement on a LH_2 target. While for recoiling, long-lived mesons (π^0, η and η'), which decay outside of the nucleus, a difference in the lineshape for the two data samples is not observed, we find a significant enhancement towards lower masses for ω mesons produced on the Nb target. For momenta less than 500 MeV/c an in-medium ω meson mass of $\mathrm{M_{medium}} = [722^{+2}_{-2}(\mathrm{stat})^{+35}_{-5}(\mathrm{syst})]$ MeV/c^2 has been deduced at an estimated average nuclear density of 0.6 ρ_0.

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The modification of experimentally observable properties of vector mesons such as mass and width, when embedded in a dense medium, is one of the most fundamental research issues in hadron physics. While for composite systems like molecules, atoms or nuclei, the mass of the system is almost completely (apart from small binding energy effects) governed by the sum of the masses of the constituents, this is no longer true in the hadronic sector. Here, the hadron masses are much larger than the summed masses of the constituents, the u-, d- and s-quarks. One possible interpretation is that the masses of hadrons are generated dynamically [1]. Furthermore, hadron masses can be associated with the spontaneous breaking of chiral symmetry. In nuclear matter (and at high temperatures) this symmetry is predicted to be at least partially restored. As a consequence, the properties of hadrons are expected to be modified (see e.g. [2, 3, 4, 5, 6]).

A variety of theoretical models predict a lowering of the in-medium mass of vector mesons even at normal nuclear matter density ρ_0. For the ω meson a drop of the mass by 20 to 150 MeV/c^2 and a broadening of the width up to 60 MeV/c^2 has been predicted (e.g. [7, 8, 9, 10, 11, 12]). However, the discussion in the literature is very controversial. Even upward mass shifts [13] or the appearance of additional peaks [14] have been suggested by some authors. This situation underlines the importance of experimental results.

Several previous experiments have studied the properties of vector mesons in hot and dense matter. Dilepton spectroscopy allows to measure the in-medium properties without distortion due to final state interactions

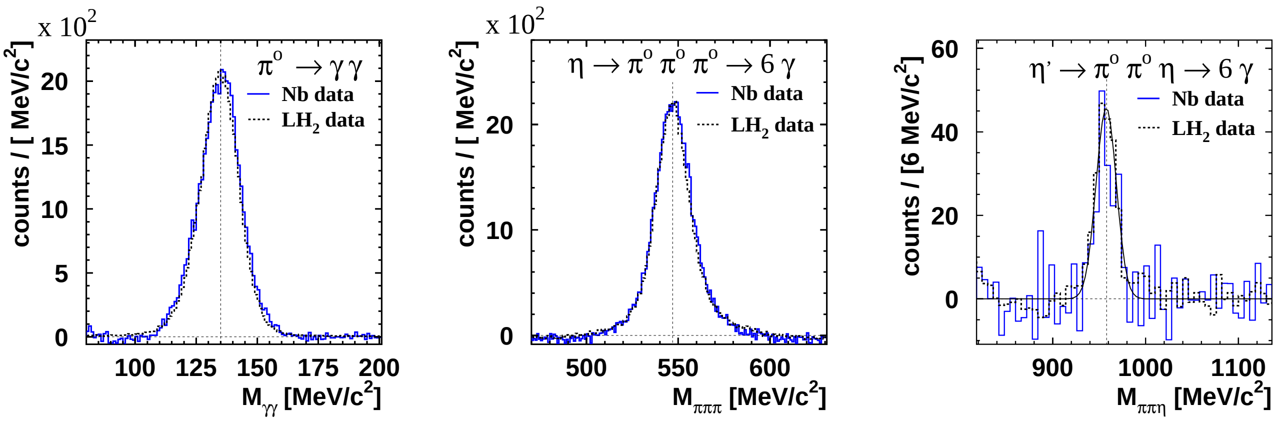

FIG. 1: (color online). Background subtracted invariant mass distributions for the long-lived mesons π^0, η and η'. The solid and dashed histograms correspond to data taken with a Nb and LH_2 target, respectively. The meson lineshapes are reproduced by Monte Carlo simulations, as demonstrated for the η' signal (solid curve).

(FSI). The CERES collaboration at CERN, for example, measured the low-mass e^+e^- pair production in heavy-ion collisions and observed an enhancement in the mass range of 0.3 GeV/c^2 $\leq \mathrm{m_{e^+e^-}} \leq$ 0.7 GeV/c^2 over the yield expected from the known sources in pp collisions [15, 16]. More recently, analyzing $\pi^+\pi^-$ pairs the STAR experiment at RHIC observed a decrease of the ρ meson in-medium mass in peripheral Au+Au collisions [17]. The KEK-PS E325 collaboration investigated $p + A$ reactions at 12 GeV [18] and reported an enhancement in the e^+e^- invariant mass spectra in the region of 0.6 GeV/c^2 $\leq \mathrm{m_{e^+e^-}} \leq$ 0.77 GeV/c^2. Presently, an experiment performed at JLAB using a photon beam is being analyzed [19]. At GSI, it has been proposed [20] to perform pion induced experiments with the HADES [21] detector system.

All e^+e^- experiments suffer from the small branching ratios (BR) of vector mesons into dileptons, which are in the order of $10^{-5} - 10^{-4}$. In addition, the comparable e^+e^- decay rates for ω- and ρ mesons make it difficult to isolate an ω signal from the e^+e^- invariant mass spectrum [9]. An alternative and promising approach to investigate in-medium modifications of the ω meson is to study the $\omega \to \pi^0\gamma$ decay mode, as pointed out in [22, 23, 24]. An essential advantage of this decay channel is the large BR of almost 9%, three orders of magnitude larger than the decay into dileptons. Furthermore, this mode is a clean and exclusive probe to study the ω in-medium properties since the $\rho \to \pi^0\gamma$ BR is only $6.8 \cdot 10^{-4}$ and therefore suppressed by two orders of magnitude relative to the ω BR into this channel. However, the disadvantage is a possible rescattering of the π^0 within the nuclear medium, which would distort the deduced ω invariant mass distribution. Pion rescattering within the nucleus proceeds predominately via the formation of an intermediate Δ resonance. Due to the kinematics of the Δ resonance decay the distorted events are predicted to accumulate at approx. 500 MeV/c^2, far below the nominal ω invariant mass. This leads to a small contribution of only about 3% in the mass range of interest, 0.6 GeV/c^2 $< \mathrm{M}_{\pi^0\gamma} <$ 0.9 GeV/c^2. Moreover, the authors of [22] and [23] have demonstrated that the constraint on the kinetic energy $T_{\pi^0} > 150$ MeV suppresses the FSI down to the 1% level.

Only ω mesons decaying inside the nucleus carry information on the in-medium properties. To enhance the in-medium decay probability, the vector meson decay length $L_\omega = p_\omega/m_\omega\Gamma_\omega$ should be less than the nuclear radius. This can be achieved by applying a kinematic cut on the 3-momentum of the ω meson. But still, only a fraction of the ω mesons will decay inside the nucleus. Thus, one expects the $\pi^0\gamma$ invariant mass spectra to show a superposition of decays outside of the target at the vacuum mass peak position (782 MeV/c^2) with modified decays inside the nucleus [22].

The experiment was performed at the **EL**ectron **S**tretcher **A**ccelerator (ELSA) in Bonn, using a 2.8 GeV electron beam. The photon beam was produced via bremsstrahlung. A magnetic spectrometer (tagger) was used to determine the photon beam energies within the tagged photon range of 0.64 to 2.53 GeV. The Nb and LH_2 targets had thicknesses of 1 mm and 53 mm, respectively, and 30 mm in diameter. The targets were mounted in the center of the Crystal Barrel detector (CB), a photon calorimeter consisting of 1290 CsI(Tl) crystals (~ 16 radiation lengths X_0) with an angular coverage of 30° up to 168° in the polar angle and a complete azimuthal angle coverage. Inside the CB, covering its full acceptance, a three-layer scintillating fiber detector (513 fibers of 2 mm diameter) was installed for charged particle identification. Reaction products emitted in forward direction were detected in the TAPS detector. TAPS consisted of 528 hexagonally shaped BaF_2 detectors (~ 12 X_0) covering polar angles between 4° and 30° and the complete 2π 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 com-

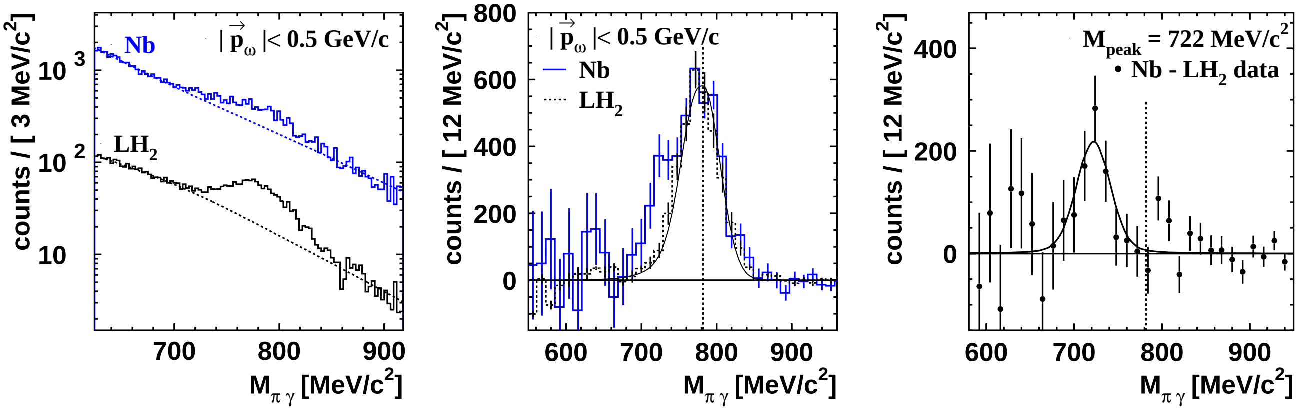

FIG. 2: (color online). Left panel: Inclusive $\pi^0\gamma$ invariant mass spectra for ω momenta less than 500 MeV/c. Upper histogram: Nb data, lower histogram: LH_2 target reference measurement. The dashed lines indicate fits to the respective background. Center panel: $\pi^0\gamma$ invariant mass for the Nb data (solid histogram) and LH_2 data (dashed 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/c^2.

bined system was 99% of 4π. The BaF_2 crystals were read out by photomultipliers providing a fast trigger, the CsI(Tl) crystals via photodiodes. For further details see [25, 26, 27].

The invariant masses of the mesons were calculated from the measured 4-momenta of the decay photons. The calibration of the Nb and LH_2 data samples was carefully cross checked by comparing the lineshapes for long-lived mesons, the π^0, η, and η'. The decay lengths ($c\tau$) of 25.1 nm (π^0), 0.153 nm (η), and 0.001 nm (η') guarantee that these pseudoscalar mesons will not decay inside the nucleus, hence the lineshapes should not exhibit any difference for the two data samples. Fig. 1 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, a difference in the lineshapes is not observed. However, when comparing the $\omega \to \pi^0\gamma$ invariant mass distributions, we find a significant change in the lineshapes. The left panel of Fig. 2 shows the $\pi^0\gamma$ invariant mass distribution without further cuts except for a three momentum cutoff of $|\vec{p}_\omega| < 500$ MeV/c. The dominant background source is two pion production where one of the four photons escapes the detection. This probability was determined by Monte Carlo simulations to be 14%. The resulting three photon final state is not distinguishable from the $\omega \to \pi^0\gamma$ invariant mass. The central panel of Fig. 2 shows the invariant mass distribution obtained after background subtraction. We observe the expected superposition of decays outside of the nucleus at the nominal vacuum mass with decays occuring inside the nucleus, responsible for the shoulder towards lower invariant masses. The high mass part of the ω mass signal appears 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 (see central panel of Fig. 2) and by 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. This is in good agreement with a theoretical prediction obtained from a transport code calculation [23, 28]. There, about 16% of the total decays are predicted to occur inside the nuclear medium ($\rho > 0.1 \cdot \rho_0$) without any FSI and 3% of the events are distorted due to FSI in the mass range of 0.6 GeV/c^2 $< M_{\pi^0\gamma} <$ 0.9 GeV/c^2. In addition, 9% of the events are moved towards lower masses due to the Δ decay kinematics. The right panel of Fig. 2 shows the resulting in-medium signal along with a Voigt fit (Breit-Wigner folded with Gaussian) to the data. We obtain an ω in-medium mass of $M_{\rm medium} = [722^{+2}_{-2}({\rm stat})^{+35}_{-5}({\rm syst})]$ MeV/c^2. This 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 ρ_0 in line with the assumptions in [22]. Consistency with a scaling of the ω-mass by $m = m_0(1 - 0.14\rho/\rho_0)$ is found [4]. Within this scenario the width is governed by the experimental resolution of $\Gamma = 55$ MeV/c^2 (FWHM). 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 Fig. 2 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 the 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 ve-

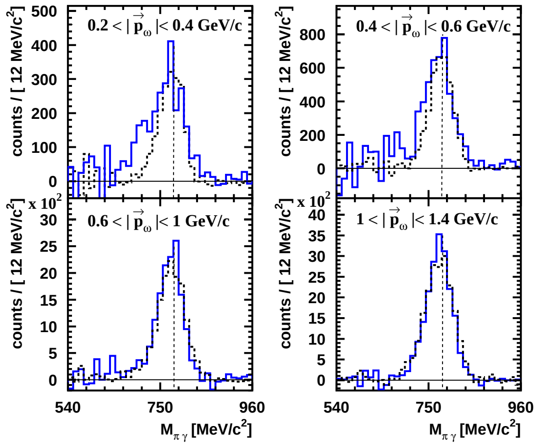

FIG. 3: (color online). $\pi^0\gamma$ mass spectrum after background subtraction and FSI suppression ($T_{\pi^0} > 150$ MeV) for different ω momentum bins. Solid histogram: Nb data, dashed histogram: LH_2 data.

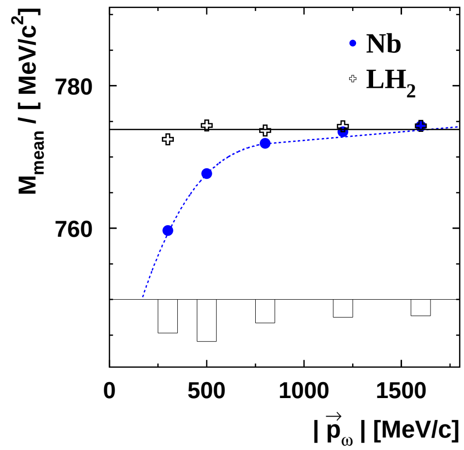

FIG. 4: (color online). Mean value of the $\pi^0\gamma$ invariant mass as a function of the ω momentum at an estimated average density of 0.6 ρ_0 for the Nb data (circles) and the LH_2 (crosses) along with a fit. The systematic errors are determined by varying the integration range of 0.65 GeV/c^2 < $M_{\pi^0\gamma}$ < 0.9 GeV/c^2 by 50 MeV/c^2 and are shown as a bar chart for the Nb data. In contrast to the peak positions the mean values do not reach the nominal vacuum mass of 782 MeV/c^2 due to the detector response function.

locity) decay inside the nucleus and carry information on the in-medium properties of the ω meson. Fig. 3 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 lineshape is only observed for ω momenta in the range of 200 MeV/c $< |\vec{p_\omega}| <$ 400 MeV/c. In Fig. 4 the mean value of the mass distribution is plotted against the three momentum for the LH_2 and the Nb data. This result might allow to extract the momentum dependence of the ω-nucleus potential [23, 28].

In summary, 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. When comparing data from a LH_2 target with data taken with a Nb target, we find a pronounced modification of the ω meson mass in the nuclear medium for ω mesons with momenta less than 500 MeV/c. The in-medium mass has been determined to $M_{\text{medium}} = [722^{+2}_{-2}(\text{stat})^{+35}_{-5}(\text{syst})]$ MeV/c^2 at an estimated average nuclear density of 0.6 ρ_0. The width is found to be $\Gamma = 55$ MeV/c^2 and is dominated by the experimental resolution. The momentum dependence of the signal shows that only low-momentum ω mesons contribute to the downward mass shift. In contrast, ω mesons with high momenta decay outside the nucleus, exhibiting an invariant mass distribution corresponding to ω decays in vacuum. First evidence for a lowering of the ω mass in the nuclear medium has been observed.

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