Modification of the ω-Meson Lifetime in Nuclear Matter

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Information on hadron properties in the nuclear medium has been derived from the photo production of ω mesons on the nuclei C, Ca, Nb and Pb using the Crystal Barrel/TAPS detector at the ELSA tagged photon facility in Bonn. The dependence of the ω meson cross section on the nuclear mass number has been compared with three different types of models, a Glauber analysis, a BUU analysis of the Giessen theory group and a calculation by the Valencia theory group. In all three cases, the inelastic ω width is found to be $130-150$ MeV/c^2 at normal nuclear matter density for an average 3-momentum of 1.1 GeV/c. In the restframe of the ω meson, this inelastic ω width corresponds to a reduction of the ω lifetime by a factor ≈ 30. For the first time, the momentum dependent ωN cross section has been extracted from the experiment and is in the range of 70 mb.

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The investigation and understanding of in-medium properties of hadrons has advanced to one of the most attractive research topics in hadron physics. Several theoretical studies (e. g. [1–5]) have led to the expectation of a partial restoration of chiral symmetry at high temperatures or increasing nuclear densities. A consistent picture of corresponding in-medium properties of hadrons has, however, not yet emerged. These investigations have stimulated a series of measurements to study the effect of surrounding strongly interacting matter on the mass and width of hadrons. For ρ mesons a broadening but no mass shift has been reported in cold [6] and heated [7] nuclear matter. In contrast, the authors in [8] report a mass shift but no broadening of the ρ meson in nuclear matter. Also for ϕ mesons with low momenta a lowering of the in-medium mass has been reported [9] as well as for the ω meson [10]. It is important to note that the analysis of the ω data [10] was not sensitive to the in-medium decay width due to the detector resolution and uncertainties in the separation of in- and out-of-medium decay contributions.

This paper describes an access to the in-medium width of the ω meson via the measurement of the transparency ratio. This method has been motivated in earlier works on the ϕ meson [11, 12] as well as more recently on the ω meson [13, 14]. The LEPS collaboration at Spring8 extracted the transparency ratio for the photo production of ϕ mesons [15] and reported an unexpectedly large in-medium inelastic cross section of ϕ mesons at normal

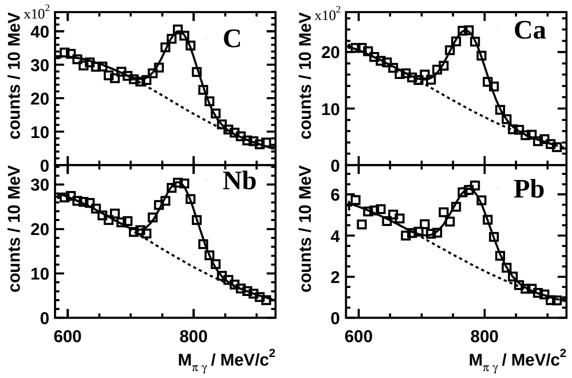

FIG. 1: Invariant mass distributions of a $\pi^0\gamma$ pair for the four different targets integrated over all momentum bins. The extraction of the ω yield is described in the text.

nuclear matter density.

The present 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, and the range of 1.2 to 2.2 GeV was used in the further analysis. The C, Ca, Nb, and Pb targets had thicknesses of 20 mm, 10 mm, 1 mm and 0.64 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 with an angular coverage of 30° up to 168° in the polar angle and a complete azimuthal angular coverage. Inside the CB, covering its full acceptance, a three-layer scintillating fiber detector was installed for charged particle detection. Reaction products emitted in forward direction were detected in the TAPS detector. TAPS consisted of 528 hexagonally shaped BaF_2 detectors 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 registration of charged particles. The resulting geometrical solid angle coverage of the combined system was 99% of 4π. The BaF_2 crystals provided a fast trigger. For further details see [16–18].

The experimental observable for extracting the in-medium width is the *transparency ratio*, defined as:

$$T = \frac{\sigma_{\gamma A \to VX}}{A\ \sigma_{\gamma N \to VX}}\ , \tag{1}$$

i. e. the ratio of the inclusive nuclear ω photo production cross section divided by A times the same quantity on a free nucleon. T describes the loss of flux of ω mesons in nuclei and is related to the absorptive part of the ω nucleus potential and thus to the ω inelastic width in the nuclear medium. To avoid systematic uncertainties when comparing to theoretical models, e. g. due to the unknown ω production cross section on the neutron or secondary production processes, the transparency ratio

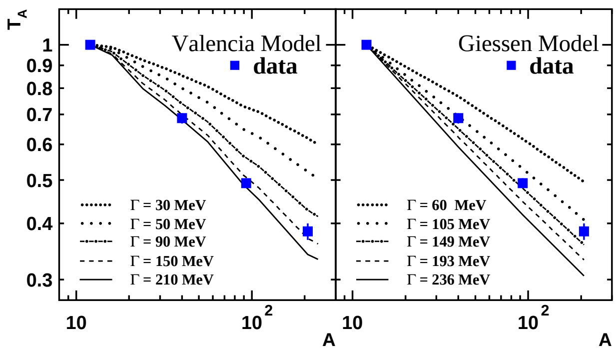

FIG. 2: (color online) Experimentally determined transparency ratio according to Eq. 2 in comparison with a theoretical Monte Carlo simulation [22, 23] (left) and a BUU calculation [20, 24] (right) varying the width at 1.1 GeV/c momentum, respectively. The width is given in the nuclear restframe. Only statistical errors are shown.

has been normalized to the Carbon data, i. e.

$$T_A = \frac{12 \cdot \sigma_{\gamma A \to VX}}{A\ \sigma_{\gamma C_{12} \to VX}}\ . \tag{2}$$

The result is thereby normalized to a light target with equal numbers of protons and neutrons.

The ω meson has been reconstructed via the mode $\omega \to \pi^0\gamma$ with the π^0 further decaying into 2 photons, thus requiring three neutral hits in the CB/TAPS detector systems. An identical analysis code has been used for all four nuclear targets. The photon flux has been determined by counting the scattered electrons in the tagging system and by correcting for the tagging efficiency. The background has been slightly reduced by eliminating events with an energy $E_{\gamma 3} < 200$ MeV of the decay photon not belonging to the π^0. Rescattering of π^0 mesons from the ω-decay distorts the $\pi^0\gamma$ mass to mostly much smaller masses. This type of events can be largely suppressed by removing events with low pion kinetic energies T_π <150 MeV, see e.g. [19, 20]). This cut is re-confirmed and used by the theoretical models ([20, 22–24]), so that the trivial loss of ω-mesons due to pion rescattering is consistently taken into account in experiment and theory. The resulting $\pi^0\gamma$ invariant mass distributions are shown in Fig. 1 for all four nuclear targets. The ratio of ω-yields has been extracted by fitting a signal and background function to the individual target data. The signal function is a standard calorimetry response function of a Gaussian superimposed with an exponential on the low mass tail. The background function is exp(a+bx+cx^2). The mass resolution of the ω-meson of this experimental setup is FWHM 55 MeV/c^2. The energy calibration has been cross checked by investigating the invariant mass response of π^0, η and η' mesons [10]. Since almost all ω mesons decay outside the nuclear target at average momenta of 1.1 GeV/c [10], neither a direct mass shift nor a broadening of the width can be observed in the $\pi^0\gamma$

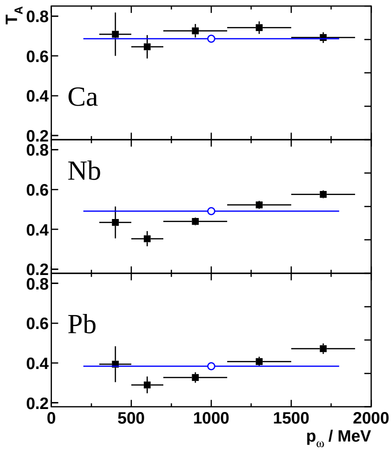

FIG. 3: (color online) Momentum dependent transparency ratio normalized to C for the three different targets Ca, Nb and Pb as full squares. The open circles show the values when integrating over all momenta and correspond to the data points shown in figure 2. Only statistical error bars are shown. More details are given in the text.

invariant mass distributions (Fig. 1). The statistical error of the fitting procedure was taken to be $\sqrt{(S+2B)}$ using the extracted signal S and background B events. The systematic errors of the extracted transparency ratios (Eq. 1) include the uncertainties of the target length, the fraction of coherent ω production and the γ conversion in the target, respectively, for each target. Contributions from coherent ω production are negligible, since the transparency ratios differ by less than 2% when comparing fully inclusive ω production (including coherent contributions) to quasi-free production with detection of a recoil proton. The quadratic addition of these individual errors yields a systematic uncertainty of 3.5%.

Knowledge of the photon flux, efficiency, and the number of measured ω mesons is sufficient to deduce the partial $\omega \rightarrow \pi^0\gamma$ decay cross section. The dependence of the cross section on the nuclear mass number A can be parameterized as:

$$\sigma(p_\omega, A) \ \propto A^{\alpha(p_\omega)} \tag{3}$$

The measured cross sections are in good agreement with an A^α scaling law. The fit to the data yields α values between $0.54-0.74$ from lower to higher 3-momenta p_ω. This result is in agreement with the data obtained by the KEK collaboration [21] and indicates a strong absorption of ω mesons in the nuclear medium.

In a next step, the transparency ratio as defined in Eq. 2 has been extracted and is shown in Fig. 2 as full (blue) circles. The data in Fig. 2 are compared to two theoretical models, a Monte Carlo type analysis by the Valencia group [23] (left panel) and a BUU transport code calculation by the Giessen group [24] (right panel). The collision width included in the Giessen BUU model is evaluated consistently from the ω collision rates using the low-density approximation, and thus is momentum dependent, while the Valencia group uses a momentum-independent width. The values given in Fig. 2 correspond to ω mesons with momenta of 1.1 GeV/c which is the average momentum of the ω mesons in the data sample. A comparison of the data to the model predictions yields an in-medium ω width in the nuclear restframe of $130-150$ MeV/c^2. In addition, we have investigated the momentum dependence of the transparency ratio to extract the momentum dependence of the ω meson inelastic collision width. These data normalized to C for the three different targets Ca, Nb and Pb are shown in Fig. 3 as full squares. The open circles show the values when integrating over all momenta and correspond to the data points shown in Fig. 2. For the heavier targets the data indicate a slight decrease of the transparency ratio with decreasing ω 3-momenta.

We have used the Glauber model in the high energy eikonal approximation to analyze these data points and to extract the momentum dependence of the ω meson inelastic width. The Glauber model [25] was first applied to photoproduction experiments by Margolis [26] to extract the inelastic ρN cross section both from coherent and incoherent ρ photoproduction off nuclei. A very detailed description and application of the Glauber model to photoproduction reactions can be found in [27]. More recently, the Glauber model has been applied to study the effects of color transparency [28] and nuclear shadowing [29] in high energy photonuclear reactions. In the Glauber eikonal approximation, neglecting Fermi motion and Pauli blocking, the total incoherent cross section for the photoproduction of a single vector meson is given by

$$\frac{d\sigma_{\gamma A\rightarrow VX}}{dp} \tag{4}$$
$$= \frac{d\sigma_{\gamma N\rightarrow VN}}{dp}\int d^3r\,\rho_N(\mathbf{r}\,)\exp\left(-\int_z^\infty \frac{dP_{\rm abs}(z')}{dl}dz'\right)$$

where $dP_{\rm abs}/dl$ denotes the absorption probability per unit length of the vector meson in nuclear matter. The absorption probability per unit length is related to the inelastic width in the rest frame of nuclear matter via

$$\frac{dP_{\rm abs}}{dl} = \frac{dP_{\rm abs}}{dt}\frac{dt}{dl} = \frac{\Gamma_{\rm inel}}{v} = \frac{E_V}{p}\Gamma_{\rm inel} \tag{5}$$

with the vector meson energy E_V at 3-momentum p and velocity v. Here, the inelastic width depends on density and on the velocity of the ω meson. Using the low-density approximation we can separate the density- and momentum-dependence

$$\Gamma_{\rm inel}(\rho_N, p) = \Gamma_0(p)\,\frac{\rho_N}{\rho_0} \tag{6}$$

with $\rho_0 = 0.16$ fm^{-3}. Carrying out some of the integrals in Eq. (4), the nuclear photoproduction cross section can be written as

$$\frac{d\sigma_{\gamma A\to\omega X}}{dp} = \frac{d\sigma_{\gamma N\to\omega X}}{dp} \times \rho_0 \frac{p}{E_V \Gamma_0(p)} \tag{7}$$
$$\times\ 2\pi \int_0^{\infty} b\, db \left[1 - \exp\left(-\frac{E_V}{p}\int_{-\infty}^{+\infty} dz'\, \Gamma_{\rm inel}(\{\mathbf{b}, z'\}, p)\right)\right]$$

Note that the width $\Gamma_{\rm inel}$ in the above equation relates to the rest frame of nuclear matter. Equation (7) has been used in order to fit the measured transparency ratios shown in Fig. 3 for fixed values of the ω meson 3-momentum by varying the ω meson inelastic width. In this way the widths $\Gamma_0(p)$ and their errors were determined separately for each target.

The values for the individual targets were combined into an error weighted average and are shown in in the lower part of Fig. 4. For the different momentum bins an increase of the ω width up to momenta of about 1 GeV/c is observed. The Glauber model analysis is in good agreement with the BUU parameterization with respect to the momentum dependence, but indicates a slightly larger width. The Monte Carlo calculation by the Valencia group agrees on average with the Glauber model analysis, but explicitly assumes no momentum dependence of the ω width. For a comparison of the ω in-medium width with the ω width in vacuum, the values shown in Fig. 2, 4 have to be transformed to the ω restframe. The observed width of 130-150 MeV/c^2 at 1.1 GeV/c momentum corresponds to a width in the restframe of the ω meson of $225 - 260$ MeV/c^2 . The upper part of Fig. 4 contains the first determination of the inelastic ωN cross section extracted by using the classical low-density relation

$$\sigma_0(p) = \frac{\Gamma_0(p)}{\rho_0}\frac{E_\omega}{p}. \tag{8}$$

Similar to the study of the ϕ meson properties in the nuclear medium [15], the cross section at large momenta exceeds by a factor ≈ 3 the inelastic ωN cross section [30] used as input in the BUU calculations [20, 24].

In summary, we have deduced the in-medium width of the ω meson from photo production experiments using the Crystal Barrel/TAPS detector systems at the ELSA accelerator facility in Bonn. It is found that the ω eigenlifetime decreases by a factor ≈ 30 for normal nuclear matter density compared to the vacuum value. Furthermore, the momentum dependence of the transparency ratio and of the extracted in-medium ω width has been determined for the first time. Deviations of the experimental data from the momentum dependence of the ω in-medium width implemented as input in the BUU code indicate room for improvement in the parameterization of the ωN cross section or a limited applicability of the low density theorem (Eq. 8).

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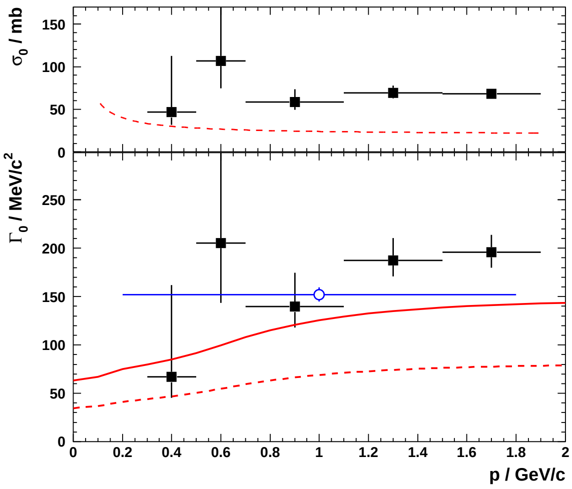

FIG. 4: (color online). Upper part: The inelastic ωN cross section extracted from the Glauber analysis (data) in comparison to the inelastic cross section used in the BUU simulation [20, 24]. Lower part: Width of the ω meson in the nuclear medium in the nuclear restframe as a function of the ω momentum in a Glauber analysis (squares), from the Giessen BUU model with the inelastic cross section from the upper figure (red dashed line) and after fit to the data of Fig. 2 with BUU (red line), and the Valencia Monte Carlo simulation (blue circle), respectively. Only statistical errors are shown.

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