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Experimental results on the ω- and η'-nucleus potential - on the way to mesic states

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Abstract. Different experimental approaches to determine the meson-nucleus optical potential are discussed. The experiments have been performed with the Crystal Barrel/TAPS detector system at the ELSA accelerator in Bonn and the Crystal Ball/TAPS at the MAMI accelerator in Mainz. Experimental results about the real and imaginary part of the η'- and ω-nucleus optical potential are presented. The imaginary part of the meson-nucleus optical potential is determined from the in-medium width of the meson by the measurement of the transparency ratio. Information on the real part of the optical potential is deduced from measurements of the excitation function and momentum distribution which are sensitive to the sign and depth of the potential. The results are discussed and compared to theoretical predictions. The data for both mesons are consistent with a weakly attractive potential. The formation and population of ω-nucleus and η'-nucleus bound states is additionally discussed.

1 Introduction

The in-medium modifications of hadron properties have been identified as one of the key problems in understanding the non-perturbative sector of QCD. Several theoretical papers discuss the possibility of a partial restoration of chiral symmetry in a strongly interacting environment [1–3]. Mesons are considered to be excitations of the QCD vacuum which has a complicated structure with non-vanishing chiral and higher order condensates. These condensates are predicted to change within a strongly interacting medium and, as a consequence, also the mass spectrum of mesons is expected to be modified [3]. This idea inspired hadronic models developed to calculate the in-medium self-energies of hadrons and their spectral functions. Mass shifts and/or in-medium broadening as well as more complex structures in the spectral function due to the coupling of vector mesons to nucleon resonances have been predicted [4, 5] (Fig.1 (left) and (middle)). The theoretical and experimental activities have been summarized in [6–8].
Recently many studies have focused on the pseudoscalar η' meson. The especially large mass of the η' meson compared to the mass of the other mesons in the pseudoscalar nonet has to be attributed to chiral and flavor symmetry breaking effects. As a consequence of a reduction of the chiral condensate a comparable drop in the $U_A(1)$ breaking part of the η' mass might be expected [9, 10]. Fig.1 (right) shows corresponding calculations which predict a dramatic drop of the η' mass already at normal nuclear density [9]. This prediction is, however, in conflict with earlier calculations within the

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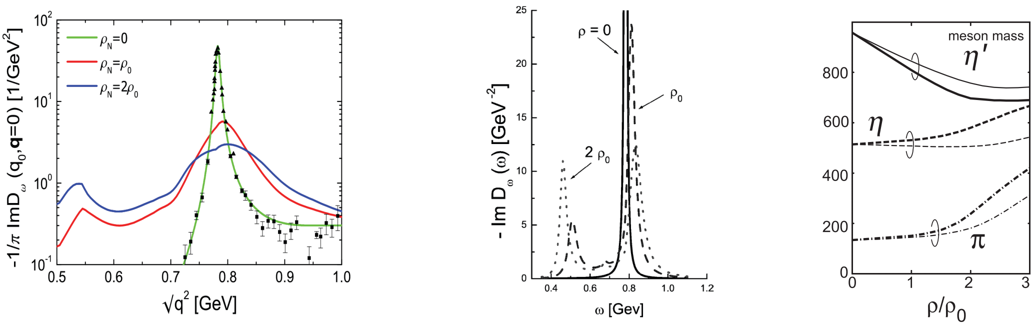

Figure 1. (left) The ω spectral function for an ω at rest in the nuclear medium [4]. The data and the solid curve describe the spectral function of the free ω meson. The other curves show the spectral function for normal density ρ_0=0.16 fm^{-3} and ρ=2ρ_0, respectively. (middle) The ω spectral function for densities ρ, ρ_0, 2ρ_0 and coupling to resonances [5]. (right) Pseudoscalar meson masses as functions of the nuclear matter density as predicted within the Nambu-Jona-Lasinio model in [9].

Nambu-Jona-Lasinio-model which expect almost no change in the η' mass as a function of nuclear density [11]. Further model calculations claim mass shift of the η' of -80, -40 MeV at normal nuclear density [12, 13]. It is obvious that these contradictory theoretical predictions call for an experimental clarification.

2 Experimental approaches for determining the meson-nucleus optical potential

Meson beams can be used to study the meson-nucleus interaction experimentally, but they are available only for long-lived mesons such a pions or kaons and not for short-lived mesons like η, ω and η' mesons. To study their interaction with nucleons or nuclei one has to produce the mesons in a nuclear reaction and analyzed the final state interaction. The meson-nucleus interaction can be described by an optical potential $U = V + iW$, comprising a real and an imaginary part. In this work we discuss the determination of the real and imaginary part of the ω- and η'- nucleus potential in photo production experiments off nuclei.

The experiments have been performed at the ELSA facility in Bonn using the Crystal Barrel (CB) and the TAPS detector system and Crystall Ball and the TAPS detector systems at the MAMI-C accelerator in Mainz. The combined system Crystal Barrel or Crystal Ball with the TAPS detector as a forward wall covered 99% of the full 4π solid angle. The high granularity of the system makes it very well suited for the detection of multi-photon final states. The ω and η' mesons are reconstructed in the $\omega \rightarrow \pi^0\gamma \rightarrow 3\gamma$ and $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ decay channels, respectively. A more detailed description of the detector setup and the running conditions has been given in [14–17].

2.1 The imaginary part of the meson-nucleus potential

The imaginary part of the meson-nucleus potential corresponds to half of the in-medium width: $ImU = \Gamma/2$, which can be extracted from the attenuation of the meson flux deduced from a mea-

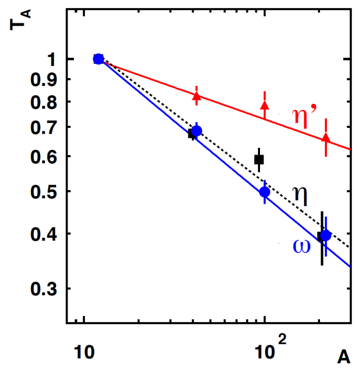

Figure 2. Transparency ratio for photo production of η' (red triangles), η (black squares), and ω mesons (blue points) as a function of the nuclear mass number, normalized to carbon [23]. The incident photon energy range is 1200 - 2200 MeV. The lines are fits to the data.

surement of the so-called transparency ratio for a number of nuclei [18]. The transparency ratio describes the loss of flux of mesons in nuclei via inelastic processes. Due to these processes the life-time of mesons in a nuclear medium is reduced leading to an increase in width as compared to the free particle width. This absorption can be determined experimentally by measuring the transparency ratio:

$$T = \frac{\sigma_{\gamma A \to \omega X}}{A \cdot \sigma_{\gamma N \to \omega X}}. \tag{1}$$

It represents the ratio of the meson production probability per nucleon within a nucleus and the production probability on a free nucleon. Without any absorption the transparency ratio would be 1. The transparency ratio is frequently normalized to the transparency ratio measured for a light nucleus like carbon to suppress distortions by two-body production and two-body absorption processes. The transparency ratio for ω and η' mesons has been measured in photo production experiments for several nuclei in a series of measurements with the CBELSA/TAPS detector system in Bonn. The results are shown in Fig. 2 together with earlier results for η mesons [19]. A strong absorption is found for η and ω mesons: within a nucleus the ω and η yields per nucleon decrease with increasing nuclear mass number and drop to about 40% for Pb relative to that for C. In contrast η' mesons exhibit much weaker absorption. In the low-density approximation the absorption cross section σ_{abs} and the in-medium width Γ at density ρ are related by:

$$\Gamma(\rho) = \hbar c \cdot \beta \cdot \sigma_{abs} \cdot \rho, \tag{2}$$

where β is the meson velocity relative to the nucleus. A comparison to theoretical calculations [20–23] yields within model uncertainties in-medium widths of (140±20) MeV and (20±5) MeV for the ω and η' meson, respectively, for recoil momenta of about 1.1 GeV/c. The corresponding imaginary part of the ω- and η'-nucleus potential then is W_{ω}=70±10 MeV and $W_{\eta'}$=10±2.5 MeV, respectively.

2.2 The real part of the meson-nucleus potential

The real part V(r) of the meson-nucleus potential is related to the in-medium mass shift Δm of the meson according to:

$$V(r) = \Delta m(\rho_0) \cdot \rho(r)/\rho_0 \tag{3}$$

where r is the distance from the center of the nucleus and ρ_0 the nuclear saturation density. The most straight forward approach to measure the in-medium mass of a meson would be to reconstruct the

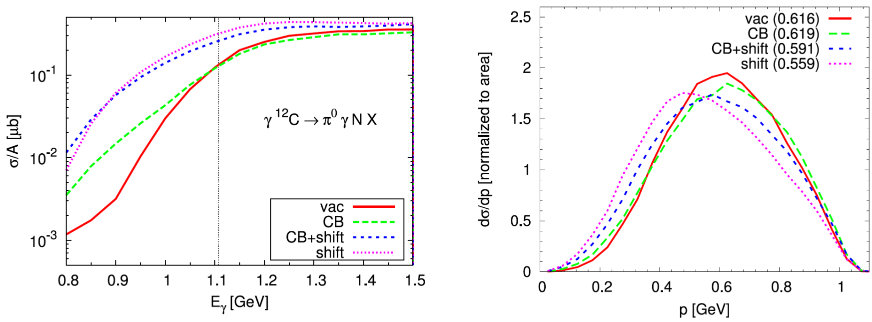

Figure 3. Calculated excitation function (left) and momentum distribution (right) for photo production of ω mesons in the $\pi^0\gamma$ decay channel on ^{12}C for four different in-medium modification scenarios [25].

invariant mass m from the 4-momentum vectors p_i of its decay products according to:

$$m \cdot c^2 = \sqrt{(p_1 + p_2)^2}. \tag{4}$$

It is important to ensure that these decays really occur in the medium and that there is no distortion of 4-momentum vectors by final state interactions of the decay products. In detailed studies it turned out that the line shape of long-lived mesons such as the ω meson ($\tau \approx 23$ fm/c) is not sufficiently sensitive to in-medium modifications [14, 17, 24] for the following reasons: (i) even when low momentum ω mesons ($p_\omega < 500$ MeV/c) are selected, less than 50% of all decays occur within the medium. (ii) A mass shifted ω signal would be smeared out due to the density profile of nuclei. (iii) The signal-to-background is further reduced by the strong in-medium broadening of the ω meson (see sec-2). (iv) Only ω mesons from decays near the surface can be reconstructed in the $\pi^0\gamma$ channel because of the strong final state interaction of the π^0 meson which may be absorbed when the decay occurs in the nuclear interior. In-medium decays of long-lived η' mesons ($\tau \approx 1020$ fm/c) are completely suppressed since these mesons are either absorbed in the nucleus or they escape from the nucleus and subsequently decay in vacuum.

J. Weil et al. [25] have, however, pointed out an indirect way to obtain information on the in-medium properties of mesons. As indicated in Fig. 3 (left) a downward mass shift of a meson would lower the production threshold and consequently - due to the enlarged phase space - a larger production cross section is expected at a given incident energy. Thus a measurement of the excitation function will provide information on the in-medium mass of a meson.

The momentum distribution of mesons is also found to be sensitive to modifications of the in-medium properties. Mesons produced in a nuclear reaction have to leave the nuclear medium with their free mass. In case of an in-medium mass drop, this mass difference has to be compensated by converting kinetic energy into mass. This process shifts the momentum distribution to lower values, as indicated in Fig. 3 (right). Both approaches have been applied to extract information on in-medium mass shifts of the ω and η' meson. Fig. 4 shows the excitation function for ω (left) [26] and η' (right) [27] mesons in comparison to theoretical calculations. The GiBUU transport model [28] has been applied to calculate the ω excitation function for 6 different scenarious allowing for mass shifts up to -125 MeV at normal nuclear density as it is shown in Fig. 4 (left). The experimental results on the excitation function of η' are compared with calculations performed for different assumptions on the real part of the η'-^{11}B potential [29] (Fig. 4 right). A χ^2-fit of the data with the calculated excitation functions for

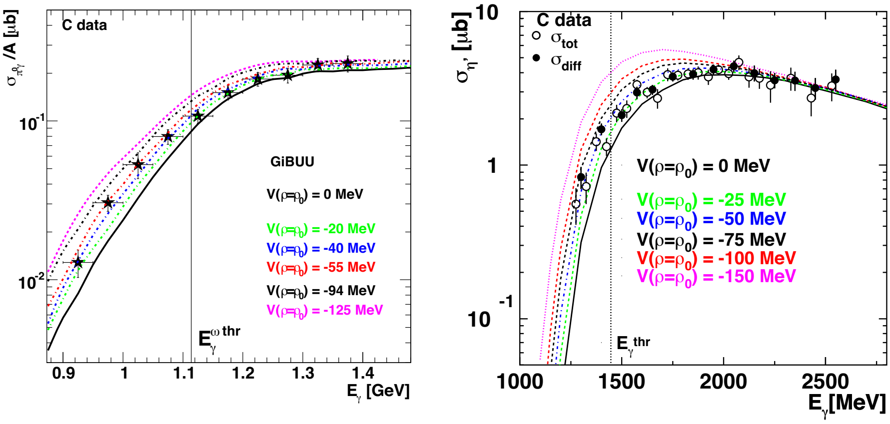

Figure 4. Measured excitation function for ω meson in comparison to GiBUU transport calculations for several in-medium modification scenarios [26] (left) and for photo production of η' mesons in comparison to calculations (right) [27, 29] .

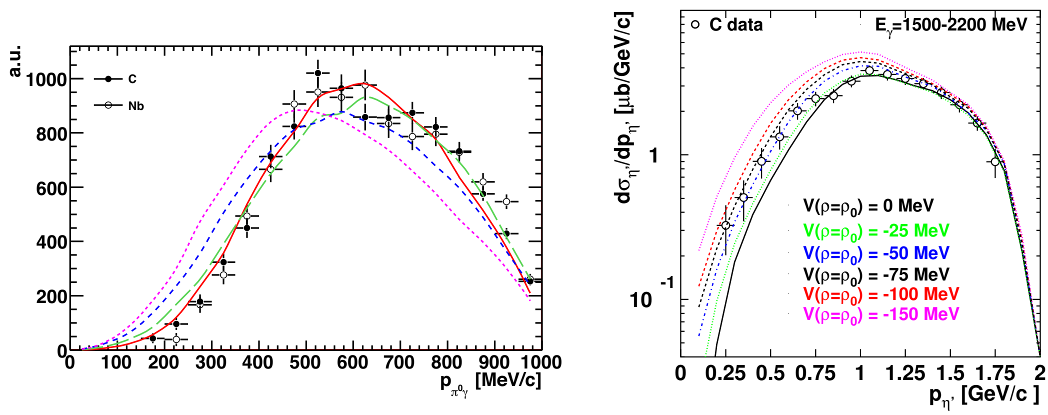

Figure 5. Left: Acceptance corrected ω momentum distribution for incident photon energies of 900 to 1300 MeV and for ^{12}C and ^{93}Nb targets, compared to the theoretical predictions for different in-medium modifications scenarios: no modification (solid red line), collisional broadening (dashed green line), collisional broadening plus mass shift (dashed blue line) and mass shift (magenta line). All distributions are normalised to the same area [17]. Right: Differential cross section for photo production of η' meson as a function of η' momentum in comparison to theoretical calculations for several in-medium modification scenarios [27].

the different scenarios gives a potential depth of $V_{\omega A}(\rho = \rho_0) = -(42 \pm 17(\text{stat}) \pm 20(\text{syst}))$ MeV and $V_{\eta' A}(\rho = \rho_0) = -(40 \pm 6(\text{stat}) \pm 10(\text{syst}))$ MeV, respectively.

Fig. 5 shows the momentum distribution of ω (left) and η' (right) mesons in comparison to theoretical calculations for different in-medium modification scenarios. The ω momentum distribution measured for near-threshold photo production off ^{12}C and ^{93}Nb, do not support calculations for mass

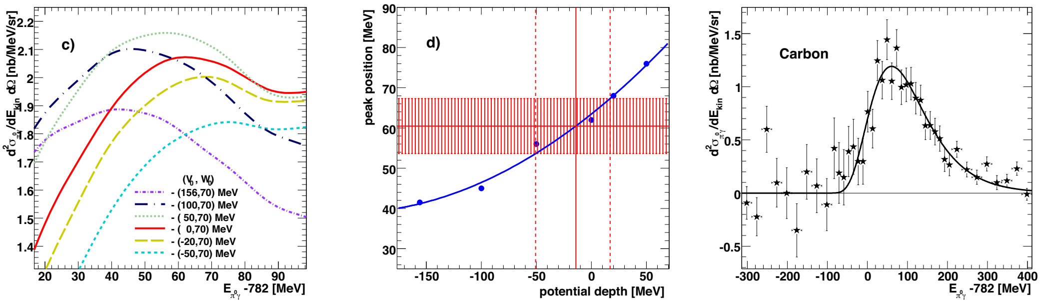

Figure 6. (left) Kinetic energy distribution for ω mesons in coincidence with a forward going proton in the $^{12}C(\gamma,\omega)$ p reaction calculated for different depths of the ω-nucleus potential. (middle) Correlation between the peak in the kinetic energy distribution and the real potential depth. (right) Measured differential cross section for ω photo production off ^{12}C in the $\pi^0\gamma$ channel in coincidence with protons in $\theta_p = 1° - 11°$ [16].

shifts as large as -16%.
A χ^2-fit to the momentum distribution data of η' yields a potential depth at nuclear saturation density of $V_{\eta' A}$=-(32±11) MeV consistent with the value deduced from the fit to the excitation function. The weighted average of both potential determinations is $V_{\eta' A}$ ($\rho = \rho_0$) = -(37±10(stat)±10(syst)) MeV. These values refer to average η' recoil momenta of 1.1 GeV/c. The experimentally determined potential depth at normal nuclear matter density is very close to results obtained within the Quark-Meson-Coupling model (QMC) which predict an in-medium mass drop of the η' meson of 37 - 59 MeV, depending on the choice of the η - η' mixing angle [13].
The results for the ω meson refer to average recoil momenta of about 600 MeV/c. Many theoretical model predictions are, however, limited to mesons at rest in the nucleus or to only low meson momenta. The in-medium properties of low momentum mesons are studied experimentally by requesting the meson to be in coincidence with a forward going participant nucleon which takes over most of the momentum of the incoming beam, leaving the meson almost at rest relative to the nucleus [16]. In this case, the kinetic energy distribution of the meson becomes sensitive to the real part of the meson-nucleus potential. An attractive interaction would slow down the mesons emerging from the nucleus, but a repulsive interaction would accelerate them. The peak in the meson kinetic energy distribution is thus sensitive to the strength and sign of the meson-nucleus potential and will be shifted to lower or higher values, respectively, as compared to a scenario with vanishing interaction.

Fig. 6 (left) shows kinetic energy distributions for ω mesons calculated for different depths of the ω-^{11}B potential. As it can be seen, the peak in the kinetic energy distribution moves to lower values for an increasing depth of the potential, i.e. increasing attraction. This correlation is shown in Fig. 6 (middle). Fig. 6 (right) shows the measured kinetic energy distribution of ω mesons in coincidence with protons detected in the angular range of $1° - 11°$. The kinetic energy distribution peaks at (60.5±7) MeV. A value of $V_{\omega A}(\rho = \rho_0) = -(15 \pm 35(\text{stat})\pm 20(\text{syst}))$ MeV has been deduced taking

in account the error in the peak determination [16]. Within the errors this result is consistent with the value of potential depth deduced from the ω excitation function. The weighted average of both measurements is $V_{\omega A}(\rho = \rho_0) = -(29 \pm 19(\text{stat}) \pm 20(\text{syst}))$ MeV. We find that the ω-nucleus attraction is very weak.
As for the ω meson, events with η' mesons in coincidence with forward going protons have been analyzed to extract the real part of the η'-nucleus potential at lower momenta ($\approx$ 500 MeV/c). The analysis is still ongoing, but preliminary results indicate no strong momentum dependence of the η'-nucleus potential.

3 Discussions and outlook

Summarizing the results from sections 2.1 and 2.2 the following ω and η' optical potentials are derived within the uncertainties of the applied model calculations:

$$U_{\omega A}(\rho = \rho_0) = (-29 \pm 19(stat) \pm 20(syst) + i(70 \pm 10))MeV \tag{5}$$

$$U_{\eta' A}(\rho = \rho_0) = (-37 \pm 10(stat) \pm 10(syst) + i(10 \pm 3))MeV. \tag{6}$$

The imaginary part of the η'-nucleus potential is much smaller than the real part, while the opposite is found for the ω meson. To check the results on the meson-nucleus potential for heavier targets data have been taken on a ^{93}Nb target and are being analyzed
In view of the very weak ω-nucleus attraction and the relatively broad in-medium width of the ω meson one cannot expect to find resolved ω-nucleus bound states. On the other hand, the η' meson appears to be a promising candidate for the search for mesic states since the imaginary part of the η'-nucleus potential is found to be smaller than the real part, i.e. the width of possible η' mesic states is expected to be much smaller than the depth of the potential. Motivated by the present experimental results and earlier theoretical predictions [30–32], three experiments have been launched to search for η' bound states using hadron and photon beams. At the Fragment Separator FRS at GSI the ^{12}C(p, d) reaction has been studied in a search for η' mesic states by missing mass spectrometry with a resolution of 1.6 MeV/c^2 [33]. The analysis of this experiment is ongoing. The LEPS2 group [34] and the BGO-OD collaboration [35] use the ^{12}C(γ, p) reaction to populate η' mesic states. In these experiments the missing mass resolution is somewhat worse ($\approx$ 10 MeV/c^2) but here one tries to identify η' mesic states by additionally looking for their decays in coincidence with forward going protons. Results from all experiments are eagerly awaited.

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