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# New experimental approaches to study the in-medium properties of the $\eta'$ meson

**Mariana Nanova**[*†]
*II. Phys. Institut, JLU - Giessen*
*E-mail:* Mariana.Nanova@exp2.physik.uni-giessen.de

In-medium properties of mesons can be studied by determination of the meson-nucleus optical potential. As discussed in [1], transparency ratio measurements provide information on the inelastic cross section and in-medium width of the $\eta'$ meson and thereby on the imaginary part of the $\eta'$-nucleus potential. Experimental approaches to learn more about the real part of the $\eta'$-nucleus optical potential are presented. The momentum distribution and the excitation function show some sensitivity to in-medium modifications and could provide information on the sign and depth of the potential. Data taken in 2009 with the CBELSA/TAPS detector on a carbon target have been analysed and compared to model calculations [2] assuming different scenarios for the real part of the potential, related directly to the in-medium mass modification of the meson. The preliminary results do not support a very deep and strongly attractive $\eta'$-nucleus potential.

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[*]Speaker.
[†]on behalf of the CBELSA/TAPS Collaboration

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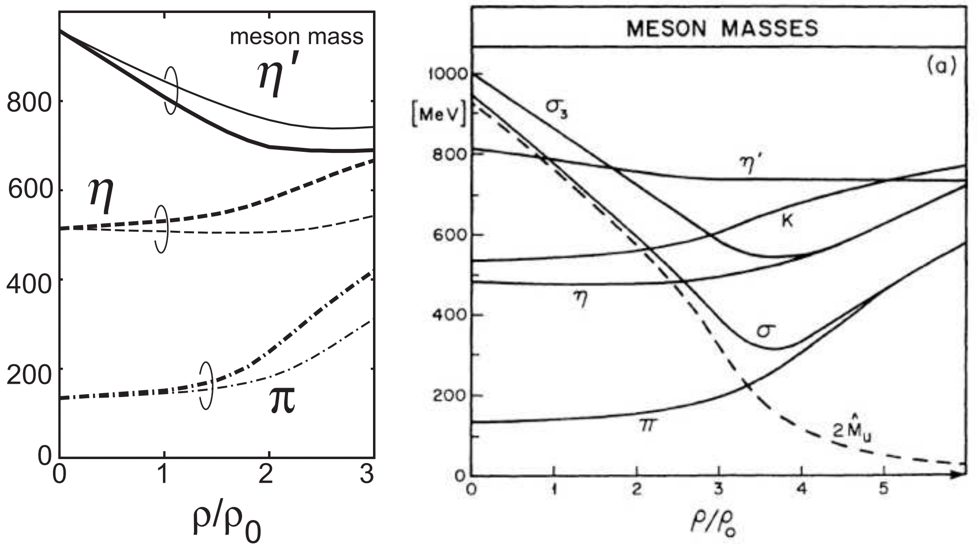


**Figure 1:** Meson masses as functions of the nuclear matter density as predicted within the Nambu-Jona-Lasinio model in [3] (left) and in [5] (right).

## 1. Introduction

Recently many studies have focused on the pseudoscalar $\eta'$ meson because of its importance for our understanding of QCD dynamics as it is linked to the $U_A(1)$ axial vector anomaly. The especially large mass of the $\eta'$ meson has to be attributed to chiral and flavor symmetry breaking effects. Several theoretical papers discuss the possibility of a partial restoration of chiral symmetry in a strongly interacting environment. As a consequence of a reduction of the chiral condensate a comparable drop in the $\mathrm{U}_A(1)$ breaking part of the $\eta'$ mass might be expected [3, 4]. Fig. 1 (left) shows corresponding calculations which predict a dramatic drop of the $\eta'$ mass at normal nuclear density. This prediction is, however, in conflict with earlier calculations within the NJL-model which expect almost no change in the $\eta'$ mass as a function of nuclear density [5] (Fig. 1 (right)). It is obvious that these contradictory theoretical predictions call for an experimental clarification. Information on the in-medium properties of the $\eta'$ meson can be gained by determinating the optical $\eta'$-nucleus potential:

$$U_{\eta'}(r) = V(r) + iW(r), \tag{1.1}$$

where V and W denote the real and imaginary parts of the optical potential, respectively, and r- is the meson-center of nucleus distance. The $\eta'$ in-medium mass shift $\Delta m(\rho_0)$ at saturation density $\rho_0$ can be related to the strength of the real part [6]:

$$V(r) = \Delta m(\rho_0) \cdot \frac{\rho(r)}{\rho_0}, \tag{1.2}$$

The imaginary part of the potential is responsible for the meson absorption in the medium and is

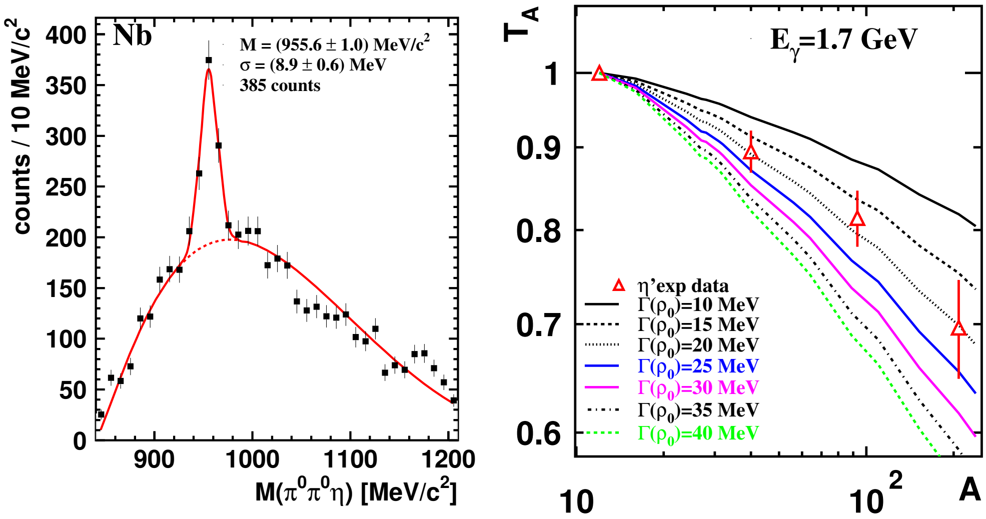


**Figure 2:** Left: Invariant $\pi^0\pi^0\eta$ mass spectrum for $^{93}$Nb for the incident photon energy range 1500 - 2200 MeV [1]. The solid curve is a fit to the spectrum. Only statistical errors are given. See text for more details. Right: Transparency ratio $T_A$ of $\eta'$ normalized to $^{12}$C, as a function of the nuclear mass number $A$. The data are compared with calculations for different values of the in-medium $\eta'$ width [1].

connected with the in-medium width $\Gamma_0$ of the meson at the normal nuclear matter density by:

$$W(r) = -\frac{1}{2}\Gamma_0 \cdot \frac{\rho(r)}{\rho_0}. \tag{1.3}$$

We will present here experimental approaches to determine the optical $\eta'$-nucleus potential as a new way to learn more about the in-medium properties of the $\eta'$ meson.

## 2. Experimental approaches to determine the optical $\eta'$-nucleus potential

### 2.1 *Determination of the imaginary part of the optical $\eta'$-nucleus potential*

Since the imaginary part of the optical potential represents the meson absorption, the experimental approach to determine it is a measurement of the in-medium width of the $\eta'$ meson. As it has been shown in [1] the in-medium width of the $\eta'$-meson can be extracted from the attenuation of the $\eta'$-meson flux deduced from a measurement of the transparency ratio for a number of nuclei. The transparency ratio $\tilde{T}_A$ is defined as [7, 8]:

$$\tilde{T}_A = \frac{\sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma N \to \eta' X}} . \tag{2.1}$$

The cross section for $\eta'$ photoproduction per nucleon within a nucleus is compared with the meson production cross section on a free nucleon $N$. The nucleus serves as a target and also as an absorber. In case of no meson absorption in nuclei as well as no medium and isospin effects on the $\eta'$ production this ratio would be equal to unity. The transparency ratio is frequently normalized to the transparency ratio measured on a light nucleus like carbon (then denoted by $T_A$), which helps to suppress the distortion of the transparency ratio by photoabsorption and two-step processes [1].

The $\pi^0\pi^0\eta$ invariant mass distribution is shown in Fig. 2 (left) for the Nb target as an example. The spectrum was fitted with a Gaussian function combined with a polynomial function for the background. The measurements were done in photoproduction experiments on four solid targets ($^{12}$C, $^{40}$Ca, $^{93}$Nb and $^{208}$Pb) with the Crystal Barrel and TAPS detector system at the ELSA facility in Bonn in 2003 [9]. The measured cross sections were used to calculate the transparency ratio $T_A$ of the $\eta'$-meson for a given nucleus $A$ from formula (2.1), normalized to the carbon data. The experimental results are shown in Fig. 2 (right) in comparison to calculations [1] for different in-medium $\eta'$ widths, based on measured photoproduction cross sections on the bound proton and bound neutron, respectively [10]. For the $\eta'$ meson an in-medium width of 15-25 MeV at saturation density is obtained at an average recoil momentum $p_{\eta'}$ = 1.05 GeV/c [1]. Taking into account Eq.(1.3) the imaginary part of the optical potential at this density is determined to: $W(\rho_0) = -(7.5 - 12.5)$ MeV.

### 2.2 *Determination of the real part of the optical* $\eta'$*-nucleus potential*

Information on a possible mass drop and thereby on the real part of the meson-nucleus potential could in principle be obtained from invariant mass plots as shown in Fig. 2. This is, however, excluded for the $\eta'$ meson by the extremely long lifetime of the $\eta'$ ($\tau \approx$1000 fm/c) such that almost all $\eta' \to \pi^0\pi^0\eta \to 6\gamma$ and $\eta' \to 2\gamma$ decays of the $\eta'$ meson, recoiling from the elementary nuclear

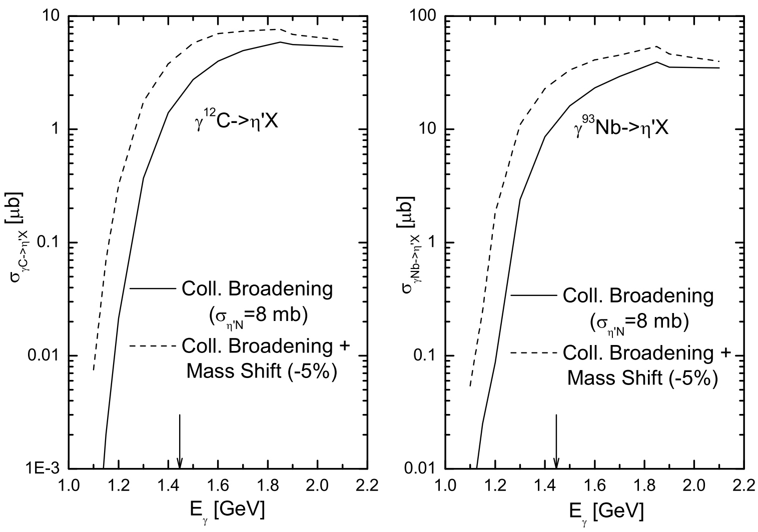


**Figure 3:** Excitation function for photo production of $\eta'$ mesons off $^{12}$C (left) and $^{93}$Nb (right), respectively. The dashed and solid curves are calculations for a collisional broadening of the $\eta'$ meson determined experimentally ($\sigma_{\eta' N} = 8mb$) [1, 2] with an average in-medium mass shift by -50 MeV and without mass shift, respectively. The arrows indicate the threshold energy for the photo production of the $\eta'$ meson on a free nucleon. The figure is taken from [2].

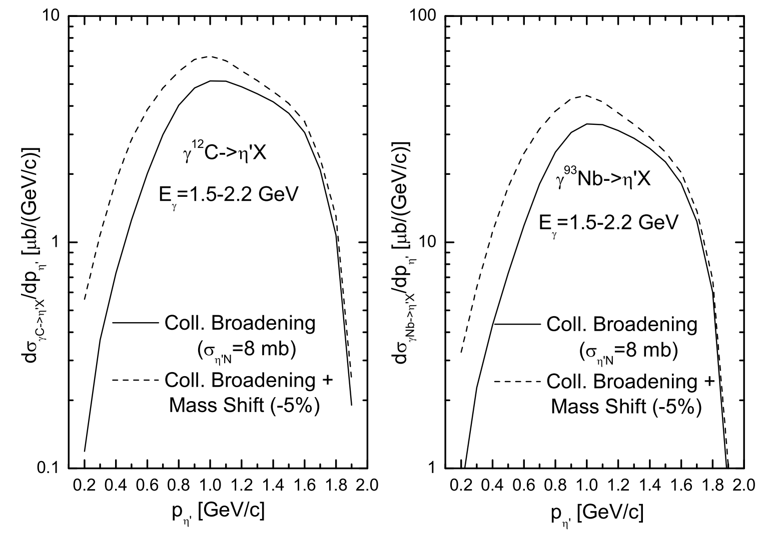


**Figure 4:** Momentum differential cross sections for the production of $\eta'$ mesons for photons of 1.5-2.2 GeV off $^{12}$C (left) and $^{93}$Nb (right). The figure is taken from [2].

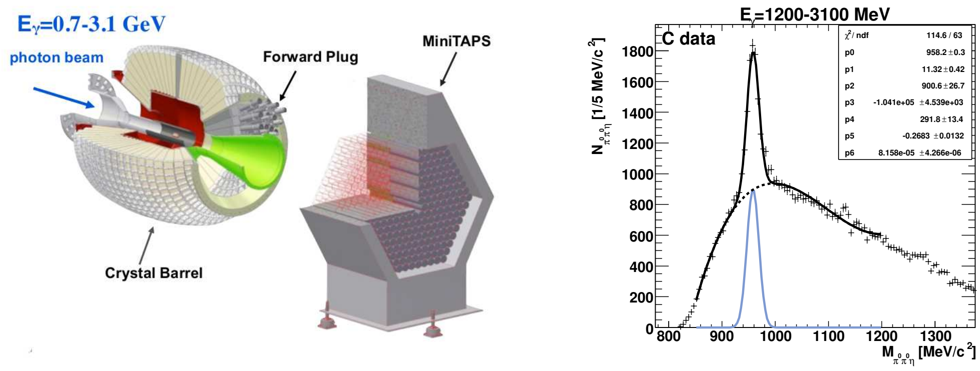


**Figure 5:** Left: Setup used in the experiment in 2009. Right: The $\pi^0\pi^0\eta$ invariant mass distribution on carbon in the incident photon energy of 1200-3100 MeV. The solid curve represents a fit to the data using a Gaussian function combined with a polynomial function for the background. The fit parameters are: $\sigma$=11.3±0.4 MeV, mass=958.2±0.3 MeV.

reactions, will occur outside of the nucleus. It has, however, been shown in [11, 12] that a measurement of the excitation function and momentum distribution of a meson is a feasible approach to extract information on the in-medium mass and thereby on the real part of the meson-nucleus potential. A downward shift of the meson mass would lower the threshold for meson photo-production. Due to the enlarged phase space, the production cross section for a given incident beam energy will increase as compared to a scenario without mass shift. Furthermore, mesons produced in a nuclear reaction leave the nuclear medium with their free mass. In case of an in-medium mass drop, this mass difference has to be compensated at the expense of their kinetic energy. As demonstrated in

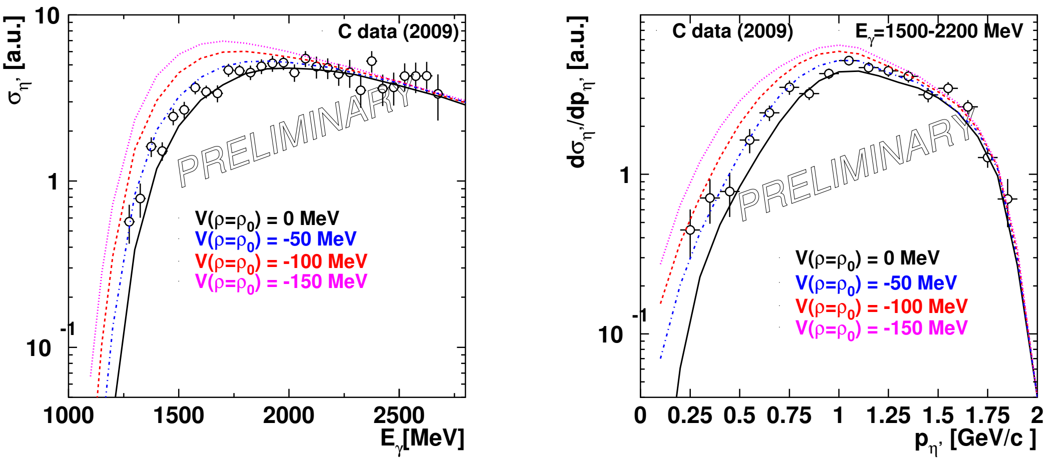


**Figure 6:** Left: Excitation function for $\eta'$ photoproduction. The experimental data (open circules) are compared with four scenarios assuming different depths of the real potential [2]: $V(\rho = \rho_0)$=0 MeV (black solid line), $V(\rho = \rho_0)$=-50 MeV (blue dotted-dashed line); $V(\rho = \rho_0)$=-100 MeV (red long-dashed line) and $V(\rho = \rho_0)$=-150 MeV (magenta dotted line). Right: Momentum distribution of the $\eta'$ meson. The curves representing the different scenarios are labeled in the same way.

GiBUU transport-model calculations [11], this leads to a downward shift in the momentum distribution as compared to a scenario without mass shift. A mass shift can thus be indirectly inferred from a measurement of the excitation function and/or the momentum distribution of the meson. For the $\eta'$ meson, this idea has independently been pursued on a quantitative level by Paryev [2]. His predictions for the $\eta'$ excitation function and the $\eta'$ momentum distribution on C and Nb are shown in Fig. 3 and Fig. 4, respectively. It can be seen that at an incident subthreshold photon energy of 1.25 GeV an increase of the $\eta'$ production cross section by a factor $\approx 7$ is predicted for a mass drop of 100 MeV at normal nuclear matter density (-50 MeV at the average nuclear density of $< \rho > \approx 0.5\rho_0$). For the same in-medium modification scenario a shift in the average $\eta'$ momentum by about 80 MeV/c is expected [2].

The subsequent data on $\eta'$ photoproduction were taken in 2009 on a carbon target with the Crystal Barrel/TAPS detector system at the ELSA accelerator in Bonn in the photon energy range 700-3100 MeV (Fig. 5 left). The main detector components were the Crystal Barrel detector with 1320 Cs(Tl) crystals, subtending polar angles of $11^0$ - $156^0$, the inner detector with 513 scintillating fibres for charged particle detection, surrounding the target in 3 cylindrical layers, and the TAPS(MiniTAPS) forward wall, comprising 216 $BaF_2$ crystals at $1^0$ -$10^0$ (Fig. 5 left). Each $BaF_2$ module was equipped with a plastic scintillator for charged particle identification. In total, 5100 $\eta'$ mesons were reconstructed in the $\eta' \rightarrow \pi^0\pi^0\eta \rightarrow 6\gamma$ channel in the photon energy range 1200 - 3100 MeV (Fig. 5 right). The preliminary experimental results shown in Fig. 6 are compared with the calculations by Paryev [2] for four different scenarios assuming a depth of the real potential at normal nuclear matter density of V=0 MeV, -50 MeV, -100 MeV and -150 MeV, respectively. The calculated cross sections have been scaled to match the experimental excitation function data at incident photon energies above 2.2 GeV where the difference between the different scenarios is very small. The excitation function data appear to be incompatible with mass shifts of -100 MeV and more at normal nuclear matter density. Within the current statistics a real part of the $\eta'-^{11}$B potential between -50 and 0 MeV is consistent with the presently available data. A comparison of the measured and calculated momentum distributions in the incident photon energy range 1500-2200 MeV also seems to exclude strong mass shifts. For a more precise determination of the real part of the $\eta'$-nucleus potential further comparison of absolute experimental cross sections (in particular, their angular dependences) and theoretical predictions is needed. Corresponding analyses are under way. For a confirmation of the preliminary results presented here a measurement on a heavier target nucleus like Nb is planned.

## 3. Conclusion

Experimental approaches to study the in-medium properties of the $\eta'$ meson are presented and discussed. The transparency ratios for $\eta'$-mesons have been measured for several nuclei. The imaginary part of the optical potential, deduced from the in-medium width of the $\eta'$-meson, is found to be -(7.5 - 12.5) MeV. The preliminary results on the real part of the potential are consistent with an attractive $\eta'$-nucleus potential with a depth less than 100 MeV. An attractive $\eta'$-nucleus potential would lower the in-medium $\eta'$ mass and might even be strong enough to form a bound $\eta'$-nucleus state. The search for such states is encouraged by the relatively small in-medium width of the $\eta'$ [13]. There are experiments proposed to search for $\eta'$ bound states via missing mass spectroscopy [14] at the FRS at GSI and in an exclusive measurement at the BGO-OD setup at the ELSA accelerator in Bonn [15]. The observation of a $\eta'$-nucleus bound states would provide important information on the in-medium properties of the $\eta'$ meson.

## 4. Acknowledgment

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