In-medium hadron properties: Experimental overview

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Hadron modifications in nuclear matter are discussed in connection to chiral symmetry restoration and/or hadronic many body effects. Experiments with photon, proton and heavy ion beams are used to probe properties of hadrons embedded in nuclear matter at different temperatures and densities. Most of the information has been gathered for the light vector mesons ρ, ω and ϕ which, due to their short life time, decay to large extent inside the medium. Decay channels involving dileptons, photons and hadrons have been selected to measure meson line shape and/or nuclear transparency in cold nuclear matter. Measurements of dileptons from heavy ion collisions allow to separate contribution from dense phase and to characterize its properties. A review of recent experimental results, focused on low energy domain, is presented.

1 Introduction

Sizable mass modifications have been predicted by various theoretical models for hadrons embedded into cold or hot and dense nuclear matter. In this respect, most attention has been focused on the light vector mesons ρ, ω, and ϕ) (for review see [1] and contribution of B.Kämpfer to this conference). Early work based on QCD sum rules suggested a direct link between changes of the meson masses and QCD vacuum properties, characterized by a reduction of the expectation value of the two-quark condensate [2, 4]. More recent work shows however that, while such a link indeed should exist, it is much more complicated and offers rather limited predictive power [1]. On the experimental side, a lot of activities have been carried out over the last years. The E325 experiment at KEK reported [3] a mass drop of the ρ meson in nucleus according to the Brown-Rho scaling [4]. This observation triggered further experimental investigations conducted at JLAB, ELSA, and MAMI using photon beams, as well as at COSY and GSI using proton beams. In heavy-ion collisions a search for vector meson mass modifications via dilepton spectroscopy was pioneered by the CERES [5] and HELIOS [6] collaborations at the CERN SPS and the DLS experiment [7] at Bevalac. A low-mass pair excess, below the ρ/ω pole, was reported and was widely discussed in many theoretical papers. However, the limited statistics of these experiments did not allow to derive firm conclusions. The breakthrough in this field was achieved with

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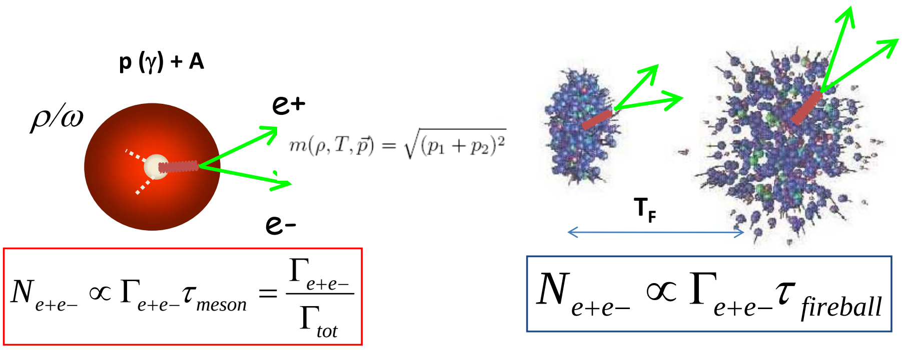
the high-statistics NA60 data set, which allowed, for the first time, to extract a spectral function of the ρ meson in hot and dense nuclear matter at SPS energies [8]. Likewise, the HADES experiment at GSI has recently provided high precision data in the low energy regime [9].



Meson	Mass [MeV/c²]	Γ [MeV/c²]	cτ [fm/c]	BR(V→e+e-)	BR in hadrons
ρ^0	770	150	1.3	4.4×10^{-5}	$\pi^+\pi^-$ (~100%)
ω	782	8.4	23.4	7.1×10^{-5}	$\pi^0\gamma$ (8%)
φ	1020	4.4	44.4	3.1×10^{-5}	K^+K^- (50%)

NO FSI ! **FSI !**

Figure 1: Schematic view of ρ/ω meson decays in $p + A$ and HI collisions. The e^+e^- yield in $p + A$ is proportional to the inverse in-medium meson width whereas in HI collisions is proportional to the life time of the fireball. The table below summarizes the vector meson properties

There are two experimental approaches to measure in-medium mass modifications of the vector mesons: (i) via the reconstruction of their invariant mass from the detected decay products and (ii) by quantifying the meson absorption from the production yields. The best suited final state are dileptons (or possibly photons), void of strong final-state interactions (FSI) with the nuclear matter but one has to cope with the small branching ratios. (see Fig.1). Notice also that there is a clear difference between experiments investigating the meson production off the nucleus and those using HI collisions. Whereas in the first case the measured yield is directly proportional to the "in-medium" branching ratio, in the second case, because mesons can be regenerated in the rather long-lived fireball of rapidly changing density and temperature, connecting yields and medium effects is more complicated. Figure 1 illustrates both situations schematically. On the other hand, the density and temperature reached in HI collisions is of course higher and larger effects can be expected. Finally, in order to access the true in-medium radiation one has to subtract the contributions of meson decaying in the late state of the HI collision, that is after the so called "freeze-out" where all interactions between the produced particles have ceased.

2 Cold nuclear matter

The standard experimental technique to measure a width of meson embedded in cold nuclear matter is based on the so-called transparency ratio (T_A), defined as the ratio of the meson production cross section in a given photon (or proton) -nucleus reaction to the cross section for this reaction on the nucleon scaled with the nuclear mass A. More insight into the transparency ratio can be obtained with a Glauber model [10, 11] which relates the nuclear cross section $\sigma_{\gamma A}$ to the elementary cross section $\sigma_{\gamma N}$ and the meson absorption, expressed in terms of the imaginary part of the meson self-energy $\Pi(q, \rho(r))$, itself directly related to the meson in-medium width in the nucleus rest frame $\Gamma_{coll}(q, \rho(r))$. Both quantities, $\Pi(q, \rho(r))$ and $\Gamma_{coll}(q, \rho(r))$, depend on the meson momentum q and the local density $\rho(r)$. The in-medium increase of width ($\Gamma_{coll} > \Gamma_{vac}$) is commonly called collision broadening.

$$\sigma_{\gamma A} = \int d\Omega \int d^3 r \rho(\overrightarrow{r}) \frac{d\sigma_{\gamma N}}{d\Omega} exp(\frac{1}{q} \int_0^{\delta \overrightarrow{r'}} dl Im\Pi(q, \rho(\overrightarrow{r'}))) P(\overrightarrow{r} + \delta \overrightarrow{r'})$$

where

$\Gamma_{coll(q)} = -\frac{Im\Pi(q)}{\omega}$, ($\omega$ is energy)

and $\overrightarrow{r'} = \overrightarrow{r} + l\frac{\overrightarrow{r}}{r}$ with $\delta \overrightarrow{r'} = \frac{v\gamma}{\Gamma_{vac}} \frac{\overrightarrow{q}}{q}$

One should keep in mind the importance of nuclear effects which have to be considered in a calculation of the meson production off the nucleus. The latter is indeed affected by initial-state interactions (not for photons) of the beam particle, shadowing and Pauli blocking. A further complication arises from two-step meson production processes, that are those who involve intermediate hadrons produced in first-chance collisions (for example pions) and are obviously not present in reactions on the nucleon. In order to reduce these effects, the transparency ratio is therefore usually defined w.r.t. a reference measurement on the carbon nucleus. But even this, as it it will be shown later, does not completely guarantee full elimination of the effects related to two-step production. On the other hand, for a non-leptonic exit channel, FSI of the decay products with the medium must be taken into account by means of an absorption factor $P(r)$.

Figure 2 shows two examples of signal extraction for the ω meson from photo-production using e^+e^- (CLAS at JLab) [12], and $\pi^0\gamma$ (CBELSA/TAPS) [13] final states and photon beams in a similar energy range ($1.1 - 3.8$ GeV for CLAS, $1.1 - 2.2$ GeV for CBELSA/TAPS). In the latter case, the ρ meson contribution is not present and the π^0 FSI is reduced by means of a cut on the reconstructed pion kinetic energy $E_K > 150$ MeV. A further advantage of the dielectron measurement is its well controlled combinatorial background subtraction based on like sign-pairs measured in the same run, but a clear limitation is its lower statistics.

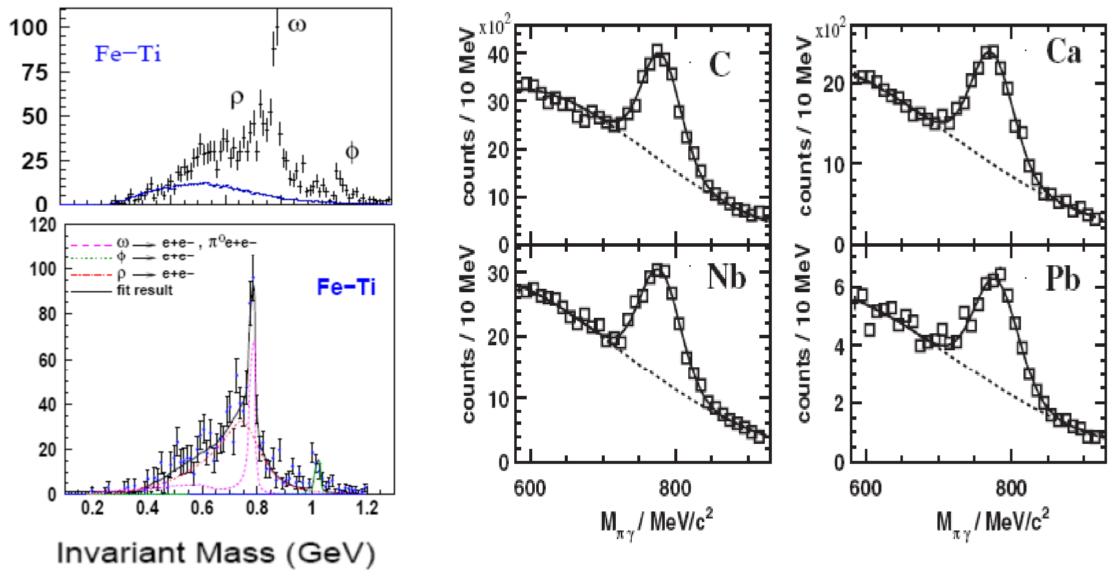


Figure 2: Left: invariant e^+e^- mass distributions from $\gamma + A$ reactions obtained by CLAS [12]. Upper part: total and combinatorial background and lower part: signal distribution compared to a fit composed of main dielectron sources. Right: invariant mass distribution of $\pi^0\gamma$ measured by CBELSA/TAPS [13] together with background fits.

The T_A obtained for the ω meson by CBELSA/TAPS and CLAS are presented in Fig. 3 (left) together with the model calculations done by the Giessen [14] and Valencia [15] theory groups. The extracted in-medium ω width $\Gamma^{\omega}_{\in-medium} \simeq 210$ MeV (in the ω rest frame) is significantly larger as compared to the vacuum value given in Fig. 1. The e^+e^- measurement [16] seems to show even slightly larger suppression, but the large error bars do not allow to derive final conclusions. In fact, the experimental point obtained on lead is an upper limit since no statistical significant ω signal could be observed there. One should also mention that both experiments measured ω decays at slightly different average momenta ($p^{CLAS}_{\omega} \simeq 1800$, $p^{CBELSA/TAPS}_{\omega} \simeq 1000$ MeV/c). Hence a more differential inspection of T_A as a function of the momentum is necessary. The respective momentum dependency of T_A is shown in the right panel of Fig. 3 for the CBELSA/TAPS data; it exhibits no strong effect. Assuming a low density approximation, also an in-medium $\omega - N$ cross section σ^*_{VN} could be estimated from the relation $\Gamma_{in-medium} \simeq v\rho\sigma^*_{VN}$. It has been found to be a factor $3-4$ larger than the typical "free" $\omega - N$ cross sections [13]. This may indicate the important role of many-particle interactions and questions the applicability of the approximation.

The impact of two-step processes on the T_A of ω, η and η' mesons has been investigated by CBELSA/TAPS by applying a condition on the kinetic energy of the outgoing meson: $E_K > 1/2(E_\gamma - m_M)$. This is discussed in more detail in the contribution of M. Nanova. The main conclusions are as follows: The measured T_A for the ω and η' exhibit no dependence

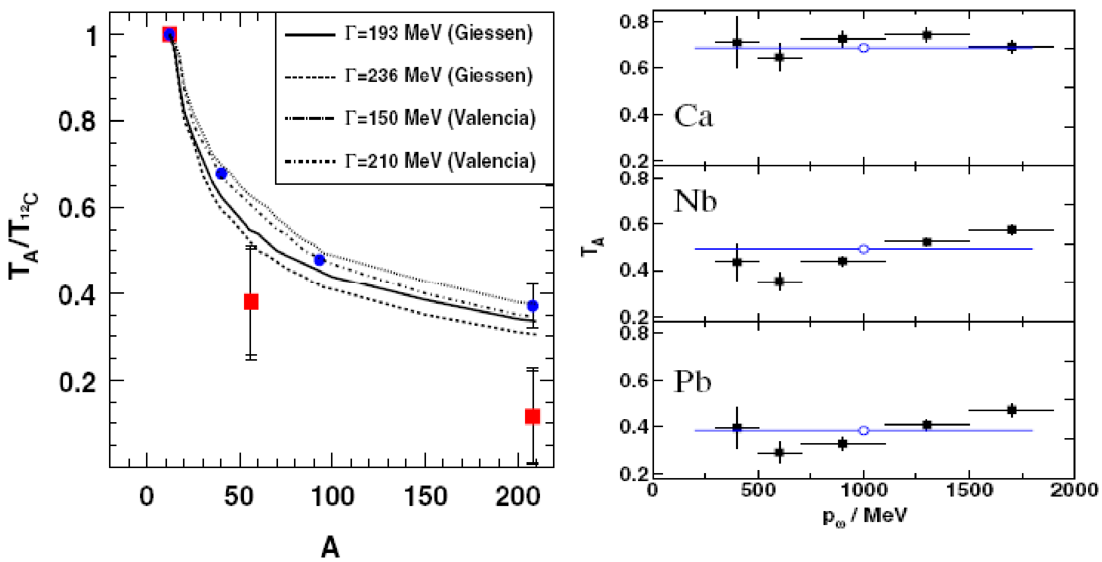


Figure 3: Left: Transparency ratios T_A measured for the ω meson by CBELSA/TAPS (blue points) and CLAS (red) as a function of mass number A [16]. Solid lines shows model predictions for the various in-medium meson widths from Valencia and Giessen groups. Right: Transparency ratio as a function of the ω momentum measured by CBELSA/TAPS for various nuclei [13]. Blue points are averaged values.

on the kinetic energy of the outgoing meson. In contrast, for the lighter η meson there is a clear reduction of T_A for the fast mesons. This can be explained by a strong reduction of two-step processes and the dominant role of the direct $\gamma - N$ reaction in the production of fast η mesons. On the other hand, the production of slow η is affected by the secondary $\pi - N$ reactions. The absence of such an effect in case of the ω and η' can be explained by the meson mass differences and hence different production threshold for the secondary productions. This conclusion is corroborated by the observed nuclear cross section scaling $\sigma_{\gamma A} \sim A^{\alpha}$ with $\alpha \simeq 2/3$ for the ω, and fast η mesons. Indeed, such a scaling is expected for surface production.

ϕ meson absorption in nuclear matter was measured in photon (CLAS [16], Spring8 [17]) and proton (ANKE [18]) induced reactions for an average meson momentum $< p_{\phi} > \simeq 1.7$ and 1.1 GeV/c, respectively. The measured T_A are, within error bars, consistent with each other, but the errors of the photo-production experiment are large. A recent high-statistics measurements from ANKE is presented in the contribution by A. Polyanskiy. The comparison with the model calculations of the Valencia, Moscow and Dresden groups indicate a ϕ-meson in-medium width of $\Gamma^{\phi}_{in-medium} \simeq 30 - 50$ MeV/c. However, the momentum distribution of the produced ϕ mesons off the nucleus indicates an enhancement over the model predictions at low momenta and calls for further investigations.

A new analysis of the ω line shape has been presented at this conference by A2 collaboration by M.Thiel. No statistically significant difference with respect to the ω vacuum spectral function is observed. Also, transport calculations done with GiBUU incorporating collisional broadening are consistent with the measured T_A (shown in Fig. 3) and demonstrate that there is almost no sensitivity of the meson line shape to in-medium ω modifications. This is due to the fact that the observed significant increase of the in-medium ω width leads to a strong suppression of the in-medium decays, as $1/\rho^2$, and hamper its observation via a line shape analysis with the presently available statistics. A similar conclusions holds also for the other long-lived mesons (η, η', and ϕ), but not for the short lived ρ meson, for which in-medium modifications should be directly visible in invariant e^+e^- mass measurements. Unfortunately, the situation concerning in-medium modifications of the ρ meson in cold nuclear matter is controversial. As it was already mentioned, the E325 experiment at KEK claims the observation of a ρ meson mass drop. On the other hand, the detailed analysis of the ρ meson invariant-mass distribution measured by CLAS [12] (see Fig. 2, lower left) reveals no mass shift, but only a slight broadening ($\Gamma^{\rho}_{in-medium} \simeq 217$ GeV). These contradicting statements might be explained by the background subtraction procedure applied to the KEK data which did not use like-sign pair background for the normalization, but a fit procedure. As discussed in [1], this could lead to an overestimation of the background in the mass region above the ρ peak, resulting in an apparent downward shift of the meson mass distribution.

New results from proton-induced reactions at a beam energy of 3.5 GeV have recently been obtained by the HADES collaboration. The large acceptance of the detector and the low beam energy allow for detection of e^+e^- pairs from π^0, η (via Dalitz decays) and the ρ, ω down to low momenta ($p_{e^+e^-} < 1.0$ GeV/c) and low invariant masses not covered by the CLAS and E325 experiments. Differential e^+e^- production cross sections as function of the e^+e^- invariant mass, momentum and rapidity have been measured for the $p + p$ and $p + Nb$ reactions and are discussed in contribution of M Weber. The direct comparison of both distributions to the yields expected from the known hadronic sources (from a Pythia calculation) reveals important unexplained strength below the vector meson pole which becomes even more pronounced in proton-nucleus collisions and low momentum dielectrons. Such increase at low $p_{e^+e^-}$ in $p + A$ reactions might be interpreted as a fingerprint of the contribution of two-step processes to meson production. It is well known that ρ couple strongly to low-lying nucleon resonances, as for example $N*(1520), \Delta(1720), ..$, which can be excited by secondary pions. On the other hand, it has also been suggested that such couplings strongly modify the in-medium ρ meson spectral function. Therefore, a more detailed comparison to model calculations for both $p + A$ and $\gamma + A$ reactions incorporating both processes are needed to derive final conclusions.

3 Heavy Ion reactions

Before we discuss new results on dilepton production in low-energy HI reactions we shall first recall results from the SPS at $\sqrt{s} = 17.3$ GeV. The CERES and NA60 experiments measured a significant low-mass (below the ρ/ω pole) pair excess above the contribution expected from the freeze-out decays. A full characterization of this excess as a function of the pair invariant mass, transverse momentum and virtual photon polarization has been established thanks to the high-quality dimuon data from NA60 [8, 19]. The excess represents radiation from the hot and dense phase of the collision and has been extracted by a model-independent subtraction of the freeze-out contribution (the so-called "hadronic cocktail") from the total measured dimuon signal.

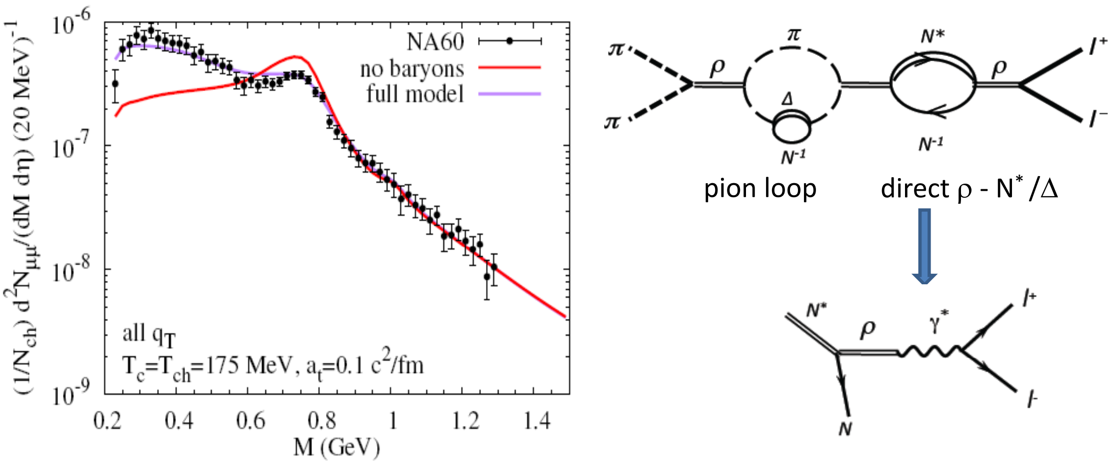


Figure 4: Left: Acceptance-corrected $\mu^+ + \mu^-$ excess as a function of the invariant mass for $In + In$ at 158 AGeV extracted by NA60 [19] compared to the model predictions of [20]. Right: schematic diagram of main contributions to the ρ meson spectral function responsible for the in-medium meson modifications. Effect of the second diagram related to baryons is visualized comparison of two lines: red (no baryons) and violet (full model).

Figure 4 shows the acceptance-corrected dimuon invariant-mass distribution of the excess obtained by the NA60 collaboration [19]. From comparisons to many model calculations one concludes that the excess is related to pions annihilating into the ρ meson and is very sensitive to the ρ in-medium spectral function. The solid lines in Fig. 4 show results from the model calculations of Rapp and Hees [20]. The spectral function of the ρ appears to be strongly affected by two main in-medium effects, schematically depicted in the right side of Fig. 4: (i) modification of the pion loop in the ρ meson selfenergy and (ii) direct rho-meson couplings to the resonance-hole excitations. It appears that the second mechanism plays the bigger role in the melting of the ρ meson visible in Fig. 4 (compare red and violet lines).

The right diagram is also directly related to an elementary process of the baryon resonance (N*, Delta) Dalitz decay into the nucleon and a virtual photon. A strong coupling to the intermediate vector meson, as also predicted by Vector Meson Dominance (VMD), should be reflected in the respective transition form-factor. Indeed, such a coupling is known for the meson Dalitz decays and is well described by VMD in case of π^0 and η, but fails for the ω Dalitz decays. On the baryon Dalitz decays there are no data yet. Hence, it is very interesting to investigate such decays at lower energy, where baryons, as we will see below, are also relevant sources for pair production.

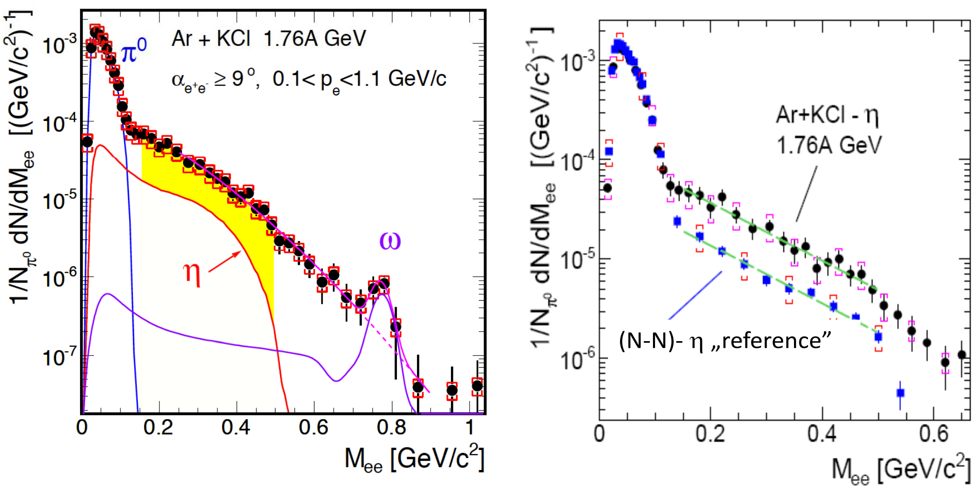


Figure 5: e^+e^- invariant mass distributions from $Ar + KCl$ collisions at 1.756 AGeV measured by HADES [9]. Left: Comparison to the expected mesonic e^+e^- sources after freeze-out. Both distributions are normalized to the π^0 yield as measured in HADES via charged pions (solid line). Right: e^+e^- invariant mass distributions from $Ar + KCl$ collisions with the subtracted η meson contribution compared to the distributions extracted from $N + N$ collisions

Indeed, in the $1 - 2$ AGeV energy range, particle production in heavy-ion collisions is dominated by pion production which originates mainly from the $\Delta(1232)$ resonance. Multiplicities of heavier mesons, like the η (related to the $N^*(1535)$), are already very low (of order $1 - 2\%$). Production multiplicities for both mesons are known from their decay into real photons from former TAPS measurements [21]. The dielectron invariant-mass distribution measured with HADES in the medium-heavy system $Ar + KCl$ at 1.756 AGeV is shown in Fig. 5, left [9]. It is compared to the expected mesonic e^+e^- sources from the π^0, η Dalitz decays, according to the measured multiplicities, and from the ω extrapolated from m_T scaling. One should note, that the ω signal is seen for the first time at such a low energy in HI collisions (below its free $N - N$ threshold). As one can see, these mesonic contributions do not explain the measured yield and leave room (yellow band) for the expected baryonic sources: resonance (here mainly $\Delta(1232)$) Dalitz decays and nucleon-nucleon bremsstrahlung, which also plays a role at these low energies.

Since the relevant baryonic contributions are not experimentally known and various model calculations differ in predictions, the cross sections for pair production have been measured in separate $p + p$ and $n + p$ runs below the η production threshold (at 1.25 GeV) with the HADES detector [22]. The averaged pair multiplicities $(1/2(M_{pp}^{e^+e^-} + M_{pn}^{ee}))$ are displayed as a function of the invariant e^+e^- mass on the right-hand side of Fig. 5 (blue points) together with the corresponding distribution from the $Ar + KCl$ system, all with their respective η Dalitz contribution subtracted. The normalization was done to the mean of the charged pion (π^+, π^-) multiplicity, measured independently by HADES, which at this energy is a good measure of neutral pion multiplicity. The normalization to the pion yield takes care about dependency of particle production on system-size via scaling with an average number of participants A_{part} [22]. As one can see, a significant excess with respect to the $N - N$ reference is visible above the π^0 mass, signaling an additional contribution from the dense phase of the HI collision. On the other hand, it has been shown that the comparison of this $N - N$ reference with the e^+e^- spectrum measured in the smaller $C + C$ system at 1 and 2 AGeV shows no such overshoot [9]. This means that going to the larger $Ar + KCl$ collision system, with $A_{part} \simeq 40$, a stronger than linear scaling of the pair production with A_{part} is observed.

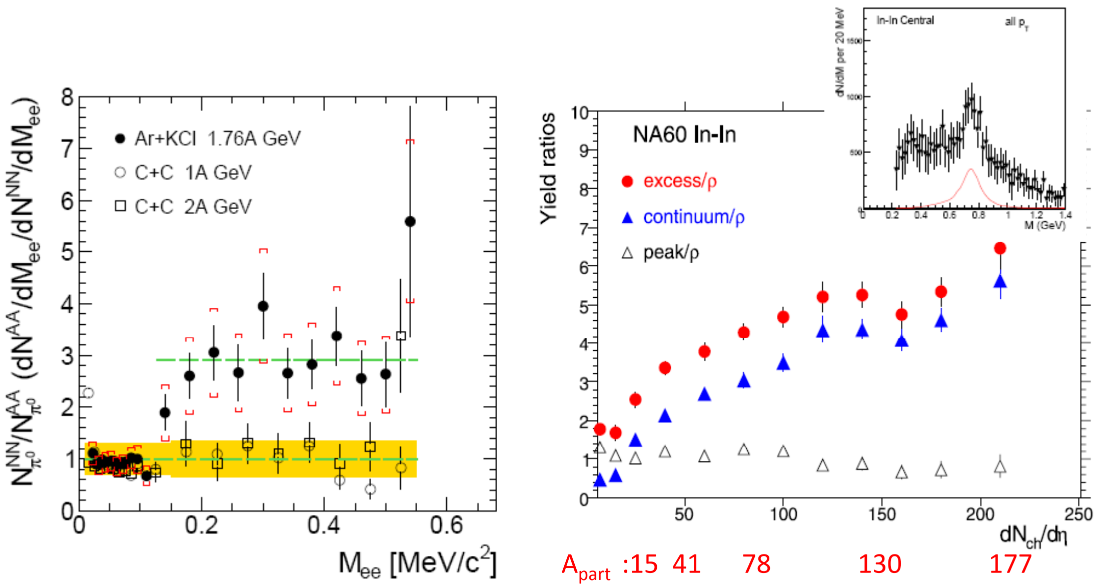


Figure 6: Left: Ratio of e^+e^- yields measured in $Ar + KCl$ and $C + C$ collisions at $1 - 2$ AGeV to the one measured in $N - N$ reactions as a function of the invariant mass, normalized to the respective π^0 yields [9]. Right: Ratios of the dimuon excess measured in $In + In$ collisions at 158 AGeV to the ρ meson yield from the freeze-out [19] as a function of centrality. The excess (shown in the insert) has been decomposed into 3 parts: total (red points), continuum (blue), peak(black).

This scaling indicates the important role of the regeneration process inside the hot and dense nuclear matter which can be observed via dilepton spectroscopy due to their unique, highly penetrating nature. A very nice example of such a behavior is the observation made by NA60 for the ρ meson, described as a "rho clock" [19]. This effect is shown on the right-hand side of Fig. 6, which presents ratios of the total excess, ρ "peak" and the "continuum" part of the excess w.r.t. the "cocktail rho" (ρ from the freeze-out defined as the ρ with the vacuum spectral function and intensity bound to the measured ω peak) as a function of centrality. From the extracted excess evolution NA60 concluded that up to 6 ρ generations are created inside the fireball in $In - In$ collisions. Following this idea, the HADES excess, shown on the left side of Fig. 6 as a function of the e^+e^- invariant mass, can be quantified to be around 3 w.r.t. the $N - N$ reference and interpreted in a way that on average 3 Δ generations are created in $Ar + KCl$ during the fireball life time. Thus an even larger increase can be expected for heavier system that will be investigated in forthcoming experiments with the $Au + Au$ collision system.

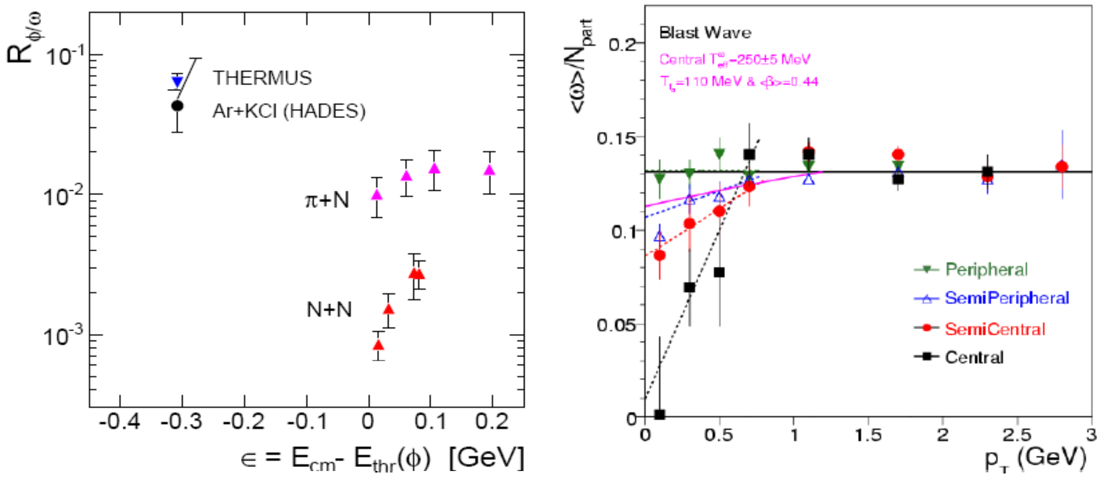


Figure 7: Left: ϕ to ω production ratio in $A + A$ [9] and $\pi + N$, $N + N$ as a function of the excess energy above the production threshold for ϕ in elementary reactions [9]. Right: ω multiplicity per participant for various centralities as a function of transverse momentum measured in $In + In$ at 158 AGeV [19]

Interesting new results on ϕ and ω production in HI collisions at energies below the nucleon-nucleon production threshold have been obtained by HADES as well. Figure 7 shows the ratio of the ϕ to ω multiplicities, $R_{\phi/\omega}$, measured in $Ar + KCl$ collisions at 1.756 AGeV, together with predictions of the statistical model THERMUS (blue circle) and results from elementary $p + p$ and $\pi + N$ reactions [9]. The data points are all plotted as a function of the excess energy for the exclusive ϕ production in $p + p$ and $\pi + N$ reactions, respectively.

One can see from this comparison that in the heavy-ion reaction $R_{\phi/\omega}$ is more than one order of magnitude larger than in $N + N$ collisions and also at least a factor $3 - 5$ larger than in pion-induced processes. On the other hand, the ratio is consistent with the thermal model assuming full thermalization and no OZI suppression. This can indicate that the ϕ meson is produced in multi-step, processes involving short-lived resonances. It could of course also be influenced by different absorption of both mesons in nuclear matter. Indeed, the results from cold matter experiments, discussed in section 2, indicate larger absorption of the ω meson as compared to the ϕ that can enhance the in-medium $R_{\phi/\omega}$.

The effect of ω absorption and the absence of such effect on the ϕ have been observed by NA60 in $In + In$ collisions at 158 AGeV [19,23]. In search for possible medium effects, NA60 studied the yield in the ω and ϕ peaks as a function of the transverse momentum of these mesons. Figure 7 displays the ω multiplicity per participant as a function of the transverse momentum for various centrality conditions. In the most central collisions one can observed a clear drop of the multiplicity at low transverse momenta. This can be explained by ω absorption, since due to the short life time of the fireball at this beam energy in-medium effects can only be expected for low-momentum mesons. A similar analysis performed for the ϕ meson does not show any such effect. Furthermore, a direct analysis of the ϕ meson line shape does not reveal any changes with respect to its vacuum shape.

4 Conclusions

Significant increase of the ω, ϕ meson widths in cold nuclear matter have been concluded from the transparency ratios measured in photon and proton induced reactions. In-medium inelastic meson-nucleon cross sections derived by means of low density approximation provide much larger values as compared to the one known from elementary reactions and can indicate important role of many-body interactions. Observed dependence of the transparency ratio on the meson momentum appears to be important observable to quantify role of secondary processes in the meson production.

Dilepton production in heavy reactions allows for the extraction of the radiation from the hot and dense phase of the collision. At SPS energies it is connected to pion annihilation and allows for the measurement of the in-medium ρ meson spectral functions. It appears to be strongly modified (broadenning) by many-body interactions with the surrounding hadron gas with dominant role of baryons. From the yield analysis of the radiation one can conclude that the mesons are regenerated inside hot and dense nuclear matter. A similar excess has also been observed at lower energies (1-2 AGeV) and can be connected to radiation from baryonic (mainly $\Delta(1232)$) resonances. It has been argued that both processes can be linked together by underlying elementary process of the Dalitz decay of baryonic resonances. In contrast to the ρ meson no changes in the ω or ϕ meson line shapes have been observed in HI collisions. However, analysis of the meson production yields as a function of the centrality and the meson transverse momentum indicate significant absorption of the ω meson, in agreement with cold matter experiments.

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