Meson and di-electron production with HADES

I. Fröhlich, G. Agakishiev, C. Agodi, A. Balanda, G. Bellia, A. Belver, A. Belyaev, A. Blanco, M. Böhmer, J. L. Boyard, P. Braun-Munzinger, P. Cabanelas, E. Castro, S. Chernenko, T. Christ, M. Dестванис, J. Díaz, F. Dohrmann, A. Dybczak, T. Eberl, L. Fabbietti, O. Fateev, P. Finocchiaro, P. Fonte, J. Friese, T. Galatyuk, J. A. Garzón, R. Gernhäuser, A. Gil, C. Gilardi, M. Golubeva, D. González-Diáz, E. Grosse, F. Guber, M. Heilmann, T. Hennino, R. Holzmann, A. Ierusalimov, I. Iori, A. Ivashkin, M. Jurkovic, B. Kämpfer, K. Kanaki, T. Karavicheva, D. Kirschner, I. Koenig, W. Koenig, B. W. Kolb, R. Kotte, A. Kozuch, A. Krása, F. Krizek, R. Krücken, W. Kühn, A. Kugler, A. Kurepin, J. Lamas-Valverde, S. Lang, J. S. Lange, K. Lapidus, L. Lopes, L. Maier, A. Mangiarotti, J. Marín, J. Markert, V. Metag, B. Michalska, J. Michel, D. Mishra, E. Morinière, J. Moussa, C. Müntz, L. Naumann, R. Novotny, J. Otwinowski, Y. C. Pachmayer, M. Palka, Y. Parpottas, V. Pechenov, O. Pechenova, T. Pérez Cavalcanti, J. Pietraszko, W. Przygoda, B. Ramstein, A. Reshetin, M. Roy-Stephan, A. Rustamov, A. Sadovsky, B. Sailer, P. Salabura, A. Schmah, R. Simon, S. Spataro, B. Spruck, H. Ströbele, J. Stroth, C. Sturm, M. Sudol, A. Tarantola, K. Teibl, P. Tlusty, M. Traxler, R. Trebacz, H. Tsertos, I. Veretenkin, V. Wagner, H. Wen, M. Wisniowski, T. Wojcik, J. Wüstenfeld, S. Yurevich, Y. Zanevsky, P. Zhou, P. Zumbusch

(HADES collaboration)

1Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, 95125 Catania, Italy
2LIP-Laboratório de Instrumentação e Física Experimental de Partículas, 3004-516 Coimbra, Portugal
3Smoluchowski Institute of Physics, Jagiellonian University of Cracow, 30-059 Kraków, Poland
4Gesellschaft für Schwerionenforschung mbH, 64291 Darmstadt, Germany
5Institut für Strahlenphysik, Forschungszentrum Dresden-Rossendorf, 01314 Dresden, Germany
6Joint Institute of Nuclear Research, 141980 Dubna, Russia
7Institut für Kernphysik, Johann Wolfgang Goethe-Universität, 60438 Frankfurt, Germany
8II. Physikalisches Institut, Justus Liebig Universität Giessen, 35392 Giessen, Germany
9Istituto Nazionale di Fisica Nucleare, Sezione di Milano, 20133 Milano, Italy
10Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia
11Physik Department E12, Technische Universität München, 85748 München, Germany
12Department of Physics, University of Cyprus, 1678 Nicosia, Cyprus
13Institut de Physique Nucléaire d’Orsay, CNRS/IN2P3, 91406 Orsay Cedex, France
14Nuclear Physics Institute, Academy of Sciences of Czech Republic, 25068 Rez, Czech Republic
15Departamento de Física de Partículas, University of Santiago de Compostela, 15782 Santiago de Compostela, Spain

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Abstract

The HADES experiment, installed at GSI, Darmstadt, measures di-electron production in $A + A$, $p/\pi + N$ and $p/\pi + A$ collisions. Here, the $\pi^0$ and $\eta$ Dalitz decays have been reconstructed in the exclusive $p + p$ reaction at 2.2 GeV to form a reference cocktail for long-lived di-electron sources. In the C+C reaction at 1 and 2 GeV/u, these long-lived sources have been subtracted from the measured inclusive $e^+e^-$ yield to exhibit the signal from the early phase of the collision. The results suggest that resonances play an important role in dense nuclear matter.

1 Introduction

One of the main subjects in physics is how hadrons are generated by the strong interaction and how hadron-hadron forces can be described. Here, effective models have to be employed to calculate properties of hadrons and their interactions at different environmental conditions. In the vacuum, e.g., One-Boson exchange (OBE) models describe the production and (de-)excitation of hadrons taking intermediate resonances into account in a coherent approach. On the other hand, the evolution of hadronic matter (like in heavy ion reactions) is usually calculated by transport models where different processes are factorized. The question of in-medium modifications of hadronic spectral functions arises additional complexity. This investigation has in particular raised by the question if chiral symmetry restoration appears in hot/dense matter which could lead to dropping masses of hadrons [1]. Therefore, the creation of nuclear matter under extreme conditions in the laboratory (possible only in A+A reactions) is a unique tool to study and understand hadronic properties.

In this context, the emission of virtual photons ($\gamma^*$), decaying into di-leptons ($e^+e^-$ or $\mu^+\mu^-$) which do not undergo strong interaction, has been proposed as an ideal probe for such studies. Hence, this undistorted “light” from the early phase of the collision allows the study what could be the nature of hadronic matter over the whole nuclear phase region (baryonic matter, meson gas, quark-gluon phase). Virtual photons, moreover, couple via virtual vector mesons ($\rho^0, \omega$) to the hadronic matter (vector meson dominance model). A possible change of vector meson properties (e.g. dropping mass, larger width) can be studied by separating the di-lepton cocktail into two parts: The radiation from short-lived resonances (as discussed above) is extracted by subtracting the long-lived components (i.e. electromagnetic de-excitation of hadrons after the freeze-out) from the measured $e^+e^-$ spectrum.

Indeed, it has been found that di-lepton spectra taken in heavy-ion collisions [2,3,4] need additional short-lived sources in the invariant-mass region $0.2 \text{ GeV}/c^2 \leq M_{ee} \leq 0.6 \text{ GeV}/c^2$. 
At least in the SPS energy range this feature has been related to modifications of the $\rho$-meson spectral function in the hadronic medium [5].

However, for a complete understanding of hadronic properties it is important to measure not only the hot, but also the dense nuclear matter. At beam energies of 1-2 GeV/u, which correspond to moderate densities (2-3 $\rho_0$) and temperatures (60-80 MeV), the production of mesons is dominated by multi-step processes with excitation of intermediate baryonic resonances like $\Delta^{\pm,0} \rightarrow N\pi^0 \rightarrow N\gamma e^+e^-$ ($\pi$-Dalitz), $N^*(1535) \rightarrow N\eta \rightarrow N\gamma e^+e^-$ ($\eta$-Dalitz) and the Dalitz decays of baryonic $\Delta$, $N^*$ resonances in $N(\omega,\rho) \rightarrow N\gamma^* \rightarrow Ne^+e^-$. This means, after removing the long-lived components (the Dalitz decays $\pi^0$, $\eta$ have a known form factor [6]) the remaining di-lepton strength represents the electromagnetic response of resonant matter, which is even on the elementary basis completely unknown. For example, the Dalitz decays of the baryonic resonances (including the $\Delta(1232)$) have not been measured. In the overall picture, these contributions are additional exchange graphs in the virtual bremsstrahlung process $NN \rightarrow NN\gamma^*$. One of the the questions recently addressed by OBE models is how the resonance contributions have to be treated among with the bremsstrahlung in coherent calculations. In this context it should be pointed out that the large pair yields in the region dominated by resonance decays (0.2-0.6 GeV/$c^2$) observed by the pioneering DLS experiment [7] in $C+C$ and $Ca+Ca$ collisions at 1 GeV/u remain to be explained satisfactorily [8]. Additional contributions from the bremsstrahlung graphs could possibly explain the missing sources but a debate on this is still ongoing [9,10]. The general conclusion is, however, that experimentally a strong isospin dependence should be visible in the mass-dependent ratio $M_{pp}^{ee}/M_{pn}^{ee}$.

To conclude this introduction, for an understanding of di-lepton spectra and resolving medium effects from the vacuum spectral functions it is crucial to fully describe the different (maybe coherent) sources in the heavy ion cocktail.

## 2 The HADES program

The High-Acceptance DiElectron Spectrometer HADES at GSI, Darmstadt, is presently the only di-lepton experiment operational in the SIS energy regime of 1-2 GeV/u, succeeding the DLS experiment. To summarize the setup at this point, HADES [11] is a magnetic spectrometer, consisting of up to 4 planes of Mini Drift Chambers (MDC) with a toroidal magnetic field. Particle identification is based on momentum and time-of-flight measurements. In addition, a Ring Imaging Cherenkov detector (RICH) and an electromagnetic Pre-Shower detector provide electron identification capabilities. To increase the acquired pair statistics, besides a charged-particle multiplicity trigger (LVL1), an online electron identification (LVL2) has been operated as part of the two-level trigger system [12].

In order to address the open questions outlined above, one of the goals of the HADES detector system is to measure the di-electron properties not only in heavy ion collisions but in elementary reactions as well. Consequently, the HADES program spans from $p+p$, $\pi+p$ to $p+A$ and $A+A$ collisions. First data has been taken in $C+C$ collisions [13,14] at 1 and 2 GeV/u, $Ar+KCl$ collisions at 1.756 GeV/u, and interactions of $d+p$ at 1.25 GeV/u, and $p+p$ at 1.25, 2.2 and 3.5 GeV.
The idea of these measurements is to fully disentangle and describe the elementary sources which are needed to understand the heavy ion case. Here, \( p + p \) and \( d + p \) measurements, which are described in detail in a separate contribution [15], allow to study the \( \Delta \) Dalitz decay which is the main di-electron contribution above the \( \pi^0 \) mass at these energies. In the \( p + p \) reaction at 2.2 GeV the \( \pi^0/\eta \) Dalitz decays can be disentangled by exclusive studies, which will be shown in the first part of this contribution. This measurement works also as a reference reaction for the long-lived components of the \( C + C \) heavy ion data. The \( p + p \) reaction at 3.5 GeV was mainly done to measure the free \( \omega \) line shape and to understand possible contributions of higher resonances. In \( C + C \) collisions we have extracted the radiation by short-lived resonances, which is discussed in this contribution. In addition, vector meson production has been measured in the \( Ar + KCl \) (described separately as well [16]). As an outlook, future perspectives of the HADES experiment are given.

3 Exclusive meson production in the \( p + p \) reaction at 2.2 GeV

One aim of the \( p + p \) experiment done at a kinetic beam energy of 2.2 GeV was to have a reference reaction for the \( C + C \) reaction at 2 GeV/u and study the Dalitz decays \( pp \rightarrow ppm^0 \rightarrow pp\gamma e^+e^- \) and \( pp \rightarrow pp\eta \rightarrow pp\gamma e^+e^- \) independently by a selection on the \( pp \) missing mass. This allows to exclude uncertainties for this part of the cocktail. But before conclusions on these decays are drawn the parameters used by simulations have to be confirmed for the acceptance correction of the di-electron spectra. Available data in \( N + N \) collisions at this energy suffers from the following. In the \( \eta \) case, the total cross section has been determined by a fit [17] taking into account data points with large errors. The \( pp \rightarrow pp\pi^0 \) total cross section is known [18], but more resonances with non-isotropic behavior are involved. For instance, the pion scattering angle distribution \( \theta^\Delta_{\pi} \) in the \( NN \rightarrow N\Delta \rightarrow NN\pi \) reaction has been found by bubble chamber experiments to be in disagreement to one-pion exchange [19].

Therefore, the \( pp \rightarrow ppM \) reactions (where \( M \) is either a \( \pi^0 \) or \( \eta \)) have been compared to simulations for which we usually employ the Pluto event generator [20]. The normalization of these distributions has been done by comparing the yield of measured mesons \( N^M \) to the yield of \( pp \) elastic events \( N^{el} \), and a model dependent Pluto simulation with the known \( pp \) elastic cross section and angular distribution [21][22]. To take detector effects into account, each measured event is corrected first for single-track detector and reconstruction inefficiencies. The simulated events, on the other hand, are filtered through an acceptance filter (a matrix \( A_{\pm}(p, \theta, \phi) \) for each track) and smeared in momentum using a parameterized resolution. After this procedure, the resulting spectra can be compared to the simulations. Uncertainties due to different production mechanisms are evaluated by varying the different parameters.

We have studied the reactions \( pp \rightarrow pp\pi^0 \) and \( pp \rightarrow pp\eta \rightarrow pp\pi^+\pi^-\pi^0 \). In both cases, the neutral \( \pi^0 \) (not detected in the setup) has been selected by the missing mass method. For the \( \eta \) simulation the polar angle distributions and resonance model from DISTO [23], obtained at a similar beam energy (the ratio \( \frac{\sigma(pp \rightarrow p\pi^+\pi^-\pi^0)}{\sigma(pp \rightarrow ppm^0)} \) is 1.38), and the \( \eta \) decay properties from Crystal Barrel [24] have been used. The preliminary results \( \sigma_{pp \rightarrow ppm^0} = 70 \pm 8 \text{mb} \) is consistent with the parametrizations. In the \( \pi^0 \) case the resonance model [18] has been adapted and included
Figure 1: Left: Di-electron mass spectra for the η (full symbols) and η (open symbols) Dalitz decay (corrected for efficiency and normalized to the number of pp elastic events). The solid curve shows the simulated η Dalitz decay (acceptance taken into account), whereas the dashed curves represent the π\(^0\) Dalitz decay (long-dashed with Δ decay angle from Ref. [19], short-dashed with one-pion exchange model.) Right: Helicity angle distribution among with a fitted function (\(a \cdot (1 + b \cdot \cos^2 \theta_{ee}^\pm)\)) for π\(^0\) (full symbols and dashed line) and η (open symbols and solid line).

Into Pluto. Unlike the η case, angular distributions (for the production of resonances as well as for their decay) play an much larger role. For the Δ and \(N^\ast\) production the strong forward-backward peaking of the polar angle distribution has been taken into account [25, 26]. For the distribution of \(\theta_e^\pm\) the measured coefficient [19] was used. In addition, the influence of applying a pure one-pion exchange model has been evaluated. Our preliminary data suggests that we need additional resonance contributions to describe the data [27]. Here, we extracted \(\sigma_{pp \rightarrow pp\pi^0} = 4.17 \pm 0.05^{\text{stat}} \pm 0.48^{\text{norm}} \text{mb}\) which is slightly above the model [18].

In the following, we used these production parameters for a di-electron cocktail simulation with η/π\(^0\) components only to compare to our exclusive data which we obtained as follows. Opposite-sign reactions \(pp \rightarrow ppe^+e^-\), as well as like-sign pp \(\rightarrow ppe^+e^+\) and pp \(\rightarrow ppe^-e^-\) events were formed and subjected to common selection criteria (e.g., an opening-angle cut of \(\theta_{ee} > 4^\circ\)). In addition, a selection on the Dalitz decays \(M \rightarrow e^+e^-\gamma\) has been done by identifying a missing γ. From the reconstructed distributions first the combinatorial background (CB) of uncorrelated pairs was calculated bin by bin as \(N_{\text{CB}} = 2\sqrt{N^{++}N^{--}}\). Then the \(e^+e^-\) pairs have been selected as a function of the \(pp\) missing mass. The \(\pi^0\) and η contribution has been evaluated by fitting the signal plus background. By repeating this method on different \(e^+e^-\) mass slices, the \(e^+e^-\) invariant spectrum can be obtained. Fig. I (left part) shows the efficiency corrected data for the \(\pi^0\) and η Dalitz decay, normalized to the number of elastic scattered pp events, and compared
to the Pluto simulation. Possible effects of the $\Delta$ decay angle are small. As a conclusion it can be drawn that the $e^+e^-$ invariant mass of the $\pi^0$ and $\eta$ Dalitz decays are well understood and the chosen production parameters match the data points.

In addition to the invariant mass the virtual photon (decaying into 2 stable particles) has 5 more degrees of freedom [28]: One of them, the helicity angle $\theta_{ee}^\pm$, is related to the longitudinal polarization of the virtual photon. From QED considerations [29] this distribution has to be $1 + \cos^2 \theta_{ee}$. In Fig. 1 (right part) the result (after a model-dependent correction) has been fitted with $a \cdot (1 + b \cdot \cos^2 \theta_{ee})$ which gave $b = 1.35 \pm 0.44$ and $b = 0.98 \pm 0.48$ for the $\pi^0$ and $\eta$, respectively, in agreement to the calculation [29].

4 Di-electron production in $C + C$ collisions at 1 and 2 GeV/u

HADES has measured di-electron spectra obtained in $C + C$ collisions [13, 14] at two different beam energies (1 and 2 GeV/u). The first data set allows to be compared to that of the former DLS experiment [7]. In order to address the open questions raised by the DLS experiment we follow the usual strategy and subtract the long-lived components.

In the pair analysis (details of the data analysis can be found in [13, 14]), opposite-sign pairs ($e^+e^-$), as well as like-sign pairs ($e^+e^+$ and $e^-e^-$) were formed and an opening-angle cut of $\theta_{ee} > 9^\circ$ has been used. From the reconstructed distributions the combinatorial background (CB) was formed and subtracted as in the previous case. For masses $M_{ee} > 0.2$ GeV/$c^2$, where statistics is small, the CB was obtained by an event-mixing procedure. Detector and reconstruction efficiencies as well as the acceptance were taken into account as described above. Here, the normalization was done by the number of charged pions $N_{\pi^0} = 1/2(N_{\pi^+} + N_{\pi^-})$, as measured also in HADES and extrapolated to the full solid angle [30]. The obtained pion multiplicity per participant nucleon, i.e. $M_{\pi}/A_{part} = 0.061 \pm 0.009$ for 1 GeV/u and $M_{\pi}/A_{part} = 0.153 \pm 0.023$.
Figure 3: **Left:** Experimental yield divided by cocktail A for 1 GeV/u (full symbols) and 2 GeV/u (open symbols) data. In addition, the ratio of cocktail B and A for 1 GeV/u data is indicated (dashed line). **Right:** Excess over cocktail A compared to the measured multiplicities of $\eta$ and $\pi^0$ as a function of bombarding energy.

for 1 GeV/u, agrees well with previous measurements of charged and neutral pions [31].

In Fig. 2 the measured $e^+e^-$ invariant mass (2 GeV/u data) is compared to a pair cocktail calculated from free $\pi^0 \rightarrow \gamma e^+e^-$, $\eta \rightarrow \gamma e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, and $\omega \rightarrow e^+e^-$ meson decays only (cocktail A), simulated with the Pluto package [20], representing the radiation from long-lived mesons. As expected, experimental data and cocktail A agree in the $\pi^0$ Dalitz region. In the mass region $M_{ee} > 0.15 \text{ GeV}/c^2$ the cocktail strongly underestimates the measured pair yield. This is not surprising, since one expects additional contributions from short-lived resonances. The cocktail B (Fig. 2 long-dashed line) considering additional $\Delta(1232)$ and $\rho$ components by a simple estimation is still not sufficient to describe the signal.

As pointed out above, by subtracting the long-lived sources, the signal from the early phase of the dense matter should become visible. This is shown for both measured beam energies in Fig. 3 (left). A structure in the vector meson region at 0.6 GeV can be clearly seen and may be attributed to a virtual $\rho^0$ excitation. In addition, a large excess over the cocktail A in the mass region $0.15 \text{ GeV}/c^2 \leq M_{ee} \leq 0.5 \text{ GeV}/c^2$ can be found. The assumption that this enhancement is caused by an underestimated $\eta$ yield and/or not well understood efficiency of the detector is, as demonstrated in the previous section, ruled out. To further understand this excess, it has been integrated and compared to the measured multiplicities of $\eta$ and $\pi^0$ as a function of bombarding energy (Fig. 3 right part). The result is that the excess scales with $\pi^0$ production. This indicates that resonances, correlated via their main decay branch to pion production, play a much larger
role than usually supposed. It should be noticed at this point that the virtual bremsstrahlung process, described in a recent OBE model \[9\], cannot be factorized into a resonance part and the elastic term. In order to understand these processes and the electromagnetic structure of the $\Delta$ resonance on an elementary basis, dedicated experiments ($p+p$ and $d+p$ at 1.25 GeV/u) have been done by HADES \[15\].

5 \ Vector meson production in $p + p$ at 3.5 GeV

In the previous two sections we have demonstrated that the di-electron contributions of $\pi^0$ and $\eta$ in elementary as well as in heavy ion collisions is well understood. The additional yield seen above the eta Dalitz cannot be explained from long-lived sources, suggesting that it comes from the early phase of the collisions and seems to be the glowing of resonant matter. But there are still some questions left region, which are (in part): 1.) what is the production mechanism of the $\omega$ (including resonances), and 2.) what is the correct description of the free $\rho$ spectral function and how does it change inside nuclear matter. To give additional constraints on these questions HADES has measured the di-electron production in the $p + p$ reaction at 3.5 GeV. Fig.\[4\] shows the (preliminary) invariant mass spectrum without any efficiency correction. The $\omega$ peak is clearly seen. Further exclusive studies can now, similar to the strategy already outlined, further disentangle the di-electron cocktail in the vector meson region and conclusions about the $\rho$ mass shape in vacuum and its coupling to resonances can hopefully been drawn. Moreover, the $\omega$ line shape obtained by this experiment can be compared to that one in cold nuclear matter. As past experiments about this questions were not conclusive \[32, 33\], HADES will take data using the $p + Nb$ collision in the near future at the same beam energy of 3.5 GeV which allows for a direct comparison of the spectra.
6 Future and outlook

HADES will continue its program at its current place at SIS, and then move to the upcoming FAIR accelerator complex. This is one of the main reason for upgrading[34] the HADES detector and its trigger and readout system[35] with the addition of the new RPC detector (“Resistive Plate Chamber”). Since the currently used data acquisition system was designed ten years ago, it was reasonable to reconsider the whole concept and make use of new technologies. Furthermore, the large data volumes, expected in experiments with heavy collision systems (Au+Au) already at SIS18 and with higher energies at the new FAIR facility, require bandwidths which cannot be achieved by the current system.

Here, HADES will continue the systematic investigation, successfully started at SIS, up to kinetic beam energies of 8 GeV/u at FAIR and step, as there is no dilepton data between 2 and 40 GeV/u so far, into complete “terra incognita”.

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