



## Review

# Study of $e^+$ , $e^-$ production in elementary and nuclear collisions near the production threshold with HADES

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### Abstract

HADES is a second generation experiment designed to study dielectron production in proton, pion, and heavy ion induced reactions at the GSI accelerator facility in Darmstadt. The physics programme of HADES is focused on in-medium properties of the light vector mesons. In this contribution we present status of the HADES experiment, demonstrate its capability to identify rare dielectron signal, show first experimental results obtained from C + C reactions at 2 A GeV and shortly discuss physics programme of up-coming experimental runs.

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## 1. Introduction

HADES (high acceptance dielectron spectrometer) is a unique apparatus currently assembled at the heavy ion synchrotron SIS at GSI Darmstadt. The main part of the HADES physics program is focused on studies of in-medium properties of the light vector mesons  $\rho$  (770 MeV/ $c^2$ ),  $\omega$  (783 MeV/ $c^2$ ) and  $\phi$  (1020 MeV/ $c^2$ ) [1, 2].

Significant changes of the vector meson spectral functions in hot and/or dense nuclear matter have been predicted by various model calculations. The meson spectral functions inside nuclear matter are directly accessible via a measurement of the dielectron invariant mass distributions of the two-body meson decays because  $e^+$ ,  $e^-$  pairs do not suffer from a strong electron–hadron final state interaction [3–7]. A low mass dielectron excess observed in heavy ion collisions by the CERES experiment on SPS at CERN [8] launched an exciting dispute about its origin. According to QCD inspired models, this spectacular excess can be considered as a signal of the partial chiral symmetry restoration in dense and hot nuclear matter. On the other hand, various hadronic models explain this enhancement by significant in-medium modifications of the  $\rho$  meson spectral function due to strong meson couplings to low lying nucleon resonances (for a recent review see [9]).

At SIS, energy domain dielectron invariant mass distributions were measured in proton–proton and light and heavy ion reactions by the DLS collaboration at the BEVELAC [10, 11]. Within the given experimental error bars, the extracted  $e^+e^-$  production rates in proton–proton reactions could be reasonably reproduced by theoretical calculations assuming free dielectron decays of various hadronic sources [12, 13]. For the heavy ion collisions, Ca + Ca and C + C, a remarkable excess of the dielectron yield in the low mass range  $200 \text{ MeV}/c^2 < M_{\text{inv}} < 600 \text{ MeV}/c^2$  as compared to the theoretical calculations was found. This dielectron excess could be explained neither by hadronic models based on the in-medium modified  $\rho$  meson spectral functions nor by the Brown–Rho scaling [14].

The HADES experiment, described below, aims at systematic studies of dielectron production in proton, pion and heavy ion induced reactions. Although beam energies available at the GSI/SIS facility are limited to the kinematic region near the vector meson production threshold, this domain is of great interest for confirming the unexplained DLS results as well as for the understanding of the importance of vector–meson hadronic couplings involved in interpretation of the CERES data. Moreover, the experiment will allow us for the first time to measure several elementary dielectron production channels in nucleon–nucleon and pion–nucleon reactions using exclusive measurements.

## 2. The HADES experiment

HADES (high acceptance dielectron spectrometer) is a magnetic spectrometer recently commissioned at the heavy ion synchrotron facility SIS at GSI Darmstadt [15]. It is designed for high resolution and high statistics dielectron spectroscopy in  $pp$ ,  $pA$ ,  $AA$  and  $\pi p$ ,  $\pi A$  reactions in the 1–2 A GeV energy range. A comparison of the dielectron invariant mass spectra from  $\pi p$  and  $pp$  reactions with  $pA$ ,  $\pi A$  and  $AA$  collisions will allow us to study vector meson spectral functions as a function of nuclear matter density and size of the collision system with an excellent mass resolution and good statistics.

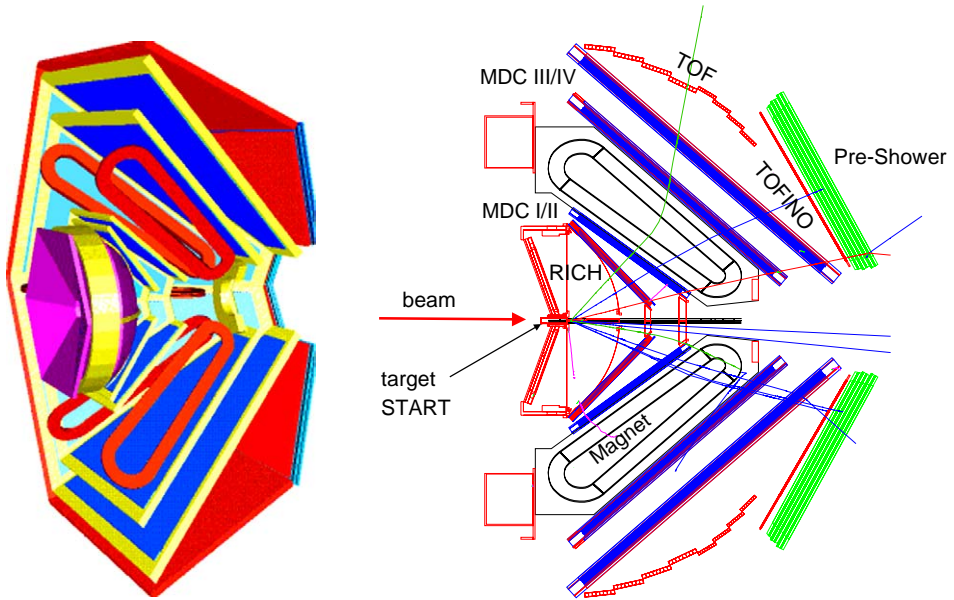


Fig. 1. Left: a three-dimensional artist's view of the HADES spectrometer (two sectors have been removed for clarity). Right: a side view of HADES. The RICH detector, consisting of a gaseous radiator, a carbon fiber mirror and a tilted photon detector, is used for electron identification. Two sets of multiwire drift chambers (MDCs) are placed in front and behind the magnetic field to measure particle momenta. A time of flight wall (TOF/TOFINO) accompanied by a Pre-shower detector at forward angles is used for an additional electron identification and trigger purposes. For a reaction time measurement, a start detector is located near the target.

The dielectron decay channels of the vector mesons are suppressed by a factor of  $\approx 10^{-5}$  as compared to hadronic decays. In typical  $AA$  reactions at SIS energies the expected total yield of dielectrons from the vector meson decays is about  $10^{-6}$  per central event [16]. Thus, the experimental challenge is to find one dielectron in one million of these central collisions each containing a background of charged hadrons and photons from  $\pi^0$  decays. This requires a system with large geometrical acceptance, high rate capabilities, sufficient granularity and a highly selective multistage trigger scheme with real time electron recognition. For a fast electron recognition, detectors with good electron/hadron separation power and dedicated trigger schemes involving image processing are necessary. Moreover, an excellent invariant mass resolution  $\delta M/M \approx 1\%$  is required for vector meson identification.

HADES, shown in Fig. 1, is a rotationally symmetric, large acceptance, toroidal spectrometer with complete azimuthal coverage [15]. The spectrometer acceptance covers polar angles between  $18^\circ$  and  $85^\circ$ . The angular and momentum acceptances have been optimized for the detection of dielectron decays of hadrons produced in the SIS energy regime. The dielectrons from such decays are emitted over the whole solid angle but with a maximum probability near  $\theta = 40^\circ$ . For dielectron invariant masses  $M < 1.5 \text{ GeV}/c^2$  and transverse momenta  $p_T < 1.5 \text{ GeV}/c$  this geometry results in a flat acceptance.

The geometrical acceptance achieved, of  $\sim 40\%$ , represents an improvement by a factor of 100 as compared to the pioneering experiments performed with the DLS spectrometer at Berkeley.

Reconstruction of the dielectron four-momentum vectors is carried out by measuring the hit positions in several detector layers and assigning them to electron and positron tracks. The electron hits are identified in special electron detectors placed in front of (RICH) and behind (TOF, TOFINO, Pre-shower) the magnetic field. They are matched with hits reconstructed in the multiwire drift chambers (MDCs). More precisely, the electron track recognition and the dielectron invariant mass reconstruction consist of three major steps:

(1) A first electron identification is obtained in a fast RICH with a gas radiator (ring imaging Čerenkov counter) [17, 18] surrounding the target in the forward hemisphere. The selection of a gaseous low  $Z$  radiator ensures complete hadron blindness of the detector as well as low multiple scattering and hence allows for determination of the electron track emission direction. Electrons with velocities  $\beta \approx 1$  radiate Čerenkov light in a cone along their tracks through the radiator. The light is reflected by a carbon fiber mirror and is focused as a ring image on a position sensitive photon detector plane. The PD is a multiwire proportional chamber with a CsI solid photocathode for photon–electron conversion, which is sensitive in the ultraviolet region.

(2) Track momentum is reconstructed from the deflection in the magnetic field. The track deflection is calculated from the directions of two track segments reconstructed in both the MDC systems [19]: I/II placed in front and III/IV behind the magnetic field. The MDC chambers consist of six-wire planes and are filled with a helium–isobutane gas mixture. The total thickness of the four MDC chambers amounts to  $x/X_0 = 2 \times 10^{-3}$  only and is comparable to the contribution of the air volume between the target to the MDC IV. The designed invariant mass resolution of  $\delta M \approx 1.0\%$  is achieved in a given field configuration with a position resolution of  $\delta y \leq 100 \mu\text{m}$  ( $\sigma$ ).

(3) Redundant identification of the electron tracks is achieved via time of flight measurement in a set of scintillating detectors arranged in two subsystems: TOF and TOFINO, forming the multiplicity and electron trigger array (META) [2, 20]. The inner TOFINO detector is accompanied by a Pre-shower detector registering electromagnetic showers of traversing particles. The second electron identification is necessary since a large fraction of electron pairs originate from  $\gamma$ -ray conversions in either the target or the RICH radiator or from  $\pi^0$  Dalitz decays. These pairs consist of low momentum electrons from which frequently none or only one from a pair manages to traverse the magnetic field, reaching the META detector. Nevertheless, since the multiplicity of these pairs is larger than 1 in a typical electron event, electrons from different decay vertices can still be combined into false dielectrons and hence form a combinatorial background. A rejection of this background is one of the most difficult problems in dielectron spectroscopy. In the HADES experiment these close pairs can be efficiently rejected by their reconstruction in front of the magnetic field in the RICH and the inner MDC I/II detectors.

The data acquisition is started by a positive first-level trigger (LVL1) decision. The first-level trigger is obtained by a fast  $t_f < 100$  ns hardware analysis of the multiplicity measurement  $M_{ch}$  performed by the TOF and TOFINO modules. The second-level trigger (LVL2) performs a three-step process [21]. In the first step a search for electron ring

images on the RICH pad plane is made. In parallel, charge clusters with the signature of an electromagnetic shower in the Pre-shower detector as well as particles with an appropriate time of flight in the scintillator TOF wall are searched for. The resulting position coordinates of electron candidates in the inner RICH and outer META detectors are compared in the matching unit (MU) in an appropriate matching window that takes into account the track deflection due to the magnetic field. The matched hits define a valid electron candidate track. In the third step the selected electron tracks with opposite charges can be combined into dielectron pairs and their invariant mass can be calculated on the basis of a look-up table which contains a mapping of the polar electron track deflection angles to momenta. In the currently investigated 2 A GeV C + C collisions a conservative LVL2 trigger condition was imposed requiring at least one electron track, which provided 92% background event rejection and high electron identification efficiency ( $\epsilon \geq 0.7$ ).

### 3. First experimental results from C + C collisions

The performance of the spectrometer was studied in several commissioning beam times by means of the C + C reaction. The typical beam intensity was  $I = 10^6$  particles/s and a 5% interaction length target was used. In the two recent experimental runs in 2001 and 2002 we collected around  $5 \times 10^7$  and  $20 \times 10^7$  LVL1 triggered events, respectively. In the second run we used for the first time the LVL2 trigger to select LVL1 events with electron tracks.

Particle identification in the HADES detector started with track reconstruction in the MDC detectors. The MDC track segments were correlated with corresponding hits in the META after the magnetic field, in order to determine the momentum of particles (no MDCIII/IV were used in the analysis presented below). Hadron identification is performed mainly on the basis of the measured momentum, velocity and energy loss in the TOF detector. The principle of the hadron identification is illustrated in Fig. 3. Particles with different mass fill different regions in the velocity versus momentum distribution. The pronounced maxima correspond to positive/negative pions protons and deuterons. The pion yields were extracted and found to be lower by 15% as compared to those obtained by the analysis of the URQMD simulation data. As an example of hadron analysis, we show in Fig. 2 transverse mass distribution for positive pions,  $1/m_T^2 d\sigma/dm_T$ , measured in this experiment. The solid line shows a thermal fit with the two temperature  $T_1 = 41 \pm 3.2$  and  $T_2 = 84 \pm 2.2$  components which described our data better as compared to a fit with one component only. Similar conclusions can also be derived from the analysis of negative pion distributions. This observation is in agreement with previous results obtained for the same collision system by the KAOS collaboration and was interpreted as an indication of a dominant role of  $\Delta$  resonance in pion production.

For the analysis of electrons the key detector is the RICH. The charged particle tracks were matched with ring centers. The matching condition was  $\Delta\theta < 1.7^\circ$  and  $\Delta\phi \times \sin\theta < 1.8^\circ$  for the polar and the azimuthal angles, respectively. For additional electron identification, the following condition on the velocity of particles was applied:  $0.8 < \beta < 1.2$  as determined by the TOF and  $0.8 < \beta$  by the TOFINO. The asymmetric  $\beta$  cut in TOFINO has been chosen since the lower granularity of this detector results in  $\sim 20\%$

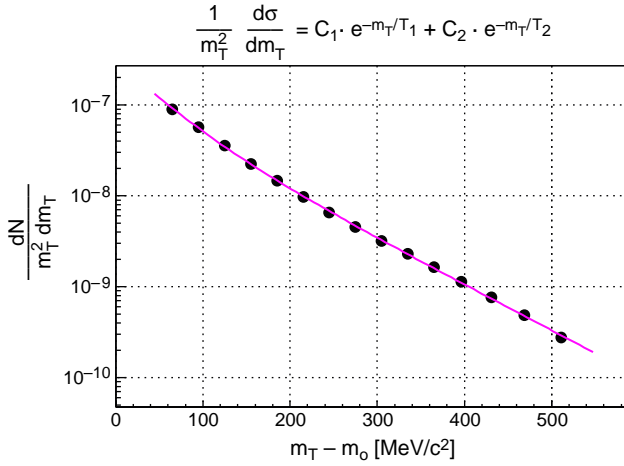


Fig. 2. The positive pion transverse mass distribution for C + C at 2 A GeV collisions. The solid line is a thermal fit with two temperature components as indicated in the figure.

double hits. In these cases the determination of the time of flight is not correct and leads to  $\beta > 1.0$ . The resulting momentum versus velocity distribution after electron identification cuts is shown in Fig. 3 (right), exhibiting a clear electron signal. The detailed investigation of electron distributions reveals that the residual contamination of the hadronic background is less than 2%. Furthermore, the shapes of the momentum spectra for electrons and positrons are very similar to each other, with an average multiplicity of  $2 \times 10^{-2}$  per LVL1 event, but measured multiplicities are lower than the simulated ones by  $\sim 25\%$ .

From the electrons identified we have constructed unlike ( $e^+e^-$ ) and like sign ( $e^+e^+$ ,  $e^-e^-$ ) pairs. For further analysis we have used only pairs that contain electron tracks producing well separated hits in all detectors and with opening angles larger than  $4^\circ$ . Most of them are due to a combinatorial background arising from multiple photon conversions and Dalitz decay of  $\pi^0$  mesons. In order to evaluate the combinatorial background  $N_{\text{com}}$  we have used like sign pairs  $N_{++}$ ,  $N_{--}$  and the formula  $N_{\text{com}} = 2\sqrt{N_{++} * N_{--}}$ . Fig. 4 (left hand side) shows unlike sign invariant mass distributions together with the corresponding combinatorial background. The expected most dominant sources of dielectron pairs are  $\pi^0$  and, to a much smaller extent,  $\eta$  Dalitz decays. We observe that the dominant signal is indeed in the invariant mass region up to  $150 \text{ MeV}/c^2$ . In the higher mass region, shown on right hand side of Fig. 4, we also observe a systematic excess of dielectron yield over the combinatorial background with an average 1:8 signal to background ratio. A more advanced analysis using close pair rejection is in progress now. Preliminary results indicate that further significant (2–3) background reduction can be anticipated. The total pair statistics, after subtraction of combinatorial background and analysis cuts described above, amounts to  $\sim 5\text{k}$  in the run with the LVL1 trigger, and is almost one order of magnitude larger in the recent run where the LVL2 trigger was used.

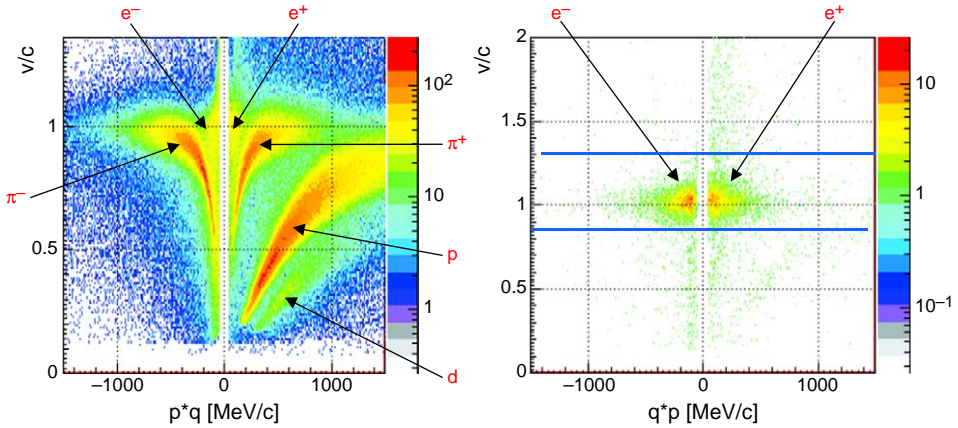


Fig. 3. Left: velocity versus sign\*(charge) momentum correlation for all reconstructed tracks from C + C at 2 A GeV collisions. Pion and proton branches are clearly resolved. Right: the same as on the left but with an additional condition on the electron identification. The intensity scale is logarithmic.

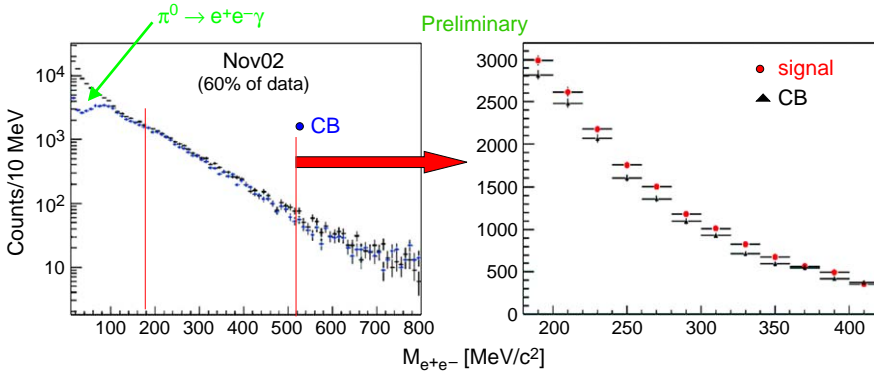


Fig. 4. Left: the dielectron invariant mass distribution and respective combinatorial background obtained for 2 A GeV C + C collisions. Right: the same as on the left but on a linear scale for  $0.4 > M_{e^+e^-} > 0.15 \text{ GeV}/c^2$ .

#### 4. Dielectron production in elementary collisions

A low mass dielectron excess observed in heavy ion collisions by the DLS experiment is an unsolved puzzle and urgently requires explanation. In order to achieve better understanding of this phenomenon new measurements of dielectron production in heavy ion and elementary reactions are needed. The latter are very important since various hadronic models predict significant in-medium modifications of the  $\rho/\omega$  meson spectral functions due to strong meson couplings to the low lying nucleon resonances ( $S_{11}(1535)$ ,  $D_{13}(1520)$ , ...).



However, these measurements are also interesting for other reasons. Dielectron production in elementary proton–proton and pion–proton collisions is a wonderful experimental method for learning about hadron electromagnetic structure. It gives direct insight into the complicated structure of hadrons when one studies the conversion process changing a strongly interacting hadron into a virtual photon materialized into a pair of simple elementary particles. According to the vector dominance model (VDM) this coupling proceeds entirely through the intermediate  $\rho/\omega$  mesons [22]. Although this theorem is very successful in the description of electromagnetic properties of several hadrons [23], it is still not clear whether it is really universal. For example, studies of the dilepton Dalitz decays of the  $\omega$  meson show significant deviations of the extracted time-like electromagnetic form factor from the VDM predictions [24]. Furthermore, practically nothing is known about the applicability of the VDM to the baryon Dalitz decays, for example  $\Delta \rightarrow Ne^+e^-$ , or to the nucleon–nucleon bremsstrahlung. Both processes are closely related to the widely discussed issue of the electromagnetic structure of the nucleon. Note that both processes also play an important role in the description of DLS data [12, 13].

The relevant meson–nucleon interaction vertices can be investigated in the less complicated environment of elementary proton–proton and pion–proton reactions and thus can provide valuable constraints for various models. Using the unique availability of proton and secondary-pion beams at GSI together with the newly constructed HADES dielectron spectrometer, we will be able to perform dedicated studies of dielectron production in exclusive proton and pion induced reactions of the type  $pp \rightarrow ppe^+e^-X$  and  $p\pi \rightarrow Ne^+e^-X$  at beam energies below and above the meson production thresholds. Exclusive measurements will allow us to disentangle different contributions to the dielectron mass distributions originating from the Dalitz decays of mesons ( $\pi^0 \rightarrow e^+e^-\gamma$ ,  $\eta \rightarrow e^+e^-\gamma$ ), from the delta resonance  $\Delta \rightarrow Ne^+e^-$ , and, at higher masses,  $M_{e^+e^-} > 0.6 \text{ GeV}/c^2$ , from the two-body  $\rho/\omega$  decays. Reactions below the production threshold for the  $\rho/\omega$  production can be used to probe the coupling of the off-shell meson to the low lying baryonic resonances. For example, the off-shell  $\omega$ – $N$  coupling discussed by Ch. Fuchs in a contribution to this conference can be studied in detail by means of exclusive  $pp \rightarrow pp\omega$  measurement. This reaction was extensively studied using the hadronic  $\omega \rightarrow \pi^+\pi^-\pi^0$  decay channel, but a large pion background from decays of abundantly produced baryonic resonances makes the  $\omega$  off-shell identification very difficult. In contrast, the dielectron decay channel offers a much better signal to background ratio [25]. This reaction will be studied with HADES in the upcoming experimental run using 2.2 GeV protons. Furthermore, the large acceptance of HADES also allows the simultaneous exclusive measurement of the  $\eta$  production in the  $pp$  reactions using  $\eta$  identification via the three-pion and dielectron decays. Since the exclusive cross sections for the  $\eta$  production in  $pp$  reactions are well known, the absolute normalization can be provided by the  $\eta$  reconstruction via pion decay channel. Thus, the reconstruction of the  $\eta \rightarrow e^+e^-\gamma$  Dalitz decay can be used as a stringent test for the HADES dielectron acceptance corrections. One should note that this decay mode is kinematically complete even without requiring an additional photon detector.

## 5. Summary and outlook

The HADES spectrometer offers a unique possibility for systematic studies of the light vector meson spectral functions by means of dielectron spectroscopy. Recent results from commissioning runs confirmed the expected superior on-line and off-line electron identification capabilities. In particular, a high statistics run with the LVL2 trigger provided the first pair data from C+C reactions at 2 A GeV. High resolution dielectron spectroscopy is now also becoming possible with the completion of the outer tracking system. First experiments aiming at exclusive  $\omega$  and  $\eta$  meson reconstruction in proton–proton reactions are planned for the upcoming year.

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