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Studies of Time-like Electromagnetic Structure of Baryons with HADES

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Abstract. We present results of studies of Dalitz decays of baryon resonances (R→Ne^+e^-) in proton-proton (*pp*) and pion-proton (πp) collisions performed by the HADES collaboration. They provided the first measurement of electromagnetic transition form factors of baryons in the time-like region and contribute to the understanding of the photon-baryon coupling and the role of Vector Dominance Model in a baryonic sector. We discuss also implications of the results to the understanding of the emissivity of dense and hot QCD matter created in heavy-ion collisions and the role played by the in-medium modification of the ρ meson. Further prospects for future studies with pion beams at GSI with HADES are given in the outlook.

1 Introduction

The main goal of the HADES experiment is to study hot and dense nuclear matter produced in heavy-ion collisions at energies of few GeV/A by means of di-electrons (e^+e^- pairs). Di-leptons are considered as penetrating probes because they leave the interaction volume undisturbed during all stages of the collision. Hence they carry away information about QCD matter at all stages of the collision and provide access to its properties. The most interesting is the early phase of the collisions starting with formation of a fireball which properties, like a temperature and an expansion driven by compression, can be inferred from the di-lepton spectra. In particular measurement of the temperature from a slope of a di-lepton invariant mass distribution is a unique feature of this probe. Furthermore, the invariant mass distribution of e^+e^- pairs below 1 GeV/c^2 is dominated by the radiation from the ρ meson and attracts a lot of attention because of connection to the chiral symmetry restoration [1]. The special role of the ρ meson is related to its short life time (1.2 fm/c), that is shorter than the life time of the fireball, and its decay branch to di-lepton pairs. ρ is a vector meson and constitutes, together with pseudo-vector a_1, a chiral dublet with a mass split of the order of 500 MeV, reflecting a scale of the chiral symmetry breaking in hadron spectra. Restoration of the chiral symmetry and hadron deconfinement have been predicted by lattice QCD (lQCD) [2] for a vanishing baryon chemical potential at a similar temperature of about 150 MeV. At lower temperatures and finite baryon chemical potentials lQCD is not applicable but various models predict a first order phase transition associated with the chiral symmetry restoration. The latter one shall be reflected in modification of spectra of chiral partners which should become

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degenerate. In this context, the in-medium spectral function of the ρ meson attracted a lot of attention and has been considered in calculations of a thermal yield of dileptons emitted from the fireball, i.e. emissivity [3, 4].

A strong broadening of the ρ meson has been observed in many experiments at a few GeV to 200 GeV energy range [1]. It has been successfully explained by model calculations of Rapp and Wambach [4]. Salient feature of the broadening is a coupling of the ρ meson to baryonic resonances. The HADES group has extracted the e^+e^- radiation from the fireball (emissivity) in Au+Au collisions at E_{kin} = 1.25 GeV. To access the emissivity, contributions from first chance NN collisions, NN bremsstrahlung, Δ Dalitz decay, and the hadronic decays after the freeze-out (mesons Dalitz and direct decays) have to be subtracted from the total e^+e^- yield. The contribution from the first chance collisions has been fixed from a reference p+p and p+n collisions at the same beam energy. The obtained excess radiation is presented in Fig. 1 as a function of the e^+e^- invariant mass in comparison to various microscopic transport calculations [5]. The HSD (Hadron String Dynamics) [6] and SMASH [7] models assuming a free ρ meson spectral function reveal a bump around $M_{ee} \sim 0.7$ GeV/c^2 not visible in the data. On the other hand, a satisfactory description of the data is achieved with models

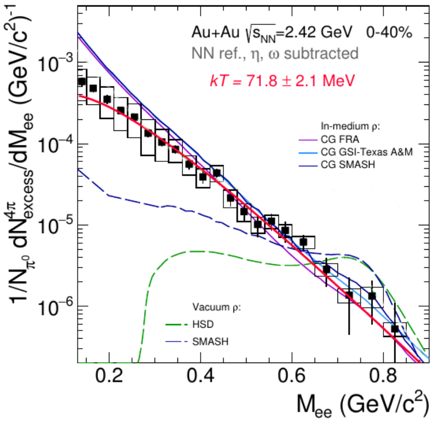

Figure 1. Dielectron excess yield extracted by subtracting the meson and the NN reference contributions and normalized to the number of neutral pions. Red curve represents thermal fit, dashed curves ρ-meson vacuum line shape from SMASH [7] and HSD [6] transport model calculations normalized to the respective number of neutral pions. The dark-blue [7], blue [8] and violet [9] are curves showing the results of three versions of coarse-grained calculations using the ρ in-medium spectral functions from microscopic calculations [4]. Figure adopted from [5].

that assume thermal emission from the ρ meson in an expanding fireball [8, 9] (see Fig. 1). These calculation use the in-medium spectral function obtained by the model of Rapp and Wambach. It confirms a strong coupling of baryon resonances to the ρ meson and its almost complete "melting" in dense baryonic matter (compare to the ρ vacuum spectral function shown by the dashed lines). The exponential shape of the excess radiation spectrum suggests thermal-like emission from the fireball. Fit with a function $dN/dM \propto M_{ee}^{3/2} exp(-M_{ee}/kT)$ reveals $kT = 71.8 \pm 2.1$ MeV.

As already mentioned, the couplings of baryonic resonances to the ρ meson is important feature of the calculations and appears to be successful in explanation of the di-electron radiation from the hot and dense nuclear matter. Particularly, good agreement with the HADES data corroborate such a mechanism because at low energies the fireball is dominated by baryons. Nevertheless, understanding of the nature of baryon-ρ couplings needs to be scrutinized from studies of elementary processes. Ideally suited for such studies are Dalitz decays of baryon resonances $N^*(\Delta) \rightarrow Ne^+e^-$ directly probing baryon-virtual photon couplings.

2 Electromagnetic transition form factors of baryons

Studies of Dalitz decays of baryonic resonances are not only important for the interpretation of the in-medium modifications of the ρ meson spectral function but are also important by itself.

Dalitz decay processes B→Ne^+e^- allow to study electromagnetic transition form factors in the time-like region with squared four-momentum transfer $q^2 = M_{ee}^2$ corresponding to the M_{ee} invariant mass range of $4m_e^2 \leq M_{ee}^2 \leq (M_B - M_N)^2$, where m_e, M_B, M_N are the electron, baryon resonance and nucleon masses, respectively. As shown in Fig. 2, this kinematic region is complementary to the space-like region ($q^2 < 0$) studied in electron scattering experiments (e.g. CLAS detector at JLab). The two regions are joined at the point $q^2 = 0$ which corresponds to the real photon. The Dalitz differential decay width is given by $d\Gamma(R \to Ne^+e^-)/dM_{e^+e^-}$ and depends on mass, spin and parity of the resonance and is usually expressed as a function of the magnetic $G_M(q^2)$, the electric $G_E(q^2)$ and the Coulomb $G_C(q^2)$ transition Form Factors (etFF). The Dalitz decay processes are therefore very important tool for investigations of applicability of the Vector Dominance Model (VDM) in the baryon sector. According to VDM, light vector mesons, which have the same quantum numbers as a photon, act as interpolating fields between hadron and a virtual photon [10].

There are two versions of VDM used in the calculations of baryon transitions. The most

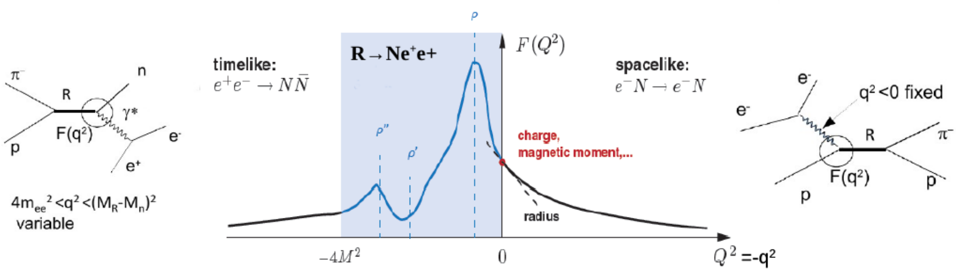

Figure 2. A schematic view of etFF evolution as a function of squared four-momentum transfer $Q^2 = -q^2$. Left diagram: sketch of the Dalitz decay process of a resonance (R→Ne^+e^-) produced in a π^-p reaction. The four-momentum transfer squared Q^2 spans the range $-4m_{ee}^2 \geq M_{ee}^2 \geq -(M_B - M_N)^2$, where M_{ee} is the e^+e^- invariant mass, m_e, M_B, M_N are the electron, baryon resonance and nucleon masses, respectively. Right diagram: excitation of a nucleon by electron scattering. The four-momentum transfer squared Q^2 is positive and fixed by the energy and angle of the scattered electron.

common one (for example used in heavy-ion transport models) assumes that the coupling of a photon to a baryon is mediated entirely via a ρ meson or in extended versions excited states are also included [11]. Following notation from [12] we refer it as VDM2. In the two-component model, referred as VDM1, two couplings are added coherently: a direct one accounting for the coupling between a photon and a baryon and the other one accounting for ρ [13]. The two versions agree at the meson pole but differ at the small invariant masses, particularly below the two-pion production threshold [14]. This range is accessible in the resonance Dalitz decay and has been recently investigated by HADES in pp and π^-p experiments. The results are presented in Sec. 4 and compared to models introduced below.

Calculations of etFF within a framework of a covariant spectator quark model assume a virtual photon coupling to the quark core and the pion cloud. etFF's have been calculated for N-Δ(1232) [15], N-N(1520) [16] and N-N(1535) [17]. The results show an important role of the pion cloud and is signalled by a strong enhancement in the invariant di-lepton mass w.r.t. calculations assuming transitions between point-like particles.

An alternative approach to etFF has been developed based on an effective Lagrangian model [18], taking into account various resonant and non-resonant amplitudes in a coherent way. In this model, two-component VMD1 is used to all baryon-photon couplings. The calculations have been performed for the $\pi^- p \rightarrow ne^+e^-$ reaction at energy of the HADES experiment.

3 The HADES detector and the pion beam facility

The High Acceptance Di-Electron Spectrometer (HADES) [19] is a detection system installed at the GSI/FAIR facility in Darmstadt and operates at SIS-18 synchrotron energies (1-2 GeV/nucleon). It has a geometrical acceptance from 20° to 80° in the polar angle and almost full coverage in the azimuthal angle. The unique feature of this detector is its ability to detect very rare di-electron (e^+e^- pairs) radiation with a very high purity.

The HADES detector is build in a six-sector planar geometry defined by coils of a superconducting toroid around the beam line and consists of a few sub-detector systems. A Ring-Imaging Cherenkov detector (RICH) operates inside the magnetic field-free region, four drift chambers (MDCs) are placed before (two) and behind (two) the magnetic field, time-of-flight META detectors: TOF (plastic scintillators at $\theta > 45°$) and RPC (resistive plates at $\theta < 45°$) and an electromagnetic calorimeter (ECAL) which covers the same angular range as RPC are located behind MDCs. Recently, the HADES setup has been equipped with the Forward Detector [20] covering the very forward polar angles ($\theta < 8°$) to detect charged particles. It consists of two straw tube tracking stations, developed originally for the PANDA detector, and a RPC time-of-flight wall. The Forward Detector has significantly increased the acceptance for hyperon reconstruction in proton induced reactions (see contributions [21, 22] to this conference). The tracking and momentum reconstruction of charged particles is provided by a track reconstruction from hits measured in MDCs. Electron identification is assured by the hadron blind RICH detector and TOF.

A trigger system is based on multiplicity measured in the META detectors. Recently the trigger capability and selectivity were improved by the inner TOF detector, located just in front of the first MDC.

The HADES detector operates with primary proton and Heavy Ion (HI) beams obtained from SIS18 and secondary pion beams. Runs with proton beams with E_{kin} = 1.25 [24], 2.2 [25], 3.5 [26] and 4.5 GeV, deuteron E_{kin} = 1.25 [27] GeV/u beams on LH-2 (liquid hydrogen) target and pion beams with E_{kin}=0.57 GeV [14, 28, 29] were conducted to study elementary processes responsible for the di-electron production.

The dedicated run to study the Dalitz decays of $N^*(1520)$ and $N^*(1535)$ resonances and their production cross sections [28, 29] has been performed using the secondary pion beam at 0.7 GeV/c. The pion beam is produced at GSI using a primary ^{14}N beam provided by the SIS18 synchrotron with an intensity of (0.8 - 1.0)$\times 10^{11}$ ions/spill and impinging on a 10 cm long beryllium target. The pions in a selected momentum range are transported through the dedicated pion beam line consisting of nine quadrupole and two dipole magnets from the production point up to the HADES target. The pion intensity at the exit of the pion beam line was about 10^6 pions/spill. To measure the pion beam momentum on event-by-event basis, tracking system consisting of two silicon strip detectors located along the beam line and a start detector right in front of HADES target was used [23].

4 HADES results for the Δ(1232) and N* Dalitz decays

Using *pp* reactions at energy of 1.25 GeV, the Δ(1232) Dalitz decay ($\Delta \rightarrow pe^+e^-$) was measured for the first time [24]. The corresponding branching ratio has been extracted $(4.19 \pm 0.62(syst) \pm 0.34(stat)) \times 10^{-5}$ and included in the Particle Data Group. The di-electron invariant mass distribution from Δ(1232) has been compared to the covariant spectator quark model of Ramahlo and Pena (see Sec. 2) and the one expected for point-like transitions (referred as QED). The ratio of the two distributions, that can be interpreted as an effective etFF of the $\Delta(1232) \to pe^+e^-$ transition, is presented in Fig. 3. The calculations reproduce the data up to $M_{inv}(e^+e^-) < 0.28$ GeV/c^2, while for the higher masses suggest even stronger contribution of the pion cloud. It is worth to stress that the analysis profits from the independent determination of the $\Delta(1232)$ production cross section obtained from the Partial Wave Analysis (PWA) of the one-pion production channels [30].

Resonance excitation in pion induced reactions has a big advantage w.r.t. proton reactions because of the dominance of s-channel and formation of the resonance with a fixed mass. In proton reactions at higher beam energies, resonance states with various masses contribute at the same time. Therefore, the HADES experiment with the pion beam at $\sqrt{s}$ = 1.49 GeV was ideally suited for studies of Dalitz decays in the second resonance region. The main goal was to investigate the ρ meson couplings to the dominant resonances: N*(1520) and N*(1535). The respective production cross sections for these resonances were obtained from

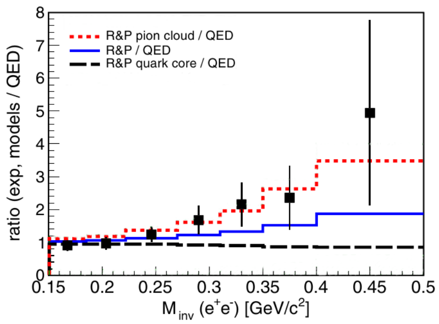

Figure 3. Ratio of the experimental data (black squares) measured in the $pp \to ppe^+e^-$ reaction at 1.25 GeV [24] to the point-like (QED) transition as a function of the e^+e^- invariant mass. The histograms represent the covariant spectator quark model predictions [15]: blue is total, dashed red is the meson cloud contribution and dashed black is the quark core component. Figure adopted from [24].

the two-pion final states: $\pi^-p \to n\pi^+\pi^-$, $\pi^-p \to \pi^-p\pi^0$ [28]. Using Bonn-Gatchina PWA the cross sections were decomposed into different partial waves and $\Delta\pi$, Nρ and Nσ isobar contributions were determined. The N*(1520) resonance was found to dominate the Nρ final state with the branching ratio BR =12.2 ± 1.9%. The extracted $N\rho^0$ contribution in the $\pi^-p \to n\pi^+\pi^-$ channel provided an important normalization for the di-electron contribution in the $\pi^-p \to ne^+e^-$ final state reconstructed in the same experiment [29]. In Fig. 4, the respective e^+e^- invariant mass distribution is shown and compared to calculations assuming VDM1 and VDM2 scenarios and the extracted ρ meson contribution. As one can see, data clearly differentiate between VDM1 and VDM2 versions supporting the two component scenario (for more details see [14, 29]). The data are also compared to the predictions of the aforementioned covariant spectator quark model which describes the data very well and supports dominance of the pion cloud contribution. The right plot shows the ratio between data and the point-like QED reference calculated for the transition between point-like particles. It can be regarded as a measure of the effective etFF. A large excess of up to a factor 5 over the QED reference can be seen. A very good description of the data is achieved by the covariant quark and the Lagrangian models applying VDM1. The Lagrangian model is also in a satisfactory agreement with the data, however, it still needs to be compared to the two-pion production channel.

5 Prospects with proton and pion beams

In February 2022 the HADES collaboration performed an experiment focused on hyperon radiative and Dalitz decays (Y'→Yγ, Y'→Ye^+e^-) in elementary pp collisions at 4.5 GeV. This measurement will provide information on the time-like structure of $\Lambda(1520)$, $\Lambda(1405)$,

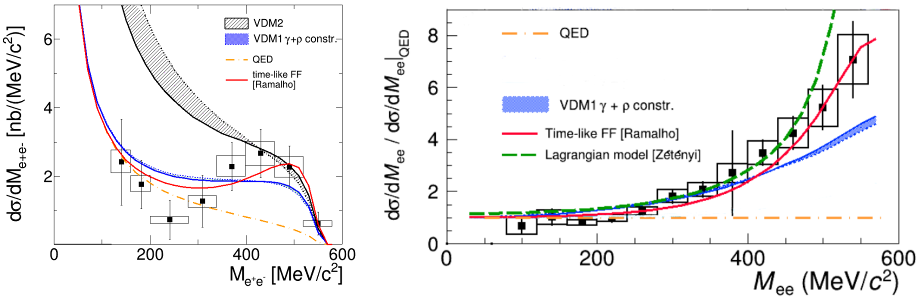

Figure 4. Differential distribution of e^+e^- invariant mass for the $\pi^- p \to ne^+e^-$ reaction. Left panel: the data (black squares) are compared to QED (dashed dot orange line), VDM2 (black curves), VDM1 with constructive sum of ρ and γ contributions (blue curves) calculations as well as to the time-like FF based on the covariant spectator quark model (solid red line). Right panel: ratios of the experimental data and the model predictions to the point-like QED transition function. The data are compared to VDM1, time-like FF based on the quark model and the calculations using the Lagrangian model (green dashed line).

Σ(1385) hyperons. Extension of the studies of Dalitz decays to the hyperon sector will be very interesting, particularly in the context of VDM and meson cloud effects [15–17, 31]. The HADES data will allow to compare the results for SU(3) flavour partners like N(1520) and Λ(1520) or Σ(1385) and Δ(1232) to get the information about the sensitivity of the baryon electromagnetic structure to the strange quark content. More information can be found in the contributions of J. Rieger [21] and K. Sumara [22] to this conference.

Follow-up experiments with the pion beam are planned in 2024-2025 to study the third resonance region ($\sqrt{s}$ = 1.7 GeV) with several high mass resonances Δ(1620), Δ(1700), N(1650), N(1675), N(1630), N(1710), N(1720),... . Production of di-electrons, strange and non-strange mesons will be studied in π^-p and π^-C reactions. In this higher energy range it is expected that a vector meson contribution will be enhanced since q^2 values closer to the vector meson poles can be reached. This gives an opportunity to study and to test predictions of the $\rho - \omega$ interference [32]. The measurements of various exclusive hadronic channels ($\pi^0\pi^-$, $n\pi^0\pi^-$, $p\pi^+\pi^-$, $n\omega$, $n\rho$, $n\eta$, $K\Lambda$, $K\Sigma$) in an energy scan are also foreseen. Therefore, these experiments will also enrich the existing data base for hadronic decay channels by at least one of order of magnitude. This will allow us for more precise determination of poorly known hadronic couplings in the third resonance region. In the context of the general interest of the HADES collaboration, the emphasis will be put on improving the knowledge of $\rho - N$, $\omega - N$ and $K - \Lambda$ couplings, which are important inputs for the modeling of the propagation of ρ mesons and strange particles in the nuclear matter.

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