Dilepton and vector meson production in elementary and in heavy ion reactions

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We present a unified description of the vector meson and dilepton production in elementary and in heavy ion reactions. The production of vector mesons is described via the excitation of nucleon resonances. Medium effects in heavy ion reactions are discussed.

Dilepton spectra from heavy-ion collisions are considered as a suitable tool to study medium modifications of vector mesons ($\rho$, $\omega$, $\phi$) in a dense nuclear environment which is produced in heavy ion reactions. Such medium effects manifest themselves in the modification of widths and masses of resonances produced in nuclear collisions. E.g., the Brown-Rho scaling \cite{1} is equivalent to a reduction of the $\rho$ meson masses in the nuclear medium. The same conclusion is obtained from QCD sum rules \cite{2}. Hadronic models \cite{3, 5} based on dispersion analyses of forward scattering amplitudes predict vector meson mass shifts are in general small and positive, whereas at low momenta they can change the sign which is in qualitative agreement with the Brown-Rho scaling and the results from QCD sum rules. Indeed, at CERN a significant enhancement of the low-energy dilepton yield below the $\rho$ and $\omega$ peaks \cite{4} in heavy reaction systems compared to light systems and proton induced reactions has been observed \cite{4}. Theoretically, this enhancement can be explained within a hadronic picture by the assumption of a dropping $\rho$ mass or, alternatively, by the formation of a quark-gluon plasma \cite{5}. A similar situation occurs at a completely different energy scale, namely around 1 AGeV incident energies where the low mass region of dilepton spectra measured by the DLS Collaboration at the BEVALAC \cite{6} are underestimated by present transport calculations compared to $pp$ and $pd$ reactions \cite{7, 8, 9}. However, in contrast to ultra-relativistic reactions (SPS) the situation does not improve when full spectral functions and/or a dropping mass of the vector mesons are taken into account. This fact is known as the DLS puzzle.

For all these studies a precise and rather complete knowledge of the relative weights for existing decay channels is indispensable in order to draw reliable conclusions from dilepton spectra. we developed a unified model for the description of vector mesons and dilepton pairs in elementary nucleon-nucleon and pion-nucleon reactions and in heavy ion reactions. The model is based on an extension of the vector meson dominance (eVMD) model which describes meson decay channels \cite{10}, including channels which have been neglected so far, such as e.g. four-body decays $\rho^0 \rightarrow \pi^0 \pi^0 e^+ e^-$. In \cite{11} a fully relativistic and kinematically complete treatment of vector meson $R \rightarrow N \rho(\omega)$ and dilepton decays
$R \rightarrow N e^+ e^-$ of nucleon resonances with arbitrary spin and parity was performed. The magnetic, electric, and Coulomb transition form factors have been determined fitting available photo- and electro-production data. The resonance model schematically depicted in Fig. 1 provides an accurate description of exclusive vector meson production in nucleon-nucleon collisions $NN \rightarrow NN\rho(\omega)$ as well as in pion scattering $\pi N \rightarrow N\rho(\omega)$ \cite{9,12} and has been successfully applied to $\phi$ production \cite{13} as well as to the dilepton production in $pp$ reactions at BEVALAC energies \cite{14}.

Fig. 2 shows the $\omega$ production in elementary $NN$ reactions. The different cross sections are shown as functions of the excess energy $\epsilon$. As discussed in \cite{12}, the resonance model (with a large $N^*(1535)N\omega$ coupling) leads to very accurate description of the measured on-shell cross section. It has, however, a very strong off-shell component which fully contributes to the dilepton production. The weak coupling scenario, on the other side, has only small off-shell component but the reproduction of the data is relatively poor in the low energy regime.

In \cite{16} it has finally been demonstrated that the resonance model is able to describe the measured $\omega$- and $\phi$-meson angular distributions in proton-proton reactions. The assumption of dominant contributions from the $N^*(1720)\frac{3}{2}^+$ and $N^*(1900)\frac{3}{2}^+$ resonances at $\sqrt{s} = 2.83$ GeV where data from COSY-TOF have been taken yields the right pattern.

Figure 1. Decay of nuclear resonances to dileptons in the extended VMD model. The $RN\gamma$ transition form factors contain contributions from ground state and excited $\rho$ and $\omega$ mesons.

Figure 2. Exclusive $pp \rightarrow pp\omega$ cross section obtained in the resonance model as a function of the excess energy $\epsilon$. The solid curve shows the full cross section including off-shell contributions while the squares show the experimentally detectable on-shell part of the cross section. Data are taken from \cite{15}. 

\begin{figure}[h] 
\centering 
\includegraphics[width=0.8\textwidth]{figure2.png} 
\caption{Exclusive $pp \rightarrow pp\omega$ cross section obtained in the resonance model as a function of the excess energy $\epsilon$. The solid curve shows the full cross section including off-shell contributions while the squares show the experimentally detectable on-shell part of the cross section. Data are taken from \cite{15}.} 
\end{figure}
for the $\omega$ angular distribution as can be seen from Fig. 3.

![Figure 3](image-url)  
Figure 3. $\omega$-meson angular distribution in $pp$ reactions at an excess energy $\epsilon = 173$ MeV assuming that the reaction goes through the $N^*(1900)^{3+}_2$ resonance. The experimental data are from COSY-TOF [15]. Results from various partial wave analyses and quark models are compared to the present eVMD model.

Although the present model is able to reproduce the vector meson and the dilepton production in elementary reactions with high precision the situation in unsatisfactory when turning to heavy ion collisions. Heavy ion collisions are described within the QMD transport model [9]. Without additional in-medium effect we observe in two distinct kinematical regions significant deviations from the dilepton yields measured by the DLS Collaboration in $C+C$ and $Ca+Ca$ reactions at 1 AGeV. As can be seen from Fig. 4 at small invariant masses the experimental data are strongly underestimated which confirms the observations made by other groups [17, 18]. Although accounting for the experimental resolution we observe further a clear structure of the $\rho/\omega$ peak which is not present in the data. The collisional broadening of the vector mesons suppresses the $\rho/\omega$ peak in the dilepton spectra. This allows to extract empirical values for the in-medium widths of the vector mesons. From the reproduction of the DLS data the following estimates for the collision widths $\Gamma_{\rho}^{\text{coll}} = 150$ MeV and $\Gamma_{\omega}^{\text{coll}} = 100 – 300$ MeV can be made. The in-medium values correspond to an average nuclear density of about 1.5 $\rho_0$ and have been used in the calculation shown in Fig. 4. The forthcoming data from HADES [17] will certainly help to constrain these values with higher precision.

The second medium effect discussed in [2] concerns the problem of quantum interference. Semi-classical transport models like QMD do generally not account for interference effects, i.e. they propagate probabilities rather than amplitudes and assume that relative phases cancel the interference on average. However, interference effects can play an important role for the dilepton production. In the present model the decay of nuclear resonances which is the dominant source for the dilepton yield, requires the destructive interference of intermediate $\rho$ and $\omega$ mesons with their excited states. The interference can at least partially be destroyed by the presence of the medium which leads to an enhancement of the corresponding dilepton yield (see Fig. 4). We proposed a scheme to treat the decoherence in the medium on a microscopic level. The account for decoherence improves the agreement with the DLS data in the low mass region. However, to attack the fundamental question of medium modifications of vector mesons seriously and to come to
Figure 4. Influence of the microscopically determined decoherent dilepton emission in C + C and Ca + Ca reactions. A strong (s), respectively, weak (w) N*(1535) – Nω coupling is used. For comparison also the coherent case (s) is shown. Data are from the DLS Collaboration [6].

firm conclusions needs, besides further theoretical efforts, much more high precision data. This will be the task for HADES in the next years.

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