Dilepton production at SIS energies with the UrQMD model

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Abstract. The production of lepton pairs in elementary and nucleus-nucleus collisions at SIS energies is studied within the Ultra-relativistic Quantum Molecular Dynamics transport approach. In comparison to previous calculations, we now included an improved treatment of the Δ1232 resonance. The resulting invariant mass and transverse momentum spectra are compared to available HADES data. In general, our results give a good description of the data. With regard to the observed overestimation of the ρ contribution, the different production channels and the respective production cross-sections are investigated. A problem remains the lack of experimental data for cross-sections and branching ratios of intermediate baryonic resonances, which are crucial for the ρ production. However, recent HADES cross-section measurements close to the ρ threshold might help to further constrain the model parameters.

1. Motivation

Dileptons are clean probes of hot and dense matter created in nuclear collisions. As they do not interact strongly, there is no interplay between them and the surrounding hadronic matter after their production. In consequence, they can provide insights to the physics of strongly interacting matter at high baryon densities and temperatures and deliver information on medium modifications of vector mesons and the restoration of chiral symmetry [1, 2]. As neutral vector mesons can directly decay into lepton pairs, one is able to deduce specific information concerning the mesons and their in-medium properties from the experimentally measured dilepton spectra.

Although several experimental and theoretical studies were conducted during the last years, it is still controversial how exactly the vector meson mass or width may change in hot nuclear matter. Proposed scenarios for in-medium effects are a dropping of the vector meson mass [3] and a broadening of the spectral function [4]. At low collision energies, dilepton measurements were conducted by the DLS experiment at BEVALAC [5]. The results showed an excess in the invariant mass spectra which could not completely be resolved by the proposed in-medium effects (the so-called “DLS puzzle”). Recently the measurements were confirmed in the same energy regime with higher precision and resolution by the HADES Collaboration [6, 7, 8, 9].

In these proceedings we present our ongoing work with a detailed study of lepton pair production in elementary and heavy-ion collisions at SIS energies. We use the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model for the calculations and compare our results with the experimental data of the HADES Collaboration.
The microscopic Ultra-relativistic Quantum Molecular Dynamics model is a hadronic non-equilibrium transport approach based on the quantum molecular dynamics concept \[10\]. It includes all baryons and mesons with masses up to 2.2 GeV. The dynamics of reactions in a nuclear collision are described in terms of a n-particle phase-space distribution.

For lower beam energies, vector meson production in UrQMD takes place via two different reaction mechanisms: Either they are produced in a two step process that proceeds via the excitation of a heavier resonance and the subsequent decay (e.g. N+N→N+N*→N+N+\(\rho\)) or directly in collision processes, e.g. \(\pi+\pi\rightarrow\rho\). The probability for a resonance decaying into a certain channel is determined by the mass dependent branching ratio which we use in accordance with the values given by the Particle Data Group \[11\]. All further details concerning the general properties of the approach can be obtained from \[12, 13, 14\].

Regarding dilepton production, several channels are included in the calculations: Direct decays of \(\rho^0\), \(\omega\) and \(\phi\) vector mesons, Dalitz decays of pseudoscalar mesons, like \(\pi^0\), \(\eta\), \(\eta'\), and of the \(\omega\) vector meson respectively. Also the lowest Delta resonance, \(\Delta_{1232}\), contributes via Dalitz decay. The Dalitz decay for pseudoscalar and vector mesons is decomposed into a two-step process, first the corresponding decay into a virtual photon and then the subsequent decay of the photon via electromagnetic conversion. The form factors used in this description are obtained by the vector meson dominance model \[15, 16\]. For the Delta Dalitz decay we
use the parametrization by Wolf [17] with a modified coupling to fit the radiative decay width [18]. To calculate the dilepton emission rates, we use the so called “shining method”, i.e. that a resonance steadily emits dileptons over its lifetime. This method increases the statistics and also includes resonances that do not decay but are reabsorbed in the medium [19].

In contrast to previous dilepton calculations with UrQMD (see ref. [20, 21, 22]) a different treatment of the $\Delta_{1232}$ resonance is now included. In general the model uses mass dependent widths $\Gamma(M)$ for the resonance decay, but the lifetime is treated mass-independent as $\tau = 1/\Gamma(m_{\text{pole}})$, with $m_{\text{pole}}$ being the pole mass, to avoid unphysically high lifetimes for low masses below the pole mass. Especially for far off-shell Delta resonances this might lead to the problem of overestimating the dilepton spectra at high masses and transverse momentum. In the $\Delta_{1232}$ case, we therefore now employ a mass-dependent lifetime for masses higher than the pole mass.

For further details on dilepton calculations within the UrQMD approach see ref. [20].

3. Results

In Figure 1 dilepton invariant mass spectra for p+p (top figure) and A+A collisions (bottom figure) are shown. At the top the UrQMD results for elementary collisions at $E_{\text{lab}} = 2.2$ and 3.5 GeV are plotted together with the experimental data [6, 7, 8, 9]. At 2.2 GeV the energy is sufficient to reach the pole mass of the $\omega$ and $\rho$ while at 3.5 GeV the full phase space is open for vector meson production. In general we see a good agreement of our calculations for p+p with the HADES data. However, around the $\rho$ pole mass a significant overestimation of the yield is
Figure 3. (Color online.) Left: Cross sections for inclusive and exclusive \( \rho^0 \) production in \( p+p \) reactions within the UrQMD model. The results are compared to the experimental data from \([9, 23]\). Right: Different contribution channels to the \( \rho^0 \to e^+e^- \) production via resonance decay and two pion reactions in the present calculations.

observed at 2.2 GeV, which is not that prominent at 3.5 GeV. In contrast, the region between 150 and 500 MeV/\( c^2 \) invariant mass is underestimated in both cases, more significantly at 3.5 GeV.

In nucleus-nucleus collisions we expect additional effects compared to elementary reactions. Here we have not only \( p+p \) but also \( p+n \) and \( n+n \) collisions and secondary interactions, depending on system size and energy. Also the Fermi momentum of the nucleus and Pauli blocking are an issue. Such effects can be treated by the UrQMD model, while no further in-medium modifications are included in the current calculations. Looking at the results for \( Ar+KCl \) at 1.76 AGeV and \( C+C \) at 2 AGeV at the bottom of Figure 1, we observe (as in elementary reactions) too many dileptons that stem from the \( \rho^0 \) resonance, especially in the high-mass tail. Comparing the three cases for reactions at similar energies around \( \sim 2 \) AGeV, we see that the Delta Dalitz contribution increases with the system size. It is larger in \( C+C \) than in \( p+p \) and becomes dominant at low masses for \( Ar+KCl \). Furthermore, there is an excess in the mass region dominated by the \( \eta \) Dalitz decay that increases with system size. However, it is not clear from the present investigation whether this might be related to additional in-medium modifications, as we see a similar effect in \( p+p \) at 3.5 GeV if compared to 2.2 GeV.

The transverse momentum distributions shown in Figure 2 describe the data at 3.5 GeV very well, especially in the low mass region dominated by the \( \pi^0 \) Dalitz decay. Here we see a clear improvement by the changed Delta lifetime treatment if we compare the spectra with previous results \([9]\) where the Delta contribution is above the data at high \( p_t \) and high masses. Also the \( \rho \) meson contribution from our calculation fits the data, with only a slight overestimation at low transverse momentum. The underestimation at intermediate energies is again visible here in the mass range from 150 to 470 MeV/\( c^2 \).

As our rho contribution in parts overestimates the data significantly, we studied the production cross-sections for \( \rho^0 \) production in elementary reactions in Figure 3 (left). The comparison with experimental data \([9, 23]\) shows a good description for the relevant inclusive channel, especially at higher energies. At threshold the recent HADES measurement at 3.5 GeV (\( \sqrt{s} = 3.17 \) GeV) indicates that the production rate is too high in the present model, leading to the observed overestimation of the invariant mass spectra. The same comparison for the \( \eta \) (which is not shown here) exhibits that this cross-section, in contrast, is underestimated at the
threshold. Considering the different channels that add to the $\rho^0$ dilepton production, e.g. for p+p at 2.2 GeV (see Figure 3, right), the main contribution below the pole mass stems from the N$^*_1(1520)$, while around the pole mass there is a multitude of different resonances that contribute. Other processes than resonance decay (e.g. $\pi\pi \rightarrow \rho$) are mostly negligible in the cases considered here. This indicates one of the difficulties of the present hadronic resonance approach: The $\rho$ cross-section is not implemented explicitly but one uses intermediate baryonic resonances. Unfortunately, for the production of these resonances and the subsequent decay the uncertainties concerning branching ratios and production cross-sections are quite high, due to little available data that could constrain these model parameters. Therefore the shape of the $\rho$ mass distribution and the resonances contributing to it differ among transport models (e.g. compare our results with recent GiBUU calculations [24]), depending largely on the implementation of intermediate resonant states and their branchings.

4. Summary and Conclusion

Dilepton production in elementary and nucleus-nucleus collisions at SIS energies has been studied within the UrQMD approach and compared to HADES data. We achieve a good description of the experimental results for invariant mass and transverse momentum spectra. Particularly the changed treatment of the Delta resonance lifetime leads to an improved description of the $p_t$ distribution. However, the comparison to data and experimental cross-sections from the HADES Collaboration also shows that the $\rho$ production rate close to the threshold might be too high while the $\eta$ cross-section seems to be underestimated. For an accurate and detailed study of possible in-medium modifications in the future further detailed investigations of the elementary reactions as a baseline are necessary.

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