PHYSICAL REVIEW C **74**, 014902 (2006)

Reconstructing ρ^0 and ω mesons from nonleptonic decays in C+C collisions at 2 GeV/nucleon in transport model calculations

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(Received 30 September 2005; published 19 July 2006)

We predict transverse and longitudinal momentum spectra and yields of ρ^0 and ω mesons reconstructed from hadron correlations in C+C reactions at 2 GeV/nucleon. The rapidity and p_T distributions for reconstructable ρ^0 mesons differs strongly from the primary distribution, while the ω distributions are only weakly modified. We discuss the temporal and spatial distributions of the particles emitted in the hadron channel. Finally, we report on the mass shift of the ρ^0 due to its coupling to the $N^*(1520)$, which is observable in both the dilepton and $\pi\pi$ channel. Our calculations can be compared to the Hades experiment at GSI, Darmstadt.

DOI: 10.1103/PhysRevC.74.014902 PACS number(s): 25.75.Dw, 25.75.Gz

I. INTRODUCTION

The Hades spectrometer at GSI [1] opens the possibility to measure dilepton yields and spectra at moderate energies with unprecedented accuracy. In addition it allows complimentary information on the most interesting dilepton sources (the ρ^0 and ω mesons) directly from the reconstruction of their hadronic decay products (i.e., the direct reconstruction of the invariant mass spectra of the resonances from two- and three-particle pion correlations). Over the last years the exploration of resonance yields and spectra from hadron correlation has been attracting a great amount of experimental [2–9] and theoretical attention [10–19].

Detailed experimental studies of hadron resonances at the full SPS and highest RHIC energies [2–9] have recently been performed. Theoretically there are still unsolved problems concerning the absorption and regeneration of resonances after chemical decoupling of the system. It is expected that the inclusion of pseudoelastic interactions between chemical and kinetic freeze-out might solve some discrepancies of statistical models for resonance yields at high energies [20–22]. At low energies, the first experimental investigations of resonances are eagerly awaited to explore in-medium effects on vector mesons near nuclear groundstate densities in the 1–2 GeV/nucleon beam energy range.

Resonances that have electromagnetic and hadronic decay channels allow deeper insights into the dynamics and lifetimes of the hot and dense hadronic matter stage created in light and heavy ion reactions. That is because the leptonic decay channel carries information from the early stages of the reaction, since the leptons can leave the dense regions undisturbed, while the hadronic decay channel triggers on the late stages (near kinetic decoupling) of the evolution.

For our studies we apply the UrQMD model. It is a nonequilibrium transport approach based on the covariant propagation of hadrons and strings. All cross sections are calculated by the principle of detailed balance or are fitted to available data. The model allows to study the full space time evolution of all hadrons, resonances and their decay products. This permits to explore the emission patterns of resonances in detail and to gain insight of their origins. For further details of the model the reader is referred to [23,24]. UrQMD has been successfully applied to study light and heavy ion reactions at SIS. Detailed comparisons of UrQMD with a large body of experimental data at SIS energies can be found in Ref. [25].

The results shown in this publication are obtained by simulations of more than 8×10^6 events of minimum bias C+C interactions at 2 GeV/nucleon. The statistical errors in the calculation are therefore small therefore if not shown explicitly, the errors are within the symbol size.

To set a baseline for the study of the ρ^0 and ω mesons, we compare our calculations with the energy dependence of the total pion multiplicities in C+C reactions as shown in Fig. 1. For the small carbon system, the UrQMD calculation (circles) is in reasonable agreement with the experimental data from the KAOS experiment [25].

Let us now turn to the HADES experiment [1] which will soon have first data on minimum bias C+C reactions at 2 GeV/nucleon. In Fig. 2 we predict the pion rapidity spectra for negative and positive charges. As expected from this isospin symmetric nuclei, the yields of π^+ and π^- are identical and reach a maximum value of $dN/dy = 0.45$ at $y_{\rm c.m.}$

II. CALCULATION

After these preliminaries, we focus for the rest of this work on the resonance production. Experimentally, the identification of resonances proceeds via the reconstruction of the invariant mass distribution (e.g., of charged pions) for each event. Then, an invariant mass distribution of mixed events is generated (here the particle pairs are uncorrelated by definition) and subtracted from the mass distribution of the correlated events. As a result one obtains the mass distributions and yields (after all experimental corrections) of the resonances by fitting the resulting distribution with a suitable function (usually a Breit-Wigner distribution peaked around the pole mass). For more informations the reader is referred to Ref. [8].

For the model calculation of the resonances, we employ a different method to extract the resonances. We follow the decay products of each decaying resonance (the daughter particles). If any of the daughter hadrons rescatters, the signal of this resonance is lost. If the daughter particles do not rescatter in the further evolution of the system,

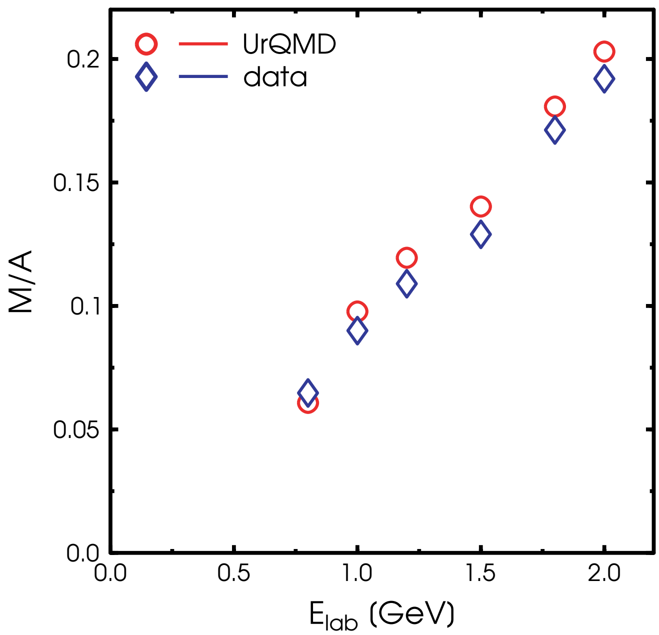

FIG. 1. (Color online) Excitation function of the pion multiplicities per participant for C+C collisions from $E_{\mathrm{beam}} = 0.8$–2.0 GeV/nucleon. Diamonds depict experimental data from the KAOS collaboration [25], squares show the UrQMD results.

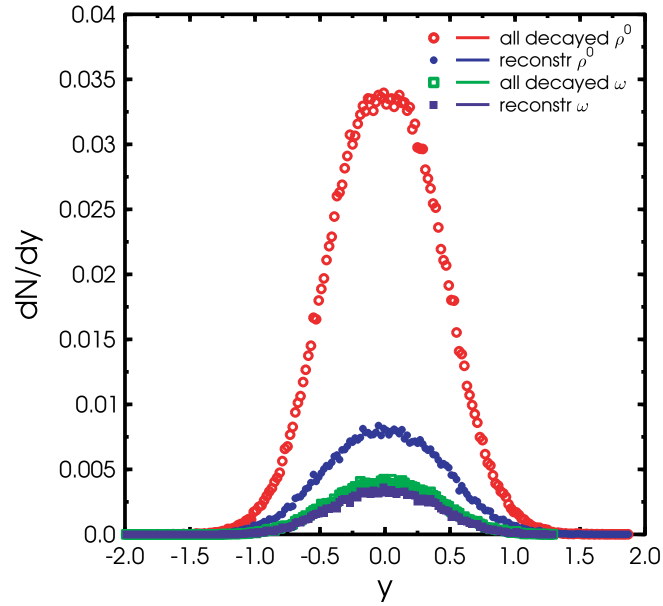

FIG. 3. (Color online) Rapidity distribution of the decayed mesons for minimum bias C+C reactions at 2 GeV/nucleon. The open circles/squares show the $\rho^0(770)$'s / ω's which can be reconstructed in the pion channel, filled circles depict all decayed ρ^0's / ω's. A strong suppression of in hadron correlations reconstructable resonances compared to those reconstructable via leptonic decays (indicated as "all decayed") is visible for the ρ^0 mesons, whereas the spectrum for the ω meson is only weakly altered. Error bars are within symbol size.

the resonance is counted as "reconstructable." Note that all decaying resonances are dubbed with the term "all decayed." These resonances are reconstructable by an invariant mass analysis of di-leptons (after multiplication with the respective branching ratio $\Gamma(R \rightarrow e^+e^-)$. The advantage of this method is that it allows to trace back the origin of each individual resonance to study their spatial and temporal emission pattern. Even more, it enables one to study the production process of the finally observed resonance itself, shedding light on the origin of mass modifications.

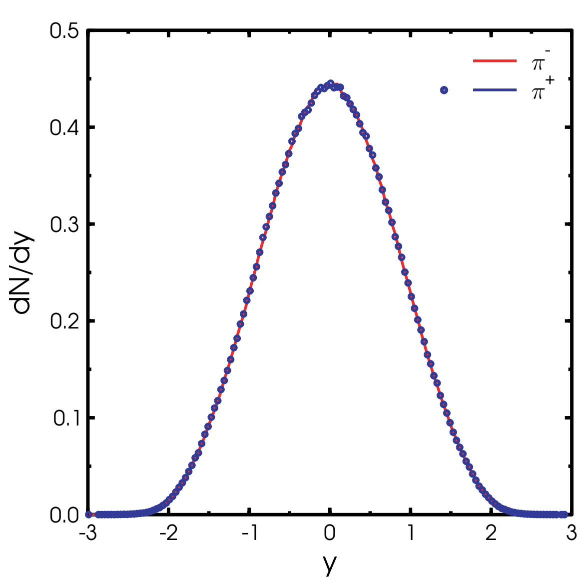

FIG. 2. (Color online) Rapidity distribution of positive and negative pions for minimum bias C+C reactions at 2 GeV/nucleon. The line depicts π^-, while circles show π^+. Error bars are within symbol size.

Figure 3 depicts the rapidity distributions of the meson resonances for minimum bias C+C interactions at 2 GeV/nucleon. The filled symbols display those ρ^0 (circles) and ω (squares) resonances which are reconstructable via hadron correlations. This means that the daughter particles do not interact after the decay of the resonance. The open symbols show the spectra for all decayed ρ^0 and ω resonances. This can be interpreted as the spectrum which can be measured via a dileptonic decay, not taking into account any interferences of the ρ and the ω. In the case of the ρ^0 one observes a drastic reduction of the observable yield at midrapidity from 3.5% (in the dilepton channel) to 0.8% in the hadronic channel. In contrast, the ω meson is only slightly altered when the reconstruction probabilities in both channels are compared. This can be traced back to the much longer lifetime of the ω compared to the ρ. Most of the ω's will leave the interaction zone before they decay, thus reducing the possibility of the rescattering of the daughters.

If this interpretation is valid, one expects a strong transverse momentum ($p_T = \sqrt{p_x^2 + p_y^2}$) dependence of the suppression pattern. One would expect a larger modification of short lived resonances at low transverse momentum. The spectrum at higher transverse momenta will only be slightly altered, because high p_T resonances are more likely to escape from the interaction region before they decay. As shown in Fig. 4 the $\rho^0(770)$ meson is suppressed, especially at

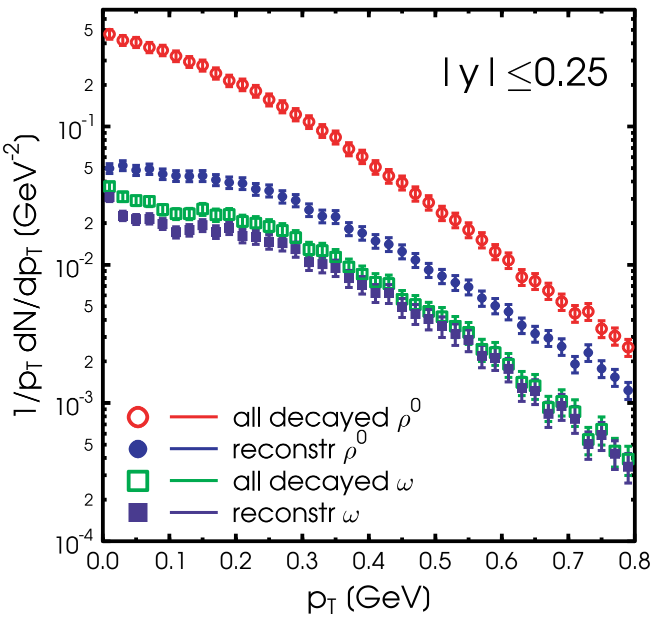

FIG. 4. (Color online) Transverse momentum distributions of ρ^0 mesons (circles) and ω mesons (squares) for minimum bias C+C reactions at 2 GeV/nucleon at midrapidity ($|y| \leqslant 0.25$). Circles depict ρ^0 mesons, squares depict ω mesons. Open symbols show all decayed resonances, whereas filled symbols show those actually reconstructable via hadron correlations. There is a huge modification for the ρ^0 meson spectrum at low p_T, whereas the high p_T part is modified less (factor of 4–5 less compared to the low p_T part). There is only a very slight modification visible for the the ω meson.

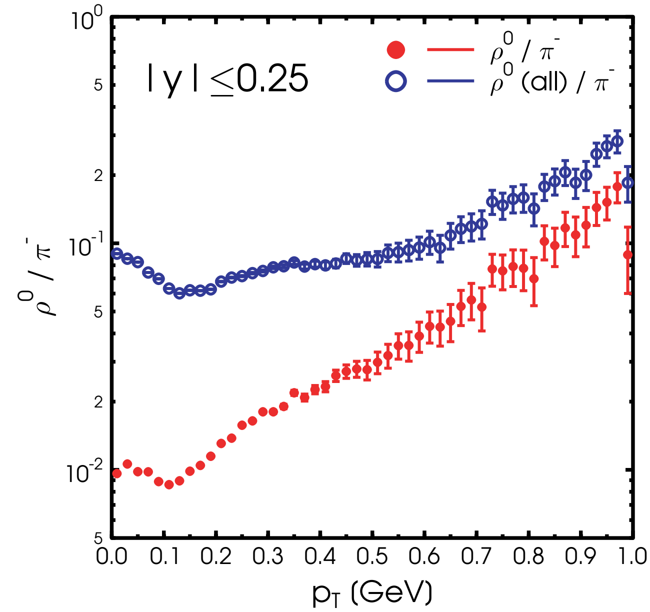

FIG. 5. (Color online) The ρ^0/π^- ratio as a function of transverse momentum for minimum bias C+C reactions at 2 GeV/nucleon at midrapidity ($|y| \leqslant 0.25$). Filled circles depict the via hadron correlations reconstructable ρ^0's over pions, whereas the blue circles depict all decayed ρ^0's over pions. It is evident that there is less suppression at higher transverse momentum.

low p_T, in line with our expectations from the rescattering picture. Only at very low transverse momenta, the $\omega(782)$ is weakly suppressed. It should be noted that a similar behavior was also found experimentally for larger systems at higher energies [8].

Figure 5 depicts the ρ^0/π^- ratio as a function of p_T. A strong suppression of the ρ^0/π^- ratio at low p_T is evident for the reconstructable resonances, which vanishes at high p_T. This also supports the rescattering scenario, since high p_T pions and ρ^0's leave the medium directly and do not experience modifications due to rescattering.

What is the temporal and spatial emission pattern of the resonances observable in the dileptonic compared to those in the hadronic channel? Figures 6 and 7 depict the temporal distributions of reconstructable and all decayed ρ^0 and ω mesons. One observes a shift by 2 fm/c in the peak of the emission times from 5.5 fm/c for the dilepton channel compared to the reconstructable ρ^0's that are emitted at later stages of the collision, around 7.5 fm/c. Overall, the ω's decay even later (notice the different scaling) at 7.5 fm/c (dilepton channel) and 13 fm/c (pion channel), i.e., outside of the collision zone. That is the reason why there is nearly no suppression of the ω meson in the hadron channel.

Figures 8 and 9 depict the transverse distance $r_T = \sqrt{r_x^2 + r_y^2}$ of the meson resonances at the point of their decay. Here it is interesting to notice that there is only a rather small difference in the peak emission radii of the ρ^0 resonances observable in the dilepton spectrum (maximal emission at $r_T = 1.3$ fm) compared to those in the hadronic correlation with $r_T = 1.8$ fm. Comparing both emission radii

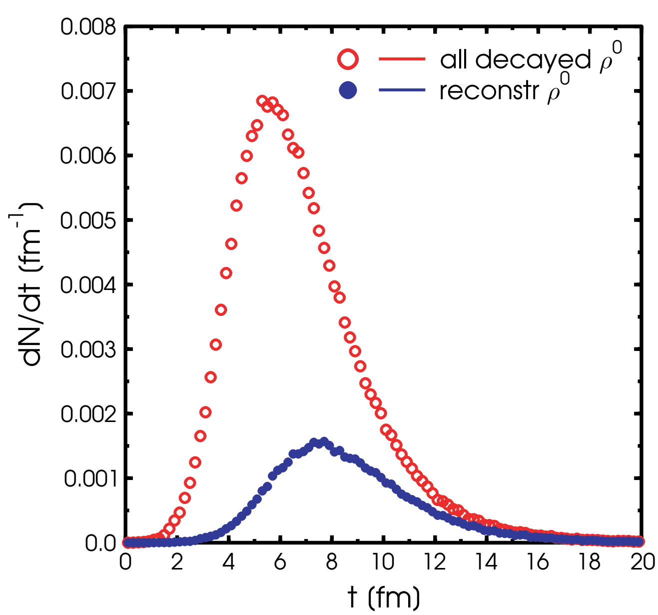

FIG. 6. (Color online) Temporal distribution of ρ^0 resonances for minimum bias C+C reactions at 2 GeV/nucleon. Open circles depict all decayed ρ^0's, filled circles the via hadron correlations reconstructable ones. Those visible via pion decay products decay at a very late stage of the collision, roughly at 7–8 fm/c. Error bars are within symbol size.

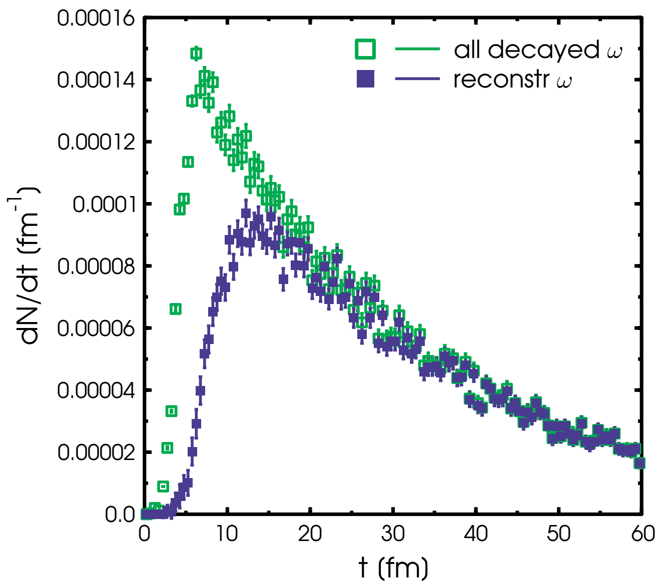

FIG. 7. (Color online) Temporal distribution of ω resonances for minimum bias C+C reactions at 2 GeV/nucleon. Open squares depict all decayed ω's, filled squares the via hadron correlations reconstructable ones. Note that the ω meson decays at a very late stage of a collision due to its long lifetime. One also observes a long tail of the distribution because of that.

to the size of the carbon nucleus ($r \sim 2.7$ fm) it seems that both reconstruction channels seem to be sensitive to similar in-medium modifications. A detailed comparison of the thermal parameters at the decay point of the resonances will be given in a followup work.

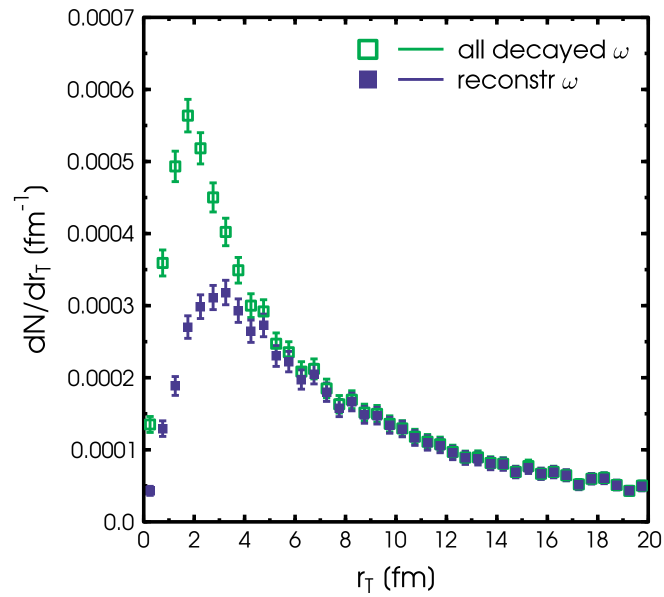

FIG. 9. (Color online) Spatial distribution of ω resonances for minimum bias C+C reactions at 2 GeV/nucleon. Filled symbols depict those resonances whose decay products did not interact after the decay, whereas open symbols depict all decayed resonances.

Let us finally discuss, one of the most interesting effects, the modification of the mass spectrum of the ρ^0 meson as has been discussed earlier for example in Refs. [26–28]. The mass distribution of the ρ^0 in minimum bias C+C reaction at 2 GeV/nucleon is shown in Fig. 10. Open circles depict all decayed ρ's (this is similar to the dileptons invariant

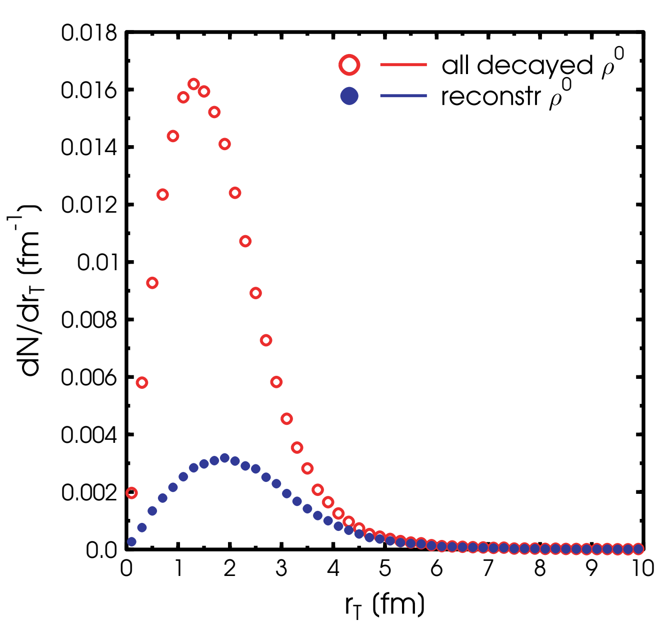

FIG. 8. (Color online) Spatial distribution of ρ^0 resonances for minimum bias C+C reactions at 2 GeV/nucleon. Filled symbols depict those resonances whose decay products did not interact after the decay, whereas open symbols depict all decayed resonances. Error bars are within symbol size.

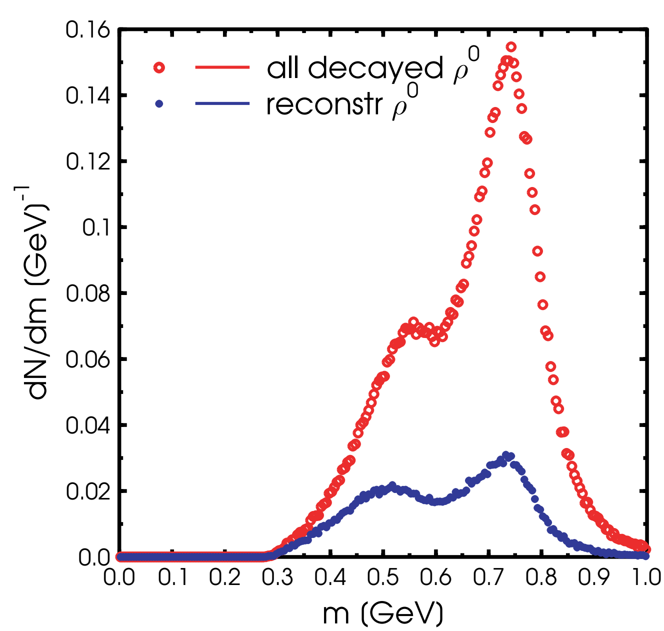

FIG. 10. (Color online) Mass distribution for ρ^0 mesons for minimum bias C+C reaction at 2 GeV/nucleon. The peak around 500 MeV is due to a strong contribution from $N^*(1520) \rightarrow p + \rho$ which amounts to 75% for masses below 600 MeV. Error bars are within symbol size.

mass distribution multiplied by the branching ratio and the vector meson dominance factor of $1/m^3$), while the ρ's reconstructable in $\pi\pi$ correlations are shown as filled circles. In both distributions, one observes a clear double peak structure, with maxima at the ρ pole mass (770 MeV) and around 500–600 MeV. Usually an enhancement of the ρ spectral function in this mass region has been attributed to strong in-medium modifications, due to finite densities and temperatures. However, in the present calculation, we do not make explicit use of any in-medium modification, but only include the coupling of the ρ to pions and baryons via the employed cross sections calculated from detailed balance.

A detailed analysis shows that the low mass peak is due to the decay chain $N^*_{1520} \rightarrow p + \rho^0$ which contributes to 75% to the reconstructable ρ mass spectrum below 600 MeV. Without in-medium modifications, this decay process restricts the mass of the ρ to $m_\rho \leqslant m_{N^*_{1520}} - m_p \sim 580$ MeV and thus feeds strongly into the low invariant mass region of the ρ. Above 600 MeV, ρ's are mostly produced from $\pi\pi \rightarrow \rho$ and heavy baryon resonance decays. It seems that a dramatic modification of the ρ spectral function is mostly due to the decay kinematics of the production channel of the ρ. However, on top of these kinematic effects additional modifications of the ρ mass spectrum might occur.

III. SUMMARY

In summary, we have explored ρ and ω production in C+C interactions at 2 GeV/nucleon. We have predicted the yields and spectra of these meson resonances when reconstructed in "dilepton-like" and hadronic channel. The present calculations show a strong difference (factor 5) between the yields observable in the dilepton and hadron channel. This can be understood due to a rescattering of the resonance daughter particles, shifting them out of the ρ peak. At midrapidity $8 \times 10^{-3} \rho^0$'s per event can be reconstructed from the pion correlations. We predict a strong transverse momentum dependence of the ρ suppression pattern leading to an apparent heatup of the ρ's observed in the hadronic channel compared to the dilepton channel. Finally, we have pointed out that the mass spectrum of the reconstructable ρs shows a strong double peak structure. This second peak around an invariant mass of 500 MeV is due to ρs from the decay of the $N^*(1520)$ which feeds directly in to the ρ mass region below 580 MeV. Our prediction are a complimentary approach to the dilepton measurements underway at HADES/GSI. The reconstruction of resonances in the hadronic channel yields additional information on the later stages of the reaction and is of special interest for direct tests of hadronic transport models and the properties of the ρ meson at low to intermediate densities without involving any dilepton "after burners."

ACKNOWLEDGMENTS

We thank Diana Schumacher and Christian Sturm for detailed discussions. Fruitful discussions with Horst Stöcker, Peter Zumbruch, and Joachim Stroth are greatfully acknowledged. The authors thank GSI and BMBF for support. The computational resources have been provided by the Center for Scientific Computing in Frankfurt.

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