Hadronic resonances at FAIR energies

Sascha Vogel
Frankfurt Institute for Advanced Studies, Ruth-Moufang-Str. 1, 60438 Frankfurt, Germany
SUBATECH, Laboratoire de Physique Subatomique et des Technologies Associées
University of Nantes - IN2P3/CNRS - Ecole des Mines de Nantes
4 rue Alfred Kastler, F-44072 Nantes Cedex 03, France
E-mail: svogel@th.physik.uni-frankfurt.de

Abstract. These proceedings cover the analysis of hadronic resonances in heavy ion collisions. The model used for these studies is the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model. The model will be briefly explained, resonance observables will be highlighted and various kinematical issues will be investigated. Special emphasis will be put on the FAIR energy regime, especially highlighting the Compressed Baryonic Matter (CBM) program.

1. Introduction
With the advent of the Facility for Anti-Proton and Ion Research (FAIR) new detailed studies of the phase diagram of nuclear matter will be possible. For the first time it will be feasible to study the region of high baryo-chemical potential with a high luminosity experiment, namely the Compressed Baryonic Matter (CBM) experiment.

The investigation of hot and dense matter created in heavy ion collision is one of the most complex challenges in present day physics. Various uncertainties go into the understanding of heavy ion collisions, with the additional complexity that a lot of input is energy-dependent. The initial state is unknown, although speculations at high energies exist [1, 2, 3, 4]. The proper theoretical treatment of interactions is still heavily debated (see e.g. [5, 6]) and the transition from a possibly deconfined phase to a hadronic phase is quite poorly understood. While Lattice QCD studies give some input at vanishing baryochemical potential $\mu_B$, the extrapolations into the high $\mu_B$ region are poorly understood (for a recent pedagogical review see e.g. [7]). In order to understand the hot and dense matter created in such collisions resonances provide an unique approach to learn about the hot and dense phase which is produced in heavy ion collisions [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26]. Strongly decaying resonances (e.g. $\rho$ or $K^*$ mesons) decay on time scales of several fm/c. That means they decay inside the hot and dense medium and thus can potentially reveal the properties of the matter they decayed in. This is of course dependent on the kinematics of the particles and will be discussed later in detail.

These proceedings are structured as follows: After a brief introduction to the theoretical model in Section 2 the effects of baryons will be presented and explained in Section 3. The possibility to explore the dense phase of heavy ion collisions using hadronic decay channels of resonances will be discussed in Section 4. The manuscript will end with conclusions.
2. Model description
For the calculations discussed in these proceedings the Ultra-relativistic Quantum Molecular Dynamics (UrQMD) model has been used. UrQMD is a non-equilibrium transport approach, which relies on the covariant Boltzmann equation. Cross sections are calculated by the principle of detailed balance and the additive quark model or are fitted to available data. Note that due to the geometrical collision criterion detailed balance is only possible up to the \(2 \rightarrow 2\) level.

UrQMD does not include any explicit in-medium modifications for vector mesons or effects to describe the restoration of chiral symmetry. The model allows to study the full space time evolution of all hadrons, resonances and their decay products in hadron-hadron or nucleus-nucleus collisions. This permits to explore the emission patterns of resonances in detail and to gain insight into their origins and decay channels. For previous studies of resonances within this model see [15, 16, 17, 18, 19, 20, 21, 22, 23, 24]. For further details about the UrQMD model the reader is referred to [27, 28]. Recent development concerning the inclusion of a hydrodynamic phase are described in [29].

Experimentally, the reconstruction of resonances is challenging. One often applied technique is to reconstruct the invariant mass spectrum for single events. Then, an invariant mass distribution of mixed events is generated (here, the particle pairs are uncorrelated by definition). The mixed event distribution is subtracted from the invariant mass spectrum of the single (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 function peaked around the pole mass of the respective resonance).

If the resonance spectral function changes in the hadronic medium this is in principle visible in the difference spectrum between true and mixed events.

However, if a daughter particle (re-)scatters before reaching the detector the signal for the experimental reconstruction is blurred or even lost. Especially for strongly interacting decay products this effect can be sizeable. It is therefore difficult to judge whether a deviation from an expected Breit-Wigner distribution is due to an initial deformation or an increase of the initial width or due to the momentum dependence of the rescattering cross section of the daughter particles.

What makes this analysis even tougher is the fact that the resonances decay over a wide range of densities and therefore only an average value is measured. If this average value is dominated by resonance decays at low density the information from the high density phase is blurred and may offer only a limited view on the high density phase of the heavy ion collision.

UrQMD offers a different technique for the extraction of resonances which we apply here. We follow the individual decay products of each decaying resonance (the daughter particles). If the daughter particles do not scatter in the further evolution of the system, the resonance is counted as ‘reconstructable’. 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. Because UrQMD follows the space time evolution of all particles it is possible to link production and decay point of each individual resonance. This method also allows to explore the reconstruction efficiency in different decay branches.

In order to calculate at which density the resonance decays we have to determine the baryonic density. The baryon density is calculated locally at the position of the resonance in the rest frame of the baryon current (Eckart frame) as \(\rho_B = j^0\) with \(j^\mu = (\rho_B, 0)\). Details on the calculation of the baryon density are discussed in [21]. In all figures we present the density in units of ground state density, where a value of 0.16 \(1/\text{fm}^3\) is assumed.

3. Baryon kinematics
In heavy ion collisions at FAIR energies the baryon density is extremely high. Thus effects, which couple to baryons are expected to be very prominent in this energy regime. One important fac-
Figure 1. (Color online) Mass spectrum for $\rho$ mesons. Shown is a detailed analysis of the various production channels, with a prominent second peak from the decay of $N_{1520}$ baryon resonance decays. For details regarding the different production channels, please refer to the legend.

Figure 2. (Color online) Average $\rho$ mass as a function of rapidity. Shown are calculations for Pb+Pb collisions at $E_{lab}=30$ AGeV (upper line) and C+C collisions at $E_{lab}=2$ AGeV (lower line). One observes a clear drop when going to higher rapidities. For more details, please refer to the main text.

Another insightful observable apart from the mass spectrum is the rapidity dependence of the average $\rho$ meson mass. Depicted in Fig. 2 is the average $\rho$ meson mass as a function of rapidity for two different collision systems and energies. One observes that it drops when going to higher rapidity, which can be explained with the same line of argument as used before. Since the baryon to meson ratio increases with increasing rapidity the aforementioned effect is quite prominent at higher rapidities. This is in line with the observation, the higher the rapidity (and thus the baryon to meson ratio) is, the lower the average $\rho$ meson mass becomes. This should be kept in mind at FAIR energies, since the baryonic contributions are quite large.
4. Density distribution of decayed resonances

![Figure 3](image1.png)

**Figure 3.** (Color online) Probability distribution of baryon density at the production vertex for various reconstructable resonances in central (b ≤ 3.4 fm) Au+Au collisions at 30 AGeV as a function of baryon density. One observes that most resonances which can be reconstructed in the hadronic decay channel originate from low baryon density.

![Figure 4](image2.png)

**Figure 4.** (Color online) Fraction of reconstructable meson resonances as a function of baryon density at the point of production. Shown are various resonances produced in Au+Au collisions at \( E_{cm} = 200 \text{ AGeV} \) (symbols) and \( E_{lab} = 30 \text{ AGeV} \) (lines). Baryon resonances are not shown, however exhibit the same qualitative behaviour.

One central question when analysing resonances is the question where and when they decay and are produced during the collisions and whether we can reconstruct them experimentally or not. Depicted in Fig. 3 is the probability distribution of baryon density at the production vertex for various reconstructable resonances in central (b ≤ 3.4 fm) Au+Au collisions at 30 AGeV as a function of baryon density. Most reconstructable resonances originate from very low baryon density. This is of course expected and despite the prominent peaks at very low densities it does not mean that all resonances originate from those low densities.

A different way to look at this is to check the percentage of reconstructable resonances (or the probability to reconstruct the resonance) as a function of baryon density. This is depicted in Fig. 4 on a scale of 0 to 1 for various mesonic resonance species (namely \( \rho, \omega, K^*(892), \phi \)). One should note that baryons exhibit exactly the same behaviour, but are not shown here for space reasons. As naively expected the probability is largest at very low densities and decreases when going to higher densities. At roughly 2 times ground state density a surprising effect sets in. The decreasing trend stops and the probability to reconstruct resonances increases when going to even higher baryon density. This effect can be explained when looking at the average transverse momentum of the produced resonances. At higher baryon density resonances have a higher average \( p_T \), which leads to the fact that they escape the collision zone before re-interacting or decaying. Even if they did not decay they are close enough to the edge of the interaction region and the decay products can then leave that region undisturbed. For a more detailed explanation please refer to [23].
5. Conclusions
Understanding the dynamics and kinematics of hadronic resonances proves to be a difficult task both experimentally and theoretically. The FAIR energy regime offers unique opportunities to explore the high density regime of the phase diagram of Quantum-Chromodynamics. Here especially the CBM experiment with its high rates and excellent detectors will play a key role in the experimental program. It will be possible to measure hadronic resonances with great detail, although one should keep in mind that kinematic effects might blur the result. As discussed in these proceedings especially baryon resonance kinematic and the effect of rescattering have a direct influence on observable spectra, particle yields and masses. Only by taking these effects into account one might be able to construct a coherent picture of hadronic resonance physics at FAIR.

References
[1] E. Iancu, A. Leonidov and L. D. McLerran, Nucl. Phys. A 692 (2001) 583
[2] E. Ferreiro, E. Iancu, A. Leonidov and L. McLerran, Nucl. Phys. A 703 (2002) 489
[3] M. Gyulassy and L. McLerran, Nucl. Phys. A 750 (2005) 30
[4] A. Dumitru, F. Gelis, L. McLerran and R. Venugopalan, Nucl. Phys. A 810 (2008) 91
[5] W. A. Horowitz and M. Gyulassy, Phys. Lett. B 666 (2008) 320
[6] W. A. Horowitz, AIP Conf. Proc. 1441 (2012) 889
[7] O. Philipsen, arXiv:1009.4089 [hep-lat].
[8] G. Agakichiev et al. [HADES], Phys. Rev. Lett. 98, 052302 (2007)
[9] X. Lopez et al., Phys. Rev. C 76, 052203 (2007).
[10] S. V. Afanasev et al. [NA49], J. Phys. G 27, 367 (2001).
[11] D. Adamova et al. [CERES], Phys. Rev. Lett. 91, 042301 (2003)
[12] J. Adams et al. [STAR], Phys. Rev. Lett. 97, 132301 (2006)
[13] B. I. Abelev et al. [STAR], Phys. Rev. C 78, 044906 (2008)
[14] P. Fachini, J. Phys. G 35, 044032 (2008).
[15] M. Bleicher and J. Aichelin, Phys. Lett. B 530 (2002) 81
[16] M. Bleicher, Nucl. Phys. A 715 (2003) 85
[17] M. Bleicher and H. Stoecker, J. Phys. G G 30 (2004) S111
[18] S. Vogel and M. Bleicher, Phys. Rev. C 74 (2006) 014902
[19] D. Schumacher, S. Vogel and M. Bleicher, Acta Phys. Hung. A 27 (2006) 451
[20] S. Vogel and M. Bleicher, Phys. Rev. C 78 (2008) 064910
[21] S. Vogel, H. Petersen, K. Schmidt, E. Santini, C. Sturm, J. Aichelin and M. Bleicher, Phys. Rev. C 78 (2008) 044909
[22] K. Schmidt, E. Santini, S. Vogel, C. Sturm, M. Bleicher and H. Stocker, Phys. Rev. C 79 (2009) 064908
[23] S. Vogel, J. Aichelin and M. Bleicher, Phys. Rev. C 82 (2010) 014907
[24] S. Vogel, J. Aichelin and M. Bleicher, J. Phys. G G 37 (2010) 094046
[25] G. Torrieri, S. Steinke, W. Broniowski, W. Florkowski, J. Letessier and J. Rafelski, Comput. Phys. Commun. 167 (2005) 229
[26] G. Torrieri, S. Jeon, J. Letessier and J. Rafelski, Comput. Phys. Commun. 175 (2006) 635
[27] S. A. Bass, M. Belkacem, M. Bleicher, M. Brandstetter, L. Bravina, C. Ernst, L. Gerland and M. Hofmann et al., Prog. Part. Nucl. Phys. 41 (1998) 255 [Prog. Part. Nucl. Phys. 41 (1998) 225]
[28] M. Bleicher, E. Zabrodin, C. Spieles, S. A. Bass, C. Ernst, S. Soff, L. Bravina and M. Belkacem et al., J. Phys. G G 25 (1999) 1859
[29] H. Petersen, J. Steinheimer, G. Burau, M. Bleicher and H. Stocker, Phys. Rev. C 78 (2008) 044901
[30] C. Markert, R. Bellwied and I. Vitov, Phys. Lett. B 669 (2008) 92
[31] R. Rapp and J. Wambach, Adv. Nucl. Phys. 25 (2000) 1
[32] H. van Hees and R. Rapp, Phys. Rev. Lett. 97 (2006) 102301
[33] H. van Hees and R. Rapp, Nucl. Phys. A 806 (2008) 339
[34] C. Amsler et al. [Particle Data Group Collaboration], Phys. Lett. B 667 (2008) 1.