The production of $\phi$ mesons in Au+Au collisions at RHIC and their propagation in a hot and dense nuclear medium is studied within the microscopic quark-gluon string model. The inverse slope parameter of the transverse mass distribution agrees well with that extracted from the STAR data, while the absolute yield of $\phi$ is underestimated by a factor 2. It appears that the fusion of strings alone cannot increase the $\phi$ yield either. Less than 30% of detectable $\phi$'s experience elastic scattering, this rate is insufficient for the full thermalization of $\phi$. The directed flow of $\phi$ at $|y| \leq 2$ demonstrates strong antiflow behavior, whereas its elliptic flow rises up to about 3.5% in the same rapidity interval. As a function of transverse momentum it rises linearly with increasing $p_t$, in agreement with the STAR data, and saturates at $p_t > 2$ GeV/c.

The investigation of nuclear matter under extreme temperatures and densities, and the search for a predicted transition to a deconfined phase of quarks and gluons, the so-called Quark-Gluon Plasma (QGP), is one of the main goals of heavy ion experiments at ultrarelativistic energies. Both theorists and experimentalists are looking for genuine QGP fingerprints, that cannot be masked or washed out by processes on a hadronic level. The $\phi$ meson was proposed about two decades ago [1,2] as one of the most promising QGP messengers because of the following reasons: Firstly, an enhancement of $s\bar{s}$ pairs in the QGP phase should lead to an enhancement of $\phi$ mesons, as well as other strange hadrons, while the production of $\phi$ in $hh$ interactions is suppressed due to the OZI rule [2]. Secondly, since the $\phi$ interaction cross section with non-strange hadrons is small, $\phi$ will keep information about the early hot and dense phase. Thirdly, the $\phi$ meson spectrum is not distorted by feeddown from resonance decays. Finally, among other channels $\phi$ decays into a pair of kaons and, more rarely, into a lepton pair. Both channels have been explored for the reconstruction of the $\phi$ yield in Pb+Pb collisions at SPS energy. It was found that the $\phi$ multiplicity extracted from the di-kaon data [3] is significantly smaller than that obtained from the dimuons [4] (the so-called $\phi$ meson puzzle). A similar effect has been observed recently by the PHENIX Collaboration [5] in Au+Au collisions at RHIC. A possible solution of this puzzle is the scattering of at least one of the daughter kaons in the nuclear medium [5] accompanied by in-medium modifications of kaon and $\phi$ masses. Note also that the width and mass of the $\phi$ meson are quite sensitive to the strangeness content of the surrounding medium.
In the present paper we study production, propagation, and freeze-out of \( \phi \) mesons in \( \text{Au+Au} \) collisions at \( \sqrt{s} = 130 \) AGeV within the microscopic quark-gluon string model (QGSM) \([10]\). The transverse mass spectra of \( \phi \) calculated for three different centrality bins are presented in Fig. 1 together with the experimental data reported by the STAR Collaboration \([11]\). Though the QGSM underestimates the \( \phi \) yield by a factor 2, it correctly reproduces the slopes of all three distributions. Results of the fit to an exponential \( \frac{dN/dy}{2\pi T(m_\phi + T)} \exp \left( -\frac{m_t - m_\phi}{T} \right) \) are plotted in Fig. 1 as well. Obtained values of the inverse slope parameter \( T \) are 378 (379\( \pm \)50) MeV, 349 (369\( \pm \)73) MeV, 370 (417\( \pm \)75) MeV for model (experimental) results, respectively. The absence of a centrality dependence in the \( m_t \)-spectra of \( \phi \) may indicate the minor role of the \( \phi \) final state interactions. The problem of a too low strangeness yield in the model can be solved by implementing the string fusion mechanism \([12]\). To check this, the yields of \( \phi \), \( h^- \), and their ratio \( \phi/h^- \) have been calculated in the string fusion model (SFM) \([13]\). Results are listed in Table 1. Compared to the non-fusion case (NF), the string fusion (F) mode significantly decreases the \( \phi \) and \( h^- \) multiplicities at midrapidity. An increase of the \( \phi \) yield can be obtained by further rescattering (F+R) of secondary hadrons via the channels \( KY \rightarrow \phi N, K\Xi \rightarrow \phi Y, K\Omega \rightarrow \phi Y \), but it is still insufficient to match the data. The agreement between the calculations and the data can be improved by increasing the string tension or dropping the constituent quark masses \([8]\), by including the OZI-violation mechanism in the model (at low \( \sqrt{s} \) this is the only channel for \( \phi \) production), and by increasing the number of \( s\bar{s} \)-pairs inside nucleons in multipomeron diagrams \([14]\).

The \( \phi \) mesons are produced either in primary nucleon-nucleon interactions via string fragmentation processes or in subsequent rescattering between produced strange hadrons. We found that in the first 4 fm/c the \( \phi \) mesons are produced solely in string processes. The string channel dominates over the rescattering one up to 20 fm/c; in the later stages the rescattering channel prevails. This dynamical picture agrees well with that obtained for the \( \phi \) production at SPS energy within the UrQMD model \([8]\). The \( dN/dt \) distributions of \( \phi, N, \pi, K, \Lambda \), which are decoupled from the fireball after the last elastic or inelastic collision, are shown in Fig. 2. Compared to AGS and SPS energies \([15]\), a substantial part of hadrons leave the system immediately after their production. Mesonic distributions

![Figure 1. \( m_t \)-spectra of \( \phi \) mesons in three centrality bins in \( \text{Au+Au} \) collisions at RHIC.](image)

Table 1

| Yields of \( \phi, h^- \), and ratio \( \phi/h^- \) at \( |y| \leq 0.5 \) in \( \text{Au+Au} \) at RHIC calculated within the SFM. |
|---|---|---|---|---|
| Centrality 0 - 11% | NF | F | F+R | exp. |
| \( \phi \) | 5.71 | 3.60 | 4.54 | 5.73\( \pm \)0.37 |
| \( h^- \) | 462 | 326 | 324 | 273\( \pm \)21 |
| \( \phi/h^- \) | 0.0123 | 0.0110 | 0.0140 | 0.021\( \pm \)0.001 |

The agreement between the calculations and the data can be improved by increasing the string tension or dropping the constituent quark masses \([8]\), by including the OZI-violation mechanism in the model (at low \( \sqrt{s} \) this is the only channel for \( \phi \) production), and by increasing the number of \( s\bar{s} \)-pairs inside nucleons in multipomeron diagrams \([14]\).

The \( \phi \) mesons are produced either in primary nucleon-nucleon interactions via string fragmentation processes or in subsequent rescattering between produced strange hadrons. We found that in the first 4 fm/c the \( \phi \) mesons are produced solely in string processes. The string channel dominates over the rescattering one up to 20 fm/c; in the later stages the rescattering channel prevails. This dynamical picture agrees well with that obtained for the \( \phi \) production at SPS energy within the UrQMD model \([8]\). The \( dN/dt \) distributions of \( \phi, N, \pi, K, \Lambda \), which are decoupled from the fireball after the last elastic or inelastic collision, are shown in Fig. 2. Compared to AGS and SPS energies \([15]\), a substantial part of hadrons leave the system immediately after their production. Mesonic distributions
have sharp peaks at $t = 8 - 10 \text{ fm}/c$, while the distributions of baryons are wider due to the large number of rescatterings, which shift their $dN/dt$ maxima to later times. Figure 3 depicts the freeze-out distribution of the $\phi$ mesons over rapidity and emission time. We see that the bulk production of $\phi$ occurs in the central rapidity window $|y| \leq 1.5$ within the first $10 \text{ fm}/c$, while in $|y| \geq 2$ areas the $\phi$ mesons are produced until the late stages of the system evolution: Because of the rapid expansion the central zone becomes quickly dilute, its energy density drops, and early freeze-out of $\phi$ mesons, which have small interaction cross section with non-strange matter, takes place. According to QGSM, about 51% of detectable $\phi$ mesons decay after decoupling from the fireball. Less than 30% of $\phi$ mesons experience at least one elastic rescattering before the freeze-out. This relatively low rate of elastic collisions may not be sufficient for the thermalization of $\phi$ mesons, however, would it be enough for the development of noticeable anisotropic flow?

- Other processes contributed to the flow evolution are production and absorption/decay of $\phi$ in dense medium. While the elastic collisions and resonance production of $\phi$ mesons increase the flow in the normal bounce-off direction, the $\phi$ absorption channel effectively reduces this normal component thus elongating the flow in the antiflow direction.

Figure 4 shows the rapidity dependence of the directed flow of $\phi$, $N$, and $K$ in minimum bias Au+Au collisions at RHIC. The slopes of the all distributions are negative at $|y| \leq 2$, i.e. the antiflow component of the $v_1$ dominates over its normal counterpart (see [16]). Similar antiflow slopes of $v_1(y)$ are developed by $\pi$ and $\Lambda$ [16,17]; its origin is traced to nuclear shadowing. At midrapidity $|y| \leq 0.5$ the directed flow of $\phi$ is quite weak.

The elliptic flow of $\phi$ mesons as a function of $\eta$ and $p_t$ is shown in Fig. 5 together with the model predictions for $\pi$ and $N$ [19], and recent experimental data [18]. The magnitude of the $\phi$ flow at midrapidity $v_2^\phi(\eta) = 3.3 \pm 1.1\%$ is similar to that of pions and nucleons. At larger rapidity $v_2^\phi(y)$ is weaker than the flow of other hadrons. As a function of $p_t$ the elliptic flow of $\phi$ rises up to 2 GeV/$c$ almost linearly with $p_t$. The agreement with the experimental results is good, although large error bars do not allow more definite conclusions. The saturation and/or possible drop of the $v_2^\phi(p_t)$ at higher $p_t$ is linked to the lack of rescattering in spatially anisotropic finite nuclear matter.

In summary, the QGSM successfully describes $m_t$-spectra of $\phi$ in different centrality
Figure 4. Directed flow $v_1(y, all\ p_t)$ of $\phi, N, K$ in minimum bias Au+Au events at $\sqrt{s} = 130$ AGeV.

Figure 5. The same as Fig. 4 but for the elliptic flow $v_2(y, all\ p_t)$ and $v_2(p_t, |y| \leq 1)$ of $\phi, N, K$. Data are taken from [18].

bins in Au+Au collisions at $\sqrt{s} = 130$ AGeV, but underestimates the total $\phi$ production. This problem cannot be cured alone by the fusion of strings. Mesons are frozen in the model earlier than baryons. The QGSM predicts unique antiflow slope at midrapidity for the directed flow of $\phi, \pi, N, K, \Lambda$, and reproduces correctly the elliptic flow $v_2^\phi(p_t)$.

Acknowledgments. Fruitful discussions with A. Capella, A. Kaidalov, M. Krivoruchenko, D. Sousa and S. Voloshin are gratefully acknowledged. This work was supported by the EGK Basel-T"ubingen under DFG contract GRK683, by the BMBF under contract 06T"U986, and by the Bergen Computational Physics Laboratory (BCPL) in the framework of the European Community - Access to Research Infrastructure action of the Improving Human Potential Programme.

REFERENCES
1. P. Koch, B. M"uller, and J. Rafelski, Phys. Rep. 142 (1986) 1.
2. A. Shor, Phys. Rev. Lett. 54 (1985) 1122.
3. S. Afanasiev et al., NA49 Collab., Phys. Lett. B 491 (2000) 59.
4. M.C. Abreu et al., NA50 Collab., J. Phys. G 27 (2001) 405.
5. D. Mukhopadhyay, PHENIX Collab., these proceedings.
6. S.C. Johnson, B.V. Jacak, and A. Drees, E. Phys. J. C 18 (2001) 449.
7. S. Soff et al., J. Phys. G 27 (2001) 449.
8. P. Filip and E. Kolomeitsev, Phys. Rev. C 64 (2001) 054905.
9. A.B. Kaidalov and K.A. Ter-Martirosian, Phys. Lett. B 117 (1982) 247;
   N.S. Amelin et al., Sov. J. Nucl. Phys. 50 (1989) 1058; Phys. Rev. C 47 (1993) 2299.
10. C. Adler et al., STAR Collab., Phys. Rev. C 65 (2002) 041901.
11. N.S. Amelin, M.A. Braun, and C. Pajares, Z. Phys. C 63 (1994) 507.
12. N.S. Amelin et al., Eur. Phys. J. C 22 (2001) 149.
13. A. Capella and A. Kaidalov, private communication.
14. L.V. Bravina et al., Phys. Lett. B 354 (1995) 196; Phys. Rev C 60 (1999) 044905.
15. L.V. Bravina et al., Phys. Lett. B 470 (1999) 27; Phys. Rev. C 61 (2000) 064902;
   E.E. Zabrodin et al., Phys. Rev. C 63 (2001) 034902.
16. L.V. Bravina et al., J. Phys. C 28 (2002) 1977; nucl-th/0107056.
17. E. Yamamoto, STAR Collab., these proceedings.
18. E.E. Zabrodin et al., Phys. Lett. B 508 (2001) 184.