Resonance recombination of quarks in the quark-gluon plasma

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A theoretical description of the hadronization process, converting quarks and gluons, as produced in hadronic or electromagnetic interactions, into colorless hadrons, remains a formidable challenge to date. For partons with large transverse momentum, p_t, the factorization theorem of QCD allows to factorize the hadronization process into universal fragmentation functions which, in principle, can be determined empirically. At low momenta the factorization breaks down and other hadronization schemes are expected to become relevant. The quark-coalescence model (QCM) assumes that constituent quarks, produced in a reaction, can recombine to form hadrons. In elementary hadron-hadron collisions (pN, πN), this approach has been successfully applied to describe flavor asymmetries in kaon and charmed-hadron spectra as a consequence of recombining valence and/or sea quarks in both target and projectile.

In heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) hadronization via quark coalescence from a thermalized Quark-Gluon Plasma (QGP) provides an intuitive and economic explanation for the observed enhancement in the baryon-to-meson ratio and for the constituent-quark number scaling (CQNS) of the elliptic flow of different hadron species, $v_2(p_T)=n_q v_{2,q}(p_T/n_q)$; here, p_T denotes the hadron's transverse momentum, v_2 its elliptic flow, and n_q the number of constituent quarks in the hadron. The universal function $v_{2,q}$ is interpreted as the underlying quark elliptic flow at the time of hadronization.

The commonly applied rather simple version of quark coalescence models is empirically very successful, but subject to limitations. E.g., the collinearity of quark transverse momenta imposed on the coalescence process implies the violation of energy conservation, restricting the QCM's applicability to sufficiently large momenta, 2 GeV$<p_T<$6 GeV (the upper bound is set by the onset of fragmentation dominance). Furthermore, it is not obvious how the resulting hadron multiplicities relate to the thermodynamic limit. To remedy these problems, two of us [1] have suggested a reinterpretation of quark coalescence as the formation of hadron-like resonances in the QGP close to the phase transition, using a kinetic-theory approach based on the Boltzmann equation (the so-called resonance recombination model = RRM). By construction, the corresponding hadron formation process satisfies both energy-momentum conservation and the correct thermodynamic limit. In the stationary limit (characterized by the equality of gain and loss terms), the Boltzmann equation can be used to extract the equilibrium form of the meson distribution function as

$$f_M^{\rm eq}(\vec{p}) = \frac{\gamma_p}{\Gamma} g(\vec{p}) \ ,$$

where γ_p is a Lorentz time-dilation factor and Γ the resonance width (reaction rate) corresponding to the formation reaction $q+qbar \leftrightarrow M$ (M: meson). The gain term, g, is given by the phase-space distributions

$$g(\vec{p}) = \int \mathrm{d}^3x \beta(\vec{x},\vec{p}) = \int \frac{\mathrm{d}^3p_1 \mathrm{d}^3p_2}{(2\pi)^6} \int \mathrm{d}^3x \ f_q(\vec{x},\vec{p}_1) \ f_{\bar{q}}(\vec{x},\vec{p}_2) \ \sigma(s) \ v_{\rm rel}(\vec{p}_1,\vec{p}_2) \ \delta^{(3)}(\vec{p}-\vec{p}_1-\vec{p}_2)$$

of quarks and anti-quarks, where σ denotes the resonance-formation cross section and v_{rel} the relative velocity of the recombining quark-anti-quark pair. In simplistic QCMs a successful description of CQNS resides on a factorization of the space and momentum dependencies in the quark and anti-quark phase-space distributions. However, space-momentum correlations are at the heart of anisotropic (elliptic) flow as a collective phenomenon in the fireball expansion of heavy-ion collisions (as, e.g., encoded in hydrodynamic simulations). It has turned out to be difficult to reconcile space-momentum correlations with CQNS within QCMs.

In the present work [2] we utilize the RRM by implementing quark phase-space distributions generated from relativistic Langevin simulations of heavy-quark diffusion in the QGP. The Langevin approach is based on in-medium resonance interactions of quarks and anti-quarks [3] in an elliptically expanding QGP fireball, as applied earlier in calculations of p_T spectra and elliptic flow for "non-photonic" single-electron spectra arising from the decay of charm and bottom mesons at RHIC [4]. We furthermore extend our calculations to strange quarks. At the quark level, the resonance interaction strength in the QGP is adjusted to obtain a maximal elliptic flow leveling off at about 7-8%, consistent with experiment [5]; when plotted as a function of kinetic quark energy, KE_t, the resulting charm- and strange-quark distributions exhibit approximate scaling behavior, see left panel of Fig. 1. Upon applying the RRM to form ϕ and J/Ψ mesons, we find the following [2]: (i) CQNS is recovered for each meson separately, $v_2(p_T)=n_q v_{2,q}(p_T/n_q)$ from p_T=0 to at least 5 GeV; (ii) the meson-v_2 is found to be "universal" (for ϕ and J/Ψ mesons) but only as a function of transverse kinetic energy, KE_T (not p_T), of the meson (cf. Fig. 1 right), in line with the experimental observations [5]. These are rather nontrivial results in view of: (a) the energy-conserving coalescence formalism (essential for applications at low p_T) ,and (b) the implementation of space-momentum correlations (essential for a realistic description of elliptic flow).

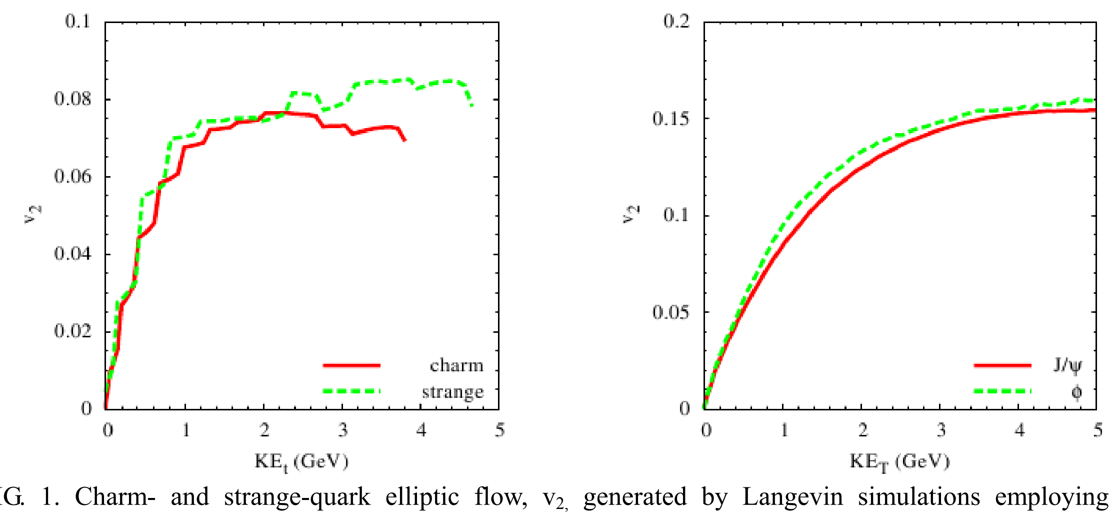

FIG. 1. Charm- and strange-quark elliptic flow, v_2, generated by Langevin simulations employing resonance interactions with light quarks and anti-quarks in the QGP (left panel) and the resulting v_2 of J/ψ and ϕ mesons after application of the resonance-recombination model for hadronization.

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