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Momentum dependent Vlasov-Uehling-Uhlenbeck calculation of mass dependence of the flow disappearance in heavy-ion collisions

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We perform calculations for different systems to study the mass dependence of flow disappearance in heavy-ion collisions in a relativistic Vlasov-Uehling-Uhlenbeck approach based on Walecka's σ-ω model. We find that the mass dependence of the energy of vanishing flow is the result of a complex interplay among the momentum dependence of the nuclear mean field, Coulomb potential, and n-n collisions. The effect of the n-n collisions is predominant and the particular scaling value ($A^{-1/3}$) of the mass dependence can be related to the scaling behavior of the collision number per nucleon.

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In recent years, the disappearance of flow which was predicted by Molitoris and Stöcker [1], Bertsch, Lynch, and Tsang [2], and Bonasera [3], draws more and more attention. In intermediate-energy heavy-ion collisions, the collective flow decreases with the decrease of the beam energy; below a certain energy, it even changes sign. The energy of vanishing flow (EVF) or balance energy ($E_{\rm bal}$) has been measured in experiments by several groups [4–8]. The EVF can be measured more precisely than the flow itself. There is a dispersion of the estimated reaction plane about the true reaction plane in the experiments, the transverse momentum needs renormalizing. At EVF, since the flow goes to zero, the renormalization procedure becomes unnecessary. The theoretical analysis of the flow disappearance was first performed for the ^{40}Ar+^{27}Al and ^{40}Ar+^{51}V collisions using a nonrelativistic Vlasov-Uehling-Uhlenbeck (VUU) approach with a local effective force [8–10]. The calculations show that the EVF is very sensitive to the in-medium n-n cross section but insensitive to the softness or stiffness of the equation of state (EOS), which is characterized only by compressibility K, and can be used to extract the in-medium cross section from the experimental data.

The analysis of the flow disappearance in ^{40}Ar+^{51}V collisions also was carried out in the relativistic VUU approach based on Walecka's σ-ω model in our previous work [11]. We have found that the EVF was only sensitive to the nucleon-nucleon cross section σ even when the momentum dependent interaction is included. The EVF is insensitive to the mean field, which is characterized by both compressibility K and effective mass m^*, as well as to the impact parameter b in central collisions when a reasonable large value of the n-n cross section is used.

Recently, systematic measurements of the flow disappearance have been performed by Westfall *et al.* for the systems C+C, Ne+Al, Ar+Sc, and Kr+Nb [12]. The experimental data show that EVF scales as $A^{-1/3}$, where A is the mass of the combined projectile-target system. The calculations of the mass dependence of EVF performed in [12] with a momentum independent VUU model could reproduce the general trend, but failed to reproduce the scaling behavior of EVF quantitatively. The calculated EVF values predicted with free cross section are systematically 10 to 20 MeV/nucleon below the experimental data. By reducing the n-n cross section, which is density dependent, the EVF values were enlarged but the slope of the mass dependence of EVF was also changed. The predicted EVF for light systems go above the experimental ones while the predicted EVF for heavier systems remain below the corresponding experimental one [12].

For a single system, the quantitative reproducing of the EVF can be reached by changing the nucleon-nucleon cross section with momentum independent potential in [9] or with the momentum dependent potential in [8]. But the mass dependence of EVF cannot be reproduced quantitatively by the VUU calculation with the momentum independent potential shown in [12]. Furthermore, it is known from Ref. [13] that the side flow is less sensitive to the n-n cross section for the momentum dependent potential than for momentum independent potential, and also it is well known that the momentum dependence of the nuclear mean field is an important feature for a fundamental understanding of nuclear matter properties. It seems to us that the momentum dependent force may play a role in changing the slope of the mass dependence of EVF, since for a light system the energy of vanishing flow is higher than that for a heavier system and thus the velocity dependent repulsion is stronger which may suppress the EVF for lighter system.

The purpose of this paper is to explore how two aspects, i.e., the momentum dependence and density dependence, of the nuclear mean field and the in-medium n-n cross section play roles on the balance energy of flow for different mass systems with the relativistic VUU approach in which the momentum dependent force is automatically included. In addition, the effect of the Coulomb force is also studied since it is obviously important for the mass dependence of the EVF.

One of the very important features of the EVF is its insensitivity to the EOS. However, this conclusion has been drawn and confirmed only for the ^{40}Ar+^{27}Al and ^{40}Ar+^{51}V collisions, as mentioned before. In this work we investigate for the first time the sensitivity of EVF to the EOS over a large range of system mass with a relativistic VUU approach, in which the momentum dependent potential is involved automatically. In the relativistic VUU (RVUU) approach [14] the mean field is determined by the coupling

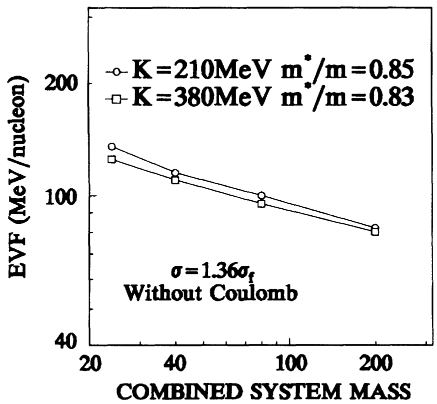

FIG. 1. Predicted EVF vs entrance-channel mass by the RVUU model for a soft (circles) and a stiff (squares) equation of state with a n-n cross section $\sigma=1.36\sigma_f$. The lines are used to guide the eye.

constants between nucleon and σ,ω mesons. The different set of coupling constants corresponds to different EOS characterized by the nucleon effective mass m^* and compressibility K. In Fig. 1 we choose two sets of mean field parameters which correspond to similar effective mass m^* and different compressibility K. The first set corresponds to an EOS with $m^*/m=0.83$ and $K=380$ MeV, which is usually referred to as a stiff EOS. The second set corresponds to an EOS with $m^*/m=0.85$ and $K=210$ MeV, which usually is referred to as a soft EOS. One can see that there is little difference between the results of the two EOS for both light and heavy systems. It is clear that the mass dependence of EVF is insensitive to K. In Fig. 2 we choose two sets of mean field parameters which correspond to a same compressibility K and different effective mass m^* to study the effect of the momentum dependence of the mean field. For the light systems, the EVF predicted with a small effective mass, which implies a strong momentum-dependent force, are remarkably lower than that with a big effective mass. It is clear that the momentum dependence of the mean field changes the slope of the mass dependence of EVF by suppressing the EVF of light systems. This is just as expected. For lighter system the energy of vanishing flow (predicted with a reasonable n-n cross section) is higher than that for heavier system and thus the velocity dependent repulsion is stronger, which suppresses the EVF for lighter system.

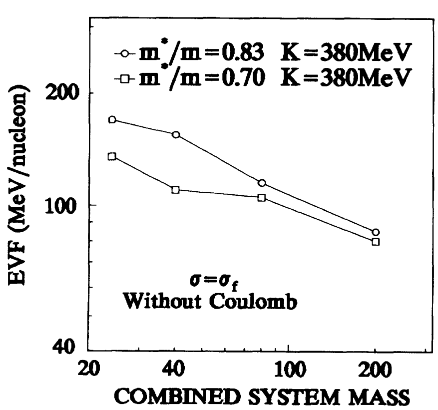

FIG. 2. Predicted EVF vs entrance-channel mass by the RVUU model for two EOS with a same compressibility K and different effective mass m^*. The lines are used to guide the eye.

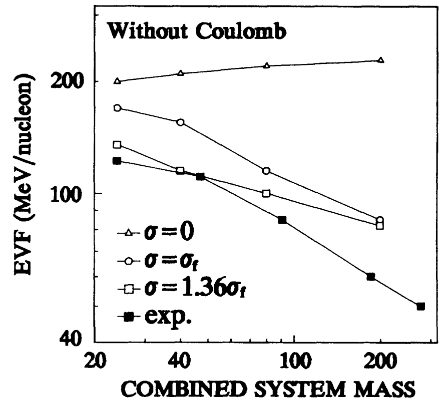

FIG. 3. Predicted mass dependence of EVF by the RVUU model without Coulomb correction for a soft equation of state. The open triangles, open circles, and open squares indicate calculations with n-n cross section $\sigma=0,1.0,1.36\sigma_f$, respectively. The solid squares indicate experimental data. The lines are used to guide the eye.

In Fig. 3 we show the mass dependence of the EVF calculated with a soft EOS ($K=210$ and $m^*/m=0.85$) and different n-n cross sections. The solid squares indicate the experimental data [8,12]. To investigate the contribution of the nuclear mean field, we first turn off the collision term and calculate the mass dependence of EVF. The open triangles in Fig. 3 indicate the result of a pure mean field without Coulomb potential and n-n collisions. One can see that the EVF increases slowly with the increase of system mass. This shows that the mean field for the heavier system is more attractive, but the difference between the EVF of different systems made by mean field is not so large, for example, that could scales as $A^{2/3}$. The mean field consists of two parts, an attractive part and repulsive part. For heavier system, the attractive part is stronger, but meanwhile the repulsive part is also stronger than that for lighter system. One can find that the difference contributed by pure mean field is small and the mass dependence of EVF is approximately flat.

The effect of n-n collisions is strong and rather complex. The open circles are the calculated result with the free n-n cross section σ_f in the Cugnon parametrization [15] and the Pauli-blocking effect is included in the numerical simulation. We see that after the collision term is added, the EVF for heavy systems are suppressed substantially while the EVF for light systems are less changed. This is mainly because, for the same n-n cross section, the collision number per nucleon for the heavier system is larger than that for the lighter system. It confirms our viewpoint in the previous work [11] in which we argued that the contribution of n-n collisions depends on the mean field, the more attractive the mean field (for heavier systems in this case), the larger the contribution of n-n collisions. However, when the n-n cross section is further enlarged, the EVF of the heavier system is changed less than that of the lighter system. The open squares are the results calculated with $\sigma=1.36\sigma_f$. We find the slope of the mass dependence is small, i.e., the EVF for

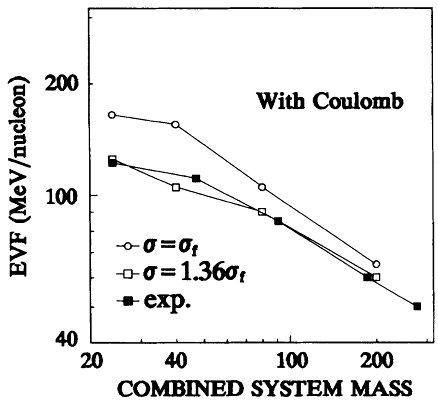

FIG. 4. Predictions of the RVUU model with Coulomb correction. Others are same as Fig. 3.

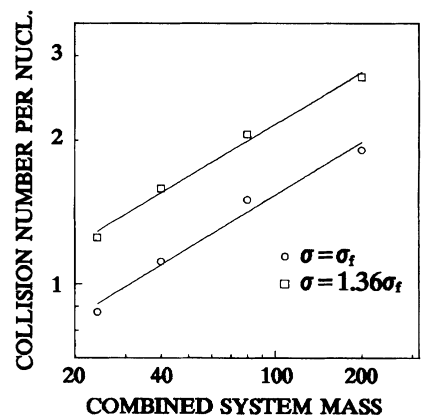

FIG. 5. Collision number per nucleon as a function of the system mass. The lines are power law fits.

the light systems are largely suppressed and meet the experimental data, while the EVF for the heavy systems change little and remain higher than the experimental ones.

However, in the above calculations, the Coulomb force has been neglected. In Fig. 4, we include the Coulomb potential in the RVUU simulation. Considering that the collision energy is not so high, we simply use a nonrelativistic Coulomb correction used in a nonrelativistic VUU calculation. Comparing Fig. 4 with Fig. 3, one can find that the EVF for the heavy systems are largely suppressed, while the EVF for the light systems do not change after Coulomb correction. After Coulomb correction, the predicted EVF with in-medium n-n cross section $\sigma=1.36\sigma_f$ meet the experimental data very well. The dual sensitivity of the mass dependence of the EVF to the effective mass m^* and n-n cross section σ makes it difficult to pin down the effective mass m^* and in-medium n-n cross section σ simultaneously. However, the EVF for the heavy system is insensitive to m^* and K and hence can be used to draw information about σ. From Fig. 4 we can get a lower limit of σ, i.e., σ_f. For σ greater than σ_f, the EVF for the heavy system is not sensitive to σ; thus we cannot pin down its upper limit. In the high-energy flow analysis [11], we have found that an effective mass $m^*/m=0.85$ was appropriate. Using this value of m^*, from the EVF of the light system in Fig. 4, we can further pin down the n-n cross section σ, about $1.36\sigma_f$.

It may be questionable that the deduced in-medium cross section $\sigma=1.36\sigma_f$ is substantially larger than the free one. As mentioned before, we should point out that the term of "free" n-n cross section in this work refers to the Cugnon parametrization [15], which is much smaller than the actual averaged free n-n cross section [16] at low and intermediate energies. For example, at a collision energy of about 85 MeV/nucleon, the deduced effective cross section ($\sigma\sim1.36\sigma_f\sim40$ mb) is higher than the Cugnon parametrization ($\sigma_f\sim30$ mb), but still much smaller than the actual averaged free n-n cross section (about 60 mb). We concluded that the medium suppresses the n-n cross section at intermediate energy and the Cugnon parametrization underpredicts the effective n-n cross section. This agrees qualitatively to the relativistic Brueckner-Hartree-Fock calculation [17] and the calculation of the effective n-n cross section based on the self-consistent RVUU approach [18], as well as the recent microscopic calculations [19].

From the calculations above we can see that the mass dependence of the EVF is in fact the result of the complex interplay among the mean field of the nuclear force, the Coulomb potential, and n-n collisions. It is easy to understand the role of the Coulomb potential. A large mass system has a large charge number and hence strong Coulomb repulsion which suppresses the EVF. The momentum dependence of the mean field can also change the slope of the mass dependence of the EVF by suppressing the EVF of the light system. Nevertheless, the effect of the n-n collisions is predominant and the particular scaling value ($A^{-1/3}$) of the mass dependence can be related to the scaling behavior of the collision number per nucleon, while the effect on changing the slope of the mass dependence of the EVF from a momentum dependence of the mean field balances that from the Coulomb force. In Fig. 5 we show the collision number per nucleon as a function of the system mass and we find it scales as A^τ, where τ equals $\sim1/3$. If the contribution of n-n collisions to flow is roughly proportional to the collision number per nucleon and the latter scales as $A^{1/3}$, then we expect the mass dependence of EVF should scale roughly as $A^{-1/3}$.

In conclusion, we have investigated the mass dependence of the energy of the disappearance of flow in heavy-ion collisions. From our systematic studies it is shown that the momentum dependence of mean field should also be taken into account, in addition to the density dependence aspect. The Coulomb interaction is essential for reproducing the mass dependence of EVF. A more reliable value of in-medium n-n cross section is extracted by the comparison of the systematic calculations with experimental data.

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