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Disappearance of transverse flow in Au+Au collisions

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The balance energy at which repulsive nucleon-nucleon scattering balances the attractive force due to the nuclear mean field is measured for the first time for the Au+Au reaction. The observed balance energy of $42\pm 3_{stat}\pm 1_{sys}$ MeV/nucleon agrees with the previously established power law dependence of E_{bal} on system mass, providing evidence that the Coulomb interaction does not suppress the attractive mean field near the balance energy, in contrast to recent theoretical predictions.

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The study of nuclear collisions at intermediate energies has aided in revealing many properties of hot and dense nuclear matter, as well as constraining the parameters of the nuclear equation of state (EOS) [1,2]. In particular, collective flow variables have uncovered such phenomena as the momentum-dependent nuclear mean field [3], the ''squeeze-out'' of particles perpendicular to the reaction plane [4], and the possible existence of a liquid-gas phase transition in excited nuclear matter [5]. The disappearance of directed (or in-plane) transverse flow occurs at an incident beam energy, termed the balance energy (E_{bal}) [6], where the attractive scattering due to the nuclear mean field balances the repulsive scattering resulting from nucleon-nucleon hard-shell collisions. The balance energy is of great importance because the parameters of the EOS and the in-medium nucleon-nucleon cross section can be related to the dominance of repulsive or attractive scattering. Previous studies have shown the impact parameter dependence [7] and isospin dependence [8] of E_{bal}, as well as the mass scaling law ($E_{bal} \sim A^{-1/3}$) for intermediate-sized systems ($24\leqslant A\leqslant 179$) [9]. However, E_{bal} has not been measured for heavier systems such as Au+Au ($A=394$). It has been suggested that the balance energy cannot be measured for heavy systems because the repulsive Coulomb force may dominate the attractive mean-field effect at low energies [10]. Previous experimental efforts only have attempted to extrapolate values of E_{bal} for Au+Au from flow measurements taken at higher energies. Values of 47 ± 11 MeV/nucleon [11] and 47 ± 5 MeV/nucleon [12] for E_{bal} were obtained via extrapolation. Most recently, another group extrapolated a value of 56 ± 21 MeV/nucleon for $Z=2$ and 65 ± 14 MeV/nucleon for $Z=3$ in semicentral collisions [13].

In this Rapid Communication we present the first direct experimental evidence for the disappearance of directed transverse flow for Au+Au. We show that, although the flow signal near the balance energy is weak compared to previously studied systems, a minimum in the excitation function of flow can be extracted. This is in contradiction to recent theoretical calculations [10], which predicted that no disappearance of the flow could be found for the Au+Au system, due to the dominance of the Coulomb interaction. We show that E_{bal} scales as $A^{-\tau}$ for heavy systems as well, in agreement with other recent theoretical predictions [14]. This agreement justifies interpreting the minimum as a balance between the attractive and repulsive components of the nuclear interaction, rather than the onset of Coulomb-dominated interactions. We attribute any difference between directly measured and extrapolated balance energies to difficulties in assigning values to finite transverse flow. Finally, we perform Boltzmann-Uehling-Uhlenback (BUU) model simulations with and without the Coulomb potential included to illustrate the importance of the Coulomb interaction in reproducing the system mass dependence, as well as to relate the system mass dependence of E_{bal} to the scaling dimensions of the collision nuclei.

The present measurements were carried out with the MSU 4π Array [15] at the National Superconducting Cyclotron Laboratory (NSCL) using ^{197}Au beams from the K1200 cyclotron. Data were taken at beam energies of 24.5, 28.2, 33.1, 38.3, 44.5, 48.4, 53.5, and 57.6 MeV/nucleon. The Au beams were focused directly onto an Au target with thickness ranging from 2 mg/cm^2 to 20 mg/cm^2. Energy loss per nucleon in the target ranged from 1.2 to 3.5 MeV, depending on incident energy and choice of target. Beam current was 10–100 electrical pA. The main ball of the 4π Array consists of 55 Bragg curve counters in front of 170 phoswich counters (arranged in hexagonal and pentagonal subarrays) covering the laboratory frame polar angles $18°\lesssim\theta_{lab}\lesssim 162°$. The Bragg curve counters served as ΔE detectors for low-energy particles, allowing the detection of low-energy charged fragments from $Z=2$ to $Z=12$. In addition, the High Rate Array consists of 45 phoswich detectors covering $3°\lesssim\theta_{lab}\lesssim 18°$, with detection of charged fragments $1\leqslant Z\leqslant 18$. By using the Bragg counters, the main ball telescopes have lower energy thresholds of approximately 4 MeV/

nucleon for ^{7}Li. The High Rate Array phoswiches have corresponding energy thresholds of $\sim$10 MeV/nucleon.

Because of the low beam energies presented here, the acceptance of the 4π Array was determined by simulating isotropic events and passing them through the 4π software filter. As expected, low energy particles in the backward direction are not recorded due to detector energy thresholds. To minimize the threshold effects, only particles in the forward hemisphere of the reaction ($y_{\mathrm{c.m.}} \geqslant 0$) are used in the flow analysis, and forward/backward reaction symmetry is assumed. This technique has been carried out previously by others studying collective flow [13].

To extract collective flow in nucleus-nucleus collisions, the impact parameter *b*, and the reaction plane first must be determined. Central collisions were selected using total transverse kinetic energy $[E_t = \Sigma_{i=1}^{N_c} E_i \sin^2(\theta_i)]$, N_c = number of charged particles]. A large value of E_t corresponds to a small impact parameter, *b*. In order to compare to previous studies, events were placed into 5 *b* bins, each containing 20% of the total events. In the present analysis, central ($b/b_{\max} < 0.39$) and semicentral ($0.39 < b/b_{\max} < 0.56$) collisions are studied. Here, $b_{\max}$ is the maximum impact parameter, $b_{\max} = R_{\mathrm{proj}} + R_{\mathrm{targ}}$.

In order to obtain the reaction plane, the azimuthal correlation method was used [16]. This method is useful when transverse flow is weak, i.e., near the balance energy. The azimuthal correlation method finds the plane which best aligns with the transverse momentum vectors. In order to avoid autocorrelation, the flow particle of interest (POI) is removed from the reaction plane determination. Therefore, an event with multiplicity *N* can be thought of as having *N* separate subevents. The technique is sensitive to the finite coverage and azimuthal granularity of the 4π Array. The resulting anisotropy in the reaction plane distribution (up to 15% difference between the highest and lowest values in the number of recorded events at a given lab angle) is corrected by applying Fourier analysis, and by smearing the final position (θ, ϕ) of each particle over the active surface of the incident detector, as determined by the 4π Array software filter.

Once the reaction plane for the event was determined, the average transverse momentum projected into the reaction plane for a particular fragment type (e.g., He fragments) was plotted as a function of the fragment's center-of-mass rapidity, $y_{\mathrm{c.m.}}$, normalized by the projectile rapidity, $y_{\mathrm{proj,c.m.}}$. Figures 1(a)–1(c) show these plots for beam energies below, near, and above the balance energy. In these plots, open squares represent experimental values, and closed squares are the experimental values reflected about $y_{\mathrm{c.m.}} = 0$ by assuming forward/backward symmetry. This symmetry has been used in previous flow studies over a wide range of energies [13,17]. The error bars are statistical, and the solid lines correspond to linear least square fits for the midrapidity region $-0.5 \leqslant (y/y_{\mathrm{proj}})_{\mathrm{c.m.}} \leqslant 0.5$. Fragments emitted in this region are emitted from the excited participant volume created by the projectile-target overlap. The slope of this fit is defined as the directed transverse flow, which is a measure of the amount of collective momentum transfer in the collision.

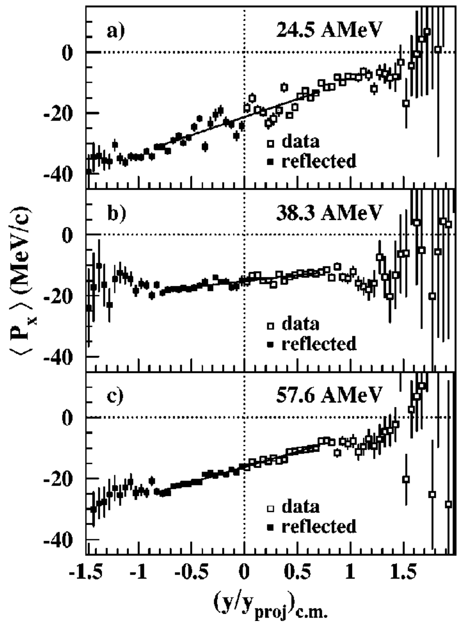

FIG. 1. Mean transverse momentum in the reaction plane plotted versus the reduced c.m. rapidity for $Z=2$ fragments from central collisions at beam energies (a) below, (b) near, and (c) above the balance energy. Open squares are experimental data, solid squares are reflected about $y=0$ assuming forward/backward symmetry, as done in Ref. [13].

Experimentally, corrections need to be made to the reaction plane to assign flow values more accurately; however, these corrections do not affect the balance energy determination.

The transverse momentum is expected to pass through $p_x = 0$ at $y_{\mathrm{c.m.}} = 0$. The negative offset in Figs. 1(a)–1(c) has been seen previously in many systems [3,6] and is attributed to two experimental biases. By removing the flow particle from the reaction plane determination (to avoid autocorrelation), an inherent lack of momentum conservation is present in the assigned reaction plane direction. However, this effect is small, because the 4π Array does not detect all particles. Furthermore, the expected reduction of this effect with increasing system mass is not seen experimentally.

A larger effect results from the likelihood of double hits in detectors which lie in the direction of the reaction plane. If a flow particle of interest (POI) is directed in the reaction plane, it is more likely to contribute to a double hit and be undetected than a POI directed to negative angles. This effect was seen in EOS data [18] and corrected by using negative-rapidity particle spectra and by considering the two-track resolution. However, these corrections are more difficult in a phoswich array, as the location of a particle cannot be pinpointed precisely enough.

The extracted flow values are plotted vs incident beam energy in Fig. 2 (solid squares) for several particles of interest. For $Z=1$, the extracted flow is very weak for all of the measured energies. This is partially due to the well-known fragment mass dependence of flow and the higher energy threshold for $Z=1$. However, for $Z=2$ and $Z=3$ the plot clearly shows that the flow goes through a minimum. Because our measurements are unable to distinguish between

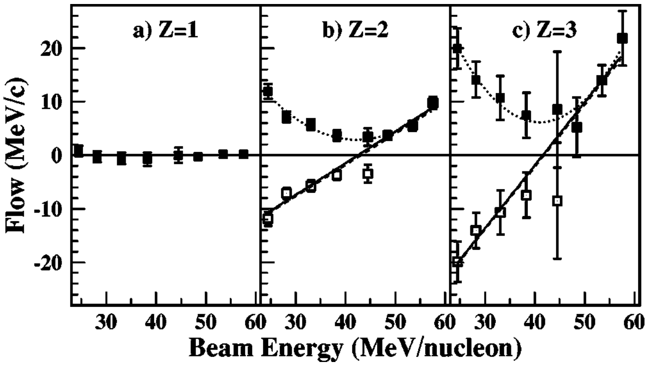

FIG. 2. Extracted flow vs incident beam energy in central collisions for (a) $Z=1$, (b) $Z=2$, and (c) $Z=3$ POI. Solid squares are experimental data, open squares are reflected about the x axis to represent attractive scattering. The dashed (solid) linear least squares fit is with the 44.5 MeV/nucleon data point reflected (not reflected). The dotted curve is a parabolic fit.

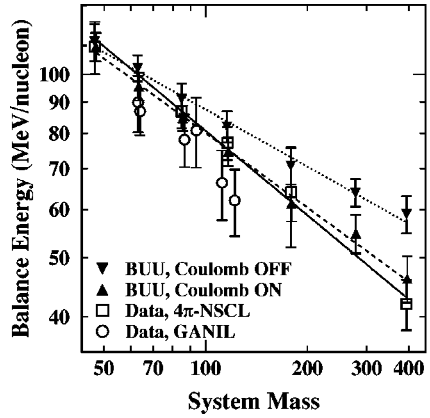

FIG. 3. Balance energy as a function of combined system mass. Open squares and circles are experimental data, and triangles represent BUU calculations with and without the Coulomb interaction included in the calculation. The GANIL data is from Ref. [19].

the *negative* attractive scattering which dominates below E_{bal} and the *positive* repulsive scattering which dominates above E_{bal}, such a minimum is indicative of the balance energy for the system. The dotted curves are parabolic fits. Also, the flow data below the minimum are reflected about the x axis to represent the attractive regime, and the dashed (solid) linear least squares fits are with the 44.5 MeV/nucleon data point reflected (not reflected). For $Z=2$, this corresponds to a balance energy of 42.5 ± 3.5 or 43.1 ± 3.6 MeV/nucleon, respectively, and for $Z=3$, the numbers are 41.6 ± 4.3 and 41.9 ± 6.1 MeV/nucleon, where the quoted errors are statistical. In the same figure, we also show the result of a parabolic fit of the kind employed previously, resulting in values of 42.3 ± 3.6 for $Z=2$ and 41.0 ± 5.2 MeV/nucleon for $Z=3$, respectively. We can see that the balance energies for $Z=2$ and $Z=3$ are the same to within error bars, in agreement with previous experimental studies that showed no dependence on particle type [9]. Combining the statistical and systematic errors, we obtain for the Au+Au system the balance energy $42\pm3_{\mathrm{stat}}\pm1_{\mathrm{sys}}$ MeV/nucleon.

The directly measured value of E_{bal} differs from the most recent extrapolated values [13]. The difference most likely results from the difficulty in experimentally assigning finite flow values, because precise transverse flow measurements need to be corrected for reaction plane dispersion and acceptance effects. Errors in the flow values will cause errors in the extrapolated balance energy. The difference may also be due to slightly different impact parameter cuts. Moreover, finite flow measurements are difficult to compare to theory because the theory needs accurate fragment formation and has to account for experimental biases. A directly measured balance energy avoids these potential complications and can be compared effectively to microscopic transport models.

Figure 3 shows the experimentally observed relationship between the balance energy and combined system mass for several systems [3,8,9,19], plotted as open squares and circles. The solid line is a power law fit to data taken with the 4π Array. The GANIL data were obtained using azimuthal correlation studies, which allow estimations of the balance energy without reaction plane determination. The balance energy for Au+Au agrees very well with the previously established power law scaling $E_{\mathrm{bal}}\sim A^{-\tau}$. We find $\tau=0.46\pm0.06$ for our data.

To investigate the effect of the Coulomb interaction on the value of τ, a numerical implementation [20] of the Boltzmann-Uehling-Uhlenback (BUU) model was used. In this model, the nucleons interact via a collectively generated mean field and with each other through two-body collisions. Previously, the BUU model successfully predicted the power law relationship between E_{bal} and system mass [21] for intermediate-sized systems. For the present calculations, a soft equation of state ($K=200$ MeV) and a 20% reduced in-medium cross section [$\sigma_{\mathrm{nn}}=\sigma_{\mathrm{free}}(1-0.2(\rho/\rho_0))$, ρ_0 = normal nuclear density] was used. Calculations were performed for systems of various masses, from Ne+Al ($A=47$) to Au+Au ($A=394$).

Figure 3 also shows the results of the BUU calculations (solid triangles). With the Coulomb interaction included in the calculation (dashed line), the simulation agrees well with the data ($\tau_{\mathrm{BUU}}=0.41\pm0.03$). When the Coulomb interaction is removed (dotted line), $\tau=0.31\pm0.03$, very close to the anticipated value of $\tau=1/3$ from scaling arguments. This result supports the notion that the mass dependence of the balance energy results from two competing factors: the competition between the attractive mean field, which can be associated with the surface area of the interacting nuclei and should scale as $A^{2/3}$; and the repulsive nucleon-nucleon scattering potential, which scales as the number of nucleons present, A. However, our calculations show that the Coulomb interaction is essential for reproducing the value of the balance energy in very heavy systems. This is in agreement with the result of de la Mota *et al.* [14].

In conclusion, we have presented the disappearance of directed transverse flow for Au+Au using the MSU 4π Array. Our results indicate that the balance energy is 42 ± 4 MeV/nucleon. We have also shown that E_{bal} scales as $A^{-\tau}$ for heavy systems as well as light systems. BUU model calculations confirm the use of a reduced in-medium σ_{nn} and soft EOS over the entire range of system sizes. When the Coulomb interaction is removed from the BUU calculations,

$\tau \approx 1/3$, which supports previous assumptions about the competing roles of the nuclear mean field and nucleon-nucleon scattering.

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