Investigation of transverse collective flow of intermediate mass fragments

Z. Kohley,[1,2,*] L. W. May,[1,2] S. Wuenschel,[1,2] A. Bonasera,[2,3] K. Hagel,[2] R. Tripathi,[2] R. Wada,[2] G. A. Souliotis,[2,4] D. V. Shetty,[2,†] S. Galanopoulos,[2] M. Mehlman,[2,5] W. B. Smith,[2] S. N. Soisson,[1,2] B. C. Stein,[1,2] and S. J. Yennello[1,2]

[1] *Chemistry Department, Texas A&M University, College Station, Texas 77843, USA*

[2] *Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*

[3] *Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, I-95123 Catania, Italy*

[4] *Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens GR-15771, Greece*

[5] *Physics and Astronomy Department, Texas A&M University, College Station, Texas 77843, USA*

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The transverse flow of intermediate mass fragments (IMFs) has been investigated for the 35 MeV/u ^{70}Zn + ^{70}Zn, ^{64}Zn + ^{64}Zn, and ^{64}Ni + ^{64}Ni systems. A transition from the IMF transverse flow strongly depending on the mass of the system, in the most violent collisions, to a dependence on the charge of the system, for the peripheral reactions, is shown. This transition was shown to be sensitive to the density dependence of the symmetry energy using the antisymmetrized molecular-dynamics model. The results present an observable, the IMF transverse flow, that can be used to probe the nuclear equation of state. Comparison with the simulation demonstrated a preference for a stiff density dependence of the symmetry energy.

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I. INTRODUCTION

Improving our understanding of the nuclear equation of state (EOS) is an important goal for the field of nuclear science. Theoretical predictions for the form of the EOS for asymmetric nuclear matter still vary widely [1] and therefore require additional experimental constraints. The symmetry term of the EOS, representing the difference in the binding energy of pure neutron matter and symmetric nuclear matter, is critical for understanding nuclear properties, astrophysical processes, and the fundamental nucleon-nucleon interaction [2,3]. In particular, the density dependence of the symmetry energy can greatly affect predictions of neutron star properties, such as the density profile, proton fraction, the mass-to-radius relationship, core-crust transition, and the cooling processes [4–8]. Heavy-ion collisions provide a unique opportunity to examine nuclear matter at temperatures, densities, and neutron-to-proton (N/Z) ratios away from that of ground-state nuclei. Thus it is necessary to discover observables that are sensitive to the nuclear EOS. The collective flow of light charged particles has been used to help constrain the EOS for symmetric nuclear matter [9–11] and is currently being investigated for applying constraints on the asymmetric part of the EOS at both high and low densities [3,12,13].

The transverse collective flow has been shown to depend on both the mass and N/Z of the colliding system. The examination of the balance energy demonstrated that the transverse flow was strongly dependent on the mass A of the colliding system [14]. The balance energy followed an $A^{-1/3}$ power law which represents a balance between the attractive mean-field potential which scales with the surface $A^{2/3}$ and the repulsive nucleon-nucleon collisions which should scale with the interaction volume A [14,15]. Pak and co-workers have shown that the transverse collective flow for light particles with $Z = 1$–3, as well as the balance energy, increases with an increasing neutron-to-proton ratio of the system (N/Z_{sys}) [16,17]. The isospin dependence of the transverse flow and balance energy was attributed to the isospin-dependent potential and in-medium nucleon-nucleon cross sections [18,19]. Along with the mass dependent mechanisms (mean-field and nucleon-nucleon collisions), theoretical simulations have also demonstrated the importance of the Coulomb potential in describing the transverse flow [20–22].

In this paper, the transverse flow for intermediate mass fragments (IMFs) from the 35 MeV/u ^{70}Zn + ^{70}Zn, ^{64}Zn + ^{64}Zn, and ^{64}Ni + ^{64}Ni systems are examined. This provides the opportunity to study the dependence of the mass N/Z and charge of the system on the transverse flow. The heavier fragments provide a new probe, in comparison to the light charged particles (LCPs), for examining the mechanisms responsible for the transverse flow and the nuclear equation of state.

II. EXPERIMENT

The Superconducting K500 Cyclotron at the Texas A&M Cyclotron Institute was used to produce 35 MeV/u beams of ^{70}Zn, ^{64}Zn, and ^{64}Ni, which were impinged on ^{70}Zn, ^{64}Zn, and ^{64}Ni self-supporting targets, respectively. The experimental data were collected using the 4π NIMROD-ISiS array (Neutron Ion Multidetector for Reaction Oriented Dynamics with the Indiana Silicon Sphere) [23]. The NIMROD-ISiS array consisted of 14 concentric rings providing coverage from 3.6° to 167° in the laboratory. The first eight rings, ranging from 3.6° to 45.0°, had the same geometry as the INDRA detector [24] and the final six rings were of the ISiS geometry [25]. Isotopic resolution was achieved, in the forward angles, for $Z = 1$–17 particles and elemental identification was obtained up through the charge of the beam. In the backward angles,

*zkohley@comp.tamu.edu

†Also at Physics Department, Western Michigan University, Kalamazoo, MI 49008.

detector thresholds allowed only for identification of $Z = 1$–2 particles. The entire charged particle array was surrounded by the 4π TAMU Neutron Ball which provided an average event-by-event neutron multiplicity.

III. EVENT SELECTION AND REACTION PLANE ANALYSIS

An estimation of the impact parameter, for the experimental data, was completed using the minimum bias two-dimensional (2D) distributions of the raw neutron multiplicity plotted against the charged particle multiplicity for each system. Five bins (0–4) were created from the 2D distributions such that each bin would represent a $b/b_{\max}$, or $b_{\rm red}$, width of 0.2 if one assumes a corresponding triangular impact parameter distribution. Molecular-dynamics simulations [26,27], filtered using a software representation of the NIMROD-ISiS array, showed that 80% (20%) of the events in the most peripheral (central) bin were correctly identified. Thus bin 0 does not necessarily contain the most central events but rather the most violent events, while the bins representing the peripheral collisions do provide a relatively accurate impact parameter estimation.

In order to calculate the in-plane transverse momentum for the fragments, the reaction plane for each event was reconstructed using the azimuthal correlation method [28]. The azimuthal correlation method does not differentiate the forward, quasiprojectile and backward, quasitarget sides of the flow. Therefore the forward flow side of the reaction plane was determined using the transverse momentum analysis method [29]. The particle of interest (POI) was removed from the calculation of the reaction plane in order to avoid autocorrelations [28–30]. Thus the reaction plane was calculated for each particle in an event rather than once for the whole event. In order to ensure that only quasicomplete events were used in the analysis, an event criterion was imposed such that the total detected charge for an event must be greater than 40% of the total charge in the colliding system.

The transverse flow is often quantified as the slope of the average in-plane momentum $\langle Px \rangle$ at midrapidity. However, in the NIMROD-ISiS array thresholds produced incomplete detection of IMFs at negative reduced rapidities ($Y_r = Y_{\rm cm}/Y_{\rm cm,proj}$). Therefore the transverse flow was quantified by calculating the average in-plane transverse momentum from $0.0 \leqslant Y_r \leqslant 0.45$ [31–33]. The flow is extracted only from the positive rapidity fragments and is designated as $\overline{\langle Px \rangle}$. However, there exists a lack of momentum conservation in the reaction plane reconstruction due to the inability to detect every particle in each event [28,31] and thus the $\langle Px \rangle$-versus-Y_r plot does not pass through the origin (0,0). In order to correctly extract the $\overline{\langle Px \rangle}$, the flow plot needs to pass through the origin. Therefore the flow plot was manually corrected by adjusting the $\langle Px \rangle$-versus-Y_r plot such that it passed through the origin (0,0).

In examining the transverse flow from experimental data (in which the reaction plane is reconstructed), one has to be aware of the effect of the reaction plane dispersion [34,35]. Following the method described in Ref. [28], the standard deviation between the reconstructed and true reaction plane ($\Delta\phi_{\rm rxn\text{-}plane}$) was estimated for each impact parameter bin of each system. The $\Delta\phi_{\rm rxn\text{-}plane}$ was consistent between systems. The average $\Delta\phi_{\rm rxn\text{-}plane}$ over the entire impact parameter selection was $\sim 27^\circ$. Since the reaction plane dispersion between all three systems is equivalent, the effects of the dispersion should be minimal in comparing the flow between systems or constructing a ratio of the flow values.

In examining the transverse flow of the IMFs, an anticorrelation between the reaction plane and the IMF's azimuthal angle was observed. The anticorrelation is due to the removal of the POI from the reaction plane calculation. For the most violent collisions, there was a significant probability that the removal of the heavy POI would result in a reaction plane oriented $\sim 180^\circ$ from the reaction plane calculated with the heavy POI, producing negative flow values. This anticorrelation for heavy fragments has also been observed by the INDRA collaboration [30]. Therefore if the difference between the reaction plane calculated without the POI and the reaction plane calculated using the entire event was greater than 90°, the POI-removed reaction plane was re-oriented (rotated 180°). The molecular-dynamics simulations showed that the magnitude of the flow could be overestimated for some IMFs by up to 43% in the most central collisions. However, the strength of the method is that the trend and correct sign of the IMF flow is reproduced, allowing for system-to-system comparisons to be studied.

IV. RESULTS AND DISCUSSION

The transverse flow $\overline{\langle Px \rangle}$ for $Z = 1$–9 particles is shown in Fig. 1 for the five centrality bins, ranging from bin 0 (the most violent collisions) to bin 4 (the most peripheral collisions). The expected increase in the transverse flow with the increasing charge of the fragments is clear [10,16,36]. However, a decrease in the magnitude of the flow from the central to peripheral bins is observed rather than the typical maximum flow in the midperipheral collisions (bin 2) [10,16]. While the unfiltered AMD-Gemini results showed a maximum flow for the midperipheral collisions, the filtered results demonstrated the same trend shown in the experimental data (Fig. 1). This was attributed to the reaction plane re-orientation method, which overestimates the magnitude of the flow in the most violent collisions (bins 0–1) with respect to the midperipheral selection.

In bin 0 the $\overline{\langle Px \rangle}$ of the IMFs from the ^{64}Ni and ^{64}Zn systems are nearly equivalent and larger than those from the ^{70}Zn system. This can be understood through the mass dependence of the transverse flow which is related to the balance energy relationship derived by Westfall *et al*. [14]. Thus one would expect the ^{70}Zn system to exhibit a decreased flow in comparison to the $A = 64$ systems since it has a lower balance energy due to the increased repulsive *nn* collisions relative to the attractive mean-field potential.

In the peripheral reactions, bins 3 and 4, the $\overline{\langle Px \rangle}$ of the IMFs from the Zn systems become similar and decreased with respect to the ^{64}Ni system. This represents a clear dependence

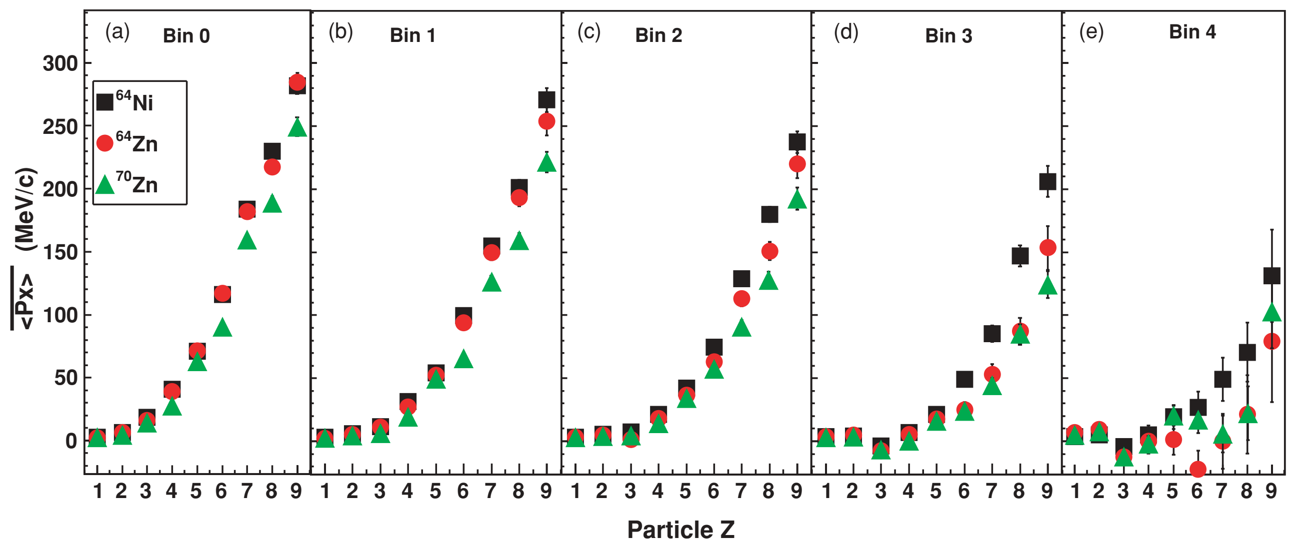

FIG. 1. (Color online) Transverse flow $\overline{\langle Px \rangle}$ for $Z = 1$–9 particles in five different centrality bins. Bin 0 (a) represents the most violent collisions, while bin 4 (e) represents the most peripheral. The results are shown for the ^{64}Ni, ^{64}Zn, and ^{70}Zn systems as shown in the legend.

of the charge of the system on the IMF flow. The larger repulsive Coulomb force in the Zn ($Z = 30$) systems causes a decreased flow in comparison to the ^{64}Ni ($Z = 28$) system. The increased effect of the charge dependent forces, relative to the mass dependent forces, in the peripheral collisions may be due to the decreased interaction volume. For example, the number of *nn* collisions would be greatly diminished in the peripheral reactions.

A separation of the IMF flow between all three systems occurs in the midperipheral reactions, bin 2, in which the IMF's $\overline{\langle Px \rangle}$ from the ^{64}Zn system is less than that from the ^{64}Ni system yet larger than the ^{70}Zn flow, exhibiting a behavior between the extremes of the mass (bin 0) and charge (bin 4) dependent flow. The difference between the IMF flow in the ^{64}Ni and ^{64}Zn systems is similar to the $(N/Z)_{\text{sys}}$ dependence observed by Pak *et al.* for LCPs in $A = 58$ systems [16]. However, in context with the results from the IMF flow of the ^{70}Zn system, which has a similar $(N/Z)_{\text{sys}}$ to the ^{64}Ni system, the difference between the $A = 64$ IMF flow appears to be due to a balancing between the mass and charge dependent mechanisms.

In order to examine this trend more quantitatively, the ratio

$$R_{\text{flow}} = \frac{\overline{\langle Px \rangle}_{^{64}\text{Zn}} - \overline{\langle Px \rangle}_{^{70}\text{Zn}}}{\overline{\langle Px \rangle}_{^{64}\text{Ni}} - \overline{\langle Px \rangle}_{^{70}\text{Zn}}} \tag{1}$$

can be used to define the magnitude of the flow from the ^{64}Zn system in comparison to the ^{64}Ni and ^{70}Zn systems. Thus when $R_{\text{flow}} = 1$ the IMF flow of the ^{64}Zn system equals that of the ^{64}Ni system and when $R_{\text{flow}} = 0$ the ^{64}Zn and ^{70}Zn systems have equivalent values of flow. In Fig. 2, the individual R_{flow} values of the $Z = 6$–9 fragments and the average R_{flow} value of $Z = 4$–9 fragments are plotted as a function of the centrality bin number. The ratio values exhibit a systematic trend from $R_{\text{flow}} \cong 1$ for the most violent collisions to $R_{\text{flow}} \cong 0$ for the most peripheral reactions. This trend, observed in Figs. 1 and 2, shows a transition from the IMF's $\overline{\langle Px \rangle}$ being strongly dependent on the mass of the system to a dependence on the charge of the system.

The observed mass-to-charge dependence of the IMF transverse flow should be sensitive to the density dependence of the symmetry energy since there is a mean-field component to the flow. Scalone *et al.* predicted that the difference in the transverse flow of LCPs from two systems with the same mass and differing $(N/Z)_{\text{sys}}$ would be sensitive to $E_{\text{sym}}(\rho)$ [37]. Therefore changing the isospin-dependent part of the mean field should affect the balance between the mass and charge dependent forces.

The antisymmetrized molecular-dynamics with wave packet diffusion and shrinking (AMD-DS) model [27] was used to investigate the sensitivity of the IMF flow to $E_{\text{sym}}(\rho)$. The dynamics of the reaction were simulated up to a time of 300 fm/c, after which the GEMINI code [38] was used to

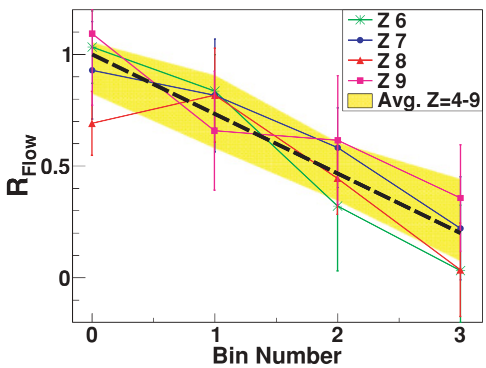

FIG. 2. (Color online) R_{flow}, as described in Eq. (1), is plotted against the centrality bin number for $Z = 6$–9 fragments. The average R_{flow} value for $Z = 4$–9 fragments is shown as the yellow (gray) filled area. The black dashed line represents a perfect transition from $R_{\text{flow}} = 1$ for bin 0 to $R_{\text{flow}} = 0$ for bin 4. The results from the most peripheral collisions (bin 4) have been excluded due to the increased error.

TABLE I. Symmetry energy [$E_{sym}(\rho_\circ)$] and slope (L) at saturation density calculated from the Gogny and Gogny-AS interactions.

Interaction	Form	$E_{sym}(\rho_\circ)$	Slope (L)
Gogny	soft	30.5 MeV	21 MeV
Gogny-AS	stiff	30.5 MeV	65 MeV

statistically de-excite the hot fragments. The AMD-Gemini simulation has been previously shown to reproduce many observables from heavy-ion collisions [39]. Additionally, we verified that the simulation satisfactorily reproduced the global observables and isotopic distributions of the experimental data. The momentum dependent Gogny and Gogny-AS effective interactions provided an incompressibility of symmetric nuclear matter of $K = 228$ MeV while allowing for the density dependence of the symmetry energy to be varied [27]. The Gogny and Gogny-AS interactions produce a soft and stiff density dependence of the symmetry energy, respectively. The form of the symmetry energy can be characterized by its value and slope, $L = 3\rho_\circ \frac{\partial E_{sym}(\rho)}{\partial \rho}|_{\rho_\circ}$, at the saturation density ($\rho_\circ$), which are presented in Table I for the Gogny and Gogny-AS interactions.

In Fig. 3 the average R_{flow} value for $Z = 4$–9 fragments is shown as a function of b_{red} from the AMD-Gemini simulations in comparison to the experimental data. The experimental results are equivalent to those presented in Fig. 2 except that R_{flow} is shown as a function of the average b_{red} of each centrality bin. The average b_{red} was determined using the filtered molecular-dynamics simulations to provide an estimate of the impact parameter range selected in each centrality bin. The impact parameter for each event of the AMD-Gemini simulation was known and therefore the average b_{red} values shown in Fig. 3 are exact. While the same experimental procedure discussed above was used to extract the IMF flow, the AMD-Gemini results (Fig. 3) were not filtered due to statistical limitations and the true reaction plane was used to calculate $\langle Px \rangle$.

The results of Fig. 3 demonstrate that the differences in the IMF flow between systems have a strong sensitivity to the density dependence of the symmetry energy. The Gogny-AS interaction, or stiff $E_{sym}(\rho)$, clearly demonstrates the best agreement with the experimental data, showing a decreasing $\langle R_{flow} \rangle_{Z=4\text{–}9}$ value with increasing b_{red}. In comparison, the soft symmetry energy parametrization, or Gogny interaction, is unable to reproduce the experimental trend. In the Gogny calculation the ^{64}Zn flow increases relative to the ^{64}Ni flow, eventually becoming larger ($R_{flow} > 1$). This is related to the larger symmetry energy at low density for the Gogny interaction, which is more repulsive for the more neutron-rich ^{64}Ni system relative to the ^{64}Zn system. The isospin-dependent part of the Gogny-AS interaction is less repulsive at low density and therefore the ^{64}Ni flow remains larger than the ^{64}Zn flow, producing agreement with the experimental data. It is clear that the isospin-dependent part of the interaction is an important component in describing the observed transition from a mass-to-charge dependence of the IMF transverse flow.

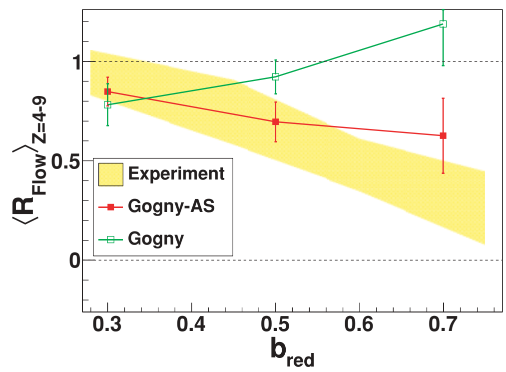

FIG. 3. (Color online) Average R_{flow} for $Z = 4$–9 fragments ($\langle R_{flow} \rangle_{Z=4\text{–}9}$) is plotted as a function of the reduced impact parameter b_{red} for the experimental data [yellow (grey) filled area] and the AMD-Gemini simulation with both a stiff (red, filled squares) and soft (green, open squares) $E_{sym}(\rho)$.

V. CONCLUSIONS

In conclusion, the transverse flow of intermediate mass fragments has been shown to be a sensitive probe of the nuclear equation of state. The transverse flow of the IMFs has been shown to be dependent on both the mass and charge of the colliding system. The results demonstrated how the mechanisms responsible for the IMF flow change as a function of the centrality of the collision. The AMD-Gemini simulation demonstrated that the differences in the IMF flow between the reaction systems are sensitive to the isospin-dependent part of the nucleon-nucleon interaction and comparison with the experiment provided strong evidence supporting a stiff $E_{sym}(\rho)$. Future research examining the IMF flow should allow for additional constraints on the nuclear equation of state.

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