Isospin Dependence of the Balance Energy

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The energy at which collective transverse flow in the reaction plane disappears, the balance energy E_{bal}, is found to depend on the isospin of the system using the reactions ^{58}Fe + ^{58}Fe and ^{58}Ni + ^{58}Ni. The more neutron-rich system exhibits higher balance energies for all measured impact parameters, in agreement with the predictions of a transport model which incorporates an isospin dependent mean field and isospin dependent in-medium nucleon-nucleon cross sections. [S0031-9007(97)02358-2]

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The study of collective transverse flow in nucleus-nucleus collisions can provide information about the nuclear equation of state (EOS) [1–5]. Transport models have been used to describe collective transverse flow in terms of nucleon-nucleon scattering in a nuclear mean field [6–10]. These models predict that collective transverse flow in the reaction plane disappears at an incident energy, termed the balance energy E_{bal} [9], where the attractive scattering (dominant at energies around 10 MeV/nucleon) balances the repulsive interactions (dominant at energies around 400 MeV/nucleon) [6,7]. The disappearance of directed transverse flow has been well established through many experiments [11–21]. Comparison of the measured impact parameter dependence of the balance energy with predictions from quantum molecular dynamics model calculations demonstrated better agreement with a formulation which incorporates momentum dependence in the mean field [22,23].

The isospin degree of freedom plays an important role in the reaction mechanisms involved in heavy-ion collisions [24–28]. Recently, collective transverse flow has been observed experimentally to depend on the isospin of the colliding system [29], confirming the predictions of a Boltzmann-Uehling-Uhlenbeck (BUU) model which incorporates an isospin dependent mean field and isospin dependent in-medium nucleon-nucleon cross sections [30]. In this Letter we show that the balance energy depends on the ratio of neutrons to protons (N/Z) of the system by measuring the disappearance of directed transverse flow in two isotopic systems with different N/Z ratios. Balance energies are larger for the more neutron-rich system at all measured impact parameters in agreement with BUU predictions.

The experiments were carried out at the National Superconducting Cyclotron Laboratory (NSCL) using heavy-ion beams from the K1200 cyclotron. The ^{58}Ni (^{58}Fe) beams were focused directly onto a ^{58}Ni (^{58}Fe) isotopically pure target ($\approx$5.0 mg/cm^2 thickness) at the center of the Michigan State University (MSU) 4π Array [31]. Beam intensities were approximately 100 electrical pA. Event characterization was accomplished with the MSU 4π Array comprised of the main ball and the High Rate Array (HRA). Data were taken with a minimum bias trigger that required at least one hit in the HRA (HRA-1 data), and a more central trigger in which at least two hits in the main ball (Ball-2 data) were required. The flow analysis described below was performed with the Ball-2 data as done in Refs. [17,21,23].

A transverse momentum analysis method [32] was used to measure directed transverse flow as done in Refs. [23,29]. For each event the impact parameter b is assigned through a simple geometric prescription [33], and the reaction plane is calculated with the method of azimuthal correlations [34]. Comparison of events from the Ball-2 trigger with those from the less selective HRA-1 trigger implies that $b_{\max} = 0.88 \pm 0.04(R_{\mathrm{proj}} + R_{\mathrm{targ}})$ for both isotopic systems. The projection of the transverse momentum into the reaction plane p_x of each particle of interest is evaluated for all events with at least four identified particles.

Figure 1 shows the mean transverse momentum in the reaction plane $\langle p_x \rangle$ plotted versus the reduced c.m. rapidity $(y/y_{\mathrm{proj}})_{\mathrm{c.m.}}$ for the two isotopic entrance channels. The solid (open) squares are for fragments with $Z = 2$ from semicentral ^{58}Fe + ^{58}Fe (^{58}Ni + ^{58}Ni) collisions at 105 MeV/nucleon. The upper limit of

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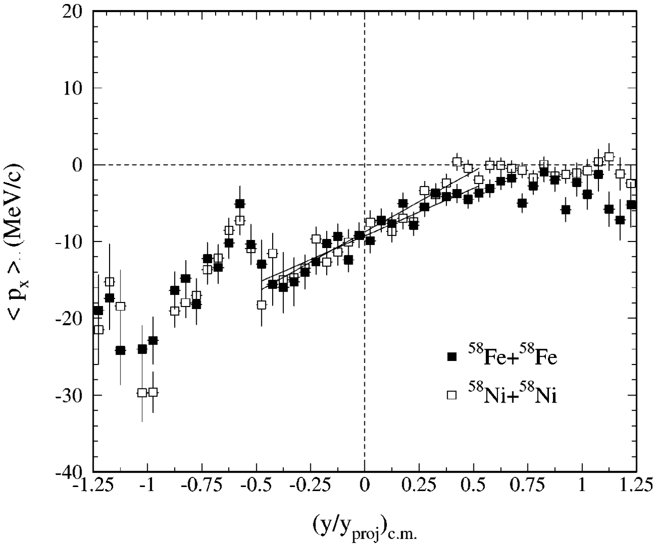

FIG. 1. Mean transverse momentum in the reaction plane versus the reduced c.m. rapidity for $Z = 2$ fragments from semicentral collisions ($b/b_{\mathrm{max}} = 0.48$) at 105 MeV/nucleon. The solid (open) squares are for $^{58}\mathrm{Fe} + {}^{58}\mathrm{Fe}$ ($^{58}\mathrm{Ni} + {}^{58}\mathrm{Ni}$). The straight lines are fits over the midrapidity region $-0.5 \leq (y/y_{\mathrm{proj}})_{\mathrm{c.m.}} \leq 0.5$.

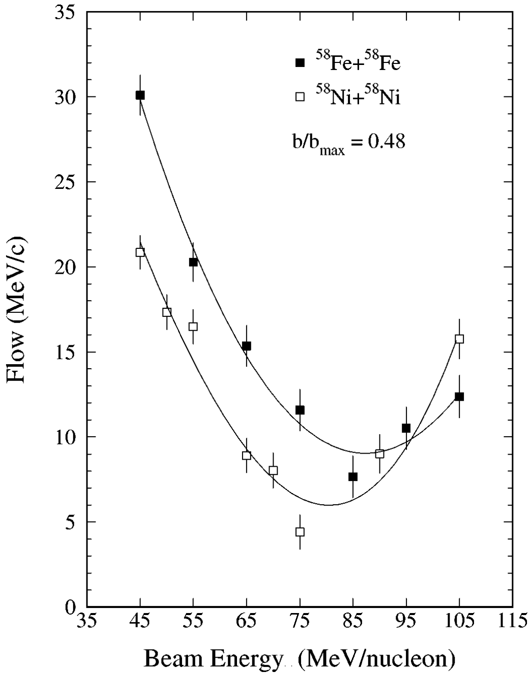

FIG. 2. Excitation functions of the measured transverse flow in the reaction plane for $Z = 2$ fragments from semicentral collisions ($b/b_{\mathrm{max}} = 0.48$). The solid (open) squares are for $^{58}\mathrm{Fe} + {}^{58}\mathrm{Fe}$ ($^{58}\mathrm{Ni} + {}^{58}\mathrm{Ni}$). The curves are included only to guide the eye.

the reduced impact parameter bin for these events is $\hat{b} = (b/b_{\mathrm{max}}) = 0.48$. The errors shown are statistical. The only difference between the two data sets is the N/Z ratio of the interacting system. The kinks in the spectra at $(y/y_{\mathrm{proj}})_{\mathrm{c.m.}} \approx -0.6$ are attributed to detector acceptance, but the transverse momentum analysis allows extraction of the flow with as little detector bias as possible [2] by not including affected regions of the spectrum. The vertical offsets from the origin occur because no recoil correction was applied in the reaction plane calculation. This does not affect the final values of the flow observables (balance energies) in this analysis [21]. Each spectrum shown in Fig. 1 is fit with a straight line over the midrapidity region $-0.5 \leq (y/y_{\mathrm{proj}})_{\mathrm{c.m.}} \leq 0.5$, and the slopes of these lines are defined as the directed transverse flow for each $A_{\mathrm{proj}} = 58 + A_{\mathrm{targ}} = 58$ systems. As expected, the directed transverse flow is similar for both isotopic entrance channels, but in what follows the difference is shown to be systematically significant in the data.

The extracted values of the directed transverse flow plotted versus the incident beam energy are shown in Fig. 2. The solid (open) squares are for fragments with $Z = 2$ from semicentral $^{58}\mathrm{Fe} + {}^{58}\mathrm{Fe}$ ($^{58}\mathrm{Ni} + {}^{58}\mathrm{Ni}$) collisions. The errors shown are the statistical errors on the slopes of the linear fits (the systematic error associated with the range of the fitting region is $+3$ and -1 MeV$/c$). The curves are included only to guide the eye. To extract the balance energy E_{bal}, the data were fit with a second-order polynomial allowing the fitting range to vary until χ^2 per degree of freedom was a minimum [23]. The second-order fits pass through minima for which the value of the abscissa corresponds to the balance energy for that particular entrance channel and $\hat{b}$ bin. The curves do not pass through zero at E_{bal} because no recoil correction was used in the reaction plane determination, as was done elsewhere [21,23,29]. Collective transverse flow is assumed to be symmetric in the vicinity of the balance energy, and our measurements are unable to distinguish the sign ($+$ or $-$) of the flow, so that a local parabolic fit is the lowest order symmetric function that can be used without *a priori* knowledge of E_{bal}.

The horizontal displacement of the minima of the curves in Fig. 2 clearly indicates that E_{bal} is higher for $^{58}\mathrm{Fe} + {}^{58}\mathrm{Fe}$ than $^{58}\mathrm{Ni} + {}^{58}\mathrm{Ni}$ at this $\hat{b}$ bin. That the balance energy is larger for the more neutron-rich system is primarily attributed to the difference in nucleon-nucleon cross sections [30]. Directed transverse flow has already been shown to be sensitive to in-medium nucleon-nucleon cross sections [17,35]. The neutron-proton cross section is approximately a factor of 3 higher than the neutron-neutron and proton-proton cross sections over the range of beam energies measured here [30]. This results in less repulsive collective flow from nucleon-nucleon scattering for the more neutron-rich system, pushing the balance energy higher in value. Below the balance energy the attractive mean field has an even more dominant effect, resulting in higher flow values for the neutron-rich system [29]. Above the balance energy where repulsive nucleon-nucleon scattering dominates, the converse is true, resulting in smaller values of the directed transverse flow for the neutron-rich system.

Additional experimental evidence for the isospin dependence of the balance energy is presented in Fig. 3. The solid (open) squares are the measured values of the balance energies for ^{58}Fe + ^{58}Fe (^{58}Ni + ^{58}Ni) extracted for four reduced impact parameter bins. These experimental values of $E_{\mathrm{bal}}(b)$ are plotted at the upper limit of each $\hat{b}$ bin, and the values for ^{58}Ni + ^{58}Ni have been slightly offset in the horizontal direction to show the error bars more clearly. The errors shown on the measured values of the balance energies are statistical (the systematic error is estimated to be +5% and 0%). The balance energy increases as a function of impact parameter for both isotopic systems in agreement with previous work [13,20,21], and $E_{\mathrm{bal}}(b)$ is systematically higher for the more neutron-rich system at all measured $\hat{b}$ bins.

The predictions of the BUU model [27,30] calculations which incorporate an isospin dependent potential and isospin dependent nucleon-nucleon scattering cross sections for ^{58}Fe + ^{58}Fe (^{58}Ni + ^{58}Ni) are shown as solid (open) circles in Fig. 3 for five $\hat{b}$ bins. The errors shown on the calculated points are statistical, and the values for ^{58}Ni + ^{58}Ni have been slightly offset in the horizontal direction to show the error bars more clearly. That the balance energy is the same value for all fragment types [17,23] facilitates comparison of the measured values of $E_{\mathrm{bal}}(b)$ to predictions of transport models calculations which involve only nucleons. The balance energy has been shown to exhibit little sensitivity to the acceptance effects of our detector array [9], allowing direct comparison between experimental values and unfiltered theoretical results.

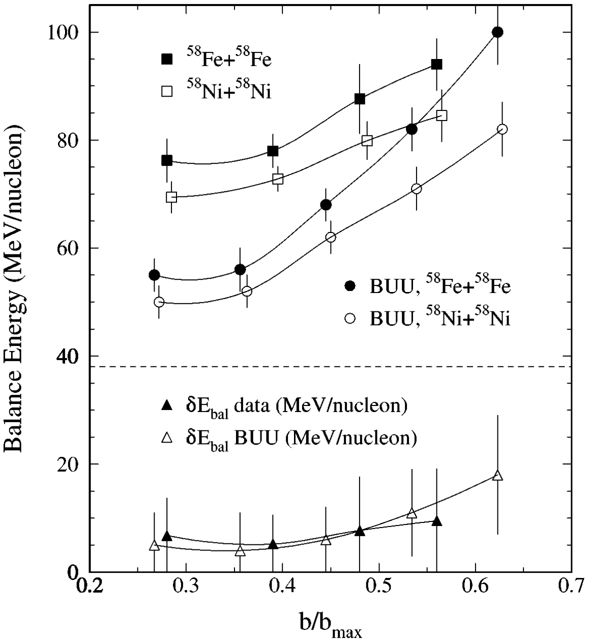

FIG. 3. Measured balance energies as a function of impact parameter compared to the predictions of BUU model calculations with an isospin dependent mean field and isospin dependent in-medium nucleon-nucleon cross sections. The solid (open) squares are measured for ^{58}Fe + ^{58}Fe (^{58}Ni + ^{58}Ni) while solid (open) circles are BUU predictions for ^{58}Fe + ^{58}Fe (^{58}Ni + ^{58}Ni). The values for ^{58}Ni + ^{58}Ni have been offset in the horizontal direction for clarity. The solid (open) triangles correspond to the difference in the balance energies between the isotopic systems at each reduced impact parameter bin for the data (BUU predictions). All curves are included only to guide the eye.

The trends in the values of $E_{\mathrm{bal}}(b)$ predicted by the BUU model with isospin dependence are consistent with those for the measured values. The balance energy increases as a function of impact parameter for both isotopic systems, and $E_{\mathrm{bal}}(b)$ is systematically higher for the more neutron-rich system at all impact parameter bins. That the overall magnitude of the values for the balance energies is underpredicted for central collisions by the BUU model has been attributed to a density dependent reduction of the in-medium nucleon-nucleon cross sections [17,35]. This effect is stronger at smaller impact parameters where the interaction volume is larger than in peripheral collisions.

More importantly here, there is agreement between the data and the BUU model predictions for the magnitude of the isospin effect, which is demonstrated explicitly with the lower set of points in Fig. 3. The solid (open) triangles are the difference between the balance energies δE_{bal} for the data (BUU predictions) for the isotopic systems at each corresponding $\hat{b}$ bin. These δE_{bal} values are given in MeV per nucleon and are plotted on the same scale as the values of $E_{\mathrm{bal}}(b)$. The errors shown are statistical. There is good agreement between the data and the BUU model predictions for the overall magnitude of δE_{bal}, which is due mainly to the different N/Z ratios of the two $A_{\mathrm{proj}} = 58 + A_{\mathrm{targ}} = 58$ systems. The difference in balance energies between isotopic systems was found to persist for BUU calculations made without Coulomb repulsion, indicating that the isospin effect is mainly due to the difference in the elementary nucleon-nucleon cross sections. The magnitude of δE_{bal} increases for more peripheral collisions where two extended neutron distributions overlap in the reaction of two neutron-rich nuclei [30].

In summary, we have experimentally demonstrated that the balance energy, the energy at which directed transverse flow disappears in nuclear collisions, depends on the isospin of the system using the reactions ^{58}Ni + ^{58}Ni and ^{58}Fe + ^{58}Fe. The more neutron-rich system systematically exhibits higher balance energies at all measured impact parameters, in agreement with the predictions of a BUU transport model which incorporates an isospin dependent mean field and isospin dependent in-medium nucleon-nucleon cross sections. Continued studies of this type will further elucidate the detailed interplay between the isospin-dependent portion of the nuclear EOS and the isospin-dependent nucleon-nucleon cross sections.

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