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Abstract

Collective transverse flow of nuclear material was measured as a function of the ratio of neutrons to protons (N/Z) of the interacting system for the first time. The collisions of three isotopically pure beams of $A = 58$ nuclei with two $A = 58$ targets were studied at 55 MeV/nucleon. The results for the flow variables demonstrate the sensitivity of transport models to elementary aspects of the nucleon-nucleon collisions.

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Collective transverse flow of nuclear matter produced in a nucleus-nucleus collision has been studied in a systematic way as a function of beam energy, system mass, and impact parameter. Such information has provided information on the nuclear equation of state (EOS) and the parameters that govern the reaction mechanisms of excited nuclear matter [1, 2, 3, 4, 5]. One theoretical approach has been to use transport models which relate the flow observables to nucleon-nucleon scattering in the nuclear mean field [6, 7, 8, 9, 10]. However, up until now there have been no attempts to relate the flow variables to a controlled change in the ratio of neutrons to protons (N/Z) of the colliding system. Such a variation in the isospin degree of freedom has been used in only a few recent studies of the isotope ratios of the outgoing particles [11, 12, 13, 14, 15], not the flow variables. However, transport models predict that the flow should depend on the isospin degree of freedom [16]. This arises because of the isospin dependence on the elementary nucleon-nucleon cross sections and the nuclear mean field [16, 17]. In this Letter we demonstrate experimentally that directed transverse flow depends on the isotopic ratio of the system by measurement of flow in three $A_{proj} = 58 + A_{targ} = 58$ systems with different N/Z at one bombarding energy of 55 MeV/nucleon. Measured flow is stronger for the more neutron-rich system in agreement with BUU predictions [16], which is due mainly to fact that the free neutron-proton cross section is approximately three times higher than the neutron-neutron and proton-proton cross sections at this incident energy. Because most of the experimental conditions (kinematics, available excitation energy, detector configuration, trigger, etc.) were held constant, the change in flow is most likely due to the different N/Z of the three systems.

The experiments were carried out at the National Superconducting Cyclotron Laboratory

(NSCL) using primary beams of $E = 55$ MeV/nucleon ^{58}Ni, ^{58}Fe and $E = 75$ MeV/nucleon ^{58}Fe from the K1200 cyclotron. The 55 MeV/nucleon beams were focused directly onto either a ^{58}Ni or a ^{58}Fe isotopically pure target ($\approx$ 5.0 mg/cm^2 thickness) at the center of the Michigan State University 4π Array [18]. The 75 MeV/nucleon ^{58}Fe beam bombarded a beryllium production target (94 mg/cm^2) in the A1200 fragment separator [19], which was operated in the medium acceptance mode with a 233 mg/cm^2 CH_2 (polyethylene) achromatic degrader wedge to select ^{58}Mn ions. An aperture placed directly after the A1200 focal plane collimated the beam of 56.6 MeV/nucleon ^{58}Mn, which was then transported and focused onto the ^{58}Fe target at the center of the 4π Array. A purity of greater than 90% at rates up to 3×10^4 per second (monitored periodically with a PIN diode at the exit of the 4π Array) was achieved for this secondary beam. Event characterization was accomplished with the MSU 4π Array upgraded with the High Rate Array (HRA). The HRA is a close-packed pentagonal configuration of 45 phoswich detectors spanning laboratory polar angles $3° \lesssim \theta \lesssim 18°$. The main ball of the 4π Array consists of 55 Bragg curve counters followed by 170 phoswich detectors covering the angles $18° \lesssim \theta \lesssim 162°$. Data were taken with a minimum bias trigger that required at least one hit in the HRA.

To measure directed transverse flow, a transverse momentum analysis method [20] was used in which the impact parameter and the orientation of the reaction plane are determined on an event-by-event basis. The impact parameter b of each event is assigned through cuts on centrality variables as calculated for each system through a straightforward geometric prescription [21]. The centrality variable chosen here was the reduced transverse kinetic energy of each event $\hat{E}_t = (E_t/E_{proj})$ [22]. Using methods similar to those already published elsewhere [23], $\hat{E}_t$ is found to be an appropriate variable to use as a centrality filter for these entrance channels at the beam energy studied, and it does not autocorrelate with the flow observables. Details of the method used for impact parameter selection are provided elsewhere [24]. The reaction plane of each event (the plane containing the beam axis and impact vector) is calculated with the method of azimuthal correlations [25], which is a reliable method to determine the reaction plane over the range of impact parameters involved here [24]. The transverse momentum in the reaction plane p_x of the particle of interest is evaluated by projecting it into this calculated reaction plane. This procedure is repeated for each particle in the event for all events with at least four identified particles. To quantify how directed transverse momentum varies along the direction of the beam axis, the mean transverse momentum in the reaction plane is plotted as a function of the reduced center-of-mass (c.m.) rapidity. From this plot the flow is extracted by fitting a straight line to the data over the midrapidity region. The slope of this line is defined as the directed transverse flow, which is a measure of the amount of collective momentum transfer in the reaction.

In Fig. 1 we display impact-parameter-inclusive distributions for three global observables from ^{58}Ni+^{58}Ni (solid histograms) and ^{58}Fe+^{58}Fe (dashed histograms) reactions at 55 MeV/nucleon. The left panel shows the total charged-particle multiplicity M_{chgd}; the center panel shows the total midrapidity charge Z_{mr} [26]; and the right panel shows the reduced total transverse kinetic energy $\hat{E}_t$ [22]. These distributions demonstrate that we are comparing similar data sets for these isotopic systems. The impact parameter distributions in the simple geometric picture resulting from the $\hat{E}_t$ spectra in the right panel are nearly identical. The enhancement at higher values of M_{chgd} and Z_{mr} for central ^{58}Ni+^{58}Ni reactions

($Z_{total} = 56$) is expected because a larger number of charged particles should be detected than in ^{58}Fe+^{58}Fe reactions ($Z_{total} = 52$). These fragments would account for a greater amount of participant charge, particularly when the system breaks into many pieces. Presumably these charges would carry off more transverse energy due to greater Coulomb repulsion tending to weaken the isospin effect for the most central collisions. These global variables could not be compared directly for the ^{58}Mn+^{58}Fe system because of poor statistics and some minor contamination (mainly ^{56}Cr) in the secondary beam.

However, impact-parameter-inclusive values of the directed transverse flow were extracted for the ^{58}Mn+^{58}Fe system as demonstrated in the top panel of Fig. 2. The mean transverse momentum in the reaction plane $\langle p_x \rangle$ is plotted versus the reduced c.m. rapidity $(y/y_{proj})_{c.m.}$ for fragments with $Z = 2$ from 55 MeV/nucleon ^{58}Mn+^{58}Fe collisions. The errors shown are statistical. This spectrum (similar to those previously published elsewhere [24, 27, 28]) is fit with a straight line over the midrapidity region -0.5 $\leq$ $(y/y_{proj})_{c.m.}$ $\leq$ 0.5. The slope of this line is defined as the directed transverse flow. The bottom panel in Fig. 2 shows the extracted values of the directed transverse flow for three different fragment types from all three entrance channels plotted as a function of the isotopic ratio of the composite projectile plus target system where $(N/Z)_{sys} = (N_{proj} + N_{targ})/(Z_{proj} + Z_{targ})$. Using this definition we have: $(N/Z)_{sys}$ =1.07 for ^{58}Ni+^{58}Ni; $(N/Z)_{sys}$ =1.23 for ^{58}Fe+^{58}Fe; and $(N/Z)_{sys}$ =1.27 for ^{58}Mn+^{58}Fe. The data for fragments with $Z = 2$ and $Z = 3$ represent the slopes of linear fits over the reduced c.m. midrapidity region -0.5 $\leq$ $(y/y_{proj})_{c.m.}$ $\leq$ 0.5. The fit range was reduced to -0.5 $\leq$ $(y/y_{proj})_{c.m.}$ $\leq$ 0.4 for all three systems for the fits for fragments with $Z = 1$ because of the presence of a broad peak at projectile rapidity for ^{58}Mn+^{58}Fe not observed in the other systems. The points for $Z = 2$ from $^{58}Ni+^{58}Ni$ and $^{58}Mn+^{58}Fe$ have been offset in value of $(N/Z)_{sys}$ for clarity. 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 +0.75 AMeV/c and -0.25 AMeV/c). The results shown in Fig. 2 demonstrate clearly there is an isospin dependence for directed transverse flow even for the impact-parameter-inclusive data. The neutron-rich system $^{58}Fe+^{58}Fe$ exhibits larger flow values than $^{58}Ni+^{58}Ni$ for all three particle types. Although the difference between the flow values extracted for $^{58}Mn+^{58}Fe$ and $^{58}Fe+^{58}Fe$ is not statistically significant, the trends are consistent with the reactions involving the two stable beams.

Additional experimental evidence for the isospin dependence of directed transverse flow is shown in Fig. 3. The extracted values of the collective transverse flow in the reaction plane are displayed as a function of the reduced impact parameter for three different fragment types from $^{58}Fe+^{58}Fe$ and $^{58}Ni+^{58}Ni$ collisions at 55 MeV/nucleon. The extracted values of the flow are plotted at the upper limit of each $\hat{b}$ bin. The errors shown are the statistical errors on the slopes of the linear fits. The neutron-rich system $^{58}Fe+^{58}Fe$ systematically exhibits larger flow values than $^{58}Ni+^{58}Ni$ for all three particle types at all reduced impact parameter bins displayed (except for $Z = 3$ in the most peripheral bin). The largest difference in the magnitude of the flow between the isotopic entrance channels occurs for heavier mass fragments in semi-central collisions. The impact parameter dependence of the directed transverse flow shown is in qualitative agreement with previous work [2, 24, 29], because the flow is maximal for semi-central events. The mass dependence of the directed transverse flow shown in Fig. 3 also demonstrates the well known increase in magnitude for heavier fragments [2, 27, 28], (note the difference in vertical scale for each panel).

These experimental results are in qualitative agreement with the predictions of BUU model [14, 16] calculations which incorporate an isospin dependent potential and isospin dependent nucleon-nucleon scattering cross sections for mass $A_{proj} = 48 + A_{targ} = 58$ systems. That directed transverse flow is greater for the neutron-rich systems is primarily attributed to the difference in nucleon-nucleon cross sections [16]. Directed transverse flow has already been shown to be sensitive to in-medium nucleon-nucleon cross sections [27, 30]. The elementary neutron-proton cross section used in the BUU calculations is approximately a factor of three higher than the neutron-neutron and proton-proton cross sections at an incident beam energy of 55 MeV/nucleon [16]. This results in less repulsive collective flow from nucleon-nucleon scattering, so that the attractive mean field has an even more dominant effect at this beam energy for the neutron-rich systems (mass dependence systematics show that flow disappears for central $A_{proj} = 58 + A_{targ} = 58$ collisions at $\approx$ 76 MeV/nucleon [27]). The isospin effect is stronger in more peripheral collisions where two extended neutron distributions overlap in the reaction of two neutron-rich nuclei [16].

In summary, we have experimentally demonstrated that collective transverse flow in nuclear collisions depends on the isospin of the system using the reactions 55 MeV/nucleon ^{58}Ni+^{58}Ni, ^{58}Fe+^{58}Fe, and ^{58}Mn+^{58}Fe. The more neutron-rich systems exhibit larger flow values, which confirms the predictions of a BUU transport model incorporating an isospin dependent potential and isospin dependent nucleon-nucleon scattering cross sections. Future studies of this type will further illuminate the interplay between the isospin-dependent portion of the nuclear EOS and the isospin-dependent nucleon-nucleon cross sections.

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Figure Captions

Figure 1: Impact-parameter-inclusive spectra for the total charged-particle multiplicity M_{chgd}, the total midrapidity charge Z_{mr}, and the reduced total transverse kinetic energy $\hat{E}_t$. Solid (dashed) histograms are for ^{58}Ni+^{58}Ni (^{58}Fe+^{58}Fe) collisions at 55 MeV/nucleon.

Figure 2: (Top panel) Mean transverse momentum in the reaction plane versus the reduced c.m. rapidity for $Z = 2$ fragments from impact-parameter-inclusive ^{58}Mn+^{58}Fe collisions at 55 MeV/nucleon. The straight line is fit over the region -0.5 $\leq$ $(y/y_{proj})_{c.m.}$ ≤ 0.5. (Bottom panel) Directed transverse flow as a function of the isotopic ratio of the composite projectile plus target system for three different fragment types from three isotopic entrance channels. The extracted values of the flow are for impact-parameter-inclusive event sets at 55 MeV/nucleon. The lines are included only to guide the eye.

Figure 3: Directed transverse flow as a function of the reduced impact parameter for three different fragment types from ^{58}Fe+^{58}Fe and ^{58}Ni+^{58}Ni collisions at 55 MeV/nucleon. The extracted values of the flow are plotted at the upper limit of each $\hat{b}$ bin. The lines are included only to guide the eye.

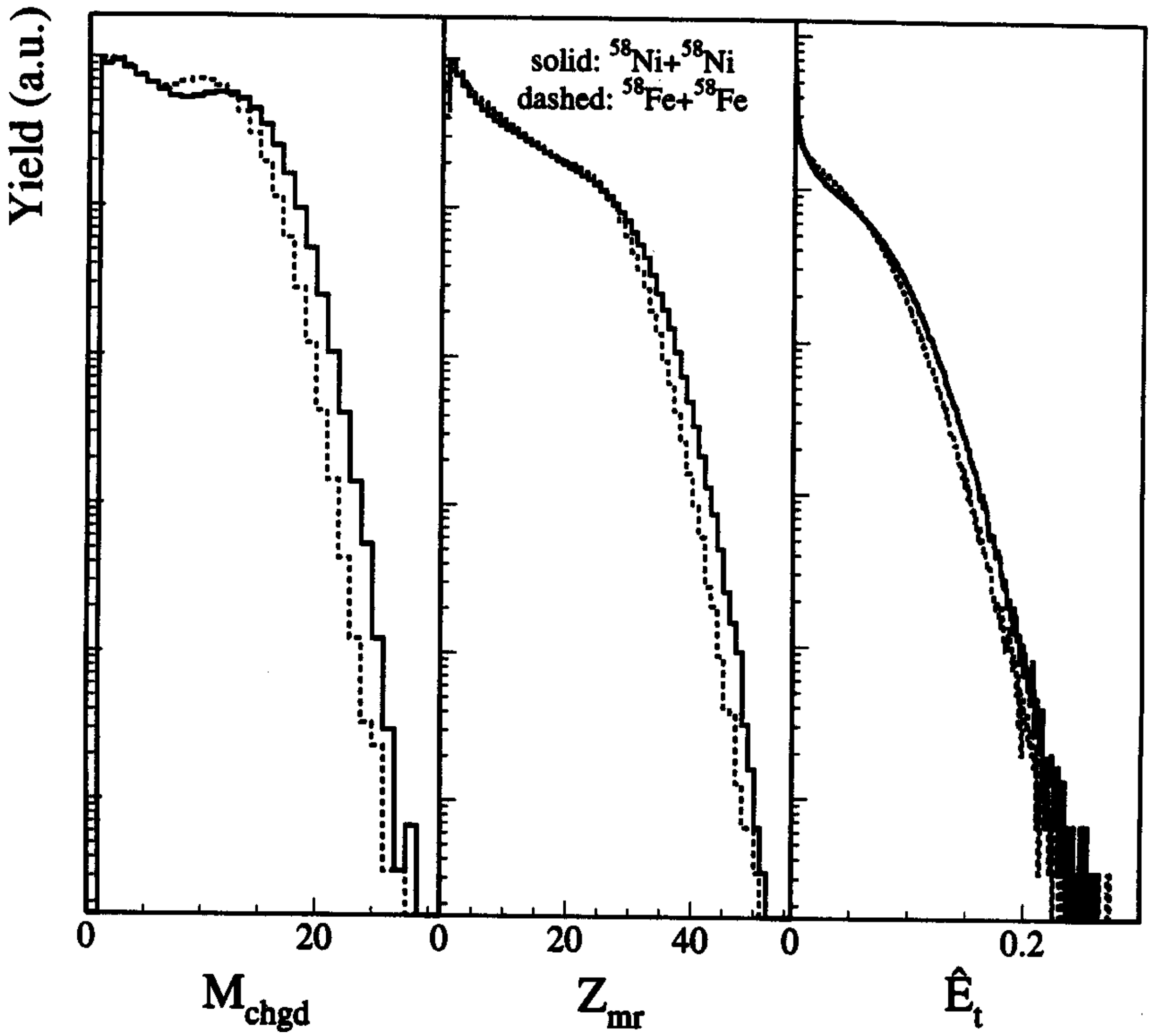
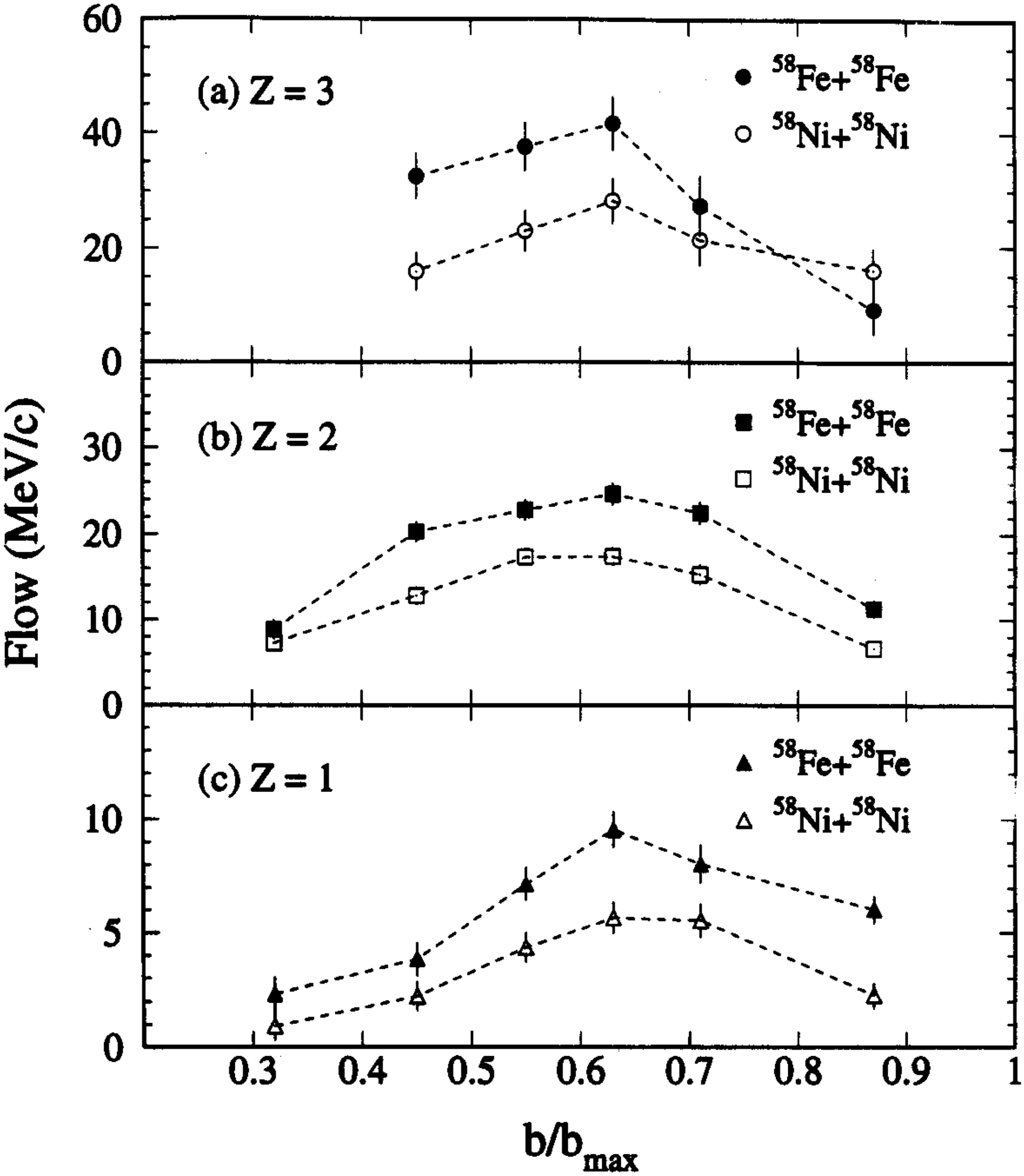

Yield (a.u.)
solid: $^{58}Ni+^{58}Ni$
dashed: $^{58}Fe+^{58}Fe$
0
20
0
20
40
0
0.2
M_{chgd}
Z_{mr}
$\hat{E}_t$

Figure 1:



(a) Z = 3
^{58}Fe+^{58}Fe
^{58}Ni+^{58}Ni
(b) Z = 2
^{58}Fe+^{58}Fe
^{58}Ni+^{58}Ni
(c) Z = 1
^{58}Fe+^{58}Fe
^{58}Ni+^{58}Ni
Flow (MeV/c)
b/b$_{max}$
0
20
40
60
10
30
5
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Figure 3: