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ABSTRACT

The impact parameter and energy dependence of the sign of the mean transverse momentum of nonequilibrium light charged particles was determined from the circular polarization of coincident γ-rays emitted from residual nuclei for ^{14}N-induced reactions on ^{154}Sm at incident energies, E/A=35, 100 and 155 MeV. These results show directly for the first time the predicted transition from mean-field dominated dynamics at low energies to nucleon-nucleon collision dominated dynamics at high energies and the evolution of this transition with impact parameter. The experimental results are compared to transport model calculations.

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Transverse momentum transfer in heavy-ion collisions is an important observable that reflects the balance between the mean field and collisional dynamics [1-4]. This balance evolves with both impact parameter and bombarding energy [5]. At low energies (E/A=10 MeV), the mean field is attractive and two-body collisions are suppressed by the Pauli exclusion principle. There, the sense of rotation of the intermediate reaction complex has been determined via measurements of the circularly polarized γ-rays emitted by the excited target residue[6,7]. Coincidence measurements between these γ-rays and the reaction products demonstrated the existence of orbiting trajectories at the Coulomb barrier [6] and predominantly negative scattering angles for nonequilibrium light particles and fragments [7].

At higher energies (E/A=400 MeV), two-body collisions are frequent and eventually the mean field becomes repulsive. These collective motions are studied in global transverse momentum analyses [8] in which the transverse momentum of each fragment is projected onto an estimated reaction plane for the event. The dominant correlation between the fragments' transverse momenta is caused presumably by collective motion, the signal of which can be deduced by averaging the transverse momentum over many events. Directed collective flow can then be defined by the slope of the average in-plane transverse momentum versus rapidity around the midrapidity region. In such global transverse momentum analyses, however, information about the overall sign of the directed momentum is lost even though transport model calculations require sidewards collective flow on the same side as the projectile for the successful interpretation of flow. Until now, the sign of the transverse flow has not been determined [1-4] though indirect conclusions may be drawn from the recent measurements of pion flow [9].

The transition from the attractive mean-field dominated dynamics of low-energy reactions to the repulsive nucleon-nucleon collision dominated dynamics of high-energy reactions is expected to occur at incident velocities comparable to the Fermi velocity where Pauli blocking becomes less effective[10]. At a particular energy, termed the balance energy, the attractive and repulsive interactions will balance and the flow should become minimum. Such a "disappearance" of flow has been deduced at bombarding energies of around 100 MeV per nucleon for light symmetric systems [11] even though a change in sign of the mean momentum transfer has not been observed. In this report, we study this transition region experimentally by determining the sign of the average emission angle of nonequilibrium light particles from the circular polarization of associated γ-rays emitted by the residual nucleus for ^{14}N-induced reactions on ^{154}Sm at E/A=35, 100 and 155 MeV.

The measurements were performed at the National Superconducting Cyclotron Laboratory at Michigan State University. The accelerator provided beams of 35A MeV, 100A MeV and 155A MeV ^{14}N which impinged on an isotopically enriched target of ^{154}Sm (98.7%) of areal density 3.15 mg/cm^2. Evaporation residue, fission and total fusion cross-sections were previously measured for this reaction over the same range of incident energies, and significant residue cross-sections were found to exist even at the highest energies [12]. In the polarization experiment, a doubly symmetric arrangement of the experimental apparatus was used. A schematic of the experimental set up is shown in Fig. 1. Two ΔE-E telescopes were positioned at ϕ=0° and ϕ=180° around the beam axis and subtended approximately $10° \leq \theta \leq 35°$, where θ and ϕ are the polar and azimuthal angles respectively. These were used to detect and identify charged particles. The ΔE detector consisted of a 5 cm x 5 cm 16-strip Si detector, 300 μm thick, and was positioned 135 mm from the target position. The E detector consisted of nine tapered CsI(Tl) detectors, 7 cm long. These were arranged in a square 3x3 geometry and placed immediately behind the Si detector. A compact cylindrical multiplicity filter, the Minitube, consisting of 58 scintillating fibers, was placed coaxially around the beam axis in the gap between the two polarimeters. The obtained information on the multiplicity of light charged particles was used to derive the reduced impact parameter, b/b_{max}, during the collision[14].

The circular polarization of γ-rays emitted perpendicular to the reaction plane defined by the beam axis and the coincident light charged particles, was measured with two forward-scattering polarimeters [13]. These were positioned at θ=90°, ϕ=90° and θ=90°, ϕ=270°. The sign convention adopted [6,7] to define the polarizations with respect to the quantization axis **n**, is given by $\mathbf{n} = \mathbf{p}_i x \mathbf{p}_f / | \mathbf{p}_i x \mathbf{p}_f |$ where $\mathbf{p}_i$ and $\mathbf{p}_f$ are the momentum vectors of the beam and the detected particle, respectively. Thus positive circular γ-ray polarizations correspond to a photon spin parallel to **n**, and a deflection of the emitted particle to negative angles by the nuclear mean field. Negative circular γ-ray polarizations correspond to a photon spin anti-parallel to **n** and a deflection of the emitted particle to positive angles, caused by repulsive effects of nucleon-nucleon collisions.

Experimentally, the count rate asymmetry, $P_\gamma A$, is measured. For the doubly symmetric detector system, the count rate asymmetry can be expressed as [13]

$$\frac{N_{21}N_{12}}{N_{11}N_{22}} = \left(\frac{1+P_\gamma A}{1-P_\gamma A}\right)^2$$

where N_{ij} are the count rates of particle detector i and polarimeter j. The analyzing power *A* corresponds to the efficiency of the overall polarimeter setup to detect circularly polarized γ-rays. The direction of the polarimeter magnetic field was reversed every hour during the experiment in order to detect and cancel out spurious count rate asymmetries.

Measurements of *A* were made using γ-ray sources and compared to theoretical simulations using Monte Carlo techniques, which lead to a value of *A* ≈1.5%[13]. The value of the effective analyzing power is considerably reduced by neutrons emitted in the reaction which interact with the detector and produce γ-rays via (n, n'γ) reactions which in turn interact with the detector as well. A comprehensive experimental study of the effects of the neutron multiplicity on the analyzing power was therefore made and values of *A* were estimated for the energies measured and impact parameter gates used in the subsequent analysis. These values were found to vary between 0.85% and 0.95%, similar to values obtained previously for the same reaction at E/A=35 MeV [7].

The measured circular polarization of γ-rays in coincidence with p, d, t and α particles is shown in Fig. 2 as a function of incident energy. Three impact parameter bins have been chosen, corresponding to central ($b/b_{max}<0.3$), mid-central ($0.26\leq b/b_{max}\leq 0.54$) and peripheral ($b/b_{max} >0.54$) collisions. To minimize pre-equilibrium emissions and contributions from evaporation, an angular gate of $25° \leq \theta \leq 35°$ and a threshold energy of 5 MeV per nucleon are imposed on the emitted particles. At all incident energies the central impact parameter bin has a polarization that is statistically consistent with zero. These data which have large error bars due to lack of statistics are not plotted here. For peripheral collisions (open points), the polarization is positive for all particles at 35A MeV and very close to zero at the two higher energies of 100A and 150A MeV. For mid-central collisions (closed points), the most striking feature is the change in sign of the α particle associated polarization from positive values at 35A MeV to negative values at 100A MeV and 155A MeV. Since the magnitude of polarization values increases [7] while the dispersion of the reaction plane decreases with fragment mass[15], polarization values are expected to be the largest in magnitude, and the change in sign the strongest, for α particles. The observed trend for deuterons and tritons is consistent with the polarization measured for the α particles when the experimental uncertainties are taken into account. This change in sign of the α particle associated polarization provides the first direct observation of the change from attractive mean field dominated dynamics at low energies ($P_\gamma>0$) to repulsive mean field dominated dynamics at the higher energies ($P_\gamma<0$).

Considerable progress has been made recently in understanding the collision dynamics of heavy ion reactions. We have performed calculations using the Boltzmann-Uehling-Uhlenbeck (BUU) [10, 16-18] and Quantum Molecular Dynamics (QMD) Models [19] for $^{14}N+^{154}Sm$ collisions at different impact parameters and different incident energies. Quantitative comparison of the experimental data and transport calculations are complicated by the following factors: First, the reaction plane is defined in the experiment by the direction of the detected particle. In the case of heavy fragments and large collective flow, this can still provide a reasonable determination of the reaction plane [2,15]. For protons, however, where thermal motion and contributions from pre-equilibrium emission are significant, the reaction plane is poorly determined. This may contribute to the very small polarization values measured in protons. Second, cluster production is not described in BUU while in QMD, the cluster production is not described quantum mechanically. Thus prediction for the mass dependence of flow is imprecise. Finally, circular γ-ray polarization is sensitive to the actual decay chain. Even though it can be calculated, current transport model calculations will not provide an accurate constraint on the transverse momentum transfer. Thus we chose to compare the calculated negative mean transverse momentum per nucleon in the reaction plane, $-\langle p_x/A\rangle$ to P_γ because it has the same sign convention as P_γ (i.e. positive values corresponding to a dominance of the attractive mean field), providing direct visual and qualitative comparisons to the experimental data.

The BUU calculation described in Refs. [16,17] includes a soft (K=215 MeV) mean field with a momentum dependent force consistent with nonlocality effects observed in nucleon-nucleus potential scattering. Free nucleon-nucleon cross-sections were used in the calculations. These transport parameters reproduced the observed trends of the impact parameter dependence of transverse flow for the Kr+Au collisions at 200A MeV[2] and Ar+Pb collisions at 400A MeV [17,18,20]. In the left panel of Fig. 3, the negative mean transverse momentum, (-$<p_x>$), of protons is plotted as a function of incident energies for two impact parameters, b=4 and 8 fm at E/A= 35, 75, 100, 120 and 155 MeV. Even though previous experimental results [2,17,18] on traverse flow at high incident energy suggest that momentum dependent forces should be included in BUU calculations, we have also performed, for comparison, BUU calculations without momentum dependent forces (right panel). The main effect of the momentum dependent forces decrease the nuclear mean field attraction. Thus, the balance energy decreases when a momentum dependent force is included, similar to results obtained previously via QMD calculations [19]. For more peripheral collisions, b=8 fm, The switch from attractive to repulsive interaction occurs at higher incident energies than for more central collisions, qualitatively consistent with the observed impact parameter dependence of P_T for the α particles in Figure 1.

One disadvantage of the BUU model is that the model does not describe cluster formation. As the effect of flow increases with fragment mass [2, 7], we turned to the QMD calculations to explore the mass difference of the mean transverse momentum $<p_x/A>$ for protons and composite particles which were chosen for a wide gate (A=2-4) in mass so as to have enough statistics for comparison with the experimental data [21]. QMD calculations were performed at E/A=35, 100 and 150 MeV for N+Sm at b=4 and b=6 fm. The transport parameters used include a stiff equation of state with momentum dependence forces and a free isospin dependent nucleon-nucleon cross-section which qualitatively reproduced the observed impact parameter dependence of the balance energy for A=40 symmetric systems [19, 22]. Figure 4 shows the negative mean transverse momentum, $-\langle p_t/A\rangle$, for proton (left panel) and composite particles (right panel). As expected, the magnitude of the flow for composite particles are slightly larger than for protons, consistent with experimentally observed trends. However the predicted proton mean transverse momentum at the highest energy seems to be too repulsive as compared to data. Calculations for the composite particles display the same qualitative behavior as seen for the α data.

In summary, we have determined the impact parameter and energy dependence of the sign of the mean transverse momentum of nonequilibrium light charged particles from the circular polarization of coincident γ-rays emitted from residual nuclei for ^{14}N-induced reactions on ^{154}Sm at E/A=35, 100 and 155 MeV. The α particle associated polarization changes sign from positive at 35A MeV to negative at 100A MeV and 155A MeV, demonstrating directly for the first time the predicted transition from nuclear mean-field dominated dynamics at low energies to nucleon-nucleon collision dominated dynamics at high energies. The observed trend can be reproduced qualitatively by BUU and QMD calculations, but quantitative discrepancies remain.

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21. Since QMD does not predict the binding energies correctly, the observed enhancement of the α particle yields due to its large binding energy is not reproduced by the QMD model. Thus, one cannot simply select A=2, Z=2 as alpha particles.

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FIGURE CAPTIONS

FIG. 1. Cross-sectional view of the detector setup inside the scattering chamber. Two Si-CsI detector arrays were placed symmetrically around the beam axis in forward direction, covering polar angles $10° \leq \theta \leq 35°$. The multiplicity of charged particles was measured with the cylindrical Minitube, mounted symmetrically around the beam axis in the gap between the two polarimeters (not shown). The inner circle indicates the outer diameter of the polarimeters mounted above and below the plane defined by the beam and the two charged particle detector telescopes.

FIG. 2. The circular polarization of coincident γ-rays emitted from residual nuclei for ^{14}N-induced reactions on ^{154}Sm as a function of incident energy for mid-central (solid points) and peripheral collisions (open points, displaced laterally for clarity) for p, d, t, and α particles.

FIG. 3. Incident energy dependence of the negative mean transverse momentum of protons calculated with the BUU model for ^{14}N + ^{154}Sm reactions for b=4 fm and b=8 fm. The left and right panels show BUU calculations with and without momentum dependent forces, respectively. The lines are drawn to guide the eye.

FIG. 4. Incident energy dependence of the negative mean transverse momentum of protons (left panel) and light composite particles (A=2-4, right panel), calculated with the QMD model with momentum dependent interactions for ^{14}N + ^{154}Sm reactions for b=4 fm and b=6 fm. The lines are drawn to guide the eye.

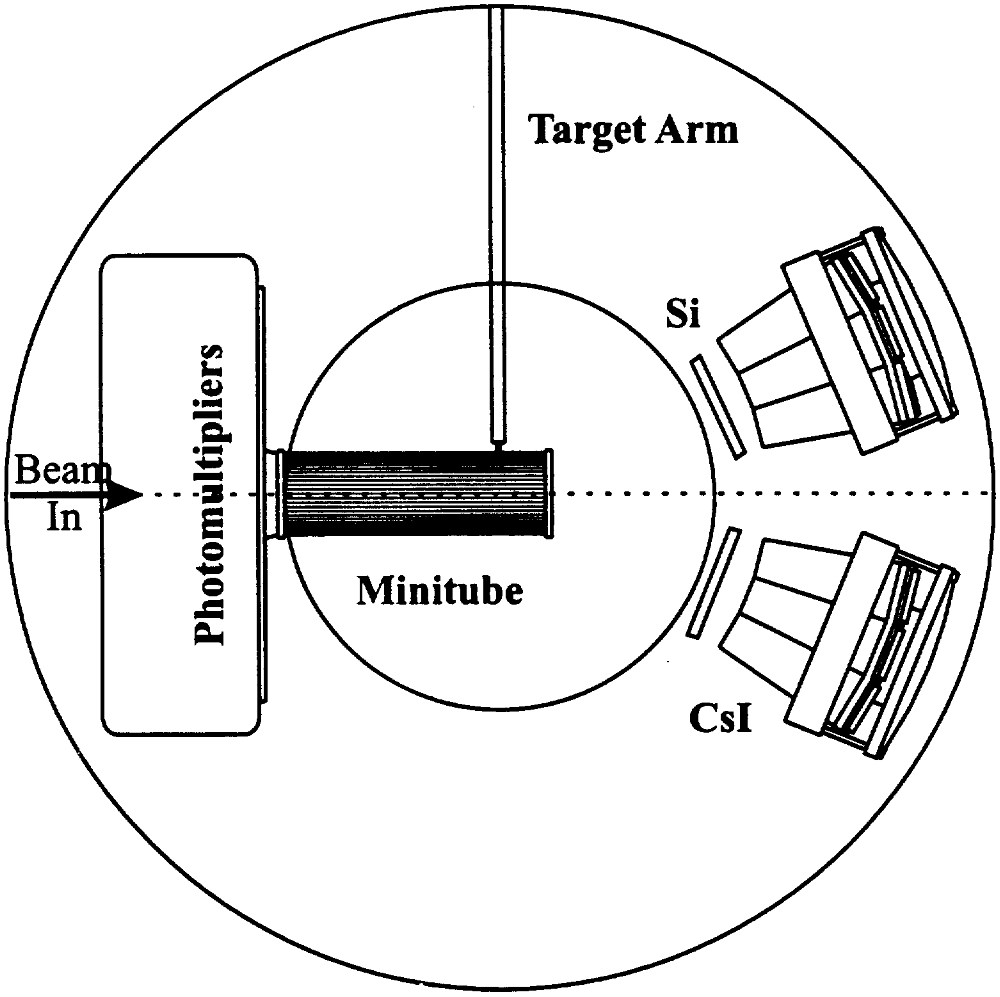


Fig 1

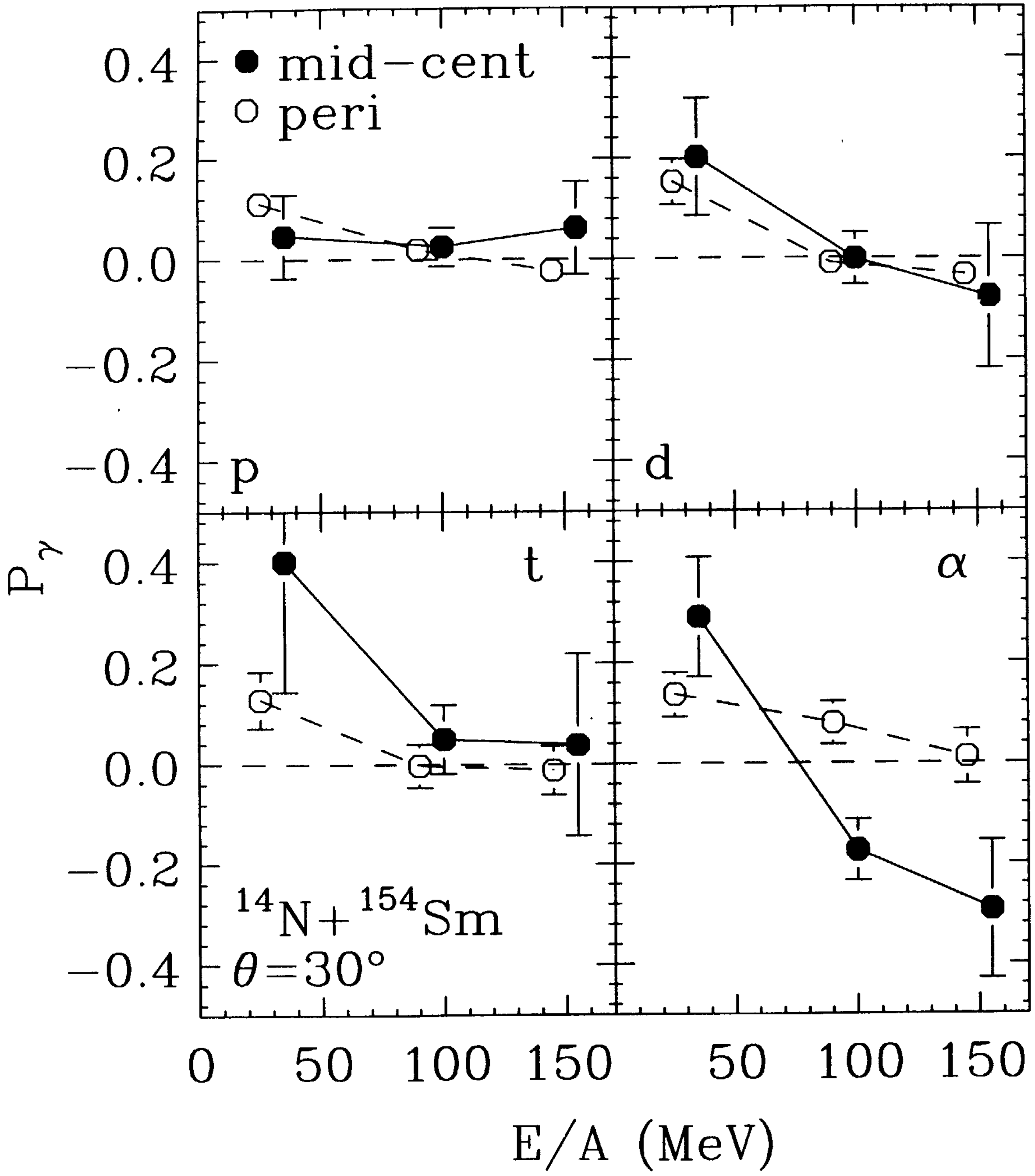

mid−cent
peri
p
d
t
α
^{14}N+^{154}Sm
θ=30°
P$_\gamma$
0.4
0.2
0.0
−0.2
−0.4
0
50
100
150
E/A (MeV)

Fig 2

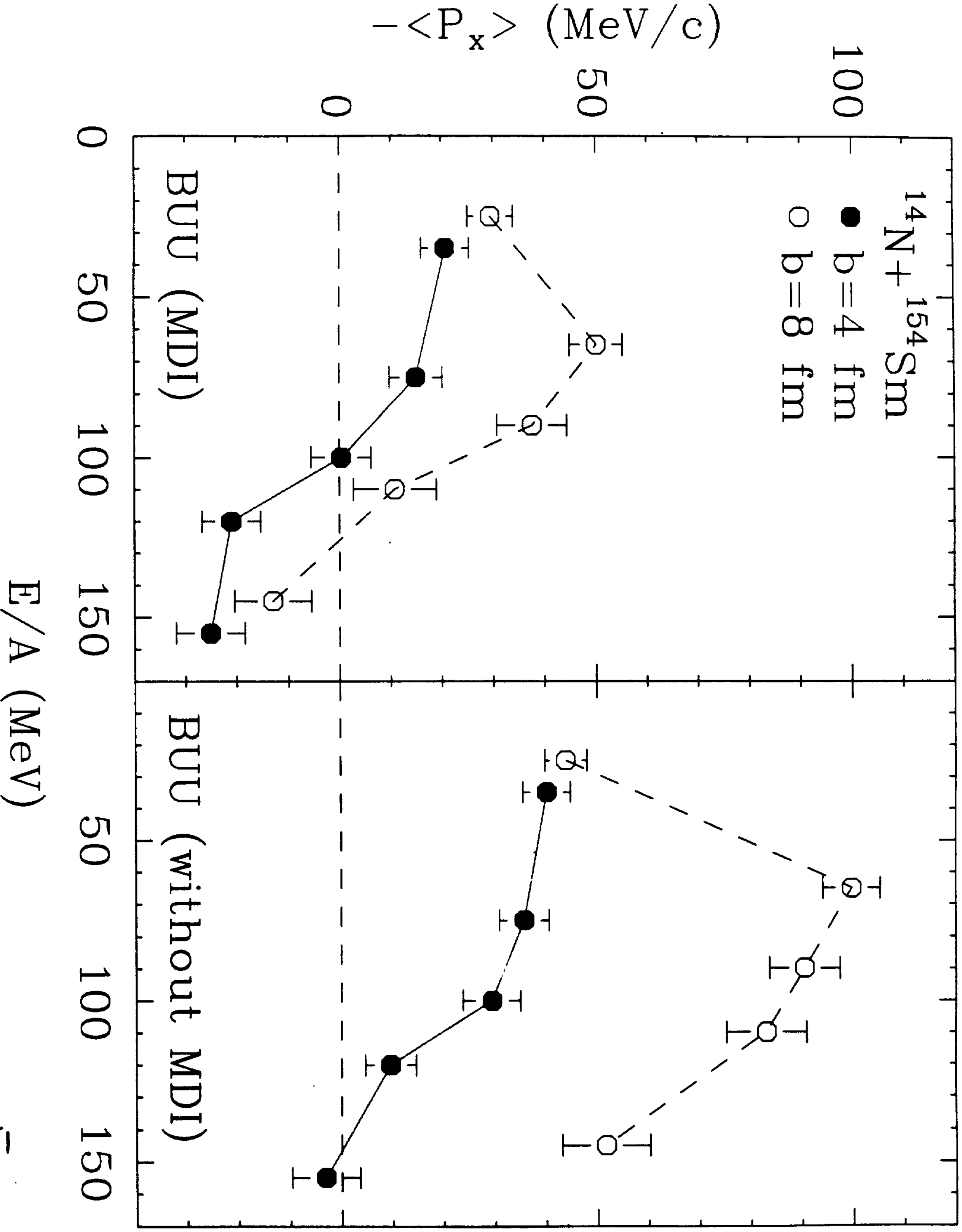
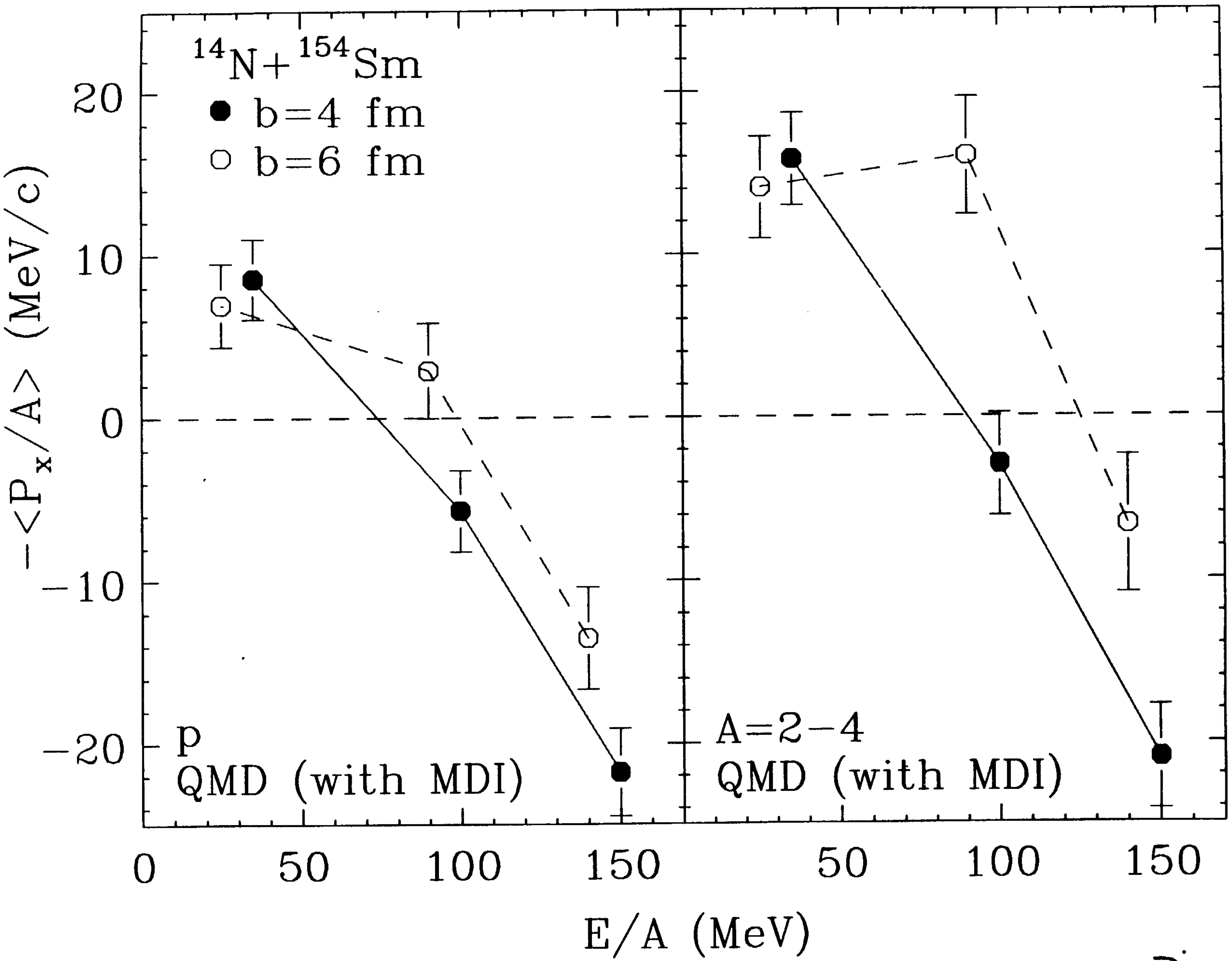

−<Px> (MeV/c)
0
50
100
^{14}N+^{154}Sm
● b=4 fm
○ b=8 fm
BUU (MDI)
BUU (without MDI)
E/A (MeV)
0
50
100
150
50
100
150

Fig 3



$^{14}N+^{154}Sm$
● b=4 fm
○ b=6 fm
p
QMD (with MDI)
A=2−4
QMD (with MDI)
$-\langle P_x/A\rangle$ (MeV/c)
20
10
0
−10
−20
0
50
100
150
50
100
150
E/A (MeV)

Fig 4