第 35 卷 第 1 期 原 子 核 物 理 评 论 Vol. 35, No. 1
2018 年 3 月 Nuclear Physics Review Mar., 2018

Article ID: 1007-4627(2018) 01-0018-05

Z-dependence Flow Pattern and Experimental Filter Effect on Transverse Flow Extraction in Intermediate-energy Heavy Ion Collisions

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Abstract: The transverse flow in the reaction of ^{40}Ca+^{40}Ca at 35 MeV/nucleon has been determined for emitted isotopes with $Z = 1$ to 9. A significant modification of the Z-dependent flow pattern caused by the experimental filters, the detector thresholds and the angular resolutions ($\Delta\phi$) of the detector array, is observed. With the application of the appropriate experimental filters, the general trend of the experimental Z-dependent flow is well reproduced by the Constrained Molecular Dynamics (CoMD) simulation, employing an effective interaction corresponding to a soft EOS ($K = 200$ MeV). This fact suggests that to determine the flow values more precisely, a detection system with lower energy threshold and better angular resolution is urgently required. Additionally, together with the parallel work of Z. Kohley *et al.* [Phys Rev C, 2012, 85: 064605], the pattern of the experimental Z dependence of transverse flow is also discussed. The shoulder patterns of Z-dependent flow for $1 \leqslant Z \leqslant 6$ can be attributed by the experimental filters, while the reduction of flow for $Z \geqslant 6$ in our experiment can be caused by the suppression of collective motion under the momentum conservation.

Key words: experimental filter; flow pattern; CoMD; intermediate energy heavy ion collision

CLC number: O571.6; P142.9 **Document code:** A **DOI:** 10.11804/NuclPhysRev.35.01.018

1 Introduction

Collective transverse flow, which can provide important information about the nuclear equation of state (EOS), symmetry energy and the mechanism of the heavy-ion reaction, has been studied systematically for more than three decades. A great number of experimental and theoretical studies have been carried out[1–19]. The important roles of the mean field, symmetry energy, Coulomb force, nucleon-nucleon collision cross sections in the flow generation at early stages have all been testified, but the mechanism of the flow generation is still under discussion.

In this paper, the experimental filter effect on the flow extraction is focused on and investigated using the Constrained Molecular Dynamics (CoMD) events[20–23]. The pattern of the experimental Z dependence of transverse flow is further investigated. This paper is organized as follows. In Sec. 2 and Sec. 3, we briefly summarize the experiment and the data analysis, respectively. In Sec. 4, the experimental filtering effects on the flow is discussed, and the experimental Z dependence of transverse flow pattern is further analyzed. In Sec. 5, a summary is given.

2 Experiment

The experiment was performed at the Texas A&M University Cyclotron Institute. ^{40}Ca beams produced by the K500 superconducting cyclotron impinged on ^{40}Ca targets at an energy of 35 MeV/nucleon. The reaction products were detected using a 4π array, NIMROD-ISiS (Neutron Ion Multidetector for Reaction Oriented Dynamics with the Indiana Silicon

Received date: 14 May 2017; **Revised date:** 23 May 2017

Foundation item: National Natural Science Foundation of China(11705242);National Basic Research Program of China (973 Program)(2014CB845405); CAS "Light of West China" Program (29Y601030)

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Sphere), which consisted of 14 concentric rings covering 3.6° to 167° in the laboratory frame[24]. In each of the forward rings with $\theta_{\rm lab} \leqslant 45°$, two special modules were set having two Si detectors (150 and 500 μm) in front of a CsI(Tl) detector (3 ~ 10 cm). The other modules in the forward and backward rings had one Si detector (either 150, 300 or 500 μm) followed by a CsI(Tl) detector. The pulse shape discrimination method was employed to identify the light charged particles with $Z \leqslant 3$ in the CsI(Tl) detectors. Intermediate mass fragments (IMFs) were identified with the telescopes using the "$\Delta E - E$" method. In the forward rings an isotopic resolution up to $Z = 12$ and an elemental identification up to $Z = 20$ were achieved. In the backward rings, because of the detector energy threshold, only $Z = 1 \sim 2$ particles were identified. In addition to the charged particle detection, a Neutron Ball surrounding the NIMROD-ISiS array also detected neutrons event by event, although this information was not used in the present analysis. Further details on the detection system, energy calibrations, and neutron ball efficiency can be found in Ref. [25].

3 Data analysis

In our data analysis, the collision centrality was evaluated utilizing the charged particle multiplicity, $N_{\rm ch}$[25, 26]. After comparing with the scaled $N_{\rm ch}$ distributions from the experimental data and the CoMD events in the forward angles[27], the events with $6 \leqslant N_{\rm ch} \leqslant 9$ were selected out, corresponding to the impact parameter interval of $b \approx 3-6$ fm in which the strongest transverse flow was expected[4, 16, 28–30]. The azimuthal correlation method[31] was utilized to determine the reaction plane from the momentum of the fragments in an event by event basis. In reconstructing the reaction plane, D^2, the deviation of the fragments in each event from the reaction plane in the momentum space was introduced using a parameter k, which is taken as the slope of the projection line of the reaction plane onto the $P_x - P_y$ plane. D^2 is defined by the summation of the perpendicular squared distance d_v^2 between that line and the momentum position of each fragment in the $P_x - P_y$ plane such that[31]

$$D^2 = \sum_{i \neq \rm POI}^{N} d_v^2 = \sum_{i \neq \rm POI}^{N} [(P_i^x)^2 + (P_i^y)^2 - \frac{(P_i^x + P_i^y \cdot k)^2}{1+k^2}]. \qquad (1)$$

In Eq. (1), the particle of interest (POI) is excluded from the summation taken over the fragments in each event to avoid the autocorrelation[31–33]. Minimizing D^2 as a function of k, the value of arctan(k) approaches to the angle (ϕ) between the reaction plane and the horizontal plane,

$$\phi = \arctan(k) = \arctan(\frac{-\Delta \pm \sqrt{\Delta^2 + 4\Pi^2}}{2\Pi}). \qquad (2)$$

where $\Delta = \sum_{i \neq \rm POI}^{N} (P_i^x)^2 - \sum_{i \neq \rm POI}^{N} (P_i^y)^2$ and $\Pi = \sum_{i \neq \rm POI}^{N} (P_i^x \cdot P_i^y)$.

In the present work, the flow is quantified as the slope of the $\langle P_x/A \rangle$ versus $Y/Y_{\rm proj}$ plots as[4, 5, 34].

$$Flow = \frac{1}{A}\frac{{\rm d}\langle P_x \rangle}{{\rm d}Y}\bigg|_{Y=0}, \qquad (3)$$

where P_x and Y are the in-plane transverse momentum and the rapidity in the center-of-mass frame, respectively, and Y is given by

$$Y = \frac{1}{2}\ln\frac{E + P_z}{E - P_z}. \qquad (4)$$

where E and P_z are, respectively, the total energy and the longitudinal momentum in the center-of-mass frame.

4 Results and discussions

The extraction of the flow from the experimental data is shown in Fig. 1, for the particles with $Z = 1 \sim 9$[27]. One may observe the evident offset from the origin in $\langle P_x/A \rangle - Y/Y_{\rm proj}$ plots. The experimental results presented by Ogilvie *et al.*[33], Pak *et al.*[4, 5, 30, 35], Cussol *et al.*[36] and Kohley *et al.*[7, 37], also show nonzero values of the average transverse momentum per nucleon, *i.e.*, $\langle P_x/A \rangle \neq 0$ at $Y/Y_{\rm proj} = 0$,

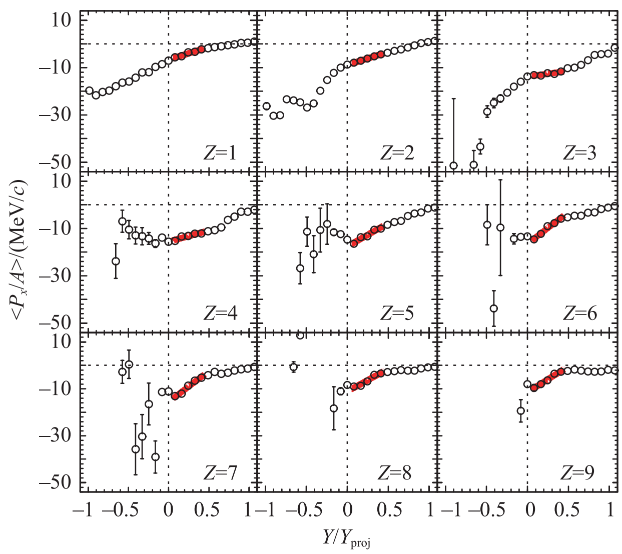

Fig. 1 (color online) Transverse flow extraction for $Z = 1 \sim 9$ particles from the experimental data[27]. The lines are the linear fits of the data points in $Y/Y_{\rm proj} = 0.05 \sim 0.45$.

as one can see in Fig. 2 for the results of Pak *et al.*[30], Cussol *et al.*[36] and Kohley *et al.*[7]. The flow difference at the origin shown in Fig. 3 is attributed to the different incident energies in the experiments. We suggest that the offset mainly originates from the asymmetric detection caused by the experimental conditions, *i.e.*, the energy threshold and the angular resolution of the detector array[27].

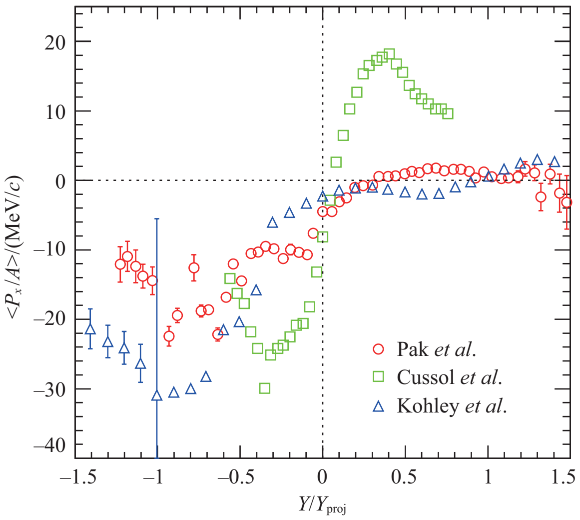

Fig. 2 (color online) Flow results of Pak *et al.*[30], Cussol *et al.*[36] and Kohley *et al.*[7]. The results all involve $Z = 2$ (or α) particles emitted from semi-central collisions.

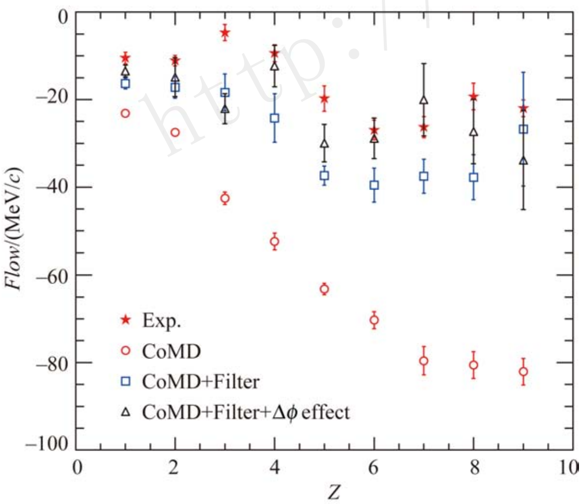

Fig. 3 (color online) Flow from the experimental data and the CoMD simulations (K = 200 MeV) with different conditions as a function of Z[27]. Dots: experiment; open circles: CoMD without the experimental filter; squares: CoMD with the experimental filter; triangles: CoMD with the experimental filter and the $\Delta\phi$ effect. The error bars are from the slope fitting errors.

The linear fits of the $\langle P_x/A\rangle - Y/Y_{\mathrm{proj}}$ plots are performed in the region $0.05 \leqslant Y_{\mathrm{red}} \leqslant 0.45$ as shown in Fig. 1, and the extracted experimental flow values are shown by dots as a function of Z, together with those of CoMD simulations employing a soft EOS ($K = 200$ MeV) in Fig. 3[27]. It should be mentioned that a negative sign is added in front of the extracted flow slopes involving Eq. (2), in order to keep consistency with the previous conclusion that the negative flow is dominant at the energy range below the balance energy[14, 38, 39].

In the following, the experimental filters, the detector thresholds and the angular resolution ($\Delta\phi$), are investigated using the CoMD simulations. As well seen in Fig. 3, the trend of the flow slopes extracted from the unfiltered CoMD events (circles) shows a monotonic increase at the negative direction as Z increases, which is quite different from that of the experiment, and the flow values are larger by a factor of 3 ~ 4 than the experimental ones (dots). When the detector thresholds, which are given by the minima energies allowing the given types of particles to pass through the Si detectors, are applied to the CoMD events, the simulated results (squares) become similar to those of the experiment, but still there is a factor of 1.5 ~ 2 difference in amplitude. When the $\Delta\phi$ from the detector window size is taken into account in the reaction plane reconstruction, the CoMD flow values (triangles) are further reduced and agree well with those of the experiment, though slight deviations beyond the error bars are seen for $Z = 3$ and 5, where the $\Delta\phi$ effect which is performed in the CoMD simulations allows for the "real" position where an emitting particle hit on the detector and obtained by adding a Gaussian width according to the detector position and window size. However it is still difficult to draw a conclusion that the soft EOS of $K = 200$ MeV is verified, because of the mixing effects, such as the in-medium nucleon-nucleon cross sections, the symmetry energy etc, which also affect the flow behaviors. Thus in order to carry out more quantitative comparisons of the flow for the experiments and model simulations, one should attempt to minimize the filter effect on the flow by reducing the detector threshold and increasing angular resolution of the detector array. Additionally, if model simulations are utilized to compare with the experimental results, the filter effect is strongly required to be taken into account.

In Fig. 3, one may notice a surprise pattern of the Z-dependent flow, *i.e.*, the absolute value of flow first decrease from Z =1 to 3; then increase from Z =3 to 6; finally, decrease slightly from Z =6 to 9. A similar pattern has been also observed in the previous work of Kohley *et al.*[8], as shown in Fig. 4. In the figure, the flow values are extracted from ^{64}Ni+^{64}Ni, ^{64}Zn+^{64}Zn and ^{70}Zn+^{70}Zn at 35 MeV/nucleon using the "average-transverse-momentum definition",

$$F_{\text{avg.}} = \frac{1}{A}\langle \text{sign}\{Y\}\cdot P_x\rangle, \tag{5}$$

where the average $\text{sign}\{Y\}\cdot P_x/A$ values are taken in the forward side in the center of mass framework, *i.e.*, $0 \leqslant Y/Y_{\text{proj}} \leqslant 0.45$, and the experimental offset has been manually corrected by adjusting the $\langle P_x\rangle$ versus Y/Y_{proj} plot such that it passed through the origin (0,0).

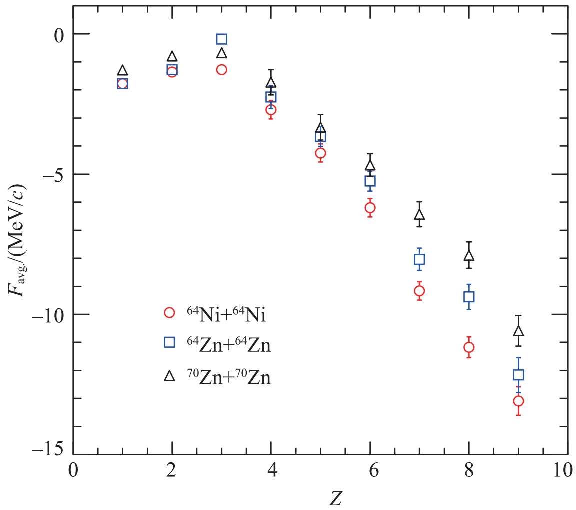

Fig. 4 (color online) *Z*-dependent flow picked up from the previous work of Kohley *et al.*[8]. The error bars are produced by the statistical errors.

The similar shoulder patterns of *Z*-dependent flow for $1 \leqslant Z \leqslant 6$ for both works shown in Figs. 3 and 4 can be attributed to the experimental filter effect. As seen in Fig. 3, the fact that the shoulder effect slightly, but not sufficiently, appears after applying the experimental filters, indicates that the experimental filter effect plays an important role in generating the shoulder pattern. However, the insufficient reproduction of the shoulder pattern may also suggest a physical mechanism. To pursue this issue, both experiments with lower detector thresholds and better angular resolutions and systematic model simulations involving different mechanisms, *i.e.*, the Antisymmetized Molecular Dynamics (AMD)[9] in which the the pre-equilibrium emission of the light clusters is predicted, are further required.

One may also notice the difference of the *Z*-dependent pattern for $Z \geqslant 6$ in Figs. 3 and 4. This difference can be attributed to the suppression of collective motion under the momentum conservation. The system size of the present investigated system, ^{40}Ca$+^{40}$Ca, is smaller than those of Kohley *et al.*, ^{64}Ni$+^{64}$Ni, ^{64}Zn$+^{64}$Zn and ^{70}Zn$+^{70}$Zn. Thus, the suppression of collective motion from the momentum conservation is stronger in the present case, so that the maximum flow value comes at a smaller mass region.

5 Summary

The *Z* dependence of the transverse flow in the reactions of ^{40}Ca$+^{40}$Ca at 35 MeV/nucleon has been determined for emitted isotopes with $Z=1$ to 9. A significant modification of the *Z*-dependent flow pattern caused by the experimental filtering is observed. With the application of the appropriate experimental filter, the general trend of the experimental *Z*-dependent flow is well reproduced by the simulation employing an effective interaction corresponding to a soft EOS with $K=200$ MeV, indicating that the experimental filter effect must be carefully considered in any quantitative comparisons between the experimental results and model predictions. To carry out more quantitative comparisons of the flow for the experiments and model simulations, one should attempt to minimize the effect of the filter on the flow by reducing the detector threshold and increasing the angular resolution of the detector array. An effective solutions is to experimentally employ time projection chamber (TPC) with high energy and isotope resolutions in the particle detection.

By comparing with the parallel work of Kohley *et al.*[8], the pattern of the *Z*-dependent flow is discussed: (1) The similar shoulder patterns of *Z*-dependent flow for $1 \leqslant Z \leqslant 6$ for both works may be partially attributed to the experimental filter effect. To pursue the physical mechanism, both experiments with lower detector thresholds and better angular resolutions and systematic model simulations involving different mechanisms are further required. (2) The different *Z*-dependent patterns for $Z \geqslant 6$ are attributed to the suppression of collective motion under the momentum conservation.

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中能重离子碰撞中横向流电荷依赖的形状以及实验条件对横向流的影响

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摘要： 从 35 MeV/nucleon ^{40}Ca+^{40}Ca 反应实验数据中提取了碎片 Z 从 1 到 9 的横向流，发现探测器阈值、探测系统的角分辨等实验条件对横向流电荷依赖的形状有显著的影响。在考虑实验条件并采用软的核物质状态方程 (K = 200 MeV) 之后，CoMD 模型计算结果很好地重现了实验中横向流电荷依赖的形状。这表明如果要更加精确地提取实验中的横向流，必须使用阈值更低、角分辨更好的探测系统。此外，结合 Kohley 等 [Phys Rev C, 2012, 85: 064605] 从实验中提取的横向流，讨论了横向流电荷依赖的形状存在异同的原因。$1 \leqslant Z \leqslant 6$ 的横向流电荷依赖呈肩峰形状可能是实验条的影响引起的，而我们的实验中 $Z \geqslant 6$ 的横向流的减小可能是由于动量守恒对集体运动的抑制。

关键词： 实验条件；横向流的形状；CoMD；中能重离子碰撞

收稿日期： 2017-05-14； **修改日期：** 2017-05-23

基金项目： 国家自然科学基金资助项目 (11705242)；国家重点基础研究发展计划资助项目 (973 项目)(2014CB845405)；中国科学院西部之光人才培养引进计划资助项目 (29Y601030)

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