Various flows of black and grey particles produced in Mg-emulsion collisions at 4.5 A GeV/c*

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Abstract: Various flow phenomena of black particles (b-particles) and grey particles (g-particles) produced in magnesium-emulsion (Mg-Em) collisions at 4.5 A GeV/c are reported. These flows are directed and elliptic transverse flows (v_1 and v_2) related by the azimuthal angle (φ), directed and elliptic reaction plane flows (v_{R1} and v_{R2}) related by the projected angle (ψ) on the reaction plane, and directed and elliptic polar direction flows (v_{P1} and v_{P2}) related by the polar angle (ϑ). We extract absolute flows as the direct experimental values minus the isotropic theoretical values. The dependence of the various flows on the target particle multiplicity and on the angles (ϑ, φ, ψ) is investigated. Our results show that the dependence of b-particle flows on the target size is obvious and for heavy targets the dependence on target particle multiplicity is slight. Compared with b-particles, g-particles have a slight dependence on the target size and target particle multiplicity.

Key words: various flows, absolute flows, b- and g-particles, Mg-Em collisions

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1 Introduction

Transverse flows of particles produced in nucleus-nucleus collisions at high energies are important experimental quantities [1, 2]. Many experiments have reported transverse flows during the past few decades. Investigations of target and projectile fragment (particle) flows are useful in order to understand the mechanisms of nuclear fragmentation. It is expected that the mechanisms of nuclear fragmentation at different energies are different.

The Dubna energy ((3–5) A GeV) is a special energy, at which nuclear limiting fragmentation applies initially. For a fairly light nucleus such as magnesium, the limiting fragmentation is expected to be (3–5) A GeV or below. Recently, the Cooling Storage Ring (CSR) at the Institute of Modern Physics at the Chinese Academy of Sciences, Lanzhou, China, was successfully brought into operation. The CSR energy is closer to and lower than the Dubna energy and gives us a new opportunuty to study limiting fragmentation and multifragmentation.

In our recent work [3, 4], we reported primarily on the experimental angular distributions of target particles produced in Mg-Em collisions at 4.5 A GeV/c. An investigation of the relative flow characteristics of b-particles produced in Mg-Em collisions at 4.5 A GeV/c was given. As a continuation of the previous work, in this paper a more systematic investigation of the absolute flows of b- and g- particles produced in 4.5 A GeV/c Mg-Em collisions is reported.

2 Experimental material

Emulsion experiments are a very useful method used to investigate nucleus-nucleus collisions [5–7]. Detailed experimental information can be found in our previous work [8] and recent work [4]. We also briefly describe the experimental materials below.

Stacks of NIKFI-BR2 emulsion of dimensions 20 cm×10 cm×600 μm were irradiated by Mg nu-

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clei with a momentum of 4.5 A GeV/c at the synchrophasotron of the Joint Institute for Nuclear Research (JINR), Dubna, Russia. The inelastic events were scanned using the "along-the-track" method under a high magnification binocular microscope and 1000 minimum-bias events were collected. In these events, the polar angle and azimuthal angles of the emission of black and grey particles were measured. Black and grey particles, combined together, are denoted as heavily ionizing particles ($N_{\rm h}$). All 1000 inelastic events were divided into three groups based on $N_{\rm h}$: events with $N_{\rm h}\leqslant 7$, $8\leqslant N_{\rm h}\leqslant 27$ and $N_{\rm h}\geqslant 28$. The first and second groups are mainly contributions from the light target HCNO and heavy target AgBr respectively. The contribution of the third group is totally due to AgBr.

3 Definitions of the various flows

One can define the nth anisotropic transverse flow generally in the form of

$$v_n=\langle\cos(n\varphi)\rangle, \tag{1}$$

where φ denotes the azimuthal angle of a particle and $\langle\cdots\rangle$ indicates an average of all particles in all events considered. The directed transverse flow corresponds to $n=1$ and the elliptic transverse flow corresponds to $n=2$ [1, 2].

Similarly, the nth anisotropic reaction plane flow and the nth anisotropic polar direction flow is given by

$$v_{Rn}=\langle\cos(n\psi)\rangle, \tag{2}$$

and

$$v_{Pn}=\langle\cos(n\vartheta)\rangle \tag{3}$$

respectively, where ψ denotes the projected angle of a particle on the reaction plane and ϑ denotes the polar angle. The directed reaction plane flow and polar direction flow correspond to $n=1$ and the elliptic reaction plane flow and polar direction flow correspond to $n=2$ [4].

To extract absolute flows, we have to consider the contribution of the emission source without flows. An isotropic emission source is an ideal emission source without flows. Using the Monte Carlo method, we can produce many particles in an isotropic emission source. Thus theoretical v_n, v_{Rn}, and v_{Pn} can be obtained. The absolute flows are obtained by subtracting the theoretical flows from the experimental flows.

4 Experimental results

The dependences of v_1, v_2, v_{R1}, and v_{R2} on ϑ for b-particles produced in 4.5 A GeV/c Mg-Em collisions are presented in Figs. 1(a)–1(d), respectively. The open squares, closed circles and open circles represent the results for events with $N_{\rm h}\leqslant 7$, $8\leqslant N_{\rm h}\leqslant 27$, and $N_{\rm h}\geqslant 28$, respectively. These flows are obtained as the difference between the experimental values and the isotropic theoretical values, i.e. they are absolute flows. In the Monte Carlo calculation the isotropic theoretical v_1 and v_2 flows are approximately equal to 0. One can see that v_1 (v_2) depends obviously on ϑ and the target size and does obviously not depend on $N_{\rm h}$ for heavy targets. v_{R1} (v_{R2}) depends weakly on ϑ and $N_{\rm h}$.

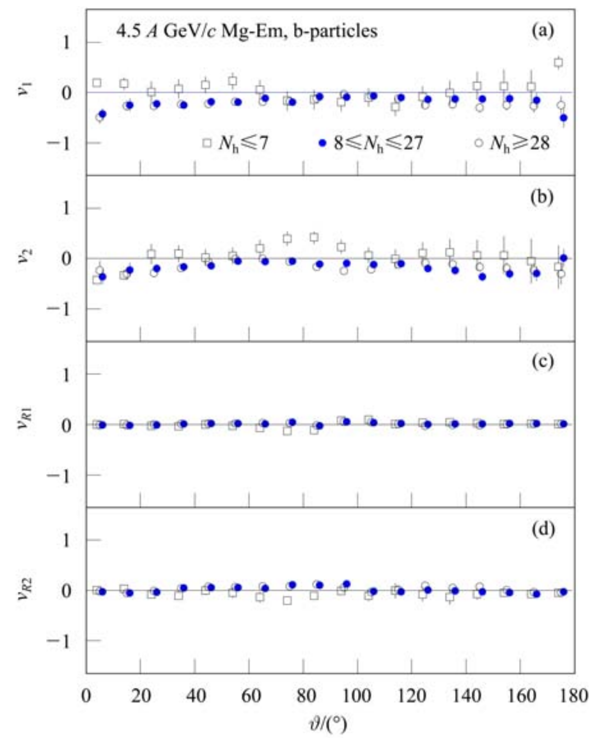

Fig. 1. The dependences of the absolute flows v_1, v_2, v_{R1} and v_{R2} on ϑ for b-particles produced in Mg-Em collisions at 4.5 A GeV/c. The open squares, closed circles and open circles represent the results for event groups with $N_{\rm h}\leqslant 7$, $8\leqslant N_{\rm h}\leqslant 27$ and $N_{\rm h}\geqslant 28$, respectively.

Figure 2 is similar to Fig. 1, but showing the results of g-particles. One can see that v_1 (v_2) depends obviously on ϑ and weakly on $N_{\rm h}$. v_{R1} (v_{R2}) depends weakly or not at all on ϑ and $N_{\rm h}$.

The dependences of v_{R1}, v_{R2}, v_{P1} and v_{P2} on φ for b-particles produced in the 4.5 A GeV/c Mg-Em collisions are presented in Figs. 3(a)–3(d), respectively. The open squares, closed circles and open circles represent the results for events with $N_{\rm h} \leqslant 7$, $8 \leqslant N_{\rm h} \leqslant 27$, and $N_{\rm h} \geqslant 28$ respectively. These flows are obtained represented as: experimental values minus isotropic theoretical values. In the Monte Carlo calculation the isotropic theoretical v_{R1} and v_{P1} flows are approximately equal to 0. One can see that the considered flows depend obviously on the target size, and do not depend on $N_{\rm h}$ for heavy targets. For light targets these flows depend obviously on φ. For heavy targets, except v_{R2}, the other flows depend unobviously on φ.

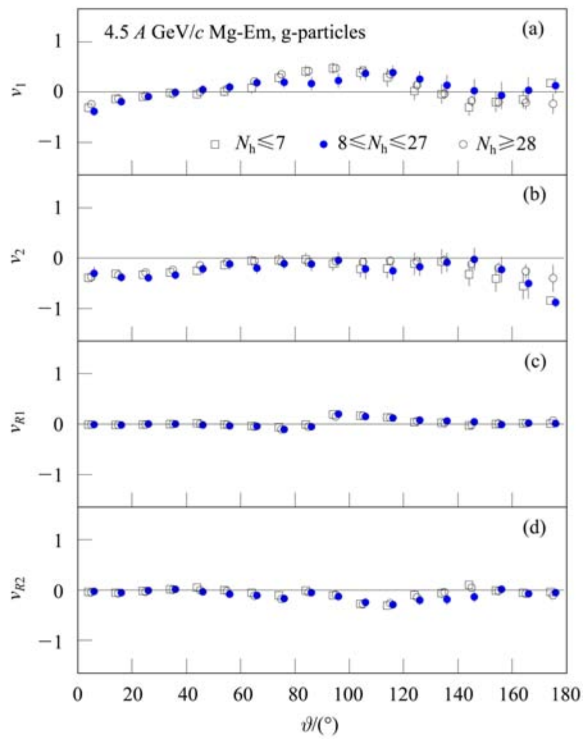

Fig. 2. The same as in Fig. 1, but for g-particles.

Figure 4 is similar to Fig. 3, but shows the results of g-particles. One can see that the considered flows depend obviously on φ and do not depend on $N_{\rm h}$.

The dependences of v_{P1}, v_{P2}, v_1 and v_2 on $|\psi|$ for b-particles produced in 4.5 A GeV/c Mg-Em collisions are presented in Figs. 5(a)–5(d), respectively. The open squares, closed circles and open circles represent the results for events with $N_{\rm h} \leqslant 7$, $8 \leqslant N_{\rm h} \leqslant 27$ and $N_{\rm h} \geqslant 28$, respectively. These flows are obtained as the experimental values minus the isotropic theoretical values. In the Monte Carlo calculation, isotropic theoretical v_1 flow is approximately equal to 0. One can see that the v_{P1} flow does not depend on $N_{\rm h}$ and $|\psi|$. The v_{P2} flow depends on the target size and does not depend on $N_{\rm h}$ and $|\psi|$ for heavy targets. For light targets v_{P2} depend on $|\psi|$. The v_1 and v_2 flows depend on $|\psi|$ and target size and do not depend on $N_{\rm h}$ for heavy targets.

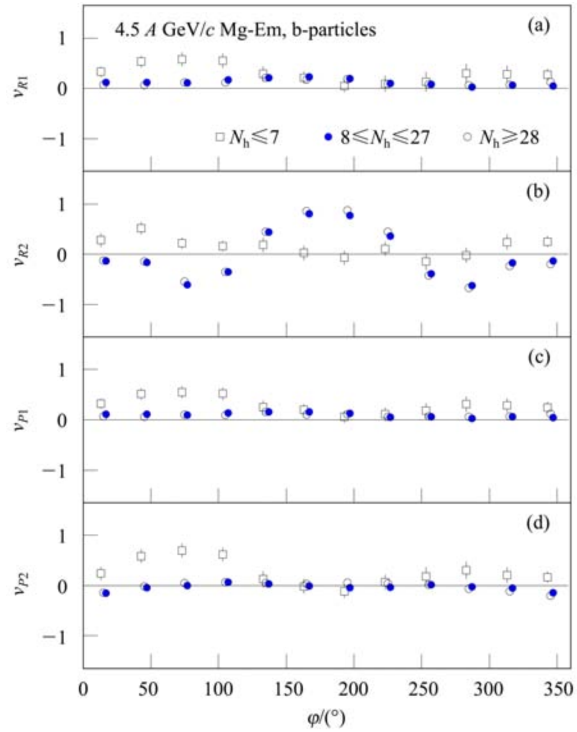

Fig. 3. The dependences of the absolute flows v_{R1}, v_{R2}, v_{P1}, and v_{P2} on φ for b-particles produced in Mg-Em collisions at 4.5 A GeV/c. The open squares, closed circles and open circles represent the results for event groups with $N_{\rm h} \leqslant 7$, $8 \leqslant N_{\rm h} \leqslant 27$ and $N_{\rm h} \geqslant 28$, respectively.

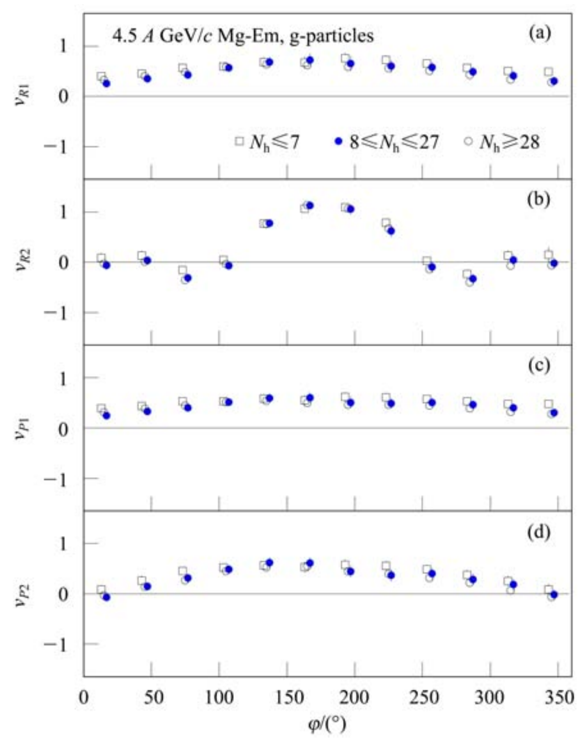

Fig. 4. The same as in Fig. 3, but for g-particles.

Figure 6 is similar to Fig. 5, but shows the results for the g-particles. One can see that the v_{P1} flow depends weakly on $|\psi|$ and the other considered flows depend obviously on $|\psi|$. The four types of flows do not depend on $N_{\rm h}$.

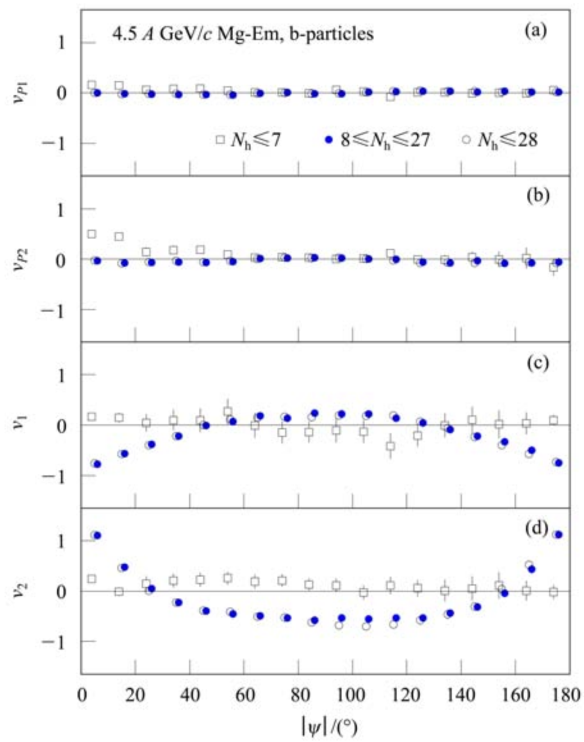

Fig. 5. The dependence of the absolute flows v_{P1}, v_{P2}, v_1 and v_2 on $|\psi|$ for b-particles produced in Mg-Em collisions at 4.5 A GeV/c. The open squares, closed circles and open circles represent the results for event groups with $N_{\rm h}\leqslant 7$, $8\leqslant N_{\rm h}\leqslant 27$ and $N_{\rm h}\geqslant 28$, respectively.

5 Conclusion

To conclude, the transverse flows, reaction plane flows and polar direction flows of b- and g-particles produced in Mg-Em collisions at 4.5 A GeV/c have been reported experimentally. The absolute flows are extracted by taking the experimental values minus the isotropic theoretical values. The dependences of the flow characteristics on angle (ϑ,φ,ψ), target size and $N_{\rm h}$ are obtained. Our results show that the dependence of the b-particle flows on the target size is obvious. For heavy targets the dependence on the target particle multiplicity is weak. Comparing with b-particles, the g-particles have a weak dependence on the target size and target particle multiplicity. These results show also that the target b- and g-particles, produced in Mg-Em collisions at 4.5 A GeV/c, are not isotropic. The directed and elliptic flows are mostly observed in the considered angular range.

In some cases the considered flows depend on the target size. This indicates that the interacting mechanisms in light and heavy targets are different. Generally, the heavy targets have a higher probability to fragment in the mode of multifragmentation. On the other hand, the heavy target has a larger cross section than the light target. The so-called cold nuclear effect in the heavy target is obvious. Both the fragmentation mode and the cold nuclear effect lead to some differences in the light and heavy target fragmentations.

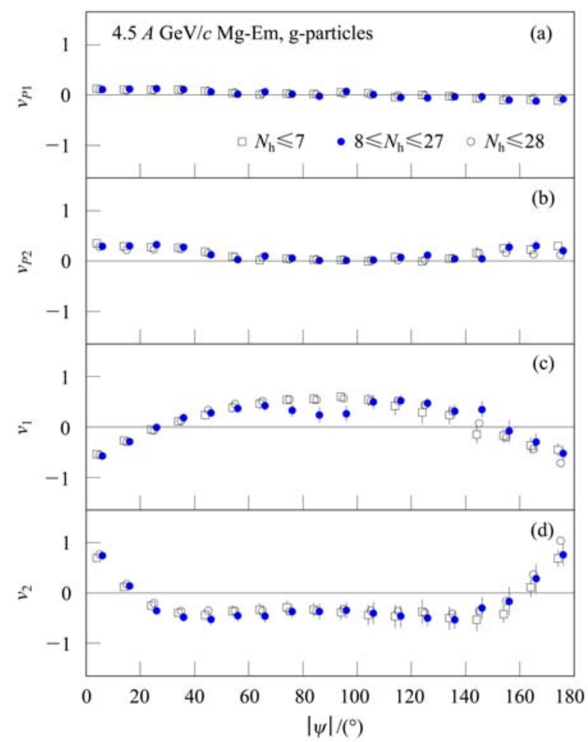

Fig. 6. The same as in Fig. 5, but for g-particles.

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