第 28 卷　第 3 期　　原 子 核 物 理 评 论　　Vol. 28, No. 3
2011 年 9 月　　Nuclear Physics Review　　Sep., 2011

Wrticle ID: 1007-4627(2011)03-0263-05

Angular Distributions of Final-state Particles Produced in Nucleus-nucleus Collisions*

TIAN Jun-long[1,2], ZHAO Hong-guang[1], HAO Hong-jun[1]

(1 *School of Physics and Electrical Engineering*, *Anyang Normal University*, *Anyang* 455000, *Henan*, *China*;
2 *Key Laboratory of Beam Technology and Material Modification of Ministry of Education*,
Beijing Normal University, *Beijing* 100875, *China*)

Abstract: The emission angular distributions of final-state particles produced in ^{16}O-Emulsion (Em) collisions at 14.6 *A*GeV, and the azimuthal angular distributions for the black particles produced in ^{28}Si-Em at 4.5 *A*GeV have been studied by an isotropic fireball model. The model including transverse flow is used to describe the azimuthal distributions of midrapidity π^- mesons and protons produced in C-Ne and C-Cu collisions at 3.7 *A*GeV. The calculated results are in agreement with the experimental angular distributions. It shows that the improved fireball model gives a good description of nucleus-nucleus collisions at high energies.

Key words: angular distribution; isotropic fireball model; target fragment; transverse flow

CLC number: O571.6　　**Document code**: A

Angular distribution is one of the important observable quantities in nuclear reactions. On one hand, the nature of the nuclear reaction can be determined by using the differences in the angular distributions of nuclear reaction products, and it seems to be important to understand the dynamical features of the reaction process. For example, angular distribution of nuclear fragments can provide information about the fragmentation mechanism and thus help trace the reaction mechanism of nucleus-nucleus collisions at high energies[1-3]. On the other hand, angular distributions may be used for verification of theoretical models of nucleus-nucleus collisions. So it is highly important for us to investigate the target fragmentation process at high energies by the angular distributions of target fragments. In addition, the angular distributions of charged particles can be obtained in emulsion experiments by using the techniques of grain, δ-ray and lacunarity measurements to identify different kinds of final particles and fragments[4-8]. As a fixed target and detector, the nuclear emulsion can give the whole picture of an interaction event and a high resolution of particle tracks. It is possible for us to study the angular distributions in the whole rapidity due to the accurate measurement of space angles of all charged particles in nuclear emulsion. In order to explain the angular distribution shape of target fragments produced in nucleus-emulsion and nucleus-nucleus collisions at high energy, an isotropic fireball (IF) model is used in this work.

According to the model[9], a fireball is formed in relativistic nucleus-nucleus collisions. The fireball is assumed to be an isotropic emission in the

---

* **Received date**: 10 Oct. 2010; **Revised date**: 24 Oct. 2010

* **Foundation item**: National Natural Science Foundation of China (11005003, 10975095, 11005002); Innovation fund of undergraduate at Anyang Normal University

Biography: Tian Junlong (1976—), male (Han Nationality), Jincheng, Shanxi, China, Vice Professor, working on nuclear physics; E-mail: tianjunlong@gmail.com fireball rest frame. Let the beam direction be the *oz* axis and the reaction plane be the *yoz* plane. As in Maxwell's ideal-gas model, the three components ($P_{x,y,z}$) of the particle momentum in the fireball rest frame are assumed to be Gaussian distributions with the same width, i. e.,

$$f_{P_{x,y,z}}(P_{x,y,z})=\frac{1}{\sqrt{2\pi}\sigma_{\mathrm{P}}}\exp\left[\frac{-P_{x,y,z}^{2}}{2\sigma_{\mathrm{P}}^{2}}\right], \quad (1)$$

where σ_{P} is the standard deviation (distribution width), as Ref. [10]. And the transverse momentum $\left(P_{\mathrm{T}}=\sqrt{P_x^2+P_y^2}\right)$ has a Rayleigh distribution,

$$f_{P_{\mathrm{T}}}(P_{\mathrm{T}})=\frac{P_{\mathrm{T}}}{\sigma_{\mathrm{P}}^{2}}\exp\left[\frac{-P_{\mathrm{T}}^{2}}{2\sigma_{\mathrm{P}}^{2}}\right]. \quad (2)$$

A Monte Carlo method is used to calculate the emission angular distributions and azimuthal distributions of target fragments. Let R_1, R_2, R_3, R_4, R_5 and R_6 denote the even random variables distributed in [0,1]. We have

$$P_x=\sigma_{\mathrm{P}}\sqrt{-2\ln R_1}\cos(2\pi R_2), \quad (3)$$

$$P_y=\sigma_{\mathrm{P}}\sqrt{-2\ln R_3}\cos(2\pi R_4), \quad (4)$$

$$P_z=\sigma_{\mathrm{P}}\sqrt{-2\ln R_5}\cos(2\pi R_6), \quad (5)$$

and

$$\theta=\arctan\left(\frac{P_{\mathrm{T}}}{P_z}\right), \quad (6)$$

$$\varphi=\arctan\left(\frac{P_y}{P_x}\right), \quad (7)$$

where σ_{P} is the parameter that characterizes the width of the momentum distribution in the source reference frame, as Ref. [10].

Because the transverse and longitudinal flows affect the emission of particles[11], the final-state transverse and longitudinal momenta measured in the fireball rest frame can be written as[12]

$$P_{\mathrm{T}}^{\mathrm{f}}=k_{xy}P_{\mathrm{T}}, \quad (8)$$

and

$$P_z^{\mathrm{f}}=k_zP_z, \quad (9)$$

where k_{xy} and k_z denote the transverse and longitudinal flow strengths, respectively. Generally speaking, $k_{xy,z}>1$ means an extension flow, $k_{xy,z}<1$ means a contraction flow, while $k_{xy,z}=1$ means that there is no flow. The physics condition gives $k_{xy,z}>0$.

The emission angle θ^* and the azimuthal angular φ^* of fragments produced in the fireball rest frame are give by

$$\theta^*=\arctan\left(\frac{P_{\mathrm{T}}^{\mathrm{f}}}{P_z^{\mathrm{f}}}\right)=\arctan\left(\frac{k_\theta P_{\mathrm{T}}}{P_z}\right), \quad (10)$$

and

$$\varphi^*=\arctan\left(\frac{P_y^{\mathrm{f}}}{P_x^{\mathrm{f}}}\right)=\arctan\left(\frac{kP_y}{P_x}\right), \quad (11)$$

where $k_\theta=k_{xy}/k_z$, $k=k_y/k_x$.

In the study of the emission angular and the azimuthal angular, we do not need to know $k_{x,y,z}$ and k_{xy}, while the ratio k is an important parameter in our calculation. $k>1$ means a transverse flow, $k<1$ means a longitudinal flow, while $k=1$ means a pure isotropic emission. The free parameter k can be obtained by fitting the experimental data.

Fig. 1 presents the emission angular distributions of black particles of target fragments, for light targets (C, N, O) (a), heavy target (Ag, Br) (b) and all targets (C, N, O, Ag, Br) (c), respectively, produced in ^{16}O-Em collisions at 14.6 *A*GeV. The histograms are the corresponding experimental data in Ref. [13]. The solid circles denote the calculated results by Monte Carlo method. The dashed curves are the fitting results by the analytic function $f_\theta(\theta)=\sin\theta/2$. From Fig. 1, one can see that the emission angular distributions seem like almost same for different targets, and show maxima at $\theta=90°$ and are symmetric with respect to $\theta=90°$. This is because most of the black particles come from the target spectator, and which get the Coulomb repulsion of projectile at 90°. Fig. 1 (a), (b) and (c) correspond to the events with $N_{\mathrm{h}}\leqslant 8$, $N_{\mathrm{h}}>8$ and $N_{\mathrm{h}}\geqslant 0$, respectively, where N_{h} denotes the number of grey particles and black particles. The Monte Carlo calculated particle number for each event group is $\langle N\rangle$, where $\langle N\rangle$ denotes the mean multiplicity of black particles in the concerned event group. One can note that the calculated results are approximately in agreement with the experimental data. And some statistical fluctuations are shown in the emission angular distributions, which due to ⟨N⟩ particles have been calculated by the Monte Carlo method. The statistical fluctuations become less and less with increasing ⟨N⟩. The isotropic fireball model almost describes the experimental data of emission angular distributions. However the experimental distribution of black particles is a little more in the range of $\theta<90^\circ$ as compared with that in the range of $\theta>90^\circ$, which is due to the fact that the emission source of black particles is struck by projectile. So the isotropic fireball model is needed to further develop for dealing with anisotropic emission experimental data in our next work.

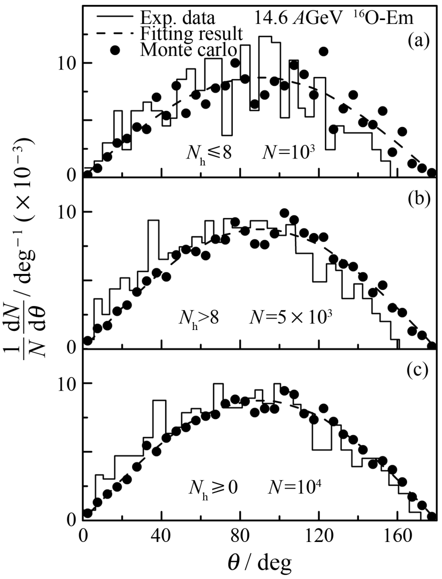

Fig. 1 The emission angular distributions of black particles of different target fragments. The experimental data are adopted from Ref. [13].

Fig. 2 shows the azimuthal angular distributions in the reaction plane for the black particles produced in ^{28}Si-Em at 4.5 *A*GeV. The solid squares with error bars are the corresponding experimental data which are quoted from Ref. [14]. The open circles are the calculated results by Monte Carlo method by means of Eq. (11). The dashed line is the fitting result by the analytic function $f_\varphi(\varphi)=1/2\pi$. From Fig. 2, one can see that the azimuthal angular distributions are flat or isotropic distributions. It has been a criterion for evaluating experimental angular measure results. One can note that the calculated results are approximately in agreement with the experimental data, and statistical fluctuations are also described with ⟨N⟩ particles by the Monte Carlo method. These results indicate that the isotropic fireball model is successful in the description of the experimental azimuthal angular distributions in nucleus-nucleus collisions at this energy region.

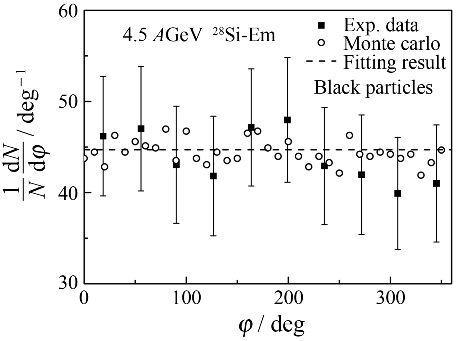

Fig. 2 The azimuthal angular distributions of black particles produced in ^{28}Si-Em at 4.5 *A*GeV.

Fig. 3 presents the azimuthal distributions with respect to the reaction plane of midrapidity π^- mesons (a), and protons (b) produced in C-Ne and C-Cu collisions at 3.7 *A*GeV. The solid circles with error bar and the triangles with error bar are the experimental data for C-Ne ($-1\leqslant y_{cm}\leqslant1$), and for C-Cu ($-1\leqslant y_{cm}\leqslant1$) interactions from Ref. [15]. For visual presentation the data on C-Cu were shifted upward, for π^- mesons the analysis was performed from 0° to 180° due to lower statistics than that for protons. The solid curves are the Monte Carlo calculated results with 10^5 particles according to Eq. (11). The free parameter k, which describes transverse or longitudinal flow, is introduced to the IF model. By fitting the experimental data, we obtained the $k=1.4$ for π^- mesons, and $k=1.5$ for protons in C-Ne and C-Cu collisions at 3.7 *A*GeV. It means that transverse flow plays an important role in nucleus-nucleus collisions at a few *A*GeV energy region.

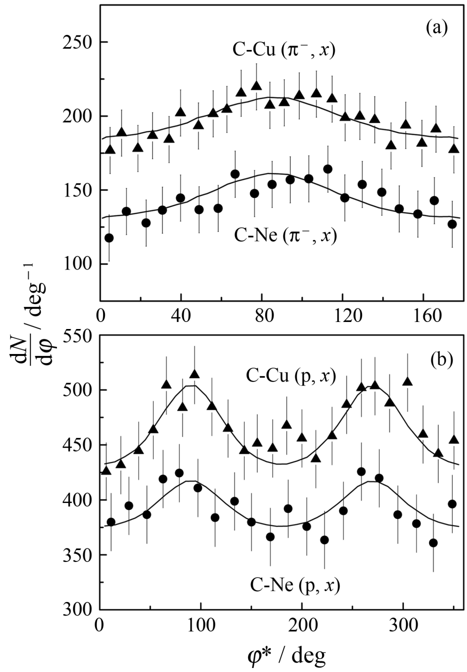

Fig. 3 The azimuthal distributions of midrapidity π^- mesons (a), and protons (b) produced in C-Ne (solid circle) and C-Cu (solid triangles) collisions at 3.7 *A*GeV.

In summary, the angular distributions of final-state particles, which are from the interactions accompanied by the emission of black particles in ^{16}O-Em collisions at 14.6 *A*GeV and ^{28}Si-Em collisions at 4.5 *A*GeV, have been studied by an isotropic fireball model. The calculated results are in agreement with the experimental data. A Monte Carlo calculation shows that the isotropic emission fireball model gives a good description for ^{16}O-Em and ^{28}Si-Em collisions at this energy region. The isotropic fireball model cannot describe the azimuthal distributions with respect to the reaction plane of midrapidity π^- mesons and protons produced in central C-Ne and C-Cu interactions at 3.7 *A*GeV. The $k=1.4$ for π^- mesons, and $k=1.5$ for protons in C-Ne and C-Cu collisions obtained by fitting the experimental data means that transverse flow plays an important role in this energy region of a few *A*GeV.

Acknowledgement We thank Prof. Liu Fuhu for reading the manuscript and for fruitful discussions.

References:

[1] Singh G, Sengupta K, Jain P L. Phys Rev, 1990, **C41**: 999.

[2] Liu F H, Abd N N, Singh B K, *et al*. Acta Phys Polon, 2006, **B37**: 2695.

[3] Li H L. Acta Phys Polon, 2008, **B39**: 641.

[4] Adamovich M I, Aggarwal M M, Alexandrov Y A, *et al* (EMU01 Collaboration). Phys Lett, 1991, **B262**: 371.

[5] Jain P L, Sengupta K, Singh G. Phys Rev, 1991, **C44**: 844.

[6] Elnadi M, Sherif M, Adamovich M, *et al*. Nuovo Cimento, 1995, **A108**: 809.

[7] Ghosh D, Roy J, Sarkar S, *et al*. Nuovo Cimento, 1990, **A103**: 423.

[8] Ghosh D, Roy J, Sengupta R, *et al*. Nuovo Cimento, 1997, **A110**: 565.

[9] Westfall G D, Gosset J, Johansen P J, *et al*. Phys Rev Lett, 1976, **37**: 1202.

[10] Adamovich M I, Aggarwal M M, Aleksandrov Y A, *et al* (EMU01 Collaboration). Phys Lett, 1995, **B352**: 472.

[11] Liu F H. Chin J Phys (Taipei), 2000, **38**: 1063.

[12] Liu F H. Phys Lett, 2004, **B583**: 68.

[13] Weng Z Q, Liu Z G, Li Y X, *et al*. Journal of Shanxi Teachers University (Natural Science Edition), 1992, **6**(4): 24 (in Chinese).
(翁智群，刘子贵，李元勋，等. 山西师大学报(自然科学版)，1992，**6**(4)：24.)

[14] Abd-Allah N N. Can J Phys, 2002, **80**: 119.

[15] Chkhaidze L, Djobava T, Kharkhelauri L. Phys Lett, 2000, **B479**: 21.

高能核-核碰撞中末态产物的角分布*

田俊龙[1,2,1)]，赵红光[1]，郝红军[1]

（1 安阳师范学院物理与电气工程学院，河南 安阳 455000；
2 北京师范大学射线束技术与材料改性教育部重点实验室，北京 100875）

摘　要：用各向同性的火球模型研究了能量为 14.6 *A*GeV 的 ^{16}O-Em 碰撞中末态产物的发射角分布和能量为 4.5 *A*GeV 的 ^{28}Si-Em 碰撞中靶核碎块中黑粒子的方位角分布。在这个模型中增加横向流可以描述能量为 3.7 *A*GeV 的 C-Ne 和 C-Cu 碰撞中靶核碎块 π^- 介子和质子的方位角分布。计算结果与实验数据符合得较好，表明改进了的火球模型能够描述高能核-核碰撞的角分布。

关 键 词：角分布；各向同性的火球模型；靶碎块；横向流

---

* **收稿日期**：2010-10-10；**修改日期**：2010-10-24

* **基金项目**：国家自然科学基金资助项目(11005003，10975095，11005002)；安阳师范学院本科生创新基金资助项目

1) E-mail：tianjunlong@gmail.com