CPC(HEP & NP), 2011, **35**(5): 436–440 **Chinese Physics C** Vol. 35, No. 5, May, 2011

Projectile spectator proton production in ^{84}Kr-emulsion interactions at 1.7 *A* GeV[*]

BAI Cai-Yan(白彩艳)[1] ZHANG Dong-Hai(张东海)[2;1)]

[1] Department of Physics, Jinzhong College, Yuci 030600, China
[2] Institute of Modern Physics, Shanxi Normal University, Linfen 041004, China

Abstract: The multiplicity distribution of projectile protons and multiplicity correlations between black particles, grey particles, shower particles, compound particles, heavily ionized track particles, projectile helium fragments and projectile spectator protons in ^{84}Kr-emulsion collisions at 1.7 *A* GeV are investigated. It is found that the projectile spectator proton multiplicity distribution becomes broader with increasing target mass. The average multiplicity of shower particles and compound particles strongly depends on the number of projectile spectator protons, but the average multiplicity of black particles, grey particles and heavily ionized track particles weakly depends on the number of projectile spectator protons. The average multiplicity of projectile helium fragments increases linearly with increasing numbers of projectile spectator protons. Finally, the multiplicity distribution of projectile spectator protons obeys a KNO type of scaling law.

Key words: relativistic heavy-ion collision, projectile spectator proton, nuclear emulsion

PACS: 25.75.Ag, 25.75.Gz, 29.40.Rg **DOI:** 10.1088/1674-1137/35/5/005

1 Introduction

The multiplicity distributions and multiplicity correlations of various secondary particles (grey particles, black particles, shower particles, and heavily ionized track particless) produced in hadron-nucleus and nucleus-nucleus interactions using different kinds of projectile with a wide range of energy have been studied in the last few years. It is believed that these studies may provide the topological properties and help us to understand the dynamical mechanism of the collisions. According to the colliding geometrical model (or spectators and participants model), nucleons in the overlapped region are called participants, and others are the spectators. In the overlapped region, violent nucleon-nucleon collisions would be expected, so that the local density and temperature would sharply increase. After the collision, the system would expand and be cooled down, and the relativistic mesons and recoiled protons would be produced. In the spectator regions, the target spectator would be evaporated and form target fragments, while the projectile spectator would be fragmented or multifragmented into projectile fragments. The projectile spectator proton is a kind of projectile fragment. In order to understand the dynamical mechanism thoroughly, it is necessary to investigate the property of projectile spectator proton production in relativistic nucleus-nucleus collisions. Up to now, only a little work has been carried out on the production of projectile spectator protons [1–9].

In this paper, we present a detailed study of projectile spectator proton multiplicity distribution and multiplicity correlations between projectile spectator protons and other secondary particles produced in ^{84}Kr-emulsion interactions at 1.7 *A* GeV.

2 Experimental details

Stacks of Ilford G-5 nuclear emulsion plates were horizontally exposed to a ^{84}Kr beam at 1.7 *A* GeV at Bevalac Berkeley. XSJ-1 and XSJ-2 microscopes with a 100× oil immersion objective and 16× ocular lenses were used to scan the plates. The tracks were picked up at a distance of 5 mm from the edge of the plates and were carefully followed until they either

---

Received 22 June 2010

[*] Supported by National Natural Science Foundation of China (10475054), Natural Foundation of Shanxi Province, China (2008011005) and Shanxi Provincial Foundation for Returned Scholars of China

1) E-mail: zhangdh@dns.sxnu.edu.cn

interacted with emulsion nuclei or escaped from the plates. Interactions that are within 30 μm from the top or bottom surface of the emulsion plates are not considered in the final analysis. All of the primary tracks are followed back to ensure that the events chosen do not include interactions from the secondary tracks of other interactions. When they are observed to do so, the corresponding events are removed from the sample.

According to the emulsion terminology [10], the particles emitted in the interactions are classified as follows:

(a) Black particles. These are target fragments with ionization greater or equal to $9I_0$, I_0 being the minimum ionization of a single charged particle. Their range is less than 3 mm, their velocity less than 0.3c and their energy less than 26 MeV. The multiplicity is denoted by $N_{\rm b}$.

(b) Grey particles. These are mainly fast target recoil protons with kinetic energy $26 \leqslant E \leqslant 375$ MeV, a few kaons with kinetic energy $20 \leqslant E \leqslant 198$ MeV and pions with kinetic energy $12 \leqslant E \leqslant 56$ MeV. They have ionization $1.4I_0 \leqslant I \leqslant 9I_0$. Their range in emulsions is greater than 3 mm and they have velocities $0.3{\rm c} \leqslant v \leqslant 0.7{\rm c}$. The multiplicity is denoted by $N_{\rm g}$.

The grey and black particles together are called heavily ionized track particles. The multiplicity is denoted by $N_{\rm h}$.

(c) Shower particles. These are produced as single-charged relativistic particles having a velocity greater or equal to $0.7c$. Most of them belong to pions contaminated by small proportions of fast protons and K mesons. The multiplicity is denoted by $N_{\rm s}$.

The grey and shower particles together are called compound particle. The multiplicity is denoted by $N_{\rm c}$.

(d) Projectile fragments (PFs). These are highly collimated tracks within a narrow cone of opening angle $\theta \leqslant 5°$. PFs are further classified according to their charges into:

(1) Singly charged PFs, or projectile spectator protons (deuton and tritium are included), which have ionization $I \leqslant 1.4I_0$ and may contain some produced pions. The multiplicity is denoted by $N_{\rm p}$.

(2) Doubly charged PFs, denoted by N_{α}. They have ionization $I = 4I_0$ and show no change in their ionization when the tracks are followed up to a distance of approximately 2 cm from the vertex of interaction.

(3) Multicharged PFs, denoted by $N_{\rm F}$ (i.e.$Z \geqslant 3$). They have ionization $I \geqslant 9I_0$ and show no change in their ionization when the tracks are followed up to a distance of approximately 2 cm from the vertex of interaction.

3 Experimental results

There are 558 unbiased inelastic ^{84}Kr-emulsion interaction events that are used in the present investigation. According to the number of heavily ionized track particles $N_{\rm h}$, the events are classified into three categories: ^{84}Kr-H, ^{84}Kr-CNO, and ^{84}Kr-AgBr events. Out of 558 events, we get 93 ^{84}Kr-H ($N_{\rm h} \leqslant 1$), 233 ^{84}Kr-CNO ($1 < N_{\rm h} < 8$), and 232 ^{84}Kr-AgBr events ($N_{\rm h} \geqslant 8$), respectively. Table 1 presents the average multiplicity of projectile spectator protons $\langle N_{\rm p}\rangle$ in ^{84}Kr-emulsion collisions at 1.7 A GeV. For comparison, the other experimental data from nucleus-emulsion interactions at a few A GeV are also listed in the table. It should be stressed that the emulsion plates in our experiment are not fully developed, so there are some missing projectile spectator protons. From the results of the table, we can conclude that $\langle N_{\rm p}\rangle$ increases with the increase in projectile mass at the same beam energy. The projectile spectator proton is produced from projectile fragmentation or multifragmentation, so the average multiplicity of projectile spectator protons increases with the increase in projectile mass at the same beam energy.

Table 1. The mean multiplicity of projectile spectator protons in relativistic heavy ion induced nuclear emulsion interactions.

beam	energy/(A GeV)	$\langle N_{\rm p}\rangle$	Ref.
^{4}He	3.7	0.61 ± 0.02	[7]
^{12}C	3.7	1.20 ± 0.04	[7]
^{12}C	3.7	0.62 ± 0.03	[5]
^{12}C	3.7	0.93 ± 0.02	[1]
^{16}O	3.7	1.45 ± 0.03	[7]
^{16}O	3.7	1.15 ± 0.08	[6]
^{22}Ne	3.3	1.55 ± 0.02	[7]
^{22}Ne	3.3	1.36 ± 0.02	[3]
^{28}Si	3.7	2.54 ± 0.05	[7]
^{28}Si	3.7	1.82 ± 0.05	[5]
^{84}Kr	1.7	2.79 ± 0.10	present work
^{132}Xe	1.0	4.6 ± 0.2	[4]

Table 2 presents the mean projectile spectator proton multiplicity of nucleus induced reactions on different emulsion targets at a few A GeV beam energy. It can be seen that $\langle N_{\rm p}\rangle$ increases with the increase in target mass. Fig. 1 shows the projectile spectator proton multiplicity distribution of ^{84}Kr induced interactions on the different emulsion targets at 1.7 A GeV. It can be seen that the $N_{\rm p}$ distribution is almost the same in shape for different emulsion targets, but becomes broader with the increase in target mass. Fig. 2 presents the dependence of $\langle N_{\rm p}\rangle$ on the target mass $A_{\rm T}$ in ^{84}Kr-emulsion collisions at 1.7 A GeV. The experimental data can be fitted quite satisfactorily by a relation of the form

$$\langle N_{\rm p}\rangle = (2.379\pm0.193)A_{\rm T}^{0.047\pm0.022}, \tag{1}$$

with $\chi^2/DOF = 0.4353$, where DOF means the degree of freedom.

Table 2. The mean multiplicity of projectile spectator protons in the relativistic heavy ion induced interactions on the different emulsion targets.

beam	energy/(A GeV)	$\langle N_{\rm p}\rangle$			Ref.
		H	CNO	AgBr	
^{12}C	3.7	0.77±0.07	1.12±0.04	0.86±0.02	[1]
^{22}Ne	3.3	1.17±0.02	1.47±0.04	1.37±0.03	[3]
^{56}Fe	1.0	2.53±0.29	3.19±0.28	4.94±0.44	[9]
^{56}Fe	1.7	2.35±0.17	3.00±0.13	3.03±0.09	[2]
^{84}Kr	1.7	2.44±0.21	2.67±0.15	3.06±0.16	present work
^{132}Xe	1.0	1.9±0.3	4.7±0.3	6.7±0.3	[4]

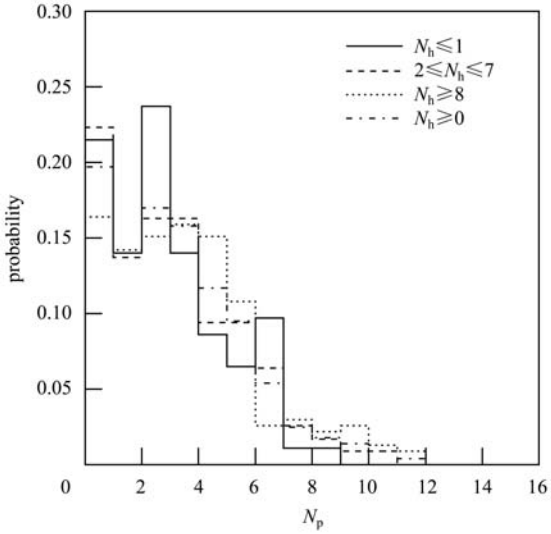

Fig. 1. Projectile spectator proton multiplicity distributions for different groups of $N_{\rm h}$ in the ^{84}Kr-nucleus interactions at 1.7 A GeV.

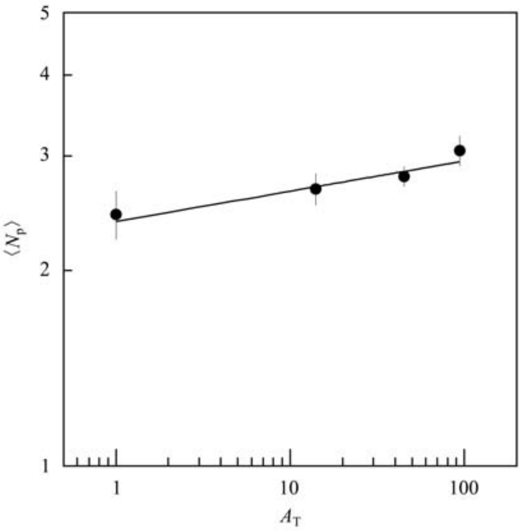

Fig. 2. Dependence of $\langle N_{\rm p}\rangle$ on the target mass in the ^{84}Kr-nucleus interactions at 1.7 A GeV.

Koba-Nielson-Olesen (KNO) scaling is a well established empirical law for multiparticle production in pp collisions [11], and it can be compared with the experimental data on the multiplicity distribution of relativistic particles, to see whether it favors the universal law. In Fig. 3, we first plot $\langle N_{\rm p}\rangle(\sigma_{\rm n}/\sigma_{\rm inel})$ versus $N_{\rm p}/\langle N_{\rm p}\rangle$ for ^{84}Kr-H, CNO, AgBr, and emulsion (Em) interactions at 1.7 A GeV, where $\sigma_{\rm n}$ denotes the partial cross section for producing n charged projectile spectator protons, $\sigma_{\rm inel}$ denotes the total inelastic cross section, and $z = N_{\rm p}/\langle N_{\rm p}\rangle$, respectively. It should be noted that the contribution of the events with $N_{\rm p} = 0$ is not included. From this figure, it can be seen that the experimental data lie on a universal curve, which can be fitted by a KNO scaling function with the form

$$\Psi(z) = Az{\rm e}^{-Bz}. \tag{2}$$

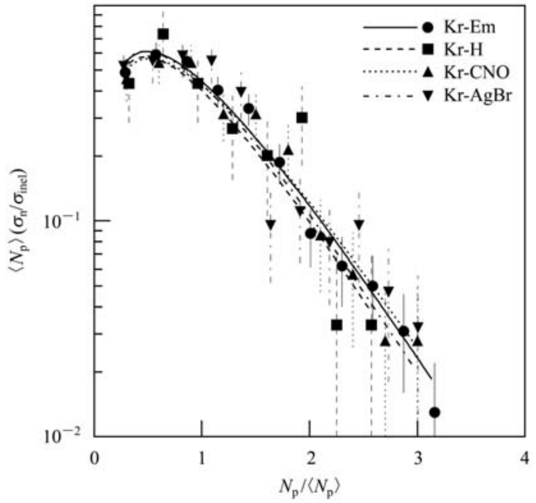

Fig. 3. Plot of $\langle N_{\rm p}\rangle(\sigma_{\rm n}/\sigma_{\rm inel})$ as a function of $N_{\rm p}/\langle N_{\rm p}\rangle$ for the ^{84}Kr-H, CNO, AgBr and emulsion interactions at 1.7 A GeV.

The best fitting parameters A and B are listed in Table 3, which are almost the same within statistical errors for the ^{84}Kr induced interactions on the different emulsion targets at 1.7 A GeV.

Table 3. Values of the best fitting parameters A and B of Formula (2) in the ^{84}Kr induced interactions on the different emulsion targets at 1.7 A GeV.

type of event	A	B	χ^2/DOF
^{84}Kr-H	3.283±0.959	2.100±0.245	0.783
^{84}Kr-CNO	3.000±0.507	1.950±0.131	0.392
^{84}Kr-AgBr	3.468±0.661	2.087±0.160	1.140
^{84}Kr-Em	3.363±0.358	2.025±0.083	0.501

Multiplicity correlations of type $\langle N_{\rm i}(N_{\rm j})\rangle$, where $N_{\rm i}$, $N_{\rm j}=N_{\rm b}$, $N_{\rm g}$, $N_{\rm s}$, $N_{\rm h}$ and $\rm i \neq j$, have been studied in hadron-nucleus and nucleus-nucleus collisions over a wide range of energy using different projectiles. But no investigation has been done into the correlations between $N_{\rm b}$, $N_{\rm g}$, $N_{\rm s}$, $N_{\rm h}$ and $N_{\rm p}$. Therefore it is necessary to make an investigation into the multiplicity correlations between the projectile spectator proton and other secondary particles produced in these collisions.

Figure 4 presents the multiplicity correlations between $\langle N_{\rm b}\rangle$, $\langle N_{\rm g}\rangle$, $\langle N_{\rm s}\rangle$, $\langle N_{\rm h}\rangle$, $\langle N_{\rm c}\rangle$, $\langle N_{\alpha}\rangle$ and $N_{\rm p}$ in ^{84}Kr-emulsion collisions at 1.7 A GeV. From the figure, it can be seen that there is a strong correlation between $\langle N_{\rm s}\rangle$, $\langle N_{\rm c}\rangle$ and $N_{\rm p}$, and a weak correlation between $\langle N_{\rm b}\rangle$, $\langle N_{\rm g}\rangle$, $\langle N_{\rm h}\rangle$, $\langle N_{\alpha}\rangle$ and $N_{\rm p}$. The experimental data can be fitted by a linear relation of the form

$$\langle N_{\rm i}\rangle = a_{\rm i}+b_{\rm i}N_{\rm p}, \qquad (3)$$

where $N_{\rm i}=N_{\rm b}$, $N_{\rm g}$, $N_{\rm s}$, $N_{\rm h}$, $N_{\rm c}$, N_{α}, and fitting parameters are listed in Table 4.

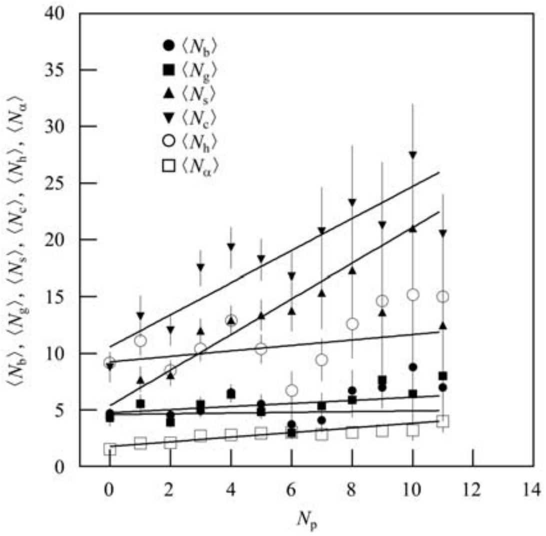

Fig. 4. Variations of $\langle N_{\rm b}\rangle$, $\langle N_{\rm g}\rangle$, $\langle N_{\rm s}\rangle$, $\langle N_{\rm h}\rangle$, $\langle N_{\rm c}\rangle$ and $\langle N_{\alpha}\rangle$ with $N_{\rm p}$ in the ^{84}Kr-emulsion interactions at 1.7 A GeV.

Table 4. Values of the inclination coefficient ($b_{\rm i}$) and intercept ($a_{\rm i}$) of the multiplicity correlations in the ^{84}Kr-emulsion interactions at 1.7 A GeV.

$\langle N_{\rm i}\rangle$	$a_{\rm i}$	$b_{\rm i}$	χ^2/DOF
$\langle N_{\rm b}\rangle$	4.752±0.309	0.135±0.086	1.164
$\langle N_{\rm g}\rangle$	4.594±0.423	0.031±0.097	2.303
$\langle N_{\rm s}\rangle$	5.378±0.587	1.568±0.171	1.165
$\langle N_{\rm h}\rangle$	9.246±0.665	0.242±0.172	1.618
$\langle N_{\rm c}\rangle$	10.572±0.907	1.412±0.219	1.341
$\langle N_{\alpha}\rangle$	1.769±0.119	0.205±0.032	0.825

The multiplicity correlations between projectile spectator protons and grey, black, shower, compound, heavily ionized track particles and projectile helium fragments can be explained by the participant-and-spectator model of nucleus-nucleus interactions. The projectile spectator proton is produced from projectile fragmentation or multifragmentation, which is a quantitative probe of degree of projectile spectator excitation or colliding centrality. In the peripheral or semi-central nucleus-nucleus collisions, with the increase in number of projectile spectator protons, the impact centrality is increased, so the production probability of shower particles, grey particles and compound particles is increased. And also with the increase in projectile spectator protons the excitation of the target spectator is increased, so the production probability of black particles and heavily ionized track particles is increased. In the projectile spectator, with the increase in the number of projectile spectator protons, the excitation of the projectile spectator is increased, so the production probability of projectile helium fragments is increased.

Figure 5(a) and (b) show the correlations between $\langle N_{\rm p}\rangle$ and $N_{\rm b}$, $N_{\rm g}$, $N_{\rm s}$, $N_{\rm h}$, $N_{\rm c}$, N_{α} in the ^{84}Kr-emulsion interactions at 1.7 A GeV. From Fig. 5, it can be seen that there is a weak dependence of $\langle N_{\rm p}\rangle$ on $N_{\rm b}$, $N_{\rm g}$, $N_{\rm h}$, and $\langle N_{\rm p}\rangle$ increases first and then becomes saturated with increasing $N_{\rm c}$ and $N_{\rm s}$. The average multiplicity of the projectile spectator protons first increases and then decreases with increasing numbers of projectile helium fragments. The experimental data can be fitted by a linear relation of the form

$$\langle N_{\rm p}\rangle = (2.631\pm0.123)+(0.007\pm0.014)N_{\rm b}, \qquad (4)$$

$$\langle N_{\rm p}\rangle = (2.617\pm0.113)+(0.004\pm0.012)N_{\rm g}, \qquad (5)$$

$$\langle N_{\rm p}\rangle = (2.673\pm0.127)+(0.002\pm0.008)N_{\rm h}, \qquad (6)$$

$$\langle N_{\rm p}\rangle = (1.178\pm0.127)+(0.256\pm0.029)N_{\rm s}, \qquad (7)$$

$$\langle N_{\mathrm{p}}\rangle = (1.152\pm0.149)+(0.197\pm0.026)N_{\mathrm{c}}, \quad (8)$$

$$\langle N_{\mathrm{p}}\rangle = (1.739\pm0.145)+(0.503\pm0.066)N_{\alpha}. \quad (9)$$

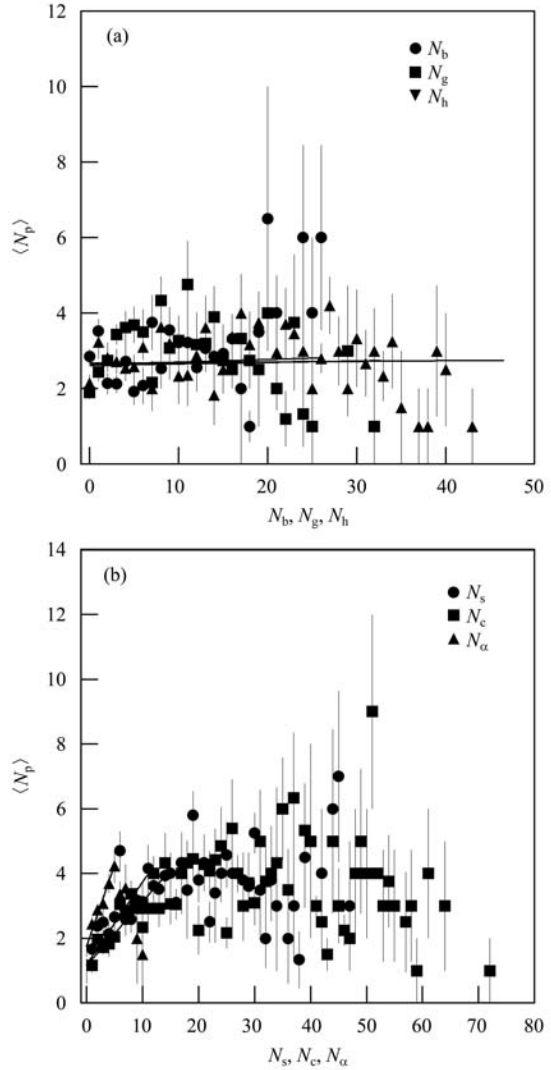

Fig. 5. Variations of $\langle N_{\mathrm{p}}\rangle$ with N_{b}, N_{g}, N_{s}, N_{h}, N_{c}, N_{α} in the ^{84}Kr-emulsion interactions at 1.7 *A* GeV.

These correlations can also be explained by the participant-and-spectator model of nucleus-nucleus interactions. In the peripheral or semi-central nucleus-nucleus collisions, with the increase in black particles and heavily ionized track particles, the excitation of the target spectator is increased, which influences the excitation of the projectile spectator. Because the excitation of the target spectator is not directly related to the projectile spectator, the average multiplicity of the projectile spectator protons is weakly increased. With the increase in the number of shower particles and compound particles, the impact centrality is increased, which directly influences the excitation of projectile spectator and the result of the production probability of the projectile spectator protons, which increases with the increase in the number of shower particles and compound particles first and then becomes saturated because of the limited projectile spectator size. Finally, with the increase in projectile helium fragments, the production probability of the projectile spectator proton is increased first and then decreased because of the limited projectile spectator size.

4 Conclusions

From the present study of projectile spectator proton production in ^{84}Kr-emulsion interactions at 1.7 *A* GeV, it may be concluded that the mean multiplicity of projectile spectator protons increases not only with the increase in the projectile mass at the same beam energy but also with the increase in target mass for the same projectile. The projectile spectator proton multiplicity distribution obeys a KNO type of scaling hypothesis. The multiplicity correlations between the projectile spectator protons and grey, black, shower, compound, heavily ionized track particles and projectile helium fragments can be explained by the participant-and-spectator model of nucleus-nucleus collisions.

We wish to thank Professor I. Otterlund from Lund University, Sweden, for supplying the emulsion plates.

References

1 Bondarenko R A, Gulamov K G, Gulyamov U G, Chernov G M. Sov. J. Nucl. Phys., 1983, **38**: 903
2 Chernov G M, Gulamov K G, Gulyamov U G et al. Nucl. Phys. A, 1984, **412**: 534
3 Andreeva N P, Anzon Z V, Bubnov V I et al. Sov. J. Nucl. Phys., 1988, **47**: 102
4 Basova E S, Navotny V Sh, Petrov N V et al. Phys. Atom. Nucl., 1997, **60**: 1650
5 Tariq M, Zafar M, Tufail A, Ahmad S. Int. J. Mod. Phys. E, 1995, **4**: 347
6 LIU Fu-Hu. Chin. J. Phys., 2003, **41**: 486
7 Fakhraddin S, Rahim M A. Phys. Scr., 2008, **78**: 015101
8 Rahim M A, Fakhraddin S. Nucl. Phys. A, 2009, **831**: 39
9 Firu E, Bradnova V, Haiduc M et al. E-print: nucl-ex/1002.1566, 2010
10 Powell P L, Fowler P H. The Study of Elementary Particles by Photographic Method. Oxford: Pergamon, 1959, 450
11 Koba Z, Neilsen H B, Olesen P. Nucl. Phys. B, 1972, **40**: 317