MULTIPLICITIES IN ^{84}Kr INTERACTIONS IN EMULSION AT 800–950 MeV/NUCLEON

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Inelastic interactions induced by ^{84}Kr nuclei at 800–950 MeV/nucleon have been studied using a high angular resolution emulsion detector. Data on multiplicities of the produced particles, projectile and target fragments are shown. Comparisons with cascade calculations have been performed.

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1 Introduction

Intense experimental and theoretical efforts are presently made to study nuclear collisions at relativistic energies where possible signals of phase transition from a hadron gas to quark-gluon plasma are expected.

At high energies a large amount of experimental data on proton to Au induced reactions in nuclear emulsion were obtained at the Dubna, BNL, CERN and BEVALAC accelerators.

These data often concern different aspects of particle production and nuclear fragmentation.

The present work is devoted to the study of multiplicities of produced particles and nuclear fragments emitted in inelastic interactions of ^{84}Kr with emulsion nuclei at energies of 800–950 MeV/nucleon.

2 Experiment

Stacks of nuclear photoemulsions NIKFI BR-2 with dimension of $10\,\mathrm{cm} \times 20\,\mathrm{cm} \times 600\,\mu\mathrm{m}$ have been irradiated horizontally by a ^{84}Kr beam at the SIS synchrotron at GSI, Darmstadt. The chemical development of emulsion stacks was carried out in the High Energy Laboratory of JINR at Dubna. Each primary track of ^{84}Kr has been followed and all events of $^{84}\mathrm{Kr} + \mathrm{Em}$ collisions registered. The mean free path of ^{84}Kr nuclei in emulsion is equal to 7.10 ± 0.14 cm. For all particles their polar (Θ) and azimuthal (Ψ) emission angles have been measured. Charge assignment for multiply charged f particles (see below) has been provided by delta-electron and/or gap density measurements.

The charged secondary particles have been divided into the following categories:

b particles (black) — slow target fragments with kinetic energy < 26 MeV/nucleon

g particles (grey) — fast target fragments, mainly recoil protons, with energy of $26 \leq T_p < 400$ MeV.

The b and g particles together are called heavily ionizing particles (h) and their number is given by $N_\mathrm{h} = n_\mathrm{g} + n_\mathrm{b}$.

s particles (shower) — singly charged relativistic particles with velocities $\beta > 0.7$, produced outside of the fragmentation cone (at angles larger than 7°);

f particles — singly and multiply charged noninteracting projectile fragments.

Experimental data are compared with calculations from the cascade-evaporation model (CEM), here in the version developed by G.J. Musulmanbekov [1]. In this model colliding nuclei are treated as dilute hadronic Fermi-gas with harmonic oscillator density distributions for $A < 12$ and Woods-Saxon distributions for $A \geq 12$. Inelastic nucleus-nucleus collisions are the results of incoherent superposition of all possible two-body elastic and inelastic nucleon-nucleon interactions. The formation time of secondaries has been taken into account. The decay of residual nuclei has been described by an evaporation model.

3 Experimental results

In Table 1 the mean multiplicities of relativistic s particles and target fragments emitted in ^{84}Kr induced interactions in emulsion are presented. A comparison with results for different beam nuclei at similar primary energies per nucleon 2–5 is made.

Table 1.

Primary nucleus	Ref.	Kin. energy (GeV/nucl.)	n_b	n_g	n_s
^{1}H	2	0.95	2.61 ± 0.11	1.11 ± 0.07	0.54 ± 0.04
^{40}Ar	3	1.0–1.2	5.3 ± 0.2	6.5 ± 0.3	5.3 ± 0.3
^{84}Kr	our	0.8–0.95	4.1 ± 0.2	7.8 ± 0.4	10.6 ± 0.4
^{139}La	4	0.6–1.2	4.4 ± 0.2	6.0 ± 0.3	11.5 ± 0.6
Li, Be, B	5	0.1–0.5	3.7 ± 0.6	4.8 ± 0.7	–
C, N, O, F	5	0.3–0.5	5.0 ± 0.5	6.8 ± 0.5	–
$Z > 3$	5	0.1–0.5	4.6 ± 0.3	6.1 ± 0.3	–
$Z > 10$	5	0.1–0.5	4.2 ± 0.5	5.8 ± 0.6	–

The multiplicity of shower particles increases fastly with increasing projectile nucleus up to mass 84. At this primary energy the group of s particles consists of produced particles, some knocked out target protons and some projectile participants deflected at large angles. The calculations made within the frame of the cascade code [1] showed that the ratio of shower pions to protons is about 1 : 3 in ^{84}Kr + Em collisions at 0.88 GeV/nucleon.

In contrast to the strong n_s dependence on the projectile mass, the multiplicity of the target fragments is practically unchanged. Moreover the numbers of g and b particles are the same as for energies of 3–4 GeV/nucleon [6–8]. Such a constant number of evaporated b particles indicates that the same excitation energy was deposited to the target residue.

Tables 2a and b show the experimental average multiplicities of secondary shower particles, projectile and target fragments in ^{84}Kr + Em interactions at ≈ 0.9 GeV/nucleon for various groups of events, namely, for those with $N_h < 7$, $6 < N_h < 28$ and $N_h > 27$. The values in parentheses are the mean multiplicities calculated in the framework of the cascade — evaporation model for ^{84}Kr + Em interactions.

The mean numbers of all types of secondary particles increase strongly as a function of the degree of disintegration of the target nucleus. The greatest increase is seen in the case of fast target fragments and shower particles. The events with $N_h < 7$ comprise all collisions on hydrogen and light target nuclei (C, N, O) and very

Table 2a.

	$N_h < 7$	$6 < N_h < 28$	$N_h > 27$	All
Events	458 (1010)	288 (609)	131 (385)	877 (2004)
$\langle n_b \rangle$	1.3 ± 0.1 (1.0)	6.7 ± 0.2 (5.7)	8.4 ± 0.4 (11.0)	4.1 ± 0.2 (4.3)
$\langle n_g \rangle$	1.7 ± 0.1 (1.1)	8.3 ± 0.3 (7.0)	27.9 ± 0.8 (34.7)	7.8 ± 0.4 (9.3)
$\langle n_s \rangle$	5.1 ± 0.3 (2.3)	11.7 ± 0.7 (8.3)	27.8 ± 1.0 (25.7)	10.6 ± 0.4 (8.6)

Table 2b.

	$N_h < 7$	$6 < N_h < 28$	$N_h > 27$	All
Events	417 (1010)	253 (609)	116 (385)	786 (2004)
$\langle n_f(Z > 2) \rangle$	1.20 ± 0.03 (0.99)	1.31 ± 0.06 (0.95)	0.71 ± 0.08 (0.73)	1.16 ± 0.03 (0.93)
$\langle n_f(Z = 2) \rangle$	1.86 ± 0.10 (0.46)	2.58 ± 0.13 (1.02)	2.18 ± 0.16 (0.44)	2.14 ± 0.07 (0.62)
$\langle n_f(Z = 1) \rangle$	3.16 ± 0.15 (2.40)	4.67 ± 0.17 (7.00)	5.16 ± 0.25 (6.90)	3.94 ± 0.11 (4.66)
$\langle Q \rangle$	32.0 ± 0.3 (34.5)	26.8 ± 0.5 (29.3)	14.0 ± 0.8 (15.2)	27.7 ± 0.4 (29.2)

peripheral ones with Br and Ag nuclei. The cascade calculation reproduces roughly the experimental mean multiplicities of secondary particles and their dependence on N_h. The theoretical numbers of projectile (PF) and target (TF) fragments are lower than the experimental ones except for event with the largest destruction of the target nuclei ($N_h > 27$). The lack of alpha spectators is noticeable in each group of N_h. To improve the description of α-spectators one needs to include α-clusters into the model of nuclear structure.

The multiplicity spectra of the PF, TF and shower particles are plotted in Fig. 1. The multiplicity distribution of target fragments is relatively wide with two maxima at $N_h = 0$–1 and $N_h = 5$ and a broad tail at large N_h values. This is caused by the yield of Kr interactions with hydrogen, light (C, N, O) and heavy (Br, Ag) emulsion nuclei, respectively. The cascade code reproduces these spectra satisfactorily.

The correlations between multiplicities of different types of particles are more sensitive for comparisons between data and theory. Some examples are plotted in Fig. 2 ($\langle n_s \rangle$ on N_h) and in Fig. 3 ($\langle n_b \rangle$ on n_g) together with the calculations (histograms). The following can be concluded.

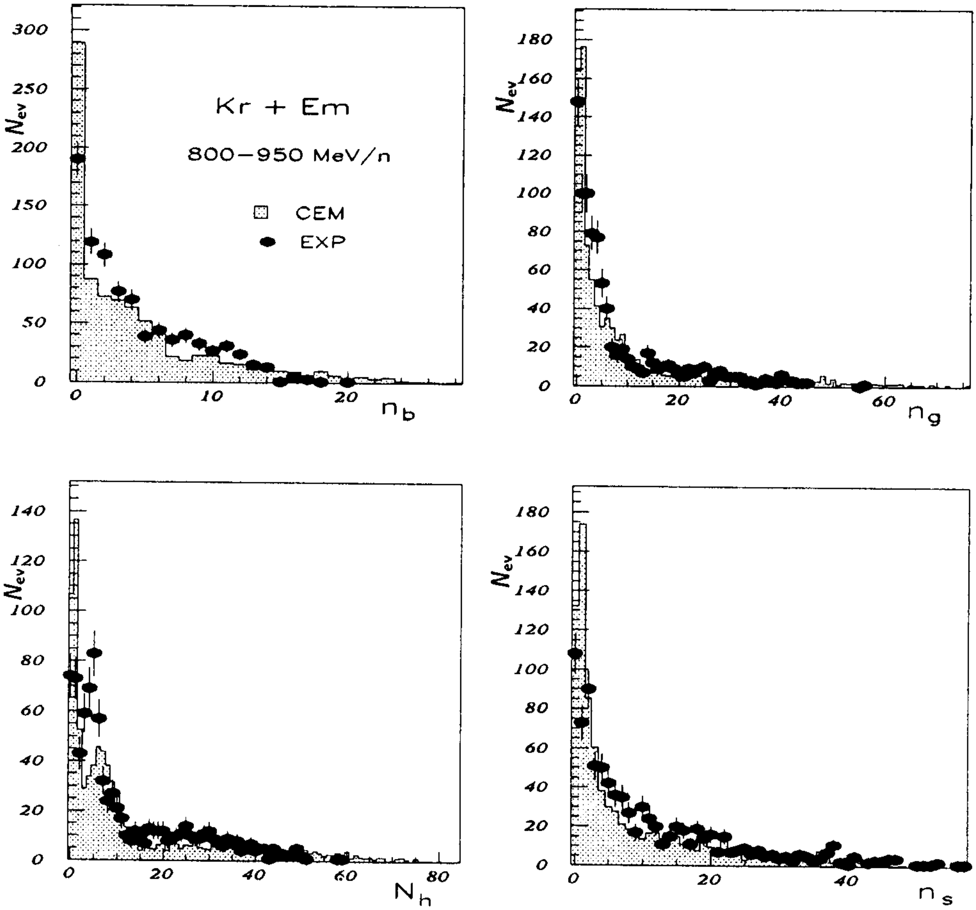

Fig. 1. The multiplicity distributions of black, grey, heavily ionizing and shower particles.

There is a strong dependence of the number of relativistic s particles on N_h with two distinct plateaus in the regions of the smallest impact parameters with light ($N_h \approx 10$) and heavy ($N_h \geq 30$) target nuclei. The calculated correlation substantially differs from the experimental one. This disagreement is caused by the overestimation of cascade rescatterings (g-particles) in the model.

The same correlation measured in [4] for ^{139}La + Em collisions has been fitted to a linear function $\langle n_s \rangle = (2.68 \pm 0.38) + (0.82 \pm 0.08) N_h$ up to the values of $N_h \simeq 40$ (solid line in Fig. 2) for 7 experimental points.

The dependence of $\langle n_b \rangle$ on the number of grey tracks n_g (Fig. 3) in ^{84}Kr + Em interactions differs in shape from those obtained in ^{139}La [4] and ^{40}Ar interactions in emulsion at 1.0–1.2 [3] and 1.8 GeV/n [9], respectively.

The measured dependence of $\langle n_b \rangle$ on n_g differs from those observed in heavy ion interactions at higher (Dubna [6–8], BNL [10], ...) energies except for the linear

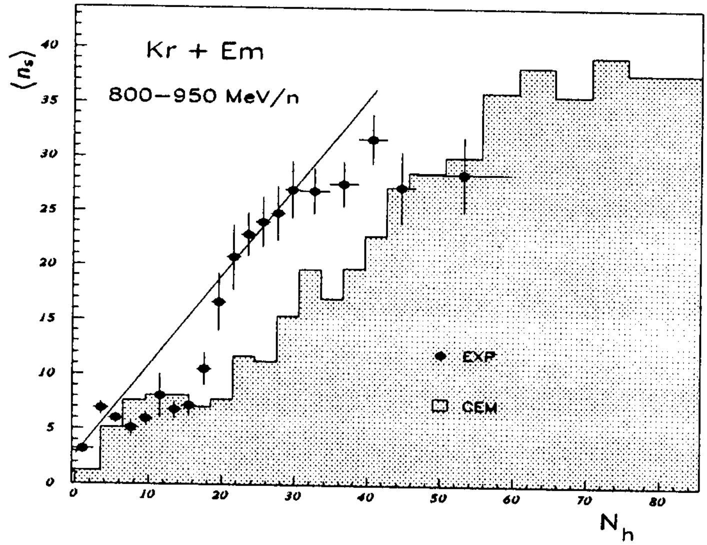

Fig. 2. The multiplicity correlation $\langle n_s \rangle$ on N_h.

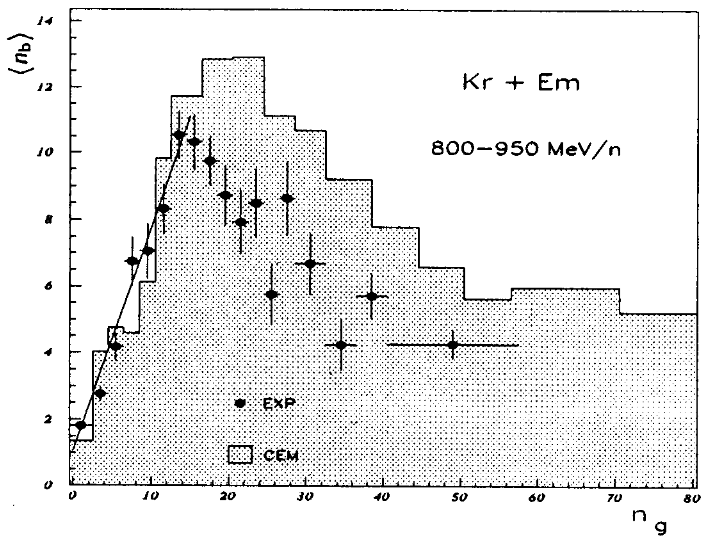

Fig. 3. The multiplicity correlation $\langle n_b \rangle$ on n_g.

increase up to values $n_g \approx 15$. The data may be fitted by linear relation of the form $\langle n_b \rangle = a_1 + b_1 n_g$ (solid line in Fig. 3). The values of the coefficients a_1, b_1 obtained from different experiments are given in Table 3.

Such linear dependence at small n_g can be related to the low degree of cascading in the light target nucleus [9] (or in peripheral collisions with a heavy target), i.e., each recoil particle gives the same contribution to the excitation energy. However,

Table 3.

Primary nucleus	Primary energy (GeV/n)	a_1	b_1
^{40}Ar	1.8	1.72 ± 0.07	0.90 ± 0.17
^{56}Fe	1.7	1.58 ± 0.26	0.80 ± 0.15
^{84}Kr	0.8–0.95	1.08 ± 0.12	0.63 ± 0.04
^{139}La	0.6–1.2	1.36 ± 0.13	0.73 ± 0.09

at higher values of n_g, $\langle n_b \rangle$ falls rapidly until it approaches the value ≈ 5 for the most central Ag, Br collisions (n_g large). In these collisions the target nucleus probably looses many nucleons (Kr projectile can cause many nucleon-nucleon collisions inside the target nucleus) and a smaller residual target nucleus is left for the final evaporation stage of the collisions. The calculations made in the frame of CEM describe satisfactorily the measured dependence for $n_g \leq 15$. The overestimation of $\langle n_b \rangle$ at the region of large number of g-particles comes again from the larger excitation energy of residual nucleus calculated by the model.

Important parameters of the nuclear interactions based on the projectile disintegration are the number $n_{\rm int}$ of participant projectile nucleons and the total charge of projectile spectator fragments Q. We define these as [6] $n_{\rm int} = A_{\rm p} - (A_{\rm p}/Z_{\rm p})Q$ and $Q = \sum_{\rm f} n_{\rm f} Z_{\rm f}$, where $A_{\rm p}, Z_{\rm p}$ are the mass and atomic numbers of the beam nucleus and $n_{\rm f}$ is the number of all projectile fragments with a charge $Z_{\rm f}$ (including singly charged).

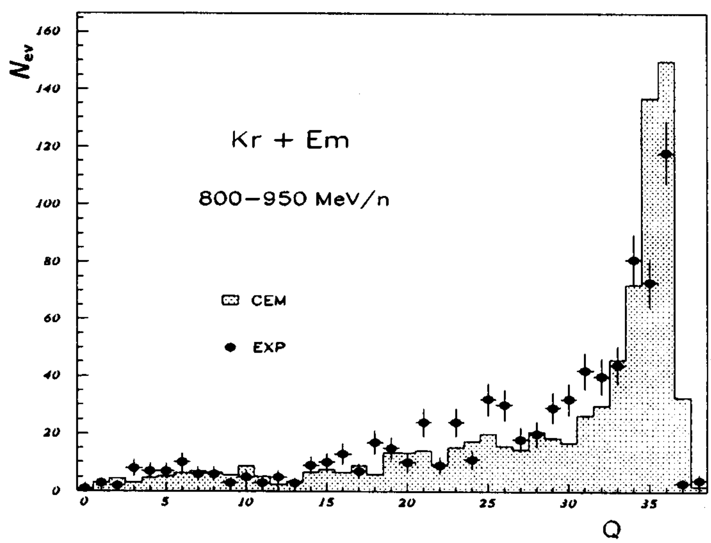

Fig. 4. The distribution of the total charge Q of projectile spectators.

The Q-distribution is given in Fig. 4 for all minimum bias events. Since $\langle Q \rangle = 27.7 \pm 0.4$ the mean number of interacting projectile nucleons is $\langle n_{\rm int} \rangle = 19.4 \pm 0.9$. The CEM reproduces data well. The values of Q or $n_{\rm int}$ should characterize the impact parameter of the interaction. We show in Fig. 5 the Q dependence on the

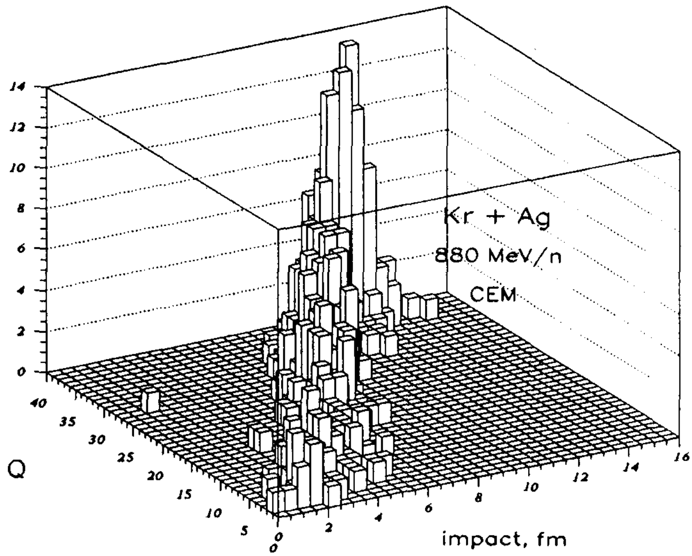

Fig. 5. The calculated (CEM) dependence of Q on impact parameter in ^{84}Kr induced collisions on ^{108}Ag target at 880 MeV/n.

impact parameter as calculated for ^{84}Kr + Ag collisions. The correlation is really very significant. So, the quantity Q (or $n_{\rm int}$) should be a convenient experimental quantity which classifies the nuclear interactions with respect to their degree of centrality well-events with small Q (large $n_{\rm int}$) are central and those with large Q (small $n_{\rm int}$) peripheral.

Figure 6 presents the dependence of the mean multiplicities of secondary particles on the Q value.

These dependences are quite different for various types of particles. The average number of shower particles increases fast and linearly with Q as we go from peripheral to central collisions. The calculated relation reproduces here the experimental one very well, probably because n_s depends only weakly on the particle producing mechanism.

The yield of fast target protons (n_g) increases slowly when going to smaller impact parameters with a saturation for the central events ($Q \leq 10$). The dependence of $\langle n_b \rangle$ on Q is similar for large impact parameters but has a dramatic change for $Q \approx 15$–20, where it reaches a local maximum on n_b. One can see the drastic difference between calculated and experimental behaviour of $\langle n_g \rangle$ on Q. This is caused again with overestimation by the model of rescatterings at large destruction of nucleus.

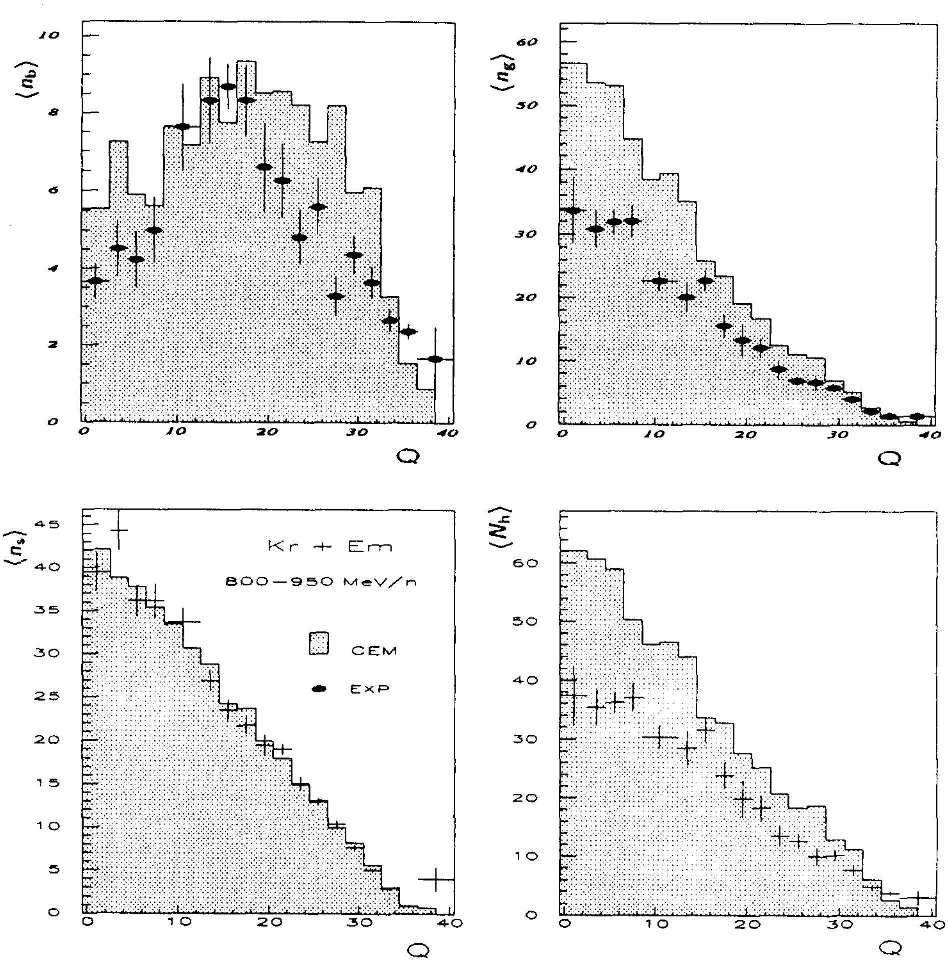

Fig. 6. The dependence of the mean multiplicities $\langle n_{\rm b}\rangle$, $\langle n_{\rm g}\rangle$, $\langle n_{\rm s}\rangle$ and $\langle N_{\rm h}\rangle$ on Q.

4 Conclusion

We summarize the main results of this paper as follows.

The mean numbers of all types of secondary particles produced in ^{84}Kr interactions at 800–950 MeV/nucleon increase strongly with the degree of target nucleus disintegration ($N_{\rm h}$). The largest increase is seen in the case of fast target fragments and shower particles. The CEM describes these behaviours reasonably well. A strong dependence on the mass number of the projectile nucleus is observed for the multiplicities of the g and s particles. On the contrary, the multiplicities of target spectator particles are practically unchanged, which means that the same excitation energy has been deposited for each of them.

The multiplicity of target fragments is relatively widely distributed with a typical form characterized by two maxima at $N_{\rm h} = 0$–1 and $N_{\rm h} = 5$. This is caused by the different targets — hydrogen, light (C, N, O) and heavy (Br, Ag) emulsion nuclei.

The number of target spectators depends linearly on the number of recoil protons up to $n_{\rm g} = 15$ followed by a decrease for higher $n_{\rm g}$, due to smaller residual target nucleus left for the evaporation.

The dependence of the numbers of shower particles on the value of Q (which measures the impact parameter) is linear and well described by the CEM.

The number of g and b particles depends strongly on Q, with decreasing Q (decreasing impact parameter) the contribution of the fast target fragments increases and the yield of the target spectators decreases. The CEM describes this behaviour except for the case of g particles.

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