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Central events in the interactions of ^{28}Si and ^{32}S with heavy emulsion targets

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Abstract. Data on the multiplicity of secondaries in central events of ^{28}Si (14.6 AGeV) and ^{32}S (3.7 AGeV) interactions with AgBr emulsion nuclei have been compiled and studied. The dependence of the multiplicities of the outgoing charged stripping particles on the number of interacting nucleons and therefore on the impact parameter, as indicated by the target size, and consequently, on the degree of centrality is investigated. The resultant multiplicity distribution of the produced pions for each studied case is fitted by both Negative Binomial (NB) and Poisson distributions. The NB distribution is valid for most of the considered cases. The transparency of the target for a projectile was found to become more pronounced as the incident energy increased.

PACS. 25.75.-q Relativistic heavy-ion collisions

1 Introduction

Many currently theoretical and experimental activities [1–8] deal with analyzing the data of high-energy interactions in terms of selecting central events. In studying the inelastic collisions of relativistic particles with AgBr nuclei using the nuclear emulsion as target and detector, the investigators are attracted by events with complete disintegration (*i.e.* without an appreciable residual nucleus). The characteristics of such events are expected to be more sensitive to the choice of interaction model than are the characteristics of the other general events *i.e.*, without special selection of the disintegration degree of the target. The selected events have been regarded as a potentially useful source of information about the underlying production processes as well as the behavior of nuclear matter in extreme states.

From a geometrical point of view, the impact parameter in an asymmetrical central collision is less than or equal to the absolute value of the difference between the radii of the interacting nuclei. Due to the fact that in emulsion experiments the impact parameter can not be experimentally measured, the development of selection criteria for central collisions becomes very important. At present, several criteria have been proposed to select central collisions [5,6].

In the present paper, central events induced by the interactions of 14.6 A GeV ^{28}Si and 3.7 A GeV ^{32}S ions with the heaviest nuclei presented in nuclear emulsion (*i.e.*, AgBr) are systematically selected and analyzed. The selection criteria based on either high degree of target destruction or high multiplicity of outgoing secondary charged particles. These two criteria are examined with and without the appearance of the non-interacting projectile fragments. The data sets are described by either NB and/or Poisson distributions.

2 Experimental technique

This work was performed using two stacks of BR-2 and FUJI types. The emulsion pellicles of these two types have respective dimensions of $10 \times 20 \times 0.06\,\mathrm{cm}^3$ and $10 \times 16 \times 0.06\,\mathrm{cm}^3$. The two stacks were horizontally exposed to 3.7A GeV ^{32}S ions in Dubna Synchrotron and to 14.6 A GeV ^{28}Si ions at Brookhaven Laboratory (BNL) Alternating Gradient Synchrotron (AGS), respectively.

For both kinds of emulsion, the grain density of singly charged relativistic particles is about 30–35 grains per 100 μm at minimum ionization. A total of 785 and 962 inelastic interactions were picked up for the two used ^{32}S and

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^{28}Si beams, respectively using the along the track doubly scanning method (fast in the forward direction and slow in the backward one). The corresponding mean free paths are 9.6 ± 0.3 and 12.7 ± 0.4 cm.

For each detected event, the charged secondaries are classified as follows:

a) Relativistic shower particles (N_s) with velocity $v \geqslant 0.7c$. These particles are mostly produced pions.

b) Grey particle tracks (N_g) with velocity $0.2c < v < 0.7c$ and range in emulsion $R > 3$ mm. These tracks are mainly due to protons with kinetic energy $20 < E_K \leqslant 400$ MeV.

c) Black particle tracks (N_b) having velocity $v < 0.2c$ and range $R < 3$ mm, corresponding to $E_K < 20$ MeV. Grey and black particles together are referred to as the heavy tracks $N_h = N_g + N_b$.

The total number of these charged secondaries per event (*i.e.* $N_s + N_g + N_b$) are denoted by N_{ch} . The projectile fragments (PFs) for each interaction are also observed. Such PF's are emitted within a fragmentation forward cone defined by a critical value of 52 and 13 mrad for 3.7A GeV ^{32}S and 14.6A GeV ^{28}Si, respectively. The total charge (or the sum of the charges) of these PF's is denoted by Q. More details about these PF's are given in ref. [9].

Concerning the criteria for selecting a central collision, it has been shown [10] that the presence of high multiplicity of fragments and pions at large angles and with intermediate energies, may be used as a distinctive feature which allows one to select near-central collisions of relativistic nuclei. From the geometrical concept, an event characterized by such a feature occurs as the result of a small impact collision parameter b within the range $0 \leqslant b \leqslant |R_1 - R_2|$, where R_1 and R_2 are the radii of the target and projectile nuclei, respectively. Heckman *et al.* [1] defined central events as interactions that exhibit the absence of projectile fragmentation (*i.e.*, $Q = 0$). However many other criteria to select central events were used, concerning high N_{ch} multiplicity [5,11] and high degree of target destruction $N_h > 28$ [6,12]. In a previous work [13], the central collisions of ^{12}C-Em at 4.5 A GeV/C were selected as those with $N_h > 28$ with and without forward cone fragments (*i.e.*, with $Q \neq 0$ and $Q = 0$).

In this work from 962 and 785 unbiased inelastic interactions of ^{28}Si (14.6 A GeV) and ^{32}S (3.7 A GeV) with emulsion, 295 and 307 events were, respectively, found to have $N_h > 7$. Such events are due to collisions with AgBr nuclei and are thought to be created by violent destruction of projectile and target nuclei at small impact parameter.

It was observed that the beam energy has an effect on the chosen criteria according to which centrality can be studied for the two used samples. The events of ^{28}Si-AgBr are categorized according to the following criteria:

1) $N_h > 7$ and $Q = 0, 1$,
2) $N_h > 18$,
3) $N_h > 18$ and $Q = 0, 1$,
4) $N_h > 22$,
5) $N_h > 22$ and $Q = 0, 1$,
6) $N_{ch} > 72$,
7) $N_{ch} > 72$ and $Q = 0, 1$.

As for the ^{32}S-AgBr events, the used criteria are

1) $Q = 0$, *i.e.* events characterized by the absence of PFs in the fragmentation cone
2) $N_h > 28$,
3) $N_h > 28$ and $Q = 0$,
4) $N_{ch} > 45$,
5) $N_{ch} > 45$ and $Q = 0$.

The mean values of interacting nucleons $\langle N\text{-}_{int}\rangle$ are experimentally determined from the formula $\langle N_{int}\rangle = A_{proj} - (A_{proj}/Z_{proj}) \sum Z_f$, where A_{proj}, Z_{proj} are the mass and charge numbers of incident beam and $\sum Z_f$ is the total charge of the non-interacting fragments from the projectile in each event.

3 Results and discussion

In tables 1 and 2, the data of multiple production in ^{28}Si (14.6 A GeV) and ^{32}S (3.7 A GeV) are tabulated, respectively. Analysis of these data leads to the following results:

1) The average multiplicity of the produced shower particles, $\langle N_s\rangle$ increases with the increase of both N_h and N_{ch}. The values of $\langle N_s\rangle$ for events characterized by $Q = 0, 1$ for ^{28}Si and $Q = 0$ for ^{32}S are found to be higher than those deduced for the corresponding events taken without any restriction on the Q value. Since the present maximum value of $\langle N_s\rangle$ (82.4 $\pm$9.51) for 76 ^{28}Si events agrees with the corresponding one obtained by EMU01 (84.5 ± 3.4) for their observed 64 central events [14], it can be said that considering the maximum limit value of the total number of outgoing secondaries ($N_{ch} \geqslant 72$) and taking $Q = 0, 1$ for 14.6A GeV ^{28}Si could be a very good way to select the most central events. Consequently, the same idea can be applied for the used ^{32}S beam taking into consideration that the limit value of N_{ch} ($\geqslant 45$) for 3.7A GeV ^{32}S is expected to be smaller than the corresponding value for 14.6 A GeV ^{28}Si ($\geqslant 72$). Since it is possible in the case of the lower used energy (3.7 A GeV) to distinguish between the projectile and target $Z = 1$ fragments in the forward cone, where their number is small, $Q = 0$ is taken as an additional parameter in selecting the central events. Moreover, since Singh and Tuli [6] as well as our previous work [15] consider that $N_h \geqslant 28$ is one of the preferable indications for centrality at 3.7A GeV, the present central selection criteria ($N_{ch} \geqslant 45$ and $Q = 0$) can be the most suitable one. Consequently, the 14.6A GeV ^{28}Si-Em events having $N_{ch} \geqslant 72$ and $Q = 0, 1$ and the 3.7A GeV ^{32}S-Em ones having $N_{ch} \geqslant 45$ and $Q = 0$, represent collisions at a very small impact parameter ($b \approx$ zero).

2) On the other hand, it can be seen that for the most central interactions the average values of grey, $\langle N_g\rangle$, and black, $\langle N_b\rangle$ tracks which are mainly target fragments of low energies seem to be nearly invariant with respect to both the impact parameter and the beam energy. This agrees with the limiting fragmentation hypothesis for the target.

3) The values of the ratio $\langle N_s\rangle/\langle N_{int}\rangle$ which represents the number of generated shower particles per projectile interacting nucleons are nearly the same for each projectile and energy. The same observation applies to the ratio

Table 1. The multiplicities of different charged secondaries, $\langle N_{\rm int}\rangle$, the ratios $\langle N_{\rm s}\rangle/\langle N_{\rm g}\rangle$, $\langle N_{\rm b}\rangle/\langle N_{\rm g}\rangle$, $\langle N_{\rm s}\rangle/\langle N_{\rm int}\rangle$, and $\langle N_{\rm g}\rangle/\langle N_{\rm int}\rangle$, and the probability for central collisions of ^{28}Si with AgBr at different criteria.

Criteria	$N_{\rm h}>7$ $Q=0,1$	$N_{\rm h}>18$	$N_{\rm h}>18$ $Q=0,1$	$N_{\rm h}>22$	$N_{\rm h}>22$ $Q=0,1$	$N_{\rm h}>72$	$N_{\rm ch}>72$ $Q=0,1$
$N_{\rm ev}$	113	122	72	71	46	105	76
Probablity %	16.1	17.8	10.3	10.1	6.6	15 %	10.8 %
$\langle N_{\rm s}\rangle$	67.6±2.49	61.8±2.54	72.2±3.15	65.9±3.00	73.2±3.67	77.6±2.00	82.4±9.51
$\langle N_{\rm g}\rangle$	8.2±0.34	9.0±0.33	9.5±0.42	10.1±0.44	10.0±0.54	8.9±0.38	8.9±1.09
$\langle N_{\rm b}\rangle$	12.4±0.38	14.6±0.31	14.3±0.43	15.9±0.35	15.7±0.45	13.0±0.41	12.9±1.53
$\langle N_{\rm int}\rangle$	27.9±0.04	23.2±0.66	27.9±0.04	24.4±0.78	27.9±0.04	26.2±0.33	27.9±0.04
$\langle N_{\rm s}\rangle/\langle N_{\rm g}\rangle$	8.2±0.45	6.8±0.38	7.6±0.47	6.5±0.41	7.3±0.54	8.6±0.43	9.2±1.53
$\langle N_{\rm b}\rangle/\langle N_{\rm g}\rangle$	1.5±0.08	1.6±0.07	1.5±0.08	1.6±0.08	1.6±0.10	1.5±0.08	1.4±0.24
$\langle N_{\rm s}\rangle/\langle N_{\rm int}\rangle$	2.4±0.09	2.6±0.13	2.6±0.11	2.7±0.15	2.6±0.13	2.9±0.09	2.9±0.34
$\langle N_{\rm g}\rangle/\langle N_{\rm int}\rangle$	0.29±0.01	0.38±0.02	0.34±0.02	0.42±0.02	0.36±0.02	0.34±0.02	0.32±0.04

Table 2. The average multiplicities of different charged secondaries, $\langle N_{\rm int}\rangle$, the ratios $\langle N_{\rm s}\rangle/\ \langle N_{\rm g}\rangle$, $\langle N_{\rm b}\rangle/\ \langle N_{\rm g}\rangle$, $\langle N_{\rm s}\rangle/\langle N_{\rm in}\rangle$ and $\langle N_{\rm g}\rangle/\langle N_{\rm int}\rangle$ and the probability for central collisions of ^{32}S with AgBr at different criteria.

Criteria	$Q=0$	$N_{\rm h}>28$	$N_{\rm h}>28$ $Q=0$	$N_{\rm ch}>45$	$N_{\rm ch}>45$ $Q=0$
$N_{\rm ev}$	68	72	24	131	52
Probablity%	8.7	9.2	3.9	16.7	6.6
$\langle N_{\rm s}\rangle$	35.5±1.58	30.9±1.60	38.5±2.34	34.8±0.97	39.6±1.38
$\langle N_{\rm g}\rangle$	9.5±0.64	11.8±0.50	12.9±0.83	10.5±0.37	10.5±0.65
$\langle N_{\rm b}\rangle$	15.6±0.73	19.6±0.46	18.3±0.82	17.2±0.41	16.5±0.65
$\langle N_{\rm int}\rangle$	32.0±0.00	26.9±0.88	32.0±0.00	24.4±0.44	32.0±0.00
$\langle N_{\rm s}\rangle/\langle N_{\rm g}\rangle$	3.8±0.30	2.6±0.17	2.9±0.26	3.4±0.15	3.8±0.27
$\langle N_{\rm b}\rangle/\langle N_{\rm g}\rangle$	1.7±0.14	1.7±0.08	1.1±0.11	1.7±0.07	1.6±0.12
$\langle N_{\rm s}\rangle/\langle N_{\rm int}\rangle$	1.1±0.05	1.1±0.07	1.2±0.07	1.4±0.05	1.2±0.04
$\langle N_{\rm g}\rangle/\langle N_{\rm int}\rangle$	0.29±0.02	0.44±0.02	0.40±0.03	0.42±0.02	0.32±0.02

$\langle N_{\rm s}\rangle/\langle N_{\rm g}\rangle$ which indicates the number of shower particles per collision. On the other hand, the ratios $\langle N_{\rm g}\rangle/\langle N_{\rm int}\rangle$ and $\langle N_{\rm b}\rangle/\langle N_{\rm g}\rangle$ (which represent the number of collisions per interacting nucleons and the number of evaporated particles per collision, respectively) are found to be nearly constant for both projectiles *i.e.* independent of the beam energy.

It is interesting to investigate for each studied projectile, the relationship between $\langle N_{\rm s}\rangle$ for the central events and the corresponding shower multiplicities for the interactions of the projectile nucleon constituents. In the previous work [13], it was shown that the multiplicity of shower particles for central events can be calculated using the equation:

$$\langle N_{\rm s}\rangle_{\rm centre} = Z_{\rm proj}\langle N_{\rm s}\rangle_{\rm p-Em} + (A_{\rm proj}–Z_{\rm proj})\langle N_{\rm s}\rangle_{\rm n-Em}, \quad (1)$$

where the value of $\langle N_{\rm s}\rangle_{\rm n-Em}$ was estimated on the basis of proton stripping events in d-Em interactions at 4.5 A GeV/c to be equal to 1.8 ± 0.1. Unfortunately, there are no available data concerning the ratio between $\langle N_{\rm s}\rangle_{\rm n-Em}$ and $\langle N_{\rm s}\rangle_{\rm p-Em}$ at 14.6A GeV. However, since this ratio could probably have small energy dependence, it may be possible to use the 4.5A GeV/c ratio (1.8/1.63) to estimate the value of $\langle N_{\rm s}\rangle_{\rm n-Em}$ at 14.6A GeV. Knowing that the corresponding value of $\langle N_{\rm s}\rangle_{\rm p-Em}$ was given in ref. [16] to be 4.9 ± 0.1. Hence, a value of 5.4 for $\langle N_{\rm s}\rangle_{\rm n-Em}$ at 14.6A GeV can be used.

Applying eq. (1) in both cases of ^{32}S-Em at 3.7 A GeV(4.5 AGe V/c) and ^{28}Si-Em at 14.6A GeV, the values of the central average multiplicity of the shower particles would be equal to 55 and 144, respectively. Since these two values are higher than the experimentally observed ones, it may be thought that some of the projectile nucleons are not involved in the studied interactions. The present data can be fitted by the following equations:

$$\langle N_s\rangle_{\rm centre(si)} = Z_{\rm proj}^{0.79}\langle N_{\rm s}\rangle_{\rm p-Em} + (A_{\rm proj} - Z_{\rm proj})^{0.79}\langle N_{\rm s}\rangle_{\rm n-Em} \quad (2)$$

and

$$\langle N_s\rangle_{\rm centre(s)} = Z_{\rm proj}^{0.88}\langle N_{\rm s}\rangle_{\rm p-Em} + (A_{\rm proj} - Z_{\rm proj})^{0.88}\langle N_{\rm s}\rangle_{\rm n-Em}\,, \quad (3)$$

where it can be noticed that as the energy of the projectile increases, the number of its participant nucleons decreases, *i.e.* the transparency of the target for a projectile, which was proved to exist in central collisions of different projectiles with AgBr emulsion nuclei at various energies [5, 17], becomes more pronounced with the increase of the incident energy.

Figures 1 and 2 show the multiplicity distributions of shower particles produced in ^{28}Si-AgBr (at 14.6 A GeV) and ^{32}S-AgBr (at 3.7 AGeV) central collisions for different groups of $N_{\rm h}$ and $N_{\rm ch}$ with and without restrictions

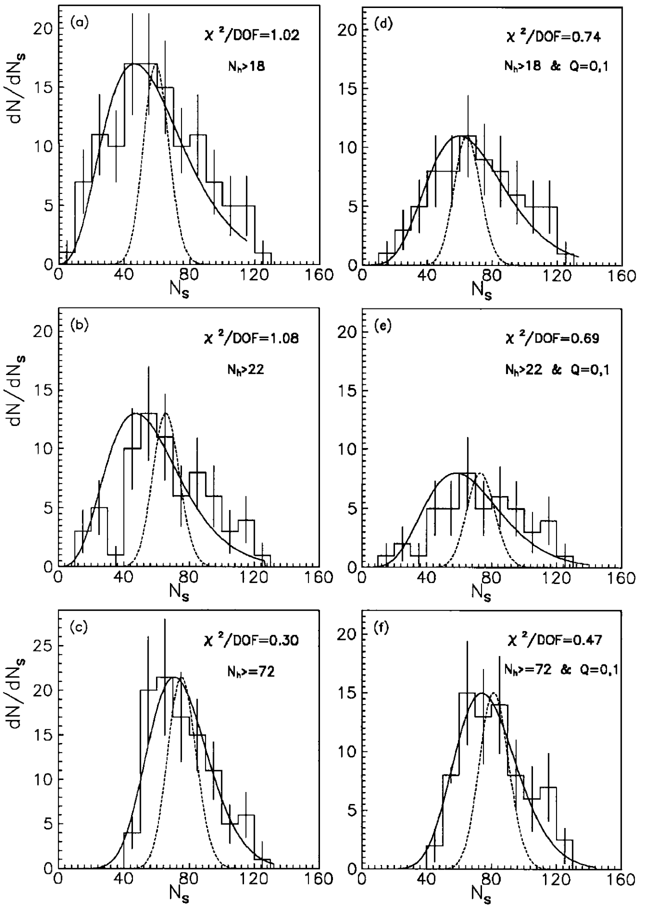

Fig. 1. Multiplicity distributions of shower particles in ^{28}Si-AgBr central events. The solid curves are the predictions of the NB distribution. The dashed curves represent the calculations according to Poisson distribution. The histograms are for the experimental events selected on the basies of the following criteria: (a) $N_{\rm h} > 18$, (b) $N_{\rm h} > 22$, (c) $N_{\rm ch} > 72$, (d) $N_{\rm h} > 18$ and $Q = 0, 1$, (e) $N_{\rm h} > 28$ and $Q = 0, 1$ and (f) $N_{\rm ch} > 72$ and $Q = 0, 1$.

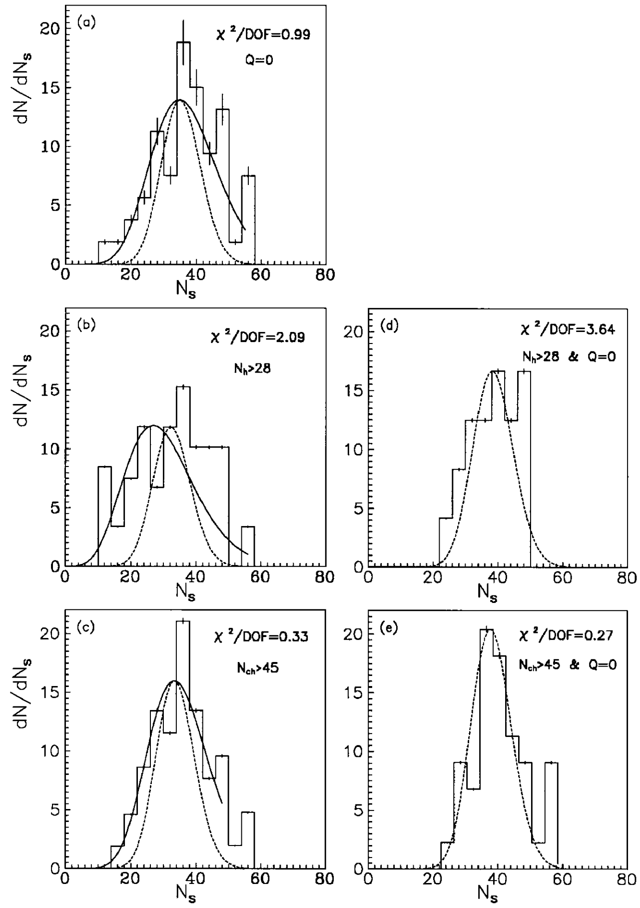

Fig. 2. Multiplicity distributions of shower particles in ^{32}S-AgBr central events. The solid curves are the predictions of the NB distribution. The dashed curves represent the calculations according to Poisson distribution. The histograms are for the experimental events selected on the basies of the following criteria: (a) $Q = 0$, (b) $N_{\rm h} > 28$, (c) $N_{\rm ch} > 45$, (d) $N_{\rm h} > 28$ and $Q = 0$ and (e) $N_{\rm ch} > 45$ and $Q = 0$.

on the value of the Q parameter (total charge of the non-interacting projectile nucleons). These experimental data are examined by predictions of both the NB[1], the solid curves, and the calculations according to Poisson distributions, the dashed curves, to check which of these yields the best distributions fit in each case. Concerning the ^{28}Si-AgBr interactions, it can be seen that the predictions of the NB distribution agree more clearly with the experimental data than do the calculations according to Poisson distribution. In refs. [18,19], it was observed that the experimental data can only be described by the NB distribution. For each pair of curves and as can be seen from tables 1 and 2, the corresponding values of $\langle N_{\rm s}\rangle$ and $\langle N_{\rm int}\rangle$ increase whenever the Q value is taken into consideration.

For ^{32}S interactions, when the Q value is considered as the only parameter to identify centrality, fig. 2 (a) indicates that while the Poisson distribution yields a reasonable agreement with the experimental results, the NB distribution is better. Moreover it was found that depending on the value of $N_{\rm h}$ or that of $N_{\rm ch}$ to select the central events and neglecting the Q parameter (fig. 2 (b) and (c)), both NB and Poisson distributions satisfactorily fit the data where the NB distribution achieves again the more acceptable fit. On the other hand, when the Q parameter is also taken into account (fig. 2 (d) and (e)), the Poisson distribution is the only one to work where it agrees well with the experimental data (since in this case the value of the parameter k in NB distribution tends to infinity which is the condition reached with the Poisson distribution) . The best fit is observed for events having $N_{\rm ch} > 45$ and $Q = 0$, where the minimum value of $\chi^2/{\rm dof}$ is obtained.

[1] The NB probability law for the multiplicity $n_{\rm s} > 0$ of single charged produced particles is given by $P(n_{\rm s}) = \frac{k(k+1)..........(k+n_{\rm s}-1)}{n_{\rm s}!}\left(\frac{\langle n_{\rm s}\rangle}{\langle n_{\rm s}\rangle+k}\right)^{n_{\rm s}}\left(\frac{k}{\langle n_{\rm s}\rangle+k}\right)^{k}$, where k is a real quantity related to the dispersion D ($D = \sqrt{\langle n_{\rm s}^2\rangle - \langle n_{\rm s}\rangle^2}$) as follows: $D^2 = \langle n_{\rm s}\rangle + \langle n_{\rm s}\rangle^2/k$.

Therefore, the events characterized by $N_{\rm ch} > 72$ and $Q = 0, 1$ for ^{28}Si and by $N_{\rm ch} > 45$ and $Q = 0$ for ^{32}S and which as previously observed from tables 1 and 2 possess the maximum values of $\langle n_{\rm s} \rangle$, yield the minimum values of χ^2/dof when compared with the NB distributions. Nevertheless, the other used criteria for centrality are also acceptable.

4 Conclusions

The study of the various selecting criteria for classifying central interactions of ^{28}Si-AgBr (at 14.6 A GeV) and ^{32}S-AgBr (at 3.7A GeV), allows us to draw the following conclusions:

1) The events characterized by $N_{\rm ch} \geqslant 72$ and $Q = 0, 1$ (for ^{28}Si) and by $N_{\rm ch} \geqslant 45$ and $Q = 0$ (for ^{32}S) possess the highest values of $\langle N_{\rm s} \rangle$ and $\langle N_{\rm int} \rangle$ therefore can be considered as the most central ones. These events are characterized by the smallest impact parameter (around zero), representing complete overlap of the projectile and target nuclei.
2) The $N_{\rm s}$ distributions of these events are also found to give the minimum values of χ^2/dof when compared with the suitable mathematical predictions (NB or Poisson distribution).
3) The number of the projectile nucleons which take part in an interaction, decreases with the increase of the projectile energy. This reflects that the transparency of the target for a projectile becomes more pronounced as the incident energy increases.

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