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REPORT NO. 1671/PH

INTERACTIONS OF 10.6 GeV/n GOLD NUCLEI WITH LIGHT AND HEAVY TARGET NUCLEI IN NUCLEAR EMULSION

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Kraków, March 1994

WYDANO NAKŁADEM
INSTYTUTU FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
KRAKÓW, UL. RADZIKOWSKIEGO 152

Kopia offsetowa, druk i oprawa: DRUKARNIA IFJ
Współpraca wydawnicza: SEKCJA WYDAWNICTW
DZIAŁU INFORMACJI NAUKOWEJ IFJ

Wydanie I zam. 35/94 Nakład 85 egz.

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ABSTRACT

We have investigated the particle production and fragmentation of nuclei participating in the interactions of 10.6 GeV/n gold nuclei in nuclear emulsions. A new criteria has been developed to distinguish between the interactions of these gold nuclei with the light (H,C,N,O) and heavy (Ag,Br) target nuclei in the emulsion. This has allowed separate analyzes of the multiplicity and pseudo-rapidity distributions of the singly charged particles emitted in Au-(H,C,N,O) and Au-(Ag,Br) interactions, as well as of the modes of breakup of the projectile and target nuclei. The pseudo-rapidity distributions show strong forward asymmetries, particularly for the interactions with the light nuclei. Heavy target nuclei produce a more severe breakup of the projectile gold nucleus than do the lighter targets. A negative correlation between the number of fragments emitted from the target nuclei and the degree of centrality of the collisions has been observed, which can be attributed to the total destruction of the relatively light target nuclei by these very heavy projectile nuclei.

1 Introduction

Nuclear emulsion detectors provide an excellent tool to study the global characteristics of nucleus-nucleus interactions, since they allow a simultaneous investigation of the processes of nuclear fragmentation and multiparticle production, and allow a study of the correlations between these processes. However, one problem encountered in interpreting the results from nuclear emulsion experiments is the non-homogeneity of the emulsion, which contains both light (H,C,N,O) and heavy (Ag,Br) target nuclei. Till now all attempts at separating the interactions in nuclear emulsion into two inclusive and pure samples of interactions with these light and heavy nuclei have not been entirely satisfactory. It appears, however, that for the interactions of these relatively high energy gold nuclei, it is possible to obtain cleaner samples than hitherto, by using the correlation between the number of created charged particles and the number of slow fragments emitted from the target nucleus.

This paper is organized as follows: Sec.2 contains a short description of the emulsion experiment BNL 868. In Sec.3 we describe the new method of separating the interactions of these high energy gold projectiles in emulsion into two samples representing the collisions with light and heavy targets. The production of charged particles and their pseudo rapidity distributions for these two samples are presented in Sec.4. Secs.5 and 6 are devoted to a description of the fragmentation processes of nuclei involved in the collision. The correlations between the fragmentation and the centrality of collision are discussed in Sec.7. Conclusions are presented in Sec.8.

Preliminary results on the multiparticle production and the fragmentation processes of nuclei participating in the collisions of 10.6 GeV/n gold nuclei in emulsion were presented in a previous paper [1]. The main objective of this particular paper is to present an analysis of a larger sample of these interactions of gold nuclei, with special emphasis on the inclusive interactions with separated light and heavy target nuclei. We defer to later papers and further improved statistics a discussion of the application of these results to considerations of statistical theories of multifragmentation [2], such as percolation [3], or shattering [4]. Similarly, we have deferred discussion of the most central interactions with complete breakup of the projectile nuclei and large multiplicities to later.

2 Experiment

Stacks composed of horizontal BR–2 nuclear emulsion pellicles were exposed at the Brookhaven National Laboratory (exp. BNL 868) to a beam of gold ions accelerated by the AGS to a kinetic energy of 10.6 GeV/n. Interactions of the gold nuclei in the top few cms of the emulsions were found by microscope scanning with moderately high magnification along the tracks of the incident projectile nuclei. Each interaction detected was analyzed in terms of the tracks produced by the various types of charged particles emitted, and classified according to the common terminology used in emulsion experiments.

The number of singly charged relativistic particles is denoted by n_s, and includes both the particles created in the interaction, mostly pions, and those singly charged particles, mostly protons, released from the projectile or knocked-on from the target. The angles of emission of these particles were measured with sufficient precision to determine the pseudo-rapidities to within 0.05 of a unit. The number of created charged particles, n_π, which, as defined, may include a few protons knocked-on from the target, is calculated for each event by charge conservation from $n_\pi = n_s - n_p$. Here n_p is the number of released protons, calculated from: $n_p = Z_{Au} - (\sum Z_F + 2N_\alpha)$, where N_α is the number of alpha particles and Z_F is the charge of heavier fragments, $Z \geq 3$, emitted from the projectile. The charges of these fragments were measured by delta ray counts, with an accuracy that was better than 5% over the entire charge range.

Slow ($\beta \leq 0.7$) charged particles emitted from the struck target nucleus, whose number per event is denoted by $N_h = (N_g + N_b)$, were separated into two groups based on their ionization relative to that of relativistic singly charged particles, I_0. The N_g "grey tracks" are those with lower ionization, $1.4I_0 < I < 10I_0$, and are mostly produced by recoil protons, deuterons and tritons. The N_b "black tracks" with higher ionization, $I \geq 10I_0$, are mostly due to low energy ($\beta \leq 0.3$) singly and multi-charged target fragments. The angles of emission of these slow particles were measured to within 1 degree, sufficient for these analyses. The mean numbers of these different classes of tracks in these interactions are given in Table 1.

The very thick tracks produced by gold nuclei in emulsion could make it difficult to detect those interactions where only a few singly charged fast particles are emitted, small n_s, with no accompanying alphas or fragments and few if any grey and/or black tracks from the target, small N_h. Thus, our sample of gold interactions could be lacking such events. However, there is a rather good agreement between the interaction mean free path found experimentally of 4.7 ± 0.2 cm [1,5] and the predicted values of 4.4 cm, based on measurements made by electronic detectors on the same beam [6], and 4.6 cm, based on parametric fits to data on other beams of heavy ions [7, 8], for the charge changing interactions of gold nuclei in emulsion. Thus, we conclude that our detected interactions of gold nuclei in emulsion represent a sample with a minimal bias.

3 Separation of interactions with light and heavy target nuclei

The separation of the interactions into two groups corresponding to those with light and heavy emulsion target nuclei has traditionally been based solely on the value of N_h. Those interactions with N_h greater than about 6–7 were assumed to have been on heavy targets from simple considerations of charge conservation. However, such a separation clearly did not identify those interactions with heavy target nuclei where the excitation of the target was such that only a few slow particles were emitted because the interactions were peripheral.

For these relatively high energy gold projectiles we find that a better separation between the two classes of target nuclei can be based on the variations of n_π with N_b. A scatter plot of these two variables for this minimum bias sample is shown in Fig. 1. In this plot we can easily distinguish two discrete groups of interactions: one with small N_b and small n_π, and the remainder. These two groups are separated by a region that is practically unpopulated except for a few events with very small values of n_π and with N_b between 5 and 7. Assigning these events to either of the two groups of interactions has a negligible influence on the total numbers of events in each group and hence on our further analysis and conclusions. We have defined a straight line boundary parameterized by $n_\pi \leq 130 - 26N_b$ and assumed that this separates the inclusive sample into the two groups of interactions with (H,C,N,O) and (Ag,Br) nuclei respectively. Choosing a slightly different parameterization would make little difference to the populations. The numbers of interactions in each group, and their mean characteristics, are given in Table 1.

There are two experimental facts which, in our opinion, confirm the assumption that this method of separation has allowed us to identify relatively clean samples of interactions on the two classes of target nuclei:

1. The fractional yields of the selected gold interactions that are assumed to be with (H,C,N,O) and (Ag,Br) nuclei are 0.57 ± 0.03 and 0.43 ± 0.03 respectively. These assumed yields are in good agreement with the values of 0.56 and 0.44 that can be calculated from the composition of emulsion and the nucleus-nucleus charge changing cross-sections [9].

2. The ratio of the mean value of n_π of created charged particles in the (Ag,Br) group to that in the (H,C,N,O) group is 5.3 ± 0.4. This may be compared with the calculated ratio of 5.9 for the mean numbers of elementary nucleon-nucleon collisions in these two groups of interactions. For these calculations we used the emulsion composition and the same nucleus-nucleus cross-sections as in item 1. Such agreement is expected based on the assumption that the interactions can be described by simple superposition models.

4 Production of charged particles

The multiplicity distributions of created charged particles, n_π, in Au–(H,C,N,O) and Au–(Ag,Br) interactions, are presented in Fig. 2. It can be seen that in both samples the probabilities are greatest that only a few particles be produced. However, for the heavy targets there is an extended tail to the distribution, and that for $n_\pi > 100$ the probability of producing many particles only falls slowly out to values of n_π of about 300. The mean numbers of created charged particles in each of these samples are given in Table. 1.

The distribution of the pseudo-rapidity variable, η, of these relativistic singly charged particles emitted in inclusive Au–Em interactions is depicted in Fig. 3a. This shows that there is a peak value of η in this distribution at η about 2.3, which is much greater than the mean value of $\eta = 1.6$ for pp collisions at the same incident energy. A pronounced forward asymmetry of the distribution with respect to η_{peak} is observed. This can be attributed to the fact that the distribution includes both the created particles and the numerous ($\langle n_p \rangle = 30.4 \pm 0.8$ c.f. $\langle n_\pi \rangle = 49 \pm 2$, Table 1) released protons from the projectile, which cannot be identified on a track by track basis. The η distribution of the released protons will differ significantly from that of the created particles. It should be strongly peaked forward, due to the appreciable fraction of spectator protons that can be expected to be included among the released protons. The forward shift and the asymmetry of the overall experimental distribution is then explained by two factors: the strong asymmetry of the interacting nuclei, with the gold projectile always being much larger than the target nucleus, and the relatively large fraction of released protons among the singly charged relativistic particles. The influence of these factors will be stronger in the interactions of gold with the light (H,C,N,O) nuclei than with the heavier targets. The fraction of released protons among singly charged particles increases from 0.31 ± 0.05 in interactions with (Ag,Br) nuclei to 0.55 ± 0.03 with (H,C,N,O) nuclei. As a result the asymmetry is more pronounced in interactions with (H,C,N,O) than with (Ag,Br), as can be seen in Fig. 3b, where the η distributions of heavy and light targets are plotted separately.

5 Fragmentation of the projectile gold nucleus

The mean numbers of fast fragments, $\langle N_F \rangle$, and their mean charges, $\langle Z_F \rangle$, are listed in Table 1, together with the mean numbers of alpha particles emitted from the projectile, $\langle N_\alpha \rangle$. We see that the average multiplicities of fragments and alpha particles do not differ appreciably between the interactions of gold with light and heavy target nuclei. However, the mean charge, $\langle Z_F \rangle$, is significantly smaller for the heavy target nuclei than for the light nuclei, showing a greater degree of breakup of the projectile by the heavy targets.

The distributions of the probabilities of emission of a given number, N_F, of fragments with $Z > 2$ in interactions of gold in emulsion, and for the interactions with the light and heavy targets, are depicted in Figs. 4a and 4b. It appears that for $N_F > 1$ the N_F distributions for the light and heavy target nuclei are nearly identical. However, in interactions with light nuclei the gold projectile is essentially never completely disrupted,

$P(N_F=0)=0.016\pm0.006$, whereas in interactions with heavy nuclei $P(N_F=0)=0.18\pm0.02$. On the other hand the probability of emission of a single projectile fragment, having a mean charge of 62.5, is significantly higher for light targets, $P(N_F=1)=0.45\pm0.03$ than for heavy targets, $P(N_F=1)=0.32\pm0.03$, where the mean charge is only 37.6.

The distributions of the probabilities for the emission of a given number of alpha particles in the three data sets are shown in Fig. 5a and 5b. For $N_\alpha > 1$ they show a similar effect to that seen for the fragments, i.e. the probabilities for the light and heavy nuclei are, within the statistics, nearly identical. For $N_\alpha \leq 1$ they are appreciably less for the heavy targets than for the light targets.

The distribution of the probabilities for the emission of the total charge $Z_{bound} = (\sum Z_F + 2N_\alpha)$ bound in multicharged fragments for interactions of gold in emulsion are presented in Fig. 6a. Those for interactions of gold with light and heavy targets are shown in Fig. 6b. The shape of the distributions is very different. We see that in interactions with light target nuclei the probabilities for events with small Z_{bound} are very small, and that the highest probabilities are for events with most of the charge still bound, Z_{bound} close to the charge of the projectile. On the other hand in the interactions with the heavy target nuclei (see Fig. 6b) the probabilities are almost independent of Z_{bound}. These differences in the probability distributions are reflected in the mean values of Z_{bound} (see Table 1). From these considerations we see that the calculated mean number of released protons, $n_p = (79 - \langle Z_{bound} \rangle)$ from gold projectiles in interactions with heavy targets is twice as large as the number of released protons in interactions with light targets. All the above observations show that the disruption of a gold nucleus is more severe in interactions with heavy than with light nuclei.

6 Fragmentation of the target nuclei

The products of the fragmentation of the residual target nucleus are very slow ($\beta \leq 0.3$) singly and multi charged fragments. These particles leave heavily ionizing black tracks in the emulsions. The N_b probability distributions are shown in Fig. 7a and 7b. The corresponding mean values are given in Table 1. One can see that for the interactions in emulsion the N_b distribution exhibits a peak at $N_b = 0$ and a long tail of large N_b values. The same behaviour of the N_b distributions has been observed previously in interactions of hadrons and light nuclei in emulsion [9]. Fig. 7b shows that this behaviour comes from the convolution of the N_b distributions for light and heavy target nuclei.

It is worthwhile to emphasize that in spite of the fact that the distributions of N_b and their mean values are very different for interactions of gold with heavy and light nuclei, the angular distributions of the black tracks, which are shown in Fig. 8, are essentially identical and do not depend on the mass of the target nuclei. Both distributions are compatible with an isotropic emission of the products of fragmentation from target nuclei that have received a small, and similar, forward velocity in the interaction . A similar shape for the angular distribution of N_b was also observed with different projectiles [10] and different degrees of centrality of collision [11].

7 Correlations between the parameters describing fragmentation processes and the centrality of collision

If we assume that the number of created particles is a measure of how central was the collision, we can use the number n_π of created charged particles as a parameter to define the degree of centrality of the collision. This is consistent with the assumprion that larger numbers of created particles are a consequence of more intranuclear nucleon- nucleon collisions. The relation between $\langle N_b \rangle$ and n_π for emulsion interactions is shown in Fig. 9a.

The same correlation has been reported previously [1] but with lower statistics. We observe a rapid fall of $\langle N_b \rangle$ for n_π values greater than about 120 which, as we have assumed above, can only be from interactions that are central collisions with heavy nuclei. This fall may be explained by assuming that beyond a certain point further increases in the number of nucleon-nucleon collisions lead to the consequence that less and less of the residual spectator matter remains as an excited nucleus that can produce slow target fragments.

The separate relationships between $\langle N_b \rangle$ and n_π for interactions with light and heavy nuclei are shown separately in Fig. 9b. We see that for both samples the mean number $\langle N_b \rangle$ of black tracks generally decreases with increasing n_π with the exception for very peripheral collisions on heavy targets characterized by very small multiplicities of created particles. The observed increase in Fig. 9a of $\langle N_b \rangle$ with increasing n_π up to about 120 is thus seen to be a consequence of the weighted combination of the interactions with both light and heavy nuclei. This artificial effect is caused by the increasing contribution of interactions with heavy (Ag,Br) nuclei at high n_π values, while the physical effect observed in separate groups of interactions of gold with (H,C,N,O) and (Ag,Br) (except for the most peripheral collisions with (Ag,Br), $n_\pi \lesssim 50$) is the same, namely the decrease of $\langle N_b \rangle$ with increasing n_π. This kind of correlation is significantly different to what we have observed previously in hadron and light nucleus interactions in emulsion at energies of up to 200 GeV/n [12,13,14], in which the number of fragments from the target increased with the centrality of collision, eventually becoming saturated for very central collisions [10], but showing no significant decreases.

Alternatively we can study the fragmentation of the gold nuclei as target nuclei in their frame of reference. In this system the gold is regarded as being bombarded by light or heavy projectiles. In this case the role of the number N_b of black tracks in the lab. system is played by the sum of the number of multicharged fragments, $N_{tot} = (N_F + N_\alpha)$ plus the number of spectator protons. Experimentally, however, this number cannot be determined because the spectator protons can not be distinguished from the singly charged produced particles. Nevertheless, we may assume that the observed relation between the total number of multicharged fragments, N_{tot}, and the number of created particles, n_π, should reflect the relation that must exist between $\langle N_b \rangle$ and n_π in interactions of light and heavy projectiles with gold target nuclei. The observed dependence of $\langle N_{tot} \rangle$ on n_π is shown in Fig. 10 for all three samples. It can be seen that for the interactions of heavy nuclei with Au nuclei, the number $\langle N_{tot} \rangle$ of multicharged fragments increases with increasing number n_π of created particles and then, for still higher n_π, decreases. As for the fragmentation of the emulsion nuclei, this corresponds to the increase in excitation of the target nucleus with increasing centrality of collision until the number of nucleon-nucleon collisions becomes so large that less and less of the gold nucleus is left to produce fragments.

For the interactions of light projectile nuclei with Au target nuclei we only see the beginnings of a small decrease of $\langle N_{tot} \rangle$ with increasing n_π, because in the case of a light projectile and a heavy target, the only observed process is the continued increase of the excitation of the target nucleus with the increasing centrality of the collision. Fig. 10 also shows the relation between $\langle N_{tot} \rangle$ and n_π for interactions of emulsion nuclei with gold nuclei. For n_π greater than about 100 the values of $\langle N_{tot} \rangle$ coincide for interactions of emulsion nuclei and heavy nuclei with gold nuclei, because, by definition, the two samples of interactions are identical. It is worthwhile to point out that the values of $\langle N_{tot} \rangle$ are practically the same for a given value of n_π, i.e. for a given number of intranuclear nucleon-nucleon collisions (in the framework of superposition models), irrespective of the mass of the projectile. Similar behavior has also been observed for 200 GeV/n oxygen and sulfur interactions in emulsion [13]. The correlations between the mean number $\langle N_b \rangle$

and n_π for these light projectiles are depicted in Fig. 11. Again the $\langle N_b \rangle$ vs n_π dependence does not change with the mass of the projectile. Since the projectiles are light nuclei (oxygen and sulfur) we observe an increase of $\langle N_b \rangle$ with increasing centrality of collision and then, for still higher degree of centrality (large n_π values) a saturation of $\langle N_b \rangle$ only, with no significant decreases.

8 Conclusions

- We have shown that, for very heavy and energetic projectiles such as the gold nuclei studied here, it is possible to achieve a better separation than hitherto of the interactions occurring in emulsion into those with the light (H,C,N,O) and heavy (Ag,Br) target nuclei in the emulsion. This separation depends on the relation between the number of created charged particles and the number of fragments emitted from the target nucleus.

- We have found on the basis of these considerations that the number of created charged particles in interactions of gold with light target nuclei does not exceed 100, while the highest observed number of created particles in interactions of gold with heavy nuclei is close to 300. However, there is still about 5% of the interactions with heavy targets that have very small multiplicities of created charged particles, less than 10.

- The pseudo rapidity distributions of the relativistic singly charged particles produced in interactions with either light or heavy target nuclei are asymmetric with respect to the peak value, η_{peak} which in turn is shifted toward higher values of η when compared with that found in pp collision at the same energy per nucleon. These effects are caused by the presence of the many released protons among the singly charged relativistic particles and by the asymmetry in mass of the colliding particles.

- The fractional yield of interactions without projectile fragments heavier than helium is about 18% for interactions of gold with heavy target nuclei, but only about 2% for interactions with light nuclei. Also the number of released protons from the gold projectile in interactions with heavy nuclei is twice as large as in interactions with light nuclei. These facts lead to the conclusion that the disruption of the residual gold nuclei is more pronounced in collisions with heavy than with light nucleus. The fragmentation of the nuclei undergoing these energetic interactions may proceed through the creation of a residual excited nucleus and then a slow de-excitation which proceeds by consecutive emission of nuclear fragments. In this process the number of nuclear fragments produced initially increases with increasing centrality of the collision. However, after reaching a certain degree of centrality, the number of nuclear fragments then decreases as the centrality increases further. This may be due either to a large number of intranuclear nucleon-nucleon collisions which result in less and less of the residual target nucleus being left as an entity, or it may indicate that a violent explosion of the target nucleus occurs in which the nuclear remnants are no longer emitted as slow particles in the rest system of the nucleus. The positive or negative correlation between the mean number of fragments emitted from the struck target nucleus and the number of created charged particles depends on the mass of the colliding nuclei and the degree of centrality of collision. In the case of the collision of a light projectile and a heavy target, essentially only the positive correlation is observed. On the other hand in the case of a projectile significantly heavier than the target, the positive correlation observed for peripheral collisions becomes a negative one as the centrality of the collisions increases.

Table 1: Mean numbers and charges of different kind of particles emitted in interactions of gold in emulsion and *with* light (H,C,N,O) and heavy (Ag,Br) emulsion target nuclei. For notations see the text.

	Emulsion	(H,C,N,O)	(Ag,Br)
N	761	434	327
$\langle n_s \rangle$	80±3	38.4±1.7	134±5
$\langle n_\pi \rangle$	49±2	17.4±1.0	92±4
$\langle n_p \rangle$	30.4±0.8	21.2±0.9	42.5±1.3
$\langle N_b \rangle$	4.0±0.2	1.0±0.1	8.1±0.2
$\langle N_g \rangle$	4.4±0.2	1.0±0.1	9.0±0.3
$\langle N_F \rangle$	2.0±0.1	2.1±0.1	1.8±0.1
$\langle N_\alpha \rangle$	4.6±0.1	4.4±0.2	4.7±0.2
$\langle Z_F \rangle$	20.3±0.6	23.3±0.8	15.4±0.8
$\langle Z_{tot} \rangle$	48.6±0.8	57.8±0.9	36.5±1.3

Acknowledgements

Dana Beavis and the staff of the Brookhaven National Laboratory AGS made this exposure possible. This work has been supported in Poland by State Committee for Scientific Research grant No. 203799101 and in USA at Louisiana State University by grants from NSF No. PHY–8907660, PHY–9213621 and INT–8913051 and at University of Minnesota by grants by DOE—grant No. DOE–DE–FG02–89ER40528.

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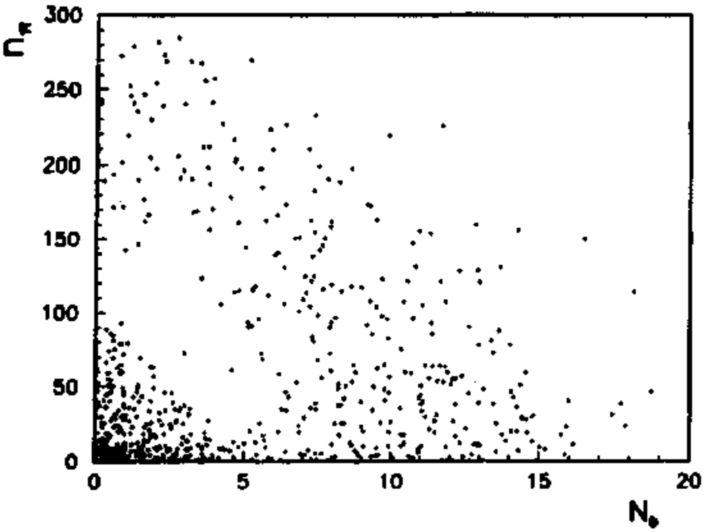

Fig.1 The relation between the number n_π of created charged particles and the number N_b of heavy ionizing particles emitted from the target nucleus in Au–Em interactions.

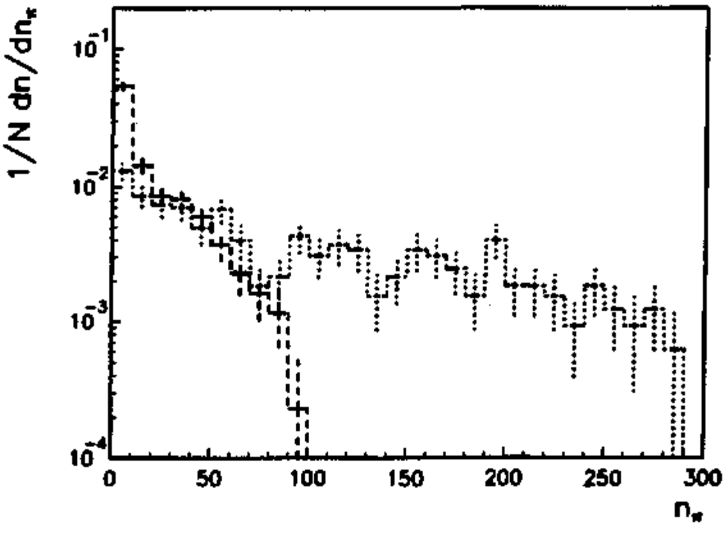

Fig.2 Multiplicity distributions of created charged particles n_π in interactions of 10.6 GeV/n gold nuclei in light (dashed histogram) and heavy (dotted histogram) target nuclei.

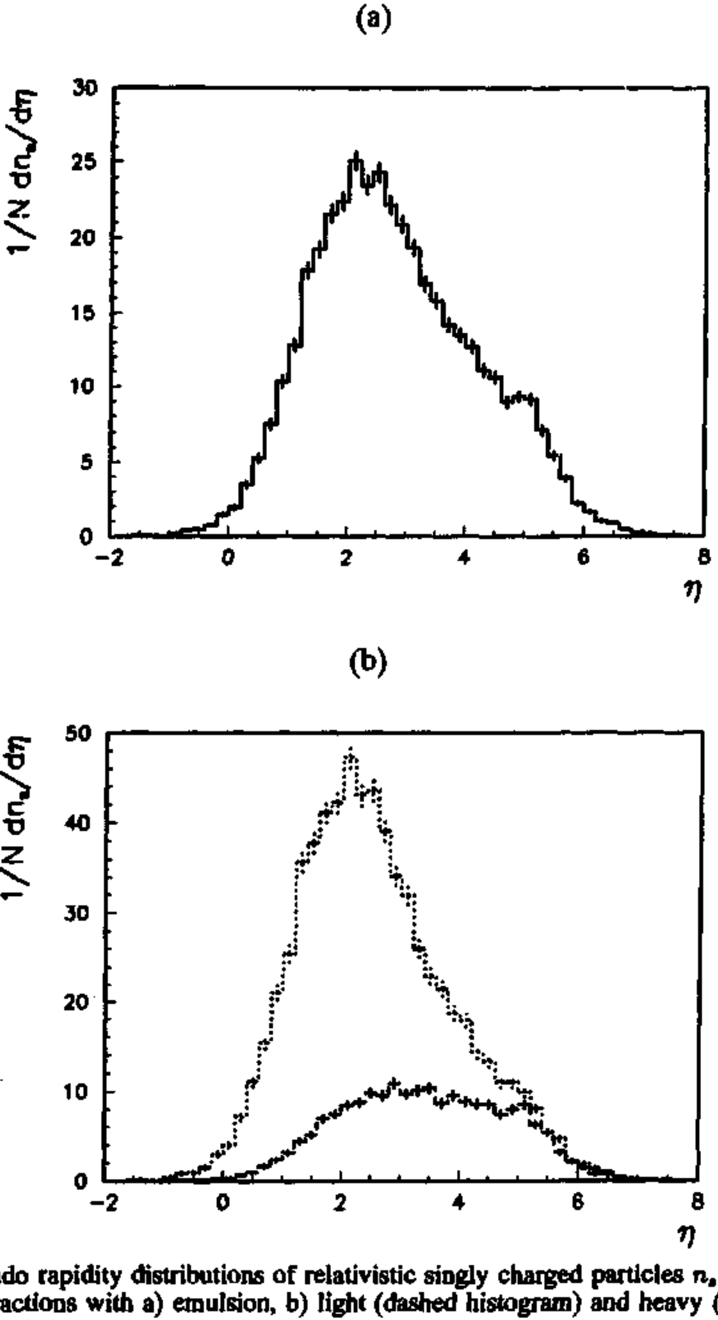

Fig.3 Pseudo rapidity distributions of relativistic singly charged particles n_s emitted in interactions with a) emulsion, b) light (dashed histogram) and heavy (dotted histogram) targets.

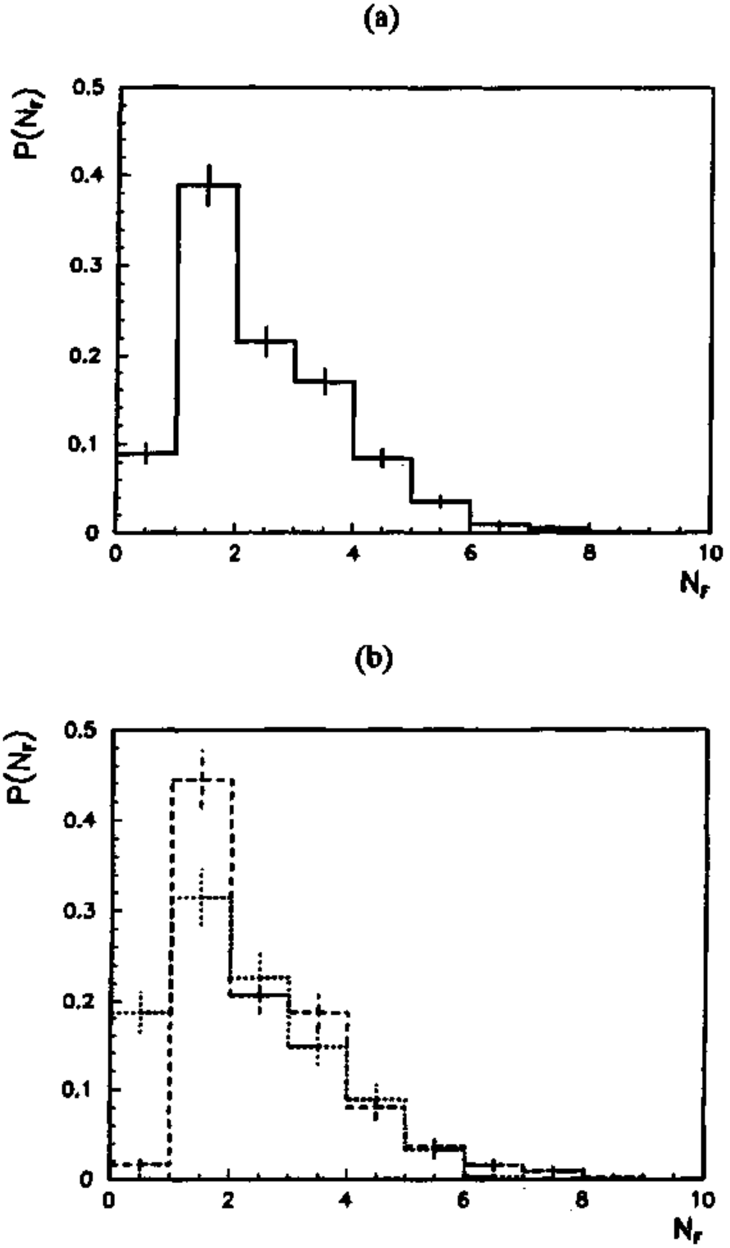

Fig.4 The distributions of the number N_F of fragments with $Z > 2$ in interactions with a) emulsion b) light (dashed histogram) and heavy (dotted histogram) targets.

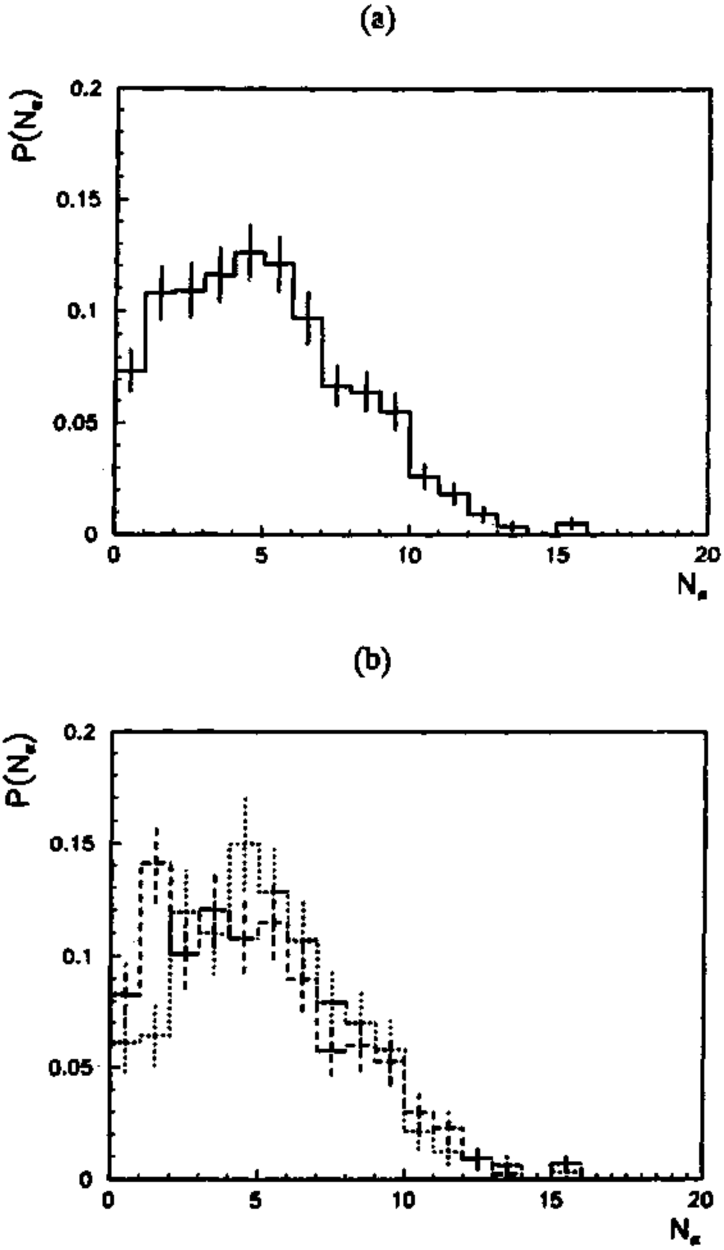

Fig.5 The distributions of the number N_α of alpha particles in interactions with a) emulsion b) light (dashed histogram) and heavy (dotted histogram) targets.

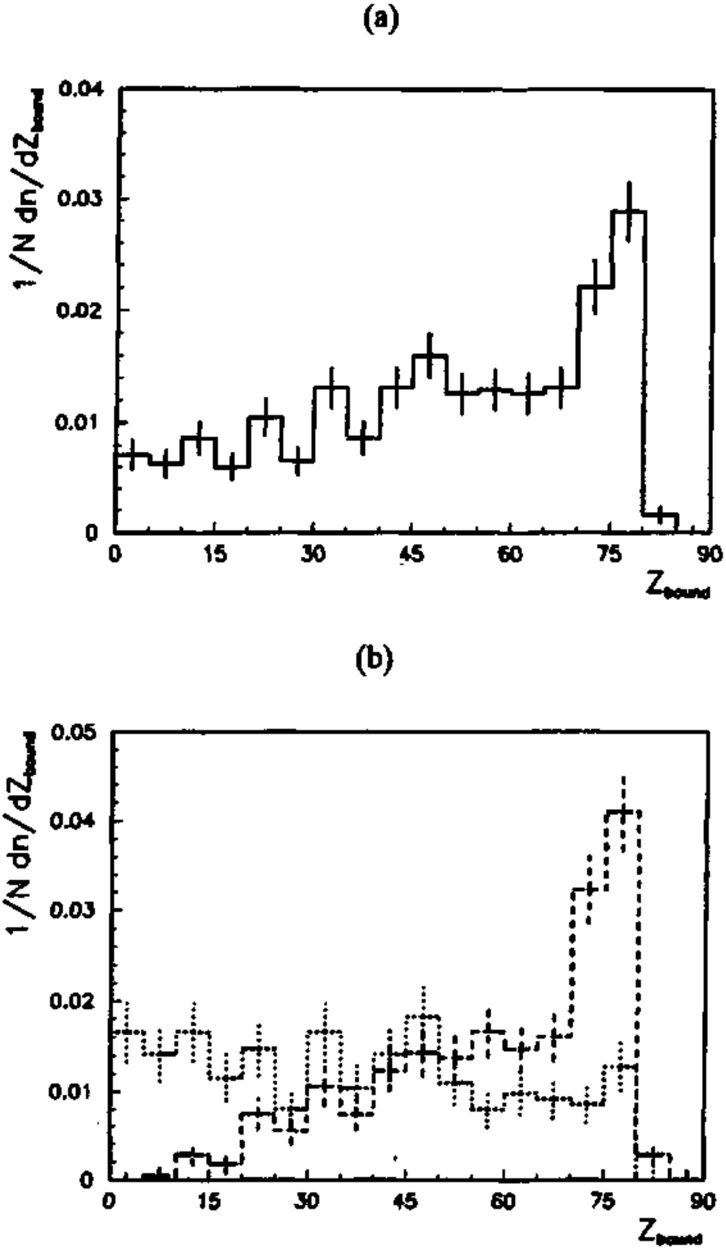

Fig.6 The distributions of the total charge Z_{bound} bounded in multicharged fragments in interactions with a) emulsion b) light (dashed histogram) and heavy (dotted histogram) targets.

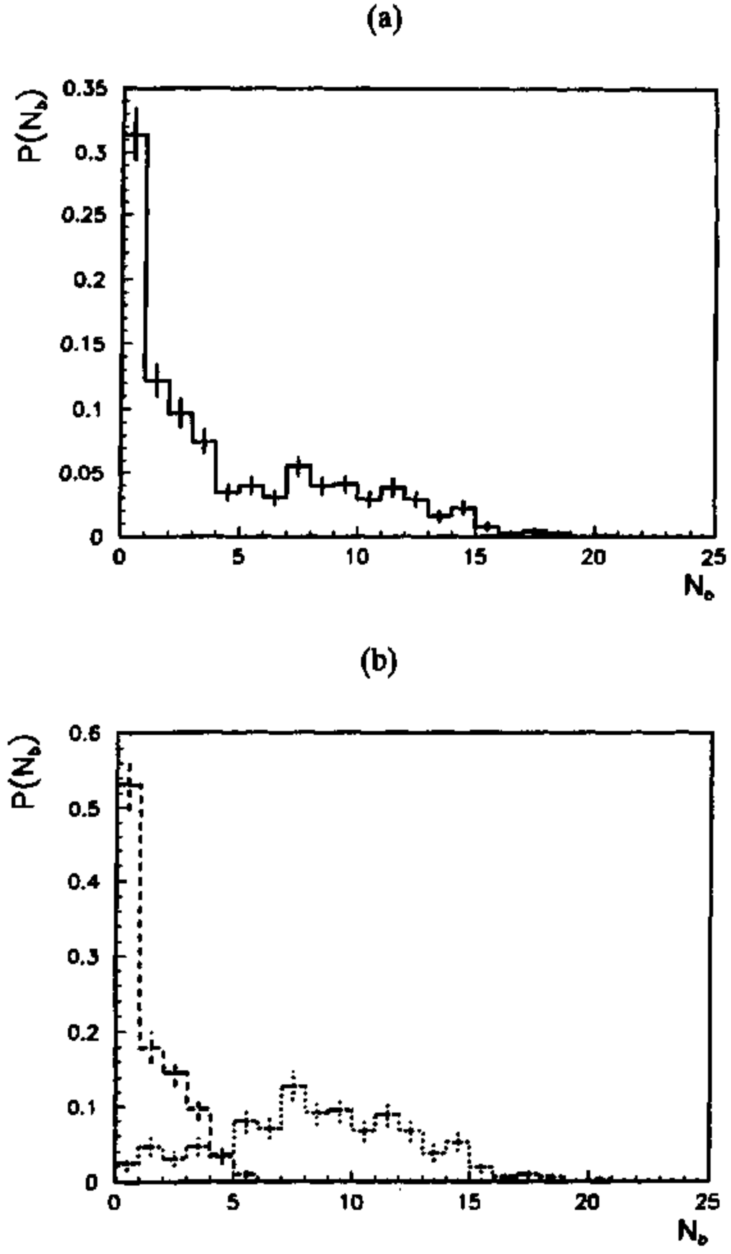

Fig.7 The distributions of the number N_b of heavy ionizing particles in interactions with a) emulsion b) light (dashed histogram) and heavy (dotted histogram) targets.

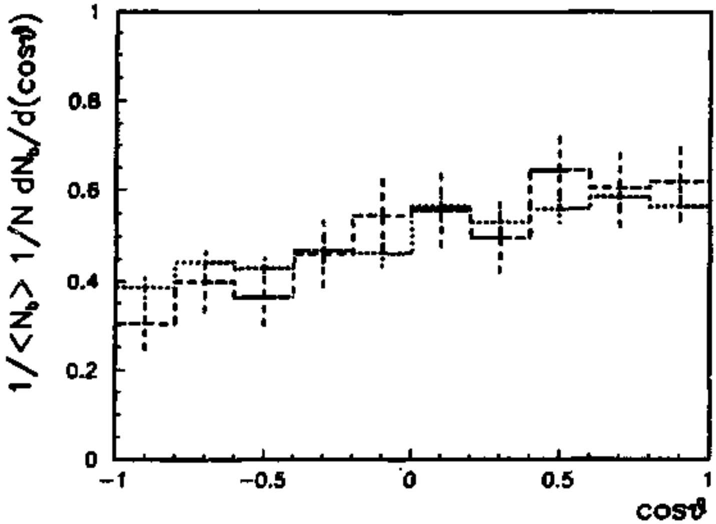

Fig.8 The angular distributions of heavy ionizing particles N_b in interactions with light (dashed histogram) and heavy (dotted histogram) targets.

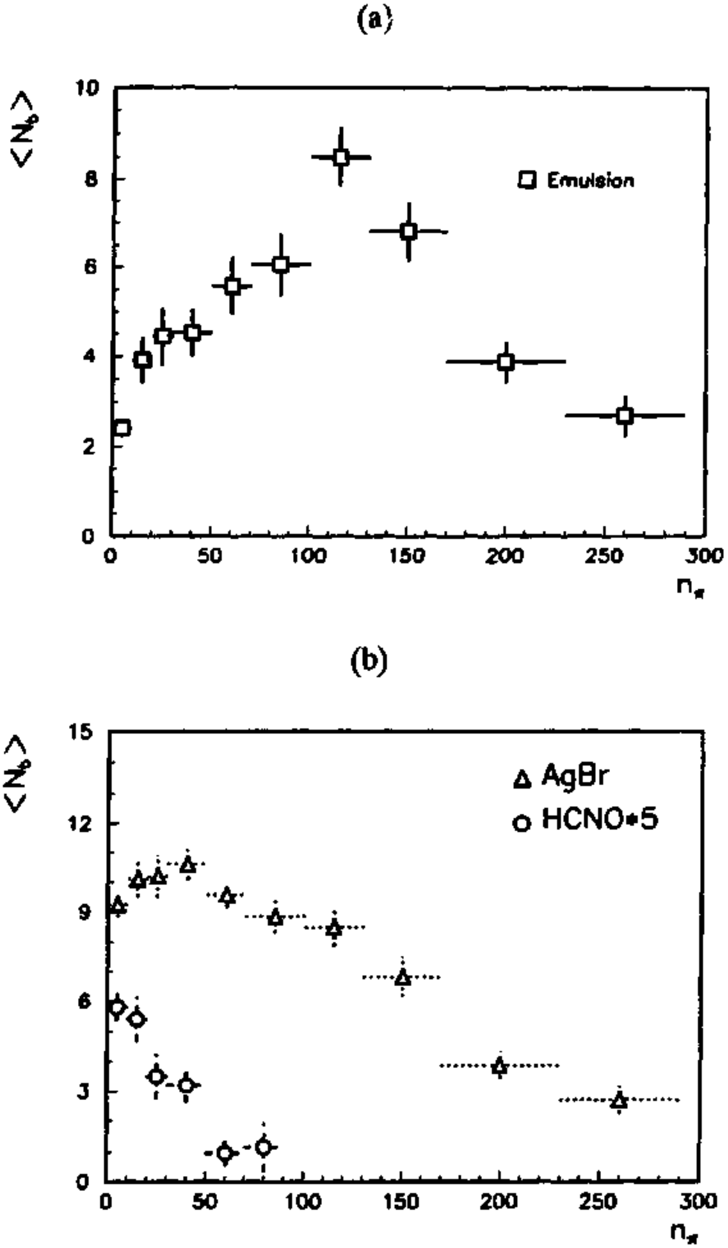

Fig.9 The relation between the mean number $\langle N_b \rangle$ of heavy ionizing particles and the number n_π of created charged particles in interactions with a) emulsion b) light and heavy targets. The horizontal bars represent the bin width.

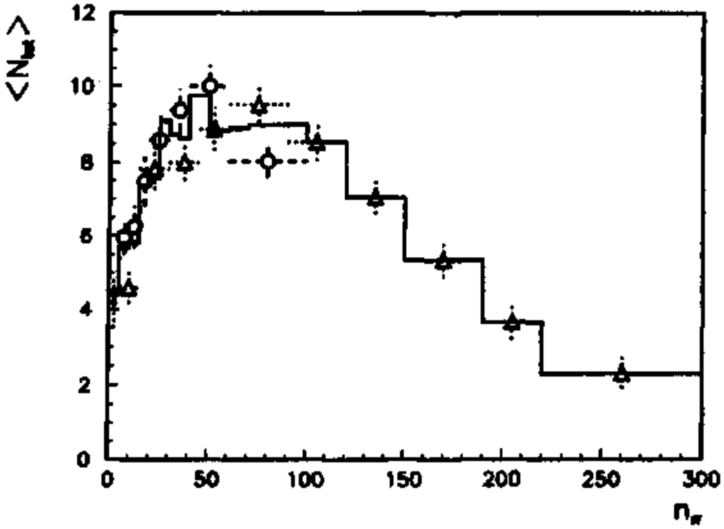

Fig.10 The relation between the average total number $\langle N_{tot} \rangle$ of projectile fragments with $Z \geq 2$ and the multiplicity of created charged particles n_π in interactions with *emulsion* (histogram), *light* (○) and *heavy* (△) targets. The horizontal bars represent the bin width.

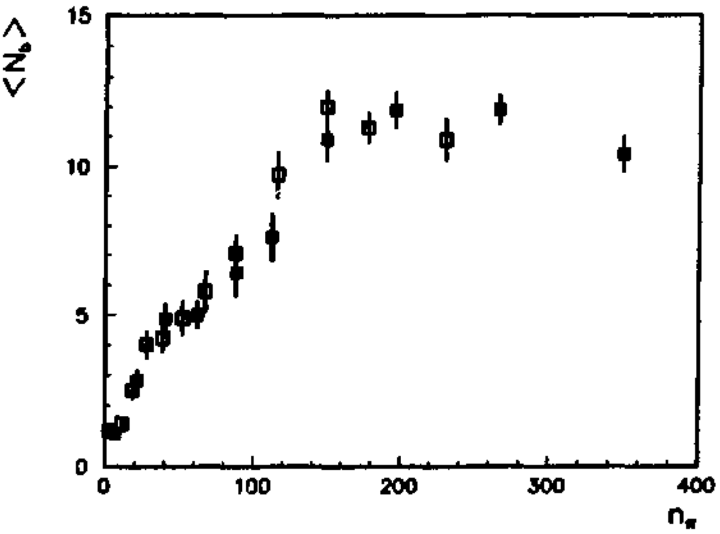

Fig.11 The relation between the mean number $\langle N_b \rangle$ of heavy ionizing particles and the number n_π of created charged particles for 200 GeV/n oxygen (□) and sulfur (■) interactions in emulsion.