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Features on Very Peripheral Collisions of ^{16}O-Em at 3.7 A GeV

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From 1540 inelastic interactions of 3.7 A GeV ^{16}O projectile with emulsion nuclei, we select samples of 87 and 61 events carefully due to interactions of neutron (n) and singly charged particles ($Z = 1$), respectively. New results concerning the topology of such events are investigated. The average multiplicities of secondary relativistic particles that appear as shower tracks for n and $Z = 1$ stay more or less constant when compared with analogous data on p-Em at similar energy. The multiplicity distributions and the average values of the various secondary charged particles are studied and compared with the corresponding predictions by the cascade evaporation model. The results assume that the n or $Z = 1$ from ^{16}O collide peripherally with an emulsion target and are considered as an expansion to the N-N collisions.

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The nuclear emulsion technique allows studies of emitted charged particles and their distributions in space with larger acceptance and higher accuracy than most of the current counter detectors. It ensures the detection of multi-particle in relativistic-fragmentation processes, which are characterized by limited statistics. The data presented in this study is based on the experiments with ^{16}O beam interactions with emulsion at 3.7 A GeV at Dubna sychrophastron. In previous work,[1–12] an extensive set of experimental data on various projectile-target combinations were investigated. To understand the behavior of hadrons and their properties in nuclear matter, we will investigate the new results on the topologies of relativistic ^{16}O nucleus fragmentation in peripheral interactions. The measurements in this work are based on charge measurements of projectile fragments PFs emitted from ^{16}O fragmentation in peripheral interactions. We will focus on a special type of events with the first seven total stripped charges of all projectile fragments in the fragmentation cone of the incident beam, i.e., total stripped charges of $\sum Z_{\rm PF} = 7$. Those events are associated with peripheral interactions in which the total charge of relativistic fragments equals 7. Such events are characterized by one single charged particle $Z = 1$ participated. The second-type events have eight total spectator charges $\sum Z_{\rm PF} = 8$. These events which have one participated neutron from ^{16}O will collide. The multiplicities of different secondary charged particles produced from both types of events have been compiled and studied. The analysis has been made analogically with the analysis of proton-emulsion interaction p-Em, at the same energy.[13] In addition, the results are compared with the prediction of the cascade evaporation model (CEM).[14]

In this work, stacks of type NIKFI-BR-2 emulsion in dimensions $20 \times 10\,{\rm cm}^2$ and in thickness 600 μm were exposed to a 3.7 A GeV ^{16}O nuclei at the sychrophastron of JINR, Dubna. The emulsion plates are scanned using along the track method where the inelastic interactions were carried out. In this investigation, we select two samples of special type of interactions. The first sample includes 87 events having total stripped charge of 8 for all possible projectile fragments $\sum Z_{\rm PF} = 8$, i.e., all eight charges of the incident ^{16}O ion were contained within the fragmentation cone. The angular interval of the fragmentation cone is determined by considering the values of Fermi momentum 0.25 GeV/c and beam momentum of 4.5 GeV/c per nucleon used in this experiment where $\langle \sin\theta_{\rm c}\rangle = P_{\rm fermi}/P_{\rm beam} = 0.25/4.5 = 0.055$ then $\theta_{\rm c} = 3^\circ$. These events are mainly due to interactions of a neutron participated from projectile nucleus. In this study, the interactions with $\sum Z_{\rm PF} = 8$ due to electromagnetic dissociation are excluded while the selected events are due to inelastic interactions that have at least one particle of type grey and or black tracks emitted as secondary target fragments in angles out of the cone of projectile fragments. The second sample of interactions includes 61 events having a total stripped charge of magnitude seven for all possible projectile fragments $\sum Z_{\rm PF} = 7$, i.e., seven charges of the incident ^{16}O ion are contained within the fragmentation cone. In these events one singly charged particle of $Z = 1$ from the projectile nucleus will participate in the collisions.

In each event of the selected samples, the charges $Z \geq 2$ of individual PFs were determined by the combination of several methods, which include grain, gap

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and δ-ray densities.[15] On the other hand, at each interaction point, the PFs with $Z = 1$ are well separated. To distinguish the proton tracks from π-meson, the concept of a fragmentation cone was used. Any shower track lying within this cone that has no noticeable change in ionization when followed up to a distance $\approx$1 cm from the point of interaction was considered proton while other single charged particles were taken as π-meson.

For each detected event we counted under high magnification up to 1500, the multiplicities of relativistic shower particles $N_{\rm s}$ correspond to single charged relativistic secondary particles with very high velocity $v > 0.7c$. These produced particles are mostly pions. Grey tracks producing particle $N_{\rm g}$ with velocity $0.3c < v < 0.7c$ are characterized by a range $R > 3$ mm. These tracks are mainly due to protons with kinetic energy $26 <$ K.E. < 400 MeV. Black tracks producing particles $N_{\rm b}$ represent a multiplicity of particles having velocity $v \leq 0.3c$, range $R < 3$ mm and corresponding to K.E. ≤ 26 MeV. We use the term of heavily ionizing charged particles denoted by $N_{\rm h}$ for all particles with K.E. < 400 MeV where $N_{\rm h} = N_{\rm g} + N_{\rm b}$.

Totally 1540 inelastic interactions are recorded for 3.7 A GeV ^{16}O with emulsion nuclei though scanned length 195.56 m. The respective mean free path is 12.7 ± 0.35 cm and the corresponding reaction cross section is 988.3 ± 27 mb. We select samples of 87 and 61 events carefully due to interactions of neutron (n) and singly charged particles $Z = 1$, respectively. These kinds of interactions are rare events with ratios $5.65 \pm 0.62\%$ and $3.96 \pm 0.51\%$ of the total number of interactions, respectively. This is due to the small value of reaction cross section compared with that for ^{16}O-Em interactions. The natures of these events are similar to nucleon-emulsion collisions such as p-Em, which have reaction cross-section 350.3 ± 27 mb and mean free path 35.83 ± 1 cm.[16,17] Experimentally, it is a large scanning distance and hard to pick one of this kind of event, which explains the limited statistics of this kind of interaction.

Table 1. Topology of 3.7 A GeV ^{16}O events having $\sum Z_{\rm PF} = 8$ and $\sum Z_{\rm PF} = 7$ in emulsion nuclei.

Channels with $\sum Z_{\rm PF} = 8$	Number of events (%) due to neutron int.	Channels with $\sum Z_{\rm PF} = 7$	Number of events (%) due to $Z = 1$ int.
$_8$O^{16} $\rightarrow _8$O	30 ($49 \pm 1.82\%$)	$_8$O^{16} $\rightarrow _7$N	32 ($37 \pm 1.23\%$)
$_8$O^{16} $\rightarrow _7$N+H	5($8 \pm 1.60\%$)	$_8$O^{16} $\rightarrow _6$C+H	19 ($22 \pm 1.18\%$)
$_8$O^{16} $\rightarrow _6$C+$_2$He	7 ($12 \pm 1.09\%$)	$_8$O^{16} $\rightarrow _5$B+$_2$He	10 ($12 \pm 1.20\%$)
$_8$O^{16} $\rightarrow$ 3$_2$He+2H	6 ($10 \pm 1.67\%$)	$_8$O^{16} $\rightarrow$ 3$_2$He+H	15 ($17 \pm 1.15\%$)
$_8$O^{16} $\rightarrow _5$B+$_2$He+H	4 ($6.5 \pm 1.62\%$)	$_8$O^{16} $\rightarrow _4$Be+$_2$He+H	5 ($5.5 \pm 1.10\%$)
$_8$O^{16} $\rightarrow$ 4$_2$He	2 ($3.2 \pm 1.60\%$)	$_8$O^{16} $\rightarrow _3$Li+2$_2$He	1 ($1 \pm 1.00\%$)
$_8$O^{16} $\rightarrow _5$B+3H	1 ($1.6 \pm 1.60\%$)	$_8$O^{16} $\rightarrow$ 2$_2$He+3H	5 ($5.5 \pm 1.10\%$)
$_8$O^{16} $\rightarrow _6$C+2H	2 ($3.2 \pm 1.60\%$)		
$_8$O^{16} $\rightarrow _4$Be+2$_2$He	4 ($6.5 \pm 1.62\%$)		
All	61	All	87

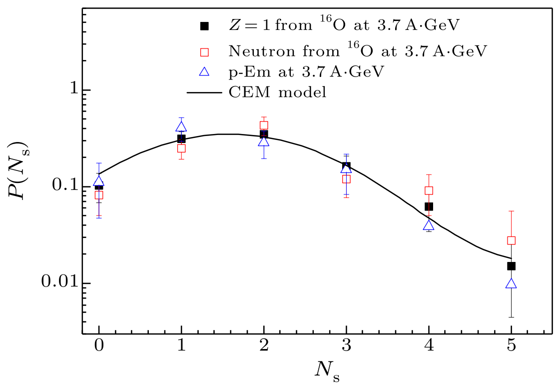

Fig. 1. Normalized multiplicity distribution of shower particles $N_{\rm s}$ produced in the participation of $Z = 1$ (solid square) and neutron (open square) from 3.7 A GeV ^{16}O with emulsion nuclei. The open triangle is the corresponding distribution from p-Em. The solid line represents the CEM predictions.

New results concerning the topology of such events are listed in Table 1; it represents the distribution of all channels of events emanating from ^{16}O fragmentation for two present samples $\sum Z_{\rm PF} = 8$ and $\sum Z_{\rm PF} = 7$ corresponding to interactions of n, and $Z = 1$ participate from ^{16}O beam at 3.7 A GeV. It is observed that when n collided, $49 \pm 1.82\%$ of its collisions include a projectile spectator with oxygen isotopes $_8$O^{15}, $20 \pm 1.69\%$ are associated with 2PFs, one of them has single charge $8 \pm 1.60\%$ or double charge $12 \pm 1.65\%$, and $31 \pm 1.70\%$ are associated with more than three PFs. On the other hand, channels of $Z = 1$ due to hydrogen isotopes participated in the interactions with a single PF of $_7$N are high probability $37 \pm 1.23\%$ more than any other possible fragments of $\sum Z_{\rm PF} = 7$. They have one projectile spectator with $Z = 7$, while $34 \pm 1.21\%$ are associated with two PFs, one of them has $Z = 1$ ($22 \pm 1.18\%$) or $Z = 2$ by $12 \pm 1.15\%$, and $29 \pm 1.19\%$ are associated with more than three PFs. Concerning helium nucleus or α-PFs production in $\sum Z_{\rm PF} = 8$ and $\sum Z_{\rm PF} = 7$ events, one can find $38 \pm 1.23\%$ and $41 \pm 1.24\%$ of events having at least one α-PF, respectively. This may reflect the presence of α-clusters inside the oxygen nuclei and it is the preferred mode of projectile fragmentations. It is important to study the effect of these criteria on the systems responsible for production of different secondary charged particles, and to search for differences on the corresponding results obtained for proton interactions with the same target and energy.

Figure 1 illustrates the experimental normalized multiplicity distribution of shower particles N_s for the two selected types according to the participation of $Z = 1$ and n from ^{16}O with emulsion nuclei at 3.7 A GeV. The data are compared with p-Em interactions and with predictions of CEM. All distributions follow the same trend and the CEM model is quite satisfying distribution for the three studied beams.

Table 2. Average values of shower N_s, grey N_g and black N_b produced from n or $Z = 1$ participated in ^{16}O interaction with emulsion in comparison with p-A collision and CEM predictions.

	Present work		p-Em[13]		CEM[14]	
	Neutron n	$Z = 1$	(All events)	$N_h < 7$	(All events)	$N_h < 7$
$\langle N_s \rangle$	1.47 ± 0.18	1.86 ± 0.21	1.63 ± 0.02	1.68 ± 0.03	1.75	1.8
$\langle N_g \rangle$	0.54 ± 0.06	0.75 ± 0.08	2.81 ± 0.06	1.21 ± 0.03	2.71	1.14
$\langle N_b \rangle$	1.35 ± 0.17	1.83 ± 0.21	3.77 ± 0.08	1.39 ± 0.04	3.29	1.0

The average multiplicity of different secondary charged particles appears in emulsion as shower, grey and black tracks due to interactions of oxygen at 3.7 A GeV with the above stated restrictions of projectile fragments are given in Table 2, and one can conclude: (1) The average $\langle N_s \rangle$ for the studied interactions and its prediction stay more or less constant compared with the values of p-Em, which proves that the process of pion production from the selected samples of interactions is similar to that observed for hadron-nucleus interactions. The invariance of $\langle N_s \rangle$ in the cases of $N_h \leq 6$ and all the samples indicate that there is independence of the target mass number and the interactions for both the samples are with a light component of emulsion nuclei (CNO). (2) The small increase in $\langle N_s \rangle$ for $Z = 1$ from ^{16}O could be due to the interacting part of $Z = 1$, which may occur through a few hydrogen isotopes since $Z = 1$ is contamination of hydrogen isotopes.

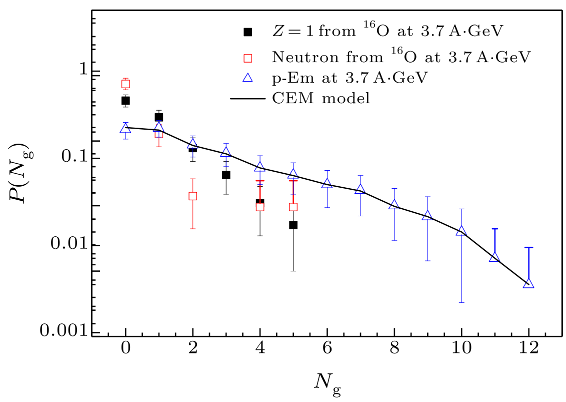

Fig. 2. Normalized multiplicity distribution of grey particles N_g produced in the participation of $Z = 1$ (solid square) and neutron (open square) from 3.7 A GeV ^{16}O with emulsion nuclei. The open triangle is the corresponding distribution from p-Em. The solid line represents the CEM predictions.

Figure 2 represents the experimental normalized multiplicity distribution of grey particles N_g for the two selected types according to the participation of $Z = 1$ (solid square) and n (open square) from ^{16}O with emulsion nuclei at 3.7 A GeV. The data are systematic compared with the corresponding distributions for proton (open triangle) and predictions of CEM (solid line). All experimental and predicted distributions are normalized to the same number of interactions. One can conclude: (1) All distributions follow the same trend but the N_g distribution for p-Em shows different trends along the tail up to $N_g = 12$. The disagreement of these results with what is obtained for p-Em may be explained from the average number $\langle N_g \rangle$ given in Table 2, which is 0.54 ± 0.06 and 0.75 ± 0.08 for n and $Z = 1$, while 2.81 ± 0.06 for p-Em. This reflects that the numbers of collisions through proton interaction are about 5 and 4 times higher than those for n and $Z = 1$, respectively. In p-Em, the proton interacts with different groups of emulsion nuclei (H, CNO, AgBr) making the number of collisions increase and producing more recoil protons (N_g). The small values of $\langle N_g \rangle$ for n and $Z = 1$ may be due to interactions of n and $Z = 1$ only with free H or CNO. It could be confirmed by investigating the comparison of these values with the magnitude $\langle N_{ch} \rangle_{pp} = 2.57 \pm 0.18$ at 3.7 GeV.[18] They nearly match the values of $\langle N_s \rangle + \langle N_g \rangle$, which are nearly equal to 2.0 ± 0.24 and 2.5 ± 0.29 for n and $Z = 1$, respectively. (2) The CEM model is not quite successful for describing the general trend of grey particles of n and $Z = 1$, while it gives a good description for that of p-Em and predicts its average value. This is because the calculations of the CEM model were performed by Monte Carlo simulation of random stars, which has considered all the compositions of nuclear emulsion.

The total interactions with emulsion nuclei are classified into two groups, first with the light component (HCNO) and have $N_h < 7$ where N_h is the multiplicity of heavily ionizing charged particles and $N_h = N_g + N_b$. The other interactions are with the heavy emulsion component (AgBr) of $N_h \geq 7$. Figure 3(a) shows the normalized multiplicity distribution for black tracks N_b, produced from interactions of the selected events with all components of emulsion nuclei. One can conclude that the N_b distributions take the same trend for both n and $Z = 1$ up to $N_b = 8$, while there is remarkable disagreement of p-Em that appears differently with a long tail up to 16. In addition, the average number $\langle N_b \rangle$ given in Table 2 is 1.35 ± 0.17 and 1.83 ± 0.21 for n and Z=1, respectively, while 3.77 ± 0.08 for p-Em. It could be explained as mentioned for grey particles by considering that the interaction of n and $Z = 1$ is mostly peripheral collisions, therefore it leads to reduced fragmentation of the target nuclei in comparison with inclusive p-Em interactions. The total sample of interactions occurs with the two emulsion components. It is characterized by the transfer of a small amount of energy, hence a small number of target fragments. The corresponding collisions for p-Em include central interactions with heavy emulsion components with probability above 50% of all the samples of interactions. It causes a large amount of energy transfer, thus the target nuclei become more excited and expanded producing a large number of target fragments that appear as black particles.

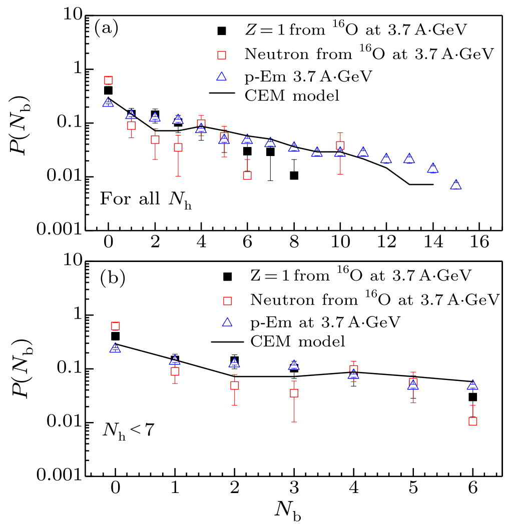

Fig. 3. (a) Normalized multiplicity distribution of black particles N_b produced in the participation of $Z = 1$ (solid square) and neutron (open square) from 3.7 A GeV ^{16}O with all emulsion nuclei. The open triangle is p-Em data. The solid line represents the CEM predictions. (b) The same comparisons for interactions with light emulsion components CNO of $N_h < 7$, where $N_h = N_g + N_b$.

Figure 3(b) shows the same normalized distributions of black particles from events with $N_h < 7$, which correspond to the interactions with light emulsion components. The prediction of the CEM model may be close to the experimental data of the present work. The mean values $\langle N_b \rangle$ for the three collisions are approximately the same due to the fixed nature of the light target and the same process or mechanism of target fragmentations.

In summary, we have studied the inelastic interactions of neutron n and singly charged particle $Z = 1$ participated from ^{16}O at 3.7 A GeV. The results obtained from this study give the following conclusions. (1) The average multiplicity of shower particles $\langle N_s \rangle$ for the two studied interactions stays more or less constant and the corresponding one obtained from p-A at similar energy is in agreement with the result predicted by the CEM. The model describes all the N_s distributions. (2) The average value $\langle N_g \rangle$ produced from n and $Z = 1$ is very small compared with those obtained from p-Em at the same energy, also CEM cannot quite successfully describe the general trend of N_g distributions. (3) The N_b distributions and mean values for n and $Z = 1$ interactions for all emulsion components are different from those of p-Em interactions and out of the prediction by CEM because the selected events contain mostly peripheral collisions and therefore lead to reduced fragmentation of the target nuclei in comparison with inclusive p-Em interactions. (4) The average value $\langle N_b \rangle$ produced from n and $Z = 1$ is in agreement with that for p-Em for events with $N_h < 7$. The CEM prediction (for $N_h < 7$) is close to the experimental data and describes well the N_b distributions.

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