Slow, target associated particles produced in ultrarelativistic heavy-ion interactions

EMU01 Collaboration

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The slow, target associated particles produced in ultrarelativistic heavy-ion interactions are a quantitative probe of the cascading processes in the spectator parts of the target nucleus. These processes are directly influenced by the proper timescale for the formation of hadronic matter. In this letter we show experimental data on singly and multiply charged particles, with velocities smaller than 0.7c, produced in ultrarelativistic heavy-ion interactions in nuclear emulsion.

Even though our understanding of high-energy heavy-ion interactions has developed during recent years, some of the observations are in disagreement with predictions from most of the current models, models predominantly based on the picture of independently fragmenting strings or chains [1]. As an example, the production of particles in the target fragmentation region is generally underestimated in these models [2], mainly because the effect of cascading in the target spectator is neglected. Some effort has been made to incorporate this effect, but due to our limited knowledge of the proper timescale for the formation of hadronic matter, this cannot be done without the introduction of a set of free parameters. In order to set constraints on these parameters and to increase our knowledge of the mechanisms involved, it is evidently of interest to collect precise data on the mass and energy dependence on the production of slow, target associated particles.

Within the EMU01 Collaboration we have performed experiments with nuclear emulsion at CERN/SPS (60 and 200 A GeV) and at BNL/AGS (14.6 A GeV) using projectiles of ^{16}O, ^{28}Si and ^{32}S. The data presented in this letter is obtained in horizontally exposed emulsion stacks, scanned along-the-track to maximize the detection probability also for the most peripheral interactions. The details on the experimental procedures have been published elsewhere [3,4]. The following experimental definitions of particle categories are used in this letter:

- Shower particles (n_s): Singly charged particles with a velocity $\beta \geqslant 0.7c$. These particles are predominantly pions produced over essentially the whole region of phase space.
- Grey prongs (N_g): Charged particles producing tracks with a range $\geqslant 3$ mm and having a velocity $< 0.7c$. These particles are mainly protons in the energy range 26–375 MeV. The admixture of pions (12–56 MeV) is estimated to be 10% and for kaons (20–198 MeV) the corresponding number is 1%. These estimates are based on Fritiof calculations [5] for 200 A GeV ^{16}O-induced interactions with emulsion, assuming that no further meson production takes place in the slow processes.
- Black prongs (N_b): Charged particles producing tracks with a range < 3 mm. These particles include low energy singly and doubly charged particles (less than 26 A MeV for p and α) and all target fragments with $Z \geqslant 3$ [#1]. The admixture of pions is estimated to be of the order of 1%.

The different data samples are summarized in table 1, where some average quantities are given. Each data sample is divided into a central and a non-central subsample based on the total charge, Q_{ZD}, observed in a narrow forward cone ($\theta_{cone} \simeq 0.6/p_{beam}$), which measures the remnant of the projectile nucleus [3,4]. For a given interacting system the Q_{ZD}-distributions are found to be independent of the bombarding energy [4], as can be naively expected due to geometrical reasons. The Q_{ZD}-cuts ($Q_{ZD} \leqslant 2$, $Q_{ZD} \leqslant 5$ and $Q_{ZD} \leqslant 6$, for ^{16}O, ^{28}Si and ^{32}S respectively) were chosen so that the central samples contain approximately 10% of the total production cross section and result in samples entirely consisting of interactions with the heavy target component in emulsion (Ag, Br). As can be seen in the table the different samples contain about the same number of events. The average number of black and grey particles are seen to depend only weakly on the beam energy and interacting system, with a variation between the samples only slightly larger than the quoted statistical errors. A possible weak decrease of $\langle N_b \rangle$ and $\langle N_g \rangle$ with increasing energy can, however, not be ruled out.

In table 1 we also give the corresponding numbers for proton induced interactions. When the average multiplicities of black and grey prong producing particles are compared with the corresponding multiplicities for proton induced interactions we see that the number of black prongs are about the same, whereas the number of grey prongs is approximately twice as large in the case of heavy-ion projectiles. For

[#1] For further information on energy-range relations in nuclear emulsion see, e.g., ref. [6].

Table 1
Summary of the experimental samples. For proton projectiles the definitions of grey and black particles may vary slightly between different experiments. Generally coherent events are excluded.

Projectile	Energy (A GeV)	Sample	Events	$\langle n_s \rangle$	$\langle N_b \rangle$	$\langle N_g \rangle$
^{16}O	14.6	total	631	20.3 ± 0.8	4.8 ±0.2	5.2 ±0.2
		non-central	567	16.0 ± 0.7	4.4 ±0.2	4.2 ±0.2
		central	64	58.1 ± 2.3	8.9 ±0.5	14.0 ±0.9
^{16}O	60	total	372	39.0 ± 2.1	4.5 ±0.2	5.7 ±0.4
		non-central	336	31.0 ± 1.8	4.0 ±0.2	4.5 ±0.3
		central	36	114 ± 6	8.6 ±0.7	17.1 ±1.5
^{16}O	200	total	503	56.5 ± 2.7	4.1 ±0.2	4.3 ±0.3
		non-central	447	42.0 ± 2.1	3.4 ±0.2	3.1 ±0.2
		central	56	172 ± 7	9.4 ±0.6	13.5 ±0.8
		$n_s \leqslant 150$	453		3.5 ±0.2	3.0 ±0.2
		$n_s > 150$	50		9.2 ±0.4	15.4 ±0.7
^{16}O		combined total	1506		4.5 ±0.1	5.0 ±0.2
		combined non-central	1350		3.9 ±0.1	3.9 ±0.1
		combined central	156		9.0 ±0.4	14.5 ±0.6
^{28}Si	14.6	total	573	28.2 ± 1.3	4.6 ±0.2	5.4 ±0.3
		non-central	509	21.1 ± 1.0	4.1 ±0.2	4.1 ±0.2
		central	64	84.5 ± 3.4	8.5 ±0.5	15.5 ±1.0
^{32}S	200	total	539	79.9 ± 4.1	3.9 ±0.2	4.7 ±0.3
		non-central	483	58.0 ± 3.0	3.6 ±0.2	3.9 ±0.2
		central	56	268 ±13	6.7 ±0.5	12.1 ±0.9
		$n_s \leqslant 225$	480		3.5 ±0.2	3.6 ±0.2
		$n_s > 225$	59		7.3 ±0.4	14.4 ±0.7
p	6.2	ref. [7]	1769	2.80± 0.04	5.62±0.12	3.13±0.07
p	22.5	ref. [7]	892	5.61± 0.11	5.03±0.16	2.94±0.12
		$n_s \leqslant 10$	814		4.66±0.16	2.61±0.11
		$n_s > 10$	78		8.88±0.58	6.45±0.52
p	67	ref. [8]	1183	9.35± 0.16	4.76±0.14	2.74±0.10
p	200	ref. [8]	2595	13.84± 0.16	5.02±0.10	2.60±0.06
p	400	ref. [9]	1036	17.41± 0.33	4.99±0.15	2.60±0.10
		$n_s \leqslant 32$	938		4.36±0.15	2.20±0.09
		$n_s > 32$	98		10.98±0.49	6.44±0.40
p	400	ref. [8]	3482	16.42± 0.17	4.62±0.08	2.79±0.06
p	800	ref. [8]	1718	20.02± 0.29	4.62±0.12	2.90±0.09
p		combined	12675		4.91±0.04	2.80±0.03

proton induced interaction a Q_{ZD}-based centrality cut is questionable, since no remnant of the projectile, except on the partonic level, is left to be detected (particles from dressed-up spectator partons will generally emerge at larger angles). The major fraction of proton-induced interactions are actually free from particles inside the Q_{ZD}-cone. For two of those samples we have instead used a cut in the shower-particle multiplicity corresponding to approximately 10% of the cross section. We see that for the black prongs this centrality cut influences the average multiplicities much the same as for heavy-ion interactions, whereas for grey particles it can be seen that the increase in the average multiplicity is larger in the heavy-ion case. For two of the heavy-ion samples a centrality cut based on shower-particle multiplicity is utilized, indicating a small increase in the average grey prong multiplicity as compared to the value obtained with the Q_{ZD}-cut.

Due to relative changes in the cross sections from proton- and oxygen-induced interactions with nuclei, there are slight differences in the effective composition of the target #2. There are furthermore some ambiguities in the classification of tracks from particles emitted at large angles relative to the emulsion plane and, furthermore, small variations in the sensitivity of the emulsions from different exposures may occur.

Multiplicity distributions for grey and black prongs from ^{16}O induced interactions with different incident energies are the same within the statistical uncertainties of our experiment [11]. The same is also true for scaled ($n_s/\langle n_s \rangle$) multiplicities of shower particles [4] #3. In fig. 1 we have compared the average multiplicity as a function of centrality for oxygen induced interactions at the three energies. No energy dependence is observed for any of the particle categories. The variation of $\langle N_b \rangle$ as a function of Q_{ZD} is, however, smaller than for the corresponding averages of the two other particle categories, indicating that of the three, the black prongs have the weakest correlation to the centrality. Furthermore $\langle N_b \rangle$ shows an indication of saturation with increasing centrality, i.e. with decreasing Q_{ZD}. This is consistent with earlier findings from proton induced interactions, where black prongs are believed to be the result of the evaporating remnant of the target, whereas grey prongs are believed to be mainly protons knocked-out in the direct process or in the subsequent cascade [13]. Already at larger impact parameters the target remnant is rather excited, and further excitation will only have a limited influence on the number of evaporated particles. In contrast to the case for incident protons, the size of the remnant target spectator is strongly varying with impact parameter, which will complicate the picture.

#2 For information on the percentage of interactions with the different emulsion components for different projectiles see, e.g. table 2 in ref. [10].

#3 A perfect scaling of shower-particle multiplicity distributions can only be expected asymptotically, as discussed in ref. [12].

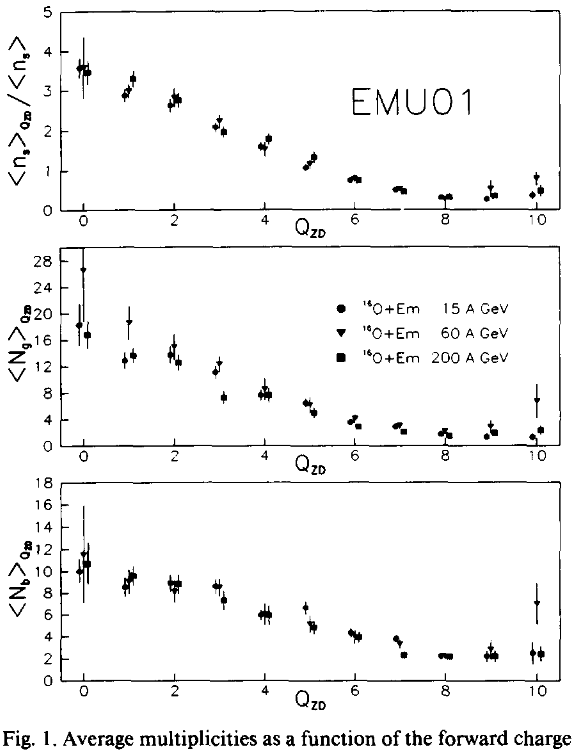

Fig. 1. Average multiplicities as a function of the forward charge flow in ^{16}O induced interactions for, top, shower particles scaled with the overall average multiplicity, middle, grey prongs and, lower, black prongs.

To illustrate the influence of the centrality on the production of different types of particles we show in fig. 2 multiplicity distributions from the combined ^{16}O sample. It is evident that the fraction of central events, as characterized by Q_{ZD}, increases with increasing multiplicity of any of the three particle categories.

The angular distributions of black and grey prongs may also carry information on the production mechanisms and can thus put constraints on the models. In fig. 3 we compare angular distributions from the different samples. The left parts of fig. 3 show angular distributions for black and grey prongs for ^{16}O-induced interactions under minimum bias conditions. The middle parts present the same distributions for ^{28}Si- and ^{32}S-induced interactions. The right parts show distributions for the combined central and non-central samples. The curves (the same for a given particle category) are fits to the distributions obtained when all samples are combined. The individual samples are only in a few cases slightly differing from the overall shapes, and if those differences are studied they show, as in table 1, no systematic trend with energy, centrality or projectile mass. The curves in the figure are parametrized as

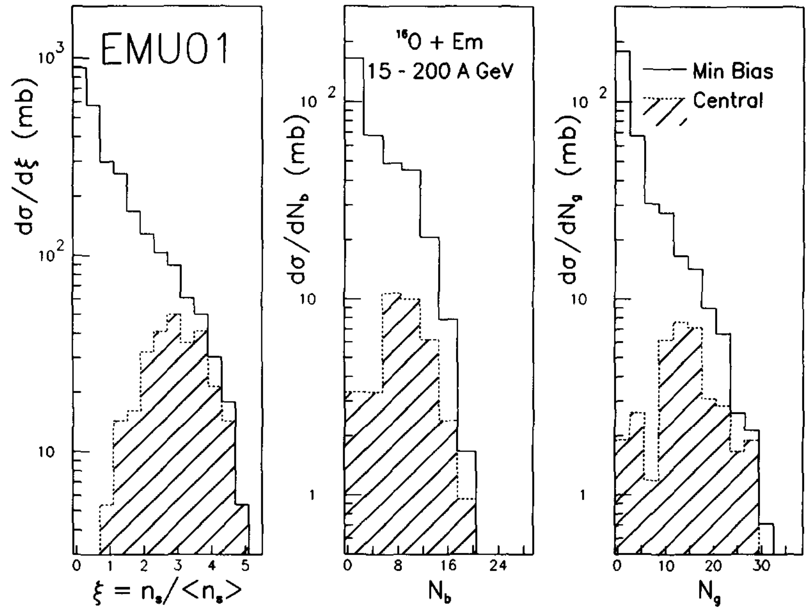

Fig. 2. Multiplicity distributions for the combined ^{16}O sample for, left, shower particles, middle, black prongs and, right, grey prongs. The hatched distributions correspond to the central sample. In the left figure the multiplicites are scaled with the average multiplicity for each energy.

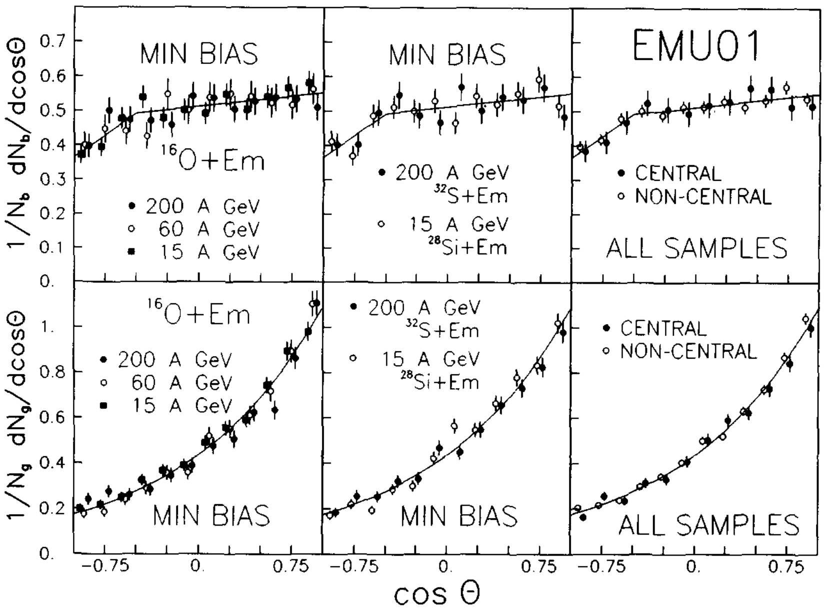

Fig. 3. Angular distributions for black and grey prongs from various samples.

$$\frac{1}{N_b}\frac{dN_b}{d\cos\theta}$$
$$=0.62+0.25\cos\theta, \quad \cos\theta<-0.50\,,$$
$$=0.51+0.04\cos\theta, \quad \cos\theta\geqslant-0.50\,,$$

and

$$\frac{1}{N_g}\frac{dN_g}{d\cos\theta}=0.44\exp(0.92\cos\theta)$$

for black and grey prongs, respectively. (For black prong particles the form of the parametrization has been choosen for convenience rather than for any other reason and different parametrizations are possible.) For proton induced interactions at similar incident energies, grey prong angular distributions have been parametrized as $\exp(0.96\cos\theta)$ [9], a result which is the same within the statistical uncertainties. There is no trivial reason why the angular distributions, particularly for the grey prongs, should be independent of projectile and centrality.

The overall slope of the black prong angular distribution can be obtained by assuming an evaporating source with a velocity of the order of $0.01c$. The drastic drop at large angles ($\theta>120°$) could be obtained in such a picture by the additional assumption that the target remnant also moves in the transverse direction. A quite good agreement with the experimental distribution is obtained with a transverse velocity in the order of $0.1c$, but such a high velocity seems unreasonable. Furthermore, it would introduce a strong ϕ-correlation among the black prongs, a correlation which is not seen experimentally. In fact, studies of ϕ-correlations indicate the absence of any transverse motion.

If we assume that the relevant distribution to study is the charge distribution rather than the particle number distribution, another more appealing possibility for the drop of the black prong distribution is revealed, namely that the charge distribution of the fragments varies with emission angle. If a multiple charged pre-fragment is produced in the forward hemisphere it has, due to the large flux of particles traversing the spectator matter, only a limited chance to survive, but when the same fragment is produced in the backward hemisphere its chance of survival is increased. Further speculations along this line have to be postponed until reliable data on charge and mass distributions of the black prong producing particles are available.

To conclude we would like to emphasize the importance of studying the particle production in the target fragmentation region in order to probe the formation of hadronic matter. Many of the features of the black and grey prongs cannot be trivially explained and put severe constraints on the models. Especially the observed stability of the angular distributions, which seems to be independent of any variable, might be of fundamental value.

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