Proton stopping in C+C, d+C, C+Ta and d+Ta collisions at 4.2A GeV/c

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The shape of proton rapidity distributions is analysed in terms of their Gaussian components, and the average rapidity loss is determined in order to estimate the amount of stopping in C+C, d+C, C+Ta and d+Ta collisions at 4.2A GeV/c. Three Gaussians correspond to the nuclear transparency and describe well all peripheral and also C+C central collisions. Two-component shape is obtained in case of d+C and C+Ta central collisions. Finally one Gaussian, found in d+Ta central collisions, corresponds to the full stopping. The calculated values of the average rapidity loss support the qualitative relationship between the number of Gaussian components and the corresponding stopping power. It is observed in central collisions that the average rapidity loss increases with the ratio of the number of target and the number of projectile participants.

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Baryon rapidity distribution can be used to estimate the nuclear stopping achieved in a collision i.e. the fraction of the projectile kinetic energy deposited in the reaction volume and converted into other degrees of freedom. When full stopping is achieved, the rapidity distribution has a maximum at midrapidity with the width determined by thermal and possibly hydrodynamic motion. If the nuclei are highly transparent to each other, the final proton distribution exhibits peaks at or near target and beam rapidities, and a sparse population of the central rapidity region. Study of the proton rapidity distribution as a function of the system size and of the impact parameter has shown that peripheral collisions resemble the p+p data \[1,2\], where a small stopping is achieved. Central collisions of light nuclei (Si+Al, S+S) reveal additional stopping with a fairly wide and flat rapidity distribution \[1–5\]. Larger, but not complete, stopping is observed in central collisions of heavier systems, such as Au+Au at AGS \[1,6\] and Pb+Pb at SPS energies \[7–9\]. Proton rapidity distribution as a function of the beam energy shows that, at Bevelac energy the complete stopping results in a single fireball, while at higher energies the distribution broadens and changes its shape \[8\]. It is found that for symmetric systems the stopping is larger for heavier systems and lower energies \[9\]. In order to estimate the amount of stopping, the corresponding average rapidity loss is used. A review of the average rapidity loss for p+p and A+A collisions at beam momenta 1-2, 11.6, 14.6 and 200 GeV/c per nucleon can be found in \[2,11\].

Here, the shape of proton rapidity distributions in peripheral and central C+C, d+C, C+Ta and d+Ta collisions at 4.2A GeV/c, is analysed in terms of corresponding Gaussian components. The corresponding average rapidity loss is calculated and its dependence on the collision centrality and system size is discussed. The study is based on a sample of 7327 C+C, 6735 d+C, 1989 C+Ta and 1475 d+Ta events. The data are obtained with the 2-m propane bubble chamber, exposed at the JINR, Dubna synchrophasotron with $^{12}$C or $^{2}$d ion beam of 4.2A GeV/c. Additionally the $^{181}$Ta target, consisting of the three foils (1 mm thick and 93 mm apart), was placed inside the chamber working in the 1.5 T magnetic field. This allows the study of inelastic interactions with carbon as well as with tantalum target. The characteristics of the chamber allow precise determination of multiplicity and
momentum of all charged particles, as well as identification of all negative particles and positive particles with momenta less than 0.5 GeV/c. The latter are classified either as protons or $\pi^+$ mesons according to their ionisation density and range. All positive particles above 0.5 GeV/c are taken to be protons, and due to this the admixture of $\pi^+$, of about (10-15)%, is subtracted, using the number of $\pi^-$ mesons with $p > 0.5$ GeV/c as follows: 

$$n_p = n_+ - n_{\pi^+}(p \leq 0.5\text{GeV/c}) - kn_{\pi^-}(p > 0.5\text{GeV/c}),$$

where $n_+$ denotes the number of single positively charged particles, $k = 1$ for collisions of isoscalar nuclei, and $k = 0.82$ for collisions with tantalum nuclei. This last value is less than one since it takes into account the proton deficit in tantalum nuclei and consequently also $\pi^+$ deficit. From the ratio $w = n_p/n_+$ for each momentum interval we determine the weight of protons which we further use when calculating distributions of other kinematical variables. From the resulting number of protons, the projectile spectator protons (with momenta $p > 3$ GeV/c and emission angle $\theta < 4^\circ$), and target spectator protons (with momenta $p < 0.3$ GeV/c) are further subtracted. The resulting number of participant protons still contains some 17% of deuterons (with momenta $p > 0.48$ GeV/c), and 11% of tritons with (momenta $p > 0.65$ GeV/c). The centrality selection is performed according to the number of participant protons $n_p$. The events with $n_p < \langle n_p \rangle$ i.e. with $n_p \leq 2$ in d+C, $n_p \leq 3$ in d+Ta, $n_p \leq 4$ in C+C and with $n_p \leq 10$ in C+Ta collisions are classified as peripheral. The selected peripheral events correspond to 50-60% cross section cut. In order to show that the criterion of peripherality is not affecting the results, we divide the peripheral events into two subgroups (which statistics allows) corresponding to different cuts in $n_p$. The events with the largest multiplicity of participant protons, corresponding to (3-5)% cross section cut, are classified as central.

Fig. 1 shows proton rapidity distributions for peripheral and central C+C, d+C, C+Ta and d+Ta collisions. For all peripheral collisions, two distinct peaks consisting of target and projectile protons can be seen, indicating the small amount of stopping. For symmetric collision system, the peaks are symmetrically positioned around center of mass rapidity ($y_{cm} = 1.1$) and distribution resembles the pp data. For asymmetric collision systems the target peak is more prominent then projectile peak. Additional stopping is achieved with
increasing centrality. In case of symmetric collisions this leads to appearance of a flat plateau in distribution. In case of asymmetric collisions the projectile-like peak disappears so that only the target-like peak with long tail towards the projectile rapidity remains. In C+C, d+C, and C+Ta collisions, the shape of $dN/dy$ distribution remains largely unchanged for a centrality cut below 10%. On the other hand, in d+Ta collisions the long tail of the rapidity distribution gradually diminishes with decreasing centrality cut, and completely disappears below 3% so that only the target-like peak remains.

Fig. 1 also shows that the shape of rapidity distributions is best reproduced by a sum of several (≤ 3) Gaussians. The exact values of the best fit parameters (peak positions and widths) can be easily acquired from the corresponding figures. According to the peak position, these Gaussians are related to the central region (the peak close to the participant center-of-mass rapidity), and the target and projectile fragmentation regions. Three Gaussians are obtained in all peripheral collisions, and C+C central collisions. With the finer cut in peripheral events, the rapidity distributions retain the three Gaussian structure so that this structure is not the result of the impact parameter superposition. Two Gaussians, central and target-like, are found in d+C and C+Ta central collisions. Finally, one target-like Gaussian, is obtained in d+Ta central collisions. The number of Gaussians depends on the collision centrality and/or stopping. Three Gaussians correspond to nuclear transparency while single Gaussian describes full stopping scenario. Since it is possible to associate each Gaussian component in rapidity distribution with single isotropic thermal source (fireball) [12,13], one arrives at simple physical picture consisting of several fireballs in relative motion. In case of symmetric collisions (such as C+C) there will be, for a given impact parameter, an overlap between the target and the projectile. After collision, the overlapping regions fuse together and partially come to rest in the center of mass frame. The halted region forms subsequently the central fireball. The two broken off parts continue in their paths after collision with reduced momentum and with smaller amount of the initial collision energy. These eventually create the two fragmentation fireballs. In central collisions of an asymmetric system (such as d+C, C+Ta), smaller projectile nucleus pene-
trates right through the target forming in the process the early stage of the central fireball. The target and/or projectile participant nucleons left behind lead subsequently to the only one, slower, fragmentation fireball. Thus one expects, for asymmetric system and central collisions only two fireballs. When $A_p \ll A_t$, as in case of d+Ta, the lighter projectile is not able to penetrate the heavy target (which looks black for projectile) and consequently only one, target-like, fireball appears.

In order to quantify the amount of stopping, the average rapidity loss (or mean rapidity shift) of projectile protons, $\langle \delta y \rangle = y_p - \langle y \rangle$, is introduced. Here, $y_p = 2.2$ is the beam rapidity, and $\langle y \rangle$ is the average rapidity of the projectile protons. In all peripheral and C+C central collisions all protons with rapidity $y > y_m = y_p/2$ are taken as projectile protons, and averaging is performed from $y_m$ to $y_p$. In central d+C, C+Ta and d+Ta collisions, the averaging is taken from $y_p$ to a rapidity $y_{low}$ determined so that the integral of the proton rapidity distribution is equal to the number of interacting projectile protons [2]. When the target and projectile protons mix strongly, the average rapidity loss determined in this manner is a lower limit. The resulting $\langle \delta y \rangle$ values for peripheral and central collisions are summarised in Table 1. For peripheral collisions, average rapidity loss is approximately independent of the collision system. In central collisions, $\langle \delta y \rangle$ has the smallest value in C+C (somewhat larger than in peripheral C+C) and the largest value in d+Ta collisions. These values for the average rapidity loss support the qualitative relationship between the number of Gaussian components in the rapidity spectra and the corresponding stopping power. The quantification of the stopping power via $\langle \delta y \rangle$ yields additional information. Evidently, the carbon nucleus as a target is less effective than the tantalum nucleus in slowing down the incident projectile nucleons. For a fixed target, the stopping depends on the size of the projectile. Generally, we find that $\langle \delta y \rangle$ increases with $A_t/A_p$ or, more correctly, with $[A_t - (A_t^{2/3} - A_p^{2/3})^{3/2}] / A_p$. Here, the numerator represents the number of target nucleons (present in the volume of a cylinder cut along a target diameter with a radius equal to that of the projectile plus the volumes of the two spherical segments at the ends of the cylinder) participating in redistribution of the initial kinetic energy. We note
that similar relationship between the stopping power and projectile size, for a fixed target, also exists at AGS energies [2]. This, apparently, is not the case at SPS energies since the stopping is found to be independent of the projectile size [14], suggesting a different stopping mechanism.

In conclusion, the rapidity distributions are examined in C+C, d+C, C+Ta and d+Ta collisions at 4.2A GeV/c, in terms of their Gaussian components. These last are interpreted as isotropic thermal sources (fireballs) in relative motion. Additionally, the corresponding amount of stopping is analysed as a function of system size and collision centrality. We found that three Gaussians are obtained in all peripheral collisions and also in C+C central collisions, two in case of d+C and C+Ta central collisions and, finally, one Gaussian in case of d+Ta collisions. The corresponding values of the average rapidity loss are calculated and they support the qualitative relationship between the number of Gaussian components in the rapidity spectra and the corresponding stopping power. It is observed that three Gaussians describe the nuclear transparency, while single Gaussian corresponds to the full stopping. Also, we find in central collisions, that the average rapidity loss increases with the ratio of the number of target and the number of projectile participants.

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TABLE I. Average rapidity loss $\langle \delta y \rangle$ in peripheral and central (3-5% cut) collisions.

| Colliding system | Peripheral collisions | Central collisions |
|------------------|-----------------------|--------------------|
|                  | $\langle \delta y \rangle$ | $\langle \delta y \rangle$ |
| $^{12}\text{C}+^{12}\text{C}$ | 0.53 ± 0.01 | 0.62 ± 0.01 |
| $^2\text{d} +^{12}\text{C}$  | 0.57 ± 0.01 | 0.86 ± 0.02 |
| $^{12}\text{C}+^{181}\text{Ta}$ | 0.56 ± 0.01 | 1.14 ± 0.01 |
| $^2\text{d} +^{181}\text{Ta}$ | 0.63 ± 0.01 | 1.42 ± 0.02 |
FIG. 1. Rapidity distributions of participant protons in peripheral and central collisions. The solid lines represent best fit to a sum of Gaussians (dotted lines).