CHIN. PHYS. LETT. Vol. 26, No. 8 (2009) 082502

Relativistic Energy Pb Projectile Fragmentation with Heavy Target Nuclei

G. Sher**, M. I. Shahzad, M. A. Rana

Physics Division, PINSTECH, Post Office Nilore, Islamabad, Pakistan

(Received 6 October 2008)

We investigate the fragmentation of 158 A GeV ^{207}Pb projectiles with Bi, Pb, Cu and Al targets using CR-39 nuclear track detectors. The exposures were made at SPS-CERN. After the etching, the detectors were scanned using an optical microscope to collect the data of etched cone diameters and lengths. We measured the partial charge-changing cross sections using the data of etched cone lengths. The predicted cross sections are compared to similar measurements reported in literature and their dependences on projectile and target mass are described.

PACS: 25. 70. Mn, 25. 75. −q

Fragmentation of heavy ions at relativistic energies predicts the characteristics and behavior of nuclear matter under extreme conditions of density and temperature. The efforts are focused on probing the signals of phase transitions between hadronic and quark–gluon phases.[1] At relativistic energies, peripheral nucleus–nucleus collisions along with strong interactions play an important part depending on the range of impact parameter of the interacting nuclei, if the impact parameter is sufficiently high, the sum of radii interaction can also contribute to nuclear reaction through the electromagnetic dissociation, eventually giving rise to the fragmentation of the excited nuclei leading to the emission of fragments with a wide mass spectrum. The experimental results of total and partial charge-changing cross sections provide information on peripheral reactions at relativistic energies. The total and partial fragmentation cross sections in relativistic heavy ion interactions are essential for the studies of the propagation of cosmic-ray nuclei through the interstellar medium.[2]

Relativistic projectile fragmentation has been investigated by a number of authors for a wide range of energies with different targets using both active and passive detection techniques.[3−9] We have used CR-39 nuclear track detectors in the present study of 158 A GeV Pb projectile fragmentation with Bi, Pb, Cu and Al targets. The CR-39 nuclear track detectors used in this experiment have been manufactured by Intercast Europe Co. Parma Italy. The response of CR-39 nuclear track detectors has been recognized towards a wide range of projectile charge at relativistic energies in various experimental studies.[5,11,13] We have earlier reported the results of total fragmentation charge-changing cross sections describing contributions of the nuclear and electromagnetic terms in the total fragmentation cross sections.[13]

Four stacks containing a target sandwiched with CR-39 nuclear track detectors of size 11.5 cm × 11.5 cm × 1 mm were exposed to 158 A GeV Pb ions at SPS-CERN at normal incidence. The total number of lead ions collected in each stack was about 7.8×10^4, which was distributed in eight spills. The central density in each spill was about 1500 ions/cm^2. Stacks contained four CR-39 sheets upstream from the target and more than 40 detectors downstream from the target. Some gaps were provided between the detectors to avoid successive fragmentation. We have selected one CR-39 detector upstream from the target and another downstream from the target from each stack for the present analysis. An ionizing particle traversing through an insulating material produces a narrow path of intense damage on an atomic scale.[8] The detectors were etched in 4N KOH aqueous solution at 45°C for 72 h. During the chemical etching, the track etch rate v_T exceeds the bulk etch rate v_B, producing a conical etch-pit at the point of entrance and exit of the particle, appearing as etched cones formed on both surfaces of the detector sheets. The base area and the height of etched cones are functions of restricted energy loss of the incident ion and thus of the charge Z.[8] To reconstruct trajectories, etched cones on each surface of the detectors were matched to those on the preceding surface.

The focused surface of the opening of the etch-pits looks like a dark circle of well defined diameter. We have measured the cone lengths and diameters using an optical microscope at a magnification of 400×. Detectors placed upstream from the target registered the total number of incident beam ions and the detectors placed after the target recorded both the surviving beam ions and fragments produced in the interaction of the Pb ions with the target. Figure 1 shows the mean values of cone height distribution for projectile ions and fragments registered in the detector placed after the target.

In the track etch detectors, the projectile and fragments with energy loss exceeding the threshold of the detector are registered.[8] Since the beam ion exposure has been performed to normal incidence to the

**To whom correspondence should be addressed. Email: gsher12000@yahoo.com

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detector surface, the projectile ions and the fragments produced as a result of fragmentation almost maintain their longitudinal velocity along the direction of beam ions, and can easily be identified as a sequence of etch cones produced on the subsequent detector surfaces. Target fragments can be separated based on their short range.

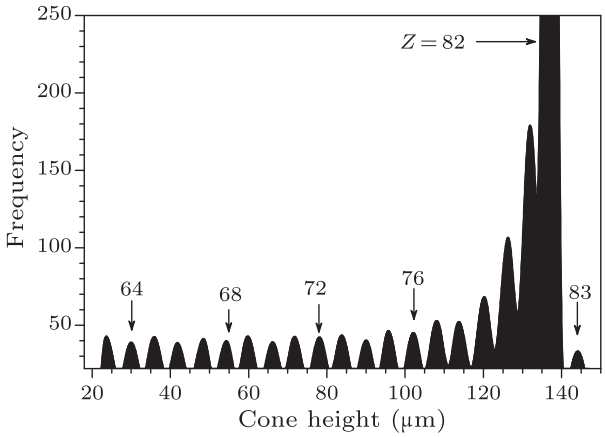

Fig. 1. Spectrum of cone lengths measured in the detector placed downstream from the target.

Opening areas of the etched cone have been found to be practical for resolution of charge in the lower charge values, while for resolution of higher charges, the etched cone length technique is more useful.[9] The well separated peaks are assigned charge values in the charge region $64 \leq Z \leq 81$ by counting downward beginning with the beam peak $Z = 82$. The peak at $Z = 83$ corresponds to a charge pickup reaction as shown in Fig. 1.

Charge resolution and calibration of CR-39 nuclear track detectors to characterize response of the detectors towards relativistic ions were reported in a previous paper.[13] We now report on the measurement of partial cross sections and charge pickup cross sections of relativistic energy Pb projectile fragmentation with heavy target materials.

At relativistic energy, heavy ion collisions in the overlapping region, called the participant region, cause multiple production of new particles to occur and the nuclear matter breaks up into nucleons. This process is very rapid, having a short time to cross the target nucleus. The remaining parts of the nuclei which do not participate in the disintegration process are called the spectator regions of the projectile and the target nuclei. During this production process, a fraction of the available energy is transferred to the colliding nuclei, leaving those nuclear remnants in an excited state, the de-excitation of the nuclear remnants takes place. This process is called the nuclear fragmentation, and the fragmentation of the relativistic projectile nucleus is of particular interest in this research. The constituents of the spectator part of the projectile (projectile fragments), as well as those of the spectator part of the target (target fragments), can be well separated at energies like ours. The projectile fragments have momentum per nucleon almost equal to that of the beam nucleus, so they are essentially emitted inside a narrow forward-angular cone centered around the direction of the incident beam, and remain relativistic. Hence, unlike the target fragments, the heavy fragments of the projectile nucleus are very easily and reliably distinguished from all other particles emitted from the collision vertex.

The numbers of surviving beam ions and fragments in the charge range $64 \leq Z \leq 82$ and charge pickup nuclei $Z = 83$ observed in the detectors placed downstream from the target have been estimated from the corresponding mean value of cone heights distribution as shown in Fig. 1.

Partial charge-changing cross sections are measured using the ratio of the number of fragment events corresponding to each assigned charge observed after the target and the total number of events due to survived projectile ions N_Z and N_S, respectively.

The partial fragmentation cross sections of Pb ions yielding fragments with charge $64e \leq Z < 82e$ in collision with Bi, Pb, Cu and Al targets have been measured using the following expression:

$$\sigma_{\Delta Z} = \frac{1}{x}\left[\frac{N_Z}{N_S}\right], \quad x = \frac{N_A \rho_T t_T}{A_T}, \tag{1}$$

where $Z = 64e$–$81e$, N_Z is the number of fragment nuclei with charge Z produced in the target, N_S is the number of un-fragmented beam nuclei, ρ_T, A_T, t_T, and N_A are the target density, mass number of the target, target thickness and Avogadro's number, respectively. The partial cross sections measured for fragment production with charge-change $-1 \leq \Delta Z \leq -18$ in the targets are shown in Fig. 2.

In the heavy ion peripheral collisions a considerable part of the nucleons have no participation in the interaction and form prefragments termed as spectators of the collision. These prefragments evaporate particles and consequently become stable preferably having an odd charge number. For all targets, the fragment production cross sections do not fall monotonically with increasing charge-change ΔZ. Instead, enhanced production of even-Z nuclei occurs (odd–even effect), Apart from projectile charge-change $\Delta Z = 1$ and 2, the cross sections for production of even-Z nuclei (even charge) are seen to be comparable to or larger than the cross sections for the species with the odd charges $(Z+1)$, and significantly larger than the cross sections for the species with the odd charges $(Z-1)$.

In order to organize these results the partial cross sections can be fitted with power-law relation

$$\sigma_{\Delta Z} = \alpha |\Delta Z|^{-\beta}, \tag{2}$$

where α and β are parameters fitted for each tar-

get listed in Table 1. The power law is not fitted to small charge-change $\Delta Z = -1$ and -2 cross sections, which clearly deviate and are assumed to be influenced by electromagnetic dissociation. The values of small change are excluded from the fit, and the power law provides reasonable fits to the values in data sets with suitable values of χ^2.

Table 1. Fitted parameters of power law relation (2) in the partial charge-changing cross sections values for each target.

Targets	α	β	χ^2
Bi	853 ± 128	0.76 ± 0.06	2.3
Pb	538 ± 78	0.67 ± 0.05	1.9
Cu	263 ± 19	0.43 ± 0.04	1.6
Al	217 ± 18	0.42 ± 0.03	1.4

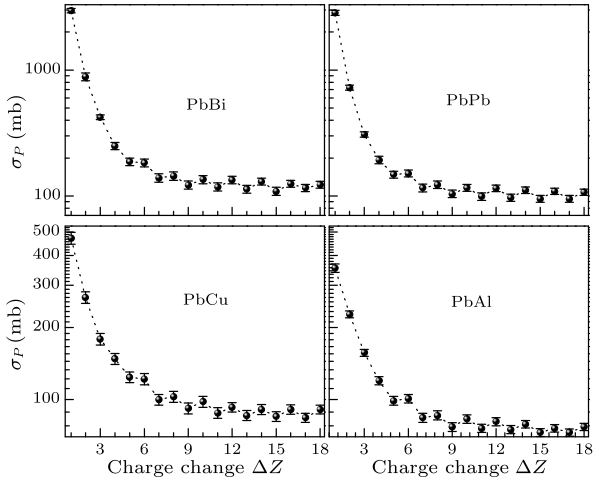

Fig. 2. Partial fragmentation charge-changing cross sections σ_P of 158 A GeV Pb ions versus projectile charge-change ΔZ in the interaction with Bi, Pb, Cu and Al target material. The errors are due to statistics of events and thickness of target materials.

The partial cross sections determined for each target are shown in Fig. 2. In every case the majority of the values of the partial cross sections are found to regularly decrease with increasing charge-change. The number of fragments produced from the projectile is large for small charge-change ΔZ and decrease with the increasing charge-change ΔZ. In fact, in all cases we find that the variation of cross sections can depend on the type of target material, and be quite well represented by either power law relation between cross section and ΔZ. The values of cross sections for $\Delta Z = 1$ and 2 appear to be anomalously high with the excess cross sections, due presumably to the additional process of electromagnetic dissociation causing proton stripping. For targets with heavy nuclei, the variation in the cross sections can be fitted with acceptable values of reduced χ^2. The parameters which characterize the power law appear to be dependent on both charge and energy of the projectile; energy dependence is ascribed due to the electromagnetic dissociation process at relativistic energy,[7] but this set of measurements is inadequate to separate these two effects. In the light target mass range our measured partial cross sections similar to the low energy of about 10.6 A GeV reveal a dominant contribution of the nuclear process.

At relativistic energies, the projectile and target are entirely non-overlapping in the peripheral collision, preventing any transfer of a target proton to the projectile, however, it can be assumed due to delta resonance formation and decay in nucleus–nucleus collisions to be the most expected process in which a projectile neutron can be converted into a proton, with subsequent absorption of the proton in projectile and emission of π^- [12] and, probably, neutrons.

In Fig. 2, a charge pickup peak is observed, as a result, relativistic projectile charge is increased by one unit during the projectile fragmentation on heavy target material. The number of events in the cone height peak at charge $Z = 83$ have been used to estimate charge pickup cross sections. The charge pickup cross sections $\sigma_{(\Delta Z=+1)}$ of the projectile ions interacting with the Bi, Pb, Cu and Al targets have been determined using the expression:

$$o_{\Delta Z=+1} = \frac{1}{x}\left(\frac{N_{83}}{N_S}\right), \quad x = \frac{N_A \rho_T t_T}{A_T}, \tag{3}$$

where A_T is the target mass number, N_A is Avogadro's number, ρ_T and t_T are the target density and thickness, respectively, N_{83} is the number of charge pickup events produced in the target, N_S is the number of non-fragmented projectile particles coming out of the target. The plot of measured pickup cross sections as a function of target mass A_T is shown in Fig. 3.

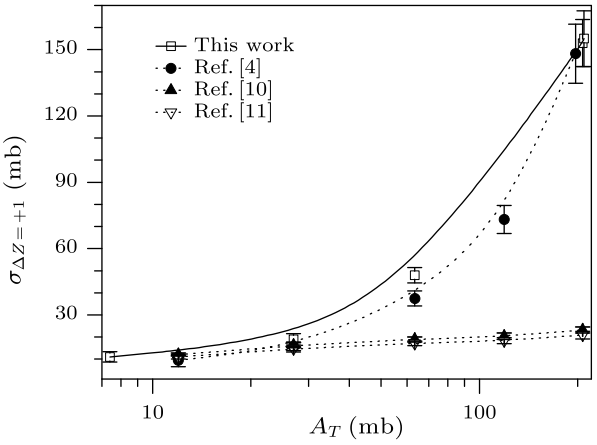

Fig. 3. Measured charge pickup cross sections ($\sigma_{\Delta Z=+1}$) as a function of target mass number A_T for 158 A GeV Pb projectiles. The solid line is the power- law fit to data with Eq. (4). The dotted lines show the data at energies 10.6 A GeV and 158 A GeV from Refs. [4,10,11]. The error bars include statistical and systematic uncertainties.

The dependence of these cross sections on target mass A_T can be represented as a power law in the form:

$$\sigma_{\Delta Z=+1} = a(A_T)^{\delta}. \tag{4}$$

The experimental data fitted to the power law equa-

tion is best described by the parameters $a = (0.43 \pm 0.24)$ mb and $\delta = 1.1 \pm 0.11$ with $\chi^2/d_f = 1.4$ (d_f is the degree of freedom). The solid line shows the fit of experimentally determined data to the empirical power law relation (3).

It has been found that measured charge pickup cross sections increase significantly with the increase in target mass A_T. Our experimental results demonstrate that for the heavy projectile collisions with high-Z nuclei the dominant contribution to charge pickup is due to electromagnetic processes of π^- production by virtual photons.[12] This contribution is entirely negligible in the data reported at 10.6 A GeV.[10,11]

Our estimated charge pickup cross sections are almost comparable to the results reported at similar energy.[4] In the light target mass A_T region our measured charge pickup cross sections are comparable to the data at about 10.6 A GeV, observing similar target dependence. Projectile charge pickup cross section dependence on the nature of the target nucleus increases in strength for the heavier target nuclei, and dependence on the projectile nuclide, at least for heavier nuclei, can be expressed in terms of neutron content of the projectile.

Nuclear track detectors achieved reat performance in this experiment, making it possible to explore charge-changing reactions and demonstrating the potential of this type of detectors. The measurements made at 158 A GeV heavy projectile collisions with heavy targets give insight into both the physics involved and the conditions established in relativistic energy heavy ion collisions. The results from this experiment exhibit the significance of nuclear and electromagnetic contributions in peripheral collisions involving large impact parameters.

We thank the technical staff of SPS-CERN for the beam exposures. We acknowledge the contribution and experimental help of Mr. Bashir Ahmad Shad at Physics Division, PINSTECH. G.S. is indebted to the Higher Education Commission (HEC) for a financial grant to present a part of this work at an international conference.

References

[1] Bass S A, Mueller B, Stephans G S F and Ullrich T 2003 *Proceedings of the 7th International Conference on Strangeness in Quark Matter SQM2003* (Atlantic Beach, USA, 12–17 March 2003)
[2] Waddington C J 1996 *Astrophys. J.* **470** 1218
[3] Waddington C J, Cummings J R, Nilsen B S and Garrard T L 2000 *Phys. Rev.* C **61** 024910
[4] Scheidenberger C, Pshenichnov I A, Sümmerer K, Ventura A et al 2004 *Phys. Rev.* C **70** 014902
[5] Dekhissi H, Giacomelli G, Giorgini M, Mandrioli G, Manzoor S, Patrizii L, Poppa V, Serra P and Togo V 2000 *Nucl. Phys.* A **662** 207
[6] He Y D and Price P B 1994 *Z. Phys.* A **348** 105
[7] Hirzebruch S E, Becker E, Hüntrup G, Streibel T, Winkel E and Heinrich W 1995 *Phys. Rev.* C **51** 2085
[8] Fleischer R L, Price P B and Walker R M 1975 *Nuclear Tracks in Solids* (California: University of California).
[9] Giacomelli G, Giorgini M, Mandrioli G, Manzoor S, Patrizii L, Popa V, Serra P, Togo V and Vilela E C 1998 *Nucl. Instrum. Methods* A **411** 41
[10] Geer L Y, Kalarman J, Nilsen B S, Waddington C J, Binns W R, Cummings J R and Garrard T L 1995 *Phys. Rev.* C **52** 334
[11] Nilsen B S, Waddington C J, Binns W R, Cummings J R, Garrard T L, Geer L Y and Klarmann J 1994 *Phys. Rev.* C **50** 1065
[12] Sümmerer K, Reinhold J, Fauerbach M, Friese J, Geissel H, Körner H, Münzenberg G, Schneider R and Zeitelhack K 1995 *Phys. Rev.* C **52** 1106
[13] Sher G, Shahzad M I and Hussain M 2007 *Chin. Phys. Lett.* **24** 2800