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Large fragmentation phenomena in relativistic Au + Al interactions(*)

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Summary. — A stack consisting of CR39 plastics and Al target has been exposed to 1.015 GeV/n Au beam at an angle of 30° from LBL BEVALAC. About 5499 cone lengths of the Au beam and their fragments have been optically measured from the etched plastics kept below the Al target and the estimated partial cross-sections of large fragments for charges Z_{F} ranging from 75 to 78 have been found comparable with the expected results from the semi-empirical model of Silberberg and Tsao. But those values are above the expected results from the abrasion-ablation model of Townsend *et al.* The observed charge pick-up cross-section for $\Delta Z = +1$ is found to lie below the global fit to the charge pick-up cross-section results surveyed by Westphal *et al.*

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1. – Introduction

The investigation on ultra heavy relativistic nuclei interaction in low-Z targets using LBL BEVALAC or BNL AGS beam is important in the study of the high-energy nucleus-nucleus collisions and for the estimation of the changes of mass composition due to the cosmic-ray propagation through the Interstellar Medium.

Earlier, Hufner *et al.* [1] have reviewed the nuclear fragmentation results at relativistic energies. Usually, spallation reactions, in which the ultra heavy nuclei produce large size

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fragments, are dominating especially for light target nuclei and such cross-sections are found to decrease with increasing $\Delta Z = Z_{\mathrm{P}} - Z_{\mathrm{T}}$. Using the ultra heavy nuclei beams from LBL BEVALAC or BNL AGS in combination with active detectors, various direct measurements [2-10] on the ultra heavy interaction phenomena have been studied. In active detector experiments the isolation of the first fragment *i.e.* the nuclear charge peak for $\Delta Z = -1$ is difficult and, bearing this in mind, some passive detector experiments have been performed by different authors [11-18] to explore this phenomenology using similar beams and targets.

More recently, Nilsen *et al.* [19] from a closure study of their active detector experiments have pointed out that, except for hydrogen target, the partial cross-section $\sigma_{\Delta Z}$ for fragments with $-20 < \Delta Z < -2$ follows the power law fit of the form $\sigma_\epsilon |\Delta Z|^{-\epsilon}$, where the energy dependence of the exponent $-\epsilon$ and the scaling parameter σ_ϵ are very weak beyond $1A$ GeV. They have shown that the partial cross-section has a target dependence with an index $-\epsilon$ which is energy dependent. Such dependence suggests that these interactions occurred by virtual pions from the target. Usually the beam dependence of the cross-section is fairly explained by the fractional neutron excess rather than the beam mass. From a closure study of the data at 0.4 and $10.6A$ GeV, they have shown that the partial cross-sections are energy independent, as indicated from the phenomenological concept of limiting fragmentation. At high energies above reaction thresholds and resonances, the fragmentation reaction would be energy independent except for corrections involving powers of $\ln(E)$ [20]. The increase of energy creates more particles or breaks up more subfragments instead of opening up new channels for the production of a particular fragment or new particles. The recent experimental data of Geer *et al.* [21] show that for Au projectiles the sum of small charge changing cross-sections is enhanced by a factor of two below the energy of about $1A$ GeV and $10A$ GeV, revealing the fact that the limiting value has certainly not been attained at BEVALAC energy. This fact shows that sufficient attention is to be paid to the A-A collision at a rather lower energy $\sim 1A$ GeV, as can be studied with BEVALAC beams with various targets. More investigations are to be made at intermediate energies to search the threshold energy of the limiting fragmentation where the phenomenon will be explicitly dependent on the projectile mass number A_{P}.

Several experiments on the fragmentation phenomena have been done using CR39 solid-state nuclear track detectors by different groups [11-18] and found adequate results compatible with active detector experiments. But for the results of $\Delta Z \leqslant -1$ the observed fragmentation has a deviation from the expected results from the semi-empirical model of Tsao *et al.* [22] and a similar fact is observed from the semi-classical abrasion-ablation model of Townsend *et al.* [23].

Using LBL BEVALAC beam on CR39 detectors Guoxiao *et al.* [24] have found charge pick-up events which have supported the active detector findings of Waddington [25]. Later, Westphal *et al.* [26] have found similar results using passive detectors like phosphate glass exposed to relativistic LBL BEVALAC U beam.

In the present work we have used a stack consisting of CR39 solid-state nuclear track detectors with Al target, exposed to 1.015 GeV/n Au beam from LBL BEVALAC. The measurements of the nuclear break-up cross-sections concerning the Au projectile nuclei of charge $Z_i (i = 79)$ in CR39 and Al targets have been done to estimate the nuclear fragments of charge $Z_j (j = 75, 76, 77, 78)$. The CR39 polymers are adequate for the measurements of a restricted energy loss of ionizing particles. The relatively low energy is required for breaking the polymeric bond in the plastics. The Landau fluctuations due to high-energy δ-ray electrons do not contribute to the latent track formation in CR39. Such radiation damage along the particle trajectory may be chemically developed to an optically

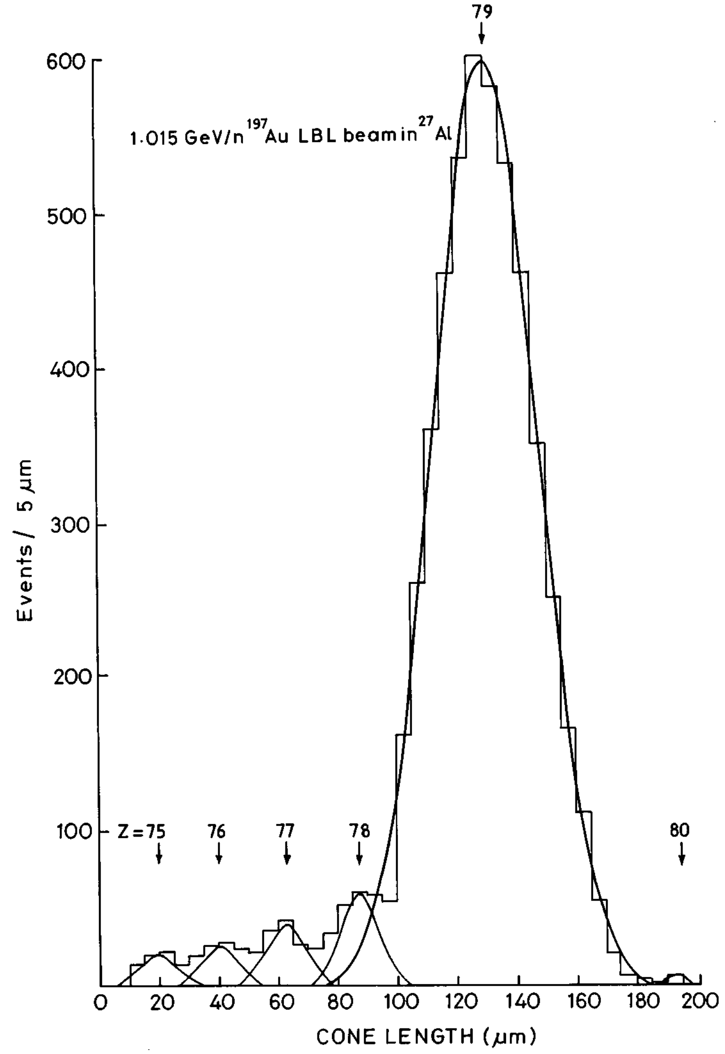

Fig. 1. – Observed cone length distribution of emergent Au projectiles after interacting in 2 cm Al target and detected in CR39 foils placed adjacent to the Al target. The curve drawn through the histogram shows the Gaussian fit to the observed distribution. The peak of the distribution shows the charges of Au nuclei ($Z = 79$) along with the fragments of charges ranging from $Z = 75$ to 78, and charge pick-up events ($Z = 80$).

visible track through a microscope. The estimated charges from the measured cone length distribution histogram have been confirmed from REL calculation. The observed partial cross-sections are compared with the derived results from the semi-empirical model of Tsao *et al.* [22] and also with that expected from the semi-classical abrasion-ablation model of Townsend *et al.* [23].

A search has been made on the charge pick-up phenomena in Au + Al interactions and the observed result has been compared with the global survey of Westphal *et al.* [26].

2. – The experiment

A stack consisting of CR39 plastic nuclei track detectors, where 10 plastic foils of dimension $5\,\mathrm{cm} \times 5\,\mathrm{cm} \times 0.045\,\mathrm{cm}$ are placed upstream and 5 foils downstream to the $2\,\mathrm{cm}$ ^{27}Al target of similar area, has been exposed to 4600 per cm^2 defocussed ^{197}Au beam nuclei of energy 1.015 GeV/n at an angle of 30° from LBL BEVALAC in 1993. CR39 plastic is a polymer of formula $\mathrm{C}_{12}\mathrm{H}_{18}\mathrm{O}_7$ with a density of 1.32 $\mathrm{g\,cm}^{-3}$ and it serves both as detector and target. After irradiation the plastic detector foils have been etched in 6.25N NaOH solution at $(70 \pm 0.1)°\mathrm{C}$ for three hours and after that particle tracks appear as visible cones on both the plastic surfaces. The foils have a thickness of $450\,\mu\mathrm{m}$ before etching. The estimated bulk etch rate of the plastic detectors is found to be $1.36\,\mu\mathrm{m/h}$. The cone lengths of the ultra heavy nuclei tracks are measured using a Leitz Ortholux microscope with a dry objective × 24 along with a filar micrometer eyepiece × 15. The parameters of the etch pits have been measured in the plastics, placed below the Al target and the cone lengths have been calculated from the track geometry formulated by Henke and Benton [27]. The etching of the plastics occurs along the trajectory of the ultra heavy nuclei of charge Z and velocity βc, at a track etch rate V_{T} when it exceeds the bulk etch rate V_{G} and, as a consequence, the conical etch pits are generated at the point of extrance and exit. The ratio $V_{\mathrm{T}}/V_{\mathrm{G}}$ of etch rates is a function of Z/β. In the present case the response $V_{\mathrm{T}}/V_{\mathrm{G}}$ of the plastic as an Au-ion detector has been estimated and found to be (31.87 ± 2.07) for $Z/\beta = 96.8$ which is 28% lower than the expected results from the universal fit to the global etch rate data [18],

$$V_{\mathrm{T}}/V_{\mathrm{G}} = A\exp[B(Z/\beta)], \tag{1}$$

where the fitting parameters are $A = 0.405114, B = 0.048554$ in the interval $27.6 < Z/\beta < 106.4$.

The charge resolution of the detector has been found to be $0.5e$ from the measurement of etch cones from both sides of the detector $(n = 2)$. Usually, such charge resolution may be improved by measuring the same track on different surfaces, following $\sigma_n = \sigma_1/(n)^{1/2}$, where n is the number of independent measurements and σ_1 is the charge resolution from single $(n = 1)$ surface measurement. In the present case the charge resolution for both the surfaces $(n = 2)$ of a single detector sheet is $(2)^{1/2}$ times the observed one and is found to be $0.71e$. The nuclear fragments with integral charges can be clearly resolved from the measurements of cone lengths on both sides of the plastic kept below the Al target. The partial cross-sections for the production of fragments of charge $Z_{\mathrm{F}} = 75$ to 78 can be estimated from the analysis of the cone length distribution.

3. – Results and discussion

About 5499 cone lengths have been measured from the scanning of plastics exposed below the 2 cm Al target. The cone lengths and the charge-changing nuclear fragments may be obtained from the measured cone length distribution peaks indicating the ionic charge state of the gold beam along with their fragments after traversing the Al target. The smaller peaks to the left of the largest one are composed of gold nuclei which fragmented to lower charge. The Gaussian fit to the observed peaks of the cone length distribution in fig. 1 maps etch pit cone length into the incident projectile charge Z that enabled us to estimate the frequency of charges Z from 79 (Au) down to 75 (Re). The number of un-

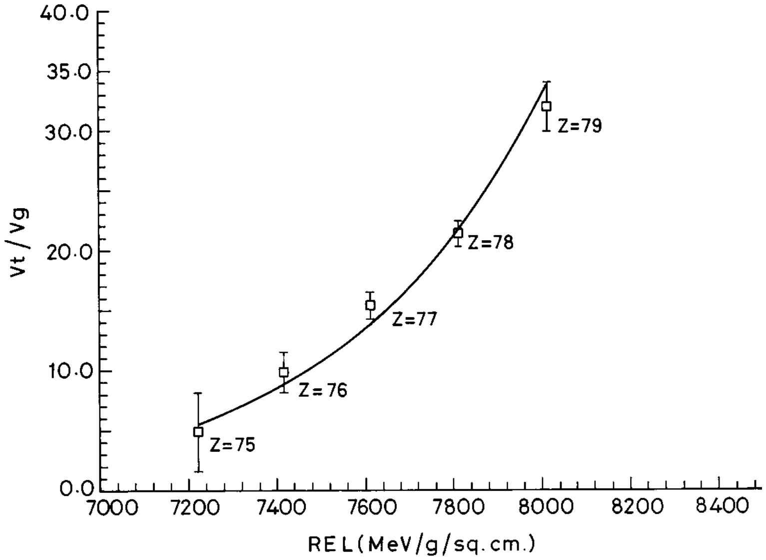

Fig. 2. – The charge assigned in the histogram in fig. 1 is confirmed by representing the etch rate ratio $V_\mathrm{T}/V_\mathrm{G}$ as a function of REL which favours an increase with REL following a power law behaviour as shown in the relation (2). The respective charge corresponding to each REL is indicated in the plot.

fragmented, fragmented and charge pick-up nuclei events have been estimated from the Gaussian fits to the cone length distribution shown in fig. 1.

The etch rate ratio $V_\mathrm{T}/V_\mathrm{G}$ has been found to increase with REL of the Au nuclei and their fragments in Al target and follows the power law fit of the form

$$V_\mathrm{T} = V_\mathrm{G} 6.15665 \times 10^{-67} (\mathrm{REL})^{17.3521}, \tag{2}$$

and is displayed in fig. 2. The etch rate ratio is found to increase with REL. Such plot confirms the proper charge assignment in the solid-state nuclear track detector. Since the

TABLE I. – *The interaction parameters used for the evaluation of the observed fragmentation and charge pick-up cross-sections in* ^{197}Au + ^{27}Al *interactions at* (0.93 ± 0.070) GeV/n, *obtained from the 5499 cone length measurements in the* CR39(DOP) *plastic sheets kept below the* $t = 2$ cm Al *target.* Z_f *and* Z_i *denote the charges of the fragment and beam elements,* N_i *is the number of unfragmented beam nuclei that emerged from the target, and* $\sigma_{\Delta Z}(Z_i, Z_\mathrm{f})$ *is the charge-changing cross-sections.*

Ion	Z_i or Z_f	N_i	N_f	ΔZ	$\sigma_{\Delta Z}(Z_i, Z_\mathrm{f})$ mb
Au	Z_i=79	5108	...	0	
Pt	Z_f=78		134	−1	(218 ± 19) mb
Ir	77		114	−2	(185 ± 17) mb
Os	76		72	−3	(117 ± 14) mb
Re	75		59	−4	(96 ± 12) mb
Hg	80		12	+1	(20 ± 6) mb

TABLE II. – *The partial cross-sections* $\sigma_{\Delta Z}(Z_i, Z_\mathrm{f})$ mb *of* Au *nuclei fragments and charge pick-up cross-sections in* Al *target obtained from the present work, compared with the derived results from the semi-empirical model of Tsao et al.* [22] *and from the semi-classical abrasion-ablation model after Townsend et al.* [23].

Fragment Z_f	Tsao *et al.* [22]	Townsend *et al.* [23]	Present work
78	214 mb	172 mb	(218 ±19) mb
77	146 mb	90 mb	(185±17) mb
76	92 mb	82 mb	(117±14) mb
75	77 mb	65 mb	(96±12) mb
80	...	...	(20±6) mb

target thickness is small when compared to the mean free path of the fragments in Al, one can safely neglect the double fragmentation process in the target and can estimate the partial cross-section using the simple formulation of Cecchini [28] by using the form

$$\sigma_{\Delta Z}(Z_i, Z_\mathrm{f}) = -\frac{1}{Kt}\ln(1 - N_\mathrm{f}/N_i), \tag{3}$$

where $\sigma_{\Delta Z}(Z_i, Z_\mathrm{f})$ is the partial fragmentation cross-section in Al of a relativistic ion with charge Z_i into a fragment of charge Z_f, K is the number of nuclei per cm^3 which is the ratio of the product of Avogadro number and target density to the mass number ratio $N = 6.02 \times 10^{22}$, the target being of thickness $t = 2\,\mathrm{cm}$; N_f is the number of fragments of charge Z_f and N_i is the total number of primary nuclei of charge Z_i reaching the plastic sheet exiting the Al target. Table I shows the observed number of Au beams and their respective fragmented nuclei in Al target as expected from the Gaussian fits displayed fig. 1. Using the relation (3) and the parameters from table I, the estimated partial cross-sections in $^{197}\mathrm{Au} + ^{27}\mathrm{Al}$ interactions are shown too. The derived partial cross-sections from the semi-empirical model of Tsao *et al.* [22] and also from the semi-classical abrasion-ablation model of Townsend *et al.* [23] have also been compared with the present result in table II. It is evident from the table that the observed cross-sections are higher than that found from the expected results. The partial cross-sections obtained from ultra heavy nuclei interactions with low-Z target have a systematic dependence on ΔZ. The cross-section for U-ions in Al target yield the highest value for $\Delta Z = -1$ and the results follow three different power law behaviours of the form

$$\sigma_{\Delta Z}^{\mathrm{Kr+CR39}} = 153.399(\Delta Z)^{-0.5862}\ \mathrm{mb}, \tag{4}$$

$$\sigma_{\Delta Z}^{\mathrm{Au+Al}} = 237.883(\Delta Z)^{-0.6067}\ \mathrm{mb}, \tag{5}$$

$$\sigma_{\Delta Z}^{\mathrm{U+Al}} = 389.486(\Delta Z)^{-0.8918}\ \mathrm{mb}. \tag{6}$$

The derived results are displayed in fig. 3.

Till now the U-ion interaction results are rarely available and the observed partial cross-sections [29-31] differ considerably from the expected results based on the semi-classical model of Townsend *et al.* [23] but slightly close to the expected results from the

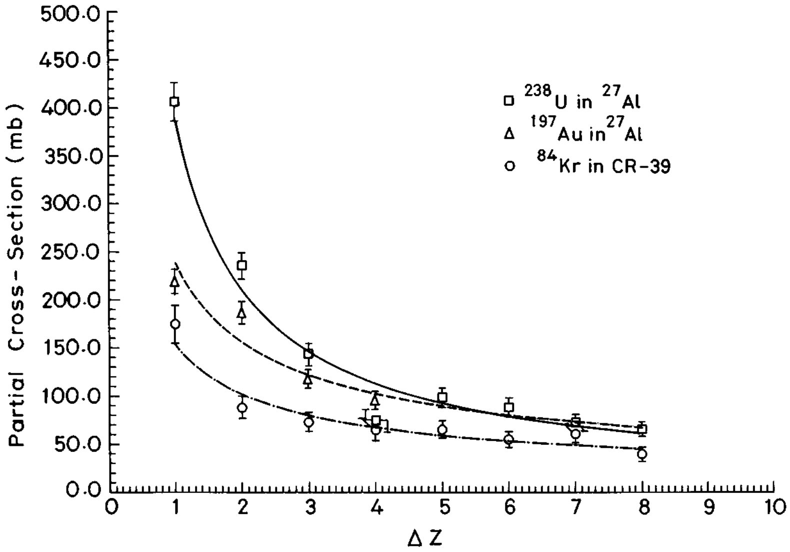

Fig. 3. – The charge-changing cross-sections for Au + Al interactions when plotted as functions of ΔZ along with the earlier experimental results with CR39 and Al targets show a dependence on the projectile charge: Experimental data: ○: ^{84}Kr [13], □ : ^{238}U [16] and △ : ^{197}Au: Present Work. Full, broken and chain curves are the power law fits to the observed results for ^{238}U, ^{197}Au and ^{84}Kr nuclei as found from the relations (4)-(6) as described in the text.

semi-empirical model of Tsao *et al.* [22]. Attention has been paid to the smallest charge peak shown in fig. 1 which is away from the unfragmented Au ions. The charge of this peak may be caused due to charge pick-up phenomena for the charge difference $\Delta Z = +1$ whose cross-section is about (20 ± 4)mb. This result has been compared with the global survey on the cross-sections for charge pick-up nuclei arose in nucleus-nucleus collisions after Westphal *et al.* [26] in fig. 4. The earlier experimental results of different authors with different targets [13, 14, 16, 17, 24, 26, 32-34, 29] have been confirmed with the phenomenological fit after Guoxiao *et al.* [24]. They found that for projectiles with energy ~ 1 GeV/n the cross-section for charge pick-up reactions varies approximately as the square of the projectile mass number. The conventional charge pick-up cross-section follows the scaling law

$$\sigma_{\Delta Z=+1} = 1.7 \times 10^{-4}(A_{\mathrm{P}}^{1/3} + A_{\mathrm{T}}^{1/3} - 1)A_{\mathrm{T}}^{2}\ (\mathrm{mb}), \tag{7}$$

where A_{P} and A_{T} are the mass numbers of the incident projectile and of the target, respectively. The above scaling formula is based on the cross-sections obtained from U-ions of energy at ~ 1 GeV/n. The charge pick-up cross-section for Au + Al interactions has been calculated from the scaling formula and yields a value of 52 mb which is 2.5 times higher than that obtained from the present experiment. On the other hand, the ratio of the observed cross-section to the expression $(A_{\mathrm{T}}^{1/3} + A_{\mathrm{B}}^{1/3} - 1)$ is found 56% lower than that predicted earlier by Westphal *et al.* [30]. Binns *et al.* [2] and Guiru *et al.* [31] have pointed out that the charge pick-up cross-section increases with decreasing energy especially at around ~ 0.5 GeV/n. In our case the Au beam energy is rela-

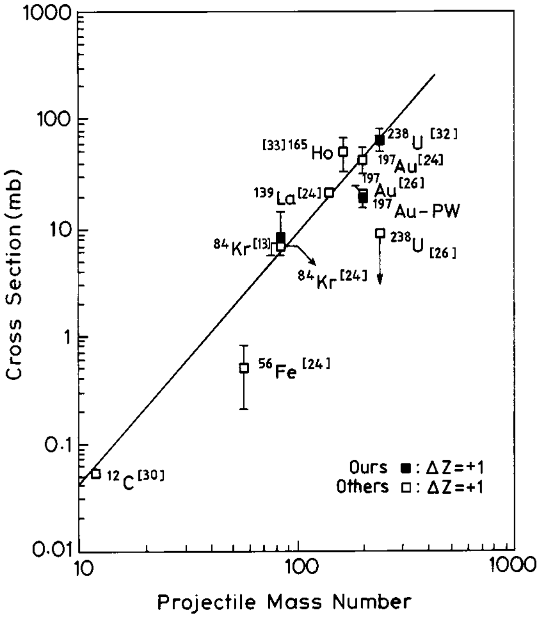

Fig. 4. – The charge pick-up cross-section obtained from the present experiment has been compared with the global survey after Westphal *et al.* [30]. ■ ^{84}Kr at 0.45 GeV/n [13], □ ^{56}Fe at 1.7 GeV/n [24], □ ^{84}Kr at 1.46 GeV/n [24], □ ^{139}La at 1.28 GeV/n [24], □ ^{197}Au at 0.80 GeV/n [24], □ ^{197}Au at 0.90 GeV/n [26], □ ^{238}U at 0.960 GeV/n [26], □ ^{12}C at 1.05 GeV/n [30], ■ ^{238}U at 0.927 GeV/n [29], □ ^{165}Ho at 0.981 GeV/n [33], ■ ^{197}Au at 1.015 GeV/n: Present Work. The full line is the expected result from the scaling law [24] as described in relation (7).

tivistic. The present charge pick-up cross-section lies below the expected results from scaling relation as is shown in fig. 4.

4. – Conclusion

The partial cross-sections of large fragments emitted in Au + Al interactions at 1.015 GeV/n energy are found higher than that expected from the semi-empirical model of Tsao *et al.* and also from that obtained from semi-classical abrasion-ablation model of Townsend *et al.* The charge pick-up phenomena has been observed whose cross-section is lower than that obtained from the scaling formula after Guoxiao *et al.*

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