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HEAVY FRAGMENTS PRODUCED IN RELATIVISTIC ^{238}U + ^{27}Al INTERACTIONS

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A stack consisting of the CR39 (DOP) plastics and an Al target has been exposed to the 927 MeV/n U beam from LBL BEVALAC at an angle of 30° to study the large fragmentation phenomena and charge pick-up reactions. The plastic plates below the Al target were etched for 29 hours in 6.25N NaOH aqueous solution at 70° C. About 4200 nuclei produced in the Al target were detected in the plastics and their etch pit diameters have been measured. The distribution of the diameters reflects the charge distribution of heavy fragments from U-projectiles with charge Z_F ranging from 88 to 91. The estimated partial cross-sections are compared with the results derived from the model of Townsend et al. The observed charge pick-up cross-section for charge change $\Delta Z = +1$ has been found to lie below the expected result from the scaling law of Guoxiao et al.

1. Introduction

Investigation on the nucleus-nucleus collisions at relativistic energies, using highly compressed matter in target nuclei, is necessary for the derivation of the nuclear equation of state under non-equilibrium conditions. It is also required for the studies of the propagation of ultra-heavy primary cosmic-ray nuclei through the interstellar medium.

Experiments using high-energy heavy projectiles will provide information on the behaviour of high-density nuclear matter at high temperatures. They also exhibit the features of extended nuclear systems. The fit to the bulk of data on the projectile fragmentation for ultra-heavy nuclei in different elements allows indirectly to derive the partial cross-sections of ultra-heavy nuclei in elemental hydrogen. The direct determination of the cross-sections in hydrogen is very difficult. Such observations are also necessary for the calibration of the space-borne cosmic-ray passive track detectors throughout a wide Z range of targets.

Many authors [1-5] have used active detectors with the BEVALAC or AGS beams of ultra-heavy nuclei to investigate the interactions of projectile nuclei with various targets and to estimate the charge-changing cross-sections.

CR39 nuclear track detectors have been used extensively to estimate the charge-changing cross-sections [6-12].

Gerbier et al. [13] and Westphal et al. [14,15] have investigated the charge pick-up phenomena by using VG13 phosphate glass for its good detection response to the heaviest nuclei. Their results were found to be comparable with the results carried out with active detectors and accelerator beams [1]. We have found that CR39 can detect U-nuclei with a charge detection response that has a non$-Z^2$ dependence [16]. Nilsen [17] has modified the parametric form of the charge-changing cross-sections depending on the projectile and target masses with the use of the beams of Kr and Ag nuclei projected into targets ranging up to U. He has shown that the partial cross-sections $\sigma_{\Delta Z}$ for fragments with charge loss ΔZ in the range $-20 < \Delta Z < -2$ follow the power law $\sigma_{\varepsilon}(\Delta Z)^{-\varepsilon}$, where ε is the energy dependent exponent obtained from the fit to the data. They have pointed out that at higher energies larger number of fragments are produced, or breakup of subfragments increases, while opening of channels for the production of new fragments is not observed. Hence, the threshold energy of the limiting fragmentation phenomena has yet to be explored.

The VG13 phosphate-glass passive detectors have been used by Westphal et al. [14] with Ho- and U-beams, taking the glass and U as the targets, to investigate the charge pick-up cross-sections. They estimated the charge pick-up cross sections per nucleon, neglecting the target dependence. But when their result is multiplied by the nucleon number to get the actual cross-section for a particular target, the result is much lower than the one obtained directly from experiments using the same target. They have explained that such reduced cross-sections appear to be due to the fission phenomena in target atoms.

In the present work, we have irradiated a stack of 10 CR39(DOP) plastic plates (each of a thickness of 450μm) with a 2 cm thick Al target by 0.927 GeV$/n$ U-ions from LBL BEVALAC. We adopted the slow-etching technique of the plastic sheets. The measured diameter distribution of the elliptic etch pit mouths has been analysed to find the heavy-fragment distribution. Attention has been paid to explore the charge pick-up phenomena. The estimated fragmentation cross-sections have been compared with the results of Townsend et al. [18].

2. *The experiment*

The compact arrangement consisting of a 2 cm thick ^{27}Al target of 5 cm $\times$ 5 cm area in contact with ten sheets of CR39, of thickness 450μm each, placed above, and five such sheets of similar area placed below the target. In May 1990, the stack was irradiated by 927 MeV$/n$ ^{238}U diffuse beam from LBL BEVALAC of a fluence of 5125 U-ions per

cm^2, at an incident angle of 30°. The plates were etched in 6.25*N* NaOH aqueous solution at 70° C for 29 hours. The etching was interrupted from time to time to replenish the NaOH solution, with the aim to maintain a constant concentration, and also for the optical checking of the quality of the tracks in the plastics.

The bulk etch rate v_G has been found to be 1.36 μm/hr, after accounting for the loss of thickness of the plastic material due to the chemical etching. This value was confirmed by weighing of the sheets before and after etching.

When a highly ionizing particle with a charge Z and velocity βc passes through the nonconducting material like plastics, latent tracks are produced. Consequently, damages appear in the polymer bonds due to the energy deposition by the projectile. During the chemical treatment, the latent tracks are enlarged by the removal of material, preferentially along the trajectory of the particle, The cone shaped etch pits develop at the surface opening of the track. The geometry of the etch pit is a measure of the ionization rate, and it allows the determination of Z/β of the ionizing particle. The diameters of the etch pits have been measured by a Leitz Ortholux Optical Microscope with a filar micrometer eye piece $\times 25$ and dry objective $\times 24$. The smallest value of our diameter measurements has been found to be 0.3μm.

3. Results and discussion

About 4200 minor axes of the elliptic cones created by ^{238}U-projectiles and their fragments (and by etching) have been measured on both surfaces of plastics below the Al target. The average values of the minor axes are shown in the histogram displayed in Fig. 1. The charge resolution of the method has been estimated from the average of the etch pit diameters obtained from both-side measurements and found to be $\sigma_q = 1\ e$. Such a charge resolution is inadequate for the exploration of nuclear fragments with a fractional charge, but the nuclear fragments with integral charges are clearly resolved with the measurement of the etch pits on both sides of the plastics. In principle, the etch-pit areas increase with increasing ion charges [19]. Measurement of the area of the etch pits is, therefore, used to estimate the charge of the fragments. The U-beam incident on the stack had an energy of 927 MeV$/n$, but it looses energy in 4500μm of plastic. The surviving U-nuclei had energies of about 0.915 GeV$/n$ and 0.775 GeV$/n$ at the top and bottom of the Al target, respectively. The unfragmented nuclei leaving the Al target were detected in the plastic sheet and their Z/β was derived and found to be 109.95 for $\beta = 0.84$. The U-ions were fully stripped and the detected charges are indicated by arrows in Fig. 1. The small peaks to the left of the largest one are due to the fragmented-U peaks (lower-charge nuclei). The Gaussian fit to the observed peaks of the cone-length distribution is displayed in Fig. 1. It maps the etch-pit minor axes into incident projectiles of charge $Z = 92$, fragmented incident projectiles down to 88 (Ra) and pick-up nuclei with $Z = 93$. The numbers of unfragmented (U), fragmented (Ra, Ac, Th, Pa) and charge pick-up nuclei (Np) have been estimated from the Gaussian fits to the etch-pit minor axes distribution displayed in Fig. 1.

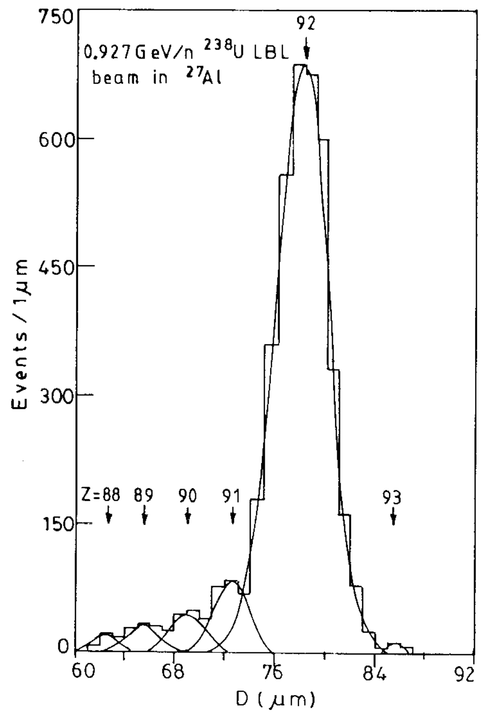

Fig. 1. Histogram of minor axes of etch pits as measured by the Leitz Ortholux microscope. The uranium peak and the peaks due to the fragments are marked by arrows and their respective charges. The curves drawn in the histogram show the Gaussian fits that were used for determination of numbers of events from various charges.

The target thickness was 5.4 g/cm^2 which is smaller than the mean-free path of U in Al (21.53 g/cm^2) calculated from the nuclear sizes obtained from the electron scattering experiments [20]. Neglecting the double fragmentation process in the target, one can estimate the charge-changing cross-sections using the standard formulation of Cecchini et al. [21]:

$$\sigma_{\Delta Z}(Z_i, Z_f) = \frac{A_T}{N_A \rho t} \ln(1 - N_f/N_i). \qquad (1)$$

$\sigma_{\Delta Z}(Z_i, Z_f)$ is the partial fragmentation cross-section in Al target for reactions initiated by a U-ion of charge Z_i into a fragment of charge $Z_f, A_T = 27$ is the target mass number, N_A is the Avogadro's number, $\rho = 2.7$ g/cm^3 is the target density, target thickness was $t = 2$ cm, N_f is the number of fragments of charge Z_f, N_i is the total number of primary nuclei of charge Z_i reaching the plastic sheet after passing the Al target. Table 1 shows the observed parameters obtained from Gaussian fits as derived from Fig. 1. By the adoption of interaction parameters from Table 1, and using relation (3), the charge-changing fragmentation cross-sections for charges between 88 and 91 have been calculated. They are shown in Table 1. In Table 2, we have shown our derived results for the charge-changing cross-sections from abrasion-ablation model of Wilson et al. [18], along with our earlier results obtained from cone-length measurements. In Table 2, we also compare the present result with the extrapolated results from the data of Binns et al. [1] It may be pointed out that the present slow-etching data on minor axes agree satisfactorily with our earlier results obtained from the cone-length measurements [10].

TABLE 1. Numbers of events used for the evaluation of the observed fragmentation and charge pick-up cross-sections in $^{238}\mathrm{U}+^{27}\mathrm{Al}$ *interactions at 0.845±0.070* GeV*/n, obtained from 4200 etch-pit minor axes measurements in* CR39 *sheets kept below the 2* cm Al *target.* Z_f *and* Z_b *denote the elements,* N_i *is the number of unfragmented nuclei that emerged from the target,* N_f *is the number of fragmented beam nuclei that emerged from the target, and* $\sigma_{\Delta Z}(Z_i, Z_f)$ *is the charge-changing cross-section (in units of* 10^{-31} m^2*).*

Ion	Z_b or Z_f	N_i	N_f	$\sigma_{\Delta Z}(Z_i, Z_f)$
U	$Z_B = 92$	3726		
Pa	91		189	438 ± 32
Th	90		123	285 ± 26
Ac	89		81	188 ± 21
Ra	88		63	146 ± 18
Np	93		18	42 ± 10

TABLE 2. The estimated charge-changing cross-sections $\sigma_{\Delta Z}$ *(in units of* 10^{-31} m^2*), obtained in the present investigation and in earlier work.*

Fragment charge Z_F	From minor axes data Present Work	From cone length data [10]	Calculated from the model [18]	From the extrapolated results [1]
88	146 ± 18			
89	188 ± 21	143 ± 12	120	112
90	285 ± 26	231 ± 15	180	126
91	438 ± 32	399 ± 20	320	217
93	42 ± 10	62 ± 7		

In Fig.1, it is found that the charge pick-up peak is well separated from the main beam peak ($Z = 92$). The estimated charge pick-up cross-section has been calculated from the conventional relation:

$$\sigma_{\Delta Z=+1} = \frac{N_{93} A}{N_{\mathrm{beam}} N_A \rho x}. \qquad (2)$$

where N_{93} is the number of charge pick-up events, N_{beam} is the number of unfragmented beam particles exiting the $x = 2$ cm Al target. The estimated charge pick-up cross-section is found to be $(42 \pm 10) \times 10^{-31}$ m^2 and this value is much lower than our short-hour-etching results $(62 \pm 7) \times 10^{-31}$ m^2. Guoxiao et al. [6] have given a peripheral scaling formula on the basis of the observed charge pick-up cross-sections and the result is:

$$\sigma_{\Delta Z=+1} = 1.7 \times 10^{-4} (A_{\text{target}}^{1/3} + A_{\text{beam}}^{1/3} - 1) A_{\text{beam}}^2. \tag{3}$$

Taking $A_{\text{projectile}} = 238$ and $A_{\text{target}} = 27$, and using the relation [3], the charge pick-up cross-section $\sigma_{\Delta Z=+1}$ has been estimated from the scaling law and found to be 78.93×10^{-31} m^2. The predicted charge pick-up cross-section from scaling $(\sigma_{\text{scaling}})$ is found to be 78.93×10^{-31}m^2, whereas the observed one (σ_{abs}) is 42×10^{-31} m^2. Using these results, the probability for fission p has been estimated at 0.47. The observed charge pick-up cross-section for Np $(Z = 93)$ formation decreases due to fission phenomena.

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References

1) W. R. Binns, T. L. Garrard, M. H. Israel, M. P. Kertzmann, J. Klarmann, E. C. Stone and C. J. Waddington, Phys. Rev. **C 36** (1987) 1870;

2) J. R. Cummings, W. R. Binns, T. L. Garrard, M. H. Israel, J. Klarmann, E. C. Stone and C. J. Waddington, Phys. Rev. **C 42** (1990) 2508; Phys. Rev. **C 42** (1990) 2530;

3) M. P. Kertzmann, Ph. D. Thesis, University of Minnesota, 1986;

4) B. S. Nilsen, C. J. Waddingtnon, W. R. Binns, J. R. Cummings, T. L. Garrard, L. Y. Geer and J. Klarmann, Phys. Rev. **C 50** (1994) 1065;

5) B. S. Nilsen, C. J. Waddington, J. R. Cummings, T. L. Garrard and J. Klarmann, Phys. Rev. **C 52** (1995) 3277;

6) B. Guoxiao, P. B. Price and W. T. Williams, Phys. Rev. **C 39** (1969) 1361;

7) J. Dreute, W. Heinrich, G. Rusch and B. Wiegel, Phys. Rev. **C 44** (1991) 1057;

8) D. P. Bhattacharyya, B. Basu, P. Pal, R. Rakshit, S. Chakrabarty and I. Hunyadi, Nucl. Instr. Meth. **B 61** (1991) 197;

9) D. P. Bhattacharyya, S. Chakrabarty, R. Rakshit, B. Basu, P. Pal and S. Biswas, Nucl. Instr. Meth. **B 73** (1993) 308;

10) D. P. Bhattacharyya, R. Rakshit, B. Basu, P. Pal and S. Biswas and N. Durgaprasad, Nuovo Cimento **15 C** (1992) 341;

11) D. P. Bhattacharyya, S. Chakrabarty, R. Rakshit, B. Basu, P. Pal and S. Biswas, Nuovo Cimento **16 C** (1993) 249;

12) D. P. Bhattacharyya, S. Saha, B. Basu, P. Pal, R. Majumdar, M. Mitra and S. Biswas, Hadronic J. **19** (1996) 101;

13) G. Gerbier, Ren Guoxiao and P. B. Price, Phys. Rev. Letters **60** (1988) 2258;

14) A. J. Westphal, J. Guiru and P. B. Price, Phys. Rev. C 44 (1991) 1687;

15) A. J. Westphal, P. Buford-Price and D. P. Snowden-Ifft, Phys. Rev. **C 45** (1992) 2423;

16) D. P. Bhattcharyya, R. Rakshit, B. Basu, P. Pal, S. Biswas and N. Durgaprasad, Nucl. Instr. Meth. **B 66** (1992) 388;

17) B. S. Nilsen, Ph. D. thesis, University of Minnesota, 1994;

18) L. W. Wilson, L. W. Townsend and F. F. Badavi, Nucl. Instr. Meth. **B 18** (1987) 225;

19) Y. D. He and M. Solarz, Nucl. Instr. Meth. **B 94** (1884) 113;

20) H. de Vries, C. W. de Japer and C. De Vries, At. Data Nucl. Data Tables, **36** (1987) 495;

21) S. Cecchini, D. Dekhissi, G. Giacomelli, G. Mandrioli, A. R. Margiotta, L. Patrizii, F. Predieri, P. Serra and M. Spurio, Astroparticle Physics **1** (1993) 369.

TEŠKI FRAGMENTI NASTALI U RELATIVISTIČKIM SUDARIMA ^{238}U + ^{27}Al

Snopom iona urana energije 927 MeV/n dobivenom iz LBL BEVALAC ozračili smo stog plastičnih detektora CR39 (DOP) pod kutom od 30°, radi proučavanja teških fragmenata i reakcija izmjene naboja. Za oko 4200 rupica nastalih prolazom brzih teških iona i jetkanjem plastičnih detektora načinili smo mjerenja promjera. Kako su promjeri rupica veći za ione većeg naboja, mogli su se odrediti brojevi dogadaja od uranovih iona koji nisu promijenili naboj, te od fragmenata s manjim nabojem (Z_f od 88 do 91) i s većim nabojem ($Z_f = 93$). Odredeni su udarni presjeci za te procese i usporedeni su sa rezultatima prema modelu Townsenda i suradnika Rezultat za udarni presjek za $\Delta Z = +1$ je manji od očekivanog prema mjerilnom zakonu Guoxia i suradnika.