# STUDY OF THE INTERACTION OF RELATIVISTIC URANIUM IONS WITH LIGHT TARGET ATOMS

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*SUMMARY: Interaction studies of uranium ions having an energy of 960 MeV/u with a CR-39 target have been made. CR-39, a polycarbonate ($C_{12}H_{18}O_7$) was used as the target as well as the detector of the incident beam and of the reaction products. Binary fission has been confirmed to be the most prominent mode of interaction. However, some higher order fission events along with events having exceptionally high multiplicities (clusters containing 30 and higher number of small tracks) have been observed. It appears from the reaction kinetics and the development properties of etch product tracks, that these high multiplicity events do not originate from radioactive contaminations within the CR-39 detector.*

*Key Words: Relativistic $^{238}$U-ions, binary and ternary fission, high multiplicity events, high multiplicity events fragmentation, CR-39 track detector, C,H,O, target atoms.*

## INTRODUCTION

The field of charged particle interactions is rather complex (1-7). A wide spectrum of interaction modes seems to exist in such encounters (Figure 1). In the experiments of low energy nuclear physics, the interaction of individual nucleons is studied. At higher energies, the break up of nucleons and the formation of new particles is of interest and has been studied with light projectiles and target atoms. High energy nuclear physics using heavy projectiles intends to study the behavior of nuclear matter i.e. the gross structures of an extended nuclear system. The experiments reported here contribute to the later type of interaction studies in which collective modes of excitation might be the basic mechanism. Greiner *et al.* (7) studied the uranium break up cross-section (total-, and fission-cross-sections) for a wide spectrum of targets (hydrogen to lead). Their results indicate that the cross-section for the central collisions increases as a function of the target mass and becomes as high as 20% of the total cross-section for the Pb-target. They also reported that the hypothesis of limiting fragmentation holds good for all the targets they studied except for hydrogen.

In this paper, we present some of the results obtained by us during our interaction studies, using relativistic projectiles of $^{238}$U ions with light target atoms of CR-39 plastic (a thermoset polycarbonate having a com position of $C_{12}H_{18}O_7$). The aim of these experiments was to study (a) the ranges and the mean-free-paths of primary and secondary relativistic fragments and (b) the fission- and 'fragmentation' - cross-sections.

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## EXPERIMENTAL DETAILS

In the present work a CR-39 plastic (a polycarbonate) was used both as the target and the detector for relativistic reaction products and projectiles. Large CR-39 sheets (thickness ~ 1.1 mm) were cut into 5x5 cm$^2$ pieces. Each sheet contained a protective layer of polyethylene (thickness ~ 140 μm) on both sides. These protective layers were previously provided by the manufacturers (Homalite Corporation, Wilmington, USA) at the time of preparation of the CR-39 sheets in order to avoid any possible contamination. Stacks consisting of different combinations of CR-39 pieces (total number ranging between 70 and 110) were prepared. The total thickness of each stack was adjusted to be slightly larger than the estimated ranges of the projectiles in the CR-39 medium (Figure 2). The stacks were exposed perpendicularly to 960 MeV/u- $^{238}$U ions at the BEVALAC, Lawrence Berkeley Laboratory, Berkeley, USA. The total fluence of the projectiles was in the range of (1-3)x$10^3$ particles/cm$^2$. After the exposures, the protective layers of the detectors were removed. This was immediately followed by etching the latent damage trails using an aqueous solution of 6N NaOH, kept at 70±1°C. All the detectors of the stack were etched simultaneously. The etching process was interrupted after every 30 minutes, followed by ultrasonic

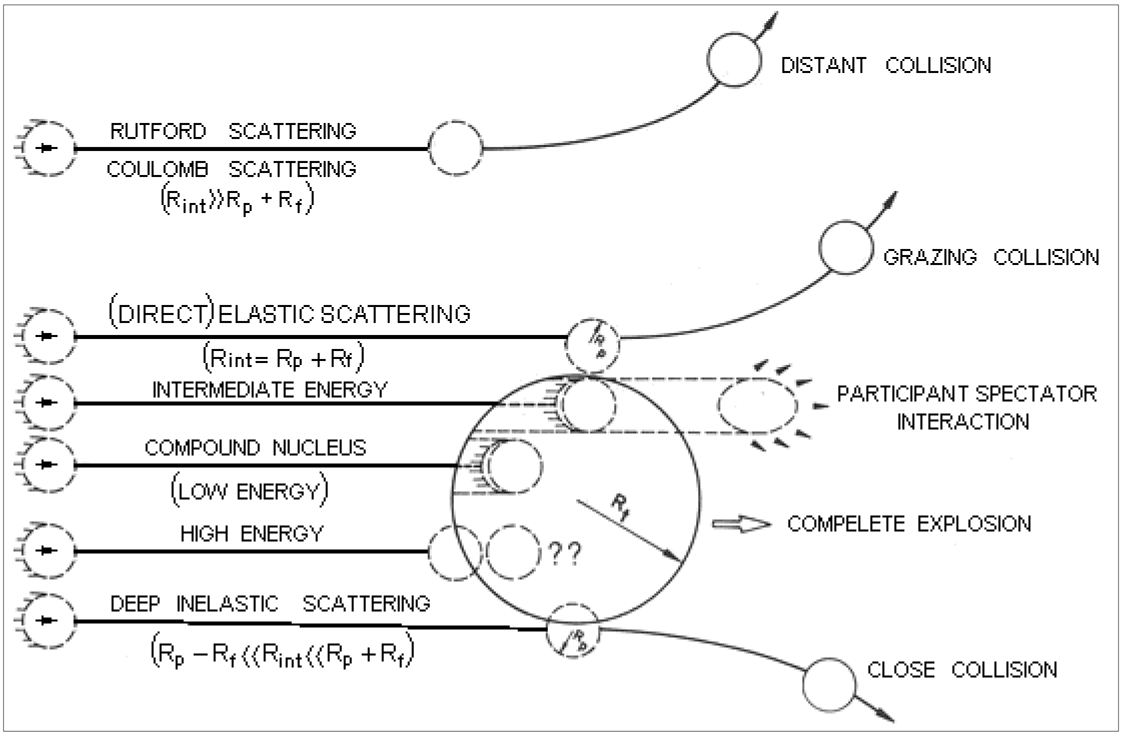


Figure 1: A sketch showing the wide spectrum of modes of interaction in charged particle encounters with a heavy nucleus. The energy of the projectiles along with the interaction radius seem to play an important role in identifying the reaction products formed in the exit channel and in determing the mode of interaction.

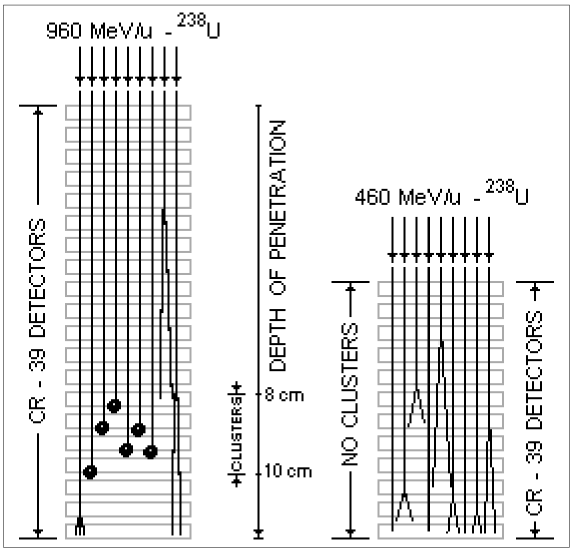


Figure 2: Stacks of CR-39 plastic track detectors exposed to $^{238}$U-ions with energies of 460 MeV/u and 960 MeV/u at BEVALAC (Berkeley). Binary fission was found to be the most dominant mode of interaction at both the energies. Some (rare) three prong events were also observed. The exceptionally high multiplicity events (clusters) were observed only in the case of the stack exposed to 960 Mev/u- $^{238}$U ions.

cleaning and drying stages, before carrying out the optical microscopic analysis. This procedure enables a systematic study of the gradual development cf the latent damage trails due to a large variety of the reaction products, which have a wide spectrum of energies and emission angles. Moreover, the procedure allows to study some of the rare type of events before they are lost due to the overlapping of the excessively etched latent damage trails of the reaction products formed in the more abundant type of fission events. The procedure was also useful to analyze changes in the multiplicity of 'multi-prong' events. Under the presently etching conditions, we can develop observable tracks due to protons (E≤10 MeV) and alpha particles (E≤40 MeV) in 5 hours' etching time (8-10).

The scanning and the etch pit parameter measurements were obtained by using a computer controlled optical microscopic system at every etching stage. Densities and parameters of different etched tracks were obtained at various etching stages. A particular attention was paid in the location and analysis of the correlated reaction products (11). In contrast to the analysis of the binary and ternary fission events analysis of the events having exceptionally high multiplicity demands extremely high precision in their analysis (11). We also carried out exposures to natural alpha particle sources such as natural uranium specks. These exposures were carried out with a view to (a) differentiate between various reaction products and (b) identify a possible presence of the light charged particles from the background sources.

RESULTS AND DISCUSSION

All the detectors comprising the stacks were analyzed for 'correlated' and 'uncorrelated' tracks at different etching stages. The analyses yielded not only binary and higher order fission events (12,13), but also some events and 3c. These events started appearing (with only a few etch pits) after a few hours' etching time. Figure 4 shows a multiplicity distribution of the exceptionally high multiplicity events (EHMEs) as obtained after etching then for 17 hours. The distribution was found to shift to the higher multiplicity side with increasing etching time. Whereas the mean value of the distribution is close to 60, some of the events have multiplicity values as high as 180. The origin of the events having multiplicity values of higher than 92 cannot be explained on the basis of the present results. In total, we observed more than 400 such "Exceptionally High Multiplicity Events (EHMEs)" 'clusters'. These were observed near or at the Bragg peak of the uranium beam.

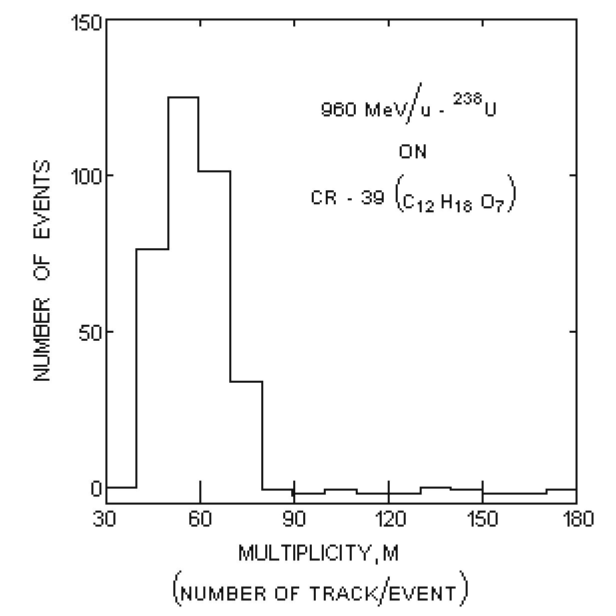


Figure 4: Multiplicity distribution of the exceptionally high multiplicity events (clusters). Whereas the mean value of the distribution is close to 60, some of the events have multiplicity values as high as 180. The origin of such events cannot be explained on the basis of the existing data.

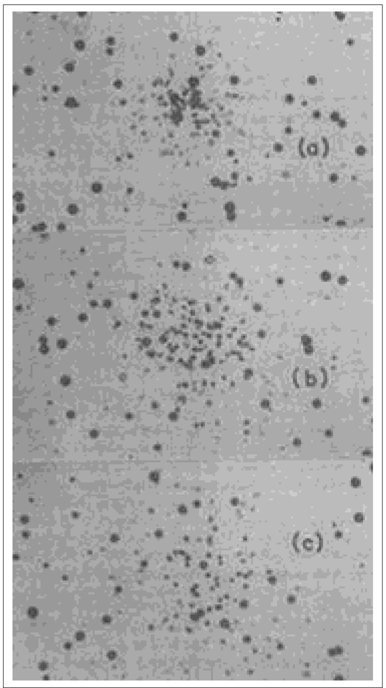


Figure 3: Photomicrographs (a, b and c) of three exceptionally high multiplicity events (or clusters) as observed in CR-39 exposed to 960 MeV/u- $^{238}U$ ions. The study of the characteristics of the etch pits comprising these events shows that most probably they were formed by some an isotropic source.

Since all the CR-39 detectors n the stack were obtained from the same batch, the mechanism behind the formation of these 'stars' should be linked to the initial 960 MeV/u- $^{238}U$ beam. It may be mentioned at this juncture that it has long been expected that interactions of relativistic heavy ions may exhibit entirely new phenomena. Thus such exceptionally high multiplicity events could be of great interest. The characteristic features of these exceptionally high multiplicity events have been described in the following paragraphs.

The microscopic observation of these events yielded a 'cluster' like pattern of shallow looking (circular and elliptic) etch pits of relatively small dimensions (Figures 3a-3c). The multiplicity of all these events was established after a careful correlation of the etch pits in a particular event under study. Experiments were carried out to study the track development characteristics of the latent damage trails comprising such events. In one of these experiments, a part of the detector, was etched in 6H NaOH at (70±1°C) for increasing time intervals, and variation in the density (number of events/cm$^2$) of such events was studied as a function of the etching time (Figure 5). A sharp rise in the density of events in the early stages (10-20 hours) of the etching process was observed. The increase in density was slower in the etching time interval of about 21 to 30 hours. Afterwards, the distribution attained a plateau, up to an etching time of about 50 hours. The tracks, with prolonged etching, got over etched and became shallow, thereby, we started losing them due to a poor optical contrast.

Figure 5 summarizes the results of the experiments, carried out to compare the etching of the latent damage trails due to the reaction products comprising three high multiplicity events with the development of track densities of a CR-39 foil exposed to alpha particles from a natural uranium speck. Alpha-particles from the uranium speck are almost fully developed in rather short etching time intervals of 6 to 8 hours. After about 16-20 hours' etching times, these tracks are over etched and are no longer detectable under an ordinary optical microscope. The significant difference between the two sets of curves (Figure 5) indicates, that the particles responsible for the exceptionally high multiplicity events have significantly lower effective charges as compared to those of alpha particles.

Most of the reaction products formed in such events seem to be very energetic light ions such as protons, and He-ions. Our previous experience concerning the development of latent damage trails of energetic light charged particles by etching shows that under the presently employed experimental conditions almost all the latent damage trails due to the commonly available alpha particles (such as from a uranium speck, 241Am, $^{252}$Cf, radon, thoron, etc.) in CR-39 are fully etched in the dimensions suitable for optical microscopic study at considerably lower etching time intervals. The present results strongly suggest the presence of the reaction products having much lower 'effective charges' as compared to those of the commonly available alpha particles from radioactive sources or from protons with an energy of about 10 MeV/u. The etchable regions of the charged particles with such low values of effective charges lie fairly deep within the detector body (Figure 6) and, therefore, require relatively much longer etching times than usually employed for the etching of low energy (energy $\leq$ 2-10 MeV/u) light charged particles. It has been estimated from the study of the etching characteristics of these reaction products that most of them could be protons or alpha particles with energies far exceeding 10-20 MeV/u (10).

We carried out a theoretical test to ensure that whether such exceptionally high multiplicity events (or clusters) are

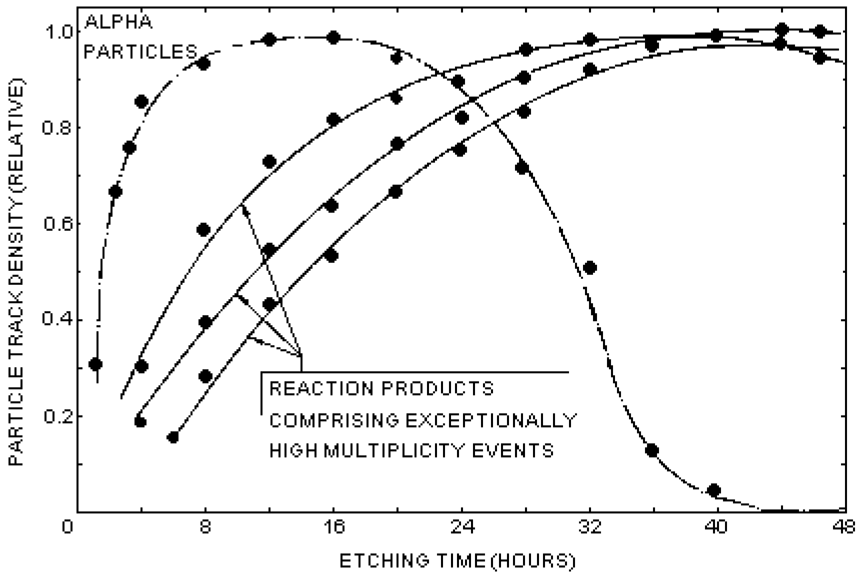


Figure 5: Figure showing a comparison of the etching propertie of the latent damage trails due to (a) the reaction products responsible for the exceptionally high multiplicity events and (b) the alpha particles from a uranium speck. The track densities have been normalized to the maximum plateau values (taken as 1). Whereas almost all the latent damage trails due to the uranium contamination were etched for an etching time of about 3 hours, some of the latent damage trails comprising the clusters required more than 15 hours of etching, showing the much higher energy and lower values of the effective charges of the reaction products comprising the clusters. These are typical results for one specific CR-39 piece.

formed by and isotopic point source situated above the detector sheet and its natural alpha activity produced a ‘flowerlike’ pattern of etch pits.

Our analysis showed (15) that the observed high multiplicity events were not caused by any contamination due to a tiny speck of natural radioactivity (as the distances are so large as compared to the range of ‘natural’ alpha particles in CR-39), nor could it be caused by the instantaneous decay of one large heavy ion into many tiny fragments (one decay in flight of a relativistic ion).

Analyses of the diametric distributions obtained on the surfaces of different CR-39 detectors were used to determine the reaction products due to ‘Central’ and ‘Peripheral’ collisions. Figure 7 shows the results obtained at four different stages (as we go deep into the stack). The main peak (B) on the extreme right of each of the four parts of Figure 7 represent the main (i.e. uranium) beam.

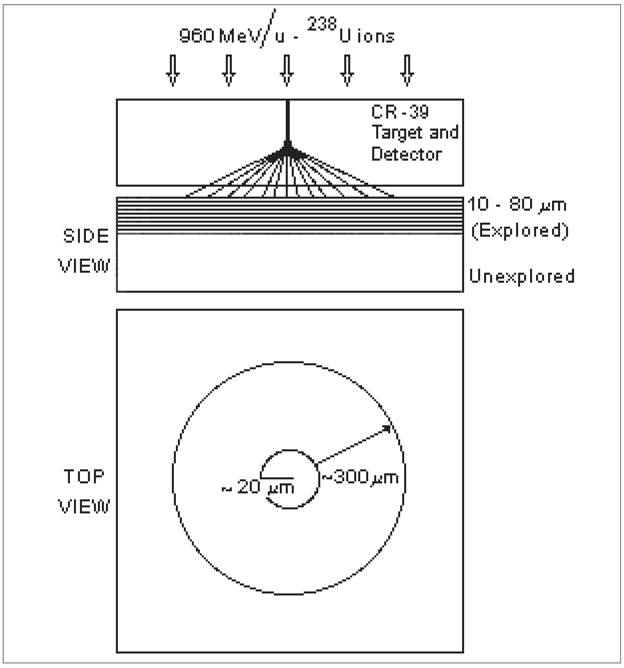


Figure 6: A sketch showing the right and top views of the geometry of exceptionally high multiplicity events in a CR-39 detector. It is quite clear that under the presently employed etching conditions the maximum thickness (-900 μm) of the detector is about 80 μm while most of the thickness of the detector remains unexplored. It is also quite clear that the reaction products so formed have ranges of the order of 300 μm or so in the CR-39 material. Such a range of light reaction products indicates that the particles have energies much higher than those emitted from the naturally available alpha particle sources (such as a uranium speck). Normal range of the naturally occurring alpha particles is of the order of 20 μm in CR-39 polycarbonate.

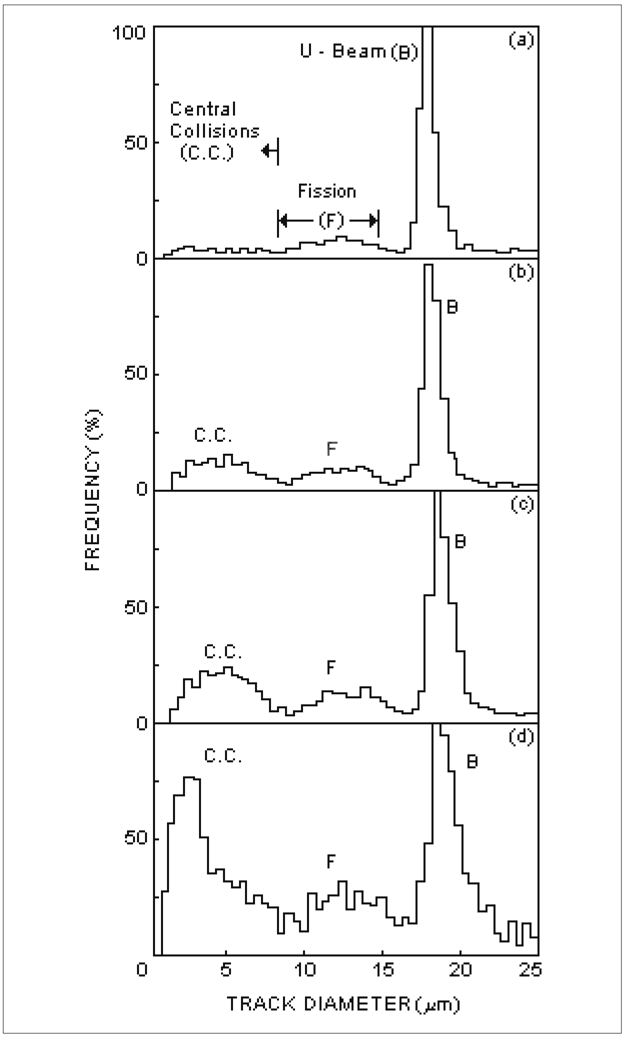


Figure 7: A set of four histograms showing diameter distributions of etch pits due to incident uranium beam (Peak 'B"), peripheral collisions resulting in fission fragments (humb 'F') and the particles formed in Central Collision (C.C.). It is quite apparent that the contribution of fission fragments and the light reaction products formed as a result of central collision go on increasing as the particle penetrates into the CR-39 stack.

The peripheral collisions result in the production of fission fragments (shown by humps 'F' in Figure 7), while the central collisions completely shatter the ‘projectile-target’ system. The light reaction products so formed produce relatively smaller etch pits. The contribution of these reaction products is shown by the humps labeled as 'C.C'. The contributions of both ‘central’ and ‘peripheral’ collisions seem to increase as we go deep into the stack.

It is worth mentioning at this juncture that the main difficulty for an interpretation of a decay of a highly excited fireball lies in its long lifetime. Most of the exceptionally high multiplicity events are found close to the Bragg peak. Therefore, the highly excited state could be created at high projectile energies which could decay close to the end of the range. The corresponding lifetime should, therefore, be in the order of the deceleration time which is roughly about $10^{-17}$ sec. Such a long lifetime is very unexpected for a highly excited state, but it could explain that these events have not been observed in counter measurements where only short living states are detected. The probability of such a high multiplicity event was found to be approximately $10^{-3}$ as compared to the intensity of the primary ions.

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