DETERMINATION OF REACTION PARAMETERS IN HEAVY ION INTERACTIONS USING TRACK DETECTORS

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SUMMARY: This paper summarizes the use of track detectors in the determination of reaction parameters in heavy ion interactions. The method is based upon an analysis of the components of two-and multi-prong events observed in the body of a track detector. This application of nuclear track detection technique has been found to have certain unique advantages over the conventional techniques in the study of multifragments emitted in the interaction of heavy ions with heavy target atoms. As an illustration, the technique has been applied in the study of the interaction of 8.12 MeVlu-^{208}. Pb ions with Pb (natural) target atoms.

Key Words: Track detectors, heavy ion interactions, reaction parameters, elastic scattering, partial- and total-cross-sections.

INTRODUCTION

Heavy ion physics, a relatively new branch of nuclear physics, deals with the behavior of a heavy nucleus under extreme conditions of temperature, density and angular momentum (1-3). It introduces entirely new phenomena, not known a few years ago (4,5). The reaction pattern in such interactions is governed by large mass and charge transfers between the colliding nuclei (6). The existing literature shows that the available experimental results are rather scanty and they do not fully support the existing theoretical models (7,8). More detailed studies are required to explain the experimental results and to attempt the theoretical models to fit them. In order to get some useful experimental information on the reaction mechanism behind such interactions, a complete correlation measurement is required. Experimentation shows that the use of the recently available sophisticated online electronic counting systems in the study of multifragments (particularly when the multiplicity of the events is larger than four) is rather limited. On the other hand, applications of track detectors such as plastics show that almost all the reaction products of interest can be registered and analyzed by selecting a suitable detector. The beauty of the technique is that inspite of its extreme simplicity it is not restricted to a small and limited number of coincident reaction products.

Here, we very briefly introduce the use of Solid State Nuclear Track Detection (SSNTD) technique for such studies and as an illustration, describe the use of mica track detectors in the determination of reaction parameters in the interaction of 8.12 MeV/u-^{208} Pb ions with natural Pb-target atoms. The track data have been related to the characteristics of the reaction products. Elastic scattering results have been used to estimate the value of the quarter point angle ($\theta_{1/4}$), which was then employed to obtain the parameters such as total reaction cross-section, maximum angular momentum, reaction radius and the interaction parameter, etc.

MATERIALS AND METHODS

General speaking, any track detector which is insensitive to light charged particles (such as beta particles, prolons, alpha particules, etc.) can be used for the registration of heavy reaction products formed in the exit channel. In the study of 'Pb+Pb' interaction, freshly cleaved mica sheets were obtained and thin layers of lead (natural) target were vaccum deposited on them. The 'target-detector' assemblies are then irradiated perpendicularly (i.e. at 90° to the detector surfaces) with the projectiles of interest (in the present case with 8.12

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MeV/u-^{208} Pb-ions). After the exposures, the target materials are dissolved, using an appropriate chemical (in the present case with a solution of HNO_3). The latent damage trails due to the reaction products are enlarged by etching the detectors in a suitable chemical (in the present work with hydrofluoric acid, kept at about 21° for 15 minutes).

Two-prong events are analyzed for elastically scattered projectiles and target atoms, and, for rare inelastic events. Three and four pronged, as well as higher order events are analyzed for the distributions of track lengths along with angles of scattering (with respect to the heavy ion beam) for the study of interaction mechanism and for getting other reaction parameters. The 2π geometry arrangement enables us to carry out complete measurements of all the reaction products formed. In the target which after formation move in the forward hemisphere.

Crose-sections can be obtained by (a) conting the inelastic two-prong events, three-prong events, four-prong events, and higher order events separately, (b) using the known thickness of the target material, and (c) experimentally determined fluence of the incident ions.

RESULTS AND DISCUSSION

The etched track detectors normally show the following microscopic features (Figure 1 is a typical example).

1. Black spots: These are the tracks of the projectiles which penetrate the target without any interaction. By counting these spots the projectile flux can be obtained, allowing an easy evaluation of the absolute reaction cross-sections.

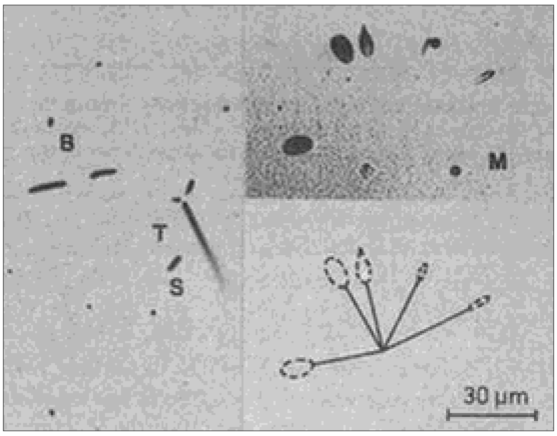

Figure 1: A set of photomicrographs showing tracks due to reaction products formed in heavy ion interaction studies. Figure on the left hang side shows a single track (S), a two prong event (B), and a three prong events (T). Figure on the right hand top corner shows a high multiplicity event (M) with a multiplicity of at least five. The drawing on the right hand bottom corner is a sketch of the five prong event.

2. Two-pronged events (B): These events consist of two correlated tracks emerging from one reaction spot indicating elastic scattering or inelastic binary reactions.

3. Three pronged events (T): These are the high multiplicity events where the projectile or the target suffers fission (mostly due to sequential fission or in a rare case because of a direct three-body break-up of a fused 'projectile-target').

4. Higher-multiplicity events (M): These events are with multiplicity higher than three. They indicate a multibody break-up or a sequential fission cascade in two or more than two steps.

In heavy ion interaction studies using track detectors, we must pay a special attention to the analysis of two-prong events. Lengths and angles of the correlated tracks in a large number of two prong events are to be measured event by event. The track lengths can be determined with in ±1.5 um (standard deviation) for the bulk of the data. The uncertainties in track angles are ±2° (standard deviation). All binary events with angles ≥170° as seen in the plane perpendicular to the beam may be interpreted as genuine two-pronged events.

The track parameters (track lengths and their angles with respect to the original direction of the beam) of the two-prong events are then converted to particle parameters (velocity, mass energy and scattering angle) assuming that the projected angle between the tracks of a two pronged event (in the plane perpendicular to the beam) equals 180°. The data thus obtained are plotted in a track length (or velocity of the particles) versus scattering angle diagram. A theoretical curve for track length (or particle velocity) versus the scattering angle is obtained using the empirical range-energy relationship in mica and elastic scattering equation (5).

To convert the track data into masses and energies of the reaction products, the following coupled equations are solved even by event:

$$\sum_{i=1}^{N} m_i \left(\ell_i , m_i \right) \vec{e}_i = P_{in} , (N = 2,3,4) \qquad (1)$$

$$\sum_{i=1}^{N} m_i = m_{total} = m_{proj.} + m_{target} \qquad (2)$$

(only for 4- and 5-pring eventh)

$$m_i + m_j = m_{ij} = m_{ij} = \text{fixed} \qquad (3)$$

(m_{ij}) is varied only for 5-pronged events)

These equations are based upon the momentum and mass conservation 1_i is the track length, e_i is the track directions, P_{in} is the incident momentum. m_p and m_t are the masses of the projectile and target, respectively. V(1,m) is an empirical relation between track length, mass and velocity. This relation has been found by independent (internal) calibration. With measured 1_i and e_i and P_{in} given by the laboratory energy of the projectile, these equations yield the unknown masses m_i for the given velocity-range relationship V(1, m). Substituting the computed masses m_i into V(1,m) with measured 1_i yields the individual velocities. Thus all other kinematical quantities of interest, particularly, the kinetic energies and the angles of emission in different moving frames are determined. It is important to note that the deduced masses and the energies depend crucially on the underlying velocity-range relationship. Careful calibartion is thus a pre-requisite for such an analysis. The average mass-resolution in track-detector technique for fission fragments is fond to be Dm ≈7 amu.

In order to separate elastic and inelastic events one can proceed as follows: The (relative) uncertainties in determining the energies of the two reaction products in two-pronged events are of the order of 4.5% and their mass resolution is known to be about 7 % (5). Events lying on the theoretical elastic curve (within the energy and mass resolution of 4.5% and 7%, respectively) are thus taken as being due to "elastic scattering" and are counted in 2° (c.m.) wide angular bins.

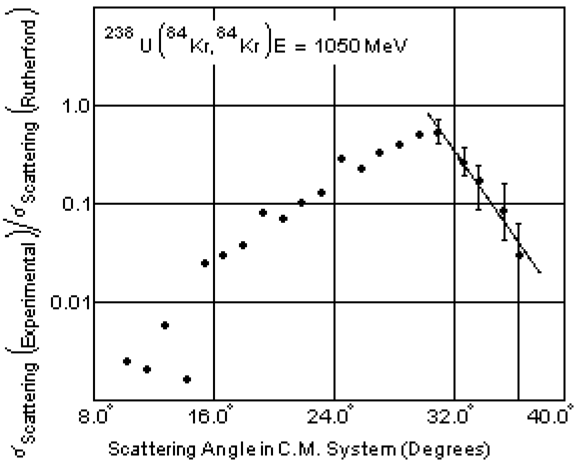

Figure 2: Variation of the ratio of experimental scattering cross-section to Rutherford scattering cross-section as a function of scattering angle in c.m. system for elastic scattering of Kr-ions on U-target atoms. The energy of the incident Kr-ion is 1050 MeV.

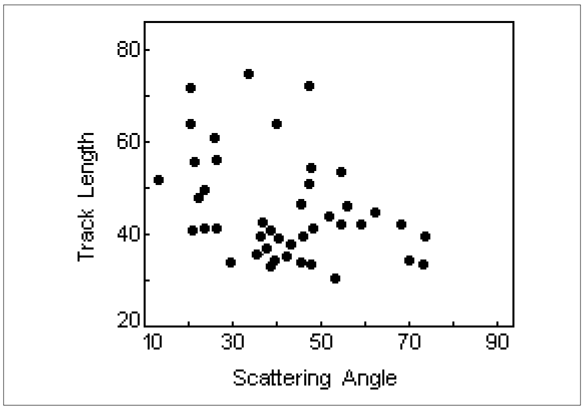

Figure 3: Variation of track length as a function of scattering angle for Pb-ions after being scattered by Pb atomS. The figure shows a trend that tract length decreases with increasing scattering angle thus indicating that the energy of the scattered ion decreases with increasing scattering angle.

The experimentally obtaied ratios of elastic- to Rutherford-cross sections (σ elastic/σ Rutherford) are obtained as a function of the scattering angle. Such a distribution obtained by using track detectors, usually shows a truncation in the angular distribution at forward angles (Figure 2). The main reason behind this function effect is a limitation of this technique. The reaction products scattered in the very forward direction $\theta_{c.m.} \leq 25°$) produce etched channels whose projected lengths are much shorter than the ones due to those reaction products, scattered at larger angles. The identification of such events as elastically scattered ones is difficult, and they are either missed or are analyzed with a low accuracy. The seriousness of this effect increases with the decreasing scattering angle. However, since in these studies we are primarily interested in angular distributions near the quarter poin angle, the above-mentioned shortcoming of the SSNTD-technique does not affect our results. Multiple particle exit states are the dominant reaction channels for the heavy masses and fairly large energies are involved in these interactions. It is, thus expected that the analysis of the type of events discussed above will not result in any significant error for the determination of the total inelastic reaction cross section.

Now as an illustration, we briefly describe some results from our studies of the reaction 8.12 MeV/u^{208} 'Pb+Pb' (natural). In these studies results were obtained for the length of the tract as a function of the

Table 1: Reaction parameters in the interaction of 8.12 MeV/u Pb-208 ions with Pb (natural) target atoms as obtained by using mica track detector.*

Parameter Reaction	$\theta_{1/4}$	R_{int} (fm)	1_{max}	R_o (fm)	$^{\sigma}$3-prong (mb)	$^{\sigma}$4-prong (mb)	$^{\sigma}$ total (mb)
^{208}Pb(^{208}Pb,^{208}Pb)	61.4° (62.9°)	16.23 (15.97)	614 (594)	1.37 (1.36)	1601±179	798±106	2399±208

* Experimentally determined value of $\theta_{1/4}$ was used to calculate these parameters.

( ) Theoretically calculated values.

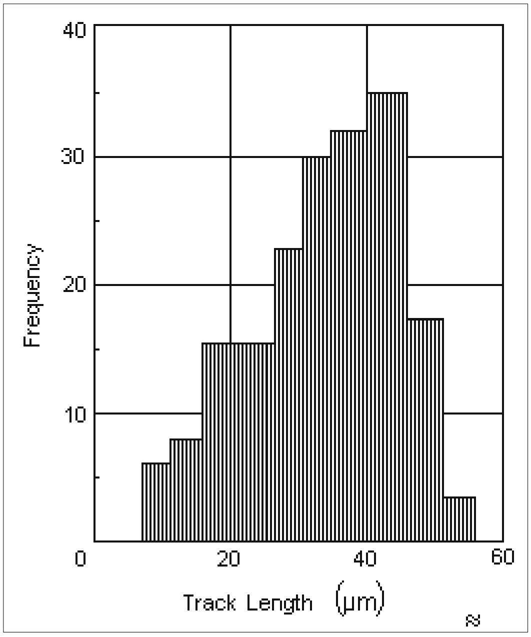

Figure 4: Frequency distribution of tracts length of all the tracks comprising the three prong events obtained in the study of the interaction of 8.5 MeV/u-Pb ions with natural target.

scattering angle (Figure 3). It was found that higher the scattering angle, smaller the length of the track. These results indicated that it was due to the elastic scattering of the projectiles by the target atoms after going through the deep inelastic collision stage. The frequency distributions of track lengths of corresponding to the two shorter tracks and that of the longest track in the three prong events were also studied. The distribution showed a peak at the track length of about 40 um, which was probably due to those tracks which were produced by the projectiles, scattered around the quarter point angle (Figure 4).

The results indicate that the projectile, after going through the deep inelastic collision stage (during which exchange of mass, charge, and energy take place), is scattered with less energy around the quarter point angle. The target gets excited and undergoes normal binary fission. In total we get three particles in the interaction, which seem to be emitted from one point. The partial cross sections and the total reaction cross section so determined have been compared with the total reaction cross section computed from the quarter point values. These results along with the values of other reaction parameters isn 'Pb+Pb' interaction have been summarized in Table 1. The two sets of values are comparable within the accuracy of our measurements.

CONCLUSIONS

The reaction cross sections obtained by using the track detection technique agree fairly well. The experimental values, however, are lower than the calculated ones. This discrepancy is due to inherent limitations of the 2π-geometry technique and due to the low "energy-resolution" of SSNTDs. Problems with insufficient separation of elastic and inelastic events may diminish with vanishing contributions of the two-particle exit channel in reactions with very fissile ions at fairly large energies.

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