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TWO-, THREE- AND FOUR-PARTICLE EXIT CHANNELS IN THE REACTION OF 14 MeV/amu BEAM OF ^{238}U WITH GOLD TARGETS

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Abstract: Mica and CR-39 track detectors were used in 2π-geometry to allow coincidence measurements to be made of multiple fragments emerging in the reaction of 14 MeV/amu ^{238}U projectiles on ^{197}Au target nuclei. Targets were produced from sheets of muscovite mica as well as CR-39, both of which were coated with gold by vacuum deposition. These targets were irradiated with a beam of ^{238}U ions, incident normally to the surface. After etching, the heavy fragments in the two-, three-, and four-particle exit channels were identified in respect of their masses and energies. Empirical velocity-range relationships in mica, which are explicitly dependent on mass, were found by fitting the Chebyshev series to the experimental data of the elastic scattering events. A correlation plot of the total kinetic energy loss (TKEL) for the two-pronged events due to elastic scattering have also been constructed. Cross sections for ternary and quarternary fission were determined and in addition, angular scattering measurements from elastic reactions were used to determine the total reaction cross section.

(Heavy ion, nuclear track detector, ^{238}U, gold, Chebyshev, cross section)

Introduction

Heavy-ion physics has attracted much attention during the last two decades. The behaviour of a heavy nucleus under extreme conditions of temperature, density, angular momentum, etc., is a very important aspect of heavy-ion physics. The reaction pattern of multibody processes is extremely complex, and a knowledge of the kinematical correlations between the reaction products is therefore very important. Since high linear and angular momenta are associated with energetic, heavy-ion collisions, they provide the opportunities to study the transfer of large amounts of mass, energy and angular momentum, along with the subsequent relaxation phenomena and the structure of nuclei at high excitation energies. Completely correlated measurements are necessary in order to understand the reaction mechanisms involved. All the reaction products need to be registered on a detector, so that the various kinematical variables may be determined from the analysis.

Experimental Techniques

The muscovite mica solid state nuclear track detector (SSNTD) is most extensively used for heavy ion studies. This is due to its favourable track registration characteristics[1], viz. high registration threshold (30 amu) and the very high ratio, V_t/V_b, of track etch velocity (V_t) to the bulk etch velocity (V_b). The tracks formed, therefore, are needle-like and act as well-defined vectors in space. CR-39 (allyl diglycol carbonate), is also widely used as a SSNTD, and it can register particles down to protons. In these studies we have used gold targets of 0.5 to 1 mg/cm^2 thickness, which were vacuum evaporated on to clean surfaces of mica or CR-39 using a sputter coating machine. These constituted the target-detector assemblies.

Each target-detector assembly was then irradiated with a beam of ^{238}U ions normal to its surface, at GSI, Darmstadt, West Germany. The fluence of ^{238}U ions (14 MeV/amu) was varied from 10^6 to 5×10^6 ions/cm^2. All the reaction products emitted into the forward hemisphere, which make an angle more than the critical one with the detector surface for track registration and which have a mass larger than the threshold for the SSNTD, produced etchable damage trails in it. After the irradiation, the gold was dissolved off with a solution of 3 parts conc. HCl and 1 part conc. HNO_3 (aqua regia). The mica samples were etched with 48% HF at room temperature for 8 min, and the CR-39 samples were etched in 6M NaOH at 70°C in successive steps of etching time, starting with an etch of a few minutes. In the case of mica, with the etching time of 8 min all latent tracks were fully etched; but low-mass particles registered in CR-39 were only revealed after several hours of etching.

Features of the Etched Track Detectors

The etched detectors showed a number of characteristic, microscopic features[2].

1. Black spots - these were tracks of projectiles that had not undergone any interaction with the gold target. The fluence of ^{238}U ions could be obtained directly by counting these black spots, and this fluence could be used in the evaluation of absolute cross sections.
2. Two-pronged events - here two, correlated tracks emerged from one reaction spot, indicating elastic scattering or inelastic binary fission reactions.
3. Three and higher-multiplicity events - here the projectile or the target or both, underwent fission. Such events gave rise to three or more tracks originating from a single point in the detector. This indicated a multibody break-up or sequential fission in more than one step. Not all multiple events registered the requisite number of tracks in the detectors. These "indirect" events were inferred when the largest angle between any two neighbouring tracks in the plane of observation was greater than 180°. This indicated that the linear momentum in the plane of observation was not conserved. In such cases we believe that at least one of the fragments that was emitted was not registered. Non-registration could be due either to the fragment being a light particle (below the detector threshold) or to the fact that it was emitted in the backward, 2π solid angle. This technique, however, was unable to distinguish between the tracks of those fragments emitted parallel to or perpendicular to the detector surface. Fig. 1 shows the relation between the track lengths, ℓ_i, and their projected values, ℓ_{ip}, together with their scattering angles (θ_i) and the corresponding projected angle, ψ. The track lengths, ℓ_i, are determined from direct measurement of the projected lengths, ℓ_{ip}, and the vertical distance, d_i, of the end of a track from the surface of the detector. The latter is measured by focussing a microscope first on the surface of the detector and then on the end of the track under investigation. The microscope is fitted with a micrometer scale and the distance that the eyepiece travels is equivalent to the value, d_i.

Analysis of Data

Elastic Scattering Events

In an elastic reaction the masses of the projectile, M_p and the target, M_t, remain unchanged after the reaction. If the projectile energy in the laboratory system is E_{lab}, and after elastic scattering the projectile and target scattering angles in the laboratory system are θ_1 and θ_2 (Fig. 1), it follows that their laboratory energies following scattering, E_1 and E_2, are given as

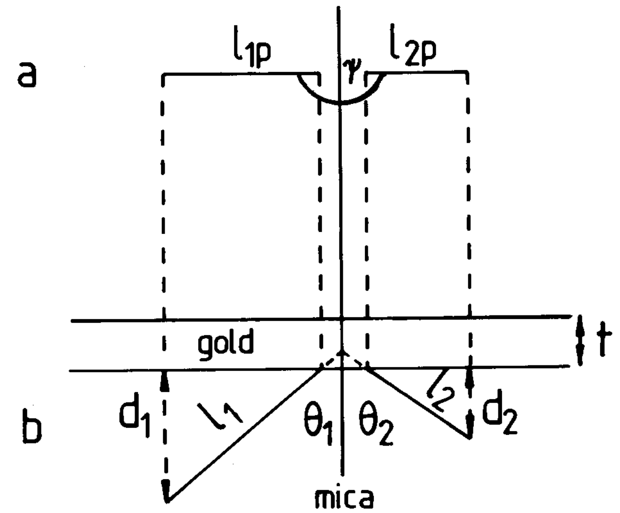

Fig. 1 A schematic representation of a typical, elastic two-prong event showing (a) the onlook view and (b) the edge-on view in the mica SSNTD.

$$\sin \theta_2 = \{(M_p/M_t).(E_1/E_2)\}^{\frac{1}{2}} \sin\theta_1$$

$$E_{lab} = [M_p{}^2/(M_p+M_t)^2]\{\cos \theta_1 + [(M_t/M_p)^2 - \sin^2\theta_2]^{\frac{1}{2}}\}^2$$

$$E_2 = E_{lab} - E_1$$

The above equations can be used for the selection of elastic scattering events. All suspected elastic events were checked for consistency in two ways:

i) both of the measured scattering angles should be correlated in accordance with the above equations,

ii) both of the measured track lengths, after converting to the equivalent energy using the standard range–energy relationship data, should also be correlated in accordance with the above equations. The data from elastic, two-prong events were used for calibration purposes.

Multiprong Events

Each track is like a well-defined vector, ℓ_i, in space, and each of the two-, three-, or four-pronged events are characterized by their corresponding correlated two, three, or four track vectors in the exit channel. In order to determine the nature of the N particles corresponding to an N-pronged track, it is necessary to know the 3N individual momenta and N individual masses, giving 4N variables to be conserved. Because, however, there is conservation of total momentum and spherical symmetry

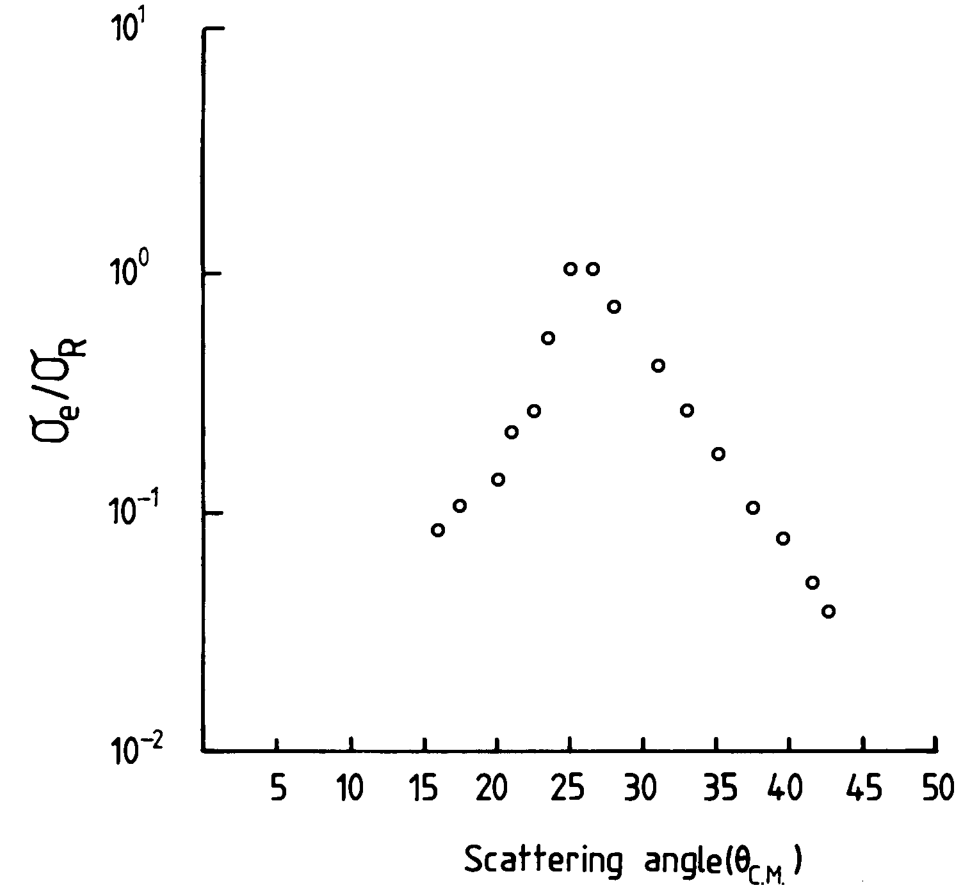

Fig. 2 The ratio of the experimentally-determined elastic to the Rutherford cross section as a function of the C.M. scattering angles, $\theta_{C.M.}$, for two-prong events.

around the beam axis, this reduces to 4(N−1) independent variables. In the measurement of multi-pronged tracks with three-dimensional coordinates, it is possible to determine 4, 8 or 11 independent variables for two-pronged, three-pronged or four-pronged events. These independent variables are the track lengths, the angles with respect to beam direction and the angles between the tracks in the plane perpendicular to the beam direction. These measured variables are enough for two- and three-pronged events. For four-pronged events, however, we need 12 independent parameters; the missing parameter can be supplied by consideration of conservation of mass during the experiments. The correlated fragment masses, M_i and velocities, V_i, from an individual multi-pronged event are calculated on the basis of the measured correlated track lengths, ℓ_i and track directions, e_i. To do this, we need to solve, event by event, the coupled equations

$$\sum_{i=1}^{N} M_i V_i(\ell_i, M_i)\, \vec{e}_i = \vec{P}_{in} \qquad (N = 2,3,4) \qquad (1)$$

$$\sum_{i=1}^{N} M_i = M_p + M_t \qquad (2)$$

where P_{in} is the incident linear momentum, and M_p and M_t are the masses of projectile and target, respectively. Equations (1) and (2) can be solved for individual fragments arising from two-, three-, and four pronged events[3].

$V_i(\ell_i,M_i)$ is an empirical relationship between track length, mass and velocity. This relationship was found to be a bi-variable polynomial, expressed as

$$V_i(\ell_i\, M_i) = \sum_{i=0}^{4} \sum_{J=0}^{2} A_{ij}\, T_i\, (L_{cap})\, T_j\, (M_{cap}) \qquad (3)$$

where T is the Chebyshev polynomial and A_{ij} is a fitting coefficient. The coefficients, A_{ij}, can be determined experimentally and the procedures are discussed by Afarideh[2]. Equation (3) is represented by a double Chebyshev series, with arguments M_{cap} and L_{cap}, and this fit has a better physical basis and causes less error during the analytical process than the polynomial fitting used by Gottschalk et al.[3]. Methods for solving Eq. 3 are discussed in detail by Afarideh[2].

Results and Discussion

Reaction Cross Sections Determined from Multi-Prong Events

The total number of direct plus indirect events, N_i, for a particular event multiplicity, i; the measured fluence, Φ, of the projectile; and the available number of target nuclei, A, can be used to determine the reaction cross section from the expression

$$\sigma_i = N_i/\Phi.A$$

where σ_i has the dimensions of cm^2. Cross sections determined for three-prong (σ_3) and four-prong (σ_4) events are listed in Table 1, along with the total cross section for these events, σ_{3+4}. Included in Table 1 are the published values for cross sections at 9.0 and 16.7

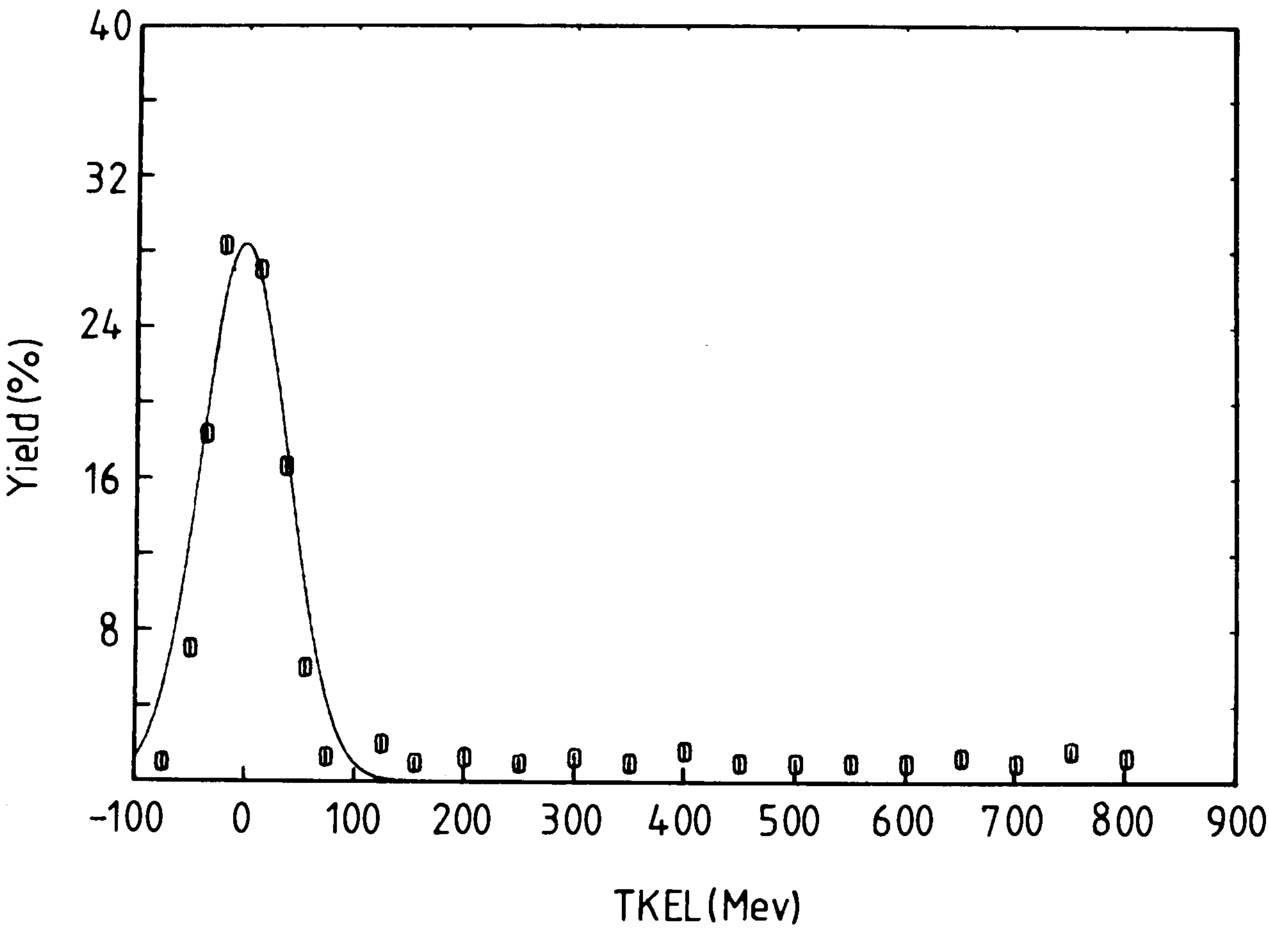

Fig 3. The distribution of TKEL for two-pronged, elastic scattering events. The centroid of the Gaussian fit to the data is around zero MeV. In fact, the centroid is actually at 2 MeV and the FWHM is 39.2 MeV.

Table 1. The cross section of three- and four-pronged events in the U + Au reaction at different projectile energies, using mica and CR-39 detectors.

Energy MeV/amu	Detector	σ_3 (mbarn)	σ_4 (mbarn)	σ_{3+4} (mbarn)
9.0	Mica	1750 ± 150	500 ± 100	2250 ± 180
14.0	-	3008 ± 373	360 ± 113	3370 ± 390
16.7	-	3300 ± 350	300 ± 100	3600 ± 360
14.0	CR-39	2610 ± 242	912 ± 217	3520 ± 360
16.7	=	2700 ± 200	1000 ± 200	3700 ± 280

MeV/amu for the (Au+U) reaction, using both mica and CR-39 detectors[3]. Table 1 indicates that the excitation functions for three-prong and four-prong events differ between mica and CR-39 detectors. This result is explained as being a consequence of the lower threshold of the CR-39 detector, enabling it to register particles as light as protons. Consequently, in a four-prong event involving the emission of a particle of mass less than 30, only CR-39 would register it.

Cross Section Determined from Angular Distribution of Two-Pronged Events

Angular distributions of two-pronged events attributed to elastic scattering may be used to determine the total cross section for such events. The necessary calculations are based on the analysis by Frahn[4]. It depends on his proposition that there exists a unique angle for the scattered particle, known as the "quarter point angle" which is the scattering angle at which the elastic scattering cross section, σ_e, is one quarter of the Rutherford value, σ_R. This quarter point angle, $\theta_{\frac{1}{4}}$, can then be used for computing the total reaction cross section, σ_T. The calculation is based on the following two equations[5]

$$\ell_{max} = \eta \cot (0.5\theta_{\frac{1}{4}})$$

$$\sigma_T = \pi \lambda^2 (\ell_{max} + 0.5)^2$$

where

ℓ_{max} is the maximum angular momentum of the incoming particle,

η is the Sommerfeld parameter,

λ is the asymptotic wavelength.

The Sommerfeld parameter, η, can be obtained from the atomic masses and nuclear charges of the projectile and target atoms together with the incident energy of the bombarding ^{238}U using the following expression:

$$\eta = 0.15746\ Z_p\ Z_t\ (M_p/E_{in})^{\frac{1}{2}}$$

where

M_p is the atomic mass of the projectile (^{238}U)

Z_p and Z_t are the nuclear charges of the projectile and target, respectively, and

E_{in} is the incident projectile energy.

Similarly, the asymptotic wavelength, λ, can be obtained from

$$1/\lambda = 0.2187\ M_t\ (M_pE_{in})^{\frac{1}{2}}/(M_t + M_p)$$

where M_t is the atomic mass of the target (Au).

The Rutherford scattering cross section, σ_R, can be calculated from the above parameters along with certain fundamental constants.

The quarter point angle was determined from a plot of the ratio, σ_e/σ_R, as a function of scattering angle (Fig. 2). The results from our data gave a value for $\theta_{\frac{1}{4}}$ of 33.1° and a total cross section of 4280 mb. These can be compared with published values of 31.7° and 4690 mb[5].

From a full analyses of the masses and velocities of the scattered nuclides derived from the track data, it was possible to determine the total kinetic energy loss (TKEL). The yield distribution of two-pronged events corresponding to elastic scattering is plotted versus TKEL in Fig. 3. It is clear that the yield peaks at a TKEL value close to 0 MeV.

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