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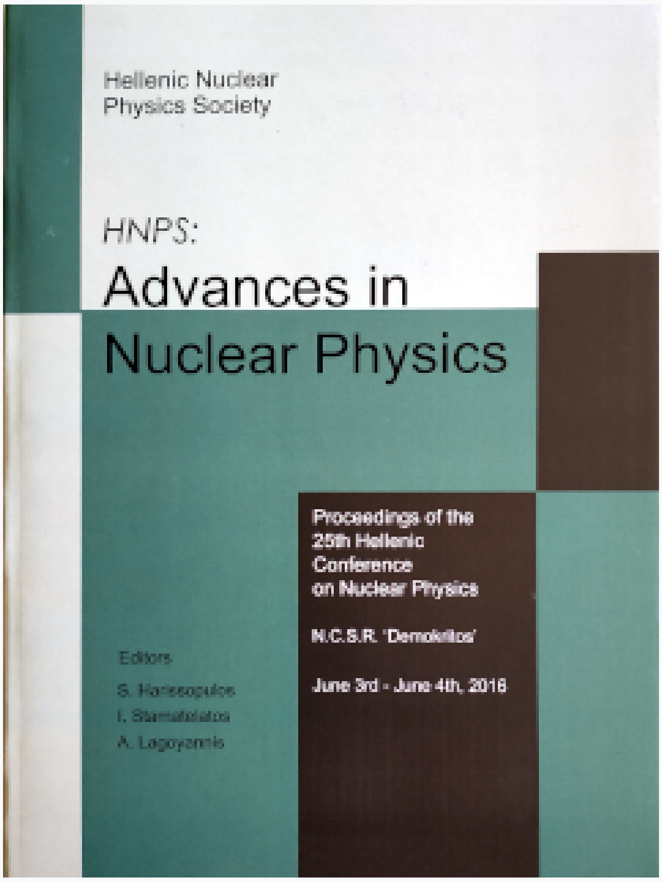

True ternary fission in high energy proton reactions with 238U and 207Pb

M. Zamani, M. Debeauvais

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True ternary fission in high energy proton reactions with ^{238}U and ^{207}Pb

M. Zamani[1)] and M. Debeauvais[2)]

1) Aristotle University of Thessaloniki, School of Physics, Nuclear and Elementary Particle Physics Dept.
2) CNRS, Strasbourg 67037

Abstract

A re-evaluation of ternary fission data collected in previous experiments of high energy proton reactions with ^{238}U and ^{207}Pb targets was made. The analysis of fragment mass distributions, fission fragment relative velocities and the kinetic energies of fragments permit to classify most of them as almost true ternary fission events. At the higher energies studied a percentage of 5% and about 2% for ^{238}U and ^{207}Pb respectively, present three equal masses and are events which belong to true ternary fission.

1. Introduction

True ternary fission is appeared in literature recent years. They have been observed in spontaneous fission of ^{252}Cf and in $^{235}U+n_{th}$ [1-5]. Ternary fission has been observed in experiments many years ago in reactions with high energy beams [6-12] as well as in heavy ion reactions [13-16].

The ternary fission has been interpreted by different authors as originating from two different mechanisms. A two step mechanism [17-19], in which part of the incoming kinetic energy is converted to intrinsic excitation energy and deformation. A part of the entrance channel angular momentum is transferred into collective rotation of the fragments. The excited nucleus decay in an asymmetric (or symmetric) channel and then the heavier fragment decays further into two fragments. This mechanism is a sequential process i.e. two sequential binary fissions. Another possible mechanism is that in the excited nucleus three fragments touching each other are formatted, i.e. trinuclear system. This system undergoes ternary fission. In case of three equal fragment masses the ternary fission is called “true ternary fission” [5].

Experimental findings support both scenarios. This is the reason why in this work we evaluate ternary fission events measured years ago [11,20]. The characteristics of ternary events were studied in an event by event analysis and the results were classified according to the characteristic signatures of fission.

2. Experimental

The irradiations of ^{238}U and ^{207}Pb targets with protons of 2.9 GeV were performed at Saclay, while the higher proton energies at CERN. The experiments cover the proton energies from 0.6 to 23 GeV.

The detectors used in the experiment were Solid State Nuclear Track Detectors (SSNTDs). Two Makcrofol sheets were used in 4π geometry with the target between them. Details are given in Refs 9, 11,20. The track lengths and angles relative to the beam direction as well as their projection to the plane perpendicular to the beam were measured under an optical microscope. An event by event analysis was follow. Then the events candidates for true ternary fission were selected between triple events according to cutoffs based on momentum conservation laws. Only events with momentum equilibration were selected for further analysis.

The cross sections of binary and ternary fission are given in Refs 11,20 for various targets and energies. Some distributions of mass and energy of fragment characteristics are also given in Refs 11,20.

3. Results and Discussion

The mass of the fragments were determined according to the appropriate calibration based on the track length, R, the track development velocity, V_T and the energy loss of the ion dE/dx Refs. 20,21. The fragment energy corresponds to the range of each fragment. The fragments of each event were classified according to their mass as the heavy, the medium and the light. In tables 1a, 1b the mean value of the mass of each kind of fragment is presented as well as the mean value of the total mass. In the last row in both tables the difference of the recoil mass from the target mass is giving. The observed missing mass can be attributed to light particle evaporation prior to fission. Considering about 12 MeV needed per particle extraction and the energy shared by each particle, the energy imparted by particle evaporation can be calculated [19].

According to the tables 1a,1b the sum of the masses of the light and the medium fragment (for both targets) is almost equal to the mass of the heavier fragment. This fact indicates a mass split of the heavier fragment (MM+ML) to MM and ML. So the first target split leads to about equal masses signaling a target breakup at high excitation energy [18,19]. In the second step of the splitting, an asymmetry of the masses MM and ML can be observed indicating that the second split takes place in further decrease of excitation energy. This scenario supports

Table 1a. Mass of the fragments ($p+^{238}U$)

Ep, GeV	2.90	11.40	18.00	23.00
MH	86.30	93.20	96.70	93.50
MM	65.10	63.70	56.30	58.60
ML	42.70	38.00	38.10	40.50
MM+ML	107.80	101.70	94.40	99.10
MR	194.10	194.90	191.10	192.60
(MT+1)-MR	44.90	44.10	47.90	46.40

(MH=Heavy, MM=Medium, ML=Light, MR=recoil mass)

Table 1b. Mass of the fragments ($p+^{207}Pb$)

Ep, GeV	2.90	11.40	18.00	23.00
MH	92.50	89.90	86.30	88.90
MM	55.40	53.90	53.60	52.70
ML	38.90	34.60	35.80	37.70
MM+ML	94.30	88.50	89.40	90.40
MR	186.80	178.40	175.70	179.30
(MT+1)-MR	21.20	29.60	32.30	28.70

(MH=Heavy, MM=Medium, ML=Light, MR=recoil mass)

that ternary fission events originate by a sequential fission process. The time between the two steps determine whether these events can characterized as a true ternary fission or it is a clear sequential emission. Another scenario could be the formation of trinuclear system of different masses. The excitation energy of the target nucleus justifies such a formation.

The total mass of the three fragments, indicated as recoil mass, MR, in the tables 1a and 1b, is less than the target mass. This difference increase with the proton beam energy. The missing mass can be attributed to evaporation of light particles before the splitting of the target nucleus.

The mean fragment kinetic energy is given in Tables 2a, 2b. The fragment kinetic energies presented low and of the order of the Coulomb repulsion energy between fission fragments. The total kinetic energy is also low, comparing to the case of binary fission. The total kinetic energy is higher for Uranium than for Lead target.

The fission signal is established to be the relative velocities between the fragments, $v_{ij} = \left|v_i - v_j\right|$. This quantity corresponds to the Coulomb repulsion energy between fragments. The relative velocity of 2.4 cm/ns is the signature of the fission mechanism [14,22]. In the present study the values of v_{ij} calculated

Table 2a. Fragment Kinetic Energy (in CM) in MeV for (p+^{238}U)

Ep, GeV	**2.90**	**11.40**	**18.00**	**23.00**
EH	54.4	50.1	43.7	48.2
EM	58.5	69.4	65.9	61.8
EL	57.5	45.3	41.8	48.8
Ec.m., Tot	**170.4**	**164.8**	**151.4**	**158.8**

Table 2b. Fragment Kinetic Energy (in CM) in MeV for (p+^{207}Pb)

Ep, GeV	**2.90**	**11.40**	**18.00**	**23.00**
EH	43.9	39.5	32.6	38.7
EM	55.4	44.2	47.8	48.1
EL	41.8	38.4	35	38.7
Ec.m., Tot	**141.1**	**122.1**	**115.4**	**125.5**

for each pair of fragments of the selected triple events and are given in Tables 3a and 3b for the cases of ^{238}U and ^{207}Pb targets. In tables 3a, 3b we remark that all the relative velocities between the three fragments are of the order of 2.4 cm/ns (within errors which vary between 7-10%). So, the three fragments originate from one fission event. The same relative velocities are valid for all energies and both targets.

Table 3a. Relative velocities between fission fragments (p+^{238}U)

	Vij (cm/ns)			
Ep, GeV	**2.9**	**11.4**	**18**	**23**
MH,MM	1.93	2.73	2.72	2.72
MH,ML	2.62	2.64	2.66	2.65
MM,ML	2.48	2.35	2.39	2.42

Table 3b. Relative velocities between fission fragments (p+^{207}Pb)

	Vij, cm/ns			
Ep, GeV	**2.90**	**11.40**	**18.00**	**23.00**
MH,MM	2.70	2.68	2.66	2.67
MH,ML	2.64	2.61	2.71	2.61
MM,ML	2.39	2.26	2.36	2.36

However, if one of the fragments corresponded to a sequential break up i.e from a quasi elastic event the relative velocities would be 2.4 cm/ns for the pair of fission fragments and of the order of 4 cm/ns for each fission fragment and the rapid one [14]. We conclude that the three fragments have emitted simultaneously. The observation of relative velocities permits to consider that if the fragments originate from a sequential mechanism of emission with the time between the two steps would be so small that according to the dynamical models for three body emission [4,23] is equivalent to a simultaneous break up and not sequential.

The angles between fragments are 138^o, 116^o and 105^o (in CM system) for HM, MM and ML pairs respectively. These values are close to 120^o (within errors) and indicate that the fragment masses are close to each other but not equal as it is shown in tables 1a, 1b. The evaluation of fragment angular distribution is in run regarding to calculate the momentum transfer and the application of the dynamical model to ternary fission events.

4. Conclusion

Ternary fission events from previous experiments were re-evaluated under calculation of their characteristics.

The mass distribution of the fragments indicates that these events originate by nucleus at high exited state. This result is valid for both targets of ^{238}U and ^{207}Pb. The mass of the medium and the light fragment equals the mass of the heavier fragment, tables 1a,1b. So it is possible that the tree fission fragments originate by a sequential process. Their relative velocities, tables 2a, 2b, pair by pair, have the same value of 2.4 cm/ns indicating that the three fragments originate by the same fission event. The kinetic energies of the fragments, tables 3a,3b correspond to the Coulomb repulsion between each pair of fragments. These quantities are the signature of a fission process so we conclude that the three fission fragments belong to true ternary fission events. However, those quantities cannot estimate the time between the two fissions in case the ternary events come from a sequential fission mechanism. But, their values are so close to the characteristics of the fission process that permits to conclude that the ternary fission events studied in this work correspond to an almost true ternary fission.

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