Pramāṇa, Vol. 12, No 5, May 1979, pp. 439-446, © printed in India

A search for rare types of fission induced in silver and bromine nuclei*

K BHATTACHARYA and T D GOSWAMI**
Department of Physics, Arya Vidyapeeth College, Gauhati 781 016
**Department of Physics, Gauhati University, Gauhati 781 014

MS received 12 June 1978; revised 27 January 1979

Abstract. Ternary and quaternary fission produced in silver and bromine nuclei have been studied with $K5$ nuclear emulsion exposed to 1·8 GeV/c K^- beams. The frequency of the ternary events is found to be $\sim$0·08 of that of the binary events produced in the same volume of the emulsion. The range ratio and range distribution of the fission fragments are studied and the angles between each pair of the fragments are determined. Ranges are found to vary from 5 to 40 μ with a maximum number lying between 5 and 10μ. The angles between the fission fragments are found to form a broad distribution extending from 40° to 180°. A few of the events have also been analysed to give them a possible identity. A possible case of quaternary fission has also been reported.

Keywords. Ternary fission; quaternary fission; cascade fission; silver nuclei; bromine nuclei.

1. Introduction

Binary fission, i.e. the division of excited nucleus into two fragments of comparable mass is the most common type of fission in excited nuclei. However, Present (1941) predicted the brobability of tripartion or ternary fission on the basis of liquid drop model for fission (Böhr and Wheeler 1939). Unlike the binary process, here the excited nucleus may break into three fragments of comparable mass. This process is comparatively rare. Various methods, such as, (i) nuclear emulsion, (ii) coincidence counting, (iii) radio chemical analysis, (iv) mica and other nuclear track detectors have been used for such a study. However, the evidence for this is meagre uptill now. A number of workers (Tsien-San-Tsiang 1947; Muga 1963, 1965, 1967; Stoenner and Hillman 1966; Brandt 1970; Becker and Katcoff 1962; have investigated this type of fission produced in different types of nuclei starting, from uranium to silver and bromine nuclei of photographic emulsion.

In addition there is another extremely rare type of fission, viz quaternary fission, where the excited nucleus may split into four fragments of different size. This was experimentally detected by Tsien-San-Tsiang (1947) in emulsion impregnated with uranium and also by Kapoor *et al* (1972) and Kataria *et al* (1973).

*This paper was presented at the Symposium on 3rd High Energy Physics held at Bhubaneswar during November 1976.

2. Experimental procedure and selection criteria

An Ilford *K5* emulsion stack exposed to 1·8 GeV/c K^- beams is used for this experiment. Preliminary area scanning was done under low magnification ($\times$ 150) using an optical microscope to record all the disintegration stars with $N_h \geqslant 8$. Here N_h represents the total number of tracks or prongs due to heavily ionising particles emitted from the disintegrating nucleus. These tracks are usually produced by protons and other heavier charge fragments of kinetic energy in the MeV region. They are identified from the estimation of their mean grain density g, since for these tracks, the value of g is such that $g > 1{\cdot}4\ g_0$, g_0 corresponding to the average grain density of the minimum ionising track produced by the relativistic primary particle. The tracks are emitted from the disintegrating nucleus and are thus a measure of the lower limit of the charge of the nucleus. This selection criterion is adopted to accept the disintegration stars produced in heavy group (Ag, Br) only and to reject those produced in light group (C, N, O) of emulsion nuclei.

Each star so obtained was then carefully examined under high magnification (2000 $\times$ oil immersion objective) to collect the disintegration stars with two or more short tracks each having ranges up to about 40 μ.

The combination of any two or more short tracks associated with a primary disintegration centre may simulate a true binary, ternary or quaternary fission events.

For binary fission, (i) the two fragments representing the fission tracks should be almost identical. They should have the characteristics of heavily ionising tracks such as (a) absence of end scattering, (b) tapering towards end and (c) absence of discontinuity along the track. Further, (ii) the two fragments should have comparable ranges with a maximum range ratio accepted being 1 : 5, and (iii) the fragments should be emitted towards opposite hemispheres with an angular separationbetween them varying from 180° to 120°.

For ternary events, either (i) all the three short tracks must have similar track characteristics (i.e., residual range, ionisation, tapering, etc.), or (ii) two prongs may have more or less identical track characteristics whereas the 3rd one may be somewhat different. The criterion (i) selects events with three fragments of comparable mass. The 2nd criterion selects ternary events with two fragments of comparable mass and a third fragment having a different mass.

In the case of quaternary events, of the four short prongs associated with the primary disintegration star we select either (i) a star containing a pair of short tracks ($R \sim 10\ \mu$m) and a pair of long tracks ($R \sim 50\ \mu$m) or (ii) three short tracks of more or less equal length and the fourth one comparatively either longer or shorter. The former selects quaternary fission into a pair of light and a pair of heavy nuclei and the latter selects events with 3 fragments of similar size while the other one is different.

3. Results and discussions

The information gathered from the samples collected in the present investigations is furnished in table 1.

Distribution of heavily ionising prongs (N_h) in the case of ternary is shown in figure 1.

Table 1. Results of analysis

Total number of primary disintegration stars scanned	30,000
Number of binary fission events observed	225
Total number of ternary fission events observed	18
Number of ternary fission into comparable masses	17
Number of cascade fission	1
Frequency of ternary expressed as a fraction of binary events	0·08
Frequency of quaternary expressed as a fraction of binary events	0·005
Cross-section of binary	0·8 mb

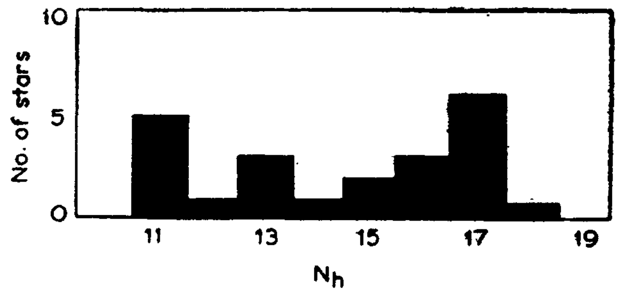

Figure 1. N_h distribution of ternary fission events in K interactions (18 events).

The mean excitation energies of the ternary and the lone quaternary events have also been calculated using the empirical formula of Powell *et al* (1959),

$$U = 42\,(N_b+1),$$

where N_b represents the average number of black prongs ($g > 6{\cdot}8\, g_0$) which is 70 % of the total number of heavily ionising prongs emitted from the disintegrating nucleus. The values obtained are found to be 500 MeV for ternary and 540 MeV for quaternary fission events respectively.

Figures 2 and 3 give the distribution of ranges and range ratio of the prongs of the ternary events. From this distribution we find that the ranges vary from 5 to 40μ with a maximum number having ranges between 5 to 10 μm. From the range ratio we also find that in most cases it is confined to a value within 2 and only in few cases it increases up to 5.

From the angular distribution (figure 4) we find that the angles between the prongs may vary over a wide range extending from 40°, when the fragments of the pair are confined to a small divergent cone, to 180° when they are emitted exactly in opposite directions. A broad distribution appears between 100° and 140° together with an isolated peak between 80° and 90°. This isolated peak supports the view that in ternary fission, frequency of alpha emission is appreciable and most of them are emitted within an angle of 80°–90° with respect to the light fragments (Fraenkel 1967).

An attempt has also been made to analyse two ternary and the lone quaternary event in order to give them a possible identity and hence to illustrate the possible types of fission processes. The data obtained from the measurements of the two ternary events are furnished in table 2.

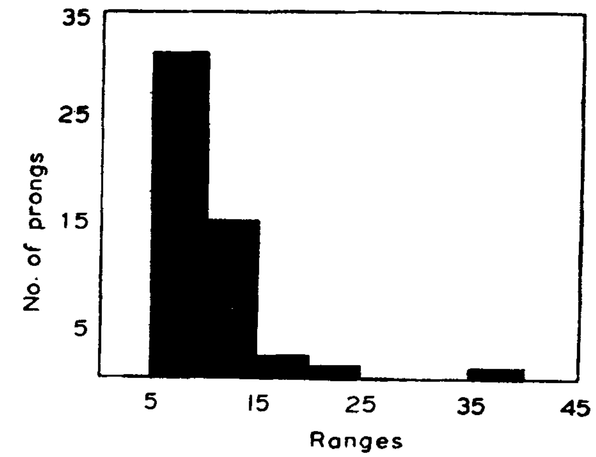

Figure 2. Range distribution of the prongs of the ternary fission events (18 events)

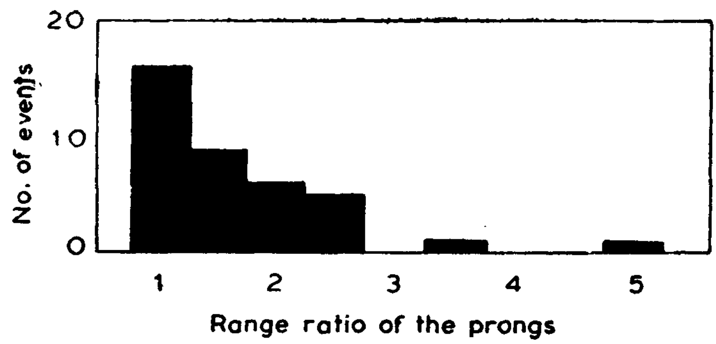

Figure 3. Range ratio distribution of the prongs of the ternary fission events (15 events)

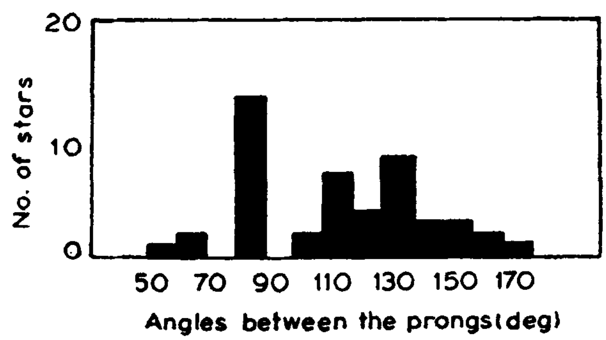

Figure 4. Angular distribution between the prongs of the ternary fission events in K interaction (18 events)

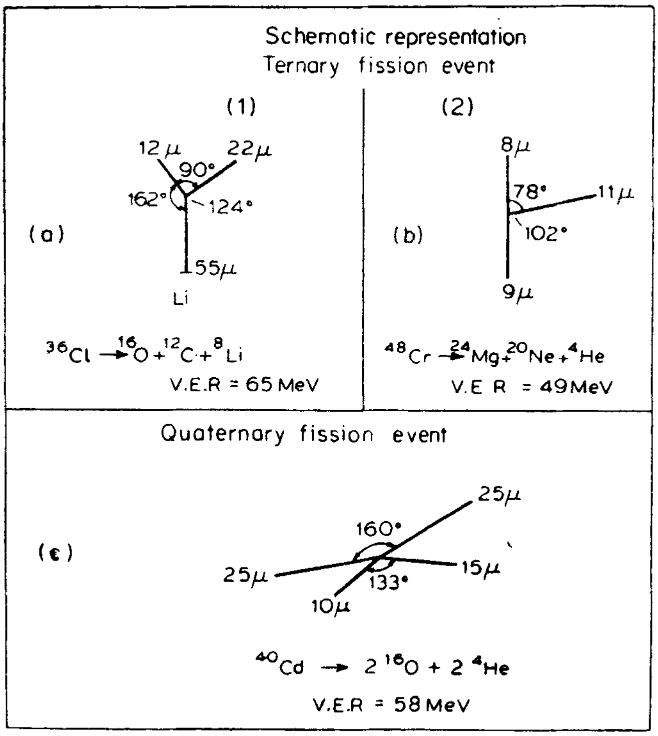

Figure 5. Schematic representation of ternary fission **a.** event 1. **b.** event 2. **c.** event 3.

Table 2. Data from ternary events

Events	Primary star	Pre-fission charge	Tracks	Possible identity	Ranges in microns	Space angle between	Visible energy release MeV	Possible fission scheme
1	(13+3F) K^-	$Z=17$	1	^{16}O	12		20	
						90°		
			2	^{12}C	22		25	$^{36}Cl \rightarrow$
						124°		$^{16}O + ^{12}C + ^{8}Li$
			3	^{8}Li	55		20	
2	(10+3F) K^-	$Z=24$	1	^{20}Ne	8		20	
						78°		
			2	^{24}Mg	9		26	$^{48}Cr \rightarrow$
						102°		$^{24}Mg + ^{20}Ne + ^{4}He$
			3	^{4}He	11		3	

3.1. *Explanation of the event* 1

A schematic diagram of event 1 is given in figure 5. The number of heavily ionising prongs emitted from the disintegrating centre is 16. This corresponds to an excitation energy of about 500 MeV. In order to estimate the charge distribution of fission fragments, the charge of the fissioning nucleus can be obtained from the estimation of total charge carried away by all the heavily ionising particles (excluding the fission fragments) emitted from the disintegrating nucleus. The charges of the heavily ionising particles are estimated by applying the usual method of charge determination wherever possible, otherwise it is taken to be unity. After determining the extent of total charge carried away by emitted particles, the residual charge or prefission charge, Z_{fission} is given by

$$Z_{\text{fission}} = Z_{\text{Ag or Br}} - \Sigma Z_i,$$
$$= 41 \pm 6 - \Sigma Z_i,$$

where ΣZ_i is equal to the total charge carried by all the heavily ionising particles excluding the pair of fission fragments. The charge of the fissioning nucleus in the present case comes out to be 17 as a lower limit when interaction in bromine is considered.

Of the three fragments for fission events, one ends in a hammer after traversing a range of 55 microns. This is also the case with ^{8}Li fragments decaying in the following scheme,

$$^8\text{Li} \xrightarrow{e^-} {}^{*8}\text{Be} \longrightarrow {}^4 2\text{He}$$

For the two tracks the possible identities are attributed in such a way that (i) the total visible energy release (VER) for the process does not differ much from that of binary (450 MeV) and (ii) a balance of momentum is obtained between these emitted fragments. It is thus found that the tracks with 12 μ range may be due to ^{16}O and that with 22 μ may be due to ^{12}C. It may be pointed out that if we consider the interaction to be in silver, then the possible identities for these short tracks will result in large VER and also the balance of momentum cannot be obtained. Hence the event may be a true ternary fission of $^{36}\text{Cl}_{17}$ nucleus into three fragments of comparable masses, such as,

$$^{36}\text{Cl}_{17} \longrightarrow {}^{16}\text{O}_8 + {}^{12}\text{C}_6 + {}^8\text{Li}_3$$

The angular separation between ^{16}O and ^{8}Li fragments is higher than that between ^{8}Li and ^{12}C. It may be due to the larger coulombic repulsion between ^{16}O and ^{8}Li than that between ^{12}C and ^{8}Li.

3.2. *Event* 2

Excitation energy and lower limit of charge of prefission nucleus in event 2 (see figure 5) have been estimated by the method discussed for event 1 and found to be 420 MeV and 24 respectively. It is found that the two tracks of ranges 8 and 9 μ are collinear and the third one is emitted almost at right angles (differing by about 12°) to them. This event may be a ternary fission event emitting a short range alpha in a direction almost normal to the heavier fragments which repel each other in opposite directions.

A similar analysis done as in the case of event 1, shows that the possible identities for the particles traversing 8 and 9 μ to be ^{20}Ne and ^{24}Mg respectively. The possible fission scheme may therefore be represented by

$$^{48}\text{Cr}_{24} \longrightarrow {}^{24}\text{Mg}_{12} + {}^{20}\text{Ne}_{10} + {}^4\text{He}_2.$$

Table 3. Data from quaternary events

Primary star	Pre-fission charge (Lower limit)	Tracks	Ranges in microns	Space angles between the tracks	Possible identity	Visible energy range MeV	Possible fissions scheme
$(13+4F)K^-$	$Z=20$	1	25		^{4}He	6	
				160°			
		2	25		^{4}He	6	
				38°			
		3	15		^{16}O	26	^{40}Ca
				133°			$^{16}2$ O+$^{4}2$ He
		4	10		^{16}O	20	

This may be a case of cascade fission (Nuzychka 1968) in which ^{48}Cr at first breaks up into two ^{24}Mg fragments in a binary process. Of these two fragments one might have exceeded the fission barrier and eventually emitted one alpha which finds itself in between the repelling ^{24}Mg and ^{20}Ne fragments. As the charge of ^{24}Mg is higher than that of ^{20}Ne, the coulombic repulsion between ^{24}Mg and alpha is slightly greater than that between alpha and ^{20}Ne. Hence the alpha particle is deviated from the normal direction.

3.3. *Quaternary fission*

The event is similar to that obtained by Tsien-San-Tsiang (1947). Necessary data obtained from the measurements are furnished in the table 3.

3.4. *Explanation of quaternary fission events*

The number of heavily ionising prongs emitted from the disintegrating centre is found to be 17. This corresponds to an excitation energy of about 540 MeV. The charge of the fissioning nucleus estimated from the identification of the heavily ionising tracks, comes out to be 20. The tracks 1 and 2 having ranges 25 μ each appear to be thin as compared to the tracks 3 and 4. Now, this event may be a possible case of quaternary fission with two alphas emitted in the same side of the fission axis as discussed by Kataria *et al* (1976).

As in the case of ternary fission, we suppose that VER in this case also does not differ much from that of binary and ternary fission.

Of all the possible identities attributed to tracks 3 and 4, it is found that if we consider both of them to be due to ^{16}O we get a reasonable VER. This event may thus be a quaternary fission of ^{40}Ca represented in the following scheme

$$^{40}\mathrm{Ca}_{20} \longrightarrow {}^{16}\mathrm{O}_8 + {}^{16}\mathrm{O}_8 + {}^{4}\mathrm{He}_2 + {}^{4}\mathrm{He}_2.$$

The mechanism of formation conforms to that of Kataria *et al* (1973). The excited prefissioning ^{40}Ca nucleus at first splits into two parts (^{20}Ne each) which at no time ($\sim 10^{-21}$ sec) after scission eject alphas from their deformed tips. The two alphas are found to have the same kinetic energies. It is perhaps due to the fact that initial spliting of ^{40}Ca is symmetric. An unbalanced momentum appears along the forward direction of heavy fragments. This may be due to fission in a moving system.

Acknowledgements

The authors are grateful to Professor A J Herz of CERN, Geneva, for lending the emulsion stack. Thanks are also due to Mr T C Deka for the scanning work. Facilities provided by the Department of Physics, Gauhati University and necessary permission granted to one of the authors (KB) by the authorities concerned to work in the Department of Physics, Gauhati University are also gratefully acknowledged.

References

Bŏhr N and Wheeler J A 1939 *Phys. Rev.* **56** 426
Brandt 1970 *J. Phys. (Paris)* **31** 21
Becker E W and Katcoff S 1962 *Phys. Rev.* **126** 729
Fraenkel Z 1967 *Phys. Rev.* **156** 1283
Kapoor S S, Chowdhury R K, Kataria S K, Murthy S R S and Ramamurthy V S 1972 *Nucl. Phys. Solid State Phys. (India)* **B15** 107
Kataria S K, Nandi E and Thompson S G 1973 *Proc. 3rd IAEA Symposium on Physics and Chemistry of Fission* (Rochester, New York) **2** 389
Kataria S K 1976 *Pramāṇa* **7** 126
Muga M L 1963 *Phys. Rev. Lett.* **11** 192
Muga M L 1965 *Symposium on Physics and Chemistry of Fission*, IAEA, Vienna
Muga M L 1967 *Phys. Rev.* **161** 1266
Nuzychka A Ju 1968 *Sov. J. Nucl. Phys.* **2** 222
Powell C F, Fowler P H and Perkins D H 1959 *The study of elementary particles by photographic method* (London: Pergamon Press)
Present R D 1941 *Phys. Rev.* **59** 466
Stoenner R W and Hillman M 1966 *Phys. Rev.* **142** 716
Talukdar G N 1971 *Fission of heavy emulsion nuclei at high energy* Ph. D. Thesis Gauhati University
Tsien-San-Tsiang 1947 *Phys. Rev.* **71** 382