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Introduction

The fission of a heavy nucleus into three parts of approximately equal mass is apparently one of the most interesting and significant aspects of the nuclear fission physics. In fact, there are no theoretical studies dealing with the problem. Some remarks concerning the possibility of this decay mode have been made by Swiatecki[1]. V.M.Strutinsky[2] introducing the liquid drop model which has determined the equilibrium forms of the nucleus leading to fission. It has been shown that along with the simplest single-neck configuration, more complicated configurations of conditional equilibrium with two and more necks are possible. However, the calculated value of the two-neck configuration potential energy is much higher than in the usual case which probably leads to a very small cross section for ternary fission.

The attempts to observe this rare phenomenon have been made in a major way while fissioning U^{235} with thermal neutrons. In each experiment the value of the ternary fission cross section was determined, however, as the measurement technique was developed, the cross section for the effect in each subsequent experiment was smaller[3].

The method of fragment detection by means of surface-barrier detectors has opened new possibilities for the investigation of ternary fission.

Muga[4] has studied the fission of U^{235} with thermal neutrons by means of this method and found that the value of the ratio of ternary fission cross section to the binary fission one is $\sigma_{3F}/\sigma_{2F} = (1.3 \pm 0.6) 10^{-6}$. He has also found[5] that in the spontaneous fission of Cf^{252} the ratio σ_{3f}/σ_{2F} is $2.2\ 10^{-6}$.

In a recent paper of Stoenner and Hillman[9] the yield of some Ar and isotopes from the fission of U^{235} with thermal neutrons has been determined by the radiochemical method. According to the paper[4] the content of the isotopes in the case of ternary fission with the given cross section should be $5.10^{-6} - 5.10^{-5}$ per cent. However, the authors have not observed these isotopes, the upper limits being from 10^{-7} to 10^{-10} per cent.

It is noteworthy that the reaction $U^{235} + n_0$ is not the only possible and probably not the best one for the detection of ternary fission, since the excitation energy and the value of Z^2/A of the nucleus in this case are rather small.

A certain advantage is aohieved in reactions with heavy ions. The compound nucleus produced from the reaction with a heavy partiole has high excitation energy and is, as a rule, neutron-deficient, i.e. with a large parameter Z^2/A.

At present, nuclei with Z^2/A up to 44 and with excitation energy above 100MeV can be easily obtained. There is a hope that the cross section for ternary fission of these nuclei will be much larger than that for $U^{235} + n_0$ and therefore this process will be more convenient for experimental study.

Up to date there have been two papers/7/,/8/ dealing with Ne^{20} and Ar^{40}. Mica with some admixture of lead or uranium was used both as a target and as a fission fragment detector. After bombarding, the samples were etched in such conditions that the ion tracks were largely different from the fission fragment tracks.

The presence of a "three-prong star" has been due to ternary fission. Similar experiments have been performed with a thoride crystal ($ThSiO_4$). The measurement results are given below:

Reaction	Z^2/A	σ_{3F}/σ_{2F}
$Ne^{20}+Pb$	36,1	$6\cdot10^{-4}$
$Ar^{40}+Pb$	40,4	$5\cdot10^{-3}$
$Ar^{40}+U$	43,4	$3\cdot10^{-2}$
$Ar^{40}+Th$	43,5	$3;3\cdot10^{-2}$

The contribution of the oross section for ternary fission is very large, in some case up to 3 per cent.

In the present paper an attempt has been made to observe ternary fission in bombarding U^{238} and Au^{197} with Ne^{22} ions, the energy of each fragment being detected.

The experiments have been conducted with the external beam of the 310 cm heavy ion cyclotron of the Laboratory of Nuclear Reactions, JINR.

Experimental

The layout of the experimental arrangement is given in Fig.1.

The Ne^{22} external beam was focused with quadrupole lenses, diaphragmed and hit the target positioned in the center of the scattering chamber. The dimensions of the beam on the target were determined by the last diaphragm, 4 mm in diameter. The incident energy was 190 MeV, the energy resolution was 2 MeV.

Thin targets of gold and uranium were used in experiments. The gold target was 200 $\mu g/cm^2$ thick, the uranium targets were made by means of electrophoresis which made it possible to obtain 300-400 $\mu g/cm^2$ layers on a thin Ni ($40 \mu g/cm^2$) or Al (100-$150 \mu g/cm^2$) backing. The target was positioned at 45° to the beam direction.

The fission fragments were detected by three $(Si+Au)$ surface-barrier detectors, each with a sensitive area of 1 cm^2, fabricated from n-type silicon crystal with specific resistance ρ = 2500 ohm/cm.

The back-bias voltage was 80 V, which corresponded to the sensitive depth of about 200 μ. In this case the range of the fragment in the sensitive layer was much less than the layer depth, however, these conditions were chosen, on one hand, to diminish the "defect of ionization"/9/ of the detector and, on the other hand, to detect the total energy of the scattered ions striking the detector. The detectors were positioned in the plane perpendicular to the direction of the incident beam. The angles between the detectors and the beam direction were 73°, the angles between the detectors in the plane perpendicular to the beam oould be varied. The experiments were conducted with two different distances between the detectors and the target: 3.5 cm and 5 cm, which corresponded to the registration efficiency of each counter ($5\cdot10^{-3}$ and $2,5\cdot10^{-3}$ respectively).

To record the ternary fission effect a fast-slow coincidence circuit with simultaneous amplitude analysis of each fragment was used. The block-diagram of the electronic circuitry is shown in Fig. 2. The pulses were applied from detectors to the charge-sensitive pre-amplifiers whose noise level was below 150 keV and then passed through to the input of the linear amplifiers. After amplification the pulses were applied in parallel to a three-fold fast coincidence circuit with time resolution 50 nsec and to a four-fold slow coincidence circuit with time resolution 500 nsec.

Each dimensional axis of the analyser consisted of 64 channels. This electronic recording system was chosen due to the following:

the 310 cm cyclotron was operated in the conditions of outer modulation with 1.2 msec pulses and duty factor 3.5. The time structure of the beam during 1.2 msec was dependent upon the acceleration conditions. In our case 10 nsec pulses were produced every 210 nsec. (τ_0)

Now one can easily show that if the proper time resolution of the coincidence system is within the limits of:

$$\cdot\ t_0 < \tau_F < \tau_0$$

the number of accidental coincidences will be determined not by τ_F , but by a certain new value $\tau_a = \tau_0/2$ = loo nsec. Since with fission fragments it was very difficult to attain time resolution lo msec, we chose another value of 5o nsec which significantly simplified the electronic circuitry. The instrumentation stability was continuously checked and was not below 1.5 per cent, the checking was carried out by means of a standard generator connected with the input of the preamplifiers.

Measurements and Results

It was found for the fixed geometry of the counters at 190 MeV that the main leading of the detectors was due to the fission fragments. Therefore the only source of the background could be accidental triple coincidences of the fragments. This required certain limitation of the beam intensity up to the value of 250-300 fragm./sec.

In the first set of experiments the detectors were positioned in the plane perpendicular to the beam, so that the two were at 180° to each other, while the third one was at 90° to to the first two.

Under these conditions real double coincidences occur between the detectors facing each othe- however, the detection of these coincidences is possible only in the case of the accidental coincidence between the binary fission event and the pulse from the third detector.

The following data have been obtained by these measurements:

1. The time resolution of the coincidence system for the real fragment pulses which was 10^{-7} sec.
2. The kinetic energy spectrum of the fragments.
3. The total energy spectrum of the binary fission fragments.
4. The detection efficiency of binary fission equal to χ =0.2 for the chosen geometry.
5. The total energy spectrum of double accidental coincidences of the fission fragments.
6. The total energy spectrum of triple accidental coincidences of the fission fragments.

The measurement results are given in Fig.3. The spectra of the fragments detected by each counter and the total kinetic energy spectrum of the fragments are in good agreement with the data/10,11/.

The distribution of the total kinetic energy of binary fission shows a maximum at $E_{2F} \approx 200$ MeV, while the spectrum of triple accidental coincidences shows a maximum at ~ 300 MeV

Therefore one could expect that the real total energy spectrum of ternary fission fragments should be between $200 < E_{3F} <$ 300 MeV.

Another set of experiments has been performed with detectors positioned at 120° to one another, the detectors being at 5 cm from the target. Twenty events of triple coincidence have been detected, the rate being ~ 0.5 event per hour. The expected amount of accidental coincidences for the whole irradiation run is about four.

Individual and total kinetic energies of the fragments are given in the table. Two groups can be easily distinguished: the main group corresponding to total energy 250 MeV and 5 events with energy above 300 MeV, which can be interpreted as accidental coincidences.

The observed effect is extremely small, therefore it is difficult to obtain good accuracy of statistics in the spectra. This , in its turn, does not permit to arrive at certain conclusions concerning the mass distribution and angular correlation of ternary fission cross section.

However, from the data obtained one can determine the upper and lower limits of the cross section if certain assumption is made concerning the fragment correlation.

Let us assume that the emission of two fragments is equally probable in all directions and that it is the third fragment which is responsible for the total momentum conservation of the system. In this case the ratio of ternary fission to binary one is the maximum value determined as: $\left(\sigma_{3F}/\sigma_{2F}\right)_{max} \approx \frac{N_{3F}}{N_{2F}} \cdot \frac{1}{\varepsilon_0 \nu(\nu-1)\chi}$

where $\nu = 3$

N_{3F} - the amount of detected ternary fission events,

N_{2F} - the total amount of fragments detected by one counter,

ε_0 - the detection efficiency of each counter in the given geometry,

χ - the detection efficiency of a strictly correlated event in the given geometry.

Here one does not take into account a possible difference in the angular distributions of ternary and binary fission fragments.

The minimum value σ_{3F}/σ_{2F} can be calculated using the assumption that all the three fragments are strictly correlated:

$$\left(\sigma_{3F}/\sigma_{2F}\right)_{min} = \frac{N_{3F}}{N_{2F}} \cdot \frac{1}{\nu\chi^2}$$

These estimates indicate that the ratio σ_{3F}/σ_{2F} is within the limits:

$$(2{,}6 \pm 0{,}7)\cdot 10^{-6} < \sigma_{3F}/\sigma_{2F} < (1 \pm 0{,}25)\cdot 10^{-4}$$

With a view of narrowing these limits similar measurements σ_{3F}/σ_{2F} have been performed, the detectors being at 3.5 cm from the target. The following values have been obtained:

$$(5 \pm 1{,}5)\cdot 10^{-6} < \sigma_{3F}/\sigma_{2F} < (1{,}5 \pm 0{,}5)\cdot 10^{-4}$$

Thus, the limits of the effect observed are:

$$(5 \pm 1{,}5)\, 10^{-6} < \sigma_{3F}/\sigma_{2F} < (1 \pm 0{,}25) \cdot 10^{-4}$$

Besides the reaction $U^{238} + Ne^{22}$, ternary fission has been studied in the reaction $Au^{197} + Ne^{22}$ at 190 MeV. The level of the triple coincidence effect in the reaction with gold was more than by a factor of 10 smaller than that in the reaction $U^{238} + Ne^{22}$ and could be due to the accidental coincidence background.

Discussion

The data obtained indicate that when U^{238} is bombarded with 190 MeV Ne^{22} ions ternary fission is observed in less than 1/10,000 of all the events. It occurs from the excited state of 102^{260} ($Z^2/A = 40.$)

It is interesting to compare these data with those given in paper/7/ in which ternary fission was studied in the reaction $Pb^{208} + Ar^{40}$ at 414 MeV. (Z^2/A =40.4).

Despite the fact that in both cases fissioning nuclei have actually the same value Z^2/A, the ratio σ_{3F}/σ_{2F} for $U^{238} + Ne^{22}$ is more than by a factor of 50 as small as that for $Pb^{208} + Ar^{40}$.

The disagreement between the data is very high, however, without any further comparison one should note a fact which is rather significant for studying ternary fission induced by heavy ions.

At high excitation energies in reactions with heavy ions the mass distribution is a symmetrical curve close to the Gaussian distribution. The width of the mass distribution is very sensitive to the nuclear temperature, and as the incident energies and the masses of the fissioning nuclei increase (with the increase of the incident particle mass) the contribution of asymmetrical fission grows rather rapidly.

If a nucleus with large mass and high excitation energy undergoes strongly asymmetrical fission, further binary fission of the heavier fragments can occur.

It is natural that the following binary fission is significantly dependent upon the mass distribution of the fragments at the first stage and the value Γ_n/Γ_f of the heavier fragment. However, the total energy of this decay mode will be probably higher than in the case of real ternary fission, therefore for a more accurate comparison of experimental data one should know the energy distribution of the fragments for each case.

In the reaction $U^{238} + Ne^{22}$ the total energy of the fragments is about 250 MeV. The energy of the following binary fission should be much higher, therefore one has ground to believe that in this case the nuclei undergo real ternary fission. In the reaction induced by 414 MeV Ar^{40} ions/7,8/, however, the contribution of the following binary fission may be significant.

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References

1. W.J.Swiatecki, Second UN Geneva Conference, p. 651,Pergamon Press Ltd.,London,1960.
2. V.M.Strutinski, Institute of Atomic Energy Report IAE - 408 (1963).
3. L.Rosen, A.M.Hudson, Phys.Rev. 78, 533, (1950).
4. M.L.Muga, Phys. Rev.Lett.,11, 129, (1963)
5. M.L.Muga, Symposium on the Physics and Chemistry of Fission 1965. (International Atomic Energy Agency, Vienna, 1965).
6. H.C.Britt, G.C.Benson, RSI 35, 842, (1962).
   H.Kobayshi, A.Nakimoto, Nucl.Instr.Meth., 34, 222, (1963).
7. P.B.Price, R.L.Fleischer, R.M.Walker,E.L.Hubbard, Proceedings of the Third Conference on Reactions between Complex Nuclei, Asilomar, California 1963, p. 332, (University of California Press, Berkeley, California, 1963).
8. R.L.Fleischer, P.B.Price. R.M.Walker, Phys. Rev., 143, 943, (1960).
9. R.W.Stoenner, M.Hillman, Phys.Rev. 142, 716, (1966).
10. E.L.Haines, Lawrence Radiation Laboratory Report, UCRL - 10342, (1962).
11. V.E.Viola, T.Sikkeland, Phys.Rev., 130, 2044, (1963).

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E_{F1}	E_{F2}	E_{F3}	$E_{TOT.}$
91	75	82	248
105	66	115	286
89	84	120	292
100	85	122	307
84	66	106	256
84	12	97	253
124	68	78	270
90	59	81	230
118	78	78	274
122	55	87	264
78	72	40	190
88	97	62	242
94	57	100	251
134	60	81	275
106	55	81	242

Table 1. The values of energies of ternary fission fragments. The accuray of the absolute energy calibration is about 5%.The relative accuracy of energy measurements is about 2%.

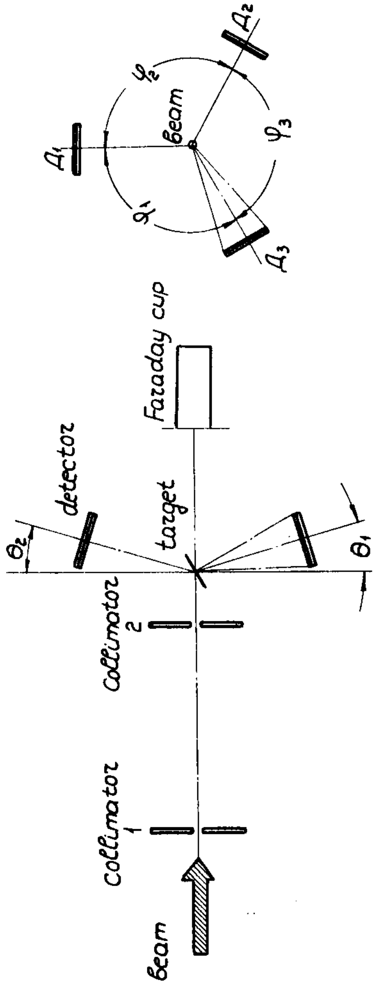

Fig.1. Scheme of the experimental arrangement.

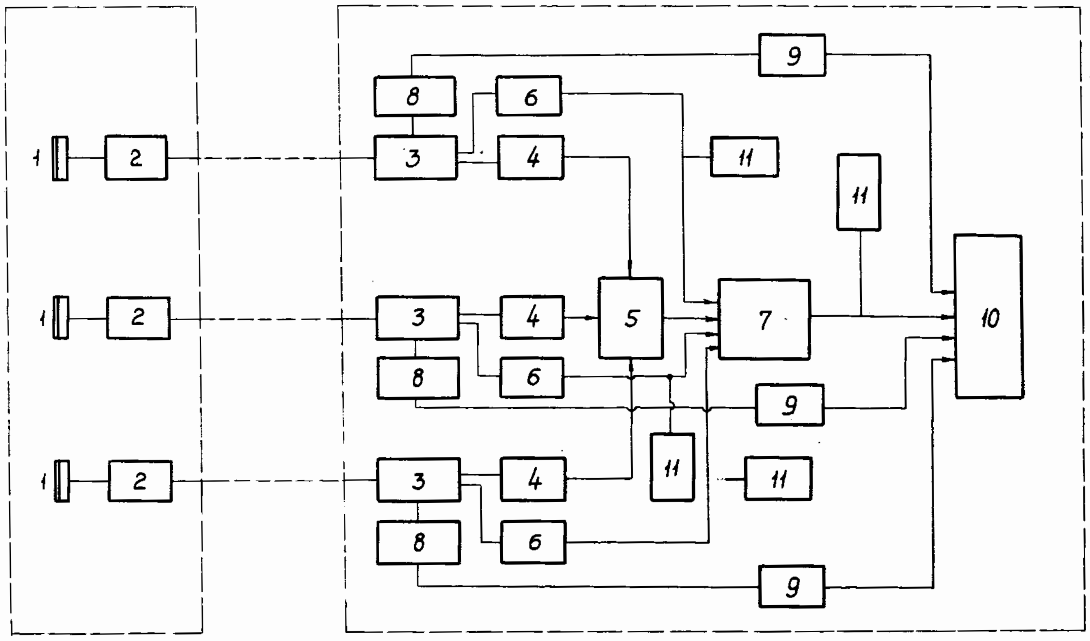

Fig.2. Block-diagram of the electronic system 1.detectors, 2.pre-amplifiers, 3.linear amplifiers, 4.fast time standardization, 5.fast coincidence, 6.slow time standardization, 7.slow coincidence system, 8.invertors, 9.followers, 10.three-dimensional analyzer, 11.scalers.

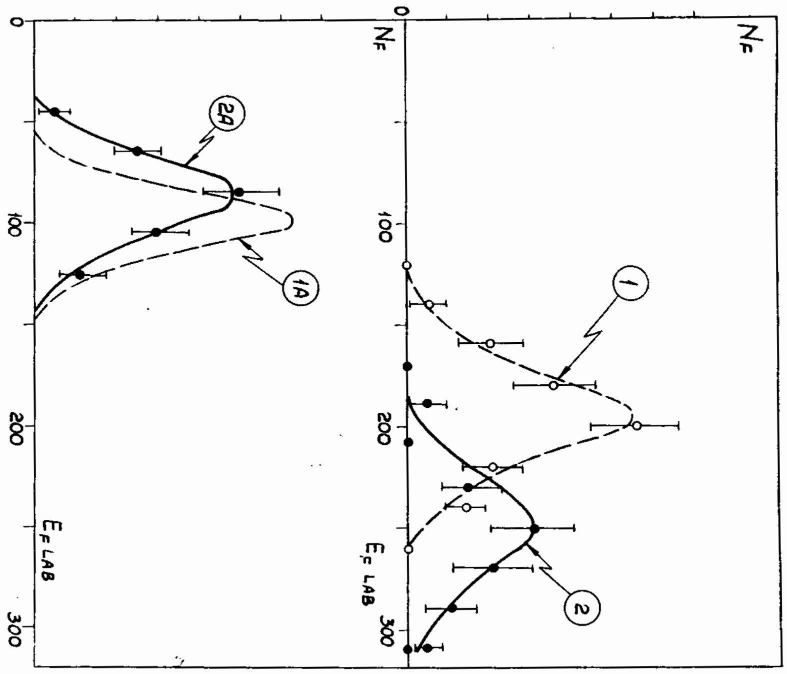

Fig.3. Single (slow) and total (above) spectra of the fission fragment kinetic energy. 1, 1A - binary fission ; 2, 2A - ternary fission.