High Energy Physics and Nuclear Physics

Volume 19, Number 1

Test of Sequential Decay of Hot Nuclei Around 3 MeV/u Excitation Energy

Wu Heyu and Dai Guangxi

(Institute of Modern Physics, The Chinese Academy of Sciences, Lanzhou, China)

The splitting of hot nuclei into three massive fragments is analyzed by using a minimization procedure of difference between relative velocity and Coulomb repulsive velocity. It is utilized in ^{40}Ar+^{209}Bi, ^{197}Au, ^{159}Tb reactions at 25 MeV/u. The kinematics of ternary fragments emitted from excited nuclei with 3 MeV/u excitation energy produced by central collisions are presented. It is shown that the ternary fragments originate from two successive independent binary splitting. This result is also supported by the fact that experimental angular distributions of ternary fragments are nicely reproduced by sequential decays.

Key words: hot nuclei, Cascade emission of fission fragments, prompt ternary fission, the total kinetic energy (TKE) of fission, angular distributions of ternary fission, the Coulomb repulsive velocity.

---

1. INTRODUCTION

One important issue in the study of heavy ion collisions in Fermi energy range is the formation of hot nuclei with high excitation energy and high spin produced in the reactions. The decay of hot nuclei is an important topic that gives us the understanding of the properties and instabilities of hot nuclei. Many decay channels are opened in this excitation energy range, the multiplicity of massive fragments and light particles is up to 40 for 25 MeV/u ^{40}Ar+^{197}Au central collision reactions for example. This is rather different from the fission and evaporation channels at low energy. The prompt

---

Received on February 3, 1994.

multifragmentation might occur at high excitation energy of 4-5 MeV/u. Ternary fission events were measured in our previous experiments of ^{12}C(47.5 MeV/u) + ^{209}Bi, ^{197}Au, ^{159}Tb with relative angle 120° and relative velocity 3.5 cm/ns in 1990 [1]. The excitation function and the probability ratios of ternary to binary fission was also obtained [2]. The experimental data could be reproduced by the calculation of statistical cascade model [3]. The deformed potential calculations showed that the cascade fission is energetically more favored than the oblate ternary fission and the prolate ternary fission [4].

We concern the mechanisms of multifragment emissions in the transition range from evaporation/usual fission to prompt multifragmentation. Do the three fission-like fragments come from cascade fissions, or from spontaneous fissions of multiple deformation, or from the transitive fissions of the two extreme ones? Very recently, some results [5-7] show that the three massive fragments emitted out at the excitation energy compatible to that in this paper can be explained by two successive binary fissions. The residue nuclei produced in incomplete fusions by HIRFL beams are suitable for such study in this excitation energy range.

In this paper, we have employed a kinematics method to select the decay mode of hot nuclei emitting 3 fragments to analyze the relationship of emission times of the fragments. If the three fragments originate from two independent binary splitting, there must exist a kinematic difference between the two splittings. The TKE is different if the emission time is different in asymmetric ternary emissions. If the three fragments are produced by two splittings sequentially passing through the scission points and the time interval of the two splittings is greater than 200 fm/c, the fragments are emitted with a constant Coulomb velocity in one's own center of mass system, respectively. But the relative velocity of the fragments coming from different splittings and the angle of the two fission axes are random. The cascade emission assumption is also supported by Ar+Au reaction at 30 MeV/u at GANIL with DELF multidetectors which measured the fragments emitted at large angles ($30° < \Theta < 150°$) with mass number above 20. In our experiment, we choose the events in which fragments emit out at large angles ($50° < \Theta < 150°$), and this thoroughly eliminates the deep inelastic collisions (DIC) events in which the projectile-like fragments are emitted accompanying sequential binary fission. The kinematics of the three fragments of DIC events are the same as those of the cascade fission for emission with Coulomb repulsion. The nature of cascade splitting is presented in this paper, and the angular distribution of ternary fission is tested.

2. METHODS AND PRINCIPLES OF ANALYSIS

2.1. Difference of TKE Between Cascade and Oblate Ternary Fission

In usual binary fission, the total excitation energy is assumed to be the deformed energy and the fragments' excitation energy. The TKE of fragments is yielded by the Coulomb potential between fragments, and the relative velocity of fragments must be a constant (v_{FF} = 2.3 cm/ns-2.1 cm/ns) due to the Coulomb repulsion [8]. The deformation needs much excitation energy in the oblate ternary fission, assuming the kinetic energy is zero and the splitting is due to Coulomb repulsion at scission then the TKE may be independent of the excitation energy of fissioning nuclei. The sum of fragments TKE in the two cascade fission processes are independent of the angle of the two fission axes.

The estimation of the TKE of cascade fission and of oblate fission are performed according to its Coulomb potential at scission at different mass asymmetry: the difference between the cascade TKE and the oblate TKE is decreasing from 30 MeV to 20 MeV when the fragments mass-asymmetry goes up, and both the cascade TKE and the oblate TKE decrease as well. The TKE of the fragments in cascade fission are different due to their different fission sequence. The difference between them is increasing from 0 MeV at symmetry case to 10 MeV at asymmetry case (see Table 1).

The above analysis about TKE doesn't mean that this difference can be used for distinguishing the mechanisms, it only means that there exists a kinematical difference. The TKE can't be measured

Table 1
The TKE (in MeV) of oblate and cascade ternary fission at different asymmetry.

A_1 Z_1	A_2 Z_2	A_3 Z_3	Oblate fission	Cascade fission I	II	III
99 38	99 38	99 38	448.86	414.44	414.44	414.44
99 38	91 34	107 42	447.05	413.86	412.87	411.94
99 38	83 30	115 46	441.06	410.16	408.32	406.36
99 38	75 26	123 50	432.46	403.28	400.43	397.72
99 38	67 22	131 54	419.55	393.15	387.42	385.98
99 38	59 18	139 58	402.74	379.64	375.13	371.10
99 38	51 14	147 62	381.85	362.62	357.42	353.02

exactly by experimental because of many uncertainties in the experiment, and it is difficult for us to calculate the TKE quantitively, because the shape of scission and the r_C value (Coulomb radii constant) are not well determined theoretically.

2.2. Determination of the Sequence of Cascade Emission

The cascade ternary fission (as shown in Fig. 1) emits fragment 1 with velocity v_1 and recoils nucleus 4 with velocity v_4 at first, then the nucleus 4 splits into fragments 2 and 3. The relative velocities v_{14} and v_{23} are all Coulomb velocities, but v_{13} and v_{12} are not constant and are dependent upon the mass of fragments and the angle of the two fission axes.

In each three fragments event, the fragments are labelled "light," "medium," and "heavy" respectively according to their masses. If the three fragments originate from two successive independent fissions of heavy residue, three categories of events must be considered: In category A, the light fragment comes from first splitting (fragment 1) and the medium and the heavy fragments come from second splitting (fragments 2 and 3); In category B(C), the medium (heavy) fragment comes first splitting (fragment 1) and the others from second splitting (fragments 2 and 3).

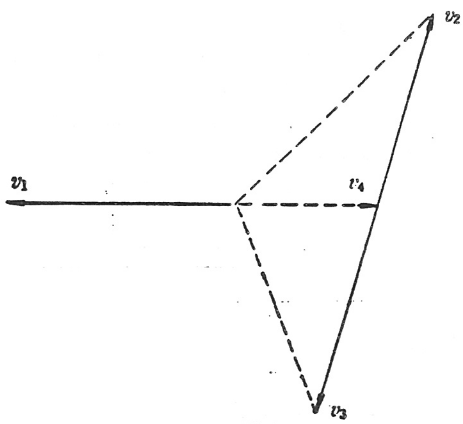

Fig. 1
Vector figure of cascade fission.

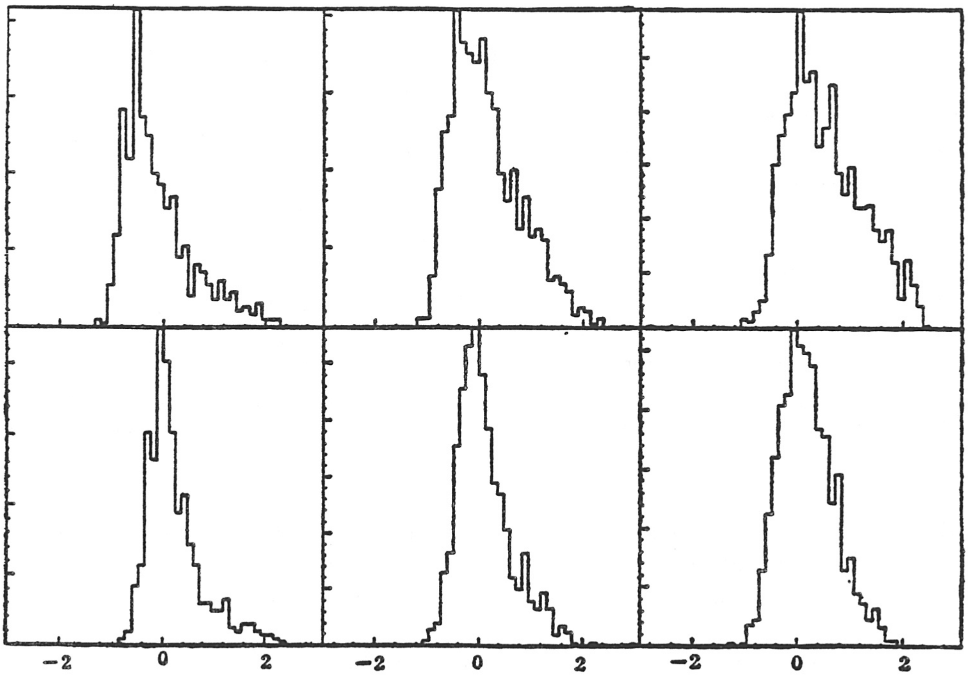

Fig. 2
The distribution of v_{14}-v_{14C} (upper plots) first splitting and v_{23}-v_{23C} (lower plots) in second splitting for Ar+Bi three body event. Left, middle and right plots correspond to the sequential splitting categories A, B and C, respectively.

One can build a quantity P to specify the categories:

$$P = [v_{14} - v_{14C}(A_1Z_1;A_4Z_4)]^2 + [v_{23} - v_{23C}(A_2Z_2;A_3Z_3)]^2$$

where v_{14C} and v_{23C} are Coulomb repulsive velocities for the first and the second splitting, respectively, which take into account the mass or charge asymmetry and remain a constant. If all the ternary fragments events come from the cascade fission passing through the scission, it must belong to one of the three categories. Experiment measurements give v_1, v_2 and v_3 straightforwardly, then the v_{14} and v_{23} are calculated according to the vectors summation and P_{I}, P_{II}, P_{III} and deduced. If P_i is the lowest in P_{I}, P_{II} and P_{III} for a event, most probably it belongs to category i, because:

(1) The distributions of differences of the relative velocity v_{14}-v_{14C} and v_{23}-v_{23C} must be centered around zero for possible category i, while these differences are far from zero and their P values are greater for wrong categories.

(2) The widths of these distributions are due to the fluctuation of physical quantities and the experimental uncertainties.

3. RESULTS AND DISCUSSION

The sustaining time of fission (about 1000 fm/c) is too small comparing with electronics accuracy (about ns). But here, the sequence of cascade splitting is successfully given by the method of kinematic

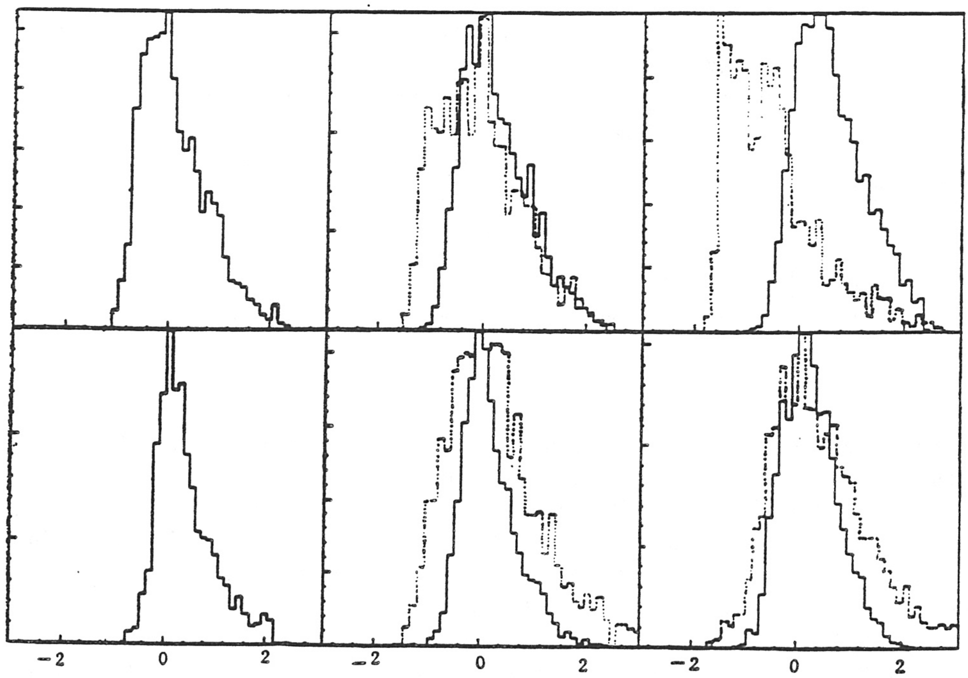

Fig. 3
Same as Fig. 2 but for Ar+Au system.

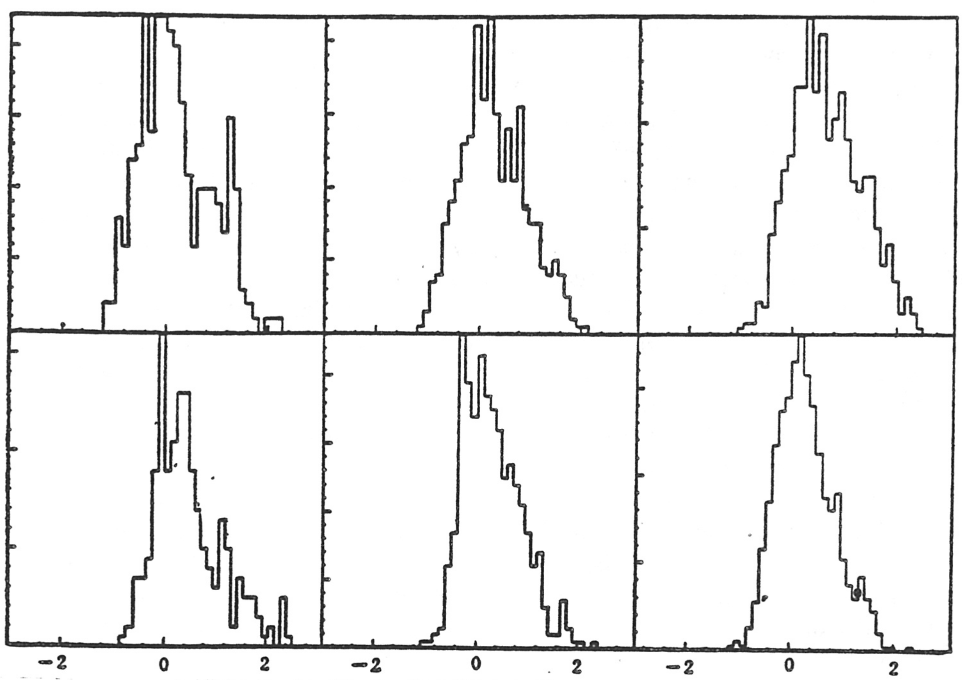

Fig. 4
Same as Fig. 2 but for Ar+Tb system.

Table 2
The relative probabilities of occurrence for different sequential splitting categories of $^{40}Ar+^{209}Bi$, ^{197}Au, ^{159}Tb reactions systems.

Probabilities of categories	Ar + Bi (25MeV/u)	Ar + Au (25MeV/u)	Ar + Au[7] (30MeV/u)	Ar + Tb (25MeV/u)
Category I	48.0%	52.1%	45%	50.5%
Category II	31.9%	29.0%	36%	28.8%
Category III	21.1%	18.9%	25%	20.5%

difference, the relative probabilities of occurrence of different categories are determined, and the mechanism of multifragment can be qualitatively understood.

The expected difference distributions of relative velocities are presented in Figs. 2, 3, and 4 for Ar+Au, Bi and Tb reaction at 25 MeV/u in the most possible category. The mean values of these distributions are close to zero and the shapes of the distributions are nearly symmetric. The influence of indirect Coulomb repulsion is checked by treating the possible category A's events as the category B's or C's and the results are shown in Fig. 3 (dashed line). In this case, the distributions are no longer centered around zero, and become much wider and asymmetric, thus indicating that this analysis is suitable for determining the cascade fission process.

The relative velocity of Coulomb repulsion can be given as a constant by the TKE of systematic of Viola, the TKE of the most possible symmetric fissions is independent of the masses of fission fragments and is dependent on the fissility [8]. Another method given repulsive velocity according to the masses and charges of the fragments, and the effective Coulomb radii are deduced from the Viola TKE of symmetric fission. The widths of the difference distributions of the velocities become smaller when using this method taking into account the mass asymmetry.

The probabilities of occurrence for the three categories in cascade emission of fissions are presented in Table 2. The similar behaviors are obtained that the smallest fragment comes from the first splitting in most events in Ar+Bi, Au and Tb reaction systems. The probabilities of occurrence ar dependent upon the excitation energy and on the mass of compound-like nuclei. Comparing with the experimental data of [7], it could be found that the probabilities of first emitting medium and heavy fragments increase with increasing excitation energy. We can deduce that the heavy hot nuclei deexcite by light particles evaporation and by usual fission at excitation energy lower than 1.5 MeV/u, and by the intermediate mass fragments (IMF) emission and sequential fissions (the asymmetric ternary fissions) at the range of 1.5-2.5 MeV/u, and by symmetric ternary fissions of the intermediate mass fragments (IMF) with increased probability at the range of 2.5-4 MeV/u, Later we will show that the decay mechanism of the excited nuclei at the range of 2.5-5.5 MeV/u evolves from cascade emissions to prompt multi-fragmentations when the difference of fragment emission times decreases and the multiplicity of fragments increases gradually.

The probabilities of occurrence for B and C (in which medium and heavy fragment come from the first splitting) are greater in Ar+Bi than that in Ar+Au at 25 MeV/u with almost the same excitation energy but with different fissilities of incomplete fusion nuclei (ICFN). The probabilities for Ar+Tb reactions lie in between those of the Ar+Au and Ar+Bi reaction systems. Although its smallest fissility of ICFN decreases its probabilities, but its biggest excitation energy increases its probabilities.

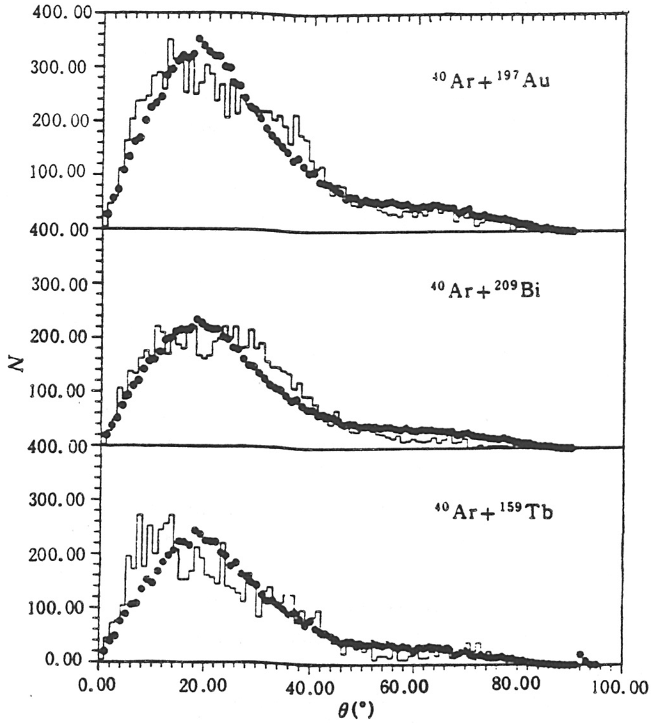

Fig. 5
Angular distribution of ternary fission.

4. CHECK OF ANGULAR DISTRIBUTIONS

The direction of usual binary fission takes along with the deformation axis. We define the direction of a ternary fission as that of the normal line of the fission plane. The deformation and emission occur in this plane in the center-of-mass system. Direction angle Θ is defined as the angle between the normal line and the projectile direction.

The binary fission of ICFN is strongly in favor of anisotropic emission in heavy ion-induced fission reactions. The fission directions show a 1/sinΘ distribution. Where Θ is the angle between the fission direction and the projectile one. All these are caused by the high spin of compound nuclei. In the ternary fission, the first splitting of cascade is anisotropic which is dependent on the angular momentum of ICFN, the direction of the second splitting is anisotropic in recoil nuclei system and is dependent upon the angular momentum of the recoil nuclei. The direction of ternary fission is blurred and it is independent of the spin of ICFN, when the angle of the two splitting axes is randomly arranged. The oblate fission is anisotropic as the deformation is affected by the spin of ICFN.

According to the above analysis, the events of cascade ternary fission are simulated by Monte Carlo method. The angle of the two axes is supposed to be random, and the distributions of mass and velocity of fragments are taken as those of experimental data. A large number of the simulated events are filtrated by the detection space of the experimental set-up, and the direction spectra of the recorded events are obtained. The expected spectra (⊗) are compared with the experimental spectra (hostgram) in Fig. 5 and the good agreement between them tells us that the measured direction distribution in ternary fission coincides with both the prediction of cascade splitting model and the result of kinematical analysis.

5. CONCLUSION

We have shown that most of the three large fragments emitted by ICFN originate from the fission process passing through the fission scission sequentially due to following reasons:

(1) The relative velocity distributions are nicely reproduced by the simulation of cascade splitting, within the experimental uncertainties and statistical errors.

(2) The probabilities of occurrence for different sequential splitting categories show the nature of transition from evaporation/fission to symmetry ternary fission. The occurrence of smallest fragment emitted first is most probable at low excitation energy. The decays of IMF emission (asymmetric fission) following fission (symmetric one) are similar to that of evaporation/fission. The probability increase with excitation energy, and the mass of first fragment increases, too. Finally, the three categories are blurred and possess almost same probabilities.

(3) The angular distributions of ternary fission can be reproduced by the fission of sequential emissions, and this supports the result of kinematic analysis.

(4) The cascade fission and the fission of cascade emission are different concepts. The former is the process of a usual binary fission followed by another binary fission, the later means that the fragments are emitted at different time. If the time interval of emissions is greater than the deformation time of fission, both fissions become identical. It might be difficult for cascade fission taking place, because a lot of light particles are emitted with large excitation energy. But for the fissionable fragment of first splitting, a lot of excitation energy stored as deformed energy can hardly be taken away by light particle emissions, and it results in the multiple vibration and thus reduces the barrier of the second fission. The probability of cascade fissions increases with the excitation energy of the primary nuclei, and it could be possible that the deformation of second splitting has occurred before the first splitting pass through the fission scission.

We have shown that the decay of multifragment is through successive splitting and sequential emission at low excitation energy about 3 MeV/u, and through prompt emission at high excited nuclei. We will show the transition nature between cascade fission and prompt fission with angular correlation measurements lately.

REFERENCES

[1] Dai Guangxi *et al.*, *China Jour. Nucl. Phys.*, **15**(1993), p. 101.

[2] We Heyu, Dai Guangxi *et al.*, *China Jour. Nucl. Phys.*, **15**(1993), p. 185. Wu Heyu, Dai Guangxi, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **17**(1993), p. 680.

[3] Wu Heyu and Dai Guangxi, *High Energy Phys. and Nucl. Phys.* (Chinese Edition), **18**(1994), p. 729.

[4] Wu Heyu and Dai Guangxi, *Academia of Physics* (Chinese), **43**(1994), p. 540.

[5] A. Badala *et al.*, *XXVIII Int. Meeting on Nuclear Physics*, Bormio, (1990), p. 314.

[6] M. Louvel *et al.*, *Proceedings of Nikko Workshop*, Japan (1991).

[7] G. Bizard, D. Durand, and A. Genoax-Lubain, *Preprint LPCC91-10* (submit to Physics Letters).

[8] V. Viola *et al.*, *Phys. Rev.*, **C31**(1985), p. 1550.