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ON THE PLANE FRAGMENTATION BARRIERS

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Abstract : The symmetric emission of fragments in a same plane has been studied within the generalized liquid-drop model taking into account the nuclear proximity energy and the temperature. For all usual nuclear masses, the plane fragmentation barrier heights increase rapidly with the multiplicity of the fragmentation but they are always lower than the three dimensional fragmentation barrier heights. For very heavy and evanescent nuclear systems, all the plane fragmentation barriers have almost the same height. The kinetic energies of the fragments are lower for the plane fragmentation than for the three dimensional fragmentation.

Highly excited nuclear systems can now be formed using nucleus-nucleus collisions in the intermediate energy domain (20-100 MeV u^{-1}). The nucleus is more stable against thermal excitation than predicted by static calculations and it supports temperatures as high as 5 or 6 MeV (Guerreau 1989, Galin 1991). The binary fission remains an important exit channel. Nevertheless, the ternary, quaternary, quinary, ...decays have been observed at high excitation energies (Bowman et al 1991, De Souza et al 1991, Louvel et al 1993, Bougault et al 1994). The interpretation of this multifragment production is still elusive. Several explanations have been advanced : dynamically induced density fluctuations (Peilert et al 1989), expansion of an initially compressed source (Friedman 1990), statistical decays (Lopez and Randrup 1990, Moretto et al 1993), rapid sequential binary fission, ...

Some recent experimental data seem to indicate that the branching ratios for binary, ternary, quaternary and quinary decays depend almost exclusively upon the excitation energy E^* of the fused system and very little upon the target-projectile combination or even the bombarding energy (Moretto et al 1993). For E^* around 5 MeV u^{-1} the life-time of the excited nucleus is about 100-150 fm/c. The time interval between the emission of two fragments evolves from more than 1000 fm/c (sequential decay) when E^* equals 2-3 MeV u^{-1} to a very small value lower than 50 fm/c (simultaneous decay) for E^* around 5 MeV u^{-1} (Aboufirassi et al 1994).

In a previous work, starting from the idea that the n fragments are emitted by a thermalized system, we have determined the three dimensional fragmentation barriers within the liquid drop model including the nuclear proximity energy and the temperature (Haddad and Royer 1992). The oblate ternary fission and the fragmentation into four, six and eight spherical nuclei were described from the contact point between nascent fragments spatially symmetrically arranged : equilateral triangle for the ternary case, tetrahedre for the quaternary configuration, spheres at equal distance along three cartesian axes for six fragments and cubic arrangement in the last case. Within the same geometry but using cassinian ovaloid-like shapes the multifission barriers have also been calculated recently (Dai et al 1994).

Some recent experimental data (Kugler et al 1994) and simulations within the Boltzmann-Uehling-Uhlenbeck model (Xu et al 1994) or Landau-Vlasov approach (Abgrall 1994) seem to point out that, for very violent collisions, the thermal source expands in a plane perpendicular to the line connecting the centres of projectile and target. This transverse focalization is due to the initial compression which induces strong oblate deformations leading to roughly toroidal nuclei in which Rayleigh instabilities develop allowing the plane multifragment emission.

The purpose of the present work is to determine the characteristics of the fragmentation in a same plane and to compare with the three dimensional fragmentation. Assuming the thermal equilibrium and small changes of density after the fragment separation, the calculations of the deformation energy of these exotic plane nuclear systems have been done within the generalized liquid-drop model at finite temperature (Royer and Mignen 1992). The binary and oblate ternary fission and the plane fragmentation into four, six, eight and twelve spherical nuclei have been described from the contact point between nascent fragments spatially symmetrically arranged to infinity. Then, the n spherical fragments initially in contact separate in keeping their plane geometric configuration; respectively : straight line, equilateral triangle, square, regular hexagon, octagon and dodecagon.

Assuming volume conservation, the deformation energy is only the difference between the sum of the surface, proximity and Coulomb energies of the n fragments and the energy of the initial spherical nuclear system.

$$E_{def} = \frac{3e^2 Z^2}{5R_0} (B_c - 1) + a_s (1 - 2.6I^2) A^{2/3} (B_s - 1) + E_{prox}.$$

B_s and B_c are the surface and Coulomb shape dependent functions (energy of the deformed system divided by the corresponding sphere energy) which, for n separated fragments, are simply the relative surface energy of the n bodies and the sum of their relative Coulomb interaction and self-Coulomb energies. To calculate the proximity energy, the fragments are taken in pairs and, for two fragments (see Haddad and Royer 1992) :

$$E_{prox} = (a_s / 1.5) (1 - 2.6I^2) \int \phi(D/b) h dh,$$

where h is the distance in the transverse plane and D the corresponding distance between the infinitesimal elements of surface. This term allows to take into account the finite range effects of the nuclear force in the gap between the nascent fragments. It is particularly important for an accurate description of the bubble and toroidal nuclei. For example, for a ^{240}Pu nucleus breaking in twelve nuclei located on a dodecagon, the proximity reaches -250 MeV at the contact point.

The temperature dependences of the surface coefficient, the effective sharp radius and the surface width are defined as :

$$\begin{aligned} a_s &= 17.9439(1 + 1.5 \frac{T}{17})(1 - \frac{T}{17})^{3/2} \text{ MeV}, \\ R_0 &= (1.28A^{1/3} - 0.76 + 0.8A^{-1/3})(1 + 0.0007T^2) \text{ fm}, \\ b &= 0.99(1 + 0.009T^2) \text{ fm}. \end{aligned}$$

The root-mean-square radius of the distribution of matter has been used to compare the deformations (see also De Lima Medeiros and Randrup 1991). For n equal spherical fragments at the tops of symmetric shapes characterized by the distance l from the centre of each fragment to the mass centre of the total system, one has :

$$\langle r^2 \rangle = l^2 + \frac{3}{5} R_0^2 n^{-2/3}.$$

In figures 1,2 and 3 the barriers of fragmentation in n fragments emitted in the whole three-dimensional space (a) and in a particular plane (b) are compared for three selected nuclear systems covering the whole mass range available in heavy-ion collisions. Obviously, the binary and ternary decay paths are the same in the two fragmentation approaches. In all cases, the barrier tops correspond to n separated fragments maintained in unstable equilibrium by the balance between the repulsive Coulomb forces and the attractive nuclear forces. For all masses, the fragmentation barriers are lower when the emission is focalised in a same plane since the proximity forces act at larger deformations and, then, for smaller Coulomb repulsion. In the case of the three dimensional emission, the barrier heights increase strongly with the number of fragments, even for very heavy systems and very high temperatures. In the case of the plane multi-fragment emission, the situation is reverse for the heaviest systems (for example, evanescent residues in the reactions such as $\text{Gd} + \text{U}$, $\text{Pb} + \text{Au}$, $\text{Au} + \text{Au}$). Indeed, apart the binary fission mode, the potential barrier heights become comparable and even decrease slightly with the number of fragments. This effect is

enhanced by the temperature. Naturally, the evaporation mode is not taken into account in this rough approach but, in reality, the nucleon evaporation does not change the above mentioned general trends since the barrier profile and height vary very smoothly with the mass number.

In recent experiments (Moretto et al 1993), it has been shown that the logarithms of the branching ratios for binary, ternary, quaternary and quinary decays for the 60 MeV u^{-1} $^{197}\text{Au} + ^{27}\text{Al}$, ^{51}V and $^{\text{nat}}\text{Cu}$ reactions depend linearly on $E^{*-1/2}$ which strongly suggests a statistical competition between the various multifragmentation channels. For all the excitation energies, the n event probabilities decrease with the fragment number but the yield of threefold, fourfold and fivefold events increases with the excitation energies. This behavior can be understood if one looks at the fragmentation barriers. At low excitation energies, the barrier height plays the major role and the binary and ternary fission is dominant. In contrast, for high excitation energies, only a small part of the available energy is absorbed during the heating of the residual system while the other remaining and non thermalized part is so important that the investigation of all the fragmentation channels are possible. Even if crude hypotheses have been asserted, our calculations seem to indicate that the emission of the fragments in a same plane might be somewhat favoured.

The situation is different for the heaviest systems. All the multi-fragmentation events in a same plane seem to have roughly the same probability even for low excitation energies. Furthermore, a potential pocket exists when n is sufficiently high which could favor the relaxation of the nuclear matter and the development and propagation of Rayleigh instabilities. The problem to form these very heavy systems, which are only evanescent mixture of matter with no binary fission barrier, is to overcome the deep-inelastic regime and low excitation energies are perhaps not sufficient to solve this problem.

In figure 4, the total kinetic energy of the fragments is displayed for the plane and three dimensional fragmentations. It corresponds to the Coulomb repulsion energy at the scission point where the proximity forces end to act ($E_{\text{prox}} < 0.1$ MeV). This point is located well below the barrier top. The fragment kinetic energy is lower when the emission is focalised in a same plane. Precise experimental data on this observable might allow to better know the nature of the fragmentation process.

REFERENCES

- Abgrall P 1994 private communication
- Aboufirassi M et al 1994 Hirschegg, International Workshop XXII on Gross Properties of Nuclei and Nuclear Excitation (ed Feldmeier H and Norenberg W, Darmstadt : GSI) p 152
- Bougault R et al 1994 XXXII International Winter Meeting on Nuclear Physics Bormio, in press
- Bowman D R et al 1991 Phys. Rev. Lett **67** 1527
- Dai G X, Natowitz J B, Wada R, Lou Y N, Hagel K and Xiao B 1994 Nucl. Phys. A **568** 601
- De Lima Medeiros E and Randrup J 1991 LBL Report 30802
- De Souza R T et al 1991 Phys. Lett. B **268** 6
- Friedman W A 1990 Phys. Rev. C **42** 667
- Galin J 1991 Ganil report 91-10
- Guerreau D 1989 Nuclear Matter and Heavy-ion Collisions (New-York : Plenum) p 187
- Haddad F and Royer G 1992 J. Phys. G : Nucl. Part. Phys **18** L153
- Kugler A, Pleskac R, Wagner V, Pachr M, Sumbera M, Simon R S and Hlavac S 1994 Hirschegg, International Workshop XXII on Gross Properties of Nuclei and Nuclear Excitation (ed Feldmeier H and Norenberg W, Darmstadt : GSI) p 125
- Lopez J A and Randrup J 1990 Nucl. Phys. A **512** 345
- Louvel M et al 1993 Nucl. Phys. A **559** 137
- Moretto L G, Delis D N and Wozniak G J 1993 Phys. Rev. Lett. **71** 3935
- Peilert G, Stöcker H, Greiner W, Rasenhauer A, Bohnet A and Aichelin J 1989 Phys. Rev. C **39** 1402
- Royer G and Mignen J 1992 J. Phys. G : Nucl. Part. Phys. **18** 1781
- Xu H M, Gagliardi C A and Tribble R E 1994 Nucl. Phys. A **569** 575

FIGURE CAPTIONS

Figure 1 : Fragmentation barriers (potential energy relatively to the initial sphere energy) as functions of the number of fragments and the temperature (in MeV) for the ^{80}Br nucleus. The left column (a) corresponds to the three dimensional emission of the fragments while the plane fragmentation barriers are displayed in the right column (b).

Figure 2 : Same as figure 1 but for the ^{240}Pu nucleus.

Figure 3 : Same as figure 1 but for the $^{400}_{147}\text{X}$ nuclear system.

Figure 4 : Translational kinetic energy as a function of the fragment number, in the β stability valley. The dashed lines correspond to the three dimensional emission of the fragments while the solid curves give the TKE for the plane fragmentation.

Figure 1

Figure 2

Figure 3

Figure 4