नाभिकीय अभिक्रिया

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विखंडन की असामान्य विधि

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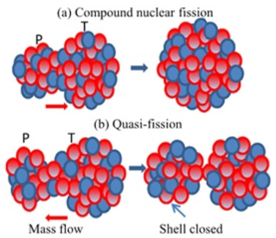

आंशिक-विखंडन में अवलोकित कोश प्रभाव का चित्रण।

सारांश

इस आलेख में, भापअ केंद्र-टीआईएफआर पेलेट्रॉन लीनॉक (एलआईएनएसी) सुविधा का उपयोग करके विखंडन माप में हाल ही में देखे गए विखंडन के असामान्य विधियों के कुछ उदाहरण दिए गए हैं। इन अवलोकनों में निम्नवत शामिल हैं : (क) ^{257}Md नाभिक के विखंडन के लिए सबसे दुर्लभ विखंडन क्षय विधि में से एक, जिसे सुपरशॉर्ट विधि के रूप में जाना जाता है। (ख) 70 MeV तक की उच्च उत्तेजना ऊर्जा पर विखंडन खंड द्रव्यमान वितरण पर कोश प्रभाव, और; (ग) धीमे आंशिक-विखंडन में कोश प्रभाव का प्रमाण ।

Nuclear Reactions

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Exotic Modes of Fission

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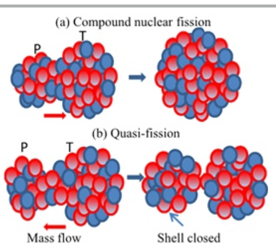

Depiction of observed shell effect in quasi-fission.

ABSTRACT

A few examples on exotic modes of fission observed recently in the fission measurements using the BARC-TIFR Pelletron Linac facility are briefed in this article. These observations include: (a) One of the rarest fission decay modes, known as Supershort mode, for the fission of ^{257}Md nucleus (b) Shell effect on the fission fragment mass distribution at excitation energy as high as 70 MeV and (c) Evidence of shell effect in slow quasi-fission.

KEYWORDS: *Super-short mode of fission, multi-chance fission, slow quasi-fission*

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Introduction

Nuclear fission continues to be a very fascinating topic due to its ever impressive varieties in its reaction mechanism. With the observation of several new modes of fission at specific compound nucleus mass region these studies have become even more attractive. A few examples on exotic modes of fission observed recently in the fission measurements using the BARC-TIFR Pelletron-Linac facility are: (a) Observation of one of the rarest fission decay modes, known as Super-short mode, for the fission of ^{257}Md nucleus, (b) Shell effect on the fission fragment mass distribution at excitation energy as high as 70 MeV and (c) Evidence of shell effect in slow quasi-fission.

Observation of Super-short Mode of Fission from Heavy Actinide (^{257}Md)

Super-short mode of fission is generally observed when both the nascent fission fragments have the atomic and neutron numbers close to that of the doubly magic ^{132}Sn. This is a very rare mode of fission which is generally observed from the neutron rich fissioning nuclei with A>257 [1-5]. In order to search for the presence of such mode in ^{257}Md nucleus, it was populated using ^{19}F+^{238}U fusion reaction and the mass and TKE (total kinetic energy) distributions of fission fragments produced from the ^{257}Md compound nuclei for E_{beam} = 87.1, 93 and 98 MeV were measured [6]. As shown by open circles in Figs. 1(a-c), it can be observed that, for all the beam energies, the TKE distributions peak at energies close to 198 MeV, as expected from the Viola systematic- the empirical relationship developed by V.E. Viola and colleagues to predict the total kinetic energy (TKE) of fission fragments based on the Coulomb parameter of the fissioning nuclei. Due to the skewness in the shape of the TKE distributions, particularly for the first two beam energies (87.1 and 93.0 MeV) with equivalent compound nuclear excitation energies E*=37.5 and 42.9 MeV respectively, the best fit could only be achieved with two Gaussian distributions: one around 193 MeV and the other around 230 MeV, as shown by filled gray and cyan regions, respectively, in Figs. 1(a-c). It may be observed that in these two plots the peak corresponding to low TKE is much closer to the value obtained from the Viola systematics, whereas the peak corresponding to high TKE is possibly due to the super-short mode of fission, where large Coulomb repulsion between the two compact fragments is expected to generate higher TKE. At E_{beam} = 98 MeV with E*=57.6 MeV as shown in [Fig.1(c)], the TKE distribution shows a very small contribution from super-short mode, indicating the weakening of the super-short mode at higher beam energies. To confirm that the above super-short mode observed in ^{257}Md, populated in the ^{19}F+^{238}U reaction, is not due to some structure of the delivered pulsed beam or any target related issues, the results have been compared with different reactions measured using same beam (^{19}F) but a different target (^{232}Th) and then using the same target (^{232}Th) but different beam (^{18}O) in the same experimental setup [6]. From the ^{19}F+^{232}Th reaction at E_{beam} = 93 and 98 MeV, corresponding to E* = 47.6 and 52.4 MeV, the TKE distributions were found to be perfectly Gaussian in shape, as expected [see Figs.1(e) and 1(f)]. Similarly, the results were compared with the other compound nucleus ^{256}Fm, populated in the ^{18}O+^{238}U reaction, at E_{beam} = 80.9 MeV, corresponding to E* = 36.3 MeV, the excitation energy region where the super-short mode has been observed for the ^{257}Md nucleus. It was found that the TKE distributions for ^{256}Fm could also be fit by using a single-Gaussian function [see Fig.1(d)], thereby confirming the presence of the super-short mode in the fission of the present ^{257}Md nucleus. The above observation suggests that the onset of the super-short mode of fission can be considered to be from ^{257}Md [6].

Shell Effect at High Excitation Energy: Role of Multi-chance Fission

The shells of the fission fragment nuclei are known to play an important role in deciding the number of nucleons in the fragments leading to an asymmetric mass distribution [7]. However, this shell effect on the fission mechanism is expected to wash out at higher excitation energies (E*) of the compound nuclei [8]. To search for the limit on E* beyond which the shell effect do not play any role, fission fragment mass distributions have been measured in the ^{11}B+^{238}U reaction system populating the compound nucleus at E* in the range of ~37-70 MeV. The mass-TKE correlation plots obtained for different beam energies (E_{beam}=53-87.4 MeV) are shown in Fig.2 (a-j). The corresponding mass distributions, i.e., projections of Fig.2 (a-j) on X axis, shown as open circles in Fig.2 (a'-j') are not perfect Gaussians. At low beam energies, the distributions are either double peaked or having flat tops. One of the peaks observed around A ~140 confirms the presence of a known asymmetric mode which is in strong competition with the symmetric mode described by the Liquid drop model. In order to find out the contribution from each modes, the measured distributions have been fitted using three Gaussian functions corresponding to one symmetric component (grey filled area) and two asymmetric components (cyan filled areas) as shown in Fig.2 (a'-j'). Interestingly, the asymmetric component is nonzero even at the highest excitation energy E*=70 MeV corresponding to E_{beam}=87.4 MeV. From different theoretical model calculations, the shell effect is predicted to wash out at an excitation energy 40 MeV, thus the presence of asymmetric mode observed at such high energies may actually be due to the reduced

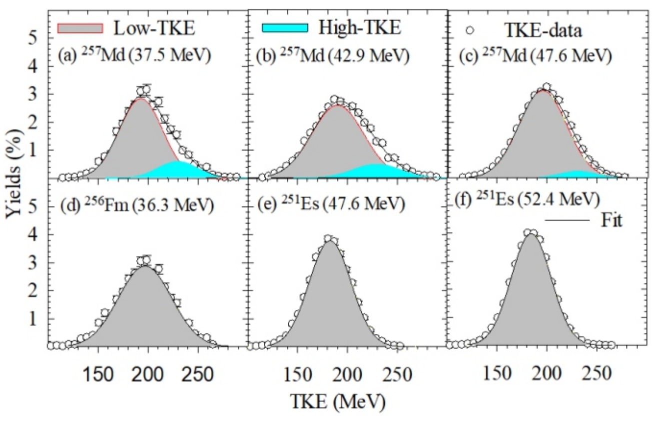

Fig.1: Measured total kinetic energy (TKE) distributions corresponding to ^{257}Md, ^{256}Fm and ^{251}Es at different excitation energies are shown by hollow circles. Contributions from low-TKE and high-TKE are represented by grey and cyan colours respectively. Solid lines represent sum of both the contributions.

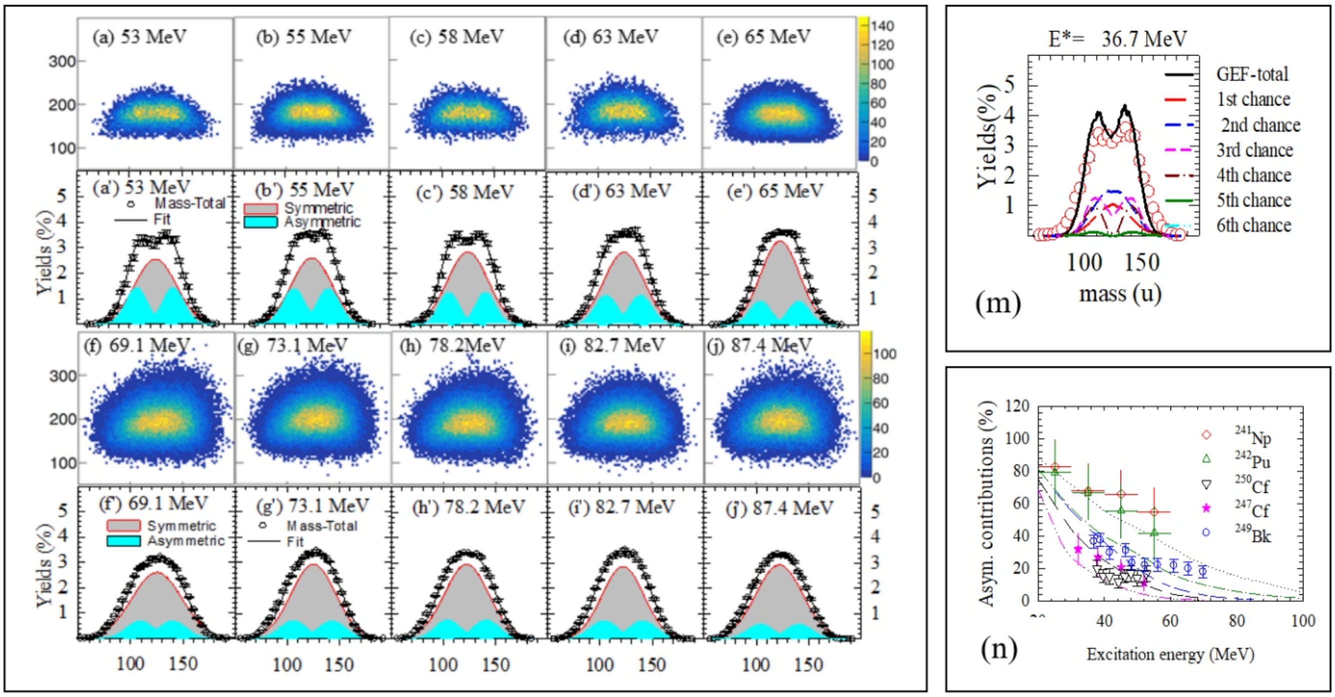

Fig.2: (a'-j') Mass-TKE correlation and (a'-j') fission fragment mass distributions (FFMD) for ^{249}Bk nuclei at different beam energies (E_{beam}=53-87.4 MeV), (m) FFMD for different chance fission for a typical beam energy E_{beam}=53 MeV (E=36.7 MeV) and (n) a systematic of asymmetric contributions as a function of excitation energy E* for different fissioning nuclei.*

effective excitation energies (E^*_{eff}) of the fissioning nuclei. This could be understood in terms of multi-chance fission (MCF) where neutrons successively get evaporated from the compound nucleus thereby reducing E^*_{eff} of the residual composite nuclei.

The semi empirical model code GEF has been used to calculate the mass distributions for different chance fission. For a typical initial compound nucleus excitation energy of E*=36.7 MeV, the contributions for different chance fissions are shown by different lines in Fig.2(m). It was observed that for all energies the calculated mass distributions corresponding to the first chance-fission are symmetric and cannot explain the experimental mass distributions. However, the presence of MCF up to 6th chance with varying probabilities with reduced *E** has introduced the asymmetric components. The sum total of mass distributions weighted over different chance fission, shown by the black solid lines in Fig.2(m), provides a reasonable agreement with the overall behavior of the measured mass distributions. The GEF calculations have been extended further for a wide range of excitation energies (25-85 MeV) to not only compare with the measured data at remaining energies but also estimate the highest value of *E** where shell effect washes out after incorporating the effect of multi-chance fission. We find that the shell effect that leads to asymmetric modes of fission in ^{11}B + ^{238}U start to disappear when the initial CN excitation energy E*~ 70 MeV, which is much higher than the results reported earlier. The systematic study made using the literature data and GEF predictions, as shown in Fig.2(n), suggest that shell effect washes out for initial *E** > 70 MeV for all the systems considered [9].

Shell Effect in Slow Quasi-fission Process

In order to search for shell effect in quasi-fission process, the Fission fragments have been measured for the ^{19}F + ^{238}U reaction at energies ranging from 99.7 to 142.1 MeV. The derived mass distributions are normalized to 200 % as shown in Fig.3(e-h) (left panel) by black circles. Data from our previous measurement on the same reaction at lower energies are shown in Fig.3 (b-d) (left panel) by green circles. The measured distributions were compared with the calculations (red solid lines in Fig.3 (left panel)) using a semi-empirical model code GEF (a model well validated for light particle induced fission) based on compound nuclear fission and found to be wider, especially at lower beam energies. To rule out the fact that the broadening of the measured data is due to the limited mass resolution of the experimental setup, the calculated distributions have been broadened incorporating the mass resolution of the experimental setup, sigma ~6 u, as shown by blue dashed lines in Fig.3 (left panel). But, they failed to explain the much wider measured data and hint at possibilities of having admixture of quasi fission along with the compound nuclear fission. Now the contribution from slow quasi-fission have been segregated by subtracting the GEF results (normalized at the peak position) from experimental data at all the measured energies (Fig.3 (a-d) (right panel)), which shows doubly peaked distributions, suggesting the role of shell effect in SQF process.

Similar analyses have been performed for the mass distribution data of other reaction systems involving heavy projectiles and heavy targets available in the literature. The mass distributions corresponding to QF process have been

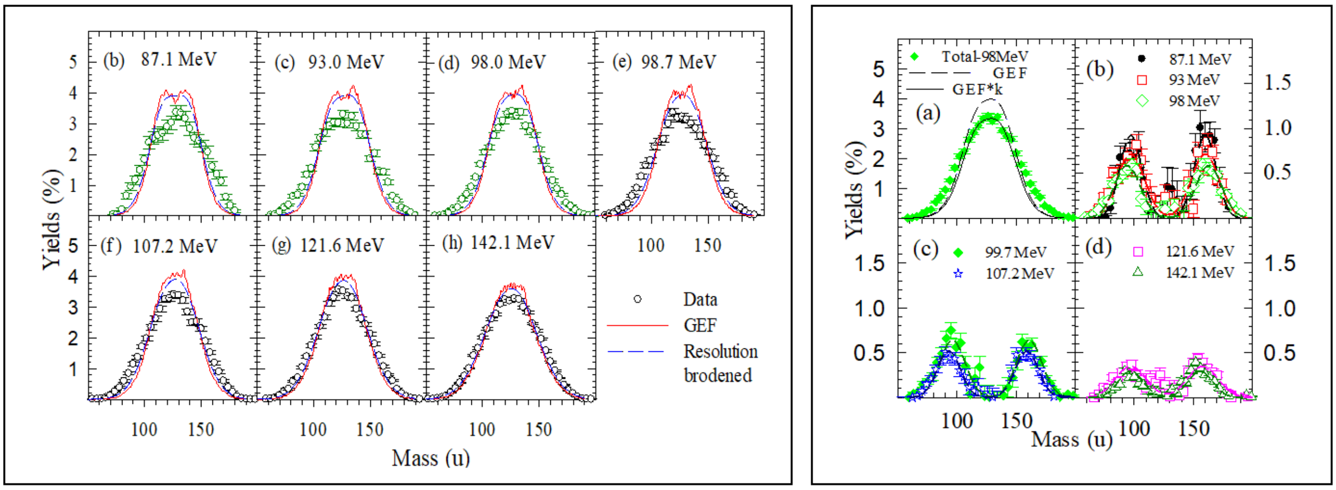

Fig.3: (left) Comparison of measured FFMD (hollow circles) with the compound nuclear fission model (lines); (right) segregating quasi-fission part by subtracting GEF results (normalized at the peak position) from the experimental mass distributions.

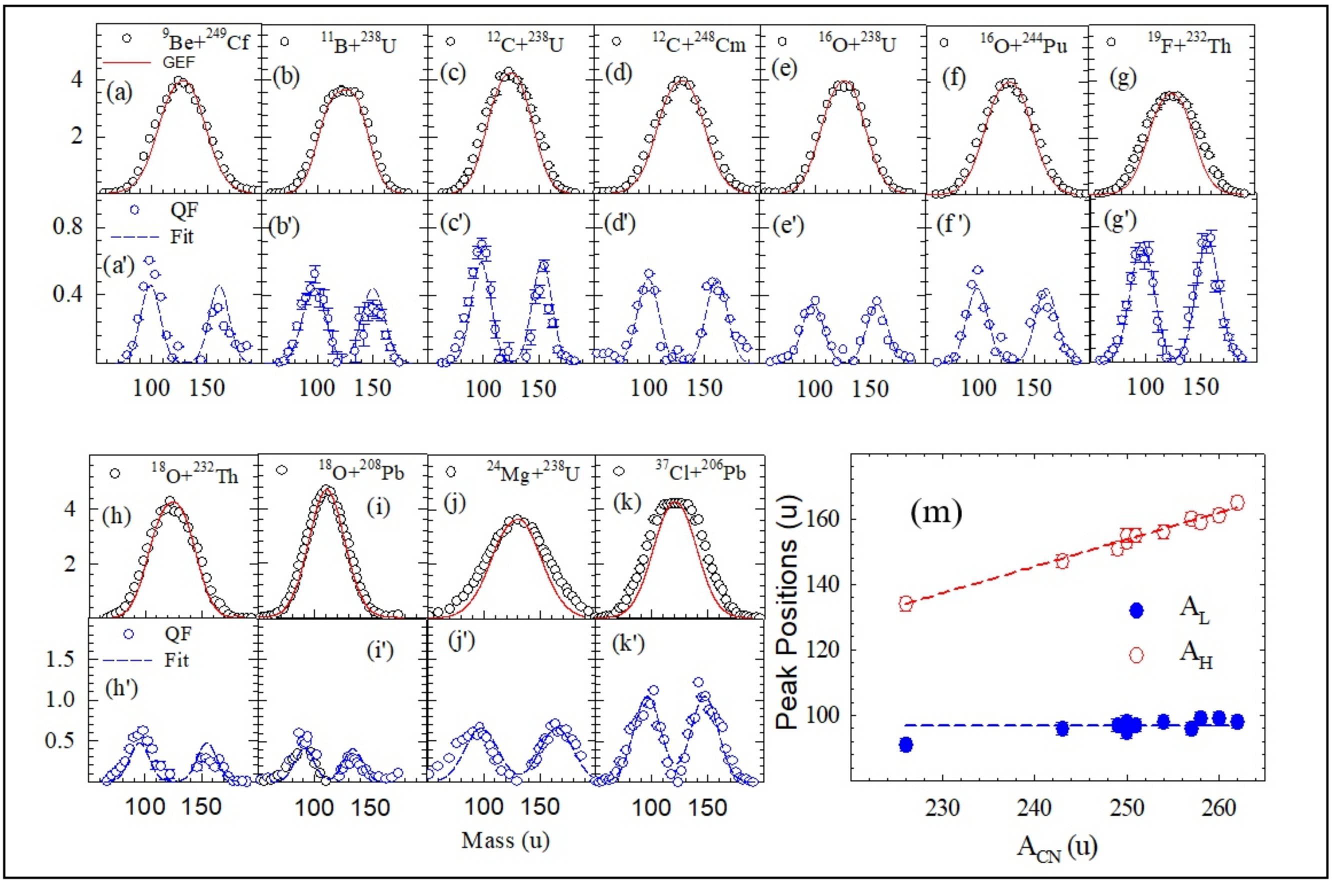

Fig.4: (a-k) & (a'-k') Segregation of QF modes from the data available in literature for eleven systems; (m) Comparison of the peak positions for both low and high masses of the quasi-fission mass distributions as a function of the masses of the fissioning nuclei A_{CN}, showing linear behaviour with mass of the lower peak A_L remaining constant and that of higher peak A_H increasing with A_{CN}.

obtained for different reaction systems at different excitation energies. The experimental FF mass distributions and the GEF calculations at excitation energies around 50 MeV have been shown for the reaction systems ^{9}Be+^{249}Cf, ^{11}B+^{238}U, ^{12}C+^{238}U, ^{12}C+^{248}Cm, ^{16}O+ ^{238}U, ^{16}O+ ^{244}Pu, ^{18}O+ ^{232}Th, ^{18}O+ ^{208}Pb, ^{24}Mg+^{238}U and ^{37}Cl+^{206}Pb in Fig.4(a-k). The corresponding QF modes for each system derived using the same method have been shown just below the respective mass distribution plots in Fig.4(a'-k'). It can be observed that the QF mass distributions are clearly doubly peaked for all the systems.

The QF mass distributions for all the above systems have been fitted with double Gaussian functions and the peak positions of the light and heavy fragments are plotted as a function of compound nuclear mass A_{CN} in Fig.4(m). It is interesting to note that the peak position corresponding to the light fragment is more or less constant around A=96, whereas the mass of the heavy fragment increases with the mass of the fissioning nuclei. This observation is very analogous to the one for asymmetric fission in actinides where the mass of the heavy fragment does not change with the mass of the fissioning nuclei, but the light fragment does. The fixed position of the peak of the heavier fragments in the asymmetric fission of actinides confirms the role of deformed shell closed nuclei with Z_H ~52 - 56. Similarly, the fixed peak position of the lighter fragments in the asymmetric fission of sub-Lead nuclei suggests the role of shell closed nuclei with Z_L ~34 - 38. Using the same analogy, the present observation of the fixed position of the lighter mass peak in the SQF mass distribution can be treated as a clear evidence of the shell effect in slow-quasi-fission process. Here, the lighter fragments are most probably the nuclei around the magic nuclei ^{96}Zr or ^{94}Sr [10].

Summary

Three interesting topics on fission manifesting different exotic modes have been discussed. The first of these is on the observation of a fission mode with very short elongation for the neutron-rich ^{257}Md nucleus at high excitation energy. To arrive at this conclusion we measured the mass and TKE distributions for three different reactions ^{19}F+^{238}u, ^{19}F+^{232}Th and ^{18}O+^{238}U producing ^{257}Md, ^{251}Es and ^{256}Fm respectively using the same experimental setup. The comparison shows clear observation of exotic supershort mode of fission in ^{257}Md for the first time.

The second interesting result was on finding the upper limit on the compound nuclear excitation energy up to which the effect of nuclear shell on fission fragment mass distribution persists. This limit was found to be 70 MeV, much higher than the existing limit of around 40 MeV based on available experimental data and theoretical understanding.

The third and the last topic was on the observation of shell effect on slow quasi-fission. A systematic analysis of the available data for about a dozen reaction systems in the literature along with a newly measured data on ^{19}F+^{238}U shows that the mass distributions of the quasi fission components are asymmetric in nature. The most importantly, the peak position of the low mass fragments is found to remain constant for different compound nuclear mass. This behavior, observed for the first time, is a clear indication of the shell effect on the mass distribution of quasi-fission.

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