Effect of Shell Structure on Fission Isoscaling

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Recently, the fragment yield ratios were investigated in the fission of $^{238,235}$U targets induced by 14 MeV neutrons. The effect of the deformed shell structure around $N=64$ on the dynamics of scission was suggested as an explanation of the observed breakdown of the isoscaling behavior. As an alternative explanation, the effect of binding energy of final fragments, in particular the neutron shell closure of the complementary fragment around $N=82$, was suggested by Friedman. When applying that concept consistently, the observed two breakdowns of the isoscaling behavior around $N=62$ and $N=80$ signal the effect of two shell closures ($N=82$ and $N=64$) on the dynamics of scission. To separate the two effects, we examine the isoscaling plots obtained using fission fragment yield data from the spontaneous fission of the heavier nuclei $^{248,244}$Cm and find that the breakdown of isoscaling around $N=64$ persists even if it can not be related to shell closure of the complementary fragment and thus it manifests the effect of the deformed shell structure in the scission configuration.

Isoscaling phenomena were observed in the isotopic composition of light fragments originating from de-excitation of hot nuclei and also in heavy residue data in wide mass range. Isoscaling is observed when a ratio of isotope yields from two reactions, differing in isospin asymmetry while other conditions are identical, exhibits an exponential dependence on N and Z of the form $R_{21}(N, Z) \propto \exp(\alpha N + \beta Z)$. In our recent study, we presented the results of an isoscaling analysis of the fragment yield data from the fission induced by fast neutrons. The evaluated independent fragment yields from the fission of $^{235,238}$U targets induced by 14 MeV neutrons were used.

The isoscaling behavior (Fig. 1) was typically observed for isotopic chains ranging from the most proton-rich to most neutron-rich ones. A breakdown of the isoscaling behavior was observed around $N=64$ which we suggested as a signal of the effect of the deformed shell structure on the dynamics of scission. This can be possibly related to the effect of the deformed neutron shell at $N=64$ with quadrupole deformation $\beta_{quad}=0.6$. According to the fission model of Wilkins et al., this deformed shell closure plays a crucial role in the dynamics of scission. As an alternative explanation, a simple model based on the effect of the binding energy of final fragments was suggested by Friedman. Assuming Boltzmann statistics with a single temperature for both fragments, the isoscaling yield ratio $R_{21}$ for a given fragment $(A_1, Z_1)$ is determined by the Boltzmann factor containing the difference of binding energies of the complementary fragments of the two fissioning systems.

$$R_{th}(A_1, Z_1) \propto \exp(\frac{\Delta B_{ld}^{Z_{fiss}-Z_1}}{T}) \exp(\frac{\Delta B_{sh}^{Z_{fiss}-Z_1}}{T})$$

where $\Delta B_{ld}^{Z_{fiss}-Z_1}$ and $\Delta B_{sh}^{Z_{fiss}-Z_1}$ are differences of the liquid-drop and shell structure terms of the binding energies of the complementary fragments with charge $Z_{fiss} - Z_1$. The binding energies of the liquid drop model (first factor) lead to isoscaling behavior while the introduction of shell corrections around $N=82$ was shown to produce an effect around $N=60-65$, analogous to the effect observed in the data. The model uses shell corrections derived from the experimental ground state masses and thus corresponding to spherical nuclei. The deformations in the scission configuration are expected to be significant, with exception of mass splits with one fragment around $Z=50$ which is expected to be spherical. The isoscaling behavior obtained when assuming the liquid drop ground state binding energies will possibly not change qualitatively also when deformation will be introduced into the liquid drop model. The effect of deformation on the shell structure can again be expected to lead to isoscaling breakdowns corresponding to deformed shell closures. For the nuclei around $N=82$, the deformed shell closures are predicted for $N=80$ and $N=88$, which may in principle lead to similar effect on isoscaling as the spherical neutron shell $N=82$. It is worthwhile to note that, within the model of Friedman, the neutron shell $N=50$ should result in an effect of similar strength in the region around $N=94$. However, such effect can not be identified unambiguously. On the other hand, the observed breakdown of isoscaling around $N=78-80$ can be, within the model of Friedman, explained by the existence of shell closure around $N=62-69$, where no spherical shell is predicted, which again points to the influence of deformed shell closure around $N=64$. Thus, the observed behavior supports the presence of the deformed shell around $N=64$.
As already mentioned, the model framework of Friedman [2] is based on the assumption that the probability of a given binary fission channel is determined by a Boltzmann factor depending on the sum of binding energies of two complementary fragments in the scission configuration. The observed data represent the inclusive yields corresponding to various multiplicities of neutrons emitted during fission. The neutron multiplicity distributions are rather wide, even for spontaneous fission [3, 4], and thus the concept of a unique complementary fragment is approximate. The next logical step in the analysis of influence of complementary fragments would be to examine the isoscaling behavior of fissioning systems with different mass. The systematic fission data for nuclei heavier than uranium are rather scarce, one nevertheless can find a good candidate in evaluated independent fragment yield data from spontaneous fission of $^{248,244}\text{Cm}$ [5]. The spontaneous fission is a much colder process where additional phenomena such as barrier penetration and potential energy surface can play a crucial role, it is nevertheless interesting to explore it in the context of isoscaling. The isoscaling plot for the spontaneous fission of $^{248,244}\text{Cm}$ is shown in Fig. 2.

In the spontaneous fission of $^{248,244}\text{Cm}$, the overall isoscaling behavior can be observed from the most populated parts of the mass distribution towards asymmetric mass splits. The breakdowns featuring rather the slope change than the structures observed in the previous case are observed around $N=50$ and $N=62$. A strong effect is observed around $N=68-70$ (with the complementary fragment around $N=82$), which nevertheless can be a sign of transition into the symmetric region around $N=74-76$ where the behavior is rather irregular. Furthermore the isoscaling behavior is quite regular up to the heaviest fragments (with exception of the region around $N=94$ where a hint of isoscaling breakdown can be observed). The overall behavior can not be explained using the model of Friedman [2] which is logical when assuming that the process is cold and the validity of statistical picture is questionable. It is however remarkable that isoscaling breakdown (slope change) is again observed around $N=62$ (along with $N=50$). This again possibly points to the role of shell structure, which may influence the potential energy surface and thus the probability of a given fission channel. While around $N=50$ the shell structure can be identified with a spherical fragment, for the region around $N=62$ the influence of the deformed shell is the most plausible. The observed isoscaling behavior

FIG. 1: Ratios of the fragment yields from the fission of $^{238,233}\text{U}$ targets induced by 14 MeV neutrons [5]. The data are shown as alternating solid and open circles. The labels apply to the larger symbols. The lines represent exponential fits. For clarity, the $R_{21}$ dependences are shifted from element to element by one unit. Nearly vertical lines mark major isoscaling breakdowns.
FIG. 2: Ratios of the fragment yields from the spontaneous fission of $^{248,244}$Cm. The data are shown as alternating solid and open circles. The labels apply to the larger symbols. The lines represent exponential fits. For clarity, the $R_{21}$ dependences are shifted from element to element by one unit. Vertical lines mark major isoscaling breakdowns.

in the spontaneous fission of $^{248,244}$Cm, despite a more complex interpretation, nevertheless again appears to signal the role of the deformed shell closures (in particular around N=64) in the fission of actinides. Since the isoscaling studies of fission enable to observe details of scission dynamics it is of interest to study the isoscaling behavior within the advanced models of fission, possibly in terms of transport theory, as indicated in [1].

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