Observation of the competing fission modes in $^{178}$Pt

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Fragment mass distributions from fission of the excited compound nucleus $^{178}$Pt have been deduced from the measured fragment velocities. The $^{178}$Pt nucleus was created at the JAEA tandem facility in a complete fusion reaction $^{39}$Ar + $^{142}$Nd, at beam energies of 155, 170 and 180 MeV. The data are indicative of a mixture of the mass-asymmetric and mass-symmetric fission modes associated with higher and lower total kinetic energies of the fragments, respectively. The measured fragment yields are dominated by asymmetric mass splits, with the symmetric mode contributing at the level of $\approx 1/3$. This constitutes the first observation of a multimodal fission in the sublead region. Most probable experimental fragment-mass split of the asymmetric mode, $A_L/A_H \approx 79/99$, is well reproduced by nuclear density functional theory using the UNEDF1-HFB and D1S potentials. The symmetric mode is associated by theory with very elongated fission fragments, which is consistent with the observed total kinetic energy/fragment mass correlation.

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1. Introduction

Understanding of the nuclear fission process is important for many areas of fundamental science, technology, and medicine. In particular, fission is crucial for the existence of many transuranium nuclei, including the predicted long-lived superheavy isotopes [1,2], as well as for the heavy element formation in the astrophysical $r$-process [3–6]. Better knowledge of fission properties is also essential for our understanding of the antineutrino flux from nuclear reactors [7,8]. Regardless of the area, one needs detailed information on fission rates and fission fragment (FF) mass distributions (FFMDs).

At present, our experimental knowledge of fission is primarily limited to nuclei close to the stability line [9,10] and within a fairly narrow isospin range $N/Z \sim 1.48–1.58$. Extrapolation of this knowledge to higher neutron-excess regions ($N/Z > 1.8$) relevant to the $r$-process is highly model dependent [3,5,6]. While there has been exciting progress in global modeling of nuclear properties, facilitated by advanced computing, a comprehensive, microscopic explanation of nuclear fission is still difficult to achieve, due to complexity of the process [11,12]. To advance theoretical modeling of fission, experimental FFMDs data are needed in broader range of $N/Z$-values, to test the isospin dependence of model predictions.

Due to its experimental accessibility, the neutron-deficient sublead region ($N/Z \sim 1.3$) provides excellent testing ground for studies of the isospin dependence of fission observables. Due to its exotic $N/Z$ ratio, new facets of the fission process can be expected. Indeed, the observation of asymmetric fission of $^{178,180}$Hg [13,14] attributed to shell effects in pre-scission configurations [15–18] has generated an appreciable interest in this region, both experimentally and theoretically. Inspired by the $^{180}$Hg results, FFMDs

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have been experimentally studied for several neutron-deficient sub-lead nuclei [14,19–21]. As shown by theory [15–17,22–25], the topology of potential energy surfaces (PES) in sub-lead nuclei is significantly different (flat, broad and rather structureless) from those in the actinides, which explains fairly low dependence of the corresponding experimental FFMDs on the compound nucleus (CN) excitation energy [cf. [19]]. According to the global survey of calculated FFMDs [26], a new extended region of asymmetric fission is expected in neutron-deficient Re–Pb isotopes with 98 ≤ N ≤ 116. It is separated from predominantly asymmetrically-fissioning actinides by a zone of symmetric fission around Ir–At in the vicinity of N ~ 120–126 [9], whose properties were extensively investigated in the past (cf., e.g., Refs. [27,28]). The experimentally studied neutron-deficient 178, 180, 182, 190, 193Hg and 179, 180Au isotopes [13,14,19–21] lie on the northern border of this region. As concluded in Ref. [26], new high-quality FFMDs data for selected sub-lead isotopes are needed to test and guide theoretical developments.

In the transitional regions between asymmetrically and symmetrically fissioning sub-lead nuclei, an interplay between different fission modes might exist, by analogy to light [29,30] and heavy [31,32] actinides. In view of PES properties in the sub-lead region [13,15–17], an observation of a competition between fission modes will shed light on the nature of near-scission configurations of nuclei, which are some 60 nucleons lighter and greatly deficient in neutrons, as compared to actinides and transactinides. This Letter provides the first experimental demonstration of the existence of asymmetric and symmetric fission modes through measurements of FFMDs from fission of 178Pt.

Table 1

| E_{beam} | E_{CN}^2 | E^2 | B_j | E_{int} | E_{CN}^{eff} | TKE\text{low} | σ_{TKE\text{low}} | TKE\text{high} | σ_{TKE\text{high}} | σ_{TKE\text{av}} |
|----------|----------|-----|-----|--------|-------------|---------------|----------------|--------------|----------------|--------------|
| 155.0(153.9) | 38.6 | 9.0 | 12.7 | 0.3 | 0.7 | 24.9 | - | - | - | - |
| 170.0(168.8) | 50.5 | 28.2 | 10.1 | 9.9 | 5.0 | 25.5 | 114.7(43) | 12.6(13) | 133.4(13) | 19.4(4) |
| 180.0(178.8) | 58.4 | 37.6 | 8.1 | 16.3 | 8.5 | 25.5 | 114.6(64) | 15.4(16) | 131.2(9) | 12.6(3) |

4 Derived from the coupled-channel calculation of the CN production probabilities [34].
5 Initial values from [35] corrected for rotation [36].
6 Calculated in accordance with procedure described in [19].
This is a direct indication of presence of symmetric-fission events in the data.

The mass numbers \( A_L \) and \( A_H \) of light and heavy FF groups, respectively, along with their respective total kinetic energy (TKE), can be readily derived from the fragments' velocities \( v_L \) and \( v_H \), under assumption of no particle emission (i.e., \( A_L + A_H = A_{CN} \)) from the compound nucleus \( A_{CN} \). During the pre-fission stage: \( A_L v_L = A_H v_H \) and \( \text{TKE} = 0.5M_{CN}v_L v_H \), \( M_{CN} \) being mass of the compound nucleus. An example of the deduced TKE-mass data is shown in Fig. 2b. Projection of the data in Fig. 2b on the TKE-axis gives the TKE distribution (Fig. 2a), whose average value \( \text{TKE} \) and width \( \sigma_{\text{TKE}} \) are found to slightly change with the increasing beam energy \( \Delta \text{TKE} = -1.9(2) \text{ MeV}, \Delta \sigma_{\text{TKE}} = 1.2(2) \text{ MeV} \) for the measured \( E_{\text{beam}} \) range). This corroborates recent results on the TKE parameters' behavior in \(^{190,192}\text{Hg} \) \([19]\) and is generally inline with positive and negative slopes in \( \frac{\Delta \text{TKE}}{\Delta E_{\text{CN}}} \) and \( \frac{\Delta \sigma_{\text{TKE}}}{\Delta E_{\text{CN}}} \), respectively, known for actinides (cf., e.g., \([37]\)).

The TKE distribution in Fig. 2a is clearly skewed. The simulated FF energy stragglng in the target and TOF detectors’ foils could
not reproduce the observed asymmetry effect in the TKE, unless unrealistic assumptions are made about the inhomogeneity of the MCP foil (thickness varying from zero till 10 times the nominal value of 0.5 μm). Similarly-skewed TKE distributions were obtained also at $E_{\text{beam}} = 155$ and 180 MeV. Based on the velocity analysis, an unconstrained two-Gaussian fit was carried out to describe the TKE data. This fit, statistically reliable only at the two higher energies, yields two TKE components placed at $TKE^{\text{low}}$ (maximum of the shadowed-area curve in Fig. 2a) and $TKE^{\text{high}}$ (maximum of the other dashed curve); their numerical values are given in Table 1.

The TKE components $TKE^{\text{low}}$ and $TKE^{\text{high}}$ are linked to the symmetric and asymmetric fission modes. This is demonstrated by the difference in the shape of the partial MDs constructed with events in Fig. 2b in the regions below $TKE^{\text{low}}$ and above $TKE^{\text{high}}$ and projected on the mass-axis (cf. the dotted lines and arrows in the Figure): narrow and clearly symmetric in Fig. 2d and wide and flat-top in Fig. 2c. The best-fit descriptions of partial MDs in Figs. 2c–d are achieved with one- and two Gaussians, respectively. The latter determines the light ($A_l = 79(1)$ amu) and heavy ($A_h = 99(1)$ amu) FF peak positions. Thus, our experimental results shown in Fig. 2c–d offer the first direct experimental evidence of the co-existing symmetric and asymmetric fission modes in the $^{178}\text{Pt}$ nucleus and in the sublead region. Contrary to the Mulgin et al. [38] who interpreted earlier experimental data close to the $\beta$-stability line around $A \sim 200$ [27,28] within a liquid-drop model with phenomenological shell corrections added, our conclusion on the coexistence of two modes in $^{178}\text{Pt}$ is based on the assumption-free deconvolution of experimental TKE-mass data which makes the result unambiguous.

The experimental total FFMDs are shown in Figs. 2e–g by the black circles. One observes that the MD shape evolves with the excitation energy $E^{\text{CN}}$; it becomes wider when $E^{\text{CN}}$ increases. The effect of the MD broadening is well-known for actinides (cf., e.g. Ref. [39]); it scales with the nuclear temperature. The expected linear dependence of the MD variance with $E^{\text{CN}}$ for nuclei in the region of interest has already been demonstrated in fission of $^{180,190}\text{Hg}$ isotopes (cf. Fig. 3 of Ref. [19]): present experimental data follow the same trend.

Solid red and dashed lines drawn in Figs. 2e–g are results of the analysis in terms of two fission modes, with the fit function composed of three Gaussians with fixed positions as obtained above. Overall, a good description of the experimental data is achieved. The asymmetric mode is found to be dominant, in accordance with the velocity analysis. The weight of the symmetric mode amounts to $\sim 31\%$ at the three considered beam energies. Thus, in contrast to actinides [37], the balance between symmetric and asymmetric modes in the FFMDs does not seem to be significantly affected by the excitation energy. This can be explained in terms of the energy considerations of Table 1: corrections to the excitation energy $E^{\text{CN}}$ due to possible neutron emission $E_{n}$, rotational energy $E_{\text{rot}}$ of the CN and the rotation-dependent fission-barrier height $B_{\text{f}}^\perp$ reduce the initial spread of 20 MeV in $E^{\text{CN}}$, resulting in practically identical ($\sim 25$ MeV) effective excitation energy $E^{\text{eff}}_{\text{CN}}$.

4. Interpretation

Nuclear density functional theory (DFT) calculations made prior the experiment within two Hartree–Fock–Bogolyubov frameworks employing the Skyrme UNEDF1-HFB [41] and Gogny D1S [42] energy density functionals (cf. Figs 3 and 4, respectively) help to interpret the obtained experimental results.

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Footnote: 2 Proton emission has been neglected as it affects less than 10% of fission events at the highest excitation energy, as estimated with the statistical code GEF [46].
of a nearly-spherical cluster around $^{80}$Sr and a lighter deformed pre-fragment. Such a structure results in FFs around $^{58}$Mo and $^{80}$Kr. As far as the symmetric configuration “c” is concerned, its pre-fragments can be associated with spherical $^{64}$Ni nuclei.

The static fission valley in Figs. 3 and 4 evolves on a fairly flat landscape, in contrast to a typical situation in heavy actinides (see e.g. [17, 23]). Absence of any ridge in the area of low octupole moments, along with a fairly small energy difference between the asymmetric and symmetric paths, suggests a possibility for a competition between different fission modes. At present, a detailed description of this competition is difficult to assess theoretically, as the post-scission configurations associated with fusion valleys [16] enter the picture and produce a sudden drop in TES at very large elongations (cf. Figs. 3 and 4a), which makes it practically impossible to follow adiabatically the original fission trajectory.

A detailed analysis of the TES in Fig. 4b shows that the plateau predicted for nearly-symmetric shapes around $Q_{40} = 190$ b in the region between the paths CD and cd, has a rather complicated structure. Namely, at the same values of quadrupole and octupole moments, two local symmetric PES minima with similar energies but distinct hexadecapole moments and nuclear density distributions are found. One of these solutions, with $Q_{40} ≈ 60$ b², corresponds to compact fragments, while that with $Q_{40} ≈ 85$ b² can be associated with very elongated fragments. In both models, the symmetric pathway associated with elongated-fragment configurations, expected to have lower TKE, is predicted to be energetically slightly more favorable than that associated with compact fragments. Therefore, it cannot be excluded that the symmetric fission mode seen experimentally contains contributions from both structures. It is interesting to see that competing fission pathways involving similarly asymmetric, compact, or elongated shapes have been predicted for multimodally fissioning nuclei in the fermium region [45, 46], i.e., for nuclei with much larger values of $A_{CN}$ and $N/Z$.

Experimentally, we find that both symmetric and asymmetric fission modes follow the trend previously observed in heavier, trans-lead, nuclei [47]. In particular, higher values of TKE in the asymmetric mode (cf. Table 1) – which also match well the TKE = 135.9 MeV value expected from the Viola systematics [48] – are indicative of less deformed scission configurations, whereas for the symmetric mode, highly elongated FF shapes are expected from its lower TKE values. This finding is consistent with the shapes of nucleon localizations shown in Fig. 3: symmetric configuration “d” corresponds to highly deformed fragments without a well-defined neck. As discussed above, a similar configuration associated with symmetric elongated fragments has been predicted in the DIIS model: in Fig. 4b it is marked by a black dot at $Q_{40} ≈ 85$ b² and $Q_{30} = 0$.

5. Conclusions

In summary, the FFMDs of $^{178}$Pt produced in a complete fusion reaction $^{40}$Ar + $^{142}$Nd are found to be predominantly asymmetric, with the most probable mass division $A_{L} ≈ 79$ and $A_{H} ≈ 99$. The combined analysis of the FFMDs and TKE distributions made it possible to separate asymmetric and symmetric fission modes. It is found that the asymmetric mode is associated with larger TKE values than the symmetric mode. Moreover, its average TKE follows the systematics [48] established for nuclei with $N/Z ≈ 1.5$, which suggests the asymmetric mode’s insensitivity to the isospin of the CN, at least for $A_{CN} > 177$.

The UNEDF1-HFB and DIIS calculations support the experimental results. Namely, they correctly reproduce the measured mass division associated with the dominant asymmetric fission mode, and they predict highly elongated pre-scission configurations along the symmetric fission path, which is in accordance with the lower experimental TKE value for this mode.

The present work provides new experimental information on the extension of the recently-discovered island of asymmetric fission towards lower atomic numbers. For the first time, the interplay between different fission modes has been found in a nucleus from the sublead region. The result provides strong motivation for extending microscopic models of fission to FFMDs and TKE distributions at nonzero excitation energies. Finally, beyond-DFT extensions of the current formalism are needed, as the PES predicted for pre-lead nuclei are generally very flat in the pre-scission region, resulting in possible interferences between asymmetric and symmetric fission modes.

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A.V. L. 588

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