First observation of the competing fission modes in the neutron-deficient sub-lead region

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Fragment mass distributions produced in the fission of excited $^{178}$Pt – synthesized in a complete fusion reaction $^{46}$Ar + $^{142}$Nd, at beam energies of 155, 170 and 180 MeV – have been deduced. The data are indicative of a mixture of the mass-asymmetric and mass-symmetric fission modes associated with different kinetic energies of the fragments. This constitutes the first observation of a multimodal fission in the sub-lead region. The measured fragment yields are dominated by asymmetric mass splits, with the symmetric mode contributing at the level of $\approx 1/3$. The experimental fragment-mass asymmetry of the asymmetric mode, $A_L/A_H \approx 79/90$, is well reproduced by nuclear density functional theory. According to theory, the lower-energy symmetric mode is associated with very elongated fission fragments, which is consistent with the total kinetic energy/fragment mass correlation.

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 transuranic nuclei, including the predicted long-lived superheavy isotopes [1], as well as for the heavy element formation in the astrophysical r-process [2–4]. Better knowledge of fission properties is also essential for our understanding of the antineutrino flux from nuclear reactors [5, 6]. 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 [7, 8], which corresponds to a fairly narrow isospin range $N/Z \approx 1.48 \sim 1.58$. Projection of this knowledge to high $(N/Z > 1.8)$ neutron-excess regions relevant to the r-process is highly model dependent [2–4]. While there has been exciting progress in global modeling of nuclear properties, facilitated by advanced computing, a comprehensive, microscopic explanation of nuclear fission is difficult to achieve, due to complexity of the process [9, 10]. 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 approachability, the neutron-deficient sub-lead region $(N/Z \approx 1.3)$ provides excellent testing ground for studies of the isospin dependence of fission observables. Due to exotic $N/Z$ ratio, new facets of fission process can be expected. Indeed, the observation of asymmetric fission of $^{180}$Hg [11] and $^{178}$Hg [12] attributed to shell effects in pre-scission configurations [11, 13–15] has generated an appreciable interest in this region, both experimentally and theoretically. Inspired by the $^{180}$Hg results, FFMDs have been experimentally studied for several neutron-deficient sub-lead nuclei [12, 16–18]. As shown by theory [13–15, 19–22], the topology of potential energy surfaces (PES) in sub-lead nuclei is significantly different from those in the actinides, and the corresponding FFMDs exhibit fairly low dependence on the compound nucleus (CN) excitation energy. According to the global survey of FFMDs [23], a new region of asymmetric fission is expected in neutron-deficient Re-Pb isotopes with $98 \leq N \leq 116$, separated from predominantly asymmetrically-fissioning actinides by a zone of symmetric fission [7], whose properties, especially in the Pb region, were extensively investigated in Refs. [24–26]. The experimentally studied Hg and Au isotopes [11, 12, 16–20] lie on the northern border of this region. As concluded in Ref. [23], 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 [20, 27] and heavy [28, 29] actinides. In view of PES properties in the sub-lead region [11, 13–15], an observa-
tion 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 demonstration of the existence of competing fission modes in sub-lead nuclei, by revealing the presence of asymmetric and symmetric fission modes through measurements of FFMDs from fission of $^{178}$Pt.

Experiment. – $^{178}$Pt was produced at the JAERI tandem accelerator [30] in a complete fusion reaction $^{36}$Ar + $^{142}$Nd → $^{178}$Pt$. The 75 µg/cm²-thick $^{142}$Nd target was made by sputtering of the NdF₃ material (isotopically enriched to 99%) onto a thin (42 µg/cm²) carbon backing. The $^{36}$Ar beam intensity was a few pnA, and the measurements were performed at three beam-energy settings (155, 170, and 180 MeV). Table I gives details on the energy balance of the formed CN.

The fission fragments of $^{178}$Pt were detected with a two-arm time-of-flight (TOF) setup, with TOF arms positioned symmetrically (±60° with acceptance of ±15°) relative to the beam axis. The chosen detection angles allowed for similar angular acceptance for both mass-symmetric and mass-asymmetric fission events and, thus, excluded influence of the setup geometry on the observed fission properties. Each TOF arm was comprised of a micro-channel plate (MCP) based detector and a position-sensitive multi-wire proportional counter (MWPC), providing timing START and STOP signals, respectively. The target–MCP distance was 67 mm, and the TOF base of 243 mm was identical for the two TOF arms. The MWPCs (active area of 200 × 200 mm²) were operated with isobutane gas at a pressure of 1.5 Torr and had a 2 µm aluminum-coated Mylar entrance window, whereas the MCP-based detectors were equipped with a thin (0.5 µm) Mylar foil coated with Au and CsI.

Results. – Figure 1(a) shows a sample of measured data. To make the clean selection of fission events, in addition to the TOF condition shown as a contour in Fig. 1(a), we made use of the energy deposited by charged particles in the MWPC detectors [10]. For every identified fission event, FF velocities in the laboratory (LAB) frame were derived from the measured TOF values and the FF positions in the MWPC and were converted to the center-of-mass (CM) frame. The resulting FF velocities were calibrated with the scattered beam, as well as corrected for attenuation in the target and TOF detectors.

Figure 1(b) shows the FF velocities for one of the TOF arms. The striking feature of these distributions is their pronounced non-symmetric character. A good description of such velocity spectra is achieved with a two-Gaussian fit, as demonstrated in the inset of Fig. 1(b). This allows one to conclude that the fission of $^{178}$Pt is predominantly asymmetric. It is to be noted that the two-component velocity fits as in Fig. 1(b) do not yield the same integral for the light and heavy fragment groups.

FIG. 1. (a) Two-dimensional TOF1-TOF2 spectrum for coincident FF as measured at $E_{\text{beam}} = 170$ MeV. Events in the solid black contour are from fission; remaining more abundant events are from the projectile-target scattering. (b) FF CM velocities after calibration with the $^{36}$Ar peak position in the TOF spectrum, corrected for attenuation in the target and TOF detectors. The inset shows a typical best fit of the data at $E_{\text{beam}} = 170$ MeV.

This is a direct indication of presence of some symmetric fission in the data.

The mass numbers $A_L$ and $A_H$ of light and heavy FF groups, respectively, and their total kinetic energy (TKE), can be readily derived from the fragments’ CM velocities $v_L$ and $v_H$, under assumption of no particle emission (i.e., $A_L + A_H = A_{\text{CM}}$) from the compound nucleus $A_{\text{CM}}$ during the pre-fission stage: $A_L v_L = A_H v_H$ and $\text{TKE} = 0.5 A_{\text{CM}} v_L v_H$. Figure 2 displays the correlation between TKE and fragment-mass data. Projection of Fig. 2(b) on the TKE-axis gives the TKE distribution (Fig. 2a), whose average value $\langle \text{TKE}\rangle$ and width $\sigma_{\text{TKE}}$ are found to change little with the beam energy ($\Delta \text{TKE} = 1.9(2)$ MeV, $\Delta \sigma_{\text{TKE}} = 1.2(2)$ MeV). The distribution in Fig. 2(b) is clearly skewed. In fact, simulated FF struggling in the target and TOF detectors 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 0.5µm). Similarly-skewed TKE distributions were obtained also at $E_{\text{beam}} = 155$ and 180 MeV. Based on the velocity analysis, a two-Gaussian fit was also carried out to describe the TKE data. This fit, statistically reliable only at the two higher energies, yields two TKE components placed at $\text{TKE}^{\text{low}}$ (maximum of the shadowed-area curve in Fig. 2a) and $\text{TKE}^{\text{high}}$.
TABLE I. Initial beam energy $E_{\text{beam}}$ and its value (in brackets) at a mid-thickness of the target; CN excitation energy $E_{\text{CM}}^*$ obtained from the reaction mass balance; average induced angular momentum $\bar{\ell}$; calculated fission-barrier height $B_{f,\ell}$; average energy $\bar{E}_\nu$ taken away by pre-fission neutrons; rotational energy $E_{\text{rot}}$; effective excitation energy $E_{\text{CM}}^\text{eff}$ derived as $E_{\text{CM}}^* - B_{f,\ell} - \bar{E}_\nu - E_{\text{rot}}$; TKE distribution components TKE$^{\text{low}}$ and TKE$^{\text{high}}$; and their widths $\sigma_{\text{TKE}^{\text{low}}}$ and $\sigma_{\text{TKE}^{\text{high}}}$. All values are in units of MeV, except for $\bar{\ell}$ expressed in h. The uncertainties are of statistical origin.

| $E_{\text{beam}}$ (amu) | $E_{\text{CM}}^*$ (MeV) | $\bar{\ell}$ | $B_{f,\ell}^{\text{b}}$ (MeV) | $\bar{E}_\nu^{\text{c}}$ (MeV) | $E_{\text{rot}}$ (MeV) | $E_{\text{CM}}^\text{eff}$ (MeV) | TKE$^{\text{low}}$ (MeV) | $\sigma_{\text{TKE}^{\text{low}}}$ (MeV) | TKE$^{\text{high}}$ (MeV) | $\sigma_{\text{TKE}^{\text{high}}}$ (MeV) |
|------------------------|---------------------|-------------|------------------|-------------------|-----------------|---------------------|----------------|----------------|----------------|----------------|
| 155.0 (153.9)          | 38.6                | 9.0         | 12.7             | 6.3               | 0.7             | 24.9                | 114.7 (43)     | 12.6 (13)      | 133.4 (13)     | 10.9 (4)       |
| 170.0 (168.8)          | 50.5                | 28.2        | 10.1             | 9.9               | 5.0             | 25.5                | 114.6 (64)     | 15.4 (16)      | 131.2 (9)      | 12.6 (3)       |
| 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)       |

a derived from the coupled-channel calculation of the CN production probabilities. 

b initial values from [32] corrected for rotation [33].

c calculated in accordance with procedure described in [16].

FIG. 2. (a) TKE distribution for $E_{\text{beam}} = 170$ MeV (projection of (b) onto the TKE-axis) de-convoluted into two components with derived positions of TKE$^{\text{high}}$ and TKE$^{\text{low}}$, shown by dotted horizontal lines, see text for details. (b) TKE – FF mass correlation. TKE scale is identical for both (a) and (b). Mass spectra gated on events above TKE$^{\text{high}}$ (c) and below TKE$^{\text{low}}$ (d) fitted with a double- and single-Gaussian unconstrained function; fit results given by red lines. (e-g) Total FFMDs at different CN excitation energies (cf. Table I). Solid red lines result from a fit with fixed symmetric and asymmetric mode positions. Blue and black dashed lines show the asymmetric and symmetric fit components, respectively. Experimental mass resolution is $\sigma_A^\text{exp} = 2.9$ amu, as deduced from the width of the $^{36}$Ar peak (not shown).

(maximum of the other dashed curve); their numerical values are given in Table I.

The TKE components TKE$^{\text{low}}$ and TKE$^{\text{high}}$ are linked to the symmetric and asymmetric fission modes. This is demonstrated by 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: narrow and clearly symmetric in Fig. 2a and wide and flat-top in Fig. 2b. The best-fit description of the partial MDs is correspondingly achieved with one- and two Gaussians. The latter determines the light ($A_L = 79(1)$ amu) and heavy ($A_H = 99(1)$ amu) FF peak positions.

The experimental total FFMDs are shown in Figs. 2a–g by the black circles. Solid red and dashed lines 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 measured energies, as can be deduced directly from Figs. 2a–g. Thus, in contrast to actinides [31], the symmetric-mode contribution to the FFMDs does not significantly change with excitation energy. This can be explained in terms of the energy considerations of Table I: corrections to the excitation energy $E_{\text{CM}}^*$ due to possible neutron emission $\bar{E}_\nu$ (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 [35]), rotational energy $E_{\text{rot}}$ of the CN and the rotation-dependent fission-barrier height $B_{f,\ell}$ reduce the initial spread of 20 MeV in $E_{\text{CM}}^*$, resulting in practically identical ($\sim 25$ MeV) effective excitation energy $E_{\text{CM}}^\text{eff}$.

Interpretation. To interpret experimental results, nuclear density functional theory (DFT) calculations have been performed within two Hartree-Fock-Bogolyubov frameworks employing the Skyrme UNEDF1-HFB [36] and Gogny D1S [37] energy density functionals (cf. Figs. 3 and 4 respectively). The constrained calculations were performed in the collective space of quadrupole ($Q_{20}$) and octupole ($Q_{30}$) moments, and also in the hexadecapole direction $Q_{40}$ in the D1S model. It is encouraging to see that both approaches yield very similar picture of
PES. In both calculations, the static fission path leads to the mass-asymmetric \( A_L/A_H \approx 80/98 \) split, which matches the experimental result very well. (We note that the Brownian shape-motion method Ref. [23] predicts a strongly asymmetric split with \( A_L/A_H \approx 70/108 \) at the CN excitation energy of 16.5 MeV.)

To understand the formation of fragments corresponding to the \(^{178}\text{Pt}\) fission pathways, we use the concept of nucleon localization functions (NLFs) [38]. Within this framework, the elongated configurations on the way to scission are composed of two clusters (pre-fragments) connected by a neck. At scission, the neck nucleons are redistributed into pre-fragments, producing the final fission fragments. As shown in Ref. [39], NLFs quantify the appearance of pre-fragments more efficiently than nucleonic density distributions as the concentric patterns in NLFs – due to shell structure in the nuclear interior – are averaged out in density distributions. Figure 3 displays the resulting NLFs along the two fission pathways: asymmetric (ABCD) and symmetric (ABed). Based on the analysis of NLFs according to the procedure of Ref. [39], the asymmetric pre-scission configurations marked “C” and “D” in Fig. 3 are composed of a nearly-spherical cluster around \(^{86}\text{Sr}\) and a lighter deformed pre-fragment. Such a structure results in FFs around \(^{98}\text{Mo}\) and \(^{80}\text{Kr}\). As far as the symmetric configuration “c” is concerned, its pre-fragments can be associated with spherical \(^{64}\text{Ni}\) nuclei.

![Figure 3](image)

**FIG. 3.** PES of \(^{178}\text{Pt}\) in the \((Q_{20}, Q_{40})\) plane calculated in UNEDF-HFB. The solid thick line indicates the static fission path obtained by the local minimization of PES. To illustrate the shapes on the way to fission, and the emergent pre-fragments, the neutron localization functions [38, 39] corresponding to various intrinsic configurations along the asymmetric (ABCD) and symmetric (ABcd) paths are plotted.

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. [15, 20]). 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 [14] enter the picture and produce a sudden drop in PES at very large elongations (cf. Figs. 3 and 4), which makes it practically impossible to follow adiabatically the original fission trajectory.

A detailed analysis of the PES in Fig. 4 shows that the plateau predicted for nearly-symmetric shapes around \(Q_{20} = 190\) 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 \(Q_{40} \sim 60\) b\(^2\), corresponds to compact fragments, while that with \(Q_{40} \approx 85\) b\(^2\) 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 favored 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 [40, 41], i.e., for nuclei with much larger values of \(A_{CN}\) and \(N/Z\).

![Figure 4](image)

**FIG. 4.** PES of \(^{178}\text{Pt}\) in the \((Q_{20}, Q_{40})\) plane (a) and in the \((Q_{30}, Q_{40})\) plane at \(Q_{20} = 190\) b (b) obtained in D1S. The solid thick line in (a) indicates the static fission path obtained by the local minimization of PES. Dashed lines in (b) indicate the symmetric PESs corresponding to compact (smaller \(Q_{40}\)) and elongated (larger \(Q_{40}\)) fragments. The minimum corresponding to the static fission path in (a) is marked by the red dot.

Experimentally, we find that both symmetric and asymmetric fission modes follow the trend previously observed in heavier, trans-lead, nuclei [22]. In particular, higher values of TKE in the asymmetric mode (cf. Table [3] – which also match well the TKE=135.9 MeV value expected from the Viola systematics [43] – are indica-
tive 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 D1S model: in Fig. 3 it is marked by a black dot at \(Q_{40} \approx 85 \text{b}^2\) and \(Q_{30} \approx 0.9\).

**Conclusions.**-- In summary, the FFMDs of \(^{178}\text{Pt}\) produced in a complete fusion reaction \(^{36}\text{Ar} + ^{142}\text{Nd}\) are found to be predominantly asymmetric, with the most probable mass division \(A_L \approx 79\) and \(A_H \approx 99\). 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 systematic [43] established for nuclei with \(A \approx 1\).

The UNEDF1-HFB and D1S calculations are consistent with 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 PESs predicted for pre-lead nuclei are generally very flat in the pre-scission region, resulting in possible interferences between asymmetric and symmetric fission modes.

The authors express their gratitude to the JAEA tandem crew for the help in performing the \(^{178}\text{Pt}\) experiment and to the GSI target group for making the \(^{142}\text{Nd}\) target. This work was in part supported by the JAEA Reimei and STFC (UK) grants; by the U.S. Department of Energy under Awards No. de-na0002847 (NNSA, the Stewardship Science Academic Alliances Program) and No. de-sc0018083 (Office of Science, Office of Nuclear Physics NUCLEI SciDAC-4 Collaboration); and by the Polish National Science Centre under Contract No. 2016/21/B/ST2/01227.

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[1] Y. T. Oganessian and V. K. Utyonkov, Rep. Prog. Phys. 78, 036301 (2015)
[2] S. Goriely, J.-L. Sida, J.-F. Lemaître, S. Panebianco, N. Dubray, S. Hilaire, A. Bauswein, and H.-T. Janka, Phys. Rev. Lett. 111, 242502 (2013)
[3] F.-K. Thielemann, M. Eichler, I. Panov, and B. Wehmsy, Ann. Rev. Nucl. Part. Sci. 67, 253 (2017)
[4] S. A. Giuliani, G. Martinez-Pinedo, and L. M. Robledo, arXiv:1704.00554 (2017)
[5] F. P. An et al. (Daya Bay Collaboration), Phys. Rev. Lett. 118, 251801 (2017)
[6] C. Giunti, Phys. Rev. D 96, 033005 (2017)
[7] A. N. Andreyev, K. Nishio, and K.-H. Schmidt, Rep. Prog. Phys. 81, 016301 (2018)
[8] F. P. Heßberger, Eur. Phys. J. A 53, 75 (2017)
[9] N. Schunck and L. M. Robledo, Rep. Prog. Phys. 79, 116501 (2016)
[10] H. Kruppe and K. Pomorski, *Theory of Nuclear Fission: A Textbook* (Springer Berlin Heidelberg, 2012).
[11] A. N. Andreyev, J. Elseviers, M. Huyse, P. VanDuppen, S. Antalic, A. Barzakh, N. Bree, T. Cocolios, V. Concas, J. Diriken, D. Fedorov, V. Fedosseev, S. Franchoo, J. Heredia, O. Ivanov, U. Koster, B. Marsh, K. Nishio, R. Page, N. Patronis, M. Seliverstov, I. Tsekhonovich, P. Vandenbergh, J. VanDeWalle, M. Venhant, S. Vermote, M. Veselsky, C. Wagemans, T. Ichikawa, A. Iwamoto, and A. Möller, P.and Sierk, Phys. Rev. Lett. 105, 252502 (2010)
[12] V. Liberati, A. Andreyev, S. Antalic, A. Barzakh, T. Cocolios, J. Elseviers, D. Fedorov, V. Fedosseev, M. Huyse, D. Joss, Z. Kalaninova, U. Koster, J. Lane, B. Marsh, D. Mengoni, P. Mollanov, K. Nishio, R. Page, N. Patronis, D. Pauwels, D. Radulov, M. Seliverstov, M. Sjodin, I. Tsekhonovich, P. VandenBergh, P. VanDuppen, M. Venhant, and M. Veselsky, Phys. Rev. C 88, 044322 (2013)
[13] P. Möller, J. Randrup, and A. Sierk, Phys. Rev. C 85, 024306 (2012)
[14] M. Warda, A. Staszczak, and W. Nazarewicz, Phys. Rev. C 86, 024601 (2012)
[15] J. D. McDonnell, W. Nazarewicz, J. A. Sheikh, A. Staszczak, and M. Warda, Phys. Rev. C 90, 021302 (2014)
[16] K. Nishio et al., Phys. Lett. B 748, 89 (2015)
[17] E. Prasad, D. Hinde, K. Ramachandran, E. Williams, M. Dasgupta, I. Carter, K. Cook, D. Jeung, D. Luong, S. McNeil, C. Palshetkar, D. Rafferty, C. Simenel, A. Wahle, J. Khuyagbaatar, C. Dullmann, B. Lommel, and B. Kindler, Phys. Rev. C 91, 064605 (2015)
[18] R. Tripathi et al., Phys. Rev. C 92, 024610 (2015)
[19] A. V. Andreev, G. G. Adamian, and N. V. Antonenko, Phys. Rev. C 86, 044315 (2012)
[20] T. Ichikawa, A. Iwamoto, P. Möller, and A. J. Sierk, Phys. Rev. C 86, 024610 (2012)
[21] A. V. Andreev, G. G. Adamian, N. V. Antonenko, and A. N. Andreyev, Phys. Rev. C 88, 047604 (2013)
[22] L. Ghys et al., Phys. Rev. C 90, 014301 (2014)
[23] P. Möller and J. Randrup, Phys. Rev. C 91, 044316 (2015)
[24] M. Itkis, V. Okolovich, A. Rusanov, and G. Smirenkin,
Sov. J. Nucl. Phys. 41, 544 (1985).
[25] M. Itkis, N. Kondrat’ev, S. Mulgin, V. Okolovich, A. Rusnanov, and G. Smirenkin, Sov. J. Nucl. Phys. 53, 757 (1991).
[26] K.-H. Schmidt, S. Steinhäuser, C. Böckstiegel, A. Grewe, A. Heinz, A. Junghans, J. Benlliure, H.-G. Clerc, M. de Jong, J. Müller, M. Pfützner, and B. Voss, Nucl. Phys. A 665, 221 (2000).
[27] C. Böckstiegel et al., Nucl. Phys. A 802, 12 (2008).
[28] E. K. Hulet et al., Phys. Rev. Lett. 56, 313 (1986).
[29] E. K. Hulet et al., Phys. Rev. C 40, 770 (1989).
[30] https://www.jaea.go.jp/english/04/ntokai/kasokuki/.
[31] K. Hagino, N. Rowley, and A. Kruppa, Comput. Phys. Commun. 123, 143 (1999).
[32] P. Möller, A. J. Sierk, T. Ichikawa, A. Iwamoto, and M. Mumpower, Phys. Rev. C 91, 024310 (2015).
[33] A. J. Sierk, Phys. Rev. C 33, 2039 (1986).
[34] C. Straede, C. Budtz-Jørgensen, and H.-H. Knitter, Nucl. Phys. A 462, 85 (1987).
[35] K.-H. Schmidt, B. Jurado, C. Amouroux, and C. Schmitt, Nuclear Data Sheets 131, 107 (2016) special Issue on Nuclear Reaction Data.
[36] N. Schunck, J. D. McDonnell, J. Sarich, S. M. Wild, and D. Higdon, J. Phys. G 42, 034024 (2015).
[37] J. Berger, M. Girod, and D. Gogny, Comput. Phys. Commun. 63, 365 (1991).
[38] C. L. Zhang, B. Schuetrumpf, and W. Nazarewicz, Phys. Rev. C 94, 064323 (2016).
[39] J. Sadhukhan, C. Zhang, W. Nazarewicz, and N. Schunck, Phys. Rev. C 96, 061301 (2017).
[40] M. Warda, J. L. Egido, L. M. Robledo, and K. Pomorski, Phys. Rev. C 66, 014310 (2002).
[41] A. Staszczak, A. Baran, J. Dobaczewski, and W. Nazarewicz, Phys. Rev. C 80, 014309 (2009).
[42] Y. L. Zhao et al., Phys. Rev. Lett. 82, 3408 (1999).
[43] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C 31, 1550 (1985).