[illegible]

Ibrahim Abdurrahman,[1] Matthew Kafker,[2] Aurel Bulgac,[2] and Ionel Stetcu[1]
[1]Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[2]Department of Physics, University of Washington, Seattle, Washington 98195–1560, USA

(Received 7 September 2023; revised 22 November 2023; accepted 30 April 2024; published 12 June 2024)

Just before a nucleus undergoes fission, a neck is formed between the emerging fission fragments. It is widely accepted that this neck undergoes a rather violent rupture, despite the absence of unambiguous experimental evidence. The main difficulty in addressing the neck rupture and saddle-to-scission stages of fission is that both are highly nonequilibrium processes. Here, we present the first fully microscopic characterization of the scission mechanism, along with the spectrum and the spatial distribution of scission neutrons (SNs), and some upper limit estimates for the emission of charged particles. The spectrum of SNs has a distinct angular distribution, with neutrons emitted in roughly equal numbers in the equatorial plane and along the fission axis. They carry an average energy around 3 0.5 MeV for the fission of ^{236}U, ^{240}Pu, and ^{252}Cf, and a maximum of 16–18 MeV. We estimate a conservative lower bound of 9%–14% of the total emitted neutrons are produced at scission.

DOI: 10.1103/PhysRevLett.132.242501

Nuclear fission was experimentally discovered by Hahn and Strassmann [1] in 1939. Later in 1939, it was named and its main mechanism was explained by Meitner and Frisch [2]. It is a quantum many-body process of extreme complexity, with various parts of the process occurring at vastly different timescales. The total time it takes, from the moment a neutron initiates the formation of a compound nucleus until all final fission products have attained their equilibrium state after β decay, can be on the order of billions of years [3], and is greater by enormous orders of magnitude relative to the time it takes a nucleon to cross a nucleus, $\mathcal{O}\ 10^{-22}$ sec.

The compound system, formed by a low-energy neutron [1] interacting with a target nucleus, evolves through many distinct stages. The first stage is a relatively slow quasiequilibrium evolution, that lasts until the compound system [4] reaches the outer saddle point at $\approx 10^{-14}$ sec [3]. During this stage, the nucleus, with an initial prolate intrinsic shape and axial symmetry, evolves into a nucleus with triaxial shape, and eventually into a reflection asymmetric and axially symmetric elongated shape near the outer fission barrier [5]. The second stage is a highly nonequilibrium evolution from saddle to scission [6–8], when the primordial fission fragments' (FFs) properties are defined within a duration of $\approx 5 \times 10^{-21}$ sec [3]. Even though this second stage is much faster than the first stage, it corresponds to rather slow dynamics, relative to the third stage (scission). In thisIOdc, followed by the

adjustment of many parameters [14]. On
fferent approaches to FF mass
lead to agreement with experi-
gh they rely on clearly contra-
ons, which simply demonstrates
e not very sensitive measures of
pproximately at the top of the
s starts forming a barely seen
ly the neck between the two FFs
e tends to appear when the
a very early stage during the

available from fluctuations [20–24]. At the top of the outer saddle the nucleus starts a relatively slow dissipative evolution towards scission [6–8]. During this period, the fissioning nucleus gets more elongated and the neck becomes more and more pronounced. The nuclear fluid behaves as nuclear molasses, with a very small collective velocity [6–8], while at the same time the intrinsic temperature of the system gradually increases. The bond between the two fission partners slowly weakens until the neck, which was still keeping them together, reaches a critical small diameter of approximately 3 fm and ruptures, exactly where the initial wrinkle formed much earlier at the top of the outer saddle. This dramatic separation of the two emerging FFs is a rather short-time event. For Brosa et al. [25] scission was the defining stage of fission, where the total kinetic energy (TKE) of the FFs is defined along with the average FF properties. The Brosa model assumes that the nucleus is a very viscous fluid, with a long neck that ruptures at a random position, and is widely invoked today in many phenomenological models [26–33], even though it has no microscopic justification and its claimed grounding in experimental data does not necessarily support a unique interpretation. Additionally, the Brosa random neck rupture model contradicts the theoretical assumptions of other popular approaches, such as the scission-point model of Wilkins et al. [34], where the FF formation is based on statistical equilibrium [35,36], and Brownian motion or Langevin models [14,17,37–39]. The drama of scission is followed by unavoidable debris characteristic of such dramatic separations, the scission neutrons (SNs), envisioned as early as 1939 by Bohr and Wheeler [40]. Potentially other heavier fragments, usually termed as ternary fission products [41–43], are created as well. We relegate a brief review of the history of SNs as online Supplemental Material [44], with additional references [41,42,45–88], where we also present many more details of our study.

In these simulations, we started by placing the initial compound nucleus near the top of the outer barrier in a very large simulation volume, in order to allow the emitted nucleons enough time to decouple from the FFs after the neck rupture. We have performed a range of simulations for ^{235}U $n_{th}; f$, ^{239}Pu $n_{th}; f$, and ^{252}Cf sf , using the nuclear energy density functional (NEDF) SeaLL1 [89] in simulation volumes $48^2 \times 120$ and $48^2 \times 100$ fm^3, with a lattice constant of 1 fm, for further technical details see Ref. [90]. The SeaLL1 NEDF is defined by only eight basic nuclear parameters, each related to specific nuclear properties known for decades, and contains the smallest number of phenomenological parameters of any NEDF to date [89,91]. We started the simulations at various deformations Q_{20} and Q_{30}, as listed in Ref. [44], near the outer fission barrier rim; and see Refs. [6–8], where one can find more details about how the FF properties vary with the choice of initial conditions. Our simulation volume of $48^2 \times 120$ fm^3 required the use of the entire supercomputer Summit (27 648 GPUs), corresponding to 442 TBs of total GPU memory, with further details provided in Ref. [44]. Despite this, we still could not follow the emission of nucleons for a long time, since the emitted nucleons are reflected back at the boundary relatively rapidly, see the lowest two rows of Fig. 1, where interference patterns emerge. In the transversal direction the reflection from the boundaries occurs earlier than along the fission axis, and that has affected some of the properties of the nucleons emitted perpendicular to the fission axis. However, the effect is minor, see Ref. [44].

From here, we will concentrate on the dynamics of the neck formation and rupture, followed by the emission of nucleons, all treated within the time-dependent density functional theory extended to superfluid fermionic systems [92]. The integrated neck density, shown in Fig. 2, is defined as

$$n_{\mathrm{neck};\tau} \quad t$$

punctured balloon, which would rapidly escape the enclosure, due to the presence of the nuclear “skin” and strong surface tension, the nucleus behaves as a fluid. The surface tension quickly “heals” the “wound,” models. Additionally, it appears that the neck rupture has similar dynamics for a large class of asymmetric fission events, irrespective of the nucleus considered or the initial conditions, beyond the top of the outer fission barrier. This universality carries over to the emission of SNs, whose signal always appears as three distinct clouds, one transverse to the fission axis and two in front of each FF, in almost equal proportions. The aspects of the neck dynamics discussed above, can serve as a theoretical input for any semiphenomenological approach to study FF properties [27–30].

The idea of SNs, proposed by Bohr and Wheeler [40], is almost as old as nuclear fission itself. The existence of SNs has been debated over the years [45,48,52,97–118], see also Historical Note in Ref. [43], and their experimental confirmation is still an open question. While neutron properties in earlier studies using simplified models [52,99,100] have some features somewhat similar to what we find, they are missing the major componeoft1.3(earl203.95to)-sioneatoe W63e i68vW63es

[26] S. Oberstedt, F.-J. Hambsch, and F. Vivès, Fission-mode calculations for 239U, a revision of the multi-modal random neck-rupture model, Nucl. Phys. , 289 (1998).

[27] R. Vogt, J. Randrup, J. Pruet, and W. Younes, Event-by-event study of prompt neutrons from ^{239}Pu $n;f$, Phys. Rev. C **0**, 044611 (2009).

[28] B. Becker, P. Talou, T. Kawano, Y. Danon, and I. Stetcu, Monte Carlo Hauser-Feshbach predictions of prompt fission γ rays: Application to n_{th} ^{235}U, n_{th} ^{239}Pu, and ^{252}Cf (sf), Phys. Rev. C , 014617 (2013).

[29] P. Talou, I. Stetcu, P. Jaffke, M. E. Rising, A. E. Lovell, and T. Kawano, Fission fragment decay simulations with the CGMF code, Comput. Phys. Commun. , 108087 (2021).

[30] O. Litaize, O. Serot, D. Regnier, S. Theveny, and S. Onde, New features of the FIFRELIN code for the investigation of fission fragments characteristics, Phys. Procedia **1**, 51 (2012).

[31] A. E. Lovell, T. Kawano, S. Okumura, I. Stetcu, M. R. Mumpower, and P. Talou, Extension of the Hauser-Feshbach fission fragment decay model to multichance fission, Phys. Rev. C **10** , 014615 (2021).

[32] K. Fujio, A. Al-Adili, F. Nordström, J.-F. Lemaître, S. Okumura, S. Chiba, and A. Koning, TALYS calculations of prompt fission observables and independent fission product yields for the neutron-induced fission of ^{235}U, Eur. Phys. J. A , 178 (2023).

[33] T. Najumunnisa, M. M. Musthafa, C. V. Midhun, Muhammed Aslam, K. K. Rajesh, P. Surendran, J. P. Nair, A. Shanbhag, and S. Ghugre, ^{105}Rh yield from the proton induced fission of uranium, Nucl. Phys. **10** , 122611 (2023).

[34] B. D. Wilkins, E. P. Steinberg, and R. R. Chasman, Scission-point model of nuclear fission based on deformed-shell effects, Phys. Rev. C **1** , 1832 (1976).

[35] J.-F. Lemaître, S. Panebianco, J.-L. Sida, S. Hilaire, and S. Heinrich, New statistical scission-point model to predict fission fragment observables, Phys. Rev. C , 034617 (2015).

[36] J.-F. Lemaître, S. Goriely, A. Bauswein, and H.-T. Janka, Fission fragment distributions and their impact on the r-process nucleosynthesis in neutron star mergers, Phys. Rev. C **10** , 025806 (2021).

[37] J. Randrup and P. Möller, Brownian shape motion on five-dimensional potential-energy surfaces:Nuclear fission-fragment mass distributions, Phys. Rev. Lett. **10** , 132503 (2011).

[38] M. Albertsson, B. G. Carlsson, T. Døssing, P. Möller, J. Randrup, and S. Åberg, Excitation energy partition in fission, Phys. Lett. B **0** , 135276 (2020).

[39] M. Verriere and M. R. Mumpower, Improvements to the macroscopic-microscopic approach of nuclear fission, Phys. Rev. C **10** , 034617 (2021).

[40] N. Bohr and J. A. Wheeler, The mechanism of nuclear fission, Phys. Rev. , 426 (1939).

[41] R. Vandenbosch and J. R. Huizenga, Nuclear Fission (Academic Press, New York, 1973).

[42] H. J. Rose and G. A. Jones, A new kind of natural radioactivity, Nature (London) **0** , 245 (1984).

[43] The Nuclear Fission Process, edited by C. Wagemans (CRC Press, Boca Raton, 1991).

A. Saxena, O. Serot, O. A. Shcherbakov, N.-C. Shu, D. L. Smith, P. Talou, A. Trkov, A. C. Tudora, R. Vogt, and A. S. Vorobyev, Prompt fission neutron spectra of actinides, Nucl. Data Sheets **1 1**, 1 (2016), special Issue on Nuclear Reaction Data.

[100] N. Carjan and M. Rizea, Structures in the energy distribution of the scission neutrons: Finite neutron-number effect, Phys. Rev. C , 034613 (2019).

[101] R. R. Wilson, Directional properties of fission neutrons, Phys. Rev. , 189 (1947).

[102] R. W. Fuller, Dependence of neutron production in fission on rate of change of nuclear potential, Phys. Rev. **1** , 684 (1962).

[103] H. R. Bowman, S. G. Thompson, J. C. D. Milton, and W. J. Swiatecki, Velocity and angular distributions of prompt neutrons from spontaneous fission of Cf^{252}, Phys. Rev.