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Fission in inverse kinematics

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SOFIA COLLABORATION

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Summary. — Fission is a unique tool to study nuclear properties. The SOFIA Collaboration takes advantage of the inverse kinematics technique to measure fission yields for a large range of systems, including exotic nuclei. Both fragments are fully identified in charge and mass, a unique feature. The use of Coulomb interaction as fission trigger results in a low excitation energy in the fissioning system, allowing to study the influence of nuclear structure on fission. Using samples of SOFIA results, this paper addresses some open questions about fission such as the evolution of elemental yields with mass and the transition between asymmetric and symmetric fission.

1. – The diverse motivations of fission studies

Besides its intrinsic interest as a complex nuclear phenomena, fission is also studied for applied purposes. Nuclear energy comes to mind first. In order to precisely estimate all the parameters of a nuclear reactor and the evolution of its fuel, a lot of information has to be gathered: not only the cross sections of the various neutron-induced reactions (fission, capture, inelastic scattering…) but also the fission products yields. Indeed, the fission products play many roles in the core: they are the source of the delayed neutron (essential to the reactor control); some of them act as neutron poisons (decreasing significantly the reactivity); they are the main source of the radioactivity and residual power of the fuel. The precision of simulations has become a major request, especially for the design of a new generation of nuclear reactors. High-quality nuclear data are a key ingredient to achieve this objective.

Besides nuclear power, astrophysics is also a subject of application for fission data and modeling. Fission acts as the termination of the r-process, the building of the heaviest nuclei during huge neutron bursts caused by cataclysmic events such as the merging of neutron stars. In that case, one is interested in the fission of very neutron-rich nuclei at

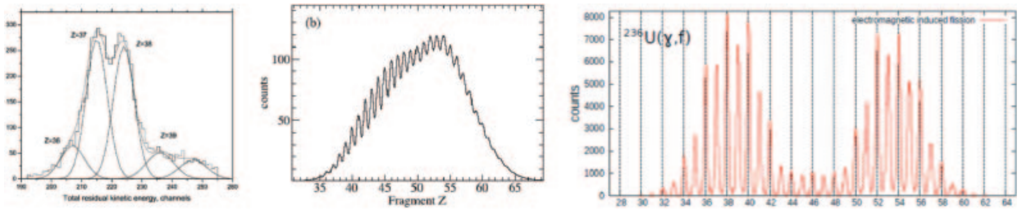

Fig. 1. – Examples of charge measurements for 3 cases of kinetic energies of fission fragments: from left to right, fission energy (approx. 1 A MeV, Lohengrin spectrometer at ILL [1]), Coulomb energy (approx. 6 A MeV, VAMOS spectrometer at GANIL [2]), relativistic energy (approx. 600A MeV, SOFIA experiments at GSI).

the drip-line: estimating fission barriers and fission yields of such exotic nuclei is highly challenging.

Yet, an essential motivation for studying fission is basic nuclear science. Fission is a unique probe for nuclear dynamics, rising many questions. To which extent do closed shells act as attractors for the fragment formation? Do N and Z shell behave similarly or not? How are shell effects dampened by excitation energy? How does the large deformations impact the above questions? Are shell effects the sole responsible for asymmetric fission? Microscopic models using shell effects as correction offer a seemingly satisfactory description of the static potential at scission; however the dynamics of the process is still the subject of intense theory work. The influence and dampening of pairing can also be studied carefully using fission, through the measurement of the even-odd staggering in the yields. More recently, the question of the splitting of the excitation energy among the nascent fragments has been the subject of theory developments [3], hence motivating new experimental activities.

2. – Advantages of the inverse kinematics technique

The inverse kinematics is based on using the fissioning system or its precursor as the projectile. The fission is triggered in-flight, using either a nuclear or electromagnetic interaction. This is a first asset of inverse kinematics: the fission of very short-lived systems can be studied with relative ease. The second asset is related to kinematics: since the fragments and the emitted neutrons inherit the momentum of the center-of-mass of the system, they are forward-focused and can be identified in a recoil spectrometer with a high efficiency. This large kinetic energy lead to a good and possibly excellent, direct measurement of the nuclear charge (see fig. 1).

The use of inverse kinematics in fission experiments is relatively recent in the history of nuclear physics. The pioneering experiment was conducted by Schmidt at GSI at the end of the nineties [4]. Several large projects have started in the last decade, at GANIL (transfer experiments, see Caamaño's paper), GSI (SOFIA experiments, discussed below), and more recently at RIKEN.

3. – The SOFIA program

The aim of the SOFIA experiments, conducted at GSI, is to perform high-precision measurements of fission yields. It is the only setup worldwide that allows the direct measurement of the mass and charge of both fragments. Additional information such as the kinetic energy released in fission and the total number of neutrons emitted for each fission are also obtained.

The fissioning system of interest is produced by the fragmentation of a 1 A GeV ^{238}U beam. The Fragment Separator (FRS [5]) is used to purify the cocktail-beam and identify each nuclei in charge (using an ionization chamber) and mass (combining Bρ, charge and time-of-flight measurement). This secondary beam is then sent to the SOFIA system, acting as a large-acceptance recoil spectrometer.

At the entrance of the SOFIA setup, a uranium target triggers the fission through Coulomb excitation. Nuclear reactions also occur in the target, but they are discarded during the data analysis. The nuclear charge of both fragments is then derived in the same way as the secondary beam. Note that the performance on time-of-flight measurement is especially remarkable, with a time resolution better than 40 ps FWHM. See [6] for a detailed description of the setup and analysis method.

The motivation for using the Coulomb interaction is twofold. First, its cross section is very large (roughly 3 barns): this is a real asset when working with a secondary beam. Second, it puts a very limited excitation energy in the system (14.1 MeV on average in our case, distributed mostly between 6 and 30 MeV). In such an excitation energy range, the system is still very sensitive to structure effects, while a nuclear reaction happening at 600 A MeV would put hundreds of MeV in the system and wash out any shell effect. The downside of this method is that the excitation energy is not measured event-by-event; however the distribution can be estimated reliably by folding the electromagnetic differential cross section and the fission probability.

In the first 2 SOFIA measurements, fission yields of several isotopes in the Th-U region were measured. The fission of ^{236}U* was of particular interest since it is the analog of ^{235}U+n, the key reaction in nuclear reactors. A constant feature of the SOFIA data is their high precision: the yields are obtained with a relative resolution better than 1%.

4. – Elemental yields and even-odd staggering in fragments

Figure 2 displays a comparison of the elemental yields of the fission of 4 uranium isotopes (234, 235, 236 and 238). A first feature is the evolution along the uranium chain: the lighter the system, the larger the Z asymmetry. A strong even-odd staggering is visible. A comparison to data obtained at lower energy (thermal neutron [7], hence 6.4 MeV excitation instead of 14.1 MeV for SOFIA) reveals that the protons even-odd staggering is significantly dampened by the excitation energy. As the excitation of the fragments is very limited, no proton emission can occur: therefore, the partition of protons is fully decided at the scission point. Pair-breaking is energy consuming, so that it is more and more unfavored for lower excitation energy. On the other hand, neutrons exhibit a very small even-odd staggering. This is due to the fact that neutrons can be emitted by the fragments: therefore, even though the pairs of neutrons are expected to behave similarly to the proton ones at scission, the final neutron distribution is governed by the excitation energy of the fragments, which is smooth and has a distribution large of several MeV. The shell at $N = 82$ is clearly visible and can be understood as a signature of the doubly magic ^{132}Sn and its direct neighbors, formed with no or a very limited deformation energy (see below for more evidence about this).

Measurement of the kinetic energy (fig. 3, left) provides insight about the shape of the fragments: spherical shapes are associated with a reduced distance between the nascent fragments, hence, a stronger coulomb repulsion. The number of emitted neutrons is

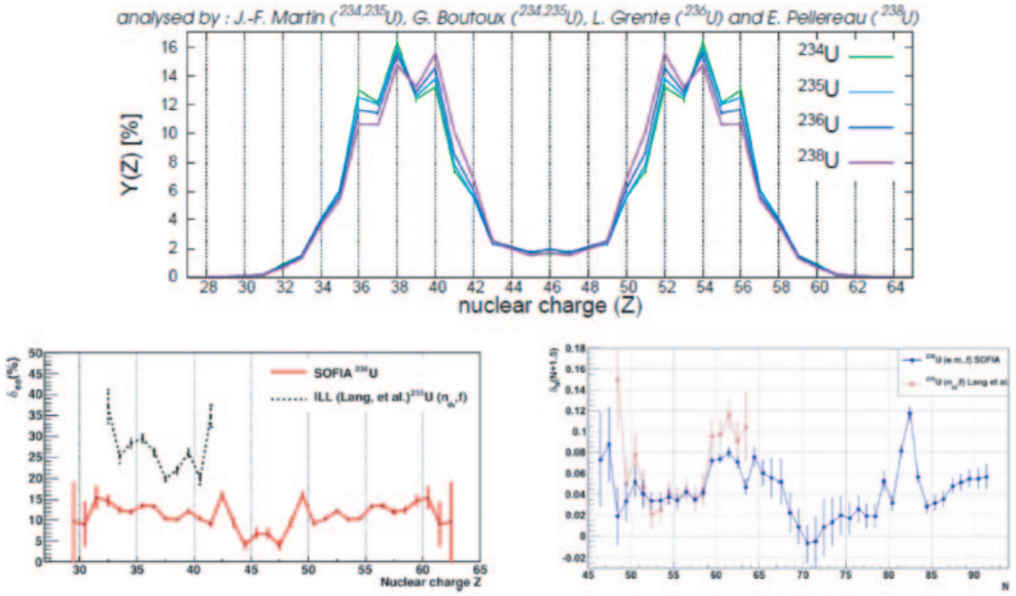

Fig. 2. – Elemental yields in the fission of ^{234,235,236,238}U (top). Comparison of Z (bottom left) and N (bottom right) even-odd staggering in the fission of ^{236}U at ILL (thermal neutrons) and SOFIA (coulomb excitation).

obtained event-by-event by subtracting the masses of the 2 fragments from the mass of the fissioning nuclei. Neutrons are the favored de-excitation channel: therefore, the neutron yield is a direct probe of the sum of the excitation energy of the two fragments. This energy has two components: intrinsic excitation and deformation. As seen on fig. 3 (right), symmetric channels are associated with an average neutron yield increased by 2.5 units with respect to asymmetric channels. The combination of data about the kinetic energy and the prompt neutrons yields indicates that the additional energy in the symmetric channel is deformation energy: both fragments are formed with a significant elongation and are prone to neutron emission, while a ^{132}Sn-like fragment will have no or little deformation energy.

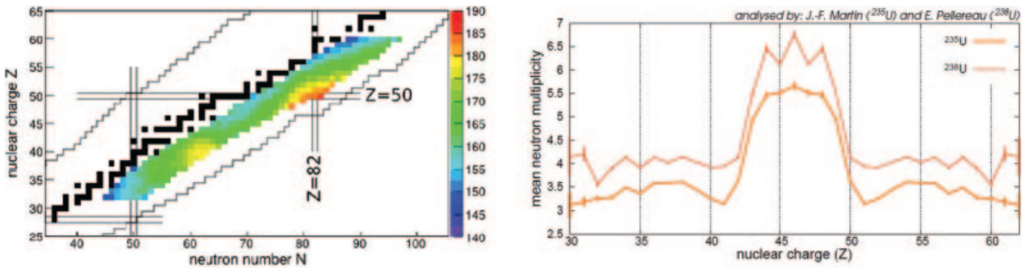

Fig. 3. – Kinetic energy released in the fission of ^{235}U (left) and mean neutron multiplicity in the fission of ^{235}U and ^{238}U as a function of the fragment charge (right). Both pictures taken from [8].

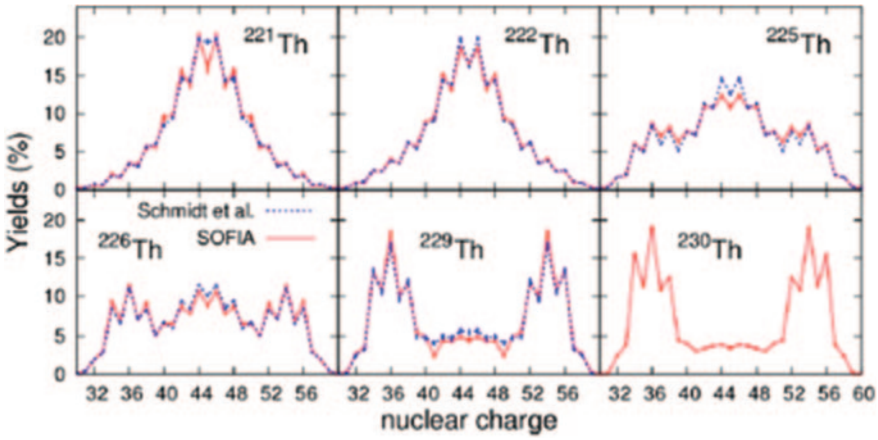

Fig. 4. – Fission evolution along the thorium chain. Preliminary results from SOFIA (courtesy A. Chatillon).

5. – Symmetry and asymmetry in fission

A simple, macroscopic view of the nuclei explains fission energetically, but implies a symmetric partition. Experiments reveal a very different behavior: the asymmetric fission is clearly the dominant phenomenon at low excitation energy in the region around natural uranium. This is generally understood as a consequence of the influence of spherical/deformed shells, especially $N = 82$ and/or 88; the question of the influence of proton shells at $Z = 50$ and/or 54 has been debated for decades. For a large variety of systems, the heavy fragment distribution is practically unchanged along the area of long-lived actinides. The asymmetry gradually vanishes in the regions of masses 220 and 250. For heavier systems, the light fragment becomes closer and closer to the heavy one, the symmetry being reached in the heavy Fm isotopes (fission of ^{256}Fm is still significantly asymmetric; fission of ^{258}Fm is symmetric). For lighter systems, since the light fragment is the adjusting partner of the fission, the asymmetry becomes more and more stringent, reaching a point where it becomes unfavored energetically.

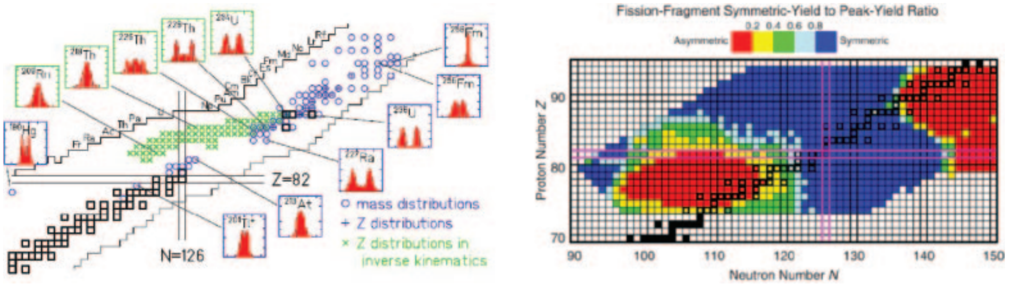

Fig. 5. – Evolution of fission symmetry/asymmetry accross the nuclear chart. Synthesis of experimental trends (left, courtesy K.-H. Schmidt) and results from calculations by P. Möller (right).

This transition toward symmetry had been observed once previously [4] but SOFIA data will be the first ever to combine mass (in the light fragment region) and charge measurement in this region. Figure 4 displays examples of results on the nuclear charges. Note the remarkable agreement with the previous data of Schmidt *et al.* for the element yields. The mass and neutron yields are yet under analysis but should be published in 2019. Confronting these data to fission models will certainly provide a stringent test of the description of the collective effects.

Even more surprising was the discovery, in 2010, of the asymmetry in the fission of ^{180}Hg [9]. As seen on fig. 5, the transition between symmetry and asymmetry is not unique as was once thought: asymmetry appears as the dominant fission mode for low-mass systems. This experimental result led to intense theory work based on complex potential energy landscape, since in this area no closed-shell effect could be invoked. 5D calculations by Möller and Randrup [10] offer promising results, reaching a satisfactory description of the general trend of fission symmetry/asymmetry in a wide range of nuclear systems. However, the region of neutron-deficient isotopes below thorium is still unexplored for the largest part. Mapping the transition to asymmetry by measuring several tens of fissioning systems in this region will be the focus of the next SOFIA experiment in 2019.

6. – Summary and outlook

Renewed interest in fission, for fundamental and applied purposes, has led to a new generation of fission experiments, combining high-resolution measurements, wide range of fissioning systems and increased number of combined observables. By measuring simultaneously the mass and charge of both fragments, SOFIA brings unique datasets to the nuclear physics community. The SOFIA setup will continue to grow in the next years: the coupling to the new neutron wall NeuLAND [11] will provide a tagging of the neutrons emitted during fission, and the coupling to the CALIFA calorimeter [12] will provide a direct measurement of the gamma multiplicity associated with each fission. Another exciting perspective is a measurement in the Pu chain, including ^{240}Pu*, the analog of the ^{239}Pu+n reaction, the second most important reaction for nuclear reactors. Such a measurement requires the development of a ^{242}Pu beam at GSI, a serious (but not out-of-reach) challenge in terms of radio-protection.

On a longer time frame, electron-induced fission on storage rings seem the best option in order to measure simultaneously the excitation energy in the fission system and the products yields. The Super-FRS exotic beam will also open new windows on fission by providing neutron-rich beams in the thorium-uranium region or very heavy beams.

On a more general scope, among the many questions that remains unanswered at the moment concerning the fission mechanism, let us emphasize the question of the origin of the angular momentum of the fragments and the question of the fission timing. The latter, in particular, has led to contradictory measurements (by several orders of magnitude). This is certainly a puzzle that will need lots of creativity to be solved.

REFERENCES

[1] Rochman D. *et al.*, *Nucl. Phys. A*, **710** (2002) 1.
[2] Ramos D. *et al.*, *Phys. Rev. C*, **97** (2018) 054612.
[3] Schmidt K. H. and Jurado B., *Phys. Rev. C*, **84** (2011) 059906(E) and references therein.

[4] Schmidt K.-H. *et al.*, *Nucl. Phys. A*, **665** (2000) 221.
[5] Geissel H. *et al.*, *Nucl. Instrum. Methods B*, **70** (1992) 286.
[6] Pellereau E., Taieb J., Chatillon A. *et al.*, *Phys. Rev. C*, **95** (2017) 054603.
[7] Lang W. *et al.*, *Nucl. Phys. A*, **345** (1980) 34.
[8] Martin J. F. *et al.*, *Eur. Phys. J. A*, **174** (2015) 51.
[9] Andreyev A. N. *et al.*, *Phys. Rev. Lett.*, **105** (2010) 252502.
[10] Möller P. and Randrup J., *Phys. Rev. C*, **91** (2015) 044316.
[11] Boretzky K. *et al.*, Scientific Report 2016 GSI Report (2017).
[12] Cortina-Gil D. *et al.*, *Nucl. Data Sheets*, **120** (2014) 99.