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Complete kinematics studies of fission reactions induced by quasi-free nucleon scattering collisions

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Abstract. Measurements of spallation, fragmentation and Coulomb-induced fission reactions in inverse kinematics have provided valuable data in the last decades to accurately investigate the fission dynamics and nuclear structure at large deformations of a large variety of stable and non-stable heavy nuclei. To go further, quasi-free scattering (QFS) reactions in inverse kinematics are proposed as a new surrogate method to induce fission, which allows to reconstruct the excitation energy of compound fissioning systems by using the four-momenta of the two outgoing nucleons. This new approach would permit therefore to correlate the excitation energy with the charge and mass distributions of the fission fragments and with the fission probabilities, given for the first time direct access to the simultaneous measurement of the fission yield dependence on temperature and fission barrier heights of exotic heavy nuclei, respectively. The first experiment based on this approach was recently performed at the GSI/FAIR facility and a description of the methodology based on model calculations is given here.

1 Introduction

Nuclear fission is the process by which a heavy atomic nucleus divides into two lighter fragments, the so-called fission fragments, and represents the clearest example of large-scale collective excitations in nuclei. Since its discovery by Hahn, Meitner, Strassmann and Frisch in 1939 [1, 2], the progress in the understanding of the fission process has been driven by new experimental results. In a general sense, fission offers a rich laboratory for a broad variety of scientific research on nuclear properties and general physics. Fission is a unique decay process to investigate the nuclear potential-energy landscape and its evolution as a complex function of mass asymmetry, elongation, spin, and excitation energy, from the single compound nucleus system passing over the fission barrier and going further up to reach the scission configuration, where the fission fragments are produced [3]. This dynamical evolution involves a subtle interplay of collective (macroscopic) and single-particle (microscopic) effects, such as shell effects and pairing, all of them considered both for the initial compound nucleus and for the fission fragments at large deformations. The relatively flat potential energy of fissile nuclei reaching very large deformations, when compared to lighter nuclei, allows for the study of nuclear properties such as shell effects in hyper- and super-deformed shapes [4].

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Moreover, dynamical phenomena connected with the decay of the quasi-bound nuclear systems beyond the saddle point can also provide information on nuclear transport properties like nuclear dissipation [5–8] and heat transfer between the nascent fragments [9]. Recently, the fission process has also been proposed as a tool to investigate in inverse kinematics the dynamical properties of heavy hypernuclei [10].

Fission also plays an important role in the r-process itself by fission cycling, for instance, in neutron star mergers where it determines the region of the nuclear chart at which the flow of neutron captures and β-decays stops [11]. Moreover, fission has also been pointed out to produce a robust r-process pattern [12], in which the abundances of nuclei with $A \lesssim 140$ are determined during the r-process freeze-out from the fission yields of nuclei with $A \lesssim 280$ [13]. The recent observations of the merging of binary neutron-star systems [14, 15] confirmed the importance of this scenario for the r-process nucleosynthesis.

Since the pioneering experiment carried out by Schmidt and collaborators [16] to induce fission reactions of different neutron-deficient actinides and preactinides between the At and U elements, a great effort was made by the SOFIA (Studies On FIssion with Aladin) and R^{3}B collaborations to overcome the restrictions of conventional fission experiments and to provide complete isotopic measurements of both fission fragments [20, 21] by inducing fission through spallation, fragmentation, and electromagnetic-excitation reactions. An example of the fission-fragment distributions measured in the last two decades at GSI is shown in the Fig. 1 together with other measurements based on particle-induced and spontaneous fission

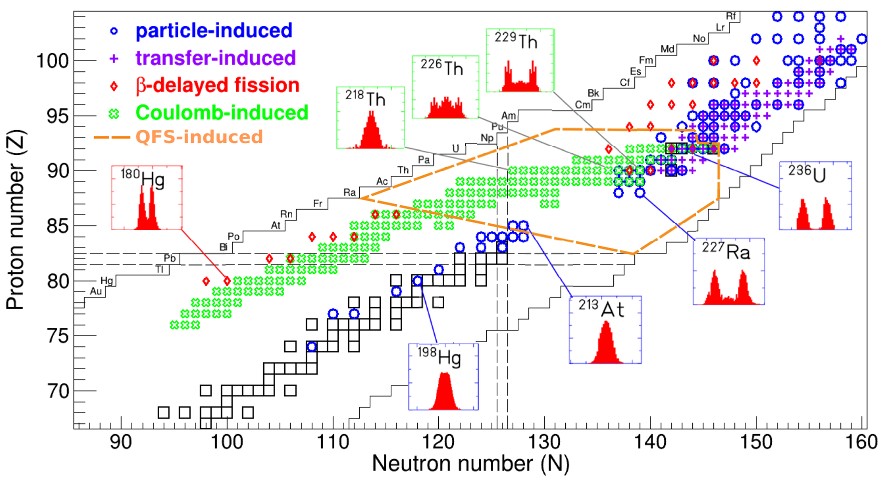

Figure 1. (Color online) Overview of fissioning systems investigated up to 2023 in low-energy fission with excitation energies up to ~15 MeV above the fission barrier. In addition to the systems where fission-fragment mass distributions were previously obtained in particle-induced and spontaneous fission (blue circles), the nuclei for which the fission-fragment charge distributions after electromagnetic excitations were measured by Schmidt and collaborators in 1996 [16] and in the recent SOFIA/R^{3}B [17–19] experiments in inverse kinematics at GSI are displayed with green crosses. Moreover, fissioning daughter nuclei studied in β-delayed fission (red diamonds) as well as around 70 fissioning systems investigated with transfer-induced fission reactions (plus symbols) are also shown. Several examples of the measured fission-fragment distributions are also displayed to illustrate the transitions. For orientation, the primordial stable isotopes are indicated with black open squares. The region that would be investigated with QFS reactions is indicated with a long-dashed line.

(blue circles) [22, 23], β-delayed fission (red diamonds) [24, 25], and transfer-induced fission reactions (plus symbols) [26–28].

The present R^{3}B experimental setup [29] permits to identify simultaneously both fission fragments in terms of their mass and atomic numbers. This approach became possible to extract correlations between fission observables sensitive to the dynamics of the fission process [30–33] and the nuclear structure at the scission point [17–19, 34]. The forthcoming GSI-FAIR facility will allow for extending the electromagnetic-induced fission measurements to very neutron-deficient and neutron-rich fissioning systems to systematically investigate the transitions from asymmetric to symmetric fission regions of each isotopic chain [35]. Unfortunately, the Coulomb-induced fission mechanism does not allow for the determination of the excitation energy of fissioning compound nuclei with high precision due to the width of the GDR excitation. To go further, those measurements can be combined with quasi-free scattering (QFS) reactions, such as (p, pn) and $(p, 2p)$, which have been proposed as a surrogate mechanism to induce fission of heavy nuclei [29, 36, 37]. This new approach would allow for reconstructing the excitation energy of a large variety of fissioning compound systems, as indicated by the long-dashed line of Fig. 1, by measuring the four-momenta of the outgoing nucleons. Here fission is induced by particle-hole excitations left by the removed nucleon, whose excitation energy ranges from few to ten's of MeV.

2 QFS-induced fission

Quasi-free (p, pn) and $(p, 2p)$ scattering reactions have been used in the last decade to study the nuclear structure of different exotic nuclei produced far away from the stability valley [38, 39]. This approach can also be used as a surrogate method to induce fission of exotic heavy nuclei. In the case of quasi-free (p,2p) scattering reactions the excitation energy of the compound nucleus is reconstructed by means of the four-momenta of the two outgoing protons. Figs. 2(a) and 2(b) show an example of the proton polar angle correlation for single-proton knockout reactions inducing fission of ^{238}U nuclei in inverse kinematics at 560 MeV/u, calculated with the Liège intranuclear cascade model INCL coupled to the de-excitation code ABLA [40]. The two outgoing protons are mostly emitted in the reaction

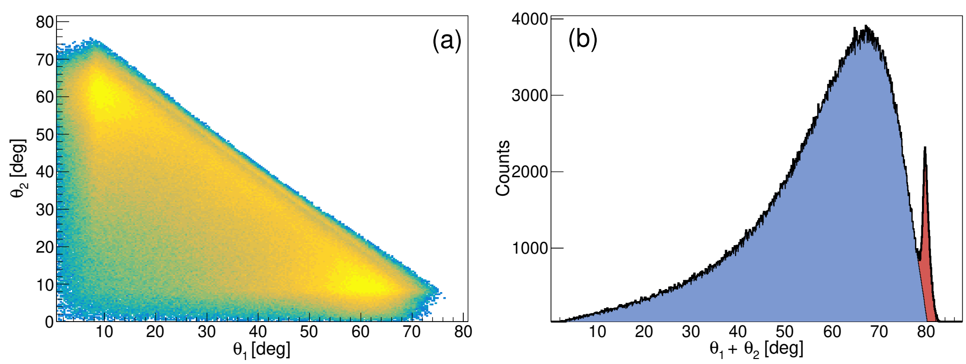

Figure 2. (Color online) (a) Polar angle correlation from proton knockout reactions inducing fission of ^{238}U nuclei in inverse kinematics after impinging onto a proton target. (b) Opening angle (θ_1 + θ_2) distribution in which the small peak on the right side corresponds to (p,2p)-induced fission reactions of ^{237}Pa compound nucleus, while the second component of the spectrum corresponds to (p,2pXn)- and inelastic-induced fission reactions of Pa compound nuclei.

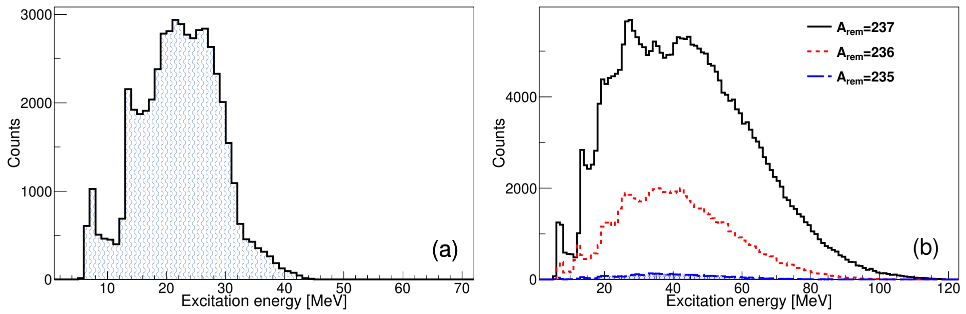

Figure 3. (Color online) (a) Excitation energy gained by the compound nucleus ^{237}Pa after the (p,2p)-fission reactions by selecting opening angles larger than 77º. (b) Excitation energy of different compound nuclei of Pa produced in (p,2pXn)- and inelastic-induced fission reactions, which were selected with the condition of opening angles larger than 70º.

plane for quasi-free (p,2p) reactions with opening angles ($\theta_1 + \theta_2$) of around 80º, whereas multi-scattering reactions in which some neutrons are also knocked out as well as inelastic collisions exciting baryonic resonances like the Δ(1232) contribute to smaller opening angles (blue histogram). These angles can be measured with target-recoil tracking systems based on pixel silicon detectors with resolutions of around 2mrad (FHWM), while the energy can be obtained from the CALIFA calorimeter [41].

Combining the kinematics of the two outgoing protons and applying the missing-mass methodology, one can obtain the excitation energy as shown in Fig. 3(a). To reconstruct this excitation energy properly it is very important to select the QFS peak shown in Fig. 2(b) because a wrong selection can introduce contaminations from neighbouring Pa compound nuclei as displayed in Fig. 3(b), where the fission events were selected with the condition of opening angle larger than 70º. Under this selection, the excitation energy cannot be used to study the fission process because part of the energy carried by the other particles is missing.

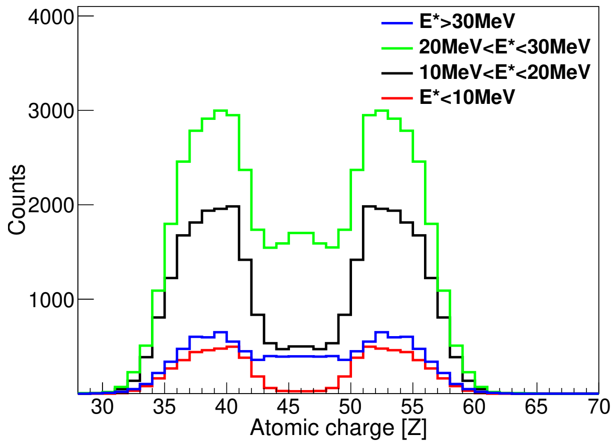

Figure 4. (Color online) Charge fission yield evolution with the excitation energy gained by the compound nucleus ^{237}Pa during the quasi-free (p,2p)-fission reaction (see Fig. 3(a)).

Taking into account that fission-fragment yields are characterized by several components in the mass distributions from different fission channels that are attributed to shell effects in the potential energy and by an odd–even staggering in the proton and neutron numbers due to the influence of pairing correlations, the measurement of the excitation energy in correlation with the atomic and mass number distributions of the two fission fragments represents a powerful tool to investigate the temperature dependence of shell effects [42, 43] and pairing correlations [44] for many exotic nuclei. Moreover, this can also be used to study with high accuracy the energy sharing between the nascent fragments [9] by correlating the neutron excess of both fission fragments. An example of the use of QFS reactions to investigate the fission yield evolution with the excitation energy is shown in Fig. 4, where the fission fragment charge distribution produced by excited ^{237}Pa compound nuclei is displayed as a function of the excitation energy.

3 Conclusions

Fission reactions induced by quasi-free (p,pn) and (p,2p) collisions would open new opportunities to investigate fission decays of exotic heavy nuclei produced through fragmentation reactions in inverse kinematics at the international GSI/FAIR facility located in Darmstadt, Germany. The first (p,2p)-fission experiments were performed recently with projectiles of ^{238}U and exotic isotopes of $^{199-211}$At at relativistic energies of 560 MeV/u impinging onto a liquid hydrogen target [29, 37]. This measurement will allow to correlate the fission yields with the excitation energy of the fissioning compound nucleus and to study the energy sharing between the nascent fission fragments. Here the main ideas and observables are presented from a theoretical point of view with calculations based on the coupling of INCL+ABLA models [40] to illustrate the capabilities of QFS reactions for fission studies. Future fission experiments using the Super-FRS fragment separator [45] together with the R^{3}B setup [29] will permit to use this methodology to investigate the fission decay of exotic neutron-deficient and neutron-rich heavy nuclei, providing new data like fission yields and fission barrier heights for improving the predictions of reaction models and astrophysical r-process calculations [11].

Acknowledgments

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