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The SOFIA experiment

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Abstract

SOFIA (Study On FIssion with Aladin) is an innovative experimental programme on nuclear fission carried out at GSI. In August 2012, we used relativistic secondary beams of neutron-deficient actinides and pre-actinides provided by the FRS and studied their fission, induced by electromagnetic interaction, in inverse kinematics. This experiment will provide for the first time complete isotopic yields (nuclear charge and mass) for both fragments over a broad range of fissioning nuclei from ^{238}Np down to ^{183}Hg. In this article, we discuss the experimental set-up and present promising preliminary results.

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Keywords: Electromagnetic fission, Isotopic yields, Inverse-kinematics, Relativistic secondary radioactive beams

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1. Introduction

The investigation of fission fragment yield distributions has re-gained interest in the last decade. On the one hand, more and more precise simulations are required for applications. Fission fragments yields are a necessary input for simulation codes and it is crucial to take their effects into account for the design of the next generation of nuclear reactors, especially to provide high-precision predictions on safety and waste management issues. In astrophysics, a comprehensive knowledge of fission yields is needed to include the role of fission in nucleosynthesis r-process codes

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and to understand the abundance of medium-mass nuclei and actinides in the universe. On the other hand, fission is one of the most complex phenomena on the nuclear scale, and its theoretical description remains largely incomplete. Since shell effects in the fragments are responsible for the well-known double-humped structure, experimental mass and charge distributions are precious observables to survey fission at low excitation energy. By measuring fission fragments yields, the fission process, in its evolution from from the saddle point to the scission configuration, allows to investigate fundamental nuclear features such as neutron and proton shell effects at large deformations. Pairing effects can reflect the energy the fissionning nucleus dissipates as it deforms. However, despite several decades of intense work, the experimental information on isotopic fission yields is still rather limited. Fission yields can be inferred in neutron-induced experiments using actinide targets. A difficulty from the experimental point of view is that the charge of the heavy fragment cannot be measured with sufficient resolution because of charge-state fluctuations inside the detectors. That prevents a complete isotopic identification of the fragments in direct-kinematics fission experiments. Moreover direct-kinematics measuremements are limited to sufficiently long-lived actinides because of severe restrictions on availability, handling and isotopic purity of targets. To overcome these difficulties and obtain complete identification of all fission products, it is possible to boost the kinetic energies of the fission fragments in inverse-kinematics experiments. This allows to improve the nuclear charge resolution and to use a magnetic recoil-spectrometer to measure nuclear mass numbers. In the last years, two innovative experiments are aiming at studying fission fragment isotopic distributions using the inverse-kinematics technique. Comprehensive studies on transfer-induced fission of non-relativistic ^{238}U projectiles at 6.1 MeV/u have been recently performed in GANIL (Farget et al., 2012). In-flight fission was detected with the VAMOS spectrometer. In this experiment, the isotopic fission yields of several major and minor actinides has been obtained for the first time. In august 2012 we performed the SOFIA (Study On FIssion with Aladin) experiment at GSI. In this ambitious experiment, electromagnetic-induced fission of neutron-deficient radioactive nuclei, produced as projectile fragments from a ^{238}U primary beam at 1 GeV/u, has been studied at relativistic energies in inverse kinematics. By using the full-acceptance recoil-spectrometer ALADIN, the SOFIA experiment allows for the simultaneous identification of both fragments in A and Z with unprecedented resolution. Kinetic energies of the two fragments are also measured. This experiment is an improvement of one performed by K.H Schmidt et al. (Schmidt et al., 2000). We would like to stress that GSI and GANIL experiments are complementary. In the GANIL case, the fission of heavy actinides with mass above A=238 is studied, whereas in the SOFIA experiment, the focus is on light actinides and preactinides with masses of A=238 and below. The SOFIA experiment is therefore unique to provide isotopic fission yields over a large amount of neutron-deficient nuclei and new insights on fission of exotic nuclei in the interesting mass region at A=180-210.

2. Overview of the SOFIA experiment

GSI is the unique facility as it is able to provide the ^{238}U primary beam at an energy of 1 GeV/u, which was used in this work. The beam, impinging on a Beryllium target, produced cocktail beams of mostly neutron-deficient nuclei with A≤238 and lifetimes down to 1 μs. The forward-focused reaction products enter the FRS (FRagment Separator) where they are separated in-flight according to their ratio of mass A over ionic charge q following the equation of the magnetic rigidity Bρ of a charged particle in a uniform magnetic field B:

$$B\rho = \frac{p}{q} = \frac{A}{q}\,\beta\gamma\, u\, c \qquad (1)$$

where ρ is the deflection radius, p the momentum, q the ionic charge in units of the electron charge, c the speed of light in vacuum, u the atomic mass unit and βγ the reduced momentum deduced from the Lorentz parameters. Thus, by choosing a Bρ setting for the FRS, the transmission of the fragmentation products is limited to several isotopes with a similar A/q ratio. The transmitted nuclei form the secondary cocktail beam, which is transmitted to Cave C, where fission is induced. The first step of the experiment is to identify these nuclei using the Bρ-ΔE-ToF technique. A schematic view of the FRS and the experimental set-up used for the identification is shown on the left part of Fig. 1. The nuclear charge Z of the secondary beam ion is determined by measuring the energy loss ΔE in two successive MUlti-Sampling Ionization Chambers (MUSICs). The magnetic rigidity is deduced from the known fields of the FRS dipoles and from tracking the ion trajectory. Position measurements at focal planes are performed by time-projection chambers (TPC) and by plastic scintillators. These plastic scintillators are separated by 135 meters and provide, via a time-of-flight (ToF) measurement, the velocity of the ion. The mass is then directly deduced from the latter quantities using eq. 1. The second step of the experiment takes place in Cave C where the secondary beam ($\approx$ 700MeV/u) impinges on the active target, where electromagnetic fission is induced in inverse kinematics. In the SOFIA experiment we have no way to measure the excitation energy of the fissioning system directly. However, we precisely know the electromagnetic excitation function that is mainly governed by the Giant Dipole Resonance (GDR) excitation, which peaks at about 11 MeV for the nuclei investigated here. The active target is made of several successive heavy mass targets. Two 600 μm thick depleted-uranium targets are used to maximize the electromagnetic interaction. We also use a 125 μm lead target for a precise Total Kinetic Energy (TKE) measurement. The active target is a target as well as a detector: it is a multiple ionization chamber in which the targets are used as cathodes. That permits to localize in which target the fission is induced and to be sure that the fission does not take place in any other layer of matter. When fission occurs, the forward-focused fragments are identified in-flight with a dedicated set-up build around the 1.6 T ALADIN magnet in Cave C. To achieve a proper identification, our collaboration has developed new detectors that allow to reach a precision better than 1 % in energy loss, 200 μm FWHM in tracking position and 40 ps FWHM in ToF. This new set-up is illustrated on the right part of Fig.1. First, the nuclear charges Z_1 and Z_2 of the fragments are determined by measuring their energy loss in a double MUlti-Sampling Ionization Chamber (Twin-MUSIC) made of two identical active volumes symmetric with respect to a common vertical cathode plane. The Twin-MUSIC provides 10 successive energy and drift time measurements for both fragments that allow for a 2% energy loss ΔE resolution and a 50 μm resolution FWHM for the horizontal positions. Secondly, the masses A_1 and A_2 of the fragments are determined from their magnetic rigities in ALADIN that are deduced from tracking the fragments on both side of ALADIN. In front of ALADIN, positions are obtained with a precision better than 200 μm FWHM using a 200x200 mm Multi-Wire Proportional Chamber (MWPC), while incoming angles are inferred from the drift time measurements within the Twin-MUSIC. Behind ALADIN, positions are given with a 300 μm FWHM resolution by a large 900x600 mm^2 MWPC. Note that we use low-Z gas-filled detectors with thin aluminized Mylar windows and Helium-filled pipes along the fission fragment trajectories in order to minimize the angular straggling. This reduces the uncertainties that enter the trajectory reconstruction. The magnet ALADIN is also filled with Helium. To extract resolved masses using the Bρ-ΔE-ToF technique, a resolution of 40 ps FWHM in ToF is crucial. The velocities of each fission fragments are obtained from the time-of-flight (ToF) between ultra-fast plastics scintillators separated by 8.3 m. The start 50x32x1.5 mm^3 plastic scintillator is placed 80 cm upstream from the active target. The so-called ToF wall is made of 28 32x600x5 mm^3 plastic slats and is placed 7.5 m downstream from the active target. When two slats are hit by fission fragments, the ToF wall is used as the trigger of the data acquisition and as the stop detector for the ToF. To conserve the excellent properties of timing signals, we use high-quality Constant-Fraction Discriminators (CFD) in combination with Time-to-Digital Converters (TDC) with a precision better than 20 ps FWHM. To reach such performance, our collaboration initiated the development of a TDC module that enables 17 ps FWHM intrinsic resolution. This new TDC is based on a Wave Union algorithm implemented on a FPGA 16-channel VME module.

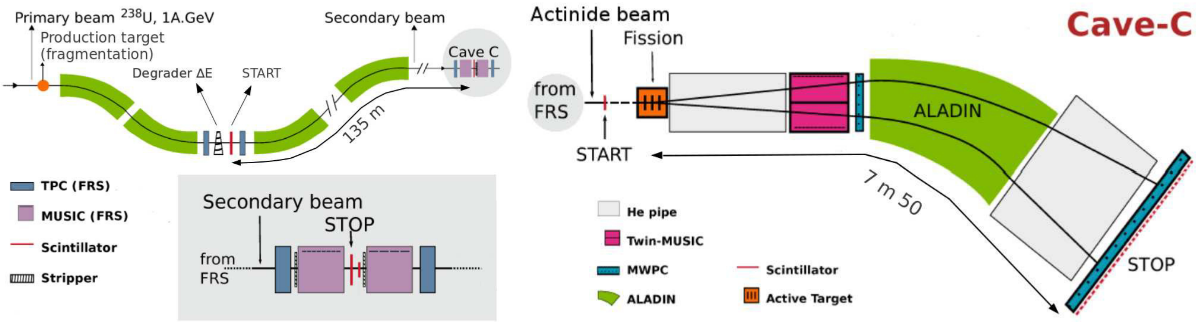

Fig. 1. (Color online) Schematic view of the SOFIA experiment. On the left side of the figure, the residues produced by fragmentation of a ^{238}U primary beam in a Be target are separated in-flight by the FRS spectrometer and then transmitted to Cave C where fission is induced. Each fissioning system is identified in (A,Z). On the right side, fission of the secondary beams is induced by Coulomb interaction in inverse kinematics in the active target. The fission fragments are identified in A and Z with the dipole ALADIN and the surrounding detectors.

3. Identification of secondary beams: preliminary results

We performed FRS magnetic settings centred on the following nuclei: ^{238}Np, ^{230,226,222}Th, ^{217}Ac, ^{209}Ra and ^{202,200}Rn. Note that this is the first time that secondary beams of actinides have been transmitted to and identified at Cave C. The obtained identification spectra for the two extreme settings, centred on ^{238}Np and ^{200}Rn respectively, are shown as example in Fig.2. At our beam energies, projectiles with $Z<80$ are fully stripped but heavier ions have different ionic charge states, mainly $0e^-$, $1e^-$ and $2e^-$. This charge state distribution is responsible for the broadening of the energy loss signal that makes the charge identification difficult. However, by using two MUSIC chambers, both equipped with 86 mg/cm^2 Nb stripper foils upstream, we are able to fold two independent measurements of the energy loss and extract an effective charge. As can been observed for the U isotopes, see the identification spectrum on the left part of Fig.2., around 97% of ^{235}U ions are fully stripped. It is possible to identify their nuclear charge Z unambiguously due to the excellent isotopic separation. Note that the excellent mass separation is possible due to the long flight path used, i.e. 135 meters. The identification plot for the ^{200}Rn setting illustrates how the identification of the actinides becomes easier as their nuclear charge decreases. To give an overview of the the large range of fissioning nuclei that we will study, fig. 3 provides a view of nuclei that are transmitted for each FRS magnetic setting used in the present work. A preliminary number of fission events for each nuclei is also given.

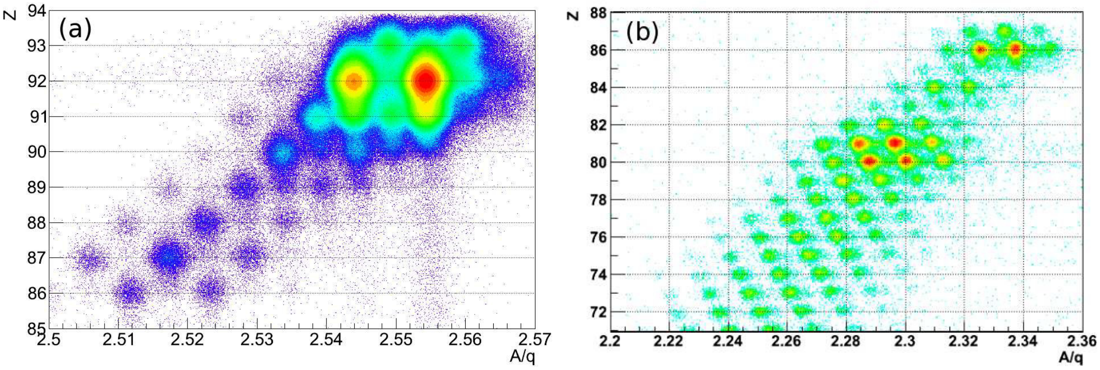

Fig. 2. (Color online) (a) Identification plot Z versus A/q of the fissioning secondary beam for the FRS setting centred on ^{238}Np. (b) The same as (a) but for the most exotic FRS magnetic setting, centred on ^{200}Rn.

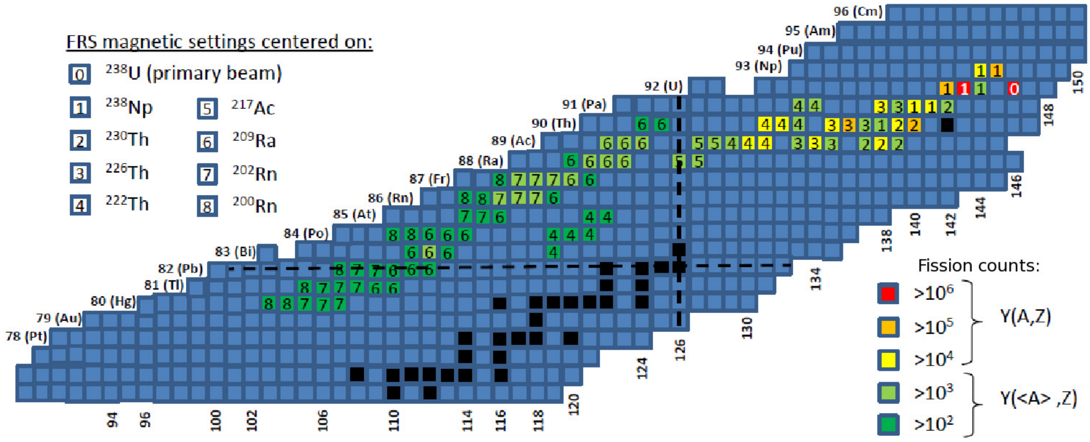

Fig. 3. (Color online) Isotopes investigated in the SOFIA experiment. The numbers are associated with the corresponding FRS magnetic settings. The colours indicate the preliminary number of fission events observed for each isotope.

The SOFIA experiment will allow us to study many fissioning nuclei from ^{238}Np to ^{183}Hg. We expect to provide complete isotopic yields for nuclei for which we have more than 10^4 fission events, i.e. many isotopes from Np to Ac that cover the transition from asymmetric to symmetric fission around mass 226. For exotic nuclei, statistics is rather low but sufficient to infer the shape of the charge distribution and to extract the average mass $<A>$ per charge.

4. Fission-fragment charge and mass distributions: preliminary results

A fission event is considered if fission occurs within the active target. If the fission fragments are detected in each side of the Twin-MUSIC, the nuclear charge Z_1 and Z_2 of the fully stripped fission fragments can be directly obtained from energy-loss ΔE measurements. To provide the best resolution, the ΔE measurements are corrected for the absorption of electrons along the drift path in the ionization chamber and for the dependence of the energy loss with the velocity of the fission fragment. In order to extract fission-fragment charge yields after electromagnetic-induced fission, fission events originating from nuclear interactions with the uranium and lead targets have to be suppressed. To remove the major part of the nuclear contribution, which results mostly in high-energy fission and is usually preceded by light charged particles emission, we require in the analysis that the sum of the charges of the fragments is equal to the charge of the fissioning system, namely $Z_1+Z_2=Z$. However, the part of the nuclear contribution, in which only neutrons are emitted before fission, still distorts the nuclear charge yields. This remaining contribution is subtracted with appropriately weighted nuclear-charge distibutions obtained from nuclear-induced fission in the aluminium anodes of the active target. Fig. 4 illustrates our preliminary results for the charge yields of the fission products emerging from electromagnetic excitations of the selected ^{235}U secondary beam. Our results highlight the excellent charge resolution of about 0,5 FWHM. Note that the even-odd staggering is also clearly visible.

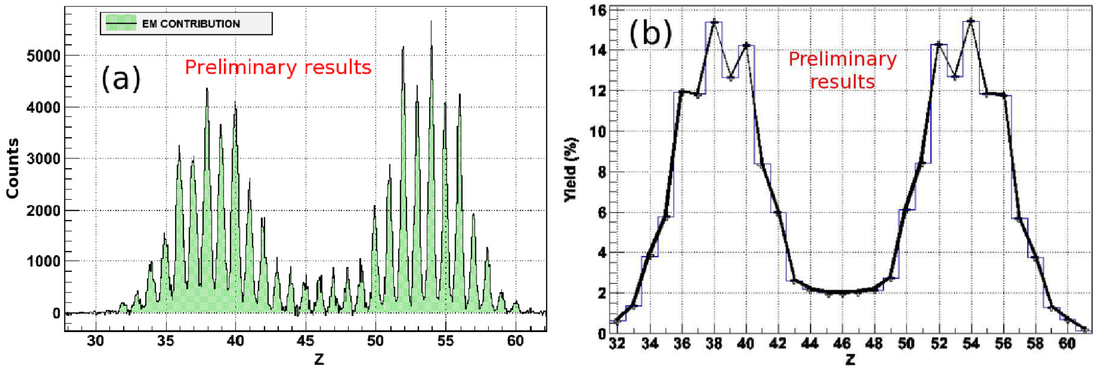

Fig. 4. (a) Nuclear-charge spectrum of fragments as obtained for the electromagnetic-induced fission of ^{235}U and (b) associated charge yields.

Since we cannot provide any mass yields at the current state of the ongoing data analysis, we provide in this article the expected mass resolution using a simulation of our experimental set-up. By assuming a uniform magnetic field in ALADIN, the magnetic rigity of each fragment can be inferred using a geometrical approach that depends only on the positions of each fragment before and after ALADIN and their incoming angles. To simulate our mass resolution, we applied this approach in an adapted version of the CONFID code (Schmidt , 2011). According to our preliminary results, we fixed in the code the following conditions: fully-separated nuclear charges Z, a 200 μm FWHM position resolution upstream of ALADIN, a 300 μm FWHM position resolution downstream from ALADIN and a 40 ps FWHM ToF resolution. We used the fission fragment yields provided by the GEF code (Schmidt et al., 2013) as input of the CONFID code to infer the expected mass distributions, see Fig. 5. Angular straggling and energy loss in the different layer of matter in the experiment are taken into account. The expected mean mass resolution is found to be 0,45 and 0,6 FWHM for light and heavy fragments groups, respectively. Heavy fragments are less deflected by the magnet than the light ones. This impacts the Bρ resolution. That is why the fragment-mass resolution is found to decrease as A increases. We would like to stress again that this is just a simulation while the results of the on-going analysis should confirm these expected very good resolutions.

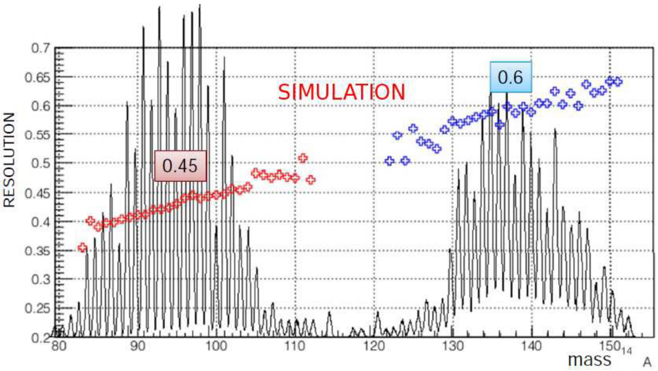

Fig. 5. (Color online) Simulation of the mass separation of fission fragments obtained for thermal fission of ^{238}U using the GEF and CONFID codes. The corresponding mass resolutions are also given (crosses).

5. Perspectives

In the context of R^{3}B (Reaction studies with Relativistic Radioactive Beams) at the FAIR (Facility for Antiproton and Ion Research) project, the possibilities to study fission at GSI are more and more exciting. First, ALADIN will be replaced by a twice stronger magnet called GLAD. This improvement will result in a better mass separation. Second, the availability of the NeuLAND high-granularity neutron detector (new Large-Area Neutron Detector) could provide the neutron multiplicity per fragment. This observable is very interesting to understand how the excitation energy is shared at scission. As a third point, we would like to surround our active target by the high-efficiency gamma-ray and proton calorimeter CALIFA. This calorimeter is a unique opportunity to obtain fission gamma spectra, to study ternary fission, and high energy fission. All these new experimental capabilities promise huge possibilities for nuclear fission studies at GSI. Finally, there is a longer term project associated to the ion-electron collider facility (ELISe) planned at FAIR, where we would like to study the isotopic distribution of fission fragments produced in the interaction of the electron and the secondary actinide beams. The fissioning nucleus will be fully characterized in (A,Z,E*,J) and a complete set of fission observables will be precisely measured as a function of E* (Taieb et al., 2009).

6. Conclusion

SOFIA (Study On FIssion with Aladin) is an innovative experimental program on nuclear fission performed at GSI. In august 2012, we used relativistic secondary beams of neutron-deficient actinides and pre-actinides and investigated their electromagnetic fission in inverse kinematics. The SOFIA set-up was installed at Cave C around the ALADIN magnet to identify the two fission fragments. This new set-up, based on energy loss, tracking and time of flight, allows to reach a precision better than 1 % in energy, 200 μm FWHM in position and 40 ps FWHM in ToF. The SOFIA experiment enables the study of complete fission yields with unprecedented charge and mass resolutions over a large range of pre-actinides and light actinides from ^{183}Hg up to ^{238}Np. It will provide new and high-quality data, which will surely give new insights in the field of nuclear fission.

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