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The SOFIA experiment

Measurement of ^{236}U fission fragment yields in inverse kinematics

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Abstract. The SOFIA (Studies On FIssion with Aladin) experiment aims at measuring fission-fragments isotopic yields with high accuracy using inverse kinematics at relativistic energies. This experimental technique allows to fully identify the fission fragments in nuclear charge and mass number, thus providing very accurate isotopic yields for low-energy fission of a large variety of fissioning systems. This report focuses on the latest results obtained with this set-up concerning electromagnetic-induced fission of ^{236}U.

1 Introduction

The precise knowledge of fission isotopic yields is of great interest in many domains: for fundamental purposes, where it is a unique tool to investigate nuclear structure and collective effects in heavy nucleus and where it has a great influence on our understanding of the r-process nucleosynthesis, as well as for applications where it leads, for example, to a better prediction of the neutron flux in a reactor core and the decay heat after a core shutdown. Despite several decades of experimental investigations on fission, the need for accurate fission-product yields remains.

Indeed, the measurement of isotopic yields is an experimental challenge, and more specifically the measurement of the nuclear charges. Most of the isotopic-yield data originate from neutron-induced fission of actinide targets. Such experiments in direct kinematics are necessarily limited to the charge of the light fragments, because of charge-state fluctuations in the detectors degrading the resolution for the heavier nuclei. Moreover, the use of actinide targets also restrains the study to the

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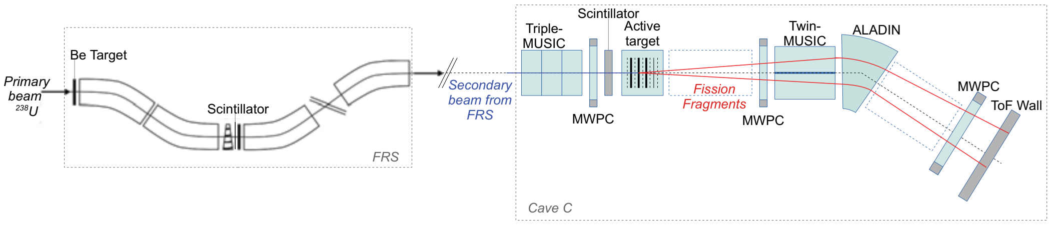

Figure 1. Experimental set-up : production and selection in the FRagment Separator (FRS) of the secondary beam, SOFIA set-up at Cave C.

fission of long-lived nuclei. The alternative method using the inverse kinematics allows to overcome these limitations. The kinematical boost then transmitted to the fission fragments gives access to the charge of the heavier nuclei, with a resolution increasing with their kinetic energy. In addition, this technique offers the possibility of studying a large range of fissioning nuclei thanks to the availability of radioactive beams.

A new type of experiments using this method was introduced at GSI in the 90's [1], representing a breakthrough in the fission-yield measurement : nuclear charges were measured with a good resolution over the whole range of fragments, for the two products of the fission of a large variety of light actinides and pre-actinides. SOFIA (Studies On FIssion with Aladin) falls into the same category of experiments, taking advantage of the inverse kinematics at relativistic energies permitted at GSI, with the objective, this time, of measuring nuclear charges as well as the mass number of the fission fragments. A first set of measurements was performed in 2012 with this set-up where isotopic yields for the low-energy fission of many actinides and pre-actinides were successfully measured [2, 3]. A few extra-shifts were granted in 2014 in order to complete these data, in particular by fission of ^{236}U which is of great interest for the nuclear-reactor community. Neutron-induced fission of ^{235}U occuring in reactors involves indeed the same compound nucleus. First results concerning this recent measurement are presented here.

2 Experimental set-up

SOFIA is a dedicated set-up built around the ALADIN large-acceptance dipole magnet located at GSI (Darmstadt), whose detectors have been specially designed for the study of fission through the simultaneous identification of the nuclear charge and the mass number of both fission fragments, as well as that of the fissioning nuclei. Furthermore, the kinetic energy of the fission fragments is measured, and the total neutron multiplicity is deduced.

2.1 Secondary beam identification

The GSI facility provides an intense primary beam of ^{238}U at 1 A.GeV. The products of the fragmentation reaction of the ^{238}U primary beam on a Be target are selected according to their mass and charge in the FRS (FRagment Separator), a high-resolution recoil spectrometer [4]. The secondary beam of the selected ions of interest is transmitted to the Cave C experimental area where the SOFIA set-up was installed (cf. Figure 1). Those actinides and pre-actinides whose energy is close to 700 A.MeV are fully identified event by event in mass and charge numbers thanks to the simultaneous measurement of their energy loss, magnetic rigidity and time of flight (ΔE - Bρ - ToF technique). A Triple MUSIC

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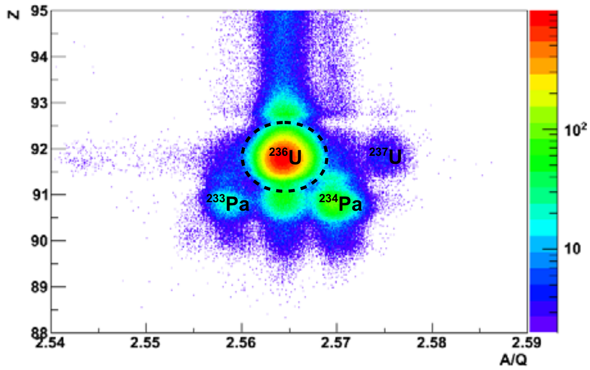

Figure 2. Correlation of the nuclear charge with the ratio of the mass over the charge state for the secondary beam, allowing the identification of the ^{236}U secondary beam.

detector (MUltiple Sampling Ionization Chamber) performs both the energy-loss measurement and the tracking, providing the horizontal angle of the secondary beam. The combination of this angle with the position measurement in a MWPC (Multi-Wire Proportional Chamber) at Cave C gives the magnetic rigidity. The time of flight is measured with two plastic scintillators between the FRS and the Cave C (see figure 1). Figure 2 illustrates the full isotopic identification thus obtained.

2.2 Fission events selection

The fission of the secondary beam nuclei is induced in the active target, a succession of ionization chambers in which four cathodes (two of them made of uranium, one of aluminium and one of lead) act as the targets. The collected anode signals allow to identify in which material the fission takes place. In the frame of this low-energy fission study, one takes an interest only in the electromagnetic-induced fission. This reaction occurs when a target nucleus exchanges a virtual photon with a projectile nucleus going through the target, leading mainly to the excitation of the giant dipole resonance (GDR) of the secondary beam. The latter may then decay through fission. The excitation energy is not measured event by event but its average value is 12 MeV.

Any event corresponding to a nuclear interaction of the secondary beam with a target nucleus has to be discarded, because the fissioning nucleus differs from the one identified before the target, due to a neutron and/or proton removal. Moreover the fragmentation reaction leads, on average, to higher energy fission than the GDR excitation. In the uranium and lead targets, the predominant reaction channel is Coulomb-induced fission and the remaining of the detected fissions follow a nuclear interaction. Conversely, the fissions occuring in the aluminium target are almost only induced by a fragmentation reaction. Based on the limiting-fragmentation hypothesis, the nuclear contribution is deduced from the measurement in the aluminium target and subtracted from the measurement in the uranium and lead targets.

2.3 Fission fragments identification

The fission fragments produced in the active target are emitted in forward direction within a narrow cone of approximately 30 mrad around the secondary beam axis and are deflected in the ALADIN

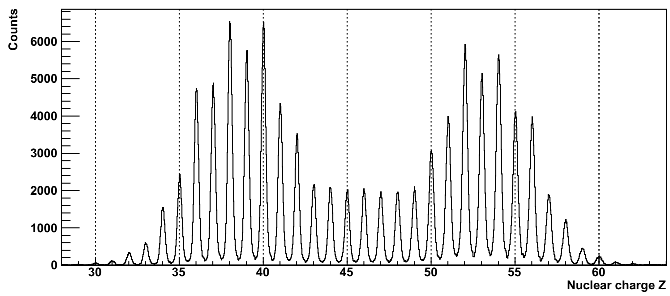

Figure 3. Fission fragments nuclear charge distribution for the electromagnetic-induced fission of ^{236}U.

magnet. The ΔE - Bρ - ToF technique is again applied to each of the two fission fragments. The Twin-MUSIC detector, a double segmented ionization chamber with a common central cathode, performs simultaneously the energy-loss measurement of the two fission products and the tracking, providing their nuclear charge and horizontal angle. The time of flight is measured between the plastic scintillator at the entrance of Cave C and the time-of-flight wall at the very end of the set-up, made of 28 plastic scintillators [5]. Besides the Twin-MUSIC, the complete tracking of the nuclei through the set-up is ensured by two MWPC measuring the coordinates in the plane perpendicular to the spectrometer axis. The mass and the charge numbers of both fission fragments are deduced from these measurements. The analysis of the latest experiment is still ongoing, this report focuses on the nuclear-charge results.

3 Nuclear-charge yields

Figure 3 represents the nuclear-charge distribution of the ^{236}U electromagnetic-induced fission fragments. A very high Z-resolution is reached, slightly reduced for the heavier fragments but at least as good as 0.35 charge unit (FWHM) over the whole range.

Through simulations taking into account the geometry and some cutoff effects of the detectors, the efficiency of the set-up is carefully estimated as a function of the charge and the mass of the detected nuclei, resulting in an average efficiency of 90 % for the last version of the set-up. Elemental yields are then calculated after correction of the fission-fragment charge distributions by this efficiency. Elemental yields for the electromagnetic-induced fission of ^{234,235}U [6] and ^{238}U [7], measured in 2012, and of ^{236}U, measured during the last run in 2014, are compared on figure 4 (top), illustrating the complete consistency between the data from both measurements: whatever the value of Z considered, the yield evolves steadily as a function of the mass of the fissioning uranium isotope.

The bottom of figure 4 highlights the relative statistical uncertainty on the ^{236}U fission yields. The very high statistics gathered for this reaction leads to a relative uncertainty lower than 0.5 % for the most populated fragments and lower than 2 % in the symmetric fission region.

Figure 5 represents the local proton even-odd staggering, expressed following the prescription of [8], as a function of Z for the four reactions ^{234,235,236,238}U (γ,f). A similar trend of an increase of the even-odd effect with the asymmetry of the fission is observed, in accordance with a general phenomenon already observed [9] and explained as the manifestation of the energy sorting mechanism [10] : a common relatively low even-odd effect is observed in the four cases around Z = 46 and is then regularly increasing with the asymmetry.

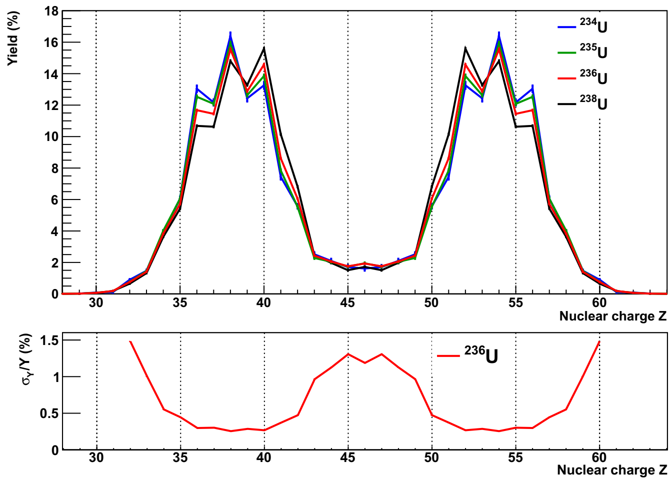

Figure 4. Nuclear charge yields measured with SOFIA for the electromagnetic-induced fission of different Uranium isotopes (top). Relative statistical uncertainty on the elemental yields for the electromagnetic-induced fission of ^{236}U (bottom).

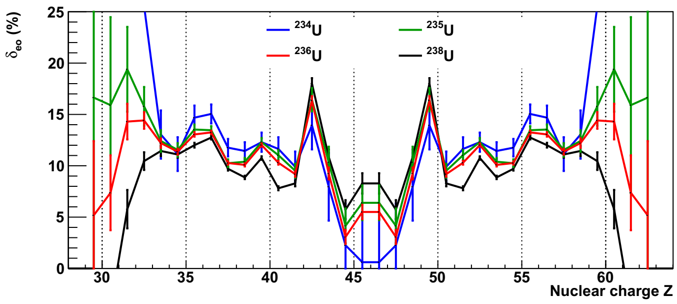

Figure 5. Local even-odd staggering in nuclear-charge yields as a function of the nuclear charge of the fission fragments, for the electromagnetic-induced fission of different U isotopes measured with SOFIA in 2012 for ^{234,235,238}U and in 2014 for ^{236}U.

Finally, elemental yields for the fission of ^{236}U are compared with evaluated data from two libraries, B-VII.1 and JEFF-3.1, for Neutron-induced fission of ^{235}U at different energies on figure 6. A striking feature of this comparison is the very low uncertainty of the SOFIA data compared to evaluated data. One can also note the consistency of the evaluations with an expected mean excitation energy of 12 MeV for the reaction ^{236}U (γ,f), i.e. a neutron energy of approximately 6 MeV for the analog reaction ^{235}U(n,f), by observing the ratio of the yield at the symmetry to the one at the asymmetry which is expected to grow with the excitation energy of the fissioning nuclei.

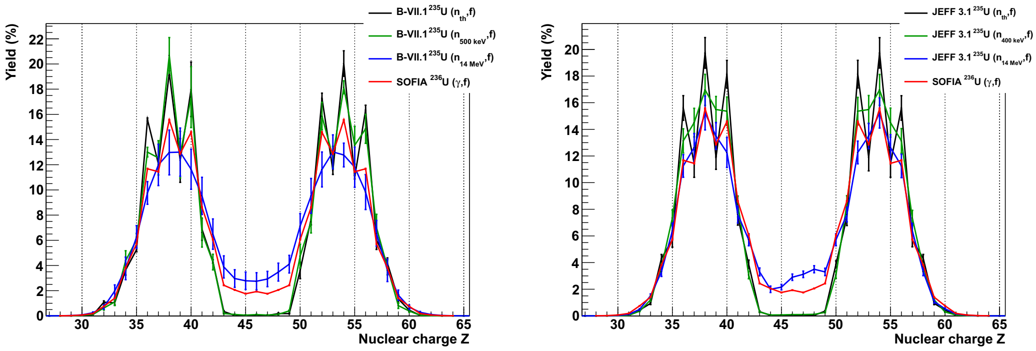

Figure 6. Comparison of the nuclear-charge yields measured with SOFIA for electromagnetic-induced fission of ^{236}U with two different sets of evaluation, B-VII.1 on the right and JEFF-3.1 on the left for the reaction ^{235}U(n,f) at three different neutron energies. Error bars are indicated.

4 Conclusion

Electromagnetic-induced fission of ^{236}U has recently been measured with the SOFIA set-up using inverse kinematics at relativistic energies. The ongoing analysis already reveals the high quality of the data with nuclear-charge yield uncertainties as low as 0.5 % and an unprecedented Z-resolution reaching 0.35 charge unit (FWHM). The comparison with the previous results on the fission of ^{234,235,238}U shows complete consistency.

The ongoing analysis of the fission-fragment masses looks very promising. Very accurate isotopic yields for the ^{236}U fission are thus expected. The kinetic energy and total mean neutron multiplicity, also accessible with SOFIA, still has to be extracted from the data to complete these preliminary results.

Further experimental studies on fission with the SOFIA set-up within the R3B (Reactions with Relativistic Radioactive Beams) collaboration are considered for the near future [2]. The coupling of the SOFIA recoil spectrometer with detectors such as NeuLAND (new Large-Area Neutron Detector) or CALIFA (CALorimeter for the In Flight detection of γ rays and light charged pArticles) would allow to further extend the number of accessible observables of fission in order to get an even more precise insight into the complex phenomenon of fission.

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