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Fission activities of the nuclear reactions group in Uppsala

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Abstract

This paper highlights some of the main activities related to fission of the nuclear reactions group at Uppsala University. The group is involved for instance in fission yield experiments at the IGISOL facility, cross-section measurements at the NFS facility, as well as fission dynamics studies at the IRMM JRC-EC. Moreover, work is ongoing on the Total Monte Carlo (TMC) methodology and on including the GEF fission code into the TALYS nuclear reaction code. Selected results from these projects are discussed.

Keywords: Fission, IGISOL, TMC, NFS, independent fission yields;

1. Introduction

The nuclear reactions group at the division of Applied Nuclear Physics, Uppsala University, has several ongoing projects related to nuclear fission. Experimental activities are dedicated to, for example, fission yields, prompt fission neutrons and cross section measurements. In addition the Total Monte Carlo approach is used to enhance the methods of nuclear data evaluation and the assessment of nuclear data uncertainties. In this paper we briefly discuss the different projects and present some results and developments up to date.

2. Cross section measurements at the NFS facility

Cross sections are important observables both for nuclear model development as well as for nuclear applications. High precision measurements are often desired to restrict the levels of uncertainty to a few percent. One major problem in many data-sets is the cross-correlations between experiments e.g. by the use of a common reference.

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Experimental systematic uncertainties are hard to assess and the disentanglement of uncertainty correlations can be a complex procedure. The Uppsala group is planning to measure standard cross sections at the Neutrons For Science (NFS) facility in GANIL, France [Ledoux et al. (2014)]. The main goal is to minimize the systematic uncertainties of three neutron standards which are often used as references. The reactions are going to be measured relative to each other in the same neutron beam and by utilizing the same experimental detectors. The NFS facility will produce a white-spectrum neutron beam with neutron energies up to 40 MeV. Within this energy range, the fission cross sections of ^{235}U and ^{238}U in addition to the neutron-proton elastic scattering are all used as neutron standards [Carlson (2011)].

2.1. Measurement technique

The Medley set-up has successfully been used for the last decades to measure light-ion production at the TSL facility in Uppsala [Pomp et al. (2010)]. Eight Si-Si-CsI detector telescopes were put in the chamber at different angles relative to the target. Particles from various reaction channels were identified via the $\Delta E - \Delta E - E$ technique [Bevilacqua et al. (2011)]. Currently, Medley is undergoing an upgrade to be used for the NFS measurements. The target planned to be used consists of ^{235}U-CH_2-^{238}U layers. An incoming neutron can either induce fission in the U (giving rise to emitted fission fragments) or undergo elastic scattering H(n,n), in the polyethylene (where we detect the recoil proton). The emitted residuals can be counted after being detected in the telescopes at different emission angles. In order to determine the impinging neutron energy, a time of flight measurement will be carried out. PPAC detectors, having a very good timing resolution, will be installed close to the target on both sides, in order to give a trigger signal when a fission fragment passes through it.

2.2. Selected results and outlook

The first commissioning experiment at the NFS facility is expected to be performed in 2016. Geant4 simulations have been performed in order to optimize the design of the different parts of Medley [Jansson et al. (2014)]. The simulations puts a maximum limit to the U target thickness of about 2 μm in order for the fission fragments to reach the detectors with sufficient energy. In addition, in order to have similar statistics the polyethylene target has to be around 100 μm in thickness. The uncertainty in neutron energy has also been estimated based on the simulation results. The uncertainty increases as a function of incident neutron energy. However, for fission fragments it stays below 0.5 MeV. For recoil protons the corresponding uncertainty is always below 1 MeV.

Currently the Medley upgrade is still ongoing and testing will be done with a Cf(sf) source. Beyond the main goal to measure cross sections, Medley will also be able to investigate the phenomenon of fission fragment angular anisotropy. The NFS energy range opens the possibility to measure the anisotropy as new fission channels open. This is of particular interest as new transition states open with new multi-chance fission channels.

3. Independent fission yields at the IGISOL facility

The Uppsala group is involved in measurements of independent fission yields at the IGISOL facility in Jyväskylä, Finland [Penttilä et al. (2012)]. Proton-induced fission yields have earlier been measured at the IGISOL facility. The Uppsala group is responsible for development and characterization of a proton-neutron converter, Be(p,n), to study neutron-induced fission. A 30 MeV proton beam will be used to produce both fast- and thermal neutron spectra [Solders et al. (2014)]. The goal is to minimize uncertainties in fission yields in the nuclear data libraries, because they are important ingredients in reactor calculation codes. In addition, isomeric yield ratios in neutron-induced fission are planned to be measured with the high-precision Penning-trap technique. The first experiment with neutrons is foreseen in 2015.

3.1. Measurement technique

Accelerated protons from the cyclotron impinge on a fissionable target and produce fission fragments. The reaction chamber is filled with He gas which acts as stopping and buffer gas for the ions. The collected ions are guided by a flow of He into a mass separator. The first mass separation is done in the isotope separator on-line (ISOL), via a dipole magnet based on the charge-to-mass ratio. After an RFQ buncher and cooler, the accumulated ions are transported to a Penning trap where a second, more precise separation is performed. The achieved mass resolution after the Penning trap is in the order of $\Delta A/A = 10^{-5}$. In fact it is so powerful that one is able to separate isomeric states from the ground state down to about 200 keV. For neutron-production a Be target has been chosen. The proton beam will impinge on the Be target and fully stop in the cooling water on the back side of the Be target. In this way the cooling requirements can be fulfilled and hydrogen build-up in the target is avoided [Solders et al. (2014)].

3.2. Selected results and outlook

A characterisation of the Be target was performed at the TSL facility in Uppsala by means of two different measurement techniques, time-of-flight measurement and Bonner sphere spectroscopy [Mattera et al. (2014)]. The prototype Be target was 5 mm thick followed by a 10 mm water layer for cooling. Simulations of the expected neutron fluxes have been done using both FLUKA and MCNPX [Lantz et al. (2014)].

Simulations were also done to investigate the fission fragment (FF) counting efficiency in the reaction chamber. It was unclear to what extent the ion counting depends on mass, charge and energy. Both Geant4 and SRIM were used to simulate the stopping power of a large subset of possible fission products. In total 14 masses were chosen sampled from the entire mass distribution. Five characteristic kinetic energies were selected for each mass which covered the entire energy distribution. The results showed that less than 1% of all emitted ions from the target are stopped in the buffer gas. The changes in stopping efficiency as a function of mass are rather small compared to other sources of systematic uncertainties. At most about 9% more light fragments are stopped than heavier fragments. Due to normalization to neighbouring masses this effect is not large on the measured yields. The thickness of the U target was found to play a major role in altering the mass-dependence. If half the 15 mg/cm^2 thick U target is used, the effects is much larger fluctuations in the number of stopped ions. Different parameters were changed to investigate their influence on the observed counting efficiency. Full details can be found in Ref. [Al-Adili et al. (2014)].

In the future we plan to simulate the optimum chamber geometry for the neutron-induced case. Moreover the charge states of the ions need to be studied as it affects the extraction of the ions through the ion guide. The Be target will be installed in the coming year to allow for neutron-induced fission-yield studies.

4. Fission-dynamics studies at the JRC-IRMM facility

Another experimental activity of the Uppsala group concerns low-energy fission dynamics. The focus is put on the fission fragment mass-, energy- and angular distributions in addition to prompt fission neutrons. These experiments are done in collaboration with the Joint Research Centre, Institute for Reference Materials and Measurements (JRC-IRMM) in Geel Belgium. The main objective is to contribute to the fundamental modelling of nuclear fission. As we still lack a complete fission theory, many puzzles are yet unsolved. Correlation measurements are needed for various systems and energies to study e.g. fission barrier properties, share of excitation energies and the properties of prompt neutrons and gamma rays.

4.1. Measurement technique

The main instrumentation we use in these measurements is the Frisch-grid ionization chamber for fission fragment spectroscopy and liquid scintillators for neutron detection. Neutrons are produced via the 7 MV Van de Graaff accelerator and induce fission in an enriched actinide target in the centre of the chamber. Following a fission event both fragments exit the transparent target in a back-to-back kinematics. The fragments ionize the counting gas (P-10) and induce signals on the different electrodes. The signals reveal both the energies and emission angles of the fragments. Pre-neutron emission masses are calculated following an iteration process. The neutron detectors are used to obtain information on the average prompt neutron emission per fragment mass.

4.2. Selected results and outlook

The fissioning system ^{234}U(n,f) was measured using the conventional 2E technique [Al-Adili (2013)]. Fragment mass-, energy and angular distributions were determined. The energy range was 0.2 - 5 MeV incident neutron energy, and special focus was put in the vicinity of vibrational resonances [Al-Adili et al. (2012b)]. In addition, the effect of prompt neutron corrections were assessed on the measured mass yields. Because no neutrons are measured in the 2E-technique one needs to make an assumption on the $\overline{\nu}(A)$. A rather large impact (20-30 % relative differences) was found based on different assumptions on the change of $\overline{\nu}$ at higher excitation energies [Al-Adili et al. (2012a)]. Therefore, and to contribute to the development of fission models, our plan is to measure the prompt neutron emission as a function of mass and excitation energy. The last issue will also be addressed in the IGISOL technique where the yield will be measured as a function of excitation energy, by using a thin Be target producing quasi-monoenergetic neutrons.

5. Total Monte Carlo and the GEF fission code

Finally, the group has been part of developing the Total Monte Carlo (TMC) methodology in collaboration with the colleagues at NRG Petten. The TALYS reaction code is the central component in this procedure where model parameters are randomized to produce nuclear data files, each file containing a unique set of model parameters [Koning and Rochman (2012)]. The random files are processed into reactor code calculations to obtain distributions in various quantities (e.g. k_{eff}). From these distributions, nuclear data uncertainties can be extracted [Alhassan et al. (2014)]. Also, a best file or evaluation can be selected by comparison to experimental data [van der Marck et al. (2014)]. Moreover, efforts have been put into merging the GEF fission code into TALYS. GEF has proven to be a powerful code for reproducing experimental fission fragment characteristics. TALYS being one of the leading reaction codes available, would benefit from including GEF since it enhances the fission calculations.

5.1. Selected results and outlook

The TMC approach has been successfully applied to ELECTRA (The European Lead-Cooled Training Reactor) [Sjöstrand et al. (2014); Alhassan et al. (2014)], in thorough comparisons of nuclear-data uncertainties in UO_2 and MOX fuel [Helgesson et al. (2014)] and the n+^{56}Fe reaction [Duan et al. (2014)]. An important ongoing development of TMC is the inclusion of experimental information in a statistically rigorous way [Helgesson et al. (2015)].

The GEF fission code is since TALYS v 1.6 included as one out of two available fission models. The TMC approach has been applied to measured fission yields of ^{234}U(n,f) [Al-Adili (2013)] and ^{232}Th(n,f) [Simutkin et al. (2014)] by varying the GEF parameters in TALYS. By doing so a better agreement was found with the experimental data [Pomp et al. (2014)].

6. Summary

In this paper we have summarized the main fission related activities of the nuclear reactions group at the Applied Nuclear Physics division in Uppsala University. Four main projects are dedicated to both experimental fission activities as well as for nuclear data evaluation and uncertainty propagation. The experimental activities are focused towards three neutron beam facilities; NFS, IGISOL and JRC-IRMM. High precision measurements are planned e.g. on standard cross sections, fission angular anisotropy, independent fission yields, fission fragment properties and neutron emission.

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