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Fusion-induced fission measurements with the MUSIC active target detector

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Abstract. The rapid neutron capture process (*r-process*) is believed to be responsible for about half of the production of the elements heavier than iron and it may also contribute to abundances of some lighter nuclides. Great excitement was recently generated by evidence for *r-process* nucleosynthesis in binary neutron star mergers via multi-wavelength observations of kilonova emission and gravitational waves. In order to interpret the observations and validate theoretical predictions, an understanding of the fission process, in particular of the evolution of fission barrier heights, is needed. An experimental study of fusion-induced fission cross sections using active-target detectors is a promising idea since the fission excitation function can be studied with a single beam energy. The Multi-Sampling Ionization Chamber (MUSIC) is an active-target detector in which a gas serves as both, counting gas and target nuclei. A proof-of-principle experiment to explore the ability to identify fission events with MUSIC was recently performed at Argonne National Laboratory. In this work, ideas, results and perspectives will be discussed.

1 Introduction

Understanding of the fission process is crucial in applied as well as fundamental research. Fission models are needed for nuclear energy applications, nuclear structure and nuclear astrophysics studies. Theoretical predictions of the fission barriers of exotic systems drive the quest for super-heavy nuclei [1]. The reliable determination and theoretical prediction of fission barriers, fission fragment distributions, as well as the balance between the neutron separation energy and fission-barrier heights, are decisive for determining the behavior of different isotopes in a nuclear reactor as well as the nature of the termination of stellar nucleosynthesis in the *r-process* [1, 2]. The *r-process* path ends when it reaches an area in the nuclear chart where fission dominates over further neutron captures. The position of this point is determined by the fission barriers and the neutron separation energies of the nuclei involved. The *r-process* reaction path proceeds through very neutron-rich nuclei that cannot (yet) be studied experimentally. This means that *r-process* reaction networks need to rely on theoretically predicted nuclear properties [3, 4]. The fission probability of a nucleus depends

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directly on the fission barrier and, thus, fission barriers are crucial to determine the end of the *r-process* path, having a direct influence on the final abundance distribution.

Experimental investigations are needed to validate the theoretical efforts and provide benchmark information to reliably extrapolate theoretical calculations, particularly around closed shells where barrier heights are expected to rise, greatly influencing the path of the *r-process* [4]. Fission cross section measurements using active-target detectors are a promising idea. The measurements can be performed with a single beam energy by studying the fission excitation function as the beam travels through the detector. Recently, a proposal has been accepted by the NSCL PAC to measure fission using the AT-TPC at NSCL [5]. A fission TPC is also being developed by the NIFFTE collaboration at LANL [6]. A measurement using the MAYA active-target detector of fission induced by the ^{238}U+^{12}C system was recently performed at GANIL [2].

We are currently investigating the ability to measure fusion-induced fission excitation functions with the MUSIC detector.

2 The MUlti Sampling Ionization Chamber (MUSIC) detector

The MUlti Sampling Ionization Chamber (MUSIC) detector [7] is an active target detector developed at Argonne National Laboratory (ANL) that measures energy losses as the beam passes through the detector. A segmented anode allows for a measurement of an excitation function covering a large energy range using a single beam energy. The range of the excitation function is determined by the beam energy and the pressure of the gas inside the detector. The anode is segmented in 18 strips. The first and last strips are used as control strips. The other 16 strips are subdivided in left and right to measure the multiplicity of events. MUSIC was originally designed to measure fusion events. A sudden increase in the energy loss in the strip where the reaction occurs is a signature of a fusion event. MUSIC can be filled with several gases e.g. methane, helium, neon and argon. MUSIC has been successfully used to measure fusion excitation functions of exotic beams [8] as well as (α,p) and (α,n) reactions [9, 10].

3 Proof-of-Principle Experiment

A proof-of-principle experiment to explore the ability to identify fission events in MUSIC was already performed at the ATLAS facility at ANL. A 1000 MeV ^{165}Ho beam was used to bombard MUSIC which was filled with ^{40}Ar gas at 113 Torr. In MUSIC, a fusion-induced fission reaction is identified by a sudden 'jump' in the energy loss signal characteristic of fusion, followed by two big signals in both sides of the detector from the two fission fragments. A schematics of fusion-fission events along with the schematics of the segmented anode in MUSIC are shown in figure 1.

Fission fragments induced by the ^{165}Ho+^{40}Ar→^{205}At reaction in the $E_{cm} = 130 - 160$ MeV energy range in the center of mass were identified by their traces in MUSIC. A simulation of the traces from fission reactions occurring in MUSIC was performed and compared with the experimentally extracted traces showing a good agreement between them. The preliminary experimental cross sections of the fusion-induced fission from the ^{165}Ho+^{40}Ar→^{205}At reaction measured with MUSIC are shown in figure 2. Previously measured data is also shown for comparison [11]. The good agreement give us confidence in the ability to reliably identify fission events in MUSIC. Fission cross sections were also calculated with the code PACE4 [12]. The experimental values for the fission cross sections measured with MUSIC and previously reported data from Ref. [11] are within 20% of the fission cross sections calculated with PACE4. However, a significant disagreement was observed

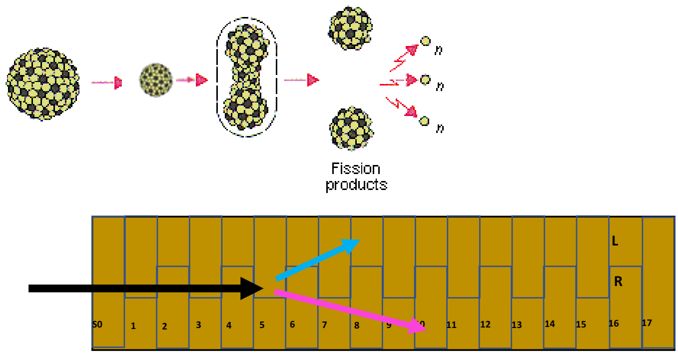

Figure 1. Schematics of a fusion-induced fission event and the segmented anode in MUSIC representing a fission event occuring in strip 5.

when comparing experimental data from the literature with fission cross sections calculated with the PACE4 for other systems. The PACE4 calculated cross sections were zero despite existing experimental data with significant cross sections as shown in table 1. Default settings were used for such calculations, same that predicted well the cross section for the ^{205}At case. It is therefore crucial to validate and benchmark the theoretical predictions for fission cross sections where experimental data is available in order to reliably extrapolate to exotic regions where experiments are not yet possible.

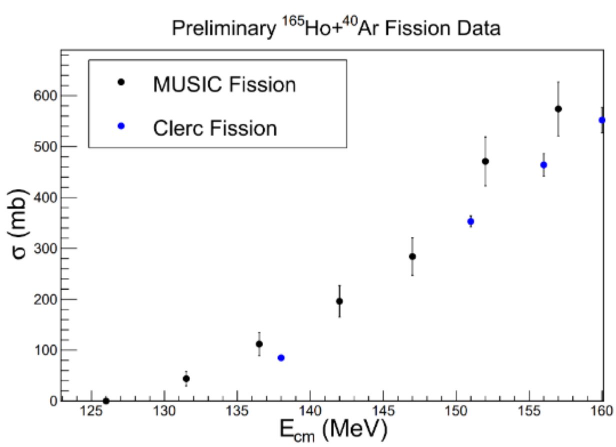

Figure 2. Preliminary experimental cross section of fusion-induced fission events measured in MUSIC for the ^{165}Ho+^{40}Ar→ ^{205}At system compared with data from Ref. [11].

Table 1. Experimental fission cross sections reported in the literature compared with PACE calculations for different systems. A strong disagreement is observed for some systems.

System	E_{cm} (MeV)	Experimental σ (mb)	PACE Calculated σ (mb)
^{165}H0+^{40}Ar→ ^{205}At	156	464 ± 22 [11]	361
	160	552 ± 25 [11]	416
	166	596 ± 29 [11]	510
^{96}Mo+^{40}Ar→ ^{136}Nd	140	141 ± 30 [14]	0
	209.5	160 ± 15 [14]	0
^{110}Pd+^{40}Ar→ ^{150}Gd	144	290 ± 40 [13]	0
	165	380 ± 40 [13]	0
	192	610 ± 60 [13]	0

4 Summary and Outlook

Fusion-induced fission reactions can be studied with the MUSIC active target detector. For the near future, stable Mo beams from ATLAS and radioactive ^{104,106}Mo beams from CARIBU would be used to bombard the MUSIC detector filled with Argon gas. A systematic study the fission excitation functions and the evolution of the fission barrier around neutron number $N \sim 82$ would be performed. The rates of the ^{104,106}Mo CARIBU beams (a few thousand pps) are ideal for this study. A comparison with theoretical predictions would allow to benchmark fission models. This is the first step towards a systematic study of the evolution of fission barriers around neutron closed shell $N = 128$, where the strongest influence on the *r-process* path is expected [1, 4]. Future measurements with other CARIBU beams will be proposed in preparation for beams from FRIB.

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