EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Search for new fission modes in light systems around Z=60: The cerium case

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Abstract: Fission is a complex process where the output is determined by the competition between macroscopic and microscopic features of the nuclear matter under extreme deformation. A prime example of this competition is the asymmetry in the fragment mass distribution of fission in actinides, which is determined by the effect of specific deformed shells. Asymmetric yields were also measured in the sub-lead region and hinted in high-energy fission of systems around Z=60. As in the case of actinides, the existence of favoured deformed shells was among the explanations for these measurements. Unfortunately, below Z=70, scarce statistics prevents any firm conclusion about such asymmetric character. We propose to use the tilted PPACs ensemble at n_TOF/EAR1 with ^{nat}Ce samples to measure the cross-section, angular distribution and the mass distribution of high-energy neutron-induced fission reactions from a Z≈60 system. These observables will be acquired with one order of magnitude more statistics than in previous experiments, allowing a firm conclusion on the asymmetric character of fission of Z≈60 systems and the role of nuclear structure, which may reveal a new fission mode.

Requested protons: 3×10^{18} protons on target
Experimental Area: EAR1

1 Scientific Motivation

Our understanding of nuclear systems and phenomena is a combination of macroscopic/collective properties and microscopic/intrinsic features. The interplay between these two regimes is one of the key aspects of the nuclear fission decay, making it a good experimental playground to test our knowledge about many-body nuclear interaction and dynamics. Historically, fission features related with nuclear structure, such as shell effects, pairing, etc, were understood as perturbative components of a liquid-drop behaviour [1, 2, 3, 4, 5]. Some of these effects were suspected to be behind one of the most striking properties observed of low-energy fission in actinides: the fragment mass distribution was not only asymmetric, but the heavy-fragment mass was basically independent on the fissioning system [6]. Theoretical models tried to establish the moment in the process in which the identity of the fragments is defined, whether at the barrier [2], along the potential-energy surface [5], or at the scission point [4], while different shells were singled out for this behaviour, from spherical-closed shells around ^{132}Sn [5] to quadrupole-deformed dips in the potential energy [3, 4]. However, none of these models gave a satisfactory and complete answer to one of the main experimental results in fission of the last decades: favoured shells were found in the proton number [7] and correspond to Z$\sim$52 and $\sim$56 [8]. A recent study of the time evolution of fission modelled with a microscopic, energy-density functional description proposed an alternative explanation: the favoured shells were octupole deformed, with shapes similar to those of pre-fragments right after the barrier [9]. Within the same work, octupole deformation also opens shell gaps around Z=34 and 44, which might be responsible for shells effects in the fission of sub-lead nuclei [10].

In this sub-lead region, the unexpected measurement of asymmetric fission in mercury isotopes [11] has increased the interest for further structure effects [12, 13], and even incited a recent global description of fission based on particular shells [14]. In the light of this continuous expansion of structure-related studies in fission, it is only natural to go further down in the nuclear chart and search for new instances of asymmetric fission in systems well below mercury that may reflect the influence of particular nuclear shells.

From the experimental point of view, the study of fission in very light systems is quite difficult. Around Z=60, fission barriers rise above 30 MeV, forcing experiments to work at excitation energies well above the barrier height, due to the competition with evaporation channels. In the search for the Businaro-Gallone point [15, 16], a series of experiments measured the mass-ratio distributions of proton-induced fission of light systems from $_{70}$Yb down to $_{39}$Y with proton energies between $\sim$200 MeV and beyond 1 GeV [17, 18, 19, 20, 21, 22, 23, 24, 25, 26] (Figure 1 shows a selection of these measurements). In all these experiments, the induced high excitation energy opens a number of channels, including a collection of systems that may fission after an evaporation chain of protons and neutrons. However, measured data suggest that the probability of fissioning at the end of the evaporation chain, with an excitation energy relatively close to the fission barrier is very small, thus fission at high excitation energy would be favoured [20].

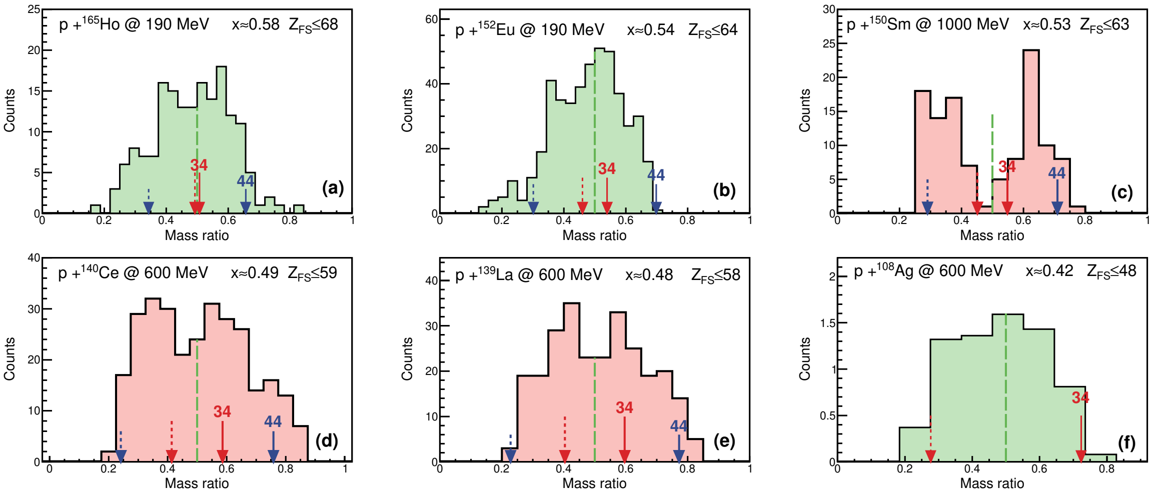

Figure 1: Fragment-mass ratio from high-energy proton-induced fission of (a) ^{165}Ho [22], (b) ^{152}Eu [22], (c) ^{150}Sm [24], (d) ^{140}Ce [20], (e) ^{139}La [18], and (f) ^{108}Ag [19]. The arrows show rough locations of shells Z=34 (red) and Z=44 (blue), and of the complementary fragments (dashed-line arrows). Long-dashed green lines show the symmetry. The approximated fissility x and atomic number Z_{FS} of the compound system are also indicated.

Some conclusions can be drawn from the results shown in Fig. 1: *a)* clear asymmetric components can be identified for ^{139}La, ^{140}Ce, and ^{150}Sm targets; *b)* a small change in fissility seems to have a strong effect on the fragment-mass distribution; and *c)* the asymmetric components do not follow the liquid-drop behaviour, in which a change from a symmetric maximum to a very asymmetric distribution is expected at the Businaro-Gallone point [15, 16, 27]. Altogether, these observations suggest a possible effect of nuclear shells, as in the case of fission from actinides. Moreover, the asymmetric peaks observed in panels (c), (d), and (e) of Fig. 1 seem to be located close to the position of Z=34, considering the approximate relation between the ratio of the fragment masses and their proton content. In general, the effect of Z=44 is more difficult to assess due to the low statistics and the different experimental conditions affecting the tails of the distributions. Low statistics is a general feature of all these results, with fragment distributions often built with less than 300 counts.

In the light of these data, two questions remain: the actual asymmetric character of the fragments distributions from Z≈60, which low statistics does not allow to firmly establish so far; and the possible influence of nuclear structure, should the asymmetry exists. This proposal aims at addressing the question of the asymmetric character, while the answer to the influence of nuclear structure will be explored in a complementary experiment to study fusion-induced fission in inverse kinematics at GANIL [28]. Together, these two experiments will allow a systematic study on the fission of very light systems with different techniques and reaction channels.

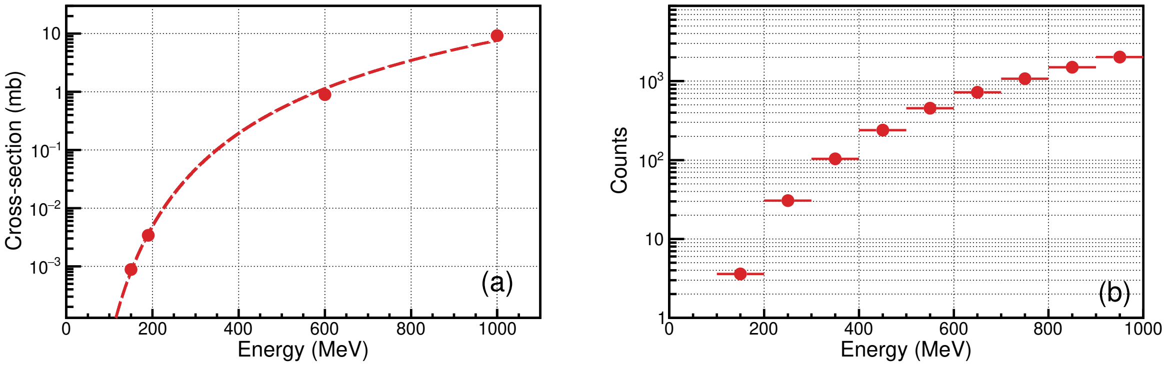

Figure 2: (a) Estimation of the fission cross-section for ^{140}Ce. The symbols correspond to data compiled in [22], while the line is an interpolation following the prescription of [32]. (b) Expected counts in 100-MeV bins for seven 1.2-mg/cm^2 samples of CeO$_2$, and $3{\times}10^{18}$ protons on target.

2 Proposed Experiment

Our proposition is to study neutron-induced fission of $^{nat}_{58}$Ce (88.4% ^{140}Ce, 11.1% ^{142}Ce) up to an energy of 1 GeV, with the tilted PPACs setup [29] in EAR1. This study is to be performed in a qualitative way, focusing on the impact on the underlying physics rather than on absolute precision. The main goals are:

- To assess the symmetric or asymmetric character of the fragment mass distribution.
- To measure the fragment angular distribution.
- To measure the fission cross-section.

2.1 Experimental setup

The measurement will be performed with the PPACs ensemble in the tilted configuration, which allows the access to the full angular distribution with an efficiency of ∼50% [29]. But more crucially, the PPACs setup has proven to be sensitive to the fragment mass distribution. The time difference between the detection of the two fragments is related to their mass difference, and thus fragment mass distributions can be recovered from the time measurements. This possibility was shown in [30], where the evolution of the asymmetric and symmetric fission modes of ^{232}Th as a function of the excitation energy can be clearly observed. A closer inspection reveals a mass resolution of about 12 u [31], enough to separate the two peaks expected in the asymmetric fragment distributions of Z∼60 systems[1].

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[1] The separation in mass between peaks produced by a Z=34 shell in ^{nat}Ce would be of the order of 28 u. The FWHM of the peaks is most likely smaller than 9 u [7], which becomes ∼15 u when folded with the mass resolution.

The PPACs ensemble includes nine sample slots. We plan to use seven slots for samples containing ^{nat}Ce, one for a gold sample, and one for ^{238}U since, up to 200 MeV it is considered as a standard reference, and can be convenient up to 1 GeV. Each cerium sample is to be produced by electroplating 1.2 mg/cm^2 of CeO$_2$ onto a 2-μm-thick aluminium foil with an area covering the beam profile.

Concerning statistics, the number of expected fission events can be estimated from the previous measurements of proton-induced fission reactions: at energies well above 100 MeV, the reaction channels are mostly dominated by hadronic interactions. This assumption will be also tested with the gold sample: while proton-induced measurements exist in literature, there is a lack of reliable, extensive measurements of neutron-induced fission. In addition, there are experimental indications of gold displaying asymmetric fission [33], following the tendency of other sub-lead systems.

Figure 2(a) shows the fission cross-section for ^{140}Ce as estimated from the compilation that can be found in [22], while Figure 2(b) shows the expected fission counts collected with 3×10^{18} protons on target. The statistics range from some tens of counts around 200 MeV to thousands above 800 MeV. Crucially, but also interestingly, previous data suggest that the asymmetric character of fission in these light systems is quite robust with respect to the initial excitation energy: asymmetric distributions can be observed between 190 and 1000 MeV, even in the same system (see the example of ^{140}Ce in [20, 22]). This will allow to study fragment distributions in large energy bins, and compensate low statistics, if necessary.

Summary of requested protons: 3×10^{18} protons on target.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

Please describe here below the main parts of your experimental set-up:

Part of the experiment	Design and manufacturing
If relevant, write here the name of the fixed installation you will be using Fission collimator	☒ To be used without any modification ☐ To be modified
If relevant, describe here the name of the flexible/transported equipment you will bring to CERN from your Institute Tilted PPACs ensemble	☐ Standard equipment supplied by a manufacturer ☒ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT

Additional hazard from flexible or transported equipment to the CERN site:

Domain	Hazards/Hazardous Activities		Description
Mechanical Safety	Pressure	☐	
	Vacuum	☒	6 mbar, 100 l
	Machine tools	☐	
	Mechanical energy (moving parts)	☐	
	Hot/Cold surfaces	☐	
Cryogenic Safety	Cryogenic fluid	☐	[fluid] [m3]
Electrical Safety	Electrical equipment and installations	☐	[voltage] [V], [current] [A]
	High Voltage equipment	☒	600 V
Chemical Safety	CMR (carcinogens, mutagens and toxic to reproduction)	☐	[fluid], [quantity]
	Toxic/Irritant	☐	[fluid], [quantity]
	Corrosive	☐	[fluid], [quantity]
	Oxidizing	☐	[fluid], [quantity]
	Flammable/Potentially explosive atmospheres	☐	[fluid], [quantity]
	Dangerous for the environment	☒	C_3F_8 gas, 5 kg
Non-ionizing radiation Safety	Laser	☐	[laser], [class]
	UV light	☐	
	Magnetic field	☐	[magnetic field] [T]
Workplace	Excessive noise	☐	
	Working outside normal working hours	☐	
	Working at height (climbing platforms, etc.)	☐	

	Outdoor activities	☐	
Fire Safety	Ignition sources	☐	
	Combustible Materials	☐	
	Hot Work (e.g. welding, grinding)	☐	
Other hazards	Use of radioactive material	☒	^{238}U sample 12 mg, 150 Bq