The *n*ELBE (*n*,fis) experiment

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Abstract
Simulations of the *n*ELBE ^{235}U and ^{242}Pu parallel plate fission ionization chambers are presented using finite element methods and extensive GEANT4 simulations. The homogeneity of the electrical field was improved and the optimal amount of target material determined. Pile-up effects due to the high α activity of the plutonium targets have been considered in a realistic geometry.

1 Introduction

The simulation of transmutation in innovative reactor systems or accelerator driven systems (ADS) requires accurate nuclear data [1]. Sensitivity studies [2, 3] show that the total uncertainty of cross section data has to be reduced below 5 % to enable reliable neutron physical simulations. However, neutron-induced fission cross sections of plutonium and minor actinides in part show high uncertainties in the fast-neutron range. For example, available data on ^{242}Pu are discrepant by about 21 % (see for example Fig. 1), where the target uncertainties are in the order of 7 %.

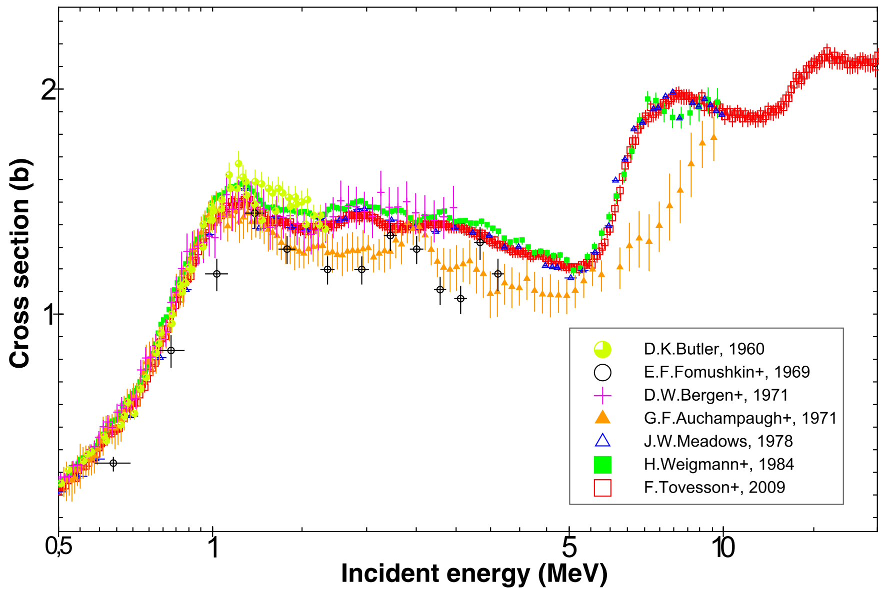

Fig. 1: Selected fast neutron-induced fission cross sections on ^{242}Pu taken from the EXFOR database [4] (graph taken from Janis 3.4 [5]). Large discrepancies are visible above the fission threshold at around 2 MeV.

The *n*ELBE neutron time-of-flight facility at the new National Center for High-Power Radiation Sources at Helmholtz-Zentrum Dresden-Rossendorf (HZDR) will be used to face the challenging task of reducing nuclear data uncertainties. Improved experimental conditions (low-scattering environment) and beam power, paired with the adequate spectral shape of the neutron beam will provide excellent conditions to achieve this aim.

Table 1: Isotopic composition of the targets.

(a) Plutonium target

Isotope	rel. abundance (%)
^{238}Pu	0.003
^{239}Pu	0.005
^{240}Pu	0.022
^{241}Pu	0.009
^{242}Pu	99.959
^{244}Pu	0.002

(b) Uranium target

Isotope	rel. abundance (%)
^{234}U	0.0100
^{235}U	87.9600
^{236}U	0.0039
^{238}U	12.0261

2 Design of the *n*ELBE fission chambers

Two parallel-plate fission ionization chambers are currently under development at the HZDR. The fission chambers will measure fission fragments from thin and homogeneous (cf. Fig. 2) minor actinide layers.

The target material is deposited on eight 400 μm silicon wafers by molecular plating [6]. To ensure good electric conductivity, the wafers will be coated with a 100 nm titanium layer. The target diameter (74 mm) was chosen to be larger than the neutron beam diameter to avoid uncertainties related to beam profile effects.

Eight uranium targets with a total amount of 160 mg ($n_A \approx 450$ μg/cm^2) uranium (the isotopic composition is shown in Table 1) have already been produced at the Institute for Nuclear Chemistry of the University of Mainz. With the neutron flux of *n*ELBE a neutron-induced fission count rate of 2-5 per second can be achieved. The production of the plutonium targets ($m_{\mathrm{Pu}} \approx 50$ mg, $n_A \approx 150$ μg/cm^2) is still in progress.

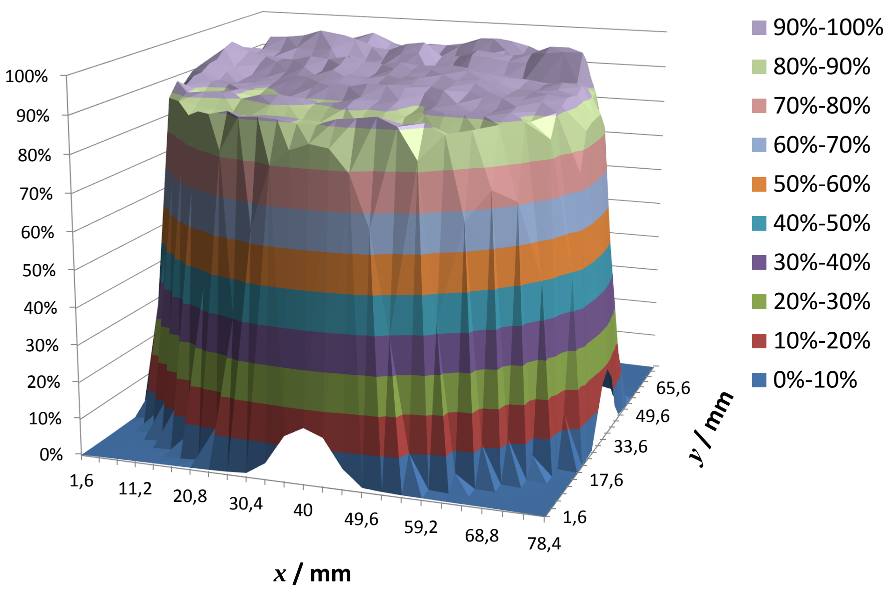

Fig. 2: Radiographic image of an ^{235}U target produced by the Institute for Nuclear Chemistry of the University of Mainz. The image plate is sensitive to the α activity of the target isotopes and reflects the distribution of uranium within the sample. A homogeneous target is important for the precise examination of neutron induced fission cross sections.

Due to the high radiotoxicity, the plutonium samples will be placed in a metal-sealed vacuum chamber (Fig. 3). A continuous gas flow of P10 (90 % Argon + 10 % Methane) gas at 1 atm will be applied in combination with ultra high purity gas ceramic filters. Sealing and filtering are necessary to protect against release of radioactive particles with the counting gas flow.

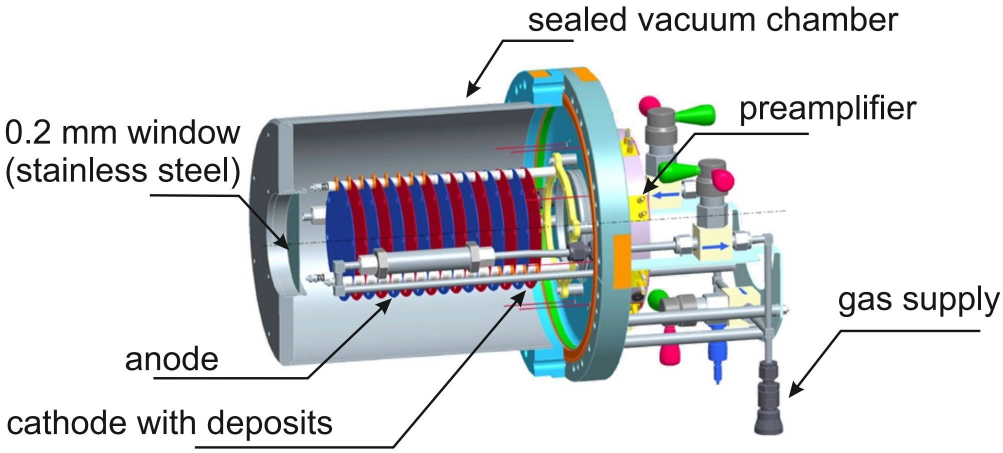

Fig. 3: Computer-aided design of the fission chamber.

The influence of the stainless steel filter housing on the electrical field homogeneity was examined using the finite element simulation COMSOL Multiphysics®. Small perturbations of the field are clearly visible in Fig. 4. An optimization was achieved by a re-arrangement of the filters and an improvement in the design of the support rods and the copper clamps used to contact the layers with the voltage supply and the preamplifier.

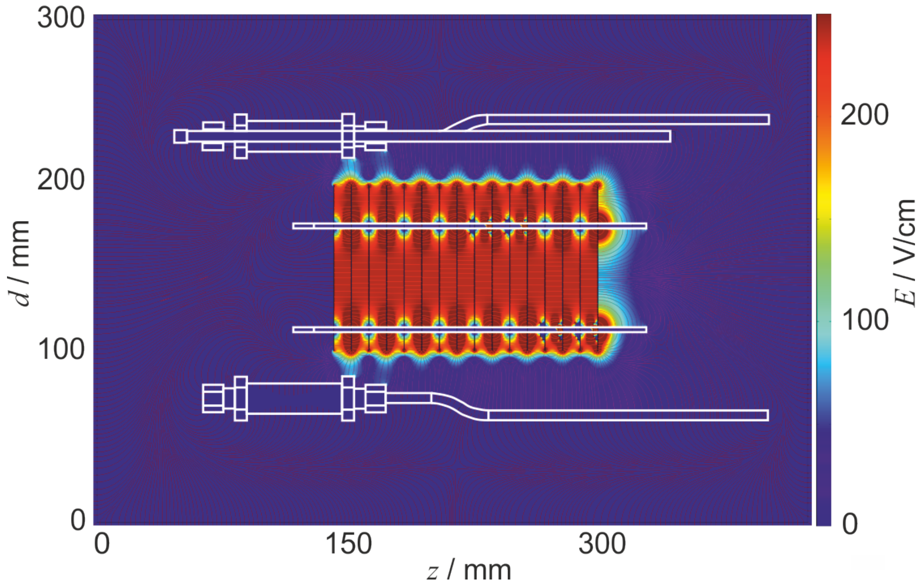

Fig. 4: Finite element simulation of the electric field within the fission chamber. The stainless steel ultra high purity gas filters and support rods are framed in white. Small perturbations of the field homogeneity are clearly visible arising from the small distance between filters and electrodes.

3 Simulations of pile-up

To handle the high specific α activity of the Pu targets, a combination of fast preamplifiers and digital signal processing has been developed to suppress pile-up effects. A fast charge-sensitive preamplifier was developed at HZDR that produces total signal times in the order of 300 ns and shows identical performance in terms of time and energy resolution compared to conventional preamplifiers with $10-100\ \mu$s decay constants. Nevertheless, pile-up events related to the α decay will influence the measurement. The α-decay rate per sample is expected to be 1.51 million per second. Occurring within a time window of typical signal rise-times of 110 ns, the probability of higher (2^{nd}, 3^{rd} and even 4^{th}) order pile-up is not negligible. This could lead to a misinterpretation of fission events. To optimize the target thickness and total mass, simulations have been performed using the GEANT4 framework [7].

To use an accurate distribution of fission fragments in the GEANT4 simulation, the charge, mass and kinetic energies of the fission fragments were simulated using the General Description of Fission Observables (GEF) code [8]. Accurate data describing the α decay of plutonium was provided by the radioactive decay package of GEANT4 (G4RadioactiveDecay).

The probability P_n of detecting n additional α particles to the primary particle is given by

$$P_n(R,\tau) = \frac{(R\tau)^n e^{R\tau}}{n!}, \tag{1}$$

where R denotes the expected detection rate and τ the time window, in which these events should occur. The fission rate was scaled with respect to a measurement at *n*ELBE using the ^{235}U fission chamber H19 [9] of the Physikalisch-Technische Bundesanstalt (PTB) Braunschweig. Within the simulation, pile-up up to the 4^{th} order was considered.

To create a realistic charge spectrum one also has to include the signal generation process into the simulation. The generated charged particle looses energy in the counting gas of the chamber and produces electron-ion pairs. Applying an electrical field between to electrodes, these charge carriers starting to drift in opposite directions. The induced charge on the anode [10] can be calculated by:

$$\begin{aligned} Q &= \int_0^D \frac{n_e(z)ez}{D}\mathrm{d}z \qquad \text{with:} \qquad n_e(z) = \frac{1}{W}\int_0^D \left(-\frac{\mathrm{d}E}{\mathrm{d}z}\right)\mathrm{d}z \\ &= \frac{e}{WD}\int_0^D \left(-\frac{\mathrm{d}E}{\mathrm{d}z}\right) z\mathrm{d}z \end{aligned} \tag{2}$$

Discretization:

$$= \sum_i \frac{e}{WD} E_i \begin{cases} (D - z_i) & \text{forward bias (anode readout)} \\ z_i & \text{reverse bias (cathode readout)} \end{cases} \tag{3}$$

Equation 3 is a sum over all steps of a simulated event and sums the created charge at position z ($n_e(z)e$) multiplied by the ratio of their travel length to the anode and the distance (D) between anode and cathode. The number of produced electron-ion pairs can be calculated by dividing the locally deposited energy E_i by the average energy per ion pair (W) [11]. The outcome of this procedure is given in Fig. 5.

With 50 mg of plutonium and an electrode distance of 5 mm, a separation of α-induced background events from the main part of the fission fragment distribution is only possible for the reverse bias case, where the amount of fission events below the threshold is higher than for the forward one and the induced charge is much smaller. An increase of the layer spacing to 7 or 9 mm (cf. Fig. 6) will be performed, if this will not worsen the time resolution too much. Simulations with this spacing predicted the number of fission fragments below a threshold of $Q_{\mathrm{FF}} \leq 100$ fC to be less then 0.9%. The distribution of fission fragments in the low energy range drops firstly linearly to rise again below 15 fC.

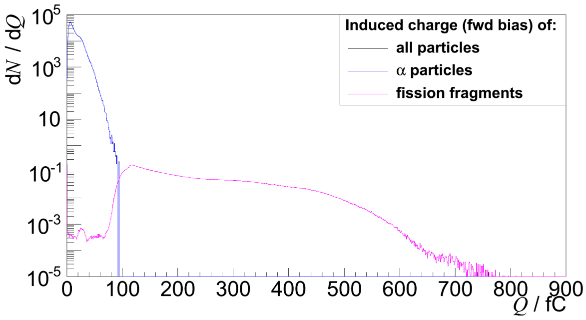

Fig. 5: GEANT4 simulated pulse height spectra of the decay products (blue) and fission fragments (magenta) from neutron-induced fission of the *n*ELBE plutonium target material in P10 counter gas. On the left side the forward biased case and on the right hand side the reverse biased case. The distance between anode and cathode was 5 mm.

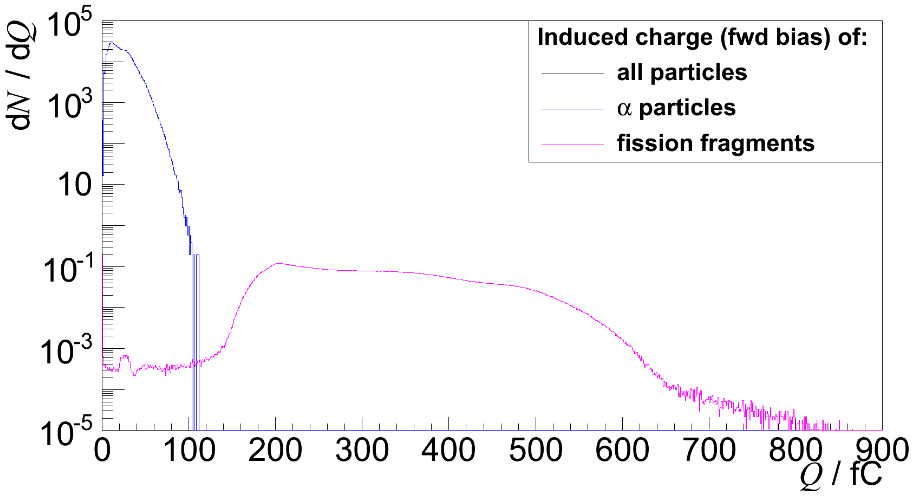

Fig. 6: Simulated forward biased charge spectrum for an electrode spacing of 9 mm. The used colour code is identical to Fig. 5.

4 Conclusions

Fast neutron-induced fission experiments on ^{235} U and ^{242}Pu will be performed at the neutron time-of-flight facility *n*ELBE in the near future. Fission cross sections will be examined using a parallel-plate fission ionization chamber. Different chamber parameters have been optimized by using extensive GEANT4 simulations and finite element methods. For the announced 50 mg of plutonium and the resulting target thickness, the loss of fission events below the trigger threshold is negligible low ($\approx 0.7\%$) and the calculated neutron-induced fission rate is high enough to perform experiments with sufficient statistics in less than one week. The construction of the uranium chamber was successfully completed and the analysis of the first *n*ELBE data is ongoing.

Acknowledgements

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