Excitation energy dependence of prompt fission γ-ray emission in fast neutron induced fission of ^{232}Th

Sukanya De[1,2], R. G. Thomas[1,2], G. Mishra[1], A. Mitra[1], Ajay Kumar[1]

[1]*Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400085, India*
[2]*Homi Bhabha National Institute, Anushakti Nagar, Mumbai-400094, India*

Introduction

Measurement of prompt fission gamma and neutron spectra for fast neutron induced fission of actinides has gained renewed interest due to its importance in the development of upcoming Generation IV reactors and accelerator driven systems for the transmutation of nuclear waste [1]. Prompt fission gamma spectra (PFGS) are essential for understanding the state of the fragments just after scission because they compete with the neutron emission at excitation energies greater than the neutron binding energy in the fragment and carry the majority of the angular momentum generated in fission. Furthermore, prompt gammas can deposit energy far away from where they are emitted, creating potential heating challenges in nuclear reactors [2]. Model calculations consistently under-predicted the prompt heat deposition by up to 28% [3]. Most of the computational models such as GEF, FREYA, CGMF, FIFRELIN, are data driven and depend on experimental data to benchmark their calculations. At present, very limited such experimental data exist where the PFGS have been extracted for more than a few excitation energies. Hence, we have initiated a program to study the PFGS obtained in the fast neutron induced fission of ^{232}Th at varying incident neutron energies. In an earlier work, we have carried out measurements at average incident neutron energies of 1.5 MeV and 2.8 MeV [4]. In this work, we report the results obtained from the measurements performed at a much lower threshold (~ 80 keV) in order to probe the variation in PFGS with varying excitation energies.

Experimental set-up

The experiment was performed at the Folded Tandem Ion Accelerator (FOTIA) facility, BARC, Mumbai. The primary quasi mono-energetic neutrons were obtained using the ^{7}Li(p,n)^{7}Be reaction [5] by bombarding the proton beam on a natural ^{7}Li metallic target of thickness ~ 4.0 mg/cm^2. Two 1.0 cm × 1.0 cm foils of ^{232}Th of thickness ∼ 2.0 mg/cm^2 were placed on either side of the cathode of a twin section parallel plate trigger ionization chamber. The cathode and the anode diameter were 7.5 cm and were separated from each other by 2.0 mm Teflon spacer rings. Each of the two sections functions as a separate fission trigger detector, thereby improving the fission detection efficiency. The fission fragments deposit a fraction of their energies within the trigger chamber by generating electron-ion pairs which produce an electrical signal.

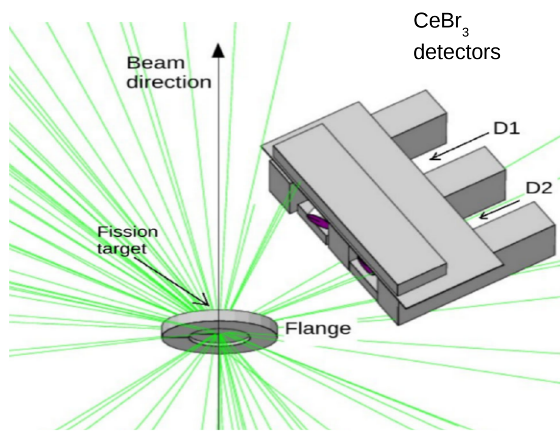

Fig. 1 Experimental setup modeled in GEANT4

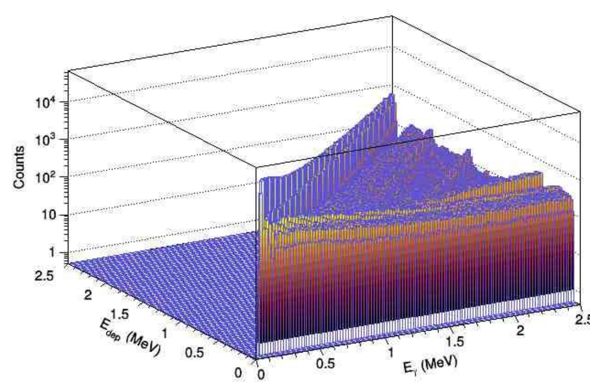

Fig. 2 Response matrix of one of the $CeBr_3$ detectors simulated using GEANT4

The γ-rays were recorded using two 1.5” × 1.5” cylindrical $CeBr_3$ detectors placed at distances of 20 cm and 22 cm from the fission detector. Negative voltages of 760 V and 800 V were applied to the PMT of the $CeBr_3$ detectors. The energy calibration of the detectors were carried out using three standard radioactive sources; namely ^{22}Na, ^{60}Co and ^{137}Cs [6]. A shielding arrangement was made using lead bricks in order to reduce the contribution due to background γ-rays. Total 10 lakh fission events were recorded at each incident neutron energy and ~ 10,000 gammas were measured in each of the $CeBr_3$ detector.

Analysis of experimental data

The analysis of experimental data was performed in the ROOT framework to extract all the observables. A coincidence prompt time window of ±10 ns was used in the data analysis. In order to extract the emission spectrum, the measured spectrum recorded in the $CeBr_3$ detector needs to be unfolded with the help of the response matrix of the detecting system. Simulations were performed using GEANT4 version 10.6 by incorporating the parameters obtained by fitting the energy spectrum of ^{60}Co and ^{137}Cs γ-ray sources in order to obtain the response matrices for both the $CeBr_3$ detectors in the experimental configuration [7]. The experimental setup modeled in GEANT4 is shown in Fig.1. A 3-D plot of the response matrix thus obtained for one of the $CeBr_3$ detectors is shown in Fig.2.

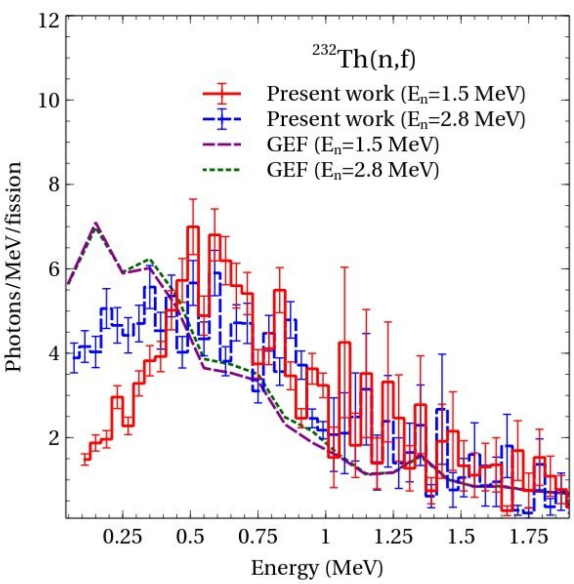

Fig. 3 The PFGS obtained from the present work for both the incident neutron energies along with the predictions of the GEF model.

The measured spectrum recorded in each of the individual $CeBr_3$ detectors for ^{232}Th(n,f) at both the incident neutron energies, were unfolded separately with the help of GRAVEL algorithm (iterative method) [8] using the corresponding response matrix of each detector. The final emission spectrum is then obtained by adding the emission spectra extracted for both the detectors which is normalized to the number of fission events. The unfolded PFGS for both the energies for ^{232}Th(n,f) along with the predictions of the GEF model are shown in Fig.3. It is quite evident that there is wide discrepancy between the experimental data and the GEF model predictions of the PFGS in ^{232}Th(n,f) at low gamma energies (<0.5 MeV). The statistical uncertainties, propagated through the γ-ray deconvolution algorithm have also been taken into account. The fragments de-excite via neutron evaporation until the available intrinsic energy falls below the neutron separation energy. Statistical photons are then emitted with a black-body spectrum modulated by a giant dipole resonance form factor. Changes in the PFGS characteristics with incident neutron energy can occur due to two different effects [9]. The first is due to variation in the fission yields where the relative contributions from each fission fragment depends on the incident neutron energy. The second is from the extra total fragment excitation energy (TXE) available for both neutron and γ-emission. In the low-energy region, the discrete γ-rays are mainly from electrical quadrupole transitions E2 along the Yrast line of the fission fragments. These low-energy contributions are superimposed on a continuous spectrum of statistical γ -rays, which are mainly E1 transitions [9]. Rigorous modeling of characteristic gamma emission is required to quantitatively understand the PFGS in the low energy region. Details will be presented in the symposium.

References

1. N. Colonna, et al., Energy Environ. Sci. 3, 1910–1917 (2010).
2. D. Gjestvang, et al., Phys. Rev. C 103, 034609 (2021).
3. S. Oberstedt et al., Physics Procedia 64 (2015) 83-90.
4. Sukanya De et al Eur. Phys. J. A 58 (2022) 217.
5. J.W. Meadows, et al., Argonne National Laboratory Reports, ANL 7938 Physics (1972).
6. G. Mishra et al NIMA 921 (2019) 33.
7. Sukanya De et al Eur. Phys. J. A 56 (2020) 116.
8. S. De, et al., JINST 13, T02010 (2018).
9. L. Qi et al., Phys. Rev. C 98, 014612.