

Measurements of γ -ray Energy and Multiplicity from $^{235}\text{U}(n_{\text{thermal}})$ using STEFF

A.J. Pollitt^{1,a}, A.G. Smith², I. Tsekhanovich³, J.A. Dare² and L. Murray²

¹Institut Laue-Langevin (ILL), 71 avenue des Martyrs, 38042 Grenoble, France

²Schuster Laboratory, University of Manchester, Manchester, M13 9PL, United Kingdom

³CENBG, Chemin du Solarium, 33175 Gradignan, France.

Abstract. The amount of energy carried by γ -rays during the fission process is an important consideration when developing new reactor designs. Many studies of γ -ray energy and multiplicity, from a multitude of fissioning systems, were measured during the 1970s. However the data from such experiments largely underestimates the heating effect caused by γ -rays in the structure of a reactor. It is therefore essential to obtain more accurate measurements of the energy carried during γ -ray emission. As such, the OECD Nuclear Energy Agency has put out a high priority request [1] for measurements of the mean γ -ray energy and multiplicity to an accuracy better than 7.5 percent from several fissioning systems; including $^{235}\text{U}(n_{\text{thermal}})$. Measurements of the γ -rays from these fissioning nuclei were performed with the SpecTrometer for Exotic Fission Fragments (STEFF).

1 Introduction

The study of the Nuclear Fission Process is essential for the development of new reactor designs. During the most common mode of fission, binary fission, a parent nucleus fissions into two daughters. The kinetic energy received by the fission fragments is approximately 90% of the reaction Q-value. For $^{235}\text{U}+n_{\text{thermal}}$, the Q-value is around 200 MeV.

The remaining 10% of the Q-value that is left over is emitted in the form of neutrons and γ -rays. Initially neutrons are emitted until the energy drops below the neutron binding energy of the fragments, the remainder is emitted in the form of γ -rays. Therefore the emitted γ -rays have energies which extend up to a maximum energy of around 8 MeV.

Although the fraction of the Q-value energy carried by γ -rays is relatively small, understanding exactly how much energy they carry is of paramount importance. This is due to the fact that γ -rays are not localised and can propagate relatively easily to the outer regions of the reactor. Therefore when considering the shielding of the reactor core and the materials used in the reactor outer regions, it is very important to understand the γ -ray dose as a function of γ -ray energy.

Recent investigations into reactor core heating have discovered that there is a discrepancy between simulation codes and measurements with the simulation codes underestimating the core heating by as much as 16% [2]. This has largely been attributed to deficiencies in the data-files that are used by simulations. When several data libraries (JEFF3.1, ENDF/B-VI.8 and JENDL3.3) were examined further, it was found that the γ -ray data measurements

were performed in the 1970s. This led to an OECD Nuclear Energy Authority (NEA) high priority request [1] being created for new measurements of γ -ray data from several fissioning systems. This included the total γ -ray energy and multiplicity from $^{235}\text{U}+n_{\text{thermal}}$.

2 Measurements

In pursuit of addressing the NEA high priority request, measurements were performed with the SpecTrometer for Exotic Fission Fragments (STEFF). This is a 2-velocity, 2-Energy spectrometer which can independently measure both the mass and kinetic energy of both fission fragments in binary fission. A diagram of the spectrometer can be seen in Figure 1.

The velocity of each fission fragment is measured by the fragment time-of-flight sections and the kinetic energy of the fragments is measured by the pulse height of the signals in the respective ionisation chambers. The mass and energy resolutions for light mass fragments have been determined to be $\Delta A \sim 4u$ and $\Delta E \sim 1$ MeV respectively. The spectrometer is also sensitive to the atomic number, Z of the fission fragments. A recent X-ray experiment enabled the calibration of the ionisation chambers in terms of Z .

Two measurements were performed with STEFF: the first with a $^{252}\text{Cf}(sf)$ source at the University of Manchester (for developing the analysis methods) and the second with a ^{235}U target on the PF1B neutron beam line (moderated to thermal neutrons) at the ILL, Grenoble.

3 Data Treatment & Results

In order to measure the true γ -ray spectrum from the studied fissioning systems, one must remove contributions

^ae-mail: pollitt@ill.fr

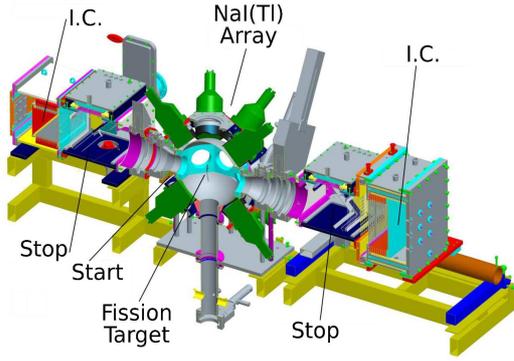


Figure 1. A diagram of the SpecTrometer for Exotic Fission Fragments (STEFF). The fission source/target is located at the centre of the NaI(Tl) γ -ray detector array. Time-of-flight sections are located on each arm of the spectrometer between a central common MCP-secondary electron start detector and an MWPC secondary electron mirror stop detector. The kinetic energy of the fragments is measured by ionisation chambers (I.C.) located at the extremities of each arm.

from other effects in measured γ -ray spectra. The first of these effects are the neutrons measured by the NaI(Tl) detectors. These are removed by considering the time-of-flight difference between neutrons and γ -rays from the source/target to the NaI detectors. The neutrons are considered to have an energy distribution characterised by a Watt distribution [3]. Using this empirical distribution (which is individual to the particular fissioning system) one can set a timing cut off to remove the neutron contribution in the NaI(Tl) timing spectra as shown in Figure 2.

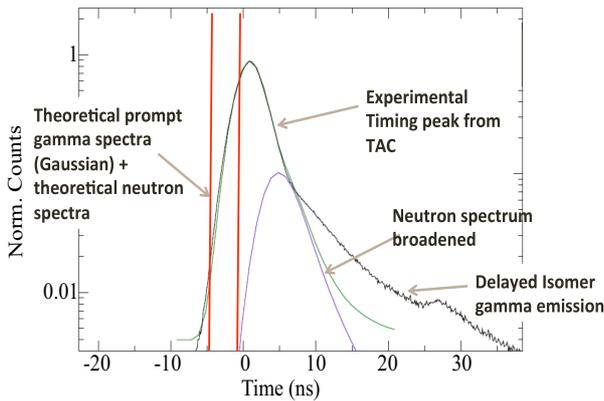


Figure 2. Timing spectra from an NaI(Tl) detector with gating region for γ -rays shown in red.

3.1 γ -ray Energy Measurements

The remaining spectra (post neutron removal), f , are a convolution between the emitted γ -ray energy spectrum (u) from the target/source material and the detector response

functions,

$$f = Ru. \quad (1)$$

Here R is a matrix of detector response functions, that is an array of response functions to monochromatic γ -ray lines as a function of γ -ray input energy. The unfolded spectrum is then obtained by inverting this matrix,

$$u = R^{-1}f. \quad (2)$$

In order to produce a response function array, one should normally measure a series of monochromatic γ -ray sources over and beyond the range of the spectra which are to be deconvolved. Then an interpolation is performed to generate the intermediate matrix elements. This however would require the use of monochromatic γ -ray sources with emitted gamma-ray energies up to and beyond 8 MeV, something that was not available. Instead, the response function matrix was produced by performing a large series of Geant4 simulations of monochromatic sources. The geometry of the STEFF spectrometer was simulated and simulations were performed at 10 keV intervals from 10 keV to 20 MeV, covering the energy region required for deconvolution. These were compared with measured (with STEFF) lines from ^{60}Co and ^{137}Cs to determine whether the Geant4 geometry was correct. Figure 3 shows a deconvolved $^{235}\text{U}(n_{\text{thermal}})$ spectrum with mean γ -ray energy of 1.13 MeV. Presently the systematic error for high energy gamma-rays is being investigated due to discrepancies with other works.

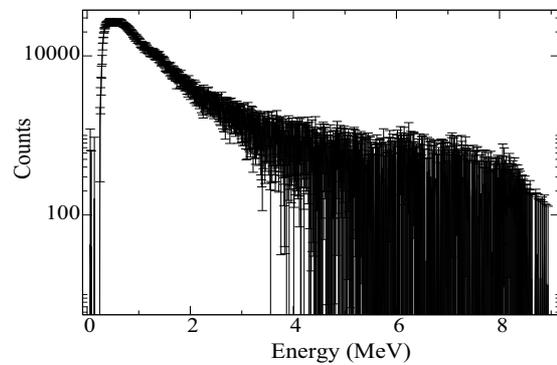


Figure 3. Unfolded γ -ray spectrum (from all detectors summed together) from $^{235}\text{U}(n_{\text{thermal}})$ data taken at the ILL.

During the Geant4 simulations, each γ -ray event is performed sequentially. However, often during γ -ray measurements, two or more γ -rays will be detected in parallel (within the timing resolution of the NaI(Tl) detectors). This leads to an event falsely being measured to be sum of the individual γ -ray energies. This was corrected by employing the following procedure: A deconvolved γ -ray spectrum (for a single detector) was used to produce a cumulative distribution function (CDF) for γ -ray energy. The CDF was used to determine the input energies for Geant4 for a large series of simulations. By using the Geant4 γ -ray output data, along with the determined multiplicity distribution (see Section 3.2) one can determine whether, during

a fission event, more than one γ -ray has been detected by a single detector. The falsely measured γ -ray events can be quantified in terms of their occurrence as a proportion of the number of measured events as a function of γ -ray. This is known as the multiple hit fraction and can be seen in Figure 4.

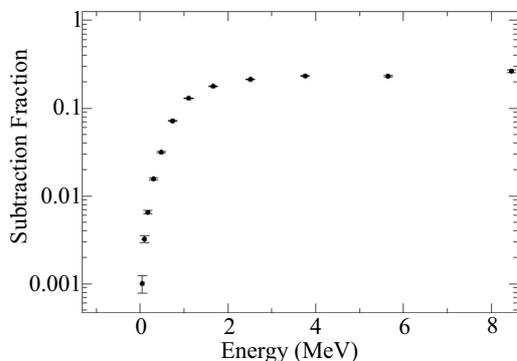


Figure 4. Multiple hit fraction for several γ -rays entering a detector simultaneously as a function of measured γ -ray energy.

3.2 γ -ray Multiplicity Measurements

STEFF does not have the ability to directly measure the mean γ -ray multiplicity of fission targets such as $^{235}\text{U}(n_{\text{thermal}})$. This is because the multiplicity distribution has contributions from multiplicities which are greater than the number of NaI(Tl) detectors in the STEFF array.

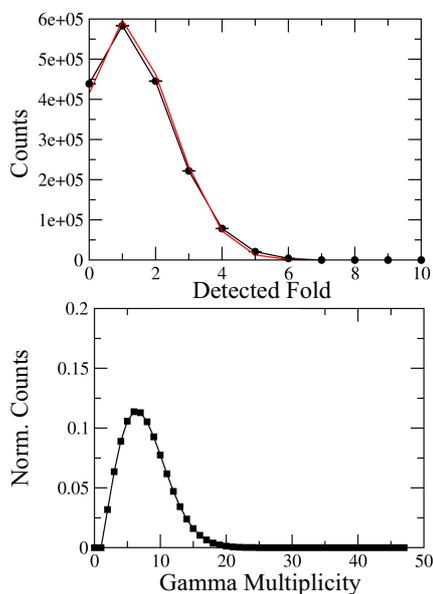


Figure 5. Top: Fold distribution measured by STEFF (black) compared with idealised fold distribution (result of Monte Carlo - red); Bottom: Multiplicity distribution used to generate idealised fold distribution.

However STEFF does have the ability to measure a fold distribution. A Monte Carlo simulation code has been developed in which a idealised multiplicity distribution is generated, this is then combined with the efficiency of the NaI(Tl) detector array to produce an idealised fold distribution. This is compared to the measured fold distribution and by varying the width and peak position of the idealised multiplicity distribution, the χ^2 can be minimised as shown in Figure 5. This therefore enables a determination of the multiplicity distribution of the fission source/target. The multiplicity distribution is generated using a skewed Gaussian distribution based upon the Huizenga and Vandebosch [4] statistical model of γ -ray de-excitation from a fission fragment.

A current value of the mean multiplicity from $^{235}\text{U}(n_{\text{thermal}})$ is 7.76 ± 0.23 .

4 Conclusion

Measurements of average γ -ray energy and average γ -ray multiplicity from $^{235}\text{U}(n_{\text{thermal}})$ have been performed with the STEFF spectrometer at the ILL. Methods of analysing the data have been developed, including the removal of neutrons and the deconvolution of detector responses. Current values of the average γ -ray energy and average γ -ray multiplicity are 1.13 MeV and 7.76 ± 0.23 respectively. This would indicate a total γ -ray energy of 8.77 MeV. However, presently there are discrepancies in the high energy γ -ray region between measurement and other works. Systematic effects are being investigated.

Acknowledgements

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References

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