# Gamma-ray multiplicity measurements using STEFF

A.J. Pollitt<sup>1</sup>, A.G. Smith<sup>1</sup>, I. Tsekhanovich<sup>2</sup> and J.A. Dare<sup>1</sup>

<sup>1</sup>School of Physics and Astronomy, University of Manchester, Manchester, M13 9PL, The United Kingdom

<sup>2</sup>Université Bordeaux 1, CNRS/IN2P3, Centre dEtudes Nucléaires de Bordeaux-Gradignan, CENBG, Chemin du Solarium, BP 120, 33175 Gradignan, France

E-mail: andrew.pollitt@postgrad.manchester.ac.uk

Abstract. An ongoing investigation into the angular momentum generated during the fission of  $^{252}$ Cf is currently under way using the SpecTrometer for Exotic Fission Fragments (STEFF). Measurements have been made of the fold distribution (measured multiplicity) with STEFF. These have been compared to a Monte-carlo simulation to determine a value for the average angular momentum  $J_{rms} = 6\hbar$  which is comparable to previous measurements [1]. Measurements of the gamma-ray multiplicity were performed whilst gating on different fragment mass regions. The result was compared with a sum of the lowest  $2^+$  energies from both fragment and complementary in the mass gate. The results support the view that gamma-ray multiplicity is largely determined by the decay of the nucleus through near yrast transitions that follow the statistical decay.

#### 1. Introduction

Nuclear fission process, is a process by which a heavy unstable nucleus (with zero angular momentum in the case of  $^{252}$ Cf in the ground state [2]) breaks up into smaller, more tightly bound fission fragments. Most of the excess energy from this process manifests itself as kinetic energy of the fragments. The fragments also gain some angular momentum during the process.

As the fission fragments decay from a state of high energy and angular momentum, they emit neutrons and gamma-rays carrying away energy and angular momentum as shown in Figure 1. The angular momentum taken by neutrons is considered to be small [3] and has provisionally been neglected in this model. The gamma-ray emission takes two distinct forms in the deexcitation: statistical gamma-rays and yrast gamma-rays. Statistical gamma-rays are high in energy, typically > 1 MeV, and carry relatively small amounts of angular momentum. The number of statistical gamma-rays per fission is roughly constant for <sup>252</sup>Cf [4]. In contrast, yrast gamma-rays are lower in energy but are the predominant way in which angular momentum is carried away. The yrast gamma-rays are considered to be proportional in number to the units of angular momentum possessed by the fragment after neutron and statistical gamma-ray emission.

The purpose of this work is to investigate the relationship between this angular momentum generated and the gamma multiplicity.

#### 2. SpecTrometer for Exotic Fission Fragments (STEFF)

The SpecTrometer for Exotic Fission Fragments (STEFF) is a device constructed for the purpose of the identification fission fragments through their mass, A and atomic number, Z. STEFF



**Figure 1.** A diagram to illustrate the decay of a fission fragments through neutron, statistical gamma-ray and yrast gamma-ray emission.

is a 2-velocity, 2-energy (2v2E) spectrometer which means that it can be used to determine the velocity and the kinetic energy of both fragments in a single fission event independently. The advantage of making such independent measurements is that the uncertainty in the mass measurements due to neutron evaporation is eliminated. The mass of each fission fragment is calculated through the simple relation  $A = 2E_{kin}/v^2$ , where A is the mass,  $E_{kin}$  is the kinetic energy and v is the velocity, of the fragment.

Figure 2 shows a schematic diagram of STEFF. Situated at the centre is the central reaction chamber which houses the source/target. Surrounding this chamber is an array of 12 NaI(Tl) scintillation detectors, used for gamma-ray and neutron measurements. Attached to the central chamber along one axis are two arms, each arm has a time-of-flight section, used to measure the velocity of the fission fragments over a known distance. The start detector is common to both arms and consists of an aluminised foil, an electrostatic mirror and a microchannel plate. As fission fragments pass through the foil, they liberate secondary electrons, these electrons are accelerated through 90 degrees into the microchannel plate. The stop detectors have similar design features except they are larger in size to conserve solid angle. Instead of using microchannel plates, they use segmented multi-wire proportional counters (MWPC's) to detect secondary electrons. Just beyond the position of the stop detectors on each arm, there is an ionisation chamber used to determine the total kinetic energy of an individual fragment  $(E_{kin})$ .

Another application of the ionisation chambers is to determine the atomic number Z of the fragments. The geometry of the anode and electric field guide rings are orientated to create an axially symmetric electric field inside the ionisation chamber. As fission fragments pass into the chamber, they create a trail of ionisation. The electrons liberated during the ionisation process drift towards the anode at a constant velocity, preserving the shape of the pulse trace. Analysis of pulse traces of this kind for the purpose of Z determination was attempted with limited success in the 1980's, using conventional analogue electronics to discriminate pulses [5]. Through the advancements in digital electronics, each pulse trace can now be stored on an event



Figure 2. A cross sectional diagram of the SpecTrometer for Exotic Fission Fragments. This shows the positions of the start detector, stop detectors and axial ionisation chambers.

by event basis. This allows one to perform pulse shape analysis on the stored pulse traces for the determination of Z.

A recent calibration measurement of pulse traces from fission fragments of differing mass and atomic number has been carried out. It was performed using a FIFI ionisation chamber attached to the Lohengrin (PN1) mass separator at the Institut-Laue-Langevin (ILL), Grenoble, France. The analysis of these data is currently being performed.

### 3. Mass and Energy calibration

The mass and kinetic energy measurements are calibrated using a prescription given by Schmitt et al [6]. This uses a jacobian matrix transformation to transform from a raw pulse amplitude (in the ionisation chamber) vs time-of-flight matrix into a calibrated kinetic energy vs calibrated mass matrix. The transformation takes the form of,

$$F(M,E)\Delta M\Delta E = G(x_E, x_t) \begin{pmatrix} x_E & x_t \\ M & E \end{pmatrix} \Delta M\Delta E,$$
(1)

where E is the calibrated kinetic energy, M is the calibrated mass,  $x_E$  is the raw energy measurement,  $x_t$  is the raw time-of-flight measurement,  $G(x_E, x_t)$  is the number of counts at  $x_E, x_t$  in the raw matrix and F(M, E) is the number of counts at M, E in the mass-energy matrix. The relations used in the transformation are as follows,

$$t_f = c_t + a_t x_t^2 - b_t x_t, (2)$$

$$E = (a + a'M)x + b + b'M,$$
(3)

where  $t_f$  is the calibrated time-of-flight,  $x_f$  is the raw time-of-flight, E is the calibrated kinetic energy and M is the calibrated mass. All other parameters are constants dependent upon the system used.

Figure 3 illustrates the process of mass and energy calibration. Initially estimates of the constants are made, a transformation from the raw matrix to the calibrated mass-energy matrix is performed. The axis of this matrix are projected out into two 1-dimensional spectra, each of these (mass and energy spectra) are compared with previous measurements. A least square fit measurement between the spectra is calculated and a simplex routine is used to minimise the  $\chi^2$ . From this, one can determine the overall mass and energy resolutions to be 4.0 u and < 1 MeV respectively.



Figure 3. Flow diagram to illustrate the process of calibrating mass and kinetic energy.

This was originally used for measurements taken with silicon detectors, however it is suitably generic that one can apply it to ionisation chambers. The benefit of using the prescription as a calibration is that is constrains the co-varying mass and calibrated energy calibration coefficients.

### 4. Gamma-ray Multiplicity Measurements

As one can see in Figure 4 (left), the multiplicity distribution of <sup>252</sup>Cf has components above multiplicity 15. The STEFF NaI(Tl) array only contains 12 detectors, therefore this limits a direct measurement of the multiplicity up to multiplicity 12 events. This means direct measurements are not feasible with the current detector array.

A Monte-carlo code has been created to simulate a multiplicity distribution for a given root mean square (rms) angular momentum of the primary fission fragments. The angular momentum of each fission fragment is simulated through a statistical model [7] (with rms angular momentum being an input parameter). A simple linear relationship between the fragment angular momentum and the number of gamma-rays required to carry it away is used. This makes up the yrast contribution to the multiplicity, therefore the addition of the statistical gamma-rays is required to get the overall multiplicity of gamma-rays. This is simulates for many fragments ( $\sim 10^6$ ) to produce a distribution.

A  $^{60}$ Co calibration source was used to determine the efficiency and scattering properties of the NaI(Tl) array. Using these array properties and the simulated multiplicity, an idealised fold spectrum (measured multiplicity distribution) was created. Using a least square routine one can compare the idealised spectrum with a fold spectrum measured by STEFF. By varying the rms

angular momentum of the fragments as an input parameter to the model, one can minimise the  $\chi^2$ , determining the rms angular momentum of the angular momentum distribution. The result of such a minimisation for <sup>252</sup>Cf gave the values of  $J_{rms} = 6\hbar$  (similar to A.G. Smith et al [1]) with a modal multiplicity of ~ 7, as shown in Figure 4 (right). One can compare this with previous a measurement of the multiplicity distribution, shown in Figure 4 (left), which has a similar modal value.



Figure 4. Left: Theoretical predictions [8] and previous experimental [9] measurements of the gamma-ray multiplicity distribution for  $^{252}$ Cf. Right: The gamma-ray multiplicity distribution from this work.

Since with STEFF there is the ability to gate on different masses, one can see how this varies across the different mass regions of the fission fragments. However, the overall multiplicity when gating on different masses also includes the gamma-rays from the complementary fragment. Figure 5 (left) shows the overall gamma-ray multiplicity gating over the light mass region.

In order to get a feeling for how the nuclear structure of the fragments affects the gamma-ray multiplicity; one has to construct a nuclear structure parameter dependent upon the structure of both the gated fragment and its complimentary. This was done by summing the lowest  $2^+$  energies for the nucleus with the highest yield (for  ${}^{252}$ Cf fission) in the mass gate and the most probable complimentary. The data were taken from the National Nuclear Data Center (NNDC) [10], Figure 5 (right) shows this parameter plotted over the same mass region as the multiplicities.

If we assume rotational energy levels then there is a simple connection between the energy of the levels and the moment of inertia, given by  $E = I(I+1)\hbar^2/2\mathcal{J}$ . Where E is the energy of the state, I is the angular momentum of the state and  $\mathcal{J}$  is the moment of inertia of the nucleus. It is well known that these states are much lower in energy than single particle states; typically 90 keV for the lowest  $2^+$  state. Therefore a collective nucleus will have more energy levels within the available excitation energy from fission than a spherical nucleus. Hence a deformed nucleus will give rise to a higher gamma-ray multiplicity. Comparison of the graphs in Figure 5 suggest this relation between the multiplicity and the nuclear structure of the fission fragments is observed.

## 5. Conclusion

STEFF has been calibrated for mass and energy and has been used to perform gamma-ray multiplicity measurements. These measurements have been used to investigate the angular momentum generation in the nuclear fission process. The results support the view that gamma-ray multiplicity is largely determined by the decay of the nucleus through near yrast transitions that follow the statistical decay. The number of these transitions is linked to the rotational level density and thereby the moment of inertia.



Figure 5. Left: A plot to show the sum of the gamma-ray multiplicity from the mass gated light mass fragment and its complimentary heavy mass fragment. Right: A plot to show the sum of the energies from the lowest  $2^+$  states in the mass gated light mass fragment and its complimentary heavy mass fragment. Data from NNDC [10]

### 6. Aknowledgements

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