High–Energy γ–Rays in Heavy–Ion Fusion–Fission

J. B. Fitzgerald
Max–Planck–Institut für Kernphysik, W-6900 Heidelberg FRG

Recent experimental studies have provided extensive information on the de-excitation of fission fragments from heavy–ion fusion–fission reactions [1]. All of the measured contributions – γ-ray emission (measured for $E_\gamma \leq 3$MeV), neutron evaporation (see also [2]) and fragment TKE – are either constant with mass or rather smooth. However, the calculated energy release, from ground-state mass evaluations, shows a local maximum when the heavy fragment is in the A$\sim$132 region with spherical ground-state configurations (rather than near symmetry, in the A$\sim$100 region of deformation). This poses the question: where does the additional energy release go to, if not neutrons and low-energy γ-decay?

It was proposed [1] that the difference between the observed decay energy (in γ-rays below 3MeV and neutrons) might be carried by higher-energy γ-rays. It would be surprising if the γ-ray spectrum above 3MeV showed large variations as a function of mass; the very low-energy part of the spectrum shows small differences in the discrete component (the "E2–bump") related to nuclear structure properties of the fragments, and these differences are well understood. The statistical component however appears to be similar for all masses (up to $E_\gamma \leq 3$MeV). On the other hand, there have been recent direct and indirect indications of possible radiative transitions accompanying large shape changes in fission fragments. In the thermal neutron induced fission of ^{248}Cm [3], "hot" fission events (those with low TKE and long scission configurations) appear to show lower than expected neutron emission, and it has been suggested that the fragments may relax from these highly deformed states to their ground-states without particle emission. In the spontaneous fission of ^{252}Cf [4],[5], an increased so-called "non-statistical" component has been observed at 3–8MeV in the γ-spectrum near symmetric mass splits (A$\sim$126).

In order to investigate this surprising possibility, an experiment has been performed with the Heidelberg-Darmstadt Crystal Ball 162 element 4π NaI scintillator array. A total of 5 million fragment–fragment–γ coincidence events were recorded from the heavy-ion fusion-fission reaction ^{197}Au(^{19}F,f) at a beam energy of 115MeV, with the fragments detected in a pair of symmetrically placed position-sensitive parallel-plate avalanche counters (PPAC) for determination of the fragment mass asymmetry. The Crystal Ball was used to record γ-ray spectra up to 20MeV as a function of fragment mass.

The Crystal Ball allows clean separation of neutrons and γ's by time-of-flight. The γ–ray spectra in coincidence with symmetric mass-splits (in the mass region 94≤A≤119) and with events with one fragment in the mass region 130≤A≤135 are shown in figure 1. The spectra are normalised on the number of fission events in each mass cut, and as expected are rather similar below 3MeV and above 9MeV (the entrance channel GDR region). However, in the region 3–9MeV, the asymmetric masses show clearly enhanced γ-ray intensity. In total, the yield in this region is increased by 32% for 130≤A≤135. Figure 2a shows the ratio of the γ-ray intensity for A∼132 to that for symmetric mass splits as a function of γ-ray energy. The yield at 6MeV is increased by a factor of 1.8, corresponding to a very large enhancement.

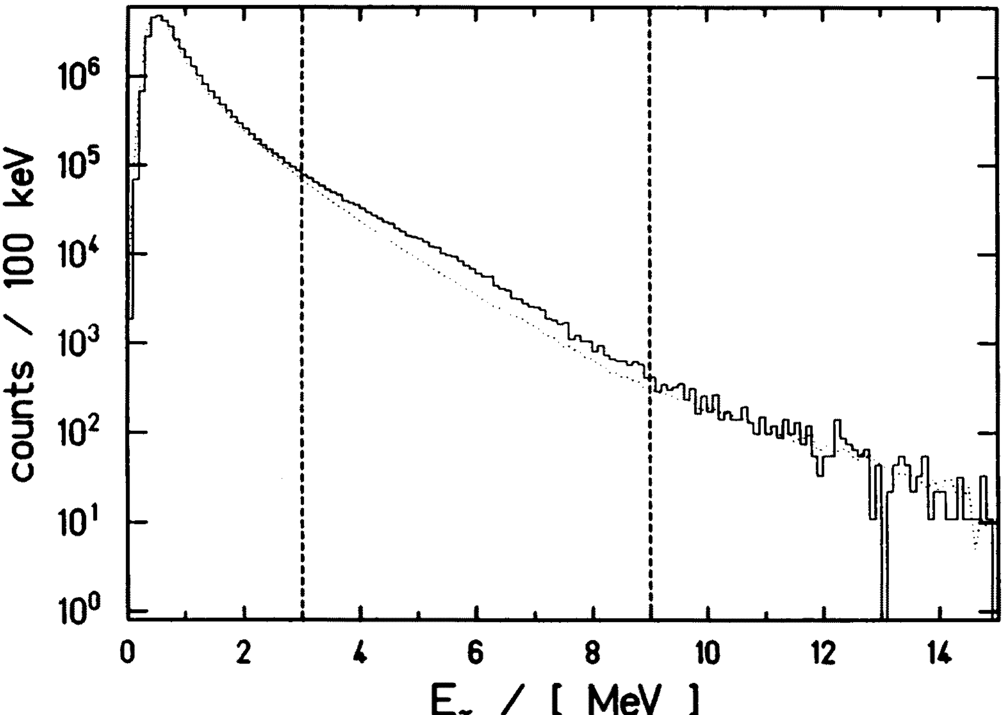

Figure 1: Energy spectrum for γ-rays from 130≤A≤135 (solid) and from symmetric mass splits (dotted line)

The increased yield in the region 3–9MeV (compared to the yield at symmetry) is plotted as a function of fragment mass in figure 2b. Since the γ-ray is observed in coincidence with both fragments, and there is no means of assigning it to one or other of the fragments on an event-by-event basis, the yield is plotted against both fragment masses. The observed yield in this "bump" (uncorrected for detector efficiency) reaches a maximum of 6.5 γ's per 100 fissions at A=132, with a mean energy of nearly 5MeV. Correcting for the Crystal Ball response function, and taking account of the broadening introduced by the PPAC mass resolution, suggests a figure of ∼15 γ's per 100 fissions (A=132), or around 1MeV per fission on average. If the yield of such γ-rays shows fine structure as a function of fragment mass (or of neutron

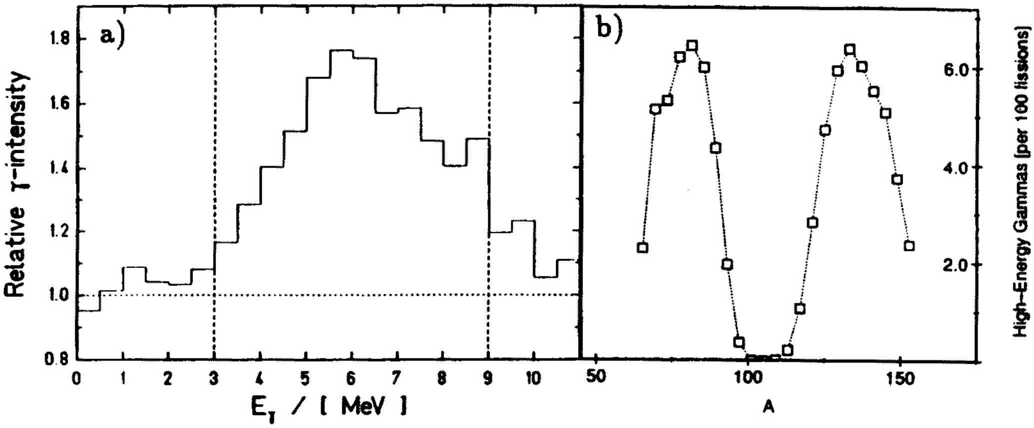

Figure 2: a) Ratio of γ-yield for $130 \leq A \leq 135$ to yield at symmetry
b) Excess γ-yield (compared to symmetry) vs fragment mass

or proton numbers) then the maximum yield for a given fragment may be even higher. This new component is clearly a very significant contribution to the total fission decay energy. It should be noted that, by plotting the γ-ray excess yield divided by the fragment yield, mass resolution effects lead to an overestimate of the true γ-yield for very asymmetric fissions (where the mass yield is sharply dropping).

The distribution of the high-energy γ-ray excess yield is very similar, for the heavy fragment only, to that from ^{252}Cf [5], suggesting that this effect is indeed associated with the A$\sim$132 region (rather than, for example, special symmetry properties of the system). Furthermore, in both systems, the total excess yield is around 20 times higher than the yield of any strongly produced product nucleus in the mass region where the "bump" is observed. If only one nucleus were emitting such γ's, this would correspond to $\sim$100MeV per nucleus. A more realistic estimate, assuming 1 γ is emitted per nucleus, suggests that at least 20 isotopes are involved in producing the "bump". In fact more neutron rich products are formed by ^{252}Cf s.f. than by ^{19}F+^{197}Au, indicating that a rather large area of the N-Z plane is responsible. The effect cannot therefore be ascribed to the spectroscopic properties of a single nucleus or even a few nuclei, or to a special proton or neutron number, but is associated with a large range of nuclei.

The mechanism producing such high-energy γ's is unknown, but the data strongly suggest an association with the mass 120–140 region, where a large shape change is undergone on passing from the scission point to the ground-state. Such nuclei also exhibit relatively "hard" shapes or increased "stiffness" at some point during this process, and it has been suggested that this property may be associated with the increased yield of high-energy γ's. Alternative theories have suggested that the emission of the γ-ray is related to vibrations or oscillations of the combined system following scission [6]. In this model, however, the excess γ yield was predicted at (and symmetically about) half the mass of the fissioning system. The comparison of data from the two systems now investigated does not therefore support this alternative description.

Additional systems have now been studied experimentally to provide further data on this new phenomenon, and the analysis is underway; in particular, the reactions $^{18}O+^{232}Th$ and $^{18}O+^{238}U$ should give results for a different spread of isotopes in the N-Z plane (between $^{19}F+^{197}Au$ and ^{252}Cf in terms of neutron-richness). The data should also provide a comparison to the ^{252}Cf data, for which the total mass is similar, but the heavy-ion reactions show symmetric fission yields rather than the asymmetric yield observed in spontaneous fission. In addition, heavy-ion reactions can probe different shapes and fragment excitation energies. Further experimental investigations are also planned.

References

[1] J.B. Fitzgerald, Proc. 22nd Masurian Lakes Summer School on Nucl. Phys., Piaski (1991) 1 (and references therein)

[2] D.J. Hinde, D. Hilscher, H. Rossner, B. Gebauer, M. Lehmann and M. Wilpert (submitted to Phys. Rev. C)

[3] P. Koczon, M. Mutterer, J.P. Theobald, P. Geltenbort, F. Gönnenwein, A. Oed, M.S. Moore, Phys. Lett. **B191** (1987) 249

[4] P. Glässel, R. Schmid-Fabian, D. Schwalm, D. Habs, H.U. v. Helmolt, Nucl. Phys. **A502** (1989) 315c

[5] A. Wiswesser, Diploma thesis, MPI für Kernphysik Heidelberg (1992)

[6] K. Dietrich and J. Bondorf (to be published)