Proposed experimental study of ^{242,243,244}Fermium as a probe for fission away from N=152

H. M. Devaraja[1], P. K. Rath[1,*], S. Roy[1], M. Gupta[1], Y. K. Gambhir[1] and G. Münzenberg[1,2]
[1]*Manipal Centre for Natural Sciences, Manipal University, Manipal 576104, Karnataka, India,*
[2]*GSI Helmholtzzentrum für Schwerionenforschung GmbH, Planckstr. 1, D64291 Darmstadt, Germany*
**email: pk.rath@manipal.edu*

Introduction

It is well known that the heaviest elements exist only due to shell effects which serve to stabilize nuclear systems. Macroscopic liquid drop barriers disappear by the start of the Super Heavy Element (SHE) region at Rutherfordium (Z=104). The existence of shell effects allows for additional and competing decay modes including spontaneous fission. The actinides and in particular, the Fermium isotopes have exhibited interesting modes for spontaneous fission with the first observation of a symmetric mass division in ^{257}Fm confirmed by [1]. The mass split was attributed to the nuclear structure of the fragments attracting them to the doubly magic configuration around ^{132}Sn (Z=50, N=82) which was reasonable. ^{258}Fm and ^{259}Fm also exhibited symmetric fission as expected. However, the surprise came with the measurements of mass yields and kinetic energy distributions for ^{258}Fm and ^{259}Fm which were very different from ^{257}Fm and exhibited unusually high TKE deviating from the well-known Unik [2] and Viola [3] systematics derived for the lighter actinides. The variance was extremely large and the possibility that this may be linked to other effects such as shape elongation of the fissioning system associated with a different fission path [*e.g.* 4] was raised. Another surprise was that an increase in excitation energy in ^{258}Fm* led to a large decrease in the yield through symmetric fission. The observation was counter-intuitive since at higher excitation energies shell effects are expected to be washed out causing the nucleus to decay like a liquid drop resulting in an increase in symmetric fission with a broader distribution. By this time ^{256}Fm was already known to exhibit asymmetric fission and it was suggested that perhaps ^{257}Fm could be a “transition” nucleus exhibiting both fission modes. Recent measurements [5] for ^{257}Fm show that it decays preferentially by emitting an alpha particle making it difficult to confirm the suggested fission properties with the small SF branch of about 0.2%. However, the above observations point to the possibility that the systematic study of SF in the fermium isotopes could serve as a valuable probe of the fission process where many questions remain unanswered. For instance, with modern techniques, it is seen that there is a pronounced increase in fission half-lives of Fm isotopes around the N=152 neutron shell. A study of fission in all the lighter isotopes may reveal a point at which this stabilising effect may diminish or vanish altogether. In an early work, Ter-Akopian *et al* [6] measured an SF half-life for ^{242}Fm (0.8 ± 0.2 ms) which was only a factor of 4 less than ^{244}Fm (4 ms) but about 10^3 times that expected by systematics. Based on their observations, they postulated that the stabilising effect of the shell at N=152 would be mostly ineffectual at N=144 (^{244}Fm). They argued that the longer half-lives of the heavier isotopes could be attributed to greater stability due to a second barrier around N=152 delaying the fission process. In the absence of the second barrier around N=144 and below, SF half-lives would be shorter as they would only be determined by penetrability through the first barrier which is a much faster process. If so, a smoother trend to the fission barrier could be expected with less variations in SF half-lives [7] around N≤144. The first step in such studies would be to independently confirm the fission half-life with which various other quantities are linked. In this context, and a model example we propose a confirmation study for SF in $^{242\text{-}244}$Fm at accelerator facilities available in India. Spontaneous fission in Fermium isotopes has been studied most recently using ^{40}Ar on ^{206}Pb

(2n) [8] and ^{40}Ar on ^{204}Pb [9]. In this work, we report the calculated production cross sections for $^{242\text{-}244}$Fm using ^{40}Ar as projectile incident on ^{206}Pb. The natural abundance of ^{206}Pb (~24%) is large enough to be used as a target.

Calculated cross-sections

We have performed calculations using HIVAP [11] with the prescription developed in [12]. The calculated evaporation residue cross sections with excitation energy of the compound nucleus for the reaction ^{40}Ar+^{206}Pb leading to the synthesis of various isotopes of Fermium are shown in Fig. 1.

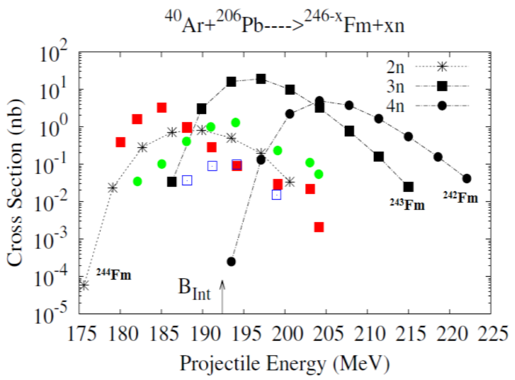

Fig. 1: Calculated cross sections for $^{242\text{-}244}$Fm. Experimental data for ^{244}Fm (red squares) and ^{243}Fm SF branch, (green circles) and alpha decay branch (blue open squares) taken from [9] are also shown for comparison. The Bass interaction barrier [13] is indicated by an arrow.

The primary decay mode for $^{242,\,244}$Fm is expected to be asymmetric SF whereas ^{243}Fm decays primarily by alpha (~91%) with a measureable fission branch (~9%) [5]. The highest cross-section of ~1 nb (2n channel) is comparable to the value of ~3 nb [9] using the same reaction and 3.6 nb (3n channel) using the ^{40}Ar +^{207}Pb [8]. Fission half-lives have been measured most recently for ^{242}Fm (0.8 ms, [6]) and for ^{244}Fm (3.3 ms, [10] and 3.47 ms, [8]) and alpha decay half-life for ^{243}Fm (231 ms, [9]). TKEs of about 193± 12 [9] and 198 ± 15 [8] have been measured for ^{244}Fm and 198± 15 [9] for ^{243}Fm.

A summary of the highest calculated ER cross-sections is provided in Table. 1.

Table. 1: Calculated ER cross-sections for the $^{242\text{-}244}$Fm isotopes in ^{40}Ar+^{206}Pb reaction

Nuclei	Channel	E_{lab} (MeV)	E_{CN} (MeV)	σ_{ER} (nb)
^{242}Fm	4n	204.2	42	4.9
^{243}Fm	3n	197.1	36	19.0
^{244}Fm	2n	189.9	30	1.0

An experiment has been proposed with the view to confirm the decay properties of ^{244}Fm and measure the fission half-lives for ^{243,242}Fm. Alternate projectile-target combinations are also under consideration and the results are promising.

References

[1] J. P. Balagna *et al.,* Phys. Rev. Lett. **26**, 145 (1971).

[2] J. P. Unik *et al.,* Proc IAEA Symp. Phys. Chem. of Fission, 3rd, Rochester, New York, 1973, Vol.11 (IAEA, Vienna, 1974) 19.

[3] V. Viola, Nucl. Data **1,** 391 (1966).

[4] C. Wagemans, The Nuclear Fission Process, CRC Press, (1991) page 280.

[5] Live Chart of Nuclides, https://www-nds.iaea.org (accessed on 27 August 2017).

[6] G. M. Ter-Akopyan *et al.,* Nucl. Phys. A **255**, 509 (1975).

[7] M. Brack, J. Damgaard, A. S. Jensen, H. C. Pauli, V. M. Strutinsky and S. V. Wong, Rev. Mod. Phys. **44**, 320 (1972).

[8] A. I. Svirikhin *et al.*, EPJA **48,** 121 (2012).

[9] J. Khuyagbaatar *et al.*, EPJA **37**, 177 (2008).

[10] M. Nurmia *et al.*, Phys Lett B **26**, 78 (1967).

[11] W. Reisdorf and M. Schädel, Zeitschrift für Physik A Hadrons and Nuclei **343**, 47 (1992).

[12] H. M. Devaraja, Y. K. Gambhir, M. Gupta, and G. Münzenberg, Phys. Rev. C. **93**, 034621 (2016).

[13] R. Bass , Phys. Lett. B **47**, 139 (1973) and Nucl. Phys. A **231**, 45 (1974).