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# FISSION INDUCED BY HEAVY IONS: NEW RESULTS FROM EUROGAM ARRAY*

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About thirty nuclei in the $A \sim 100$ mass region have been produced as fission fragments in the reaction $^{36}$S+$^{162}$Dy at 162 MeV bombarding energy. They have been individually identified from their $\gamma$-ray transitions detected using an early implementation of EUROGAM array. The mass region reached develops from $Z = 34$ (Se) to $Z = 48$ (Cd) and from $N = 46$ to $N = 66$, along the valley at stability and beyond it towards neutron-rich side. Level schemes of already known stable or neutron-rich nuclei have been extended to higher spins. From cross coincidences between transitions in complementary fragments, $\gamma$-rays de-exciting high-spin states of new isotopes have been identified and some aspects of the fission mechanism have been analyzed.

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## 1. Introduction

The study of $\gamma$-rays emitted following spontaneous fission has recently been a precious source of information about the structure of neutron-rich nuclei (see for instance [1–5]) and about the fission process itself (several neutronless fragmentations have been observed in the spontaneous fission of $^{252}$Cf [6, 7]). These studies have taken advantage of the new high-efficiency Ge arrays, providing greatly improved sensitivity and selectivity in $\gamma$-$\gamma$ coincidence spectrometry.

In reactions induced by heavy ions, fission is a major decay mechanism at high angular momentum. It is worth noting that the use of yrast $\gamma$-ray cascades to select each of the fission fragments is in its infancy: a few results have been already obtained on spectroscopy [8] and on average spins of primary fragments [9]. In this paper, we report on the individual identification of thirty fission fragments with $A \sim 100$, by means of their $\gamma$-ray transitions. The mass correlation of complementary fragments is discussed. Fission induced by heavy ions allows the production of high-spin states in neutron-rich or even stable nuclei which cannot be populated by another way. Level schemes of several $A \sim 100$ nuclei have been extended to higher spin, some of them are presented here.

## 2. Experimental method

The experiment was performed at the Van de Graaff tandem accelerator of the Nuclear Structure Facility (NSF) at Daresbury, using a beam of 162 MeV $^{36}$S ions. A 1.0 mg cm$^{-2}$ target of $^{162}$Dy was used. onto which a backing of 14 mg cm$^{-2}$ Au had been evaporated in order to stop the recoiling nuclei. The $\gamma$-rays were detected using the early version of the EUROGAM1 array [10], consisting of 30 escape-suppressed large-volume Ge detectors (individual photopeak efficiency, $\varepsilon \approx 80\%$). The data were recorded in an event-by-event mode with the requirement that a minimum of three unsuppressed Ge fired in prompt coincidence. A total of 91 million coincidence events were collected, out of which 58 million were three-fold and 13 million four-fold. The off-line analysis has consisted of both gamma-gamma sorting and inspection of multiple-gated spectra [11]. The main goal of this experiment was the high-spin study of the $^{194}$Pb nucleus, produced as the ($^{36}$S, $4n$) exit channel. Moreover we have identified about thirty $\gamma$-ray cascades belonging to $A \sim 100$ nuclei produced as fission fragments, which had stopped in the target backing before emitting $\gamma$-rays. The dominant open channel in the reaction, $^{36}$S+$^{162}$Dy at 162 MeV, is predicted by statistical models to be the fusion-fission, taking approximately 40% of the total cross section.

## 3. Results and discussion

The mass region reached develops from $Z = 34$ (Se) to $Z = 48$ (Cd) and from $N = 46$ to $N = 66$, along the valley at stability and beyond it towards the neutron-rich side where $^{90}$Sr, $^{92}$Sr, $^{98}$Zr, $^{102}$Mo, $^{106}$Ru have been observed [12]. As expected for a fissioning system having excitation energy, a symmetric yield around half the mass of the compound nucleus after neutron evaporation ($A = 97$, $Z = 40$–$42$) is observed.

Prompt $\gamma$-$\gamma$ coincidences occur between transitions in complementary fragments. For example $\gamma$-rays of $^{96}$Zr are observed in coincidence with those of $^{96-97-98}$Mo. Conversely $^{98}$Mo is obtained with $^{94-95-96}$Zr. The $\gamma$-rays deexciting high-spin states of $^{95,93}$Zr were unknown and have been established in this work (Table I). Unfortunately, due to the limited energy range used during the experiment ($E_\gamma < 2$ MeV), the level schemes could not be built, as high-energy $\gamma$-rays are expected between first excited states in these isotopes.

TABLE I

Energy, $E_\gamma$ (keV), and relative intensity, $I_\gamma$, of the main $\gamma$-rays deexciting high spin levels of $^{95,93}$Zr, in the 100–2000 keV energy range.

| $^{95}$Zr | | $^{93}$Zr | |
|---|---|---|---|
| $E_\gamma$ [a] | $I_\gamma$ [b] | $E_\gamma$ [a] | $I_\gamma$ [b] |
| 102.8 | 29 | 111.2 | 72 |
| 116.1 | 100 | 115.1 | 19 |
| 208.3 | 30 | 180.6 | 27 |
| 229.5 | 56 | 275.3 | 83 |
| 241.0 | 26 | 326.0 | 77 |
| 425.4 | 18 | 392.2 | 21 |
| 481.8 | 14 | 503.5 | 78 |
| 511.9 | 19 | 705.2 | 43 |
| 556.5 | 29 | 711.6 | 28 |
| 561.8 | 35 | 762.4 | 28 |
| 604.0 | 30 | 950.3 | 100 |
| 607.3 | 36 | 1059.9 | 49 |
| 727.8 | 31 | 1081.2 | 23 |
| 816.0 | 19 | 1168.1 | 24 |
| 837.7 | 30 | 1335.0 | 52 |
| 877.5 | 20 | 1425.1 | 100 |
| 1045.7 | 19 | | |
| 1159.5 | 10 | | |
| 1677.7 | 100 | | |
| 1793.9 | 10 | | |

[a] Uncertainties are 0.2–0.5 keV depending on $\gamma$-ray intensity.
[b] Uncertainties are 10–30%.

All the summed numbers of protons and neutrons of the observed complementary fragments lead to $Z = 82$ (Pb) and $N = 110$, 111 or 112. Complementary fragments with $\Sigma N > 112$ (the neutron number of the compound nucleus $^{198}$Pb is 116) have not been observed. Our observations are consistent with the emission of 2 pre-fission neutrons and 1 or 2 post-fission neutrons emitted by each fragment, in agreement with direct measurements [13]. It is worth noting that the yields of the complementary fragments are very different from one residue to another (Table II). This can be due to the probability of post-fission neutron emission which depends on each fragment.

TABLE II

Examples of complementary fragments

| Fragment 1 | Fragment 2 | Yield[a] |
|---|---|---|
| $^{100}_{42}$Mo | $^{94}_{40}$Zr | 30% |
| | $^{93}_{40}$Zr | 18% |
| | $^{92}_{40}$Zr | 13% |
| $^{104}_{44}$Ru | $^{90}_{38}$Sr | 12% |
| | $^{89}_{38}$Sr | 17% |
| | $^{88}_{38}$Sr | 19% |

[a]The yield is extracted from the spectrum of $\gamma$-rays coincident with the $2^+ \rightarrow 0^+$ transition of fragment 1 and is normalized to the production of fragment 1. Uncertainties are 10–30%.

The variation of summed number of neutrons is two units, this is smaller than that observed in spontaneous fission of actinides (about five units). This is probably correlated to the fact that the excitation energy of the fission fragments is lower:

1. The energy released in the fission of neutron deficient Pb (145 MeV) is lower than in the spontaneous fission of actinides (205 MeV for $^{248}$Cm and 215 MeV for $^{252}$Cf).
2. Some excitation energy of the $^{198}$Pb compound nucleus (60 MeV) has been already removed by pre-fission neutron emission. One can estimate that about 20 MeV has been removed by the emission of two pre-fission neutrons.

The level schemes of several even-even $A \sim 100$ nuclei have been extended up to spin $14\hbar$ [12]. The level schemes of $^{102-104-106}$Ru are presented in Fig. 1. High spin states of $^{102}$Ru were previously known up to spin ($16^+$), they had been populated by means of the $^{100}$Mo ($^7$Li, $p4n$) reaction [14]. In the present work, we have observed all the states up to ($14^+$). Two new transitions have been added to the high-spin level scheme of $^{104}$Ru which had been studied up to spin ($10^+$) by Coulomb excitation

[15] and $^{100}$Mo ($^{7}$Li $p2n$) reaction [14]. Likewise the ($10^+$) and ($12^+$) states of $^{106}$Ru have been identified in this work, extending the level scheme which had been populated by means of ($^{16}$O, $^{18}$O $\gamma$) reactions [16]. Unfortunately

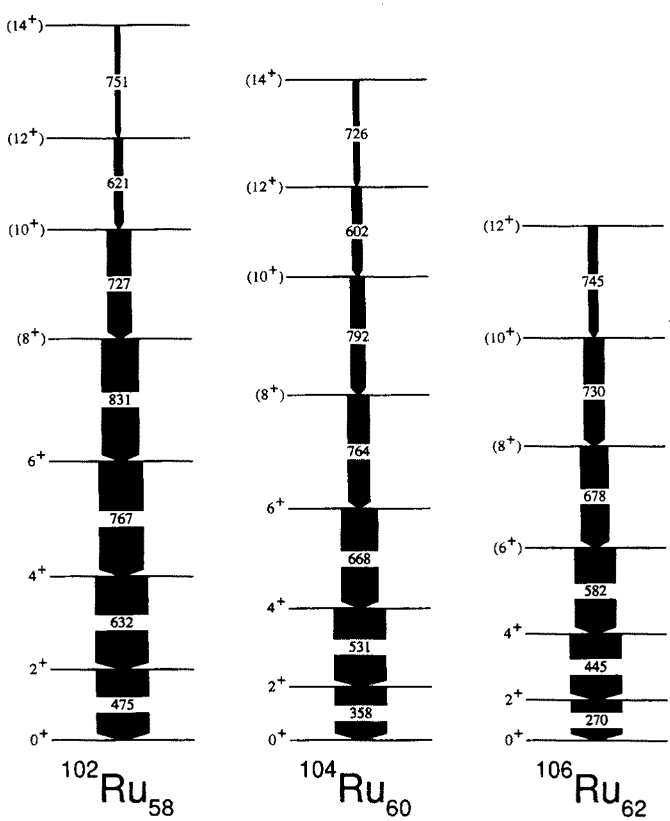


Fig. 1. Partial high-spin level schemes of $^{102,104,106}_{44}$Ru observed in this work.

we have not observed the vibrational $\gamma$-bands which are well developed in Ru isotopes, particularly in the neutron-rich isotopes, $^{108-114}$Ru [4]: most likely, these side bands, which are never yrast, are not well populated by means of fusion-fission reactions. Some additional very weak $\gamma$-rays have been observed in $^{102-104}$Ru, corresponding probably to two-particle excitations. A very high statistics data set is needed to measure properly these new states.

Spin as a function of rotational frequency for $^{102-108}$Ru are shown in Fig. 2. Backbend is observed for the lighter isotopes, while $^{106}$Ru only exhibits an upbend and the $^{108}$Ru plot is regular. This is in agreement with the alignment of $h\,11/2$ neutrons, taking into account the location of the neutron Fermi level with respect to the $h\,11/2$ subshell for $N = 58$-$60$-$62$-$64$.

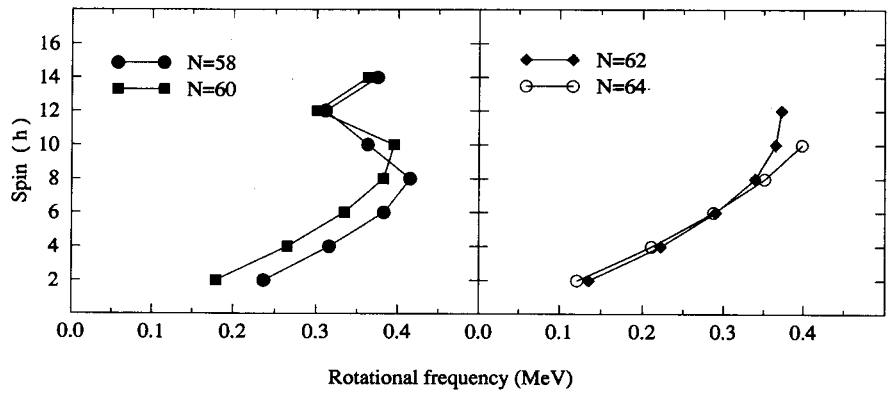


Fig. 2. Spin as a function of rotational frequency for $^{102,104,106}_{44}$Ru (this work) and $^{108}_{44}$Ru [4].

## 4. Conclusion

These data from a very preliminary study using only 30 Ge detectors have shown that a very promising technique may be developed to study high-spin states of stable or neutron-rich nuclei. Some aspects of the fission mechanism may be analyzed using the individual identification of the fission products. A new experiment will be carried out in the near future, which will take advantage of the full EUROGAM2 array [17] completed with fission fragment detectors.

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REFERENCES


[1] M.A.C. Hotchkis *et al.,Phys. Rev. Lett.* **64**, 3123 (1990) and *Nucl. Phys.* **A530**, 111 (1991).

[2] R. Aryaeinejad *et al.,Phys. Rev,* **C48**, 566 (1993).

[3] M. Bentaleb *et al.,Z. Phys.* **A348**, 245 (1994).

[4] J.A. Shannon *et al.,Phys. Lett.* **B336**, 136 (1994).

[5] A.G. Smith *et al.,Phys. Rev. Lett.* **73**, 2540 (1994).

[6] J.H. Hamilton *et al.,J. Phys. G* **20**, L85 (1994).

[7] G.M. Ter-Akopian *et al.,Phys. Rev. Lett.* **73**, 147 (1994).

[8] J.L. Durell, *Acta Phys. Pol.* **B24**, 105 (1992).
[9] Y. Abdelrahman *et al.,Phys. Lett.* **B199**, 504 (1987).
[10] P.J. Nolan, *Nucl. Phys.* **A520**, 657c (1990); F.A. Beck, *Prog. Part. Nucl. Phys.* **28**, 443 (1992); C.W. Beausang *et al.,Nucl. Instrum. Methods* **A313**, 37 (1992).
[11] I. Deloncle, M.-G. Porquet, M. Dziri–Marcé, *Nucl. Instrum. Methods* **A357**, 150 (1995).
[12] M.-G. Porquet *et al.,*to be published.
[13] J.O. Newton *et al.,Nucl. Phys.* **A483**, 126 (1988).
[14] D.R. Haenni *et al.,Phys. Rev.* **C33**, 1543 (1986).
[15] J. Stachel *et al.,Nucl. Phys.* **A419**, 589 (1984).
[16] J. Koenig *et al.,Phys. Rev.* **C24**, 2076 (1981).
[17] P.J. Nolan, F.A. Beck, D.B. Fossan, *Ann. Rev. Nucl. Part. Sci.* **44**, 5 (1994).