FISSION FRAGMENT SPECTROSCOPY

J L Durell
The Schuster Laboratory, University of Manchester, UK

1. Introduction

Fission has recently celebrated its 50th birthday, but despite its old age still presents considerable challenges to theoretical and experimental physicists. However, for the nuclear structure spectroscopist fission can be used as a well-understood mechanism for the production and study of neutron-rich nuclei. Historically the main area of study has been the β-decay of primary fission products i.e. those nuclei formed following prompt neutron emission. These β-decay studies have provided a wide-ranging and interesting body of nuclear structure physics information, and have played an important part in establishing empirically fission fragment mass and charge distributions.

In contrast to the large amount of data available from the study of delayed γ-rays (i.e. γ-rays emitted following β-decay), the study of PROMPT γ-ray emission in high resolution has been held back by the technical difficulties in resolving individual γ-rays from the very many produced by primary fission products. In the early 1970's pioneering work was done at Berkeley by Cheifetz et al. (1) who looked at prompt γ-rays from spontaneous fission. They managed to establish ground-state bands in several neutron-rich nuclei up to spins of 4 or 6. There has been a long pause in progress until improvements in the technology of γ-ray spectroscopy have now permitted more extensive studies.

With the advent of modern high-efficiency Ge arrays it is now possible to investigate in detail the prompt γ-rays from primary products from both spontaneous fission and heavy-ion induced fission. In the series of experiments undertaken by us a variety of fissioning systems have been used to determine yrast and near yrast levels up to J=12-15 in neutron-rich nuclei in the mass 80 to 150 region. Previous work, for example on the β-decay of odd-odd nuclei, has provided in many cases the starting point for our studies. Given the power of modern arrays, once even just one transition in a nucleus is known we are able to determine a partial decay scheme for the nucleus concerned.

The study of yrast structures in even-even nuclei is clearly of interest in order to learn about the nature of collectivity in these nuclei. By using fission to form neutron-rich nuclei we have the opportunity to investigate new areas of the N-Z plane which are inaccessible by traditional heavy-ion fusion reactions. The extra neutrons will occupy single-particle states different to those available near to the line of stability. This can lead to the occupation of new intruder states perhaps driving the nuclei to large deformation; or different combinations of single-particle orbitals become available, the residual interactions between which can lead to non-quadrupole deformations of the nuclei. These sorts of arguments are those, of course, being made in the physics cases for the new and exciting exotic beam facilities.

In the following sections I shall discuss those features of the fission process which determine precisely what range of nuclei can be studied; give some examples of the more technical aspects of the data analysis; and show some results of our studies.

2. The Nuclei Produced in Fission.

Two kinds of fissioning systems have been used during the course of our work: nuclei that fission spontaneously, and fissioning nuclei produced in heavy-ion fusion reactions. The range of products formed in spontaneous fission is beyond the control of the experimenter, but the range of nuclei populated in induced fission can to a certain degree be decided by us. Which primary product nuclei are actually populated in fission will be determined by the following factors:-

a) N/Z ratio of fissioning system: In spontaneous fission this factor is completely defined. In heavy-ion induced fusion-fission reactions this will be determined by the choice of projectile and target nuclei, together with the number of neutrons emitted from the compound nucleus prior to fission. This latter factor will be beam energy and compound nucleus dependent. Fortunately a detailed systematic study of neutron emission prior and post fission has been undertaken (2) and this permits reliable estimates to be made of the number of neutrons emitted pre-fission.

b) Primary fragment mass distribution: In the spontaneous fission of Cf or Cm the primary mass distribution is asymmetric, with the heavy mass peak at a mass close to 144. The light primary fragment peak is then, of course, at the mass of the fissioning nucleus minus 144. There is very little yield at the symmetric mass split. In heavy-ion induced fission, where shell effects are washed out by the high excitation energy of the fissioning system, the mass distribution is symmetric, peaking at half the mass of the fissioning system. The mass distribution for fusion-fission is rather broader than the light and heavy peaks of spontaneous fission, and has a fwhm of around 30 amu. For any given Z the isotopic distribution is fairly narrow. This is illustrated in fig. 1 which presents yield distributions determined by coincident γ-ray intensities from the interaction of ^{19}F with ^{197}Au. These distributions already contain the broadening influence of neutron emission. For both spontaneous and induced fission the primary fragments have the same N/Z ratio as the fissioning system.

c) Post-fission neutron emission: In the cold spontaneous fission process this factor is very much influenced by shell effects in the fission fragments, leading to a sawtooth distribution in the average number of neutrons emitted as a function of mass.

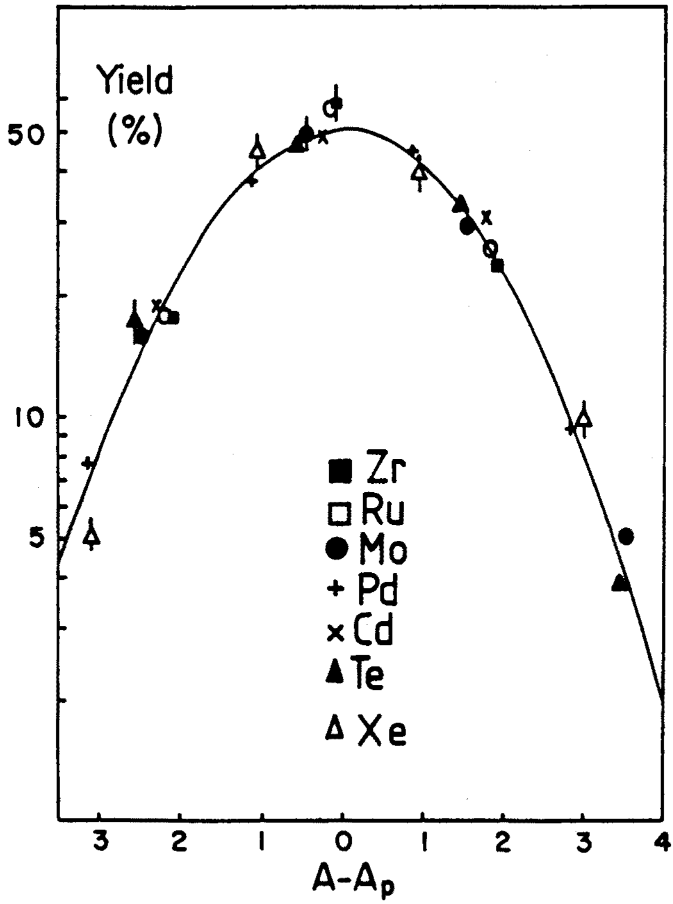

Fig. 1: Fractional yields of isotopes produced in ^{19}F + ^{197}Au reaction as a function of $A - A_p$ for the elements shown. A_p is the most probable mass for an element.

At the maxima of the fragment yields approximately two neutrons per fragment are emitted. Heavy-ion induced fusion-fission gives a smooth dependence of the post-fission neutron emission as a function of fragment mass. In fact the number of neutrons emitted from the hot fission fragments is proportional to the primary fragment mass. The average number of neutrons emitted tends to be larger than is the case for spontaneous fission, but this will of course be a function of the temperature of the primary fragments, which is determined by the energetics of the particular reaction.

By taking into account the above three factors and using published data, it is possible to reliably estimate the fission products most likely to be produced in a given reaction. In the case of heavy-ion induced fission, the experimenter is able, by a suitable choice of beam, target and beam energy, to control, to a certain degree, the range of nuclei to be studied. It must be pointed out that spontaneous fission will always lead to more neutron rich products than heavy-ion induced fission, at least for conventional beam/target combinations. This is shown in fig. 2, which presents the loci of the most probable products for four fissioning systems that we have studied.

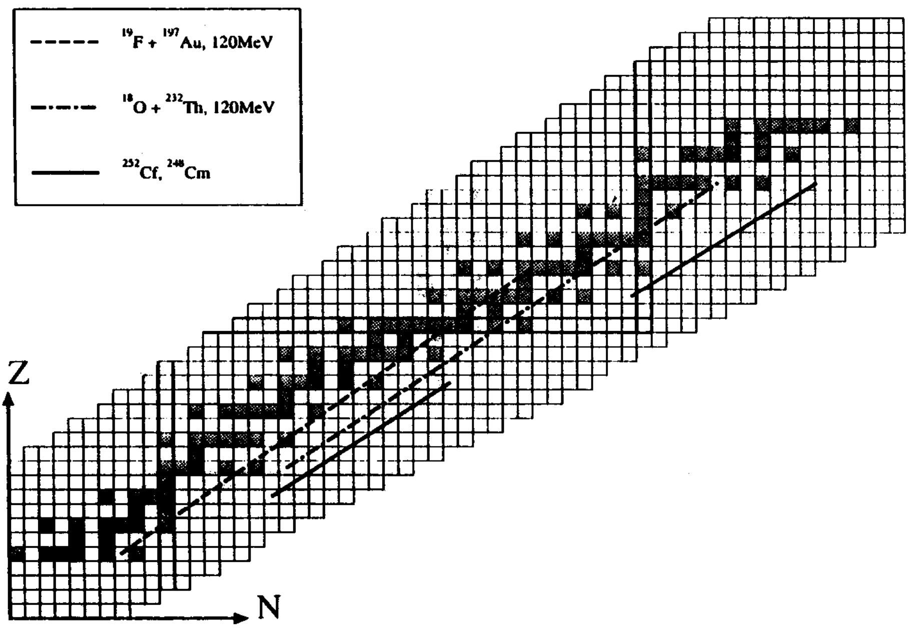

Fig. 2: The loci of the most probable products for four fissioning systems, compared to the stable nuclei from Z=34 to 64.

Another factor of interest is the angular momentum available to the fission fragments. How high in J can we expect to go? In the cold spontaneous fission process the angular momentum taken up by fission fragments will be determined by the dynamical processes along the fission path. As may be expected, the dynamics are complicated and theoretical predictions will be hard. Heavy-ion induced fission involves a hot fissioning system, at an excitation energy considerably higher than the fission barrier. The sharing of angular momentum between fission fragments should, therefore, be decided statistically and depend upon the free excitation energy (temperature) available to the fragments. We have studied (3) angular momentum sharing in fission by using the discrete spectroscopy of the even-even primary fission products as a means of measuring the average angular momentum in primary fragments. We have confirmed the dominance of statistical effects in heavy-ion fusion-fission. We have already seen that spontaneous fission has the advantage of producing more neutron-rich nuclei compared to fusion-fission. How do the two processes compare as far as spin is concerned? The average angular momentum of primary fission fragments is significantly higher in fusion-fission and the distribution in spin extends to higher J. This is illustrated in fig. 3 in which the population of discrete states in ^{104}Mo as a function of J is compared for the spontaneous fission of ^{252}Cf and the ^{18}O + ^{232}Th fusion-fission reaction. It does appear that the hotter fissioning systems provide relatively more population of yrast states at higher spin.

3. Experimental Data and Analysis.

The experiments described here have been performed at Daresbury Laboratory using TESSA3 and ESSA30, and at Argonne National Laboratory using the Argonne-Notre Dame Gamma-Ray Facility. It should be emphasised that no detection of the fission fragments is involved. This has the advantage that thick targets can be used, and the analysis proceeds through standard $\gamma - \gamma$ coincidence techniques, setting gates on the stopped peaks. Fragment identification is achieved by our precise knowledge of the energies of γ-rays associated with given nuclei. In effect we have infinitely good mass resolution. This is, of course, limited to those nuclei for which we have reliable published information and demonstrates the vital importance of previous β-decay studies. We have developed techniques for identifying γ-rays in new nuclei, previously unstudied. This will be discussed later.

The first complication that arises compared to (HI,xn) reactions is that γ-ray cascades from 60 or more nuclei are being produced within the same reaction. This increases the problems of data analysis, since many of the nuclei have γ-rays of closely similar energies. This situation implies that it is vital to have Ge detectors of the best possible resolution. Another difficulty arises from the existence of complementary fragments. When a gate is placed, say, on the 2-0 transition in a given product, not only will the prompt γ-rays within that nucleus be observed, but also γ-rays in the three or more possible complementary fragments. The building up of a partial decay scheme for one nucleus therefore requires knowledge of the strong γ-rays in several other nuclei. Although the presence of coincidencies between γ-rays in different, complementary nuclei can give problems, we have shown that such coincidencies can be used to advantage (4) in identifying new nuclei.

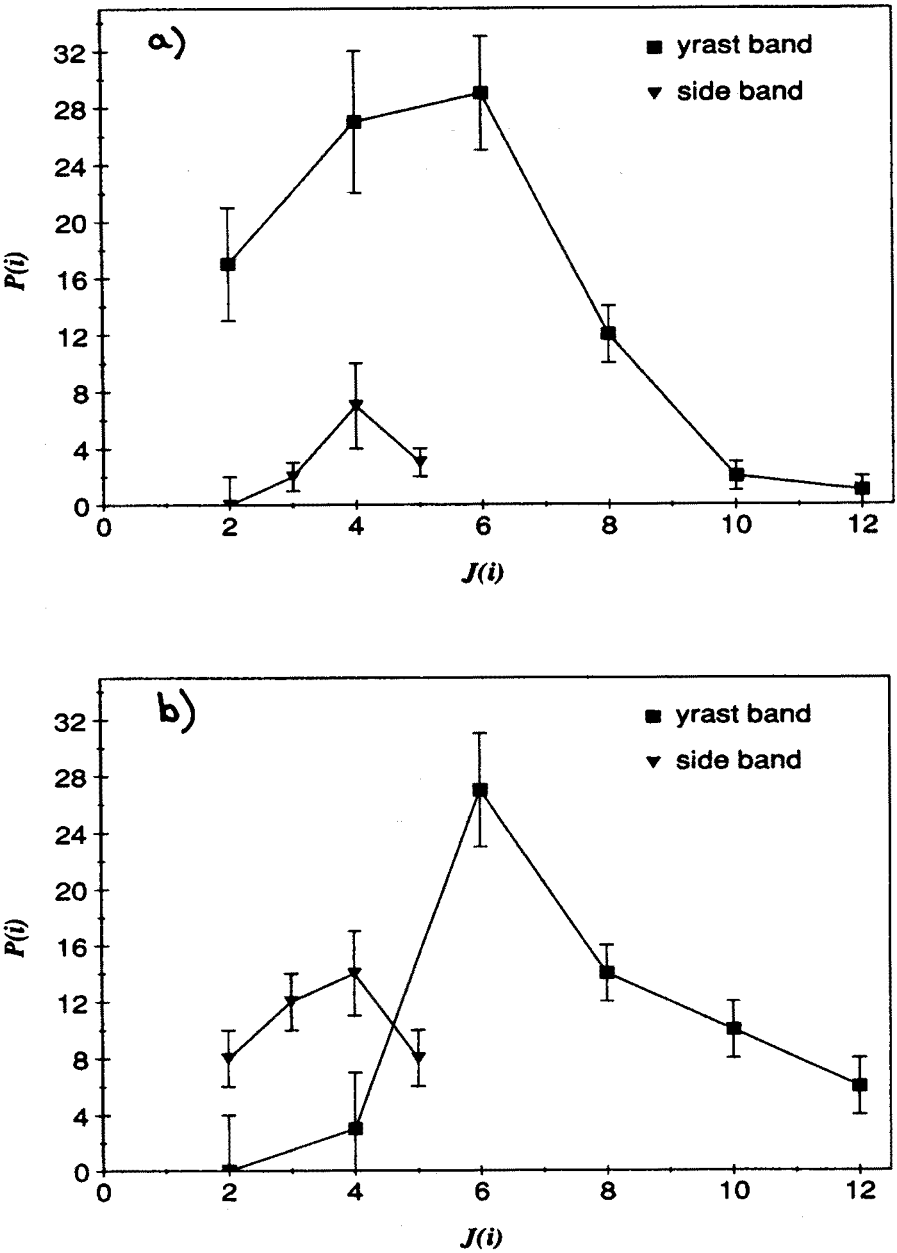

Fig 3: A comparison of the population of discrete states in ^{104}Mo following (a) spontaneous fission of ^{252}Cf and (b) the O+Th fusion-fission reaction.

A detailed description of the procedure used to identify new nuclei is given in ref.(4) and only a brief outline is presented here. Consider a fissioning nucleus (A, Z). For two complementary fragments (A_1, Z_1) and (A_2, Z_2) we know that $Z_1 + Z_2 = Z$ and $A_1 + A_2 = A - \nu$, where ν is the total number of neutrons emitted in the particular event. Since ν may take values ranging between 1 and 5, transitions in a range of isotopes of given Z_2 will appear in coincidence spectra gated on transitions in the nucleus (A_1, Z_1). Thus for a particular transition in a particular fission product, we can deduce the average mass of complementary fragments that accompany it from the relative yields of the observed γ-rays in the complementary fragments. We should expect that, for a given Z_1, the average mass of the complementary fragment should vary smoothly with A_1. In practice, because of difficulties with odd-A fragments, we have found this technique to work well only with Z_1 and Z_2 even, and using just the A_2 even γ-rays. Candidates for transitions in an unknown nucleus are sought by scanning spectra gated on known transitions in the expected complementary fragments. In our case the unknown nuclei are rather neutron rich and therefore the complementary fragments expected are those lighter in mass than at the maximum yield. Having identified possible candidates for γ-rays from unknown nuclei, spectra are obtained by gating on these transitions, and the yields of γ-rays from the well-known even-even complementary fragments determined. The average mass of the complementary fragments associated with the candidate γ-rays is then compared to the trends observed for γ-rays from known nuclei of the same Z_1. Examples of the results of applying the above procedure are shown in fig. 4. The smooth trends observed have allowed us to confirm the identification of the new isotopes ^{103}Zr, ^{104}Zr, ^{107}Mo and ^{108}Mo.

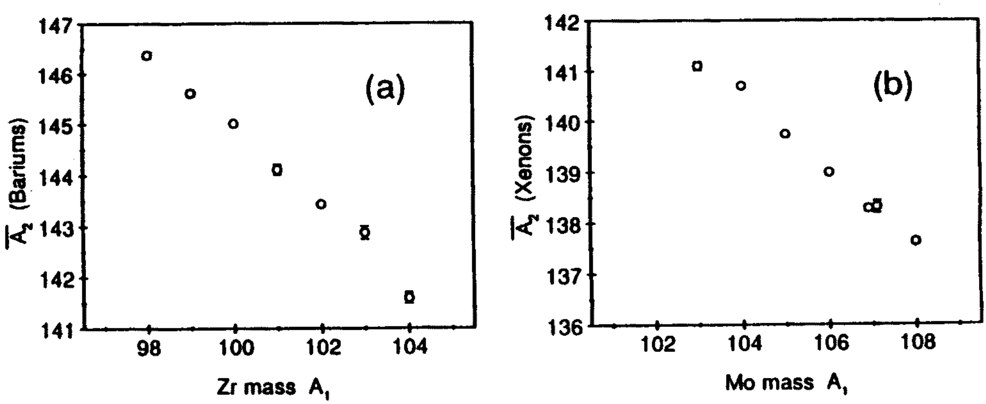

Fig. 4: Plots of the mean masses of complementary fragments used to identify new isotopes of (a) Zr, and (b) Mo. Data from a ^{248}Cm source.

The analysis of the $\gamma - \gamma$ data from several fissioning systems has enabled us not only to identify new nuclei but also to extend the partial decay schemes of many nuclei to higher spins. We are therefore able to study the systematic behaviour of nuclei as neutrons are added. Some of our results will be discussed in the following section.

4. Neutron Rich Nuclei in the A=100 to 110 Region.

One of the most interesting areas of study in the present work has been the investigation of neutron-rich isotopes of the elements from Zr to Cd. Using data from all of the fissioning systems we have been able to build up a comprehensive set of systematics. Some of this work has been published (4,5).

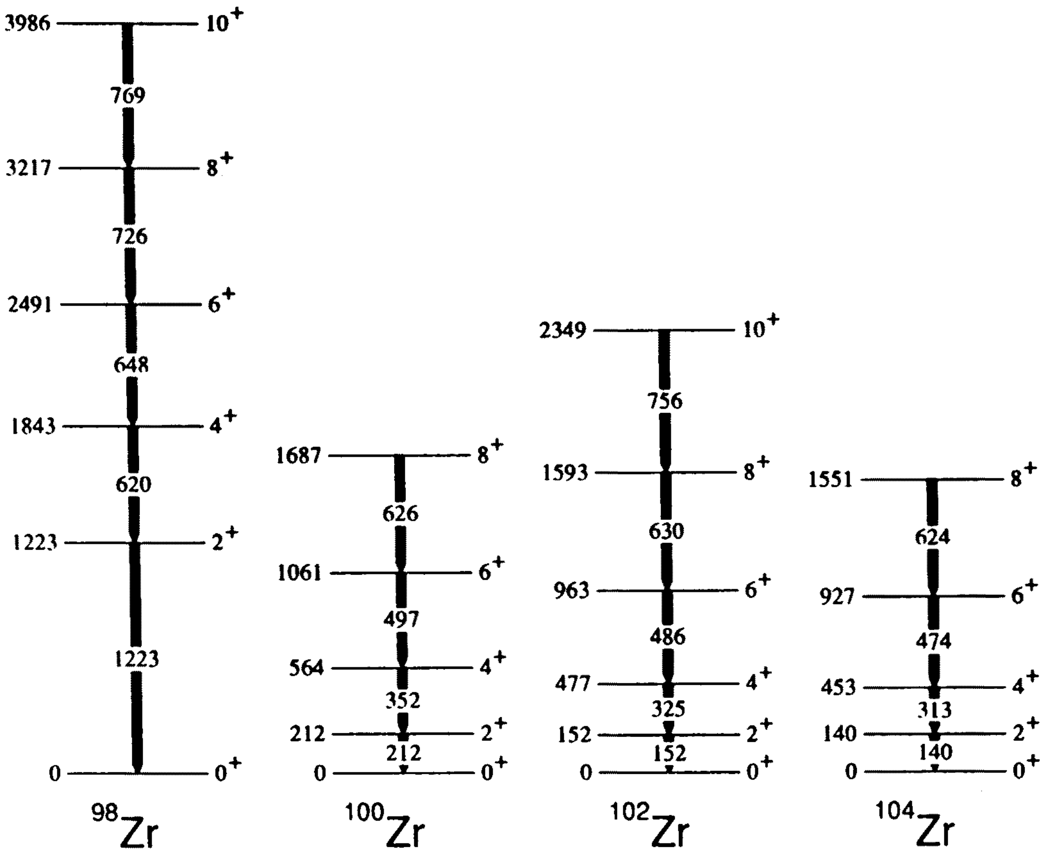

Fig. 5: Systematics of the ground-state bands of neutron-rich Zr isotopes.

Figs 5 and 6 present the systematics of the yrast levels of the neutron-rich Zr and Mo even-even isotopes. Abrupt changes in the nuclear structure of these nuclei can be seen when the neutron number changes from 58 to 60. This is particularly dramatic in the case of the Zr isotopes. The general trends in this mass region are shown in fig. 7 where the energies of the first 2^+ states and the ratios of the energies of the 4^+ and 2^+ states are plotted against neutron number for the even-even isotopes with Z=38-44. The Sr and Zr isotopic chains show an abrupt transition from spherical to highly deformed ground states at N=60. The transition is smoother for the Mo isotopes, and the deformation decreases gradually as Z increases, with the Ru isotopes having transitional structure.

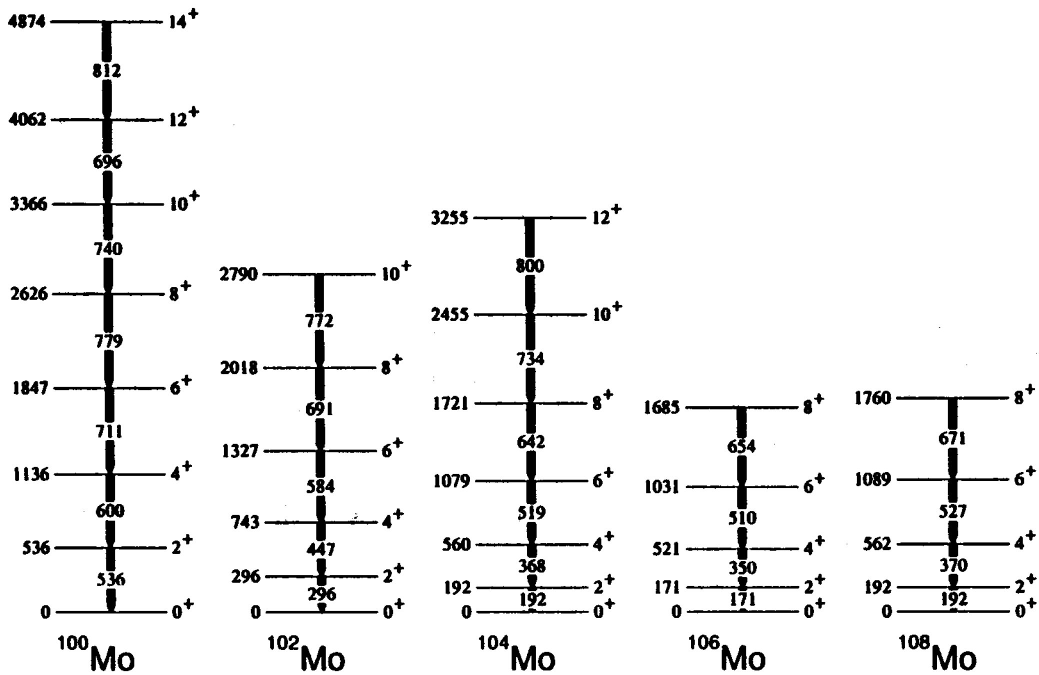

Fig. 6: Systematics of the ground-state bands of the neutron-rich Mo isotopes.

There has been considerable theoretical interest in trying to understand the underlying microscopic physics that leads to the observed trends. Some conflict has emerged between different theoretical calculations as to which single-particle orbitals are responsible for the sudden saturation of deformation in the N=60-64 region of these isotopes (see ref.(4) for details). The only way to gain some insight into this aspect of the problem is to obtain information on the yrast and near-yrast structures in neighbouring odd-A nuclei. We have been able to determine partial decay schemes for several odd mass nuclei in the critical region, and by combining our results with previous data from β-decay studies, we can come to some conclusions about the single-particle orbitals that are giving rise to the drive to large deformation. As an example, fig. 8 shows the level schemes for ^{101}Zr (N=61) and ^{103}Zr (N=63) determined from coincidence data obtained following the spontaneous fission of ^{248}Cm.

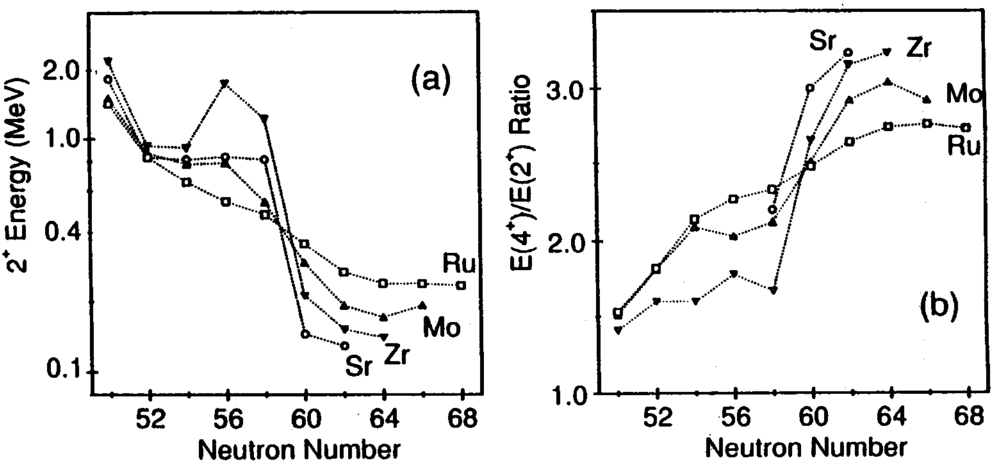

Fig. 7: Energies of the first 2^+ states and the ratios of the energies of the first excited 4^+ and 2^+ states in the even-even isotopes of Sr, Zr, Mo and Ru with $N \geq 50$.

The ground-state band of ^{101}Zr is based upon the $\frac{3}{2}^+$[411] configuration. From the decay patterns of levels in the side-band to the ground-state band we are able to deduce that it is most probably based upon the $\frac{5}{2}^-$[532] intruder configuration. This observation of a band based on a Nilsson orbital arising from the $\nu h_{\frac{11}{2}}$ spherical state, provides the first evidence of occupancy of this intruder state in the deformed Zr nuclei at neutron numbers where the shape transition occurs. Thus, although the isovector interaction between $\pi g_{\frac{9}{2}}$ and $\nu g_{\frac{7}{2}}$ particles is important in moving the nuclei away from a spherical shape, it is the occupation of deformation driving $\nu h_{\frac{11}{2}}$ orbitals that is the major factor in stabilizing the deformation at large values (β=0.3-0.4) in this region.

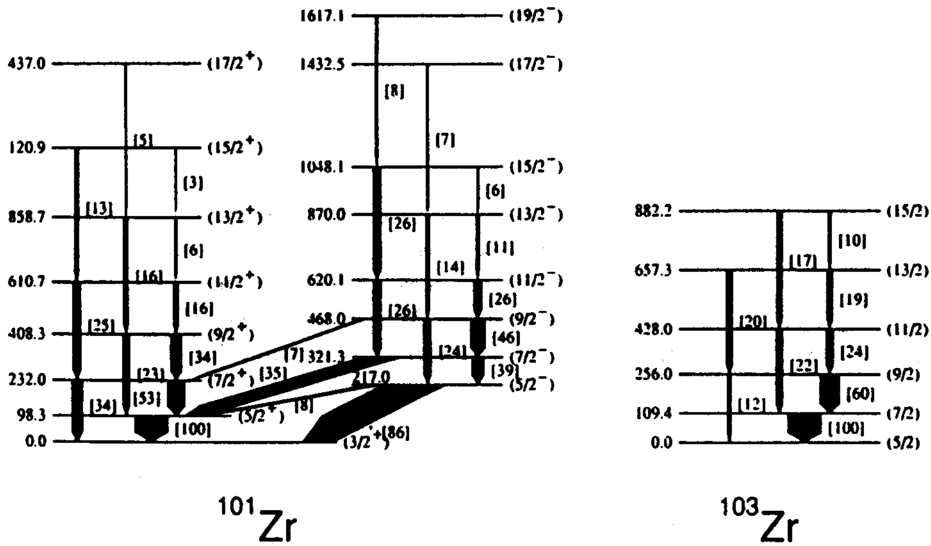

Fig. 8: Partial decay schemes of ^{101}Zr and ^{103}Zr.

5. Conclusions

We have discussed some of the more technical aspects of studying the nuclear spectroscopy of fission fragments in order to demonstrate some of the differences between this kind of work and that done, say, with (HI,xn) reactions. One example has been given of an area of nuclear structure physics which has been elucidated by the fission fragment data. Other examples exist: the investigation (6) of octupole effects in the Ba, Ce region; the improvement (5) of our knowledge of yrast states in the vibrational Pd and Cd nuclei.

Prompt γ-ray spectroscopy with fission fragments is still in a fairly primitive phase. As yet we are only finding new levels and inferring spins. To a large extent we have been restricted to even-even nuclei, although some odd-A nuclei have revealed their secrets. It is evident that one would like to see this new area of spectroscopy mature. The newly constructed, high efficiency γ-ray arrays with their greater sensitivity will certainly extend the range of nuclei and levels observable. The future availability of neutron-rich beams from radioactive beam facilities should permit the formation of compound nuclei that will fission to produce fragments further from stability than currently available, and with yields that may allow more sophisticated studies. In Manchester we are developing large solid-angle, good mass resolution, heavy-ion detectors to use with γ-ray arrays. These detectors will open up the possibility of investigating odd-odd nuclei and the difficult odd-A nuclei; and even, perhaps, permit fragment-γ correlations to be measured. There is certainly still some interesting work to done.

Acknowledgements.

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References.

(1) E Cheifetz et al., Phys Rev Lett **25** (1970) 38.
(2) D J Hinde et al., Nucl Phys **A452** (1986) 550.
(3) Y Abdelrahman et al., Phys Lett **199B** (1987) 504.
(4) M A C Hotchkis et al., Nucl Phys **A530** (1991) 111.
(5) J L Durell, Proc Int Conf on the Spectroscopy of Heavy Nuclei, Crete, IOP Conference Series **105** (1990) 307.
(6) W R Phillips et al., Phys Lett **212B** (1988) 402.