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Aspects of low energy nuclear fission

J W Boldeman

Physics Division, Australian Nuclear Science and Technology Organisation, Private Mailbag 1, Menai NSW 2234

Abstract

Since the discovery of nuclear fission in 1939 there have been numerous studies of the fission process. This paper considers several areas of research to illustrate some of the contributions that have been made. The emphasis is on neutron-induced fission at relatively modest excitation energies with some consideration of spontaneous fission.

Introduction

The fission process is defined as the division of a heavy excited nucleus into two fragments similar in mass. Since the discovery of fission (Hahn & Strassman 1939) there have been tens of thousands of research papers devoted to different aspects of the process. The two primary reasons for these extensive studies are obviously the generation of accurate data and understanding of the process for the design and subsequent safe operation of power and research reactors and the contribution that such studies can make to an improved understanding of nuclear structure. Because of the enormous range of topics and the plethora of details, this paper can address at most only a minute fraction of the current literature. The emphasis here will be on low energy neutron induced fission. Over the years there have been many excellent reviews. An extremely comprehensive book by Vandenbosch & Huizenga (1973) covered the studies to that date. A very recent book on the topic was edited by Wagemans (1991). The basis of selection of material for the various figures has been to provide a simple picture of the various processes.

In order to understand what is happening in the fission process, it is clear that there are a number of questions that must be answered. Some of the more obvious are listed below;

- if fission can occur what is it that stops all nuclei from breaking apart spontaneously?;
- what determines the fission probability?;
- when fission does occur what can be learnt from the angular distribution of the fragments?;
- how is the energy shared after fission?;
- what is the mass distribution of the fragments?;
- how are the neutrons emitted in the fission process and what are their energy distribution?; and
- what can be learnt from the yields in the symmetric region of the mass yield curve?

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The Fission Barrier

The starting point in any discussion of the fission barrier is the liquid drop model introduced before fission was actually discovered but modified almost immediately by Bohr & Wheeler (1939). In this model, the nucleus is assumed to be equivalent to a liquid drop in which the short range nuclear forces are idealised by the surface tension of the drop and the Coulomb repulsive forces are included by assuming the drop to be uniformly charged throughout its volume. Fission occurs within this model if sufficient excitation is given to the system to allow the internal vibrations to overcome the attractive surface tension of the drop. Although the liquid drop model provided, in principle, a reasonable approximation to the real world, it failed in accurately predicting many of the detailed systemmatics of the fission process.

A major advance occurred in the mid 1960's, when the model was improved dramatically by the inclusion of shell effects (Strutinsky 1967; Strutinsky & Pauli 1969). The consequence of these corrections is illustrated by plotting the potential energy hindering fission as a function of the symmetric axis deformation (Fig 1); also shown is the smooth potential barrier as originally predicted by the liquid drop model. It is seen that the single smooth barrier of the simple liquid drop model becomes double humped for nuclei in the vicinity of the uranium. This extension of the model allows many unexpected features of the fission process to be explained. It also explains why the ground state for those nuclei represented by the potential barrier in the figure (nuclei in the vicinity of the uranium nuclei) is deformed.

It is now important to introduce the concept of fission channels. In 1956, A Bohr first suggested that for a fissioning nucleus with excitation only slightly more than the fission threshold *i.e* with an energy only slightly exceeding the potential energy barrier in Fig 1, the nucleus at a deformation corresponding to the highest point in Fig 2 is cold with respect to internal excitation, all energy is bound up in potential energy of deformation and the only nuclear states at the peak of the fission barrier (the saddle point) via which fission can proceed will be collective states similar to those of the heavy deformed nuclei near their ground states *i.e* in the first well of the potential barrier in Fig 1. The transition states will be characterised by the quantum numbers I and K, where I is the total spin of the compound nucleus and K is its

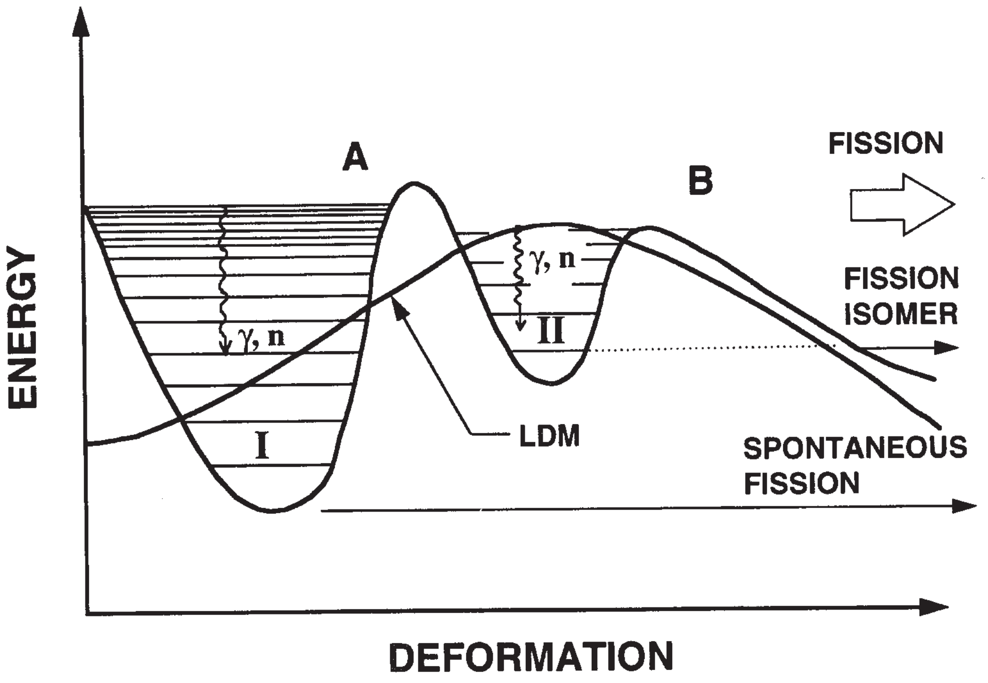

Figure 1. Double humped fission barrier, compared with the liquid drop model (modified from Strutinksky (1967).

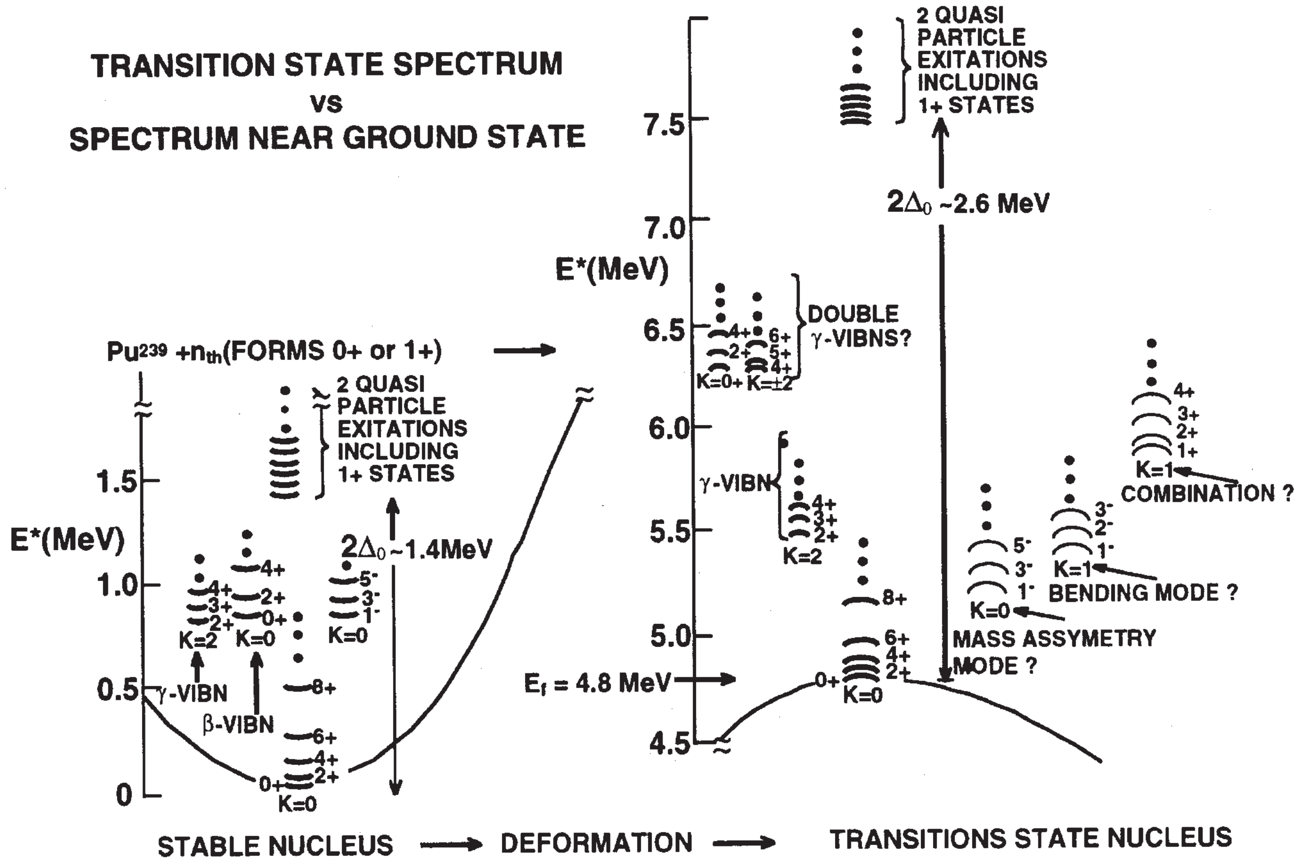

Figure 2. Comparison of transition states at the fission barrier with the spectrum of low lying states for deformed nuclei (modified from Griffin 1965).

projection on the symmetric axis *i.e.* along the axis of deformation specified by the deformation parameter in Fig 1. Extensive research, particularly in the early days of fission studies, identified a spectrum of different quantum states at the saddle point which were necessary to explain many of the details of the fission process. Figure 2, modified from Griffin (1965) illustrates the wealth of data that has been obtained principally from studies of fission fragment angular distributions. Although this information was derived originally for a simple single humped barrier, to a first approximation Fig 2 represents the spectrum of double humped transition states.

As indicated previously, the angular distribution of the fission fragments can be used to derive information regarding the spectrum of states at the saddle point of the fissioning nucleus (Fig 2). In an even-even nucleus, the spectrum of transition states at the saddle point deformation is expected to be quite similar to that found at low excitation in its permanently deformed equilibrium configuration. The ground state has total angular momentum and parity $I\pi = 0+$ and has projection of angular momentum on the nuclear symmetry axis $K = 0$. The excited states correspond to the simple vibrational modes of a liquid drop. The lowest mass-asymmetric mode has $K = 0$, but negative parity, whereas the axial-symmetric gamma vibration of lowest energy has $K\pi = 2+$. In addition, a bending mode with $K\pi = 1-$ is expected to occur at moderate excitation at the saddle point, although it has not been identified at equilibrium deformation. Since the fissioning nucleus is non-spherical, rotational bands of increasing I are built on each of these vibrational states. Simple superposition of these fundamental modes leads to further fission channels with increasingly greater excitation until, at about 1.5 MeV, sufficient energy is available to break nucleon pairs and thereafter single particle excitations combined with collective vibrations lead to a rapid increase in the complexity of the transition state spectrum.

Fission Fragment Angular Distributions

A basic assumption of the Bohr model is that the quantum number K remains a constant of the motion between saddle point and scission. Thus the measured angular anisotropy W(0°)/W(90°) can be used to provide information on the properties of the transition states at the saddle point. The most extensively studied even-even fission system studied is neutron fission of U235. Figure 3, modified from the recent study by Straede *et al.* (1987) shows the anisotropy *i.e.* W(0°)/W(90°) as a function of neutron energy. The data is readily explained in terms of the model discussed above.

For neutron fission of an even target nucleus leading to an odd fissioning system, the lowest lying fission channels are expected to be essentially single particle states which should be identifiable with the appropriate Nilsson orbits. The excess angular momentum appears as a rotation about an axis perpendicular to the symmetric axis. Thus with each intrinsic state there is associated a rotational band with energy given by

$$E(I\pi)=E_0\frac{h^2}{2j}[I(I+1)-2K^2+\delta_{K+½}\alpha(-1)^{I+½}(I+½)] \qquad \text{(eq. 1)}$$

where j is the moment of inertia associated with the band and α is the decoupling constant for the K= ½ bands. The structure in the anisotropy becomes much larger. As an example, measurements of the anisotropy for neutron fission of ^{230}Th near the large resonance in the cross section at 715 keV are shown in Fig 4.

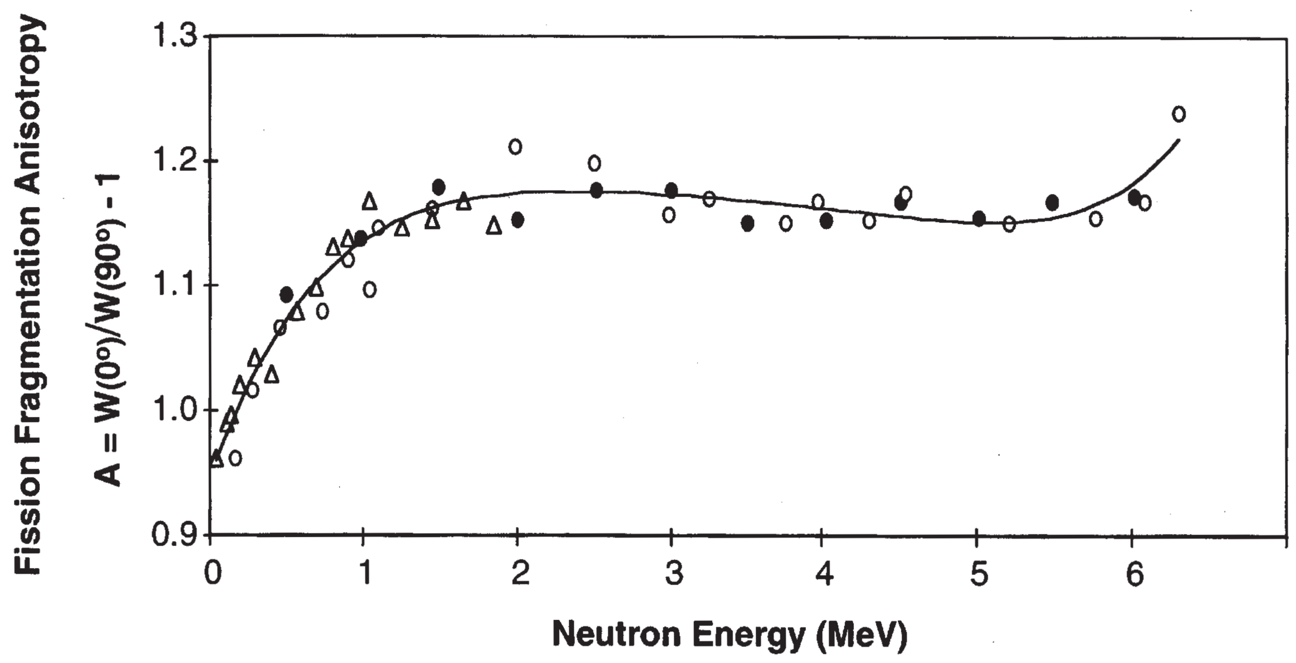

Figure 3. The ^{235}U(n,f) fission fragment anisotropy (modified from Straede *et al.* 1987).

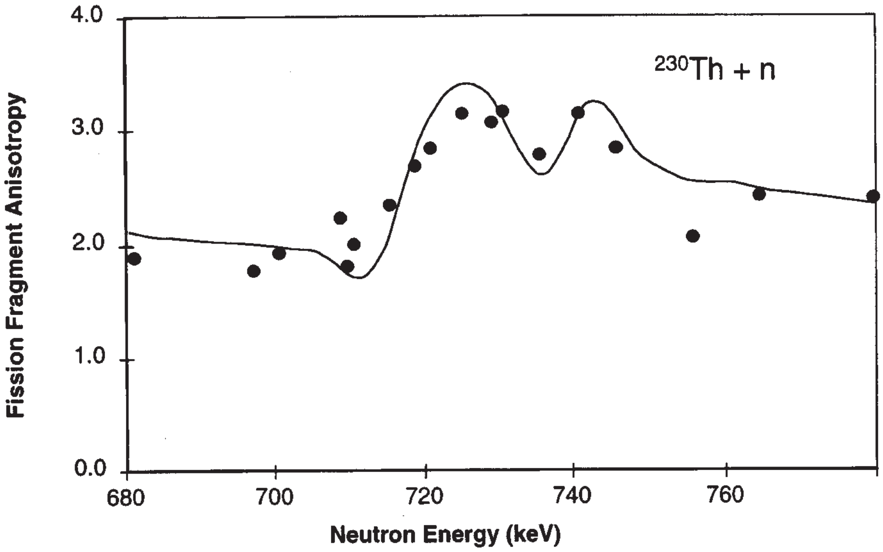

Figure 4. Fission fragment anisotropy[10] for neutron fission of ^{230}Th (adapted from Boldeman & Walsh, 1986).

Sub-barrier Fission Cross-sections

For nuclei represented by the fission barrier in Fig 1, fission can only take place if sufficient energy is given to the system to allow it to proceed either over the barrier or to tunnel through. For sub-barrier fission, the cross section is given by an expression which contains reaction information multiplied by the penetrability through the barrier. The penetrability through the simple liquid drop fission barrier is given by the expression

$$P_i = [1 + \exp\{2\pi(E_i + E^{IK\pi} - E)/h\omega_i\}]^{-1} \qquad \text{(eq. 2)}$$

where E_i is the height of the barrier, $E^{IK\pi}$ is the energy of level ($IK\pi$), E is the excitation energy and $h\omega$ is the curvature of the fission barrier. With a double humped barrier the expression becomes a little more complex

$$T_f^K = t_K + (1 - r_K - t_K)\, P_A(P_A + P_B) \qquad \text{(eq. 3)}$$

where t_K and r_K are the transmission and reflection coefficients which relate to the amplitudes of the fission wave functions inside and outside the nuclear potential and P_A and P_B are the penetrabilities for the two barriers defined as before.

Some unexpected features of the fission cross-section follow from the double humped barrier shape. The potential well between the two humps of the double humped barrier will clearly contain states similar in character to the states in the first well. However the level density at a specific excitation will be different because of the different heights above the ground state. This produces some interesting structure in the sub-barrier cross-section. Figure 5, adapted from Migneto & Theobald (1968), illustrates the influence of the coupling of states in the first well to states in the second well. The gross structure in the sub-barrier neutron fission cross section of ^{240}Pu reflects the spacing of levels in the second well of the fission barrier while the fine structure is related to the level density in the first well.

Although many nuclei have barrier shapes characterised by the doubled humped shape of Fig 1, it was predicted by Moller & Nix (1974) that, if asymmetric

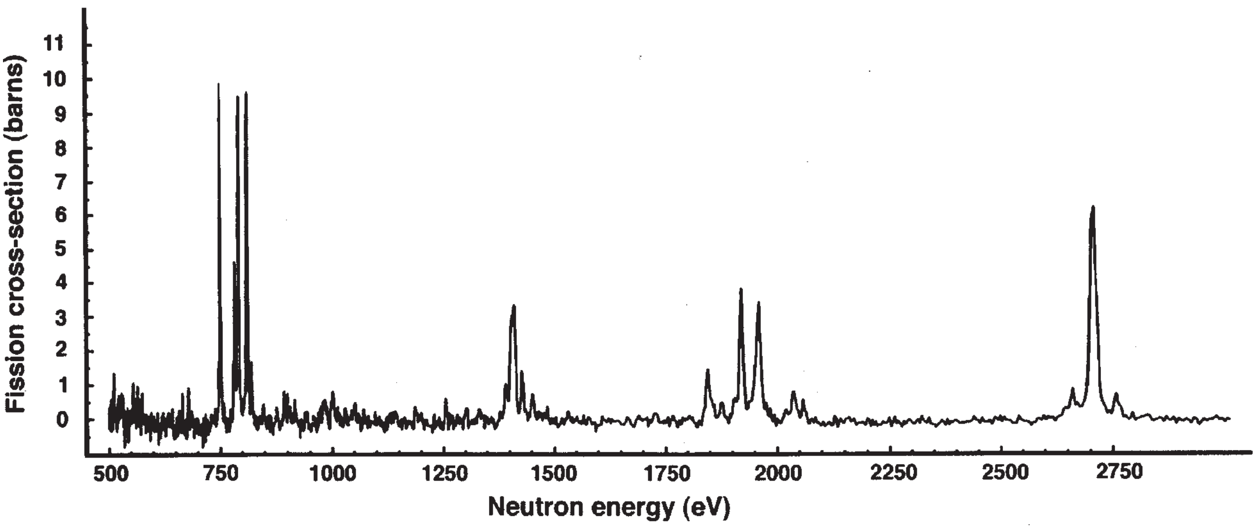

Figure 5. The neutron fission cross section of ^{240}Pu between 500 eV and 3000 eV (adapted from Migneco & Theobald 1968).

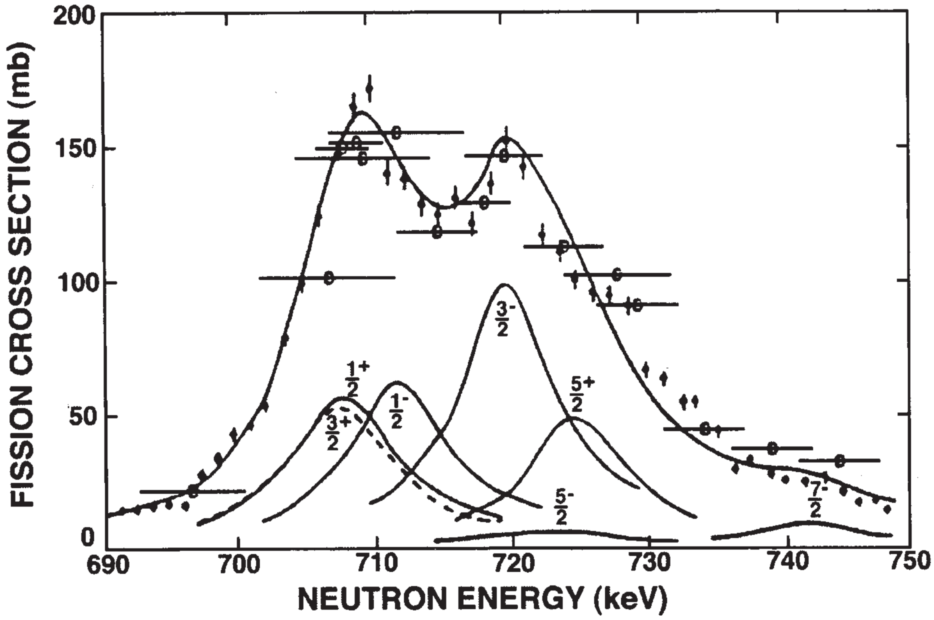

Figure 6. Calculated neutron fission cross section compared with the experimental data of Blons *et al.* (1978). Also shown are the fission cross section data from the angular distribution measurements (Boldeman & Walsh 1986).

deformations are taken into account for nuclei in the vicinity of thorium, then the second barrier should itself split into two separate peaks making the barrier triple humped in character. The consequences of this characteristic are shown in the sub-barrier neutron fission cross section of ^{230}Th as measured by Blons *et al.* (1978). The broad sub-barrier resonance in the cross-section at 715 keV is interpreted as fission through a pure vibrational state in the third well of a triple humped fission barrier. Some controversy regarding the detailed interpretation of the data exists. One interpretation (Boldeman & Walsh 1986) involving a simultaneous fit to the cross section in Fig 6 and the anisotropy data in Fig 4 is presented below.

Fission Fragment Yields and Associated Neutron Emission

One of the most extensively studied aspects of the fission process has been the systematics of the mass division. In this context, it is important to distinguish between the fission fragments and fission products and ultimately accumulated product yields. At the instant of scission, the two fission fragments are highly deformed with a high level of internal excitation, although a large proportion of the energy emitted in fission is contained in the kinetic energy of the fission fragments resulting from Coulomb repulsion. Since the fragments are neutron rich with respect to the stability line, this deformation energy is emitted primarily by neutron evaporation and by prompt gamma emission. The term fission products is used to described the resulting nuclei. Such nuclei are still radioactive and undergo further radioactive decay leading to what are called cumulative yields. Figure 7 illustrates the well known asymmetric division that is typical for low excitation neutron fission of nuclei near uranium (modified from Wahl 1965). The dominating influence in the determination of the shape of the curve is the existence of the magic number N=50 at mass 80 on the lower end of the distribution and the doubly magic nuclei Z=50, N=82 in the vicinity of mass 128. It is also known that the symmetric region between the two peaks of the mass yield curve starts to fill as the excitation increases. This can be explained quite simply as the reduction of shell effects as the excitation energy increases. Neutron emission from the individual fission fragments is a function of the mass of the fragment (Fig 8; from Nifenecker *et al.* 1973). The resulting "saw tooth" shape of the neutron emission is also consistent with the explanation presented above. The minimum in the saw tooth curve occurs in the vicinity of the closed shell nuclei. These nuclei are stiff with respect to deformation and therefore less deformation occurs in these fragments. On the contrary, near the peak of the neutron yield curve, the fragments are soft with respect to deformation and a larger proportion of the total fission energy is involved in the deformation of these fragments.

Fission Product Yields in the Symmetric Region

Studies of fission product yields in the symmetric region for thermal neutron fission of the uranium nuclei are important for at least three reasons. Although the yields are low, in a power reactor significant masses of such nuclei are produced and the management of the reactors requires this knowledge. A second reason follows from suggestions of fine structure in the fission fragment/(product) yields. The symmetric region provides an opportunity to carry out such studies since there are several elements with large numbers of isotopes (*e.g.* Sn) which therefore simplifies the chemistry. In addi-

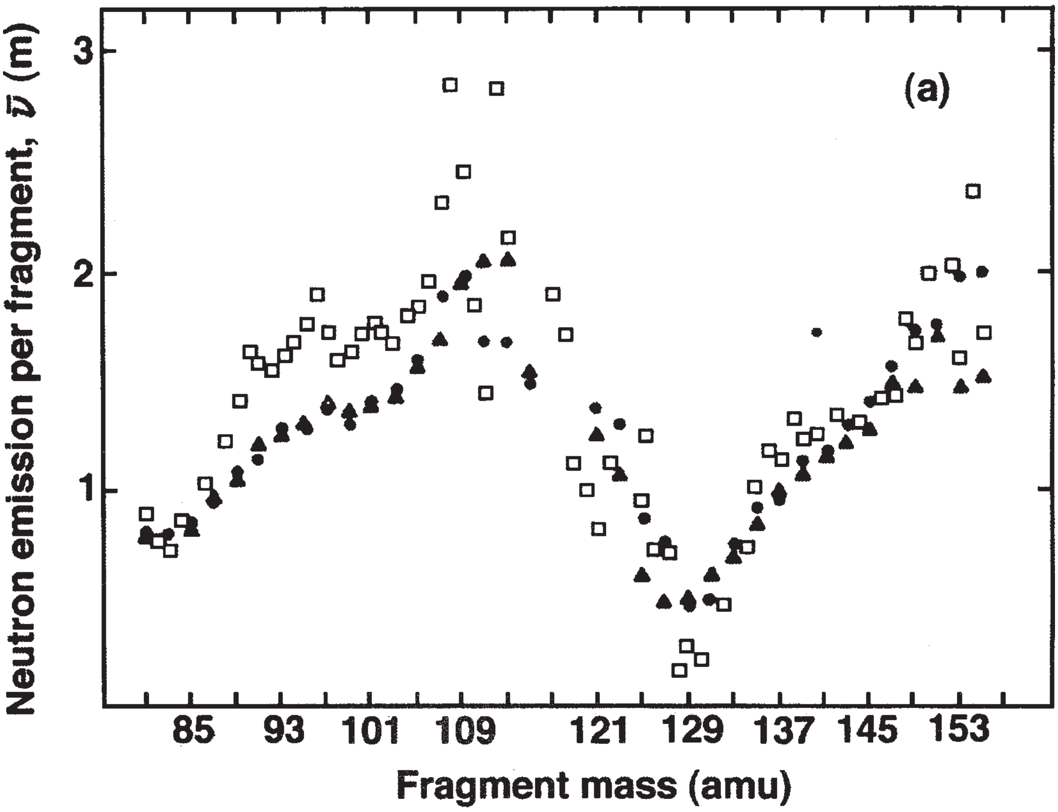

Figure 7. Fission product yields[14] for thermal neutron fission of ^{233}U, ^{235}U and ^{240}Pu and spontaneous fission of ^{252}Cf (from Wahl, 1965).

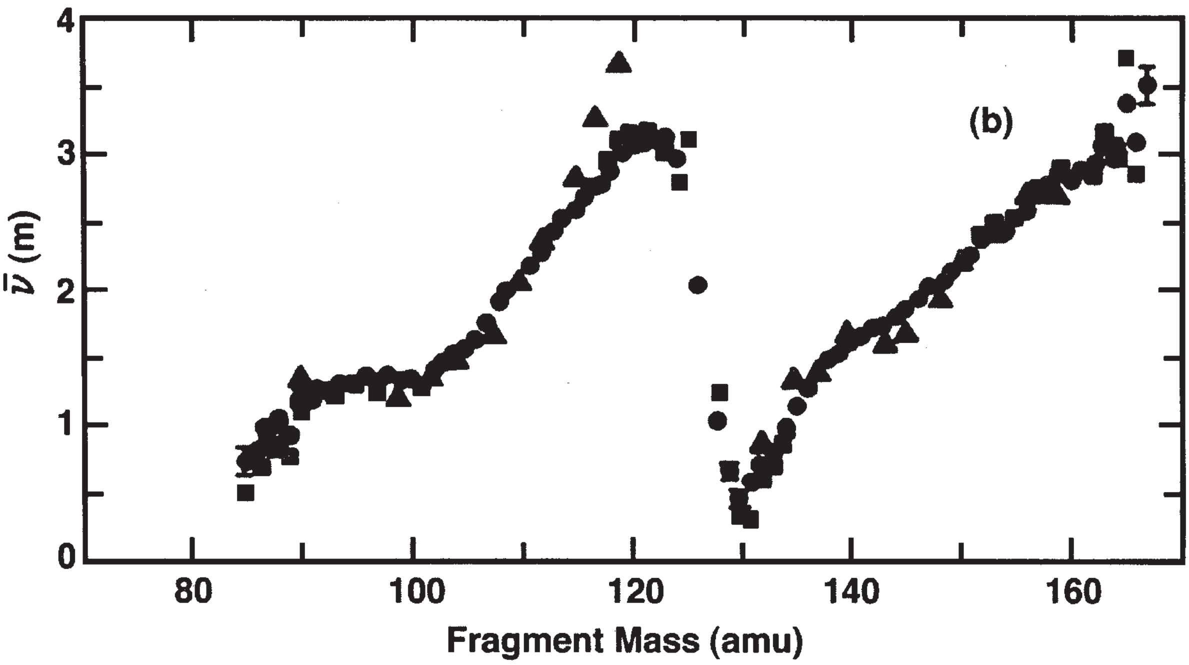

Figure 8. Average neutron emission per fragment as a function of fragment for (a) thermal neutron fission of ^{235}U and (b) spontaneous fission of ^{252}Cf (from Nifenecker *et al.*, 1974).

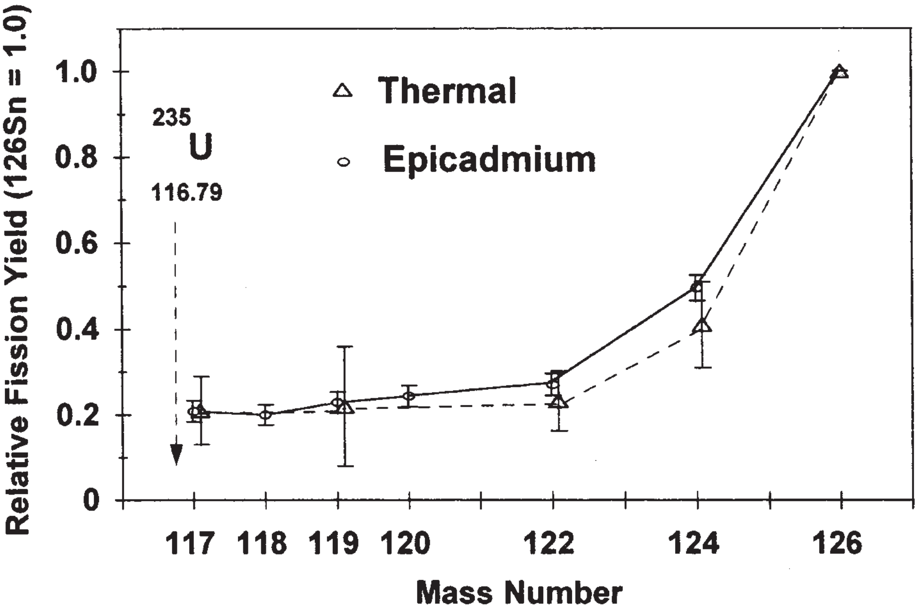

Figure 9. Relative fission yields for isotopes of tin for neutron fission of ^{235}U (thermal and epithermal) normalised to ^{126}Sn (from Rosman *et al.* 1986).

tion, there are extensive studies of earth science where spontaneous fission of the uranium nuclei produce elemental contaminations that need correction. A series of studies by Rosman *et al.* (1983) has produced considerable symmetric mass yield data. Figure 9 shows their data for the Sn isotopes in the symmetric mass yield region; an absence of fine structure is apparent.

Recent Developments of the Theory

In very recent times, there have been some important developments of the theory of fission particularly at low excitation. These developments have been summarised by Brosa *et al.* (1990). Effectively, they involve a more complete consideration of the later stages of the process effectively from the saddle point to scission. These new discoveries show that for low excitation fission there are several exit channels on paths to scission. Furthermore, when the nucleus is close to scission there is some randomness in where the neck connecting the elongated nucleus may actually rupture. These considerations are beyond the context of this paper and the reader is referred to Brosa *et al.* (1990) and other papers mentioned in that text.

References

Blons J, Mazur C, Paya D, Ribrag M & Weigmann H 1978 Rotational bands in asymmetrically deformed ^{231}Th. Physics Review Letters 41:1282-1285.

Bohr A 1956 On the theory of nuclear fission. 1st International Conference on Peaceful Uses of Atomic Energy, New York, Vol 2, 151-154.

Bohr N & Wheeler 1939 The mechanism of nuclear fission. Physics Review 56:426-450.

Boldeman J W & Walsh R L 1986 Neutron fission of ^{230}Th revisted. Radiation Effects 92/1-4:317-322.

Brosa U, Grossmann S & Muller A 1990 Nuclear scission. Physics Reports (A Review Section of Physics Letters) 197:167-262.

Griffin J J 1965 Transition states at the fission barrier. Physics and Chemistry of Fission 1:23-38.

Hahn O & Strassmann F 1939 Über den nachweis und das verhalten der bei der bestrahlung des urans mittels neutronen entstehenden erdalkalimetalle. Naturwissenschaften 27:11.

Migneco E & Theobald J P 1968 Resonance grouping structure in neutron induced subthreshold fission of ^{240}Pu. Proceedings of the International National Bureau of Standards, Specialist Publication 299, Vol 1:527-540.

Moller P & Nix J R 1974 Calculation of fission barriers. Third IAEA Symposium on the Physics and Chemistry of Fission, Rochester, Vol 1:103-143.

Nifenecker H, Signarbieux C, Babinet R & Poitou J 1974 Neutron and gamma emission in fission. Proc. Third IAEA Symposium on Physics and Chemistry in Fission, Rochester, Vol 2:117-178.

Rosman K J R, De Laeter JR, Boldeman J W & Thode HG 1983 Cumulative yields of stable and long lived isotopes of tin in neutron-induced fission. Canadian Journal of Physics 61:1490-1497.

Straede Ch, Budtz-Jorgensen C & Knitter H H 1987 The $^{235}U(n,t)$ fragment mass-, kinetic energy- and angular distributions for incident neutron energies between thermal and 6 MeV. Nuclear Physics A462:85-108.

Strutinsky V M 1967 Shell effects in nuclear masses and deformation energies. Journal of Nuclear Physics A95:420-442.

Strutinsky V M & Pauli H C 1969 Shell-structure effects in the fissioning nucleus. Second International Symposium on the Physics and Chemistry of Fission, Vienna, Vol 1, 155-181.

Vandenbosch R & Huizenga J 1973 Nuclear Fission. Academic Press, New York.

Wagemans C 1991 The Nuclear Fission Process. CRC Press, Boca Raton.

Wahl A C 1965 Mass and charge distribution in low-energy fission. Physics and Chemistry of Fission 1:317-331.