

Light Charged Particle Production
in
Heavy-Ion Induced
Fusion-Fission Reactions

by

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A thesis submitted for the degree of
Doctor of Philosophy
at the Australian National University

Canberra, December 1990

Preface

This thesis describes an investigation of proton and alpha particle emission in $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ heavy-ion fusion-fission reactions, which was carried out at the Department of Nuclear Physics in the Australian National University.

Experimental techniques were developed to enable the observation of proton and alpha particle spectra in a detector consisting of a CsI crystal coupled to a photo-diode, in coincidence with fission fragments detected in an array of thirty parallel-plate gas counters. The CsI detector and the array of parallel-plate gas counters were designed, constructed and tested by myself. The bulk of the experimental work was carried out by Dr J.R.Leigh, Professor J.O.Newton, J.X.Wei and myself. Dr Y.Chen, Dr S.Elfstrom, Dr D.J.Hinde, Dr F.Nami and Dr D.G.Popescu all contributed at various stages.

All the reduction and analysis of the data was performed by myself. The computer code "CPE" used to analyse the shapes of the measured particle spectra and the statistical model code "JOANNE" were written by myself.

I was helped at all stages of this project by many discussions with Dr J.R.Leigh and Professor J.O.Newton. Their guidance was invaluable.

No part of this thesis has been submitted for a degree at any other university.



J.P.Lestone

Canberra, December 1990.

Acknowledgements

I would like to thank my supervisors Jack and John for providing a working environment where I always felt as though they were helping me with my project, instead of me helping them with theirs. I am also grateful for their constructive criticism of preliminary drafts of this thesis.

I am indebted to Xin for the many hours he spent helping me set up and run the experiments and for his advice relating to the design of the array of parallel-plate gas counters.

My thanks also go to David, Dom, Chen, Nami and Sven for assistance in running experiments.

I would like to thank Alan(H), Alan(C) and Doug for their help in designing and building detectors; Gavin and Aidan for familiarising me with the "Versacad" computer drawing software; Anne for her patience in helping me use a Macintosh; and Gordon for advice in the computing field.

A special thanks to Bernhard and his program "MultiFig" which I used to produce most of the figures in this Thesis.

Finally a big thanks to my wife Joanne for her encouragement and support and for helping with the proof reading of this thesis.

Abstract

Energy spectra and angular correlations of protons and alpha particles were measured in coincidence with fission fragments in the three reactions $^{28}\text{Si} + ^{164,167,170}\text{Er} \rightarrow ^{192,195,198}\text{Pb}$, with ^{28}Si beam energies ranging from 140 MeV to 185 MeV. For each combination of beam energy and reaction, proton and alpha particle spectra were measured in coincidence with fission fragments in up to thirty detectors. Analysis of these particle spectra enabled the determination of the multiplicities, energy spectra and angular distributions of the various sources of proton and alpha particle emission. The proton yields consisted of ~50% emission from the compound systems (pre-scission emission) and ~50% emission from the fully accelerated fission fragments (post-scission emission). The alpha particle yields consisted of ~65% pre-scission emission; ~30% post-scission emission; and ~5% near-scission emission. The pre-scission proton emission is nearly isotropic, while the pre-scission alpha particle emission has a large anisotropy, with between 2 and 3 times more alpha particles seen perpendicular to the spin direction of the pre-scission compound systems, than seen parallel to this direction. Statistical model analysis of the pre-scission proton and alpha particle multiplicities and previously measured pre-scission neutron multiplicities indicates that for $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ fusion-fission reactions the pre-saddle delay time is less than 10×10^{-21} s, the saddle-to-scission transit time is $(70 \pm 20) \times 10^{-21}$ s; and for beam energies ≥ 155 MeV most of the pre-scission particles are emitted by the compound nuclei during their transit from the saddle-point to the scission-point.

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CHAPTER 1

INTRODUCTION

The determination of the nature and magnitude of nuclear viscosity and its effects on a complex collective phenomenon such as fission remains one of the major unsolved problems in nuclear physics. Attempts have been made to obtain information about nuclear viscosity from the dependence of the total kinetic energy of fission fragments on the fissility of the compound nucleus. Acceptable fits to the experimental systematics can be made using either one- or two-body dissipation mechanisms [DAV76]. The analysis of the total kinetic energy of fission fragments has thus shed little light on the true nature of nuclear viscosity. The clearest and most dramatic evidence of the effects of nuclear viscosity has come from the measurement of pre-scission particle multiplicities in heavy-ion fusion-fission reactions.

When a compound system is formed in a heavy-ion fusion reaction it can decay in general by light particle emission (neutrons, protons and alpha particles), gamma-ray emission or fission. Unless the system is very neutron deficient, neutron emission dominates over that for protons and alpha particles. Central collisions between heavy ions and target nuclei produce compound systems with low angular momenta. If the fissility of these systems is low, they will cool by the evaporation of light particles and gamma-rays, producing evaporation residues. Peripheral collisions will produce compound nuclei at high angular momenta, where the disruptive nature of the centrifugal force may cause the fission decay mode to become important even for systems with low fissility. Even though these systems may initially survive fission and emit one or several particles, if the excitation energy is high they may still undergo fission. The number of particles emitted by a composite system before fission (the

pre-scission particle multiplicity) reflects the relative size of the fission time scale and the lifetime of the particle emission. Measurements of pre-scission neutrons [HIN89*] and charged particles [PEA88*] in heavy-ion fission reactions have shown that fission occurs on a time scale of 10^{-20} to 10^{-19} s. These times imply that nuclear viscosity is high and that fission is overdamped, due possibly to a one-body type dissipation process.

In fusion-fission reactions the projectile is completely absorbed by the target nucleus and the composite system probably obtains the equilibrium shape before proceeding towards fission. For this to occur the rotation plus deformation energy of the composite system must have a minimum and thus the compound nucleus must have a fission barrier. Conceptually the effect of nuclear viscosity in fusion-fission reactions can be broken into two regimes. The first is the pre-saddle delay time (or transient delay time) associated with the time taken for the collective fission degree of freedom to reach equilibrium [GRA86*]. The second is the saddle-to-scission transit time [CAR86*]. In reality, back-flow over the fission barrier blurs the distinction between these two regimes. Statistical model analysis of pre-scission particle multiplicities has been used to estimate fission time scales by assuming only a transient delay time, only a saddle-to-scission transit time, or some given combination of the two times. Until now, no analysis of measured pre-scission particle multiplicities has enabled the determination of these two times separately.

If the angular momentum brought in by a projectile is high the fission barrier may be reduced to zero. That is, there is no minimum in the rotation plus deformation energy of the composite system and no equilibrium configuration exists. Such fission without a barrier is

for the rest of this chapter "*" stands for "and references therein"

generally called fast-fission and is associated with an increase in the fission mass width [GRE82*]. Pre-scission neutron multiplicities indicate that fast-fission occurs on a time scale approximately a factor of two shorter than fusion-fission [HIN89].

Another class of fission, called quasi-fission, has been observed in reactions between nuclei with a large Coulomb energy [SHE87*]. Even though a fission barrier exists for these systems, the high Coulomb repulsion prevents the fusion trajectory from passing inside the fission barrier and the equilibrium deformation is not reached. Although this process is very similar to fast-fission, the reasons for the failure of the composite system to form an equilibrated compound nucleus are somewhat different. Shen *et al.* [SHE87] have studied quasi-fission time scales as a function of mass equilibration using the correlation of fission fragment mass with detection angle. They found that the time for full mass equilibration (ie the reaction time needed to produce symmetric fission fragments) is $\sim 15 \times 10^{-21}$ s and is independent of excitation energy. The independence of this time on excitation energy supports the idea that nuclear viscosity is a one-body dissipation process where the coupling between thermal and collective energy is caused by interactions of the individual nucleons with the nuclear surface. The alternative mechanism, two-body dissipation, is expected to give rise to a bulk viscosity which is inversely proportional to the nuclear temperature. This would lead to mass-relaxation times that decrease with excitation energy.

The sensitivity of the energy spectra, the angular distribution and the probability of proton and alpha particle evaporation to nuclear shape has been discussed [BLA81,AJI86,HUI89]. The possibility that this shape dependence could assist in determining the division of the total time scale of fusion-fission reactions into its two components (pre-saddle delay time and saddle-to-scission transit time) led us to measure pre-scission protons and alpha particles from reactions with 140 MeV to 185 MeV ^{28}Si

projectiles on $^{164,167,170}\text{Er}$ targets. The main reasons for choosing these reactions were

- (1) the evaporation residue and fusion excitation functions and several pre-scission neutron multiplicities have already been measured by Hinde *et al.* [HIN83,HIN86].
- (2) the compound nuclei formed in these reactions ($^{192,195,198}\text{Pb}$) are very neutron deficient. This enhances the charged particle emission.
- (3) fusion-fission reactions are expected to be the dominant source of pre-scission particles. Only a small contribution from fast-fission reactions is expected at the highest beam energies.

In this thesis it is demonstrated for the first time that the simultaneous statistical model analysis of pre-scission neutron, proton and alpha particle multiplicities offers the opportunity to determine the pre-saddle delay time and the saddle-to-scission transit time separately. This determination does not, however, depend on the variation of evaporation with nuclear shape as discussed by [BLA81,AJI86,HUI89], but rather on the different deformation energies of daughter nuclei in the pre-saddle and saddle-to-scission regions.

The outline of this thesis is as follows; chapter 2 discusses the theoretical background of various models of interest in this work; chapter 3 describes the experimental methods; and in chapter 4 the experimental results are presented along with a statistical model analysis of the pre-scission particle data.

CHAPTER 2

THEORY

This chapter describes the theoretical background of various models of concern in this work. Section 2.1 discusses the spin distribution of compound nuclei formed in heavy-ion fusion reactions. The determination of liquid-drop-model nuclear masses and the rotation plus deformation energy of equilibrium and saddle-point configurations are discussed in section 2.2. The statistical model is described in section 2.3 and the effect of nuclear viscosity on the dynamics of the fission process is discussed in section 2.4.

2.1 Heavy-Ion Fusion

The potential between two interacting nuclei can be thought of as a sum of three terms; an attractive nuclear term and repulsive Coulomb and centrifugal terms. Expressing the nuclear term as a Woods-Saxon potential gives the nucleus-nucleus potential for angular momentum $L\hbar$, as

$$V(r) = \frac{-V_0}{1 + \exp\left(\frac{r - r_n}{\delta}\right)} + \frac{Z_1 Z_2 e^2}{r} + \frac{\hbar^2 L(L+1)}{2\mu r^2} \quad (2.1)$$

where V_0 is the depth, r_n the range and δ the surface diffuseness of the Woods-Saxon potential, μ is the reduced mass of the system and r is the distance between nuclear centres.

This expression obviously becomes invalid at distances where the surfaces of the two interacting nuclei overlap significantly ($r \lesssim 10$ fm for Si + Er). At these distances the Coulomb potential can no longer be represented as the potential between two point charges, frictional forces reduce the projectile-target relative angular momentum and mass

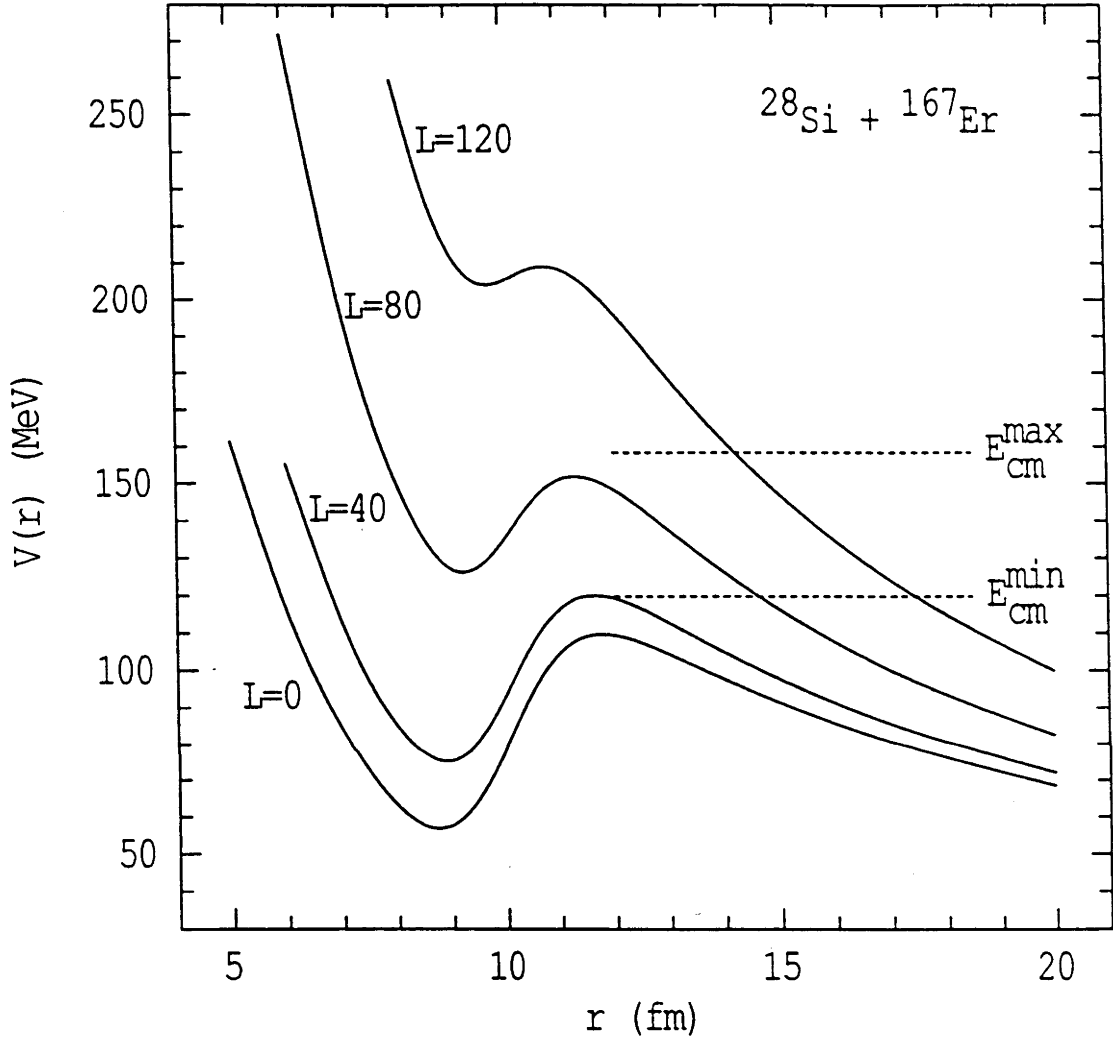


Figure 2.1 The $^{28}\text{Si} + ^{167}\text{Er}$ nucleus-nucleus potential with $L = 0, 40, 80$ and 120 . The V_0 , r_n and δ used are those of Lozano and Madurga [LOZ80]. Also shown are the maximum and minimum centre of mass energies used in the present experimental study.

transfer causes the projectile and target to lose their original identities. Figure 2.1 shows $V(r)$ for $^{28}\text{Si} + ^{167}\text{Er}$ with $L = 0, 40, 80$ and 120 .

The fusion cross section σ_{cn} can be written as

$$\sigma_{\text{cn}} = \pi \lambda^2 \sum_{L=0}^{\infty} (2L+1) T_L \quad (2.2)$$

where λ is the reduced wavelength of the projectile and the T_L are angular momentum dependent transmission coefficients for the projectile passing over or through the fusion barrier. The simplest model for the transmission coefficients is the sharp cut off model which assumes that if the centre of mass bombarding energy E_{cm} is larger than the fusion barrier $V_b(L)$, then $T_L = 1$; otherwise $T_L = 0$.

$$\begin{array}{lll} \text{ie} & T_L = 0 & \text{for } E_{\text{cm}} < V_b(L) \\ & T_L = 1 & E_{\text{cm}} > V_b(L) \end{array} \quad (2.3)$$

and thus the maximum angular momentum contributing to fusion can be determined by solving equation 2.4.

$$E_{\text{cm}} = V_b(L_{\text{max}}) \quad (2.4)$$

From figure 2.1 we see that for $^{28}\text{Si} + ^{167}\text{Er}$ at a centre of mass energy of 120 MeV , $L_{\text{max}} = 40$, and for $E_{\text{cm}} = 152 \text{ MeV}$, $L_{\text{max}} = 80$.

Substituting the sharp cut off transmission coefficients into equation 2.2 gives

$$\sigma_{\text{cn}} = \pi \lambda^2 (L_{\text{max}}+1)^2 \quad (2.5)$$

Figure 2.2 shows experimental fusion cross sections for $^{28}\text{Si} + ^{167}\text{Er}$ [HIN83]. Values of L_{max} deduced from the fit to these cross sections are displayed in figure 2.3, along with two values obtained using the $L = 40$ and $L = 80$ potentials shown in figure 2.1.

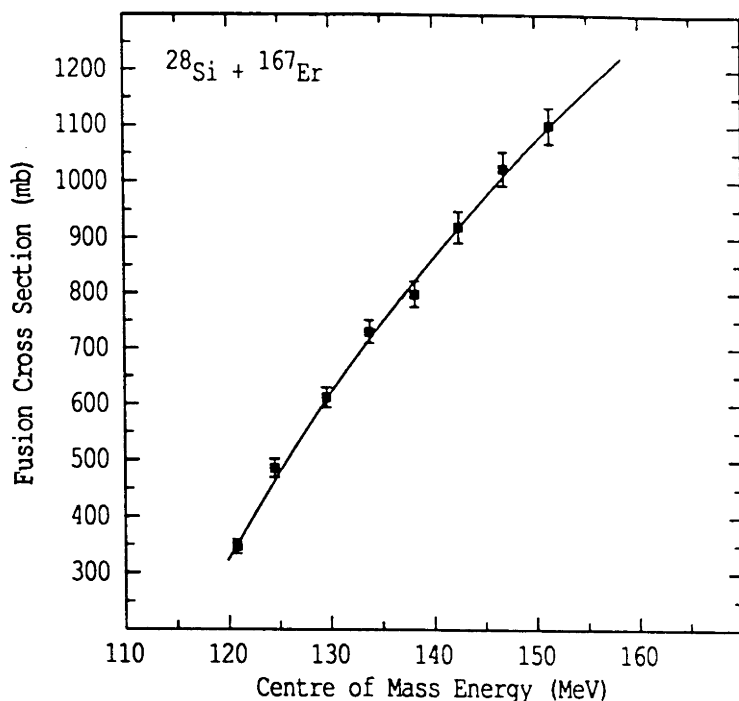


Figure 2.2 Experimental fusion cross sections for $^{28}\text{Si} + ^{167}\text{Er}$ [HIN83] in the energy range of the present study.

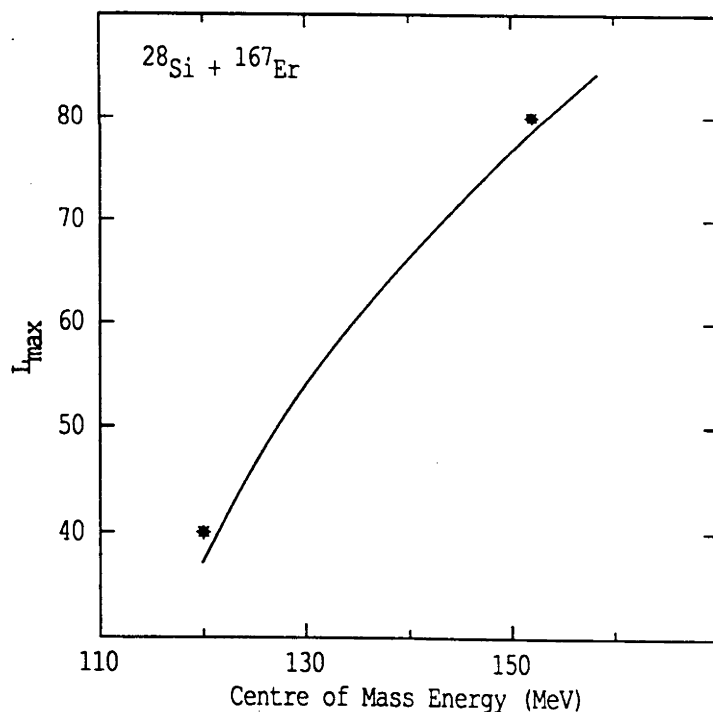


Figure 2.3 Sharp cut off model L_{max} values versus centre of mass beam energy. The smooth curve was obtained using equation 2.5 and the fit to the fusion cross sections of [HIN83]. The stars were obtained using equation 2.4 and the $L = 40$ and $L = 80$ nucleus-nucleus potentials shown in figure 2.1.

If the parabolic barrier model is used then the transmission through the barrier is given by the Hill-Wheeler expression

$$T_L = \{ 1 + \exp [2 \pi \frac{V_b(L) - E_{cm}}{\hbar \omega_L}] \}^{-1} \quad (2.6)$$

where $\hbar \omega_L$ is the angular momentum dependent width of the parabola used to approximate the true barrier. Equation 2.4 thus becomes

$$E_{cm} = V_b(L_{1/2}) \quad (2.7)$$

where L_{max} has been replaced by the angular momentum quantum number corresponding to $T_L = 1/2$. Many other factors besides barrier penetration can contribute to the spreading of the fusion spin distribution, especially at sub-barrier energies. For deformed nuclei the two most important are the effects of zero point motion and static nuclear deformation. Both cause changes to the fusion barrier, depending on the relative orientation of the target and projectile nuclei.

The fusion transmission coefficients T_L are often parameterised as

$$T_L = \{ 1 + \exp [\frac{L - L_{1/2}}{\Delta L}] \}^{-1} \quad (2.8)$$

where ΔL is the diffuseness of the fusion spin distribution, which is often assumed to be independent of projectile energy. This gives $T_L = 1$ for $L \ll L_{1/2}$; $T_L = 0$ for $L \gg L_{1/2}$ with a smooth transition region from $\sim L_{1/2} - 2 \Delta L$ to $\sim L_{1/2} + 2 \Delta L$. Substituting equation 2.8 into 2.2 gives the fusion cross section

$$\sigma_{cn} = \pi \lambda^2 \sum_{L=0}^{\infty} \frac{2L+1}{1 + \exp(\frac{L - L_{1/2}}{\Delta L})} \quad (2.9)$$

For a given ΔL , $L_{1/2}$ can be determined from measured total fusion cross sections. Fission cross sections calculated using the statistical model (see section 2.3) can be sensitive to ΔL , because increases in ΔL push more of the fusion spin distribution to larger values of L where the fission barriers are smaller (see section 2.2). Thus ΔL can be estimated from fission excitation functions. However, for reactions where the total fission

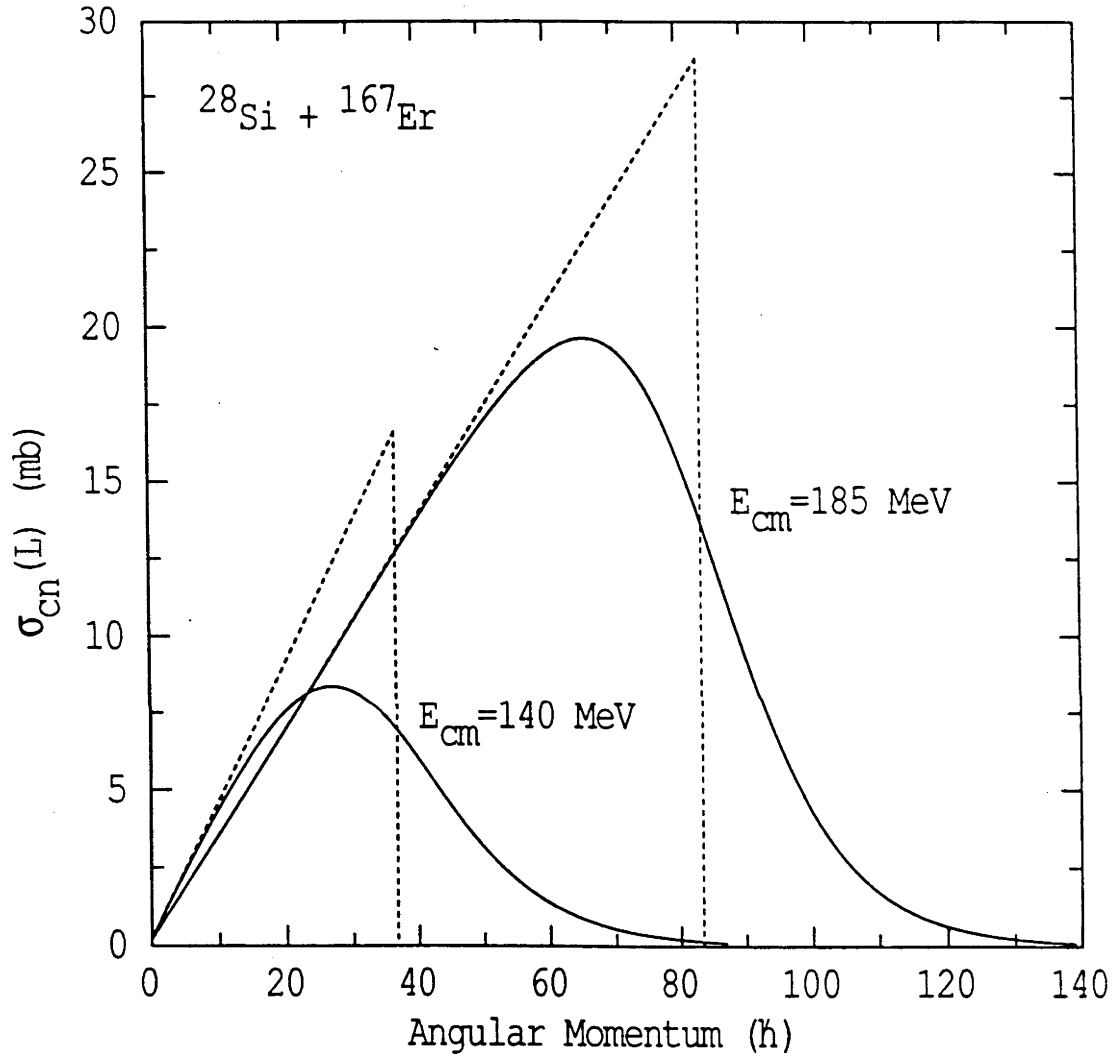


Figure 2.4 The spin distribution of ^{195}Pb following the fusion of ^{28}Si with ^{167}Er , assuming both sharp cut off transmission coefficients and T_L as given by equation 2.8 with a realistic value of $\Delta L = 9$ [HIN86].

probability is high, the sensitivity to ΔL is small, because the fission probability for the highest L values is already close to unity and any change in the distribution of the high fusion-spin values by an adjustment of ΔL does not significantly affect the fission cross sections. Figure 2.4 shows the populated spin distribution of ^{195}Pb following the fusion of ^{28}Si with ^{167}Er , assuming both sharp cut off transmission coefficients and T_L as given in equation 2.8 with a realistic value of $\Delta L = 9$ [HIN86].

2.2 Charged Liquid Drop Based Models

The compound nuclei studied in heavy-ion induced fission are, in general, at high excitation. At a high enough excitation energy, shell and pairing effects are sufficiently washed out to enable the predictions of macroscopic models to be considered reasonable.

2.2.1 Nuclear Masses

Considering nuclei as charged liquid drops provides a good description of the average trends in ground state nuclear masses with changes in Z and N over most of the periodic table ($A \gtrsim 10$). In this model the ground state masses can be written as

$$M_{\text{gs}} = M_n N + M_p Z + E_v + E_s + E_c \quad (2.10)$$

where M_n and M_p are the masses of a neutron and proton respectively, E_v is the volume energy, E_s is the surface energy and E_c is the Coulomb energy.

The volume energy reflects the fact that the nuclear force is short ranged and thus each nucleon only feels the attraction of its neighbours. Since each nucleon in the nuclear interior has on average the same number of neighbours, the total nuclear binding energy is roughly proportional to A . The volume energy is thus written as

$$E_v = -C_v A \quad (2.11)$$

Equation 2.11 ignores the fact that nucleons near the nuclear surface have fewer neighbours than those in the interior. This produces an effect completely analogous to the surface tension of a liquid droplet and gives rise to a positive energy term which is roughly proportional to the nuclear surface area, and can therefore be written as

$$E_s = E_s^0 f(\text{shape}) = C_s A^{2/3} f(\text{shape}) \quad (2.12)$$

where E_s^0 is the surface energy of a spherical nucleus and $f(\text{shape})$ is the ratio of the surface area of the desired nuclear shape to that of a sphere of the same volume.

The Coulomb energy is due to the roughly uniform distribution of Z protons in the nucleus and can be written as

$$E_c = E_c^0 g(\text{shape}) = C_c \frac{Z^2}{A^{1/3}} g(\text{shape}) \quad (2.13)$$

where E_c^0 is the Coulomb energy of a spherical nucleus, $g(\text{shape})$ is the ratio of the electrostatic energy of the desired nuclear shape to that of a spherical nucleus with the same Z and A , and C_c is a constant.

If C_v and C_s are assumed to be constants (ie independent of Z and A) then equation 2.10 requires an additional term due to the exclusion principle, which causes nuclei to be most stable for $Z \approx N$. This term is usually called the symmetry energy and can be written as

$$E_a = C_a \frac{(N - Z)^2}{A} \quad (2.14)$$

Green [GRE54] fitted experimental ground state masses, obtaining the values

$$C_v = 15.75 \text{ MeV} \quad C_s = 17.8 \text{ MeV}$$

$$C_c = 0.71 \text{ MeV} \quad \text{and} \quad C_a = 23.7 \text{ MeV}$$

The symmetry term is now usually incorporated into the volume and surface energies by assuming

$$C_v = a_v \left[1 - \kappa \left(\frac{N - Z}{A} \right)^2 \right] \quad (2.15)$$

$$C_s = a_s \left[1 - \kappa \left(\frac{N - Z}{A} \right)^2 \right] \quad (2.16)$$

where a_v , a_s and κ are constants.

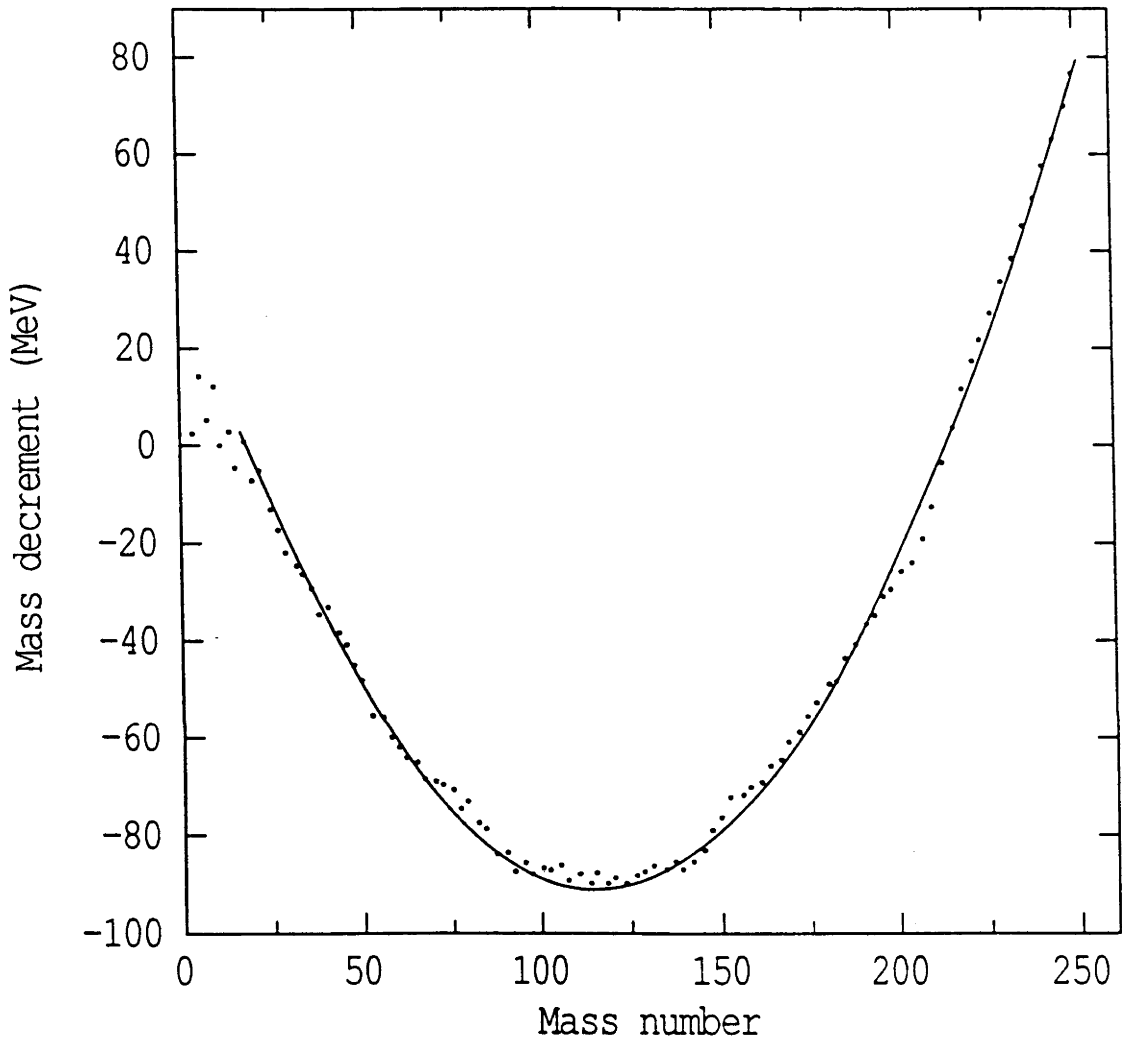


Figure 2.5 The mass decrements of 97 beta-stable nuclei compared to the liquid drop part of the Myers and Swiatecki mass formula. (adapted from [MYE66])

Myers and Swiatecki [MYE66,MYE67] have fitted experimental ground state nuclear masses with equations 2.10 to 2.13 , 2.15 and 2.16 and with parameterised shell and pairing corrections. They obtained the following expressions :

$$E_v = -15.494 \left\{ 1 - 1.783 \left(\frac{N-Z}{A} \right)^2 \right\} A \text{ MeV} \quad (2.17)$$

$$E_s^0 = +17.944 \left\{ 1 - 1.783 \left(\frac{N-Z}{A} \right)^2 \right\} A^{2/3} \text{ MeV} \quad (2.18)$$

$$E_c^0 = +0.7053 \frac{Z^2}{A^{1/3}} - 1.1529 \frac{Z^2}{A} \text{ MeV} \quad (2.19)$$

The additional term in the Coulomb energy corrects for the diffuseness of the charge distribution near the nuclear surface. Figure 2.5 compares the liquid drop part of Myers and Swiatecki mass formula with the mass decrements of 97 beta-stable nuclei.

A number of more sophisticated liquid drop mass formulae containing higher order terms have since been developed (see [MAR76]). These more complicated mass formulae do not give an improved quality of the fit to nuclear masses along the valley of beta-stability but are expected to be more reliable than the simpler liquid drop mass formulae for long range extrapolations because of the higher order effects that they consider.

2.2.2 The Liquid Drop Model of Fission

The liquid drop explanation of fission is based on the fact that the surface energy E_s and the Coulomb energy E_c are both shape dependent. Increasing the deformation of a nucleus increases its surface area and thus increases its surface energy. The average distance between protons increases with increased deformation, producing a decrease in Coulomb energy. At first, increased deformation produces an increase in surface energy larger than the decrease in the Coulomb energy, and the potential energy of a nucleus is raised. If the distortion continues to grow in size, a point is eventually reached where the rate of change of E_s is equal to the negative rate of change of E_c . This point is called the saddle-point and the

difference between its potential energy and the potential energy of the nucleus at equilibrium is called the fission barrier. Beyond the saddle, further distortion causes a reduction in potential energy because the negative rate of change of the Coulomb energy is now larger than the rate of change of the surface energy. The nucleus is then driven to higher deformation where the system eventually breaks into two fission fragments.

If only axially symmetric shapes are considered, the radius as a function of angle to the symmetry axis can be expressed as a sum of Legendre polynomials.

$$R(\theta) = \frac{R_0}{\lambda} \left[1 + \sum \alpha_n P_n(\cos\theta) \right] \quad (2.20)$$

where the α_n (even n only for symmetric shapes) specify the shape and λ is a parameter normalising the volume of the drop to the standard value of $\frac{4}{3}\pi R_0^3$. The surface and Coulomb energies for small deformations where $\alpha_{n \geq 4} \ll \alpha_2$ are given by [BOH39]

$$E_s = E_s^0 (1 + \frac{2}{5} \alpha_2^2) \quad (2.21)$$

$$E_c = E_c^0 (1 - \frac{1}{5} \alpha_2^2) \quad (2.22)$$

and thus the changes in surface energy ΔE_s and Coulomb energy ΔE_c are

$$\Delta E_s = + \frac{2}{5} E_s^0 \alpha_2^2 \quad (2.23)$$

$$\Delta E_c = - \frac{1}{5} E_c^0 \alpha_2^2 \quad (2.24)$$

For a nucleus to be stable against small distortions, the potential energy must rise when α_2 is increased from 0.

$$\text{ie} \quad - \frac{\Delta E_c}{\Delta E_s} < 1 \quad (2.25)$$

Substituting in equations 2.23 and 2.24 gives

$$\frac{E_c^0}{2 E_s^0} = x < 1 \quad (2.26)$$

where x is defined as the nuclear fissility parameter. Ignoring the small

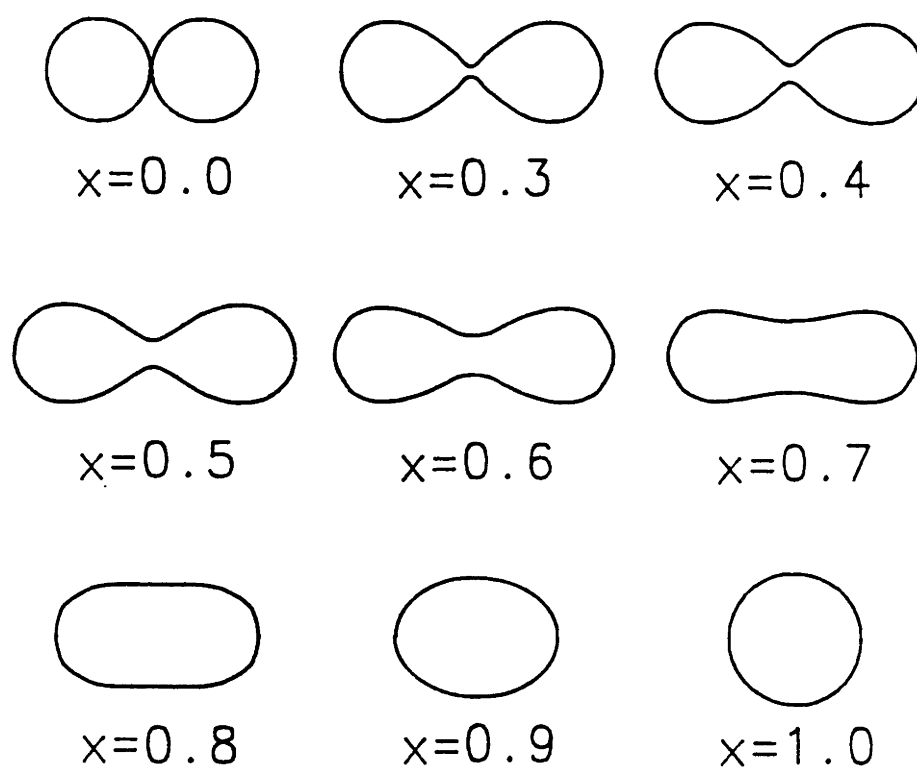


Figure 2.6 Saddle-point shapes for various values of x . (adapted from [COH63])

correction to the Coulomb energy due to the diffuseness of the charge distribution near the nuclear surface, equations 2.18 and 2.19 give

$$x = \frac{Z^2}{A} \frac{1}{50.883 [1 - 1.783 (\frac{N-Z}{A})^2]} \quad (2.27)$$

Equations 2.26 and 2.27 predict that nuclei with $Z \geq 120$ do not have a fission barrier and thus do not exist.

Cohen and Swiatecki [COH63] have studied fission barriers and saddle-point configurations using equation 2.20 (even $n \leq 18$) to parameterise the nuclear surface. They found that for $x \geq 0.7$ the saddle-point shapes are cylinder-like with α_2 and α_4 the only shape coefficients of appreciable magnitude. For $x \leq 0.7$ the saddle-point configurations develop necks, with higher order α_n 's needed. Figure 2.6 shows saddle-point shapes for various values of the fissility parameter.

A simple formula which reproduces the liquid drop fission barriers to an accuracy of < 0.75 MeV is

$$B_f = 0.38 (0.75 - x) E_s^0 \quad \text{for } 1/3 < x < 2/3 \quad (2.28)$$

$$B_f = 0.83 (1 - x)^3 E_s^0 \quad \text{for } 2/3 < x < 1 \quad (2.29)$$

Cohen and Swiatecki also studied the stability of their symmetric saddle-point configurations with respect to asymmetric distortions. They found that symmetric saddle-point shapes are stable for $x = 1$ down to the Businaro-Gallone point of $x_{bg} = 0.39$ ($A \approx 105$). Below this point their symmetric saddle-point shapes are unstable to asymmetric distortions corresponding to the sucking up of one fragment by the other.

2.2.3 The Rotating Liquid Drop Model

To study the effects of rotation on nuclei, the rotational energy of the system must be included in the energy E which can then be written as

$$E = E_s + E_c + E_r \quad (2.30)$$

where E_s and E_c are as defined in equations 2.12 and 2.13, and E_r is given by

$$E_r = E_r^0 h(\text{shape}) = \frac{L^2 \hbar^2}{2 \mathbb{I}} \quad (2.31)$$

where E_r^0 is the rotational energy of a spherical nucleus, $h(\text{shape})$ is the ratio of the moment of inertia $\mathbb{I}^0$ of a sphere about the axis of rotation to that of the desired shape $\mathbb{I}$, and $L\hbar$ is the angular momentum of the system.

Writing the rotation plus deformation energy in units of the surface energy of a sphere gives

$$\xi = \frac{E - E^0}{E_s^0} = \left(\frac{E_s}{E_s^0} - 1 \right) + \frac{E_c^0}{E_s^0} \left(\frac{E_c}{E_c^0} - 1 \right) + \frac{E_r^0}{E_s^0} \left(\frac{E_r}{E_r^0} - 1 \right) \quad (2.32)$$

$$= (f - 1) + 2x(g - 1) + y(h - 1) \quad (2.33)$$

where x is the fissility parameter and y is the ratio of the rotational energy of a spherical nucleus to its surface energy. Assuming rigid body rotation and a radius parameter of $r_0 = 1.2249$ fm

$$E_r^0 \approx 34.54 \frac{L^2}{A^{5/3}} \quad (2.34)$$

and thus

$$y = \frac{1.9249}{1 - 1.7826 \left(\frac{N - Z}{A} \right)^2} \frac{L^2}{A^{7/3}} \quad (2.35)$$

Equation 2.33 reduces the rotating liquid drop model to a study of ξ as a function of x , y and nuclear shape. Of particular interest is the study of configurations where $\delta\xi=0$ with small changes in all the deformation degrees of freedom. These configurations correspond to equilibrium or saddle-point shapes depending on the sign of the second derivatives of ξ with respect to the deformation degrees of freedom. Cohen, Plasil and

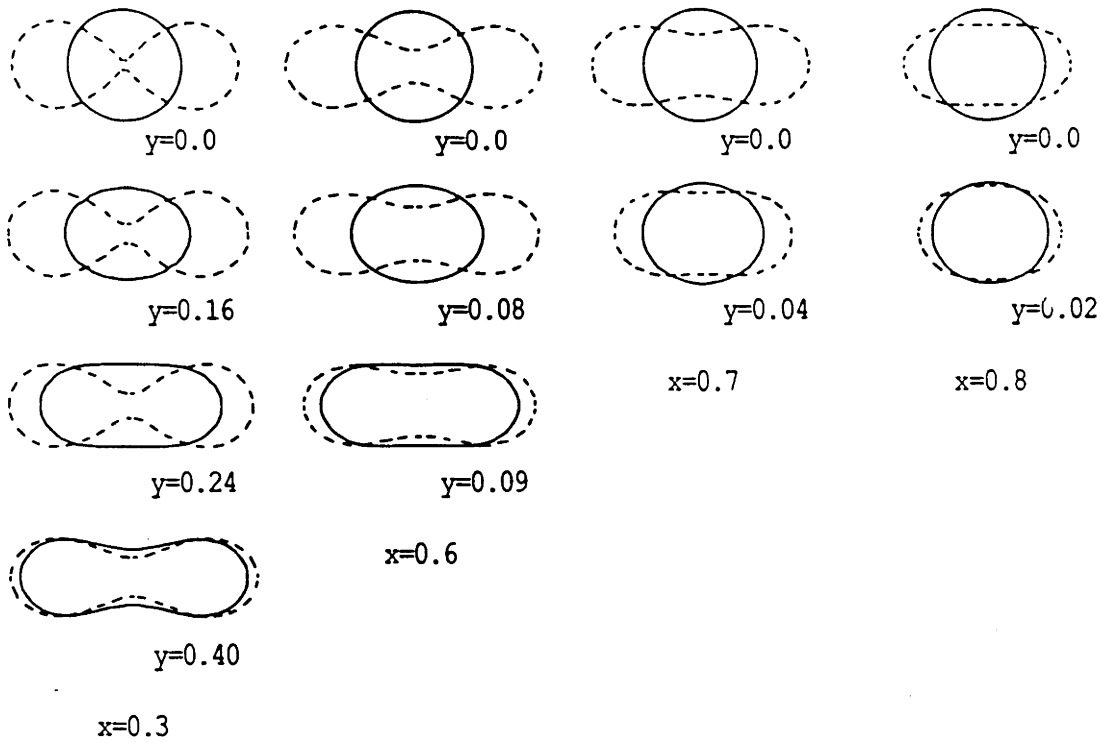


Figure 2.7 Equilibrium(solid curves) and saddle-point(dashed curves) shapes for various x and y . (adapted from [COH74])

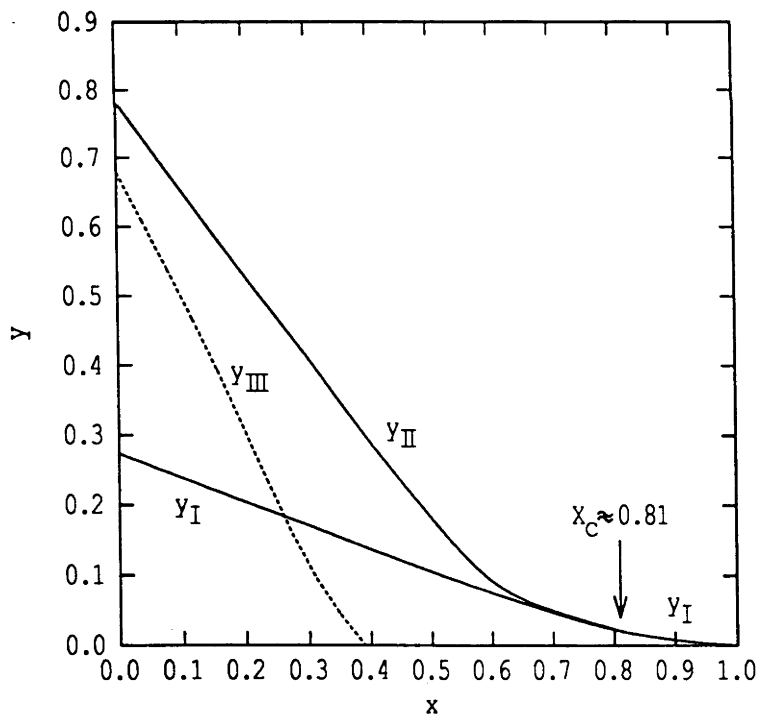


Figure 2.8 Various rotational parameters y and their dependence on the fissility parameter x . Triaxial shapes appear between y_I and y_{II} . Saddle-point shapes are unstable against reflection asymmetric distortions to the left of the dashed curve y_{III} . (adapted from [COH74])

Swiatecki [COH74] have made an extensive investigation of ξ , considering axially symmetric, asymmetric and triaxial shapes in their study. Some of their equilibrium and saddle-point shapes for various x and y are shown in figure 2.7.

If we consider a given nucleus with angular momentum $L\hbar=0$ then the liquid drop model predicts it to be spherical. As the angular momentum is increased the nucleus becomes deformed, taking on a nearly spheroidal, oblate shape which is symmetric about the axis of rotation. If the angular momentum is increased further a critical value $L_I\hbar$ is reached where the nucleus becomes unstable with respect to triaxial deformation. If the fissility parameter of the nucleus is larger than the critical value of $x_c \sim 0.81$ then no stable triaxial configuration exists and $L_I\hbar$ represents the maximum angular momentum that can be accommodated by the nucleus. If $x < x_c$ then L_I is the boundary between oblate and triaxial equilibrium configurations. As L is increased further the nucleus rapidly takes a prolate shape. Eventually a second critical value, L_{II} is reached where the fission barrier goes to zero and the nucleus becomes unstable with respect to fission. Since rotation acts in a similar way to Coulomb repulsion, it effectively increases the fissility. Hence the Businaro-Gallone point goes to smaller values of x as y increases. This is shown by the line y_{III} in figure 2.8. Various critical rotational parameters y as a function of x are shown in figure 2.8.

2.2.4 The Finite Range Liquid Drop Model

The analysis of experimental fission and evaporation residue cross sections with the aid of statistical model codes has indicated that the rotating liquid drop model (RLDM) fission barriers need to be scaled by between 0.5 and 0.9 for nuclei with $x \leq 0.7$ ($A \leq 200$). These scaling factors are believed to be mainly associated with the RLDM's failure to account for the finite range of the nuclear force. The RLDM scales the surface energy

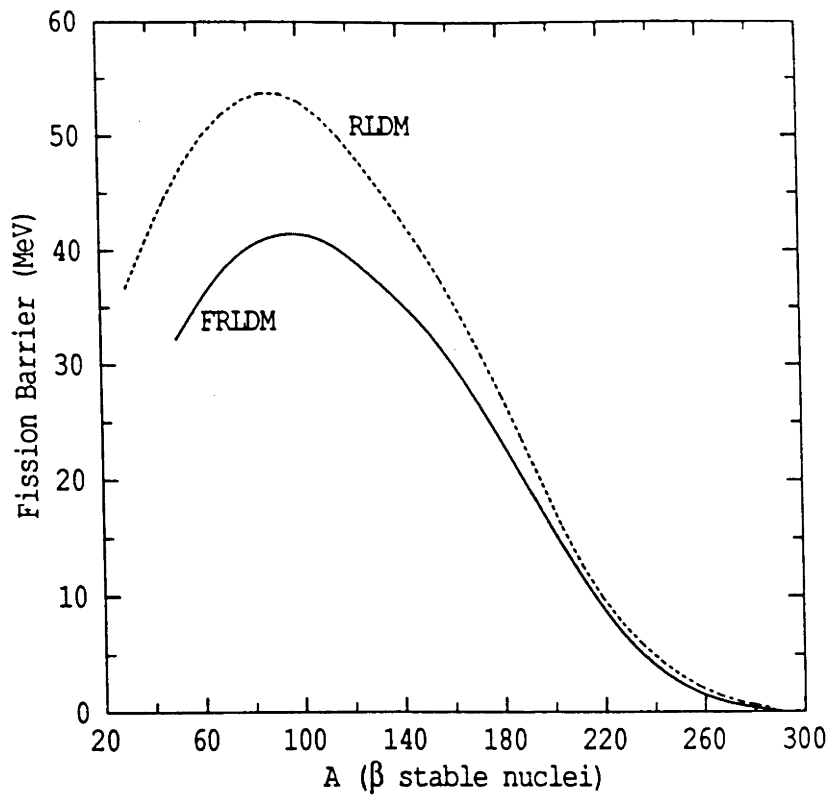


Figure 2.9 The finite range liquid drop model [SIE86] and rotating liquid drop model [COH74] fission barriers for non-rotating beta-stable nuclei.

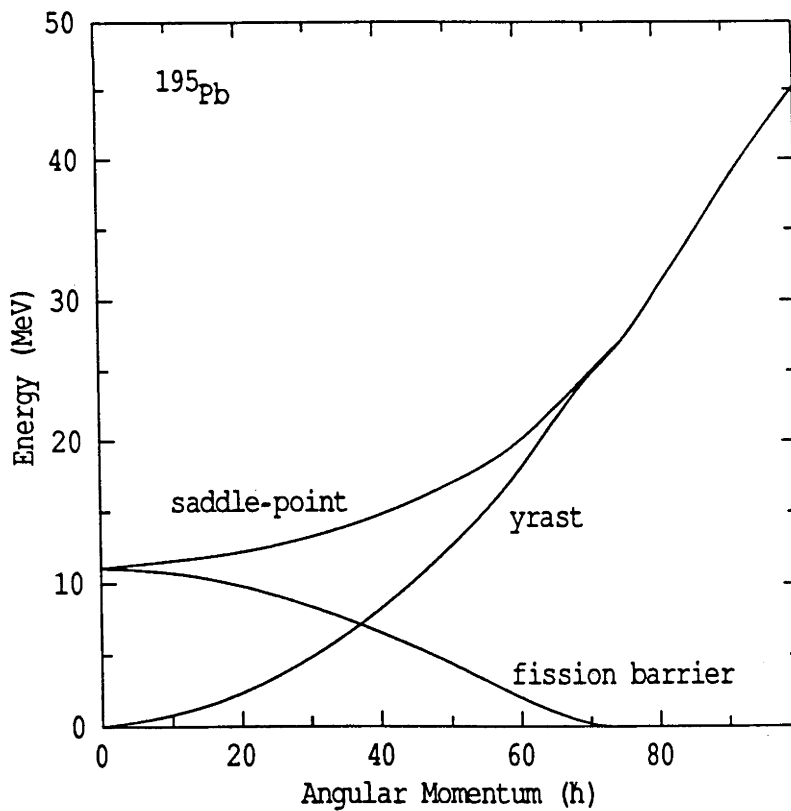


Figure 2.10 ^{195}Pb FRLDM [SIE86] equilibrium and saddle-point energies and fission barriers as a function of angular momentum.

by the ratio of the surface areas. This clearly leads to an over-estimation of the surface energy of dumbbell-like saddle-points because of the high surface curvature around the neck regions, which allows the surfaces on either side of the neck to attract each other.

Sierk [SIE86] made several improvements to the RLDM, the main ones being :

- (1) The replacement of the RLDM surface energy by a Yukawa-plus-exponential nuclear energy, which models effects of the finite range of the nuclear force, nuclear saturation and the finite surface thickness of real nuclei.
- (2) The Coulomb energy is calculated for nuclei with a realistic diffuse proton distribution at the surface.
- (3) The moments of inertia of nuclei are calculated, taking the diffuse mass distribution at the surface into account.

The finite range liquid drop model fission barriers for nonrotating beta-stable nuclei are compared to the barriers of [COH74] in figure 2.9. Figure 2.10 shows the equilibrium and saddle-point energies and fission barriers for ^{195}Pb as a function of angular momentum. The FRLDM critical angular momenta parameters L_I and L_{II} are shown in figure 2.11 as a function of A for beta-stable nuclei.

2.2.5 Temperature Dependence of Fission Barriers

The heating of a classical liquid drop to a finite temperature results in the slight expansion of the drop and a lowering of its surface tension. Thomas-Fermi model calculations can be used to show that nuclei behave in a similar fashion. Such behaviour results in the lowering of fission barriers with increased temperature. Sauer *et al.* [SAU76] scaled their Thomas-Fermi model results in order to get agreement with the liquid drop model at zero temperature and obtained the following expressions for

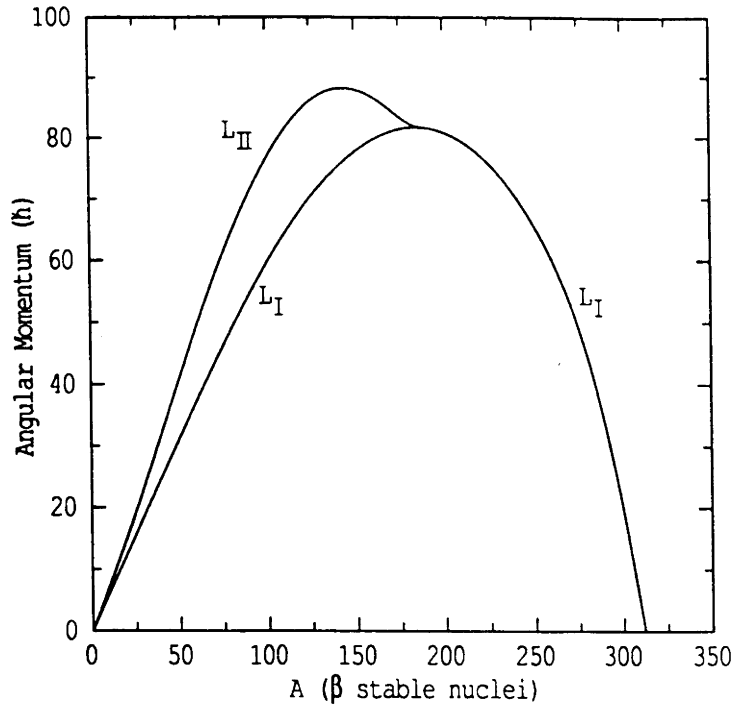


Figure 2.11 The FRLDM rotational parameters L_I and L_{II} as a function of A for beta-stable nuclei. (adapted from [SIE86])

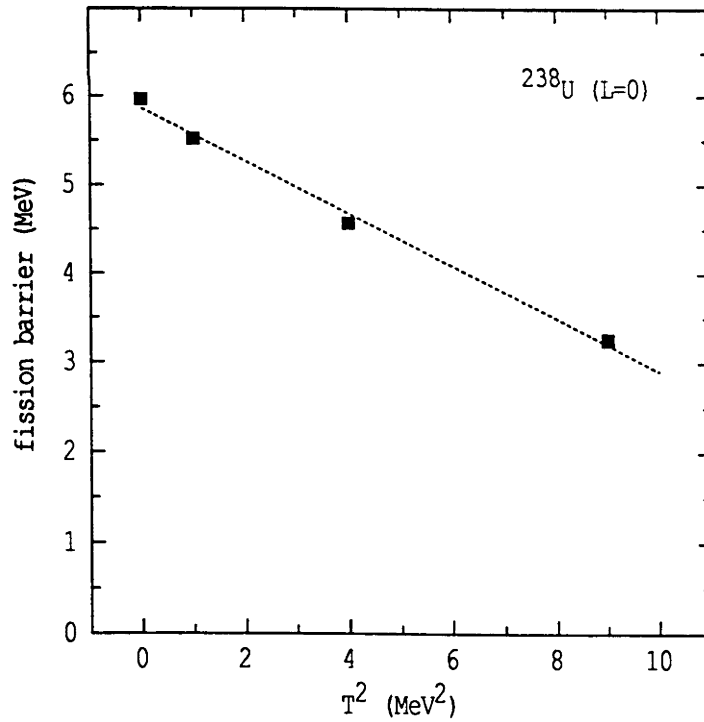


Figure 2.12 The ^{238}U ($L=0$) fission barrier as a function of the square of the temperature T^2 . The dashed line guides the eye. (adapted from [SAU76])

the Coulomb and surface energies of spherical nuclei as a function of temperature T .

$$E_c^0(T) = 0.7053 (1 - \alpha T^2) \frac{Z^2}{A^{1/3}} \text{ MeV} \quad (2.36)$$

$$E_s^0(T) = (17.944 - \beta T^2) \left\{ 1 - 1.783 \left(\frac{N-Z}{A} \right)^2 \right\} A^{2/3} \text{ MeV} \quad (2.37)$$

where $\alpha = 10^{-3} \text{ MeV}^{-2}$ and $\beta = 0.11 \text{ MeV}^{-2}$. The Fissility parameter as a function of T can then be written as

$$x(T) = \frac{E_c^0(T)}{E_s^0(T)} = \frac{Z^2}{A} \frac{1 + 5 \times 10^{-3} T^2 \text{ MeV}^{-2}}{50.883 \left[1 - 1.783 \left(\frac{N-Z}{A} \right)^2 \right]} \quad (2.38)$$

The deformation energy $\xi(T)$ of a non-rotating nucleus in units of the surface energy of the spherical system can be expressed as

$$\xi(T) = (f - 1) + 2 x(T) (g - 1) \quad (2.39)$$

where f is the ratio of the surface area of the deformed system to that of the spherical system and g is the ratio of the Coulomb energy of the deformed to that of the spherical system. The turning points in $\xi(T)$ as a function of deformation give the temperature dependent fission barriers. Figure 2.12 shows the ^{238}U ($L=0$) fission barrier as a function of the square of the temperature T^2 and illustrates the nearly linear dependence of fission barriers on T^2 .

More recent calculations of the temperature dependence of $L=0$ fission barriers can be found in [BAR85,GUE88]. Garcias *et al.* [GAR89, GAR89A,GAR90] have made calculations of the spin and temperature dependence of the fission barriers for eight nuclei covering a wide range of fissility. The variation with temperature of their spin dependent barriers can be fairly well described by [NEW90]

$$E_f(L,T) = E_f(L,0) (1 - \kappa T^2) \quad (2.40)$$

where

$$\kappa = \frac{1}{25.9 \sqrt{\ln \left[\frac{57.8 \text{ MeV}}{57.8 \text{ MeV} - E_f(L,0)} \right]}} \quad (2.41)$$

These values of κ are approximately a factor of two larger than those suggested by the earlier works of [SAU76,GUE88]. Clearly more theoretical work needs to be done to reliably establish the absolute magnitude of the dependence of fission barriers on temperature. A discussion on the inclusion of the temperature dependence of fission barriers in statistical model calculations can be found in [NEW90].

2.3 The Statistical Model

Even at the lowest beam energies used in the study of heavy-ion fusion-fission reactions, the compound nuclei are formed at excitation energies where the density of quantum states is already high. This makes the use of the statistical model an essential part of the analysis of experimental data involving such reactions.

The basic assumptions of the statistical model are :

- (1) An equilibrated compound nucleus is formed by a reaction.
- (2) The decay of the nucleus is independent of the formation except for the conservation of total energy, total angular momentum and parity.
- (3) All decay channels that are fully open have the same probability of being populated. For those channels not fully open this probability is reduced by the appropriate barrier transmission coefficient.

Section 2.3.1 discusses nuclear level densities in the framework of the non-interacting Fermi-gas model. Section 2.3.2 describes the calculation of particle decay and fission lifetimes and introduces the statistical model code "JOANNE". Fission fragment angular distributions and the determination of the spin direction of pre-scission compound systems by the observation of fission fragments is discussed in section 2.3.3. Section 2.3.4 discusses the angular distribution of evaporated

particles as a function of nuclear temperature, angular momentum and deformation of the emitting system.

2.3.1 Level Densities

If nuclei are assumed to be collections of non-interacting nucleons in single-particle orbitals then the determination of the nuclear level densities is, in principle, just a matter of counting the number of ways in which the nucleons can be arranged, such that the excitation energy lies in the range E to $E+\Delta E$. The number of combinations rises so quickly with excitation energy that the mathematical techniques of statistical mechanics need to be employed to obtain level densities, even at relatively low energies.

The total level density of a non-interacting Fermi-gas can be written as [BOH69]

$$\omega(E) = \frac{\sqrt{\pi}}{12} \frac{\exp 2 \sqrt{aE}}{E^{5/4} a^{1/4}} \quad (2.42)$$

where a is the level density parameter and is defined as

$$a = \frac{\pi^2 g_0}{6} \quad (2.43)$$

g_0 is the single-particle level density at the Fermi energy, representing the sum of the proton and neutron level densities. Bohr and Mottelson showed in their derivation of equation 2.42 that it is only valid in the range $E_{\text{Fermi}}/A \ll E \ll E_{\text{Fermi}} A^{1/3}$ where E_{Fermi} is the nuclear Fermi energy (~ 36 MeV). The concept of the nuclear temperature

$$\frac{1}{T} = \frac{1}{\omega} \frac{\partial \omega(E)}{\partial E} = -\frac{5}{4E} + \sqrt{\frac{a}{E}} \quad (2.44)$$

is often found to be useful. The condition $E_{\text{Fermi}}/A \ll E$, implies that the second term in equation 2.44 is dominant. We can thus write

$$E = a T^2 \quad (2.45)$$

A better understanding of the significance of the nuclear temperature can be obtained by considering the average occupation number $\eta(E)$ of a given

Table 2.1 Nuclear temperature (T), average number of excited nucleons (η_{ex}) and the total level density (ω) for a nucleus with ~200 nucleons and level density parameter $a=A/8.6 \text{ MeV}^{-1}$ at various excitation energies (E).

E (MeV)	T (MeV)	η_{ex}	$\omega(E) \text{ (MeV}^{-1}\text{)}$
3	0.359	7	3.1×10^5
10	0.656	13	6.7×10^{10}
30	1.136	22	8.4×10^{19}
100	2.073	41	1.7×10^{38}

one particle state of the Fermi-gas which is approximately given by [BOH69]

$$\eta(E) = \frac{1}{1 + \exp\left(\frac{E - E_{\text{Fermi}}}{T}\right)} \quad (2.46)$$

$\eta(E)$ is 1 for $E \ll E_{\text{Fermi}}$ and 0 for $E \gg E_{\text{Fermi}}$, with the transition occurring in the range $\sim T$ either side of the Fermi energy. This then leads to the average number of excited nucleons

$$\eta_{\text{ex}} = g_0 T \ln(4) \quad (2.47)$$

Substituting equations 2.43 and 2.45 into 2.47 gives the average excitation energy per excited nucleon

$$\frac{E}{\eta_{\text{ex}}} = \frac{\pi^2}{6} \frac{T}{\ln(4)} \sim T \quad (2.48)$$

For a homogenous Fermi-gas with a volume sufficiently large for effects associated with the diffuse surface to be ignored, the level density at the Fermi surface is given by

$$g_0 = \frac{3}{2} \frac{A}{E_{\text{Fermi}}} \quad (2.49)$$

where A is the number of nucleons. Substituting in equation 2.43 gives

$$a = \frac{A}{14.6} \text{ MeV}^{-1} \quad \text{ie} \quad \frac{A}{a} = 14.6 \text{ MeV} \quad (2.50)$$

This value of 14.6 MeV is approximately a factor of 1.7 higher than the values of A/a used by statistical model calculations to reproduce the spectral shape of particle and gamma-ray emission from compound nuclei. For example, Gavron *et al.* [GAV87] concluded from the analysis of their neutron spectra that $A/a=7.5$ MeV while more recent results involving statistical gamma-rays [HEN88, THO87] require a value of ~ 9 MeV.

Toke and Swiatecki [TOK81] derived a formula for the nuclear level density parameter (a) which corrects equation 2.49 for the presence of the diffuse surface region. Their formula is

$$\frac{A}{a} = \frac{14.61}{1 + 3.114 A^{-1/3} F_2 + 5.626 A^{-2/3} F_3 + \dots} \text{ MeV} \quad (2.51)$$

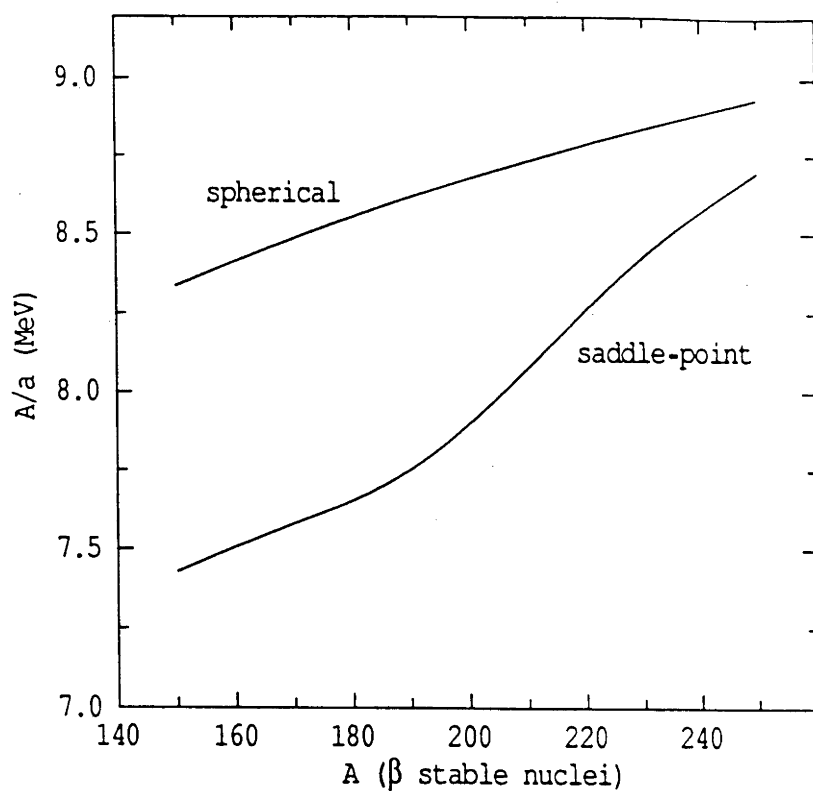


Figure 2.13 A/a_{eq} and A/a_{sp} as given by equation 2.52 for non-rotating beta-stable nuclei.

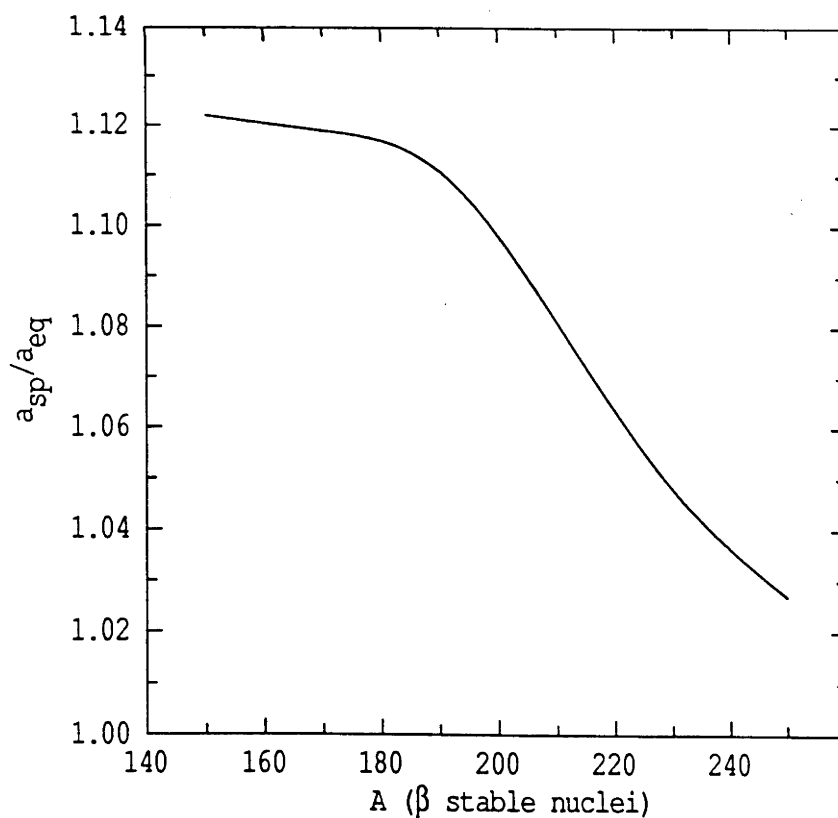


Figure 2.14 a_{sp}/a_{eq} for non-rotating beta-stable nuclei as given by equation 2.52.

The quantities F_2 and F_3 are the surface area and the integrated curvature of the nuclear surface in units of their values for the spherical shape. Due to the many assumptions used in the derivation of equation 2.51, Toke and Swiatecki explain that for many practical purposes the simpler formula

$$\frac{A}{a} = \frac{14.61}{1 + 4 A^{-1/3} F_2} \text{ MeV} \quad (2.52)$$

may be no worse than the more complicated one.

In the analysis of reactions where fission is one of the dominant decay channels, both the level density parameter of the nuclei at equilibrium, a_{eq} and that of the compound nuclei at the saddle-point, a_{sp} are of great importance. Figure 2.13 shows A/a_{eq} and A/a_{sp} as given by equation 2.52 for nonrotating beta-stable nuclei, while figure 2.14 shows a_{sp}/a_{eq} for the same systems. The rapid change in the slopes of A/a_{sp} and a_{sp}/a_{eq} around $A=195$ corresponds to the transition from cylindrical to necked in saddle-point configurations. A crude estimate of the variation of a_{sp}/a_{eq} with angular momentum as predicted by equation 2.52 for ^{198}Pb is shown in figure 2.15. The fissility parameter for ^{198}Pb is $x=0.704$ and using the F_2 values of [MYE74] gives $a_{sp}/a_{eq}(L=0) \approx 1.086$. The RLDM predicts the ^{198}Pb fission barrier to vanish at an angular momentum of $\sim 75\hbar$. A zero fission barrier means the equilibrium and saddle-point shapes coincide and thus $a_{sp}/a_{eq}(L=75) = 1.00$.

Several other authors have also made predictions of a_{sp}/a_{eq} . Using a simple Fermi-gas model involving a rectangular shaped nucleus with a trapezoidal potential well, Bishop *et al.* [BIS72] predicted a_{sp}/a_{eq} should be in the range 1.00 to 1.04 depending on the deformation at the saddle-point. Gottschalk and Ledergerber [GOT77], however, claim that Bishop's derivation is in error and using Hartee-Fock calculations have concluded $a_{sp}/a_{eq} \approx 0.98$. Carjan *et al.* [CAR79] performed microscopic calculations using a realistic set of single particle levels, obtaining $a_{sp}/a_{eq} \approx 1.065$ for ^{184}Hg at high excitation energy.

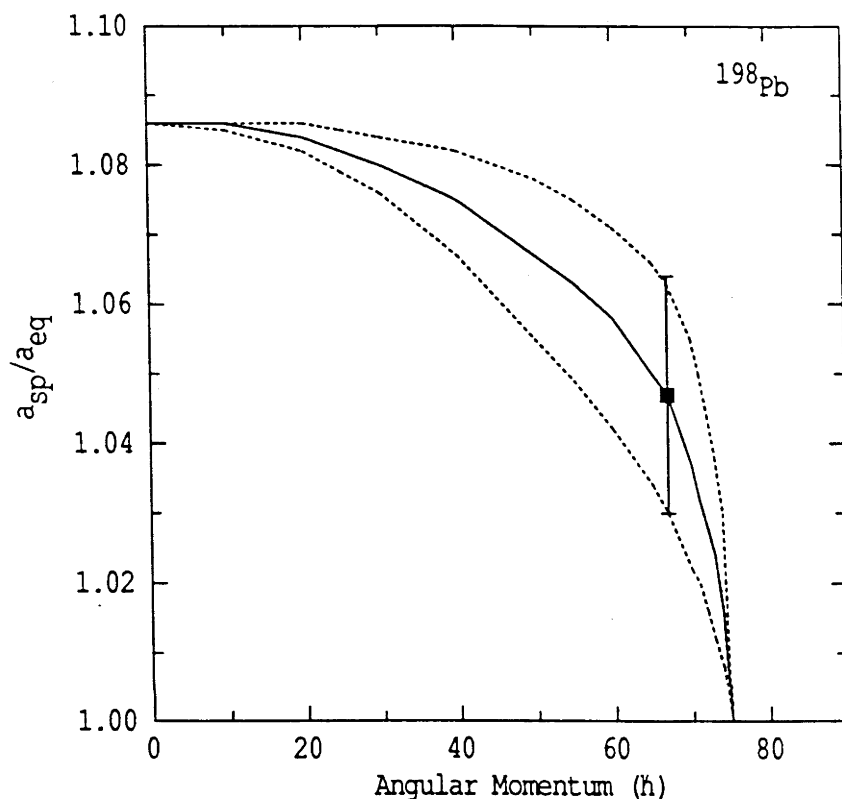


Figure 2.15 a_{sp}/a_{eq} for ^{198}Pb versus angular momentum. The a_{sp}/a_{eq} at $L=67$ was obtained using F_2 's estimated from the $x=0.7$, $y=0.04$ equilibrium and saddle-point shapes shown in figure 2.7. The error on this value reflects the uncertainty in my F_2 estimates. The smooth curves simply guide the eye.

The effect of rotational and vibrational levels on the level density of deformed nuclei adds further uncertainty to the value of a_{sp}/a_{eq} . For example, it is well known that at low excitation energies the level densities of deformed nuclei can be enhanced by factors of the order of 10^2 at the expense of higher levels. Discussions of this effect and its possible implication on statistical model calculations can be found in [MOR72,BJO73,VIG82,HAN83].

Until now, only the total level density of a Fermi-gas as a function of excitation energy $\omega(E)$ has been given. However, in most statistical model applications the density of levels for a given angular momentum is of most importance. This spin dependent level density formula is given by [BOH69]

$$\rho(E,I) = \frac{2L+1}{12} \left(\frac{\hbar^2}{2\mathbb{I}}\right)^{3/2} \frac{\sqrt{a}}{U^2} \exp 2\sqrt{a} U \quad (2.53)$$

where $L\hbar$ is the angular momentum of the system, $\mathbb{I}$ is the rigid body moment of inertia about the axis of rotation and $U=E-E_{rot}$ is the thermal excitation energy. E is the total energy and $E_{rot}=\hbar^2 L(L+1)/2\mathbb{I}$ is the rotational energy. The nuclear temperature of a compound nucleus at angular momentum $L\hbar$ can then be written as $T = \sqrt{U/a}$.

2.3.2 Decay Widths

The decay of compound nuclei formed in heavy-ion fusion reactions is a complex process. Initially nuclei are formed with a well defined excitation energy defined by the beam energy and the Q value for the reaction, but with a distribution of spin values (see section 2.1). Some of these systems may undergo first-chance fission (ie fission without the evaporation of any particles) while the rest decay by the emission of particles of various types, energies and angular momenta, producing the next generation of compound nuclei. These second generation compound nuclei can then decay by either fission or further particle emission and so on. The dominant modes of particle decay are those of neutron, proton and

alpha particle emission, with the evaporation of neutrons generally the most favoured. Eventually the particle emission (mainly neutrons) cools the surviving nuclei to excitation energies below both their fission barriers and particle binding energies. Gamma-ray emission then becomes the dominant decay process, removing the remaining angular momentum and excitation energy.

Fortunately we only need to worry about obtaining expressions for the fission decay width $\Gamma_f(E_i, J_i)$ as a function of compound nucleus excitation energy and spin and the rate of emission of particles (neutrons, protons and alpha particles) with energy ϵ and spin j , $R_{\text{part}}(E_i, J_i, E_f, J_f, \epsilon, j)$ from a compound nucleus with initial excitation energy and spin E_i and J_i and final excitation energy and spin E_f and J_f . Computer codes can then be used to model the large number of decay paths available to any hot compound system to enable the prediction of measurable quantities such as fission cross sections, evaporation residue cross sections, particle multiplicities and particle energy spectra.

The particle emission rate is [THO64]

$$R_{\text{part}}(E_i, J_i, E_f, J_f, \epsilon, j) d\epsilon = \frac{1}{h} \sum_{S=|J_f-j|}^{J_f+j} \sum_{L=|J_i-S|}^{J_i+S} T_L(\epsilon) \frac{\rho(E_f, J_f)}{\rho(E_i, J_i)} d\epsilon \quad (2.54)$$

where h is Planck's constant, $T_L(\epsilon)$ are the transmission coefficients for a particle of energy ϵ with orbital angular momentum $L\hbar$, and $\rho(E, J)$ is the spin dependent level density of the compound nucleus. The $T_L(\epsilon)$ should in fact be the transmission coefficients for the fusion of an incoming particle of energy ϵ with the compound system at excitation E_f and spin J_f . Of course, these $T_L(\epsilon)$ cannot be measured experimentally, so statistical model codes usually approximate them with optical model transmission coefficients $T_L^{\text{om}}(\epsilon)$ based on global fits to elastic scattering data. These $T_L^{\text{om}}(\epsilon)$ apply to particles incident on nuclei in their ground state, while hot rotating compound systems are likely to be more diffuse and to have a

different deformation. This is expected to have only a minor effect on neutron emission, but a greater effect on the evaporation of charged particles which feel the changes in Coulomb fields produced by increased surface diffuseness and deformation. Discussions of the dependence of transmission coefficients on deformation, and in particular its importance in alpha particle decay, can be found in [BLA81, AJI86, HUI89].

Summing equation 2.54 over all J_f , changing the ordering of the summations and assuming the spin s and orbital quantum number L of the emitted particles are small compared to J_i , the energy spectrum for the evaporation of particles from a compound system of fixed excitation energy and spin can be written as

$$S_{\text{part}}(\epsilon) \propto \sum_{L=0}^{\infty} \frac{T_L(\epsilon)}{[E_i - B_{\text{part}} - \epsilon - E_{\text{rot}}(J)]^2} \exp\left(\frac{-2\epsilon}{T}\right) \quad (2.55)$$

where B_{part} is the particle binding energy and $E_{\text{rot}}(J)$ is the minimum possible excitation energy of the daughter nucleus with angular momentum $J\hbar$.

To obtain the particle decay width Γ_{part} , equation 2.54 is summed over all J_f , integrated over all allowable particle energies and multiplied by $\hbar$, giving

$$\Gamma_{\text{part}} = \frac{1}{2\pi\rho(E_i, J_i)} \sum_{L=0}^{\infty} \sum_{S=|L-s|}^{L+s} \sum_{J_f=|J_i-S|}^{J_i+S} \int_0^{E_i - E_{\text{rot}}(J_f) - B_{\text{part}}} T_L(\epsilon) \rho(E_i - B_{\text{part}} - \epsilon, J_f) d\epsilon \quad (2.56)$$

Assuming the spin of the evaporated particle s is very much smaller than the spin of the emitting compound system, and using the Fermi-gas spin

dependent level density formula, we can rewrite the particle decay width as

$$\Gamma_{\text{part}} = \frac{(2s+1)(2J_f+1)}{2\pi(2J_i+1)} \frac{\exp 2\sqrt{a_{eq}^p} U_i}{U_i^2} \sqrt{\frac{a_{eq}^d}{a_{eq}^p}} \sum_{L=0}^{\infty} \sum_{J_f=|J_i-L|}^{J_i+L} \int_0^{E_i-E_{\text{rot}}(J_f)-B_{\text{part}}} T_L(\epsilon) \frac{\exp 2\sqrt{a_{eq}^d} U_f}{U_f^2} d\epsilon \quad (2.57)$$

where a_{eq}^p and a_{eq}^d are the level density parameters of the parent and daughter compound systems respectively. $U_i = E_i - E_{\text{rot}}^p(J_i)$ and $U_f = E_i - E_{\text{rot}}^d(J_f) - \epsilon - B_{\text{part}}$ are the thermal excitation energies of the parent and daughter nuclei respectively.

The fission decay mode can be treated in a similar fashion to that of particle emission. Instead of considering the transition from one compound system to another by the emission of a particle of energy ϵ , we consider the transition from the equilibrium to saddle-point configurations with the system having a kinetic energy of ϵ^{sp} at the saddle-point. The transition rate of a nucleus from its equilibrium deformation to its saddle-point configuration with kinetic energy ϵ^{sp} can be written as

$$R_{\text{sp}} d\epsilon^{\text{sp}} = \frac{1}{h} T(\epsilon^{\text{sp}}) \frac{\rho_{\text{sp}}(E_i - B_f - \epsilon^{\text{sp}}, J_i)}{\rho(E_i, J_i)} d\epsilon^{\text{sp}} \quad (2.58)$$

where B_f is the fission barrier, ρ_{sp} is the spin dependent level density for the saddle-point configuration and $T(\epsilon^{\text{sp}})$ are the appropriate transmission coefficients. Fission is a much more classical process than light particle emission, and in heavy-ion induced fission it is usual to take the transmission coefficient as unity above the barrier and zero below. Using the Fermi-gas spin dependent level density formula we can then write

$$\Gamma_f = \frac{1}{2\pi} \frac{\exp 2\sqrt{a_{eq}} U_i}{U_i^2} \sqrt{\frac{a_{\text{sp}}}{a_{eq}}} \int_0^{E_i - B_f} \frac{\exp 2\sqrt{a_{\text{sp}}} U_{\text{sp}}}{U_{\text{sp}}^2} d\epsilon^{\text{sp}} \quad (2.59)$$

where $U_{\text{sp}} = E_i - \epsilon^{\text{sp}} - B_f$ is the thermal excitation energy at the saddle-point.

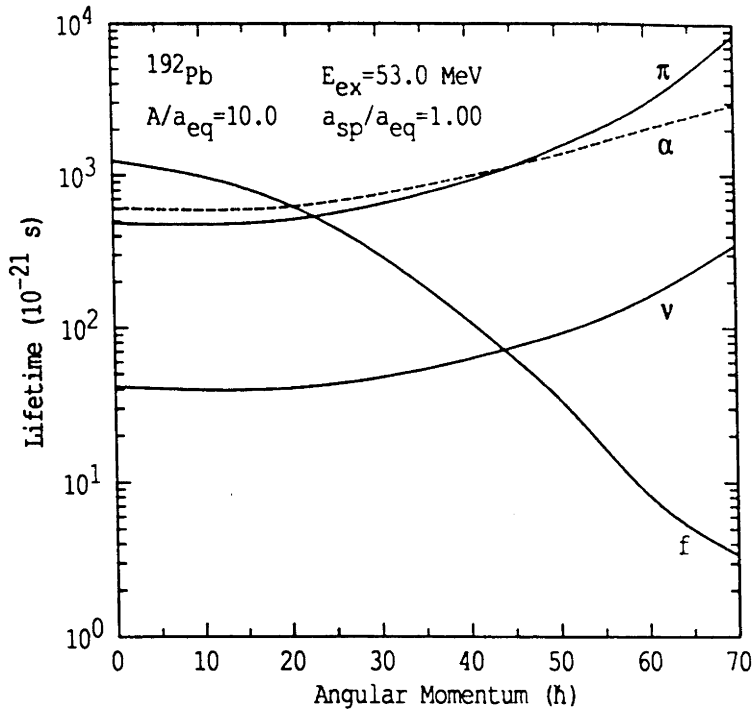


Figure 2.16 Neutron, proton, alpha and fission decay lifetimes as a function of spin for ^{192}Pb at an excitation energy of 53.0 MeV, with statistical model parameters $A/a_{\text{eq}} = 10.0 \text{ MeV}^{-1}$ and $a_{\text{sp}}/a_{\text{eq}} = 1.00$.

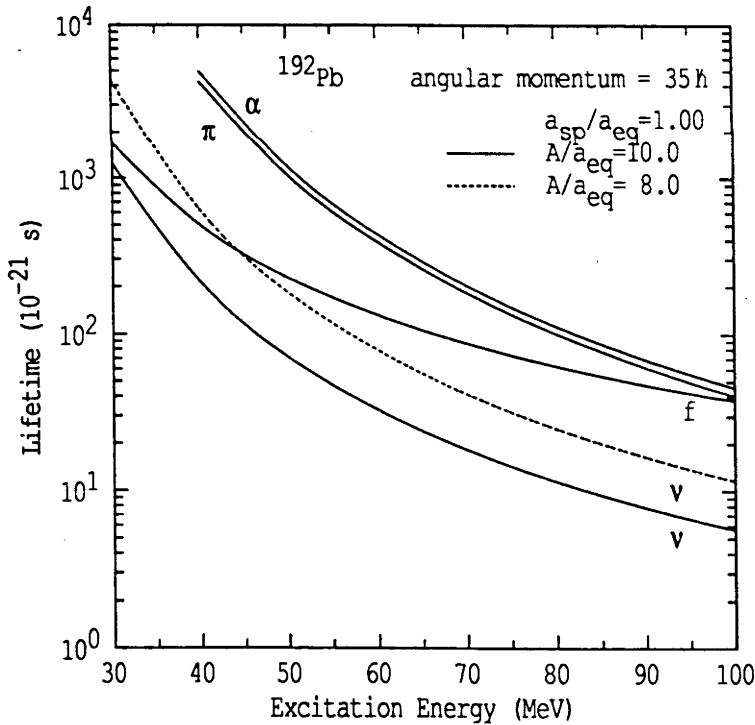


Figure 2.17 Neutron, proton, alpha and fission decay lifetimes as a function of excitation energy for ^{192}Pb at an angular momentum of $35\hbar$. The dashed curve shows the neutron emission lifetime obtained using $A/a_{\text{eq}} = 8.0 \text{ MeV}^{-1}$ and demonstrates the sensitivity of lifetimes on the level density parameter.

Many statistical model computer codes are available, for example ALICE by Blann and Plasil [BLA66,BLA72,PLA78] and PACE by Gavron [GAV80]. Unfortunately, like most people, I find it very difficult to follow large codes written by other people, so I wrote my own statistical model code called JOANNE. JOANNE is a Monte Carlo code using particle transmission coefficients determined using the optical model potentials of [PER76] for neutron and proton emission and [HUI62] for alpha particle emission. The yrast energies and fission barriers used are those of the finite range liquid drop model of Sierk [SIE86] and the particle binding energies are obtained using equations 2.10,2.17,2.18 and 2.19. Figures 2.16,2.17 and 2.18 show some of the properties of the mean lifetimes of neutron, proton, alpha particle and fission decay of ^{192}Pb as calculated by JOANNE. Figure 2.16 shows how, for a fixed excitation energy, the mean lifetime of the fission decay mode decreases with increased spin due to the falling of the fission barriers. The particle emission lifetimes increase due to the decreasing thermal excitation energy as the yrast energies increase. At high spin, alpha particle emission becomes more favourable than proton emission, due to the increasing slope of the yrast line, which enhances the emission of particles (in particular alpha particles) with higher values of orbital angular momentum.

2.3.3 Fission Fragment Angular Distributions

If we assume that fission fragments separate along the nuclear symmetry axis and that the angular momentum along the symmetry axis $K\hbar$ is a constant from saddle to scission, then the angular distribution of fission only depends on the angular momentum of the compound nuclei brought in by the projectile and the distribution of K states at the saddle-point. The angular distribution of fission fragments from a system of total

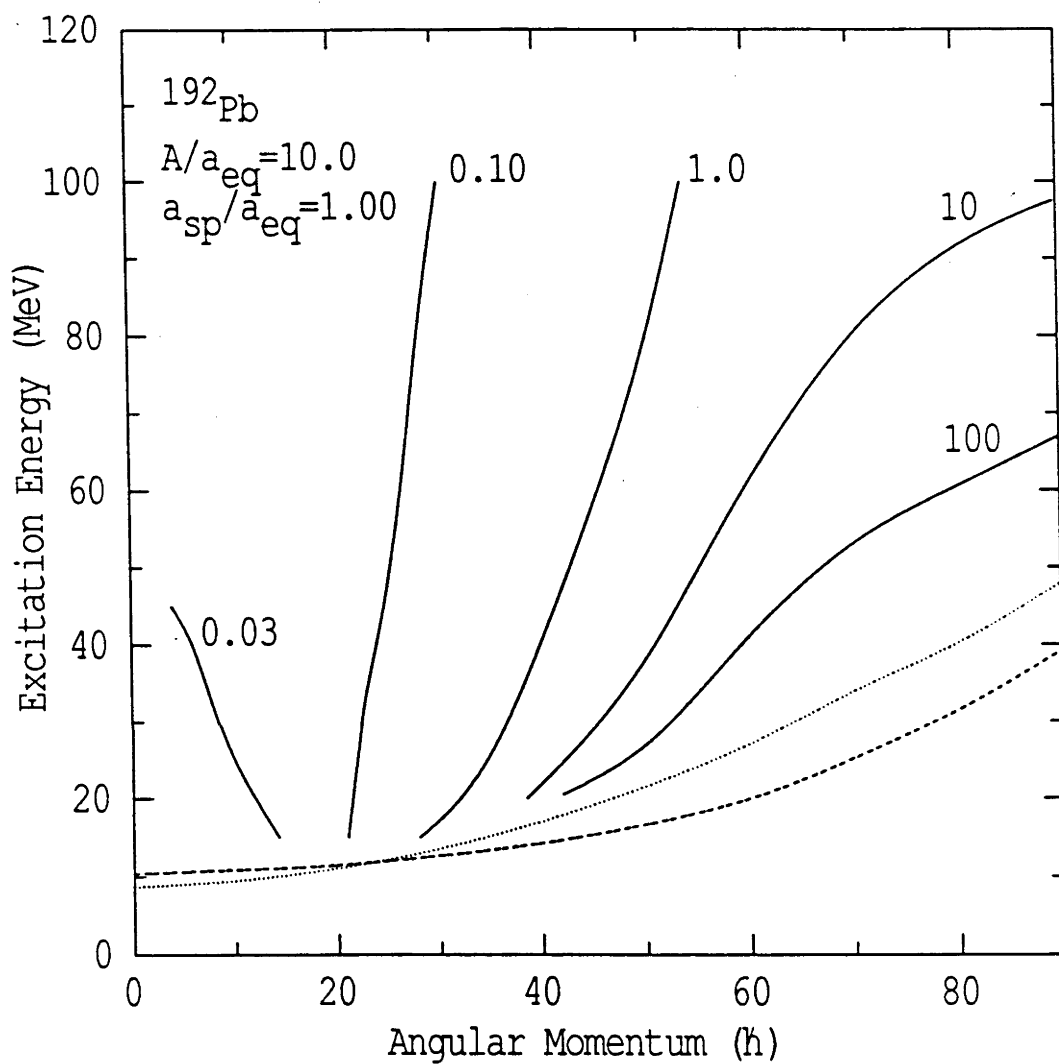


Figure 2.18 Lines of constant Γ_f/Γ_v for ^{192}Pb . The dashed and dotted curves are the saddle-point energies and yrast line plus neutron binding energy respectively.

angular momentum $J\hbar$, with a projection on the symmetry axis $K\hbar$ and projection of J on some fixed space axis M is given by [BAC78]

$$W_{MK}^J(\theta) = \frac{1}{4} (2J+1) [|d_{MK}^J(\theta)|^2 + |d_{M-K}^J(\theta)|^2] \quad (2.60)$$

where

$$d_{MK}^J(\theta) = [(J+M)! (J-M)! (J+K)! (J-K)!]^{-1/2} \times \sum_x \frac{(-1)^x (\sin \frac{1}{2}\theta)^{2x+M-K} (\cos \frac{1}{2}\theta)^{2J+K-M-2x}}{(J-M-x)! (J+K-x)! (x+M-K)! x!} \quad (2.61)$$

$x=0,1,2,3\dots$ and contains all terms in which no negative value appears in the denominator of the sum for any of the quantities in parentheses.

For a fixed excitation energy E and spin J , the statistical distribution of K states at the saddle-point can be expressed as [VAN73]

$$\begin{aligned} \rho(K) &\propto \exp\left(\frac{-K^2}{2K_0^2}\right) & K \leq J \\ &= 0 & K > J \end{aligned} \quad (2.62)$$

where

$$K_0^2 = \frac{T}{\hbar^2 \left[\frac{1}{I_{\text{paral}}} - \frac{1}{I_{\text{perp}}} \right]} \quad (2.63)$$

I_{paral} and I_{perp} are the saddle-point moments of inertia about axes parallel and perpendicular to the symmetry axis.

In general the spin of fissioning systems produced in heavy-ion reactions is high enough for the spin of the target and projectile and the angular momenta of any emitted particles to be ignored. The spin directions of these fissioning systems can then be assumed to be distributed uniformly in the plane perpendicular to the beam direction. If we then choose the beam direction as our space fixed axis (ie $M=0$), then the angular distribution of fission fragments can be written as [BAC85]

$$W_{FF}(\theta) \propto \sum_{J=0}^{\infty} b(J) \frac{\sum_{K=-J}^J (2J+1) |d_{0K}^J(\theta)|^2 \exp\left(\frac{-K^2}{2K_0^2}\right)}{\sum_{K=-J}^J \exp\left(\frac{-K^2}{2K_0^2}\right)} \quad (2.64)$$

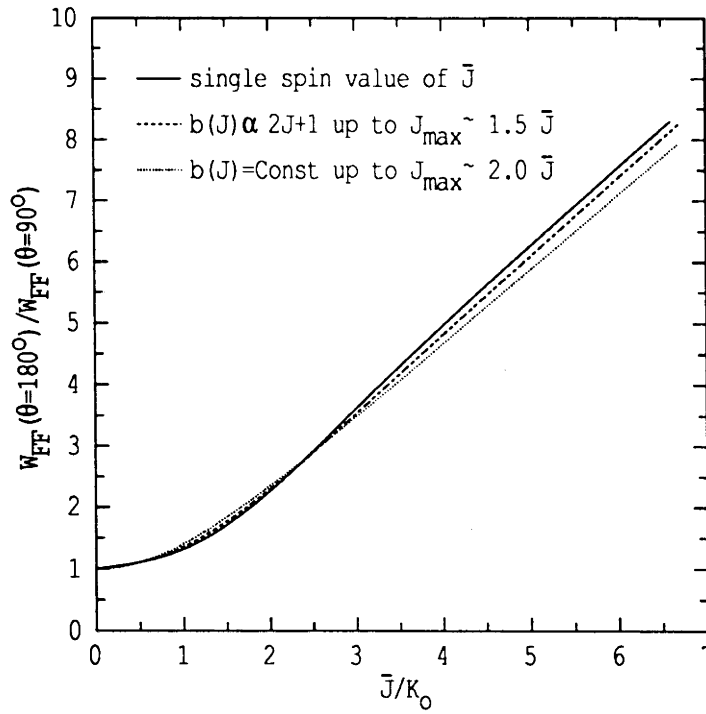


Figure 2.19 $W(\theta=180^\circ)/W(\theta=90^\circ)$ for three different types of spin distributions; a single spin value of $\bar{J}$ (solid curve); $b(J) \propto 2J+1$ up to $J_{\max}$, $\bar{J} \approx \frac{2}{3} J_{\max}$ (dashed curve); and $b(J) = \text{constant}$ up to $J_{\max}$, $\bar{J} = \frac{1}{2} J_{\max}$ (dotted curve). The $W(\theta=180^\circ)/W(\theta=90^\circ)$ shown here are for $K_0 = 5.0$, scaling both $\bar{J}$ and K_0 by a constant produces only minor changes to the calculations.

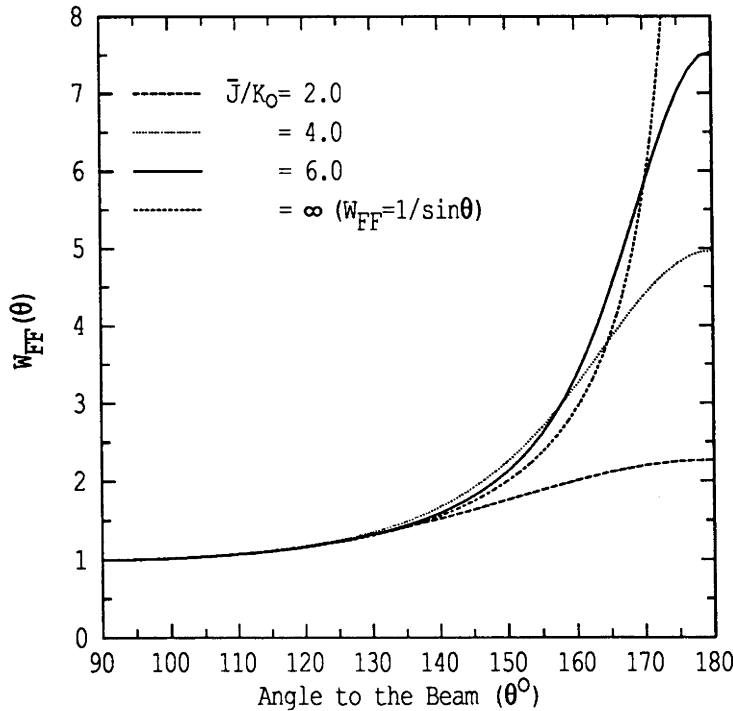


Figure 2.20 Fission fragment angular distributions relative to the beam direction $W(\theta)$ using a single spin value $\bar{J}$ for various $\bar{J}/K_0$. As in figure 2.19 the calculations shown here are for $K_0 = 5.0$.

where $b(J)$ is the probability of populating the compound system with spin J multiplied by the probability that the system with angular momentum $J\hbar$ will undergo fission and θ is the angle between the beam direction and the fission fragment. $W_{FF}(\theta)$ is, however, relatively insensitive to the form of $b(J)$ and for many practical purposes the summation over J in equation 2.64 is dropped and J is replaced by

$$\bar{J} = \frac{\sum_{J=0}^{\infty} J b(J)}{\sum_{J=0}^{\infty} b(J)} \quad (2.65)$$

Figure 2.19 shows $W_{FF}(\theta=180^\circ)/W_{FF}(\theta=90^\circ)$ versus mean spin divided by K_0 for three different types of spin distributions. Fission fragment angular distributions using a single spin value $\bar{J}$ for various $\bar{J}/K_0$ are shown in figure 2.20.

If maximum linear polarisation is assumed, ie the space fixed axis is in the same direction as J and thus $M=J$, then equation 2.61 reduces drastically, becoming

$$|d_{JK}^J(\phi)|^2 = \frac{(2J)!}{(J+K)!(J-K)!} (\sin \frac{1}{2}\phi)^{2(J-K)} (\cos \frac{1}{2}\phi)^{2(J+K)} \quad (2.66)$$

where ϕ is the angle between the spin direction of the pre-scission compound system and the fission fragment. The angular distribution of fission fragments relative to the spin direction from an ensemble of highly polarised compound systems with angular momenta $J\hbar$ can then be written as

$$W(\phi) \propto \frac{\sum_{K=-J}^J \frac{(2J+1)(2J)!}{(J+K)!(J-K)!} (\sin \frac{1}{2}\phi)^{2(J-K)} (\cos \frac{1}{2}\phi)^{2(J+K)} \exp(\frac{-K^2}{2K_0^2})}{\sum_{K=-J}^J \exp(\frac{-K^2}{2K_0^2})} \quad (2.67)$$

Figure 2.21 shows $W(\phi)$ for various values of J/K_0 , and figure 2.22 shows the half width at half maximum of the fission fragment distribution about the plane perpendicular to the spin direction versus J/K_0 .

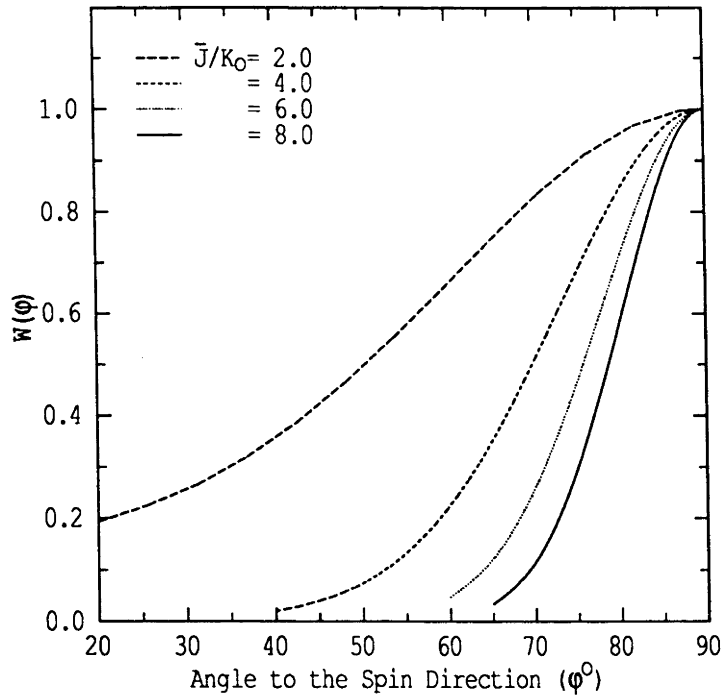


Figure 2.21 Angular distribution of fragments relative to the spin direction of an ensemble of highly polarised fissioning systems, for various J/K_0 . These calculations are for $K_0 = 5.0$.

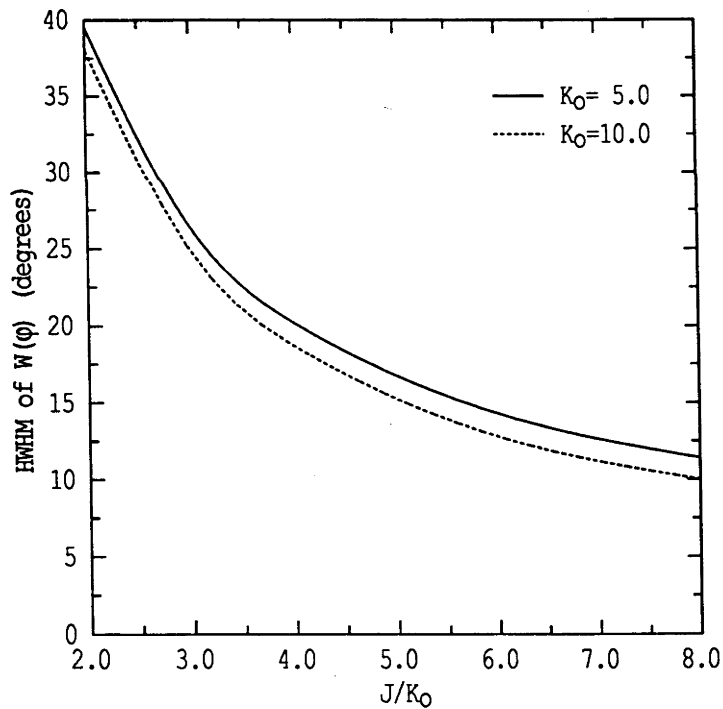


Figure 2.22 Half width at half maximum (HWHM) of the fragment distribution about the plane perpendicular to the spin direction of an ensemble of highly polarised fissioning systems versus J/K_0 . The solid and dashed curves are for $K_0 = 5.0$ and 10.0 respectively and demonstrates that fission fragment distributions depend strongly on the ratio of J to K_0 , but are relatively insensitive to their individual sizes.

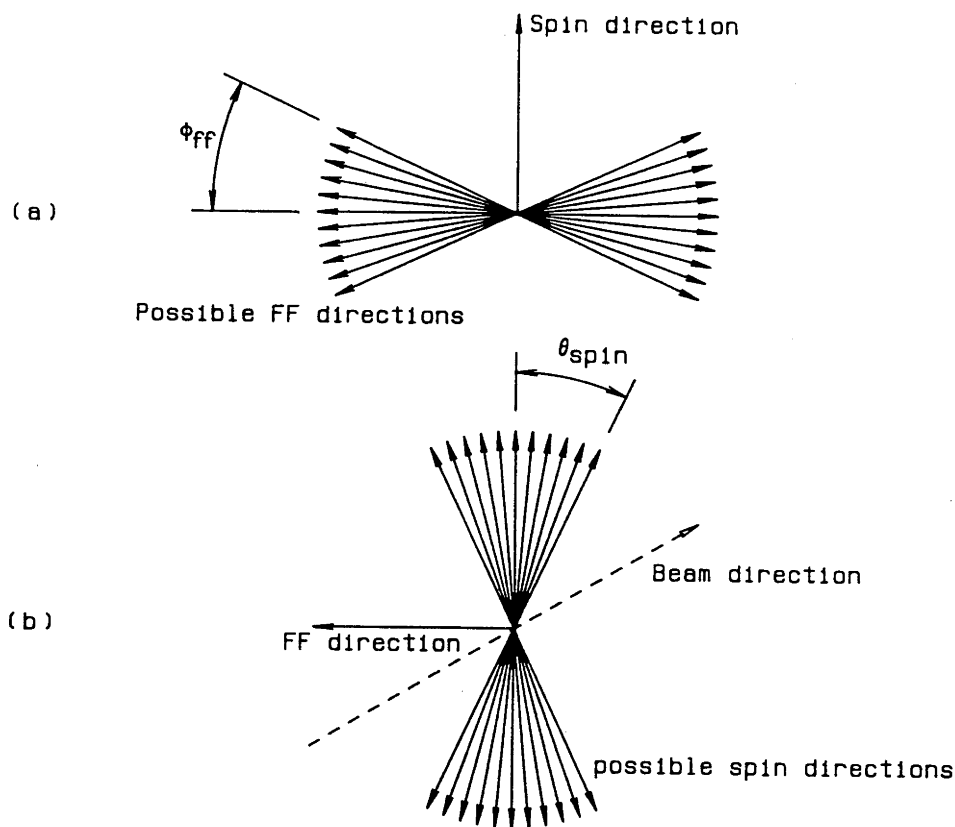


Figure 2.23 Schematic diagram of (a) a fixed spin with a range of possible fragment directions and (b) a fixed fission fragment direction and the range of possible spins, which could have lead to that fragment.

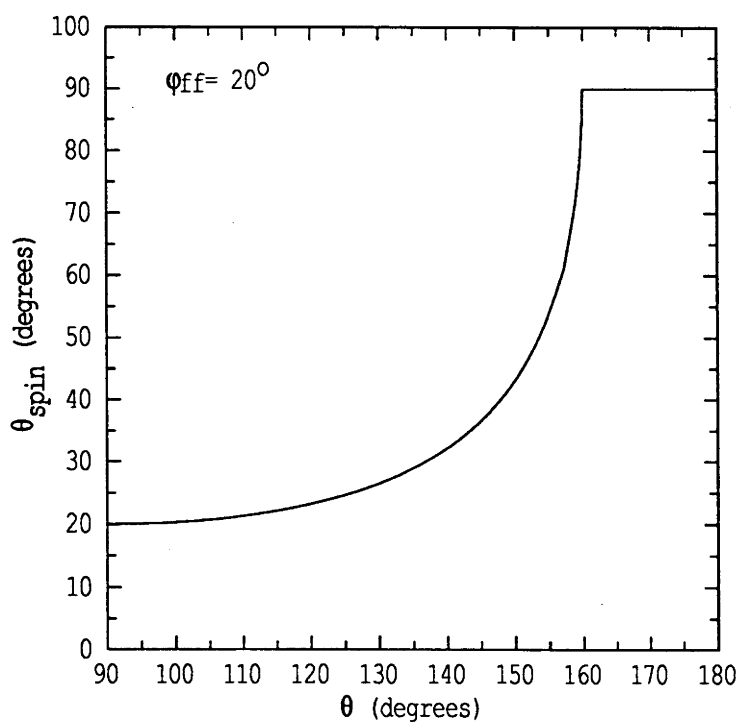


Figure 2.24 Spin range θ_{spin} versus fission fragment angle to the beam θ , for $\phi_{ff} = 20^\circ$.

Classically, all fragments would be observed perpendicular to the spin direction of the fissioning compound nuclei, enabling the observation of a fission fragment to accurately determine the spin direction of the compound system. The distribution of fission fragments about the plane perpendicular to the spin direction (see equation 2.67) results in the observation of a fragment defining a range of possible spin directions. This range depends on both $W(\phi)$ and the angle of the observed fission fragment to the beam. If, for simplicity, we assume

$$\begin{aligned} W(\phi) &= \text{constant} & 90 - \phi_{ff} \leq \phi \leq 90 + \phi_{ff} \\ &= 0 & \text{elsewhere} \end{aligned} \quad (2.68)$$

then the observation of a fission fragment at θ° to the beam restricts the spin direction of the pre-scission system to within θ_{spin} (see equation 2.69) degrees either side of the direction perpendicular to the velocity of the fragment.

$$\theta_{\text{spin}} = \sin^{-1} \left(\frac{\sin \phi_{ff}}{\sin \theta} \right) \quad (2.69)$$

Figure 2.23 shows (a) a fixed spin with a range of possible fragment directions and (b) a fixed fission fragment direction and the range of possible spins which could have lead to that particular fragment. Figure 2.24 shows θ_{spin} versus fission fragment detection angle θ for $\phi_{ff} = 20^\circ$.

2.3.4 Angular Distribution of Evaporated Particles

The relative probability for the emission of a light particle with final kinetic energy ϵ and orbital angular momentum $\tilde{L}$ at an angle ϕ with respect to the spin direction of the parent nucleus, can be written as [AJI86]

$$W(\phi, \epsilon, \tilde{L}) \propto |\tilde{L}| T_L(\epsilon) \rho_f(E_f, J_f) \quad (2.70)$$

where $T_L(\epsilon)$ is the appropriate particle transmission coefficient and $\rho_f(E_f, J_f)$ is the level density of the daughter nucleus at excitation energy E_f and spin J_f .

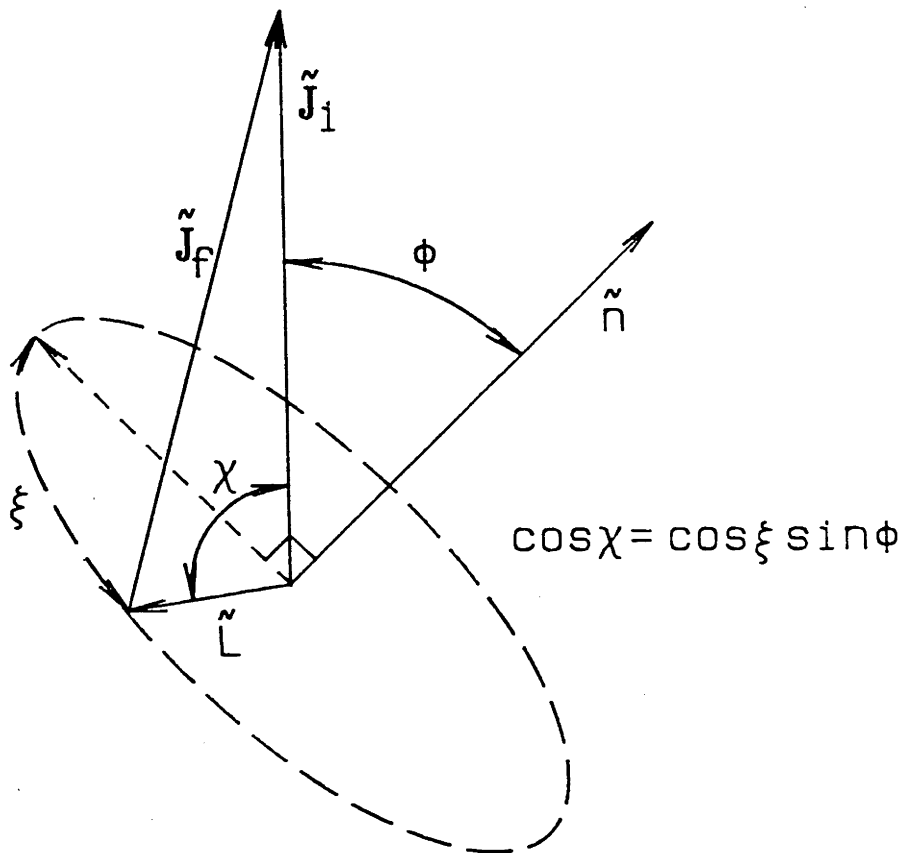


Figure 2.25 The relationship between the angular momenta of the parent nucleus $\tilde{J}_i$, the daughter nucleus $\tilde{J}_f$ and the emitted particle $\tilde{L}$, and the direction of the emitted particle $\tilde{n}$, in the classical limit where $\tilde{n} \cdot \tilde{L} = 0$, ie the particle is emitted perpendicular to its orbital angular momentum.

$$E_f = E_i - B_{\text{part}} - \epsilon \quad (2.71)$$

$$|\tilde{J}_f|^2 = |\tilde{J}_i|^2 + |\tilde{L}|^2 - 2|\tilde{J}_i||\tilde{L}| \cos(\chi) \quad (2.72)$$

where χ is the angle between the angular momentum of the parent nucleus $\tilde{J}_i$ and the orbital angular momentum of the emitted particle $\tilde{L}$. Figure 2.25 shows the relationship between the angular momenta of the parent nucleus $\tilde{J}_i$, the daughter nucleus $\tilde{J}_f$, and the emitted particle $\tilde{L}$, and the direction of the emitted particle $\tilde{n}$ in the classical limit where $\tilde{n} \cdot \tilde{L} = 0$ (ie the particle is emitted perpendicular to its orbital angular momentum).

To obtain the probability of emitting a particle at an angle ϕ to the spin of the parent nucleus, with kinetic energy ϵ , equation 2.70 is integrated over all the contributing $\tilde{L}$. In the semi-classical limit where $|\tilde{L}| = (L + \frac{1}{2}) \hbar$ and $\tilde{n} \cdot \tilde{L} = 0$ (see figure 2.25) we can write

$$W(\phi, \epsilon) \propto \int_0^\infty \int_0^{2\pi} (L + \frac{1}{2}) T_L(\epsilon) \rho_f(E_f, J_f) d\xi dL \quad (2.73)$$

In the limit of $E_{\text{rot}} \ll E_f$ the level density

$$\rho_f(E_f, J_f) \propto \exp 2\sqrt{aU} \approx \exp 2\sqrt{aE_f} \exp\left(\frac{-E_{\text{rot}}}{T}\right) \quad (2.74)$$

For the emission of particles from a deformed system, equation 2.73 becomes more complex with the $T_L(\epsilon)$ being dependent on the exit point of the emitted particles. Integrals over the angles used to describe the orientation of the deformed system are also required. For a spherical system where the transmission coefficients are independent of the exit points of the emitted particles, equation 2.73 can be rewritten as

$$W(\phi, \epsilon) \propto \exp 2\sqrt{aE_f} \int_0^\infty (L + \frac{1}{2}) T_L(\epsilon) \exp\left(\frac{-|\tilde{J}_i|^2 - |\tilde{L}|^2}{2 I_f T}\right) \int_0^{2\pi} \exp\left(\frac{2|\tilde{J}_i||\tilde{L}| \sin\phi \cos\xi}{2 I_f T}\right) d\xi dL \quad (2.75)$$

where $\mathbb{I}_f$ is the moment of inertia of the daughter nucleus and T is its nuclear temperature. Using the Modified Bessel Function

$$I_0(z) = \frac{1}{\pi} \int_0^\pi \exp(z \cos\theta) d\theta \quad (2.76)$$

equation 2.75 becomes

$$W(\phi, \epsilon) \propto \exp 2\sqrt{aE_f} \int_0^\infty (L + \frac{1}{2}) T_L(\epsilon) \exp\left[\frac{-\hbar^2((J_i + \frac{1}{2})^2 - (L + \frac{1}{2})^2)}{2 \mathbb{I}_f T}\right] \\ \times I_0(2\beta_L \sin\phi) dL \quad (2.77)$$

where

$$\beta_L = \frac{\hbar^2 (J_i + \frac{1}{2}) (L + \frac{1}{2})}{2 \mathbb{I}_f T} \quad (2.78)$$

For the special case of sharp cut off transmission coefficients

$$T_L = 0 \quad \text{for} \quad \epsilon < B + \frac{\hbar^2 (L + \frac{1}{2})^2}{2 \mu R_{\text{eff}}^2} \\ T_L = 1 \quad \text{for} \quad \epsilon \geq B + \frac{\hbar^2 (L + \frac{1}{2})^2}{2 \mu R_{\text{eff}}^2} \quad (2.79)$$

one may integrate equation 2.77 analytically over L and ϵ to obtain the following [AJI86]

$$W(\phi) \propto \exp(\beta \sin^2\phi) \quad (2.80)$$

The anisotropy parameter is given by

$$\beta = \frac{\hbar^2 (J_i + \frac{1}{2})^2}{2 \mathbb{I}_f T} \frac{\mu R_{\text{eff}}^2}{\mathbb{I}_f + \mu R_{\text{eff}}^2} \quad (2.81)$$

where B , μ and R_{eff} are the barrier height, reduced mass of the emitted particle and daughter nucleus system and the effective barrier radius respectively. The barrier radius is [WIL67]

$$R_{\text{eff}} \approx r_n + 3\delta \quad (2.82)$$

where r_n and δ are the Woods-Saxon range and surface diffuseness used in the optical model potential of the emitted particle plus daughter system.

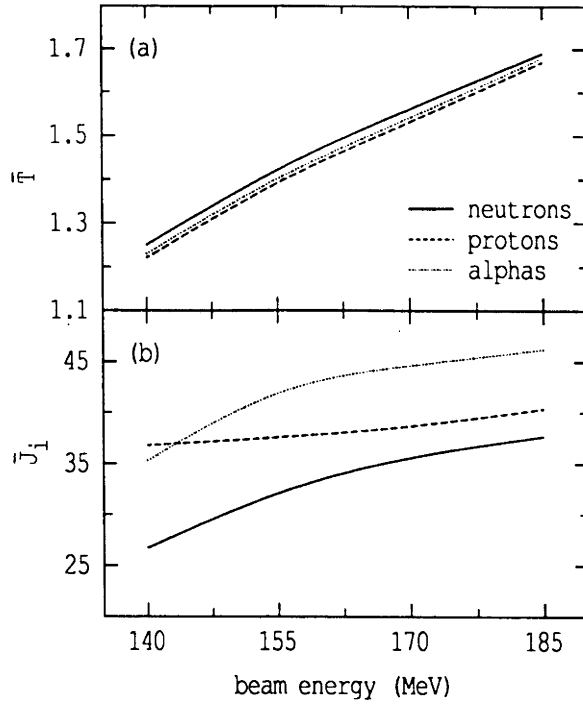


Figure 2.26 (a) the average nuclear temperature $\bar{T}$ of the daughter nuclei after the emission of pre-scission neutrons, protons and alphas, and (b) the average spin J_i of the parent nuclei emitting the pre-scission neutrons, protons and alpha particles, for the $^{28}\text{Si} + ^{167}\text{Er} \rightarrow ^{195}\text{Pb}$ system.

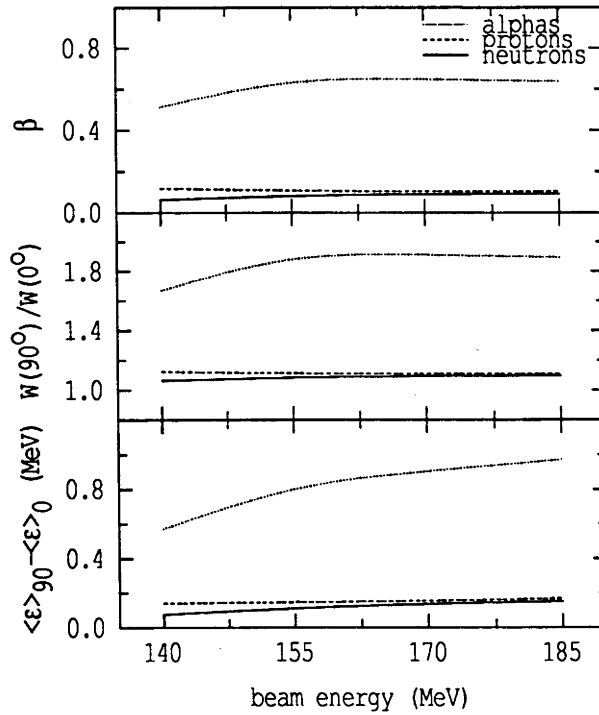


Figure 2.27 Estimates of β , $W(90^\circ)/W(0^\circ)$ and $\langle \epsilon \rangle_{90} - \langle \epsilon \rangle_0$ for the $^{28}\text{Si} + ^{167}\text{Er}$ pre-scission particle emission.

Using the potentials of [PER76] for neutron and proton emission and [HUI62] for alpha emission we can write

$$\begin{aligned}
 R_{\text{eff}}(n) &\approx (1.322 - 7.6A_f \times 10^{-4} + 4A_f^2 \times 10^{-6} - 8A_f^3 \times 10^{-9})A_f^{1/3} + 1.98 \text{ fm} \\
 &\approx 1.266 A_f^{1/3} + 1.98 \text{ fm} \quad \text{for } A_f \approx 200 \\
 R_{\text{eff}}(\pi) &\approx 1.25 A_f^{1/3} + 1.98 \text{ fm} \\
 R_{\text{eff}}(\alpha) &\approx 1.17 A_f^{1/3} + 3.50 \text{ fm}
 \end{aligned} \tag{2.83}$$

The mean energy and mean square orbital angular momentum of the emitted particles can also be determined analytically, by performing similar integrals [AJI86] giving

$$\langle \varepsilon \rangle_\phi = B + T + T \left(\frac{I_f}{I_f + \mu R_{\text{eff}}^2} \right) (1 + \beta \sin^2 \phi) \tag{2.84}$$

$$\langle \tilde{L}^2 \rangle_\phi = \frac{2\mu R_{\text{eff}}^2}{\hbar^2} \frac{I_f}{I_f + \mu R_{\text{eff}}^2} T (1 + \beta \sin^2 \phi) \tag{2.85}$$

Figure 2.26 shows (a) the average nuclear temperature $\bar{T}$ of the daughter nuclei after the emission of pre-scission neutrons, protons and alpha particles, and (b) the average spin $\bar{J}_i$ of the parent nuclei emitting pre-scission particles, from the $^{28}\text{Si} + ^{167}\text{Er}$ fusion-fission system, versus beam energy. These calculations were performed using the computer code JOANNE (see section 2.3.2) with $a_{\text{eq}} = A/10 \text{ MeV}^{-1}$ and $a_{\text{sp}}/a_{\text{eq}} = 1.0$. The ^{195}Pb fusion spin distributions were determined using equation 2.9 with $\Delta L = 9$ [HIN86] and the fusion cross sections of [HIN83]. The Q value for the fusion reaction was taken as [CHA86]

$$Q = E_{\text{P}}^{\text{EXP}} + E_{\text{T}}^{\text{EXP}} - M_{\text{CN}}^{\text{LD}} - 3\delta \tag{2.86}$$

where $E_{\text{P}}^{\text{EXP}}$ and $E_{\text{T}}^{\text{EXP}}$ are the experimental ground state masses of the projectile and target respectively, $M_{\text{CN}}^{\text{LD}}$ is the liquid-drop mass of the compound nucleus [MYE66, MYE67] (see section 2.2.1) and δ is the pairing energy taken as $11/A_{\text{cn}}^{1/2} \text{ MeV}$. The finite range liquid-drop fission barriers of [SIE86] were scaled by $k_f = 0.85$ to reproduce the fission and evaporation residue cross sections of [HIN83]. Figure 2.27 shows estimates of β , $W(90^\circ)/W(0^\circ)$ and $\langle \varepsilon \rangle_{90} - \langle \varepsilon \rangle_0$ for the $^{28}\text{Si} + ^{167}\text{Er}$ pre-scission particle emission, using the $\bar{T}$ and $\bar{J}_i$ shown in figure 2.26.

Ajitanand *et al.* [AJI86] have developed a Monte Carlo code to investigate the emission of particles from deformed nuclei. Figure 2.28 shows their calculations of mean energy, the root mean squared orbital angular momentum at 0° and 90° to the spin, and the anisotropy for the emission of alpha particles from the 485 MeV $^{56}\text{Fe} + ^{197}\text{Au} \rightarrow ^{253}105$ system, as a function of compound nucleus shape. Figure 2.29 is the same as figure 2.28 but for the 190 MeV $^{40}\text{Ar} + ^{27}\text{Al} \rightarrow ^{67}\text{Ga}$ system. These two cases illustrate the limiting situations discussed by [DOS77]: the Coulomb forces dominated region, $\beta_{\text{sphere}} \ll 1$; and the centrifugal forces dominated region, $\beta_{\text{sphere}} \gg 1$. For spherical nuclei, the difference between 0° and 90° values of the root mean squared orbital angular momentum and mean energy, as well as the angular distribution of the particles, is due solely to the nuclear rotation. In the region dominated by centrifugal forces, the anisotropy from spherical emitters is very large (see figure 2.29), and decreases rapidly with increasing deformation due to the increasing moment of inertia about the axis of rotation. In the Coulomb forces dominated region (see figure 2.28), the anisotropy of the particle emission is expected to increase with deformation due to the lowering of the emission barriers along the symmetry axis. Another interesting effect is the decrease of the mean particle energy at 90° to the spin direction with increased deformation which, in the Coulomb forces dominated region, can lead to a lower mean particle energy at 90° than at 0° to the spin direction (see figure 2.28).

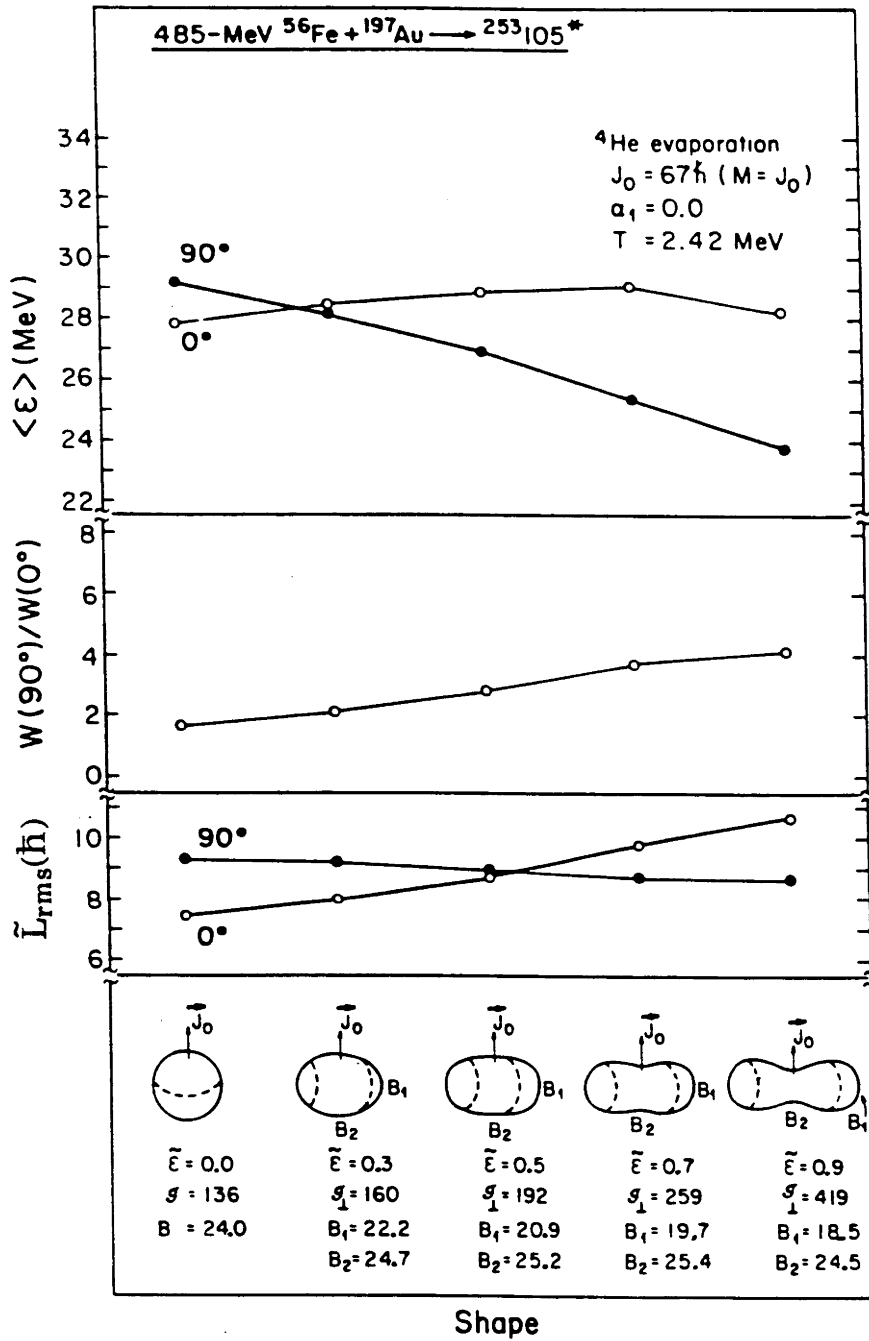


Figure 2.28 Mean energy $\langle \epsilon \rangle$ and root mean squared orbital angular momentum $\tilde{L}_{\text{rms}}$ at 0° and 90° to the spin, and anisotropy $W(90^\circ)/W(0^\circ)$, for the emission of alpha particles from the 485 MeV $^{56}\text{Fe} + ^{197}\text{Au} \rightarrow ^{253}_{105}$ system ($T=2.4$ MeV, $J_i=67\hbar$, $\beta_{\text{sphere}}=0.61$). The units of the barrier heights and the moments of inertia are MeV and $\hbar^2$ MeV, respectively. (from [AJI86])

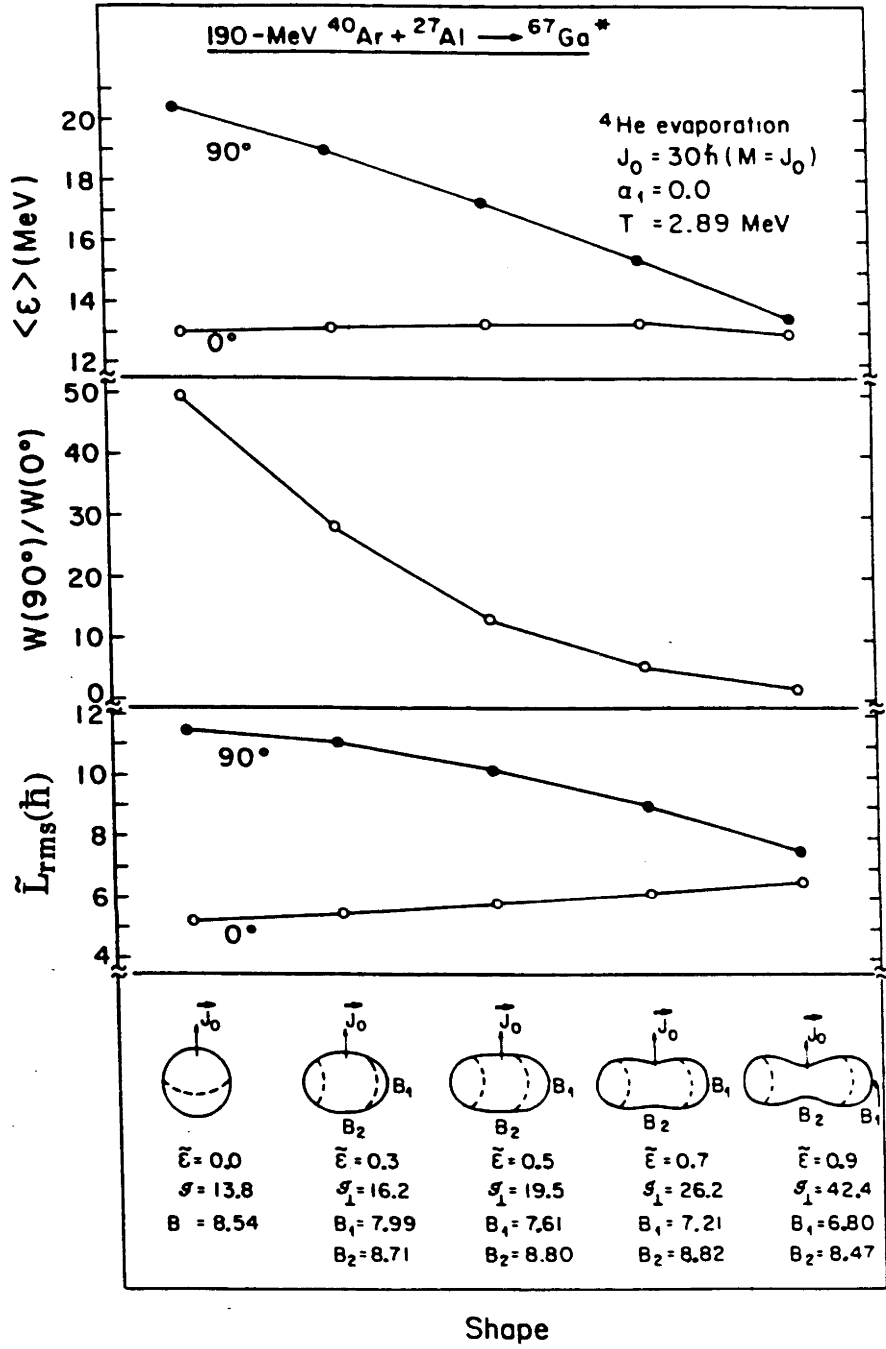


Figure 2.29 As for figure 2.28 but for the 190 MeV $^{40}\text{Ar} + ^{27}\text{Al} \rightarrow ^{67}\text{Ga}$ system ($T=2.9\text{MeV}$, $J_i=30\hbar$, $\beta_{\text{sphere}}=4.0$). (from [AJI86])

2.4 Nuclear Viscosity

In the case of a sphere injected into a viscous liquid with zero gravity, the velocity of the sphere $u(t)$ as a function of time t is given by

$$u(t) = u_0 \exp \left(-t \frac{6 \pi \eta R}{M} \right) = u_0 \exp \left(\frac{-t}{\tau} \right) \quad (2.87)$$

where M and R are the mass and radius of the sphere, τ is the relaxation time and η is the viscosity of the fluid. The movement of the sphere through the liquid tends to set up an ordered flow pattern around the sphere. The random motion of the particles making up the fluid disrupts this ordered flow by transporting momentum across the velocity gradients in the fluid. In this way the initial collective energy of the sphere is transferred into an increased thermal motion of the particles in the fluid.

The meaning of viscosity, dissipation or friction in nuclei is not as obvious as in this simple example. The nucleus is a unique, superdense, quantum Fermi-liquid capable of collective motions such as rotations and vibrations. The theory of nuclear viscosity attempts to describe the coupling between collective nuclear motion and the thermal motion of the nucleons making up a given nuclear system. It can be useful to consider the nearest analogue to the nucleus, liquid ^3He , which is also a quantum Fermi-liquid. The mean free path λ for collisions between ^3He atoms is normally much smaller than the dimensions of the system and thus is affected by the well known "two-body viscosity". For any system of weakly interacting particles the bulk viscosity is given by the expression

$$\eta = \frac{1}{3} \rho \lambda(T) \bar{v} \quad (2.88)$$

where ρ is the density, $\bar{v}$ is the average speed of the particles and $\lambda(T)$ is the mean free path. For a system of fermions, collisions between the particles are inhibited by the Pauli principle so that λ decreases with temperature as $\sim T^{-2}$. The mean velocity of fermions remains fairly constant with temperature and thus η varies as $\sim T^{-2}$. There is, however, a critical temperature T_c below which ^3He is a superfluid (ie $\eta=0$).

If we were to set a droplet of liquid ${}^3\text{He}$ ($T > T_c$) into vibration, then the two-body viscosity would cause the irreversible transformation of the collective motion into increased thermal motion of the ${}^3\text{He}$ atoms. The probability of the ${}^3\text{He}$ droplet ever spontaneously regaining its original collective motion at the expense of the droplet's thermal energy is essentially zero, because of the large number of individual ${}^3\text{He}$ atoms involved. Nuclei, however, only contain a relatively small number of nucleons and the probability of a hot compound system obtaining a sizeable collective motion at the expense of its thermal energy is far from zero. Another main difference between a droplet of liquid ${}^3\text{He}$ and a nucleus is that in a droplet of liquid ${}^3\text{He}$ the mean free path is much smaller than the size of the droplet. In the nuclear case the mean free path in the nuclear interior can be larger than the diameter of the nucleus. The loss or gain of collective energy through two-body collisions inside the nucleus is thus small and nuclear viscosity is expected to be mainly due to the collisions of nucleons with the nuclear surface.

The simplest example of "one-body dissipation" is that of a Knudsen gas. In such a gas, a particle colliding with the walls of the container is assumed to first stick and then be emitted in a random direction with a velocity distribution appropriate to the temperature of the gas. The essential property of a Knudsen gas is that a particle hitting the container loses all memory of the collision before striking the walls again. The dissipative energy loss from such a system is given by the wall formula [BLO78,RAN84]

$$\frac{\partial E}{\partial t} = \rho \bar{v} \int (\dot{n} - D)^2 ds \quad (2.89)$$

where $\dot{n}$ is the velocity of a surface element ds , D is the normal drift velocity of the particles about to strike the surface element ds , $\bar{v}$ is the average thermal speed of the particles and ρ is the mass density.

In real nuclei, nucleons are expected to retain some memory of their previous collisions. This reduces the rate of dissipative energy loss

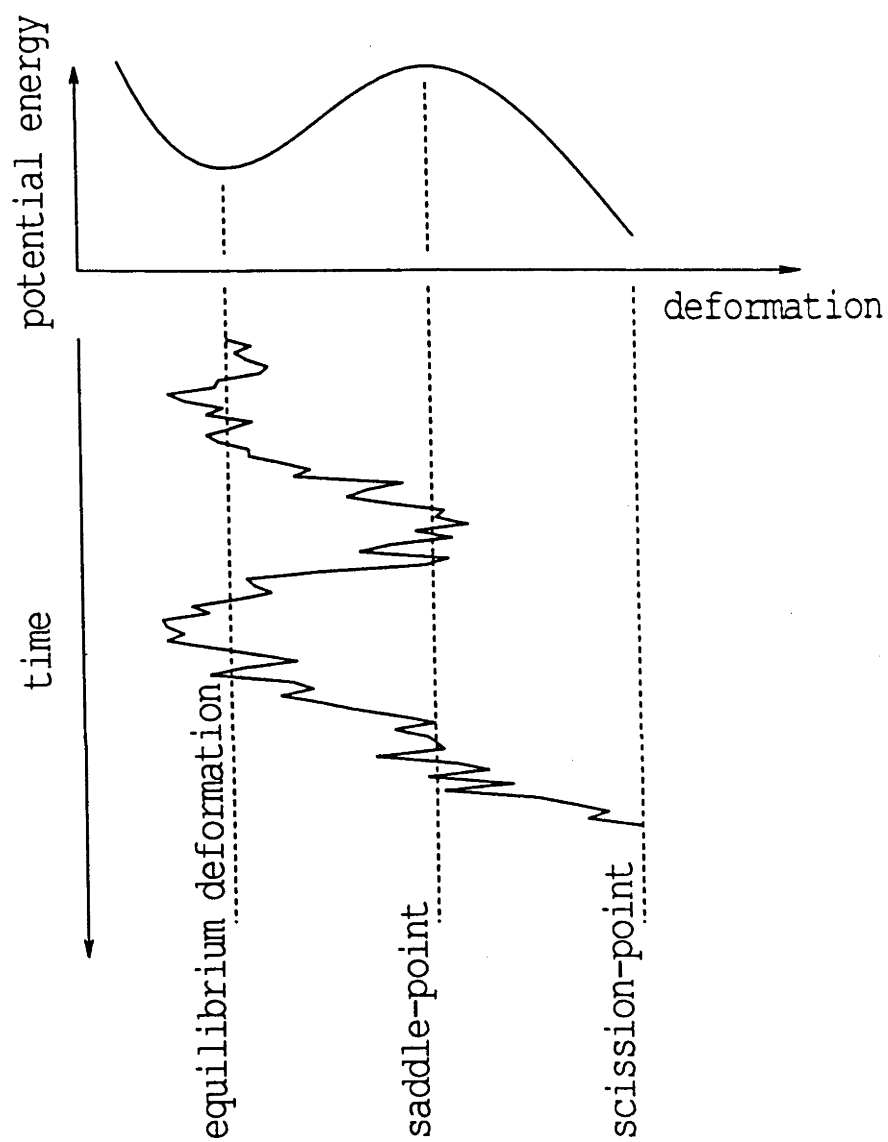


Figure 2.30 Schematic diagram of the possible time evolution of a hot compound system with no initial collective motion.

and the right hand side of equation 2.89 is usually scaled by a constant K_s . The value of K_s is not at all clear and could depend upon both the nuclear excitation energy and the type of collective motion involved. Using random-phase approximation calculations for spherical nuclei, Griffin, Dworzecka and Yannouleas [GRI86,YAN85] have shown, by replacing some of the assumptions used to derive the wall formula by more realistic features appropriate to real nuclei, that $K_s \approx 0.1$. Nix and Sierk [NIX86] have used the widths of isoscalar giant quadrupole and giant octupole resonances and obtained a value of $K_s \approx 0.27$.

For dumbbell-like shapes the transfer of nucleons between the two portions leads to an additional dissipative energy loss that is analogous to the classical window formula [RAN84]

$$\frac{\partial E}{\partial t} = \frac{1}{4} \rho \bar{v} (2 \dot{z}^2 + \dot{x}^2) a + \frac{16}{9} \frac{\rho \bar{v}}{a} \dot{V}_1 \quad (2.90)$$

where $\dot{z}$ and $\dot{x}$ are the relative velocities of the two halves of the dumbbell along and at right angles to the normal through the window, a is the area of the window and $\dot{V}_1$ is the rate of change of the volume on one side of the window. Although this equation is derived using the assumptions of a Knudsen gas, for a small window there is no need for a scaling factor because nucleons have a low probability of returning through the window while still retaining memory of their previous passage.

It must be emphasised that equations 2.89 and 2.90 only give the average dissipative energy loss. The collective energy of a given nuclear system will fluctuate about the smooth trends predicted by these equations, because of the small number of nucleons involved. These fluctuations play a crucial role in the dynamics of fission. Without them a newly formed hot compound system, with no initial collective energy, could never obtain the deformation of the saddle-point and thus would never undergo fission. A schematic diagram of the time evolution of a hot compound system with no initial collective motion is shown in figure 2.30.

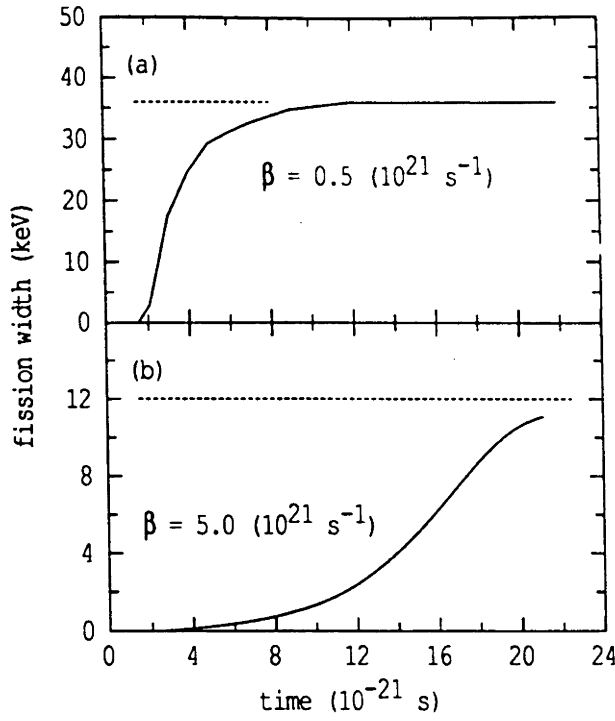


Figure 2.31 The time dependence of the fission decay width of ^{158}Er at an angular momentum of $65\hbar$, formed in the fusion of 207 MeV ^{16}O on ^{142}Nd for (a) $\beta = 0.5 \times 10^{21} \text{ s}^{-1}$, (b) $\beta = 5.0 \times 10^{21} \text{ s}^{-1}$. (adapted from [GRA86])

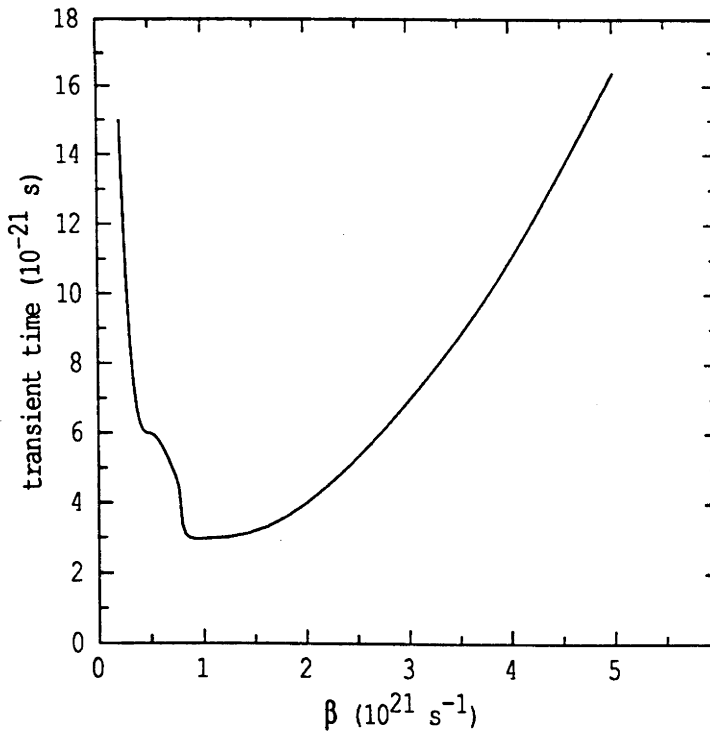


Figure 2.32 The transient time as a function of the reduced dissipation constant β , for the 207 MeV $^{16}\text{O} + ^{142}\text{Nd} \rightarrow ^{158}\text{Er}$ system at an angular momentum of $65\hbar$. (adapted from [GRA86])

The fission decay width of equation 2.59 was derived using the transition state model of Bohr and Wheeler [BOH39]. This model assumes that the coupling between the thermal energy and the collective degrees of freedom is small and that a nucleus becomes committed to fission once it has just passed its saddle-point deformation. If the nuclear viscosity is large enough then it is possible for a nucleus to pass over the saddle-point and then, due to fluctuations in its collective energy, to return back to its equilibrium deformation (see figure 2.30). Kramers [KRA40] developed a diffusion model applicable to nuclear fission and showed that

$$\Gamma_f = \Gamma_f^0 \left[\left\{ 1 + \left(\frac{\beta}{2\omega_0} \right)^2 \right\}^{1/2} - \frac{\beta}{2\omega_0} \right] \quad (2.91)$$

where ω_0 is the frequency of the inverse harmonic-oscillator potential of the fission barrier at the saddle-point, and β is the "reduced frictional constant". Equation 2.91 is valid for all but very small values of β/ω_0 : in the limit $\beta \rightarrow 0$ the width Γ_f should approach zero instead of Γ_f^0 . For most practical situations Γ_f^0 is assumed to be the standard statistical model fission decay width, even though in Kramers' derivation of equation 2.91, Γ_f^0 differs from the standard statistical model width. Using Kramers diffusion model, Grange and Weidenmuller [GRA80] found that the full fission decay width takes a finite time to become established. More recent theoretical studies of the time dependence of fission decay widths can be found in [GRA83,WEI84,HAS84,GRA86,BHA86]. The time dependence of the fission decay width of ^{158}Er at an angular momentum of $65\hbar$ formed in the fusion of 207 MeV ^{16}O on ^{142}Nd , as calculated by Grange *et al.* [GRA86] for $\beta=0.5 \times 10^{21} \text{ s}^{-1}$ and $\beta=5.0 \times 10^{21} \text{ s}^{-1}$, is shown in figure 2.31. The time τ required for the fission decay width to reach 90% of its quasistationary value is usually referred to as the transient time. Figure 2.32 shows the transient time as a function of the reduced frictional constant for the 207 MeV $^{16}\text{O} + ^{142}\text{Nd} \rightarrow ^{158}\text{Er}$ system at an angular momentum of $65\hbar$.

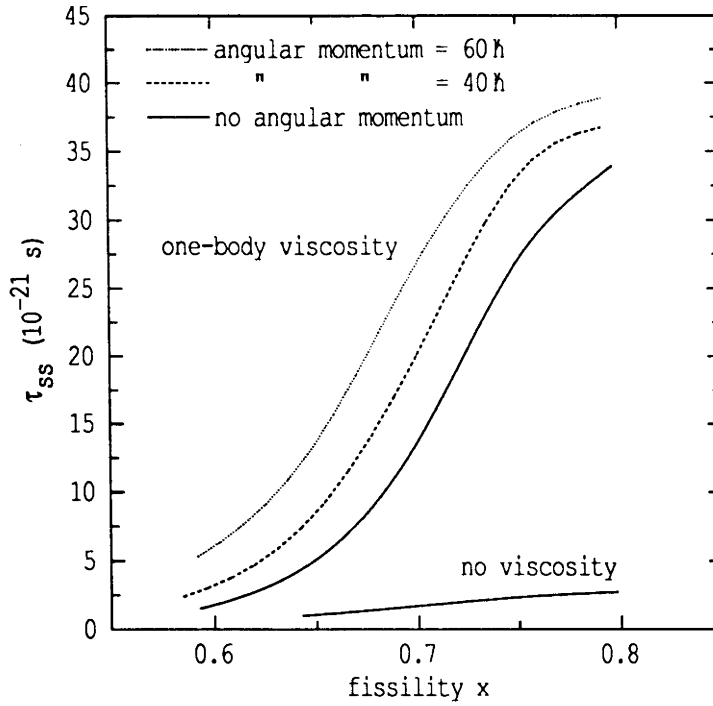


Figure 2.33 Saddle-to-scission time for full one-body viscosity and for no viscosity as functions of fissility. The results were taken from the $J=0$ calculations of [CAR86]. The results for $J=40$ and $J=60$ were estimated by the method of effective fissility [BLA82A]. Values for one-body viscosity for $x \leq 0.65$ are not very accurate since they were extrapolated from the curves of [CAR86]. (adapted from NEW88)

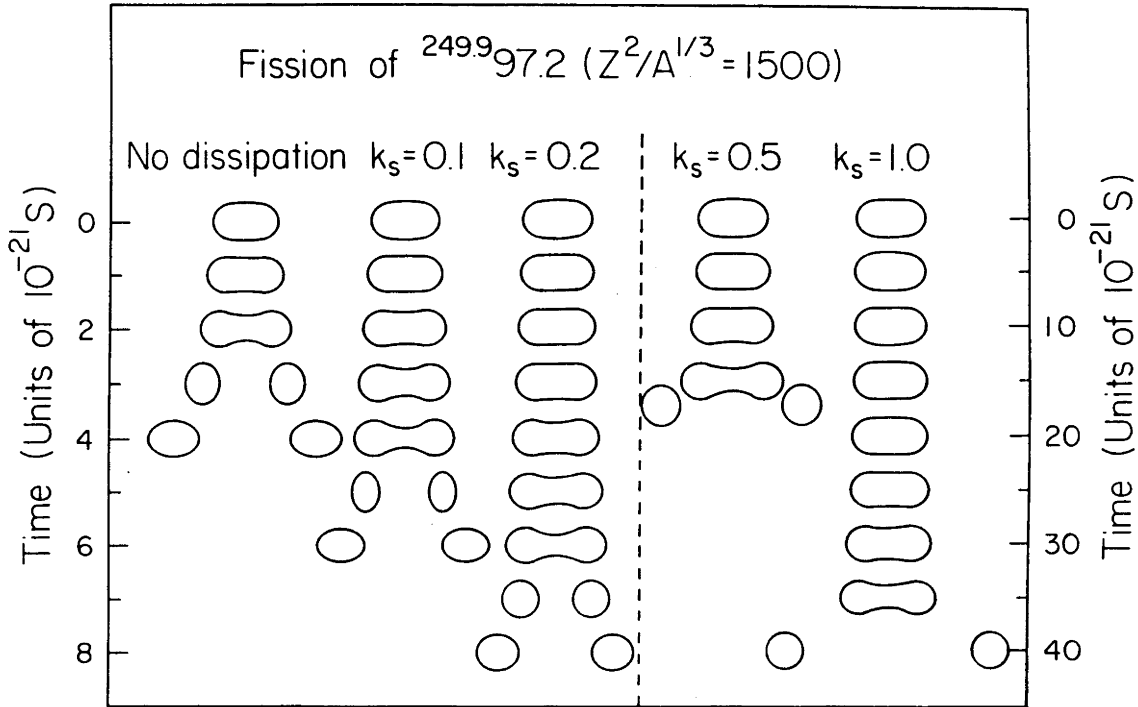


Figure 2.34 The post-saddle evolution of a nonrotating nucleus with $Z^2/A^{1/3} = 1500$ in Green's valley of stability. The nuclear temperature is taken to be 2 MeV. (from [NIX87])

Another important effect of nuclear viscosity on the dynamics of fission is the slowing down of the path from saddle to scission. Nix, Sierk and collaborators [CAR86,NIX84,NIX86A,NIX87] have made numerous contributions to the theory of post-saddle fission dynamics. Figure 2.33 shows saddle-to-scission times τ_{ss} for full one-body dissipation (ie $K_s=1.0$) and no viscosity as a function of fissility. Two-body dissipation through the bulk of the nuclear fluid gives saddle-to-scission times only slightly longer than those calculated with no viscosity [CAR86]. Figure 2.34 shows the post-saddle evolution of a nonrotating nucleus, with $Z^2/A^{1/3} = 1500$ in Green's valley of stability, for various strengths of the one-body dissipation, and illustrates that saddle-to-scission times are roughly proportional to K_s . Nix and Sierk [NIX87] have used their surface (modified wall) plus window dissipation model to reproduce the mean kinetic energy of experimentally observed fission fragments. They require values of K_s ranging from ~ 0.5 for lighter systems to ~ 0.2 for the heaviest, in order to get good fits.

Standard statistical model calculations, which ignore the effects of nuclear viscosity and assume all particle emission from the compound system occurs before the saddle-point is reached, fail to reproduce measured pre-scission neutron multiplicities ν_{pre} (for example [HIN86,GAV87]). Hinde *et al.* measured ν_{pre} excitation functions for a range of systems from ^{168}Yb to ^{251}Es . Assuming the fission width varies with time according to

$$\Gamma_f = \Gamma_f(\infty) [1 - \exp(-\frac{t}{\tau_d})] \quad (2.92)$$

and using various simplifying assumptions in an attempt to model saddle-to-scission particle emission, Hinde *et al.* could obtain good fits to all their

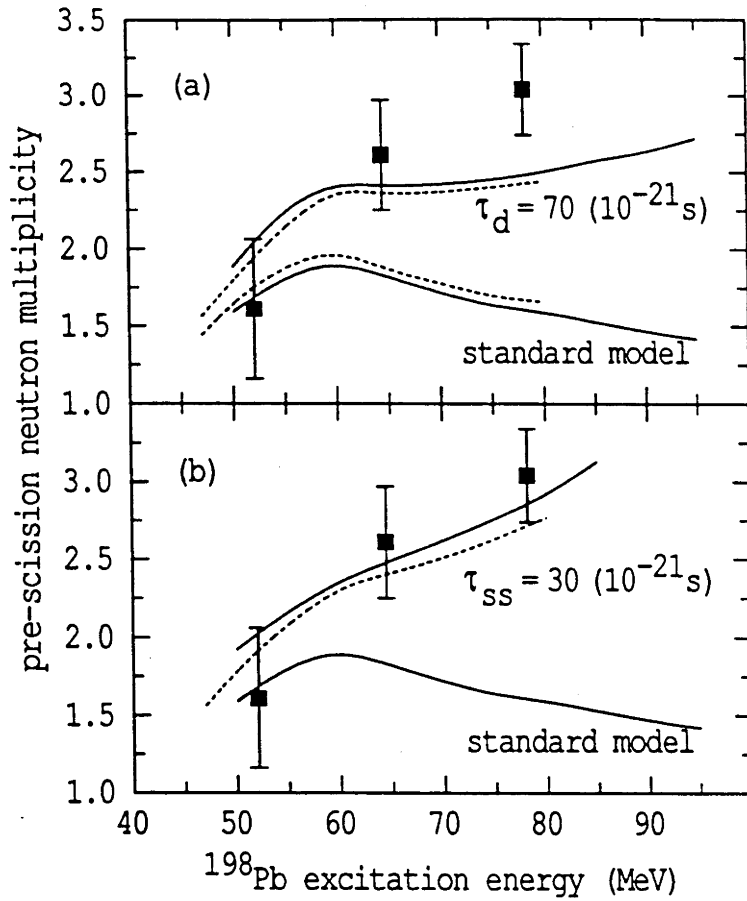


Figure 2.35 Theoretical calculations of pre-scission neutron multiplicities for the $^{28}\text{Si} + ^{170}\text{Er} \rightarrow ^{198}\text{Pb}$ system, made by a modified version of the program ALERT1 [BLA82,HIN86] (dashed curves) and by my own statistical model code JOANNE (solid curves). Both sets of calculations were performed using $a_{sp}/a_{eq}=1.0$ and $a_{eq}=A/10.0 \text{ MeV}^{-1}$, and their respective fission barriers were scaled to reproduce the measured evaporation residue cross sections of [HIN83]. The fusion spin distributions were determined using equation 2.9 with $\Delta L=9$ [HIN86] and the fusion cross sections of [HIN83]. The standard model refers to $\tau_d=\tau_{ss}=0$. Calculations with (a) $\tau_d=70 (10^{-21} \text{ s})$, $\tau_{ss}=0$ and (b) $\tau_{ss}=30 (10^{-21} \text{ s})$, $\tau_d=0$ are shown. The experimental points are those of [HIN86].

data using $a_{sp}/a_{eq}=1.0$, $a_{eq}=A/10.0$ MeV⁻¹ and $\tau_d=70\times 10^{-21}$ s, or $\tau_d=\tau_{ss}=20\times 10^{-21}$ s or $\tau_{ss}=30\times 10^{-21}$ s. Gavron *et al.* [GAV87] have measured v_{pre} for ¹⁵⁸Er formed with a range of beams from ¹⁶O to ⁵⁰Ti. Grange *et al.* [GRA86] have analysed the reaction ¹⁶O + ¹⁴²Nd $\rightarrow$ ¹⁵⁸Er at 207 MeV, where 2.7 ± 0.4 neutrons prior to scission were measured [GAV87] compared to 1.6 neutrons calculated with a standard statistical model. This result suggests a value of $\beta \leq 5\times 10^{21}$ s⁻¹, which implies a value of the transient time $\tau \leq 20\times 10^{-21}$ s and a saddle-to-scission time $\tau_{ss} \leq 5\times 10^{-21}$ s. The ²⁴Mg and ³²S induced reactions exclude the region of low β and indicate a value of $\beta \sim 6\times 10^{21}$ s⁻¹ [GAV87], a value 2-3 times that required for critical damping. Hinde *et al.* [HIN89] claimed that the multiplicities of [GAV87] are too low, and made a new measurement for the reaction of 178 MeV ¹⁶O + ¹⁴²Nd which resulted in a v_{pre} of 3.95 ± 0.30 , considerably higher than the 207 MeV result of Gavron *et al.* This new result leads to much longer transient and saddle-to-scission times and a higher value of the reduced frictional constant than concluded from the measurements of [GAV87].

Figure 2.35 compares the measured v_{pre} of [HIN86] for the ²⁸Si + ¹⁷⁰Er $\rightarrow$ ¹⁹⁸Pb system to theoretical calculations made by a modified version of the program ALERT1 [BLA82,HIN86] and by my own statistical model code JOANNE (see section 2.3). JOANNE assumes that each compound system is formed at time $t=0$ and that the fission decay width varies with time according to

$$\Gamma_f = f(t) \Gamma_f(\infty) \quad (2.93)$$

where $\Gamma_f(\infty)$ is the standard statistical model fission decay width (see equation 2.59), and $f(t)$ is a function of the user's choice. For the calculations shown in figure 2.35, Γ_f was assumed to vary with time according to equation 2.92. After JOANNE decides that a given compound system will undergo fission, saddle-to-scission particle emission is

allowed for a time τ_{ss} . The particle emission transmission coefficients are assumed to be independent of deformation and the level density parameter at the saddle-point a_{sp} is used. The rotation plus deformation energies of the post-saddle nuclei are assumed to be the average of that at the saddle-point and that for spherical fragments at scission, that is

$$E_{rot} = 0.5 \times \{ E_f(J) + 2 M_{FF}^{LD} - M_{CN}^{LD} + KE + \frac{\hbar^2 J(J+1)}{2 I_{scis}} \} \quad (2.94)$$

where $E_f(J)$ is the fission barrier, M_{FF}^{LD} and M_{CN}^{LD} are the liquid-drop masses of a symmetric fission fragment and the compound system respectively and I_{scis} is the moment of inertia at scission. The final kinetic energy of the symmetric fragments is taken to be [VIO85]

$$KE = 0.755 \frac{Z_{FF}^2}{2 A_{FF}^{1/3}} + 7.3 \text{ MeV} \quad (2.95)$$

where Z_{FF} and A_{FF} are the atomic and mass numbers of the symmetric fragments.

CHAPTER 3

EXPERIMENTAL METHODS

This chapter describes the experimental methods used in the present study of protons and alpha particles in coincidence with fission fragments following heavy-ion induced fusion-fission reactions. The charged particle yields in these reactions are from several different sources, the main two being emission from the equilibrated compound system and emission from the fission fragments. Smaller contributions may be seen from pre-equilibrium emission (at forward angles) and near-scission emission (at $\sim 90^\circ$ to the scission axis). The observation of proton and alpha particle spectra in a single detector in coincidence with fission fragments in a single detector yields little information about the various sources of particle emission. Fortunately the different sources all have different angular distributions, and the measurement of particle spectra at various angles in coincidence with fission fragments in a single detector, or the measurement of particle spectra in a single detector in coincidence with fission fragments at various angles, or a combination of these, can be used to determine the intensity, energy spectra and angular distributions of the various sources.

All experiments were performed at the Department of Nuclear Physics of the Australian National University. Beams of protons, alpha particles and ^{28}Si ions were obtained from the ANU 14UD Pelletron Accelerator. The proton and alpha beams were used for calibration purposes and ^{28}Si beams for the study of protons and alpha particles in coincidence with $^{28}\text{Si} + \text{Er}$ fusion-fission reactions. After passing through their associated electronics, the signals obtained from the detectors were collected event by event on magnetic tape, via an ANU interface connected to a VAX 11/750 computer.

Section 3.1 describes the use of a CsI(Tl) crystal, coupled to a photodiode, for the detection of protons and alpha particles and section 3.2 describes the array of proportional gas detectors used to observe fission fragments. Section 3.3 describes the measurement of proton and alpha particle spectra in coincidence with fission. The method of analysis is discussed in section 3.4.

3.1 The Proton and Alpha Particle Detector

The light output from a CsI(Tl) crystal following the passage of an energetic charged particle is characterised by a fast rise followed by a two component exponential decay. Storey *et al.* [STO58] found that the light output was well represented by

$$L = A \exp\left(\frac{-t}{T_1}\right) + B \exp\left(\frac{-t}{T_2}\right) \quad (3.1)$$

where T_1 varies from 0.4 μsec to 0.7 μsec for particles other than electrons. The exact value of T_1 depends on the type of particle and more precisely on the average energy density deposited in the crystal. T_2 is approximately 7 μsec and independent of particle type. Although the slow decay contains ~30% of the light, the amplitude B is only ~3% of the amplitude A , and thus the time dependence of the light output is dominated by the faster decay during the first microsecond or so. The dependence of T_1 on the average energy density deposited in the crystal enables the use of pulse shape identification techniques to distinguish between protons, alpha particles and heavier particles.

Initially the properties of a detector system consisting of a CsI(Tl) crystal coupled to a photomultiplier tube were investigated. The output signals of such a system were found to decrease in size with increased detector counting rate. For example, the signal due to 12 MeV protons was observed to fall by approximately 5% with an increase in counting rate from $\sim 10^2$ to $\sim 10^3$ counts/second. This problem may have been overcome with the design of a more sophisticated base for the photomultiplier tube.

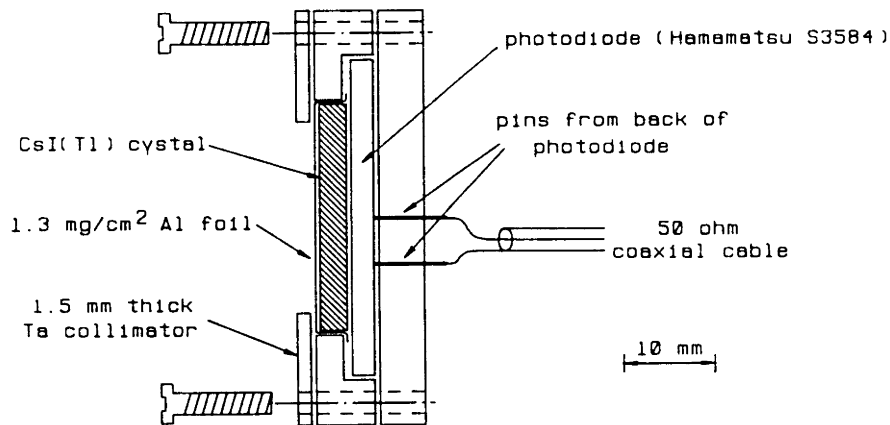


Figure 3.1 Sectional view of CsI detector.

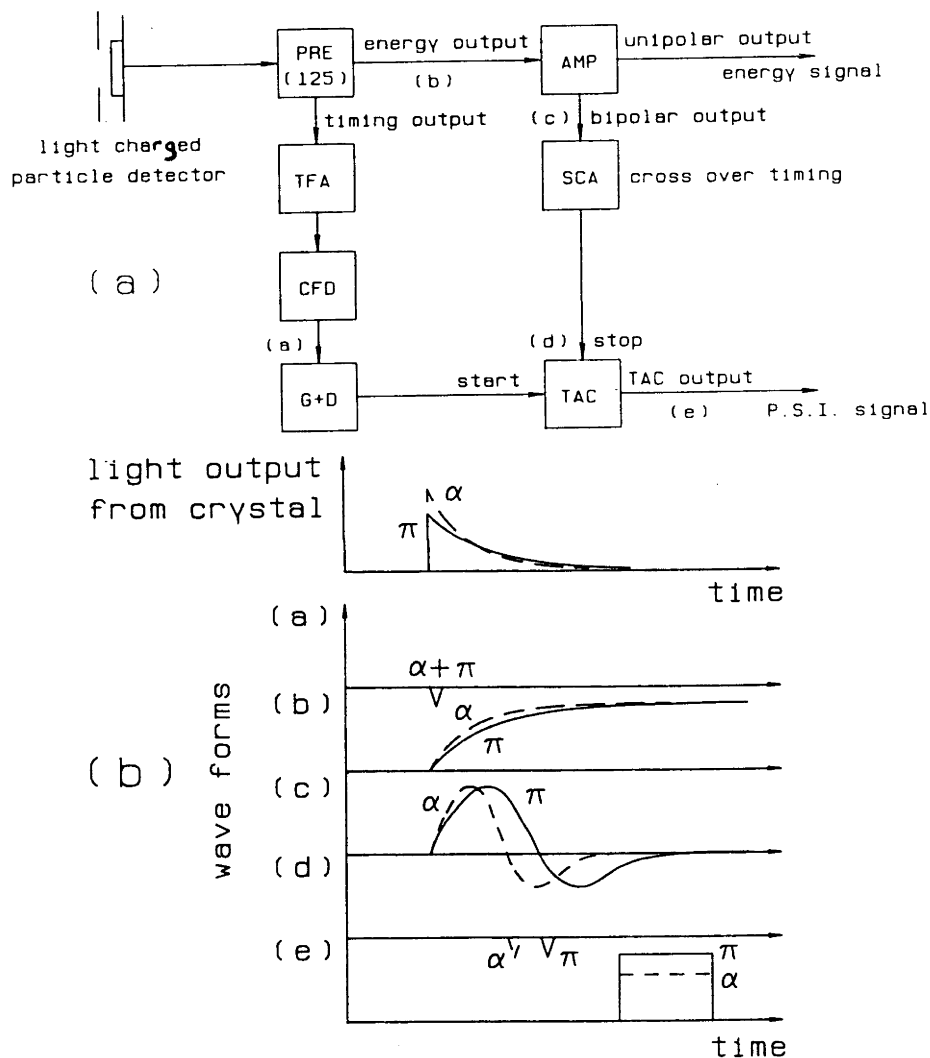


Figure 3.2 (a) Electronic system used to obtain the energy and pulse shape identification signals from the light charged particle detector. (b) Schematic representation of the wave forms at various indicated points around the circuit shown in (a), produced by a proton and alpha particle with equal integrated light outputs from the CsI(Tl) crystal. The electronic units are identified in table 3.4.

However, with the additional problem of having to fit the CsI detector close to a target, along with an array of fission fragment detectors, it was decided to replace the photomultiplier tube with a photodiode thus dramatically reducing the size of the detector system.

The CsI detector used in the present study to detect and identify protons and alpha particles in coincidence with fission consists of a photodiode (Hamamatsu S3584) with an active area of $28\text{mm} \times 28\text{mm}$ optically coupled (using silicone oil) to a CsI(Tl) crystal $25\text{mm} \times 25\text{mm} \times 3\text{mm}$. To aid in light collection and shield the detector from any electrons and light produced by the passage of the beam through the target, the front face of the crystal is covered with a 1.3 mg/cm^2 Al foil. To avoid any particles interacting near the edge of the crystal where light collection may be poor, the CsI(Tl) crystal is collimated by 1.5mm thick Ta, with a $21\text{mm} \times 21\text{mm}$ square opening. The thickness of the collimator was chosen to stop up to 32 MeV protons. Figure 3.1 shows a sectional view of the CsI detector. Figure 3.2 shows the electronics used to obtain the energy and pulse shape identification (P.S.I.) signals, and the wave forms at various points around the circuit.

The response of the system to mono-energetic protons was measured by selecting protons elastically scattered from a ^{197}Au target using an Enge split-pole spectrometer. The detector was mounted in the focal plane. The response as a function of counting rate was investigated, and no noticeable dependence was observed up to a rate of $\sim 4 \times 10^3$ counts/second. Figure 3.3 shows the detector's response to 20 MeV protons. Essentially all detected events have the full energy ($< 0.5\%$ in a low energy tail). To calibrate the detector, beams of protons and alpha particles were elastically scattered by a ^{232}Th target into the detector at 40° to the beam. Figure 3.4 shows the proton and alpha particle calibrations and the full width at half maxima. A typical plot of energy versus pulse shape identification is shown in figure 3.5.

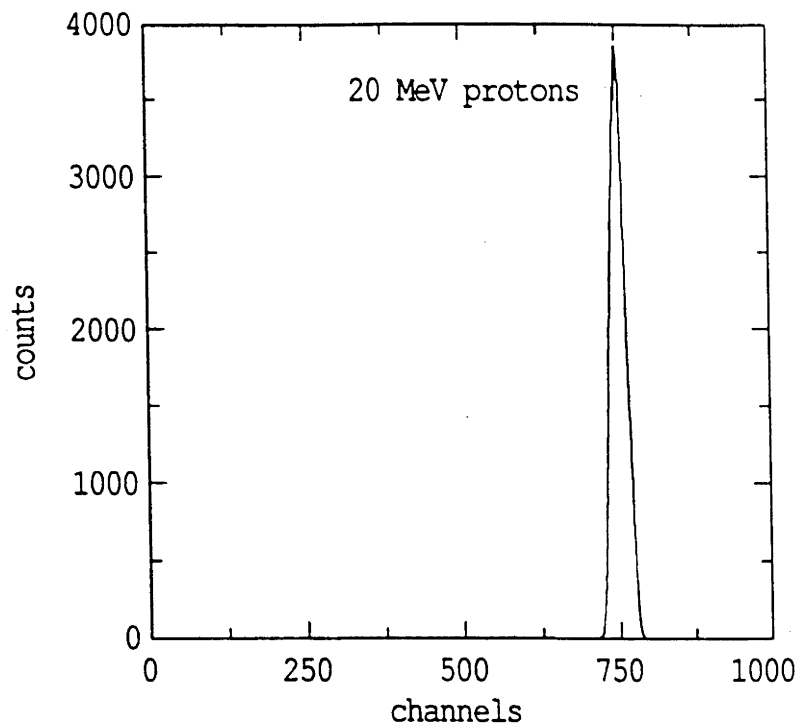


Figure 3.3 The CsI detector's response to 20 MeV protons.

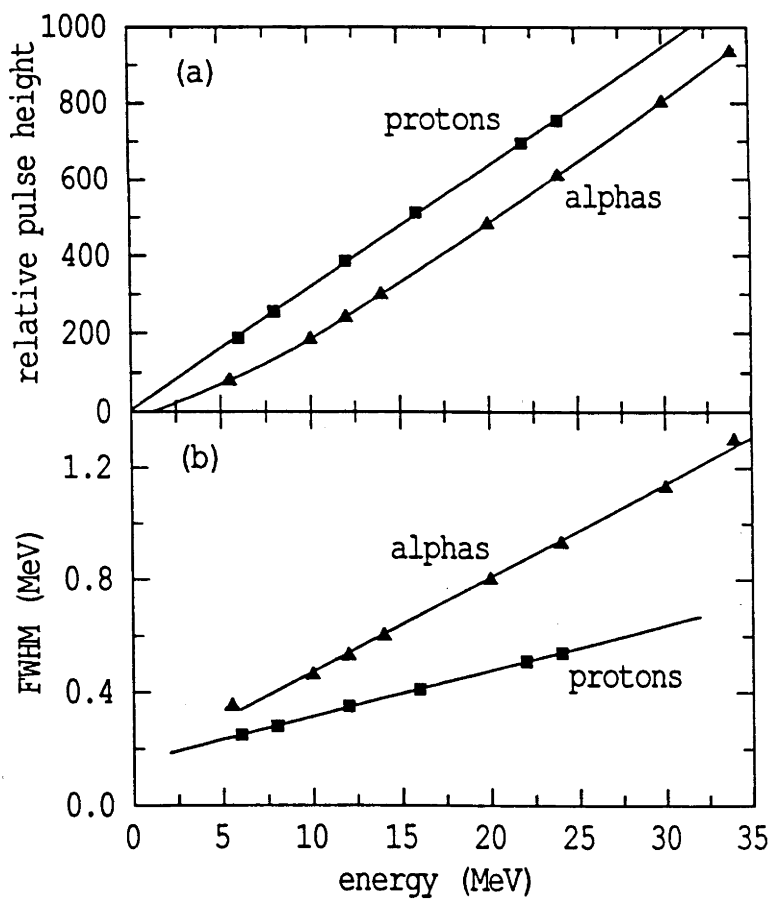


Figure 3.4 (a) Calibration and (b) FWHM for protons and alpha particles in the CsI detector.

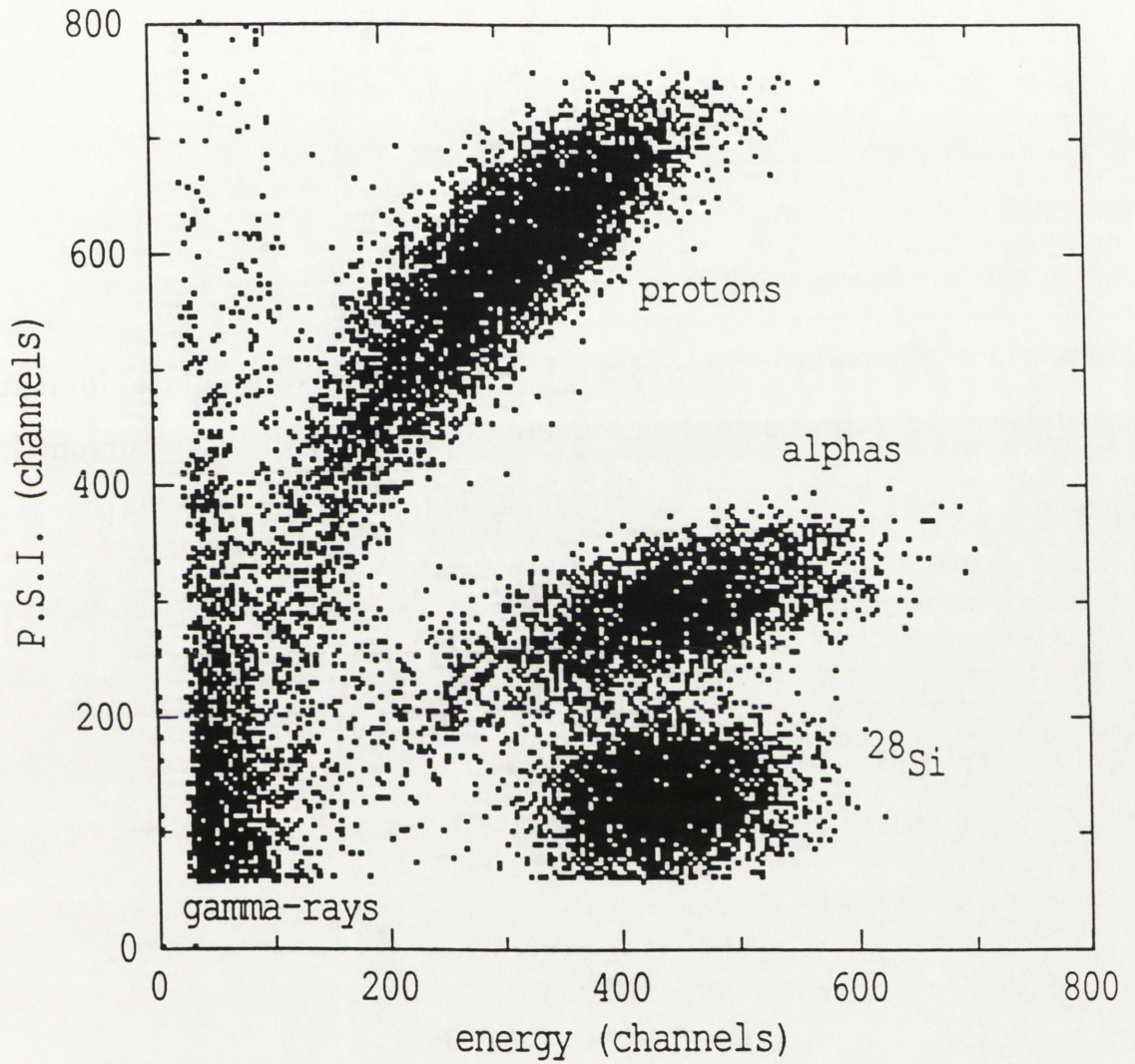


Figure 3.5 Energy versus P.S.I. following the reaction $162.5 \text{ MeV } ^{28}\text{Si} + ^{167}\text{Er}$. The CsI detector was at 90° to the beam.

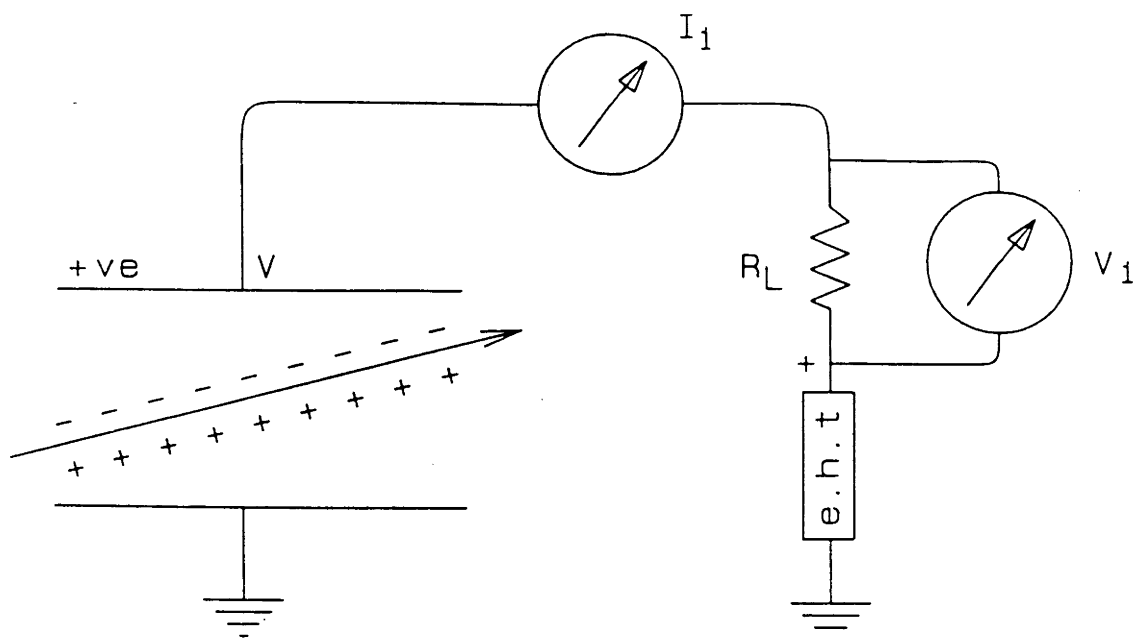


Figure 3.6 Schematic diagram of a simple parallel-plate ionisation chamber. The output signal can be obtained from either the current I_i , or the voltage V_i across the bias resistor R_L . (adapted from [ENG74])

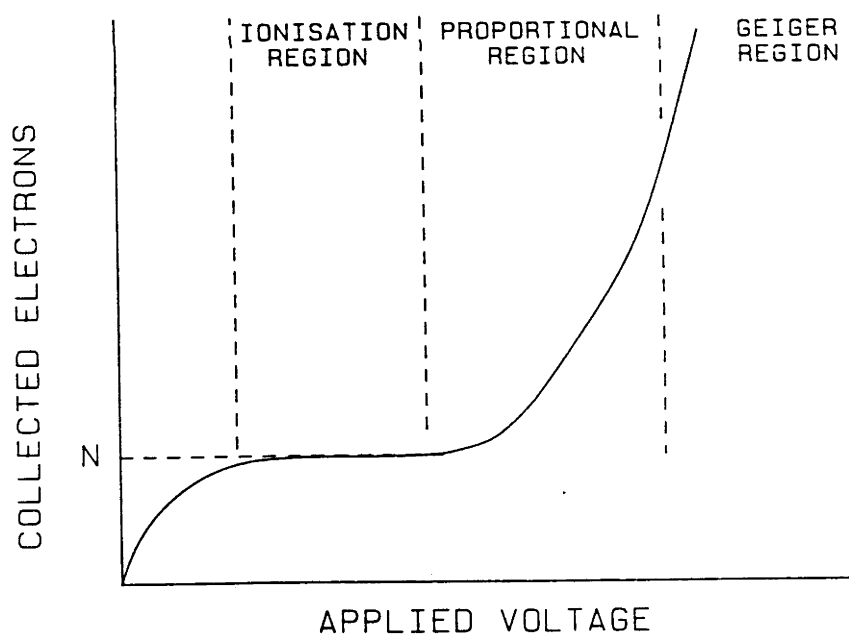


Figure 3.7 Schematic diagram of the variation of the number of collected electrons versus applied voltage, for a parallel-plate ionisation chamber where the ionising particle creates N electron-positive ion pairs. (adapted from [ENG74])

3.2 Fission Fragment Detection

3.2.1 Introduction to Gas Counters

A charged particle passing through a gas produces ionisation, excitation and dissociation of the gas molecules along its path. Gas counters use the ionisation to generate their signals. On average approximately each 30eV loss in charged particle kinetic energy produces an electron-ion pair. Electric fields are used to collect the electrons on an anode and the positive ions on a cathode. The time taken for the positive ions to reach the cathode is quite long (~msec) and usually only the fast component of the signal generated by the movement of the electrons is used. Figure 3.6 shows a schematic diagram of a simple parallel-plate gas counter. A schematic diagram of the number of electrons collected as a function of voltage across a parallel-plate gas counter is shown in figure 3.7. At low electric fields there is a large amount of recombination and trapping of the electrons and ions in the gas and the number of electrons collected is less than the number N formed by the passage of the charged particle through the gas. As the applied voltage increases, the collection efficiency approaches 100%. The voltage region where the number of collected electrons is approximately independent of the applied voltage is called the ionisation region. In this region the number of collected electrons, and thus the output signal, is proportional to the energy deposited in the gas. To generate signals of an appreciable size from a small gas volume it is often useful to operate gas counters in the proportional region. In this region the electric fields are high enough for secondary ionisation to be produced in collisions between accelerated electrons and molecules in the gas. In a simple parallel-plate gas counter, the amount of secondary ionisation is dependent on the position of the path of the charged particle passing through the gas volume. One method of overcoming this problem is to use electrodes transparent to the incident particles and to allow the particles to pass from one electrode to the other.

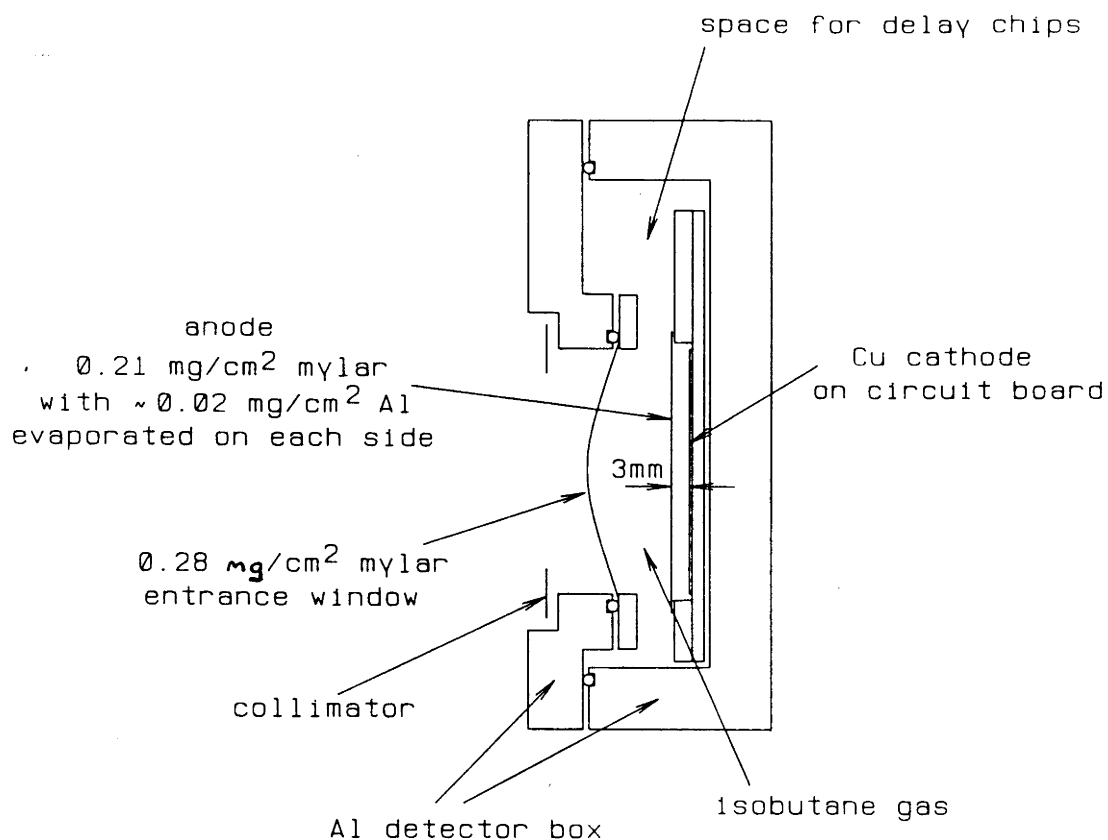


Figure 3.8 A sectional view of one of the gas counters used in the present study to detect and identify fission fragments.

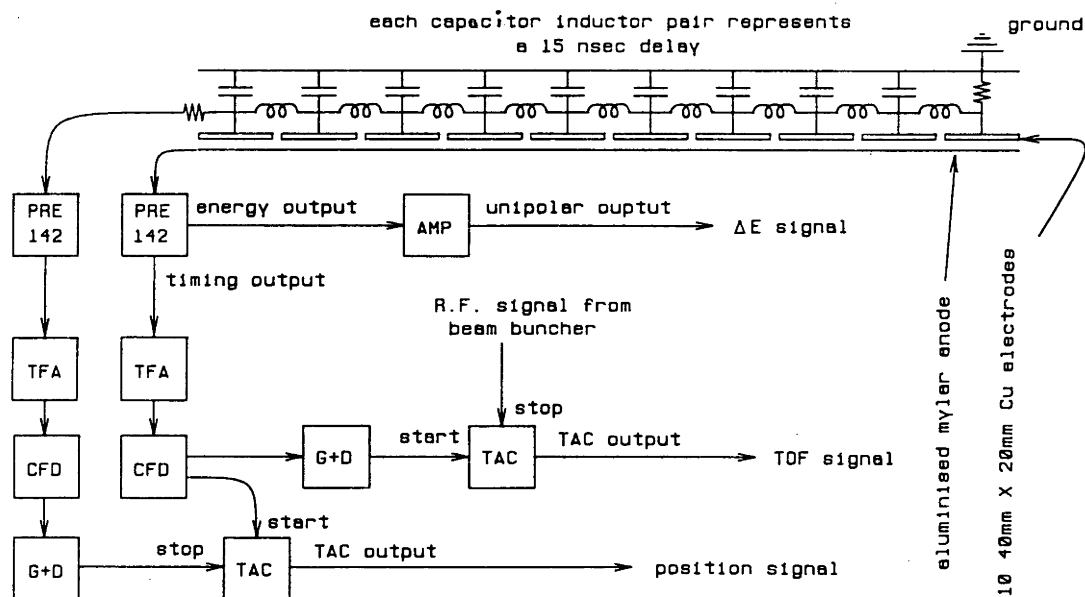


Figure 3.9 Schematic representation of a fission fragment detector and the electronics used to obtain the energy loss (ΔE), time of flight (TOF) and position signals. The electronic units are identified in table 3.4.

At higher field strengths the amplification due to secondary ionisation becomes so large that the gas volume forms a plasma and a Geiger discharge occurs. In this region the output signal size is essentially independent of the energy loss of the particle incident on the detector.

3.2.2 The Fission Fragment Detectors

An array of three parallel-plate gas counters, each with an active area of $40\text{mm} \times 200\text{mm}$, was used for the detection of fission fragments. Figure 3.8 shows a sectional view of one of these detectors. In order that positional information can be obtained, the Cu cathode is not a single electrode, but consists of ten stripes, $40\text{mm} \times 20\text{mm}$, connected in series by 15nsec delays. Figure 3.9 shows a schematic diagram of a fission fragment detector and the electronics used to obtain the energy loss (ΔE), time of flight (TOF) and position signals. Tests on the response of the detectors to fission fragments from a ^{252}Cf source lead to the choice of an operating anode voltage of +475 Volts, with the detectors filled with isobutane gas at 5 torr. The dependence of the size of timing signals, from the pre-amplifier attached to the anode, on the potential of the anode is shown in figure 3.10 and demonstrates the large amplification in signal size that can be obtained if the detectors are operated in the proportional region.

To avoid very large elastic scattering counting rates, it was decided to detect fission fragments only in the backwards hemisphere. To obtain a large spread in the observed fission fragment directions with respect to both the beam and the CsI detector, the three fission fragment detectors were arranged to detect fragments in three nearly perpendicular planes. Figure 3.11 shows the setup of the fission fragment detectors. Detectors no.1 (stripes 1-10), no.2 (stripes 11-20) and no.3 (stripes 21-30) detected particles emitted in the plane normal to the beam (YZ plane), in the

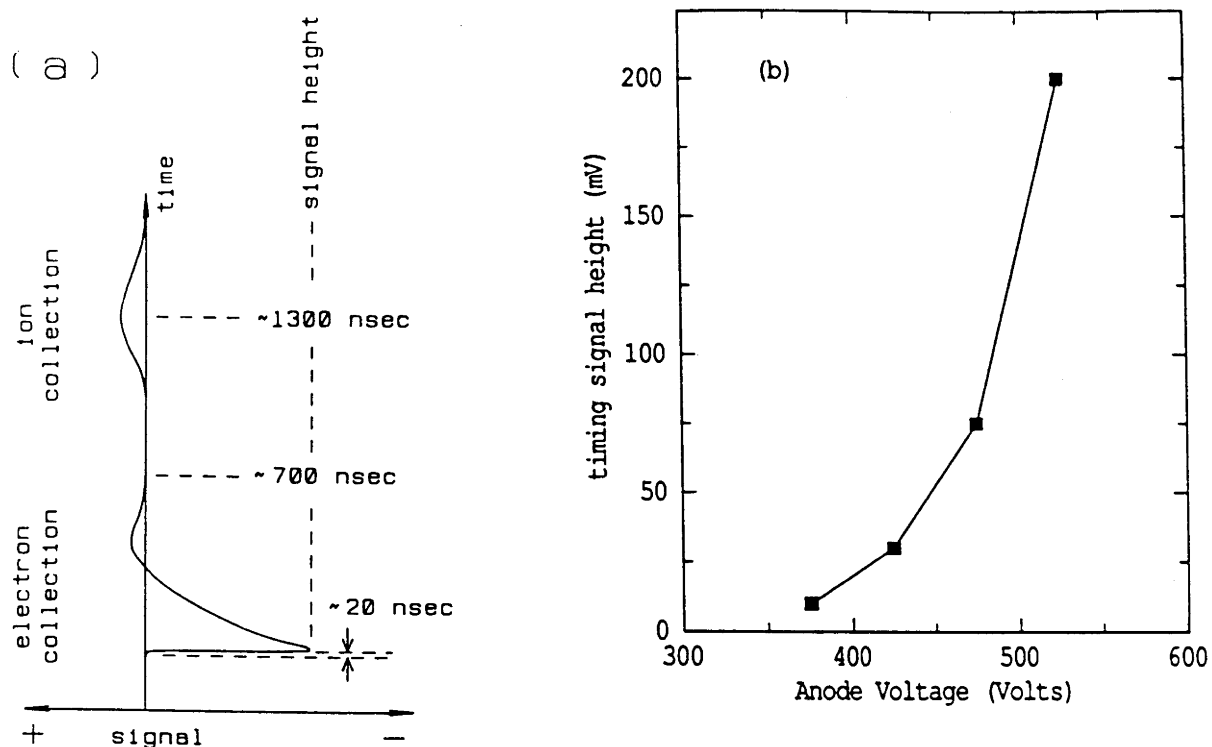


Figure 3.10 (a) The shape of the timing signals from the pre-amplifier attached to the anode (see figure 3.9), produced by fission fragments from a ^{252}Cf source. (b) The height of these signals as a function of anode voltage. The detector gas was isobutane at ~ 5 torr.

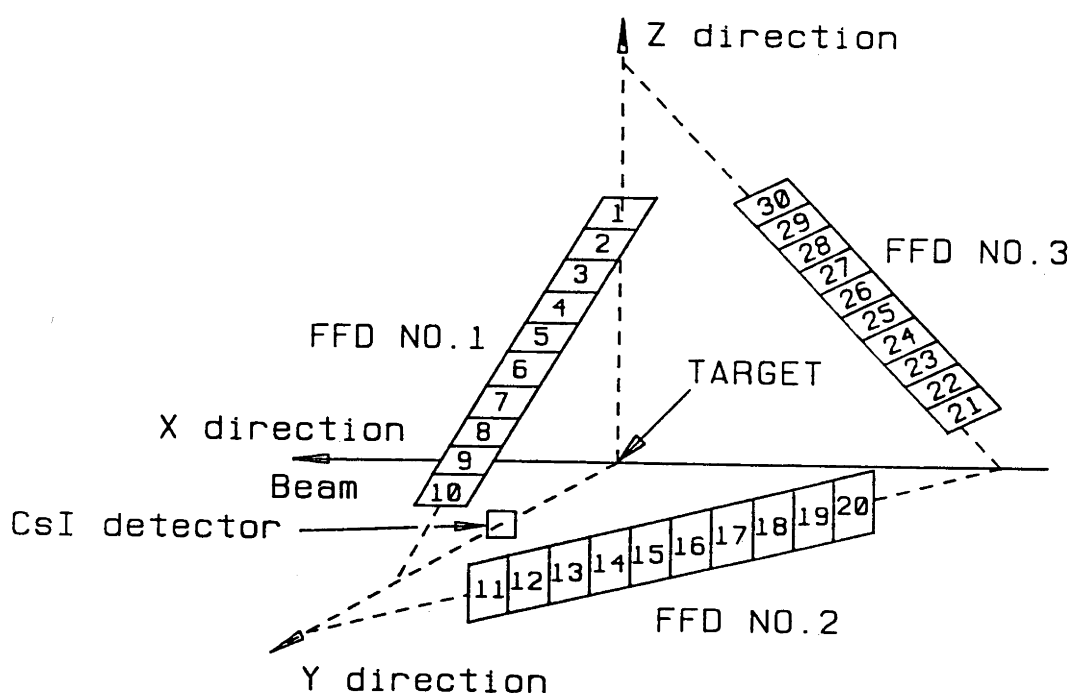
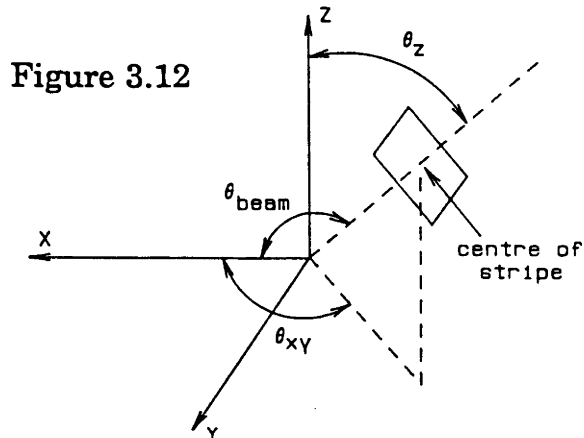


Figure 3.11 Schematic diagram showing the positions of the three fission fragment detectors. The numbers from 1 to 30 represent the individual detecting stripes. Also shown is the position of the CsI detector used in all but two of the measurements (see section 3.3).

Table 3.1 The angular positions (θ_{beam} , θ_{xy} and θ_z) and distance from the target (d) to the centres of each of the 30 detecting stripes, geometrically determined relative solid angles (Ω_{rel}) and the uncertainty in the direction of the pre-scission compound nucleus spin ($\phi_{\text{spin}}^{\text{stripe}}$), produced by the finite size of each of the stripes. Figure 3.12 defines θ_{beam} , θ_{xy} and θ_z .

Stripe	$\theta_{\text{beam}}(^{\circ})$	$\theta_{xy}(^{\circ})$	$\theta_z(^{\circ})$	$d(\text{mm})$	Ω_{rel}	$\phi_{\text{spin}}^{\text{stripe}}(^{\circ})$
1	90	90	0	170	11.9	2.4
2	90	90	5	156	15.4	2.8
3	90	90	11	145	19.2	3.3
4	90	90	18	135	24.0	3.8
5	90	90	26	127	28.6	4.3
6	90	90	34	122	32.2	4.6
7	90	90	45	121	33.7	4.7
8	90	90	54	122	32.4	4.6
9	90	90	63	127	28.8	4.3
10	90	90	71	135	17.8	3.8
11	111	111	90	190	7.1	5.9
12	117	117	90	184	12.8	6.4
13	123	123	90	180	13.8	7.0
14	129	129	90	176	14.7	7.7
15	136	136	90	174	15.0	8.6
16	143	143	90	176	14.6	9.7
17	149	149	90	180	13.7	11.0
18	155	155	90	185	12.5	12.9
19	161	161	90	192	11.1	15.4
20	166	166	90	200	9.7	19.2
21	167	-172	77	224	6.5	13.4
22	163	-171	73	214	8.5	12.2
23	157	-170	68	206	9.6	10.8
24	152	-170	63	200	10.6	9.7
25	146	-169	57	194	11.4	8.7
26	140	-168	51	192	11.9	7.8
27	134	-166	45	190	12.1	7.1
28	128	-165	40	192	11.8	6.5
29	122	-163	34	196	11.3	6.0
30	117	-160	28	200	4.9	5.6



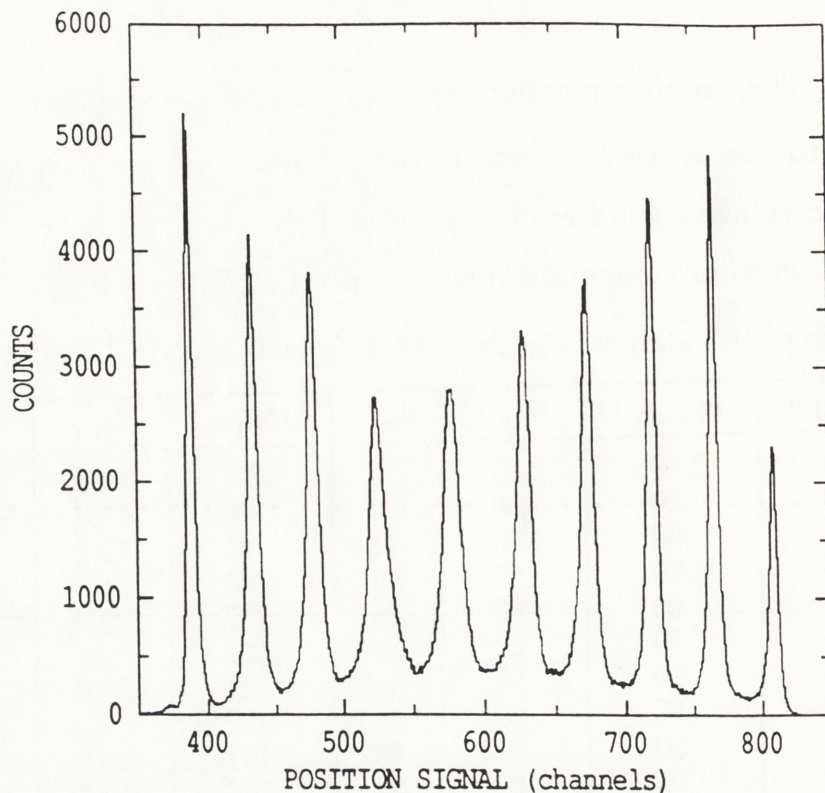


Figure 3.13 Position spectrum for fission fragment detector number 3, for $162.5 \text{ MeV } ^{28}\text{Si} + ^{164}\text{Er}$.

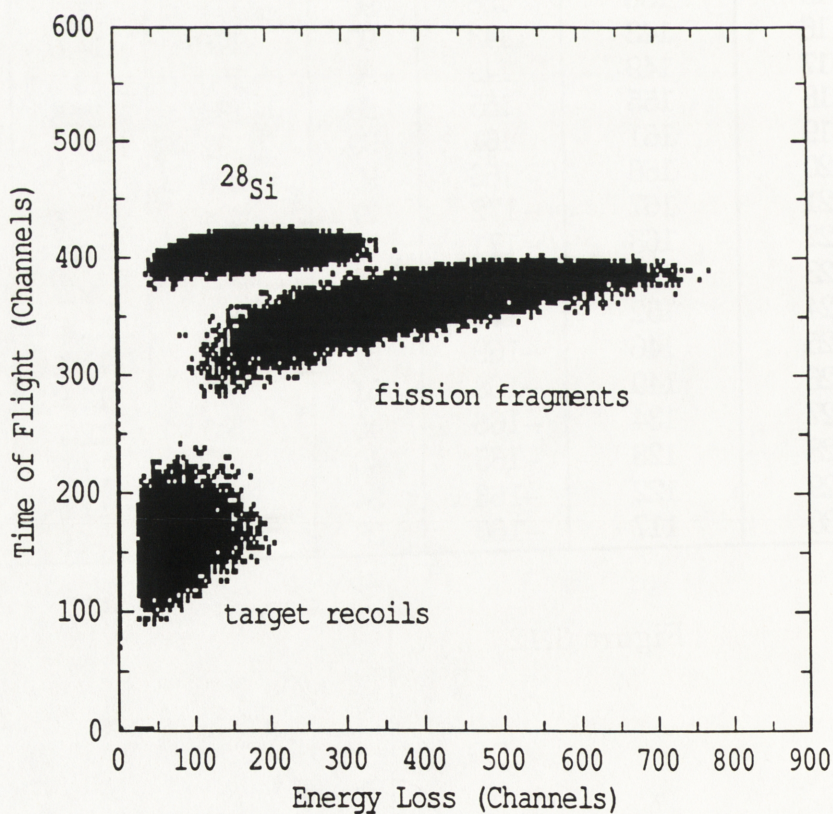


Figure 3.14 Energy loss versus time of flight for the whole of detector number 1, for $162.5 \text{ MeV } ^{28}\text{Si} + ^{164}\text{Er}$. The time of flight increases down the page by $\sim 0.2 \text{ ns/channel}$.

horizontal plane (XY plane) and close to the vertical XZ plane respectively. Table 3.1 gives the angular positions and distances from the target to the centres of each of the 30 detecting stripes, along with geometrically determined relative solid angles and the uncertainty in the direction of the spin of the pre-scission compound system produced by the finite size of each of the stripes.

Figure 3.13 shows a typical position spectrum; each of the peaks corresponds to a single detecting stripe. A plot of energy loss versus time of flight for the whole of detector no.1, for 162.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ is shown in figure 3.14. The target recoils seen in this detector are due to multiple scattering in the thick targets used ($\sim 1\text{mg}/\text{cm}^2$). No recoils are seen at angles larger than 90° and the elastic scattering decreases rapidly with increasing angle to the beam. The detecting stripes are thus increasingly dominated by fission fragments with increasing angle.

3.3 The Coincidence Experiments

Beams of ^{28}Si ions of various energies ranging from 140 MeV to 185 MeV were focussed onto various Er targets. The targets were orientated at 45° to both the beam and z directions, with the normal to the targets pointing approximately to the middle of the triangle formed by the three gas counters (see figure 3.11). The ^{28}Si beams were collimated by two pieces of $\sim 0.13\text{mm}$ thick Ta, with $\sim 1.5\text{mm}$ diameter holes, $\sim 500\text{mm}$ and $\sim 1000\text{mm}$ upstream from the target. The target beam spots were approximately 2mm in diameter. To enable the measurement of the time of flight of particles from the target to the gas counters, the beams were pulsed. The time between pulses was 106 nsec with the full width at half maximum of each pulse being approximately 1 nsec. Table 3.2 shows the various beam and target combinations used. The principal properties of the three targets used are shown in table 3.3. All targets were prepared by rolling and their thicknesses determined by weighing.

Table 3.2 The various beam and target combinations used in the measurement of protons and alphas in coincidence with fission. The targets are labelled by their dominant Er isotope. See table 3.3 for the isotopic analysis of the targets.

	Target label		
E _{beam} (MeV)	¹⁶⁴ Er	¹⁶⁷ Er	¹⁷⁰ Er
140.0	✓	—	—
147.5	✓	—	—
155.0	✓	✓	✓
162.5	✓	✓	✓
170.0	✓	✓	—
177.5	✓	✓	✓
185.0	✓	—	✓

Table 3.3 The principal properties of the targets. The atomic percentage of the dominant Er isotope in each of the targets is underlined.

		Atomic percentage				
Target label	thickness mg/cm ²	¹⁶⁴ Er	¹⁶⁶ Er	¹⁶⁷ Er	¹⁶⁸ Er	¹⁷⁰ Er
¹⁶⁴ Er	0.8	<u>73.60</u>	14.97	5.50	4.42	1.51
¹⁶⁷ Er	0.8	0.06	2.93	<u>91.54</u>	5.14	0.33
¹⁷⁰ Er	0.6	0.04	0.87	0.72	1.46	<u>96.89</u>

For all beam energies ≥ 147.5 MeV the measurements were performed with the CsI detector at 90° to the beam, as shown in figure 3.11. At 140 MeV the elastic scattering counting rate at 90° to the beam was considered too high for the CsI detector, and it was moved to 150° where it shadowed stripes 15 to 19 from the target. To check for any dependence of the results extracted from the shapes of the measured particle spectra on the position of the CsI detector, the 162.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement was remeasured using this configuration. For all measurements the CsI detector was 87.5mm from the centre of the target, resulting in a solid angle of $4.52 \times 10^{-3} \times 4\pi$ sr. Uncertainties in the exact size of the collimator, the position of the detector and the position of the beam spot lead to an uncertainty in this solid angle of approximately 2.5%. A photograph of the experimental setup showing the three gas counters and the light charged particle (CsI) detector at 90° to the beam direction is shown in figure 3.15.

All events where the CsI detector and any one of the gas counters fired within ~ 1 μsec of each other were collected event by event on magnetic tape. These coincidence events each consisted of six signals: the particle energy (PE) and pulse shape identification (PSI) signals from the CsI detector; the time difference between the firing of the CsI detector and the appropriate gas counter (COINC) and the energy loss (ΔE), time of flight (TOF) and position (POS) signals from that gas counter. The PE and PSI signals are used to identify protons and alpha particles; the ΔE and TOF signals to identify fission fragments; the POS signal to identify the detecting stripe and the COINC signal to identify the event as a true particle-fission coincidence or a random event produced by a particle and a fission fragment from independent reactions. To enable the determination of the absolute intensity of the proton and alpha particle spectra measured in coincidence with each of the fission fragment

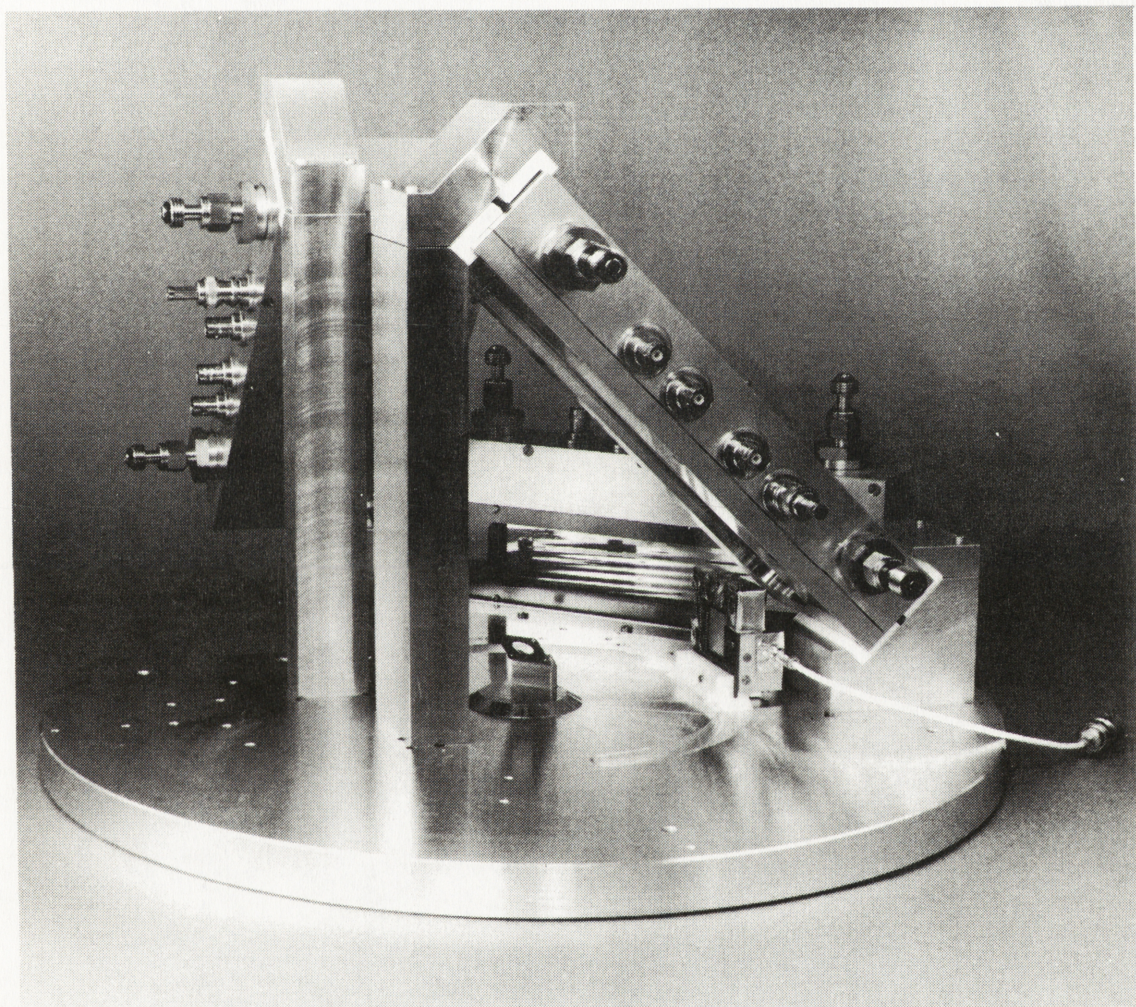


Figure 3.15 Photograph of the experimental setup showing the 3 gas counters and the light charged particle detector at 90° to the beam direction.

directions, a fixed fraction of the singles events from each of the gas counters was collected event by event along with the coincidence events. Singles scaling factors of 1/100 and 1/1000 were used. A schematic representation of the electronics used is shown in figure 3.16.

Beam currents ranged from $\sim 10\text{nA}$ to $\sim 50\text{nA}$ and were typically adjusted to obtain a fission fragment detection rate in the gas counters of between 4000 and 8000 counts/sec. The time spent on each measurement with the beam on target varied from several hours to just over one day, and depended on the desired number of coincidence events, the data collection rate and the availability of beam time.

3.4 Method of Analysis

This section describes the analysis of the data collected in the experiments discussed in section 3.3. The analysis consists of two stages. Section 3.4.1 discusses the first stage where the proton and alpha particle spectra, in coincidence with fission, are extracted from the events stored on magnetic tape. Section 3.4.2 describes the model used to extract the intensity, energy spectra, and angular distribution of the various sources of proton and alpha particle emission from the measured particle spectra.

3.4.1 Determination of the Particle Spectra

Once the protons and alpha particles were identified using the PE and PSI signals from the CsI detector, and the fission fragments were identified using the ΔE and TOF signals from the gas counters, spectra of the time difference between the arrival of the proton and alpha particle signals and the arrival of the fission fragment signals were obtained using the COINC signal (see figure 3.16). Figure 3.17 shows the time difference between the arrival of (a) proton signals and (b) alpha particle signals and the arrival of fission fragment signals for the 162.5 MeV ^{28}Si + ^{164}Er measurement with the CsI detector at 90° to the beam. The peaks in

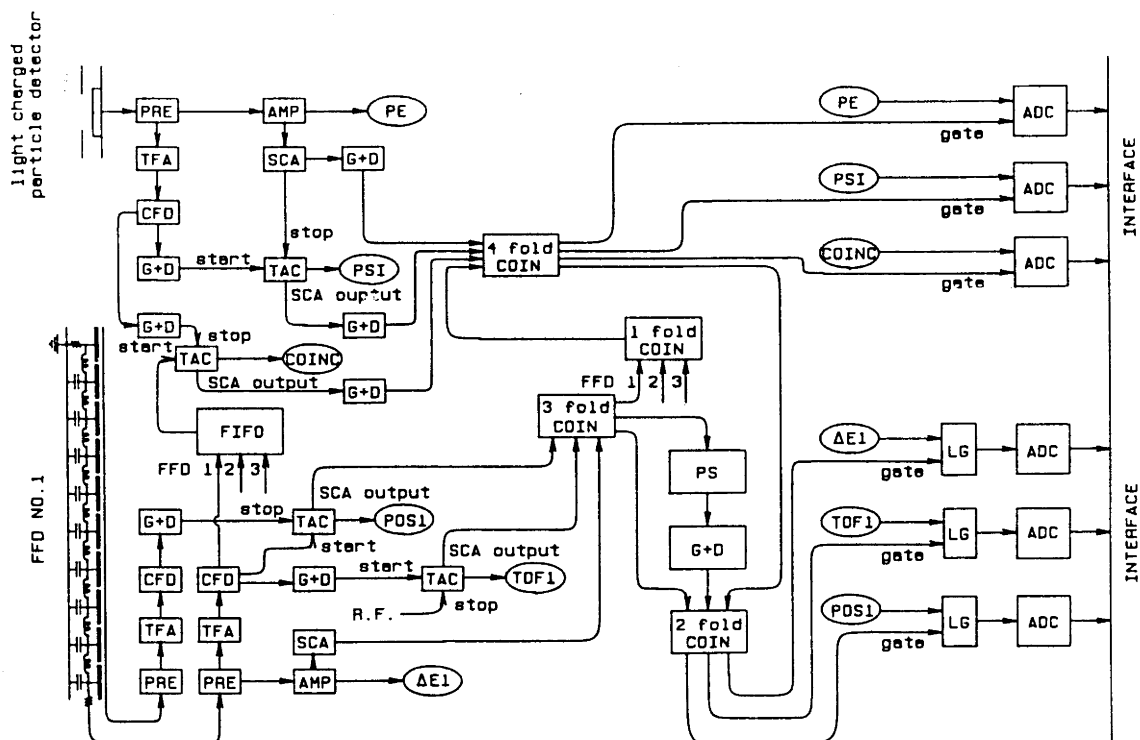


Figure 3.16 Schematic representation of the electronics used for the collection of the coincidence events and a fixed fraction of the singles events from each of the gas counters. The electronic units are identified in table 3.4.

Table 3.4 Electronic units utilised in the electronics schemes shown in figures 3.2, 3.9 and 3.16.

AMP	Tennelec 203 BLR Linear Amplifier
SCA	Canberra 1437 or 2037 Timing Single Channel Analyser
TAC	Canberra 1443 or Ortec 467 or 437 Time Analyser
PRE	Ortec 125 or 142B Pre-amplifier
TFA	Ortec 454 or 474 Timing Filter Amplifier or LeCroy 612A 12 Channel Amplifier
CFD	Ortec 473 or 473A or LeCroy 934 Constant Fraction Discriminator
G+D	Ortec 416A Gate and Delay Generator or two LeCroy 821 Quad Discriminators or Canberra 1455A Logic Shaper and Delay
FIFO	LeCroy 429A Logic Fan-In/Fan-Out
COIN	Canberra 1446 Coincidence Unit
PS	ANU Pre Scaler
LG	Canberra 1454 Linear Gate and Stretcher
ADC	Silena 7423/UHS or 7420/G or Canberra 8077 Analogue to Digital Converter

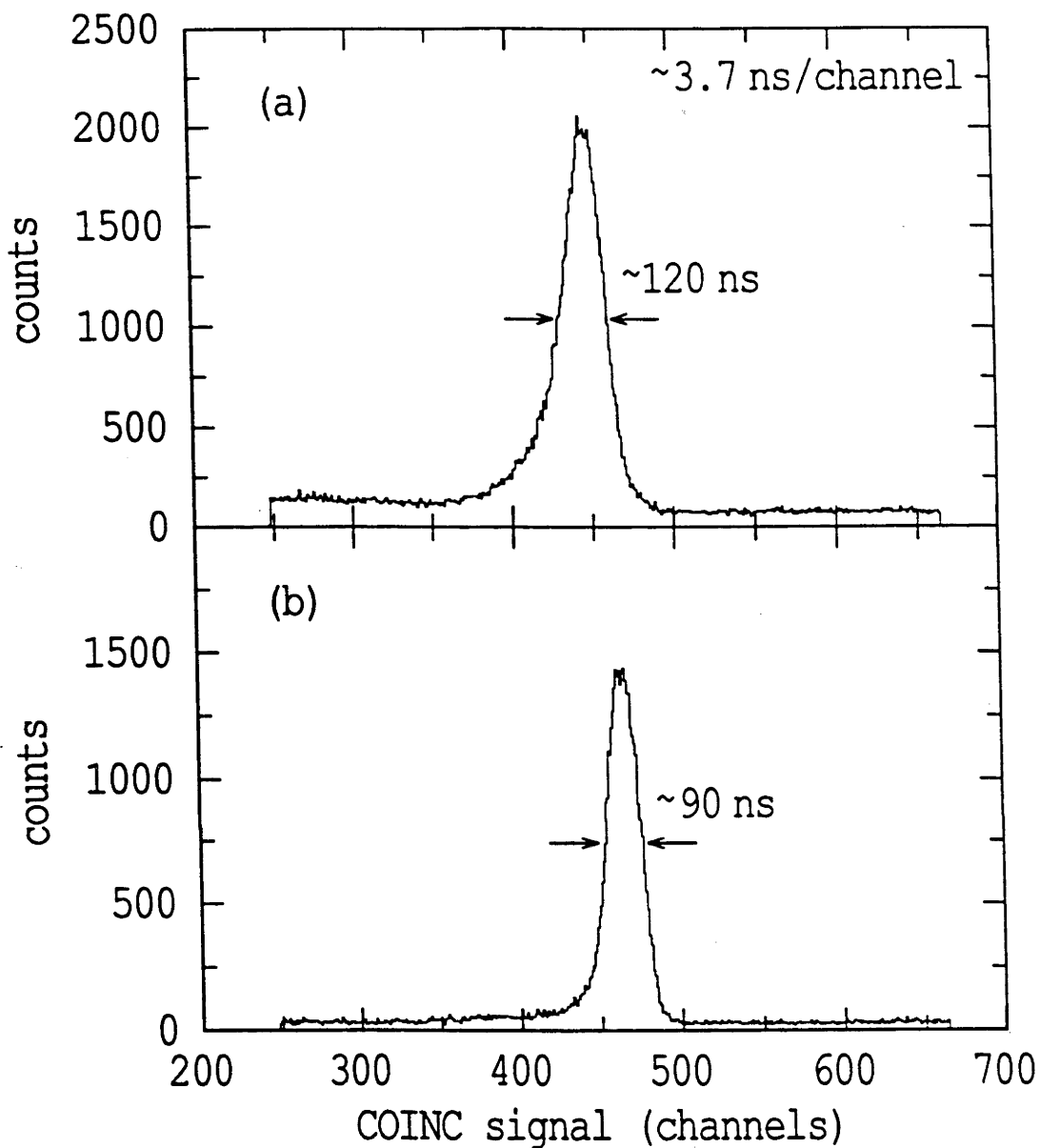


Figure 3.17 The time difference between the arrival of (a) proton signals; and (b) alpha particle signals and the arrival of fission fragment signals for the 162.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement with the CsI detector at 90° to the beam. The faster response of the CsI to alpha particles gives a sharper coincidence peak.

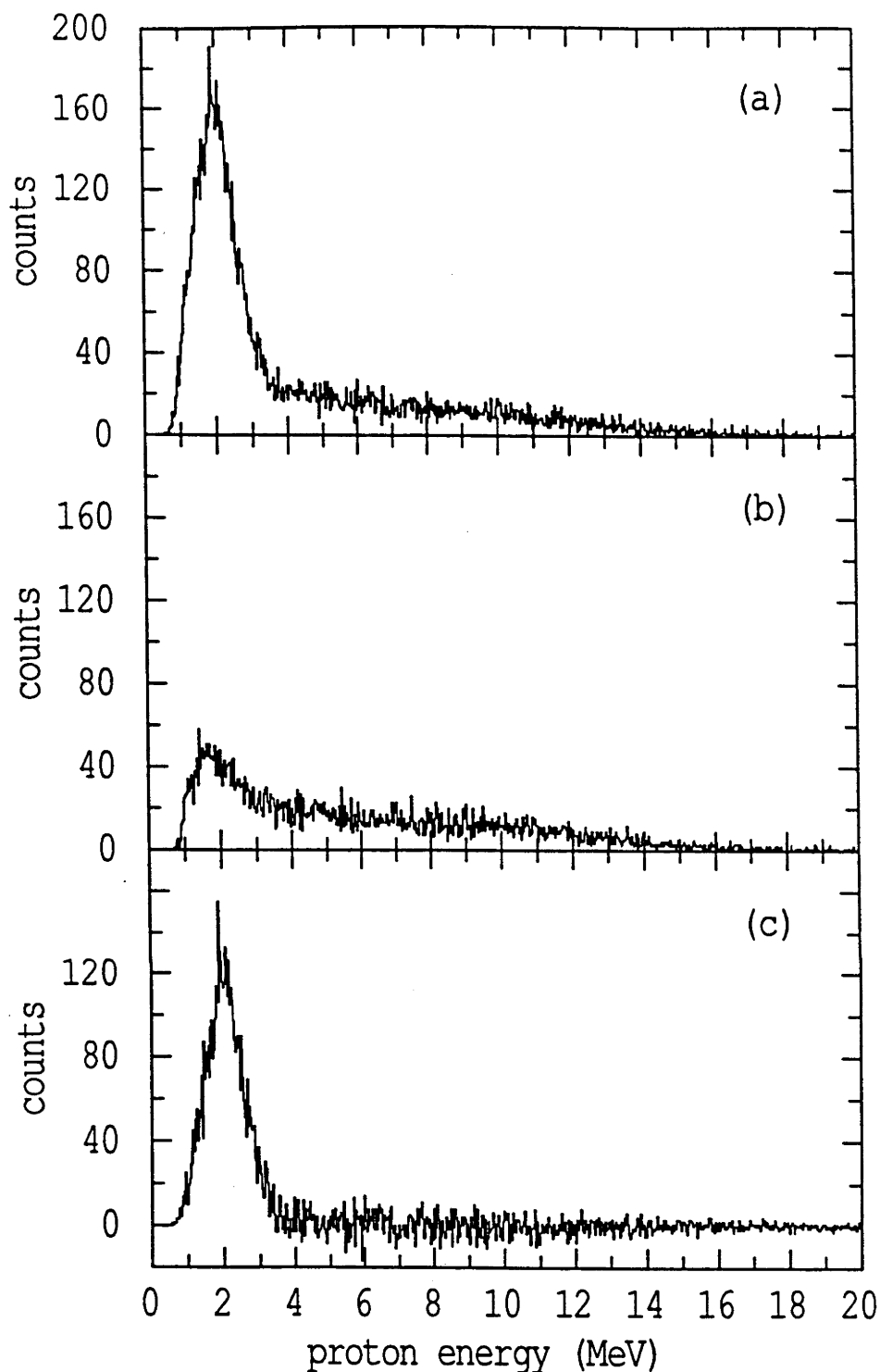


Figure 3.18 The energy spectrum of the events inside the proton gate, associated with COINC signals in the region (a) to the left of the peak from channels 260 – 350; and (b) to the right of the peak from channels 510 – 600, for the 162.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement with the CsI detector at 90° to the beam; (c) shows the difference between the spectra shown in (a) and (b).

these spectra are due to real particle-fission coincidences and most of the background is due to random coincidences between particles and fission fragments from independent reactions. The widths of the peaks are essentially due to the response of the CsI detector and its associated electronics, and do not reflect the distribution of relative particle - fission fragment flight times. A closer inspection of the COINC spectra reveals a significant asymmetry in the background on either side of the particle-fission coincidence peaks. The higher background to the left of the peaks (see figure 3.17) is due to true gamma ray - fission coincidences, caused by the failure of the PE and PSI signals to distinguish between gamma-rays and low energy particles and the very poor timing response of the CsI detector to gamma-rays. Figure 3.18 shows the energy spectrum of the events inside the PE versus PSI proton gate, associated with COINC signals in the region (a) to the left of the peak from channels 260 – 350, and (b) to the right of the peak from channels 510 – 600, for the 162.5 MeV ^{28}Si + ^{164}Er measurement with the CsI detector at 90° to the beam; (c) shows the difference between the spectra shown in (a) and (b). This figure clearly shows gamma-ray contamination in the proton gate at energies less than 4 MeV. Similar gamma-ray contamination is also found in the alpha particle gates, below the pulse height corresponding to 7.5 MeV alphas.

Particle spectra in coincidence with fission fragments in each of the available detecting stripes were obtained with COINC signals in (a) the region of the particle-fission coincidence peak; (b) a region ~ 100 channels wide to the left of the peak; and (c) a region of the same width (~ 100 channels) to the right of the peak. The spectra associated with the COINC background regions to the left and the right of the particle-fission coincidence peak were added together. These combined background spectra were then scaled by the ratio of the number of channels in the peak region to the number of channels in the combined left and right background regions. The scaled background spectra were then subtracted

from the particle spectra associated with the coincidence peak to give the background-corrected particle spectra. This procedure corrects for the uniform background produced by random coincidences. It is unclear what effect it has on the gamma-ray contamination seen in the proton and alpha particle spectra below 4 MeV and 7.5 MeV respectively. Thus in subsequent analysis threshold energies were applied.

Each of the measurements with a beam energy ≥ 155.0 MeV and with the CsI detector at 90° to the beam lead to the determination of 60 background-corrected particle spectra; that is, a proton spectrum and an alpha particle spectrum in coincidence with fission fragments in each of the 30 detecting stripes. For the measurements at 140 MeV and 147.5 MeV, the large elastic scattering counting rate and the low multiplicities made the identification of the alpha particles difficult and only proton spectra were extracted from the data. At 140 MeV the large elastic scattering counting rate made the identification of the fission fragments in stripes 1-10 impossible, restricting the measurement to the backward stripes.

The number of fission fragments incident on each of the stripes, needed for the determination of the absolute intensities of the particle spectra, were obtained by dividing the number of collected singles fission fragments by the appropriate singles scaling factor and then adding the number of fission fragments collected in coincidence with signals from the CsI detector.

3.4.2 Extraction of Particle Source Properties

The computer program CPE (Charged Particle Emission) was written to enable the extraction of the multiplicities, energy spectra and angular distributions of the various sources of proton and alpha particle emission, from the measured particle spectra in coincidence with fission. This program can be used to model the emission from an equilibrated compound system, the emission from the fully accelerated fission

fragments and, if necessary, near-scission emission, using a range of parameters.

The velocity of the compound systems responsible for the emission of pre-scission and near-scission particle emission is assumed to be in the beam direction and to have a magnitude of

$$V_{cn} = 0.98 \times \left(\frac{2 E_{lab}}{A_b} \right)^{1/2} \frac{A_b}{A_b + A_t} \quad \text{cm/nsec} \quad (3.2)$$

where E_{lab} is the beam energy in MeV and A_b and A_t are the mass numbers of the beam and target nuclei respectively.

The determination of the laboratory velocities of the fission fragments responsible for the post-scission particle emission is more complicated because it must be calculated separately for each of the available detecting stripes: both the observed and complementary fragments are sources of post-scission particle emission, and the fragments have a distribution of velocities. In the present analysis, all the post-scission particle emission is assumed to occur from fragments with a single centre of mass velocity. This velocity is defined by the parameter Z_0 , which can be thought of as the mean atomic number of the fission fragments responsible for the post-scission particle emission. The final kinetic energy of these fragments in the centre of mass reference frame is assumed to be [VIO85]

$$KE = 0.755 \frac{Z_0 (Z_{cn} - Z_0)}{\left(\frac{Z_0}{Z_{cn}} A_{cn} \right)^{1/3} + \left(\frac{Z_{cn} - Z_0}{Z_{cn}} A_{cn} \right)^{1/3}} + 7.3 \text{ MeV} \quad (3.3)$$

where Z_{cn} and A_{cn} are the atomic and mass numbers of the compound nucleus. If Z/A is assumed to be constant for all fragments then the centre of mass velocity of the fragments responsible for the post-scission particle emission is given by

$$V_{ff}^{cm}(Z_0) = 0.98 \times \left(\frac{Z_{cn} - Z_0}{Z_0 A_{cn}} 2 KE \right)^{1/2} \text{ cm/nsec} \quad (3.4)$$

The laboratory velocities of the observed (complementary) fragments responsible for the post-scission emission are defined by the requirement that the fragments of atomic number Z_0 ($Z_{cn} - Z_0$) are observed in the available fission fragment detecting stripes.

The angular distribution of pre-scission particle emission in the centre of mass reference frame is assumed to be (see equation 2.80)

$$W(\phi) \propto \exp(\ln(ANI) \sin^2(\phi)) \quad (3.5)$$

where ϕ is the angle to the spin direction of the compound system and $ANI(\text{anisotropy}) = W(90^\circ)/W(0^\circ)$. The direction of the spin of the pre-scission compound system is assumed to be uniformly distributed in the plane perpendicular to the beam direction, ϕ_{spin} degrees either side of the direction perpendicular to the velocity of the observed fission fragment. The uncertainty in the spin direction ϕ_{spin} is taken to be

$$\phi_{\text{spin}} = \{ [\phi_{\text{spin}}^{\text{stripe}}]^2 + [\phi_{\text{spin}}^{\text{ang}}]^2 \}^{1/2} \quad (3.6)$$

where $\phi_{\text{spin}}^{\text{stripe}}$ and $\phi_{\text{spin}}^{\text{ang}}$ are the uncertainties in the spin direction of the pre-scission compound system produced by the finite size of the fission fragment detecting stripes (see table 3.1) and the angular distribution of the fission fragments relative to a given spin direction. For simplicity the angular distribution of the fission fragments relative to a given spin direction is assumed to be of the form given in equation 2.68. The uncertainty in the spin direction due to this fission fragment angular distribution is given by equation 2.69

$$\phi_{\text{spin}}^{\text{ang}} = \sin^{-1} \left(\frac{\sin \phi_{\text{ff}}}{\sin \theta_{\text{cm}}} \right) \quad (3.7)$$

where ϕ_{ff} is the half width at half maximum of the angular distribution of the fission fragments about the plane perpendicular to the spin direction of the pre-scission system, and θ_{cm} is the angle of the observed fission fragment to the beam in the centre of mass reference frame.

The energy spectrum $\rho_{cn}(E)$ of the pre-scission particle emission in the centre of mass reference frame is taken to be defined by three parameters D_{cn} , T_{cn} and B_{cn} and of the form

$$\begin{aligned} \rho_{cn}(E) &= 0.0 & E \leq B' \\ &\propto C (E - B')^{D_{cn}} \exp(-E/T_{cn}) & B' < E \leq T_{cn} + B_{cn} \\ &\propto (E - B_{cn}) \exp(-E/T_{cn}) & T_{cn} + B_{cn} < E \end{aligned} \quad (3.8)$$

where $B' = (1.0 - D_{cn}) T_{cn} + B_{cn}$ and $C = T_{cn} / (D_{cn} T_{cn})^{D_{cn}}$. This gives a smooth particle spectrum with a maximum at $T_{cn} + B_{cn}$. The parameter T_{cn} controls the exponential tail above $T_{cn} + B_{cn}$, while D_{cn} controls the shape of the low energy end of the spectrum below $T_{cn} + B_{cn}$. The three parameters D_{cn} , T_{cn} , and B_{cn} can be thought of as measures of the diffuseness and curvature of the particle emission barrier, the nuclear temperature of the emitting system and the mean height of the particle emission barrier respectively. These definitions are only to help give a better feel for the parameters D_{cn} , T_{cn} , and B_{cn} and should not be taken too literally. The post-scission particle emission is assumed to be isotropic relative to the emitting fission fragments and to have an energy spectrum of the same form as that given to the pre-scission particle emission. The three parameters specifying the spectral shape of the particle emission from the fission fragments will be referred to as D_{ff} , T_{ff} , and B_{ff} .

It is well known that near-scission particle emission in coincidence with spontaneous fission has a nearly Gaussian energy distribution and a noticeable dependence of the angular distribution on the energy of the emitted particles [SIN89]. For simplicity, in the present analysis the energy spectrum and angular distribution of the near-scission particles

are assumed to be independent of each other. The energy spectrum of the near-scission emission relative to the emitting composite system is taken as

$$\rho_{\text{nse}}(E) \propto \exp \left\{ \frac{-(\bar{E}_{\text{nse}} - E)^2}{2(\sigma_{\text{nse}}^{\text{energy}})^2} \right\} \quad (3.9)$$

and the angular distribution as

$$W_{\text{nse}}(\phi_{\text{scis}}) \propto \exp \left\{ \frac{-(90^\circ - \phi_{\text{scis}})^2}{2(\sigma_{\text{nse}}^{\text{ang}})^2} \right\} \quad (3.10)$$

where $\bar{E}_{\text{nse}}$, $\sigma_{\text{nse}}^{\text{energy}}$, $\sigma_{\text{nse}}^{\text{ang}}$ are the mean energy, the standard deviation of the energy spectrum and the standard deviation of the angular distribution of the near-scission particles respectively, and ϕ_{scis} is the angle between the near-scission particle and the scission axis, in the centre of mass reference frame. The scission axis is assumed to be defined by the target, the position of the appropriate fission fragment detecting stripe and the velocity of the fissioning system.

For a given set of the parameters D_{ff} , T_{ff} , B_{ff} , D_{cn} , T_{cn} , B_{cn} , ANI , Z_0 , ϕ_{ff} , $\bar{E}_{\text{nse}}$, $\sigma_{\text{nse}}^{\text{energy}}$ and $\sigma_{\text{nse}}^{\text{ang}}$, CPE calculates the expected contribution to the particle spectra observed in the CsI detector in coincidence with fission in each of the available detecting stripes, associated with (a) the post-scission emission of one particle per fragment; (b) the pre-scission emission of one particle per compound system; and (c) the near-scission emission of one particle per compound system. Estimates of the values of the 12 parameters D_{ff} , ..., $\sigma_{\text{nse}}^{\text{ang}}$ and the pre-scission (μ_{pre}), post-scission (μ_{post}), and near-scission (μ_{nse}) particle multiplicities, are made by minimising the χ^2 defined as

$$\chi^2 = \sum_{n=1}^{30} \sum_{\epsilon=0,1,2,\dots}^{\infty} \left\{ \frac{\text{OBS}_n(\epsilon) - \mu_{\text{pre}} \text{PRE}_n(\epsilon) - \mu_{\text{post}} \text{POST}_n(\epsilon) - \mu_{\text{nse}} \text{NSE}_n(\epsilon)}{\Delta \text{OBS}_n(\epsilon)} \right\}^2 \times \frac{1}{\text{number of degrees of freedom}} \quad (3.11)$$

where $\text{OBS}_n(\epsilon)$ is the number of observed particles of type μ (protons: π or alpha particles: α) in coincidence with fission fragments in stripe

number n , with a particle energy between $\epsilon(\Delta\epsilon)$ and $(\epsilon+1)(\Delta\epsilon)$, divided by the number of fission fragments incident on stripe number n ; and $\Delta\text{OBS}_n(\epsilon)$ is the experimental uncertainty in $\text{OBS}_n(\epsilon)$. The quantity $\Delta\epsilon$ is a compression factor and was typically set to 1 MeV. The $\text{PRE}_n(\epsilon)$, $\text{POST}_n(\epsilon)$, and $\text{NSE}_n(\epsilon)$ are the model predictions of the contributions to the particle spectra from the pre-scission emission of one particle per compound system, the post-scission emission of one particle per fission fragment and the emission of one near-scission particle per compound system respectively. The total particle multiplicity is given by

$$\mu_{\text{tot}} = \mu_{\text{pre}} + 2 \mu_{\text{post}} + \mu_{\text{nse}} \quad (3.12)$$

The code CPE can be used to minimise χ^2 with respect to any combination of the 12 parameters $D_{\text{ff}}, \dots, \sigma_{\text{nse}}^{\text{ang}}$. If there is no evidence of any significant contribution to the particle spectra from near-scission emission then the parameters controlling its energy spectra and angular distribution can be ignored and its multiplicity set to zero.

The program CPE also corrects for the recoil of compound nuclei and fission fragments caused by the emission of the particles which are observed by the CsI detector. The recoil corrections performed by CPE compensate for the following effects:

- (1) The observation of a particle from the compound system causes a deflection of the fissioning system away from the CsI detector and affects the angular distribution of the fission fragments observed in coincidence with such particles.
- (2) The emission of a post-scission particle from an observed fission fragment causes a deflection of the fission fragment on its way to the detecting stripes. The velocity of the fission fragment before the emission of the post-scission particle is defined by the position of the detecting stripe, the position of the CsI detector and the momentum of the emitted particle.

CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

The code CPE discussed in section 3.4.2 was used to extract the multiplicities, energy spectra and angular distributions of the various particle emission sources from the measured particle spectra. Because of the gamma-ray contamination in the proton spectra below 4.0 MeV and in the alpha particle spectra below 7.5 MeV (see section 3.4.1), these regions were not used in the determination of the χ^2 defined in equation 3.11. Statistical uncertainties in the values of the parameters $D_{ff} \dots \sigma_{nse}^{ang}$ and the particle multiplicities were estimated by dividing the events stored on magnetic tape from each measurement into three nearly equal groups. Each of these three sets of data was then analysed independently and the scatter of these results about those obtained by analysing the data as a whole was used to estimate the statistical uncertainties. An additional error of 1% was added to the parameters B_{ff} , B_{cn} and $\bar{E}_{nse}$ due to the uncertainty in the energy calibration of the CsI detector. An additional 2.5% uncertainty was added to the particle multiplicities due to the uncertainty in the absolute solid angle of the CsI detector.

Good fits to the data were obtained, with χ^2 's ranging from ~ 1.0 to ~ 1.35 for the proton data and from ~ 1.1 to ~ 1.45 for the alpha particle data. Figures 4.1 and 4.2 show the fits to the proton and alpha particle spectra from the 177.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement, obtained using the code CPE. This is the measurement with the highest number of observed particle - fission fragment coincidences and is thus the data most likely to show any discrepancies between the measured spectra and the model discussed in section 3.4.2. There are no significant discrepancies between

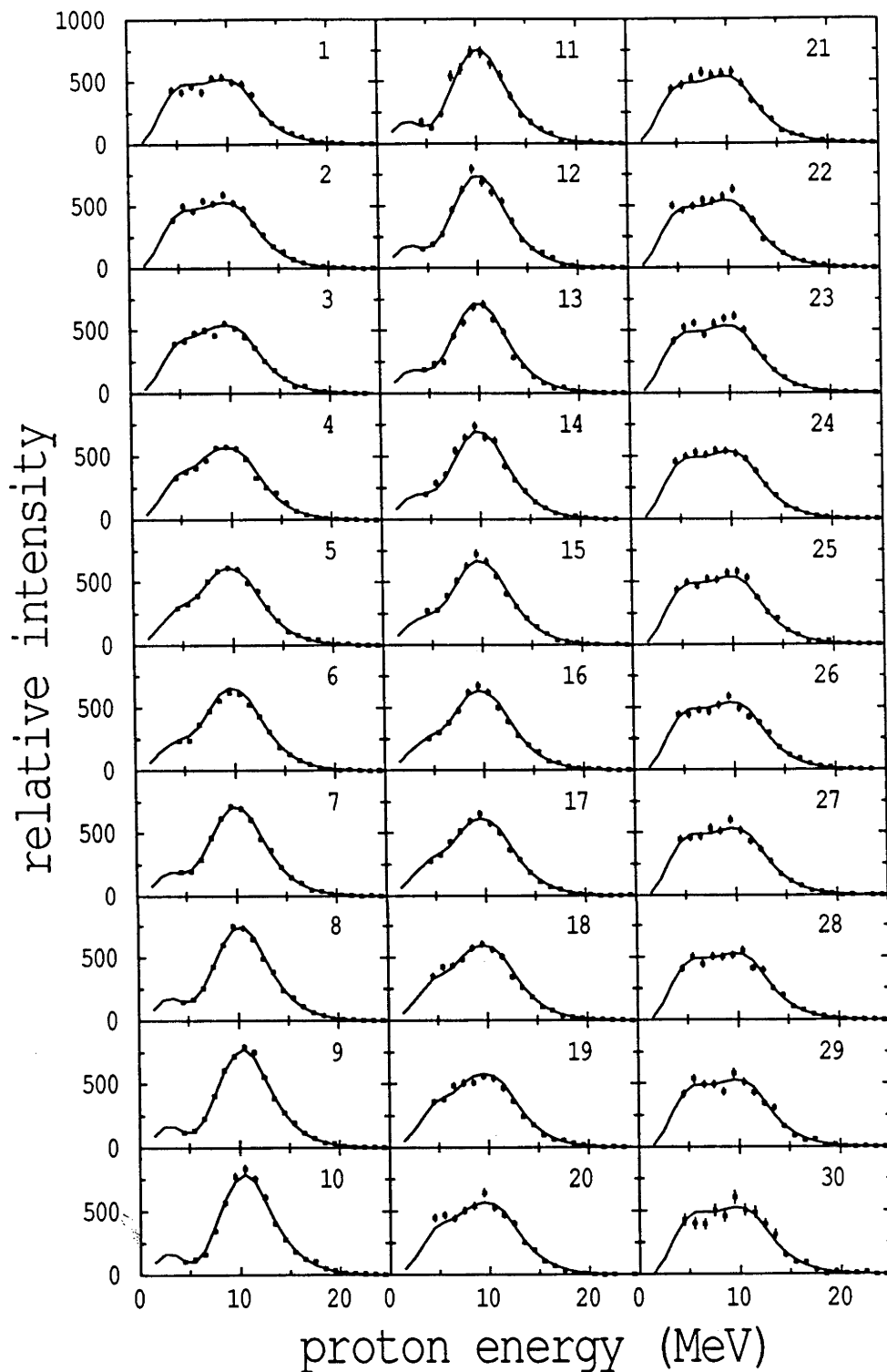


Figure 4.1 The fit to the proton spectra measured in coincidence with fission fragments from the 177.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement, obtained using the code CPE. The numbers from 1 to 30 identify the fission fragment detecting stripes (see figure 3.11).

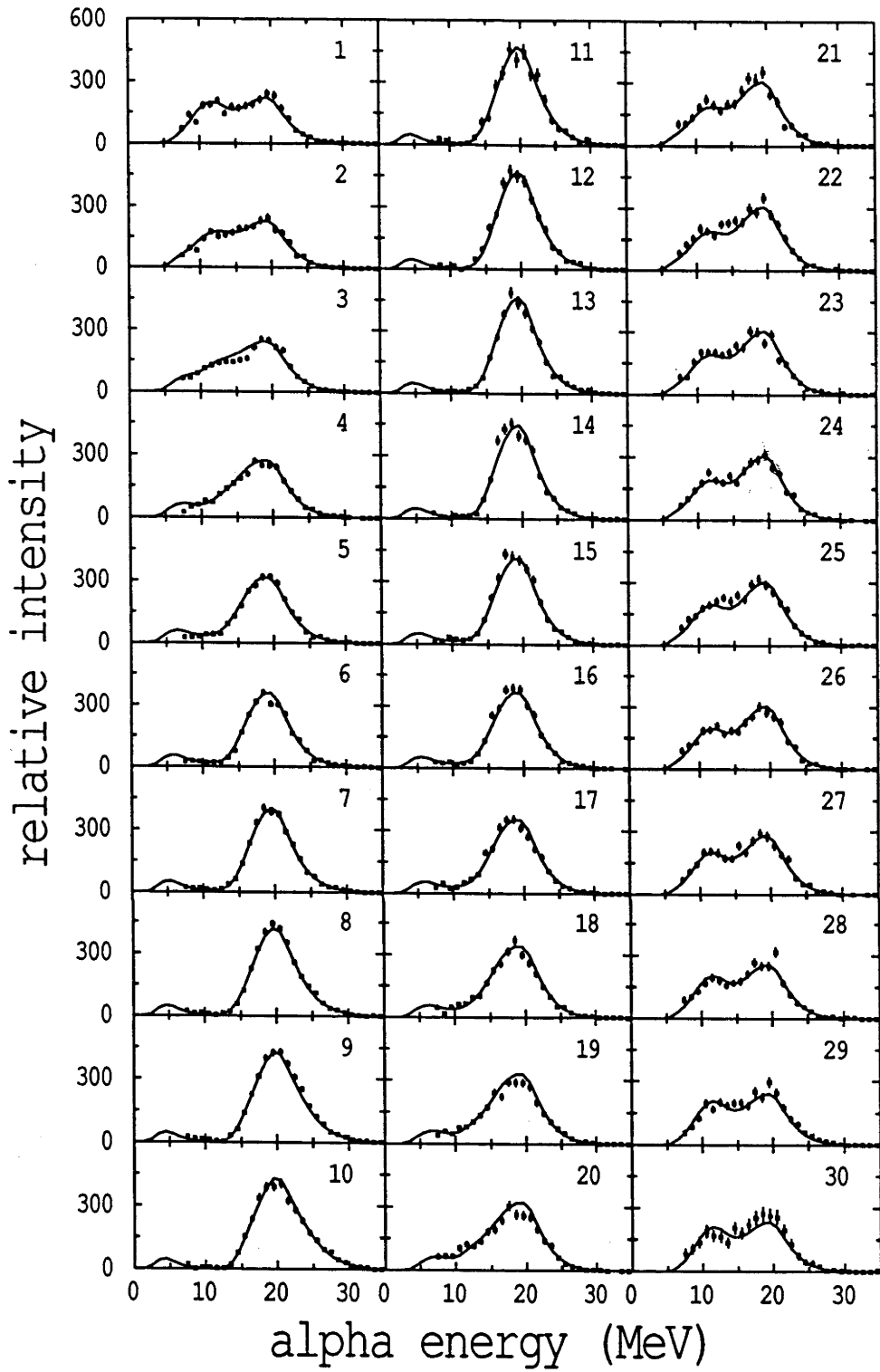


Figure 4.2 As for figure 4.1 but for the alpha particle spectra.

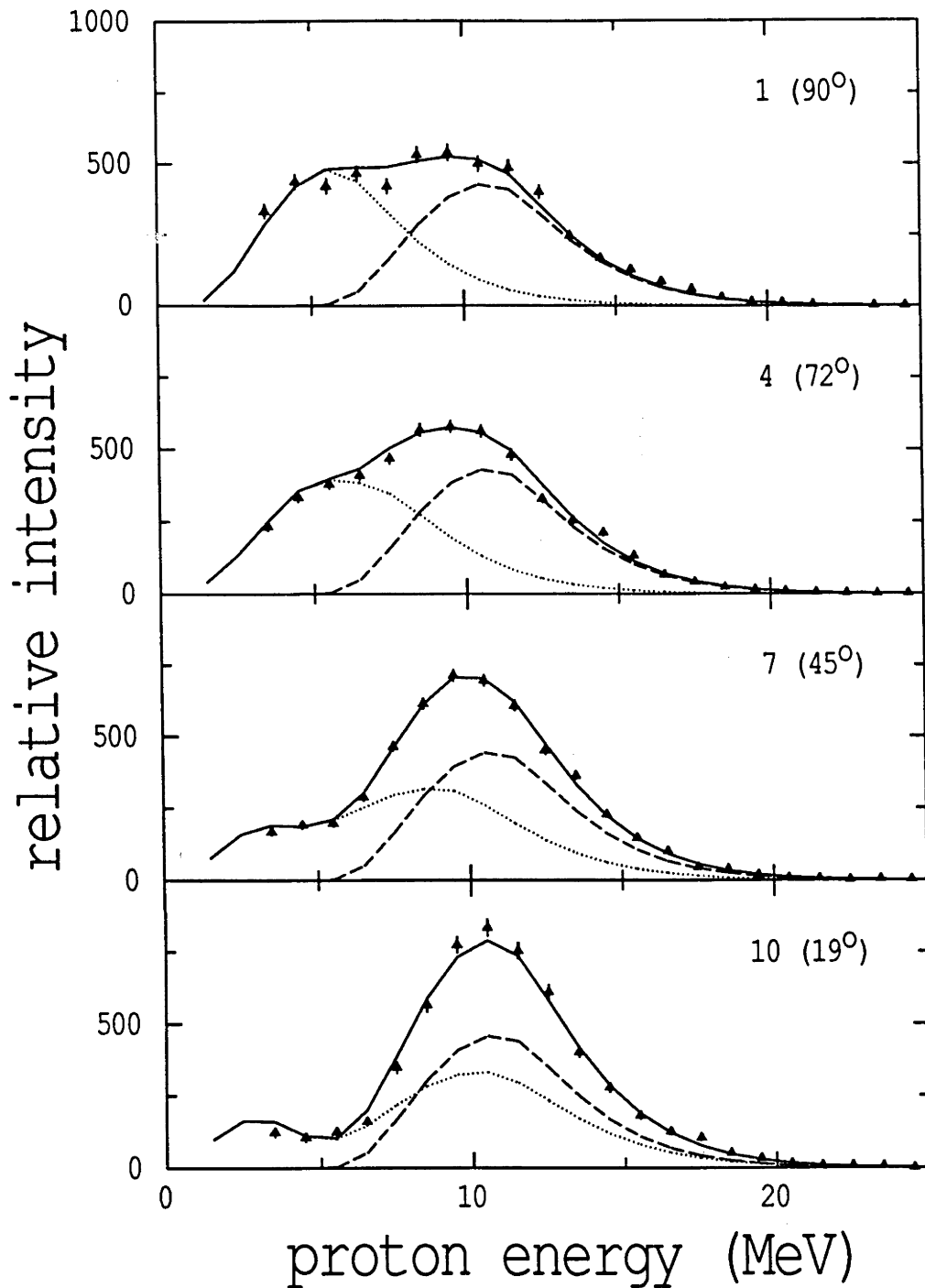


Figure 4.3 The proton spectra from figure 4.1 associated with fission fragment detecting stripes 1, 4, 7 and 10. The dotted and dashed curves are the components due to the post-scission and pre-scission emission respectively. The solid curves are the total fits as shown in figure 4.1. The angles between the CsI detector and the fission fragment detecting stripes are given to the right of the numbers indentifying the stripes.

the model and the proton data. A significant discrepancy between the model and the alpha particle data occurs in coincidence with fission fragments in stripe 3, where the model noticeably over-estimates the alpha particle intensity from ~ 13 MeV to ~ 16 MeV.

4.1 The Proton Data

Good quality fits to the proton data were obtained using only emission from the compound system and from the fully accelerated fission fragments. This suggests that other sources of emission are not important. All fits to the proton spectra were performed assuming a near-scission proton multiplicity of zero. Figure 4.3 shows the extracted pre-scission and post-scission proton spectra associated with stripes 1, 4, 7 and 10 from the 177.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement. These four stripes are all at 90° to the beam direction with the angle between the stripes and the CsI detector ranging from 90° for stripe 1, to 19° for stripe 10 (see figure 3.11 and table 3.1). The dashed curves show the pre-scission proton emission which is nearly isotropic, $W(\phi=90^\circ)/W(\phi=0^\circ) \approx 1.2$, where ϕ is the angle to the spin direction of the pre-scission compound system. The dotted curves show the post-scission proton components which change shape depending on the velocities and angles of both the observed and complementary fission fragments, relative to the CsI detector. For example, in coincidence with stripe 1 both the observed and complementary fission fragments travel at 90° to the CsI detector, and contribute roughly equally to the post-scission proton emission centred at approximately 6 MeV. In contrast, most of the post-scission protons in coincidence with stripe 10 are centred about 10 MeV and are associated with emission from the observed fission fragments travelling towards the CsI detector. Only a small low energy component centred around ~ 3 MeV is observed from the complementary fission fragments travelling away from the CsI detector.

Table 4.1 The parameters D_{ff} , T_{ff} , B_{ff} , D_{cn} , T_{cn} , B_{cn} , ANI, Z_o and ϕ_{ff} ; and the post-scission (π_{post}), pre-scission (π_{pre}) and total (π_{tot}) proton multiplicities, extracted from the $^{28}\text{Si} + ^{164}\text{Er}$ measurements. No.Coinc. is the number of observed true proton - fission fragment coincidences and θ_{det} is the angle of the light charged particle detector to the beam direction.

$E_{lab}(\text{MeV})$	140.0	147.5	155.0	162.5	162.5	170.0	177.5	185.0
$\theta_{det}(\text{deg})$	150	90	90	90	150	90	90	90
D_{ff}	4.0 ± 1.0	2.5 ± 0.3	3.4 ± 0.4	2.5 ± 0.1	3.6 ± 0.5	4.9 ± 1.1	3.1 ± 0.2	3.8 ± 0.3
$T_{ff}(\text{MeV})$	1.16 ± 0.06	1.39 ± 0.10	1.43 ± 0.03	1.59 ± 0.02	1.36 ± 0.04	1.32 ± 0.14	1.51 ± 0.02	1.51 ± 0.08
$B_{ff}(\text{MeV})$	4.7 ± 0.3	4.96 ± 0.11	5.12 ± 0.08	4.80 ± 0.06	5.02 ± 0.06	5.4 ± 0.2	4.95 ± 0.07	5.0 ± 0.2
D_{cn}	7.5 ± 5.0	5.1 ± 2.2	4.6 ± 0.7	4.3 ± 0.4	4.9 ± 0.5	4.2 ± 0.6	3.6 ± 0.2	4.4 ± 0.5
$T_{cn}(\text{MeV})$	1.19 ± 0.15	1.29 ± 0.07	1.34 ± 0.06	1.43 ± 0.06	1.44 ± 0.02	1.59 ± 0.06	1.64 ± 0.01	1.70 ± 0.03
$B_{cn}(\text{MeV})$	9.3 ± 0.3	9.19 ± 0.28	9.4 ± 0.3	9.58 ± 0.14	9.2 ± 0.1	9.6 ± 0.2	9.41 ± 0.10	9.55 ± 0.16
ANI	1.19 ± 0.20	1.15 ± 0.18	1.41 ± 0.14	1.20 ± 0.03	1.13 ± 0.20	1.06 ± 0.18	1.12 ± 0.03	1.25 ± 0.13
Z_o	43.5 ± 8.0	44.4 ± 7.6	46.4 ± 2.6	45.1 ± 0.9	45.8 ± 0.7	41.8 ± 3.3	43.1 ± 0.6	39.1 ± 2.2
$\phi_{ff}(\text{deg})$	26.4 ± 6.0	21.0 ± 4.7	27.4 ± 2.8	24.9 ± 1.0	30.2 ± 6.0	32.1 ± 2.8	24.2 ± 2.2	35 ± 7
π_{post}	0.0103 ± 0.0012	0.013 ± 0.002	0.0192 ± 0.0005	0.0257 ± 0.0009	0.0262 ± 0.0025	0.0304 ± 0.0015	0.0364 ± 0.0009	0.0432 ± 0.0019
π_{pre}	0.0085 ± 0.0014	0.017 ± 0.003	0.0350 ± 0.0011	0.0457 ± 0.0014	0.0466 ± 0.0039	0.0666 ± 0.0031	0.0733 ± 0.0019	0.099 ± 0.006
π_{tot}	0.0291 ± 0.0009	0.042 ± 0.0010	0.0738 ± 0.0021	0.0972 ± 0.0025	0.0990 ± 0.0026	0.1275 ± 0.0077	0.1461 ± 0.0037	0.185 ± 0.006
χ^2	1.20	1.04	1.17	1.31	1.35	1.16	1.34	1.07
No.Coinc.	~15 000	~10 000	~20 000	~70 000	~50 000	~10 000	~170 000	~30 000

The extracted multiplicities and their associated parameters $D_{ff} \dots \phi_{ff}$ are given in tables 4.1 to 4.3. Figures 4.4 to 4.7 show these results graphically. There appears to be no significant dependence of the parameters $D_{ff} \dots \phi_{ff}$ on the mass of the target and the parameters D_{ff} , B_{ff} , B_{cn} , ANI , Z_0 , and ϕ_{ff} seem to be independent of the beam energy. The mean atomic number of the fission fragments responsible for the post-scission proton emission Z_0 is ~ 43 and suggests that the post-scission protons are preferentially emitted from fragments with atomic numbers only slightly larger than those associated with symmetric fragments. The half width at half maximum (HWHM) of the distribution of fission fragments about the plane perpendicular to the spin direction of the systems responsible for the pre-scission protons (see figure 4.6) is $\sim 26^\circ$ and suggests a value of $J/K_0 \approx 3.0$ where J is the spin of the compound system and K_0 is the standard deviation of the projection of this spin on the nuclear symmetry axis (see figure 2.22). The parameters T_{cn} and T_{ff} both increase with beam energy and reflect the increasing temperatures of the pre-scission compound systems and fission fragments with increasing beam energy. The slope of T_{ff} versus beam energy is approximately half the slope of T_{cn} versus beam energy. This is consistent with the total pre-scission particle multiplicity increasing with beam energy, thus only allowing a part of the increased thermal energy of the pre-scission systems produced by the increased beam energy to end up as an increased thermal energy of the fission fragments.

When comparing the values of the parameters D_{ff} and T_{ff} to the parameters D_{cn} and T_{cn} , it should be remembered that the present analysis takes a simplistic view of the post-scission emission and assumes all particles of a given type (protons or alpha particles) are emitted by fragments with a fixed atomic number Z_0 , which is then used to define the centre of mass velocity of the emitting fragments using Viola's systematics [VIO85]. The post-scission emission is, of course, from

Table 4.2 As for table 4.1 but for the $^{28}\text{Si} + ^{167}\text{Er}$ measurements.

Elab(MeV)	155.0	162.5	170.0	177.5
D _{ff}	4.4±0.7	2.8±0.8	3.1±0.4	3.3±0.4
T _{ff} (MeV)	1.38±0.13	1.55±0.14	1.54±0.09	1.56±0.09
B _{ff} (MeV)	5.26±0.06	4.9±0.3	5.08±0.15	4.9±0.1
D _{cn}	5.1±1.1	5.1±0.7	4.2±0.8	4.0±0.4
T _{cn} (MeV)	1.26±0.05	1.32±0.06	1.53±0.08	1.61±0.06
B _{cn} (MeV)	9.4±0.2	9.75±0.17	9.66±0.21	9.64±0.13
ANI	1.09±0.19	1.11±0.07	1.39±0.22	1.28±0.23
Z ₀	40.6±1.2	43.2±2.7	44.5±1.7	40.8±1.6
φ _{ff} (deg)	29.6±0.5	31.9±1.7	40±20	26±8
π _{post}	0.0105 ±0.0005	0.0134 ±0.0008	0.0184 ±0.0009	0.0232 ±0.0008
π _{pre}	0.0175 ±0.0017	0.0274 ±0.0014	0.0429 ±0.0013	0.0595 ±0.0030
π _{tot}	0.0384 ±0.0012	0.0543 ±0.0015	0.0796 ±0.0022	0.106 ±0.003
χ ²	1.14	1.14	1.06	0.98
No.Coinc.	~25 000	~25 000	~50 000	~25 000

Table 4.3 As for table 4.1 but for the $^{28}\text{Si} + ^{170}\text{Er}$ measurements.

$E_{\text{lab}}(\text{MeV})$	155.0	162.5	177.5	185.0
D_{ff}	4.2 ± 0.8	3.1 ± 0.4	2.3 ± 0.1	3.2 ± 0.4
$T_{\text{ff}}(\text{MeV})$	1.29 ± 0.13	1.42 ± 0.14	1.66 ± 0.09	1.52 ± 0.10
$B_{\text{ff}}(\text{MeV})$	5.5 ± 0.2	5.2 ± 0.3	4.8 ± 0.1	5.1 ± 0.1
D_{cn}	5.0 ± 0.2	4.6 ± 0.7	3.6 ± 0.3	3.1 ± 0.2
$T_{\text{cn}}(\text{MeV})$	1.28 ± 0.04	1.43 ± 0.04	1.64 ± 0.06	1.78 ± 0.04
$B_{\text{cn}}(\text{MeV})$	9.51 ± 0.10	9.57 ± 0.12	9.49 ± 0.15	9.36 ± 0.14
ANI	1.14 ± 0.25	1.16 ± 0.03	1.23 ± 0.03	1.32 ± 0.04
Z_0	43.7 ± 2.3	44.8 ± 1.0	43.6 ± 0.6	43.7 ± 0.8
$\phi_{\text{ff}}(\text{deg})$	21.3 ± 2.5	16.7 ± 0.8	19.1 ± 1.5	27 ± 6
π_{post}	0.0054 ± 0.0002	0.0071 ± 0.0004	0.0133 ± 0.0008	0.0155 ± 0.0010
π_{pre}	0.0091 ± 0.0004	0.0168 ± 0.0006	0.036 ± 0.001	0.0507 ± 0.0028
π_{tot}	0.0197 ± 0.0005	0.0311 ± 0.0009	0.062 ± 0.002	0.0818 ± 0.0021
χ^2	1.09	1.12	1.04	1.23
No.Coinc.	~30 000	~40 000	~40 000	~50 000

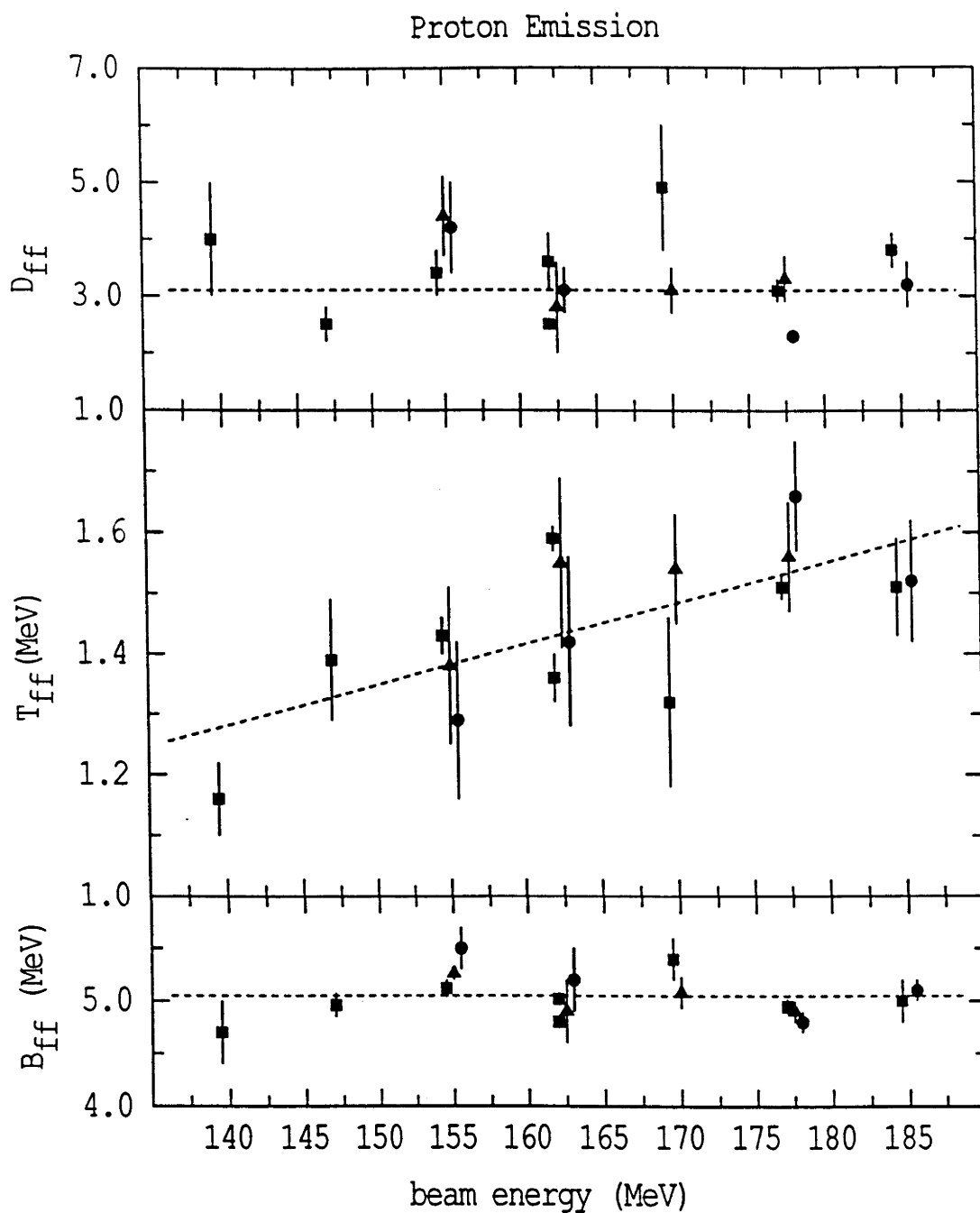


Figure 4.4 The post-scission proton spectral shape parameters D_{ff} , T_{ff} and B_{ff} versus beam energy. The squares, triangles and circles are the ^{28}Si + $^{164,167}\text{Er}$ and ^{170}Er results respectively. The ^{164}Er and ^{170}Er target measurements have been shifted by -0.5 MeV and $+0.5$ MeV respectively. The dashed lines indicate the trends in the data.

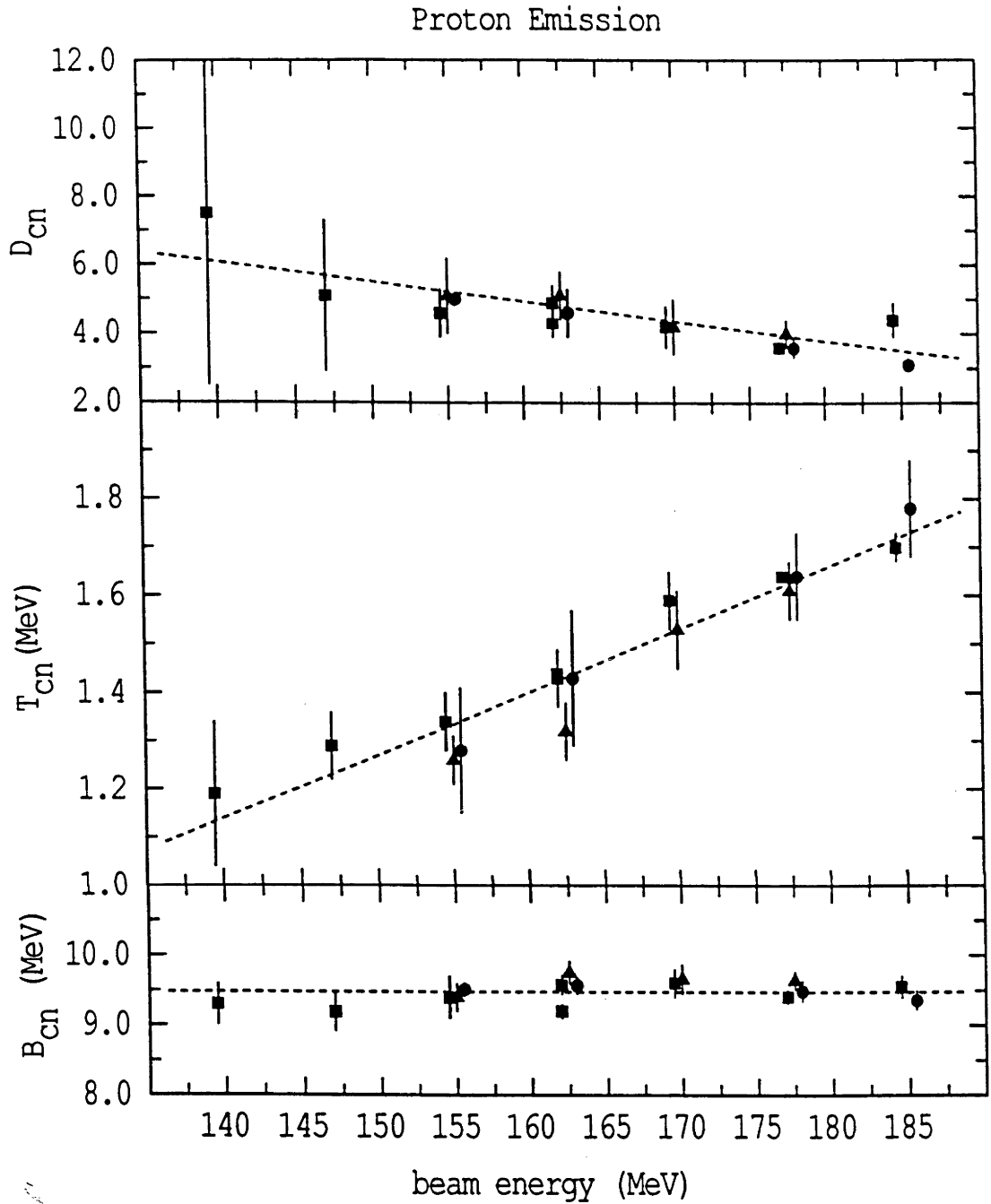


Figure 4.5 The pre-scission proton spectral shape parameters D_{cn} , T_{cn} and B_{cn} versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ results respectively. The dashed lines indicate the trends in the data.

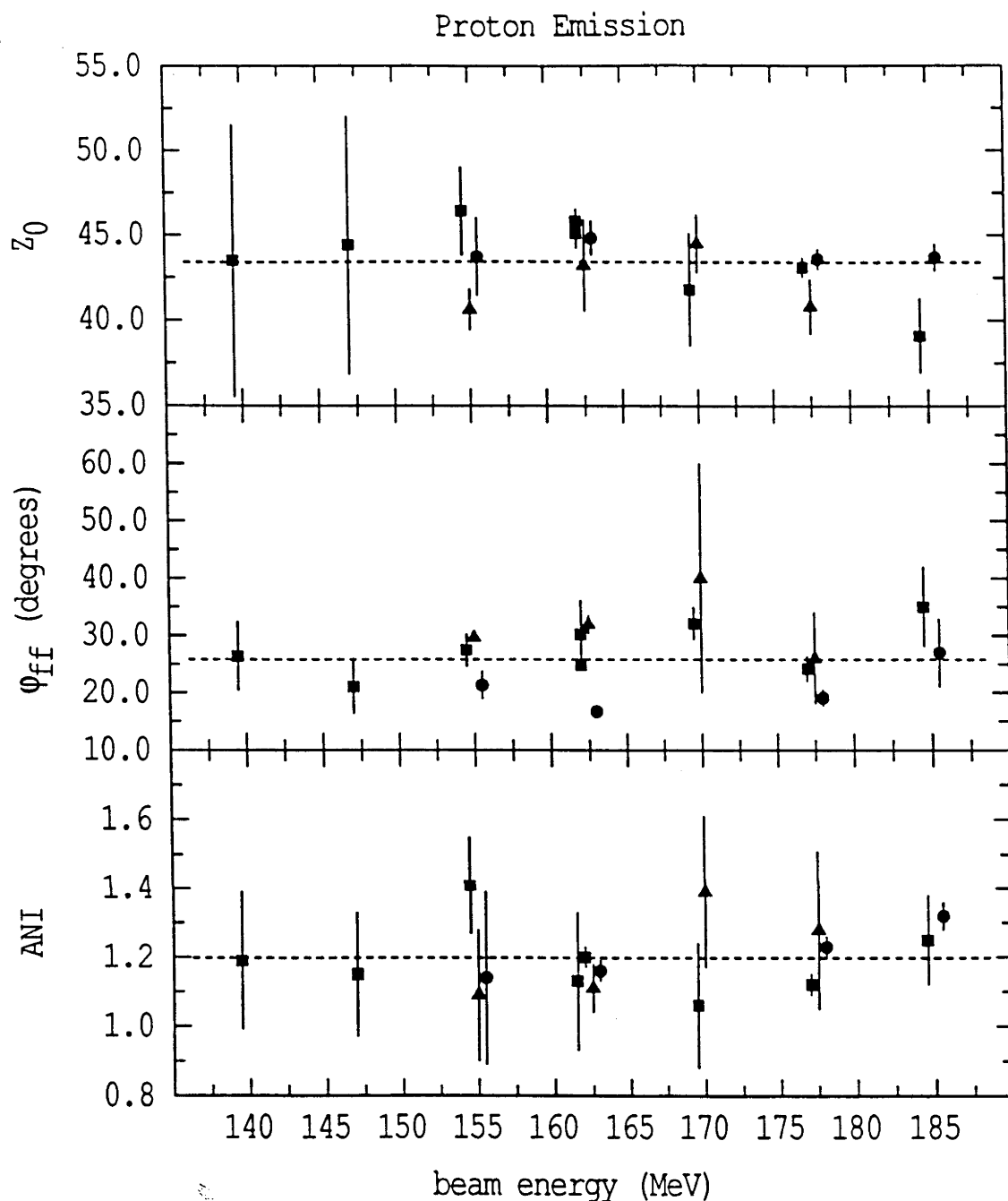


Figure 4.6 The mean atomic number of the fragments responsible for the post-scission proton emission Z_0 ; the half width at half maximum (HWHM) of the distribution of fission fragments about the plane perpendicular to the spin direction for the systems responsible for the pre-scission proton emission ϕ_{ff} ; and the anisotropy of the pre-scission proton emission ANI versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ results respectively. The dashed lines indicate the trends in the data.

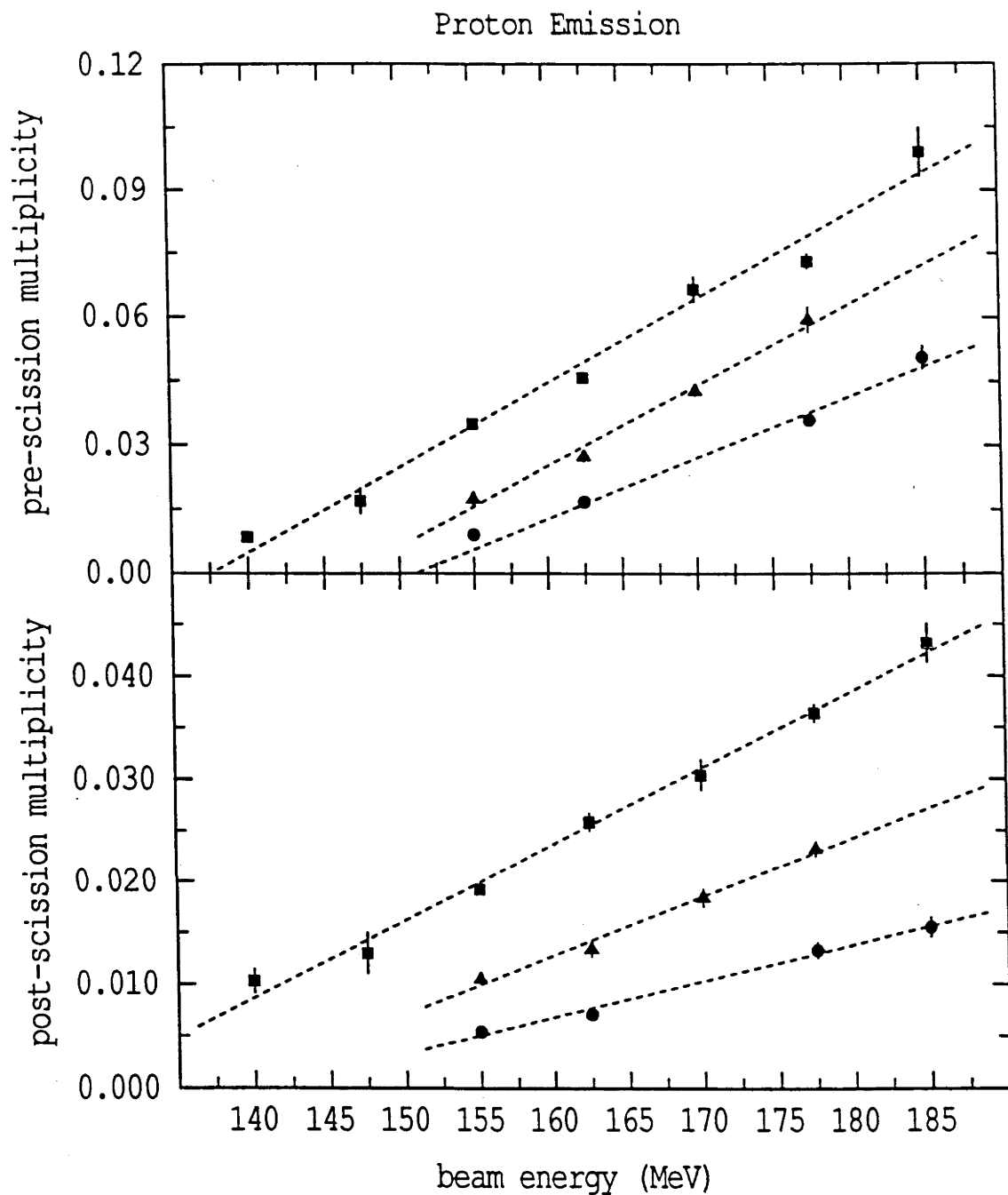


Figure 4.7 The pre-scission and post-scission proton multiplicities versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ and ^{170}Er results respectively. The dashed lines indicate the trends in the data.

fragments with a range of atomic numbers, and thus with a range of velocities and emission barriers. This distribution of fragment velocities and emission barriers will smear out the energy distribution of the post-scission particles as seen in the laboratory reference frame in a way not modelled by the code CPE. For this reason the values of the parameters D_{ff} and T_{ff} extracted from the data are expected to be larger than those appropriate to the spectral shape of the particles emitted from fragments of atomic number Z_0 .

The pre-scission and post-scission proton multiplicities increase monotonically with increasing beam energy and also show an obvious dependence on the mass of the target. This mass dependence is mainly due to the increasing proton binding energy of the emitting systems with increasing mass.

4.2 The Alpha Particle Data

The main differences between the alpha particle and proton data are:

- (1) the alpha particle emission barriers are observed to be approximately a factor of two higher than the proton emission barriers.
- (2) the velocities of the emitted alpha particles are on average ~30% less than the velocities of the protons. The observed energy distribution of the post-scission alpha particles is therefore more sensitive than the protons to the velocities and angles of the fission fragments relative to the CsI detector.
- (3) the pre-scission alpha particles are found to have a large anisotropy, with between ~2 and ~3 times more alpha particles seen perpendicular to the spin direction of the pre-scission compound systems than seen parallel to this direction.
- (4) good quality fits to the measured alpha particle spectra can only be obtained with the inclusion of near-scission emission.

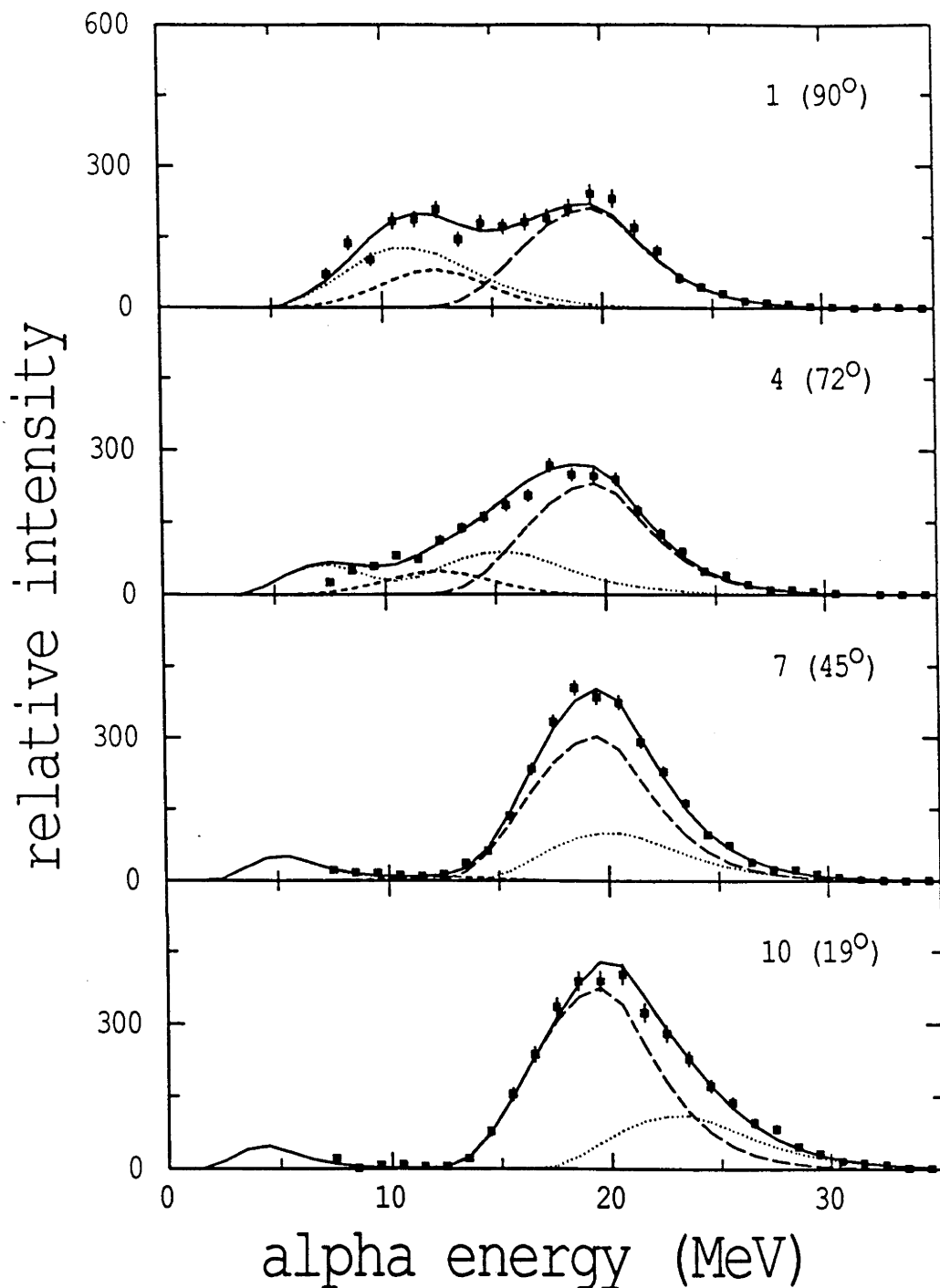


Figure 4.8 The alpha particle spectra from figure 4.2 associated with fission fragment detecting stripes 1, 4, 7 and 10. The longer dashed, dotted and shorter dashed curves are the components due to the pre-scission, post-scission and near-scission emission respectively. The solid curves are the total fits as shown in figure 4.2. The angles between the CsI detector and the fission fragment detecting stripes are given to the right of the numbers indentifying the stripes.

Figure 4.8 shows the pre-scission, post-scission and near-scission components responsible for the alpha particle spectra associated with stripes 1, 4, 7 and 10 from the 177.5 MeV $^{28}\text{Si} + ^{164}\text{Er}$ measurement. The longer dashed, dotted and shorter dashed curves are the pre-scission, post-scission and near-scission components respectively. The increasing intensity of the pre-scission component in coincidence with fragments in stripes 1 to 10 is due to the changing direction of the spin of the pre-scission systems, defined by the direction of the observed fission fragments.

Tables 4.4 to 4.6 contain the values of the parameters $D_{\text{ff}} \cdots \sigma_{\text{nse}}^{\text{ang}}$ and the post-scission, pre-scission, near-scission and total alpha particle multiplicities extracted from the measured alpha particle spectra using the code CPE. Figures 4.9 to 4.14 show these results graphically. As with the proton data, there appears to be no significant dependence of the parameters $D_{\text{ff}} \cdots \sigma_{\text{nse}}^{\text{ang}}$ on the mass of the target; and the parameters B_{ff} , B_{cn} , Z_0 , ϕ_{ff} and $\sigma_{\text{nse}}^{\text{energy}}$ seem to be independent of the beam energy. The mean atomic number of the fission fragments responsible for the post-scission emission Z_0 is ~ 46 , larger than the value of ~ 43 obtained from the proton data. The HWHM of the angular distribution of the fission fragments about the plane perpendicular to the spin of the systems responsible for the pre-scission alpha particle emission ϕ_{ff} is $\sim 23^\circ$, lower than the value of 26° obtained from the proton data. This lower value of ϕ_{ff} suggests that the pre-scission alpha particles come from systems with larger values of J/K_0 than those responsible for the pre-scission proton emission (see figure 2.22). As with the proton multiplicities, the pre-scission and post-scission alpha particle multiplicities increase with increasing beam energy and decrease with increasing mass of the target.

The mean energy of the near-scission alpha particle emission $\bar{E}_{\text{nse}}$ ranges from ~ 13 MeV to ~ 14.5 MeV, and appears to decrease with

Table 4.4 The parameters D_{ff} , T_{ff} , B_{ff} , D_{cn} , T_{cn} , B_{cn} , ANI, $\bar{E}_{nse}$, σ_{nse}^{energy} , σ_{nse}^{ang} , Z_0 and ϕ_{ff} ; and the post-scission (α_{post}), pre-scission (α_{pre}), near-scission (α_{nse}) and total (α_{tot}) alpha particle multiplicities, extracted from the $^{28}\text{Si} + ^{164}\text{Er}$ measurements. No.Coinc. is the number of observed true alpha particle - fission fragment coincidences.

$E_{lab}(\text{MeV})$	155.0	162.5	170.0	177.5	185.0
D_{ff}	5.0 ± 0.8	5.1 ± 0.6	3.8 ± 1.6	3.2 ± 0.2	4.4 ± 0.5
$T_{ff}(\text{MeV})$	1.51 ± 0.05	1.53 ± 0.08	1.64 ± 0.18	1.62 ± 0.05	1.68 ± 0.06
$B_{ff}(\text{MeV})$	12.1 ± 0.2	12.1 ± 0.3	11.5 ± 1.1	11.5 ± 0.1	11.8 ± 0.1
D_{cn}	8.7 ± 1.4	6.1 ± 0.3	5.5 ± 0.4	5.48 ± 0.07	5.1 ± 0.3
$T_{cn}(\text{MeV})$	1.24 ± 0.15	1.44 ± 0.04	1.47 ± 0.13	1.61 ± 0.02	1.64 ± 0.05
$B_{cn}(\text{MeV})$	19.1 ± 0.3	18.9 ± 0.2	18.9 ± 0.2	18.6 ± 0.2	18.7 ± 0.2
ANI	2.27 ± 0.31	2.00 ± 0.08	3.33 ± 1.44	2.17 ± 0.10	2.17 ± 0.24
$\bar{E}_{nse}(\text{MeV})$	15.0 ± 1.8	13.8 ± 0.4	14.5 ± 0.4	12.9 ± 0.2	13.5 ± 0.4
$\sigma_{nse}^{energy}(\text{MeV})$	4.4 ± 0.5	2.4 ± 0.2	2.3 ± 0.6	2.34 ± 0.10	2.0 ± 0.3
$\sigma_{nse}^{ang}(\text{deg})$	11 ± 4	12.8 ± 1.4	13.7 ± 3.9	19.8 ± 1.8	17.4 ± 1.6
Z_0	46.8 ± 1.7	46.9 ± 0.6	44.3 ± 3.2	47.5 ± 0.3	46.7 ± 0.8
$\phi_{ff}(\text{deg})$	21.2 ± 2.6	23.1 ± 1.4	29.4 ± 4.5	23.7 ± 0.9	22.8 ± 2.2
α_{post}	0.0075 ± 0.0016	0.0085 ± 0.0008	0.0111 ± 0.0016	0.0126 ± 0.0006	0.0185 ± 0.0023
α_{pre}	0.0217 ± 0.0025	0.0353 ± 0.0012	0.0477 ± 0.0043	0.0603 ± 0.0017	0.0691 ± 0.0025
α_{nse}	0.0033 ± 0.0016	0.0036 ± 0.0004	0.0055 ± 0.0027	0.0055 ± 0.0006	0.0045 ± 0.0017
α_{tot}	0.0414 ± 0.0016	0.0561 ± 0.0020	0.0760 ± 0.0030	0.0910 ± 0.0024	0.1109 ± 0.0030
χ^2	1.11	1.44	1.28	1.43	1.18
No.Coinc.	~10 000	~40 000	~6 000	~100 000	~20 000

Table 4.5 As for table 4.4 but for the $^{28}\text{Si} + ^{167}\text{Er}$ measurements.

$E_{\text{lab}}(\text{MeV})$	155.0	162.5	170.0	177.5
D_{ff}	5.1 ± 1.4	5.3 ± 3.0	3.8 ± 0.3	5.6 ± 2.7
$T_{\text{ff}}(\text{MeV})$	1.24 ± 0.26	1.24 ± 0.26	1.61 ± 0.06	1.48 ± 0.22
$B_{\text{ff}}(\text{MeV})$	12.1 ± 0.4	12.4 ± 0.8	11.7 ± 0.2	12.3 ± 0.7
D_{cn}	8.3 ± 2.2	6.6 ± 1.2	6.4 ± 0.2	5.6 ± 0.6
$T_{\text{cn}}(\text{MeV})$	1.28 ± 0.13	1.42 ± 0.09	1.52 ± 0.03	1.69 ± 0.02
$B_{\text{cn}}(\text{MeV})$	18.1 ± 0.6	18.7 ± 0.4	19.0 ± 0.2	18.9 ± 0.2
ANI	2.04 ± 0.29	2.86 ± 0.41	2.67 ± 0.17	2.78 ± 0.46
$\bar{E}_{\text{nse}}(\text{MeV})$	13.6 ± 0.2	13.4 ± 0.3	13.3 ± 0.2	13.5 ± 0.5
$\sigma_{\text{nse}}^{\text{energy}}(\text{MeV})$	1.9 ± 0.5	1.9 ± 0.3	2.23 ± 0.09	2.0 ± 0.3
$\sigma_{\text{nse}}^{\text{ang}}(\text{deg})$	9.1 ± 1.6	15.1 ± 1.5	14.7 ± 1.1	18.6 ± 4.1
Z_0	46.5 ± 0.4	46.2 ± 1.0	46.0 ± 1.2	45.2 ± 1.2
$\phi_{\text{ff}}(\text{deg})$	26.5 ± 0.6	22.7 ± 2.8	26.3 ± 4.6	25.0 ± 3.8
α_{post}	0.0036 ± 0.0004	0.0041 ± 0.0004	0.0064 ± 0.0004	0.0097 ± 0.0005
α_{pre}	0.0152 ± 0.0004	0.0271 ± 0.0016	0.0387 ± 0.0011	0.0534 ± 0.0030
α_{nse}	0.0013 ± 0.0002	0.0027 ± 0.0004	0.0029 ± 0.0003	0.0039 ± 0.0010
α_{tot}	0.0240 ± 0.0008	0.0384 ± 0.0020	0.0553 ± 0.0016	0.0762 ± 0.0036
χ^2	1.20	1.29	1.43	1.46
No.Coinc.	~15 000	~15 000	~30 000	~15 000

Table 4.6 As for table 4.4 but for the $^{28}\text{Si} + ^{170}\text{Er}$ measurements.

$E_{\text{lab}}(\text{MeV})$	155.0	162.5	177.5	185.0
D_{ff}	4.8 ± 2.8	4.2 ± 0.4	3.4 ± 0.4	3.0 ± 0.5
$T_{\text{ff}}(\text{MeV})$	1.32 ± 0.27	1.54 ± 0.11	1.79 ± 0.03	1.80 ± 0.06
$B_{\text{ff}}(\text{MeV})$	11.7 ± 0.5	11.9 ± 0.2	11.8 ± 0.2	11.5 ± 0.2
D_{cn}	11 ± 5	7.2 ± 0.5	5.3 ± 0.4	5.3 ± 0.3
$T_{\text{cn}}(\text{MeV})$	1.10 ± 0.09	1.39 ± 0.03	1.63 ± 0.03	1.68 ± 0.05
$B_{\text{cn}}(\text{MeV})$	18.5 ± 0.6	18.2 ± 0.3	18.6 ± 0.3	18.7 ± 0.2
ANI	1.85 ± 0.14	2.44 ± 0.30	2.63 ± 0.14	2.63 ± 0.07
$\bar{E}_{\text{nse}}(\text{MeV})$	14.4 ± 0.7	14.1 ± 0.5	13.0 ± 0.6	13.1 ± 0.3
$\sigma_{\text{nse}}^{\text{energy}}(\text{MeV})$	2.2 ± 0.3	2.35 ± 0.34	2.6 ± 0.3	2.6 ± 0.3
$\sigma_{\text{nse}}^{\text{ang}}(\text{deg})$	8.7 ± 2.8	10.2 ± 3.2	14.7 ± 5.4	17.4 ± 1.5
Z_0	47.1 ± 0.9	47.4 ± 0.7	48.8 ± 0.7	46.4 ± 0.6
$\phi_{\text{ff}}(\text{deg})$	15.6 ± 5.2	22.2 ± 1.6	19.1 ± 0.3	20.4 ± 0.4
α_{post}	0.0024 ± 0.0003	0.0036 ± 0.0004	0.0070 ± 0.0011	0.0069 ± 0.0007
α_{pre}	0.0087 ± 0.0004	0.0170 ± 0.0005	0.0378 ± 0.0017	0.0511 ± 0.0016
α_{nse}	0.00109 ± 0.00015	0.00127 ± 0.00015	0.0028 ± 0.0011	0.0042 ± 0.0006
α_{tot}	0.0146 ± 0.0008	0.0254 ± 0.0008	0.0551 ± 0.0016	0.0688 ± 0.0021
χ^2	1.39	1.16	1.26	1.36
No.Coinc.	~25 000	~30 000	~35 000	~40 000

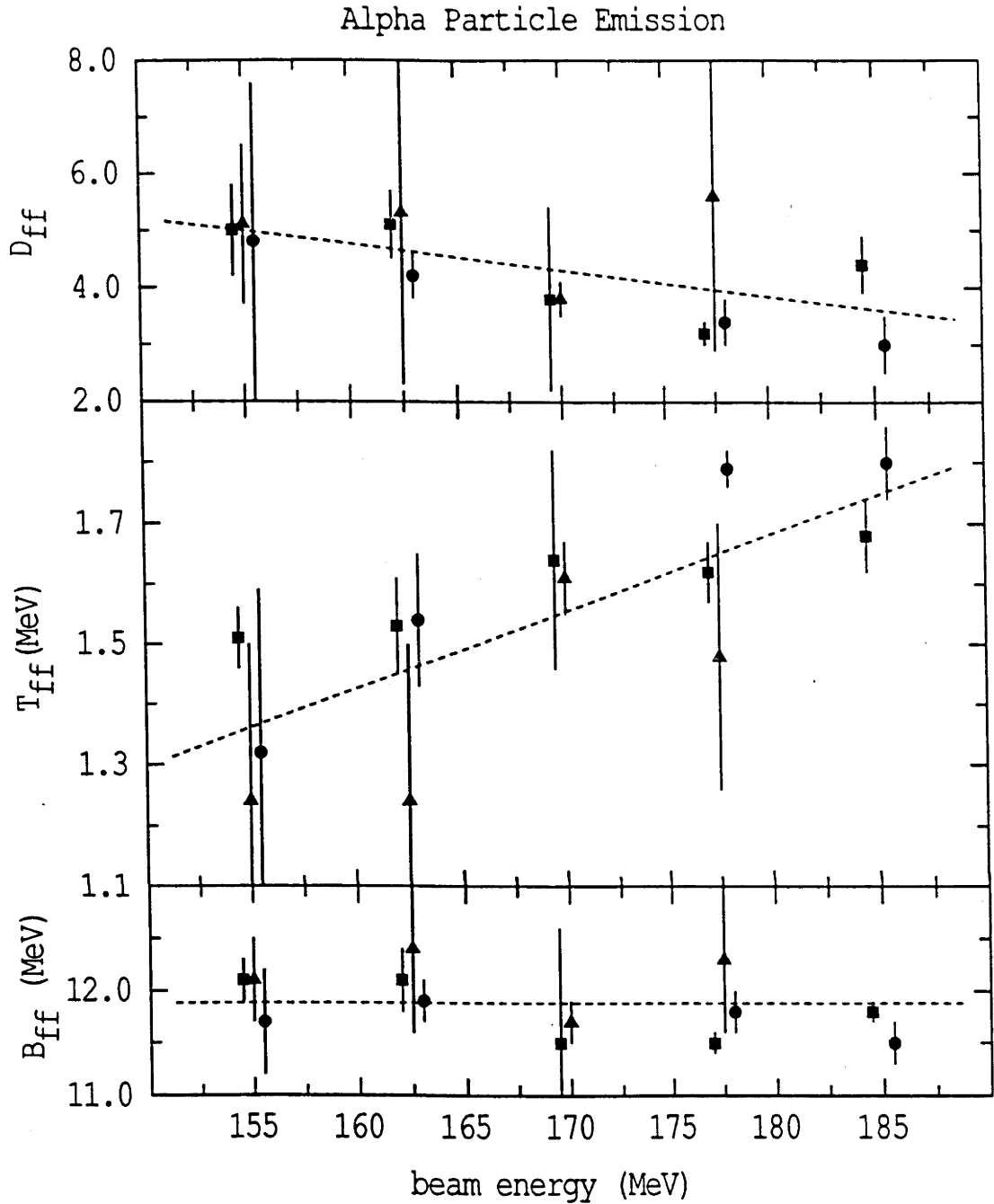


Figure 4.9 The post-scission alpha particle spectral shape parameters D_{ff} , T_{ff} and B_{ff} versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ and ^{170}Er results respectively. The ^{164}Er and ^{170}Er target measurements have been shifted by -0.5 MeV and $+0.5$ MeV respectively. The dashed lines indicate the trends in the data.

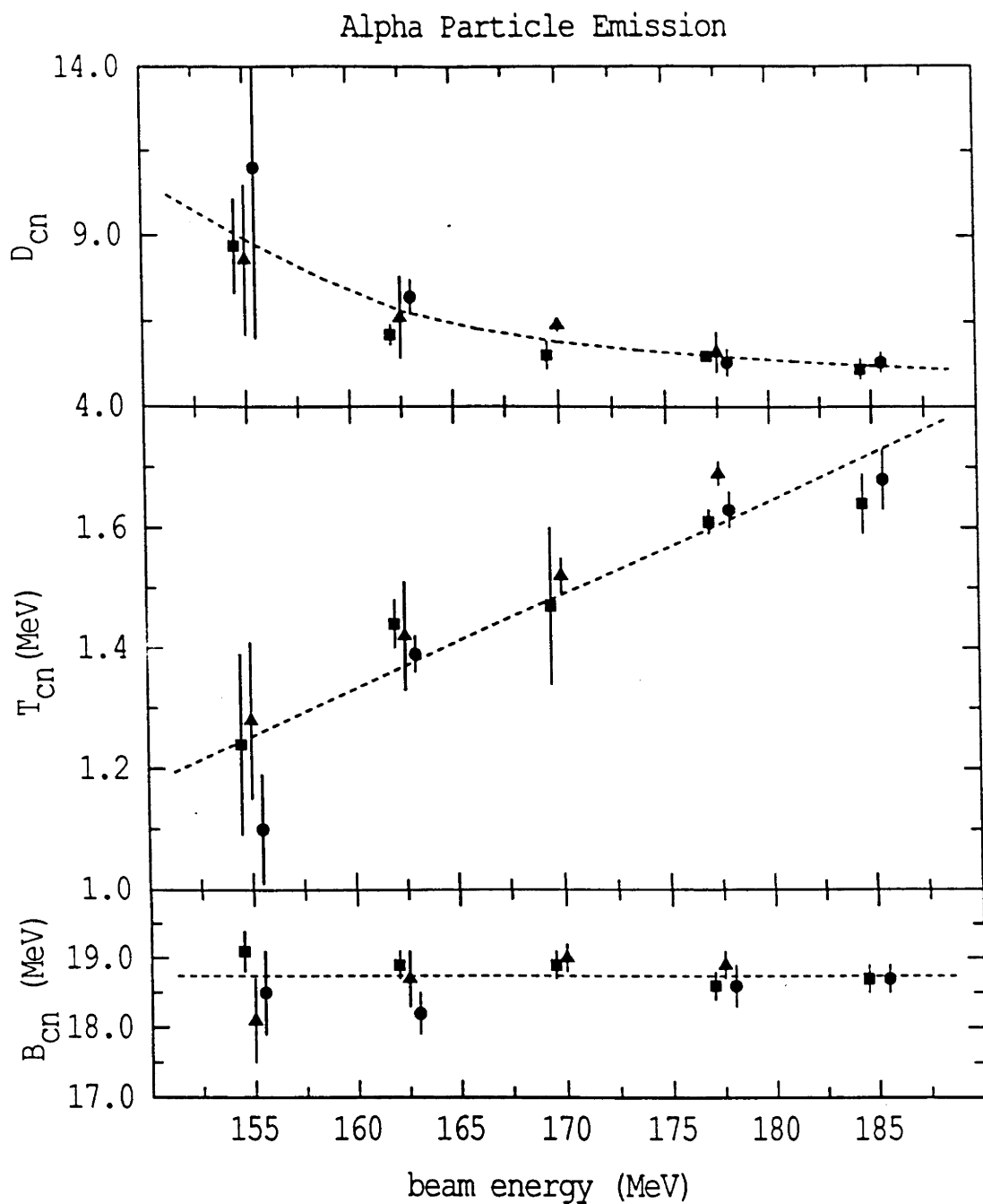


Figure 4.10 The pre-scission alpha particle spectral shape parameters D_{cn} , T_{cn} and B_{cn} versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ results respectively. The dashed lines indicate the trends in the data.

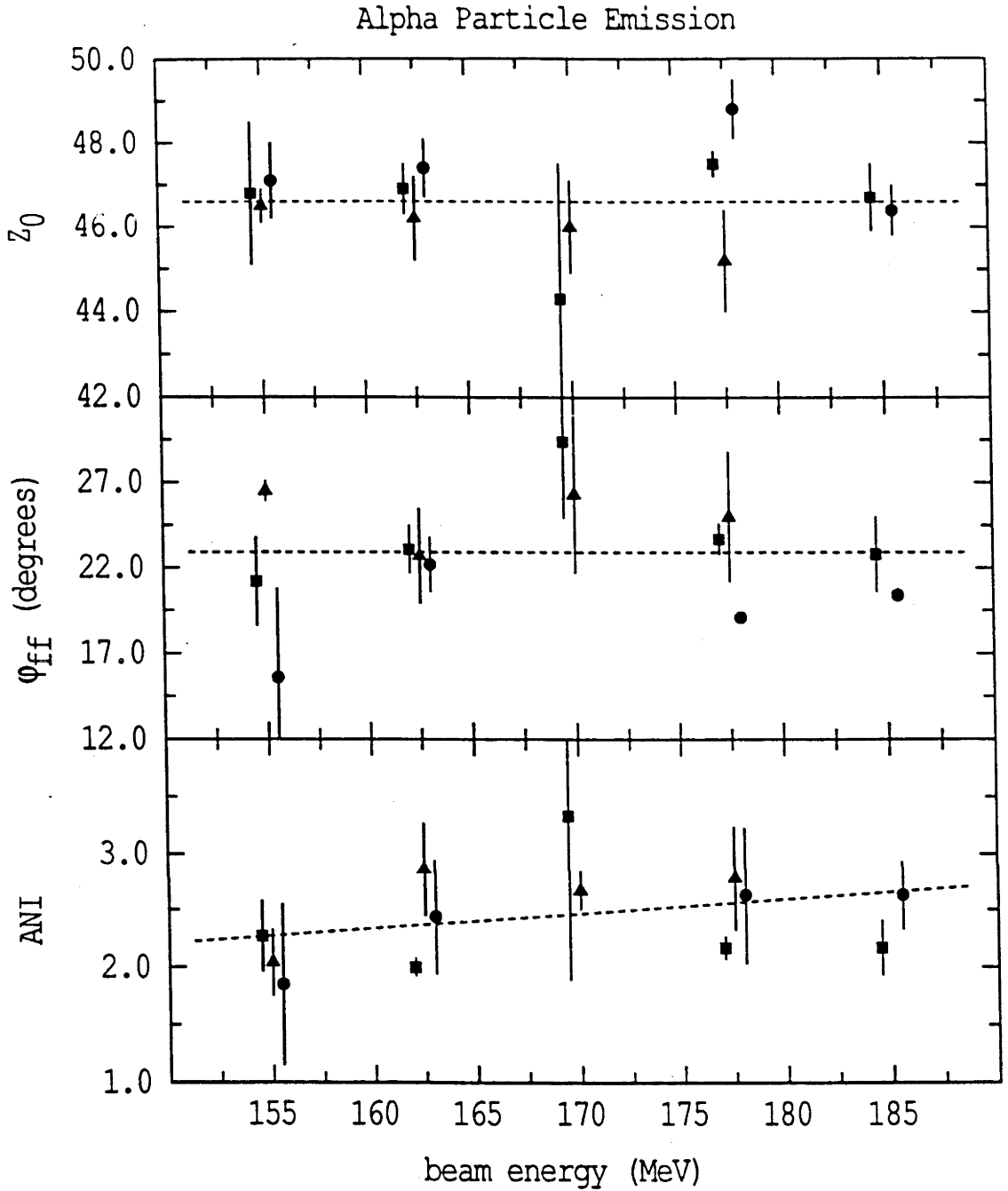


Figure 4.11 The mean atomic number of the fragments responsible for the post-scission alpha particle emission Z_0 ; the HWHM of the distribution of fission fragments about the plane perpendicular to the spin direction for the systems responsible for the pre-scission alpha particle emission ϕ_{ff} ; and the anisotropy of the pre-scission alpha particle emission ANI versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ and ^{170}Er results respectively. The dashed lines indicate the trends in the data.

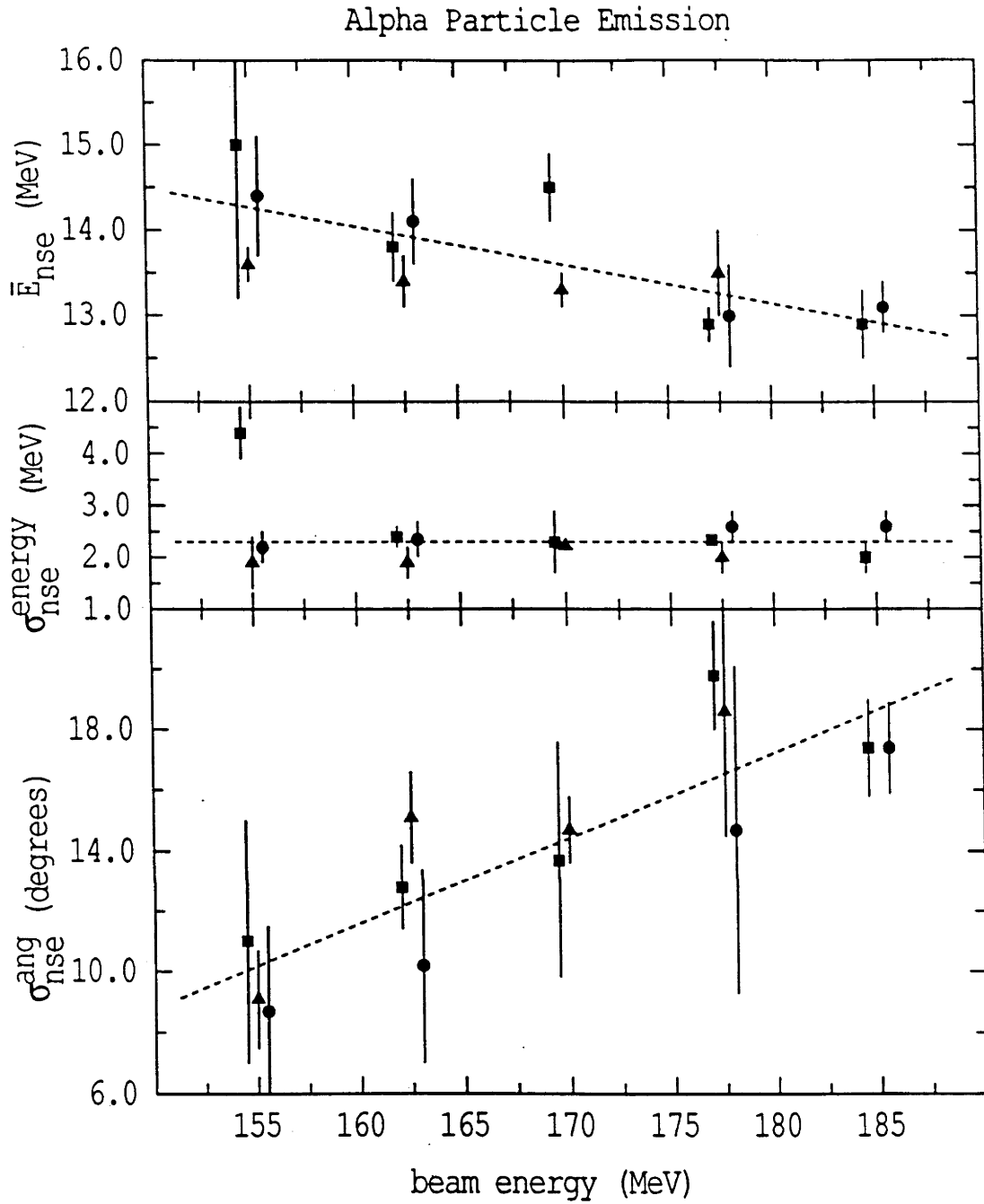


Figure 4.12 The mean energy $\bar{E}_{nse}$; the standard deviation of the energy distribution σ_{nse}^{energy} ; and the standard deviation of the angular distribution σ_{nse}^{ang} of the near-scission alpha particle emission. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ results respectively. The dashed lines indicate the trends in the data.

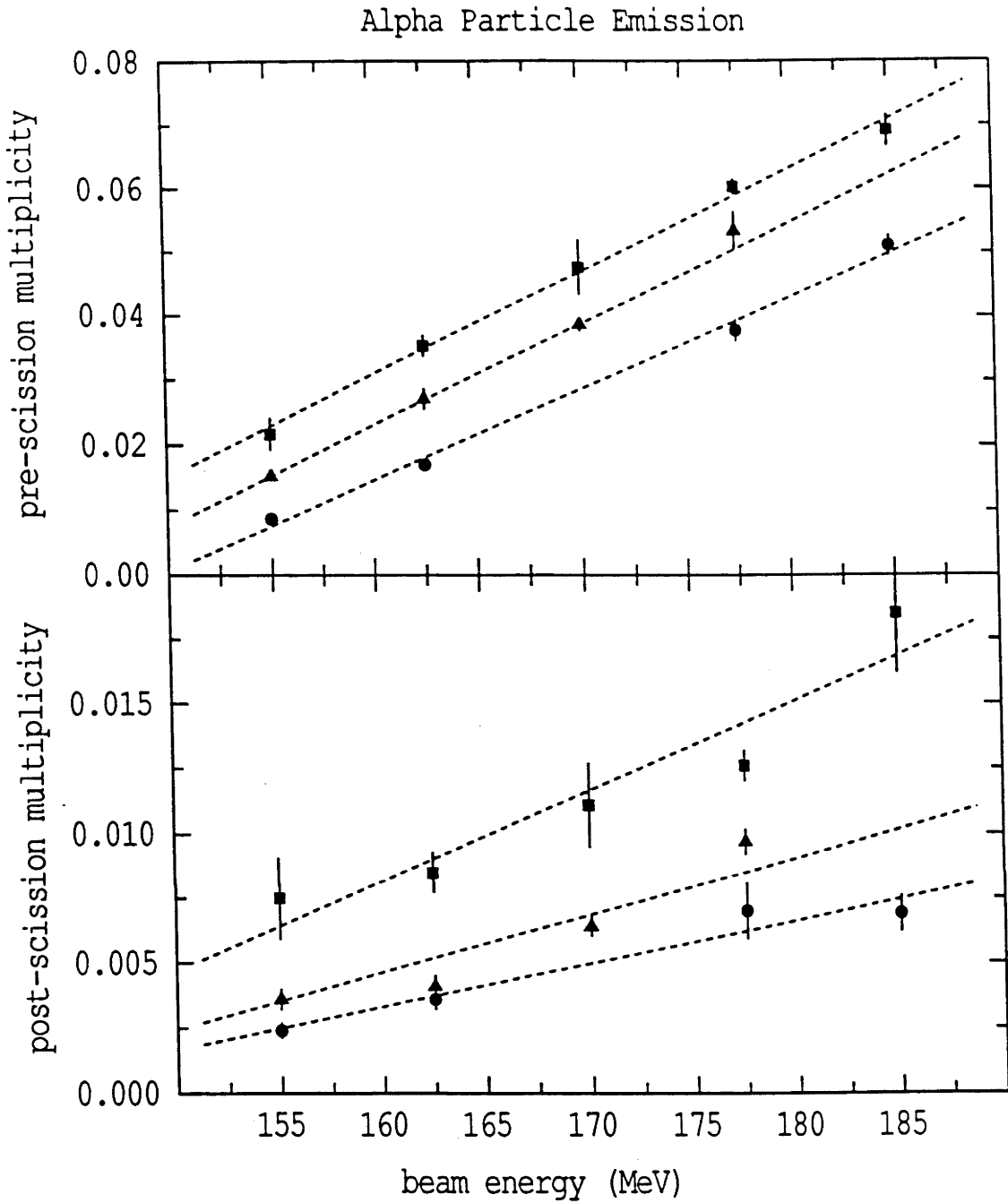


Figure 4.13 The pre-scission and post-scission alpha particle multiplicities versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}\text{Er}$ and ^{170}Er results respectively. The dashed lines indicate the trends in the data.

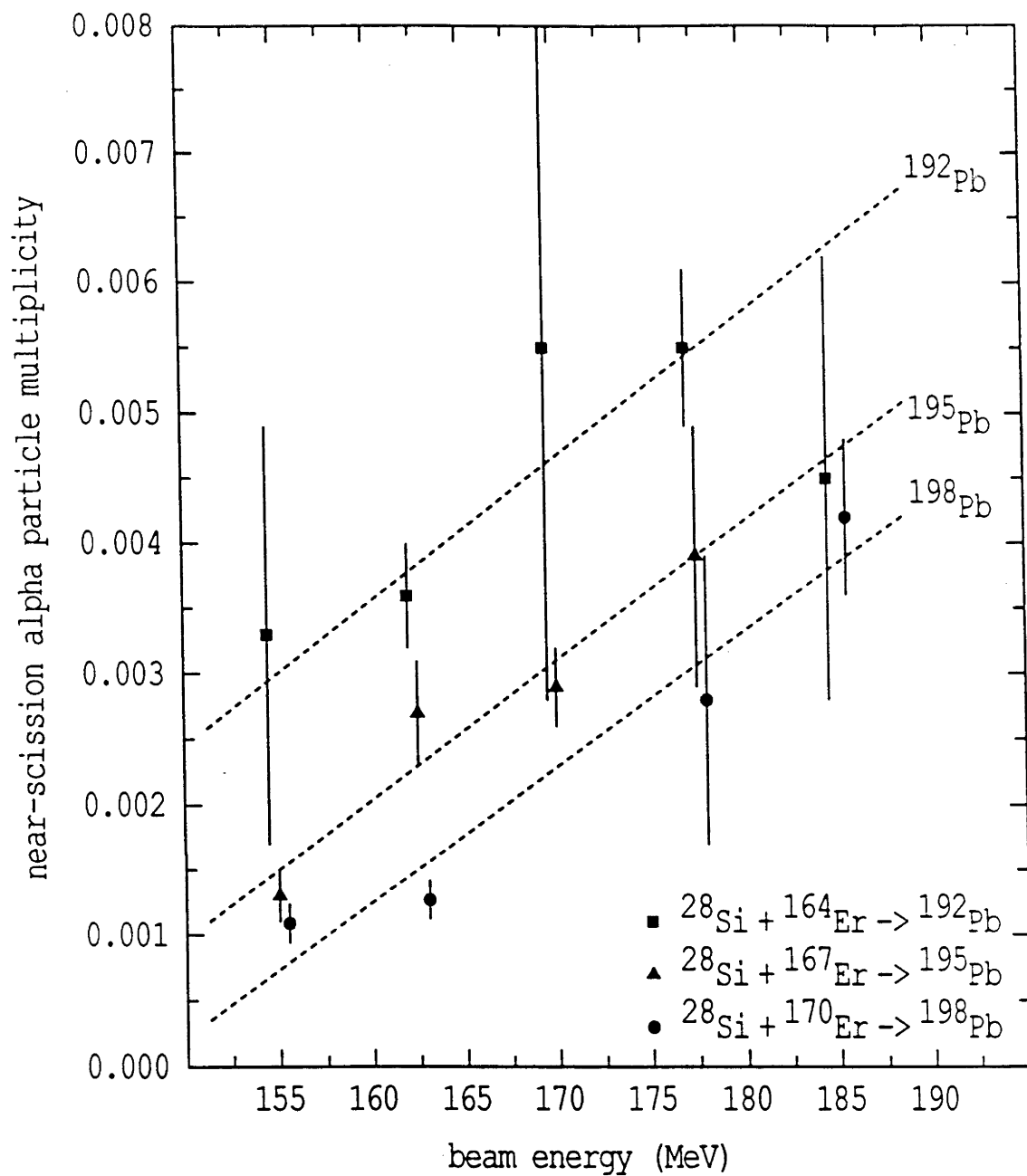


Figure 4.14 The near-scission alpha particle multiplicities versus beam energy. The squares, triangles and circles are the $^{28}\text{Si} + ^{164,167}$ and ^{170}Er results respectively. The dashed lines indicate the trends in the data.

beam energy (see figure 4.12). The FWHM of the energy distribution of the near-scission alpha particles is ~ 5.5 MeV. These mean energies and FWHM are consistent with the values obtained in other studies. For example, Wild *et al.* [WIL85] observed the near-scission alpha particles in coincidence with the spontaneous fission of ^{256}Fm to have a mean energy of ~ 15.5 MeV and a FWHM of ~ 11.3 MeV; Sowinski *et al.* [SOW86] obtained a mean energy of ~ 14 MeV and a FWHM of ~ 6 MeV for near-scission alpha particle emission in the reaction $108 \text{ MeV } ^{12}\text{C} + ^{197}\text{Au} \rightarrow ^{209}\text{Po}$; and Lindl *et al.* [LIN87] have identified near-scission alpha particles with a mean energy and FWHM of ~ 10 MeV and ~ 3 MeV respectively in the reactions $^{37}\text{Cl} + ^{124}\text{Sn} \rightarrow ^{161}\text{Ho}$ and $^{28}\text{Si} + ^{141}\text{Pr} \rightarrow ^{169}\text{Ta}$. In the present study, the FWHM of the angular distribution of the near-scission alpha particles about the plane perpendicular to the scission axis ranges from $\sim 24^\circ$ at a beam energy of 155 MeV to $\sim 42^\circ$ at a beam energy of 185 MeV (see figure 4.12). These values are much larger than the FWHM of $\sim 18^\circ$ observed in spontaneous fission, thermal- and fast-neutron induced fission, 11 to 21 MeV proton induced fission and 13.5 MeV deuteron induced fission [SIN89]. The dependence of the present near-scission alpha particle multiplicities on the beam energy and the mass of the target is similar to the dependence of the pre-scission and post-scission multiplicities on these quantities. This supports the conjecture that the near-scission emission in heavy-ion induced fission is a statistical decay process, but does not rule out a dynamical process such as the snapping of the neck at scission which may depend on excitation energy and/or angular momentum. Three body trajectory calculations indicate that a mean energy of ~ 14 MeV for the near-scission alpha particle emission can only be accounted for by emission from a region between the fission fragments and close to the scission axis (ie from the neck region). Near-scission emission from the fragments, away from the neck region as

Table 4.7 The $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission proton (π_{pre}) and alpha particle (α_{pre}) multiplicities. E_{lab} is the laboratory energy of the beam, $\bar{E}_{\text{target}}$ the mean energy of the beam in the target (estimated using the electronic stopping powers of [NOR70]), and E_x is the excitation of the ^{192}Pb nuclei immediately following fusion, using $\bar{E}_{\text{target}}$ as the kinetic energy of the ^{28}Si and a Q value for the fusion reaction calculated using equation 2.86. All energies in MeV.

E_{lab}	$\bar{E}_{\text{target}}$	E_x	π_{pre}	α_{pre}
140.0	138.1	51.4	0.0103 ± 0.0019	—
147.5	145.7	57.9	0.020 ± 0.003	—
155.0	153.2	64.3	0.0405 ± 0.0014	0.024 ± 0.003
162.5	160.7	70.7	0.052 ± 0.002	0.0379 ± 0.0013
170.0	168.3	77.2	0.075 ± 0.004	0.0506 ± 0.0046
177.5	175.8	83.6	0.078 ± 0.004	0.0626 ± 0.0018
185.0	183.3	90.0	0.106 ± 0.007	0.0734 ± 0.0027

Table 4.8 As for table 4.7 but for the reaction $^{28}\text{Si} + ^{167}\text{Er} \rightarrow ^{195}\text{Pb}$

E_{lab}	$\bar{E}_{\text{target}}$	E_x	π_{pre}	α_{pre}
155.0	153.2	67.5	0.0175 ± 0.0017	0.0152 ± 0.0004
162.5	160.7	73.9	0.0274 ± 0.0014	0.0271 ± 0.0016
170.0	168.3	80.4	0.0429 ± 0.0013	0.0387 ± 0.0012
177.5	175.8	86.9	0.0595 ± 0.0031	0.0534 ± 0.0030

Table 4.9 As for table 4.7 but for the reaction $^{28}\text{Si} + ^{170}\text{Er} \rightarrow ^{198}\text{Pb}$

E_{lab}	$\bar{E}_{\text{target}}$	E_x	π_{pre}	α_{pre}
155.0	153.7	71.9	0.0089 ± 0.0004	0.0085 ± 0.0004
162.5	161.2	78.3	0.0165 ± 0.0006	0.0167 ± 0.0005
177.5	176.2	91.2	0.035 ± 0.001	0.0373 ± 0.0017
185.0	183.8	97.7	0.0499 ± 0.0028	0.0508 ± 0.0016

suggested by [BRU87], would produce alpha particles with energies substantially larger than those observed.

4.3 Statistical Model Analysis of Pre-scission Particle Emission

Before the pre-scission multiplicities extracted from the measured particle spectra can be compared to values from statistical model calculations, they need to be corrected for the atomic abundances of the non-dominant Er isotopes (see table 3.3). The pre-scission multiplicities from the ^{164}Er target measurements required increases ranging from +20% at a beam energy of 140 MeV, to +6% at a beam energy of 185 MeV. The ^{167}Er target measurements required no significant corrections since the contributions from the surrounding isotopes cancel each other out. The ^{170}Er target measurements required small decreases ranging from approximately -1% to -2%. Tables 4.7 to 4.9 contain the corrected pre-scission proton and alpha particle multiplicities.

All statistical model calculations shown in this section were carried out with the code JOANNE, discussed in sections 2.3 and 2.4. The inputs required by this code are: the mass and atomic numbers of the projectile and target nuclei; the beam energy; the Q-value for fusion (determined using equation 2.86); the level density parameter of the nuclei at the equilibrium deformation a_{eq} ; $a_{\text{sp}}/a_{\text{eq}}$, where a_{sp} is the level density parameter at the saddle-point; a scaling factor to vary the Sierk fission barriers k_f ; the fusion cross section (those of [HIN83] were used); the diffuseness of the fusion spin distribution ($\Delta L=9$ [HIN86] was taken for all calculations shown in this section); the pre-saddle delay time τ_d and the saddle-to-scission time τ_{ss} . In some recent attempts to determine transient delay times using measured pre-scission particle multiplicities, the fission decay width $\Gamma_f(t)$ has been assumed to vary with time according to equation 2.92 [HIN86, IKE90]. Theoretical calculations indicate that $d\Gamma_f(t)/dt$ is small for $t \ll$ the transient delay time and initially increases

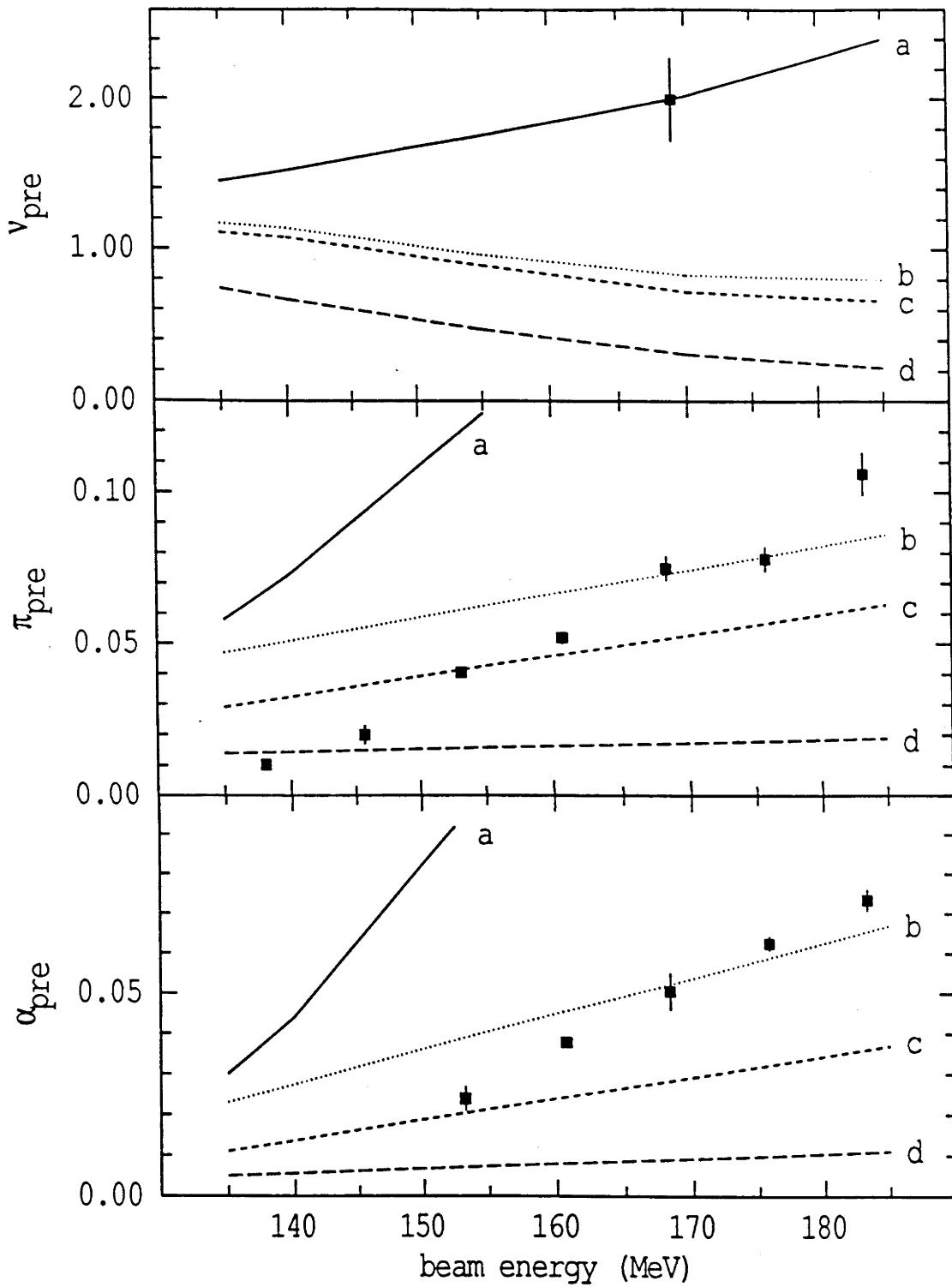


Figure 4.15 The $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron multiplicity of [HIN86] and the proton and alpha particle multiplicities from the present study, versus beam energy. The curves represent various statistical model calculations (see text).

with time (see figure 2.31). This suggests it is unrealistic to assume that $\Gamma_f(t)$ varies according to equation 2.92. In the analysis presented here, $\Gamma_f(t)$ is assumed to vary according to

$$\begin{aligned}\Gamma_f(t) &= 0 & \text{for } t < \tau_d \\ \Gamma_f(t) &= \Gamma_f(\infty) & t \geq \tau_d\end{aligned}\quad (4.1)$$

where $\Gamma_f(\infty)$ is the standard statistical model fission decay width. If the transition from low Γ_f to $\Gamma_f(\infty)$ does occur quickly then values of τ_d extracted from pre-scission particle multiplicities assuming $\Gamma_f(t)$ varies with time according to equation 4.1, are expected to be good estimates of the fission transient delay time, ie the time for $\Gamma_f(t)=0.9\times\Gamma_f(\infty)$. However, if this transition is slow, then fission may occur long before the fission width reaches its asymptotic value. In this case, the extracted values of τ_d will be estimates of the time taken for fission to compete favourably with the particle decay and may be very much smaller than the transient delay time.

Figure 4.15 compares the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron multiplicity of Hinde *et al.* [HIN86] and the proton and alpha particle multiplicities from the present study, to various statistical model calculations. Calculation (a) is with $a_{\text{eq}}=A/10.0 \text{ MeV}^{-1}$ and $a_{\text{sp}}/a_{\text{eq}}=1.00$ [HIN86]. To reproduce the evaporation residue excitation function and the neutron multiplicity, the Sierk barriers (see section 2.2.4) were scaled by $k_f=0.80$ and the pre-saddle delay was set to $\tau_d=70\times 10^{-21} \text{ s}$. Although the evaporation residue cross sections and the neutron multiplicity are reproduced by this calculation, the charged particle multiplicities are over-estimated by as much as a factor of six. Calculation (b) is with the same a_{eq} and $a_{\text{sp}}/a_{\text{eq}}$ as in calculation (a), with no pre-saddle delay and the Sierk barriers scaled by $k_f=0.83$ to fit the evaporation residue cross sections. With no fission delay, the fact that this calculation still over-

predicts the low energy charged particle multiplicities indicates that the statistical model parameters $a_{eq}=A/10.0 \text{ MeV}^{-1}$ and $a_{sp}/a_{eq}=1.00$ are not appropriate for nuclei with approximately 200 nucleons.

Calculations (c) and (d) are with $a_{eq}=A/7.5 \text{ MeV}^{-1}$ and $a_{sp}/a_{eq}=1.00$ and 1.05 respectively and no pre-saddle delay. These calculations show the sensitivity of the pre-scission particle multiplicities to the statistical model parameters a_{eq} and a_{sp}/a_{eq} and suggest the appropriate values for these parameters are larger than $A/10 \text{ MeV}^{-1}$ and 1.00 respectively. For calculation (c) the Sierk fission barriers were scaled by $k_f=0.87$ to reproduce the evaporation residue excitation function, while for calculation (d) with $a_{sp}/a_{eq}=1.05$, no simple uniform scaling of the fission barriers would reproduce the evaporation residue excitation function. Calculation (d) with $k_f=1.00$ only reproduces the evaporation residue cross section at the beam energy of 140 MeV and then increasingly underestimates the evaporation residue cross sections with increasing beam energy.

Two possible ways of removing this discrepancy are to allow k_f to increase with beam energy or to allow a_{sp}/a_{eq} to decrease with increasing beam energy. Fission barriers are expected to decrease with increasing temperature (see section 2.2.5), and so allowing k_f to increase with beam energy seems unphysical. However, the ratio of the level density parameters a_{sp}/a_{eq} is expected to decrease with spin (see section 2.3.2). Even though most statistical model codes (including JOANNE) take a_{sp}/a_{eq} to be independent of spin, this is not expected to significantly affect the calculation of evaporation residue cross sections if an appropriate effective value of a_{sp}/a_{eq} is used. This is because at high spins the fission probability of compound nuclei is close to unity, at low spins the fission probability is close to zero, and only in a limited spin region does the fission probability differ significantly from 1 or 0 and thus depend on the

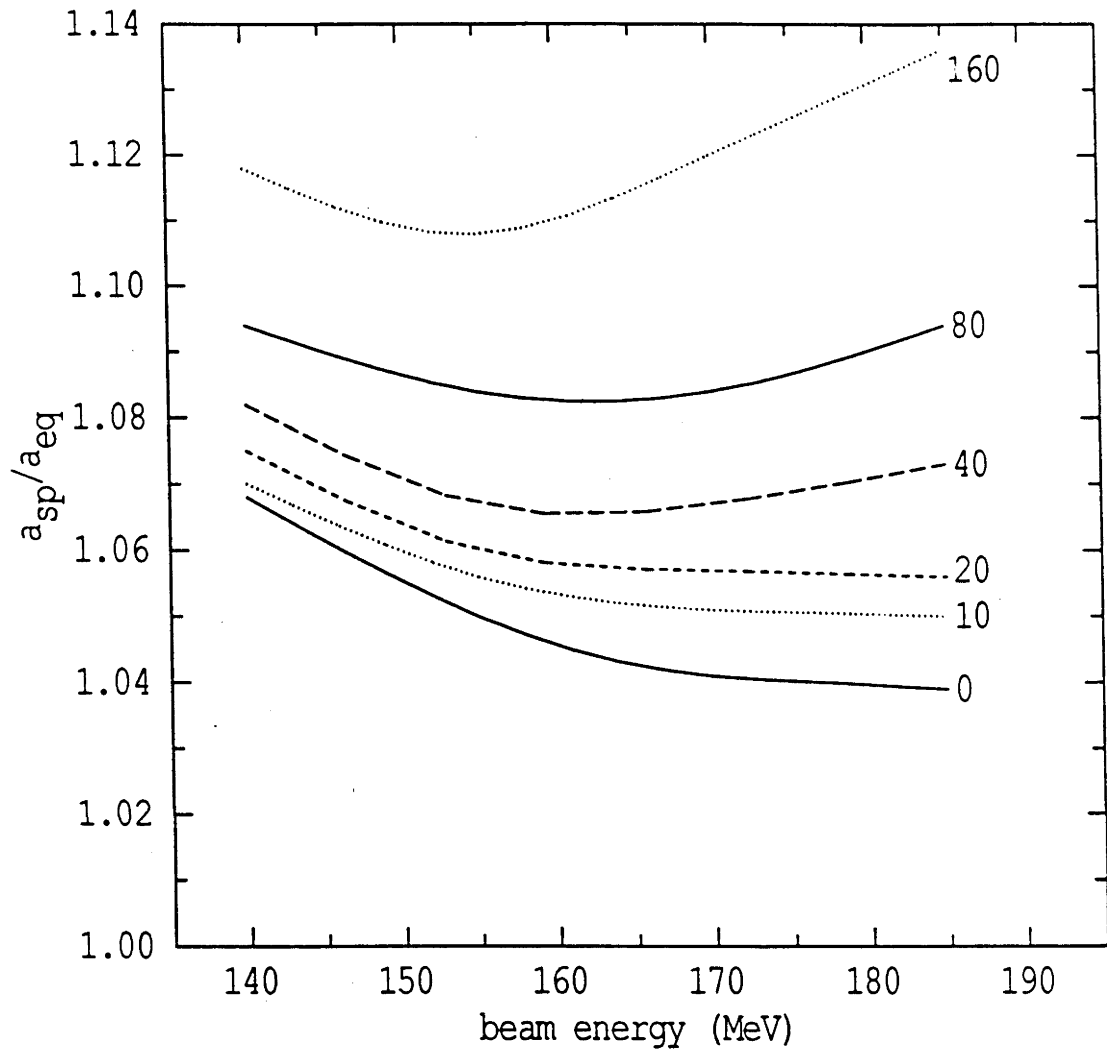


Figure 4.16 The a_{sp}/a_{eq} required to reproduce the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ evaporation residue excitation function of [HIN83] with $a_{eq}=A/8.6 \text{ MeV}^{-1}$ and $k_f=1.00$. The numbers to the right of the curves are pre-saddle delay times τ_d in units of 10^{-21} s .

precise value of the statistical model parameter a_{sp}/a_{eq} . As the beam energy increases and the fusion spin distribution moves through the spin region where the fission probability significantly differs from 1 or 0, the effective value of a_{sp}/a_{eq} required to reproduce the evaporation residue cross sections is expected to drop, as the mean spin in the critical region increases. Eventually, increases in beam energy (and thus fusion cross section) will only change the fusion spin distribution above the critical region and thus the effective value of a_{sp}/a_{eq} required to reproduce the evaporation residue cross sections will become independent of the beam energy. This suggests that if values of a_{sp}/a_{eq} much larger than 1.00 are being used in statistical model codes that take a_{sp}/a_{eq} to be independent of spin, then allowing a_{sp}/a_{eq} to decrease with increasing beam energy to fit evaporation residue excitation functions is more reasonable than allowing k_f to increase with beam energy.

In an attempt to obtain information about the pre-saddle delay time τ_d and the saddle-to-scission transit time τ_{ss} , from the $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ pre-scission particle multiplicities, using the statistical model code JOANNE, the following procedure was used: (1) the level density parameter of the daughter nuclei, after particle emission, was assumed to be $a_{eq}=A/8.6 \text{ MeV}^{-1}$ as predicted by equation 2.52 for nuclei with $A \approx 195$; (2) the Sierk barriers were not scaled, ie $k_f = 1.00$; and (3) for each pre-saddle delay time τ_d , a_{sp}/a_{eq} was allowed to vary with beam energy to reproduce the appropriate evaporation residue excitation function of Hinde *et al.* [HIN83].

Figure 4.16 shows the a_{sp}/a_{eq} needed to reproduce the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ evaporation residue excitation function of [HIN83] with $a_{eq}=A/8.6 \text{ MeV}^{-1}$ and $k_f = 1.00$. Note that for $\tau_d \lesssim 20 \times 10^{-21} \text{ s}$, a_{sp}/a_{eq} varies with beam energy as discussed above, ie a_{sp}/a_{eq} initially decreases with beam energy and approaches a constant value at the higher beam

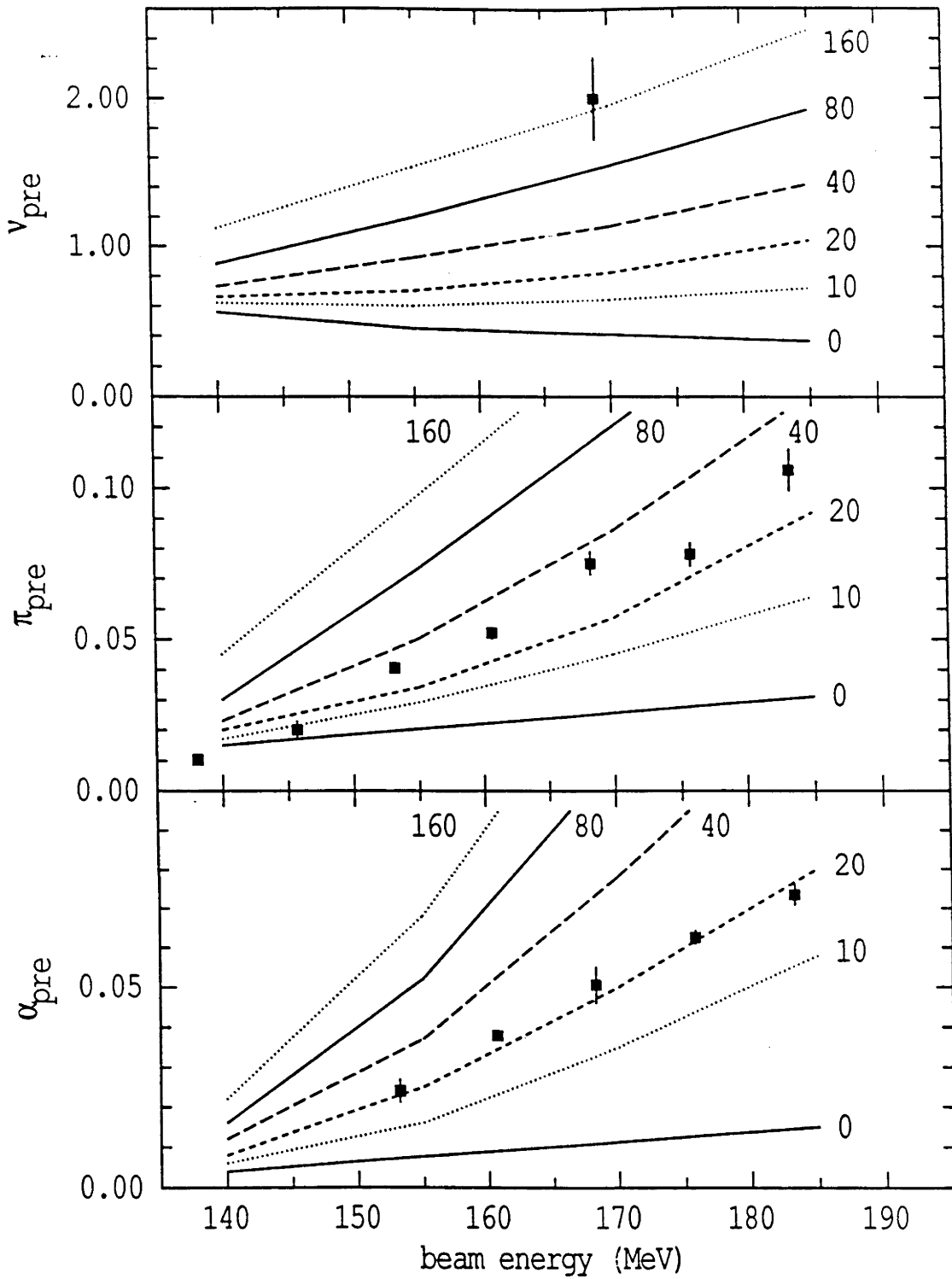


Figure 4.17 The experimental $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities and statistical model calculations with various pre-saddle delays τ_d ; the saddle-to-scission time τ_{ss} set to zero; $a_{eq}=A/8.6 \text{ MeV}^{-1}$; $k_f=1.00$ and the parameter a_{sp}/a_{eq} adjusted to fit the evaporation residue excitation function of [HIN83]. The numbers at the right hand end of the curves representing the calculations are pre-saddle delay times in units of 10^{-21} s .

energies. Figure 4.17 compares statistical model calculations of the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities with various pre-saddle delays τ_d ($\tau_{ss}=0$) to the measured multiplicities. With $\tau_{ss}=0$ the pre-saddle delays required to fit the experimental pre-scission neutron, proton and alpha particle multiplicities are 160×10^{-21} s, 30×10^{-21} s and 20×10^{-21} s respectively. The small τ_d required to fit the alpha particle multiplicities compared to the τ_d required to fit the neutron multiplicities is in qualitative agreement with the recent measurement and statistical model analysis of pre-scission alpha particle emission from the reaction $^{19}\text{F} + ^{197}\text{Au}$ by Ikezoe *et al.* [IKE90]. Ikezoe *et al.* concluded that their results support the conjecture that the decay width of alpha particle emission grows on a similar time scale to that of fission. If this conjecture was true then the present proton data would suggest the proton decay width also grows on a similar time scale to that of fission. Even if one was willing to believe that the decay width for the emission of a particle as simple as an alpha particle grew on a time scale roughly equal to that of fission, it would be unrealistic to believe that the decay width for the emission of a single nucleon would grow on such a long time scale.

A more plausible explanation of the apparent discrepancy between the pre-saddle delay times τ_d required to fit the light charged particle multiplicities and the much larger value of τ_d required to fit the neutron multiplicities with the saddle-to-scission time τ_{ss} set to zero, is that τ_d is less than 20×10^{-21} s; τ_{ss} is long enough to allow a significant number of neutrons to be emitted by the post-saddle compound systems; and the proton and alpha particle emission rates are suppressed relative to the neutron emission rate by the deformation of the post-saddle compound systems. A suppression of the light charged particle emission rates

Table 4.10 Estimates of the change in the deformation energy of non-rotating ^{192}Pb compound nuclei at the saddle- and scission-points, following neutron, proton and alpha particle emission.

	change in deformation energy (MeV)	
	Saddle-point	Scission-point
neutron emission	-0.2	-0.4
proton emission	1.3	2.7
alpha particle emission	2.1	4.5

relative to the neutron emission rate with increasing deformation may, at first, seem unrealistic. One might expect an increase in the proton and alpha particle emission relative to the neutron emission due to the reduction in the charged particle emission barriers that comes with increased deformation. The increase in deformation energy of daughter nuclei following proton and alpha particle decay, relative to that for neutron emission is, however, often overlooked. This effect causes a suppression of the charged particle emission relative to neutron emission with increasing deformation. This is easily illustrated in the case of particle emission from a nucleus at the saddle-point deformation, where it is well known that the fission barrier decreases when a neutron is removed but increases following the emission of charged particles. Proton and alpha particle emission from a nucleus at the saddle-point deformation is thus hindered by the increase in the deformation energy of the daughter nucleus. This effect is larger for alpha particle decay than for proton decay and becomes larger with increasing deformation. The code JOANNE models this effect by taking the rotation plus deformation energies of the parent and daughter nuclei associated with post-saddle particle emission to be equal to the average of their respective saddle- and scission-point configurations. Table 4.10 contains estimates of the change in the deformation energy of non-rotating ^{192}Pb compound nuclei at the saddle- and scission-points, following neutron, proton and alpha particle emission.

Another factor which contributes to the suppression of the alpha particle emission relative to the neutron emission, with increasing deformation, is the reduction in the slope of the rotation plus deformation energy of compound nuclei as a function of spin, with increasing moment of inertia. As mentioned in section 2.3.2, the emission of alpha particles is enhanced relative to the emission of protons and neutrons with increasing

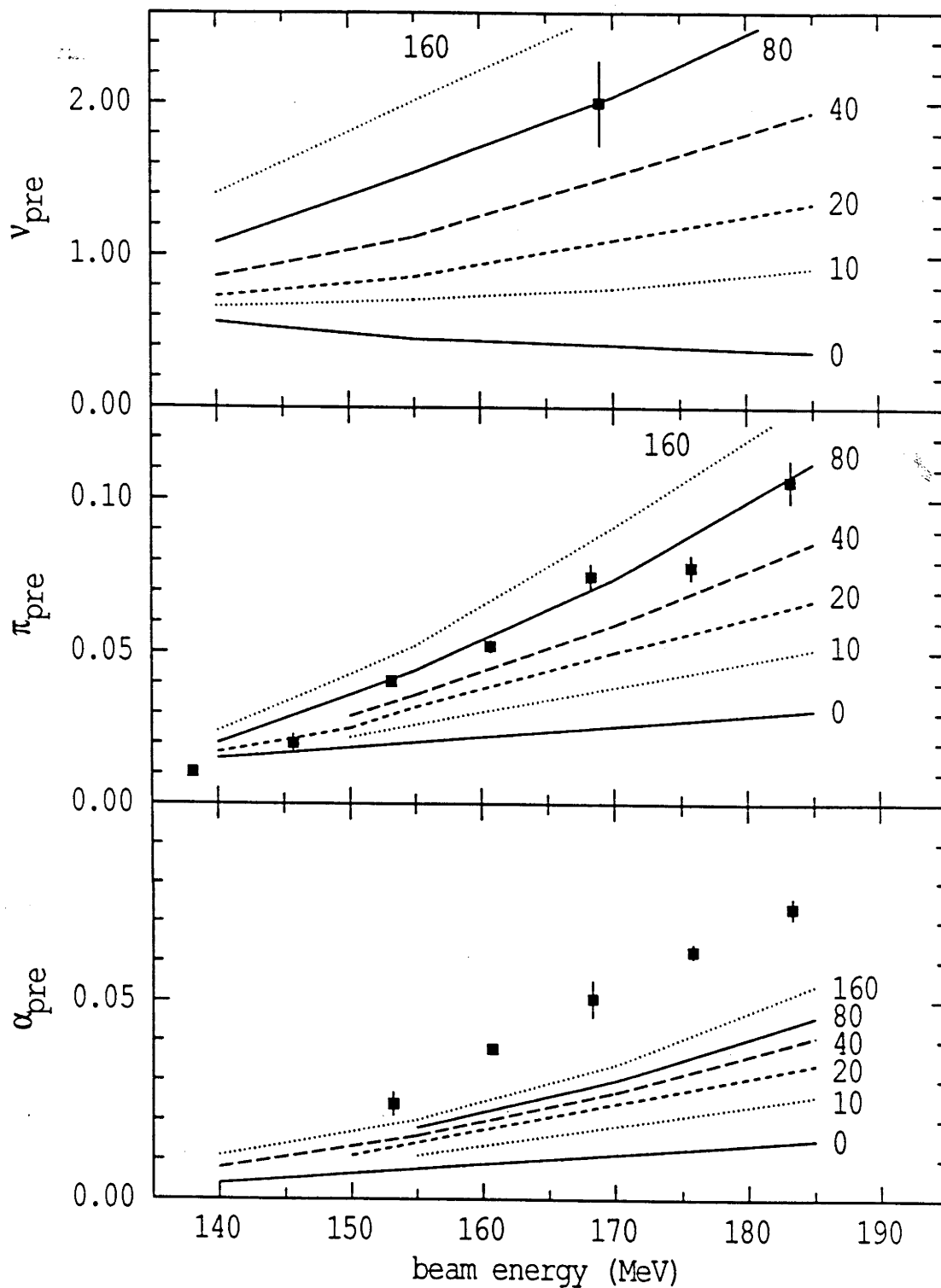


Figure 4.18 The experimental $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities and statistical model calculations with various saddle-to-scission times τ_{ss} and the pre-saddle delay time τ_{d} set to zero. The numbers at the right hand end of the curves representing the calculations are saddle-to-scission times in units of 10^{-21} s.

spin due to the increasing slope of the rotation plus deformation energy of the daughter nuclei with increasing angular momentum (see figure 2.16). A decrease in the slope of the rotation plus deformation energy as a function of spin, caused by an increase in the moment of inertia of the compound nuclei, reduces this enhancement of the alpha particle emission and thus produces a suppression of the alpha particle emission relative to the neutron and proton emission.

Figure 4.18 compares statistical model calculations of the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities, with various saddle-to-scission times τ_{ss} ($\tau_d=0$), to the experimental multiplicities. With the pre-saddle delay time τ_d set to zero, both the measured neutron and proton multiplicities can be fitted with a saddle-to-scission time of $\tau_{ss}=80 \times 10^{-21}$ s. A time much larger than 160×10^{-21} s would be required to fit the alpha particle multiplicities. Figure 4.19 shows combinations of τ_{ss} and τ_d that can be used to give reasonable fits to the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities. The combination that gives the best simultaneous fit to all three sets of multiplicities (ν , π and α) is $\tau_d \approx 11 \times 10^{-21}$ s and $\tau_{ss} \approx 53 \times 10^{-21}$ s. Figure 4.20 compares the experimental mean energies of the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission protons and alpha particles to the mean energies predicted by JOANNE using $\tau_d = 11 \times 10^{-21}$ s and $\tau_{ss} = 53 \times 10^{-21}$ s. The calculated mean proton energies seem to be in reasonable agreement with the measured values. The mean alpha particle energies are, however, over-predicted in the statistical model calculations by ~ 1 MeV. This suggests the alpha particle transmission coefficients determined using the optical model potentials of [HUI62] are inappropriate for calculating pre-scission alpha particle emission in the $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ reactions.

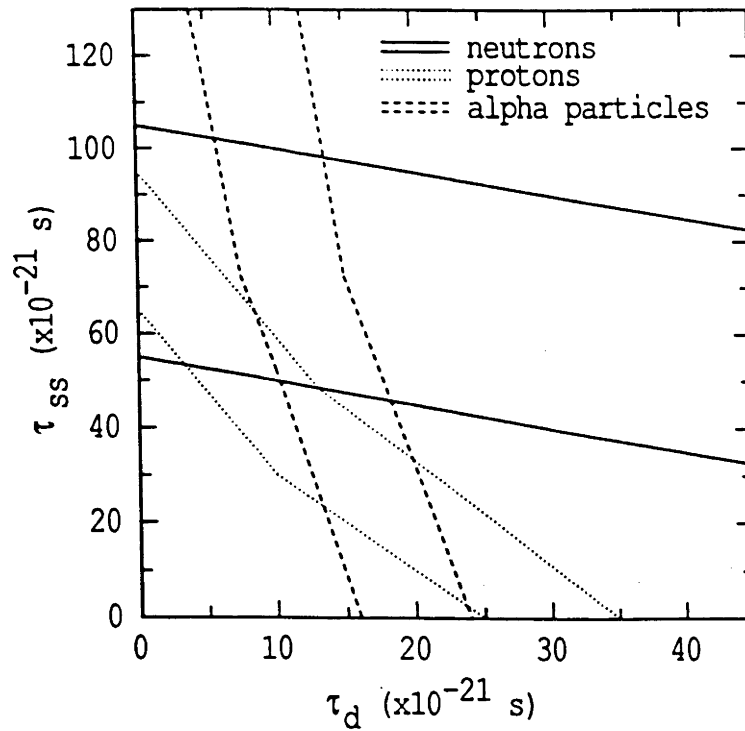


Figure 4.19 The combinations of τ_{ss} and τ_d between the solid, dotted and dashed curves can be used to give reasonable fits to the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities respectively.

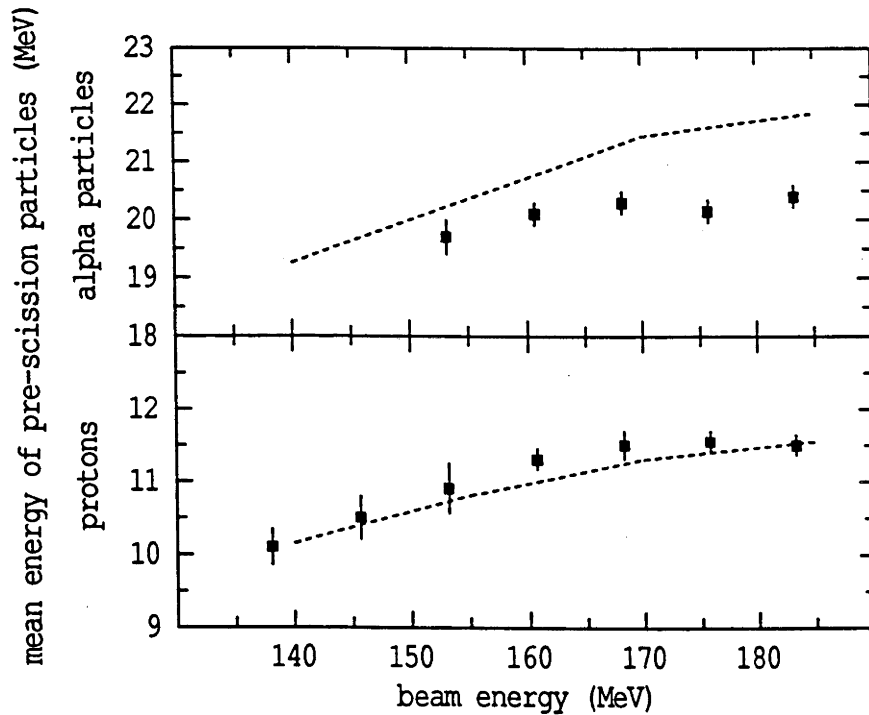


Figure 4.20 The experimental mean energies of the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission protons and alpha particles and the mean energies predicted by JOANNE using $\tau_d = 11 \times 10^{-21}$ s and $\tau_{ss} = 53 \times 10^{-21}$ s.

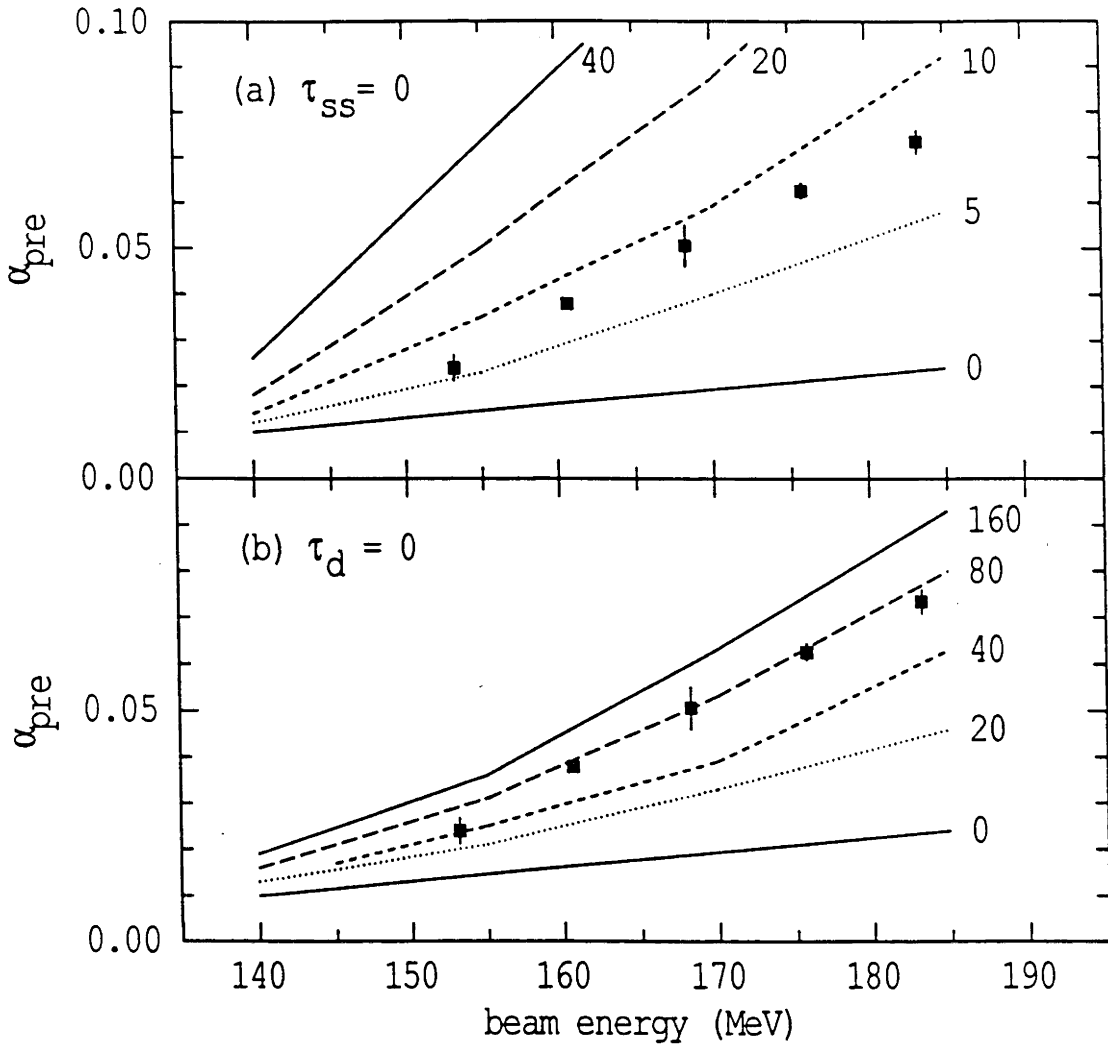


Figure 4.21 The experimental $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission alpha particle multiplicities and statistical model calculations with the standard alpha particle transmission coefficients shifted towards lower energies by 1 MeV. (a) $\tau_{\text{ss}}=0$ and the numbers at the right hand end of the curves representing the calculations are pre-saddle delay times τ_d in units of 10^{-21} s. (b) $\tau_d=0$ and the numbers at the right hand end of the curves representing the calculations are saddle-to-scission times τ_{ss} in units of 10^{-21} s.

To obtain a better agreement between the calculated and measured mean energies of the pre-scission alpha particles, calculations were performed with the standard alpha particle transmission coefficients (determined using the potentials of [HUI62]) artificially shifted towards lower energies by 1 MeV. The enhancement of the alpha particle emission rate produced by this 1 MeV shift of the alpha particle transmission coefficients produces an increase of $\sim 1\%$ in the values of a_{sp}/a_{eq} required to fit the evaporation residue cross sections of [HIN83]. Figure 4.21 compares the measured $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission alpha particle multiplicities to statistical model calculations with the standard alpha particle transmission coefficients shifted towards lower energies by 1 MeV and (a) $\tau_{ss}=0$ and various values of τ_d and (b) $\tau_d=0$ and various values of τ_{ss} . The neutron and proton multiplicities are relatively unaffected by the enhanced alpha particle emission. Figure 4.22 shows combinations of τ_{ss} and τ_d that can be used to give reasonable fits to the neutron, proton and alpha particle multiplicities when the standard alpha particle transmission coefficients are shifted towards lower energies by 1 MeV. The combination that gives the best simultaneous fit to all three sets of multiplicities (ν, π and α) is $\tau_d=0$ and $\tau_{ss} \approx 80 \times 10^{-21}$ s. Figure 4.23 compares the experimental mean energies of the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission alpha particles to the mean energies predicted by JOANNE with the 1 MeV shift in the alpha particle transmission coefficients, $\tau_d=0$ and $\tau_{ss} = 80 \times 10^{-21}$ s. The simultaneous fits to the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities with (a) no adjustment of the alpha particle transmission coefficients, $\tau_d = 11 \times 10^{-21}$ s and $\tau_{ss} = 53 \times 10^{-21}$ s and (b) a 1 MeV shift in the alpha particle transmission coefficients to lower energies, $\tau_d=0$ and $\tau_{ss} = 80 \times 10^{-21}$ s are shown in figure 4.24.

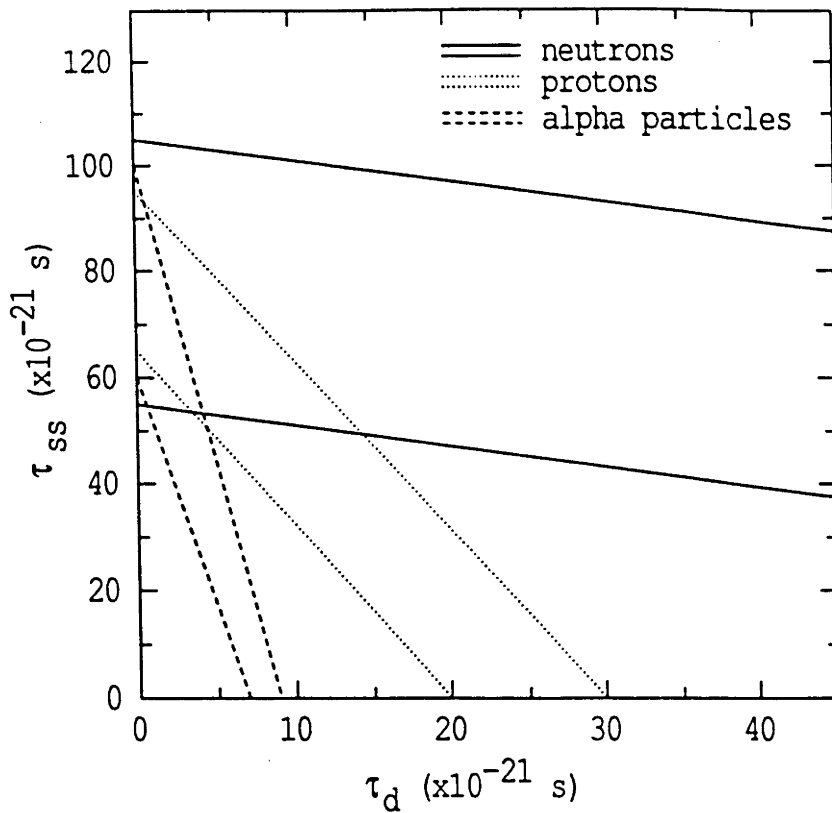


Figure 4.22 The combinations of τ_{ss} and τ_d between the solid, dotted and dashed curves can be used to give reasonable fits to the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities respectively when the alpha particle transmission coefficients are shifted towards lower energies by 1 MeV.

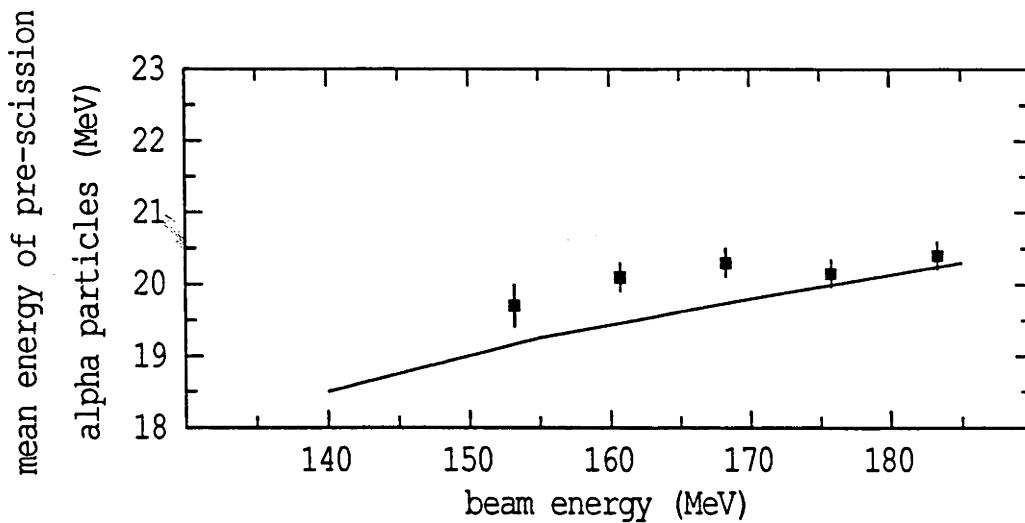


Figure 4.23 The experimental mean energies of the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission alpha particles and the mean energies predicted by JOANNE with the standard alpha particle transmission coefficients shifted towards lower energies by 1 MeV, $\tau_d=0$ and $\tau_{ss}=80 \times 10^{-21}$ s (solid curve).

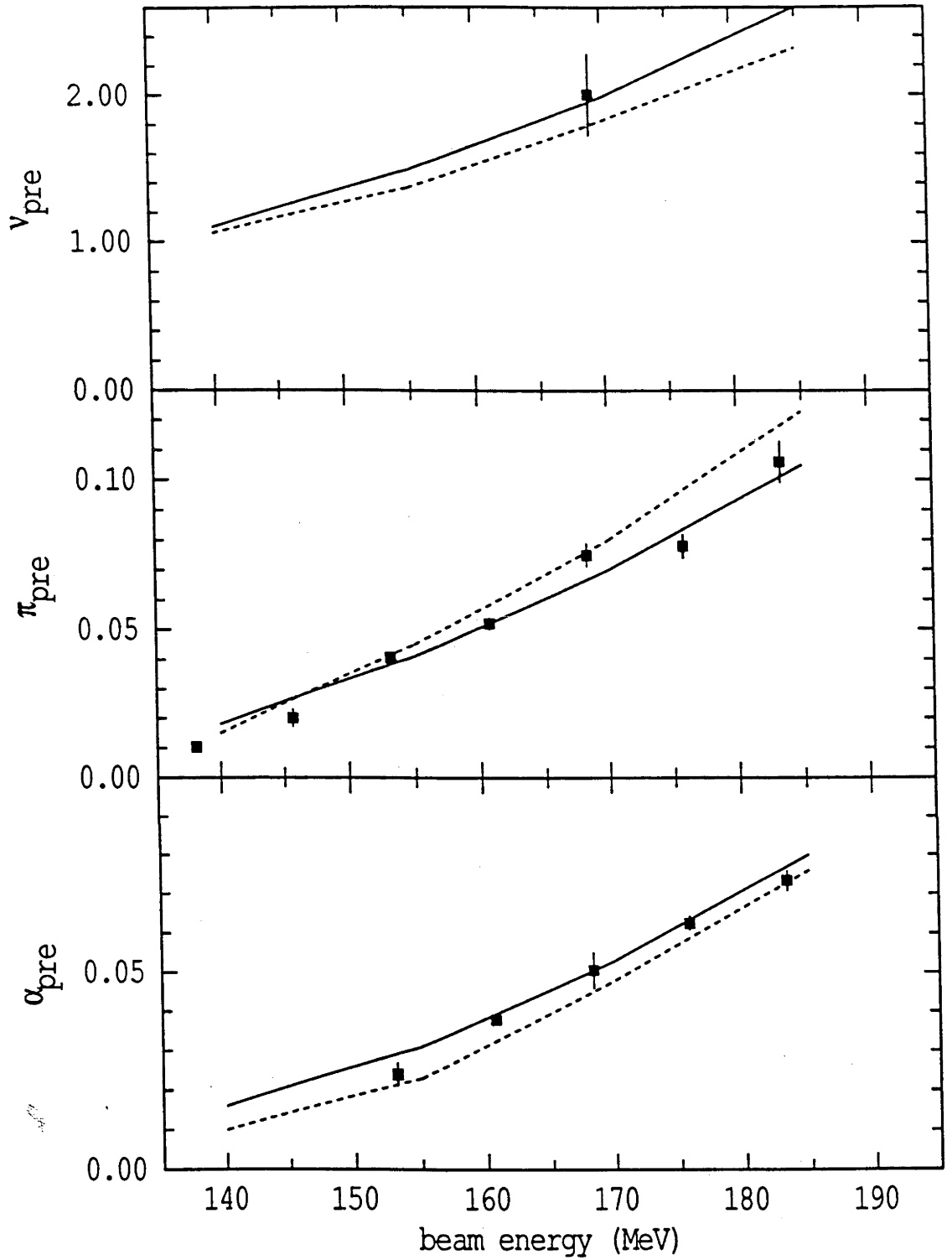


Figure 4.24 The simultaneous fits to the $^{28}\text{Si} + ^{164}\text{Er} \rightarrow ^{192}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities with no adjustment of the alpha particle transmission coefficients, $\tau_d=11 \times 10^{-21}$ s and $\tau_{\text{ss}}=53 \times 10^{-21}$ s (dashed curves); and a 1 MeV shift in the alpha particle transmission coefficients to lower energies, $\tau_d=0$ and $\tau_{\text{ss}}=80 \times 10^{-21}$ s (solid curves).

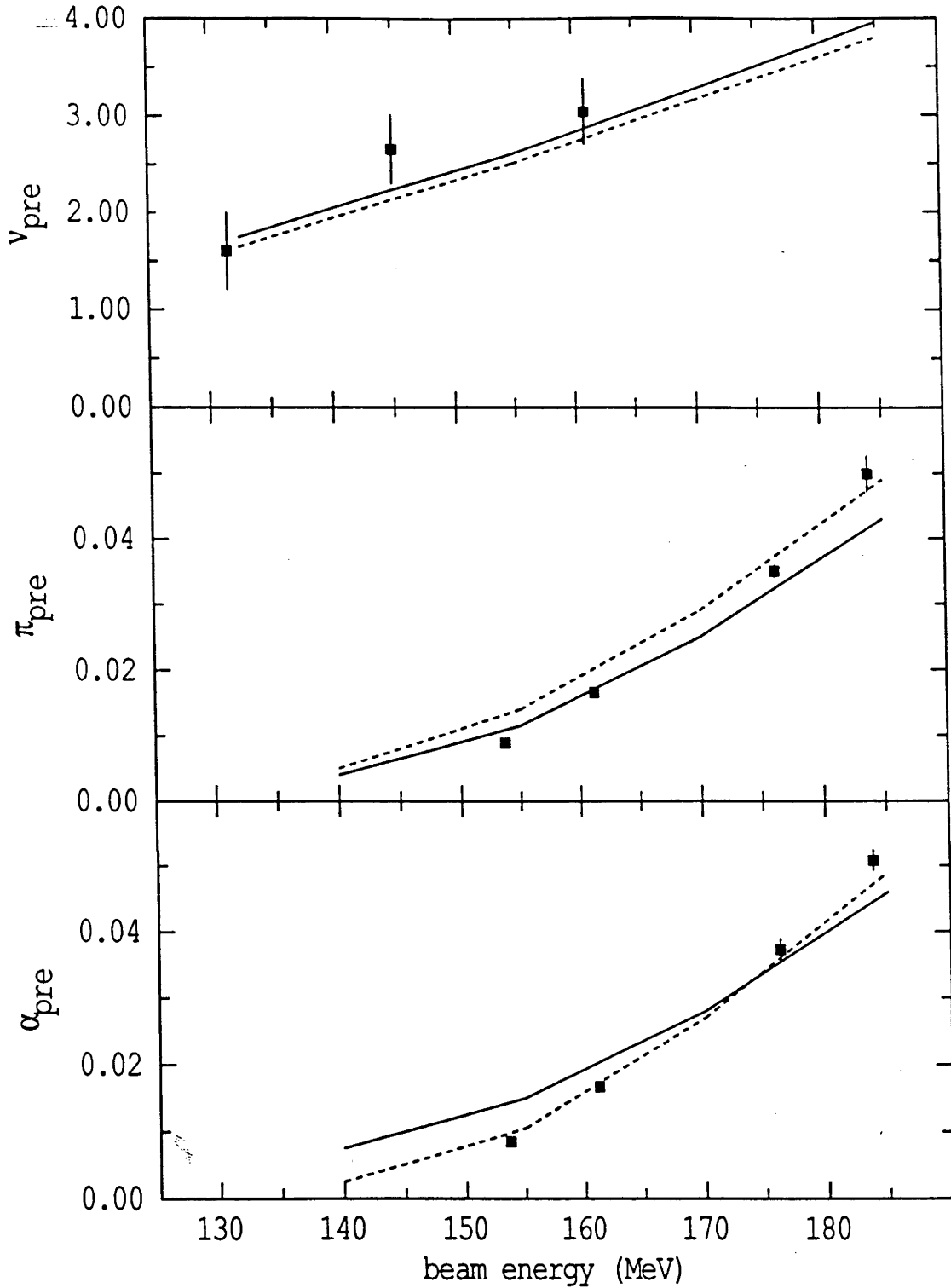


Figure 4.25 The simultaneous fits to the $^{28}\text{Si} + ^{170}\text{Er} \rightarrow ^{198}\text{Pb}$ pre-scission neutron multiplicities of [HIN86] and the proton and alpha particle multiplicities from the present study, with no adjustment of the alpha particle transmission coefficients, $\tau_d = 12 \times 10^{-21} \text{ s}$ and $\tau_{ss} = 60 \times 10^{-21} \text{ s}$ (dashed curves); and a 1 MeV shift in the alpha particle transmission coefficients to lower energies, $\tau_d = 0$ and $\tau_{ss} = 80 \times 10^{-21} \text{ s}$ (solid curves).

Similar calculations were also performed for the $^{28}\text{Si} + ^{167,170}\text{Er} \rightarrow ^{195,198}\text{Pb}$ reactions. The best simultaneous fits to the $^{28}\text{Si} + ^{170}\text{Er} \rightarrow ^{198}\text{Pb}$ pre-scission neutron, proton and alpha particle multiplicities with (a) no adjustment of the alpha particle transmission coefficients, $\tau_d = 12 \times 10^{-21}$ s and $\tau_{ss} = 60 \times 10^{-21}$ s and (b) a 1 MeV adjustment of the alpha particle transmission coefficients to lower energies, $\tau_d = 0$ and $\tau_{ss} = 80 \times 10^{-21}$ s are shown in figure 4.25. The measured $^{28}\text{Si} + ^{167}\text{Er} \rightarrow ^{195}\text{Pb}$ pre-scission proton and alpha particle multiplicities (no neutron measurements presently exist) are compared to statistical model calculations with (a) no adjustment of the alpha particle transmission coefficients, $\tau_d = 12 \times 10^{-21}$ s and $\tau_{ss} = 55 \times 10^{-21}$ s and (b) a 1 MeV adjustment of the alpha particle transmission coefficients to lower energies, $\tau_d = 0$ and $\tau_{ss} = 80 \times 10^{-21}$ s are shown in figure 4.26. The mean alpha particle energies, predicted by the calculations shown in figures 4.25 and 4.26, are compared to their experimental values in figure 4.27.

The statistical model calculations, with the 1 MeV shift in the alpha particle transmission coefficients, tend to under-estimate the mean energies of the pre-scission alpha particles by $\lesssim 0.5$ MeV, while the calculations with no adjustment of the alpha particle transmission coefficients over-estimate the mean pre-scission alpha particle energies by ~ 1 MeV. This suggests the true values of the pre-saddle delay time τ_d and the saddle-to-scission time τ_{ss} , are somewhere between those values obtained using the calculations with and without the 1 MeV shift in the alpha particle transmission coefficients. The analysis presented here indicates that for $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ fusion-fission reactions $\tau_d < 10 \times 10^{-21}$ s, $\tau_{ss} = (70 \pm 20) \times 10^{-21}$ s and for beam energies ≥ 155 MeV most of the pre-scission particles are emitted by the compound nuclei during their transit from saddle to scission. Although the calculations shown in figures 4.24 to 4.26, qualitatively reproduce the overall trends in the pre-scission

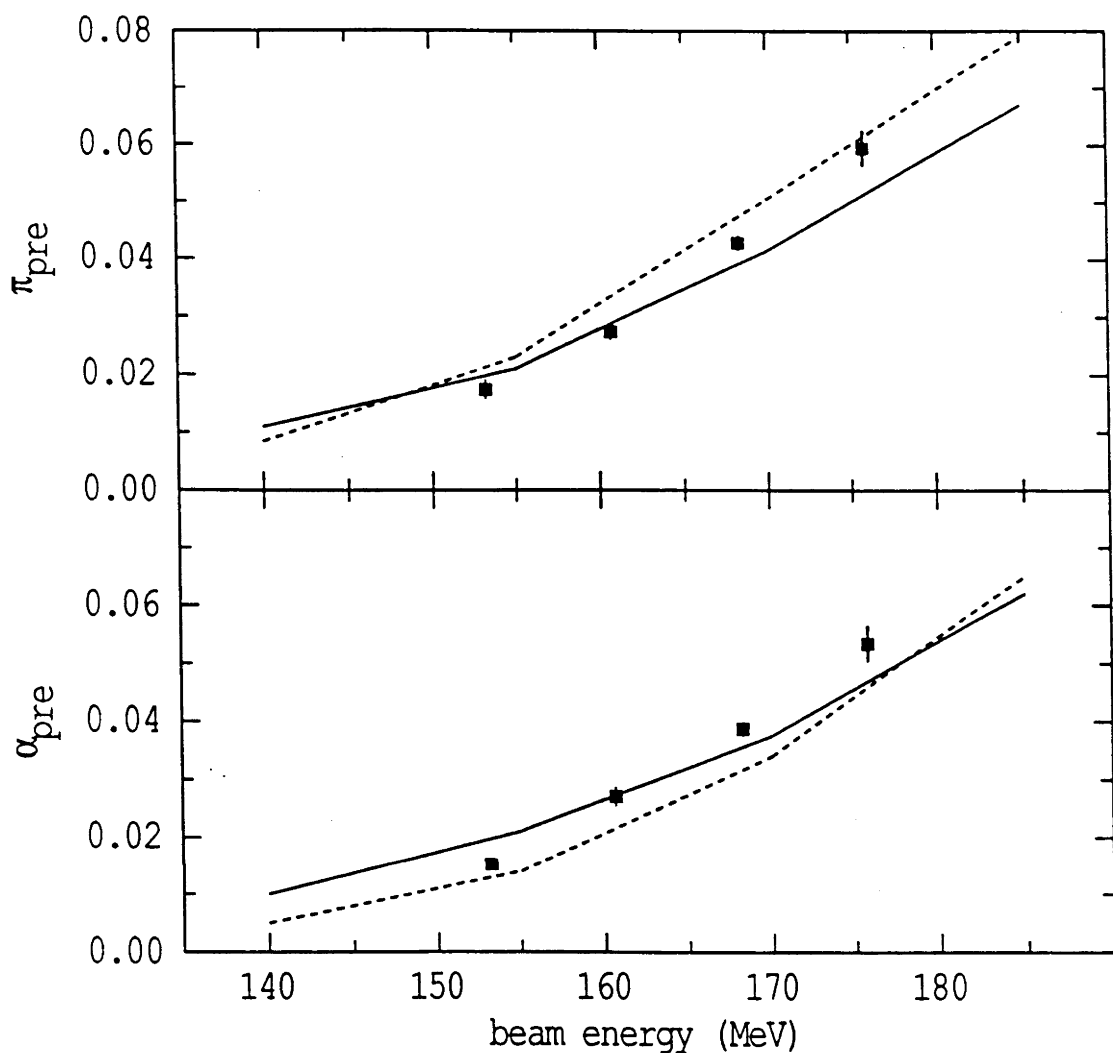


Figure 4.26 The experimental $^{28}\text{Si} + ^{167}\text{Er} \rightarrow ^{195}\text{Pb}$ pre-scission proton and alpha particle multiplicities and statistical model calculations with no adjustment of the alpha particle transmission coefficients, $\tau_d = 12 \times 10^{-21}$ s and $\tau_{ss} = 55 \times 10^{-21}$ s (dashed curves); and a 1 MeV shift in the alpha particle transmission coefficients to lower energies, $\tau_d = 0$ and $\tau_{ss} = 80 \times 10^{-21}$ s (solid curves).

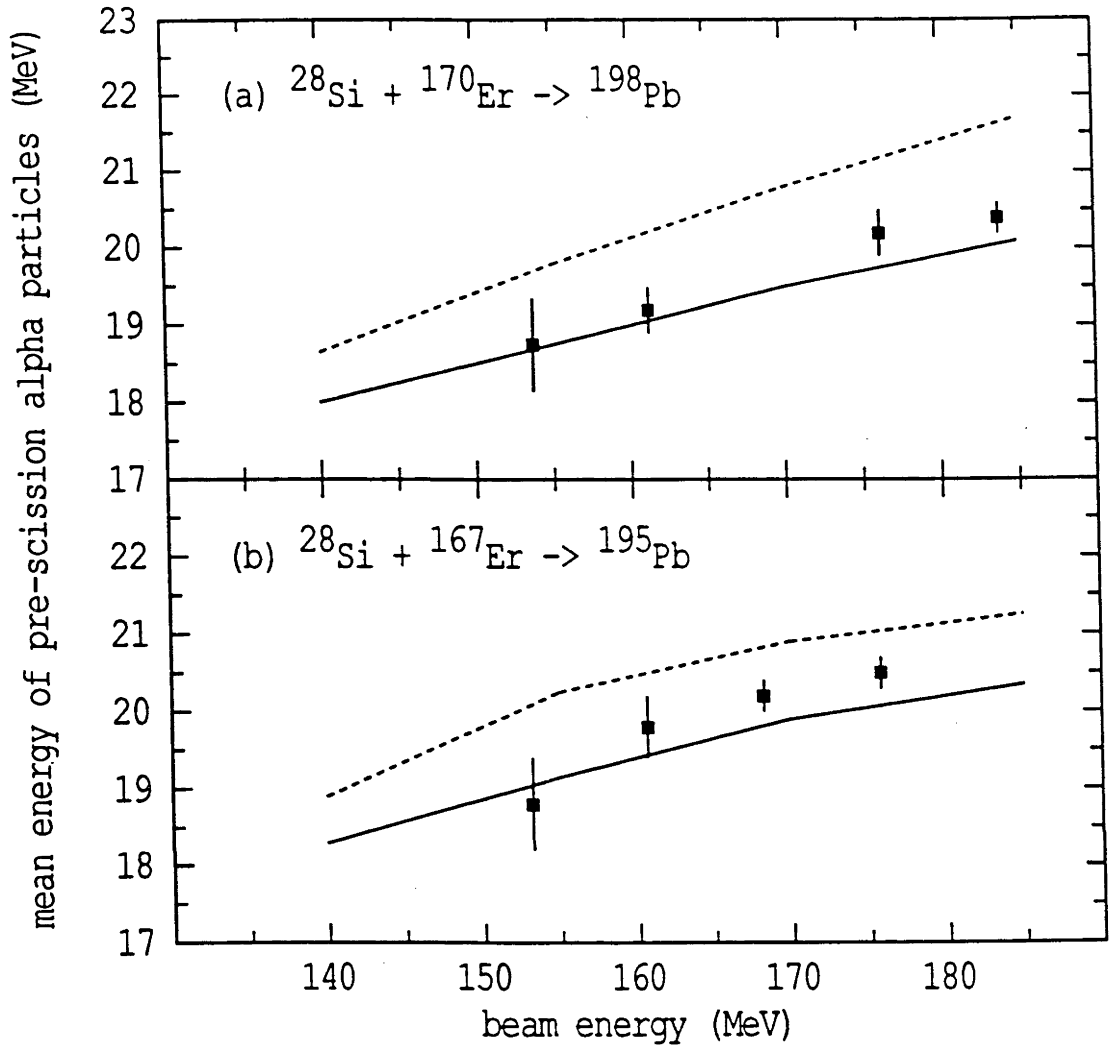


Figure 4.27 The experimental mean energies of the $^{28}\text{Si} + ^{167,170}\text{Er} \rightarrow ^{195,198}\text{Pb}$ pre-scission alpha particles and the mean energies predicted by the calculations shown in figures 2.25 and 2.26. No adjustment of alpha particle transmission coefficients (dashed curves); and 1 MeV shift in the alpha particle transmission coefficients towards lower energies (solid curves).

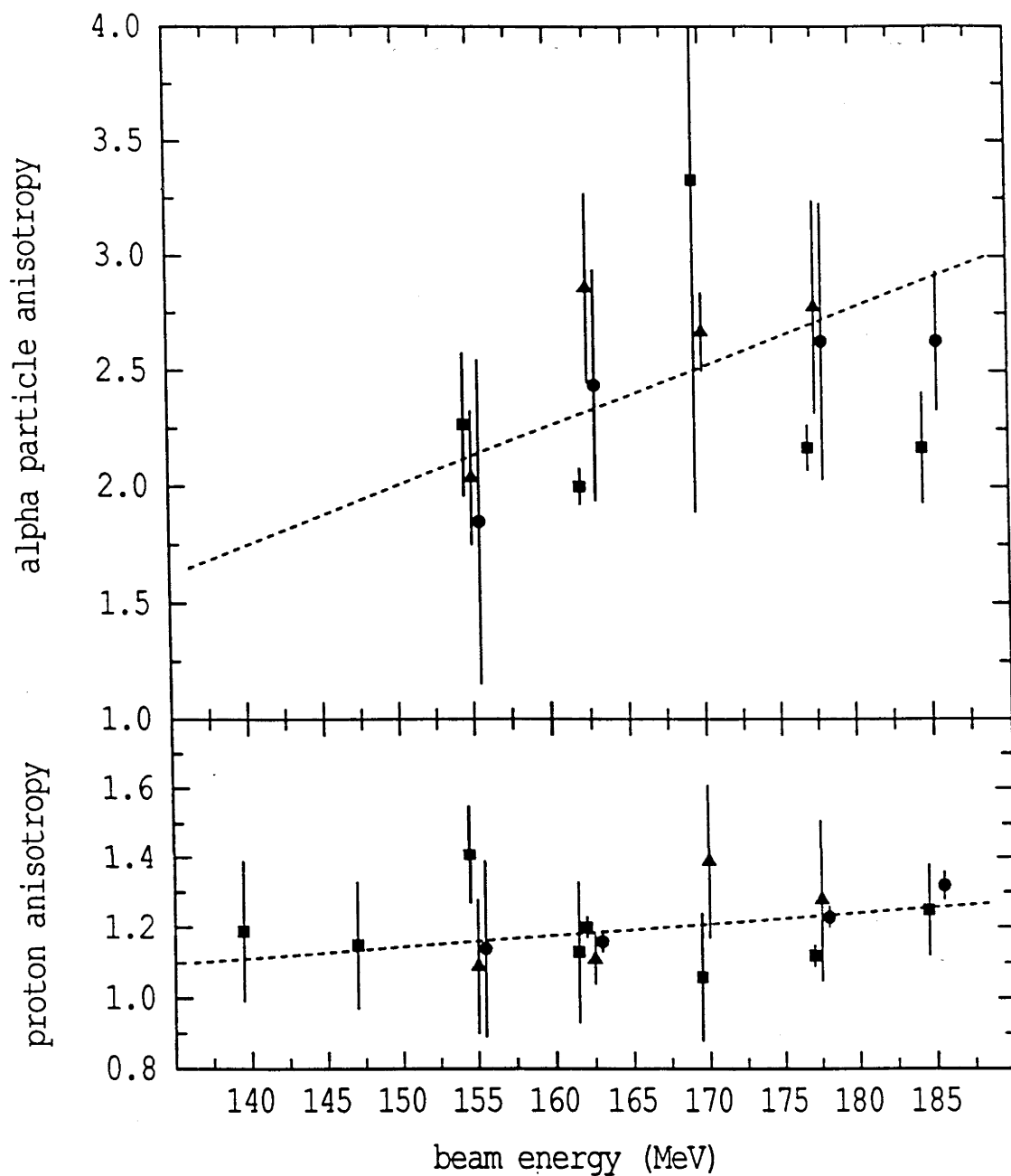


Figure 4.28 The measured anisotropies for the $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ pre-scission proton and alpha particle emission. The squares, triangles and circles are the ^{164}Er , ^{167}Er and ^{170}Er target results respectively. The dashed curves are calculated anisotropies, averaged over the three reactions (see text).

particle multiplicities as a function of both beam energy and mass, quantitatively there are discrepancies between the calculations and the experimental charged particle multiplicities. These discrepancies are most likely due to the many simplifying assumptions used in calculating the multiplicities. For example: (1) the particle emission was assumed to come from compound nuclei, either at their equilibrium deformation or at a point half way between the saddle-point and the scission-point; (2) for a given beam energy, the equilibrium and saddle-point level density parameters were assumed to be independent of the spin of the compound systems; (3) the level density parameter used in calculating the post-saddle particle emission was assumed to be the same as the saddle-point level density parameter; (4) the particle transmission coefficients were assumed to be independent of deformation; and (5) the pre-saddle delay time and the saddle-to-scission time were assumed to be independent of spin and excitation energy.

Figure 4.28 shows calculated anisotropies for the pre-scission proton and alpha particle emission, averaged over the three reactions $^{28}\text{Si} + ^{164,167,170}\text{Er} \rightarrow ^{192,195,198}\text{Pb}$. These anisotropies were estimated using equations 2.80 and 2.81 and moments of inertia appropriate to spherical nuclei. The mean nuclear temperatures of the daughter nuclei $\bar{T}$ and the mean spins of the parent nuclei $\bar{J}_i$ were determined using JOANNE with the 1 MeV shift in the alpha particle transmission coefficients towards lower energies, $\tau_d = 0$ and $\tau_{ss} = 80 \times 10^{-21}$ s. These calculations are qualitatively in good agreement with the experimental anisotropies, despite the assumption of spherical emitters used in the derivation of equations 2.80 and 2.81.

The conclusion that at high excitation energy most of the pre-scission particles are emitted post-saddle, is in contradiction with the recent conclusion by Natowitz *et al.* [NAT90] that the bulk of the pre-scission emission occurs prior to the saddle-point. Natowitz *et al.* claim it

is possible to determine first-chance fission probabilities in heavy-ion reactions using only the excitation energy dependence of total fission probability. To calculate first-chance fission probabilities at an excitation energy of E_1 , Natowitz *et al.* use the equation

$$P_F^{1st}(E_1) = \frac{P_F^{total}(E_1) - P_F^{total}(E_2)}{1 - P_F^{total}(E_2)} \quad (4.2)$$

where $P_F^{1st}(E)$ is the first-chance fission probability at an excitation energy of E ; $P_F^{total}(E)$ is the total fission probability of a compound system at excitation energy E formed in a heavy-ion fusion reaction; and $E_2 = E_1 - \Delta v$ where Δv is the average reduction in excitation energy caused by the emission of a neutron. Natowitz *et al.* have estimated first-chance fission probabilities as a function of excitation energy using equation 4.2 for the reactions $^{16}\text{O} + ^{141}\text{Pr}$, ^{165}Ho , ^{175}Lu and ^{197}Au ; $^{12}\text{C} + ^{169}\text{Tm}$ and $^{22}\text{Ne} + ^{159}\text{Tb}$. Their first-chance fission probabilities initially increase with excitation energy, reach a maximum and then decrease. Natowitz *et al.* attributed the decrease in their first-chance fission probabilities at the high excitation energies to a suppression of the fission decay mode caused by a transient delay. Analysis of their first-chance fission probabilities gives transient delay times that are in good agreement with delay times derived from pre-scission neutron measurements. Equation 4.2 is, however, based on the assumption that the first-chance fission probability of a given compound system is only a function of excitation energy and independent of angular momentum. This assumption is invalid. It would be better to assume that the first-chance fission probability is only a function of angular momentum and independent of excitation energy (eg see figure 2.18). At low beam energies, fusion cross sections and the maximum spins contributing to the fusion spin distribution increase rapidly with beam energy. The rapidly increasing fusion spin values produce a rapidly increasing total fission probability, because of the increase in fission probability with spin. Equation 4.2 assumes this

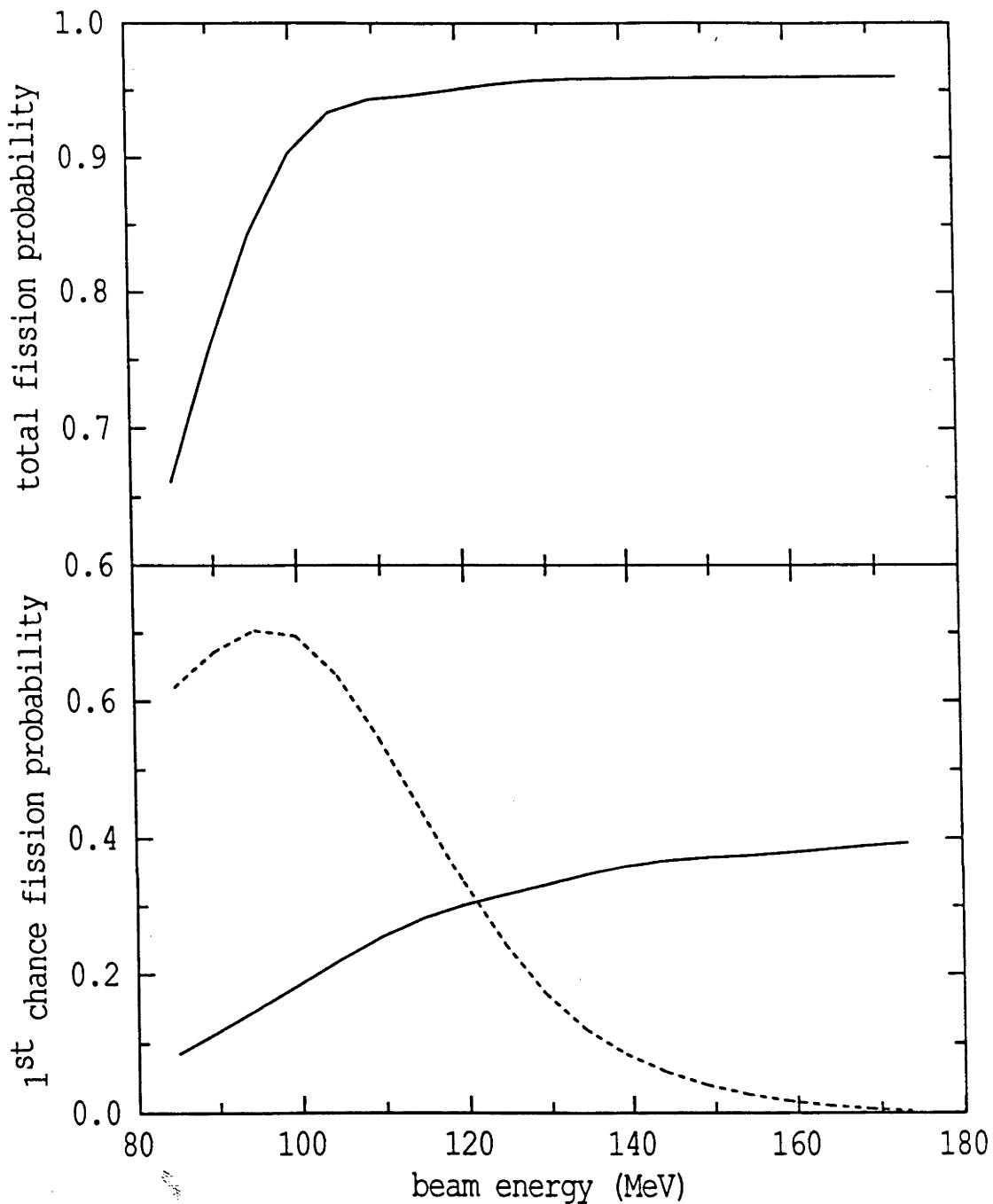


Figure 4.29 First-chance and total fission probabilities for the reaction $^{16}\text{O} + ^{197}\text{Au} \rightarrow ^{213}\text{Fr}$ assuming Bass model fusion cross sections; $a_{\text{eq}} = A/8.6 \text{ MeV}^{-1}$; $a_{\text{sp}}/a_{\text{eq}} = 1.00$; $k_f = 1.00$; $\Delta L = 0.0$ and no pre-saddle delay time (solid curves). The dashed curve represents first-chance fission probabilities estimated using equation 4.2 and the statistical model calculations of the total fission probabilities, with $\Delta v = 13 \text{ MeV}$ as suggested by [NAT90].

increase in total fission probability is associated with an increase in the first-chance fission probability with excitation energy and thus over-estimates the true first-chance fission probabilities. At high beam energies where fusion spin distributions become relatively insensitive to the beam energy, the depletion of the high spins by first-chance fission will cause equation 4.2 to under-estimate the true first-chance fission probabilities. I have calculated first-chance and total fission probabilities for the reaction $^{16}\text{O} + ^{197}\text{Au} \rightarrow ^{213}\text{Fr}$ assuming Bass model fusion cross sections [BAS77]; $a_{\text{eq}} = A/8.6 \text{ MeV}^{-1}$; $a_{\text{sp}}/a_{\text{eq}} = 1.00$; $k_{\text{f}} = 1.00$; $\Delta L = 0.0$ and no pre-saddle delay time. First-chance fission probabilities estimated using equation 4.2 and the statistical model calculations of the total fission probabilities, with $\Delta v = 13 \text{ MeV}$ as suggested by [NAT90], are compared to the statistical model calculations of the first-chance fission probabilities in figure 4.29. The lack of correlation between the two sets of first-chance fission probabilities clearly demonstrates that equation 4.2 can not be used to determine first-chance fission probabilities in heavy-ion fusion reactions.

4.4 Summary and Conclusions

Energy spectra and angular correlations of protons and alpha particles have been measured in coincidence with fission fragments in the three reactions $^{28}\text{Si} + ^{164,167,170}\text{Er} \rightarrow ^{192,195,198}\text{Pb}$, with ^{28}Si beam energies ranging from 140 MeV to 185 MeV. For each combination of beam energy and reaction, proton and alpha particle spectra were observed in a detector consisting of a CsI crystal coupled to a photodiode, in coincidence with fission fragments observed in an array of up to thirty parallel-plate gas counters. The shapes of the particle spectra are sensitive to the relative positions of the CsI detector and the parallel-plate gas counters. Analysis of the shape changes of the particle spectra as a function of the position of the fission fragment detectors (gas counters) enabled the determination of

the multiplicities, energy spectra and angular distributions of the various sources of proton and alpha particle emission.

The proton yields consisted of ~50% emission from the compound systems (pre-scission emission) and ~50% emission from the fully accelerated fission fragments (post-scission emission). The alpha particle yields consisted of ~65% pre-scission emission; ~30% post-scission emission and ~5% near-scission emission. The pre- and post-scission proton emissions have mean energies relative to their emitting systems of ~11 MeV and ~7 MeV respectively. The pre- and post-scission alpha particle emissions have mean energies relative to their emitting systems of ~20 MeV and ~14 MeV respectively. The pre-scission proton emission is nearly isotropic, while the pre-scission alpha particle emission has a large anisotropy with between 2 and 3 times more alpha particles seen perpendicular to the spin direction of the pre-scission compound systems, than seen parallel to this direction. The near-scission alpha particle emission has a mean energy which ranges from ~13 MeV to ~14.5 MeV and appears to decrease with increasing beam energy. The FWHM of the energy distribution of the near-scission alpha particle emission is ~5.5 MeV. The FWHM of the angular distribution of the near-scission emission ranges from ~24° at a beam energy of 155 MeV to ~42° at a beam energy of 185 MeV.

To obtain information about the dynamics of the fission process from the pre-scission particle emission data, the statistical model code JOANNE was written. The fission barriers were assumed to be those of the finite-range liquid-drop model [SIE86] and the level density parameter of nuclei at their equilibrium deformation was assumed to be $A/8.6 \text{ MeV}^{-1}$. The particle transmission coefficients were determined using the optical model potentials of [PER76] for neutron and proton emission and [HUI62] for alpha particle emission. The pre-saddle particle

emission was assumed to be from compound systems at their equilibrium deformations. The post-saddle particle emission was assumed to be from compound systems with rotation plus deformation energies equal to the average of those at the saddle-point and those for spherical fragments at scission, as given in equation 2.94. For a given pre-saddle delay time the ratio of the level density parameter at the saddle-point to the level density parameter at equilibrium was varied with beam energy to reproduce the appropriate evaporation residue excitation function of [HIN83]. The level density parameters used in calculating the post-saddle particle emission were assumed to be the same as the level density parameters at the saddle-points.

Reasonable simultaneous fits to the present pre-scission proton and alpha particle multiplicities and the pre-scission neutron multiplicities of [HIN86] are obtained using the code JOANNE with a pre-saddle delay time $\tau_d \approx 10 \times 10^{-21}$ s and a saddle-to-scission time $\tau_{ss} \approx 55 \times 10^{-21}$ s. The mean proton energies predicted by these calculations are in good agreement with the measured values. The mean alpha particle energies are, however, over-predicted by ~ 1 MeV. In an attempt to obtain a better agreement between the calculated and measured mean energies of the pre-scission alpha particles, calculations were performed with the standard alpha particle transmission coefficients shifted towards lower energies by 1 MeV. With this 1 MeV shift in the alpha particle transmission coefficients, the best simultaneous fits to the experimental pre-scission neutron, proton and alpha particle multiplicities are with $\tau_d \approx 0$ and $\tau_{ss} \approx 80 \times 10^{-21}$ s. These calculations tend to under-estimate the mean energies of the pre-scission alpha particles by $\lesssim 0.5$ MeV. This suggests the true values of τ_d and τ_{ss} are somewhere between those obtained using the calculations with and without the 1 MeV shift in the

alpha particle transmission coefficients. The statistical model analysis presented in this chapter indicates that for $^{28}\text{Si} + \text{Er} \rightarrow \text{Pb}$ fusion-fission reactions $\tau_d < 10 \times 10^{-21}$ s, $\tau_{ss} = (70 \pm 20) \times 10^{-21}$ s and for beam energies ≥ 155 MeV the bulk of the pre-scission particles are emitted by compound nuclei during their transit from the saddle-point to the scission-point. The requirement that τ_d be less than 10×10^{-21} s seems consistent with our present understanding of nuclear viscosity. The saddle-to-scission transit time $\tau_{ss} \approx 70 \times 10^{-21}$ s is more than a factor of two larger than predictions made using full one-body viscosity (see figure 2.33) and ~ 30 times longer than calculations based on two-body dissipation through the bulk of the nuclear fluid [CAR86]. The discrepancy with the one-body dissipation calculations becomes even larger if they are scaled by between 0.2 and 0.5, as indicated by the mean kinetic energy of experimentally observed fission fragments [NIX87].

In summary, we have demonstrated for the first time that pre-scission neutron, proton and alpha particle multiplicities show very different sensitivity to the pre-saddle and saddle-to-scission delay times. The alpha particle multiplicities place strict limits on τ_d , while the neutron data are more effective in defining τ_{ss} . Clearly there is considerable need for improvement in the models used to interpret particle multiplicities in terms of delay times. The theoretical calculations of these times are in their infancy and also need further development. More measurements of charged particle multiplicities for nuclei of different fissility are necessary and, in conjunction with neutron data, will undoubtedly help our understanding of dynamical effects in fission.

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