Limitations to presaddle neutron emission from fission-fragment charge distributions

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The effect of including mass-asymmetry dependent fission delay times into the statistical model has been investigated. The shape of the predicted charge distribution of fission fragments is found to be very sensitive to the magnitude and mass-asymmetry dependence of these delay times. Measured mass-asymmetry dependent prefission neutron multiplicities were fit with calculated presaddle values by varying the fission delay times. The resultant predictions for the charge distributions are found to have shapes inconsistent with those measured for similar mass systems, indicating that measured prefission multiplicities cannot be accounted for by presaddle emission alone. Limitations to the magnitude of the presaddle component are discussed.

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I. INTRODUCTION

Bohr and Wheeler [1] included the fission decay mode into the statistical model using the transition state formalism developed for chemical reaction rates. This formalism has been successfully used in calculating the fission probability for compound nuclei covering a wide range of masses, excitation energies, and angular momenta. For example, in heavy-ion fusion reactions, fission excitation functions have been fit over a wide range of compound nucleus masses [2–5], using angular momentum dependent, macroscopic fission barriers [6] and Fermi gas level densities.

Moretto [7] extended the transition state formalism to include both symmetric and asymmetric binary divisions of the compound nucleus. In this formalism, symmetric fission and light particle evaporation represent two extremes of a generalized binary decay process. The predicted charge or mass distribution of fragments emitted by the compound nucleus is continuous and the overall shape is determined predominantly by the dependence of the potential energy surface (PES) on the fission and mass-asymmetry coordinates. For heavier nuclei above the Businaro-Gallone (BG) point [8], the ridge in the PES separating ground-state from scission configurations has minima for both symmetric and very asymmetric divisions. These minima are associated with the dominant decay modes of symmetric fission and light particle evaporation, respectively. For nuclei with mass below the BG point, the minimum for symmetric division is replaced by a maximum. As a result, the predicted charge distributions for near symmetric divisions show a transformation from a fission peak above the BG point to a minimum below the BG point [7]. For compound nuclei at the BG point, the charge distribution is predicted to be flat for near symmetric divisions.

Experimentally these trends have been amply confirmed. Charge distributions measured for heavy systems above the BG point show a fission peak [9,10], while systems at and below the BG point are flat [9,11] and have a minimum [11–14], respectively, in the measured charge distributions for near symmetry divisions. Also, by increasing the angular momentum of a system, one can move it from below to above the BG point and subsequently change the shape of the charge distribution. Such transitions have been observed [15]. Quantitative agreement with both the measured shape and magnitude of the charge or mass distributions has been obtained for many systems [9–14].

Despite the success of the statistical model, recent measurements of large prefission particles [16–18] and gamma ray emissions [19] have been interpreted as implying a role for dynamics in determining the fission decay probability. Let us consider prefission neutron measurements. The separation of the neutrons which accompany fission decay into prefission and postfission components is achieved using the kinematical focusing of the post-fission neutrons by the fission fragments. The spectra of neutrons emitted in coincidence with fission fragments are fitted with three sources: One source (prefission) with the velocity vector of the compound nucleus and two sources (postfission) with velocity vectors corresponding to that of the fully accelerated fission fragments. (Sometimes a pre-equilibrium source is also included.) Because only three sources are included, neutrons emitted before the fission fragments obtained a large fraction of their asymptotic velocities are classified as prefission. The remaining prefission neutrons are presaddle, emitted before the system reached the saddle-point configuration, and saddle-to-scission, emitted from the fissioning system during the descent from the saddle to the scission point. As the statistical model only predicts the presaddle neutron multiplicity, care should be taken in comparing it to measured prefission neutron multiplicities.

Using the statistical model decay widths for neutrons, the large measured prefission neutron multiplicities have been converted to fission times of 10–100 zs [17] (1 zs=10−21 s). This time is, in principle, the time until the fission fragments have obtained a large fraction of their final velocities, but as the time scale for the acceleration of the fission fragments is only ≈1 zs [20], this
time scale essentially represents the total time until scission [18]. Measured post-fission neutron multiplicities are generally low, indicating that the fission fragments are created cold \( (E^* \approx 0.33 \text{ MeV/A} [18]) \) or, more strictly, were cold at least by the time they obtained a large fraction of their asymptotic velocities.

The large measured fission times have been interpreted as resulting from the saddle-to-scission transition time plus the effect of a transient fission decay width. The latter results from a dynamical theory where the initial shape degrees of freedom of the "compound nucleus" are not equilibrated [21–25]. In these theories, all compound nuclei are initially at the ground state and the fission decay rate, or more specifically the flux over the saddle point, is zero. The flux starts to build up as the shape distribution of the compound nuclei diffuses out to larger deformations. As the shape distribution approaches its equilibrium value, the fission decay rate approaches the transition state value. As a first step, a number of studies have attempted to incorporate the above dynamical effect into the statistical model, by turning off fission competition for an initial period of time (fission delay time). Subsequently, the fission rate is given by the transition state value. However, during the delay time, light particle evaporation is possible, enhancing the pre-fission neutron and charge particle multiplicities. Calculations have also been performed with more gradual increases in the fission decay width [26,27].

The above scenario can be extended to include the mass-asymmetry degree of freedom. An initial non-thermalized distribution of compound nuclei diffuses out along both the mass-asymmetry and fission coordinates of the PES. The time required for the flux across the ridge line to approach its equilibrium value will depend on the diffusion rates along both coordinates, giving rise to a mass-asymmetry dependent fission delay time.

The inclusion of fission delay times not only affects the predicted presaddle light particle multiplicities, but can also greatly influence the fission probability. This is especially true for low fission probabilities and high excitation energies, where a significant number of light particles can be emitted during the delay time, lowering the mass, excitation energy, and angular momentum of the compound nucleus. On the other hand, the saddle-to-scission time scale is irrelevant to the fission probability. Thus in principle it may be possible to separate the presaddle and the saddle-to-scission components of the measured fission times from an analysis of the fission probability. An initial attempt along such lines [28] has been strongly criticized [29]. Other investigations of reduced fission yield [30] or the complementary quantity, enhanced evaporation residue yield [31,32], are in the end limited by uncertainties in the predicted fission probability of the statistical model against which any reduction or enhancement must be judged. Unfortunately, a number of the statistical model parameters, and in some cases the spin and excitation energy distributions of the compound nuclei, are uncertain making accurate predictions difficult.

In this work, it will be shown that the inclusion of mass-asymmetry dependent fission delay times alter the shape of the charge and mass distributions of fission fragments. Unlike the total magnitude of the fission cross section, the overall shape of the predicted charge distribution is less sensitive to the compound nuclei spin and excitation energy distributions. Also, uncertainties in statistical model parameters such as the level densities and transmission coefficients for light particle evaporation affect the magnitude more than the shape of the distributions. However, it will be shown that any large mass-asymmetry dependence of the fission delay times radically changes the shape of the charge distribution, allowing one to limit the magnitude of the fission delay times.

The above ideas will be discussed in relation to recent measurements of pre-fission neutron multiplicities performed as a function of mass-asymmetry by Hinde et al. [18]. Specifically, calculations and data for the 288 MeV \(^{18}\text{O} + ^{109}\text{Ag}\), and the 159 MeV \(^{18}\text{O} + ^{144}\text{Sm}\), \(^{154}\text{Sm}\) reactions will be compared. This study was limited to light compound nuclei where the difference in deformation between saddle-point and scission configuration is small, thus enhancing the role of presaddle time relative to the saddle-to-scission time.

II. INCLUSION OF MASS-DEPENDENT FISSION DELAYS IN THE STATISTICAL MODEL

For the case of a single fission channel, the introduction into the statistical model of a delay time \( t_{\text{delay}} \), before which fission is totally suppressed, results in the single-step fission probability decreasing by the factor \( \exp(-\Gamma_{\text{evap}} t_{\text{delay}}/\hbar) \), where \( \Gamma_{\text{evap}} \) is the decay width for light particle evaporation. This factor represents just the probability of decay by light particle emission during the delay time.

For a large number of fission channels each with different delay times, the reduction in the probabilities is not easy to calculate. However, in a Monte Carlo simulation of the decay process, there is a simpler, more flexible algorithm for choosing the decay channel. First consider the case where there are no delays at all. For a single decay channel, in the absence of competing channels, the time for statistical decay follows an exponential distribution. It can be selected in a Monte Carlo simulation by

\[
t_{\text{stat}}^i = -\frac{\hbar}{\Gamma_i} \ln(x),
\]

where \( \Gamma^i \) is the partial decay width for that channel and \( x \) is a random number with uniform probability between zero and unity. Competition between channels can be included by choosing a time for each channel according to the above equation, and then selecting the channel with the earliest decay time.

The above algorithm is easily extended by adding a mass-asymmetry dependent delay time to the statistical time for each channel. Also, for second or higher order chance fission, the delay time is decreased by the elapsed time \( t_{\text{elapsed}} \). Therefore the time for each channel is determined as
\[ t^i = \begin{cases} \tau_{\text{delay}}^i + \tau_{\text{stat}}^i, & t_{\text{elapsed}} < t_{\text{delay}} \\ t_{\text{elapsed}} + \tau_{\text{stat}}^i, & t_{\text{elapsed}} \geq t_{\text{delay}}. \end{cases} \]  

The mass asymmetry is defined by

\[ \eta = \frac{m_1 - m_2}{m_1 + m_2}, \]

where \( m_1 \) and \( m_2 \) are the masses of two primary fragments produced in the binary decay step of the decaying nucleus. The value of \( \eta \) ranges from zero for symmetric fission to almost unity for light particle evaporation. With this definition, the mass-asymmetry dependent delay time was chosen to have a Gaussian shape

\[ t_{\text{delay}}(\eta) = t_{\text{delay}}(0) \exp \left( -\frac{\eta^2}{2 \sigma_\eta^2} \right) \]

with a maximum delay of \( t_{\text{delay}}(0) \) for symmetric division. For the values of the width \( \sigma_\eta \) used in this work, the delay time for light particle evaporation (\( \eta \approx 1 \)) was much smaller than the respective time scale for statistical emission (\( \hbar/T_{\text{vap}} \)). Hence, light particle evaporation is essentially statistical as is usually assumed when extracting fission time scales from prefission multiplicities.

The above algorithm was incorporated into a version of the statistical model code GEMINI [10, 11]. This version of the code was modified so that light particle (\( Z \leq 2 \)) decay widths were calculated with the Hauser-Feshbach formalism, using diffuse transmission coefficients obtained from the incoming wave boundary condition model as suggested by Alexander et al. [33]. Unlike in Ref. [11], explicit integrations over fragment kinetic energy and summands over all allowed combinations of fragment spin, orbital angular momentum, and residual spin were performed. Decay widths for other binary divisions of the compound nucleus were calculated using the transition state formalism of Moretto as in Ref. [11]. Conditional fission barriers as functions of mass asymmetry and the compound nucleus charge, mass, and spin were interpolated from calculations performed by Sierk [34] and Carjan [35], using the rotating finite range model [6, 36].

Level densities were assumed to be of the Fermi gas form. As the level density parameter for the saddle-point configuration is very important for determining the presaddle neutron multiplicity [37, 38], its mass-asymmetry dependence was considered. Apart from the volume (or \( A \)) dependence of the level density parameter, higher order corrections dependent on the surface area and curvature have been predicted. In this work, only the surface area correction will be considered because the influence of the curvature correction can be mocked up by a small increase in the surface area term [39]. If \( B_s \) is the surface area of the saddle-point configuration relative to that for a spherical deformation, then

\[ a(\eta) = a_\nu A + a_\sigma B_s(\eta) A^{2/3}. \]

Three sets of the constants \( a_\sigma \) and \( a_\nu \) listed in Table I were considered, and were obtained from the models of Tóke and Świątek [39] (TS), Ignatyuk et al. [40] (Ign), and Gottschalk and Ledergerber [41] (GL). As values of \( B_s(\eta) \) are not generally available as functions of mass asymmetry for all nuclei, they were estimated from the surface area of two spheres. Comparisons of such values to predictions obtained by Sierk for \( ^{106}\text{Sn} \) [34] indicate that this approximation gives almost the correct \( \eta \) dependence but overestimates the magnitude of \( a(\eta) \) somewhat. However, the error in the level density parameter caused by using the two-sphere approximation is small compared to the variations associated with using the different \( a_\sigma \) values in Table I. With the two-sphere approximation, the ratio \( a_\sigma/a_\nu = a(0)/a(1) \) takes the values of 1.11, 1.05, and 0.99 in the above three models, respectively. These values span the range of \( a_\sigma/a_\nu \) values extracted by fitting fission excitation functions [2–5] and pre-fission neutron multiplicities at low excitation energies [38] when, in both cases, the macroscopic fission barriers of Ref. [6] are assumed. Even larger values would be obtained using the model of Prakash et al. [42], which also includes the role of the effective mass.

### III. Calculations

Calculations were performed for the 159 MeV \( ^{18}\text{O} + ^{154}\text{Sm} \), \( ^{154}\text{Sm} \), and \( 288 \text{MeV} \) \( ^{16}\text{O} + ^{109}\text{Ag} \) reactions measured by Hinde et al. [18]. The compound nucleus angular momentum distributions were assumed to have the form

\[ \sigma_{\text{fusion}}(\ell) = \pi \lambda^2 \frac{(2\ell + 1)}{1 + \exp(\frac{\delta\ell}{\hbar})}, \]

where \( \delta\ell \) was set to \( 2 \hbar \). Values of \( \ell_0 \) along with the compound nucleus excitation energies used in the calculations are listed in Table II for the three reactions. These values are identical to those assumed in Ref. [18].

As a reference, calculations were first performed without the inclusion of fission delays. Figure 1 shows the predicted charge distributions \( [\sigma(\ell)] \) for the \( ^{16}\text{O} + ^{154}\text{Sm} \) reaction and the predicted average presaddle neutron multiplicity as a function of mass asymmetry. The predictions obtained with the TS, Ign, and GL density pa-

<table>
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<th>Reference</th>
<th>( a_\nu )</th>
<th>( a_\sigma )</th>
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<td>Tóke and Świątek [39]</td>
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<tr>
<td>Ignatyuk et al. [40]</td>
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<td>Gottschalk and Ledergerber [41]</td>
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<table>
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<th>( \ell_0 ) (\hbar)</th>
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<td>73</td>
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<tr>
<td>( ^{18}\text{O} + ^{154}\text{Sm} )</td>
<td>121</td>
<td>76</td>
</tr>
<tr>
<td>( ^{18}\text{O} + ^{109}\text{Ag} )</td>
<td>194</td>
<td>80</td>
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</table>
rameters are indicated by the solid, dashed, and dotted lines, respectively. The predicted presaddle multiplicities are small and show little dependence on mass asymmetry for all but the largest values of $\eta$. This is not unexpected, as the presaddle multiplicities depend mainly on the $a(\eta)/a(1)$ ratio which is relatively constant for near-symmetric fissions. A small increase in the multiplicities is predicted in changing from the TS, to Ign, to GL level density parameters. This is consistent with the decreasing trend of the $a(\eta)/a(1)$ ratios [37,38]. However, none of the predicted presaddle multiplicities can account for the measured prevision values indicated by the circular data points in Fig. 1. On the other hand, the predicted charge distributions $\sigma(Z)$ exhibit the expected fission peak centered at $Z \approx 34$ ($\eta \approx 0$) associated with near-symmetric decay. The predicted shape and yield in this peak region depend somewhat on $a(\eta)$. To help link the mass-asymmetry axis with the secondary $Z$ value of the fragments, approximate values of the mass asymmetry are indicated by the arrows for selected $Z$ values in Fig. 1.

The predicted mass-asymmetry dependence of the total average neutron multiplicity (pre- + postfission) is also compared to the experimental data in Fig. 1. In GEMINI, the excitation energy at the saddle point is divided thermally between the two fission fragments, which are then allowed to decay statistically [10]. The predicted post-saddle neutron multiplicity must be considered a lower limit because if any extra energy is dissipated during the saddle-to-scission motion, then the post-saddle and subsequently the total neutron multiplicity will be increased. As such, the predictions are all consistent with the data.

Similar results obtained for the $^{18}\text{O}+^{154}\text{Sm}$ and $^{16}\text{O}+^{109}\text{Ag}$ reactions are illustrated in Figs. 2 and 3. Note that the compound nucleus for the latter reaction is close to the BG point and so the predicted $\sigma(Z)$ distributions are flat or show a broad maximum around $\eta=0$ ($Z=25$). As the compound nuclei for the two $^{18}\text{O}$ reactions are above the BG point, the predicted charge distributions contain fission peaks. The predictions are qualitatively confirmed by the raw experimental mass distributions shown in Figs. 9 and 10 of Ref. [18] for the $^{16}\text{O}+^{109}\text{Ag}$ and $^{18}\text{O}+^{154}\text{Sm}$ reactions, respectively. No attempt was made for a quantitative comparison with these data as it was not clear what mass-dependent efficiency corrections needed to be applied. However, quantitative agreement between predicted and experimental charge distributions has been obtained for similar systems, e.g., $^{139}\text{La}+^{12}\text{C}$ [10] and $^{93}\text{Nb}+^{12}\text{C}$ [11], when $\eta$-independent level density parameters and reasonable compound nuclear angular momentum distributions are assumed. The predictions with $\eta$-independent level density parameter ($a_*=0$) are most similar to those obtained with the GL values in this work.

The predicted total neutron multiplicity for the
**LIMITATIONS TO PRESADDLE NEUTRON EMISSION FROM**

The success of the statistical model calculations in reproducing the shape of experimental charge/mass distributions raises the question of whether one can discount the need for any transient fission effects and account for the difference between measured presaddle and the predicted presaddle multiplicities as arising mostly from saddle-to-scission neutron emission. In answering this question, first consider the other extreme assumption that all the measured presfission neutrons are entirely presaddle in origin. It will now be shown that the measured charge distributions are inconsistent with this assumption.

Mass-asymmetry fission delay times were adjusted through the parameters \( t_{\text{delay}}(0) \) and \( \sigma_\eta \) of Eq. (4) so as to fit the measured presfission multiplicities with the predicted presaddle values. Due to the large CPU time required for these calculations, no attempt was made to map out the \( \chi^2 \) surface and determine the uncertainties in the fitted parameters. However, the conclusions drawn from this section are valid as long as there is a reasonable mass-asymmetry dependence of the fission delay times. The fitted values are listed in Table III for the three reactions and for each of the three level density parameters. The fits with the GL level density parameter require the smallest fission delay times, as they are associated with the largest presaddle multiplicities in the absence of any delay. The opposite is true for the calculations with the TS parameters. There is no large dependence of the fitted \( \sigma_\eta \) values on the choice of the level density parameter. The fits are compared to the experimental data in Figs. 4–6, together with the resultant predictions for the charge distributions.

Clearly, the predicted charge distributions are inconsistent with the shape of experimental mass/charge distributions. The inclusion of the large \( \eta \)-dependent delay times has changed the peak in the distributions around \( \eta=0 \) to a minimum for both \(^{16}\text{O} \) induced reactions. For the \(^{16}\text{O} \) induced reaction, the flat or near flat distribution around \( \eta=0 \) (\( Z=25 \)) had been changed to a valley. This behavior is not unexpected, as the larger the fission delay time, the more the probability for that channel is reduced. The effect of mass-asymmetry dependent de-

<table>
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<th>( \sigma_\eta )</th>
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<td>(^{16}\text{O}+^{144}\text{Sm} )</td>
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</tr>
<tr>
<td></td>
<td>Ign</td>
<td>9</td>
<td>0.25</td>
</tr>
<tr>
<td></td>
<td>GL</td>
<td>7</td>
<td>0.23</td>
</tr>
<tr>
<td>(^{16}\text{O}+^{154}\text{Sm} )</td>
<td>TS</td>
<td>16</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>Ign</td>
<td>7</td>
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</tr>
<tr>
<td></td>
<td>GL</td>
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<td>0.26</td>
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<tr>
<td>(^{16}\text{O}+^{109}\text{Ag} )</td>
<td>TS</td>
<td>15</td>
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<tr>
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<td>GL</td>
<td>8</td>
<td>0.40</td>
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\(^{16}\text{O}+^{109}\text{Ag} \) reaction is inconsistent with the experimental data when the TS level density parameter is used (solid curve, Fig. 3). The difference between the predictions obtained with the TS and the other two level density parameters results because \( \rho(1) \) is larger for the former. Subsequently the temperature and the kinetic energy of emitted particles is smaller and hence the total neutron multiplicity is larger. Consistent total neutron multiplicities could be obtained keeping the \( \eta \) dependence of the TS level density parameter, but reducing its magnitude. The resultant presaddle neutron multiplicities and fission-fragment charge distributions would not change substantially.

The dependence of the predictions on the assumed compound nucleus spin distributions was investigated by repeating the above calculations with values of \( \ell_0 \) a factor of 5 \( \hbar \) less than those in Table II. The resulting charge distributions and neutron multiplicities show little change. The largest effect was obtained for the calculations with the GL level densities, where the magnitude of \( \sigma(Z) \) for near-symmetric divisions decreased by 40\% and the presaddle neutron multiplicity increased by 0.2. However, the shape of the fission-fragment charge distribution remained essentially unchanged. Much larger modifications to the compound nucleus spin distributions are required to produce substantial changes in the shape. Thus in these standard statistical model calculations (i.e., without fission delays), the shape of the fission fragment charge (or mass) distributions is determined predominantly by the PES and to a lesser extent by the \( \eta \) dependence of the level density parameter. Uncertainties in the other statistical model parameters and in the spin and excitation energy distribution of the compound nu-

**FIG. 3.** As for Fig. 1, but for the 288 MeV \(^{16}\text{O}+^{109}\text{Ag} \) reaction.
lay times in these calculations overrides the role of the PES and the yield for \( \eta = 0 \) with the largest delay time becomes a minimum. The shapes of the predicted charge distributions are only altered in the region where \( t_{\text{delay}} \) is of the order of, or larger than, the average emission time without fission delay. For the \( { }^{180} \text{O} + { }^{144}\text{Sm} \) reaction, these \( Z \) regions are 10–60 and 20–50 for the calculations with TS and GL level density parameters, respectively. It is interesting that within these regions, the predicted cross sections are independent of the assumed level density parameter. Outside of these regions, the shape of the distributions remains unchanged, except that due to the reduced competition from symmetric fission, the yield is increased.

The predicted total neutron multiplicities for the \( { }^{180} \text{O} + { }^{109}\text{Ag} \) reactions are now all consistent with the experimental data in Fig. 6. However, for the \( { }^{180} \text{O} \) induced reactions, the predictions fall below the experimental data in Figs. 4 and 5. Given that in fitting experimental prefission neutron multiplicities with the calculated pre-saddle values implies a rapid saddle-to-scission motion, then dissipation during this motion should be minimal. Therefore it is unlikely, in this scenario, that the under-prediction of the total neutron multiplicity can be associated with the neglect of the saddle-to-scission motion in GEMINI and this again may indicate that the fitted fission delay times are incompatible with the data.

The predicted shapes of the charge distributions clearly rule out the possibility that all of the measured pre-fission multiplicities are pre-saddle emissions. The extent to which limits can be placed on the magnitude of the delay times will now be investigated. In the end we are limited by the lack of experimental charge distributions.

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**FIG. 4.** Predicted charge distributions and neutron multiplicities for the 159 MeV \( { }^{180} \text{O} + { }^{144}\text{Sm} \) reaction obtained from calculations where the experimental prefission multiplicities were fit with the calculated presaddle values by adjusting the fission delay times. The data points and curves have the same meaning as for Fig. 1.

**FIG. 5.** As for Fig. 4, but for the 159 MeV \( { }^{180} \text{O} + { }^{154}\text{Sm} \) reaction.

**FIG. 6.** As for Fig. 4, but for the 288 MeV \( { }^{180} \text{O} + { }^{109}\text{Ag} \) reaction.
with which to make detailed comparison to calculations. However, even small mass-asymmetry dependent fission delay times can have a significant effect on the shape of the predicted charge distribution. This is illustrated in Fig. 7, where evolution of the charge distributions with decreasing values of \( t_{\text{delay}}(0) \) is displayed for the \( ^{18}\text{O}+^{144}\text{Sm} \) reaction. The calculations were performed with the TS level density parameter, keeping \( \sigma_p \) fixed to its fitted value in Table III. Even for \( t_{\text{delay}}(0)=0.2 \) zs, the shape of the \( \sigma(Z) \) is significantly modified relative to the prediction without any decays \( t_{\text{delay}}(0)=0.0 \) zs. Yet at the same time, the predicted presaddle neutron multiplicity is still insignificant compared to the measure prefission values. Clearly in these calculations, the presaddle component of the measured prefission multiplicity cannot be increased substantially without creating an unacceptable charge distribution.

It is interesting to note that the total fission yield, defined as

\[
\sigma_{\text{fission}} = \frac{1}{2} \sum_{Z=8}^{59} \sigma(Z),
\]

is relatively insensitive to \( t_{\text{delay}}(0) \). It only decreases by 20\% when \( t_{\text{delay}}(0) \) is increased from zero to 2.0 zs. Thus the introduction of a mass-asymmetry dependent fission delay in these calculations results predominantly in a shift in the fission yield from symmetric to more asymmetric fission processes. This is easily understood, as the fission yield originates mainly from high compound nuclear spin values where the decay widths for these fission channels are much larger than those for light particle evaporation. Only for the largest values of \( t_{\text{delay}}(0) \) is there enough angular momentum and excitation energy lost during fission delay time that the subsequent fission decay widths are less than, or of similar order to, the decay width for light particle emission and hence \( \sigma_{\text{fission}} \) is significantly reduced. The above discussion highlights an important fact that measurements of the total fission cross section are not as sensitive to presaddle fission delay times as are measurements of the charge distributions of the fission fragments. This also applies to measurements of the evaporation residue cross sections. Note that the evaporation residue yield \( (Z > 60) \) in Fig. 7 does not substantially change except for the largest delay times.

For the Ig and GL level density parameters, the limitations on \( t_{\text{delay}}(0) \) are slightly less severe. For example, using the GL parametrization, a value of \( t_{\text{delay}}(0) \approx 1.0 \) zs is required to create a distortion similar to that produced by \( t_{\text{delay}}(0) \approx 0.2 \) zs with the TS level density parameter in Fig. 7. At the same time, the prefission multiplicity is increased by \( \approx 0.5 \) at \( \eta=0 \). However, even in this calculation, the presaddle neutrons account for less than half the measured prefission multiplicity.

In the previous discussions, \( \sigma_p \) was kept fixed to its fitted value in Table III. For larger values of \( \sigma_p \), the associated distortions to the shape of the charge distributions will be reduced. In fact, if the mass-asymmetry dependence of the fission delay time is flat, at least over the region containing the fission peak, then the shape of the predicted charge distribution will have little dependence of the fission delay time. This is illustrated in Fig. 8 for the \( ^{18}\text{O}+^{144}\text{Sm} \) reactions, where predictions with a constant 7 zs fission delay for all mass asymmetries except \( Z \leq 2 \) evaporation are compared to those obtained without any fission delays. These calculations were performed with TS level density parameters. Both the shape and magnitude of the fission yield are largely unaffected by the inclusion of this flat fission delay. The fission delay time is limited in this calculation by the value required to fit the prefission multiplicity measured at the largest mass asymmetry \( (\eta \approx 0.4) \). Thus at \( \eta=0 \), the presaddle multiplicity constitutes at most approximately one-half of the measured prefission multiplicity. This limitation is also true for other values of \( \sigma_p \) and, as the saddle-to-scission component is associated with longer evaporative time scales, it implies that the saddle-to-scission time is longer than the fission delay time for \( \eta=0 \).

The above considerations are similar to those drawn by Lestone et al. for Si+Er reactions [43,44]. They were not able to fit, simultaneously, measured prefission neutron, proton, and alpha particle multiplicities with only a presaddle delay to fission. They concluded that saddle-to-scission emission is important and that the fissioning nucleus spends most of the time at deformations considerably larger than the equilibrium value.

Finally, it is of some interest to consider the case where the fission decay rate is allowed to approach the transition state value in a more gradual manner rather than

\[ ~\]
tron multiplicity for $\eta=0$ is plotted as a function of $t_0$. These calculations indicate that more abrupt time dependences of the fission decay widths are necessary to produce large presaddle multiplicities. However, even in the above calculations where the decay widths increase gradually, substantial distortions were still produced in the fission-fragment charge distributions even for small values of $t_0(\eta)$.

IV. CONCLUSIONS

The influence of mass-asymmetry dependent fission delay times on the predicted charge distribution of fission fragments has been investigated. Fission delay times were introduced into the statistical model code GEMINI using an earliest time algorithm. When fission delay times were adjusted so as to fit measured mass-asymmetry dependent prefission neutron multiplicities with the calculated presaddle values, the predicted charge distributions were found to have unexpected shapes. Such charge distributions are inconsistent with those measured for similar mass systems, indicating that the measured prefission neutrons multiplicities cannot be accounted for presaddle emission alone. On the other hand, there is no great inconsistency between experimental charge distributions and the predictions obtained with standard statistical model calculations (i.e., without fission delays). Thus there is no compelling evidence for the need to include dynamical effects associated with nonthermalized “compound nucleus” deformation distributions at the end of the fusion dynamics. However, at some point, neutron emission during the fusion dynamics may play a role [45].

Limitations to the magnitude of the presaddle component are dependent on its assumed mass-asymmetry dependence. A flat mass-asymmetry independent fission delay time was found to have little effect on the shape of the charge distribution. On the other hand, the shape was found to be very sensitive to a fission delay time with a large mass-asymmetry dependence.

The conclusions of this work are restricted by the lack of both experimental prefission neutron multiplicities and measured fission-fragment mass or charge distributions for the same reaction. However, in the end, any limitations obtained from measured charge distributions are model dependent, depending on the accuracy of the predicted shapes without fission delays. It is with respect to these shapes that distortions in experimental distributions arising from presaddle delay times can be determined. This in turn is limited by our knowledge of the potential energy surface, i.e., the conditional fission barriers and their associated level density parameters. Future studies should also investigate the effect of the Kramers factor [46] on the shapes which has been ignored in this work. Experimentally these uncertainties may be addressed by measurements of fission-fragment charge distributions at lower excitations where the effect of any presaddle delay is reduced.
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APPENDIX

The earliest time algorithm described in Sec. II for choosing the decay channels can easily be extended to cases where the fission decay width approaches its equilibrium value in a gradual manner. In this algorithm, one chooses a decay time for each channel in the absence of competition from other channels and then competition between the channels is included by choosing the channel with the earliest time.

If $\Gamma^i(t)$ is the time dependence of the partial decay width for channel $i$, then in the absence of competition from other channels, a population $N$ of compound nuclei will have the following time derivative:

$$\frac{dN}{dt} = -\Gamma^i(t) N = \frac{\Gamma^i(t)}{h} N_0 \exp \left[-\int_0^t \frac{\Gamma^i(t')}{h} dt'\right].$$

(A1)

A time can be chosen in a Monte Carlo simulation by solving the following equation:

$$\int_{t_{\text{elapsed}}}^t \frac{\Gamma^i(t')}{h} dt' = -\ln(x),$$

(A3)

where $x$ is again a random number with uniform distribution between zero and unity. The above equation is only useful in Monte Carlo simulations if it can be solved easily. An example where this is the case is for a decay width which ramps linearly up to its equilibrium value $\Gamma_0^i$:

$$\Gamma^i(t) = \begin{cases} \frac{r_i^*}{t_i^*} t, & t \leq t_i^* \\ \Gamma_0^i, & t \geq t_i^* \end{cases}$$

(A4)

In this example, decay times can be chosen as follows:

$$t^i = \begin{cases} t^*, & t^* < t_i^* \\ t_i^* - \frac{1}{t_i^*} \ln(x_2), & t_i^* \leq x_2 \\ t_{\text{elapsed}} - \frac{1}{t_i^*} \ln(x_2), & t_{\text{elapsed}} > t_i^* \end{cases}$$

(A5)

where $t^*$ is a solution of

$$t = \sqrt{\frac{2h}{\Gamma_0^i}} \ln(x_1) + t_{\text{elapsed}},$$

(A6)

and $x_1$ and $x_2$ are independent random numbers with uniform distributions between zero and unity.

[41] P.A. Gottschalk and T. Ledergerber, Nucl. Phys. A278, 16 (1977). The Coulomb term in Eq. (36) of this reference, is cancelled to first order when \( g_{\text{LDM}} \) is calculated at the deformation-dependent Fermi energy.