Binary Decay of Light Nuclear Systems

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Abstract

A review of the characteristic features found in fully energy-damped, binary-decay yields from light heavy-ion reactions with \( 20 \leq A_{\text{target}} + A_{\text{projectile}} \leq 80 \) is presented. The different aspects of these yields that have been used to support models of compound-nucleus (CN) fission and deep-inelastic dinucleus orbiting are highlighted. Cross section calculations based on the statistical phase space at different stages of the reaction are presented and compared to the experimental results. Although the statistical models are found to reproduce most of the observed experimental behaviors, an additional reaction component corresponding to a heavy-ion resonance or orbiting mechanism is also evident in certain systems. The system dependence of this second component is discussed. The extent to which the binary yields in very light systems \( (A_{\text{CN}} \leq 32) \) can be viewed as resulting from a fusion-fission mechanism is explored. A number of unresolved questions, such as whether the different observed behaviors reflect characteristically different reaction times, are discussed.

I. INTRODUCTION

As the interaction energy for a heavy-ion reaction increases above the Coulomb barrier, the reaction grazing angle moves to more forward angles so that, by a value of about 20% above the barrier, very small quasielastic and single-nucleon transfer reaction yields are expected at larger scattering angles. Instead, the incident flux that might be expected to scatter to larger angles, corresponding to smaller impact parameters, is trapped by the formation of a compound nucleus. For lighter systems, this compound system subsequently decays by light particle and \( \gamma \)-ray emission, with a very small heavy-fragment \((A > 4)\) emission component. The experimental observation of significant large-angle, elastic-scattering cross sections at energies well above the Coulomb barrier has therefore been viewed with
considerable interest. Initially seen in systems of comparable target and projectile masses \[1\], anomalous large-angle elastic cross sections have been found in a number of systems. An early explanation for these yields \[1\] was in terms of a possible elastic-transfer mechanism where, simply, the target and projectile were viewed to exchange identities. Alternatively, optical model calculations have also been found to predict enhanced back-angle yields when weak absorption is assumed for the grazing partial waves. Complicating the picture is the observation that not all systems are found to demonstrate the elastic scattering enhancements. Also, some systems which exhibit the phenomena involve the scattering of particles of very different masses. As a further complication, many of the systems demonstrating a large-angle elastic scattering enhancement are also found to show resonant behavior in scattering and transfer reaction excitation functions. An overview of the anomalous large-angle scattering (ALAS) phenomenon is given in the review paper of Braun-Munzinger and Barrette \[2\].

Although several mechanisms could be identified as possible reasons for enhanced large angle yields in elastic and quasielastic channels, it was still a surprise when Shapira et al. \[3\] discovered similar large-angle yield enhancements for strongly energy-damped inelastic channels of the \(^{12}\)C+\(^{28}\)Si reaction. The energy spectra for these channels were found to be peaked at values that one would expect if the \(^{12}\)C and \(^{28}\)Si fragments are emitted at rest from a sticking configuration of the compound system. Further, angular distributions of constant \(d\sigma/d\theta_{c.m.}\) suggest a long-lived intermediate complex. These features led to the suggestion that an orbiting, dinucleus configuration is formed that decays back to the entrance channel. Weak absorption of the grazing partial waves, as previously suggested in the elastic case, is necessary to avoid having the orbiting configuration spreading into the compound nucleus states. However, whereas for the elastic scattering enhancements it was only necessary to invoke weak absorption for the grazing partial waves, the orbiting phenomenon suggests weak absorption for even lower partial waves with values between the critical angular momentum for fusion and the reaction grazing angular momentum.

After the discovery of orbiting in the \(^{12}\)C+\(^{28}\)Si system, similar enhancements of large-
angle, binary-reaction yields were subsequently observed in somewhat heavier systems. While studying the strong resonance behaviors found in excitation functions of the $^{28}\text{Si} + ^{28}\text{Si}$ and $^{24}\text{Mg} + ^{24}\text{Mg}$ elastic and inelastic channels, a significant non-resonant background yield was discovered in the energy spectra of these channels at higher excitation energies. This yield was found to extend to larger angles. Other evidence for damped, binary yields was found in a study by Grotowski et al. of symmetric mass fragments from the $^{12}\text{C} + ^{40}\text{Ca}$, $^{9}\text{Be} + ^{40}\text{Ca}$ and $^{6}\text{Li} + ^{40}\text{Ca}$ reactions. Using coincidence techniques, they established the existence of significant decay strength to the mass-symmetric channels for these systems. It is unlikely that this behavior could arise from a direct reaction mechanism because of the large difference in mass asymmetry between the entrance and exit channels. Angular distribution and energy spectra measurements were shown to be consistent with the fission decay of the respective compound systems. Although these measurements were done at relatively forward angles, the observed angular dependence would suggest significant large-angle cross sections.

Concurrent with the experimental measurements of energy-damped, binary reaction yields in lighter systems came the development of finite-nuclear-range corrections to macroscopic-energy calculations for these systems. By taking better account of the role of the nuclear surface in determining nuclear binding energies, these calculations made it possible for the first time to obtain reasonable estimates of fission barrier heights in lighter systems. Whereas the standard rotating liquid drop model indicates high fission barriers, thereby precluding the prediction of strong fission competition in these systems, the barrier energies found with the new calculations suggest that significant fission competition might occur.

The possibility of fission competition in light systems raises the question of how one can distinguish between the orbiting and fusion-fission mechanisms. This is difficult to answer, although a clearer understanding of the respective processes has been emerging through a number of different studies, as will be discussed in this report. Some of the conceptual differences between the two mechanisms are indicated schematically in Fig. 1. Both processes
are seen to involve near-grazing impact parameters with, however, the fusion-fission mechanism viewed as proceeding through the formation of a fully equilibrated compound nucleus. The fission decay of the compound nucleus is determined by the phase space available at a “transition” configuration and, for light systems, can lead to significant population in many of the energetically allowed mass channels. For the orbiting mechanism, the system becomes trapped in a more deformed configuration than that of the compound nucleus and is inhibited from spreading into the compound nucleus states. This allows for significant decay back to the binary channels. Although orbiting can be considered as a deep-inelastic scattering mechanism, the rapid mass equilibration that is thought to occur in light systems can result in the population of channels with significantly different mass asymmetry than the entrance channel. Still, it is expected that the orbiting mechanism will retain a greater memory of the entrance channel than the fusion-fission process.

The strong resonance behavior observed in excitation-function measurements of large-angle elastic and inelastic scattering yields in several light systems suggests that some structural aspect of the compound system may be strongly influencing these yields. This behavior is most pronounced in the $^{24}$Mg+$^{24}$Mg system [7] where measurements [10] have indicated a resonance spin close to, or exceeding, the grazing angular momentum for the reaction. A possible explanation is that a highly deformed, metastable configuration for the compound system is formed. The relationship between the resonance behavior and the fission process, the latter of which is observed to occur at some level in all of the reactions studied at energies above the Coulomb barrier, is still an open question. A review of the resonance aspects of heavy-ion breakup reactions, including a discussion of earlier electrofission measurements, is found in the review article of Fulton and Rae [11].

This paper will review the status of our experimental and theoretical understanding of energy-damped, binary-decay processes in light systems. Although the relationship between these processes and that responsible for heavy-ion resonance behavior will be explored, the general topic of heavy-ion resonances in light systems will not be discussed and the reader is referred to several review papers that already cover this general topic [11–13].
Sec. II we will explore the general experimental signatures of the binary yields observed in lighter systems. In Sec. 3 the experimental techniques used to study these behaviors will be presented and some of the experimental difficulties highlighted. In Sec. 4 the various models that have been developed to explain the observed yields are discussed. In Sec. 5 we will develop the experimental systematics by presenting a system-by-system discussion of current data, comparing these data to the model calculations. In Sec. 6 we will present some of the open problems and suggest possible measurements that might address these problems. Finally, in Sec. 7 we will summarize the present review.

II. EXPERIMENTAL BEHAVIORS OF BINARY DECAY YIELDS

One way to characterize nuclear reactions is in terms of the number of nucleons exchanged between the incident particles. Alternatively, one can consider the degree to which the kinetic energy of the incident channel is transferred to internal excitation of the outgoing fragments. Clearly, there can be a significant correlation between the number of nucleons transferred and the energy damping that occurs in the reaction. In our discussion of the general reaction properties, we use a somewhat arbitrary division that is motivated by the experimental observables of mass, angle, and energy excitation of the fragments. We start with a discussion of the large-angle elastic scattering yields. We then consider the situation where one observes some energy damping, and possibly mass flow, but still do not have angular distributions of constant \( d\sigma/d\theta_{\text{c.m.}} \) that would signify a very long lived complex. Finally, we consider the situation where all degrees of freedom of the system appear to have reached full equilibration.

A. Large-angle elastic and quasi-elastic scattering

After the first observations in heavy-ion reactions involving near-identical particle systems of large-angle elastic-scattering yields in excess of the optical model expectations,
these backward-angle enhancements were found to be a relatively common feature of collisions between p-shell and sd-shell nuclei [2]. Figure 2 shows an angular distribution for the $^{16}\text{O}+^{28}\text{Si}$ reaction at $E_{\text{lab}} = 55$ MeV. The dashed curve is the prediction of an optical model calculation using the strong absorption E18 potential of ref. [14]. The large angle yield is far in excess of the model calculation and demonstrates a highly oscillatory behavior. As shown in the insert, the angular distribution suggests a single orbital angular momentum of $\ell = 26\hbar$ may dominate the large-angle yields. An excitation function of the backward angle yields for this system shows strong resonance-like enhancements. This behavior might result from the formation of nuclear molecular configurations [12,13,15], to an orbiting phenomenon [17] related to the dynamics of the interaction potential, or to compound-elastic scattering, that is, the fission decay of the compound nucleus back to the elastic channel. Two or more of these mechanisms may coexist.

The explanation for the resonance-like structures that are often found associated with backward angle elastic and quasi-elastic yields in light systems might be found in the interplay between interaction barriers and energy dissipation mechanisms. The observed large-angle cross sections suggest the formation of a long-lived nuclear molecule or dinucleus system that fragments at a large deformation. This is consistent with the sticking model of deep inelastic collision processes for which two colliding nuclei adhere to each other and undergo finite rotation before separating, with the possible transformation of orbital angular momentum into spin of the outgoing fragments and with a possible loss of kinetic energy of relative motion. The resonances might correspond to particularly simple configurations of the dinucleus complex. In a 1982 review of the “anomalous” large-angle scattering phenomenon (ALAS), however, Braun-Munzinger and Barrette [2] have shown the difficulty of attributing a specific reaction mechanism to the resonance behavior. The current focus is to establish a global systematics for the occurrence of ALAS behavior based on the occurrence of weak absorption of the near-grazing partial waves [18].
B. Deep-inelastic scattering yields

Deep-inelastic reactions between heavy nuclei \((A_{\text{target}} + A_{\text{projectile}} > 50)\) typically involve substantial rearrangement of the nuclear matter of the incident particles, with strong damping of the entrance-channel’s kinetic energy and transfer of orbital angular momenta to the spins of the outgoing fragments \([19,20]\). The composite system may reach a configuration close to the compound-nucleus saddle point before subsequent elongation and fission. Wilczynski \([21]\) has developed a qualitative interpretation of deep-inelastic reactions in terms of a nuclear orbiting process with dissipation of energy resulting from frictional forces. A schematic illustration of the progression from quasielastic scattering to nuclear orbiting in heavy-ion collisions is given in Fig. 3 (adopted from ref. \([21]\)). The two dimensional plot shows a contour of maximum cross section ("Wilczynski diagram") that contains the components of the three possible classical trajectories, as drawn in the figure. Trajectories 1 and 2 correspond to near-side and far-side scattering from the target nucleus. In trajectory 3 the dinucleus system survives long enough to complete close to, or more than, one full rotation. It is associated with an “orbiting” process and leads to emission spectra and emission probabilities that are independent of angle \([20]\). That is, there is complete energy damping resulting in the final kinetic energy of the fragments being close to the relative potential energy at the point where the fragments are closest together. Also, the fragments’ angular distributions of \(d\sigma/d\Omega\) follow a \(1/\sin\theta_{\text{c.m.}}\) angular dependence (corresponding to angular distributions of constant \(d\sigma/d\theta_{\text{c.m.}}\)) suggesting the occurrence of a long-lived dinucleus object in a sticking configuration.

This early classical picture of the orbiting phenomenon has been developed further using the classical models proposed, for example, by Bondorf et al. \([22]\) and Gross and Kalinowski \([23]\) for heavy-ion damped reactions.

The significant cross sections \((> 10 \text{ mb})\) observed for large-angle inelastic scattering yields of reactions such as \(^{20}\text{Ne} + ^{12}\text{C}\) \([3]\), \(^{27}\text{Al} + ^{16}\text{O}\) \([24]\), \(^{28}\text{Si} + ^{12}\text{C}\) \([17]\), and \(^{24}\text{Mg} + ^{12}\text{C}\) \([25]\) were initially interpreted in terms of the formation of a dinucleus, orbiting configuration.
These large yields were found to be very surprising since any system in this mass range and making such close contact, as suggested by an orbiting behavior, was expected to fuse into a compound nucleus. The picture that emerges is one where the interacting ions are trapped in a pocket of the ion-ion potential that results from the combined effects of the Coulomb, centrifugal, and nuclear interactions. The orbiting complex may act as a “doorway” to fusion, but weak absorption may also allow decay back to the binary channels, possibly after significant mass flow and rotation of the nuclear configuration. The description of an equilibrium orbiting model will be developed in Sec. IV B. In subsequent investigations it has been shown that at least some of the yield attributed to orbiting may correspond instead to the process of fusion followed by fission. Still, experimental evidence for a distinct orbiting process in light systems will be presented with the discussion of the $^{28}$Si+$^{12}$C and $^{28}$Si+$^{14}$N reactions. A non-compound origin is surmised for the reaction yields in these systems based on their entrance-channel dependence $^{[26]}$.

C. Fully energy-damped binary yields

1. Angular Distributions

Enhanced large-angle yields in heavy-ion reactions reflect a relatively long reaction time allowing significant rotation of the intermediate complex formed in the reaction. For the mechanism of fusion followed by fission, the evolving intermediate complex is taken to pass through a fully equilibrated compound nucleus. In the orbiting picture, a long-lived dinucleus configuration is envisioned. In both cases the binary yields are assumed to correspond to peripheral reactions involving incident angular momenta close to the critical angular momentum for fusion $\ell_{cr}$.

In considering the fission of heavier mass systems than those discussed here, angular distribution data have yielded significant insight on the details of the breakup mechanism $^{[27]}$. The “reference” distributions for these studies are those predicted by the standard
transition-state model of fission \(^2^8\). Using heavy-ion reactions to populate the systems, it is commonly found that the orbital angular momenta \(L\) are large compared to the projectile and target spins, resulting in the projection of the total angular momentum \(J\) on the space fixed \(z\)-axis, the beam direction, to be small. Assuming a Gaussian distribution of \(K\), the projection of \(J\) on the symmetry axis of the fissioning system, and in the limit of zero projectile and target spins, the expected fission angular distribution becomes \(^2^8\)

\[
W(\theta) \propto \sum_{J=0}^{\infty} (2J + 1) T_J \\
\times \sum_{K=-J}^{J} \frac{(2J + 1)|d_{M=0,K}^J(\theta)|^2 \exp(-K^2/2K_0^2)}{\sum_{K=-J}^{J} \exp(-K^2/2K_0^2)},
\]

where the \(T_J\)'s are the transmission coefficients giving the combined probability for formation and fission decay of a compound nucleus with \(J = L\) and \(d_{M,K}^J\) is the reduced rotation matrix.

The variance of the \(K\) distribution can be expressed as

\[
K_0^2 = I_{eff} T / \hbar^2,
\]

where

\[
\frac{1}{I_{eff}} = \frac{1}{I_\parallel} - \frac{1}{I_\perp}
\]

and \(I_\parallel\) and \(I_\perp\) are the moments of inertia about axes perpendicular and parallel to the symmetry axis, respectively. The “transition” state is typically taken as the saddle point, defined as the configuration where the potential energy of the compound system as a function of deformation and mass asymmetry is at its maximum. The temperature at the saddle point \(T\) is found by \(T = \sqrt{E_x/a}\), where \(E_x\) is the energy of internal excitation at the saddle point and \(a\) is the level density parameter. Deviations between the observed angular distributions and those predicted by the standard transition-state model using the above expression for \(W(\theta)\) have been used as evidence for faster processes than that of complete fusion followed by fission.

Deep-inelastic scattering mechanisms, where the characters of the incident nuclei are maintained, can also lead to large angle yields if a dinucleus configuration is reached that
survives for a significant fraction of the rotation period. If a large number of partial waves contribute to the reaction, the resulting angular distributions become relatively featureless. For heavy-ion reactions, where the angular momenta associated with processes leading to large angle yields tends to be high, the resulting angular distributions approach the classical limit associated with systems emitting fragments perpendicular to the rotation spin vector, with \( d\sigma/d\theta_{c.m.} = C \) or, equivalently, \( d\sigma/d\Omega = C'/\sin\theta_{c.m.} \), where \( C \) and \( C' \) are angle-independent normalization constants. For the systems considered in this report, the differences between the angular distributions predicted by the standard transition state model and the \( d\sigma/d\Omega = C'/\sin\theta_{c.m.} \) distribution that characterizes a classical, long-lived orbiting configuration are only evident at very forward and backward angles. This is illustrated for the \(^{35}\text{Cl} + ^{12}\text{C} \) reaction at \( E_{lab} = 180 \text{ MeV} \) \([29,30]\). Angular distributions of fission-like fragments are shown in Fig. 4 for the inclusive yields to different mass channels. One finds distributions of constant \( d\sigma/d\theta_{c.m.} \) for each of the measured isotopes. In Fig. 5 the angular distribution data in \( d\sigma/d\Omega \) for the Ne channel are compared to both a \( 1/\sin\theta_{c.m.} \) angular dependence and the angular dependence predicted by the transition state model (using Eqn. 2.1). For this latter calculation the transmission coefficients for the fission yields \( T_J \) were based on the transition-state calculation to be discussed later in this report and the level density parameter was taken as \( a = A_{CN}/8 \). The two models show overlapping behavior in the region of the experimental data and significant differences between the calculations are only observed at very forward and backward angles. Unfortunately, the cross sections at angles near to 0° and 180° are also very difficult to measure. Large elastic scattering yields can obscure the forward angle data and low particle energies can make the large angles yields difficult to detect. In general it has not been possible in lighter systems to deduce information about the time scales of the more strongly damped processes based on angular distribution data.

A more rapid rise in the energy-inclusive cross sections at forward angles than given by a \( 1/\sin\theta_{c.m.} \) distribution indicates a shorter lifetime of the composite system, with breakup occurring within the first revolution of the system. Such lifetimes are incompatible with
the formation of an equilibrated compound nucleus, but may still reflect significant energy
damping within a deep-inelastic mechanism. By measuring the forward peaked distributions,
it is possible to estimate the lifetime of the intermediate nuclear complex using a diffractive,
Regge-pole model. The distributions are fitted by

\[
\frac{d\sigma}{d\Omega} = \frac{C}{\sin \theta_{\text{c.m.}}} \left\{ e^{-\theta_{\text{c.m.}}/\omega t} + e^{-(2\pi-\theta_{\text{c.m.}})/\omega t} \right\}.
\] (2.2)

This expression describes the decay of a rotating dinucleus with angular velocity \( \omega = h\ell/\mu R^2 \) where \( \mu \) represents the reduced mass of the system, \( \ell \) its angular momentum (which should fall somewhere between the grazing \( \ell_g \) and critical \( \ell_{cr} \) angular momentum), and \( R \) represents the distance between the two centers of the dinucleus. Small values of the “life angle” \( \alpha (\equiv \omega \tau) \) lead to forward peaked angular distributions associated with fast processes, whereas large values of \( \alpha \), associated with longer times as compared to the dinucleus rotation period \( \tau \), are consequently associated with longer lived configurations and lead to more isotropic angular distributions. In the limiting case of a very long-lived configuration, the distributions approach a \( d\sigma/d\Omega \propto 1/\sin \theta_{\text{c.m.}} \) dependence.

One way to characterize the sensitivity of the angular distributions to the “life angle” \( \alpha \) is by considering the anisotropy function \( R(\theta) \), where

\[
R(\theta) = \frac{d\sigma}{d\Omega}(\theta, \alpha)/d\sigma/d\Omega(90^\circ, \alpha).
\]

The functional dependence of \( R(\theta) \) with \( \alpha \) is shown in Fig. 6 for \( \theta = 10^\circ \) and \( 170^\circ \). The corresponding anisotropy for an angular distribution with \( d\sigma/d\Omega \propto 1/\sin \theta_{\text{c.m.}} \) is shown by the dashed line. The plot suggests that an anisotropy measurement might be sensitive to the time scale of fast processes (\( \alpha < 90^\circ \)), but is less sensitive to the time scale of strongly damped processes with \( \alpha > 120^\circ \).

Measurements of excitation energy integrated yields of specific mass channels show, in
some systems, angular distributions which reflect the contributions of both short- and long-
lived processes. As an example, the observed distributions for inclusive, energy-summed
yields for the \( ^{16}\text{O}+^{11}\text{B} \) reaction at \( E_{\text{lab}} = 64 \text{ MeV} \) are shown in Fig. 7 [31]. It should be
noted that for this particular reaction, the isotope pairs C-N, B-O, and F-Be correspond to specific exit channels. From this figure one finds a contribution of forward peaked processes (N and F fragments) with \( \alpha < 70^\circ \), corresponding to direct mass transfer, with slower processes (C, B, and Be fragments) presenting large “life angles”, with \( \alpha \gg 180^\circ \).

2. Energy Spectra

For fully energy-damped reactions, the energy spectra are peaked at large negative \( Q \)-values, with the cross section maxima typically occurring at a value of total kinetic energy in the exit channel that corresponds to the relative potential energy of the two nascent fragments in a near-touching configuration. This observation is consistent with the idea that the composite system passes through a stationary point in the potential energy surface where the relative kinetic energy is at a minimum. The stationary point could be the saddle point of a compound nucleus undergoing fission or, alternatively, the dinucleus configuration of an orbiting binary complex. The total kinetic energy of the fragments \( \text{TKE} \) in the exit channel is then expected to equal the sum of the nuclear and Coulomb potential energies and the rotational energy of the rotating complex at the stationary point, with

\[
\text{TKE} = V_{\text{nuc}}(d) + V_{\text{Coul}}(d) + V_{\text{rot}}(d),
\]

and \( V_{\text{nuc}} \), \( V_{\text{Coul}} \), and \( V_{\text{rot}} \) are the nuclear, Coulomb, and relative rotational energy between the two nascent breakup fragments at a separation \( d \) corresponding to the stationary point. In general, the sticking limit is assumed in calculating the rotational energy contribution.

The total kinetic energy of the outgoing fragments is therefore sensitive to the deformation of the system at the time of scission [17,32–38]. In general, the most probable TKE values are well described by assuming stationary shapes consistent with the predicted saddle-point configurations of the nuclear systems [39]. The exceptions to this rule tend to occur for nuclear systems where anomalous large-angle elastic scattering (ALAS) cross sections are observed.
It should be noted that even though large kinetic energy damping is one of the experimental signatures used to distinguish a damped reaction process from direct reactions in which only a small part of the initially available kinetic energy is dissipated, it is not necessarily the case that a given fusion-fission or orbiting reaction event will have a large energy loss. The distribution of the $TKE$ values about the peak value can be large and, in some cases, may lead to the population of the ground states of the outgoing fragments, as would be the case for compound elastic scattering.

The dependence of the average energy release in fission on atomic number and mass of the compound nucleus has been widely studied for heavy systems. A linear relationship between the most probable $TKE$ release value with $Z^2/A^{1/3}$ of the fissioning nucleus has been established by the systematic work of Viola et al. [40], with this systematics more recently extended to the lighter systems in ref. [41]. The compiled $TKE$ values [42] of the symmetric fission fragments produced in light heavy-ion systems are shown in Fig. 8. The original Viola systematics [40] (dashed line) are capable of describing the whole data set except in the case of low $Z$ fissioning nuclei. In these very light systems, the diffuse nature of the nuclear surface and the associated perturbations of the necking degree of freedom, as calculated using the finite-range, liquid-drop model [43], results in a change in the predicted slope, leading to vanishing $TKE$ values as $Z$ approaches zero. This effect is observed experimentally and is reproduced by the solid curve in Fig. 8, which is calculated using [41]:

\[ TKE = \frac{Z^2}{(aA^{1/3} + bA^{-1/3} + cA^{-1})} \]

where the values of the fitting parameters are $a=9.39$ MeV$^{-1}$, $b=-58.6$ MeV$^{-1}$ and $c=226$ MeV$^{-1}$, respectively.

**III. EXPERIMENTAL ARRANGEMENTS**

Several considerations influence the experimental techniques used to study the processes considered in this report. In a given measurement most of the processes that compete with
those being studied correspond to more peripheral collisions and result in yields at angles near to or forward of the grazing angle. This requires that angular distributions be extended to larger angles where the more peripheral mechanisms have little yield, although with the possible experimental complication of the energy of the reaction fragments falling below the identification thresholds of the detectors being used.

To provide a complete description of the reaction process, it becomes necessary to determine, for each fragment, the mass ($A$), atomic number ($Z$), energy ($E$) (or velocity ($v$)), and the emission angle ($\theta$) of the particle. In cases where the fragments are emitted in binary decays, the conservation laws for mass, energy, and momentum can be used to reduce the number of quantities needed to be measured to fully specify the reaction. If one or both of the fragments is at an energy above its particle emission threshold, however, there is likely to be a secondary light particle emitted before the fragment is detected. The effects of such secondary light particle emission need to be considered.

In the simplest arrangements for detecting single particles, element identification ($Z$) and energy measurement ($E$) is generally accomplished by determining differential energy loss $\Delta E$ and the total energy $E$ in a telescope consisting of a gas $\Delta E$ counter backed by a solid-state detector. The $\Delta E$ signal is proportional to the square of the charge. By stopping the particle in the solid state detector, the residual energy is also determined and thus the total energy can be deduced. Alternatively, a Bragg-curve detector can supply the information on $Z$ and $E$. In either case, the desired cross sections tend to be low (typically, $d\sigma/d\Omega <5$ mb/sr), requiring large solid-angle detectors and, possibly, necessitating the use of position-sensitive detectors for angle determination.

For measurements done at pulsed beam facilities it is possible to determine the energy and mass of a particle through time-of-flight and total energy measurement. In this case a single, bare Si(surface-barrier) detector can be used to measure the yields. The detection of low energy particles may still be difficult, however, as a consequence of multiple scattering effects of the particle leaving the detector and the dependence of the timing signal on the energy and charge of the particle incident on the detector. In general, depending on the
preferred detection technique, experiments have either measured the charge or mass of the outgoing fragments, but not both simultaneously.

As an alternative to the singles measurement of the reaction products, for a binary decay it is also possible to determine the mass and energy of the outgoing fragments by measuring the scattering angles of both fragments and the relative timing of the two fragments. This technique has proven to be quite valuable since it allows for the use of inexpensive, large-area, position-sensitive avalanche detectors (PPACs). Figure 9 illustrates the basic variables of the measurement. The two outgoing particles are detected at laboratory scattering angles of $\theta_1$ and $\theta_2$, respectively, in detectors located at distances of $d_1$ and $d_2$ from the target. The relative time of arrival at the detectors, $\Delta t = t_2 - t_1$, can be measured directly using a time-to-amplitude circuit, or can be deduced from measurements of the individual flight times. In the non-relativistic limit, the linear momenta of the two particles in the laboratory system, $\vec{p}_1$ and $\vec{p}_2$, can be determined from the total laboratory momentum $\vec{p}_o$ and the scattering angles, with

$$p_1 = p_o \frac{\sin(\theta_2)}{\sin(\theta_1 + \theta_2)}, \text{ and}$$

$$p_2 = p_o \frac{\sin(\theta_1)}{\sin(\theta_1 + \theta_2)}.$$

The masses of the two scattered particles can be related to the above quantities and the projectile and target masses, $A_{\text{proj}}$ and $A_{\text{targ}}$, with

$$A_2 = \frac{(d_1 A_{\text{proj}} + A_{\text{targ}} + \Delta t)}{(d_2 + d_1)} p_1 \left(\frac{d_2 + d_1}{p_2 + p_1}\right), \text{ and}$$

$$A_1 = A_{\text{proj}} + A_{\text{targ}} - A_2.$$

It is then possible to determine the energies of the two particles and the corresponding reaction $Q$-value using the derived masses, with

$$E_1 = E_{\text{lab}} \frac{A_{\text{proj}}}{A_1} \frac{\sin(\theta_2)}{[\sin(\theta_1 + \theta_1)]^2},$$

16
\[ E_2 = E_{\text{lab}} \frac{A_{\text{proj}}}{A_2} \left( \frac{\sin(\theta_1)}{\sin(\theta_1 + \theta_1)} \right)^2, \text{ and} \]

\[ Q = E_1 + E_2 - E_{\text{lab}}, \]

where \( E_{\text{lab}} \) is the laboratory beam energy. If single mass resolution is achieved (the typical situation for the lighter systems being considered), then the reaction \( Q \)-value can be subsequently determined by using only the position information and the known masses. In this case, the excellent position resolution that can be achieved with the PPAC’s can result in \( Q \)-value resolutions of \(< 200 \text{ keV} \), with the limiting resolution determined largely by multiple-scattering effects as the particles leave the target.

The coincidence detection of both reaction fragments can also be useful in cases where one or both of the fragments is formed with sufficient excitation energy to result in a secondary emission of a light particle (typically an \( \alpha \) particle). On average, the emitted light particles result in a distribution of fragment velocities about their original, pre-evaporation values. In this case, the deduced mass distribution reflects the pre-evaporation values. If, in addition, the fragment mass is measured through an alternative method, one can determine the extent to which the secondary evaporation modifies the observed mass distribution from the original, preevaporation distribution [45].

An essential element of most model calculations of the binary decay yields is an estimate of the spin distribution of the compound nucleus, as usually determined through measurement of the total fusion cross section. In general, the experimental determination of the fusion cross section is obtained by measuring the evaporation residues yields and, in the case of a fusion-fission analysis, adding in the fission yields. When pulsed beams are available, the evaporation-residue yields can be measured using bare, Si(surface barrier) detectors. Otherwise, it is possible to employ time-of-flight telescopes using micro-channel-plate detectors (MCP), or to use a set of \( E-\Delta E \) telescopes.

Figure 10 shows the experimental arrangement used in a study of the binary yields from the \( ^{24}\text{Mg}^+\ ^{24}\text{Mg} \) reaction [46] that has many of the elements discussed above. The
Bragg-curve detector [44] determined the charge and energy of outgoing fragments. A large multigrid avalanche counter (MGAC 2) [47] determined the angles of the particles entering the Bragg-curve detector. A second avalanche counter (MGAC 1) was used to detect the coincident fragments and determine their angles. Finally, a number of Si(surface barrier) detectors were used for normalization purposes and to obtain a measure of the evaporation-residue cross section.

The use of angular distribution data to separate different reaction components requires that these distributions be measured over as large an angular range as possible. For a given fragment, energy thresholds set by the detectors may severely restrict the largest angle that can be reasonably measured. In the case of a binary decay, however, it may be possible to use a measurement of the corresponding recoiling fragment to extend the angular distribution. Figure 11 demonstrates this simple concept for the $^{18}\text{O}+^{10}\text{B}$ reaction going to the $^{15}\text{N}+^{13}\text{C}$ exit channel. The “beamlike” particle ($^{15}\text{N}$) going to forward center-of-mass angles is detected at forward laboratory angles, as indicated in the velocity diagram. Although “reverse kinematics” also results in forward scattering angles when the $^{15}\text{N}$ particle undergoes large center-of-mass deflection, the laboratory energy of the particle is now small, complicating particle identification. At this point, however, the “targetlike” $^{13}\text{C}$ particle is scattered to forward angles and can be easily detected. Combining the measurements for the $^{15}\text{N}$ and $^{13}\text{C}$ results in a more complete angular distribution for this channel. Although this procedure is only valid in cases where secondary light-fragment emission can be ignored, it has been found to be very useful in the analysis of lighter systems [31,48].

In studies where the interplay between the nuclear structure and reaction dynamics is investigated, one important technique has been to identify the $\gamma$-decay cascade from the excited final fragments. In this case, the low reaction cross sections mandate experimental arrangements with both large particle and $\gamma$-ray detection efficiencies. The identified particles are used for channel selection and Doppler correction of the $\gamma$-ray spectra. Such measurements have been done in studies of the $^{32}\text{S}+^{24}\text{Mg}$ [49] and $^{36}\text{Ar}+^{12}\text{C}$ [50] reactions.
IV. MODEL CALCULATIONS

A. Statistical Models

It took only a short time after the experimental observation of neutron-induced fission for a quantitative description of the process to be developed in terms of the transition-state model [51]. In this model, where fission competes with $\gamma$-ray and light-particle emission in the de-excitation of the compound nucleus, the probability for fission is determined by the most restrictive phase space (level density) encountered by the fissioning system between the equilibrated compound-nucleus configuration and the exit channel. This “transition state” is usually taken as the configuration where the macroscopic potential energy reaches its maximum value, the saddle point, although discrepancies observed in heavier systems with the angular dependence described by Eqn. 2.1 have also led to the consideration of the more deformed scission point as the transition state [52,53].

In lighter systems, where the saddle- and scission-point configurations are expected to be very close and little damping is expected as the system proceeds between the two, there is less reason to expect significant differences between calculations done at the saddle and scission points than for heavier systems where the shapes of the saddle- and scission-point configurations are quite different and significant damping can occur in moving between the two. Indeed, calculations based on saddle-point [39] and scission-point [54] transition-state configurations are found to give equivalent results in lighter systems. In this section the transition-state formalism will be reviewed and the saddle-point [39] and scission-point [54] calculations compared.

The development of saddle-point calculations in lighter systems was significantly delayed from the comparable development for heavy-system fission because of the difficulty in accounting for the finite range and diffuse nuclear surface effects that strongly influence the macroscopic energies of these systems. In light nuclei, the saddle-point shapes correspond to two deformed spheroids separated by a well-developed neck region, with the surfaces of the
two spheroids coming within close proximity of one another. This results in strong surface effects. The development of the finite-range model [9], however, has made it possible to extend the saddle-point calculations to very light systems. Within this model, saddle-point energies are found by determining the stationary points of the compound nucleus potential-energy surface as a function of spin and constrained mass asymmetry. The shape parameterization, discussed by Nix in Ref. [55], consists of three connected quadratic surfaces of revolution. The calculations explicitly account for the diffuse nature of the nuclear surface and the finite range of the nuclear interaction.

Since the development of the finite-range model, one remaining difficulty in applying its results to the fission of lighter systems has been the lengthy process of performing individual calculations for all of the necessary spin and mass-asymmetry dependent saddle-points that might be encountered as the system breaks apart. Whereas for heavier systems the mass-asymmetry dependence of the macroscopic energy favors symmetric breakup, in lighter systems an asymmetric breakup is favored. This problem has been somewhat ameliorated with the development of a simple, double-spheroid parameterization of these energies [39]. In this double-spheroid picture, the saddle-point energy is given by

\[ V_{\text{saddle}}(J_{CN}, \eta) = V_C + V_n + V_r + V_o, \]

where \( J_{CN} \) is the spin of the compound nucleus, \( \eta(= 1 - 2A_L/A_{CN}) \) is the mass asymmetry, \( V_C \) is the Coulomb energy between two deformed spheroids, \( V_n \) is the nuclear interaction energy given by the two-body, finite-range-model potential of Krappe, Nix, and Sierk [56], and \( V_r \) is the total rotational energy of the double-spheroid configuration, using a diffuse-surface corrected moment of inertia. \( A_L \) is the atomic mass of the lighter of the two fission fragments. The final term, \( V_o \), accounts for the influence of the saddle-point neck as well as other, shape-independent aspects of the macroscopic energy. The spheroid geometry is adjusted to reproduce the full finite-range-model calculations of Sierk [9].

A comparison of saddle-point energies found using the double-spheroid model and energies obtained from full macroscopic energy calculations is shown in Fig. 12 for several sys-
tems. Figure 13 (from Ref. [39]) compares some typical saddle-points shapes obtained with
the full calculations (solid curves) and the corresponding double-spheroid shapes (dashed
curves). The double-spheroid parameterization is found to closely reproduce the saddle-point
energies found with the full calculations. Moreover, the shapes obtained with the double-
spheroid model are similar (excluding the neck) to the corresponding finite-range-model
configurations. Assuming that the saddle- and scission-point configurations are similar, this
suggests that the relative energy of the two spheroids calculated within this model should
be related to the total kinetic energy $E_{K}^{\text{tot}}$ of the fragments in the exit channel.

A schematic diagram of the energy balance for a fusion-fission reaction is shown in Fig.
14, taken from Ref. [49]. Starting from the entrance channel with incident center-of-mass
energy $E_{c.m.}$, the Coulomb and centrifugal energy dominated entrance barrier must first
be overcome to form a compound nucleus with excitation energy $E_{CN}^{*}$ and spin $J$. The
effective excitation of the compound nucleus $E_{\text{eff}}^{*}$, which enters in calculating the density of
compound nucleus states, is expected to be somewhat less than $E_{CN}^{*}$ (by an amount $\Delta_{\text{eff}}$)
since, at these high energies, it is assumed that the virtual ground states corresponds to the
macroscopic-energy ground state [57]. The most restricted region of phase space, where the
density of states becomes a minimum, occurs at the saddle point. In Fig. 14, $\varepsilon$ is taken as
the kinetic energy associated with the radial motion at the saddle point. This term further
reduces the density of saddle-point states. A saddle-point shell correction $\Delta V_{\text{shell}}$ is also
taken to influence the fission decay probabilities. The excitation energy available at the
saddle point $u_{J}$, which determines the corresponding level density $\rho_{f}$, is then given by

$$u_{J} = E_{CN}^{*} - V_{\text{saddle}}(J, \eta) - \Delta V_{\text{shell}} - \Delta_{\text{eff}} - \varepsilon$$

The probability for the compound nucleus of spin $J$ to break up to a fission channel
of mass asymmetry $\eta$ is proportional to the level density $\rho_{f}$ above the corresponding spin
$J$ saddle point. Some authors have taken the scission point as the transition state, in
which case the corresponding energy of the two fragments at scission (not shown) is used
to determine the transition-state level density. It will be shown that the very small energy
difference $\delta$ believed to exist between the saddle and scission points leads to very similar fission predictions of the saddle- and scission-point models. Assuming $\delta \approx 0$, the total kinetic energy in the exit channel, and, correspondingly, the reaction $Q$-value, can then be related to the relative energy of the fragments at the saddle/scission configuration. In this case, taking $\varepsilon = 0$ for the most probable decay probability (corresponding to the highest level density),

$$E_{K}^{\text{tot}} = V_C + V_n + \frac{\hbar^2}{2\mathfrak{I}_{rel}} \ell(\ell + 1)$$

with

$$\ell = \frac{\mathfrak{I}_{rel}}{\mathfrak{I}_{tot}} J_{CN}.$$

The relative moment of inertia of the two spheroids is given by $\mathfrak{I}_{rel} = \mu r^2$ and, taking the moments of inertia of the individual deformed spheroids as $\mathfrak{I}_1$ and $\mathfrak{I}_2$, respectively, the total moment of inertia for the two spheroid configuration is then given by

$$\mathfrak{I}_{tot} = \mathfrak{I}_1 + \mathfrak{I}_2 + \mathfrak{I}_{rel}.$$

Calculation of fission cross sections in the statistical models is based on the Hauser-Feshbach formalism. For a compound nucleus of spin $J$ that is populated with a partial fusion cross section of $\sigma_J$, the partial fission cross section is given in terms of the ratio of the fission decay width $\Gamma_{fis}^J$ to the total decay width for this spin $\Gamma_{tot}^J$, with

$$\sigma_{fis}^J = \frac{\Gamma_{fis}^J}{\Gamma_{tot}^J} \sigma_J.$$

The fusion partial cross section for formation of a compound nucleus of spin $J$ from projectile and target nuclei of spins $J_p$ and $J_t$, respectively, at center-of-mass energy $E_{\text{c.m.}}$ is given by

$$\sigma_J = \frac{\pi \lambda^2}{(2J_p + 1)(2J_t + 1)} \sum_{S = |J_p - J_t|}^{J_p + J_t} \sum_{\ell = |J - S|}^{J + S} T_{\ell}(E_{\text{c.m.}}),$$

with

$$\sigma_{fus}^{\text{tot}} = \sum_{J = 0}^{\infty} \sigma_J.$$
A simple and commonly used method of representing the fusion transmission coefficient is to take

$$T_\ell(E_{c.m.}) = \frac{1}{1 + \exp\left\{\left(\ell - \ell_{cr}(E_{c.m.})\right)/\Delta\right\}},$$

where $\ell_{cr}$ is the critical angular momentum for fusion and $\Delta$ is the diffuseness of the fusion $\ell$-distribution. The critical angular momentum for fusion $\ell_{cr}$ can either be obtained from fusion model calculations or by adjusting its value to achieve consistency with measured evaporation-residue cross sections. Most of the lighter system calculations have been done using $\Delta = 1\hbar$.

For the calculation of the total decay width $\Gamma_{tot}$, it is assumed that the deexcitation of the compound nucleus is through the emission of neutrons, protons, alpha particles, $\gamma$ rays and/or fission fragments. Then

$$\Gamma_{tot} = \Gamma_n + \Gamma_p + \Gamma_\alpha + \Gamma_\gamma + \Gamma_{fis}.$$ 

Both the saddle-point calculations of Sanders [39] and the recent scission-point calculations of Matsuse et al. [54] use the code CASCADE [57] for calculating the partial widths for the three light particles and $\gamma$ rays. Here, the partial width $\Gamma_x$ for particle $x$ ($x = n, p,$ or $\alpha$) of spin $s_x$ to be emitted from the compound nucleus of excitation energy $E^{\ast}_{CN}$ and spin $J_{CN}$ to form an evaporation-residue nucleus ER of excitation energy $E^{\ast}_{ER}$ and spin $J_{ER}$ is given by

$$\Gamma_x = \int \frac{\rho_{ER}(E^{\ast}_{ER} - \Delta_{eff}, J_{ER})}{2\pi \rho_{CN}(E^{\ast}_{CN} - \Delta_{eff}, J_{CN})} \sum_{J_{ER} = |J_{ER} - S_x|}^{J_{ER} + S_x} \sum_{\ell = |J_{CN} - S|}^{J_{CN} + S} T_x^\ell(\varepsilon_x) d\varepsilon_x.$$ 

The integral is over all kinetic energies of the emitted light particle $\varepsilon_x$, and $\rho_{CN}$ and $\rho_{ER}$ are the level densities of the compound nucleus and resulting evaporation residue, respectively. The transmission coefficients $T_x^\ell(\varepsilon_x)$ are obtained from optical-model calculations using average parameters. For the higher excitation energies involved in the fission process, it is expected that shell effects should have little influence on the level densities and hence an effective macroscopic energy ground state is used to calculate these densities [57].
parameter $\Delta_{eff}$ determines the zero point of the effective excitation energy (see Fig. 14), with

$$\Delta_{eff}(MeV) = E_B(Z, A) - E^\text{macro}_B(Z, A).$$

Here $E_B$ is the measured binding energy of the nucleus and $E^\text{macro}_B$ is the corresponding macroscopic energy $^{39,57}$. The partial width for $\gamma$ decay assumes decay through the giant dipole resonance.

1. Saddle-point model

In lighter systems, the mass asymmetry dependence of the fission barrier favors the decay into mass asymmetric exit channels. This can be seen in a plot of the calculated saddle-point energies $V_{saddle}$ as a function of the fragment mass for the $^{56}$Ni compound system in Fig. 15. In this figure, $A_{\text{fragment}} = 28$ corresponds to symmetric breakup into two $^{28}$Si fragments. Typical saddle-point shapes are shown for spin $\ell = 0\hbar$ at two different mass asymmetries and for the symmetric barrier at $\ell = 36\hbar$. At low spins the very steep rise in the saddle-point barrier energy in going to more symmetric configurations leads to a strong favoring of light-fragment evaporation over heavy-fragment fission of the compound nucleus. It is only at higher spin values that the more symmetric breakup channels become able to compete in the compound-system decay. In developing a model for the fission decay of light systems, it therefore becomes important to consider the decay widths to specific exit channels, corresponding to different mass asymmetries at the saddle point, with the total width given by the sum over the widths to the individual channels:

$$\Gamma_f = \sum_{A_L} \sum_{Z_L} \Gamma_f(Z_L, A_L).$$

Here the partial widths are denoted by the charge $Z_L$ and mass $A_L$ of the lighter fragment. The corresponding mass asymmetry $\eta$ is given by $\eta = 1 - 2(A_L/A_{CN})$.

In the saddle-point model $^{39}$ the fission widths $\Gamma(Z_L, A_L)$ are obtained by considering the level density above the mass-asymmetry dependent saddle point, with
\[ \Gamma_f(Z_L, A_L) = \frac{20\text{MeV}}{2 \pi \rho_{\text{CN}}(E_{CN}^* - \Delta_{\text{eff}}, J_{CN})} \int_{\varepsilon=0}^{\varepsilon} \rho_f(u_J) T_{fCN}^f(\varepsilon) d\varepsilon, \]

and where the transmission coefficients have a sharp cutoff form, with

\[
T_{fCN}^f(\varepsilon) =
\begin{cases} 
1 & \text{for } \varepsilon \leq E_{CN}^* - V_{\text{saddle}}(J_{CN}, \eta) - \Delta V_{\text{shell}}(J_{CN}, Z_L, A_L) - \Delta_{\text{eff}} \\
0 & \text{for } \varepsilon > E_{CN}^* - V_{\text{saddle}}(J_{CN}, \eta) - \Delta V_{\text{shell}}(J_{CN}, Z_L, A_L) - \Delta_{\text{eff}}
\end{cases}
\]

The integration is over the energy of radial motion \( \varepsilon \) and is insensitive to the upper limit assuming that this limit is sufficiently large. \( V_{\text{saddle}}(J_{CN}, \eta) \) is the spin- and mass-asymmetry dependent saddle-point energy with respect to the macroscopic-energy ground state of the compound nucleus. The importance of the compound nucleus spin in determining the competition between light particle evaporation and fission to heavier fragments is illustrated in Fig. 16 where the partial cross section distribution for fusion (solid line) and fission (shaded region), as defined by binary decay to a channel where the lighter fragment has mass \( A_L \geq 6 \), are shown for the \(^{32}\text{S} + ^{24}\text{Mg} \) reaction at \( E_{\text{lab}} = 121 \text{ MeV} \). In this system, fission is found to only compete at incident partial waves close to the critical angular momentum for fusion.

Although shell effects are not expected to influence the level density of the equilibrated compound nucleus, at the much “colder” saddle-point configuration these effects can be important. This is evidenced by a strong isotopic dependence for the fission cross sections that is inconsistent with a smooth dependence of the potential-energy surface on the mass-asymmetry parameter \( \eta \). As a first approximation of the shell corrections at the saddle point, a term \( \Delta V_{\text{shell}}(Z_L, A_L) \) has been added to the barrier energies based on the sum of the Wigner energy corrections \(^{58}\) for the two nascent fragments:

\[ \Delta V_{\text{shell}}(Z_L, A_L) = W(Z, A_L) + W(Z_{CN} - Z_L, A_{CN} - A_L) \]

with

\[
W(Z, A) = (36\text{MeV}) \left[ \frac{A - 2Z}{A} \right] + \begin{cases} 
1/A, Z \text{ and } N \text{ odd and equal} \\
0, \text{ otherwise}
\end{cases}
\]
This correction to the potential energy surface has the effect of enhancing the fission cross section to channels where both fragments have \( N=Z \).

To calculate the level densities of the compound nucleus and saddle-point configurations, a Fermi-gas formula [59] is used, with

\[
\rho(u, J) = \frac{2J + 1}{12} \sqrt{a_x} \left[ \frac{\hbar^2}{23} \right]^{3/2} u^{-2} \exp(2\sqrt{a_x u})
\]

and

\[
u = \begin{cases} 
    E_{ER}^* - \frac{\hbar^2}{23} J(J+1) - \Delta, & \text{ER} \\
    E_{CN}^* - V(J_{CN}, \eta) - \Delta V_{shell}(Z_L, A_L) - \Delta_{eff} - \varepsilon, & \text{saddle point}
\end{cases}
\]

For the evaporation residues (ER), the level-density parameter \( a_x = a_n \) and the spin \( J \) and energy offset \( \Delta \) correspond to the evaporation residue. The saddle-point densities are calculated with \( a_x = a_f \) and \( J = J_{CN} \). Most of the calculations done for light systems have used \( a_n = A_{ER}/(8\text{MeV}) \) and \( a_f = A_{CN}/(8\text{MeV}) \).

In light nuclear systems, the fission breakup of the compound nucleus is often to final fragments where the density of states is low. This can result in considerable structure in the excitation spectra of the fission fragments. To explore the population of states in the final fragments while retaining the saddle-point as the “transition” state, a procedure has been developed [49] to calculate the population of specific mutual excitations assuming a stochastic process. Within the transition-state method, population of a given saddle-point level already corresponds to a commitment to fission into a particular mass partition. The partial cross section for the population of the compound nucleus with spin \( J \) that subsequently undergoes fission to mass asymmetry \( \eta \) is taken as \( \sigma_{FF}(J, \eta) \) and is calculated using the transition-state model based on the saddle-point phase space. The cross section for populating a specific mutual excitation \((\beta_1, \beta_2)\) is then given by

\[
\sigma(\beta_1, \beta_2) = \sum_J \sigma_{FF}(J, \eta) \frac{\sum_{\ell_{out}} [\beta_1 \times \beta_2]_{J,\ell_{out}} P(\eta, J, \varepsilon)}{\sum_{\lambda_1, \lambda_2, \ell_{out}} [\lambda_1 \times \lambda_2]_{J,\ell_{out}} P(\eta, J, \varepsilon)},
\]

where \([\lambda_1 \times \lambda_2]_{J,\ell_{out}}\) represents the sum of the possible spin couplings between the two fragments in states \( \lambda_1 \) and \( \lambda_2 \) with orbital angular momentum \( \ell_{out} \) and coupling to compound-
nucleus spin $J$, and $P(\eta, J, \varepsilon)$ is the probability of the compound nucleus of spin $J$ to fission with mass asymmetry $\eta$ and radial kinetic energy $\varepsilon$. This probability depends implicitly on $\ell_{\text{out}}$ through $\varepsilon$.

The radial kinetic energy $\varepsilon$ can be expressed in terms of the characteristic energies of the reaction with

$$\varepsilon = E_{\text{c.m.}} + Q_o - V_{\text{rel}}(\ell_{\text{out}}, \eta) + \delta - E_x.$$ 

The significance of each of these energies is shown schematically in Fig. 14. Here, $E_{\text{c.m.}}$ is the center-of-mass energy in the entrance channel, $Q_o$ is the ground-state $Q$ value, $V_{\text{rel}}(\ell_{\text{out}}, \eta)$ is the relative energy of the two spheroids that comprise the saddle-point shape, $\delta$ is the energy loss that occurs in moving from the saddle to scission configurations, and $E_x$ is the mutual excitation of the final fragments. In light systems $\delta$ is expected to be small.

Figure 17 from ref. [49] compares the results of this calculation to the observed excitation spectra for the $^{24}\text{Mg}(^{32}\text{S},^{28}\text{Si})^{28}\text{Si}$ reaction at $E_{\text{c.m.}} = 51.0$ and 54.5 MeV. The bold-line histograms show the experimental results. The dotted line histograms show the predicted spectra using all known levels in $^{28}\text{Si}$ up to the 14.339 MeV excitation. The thin-line histograms are the predicted spectra for only the particle-bound levels. Since the experimental results were obtained using a kinematic coincidence technique that discriminates against excitations where one or both of the populated states subsequently emits a light particle, the thin-line histograms are expected to more faithfully represent the experimental situation. The observed structure is very well reproduced by the calculations. The structure that is observed at higher excitation energies can be attributed to groupings of mutual excitations with high channel spins. The essential validity of the predicted population pattern was confirmed by a measurement of the $\gamma$-rays in coincidence with the fission fragments for this system [49], as will be discussed in Sec. V C.

One of the interesting features of the energy spectrum calculation is that it suggests that higher excitation energies correspond to smaller compound nucleus spins. The calculation also suggests significant alignment of the spin and orbital angular momenta at higher excita-
tions, with the possibility of anti-aligned configurations being prevalent at lower excitation energies. This is shown in Fig. 18 for the calculation shown in Fig. 17. The average values of the compound nucleus spin, orbital angular momentum, and channel spin is shown for each mutual excitation of the $^{28}\text{Si}+^{28}\text{Si}$ fission channel.

2. Scission-point model

In the Extended Hauser-Feshbach, scission-point model, the partial fission decay width is determined by the product of the level densities in the final nuclei, with

$$\Gamma_f(Z_L, A_L) = \sum_{(I_L, I_H)} \sum_{(L, J, I)} \int \int \int \frac{\rho_L(E_L^*)\rho_H(E_H^*)}{2\pi \rho_{CN}(E_{CN}^*, J_{CN})} \times \delta(E_L^* + E_H^* + \varepsilon + Q - E_{CN}^*) T_L(\varepsilon) dE_L^* dE_H^* d\varepsilon$$

and where $E_L^*$ and $E_H^*$ are the excitation energies in the lighter and heavier fragments, respectively, $I_L$ and $I_H$ are the spins of the fragments, $\varepsilon$ is the relative energy of the fragments in the exit channel, and $Q$ is the $Q$-value for the binary breakup. The delta function assures energy conservation. For low-lying excitations of the fragments, the integrals are replaced by summations over the discrete energy levels.

In the development of the Extended Hauser-Feshbach model, various assumptions have been made for the level densities and transmission coefficients needed to evaluate the above expression. In what is perhaps the most systematic study of this model as it applies to light systems, the level density expression is taken as given above for the saddle-point model and with level density parameters given by $a = A/(8\text{MeV})$. The transmission coefficients for this study are evaluated by using the simplified formula

$$T_L(E) = \frac{1}{1 + \exp \left\{ \left[ V(L) - E \right] / \Delta_s \right\}}$$

where the diffuseness parameter $\Delta_s$ is typically taken to equal 0.5 MeV. It has further been found possible to obtain good agreement with experiment using a simple parametric expression of the barrier height $V(L)$ at the scission point, with
\[ V(L) = V_{\text{Coul}} + \frac{\hbar^2}{2\mu_f R_S^2} \ell(\ell + 1), \]

where \( \mu_f \) is the reduced mass of the decaying complex fragments. The scission point \( R_S \) is estimated by using the radii \( R_L = r_s A_L^{1/3} \) and \( R_H = r_s A_H^{1/3} \) of two spherical fragments of mass number \( A_L \) and \( A_H \) separated by a distance \( d \), with

\[
R_S = R_L + R_H + d.
\]

The “neck” parameter \( d \) for the reactions covered by this report is found to vary from 2.5 to 3.5 fm using \( r_s = 1.2 \) fm. The Coulomb energy is calculated using the expression

\[
V_{\text{Coul}} = Z_L Z_H e^2 / R_S,
\]

where \( Z_L \) and \( Z_H \) are the atomic numbers of the lighter and heavier fragments, respectively. In general, it has been found possible to reproduce the experimental results by varying the neck parameter \( d \) in a systematic manner, leading to predicted fission cross sections comparable to those obtained with the saddle-point model. With this adjustment, the moments of inertia for the two calculations are also similar, supporting the assertion that, in lighter nuclear systems, the scission- and saddle-point configurations are similar.

Mass distribution calculations based on the saddle-point \cite{39} and scission-point models \cite{40,60}, summing the fission and evaporation-residue components for a given mass channel, are compared to experimental cross sections obtained for the \( ^{35}\text{Cl} + ^{12}\text{C} \) reaction at \( E_{\text{lab}} = 200 \) MeV and for the \( ^{23}\text{Na} + ^{24}\text{Mg} \) reaction at \( E_{\text{lab}} = 89.1 \) MeV \cite{30,60} in Fig. 19. These two reactions reach the common \( ^{47}\text{V} \) compound systems at approximately the same excitation energy of \( E_{CN}^* = 64 \) MeV. The observed and calculated values for the average total kinetic energies for the two reactions are shown in Fig. 20, although here the extended Hauser-Feshbach results for the \( ^{23}\text{Na} + ^{24}\text{Mg} \) reaction are not available. Both calculations are found to give comparably good agreement with the experimental results. In both cases, the overall fission+evaporation-residue cross sections observed experimentally were used to determine the \( \ell_{cr} \) values for the two systems. Otherwise, in the saddle-point calculations, all of the
remaining parameters are set by the general systematics of fission in light systems. In the case of the extended Hauser-Feshbach calculations, the neck separation parameter $d$ was adjusted to optimize the fit to the fission data. However, as previously indicated, this parameter is found to vary uniformly as a function of the mass of the compound system.

The saddle-point calculations have been extended to even lighter systems, most notably by the São Paulo group exploring nuclei in the mass $A=28$ region [31], using the double-spheroid model to extrapolate saddle-point energies to these systems. Again, good agreement is achieved between the calculations and experimental results.

**B. Equilibrium orbiting model**

The binary reaction yields for a number of light systems, including those for the $^{24}\text{Mg}+^{12}\text{C}$ [25], $^{28}\text{Si}+^{12}\text{C}$ [71,72], $^{24}\text{Mg}+^{16}\text{O}$ [62], and $^{28}\text{Si}+^{14}\text{N}$ [63,64] reactions, have been interpreted in terms of the formation and decay of long-lived, rotating, dinucleus complexes. A quantitative model for this behavior has been developed by Shivakumar, Ayik and collaborators [64,65] based on nucleon transport theory. However, because of the long lifetime of the orbiting complex, as indicated by the angular distribution data, the equilibrium limit of the more general transport model is used in comparisons with data. In this limit, the model is somewhat similar to the saddle-point model of fission, although the “equilibrium orbiting” model provides a more unified description of the fusion and deep-inelastic orbiting processes.

At energies near the Coulomb barrier, the collision of two heavy ions is governed by a barrier potential comprised of nuclear, Coulomb and centrifugal terms. The equilibrium orbiting model is based on the observation that at low energies, and for all partial-waves up to some maximum value $\ell_{\text{pocket}}$, the interaction potential exhibits a pocket as a function of the distance coordinates. This pocket allows for trapping of the incident particles and the subsequent fusion or orbiting behavior of the composite system. For even higher angular momenta with $\ell_{\text{pocket}} \leq \ell \leq \ell_{\text{max}}$, trapping still occurs as frictional forces can reduce the
relative energy and angular momentum to values of $\ell \leq \ell_{\text{pocket}}$. The value of the maximum angular momentum $\ell_{\text{max}}$ is set by when the centrifugal energy reaches a value that prevents the incident particles from closing to within a critical distance where the nuclear surfaces overlap.

The trapped, dinucleus complex can either evolve with complete amalgamation into a fully equilibrated compound nucleus or, alternatively, escape into a binary exit channel by way of orbiting trajectories. Orbiting can therefore be described in terms of the formation of a long-lived dinucleus complex which acts as a “doorway” state to fusion with a strong memory of the entrance channel. The observed orbiting yields correspond to the fragmentation of the dinucleus complex during the early stages of the interaction, while long-lived complexes relax towards the mono-nuclear shape of the compound nucleus.

A full description of the exchange of mass and charge between the two interacting ions requires solving coupled transport equations describing the mass flow. The equilibrium model \cite{65} is an approximation to the full transport theory that assumes the probability of fragmentation into a channel $\chi \equiv (N, Z)$ and angular momentum $\ell$ can be expressed as the product of two terms. The first term is a distribution function that is based on the density of states in $\chi$ available to the incident channel, normalized with respect to the density of states for all channels, including the fusion channel. The second term is a transitional probability that is assumed to be slowly varying with energy and is thus taken as a constant. The defining potential energy surface for the dinucleus complex is written as

$$U_J(N, Z; R) = V_n(N, Z; R) + V_C(N, Z; R) + \frac{\hbar^2}{2\Im_{\text{tot}}(N, Z; R)} J(J + 1) + Q(N, Z),$$

where $V_n$ is the nuclear interaction (taken as the empirical proximity potential of Bass \cite{66}), $V_C$ is the Coulomb interaction, $\Im_{\text{tot}}(N, Z; R)$ is the total system moment of inertia in the sticking limit, $J$ is the total angular momentum, and $Q(N, Z)$ is the ground state $Q$-value of channel $(N, Z)$ with respect to the entrance channel. For long-lived systems the decay distribution function $P_\ell(N, Z)$ is obtained from the ratio of the density of states evaluated at
the saddle point (conditional saddle) of the potential, for a given \( \ell \)-value and exit channel, to the sum over all open channels of the state densities at the respective saddle points and the corresponding state densities evaluated at the configurations corresponding to the minimum of the \( \ell \)-dependent potential-energy for each open channel. The total binary fragmentation probability is given by summing over the open channels, with

\[
P_\ell = \sum_{N,Z} P_{\ell}(N,Z)
\]

and the corresponding fusion probability is then \((1-P_\ell)\). It is therefore possible to evaluate both the binary fragment and fusion probabilities within a consistent formalism. The total production of a fragment \((N,Z)\) is given by the sum of all \( \ell \)-partial wave contributions up to the maximum angular momentum \( \ell_{\text{max}} \) for which the system can become trapped in a pocket of the interaction potential:

\[
\sigma_\ell(N,Z) = \frac{\pi k^2}{\ell_{\text{max}}} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1) P_{\ell}(N,Z)
\]

A corresponding expression gives the fusion cross section:

\[
\sigma_{\text{fus}} = \frac{\pi k^2}{\ell_{\text{max}}} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1)(1 - P_{\ell})
\]

The final total kinetic energy is determined by the sum of the nuclear, Coulomb, and rotational energies at the conditional saddle point, with:

\[
E_{K,\ell}^{\text{tot}}(N,Z) = U_o(N,Z; R_s) + \frac{\hbar^2 \ell (\ell + 1) f^2}{2 \Im_{\text{rel}}(N,Z; R_s)} - Q(N,Z),
\]

where \( f = \Im_{\text{rel}}(N,Z; R_s)/\Im_{\text{tot}}(N,Z; R_s) \) and \( \Im_{\text{rel}} \) and \( \Im_{\text{tot}} \) are the relative and total moments of inertia at the saddle point configuration with radius \( R_s \), respectively. The nuclear and Coulomb contributions to the potential energy \( U_o(N,Z; R_s) \) are evaluated at \( \ell = 0 \). The average kinetic energy in the exit-channel, taking into account the channel cross section, is found using:

\[
<TKE(N,Z) > = \frac{\pi k^2}{\ell_{\text{max}}} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1) E_{K,\ell}^{\text{tot}} P_{\ell}(N,Z) P(N,Z)
\]
with

\[ P(N, Z) = \frac{\pi}{k^2} \sum_{\ell=0}^{\ell_{\text{max}}} (2\ell + 1) P_\ell(N, Z). \]

The equilibrium orbiting model has been used to successfully explain both the observed cross sections and TKE values of the fully damped fragments for several lighter nuclear systems. It has been found that the adjustment of a single strength parameter in the Bass parameterization [66] of the nuclear potential leads to good agreement for both orbiting and total fusion yields. This is shown in Figs. 21 and 22 [63] for the $^{28}$Si+$^{12}$C reaction [17,61]. In Fig. 21 the measured total kinetic energies for the carbon, nitrogen, and oxygen channels are compared to the experimental results. Figure 22 compares the measured and calculated cross sections for the same three channels as well as for the total evaporation-residue cross section. In both of these figures the orbiting calculations are indicated by the dotted curves.

For comparison, the results of the transition-state, saddle-point calculation discussed earlier are also shown in Figs. 21 and 22 by the solid curves. The parameters used for the transition-state calculations are the same as those used to successfully describe the experimental cross sections in other light systems. For the $^{28}$Si+$^{12}$C reaction, however, the transition-state calculations tend to underestimate the observed binary yields. This is seen in the figures where the total fusion cross section has been adjusted to achieve the best general agreement of the total kinetic energies and binary reaction cross sections with experiment. This leads, however, to fission-model predictions of evaporation residue cross sections which are high compared to the experimental results and predicted carbon cross sections that are too small.

In other reactions of very light systems, such as for the $^{28}$Si+$^{14}$N reaction, the equilibrium orbiting and transition-state models result in comparable agreement with the data. For heavier systems ($A_{CN} \geq 47$), the simple form of the equilibrium orbiting model is found to be less successful [30,45]. This may reflect, however, some of the simplifying assumptions of the calculations, such as the calculation of moments of inertia based on touching, spherical fragments and the use of ground-state $Q$-values for the driving potential energy surface. To
achieve a satisfactory agreement for the $^{32}$S+$^{24}$Mg reaction within the equilibrium orbiting model \[45\], for example, it has been found necessary to introduce deformation effects by assuming a moment of inertia more similar to that of the nuclear saddle point. In this case the equilibrium orbiting and scission-point models employ very similar phase-space arguments.

The shortcomings of the equilibrium model for orbiting does not imply that the presence of an orbiting mechanism, as distinct from fission, can be ruled out in some systems. The alternative statistical models also fail to explain several important features of the orbiting reaction data, such as the strong entrance channel dependence in the $^{40}$Ca system \[62\] and spin distributions and alignments measurements for the $^{28}$Si+$^{12}$C reaction \[67\].

**C. NOC**

The relationships among the different reaction mechanisms such as fusion-fission, orbiting, and heavy-ion resonances are still not fully understood. It has been suggested \[68\], for example, that the heavy-ion resonance phenomenon observed in some light nuclear systems may reflect a strong shell correction to the fission potential energy surface and, as such, be related to the statistical fission mechanism. In the absence of a fully consistent picture relating the different reaction mechanisms, considerable effort has gone into developing the systematics of these processes. In general, the fully energy-damped yields are observed with a cross section comparable to the predictions of the transition-state calculations. The occurrence of a distinctly different orbiting or resonance component to the reaction cross section seems to be correlated with the number of open reaction channels (NOC). In lighter systems, for example, the even-even C+C, C+O, and O+O reactions all show strong resonance behavior and also have small NOC values. Underlying this correlation may be a relationship between the NOC for a given reaction and the “surface transparency” of the reaction \[69\].

The NOC calculations have been systematically extended to heavier systems \[18\] and a strong correlation found between the anomalous large-angle resonant structure and small
NOC values. For example, systems populating the $^{40}$Ca compound nucleus, for which there is significant evidence of an orbiting process [62], have low values for the NOC corresponding to the grazing partial waves. Alternatively, the energy-damped yields for several systems populating the $^{47}$V system [29,30,30], where the NOC values are large, are consistent with a fusion followed by fission picture.

The NOC for a given system is obtained by a triple summation over all possible two-body mass partitions in the exit channels, over all possible angular momentum couplings and, finally, over the allowed excitations of the two fragments:

$$N^J(E_{c.m.}) = \sum_{A_1+A_2=A_{CN}} \sum_{J=L+I_1+I_2} \sum_{E_r=E_{CN}^*-E_1-E_2-Q_{12}} T_L(E_r).$$

In this expression, $E_{c.m.}$ and $E_{CN}^*$ are the center-of-mass energies of the incident particle and the excitation energy of the compound system, respectively. $A_1, A_2, A_{CN}$ are the mass numbers of the outgoing fragments and the compound system. $I_1, I_2$ and $L$ are the intrinsic spins of the fragments and the orbital angular momentum of their relative motion. $Q_{12}$ is the reaction $Q$-value of the decay into the fragments. $E_1, E_2$ and $E_r$ are the intrinsic excitation energies of the fragments and the energy available to their relative motion, respectively. $T_L(E_r)$ is the transmission coefficient of the outgoing channel as a function of angular momentum and relative energy. The transmission coefficients have been calculated using the semi-classical, parabolic barrier penetration approximation:

$$T_L(E_r) = 1/ \left[ 1 + \exp \left[ \frac{2\pi(E_L - E_r)}{\hbar\omega_L} \right] \right]$$

where $E_L = V_L(R_B)$. The rotational frequency,

$$\hbar\omega_L = \hbar \sqrt{\left( \frac{d^2V_L(R)}{dR^2} \right)_{R=R_B}} / \mu,$$

is related to the curvature of the outer barrier. In this expression, $\mu$ is the reduced mass and $V_L(R)$ is the sum of the Coulomb, centrifugal and nuclear potentials. In more recent calculations a macroscopic proximity form has been used for the nuclear interaction [18], rather than the Saxon-Woods form employed in earlier calculations. The sum over the
energy sharing between the two fragments employs discrete energy levels of the fragments at lower energies, where these are known, and an angular momentum dependent level density expression at higher energies [18]. The sensitivity of the NOC calculations to the choice of level density expression and to the transmission coefficients is discussed in Ref. [18]. Although the quantitative results are sensitive to these choices, the qualitative behavior is not, thus preserving the predictive value of the calculations.

The expression for $N^J$ is similar to the denominator appearing in the Hauser-Feschbach formalism [70] for the compound nucleus. However, the NOC calculations include direct reaction channels in addition to the evaporation channels. This allows the phase space calculation to be extended to values of the incident angular momentum greater than the critical angular momentum for fusion $L_{gr}$.

In order to compare different systems, it is useful to normalize $N^J$ by the corresponding incident flux. The quantity $N/F$ is defined, with

$$N/F = N^J(E_{c.m.})/F^J(E_{c.m.}) .$$

Here, $F^J(E_{c.m.})$ is the incident flux for the total angular momentum $J$, as given by

$$F^J(E_{c.m.}) = \frac{\pi}{k^2} \sum_{J=L+I_1+I_2} g_J T_L(E_{c.m.}) ,$$

where $E_{c.m.} = \hbar^2 k^2 / 2\mu$, $g_J = (2J + 1)/(2I_1 + 1)(2I_2 + 1)$, and $I_1$ and $I_2$ are the intrinsic spins of the incident particles.

Examples of the NOC calculations for a number of lighter systems is given in Fig. 23. The $N/F$ values for the different systems are shown as a function of $L_{gr}$. Each of the curves shows a characteristic minimum at an $L_{gr}$ value that corresponds to an energy well above the corresponding Coulomb barrier. The initial drop in $N/F$ as a function of $L_{gr}$ is due to the increasing difficulty as $L_{gr}$ increases of dissipating the angular momentum brought into the compound system solely through the evaporation of light particles. The subsequent rise in $N/F$ occurs when an increasing number of direct channels (such as single and mutual inelastic excitation, nucleon and $\alpha$-transfer and, finally, deep-inelastic orbiting
and fusion-fission processes) become accessible. These channels are activated at somewhat higher energies because of their reaction $Q$-values.

A strong correlation has been demonstrated between systems where $N/F$ is small and the occurrence of quasi-molecular resonances in light- and medium-light heavy-ion reactions [18]. For example, it is observed from Fig. 23 that the $^{12}$C+$^{12}$C and $^{12}$C+$^{16}$O systems, where prominent resonant behavior [18] has been observed, both show very low minimum values of $N/F$ ($N/F \approx 10^{-1}$). On the other hand, for systems such as B+O, where the NOC values are much larger ($N/F > 10^4$), there is no compelling evidence for a strongly energy-damped reaction component other than what can be accounted for through the fusion-fission mechanism [31].

Typical NOC calculations for a number of heavier systems with $36 \leq A_{CN} \leq 48$ are shown in Fig. 24. These systems can be classified into two groups, with the $^{24}$Mg+$^{24}$Mg reaction having an intermediate behavior. The $^{24}$Mg+$^{12}$C, $^{24}$Mg+$^{16}$O and $^{28}$Si+$^{12}$C systems, which are composed of $\alpha$-particle-like nuclei, belong to the first group and have NOC minima corresponding to $N/F \approx 10$. For these systems, strongly oscillatory angular distributions are observed in the backward-angle elastic scattering cross sections [18] and there is evidence of a non-statistical orbiting mechanism [17,25,26]. The second group of reactions, with large values of $N/F$, show little evidence of an excess yield beyond that expected from the statistical fission mechanism.

The $^{24}$Mg+$^{24}$Mg system appears to be much more surface-transparent at large $L_{gr}$ in comparison to $^{23}$Na+$^{24}$Mg, for instance, but never achieves the low $N/F$ values of the reactions populating the $^{40}$Ca compound system. One distinguishing feature of the reaction is that the “quasi-molecular resonance window”, i.e., the region of relatively low $N/F$ values, corresponds to quite high values of $L_{gr}$. Very narrow, high-spin resonances have been observed in elastic and inelastic scattering measurements for this system [4,14] with strong correlation among the various inelastic channels. These strong, heavy-ion resonance features seem to coexist with “normal”, statistical fusion-fission yields from the $^{48}$Cr compound nucleus, as discussed in Ref. [16]. The resonances, however, correspond to compound nucleus
spin values [10] that approach the N/F minimum, but are large compared to dominant spins expected to lead to fusion-fission yields. This circumstance of having a small number of open channels for the grazing partial waves and, in addition, having the angular momentum characterizing these partial waves being greater than the dominant angular momenta for the statistical fission competition may contribute to the strength of the observed resonance structure.

D. Dynamical model of intermediate mass fragment emission

Fission in light systems can be considered as a dynamical process consisting of the gradual shape change of the compound system with the formation of a neck which subsequently narrows and breaks. It is therefore tempting to include dynamical effects into the statistical model calculations to have a better understanding of the fission process and to provide some information on the time scales which are involved during the reaction.

The statistical model developed by Dhara et al. [71] is based on the transition-state picture and involves solving the classical equations of motion to follow the change of shape of the composite system. The fission dynamics are therefore explicitly considered while evaluating the relevant physical observables. In the absence of any precise knowledge of the energy sharing between the intrinsic excitation and collective degrees of freedom, it is assumed that a random fraction of the initial compound-nucleus excitation energy goes into collective degrees of freedom to generate the fission dynamics. A standard proximity potential is used, with non-conservative frictional forces introduced by a viscosity term whose magnitude has a temporal dependence. The time evolution of this viscosity term has a strong impact on the dynamics of the fission process. The fission probability is calculated by Monte Carlo simulation for a large number of trajectories. The spin transferred to the binary fragments are computed in the sticking limit. The model still uses phase space arguments to determine the fusion-fission cross sections, however, in a manner that is quite similar to the transition-state model approach [39,72]. The two models differ primarily in
their parametric expressions describing the nuclear shapes and the saddle-point energies. Calculations using the dynamical model have been shown to reproduce reasonably well the experimental results obtained for the $^{31}$P compound system [73–75].

**E. Generalized liquid drop model**

Within the macroscopic energy models, the fission saddle-point is found by studying the potential energy surface of the compound system as a function of a specific shape parameterization. One such parameterization has been developed by Royer and Remaud [76] involving a class of shapes that evolves from a spherical mononucleus to two touching spherical fragments with a deeply creviced neck. A nuclear proximity potential is used to account for the surface interaction of the neck configuration.

An interesting aspect of this parameterization is that it is easily generalized to a three fragment configuration, allowing the study of a possible ternary fission valley [77]. The possibility of a ternary fission path has been explored through model calculations for the $^{48}$Cr compound system. In this study it is found that a prolate aligned $^{16}$O+$^{16}$O+$^{16}$O molecule configuration results in a minimum of the potential energy as a function of deformation for high spins. Such behavior could result in an enhanced cross section for ternary fission to the three $^{16}$O final channel. A shell stabilized, three $^{16}$O chain configuration of $^{48}$Cr has also been suggested by unconstrained $\alpha$-cluster model calculations by Rae and Merchant [78]. An experimental search for the three $^{16}$O breakup channel of $^{48}$Cr, as populated through the $^{24}$Mg+$^{24}$Mg reaction, has failed to find evidence for this behavior, however [79].

**V. SYSTEM-BY-SYSTEM DISCUSSION**

The compound nuclei considered in this report range in mass from $19 \leq A_{CN} \leq 80$. The low mass limit is set by the experimental difficulty of unfolding the fully energy damped yields from the more peripheral reaction yields in even lighter systems. The high end of the mass range corresponds to the transition region where, for the partial waves that lead
to fission in heavy-ion reactions, the potential energy surface becomes relatively flat as a function of mass asymmetry. For systems with mass lower than $A_{CN} \approx 80$, the potential energy surface favors fission of the compound system into fragments of unequal mass. For heavier systems, the symmetric mass fission of the compound nucleus is favored in the absence of strong shell effects. Tables 1 and 2 summarize the experiments that have been performed in lighter systems where fully energy-damped yields have been studied. In the following discussion, a somewhat arbitrary division is made between systems with $A_{CN} < 32$, $32 \leq A_{CN} \leq 44$, $44 < A_{CN} \leq 56$, and $56 < A_{CN} \leq 80$. The systems with $A_{CN} < 32$ are the most difficult ones in which to experimentally establish the fission cross sections. They also create the greatest challenge to the fission-model calculations because of the difficulty of calculating fission barriers for these very light systems and the increasing influence of shell corrections on these barriers. The mass range $32 \leq A_{CN} \leq 44$ encompasses the systems for which there is the greatest evidence of a dinucleus orbiting mechanism that is distinctly different from the expectations of the fission model calculations. In the mass region $44 < A_{CN} \leq 56$, there is good overall agreement of the expectations of fission transition state model with the observed fully energy-damped yields, although an additional heavy-ion resonance behavior is observed for several systems in this mass range. A shift to symmetric mass fission starts to become evident towards the higher end of the mass region with $56 < A_{CN} \leq 80$. 


TABLE I. Systems studied with $A_{CN} \leq 40$.

| $A_{CN}$ | Reaction a | $E_{lab}$ (MeV) | Detected Fragments | Technique | C or NOC | Ref. |
|----------|------------|-----------------|--------------------|-----------|----------|------|
| 19F      | $^9$Be$+^{10}$B | 10-40 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $1.4 \times 10^{-3}$ | 80 |
| 20F      | $^9$Be$+^{11}$B | 10-40 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $1.6 \times 10^{-2}$ | 80 |
| 20Ne     | $^{10}$B$+^{10}$B | 15-50 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $7 \times 10^{-3}$ | 82 |
| 21Ne     | $^{10}$B$+^{11}$B | 15-50 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $2 \times 10^{-3}$ | 82 |
| 22Ne     | $^{11}$B$+^{11}$B | 15-50 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $2 \times 10^{-3}$ | 82 |
| 26Al     | $^{16}$O$+^{10}$B | 22-64 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $2 \times 10^1$ | 31 |
| 27Al     | $^{16}$O$+^{11}$B | 22-64 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $5 \times 10^0$ | 31 |
|          | $^{17}$O$+^{10}$B | 22-64 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $1 \times 10^2$ | 31 |
| 28Al     | $^{17}$O$+^{11}$B | 22-64 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $9 \times 10^1$ | 31 |
|          | $^{18}$O$+^{10}$B | 22-63 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $5 \times 10^2$ | 31 |
|          | $^{19}$F$+^9$Be | 56   | $5 \leq Z \leq 9$ | $\Delta E$-E | S,C | $3 \times 10^{-3}$ | 31 |
| 29Al     | $^{18}$O$+^{11}$B | 22-64 | $5 \leq Z \leq 9$ | $\Delta E$-E | S,C | $3 \times 10^1$ | 31 |
| 31P      | $^{12}$C$+^{19}$F | 96   | $3 \leq Z \leq 11$ | $\Delta E$-E | S | $1 \times 10^2$ | 75 |
|          | $^7$Li$+^\text{nat}$ Mg | 47 | $4 \leq Z \leq 9$ | $\Delta E$-E | S | $7 \times 10^3$ | 74 |
| a$+^{27}$Al | 60 | $4 \leq Z \leq 8$ | $\Delta E$-E | S | $<100$ | 73 |
| 32S      | $^{20}$Ne$+^{12}$C | 50-80 | $Z=6$ | $\Delta E$-E | S | $7 \times 10^0$ | 3 |
| 36Ar     | $^{20}$Ne$+^{16}$O | 70-160 | $6 \leq Z \leq 9$ | $\Delta E$-E | S | $1 \times 10^1$ | 85 |
|          | $^{24}$Mg$+^{12}$C | 90-126 | $5 \leq Z \leq 9$ | $\Delta E$-E | S | $1 \times 10^1$ | 25 |
| 40Ca     | $^{24}$Mg$+^{16}$O | 75-115 | $6 \leq Z \leq 8$ | $\Delta E$-E | S | $9 \times 10^0$ | 26,62 |
|          | $^{28}$Si$+^{12}$C | 99-180 | $5 \leq Z \leq 8$ | $\Delta E$-E | S | $2 \times 10^1$ | 17,51 |
| 20Ne$+^{20}$Ne | 70-160 | $8 \leq Z \leq 10$ | $\Delta E$-E | C | $7 \times 10^1$ | 85 |

a Projectile + Target

b C–Coincidence, S–Singles
TABLE II. Systems studied with $A_{CN} > 40$.

| $A_{CN}$ | Reaction$^a$ | $E_{lab}$ (MeV) | Detected Fragments | Technique | C or NOC | Ref. |
|----------|--------------|-----------------|--------------------|-----------|---------|------|
| 42Sc     | $^{28}$Si+$^{14}$N | 100-170 | $3 \leq Z \leq 10$ | $\Delta E$-$E$ | S | $8 \times 10^3$ | 101 |
| 43Sc     | $^{27}$Al+$^{16}$O | 120-160 | $6 \leq Z \leq 9$ | $\Delta E$-$E$ | S | $7 \times 10^2$ | 21 |
| 44Ti     | $^{24}$Mg+$^{20}$Ne | 71-120 | $16 \leq A \leq 32$ | $\Delta E$-$E$ | S | $1 \times 10^1$ | 105 |
|          | $^{28}$Si+$^{16}$O | 61.79 | $6 \leq Z \leq 8$ | $\Delta E$-$E$ | S | $6 \times 10^2$ | 93 |
|          | $^{32}$S+$^{12}$C | 80-124 | $6 \leq Z \leq 8$ | $\Delta E$-$E$ | S | $7 \times 10^4$ | 30, 29 |
| 46V      | $^{6}$Li+$^{40}$Ca | 153 | $9 \leq Z \leq 11$ | $\Delta E$-$E$ | S | $>106$ | 8 |
| 47V      | $^{23}$Na+$^{24}$Mg | 89.1 | $5 \leq Z \leq 10$ | $\Delta E$-$E$ | S | $4 \times 10^4$ | 108 |
|          | $^{31}$P+$^{16}$O | 135.6 | $6 \leq Z \leq 8$ | $\Delta E$-$E$ | S | $1 \times 10^4$ | 30 |
|          | $^{35}$Cl+$^{12}$C | 180-280 | $5 \leq Z \leq 12$ | $\Delta E$-$E$, S,C | | $7 \times 10^4$ | 30, 29 |
|          | | | | kin | | | 107 |
| 48Cr     | $^{24}$Mg+$^{24}$Mg | 88.8 | $6 < A < 24$ | kin$^\dagger$ | C | $5 \times 10^2$ | 46 |
|          | $^{28}$Si+$^{20}$Ne | 87-128 | $16 \leq A \leq 32$ | kin$^\dagger$ | C | $6 \times 10^2$ | 104 |
|          | $^{20}$Ne+$^{28}$Si | 78.0 | $20 \leq A \leq 24$ | kin | C | $6 \times 10^2$ | 54, 56 |
|          | $^{36}$Ar+$^{12}$C | 187.7 | $6 \leq A \leq 24$ | kin | C | $3 \times 10^3$ | 54 |
| 49Cr     | $^{9}$Be+$^{40}$Ca | 141 | $9 \leq Z \leq 11$ | $\Delta E$-$E$ | S | $>106$ | 8 |
| 49V      | $^{37}$Cl+$^{12}$C | 150,180 | $5 \leq Z \leq 11$ | $\Delta E$-$E$, S,C | | $>106$ | 120 |
| 52Fe     | $^{12}$C+$^{40}$Ca | 74-186 | $9 \leq Z \leq 11$ | $\Delta E$-$E$ | S | $8 \times 10^4$ | 8 |
| 56Ni     | $^{28}$Si+$^{28}$Si | 85-150 | A=28 | kin | C | $2 \times 10^1$ | 111 |
|          | $^{32}$S+$^{24}$Mg | 121-142 | $12 \leq A \leq 28$ | tof, S,C | | $1 \times 10^4$ | 43, 49 |
|          | | | | kin,$^\gamma$ | | | 114 |
|          | $^{16}$O+$^{40}$Ca | 69-87 | $20 \leq A \leq 28$ | tof | S | $4 \times 10^5$ | 110 |
| 59Cu     | $^{35}$Cl+$^{24}$Mg | 275 | $5 \leq Z \leq 12$ | $\Delta E$-$E$, S,C | | $>10^6$ | 116 |
| 60Ni     | $^{16}$O+$^{44}$Ca | 69-87 | $20 \leq A \leq 30$ | tof | S | $>10^6$ | 110 |
| 64Zn     | $^{16}$O+$^{48}$Ti | 118 | $5 \leq Z \leq 15$ | $\Delta E$-$E$, S,C | | $>10^6$ | 120 |
| Projectile + Target | Energy (MeV) | Charge Range | Methods | Count Rate (>10^6) |
|---------------------|-------------|--------------|---------|--------------------|
| ^{37}Cl + ^{27}Al   | 162-200     | 5 ≤ Z ≤ 15   | ΔE-E, S,C | > 10^6             |
| 78Sr + ^{28}Si + ^{50}Cr | 150         | 12 ≤ A ≤ 58  | ΔE-E, S | > 10^6             |
| 80Zr + ^{40}Ca + ^{40}Ca | 197,231     | 7 ≤ A ≤ 62   | tof     | S > 10^6           |

*a* Projectile + Target

*b* C–Coincidence, S–Singles

† Only low-lying excitation studied.
In describing heavy-ion reaction behavior in terms of statistical models, the dominant component of the deformation-dependent binding energy of the compound system is usually obtained through macroscopic energy calculations, that is, extensions of the rotating liquid drop model. Shell corrections to the calculated energies are usually handled in only a very approximate fashion. These corrections can be difficult to obtain for the relevant shapes of the compound system and, moreover, the statistical phase space relevant for the fission process is generally required at an excitation energy of the compound system where shell corrections may already be strongly attenuated.

The lower mass limit for the validity of macroscopic description of light nuclear systems and statistical behavior of very light heavy-ion reactions has been recently pursued by investigating reactions involving light s-d shell nuclei. One of the interesting features that can be probed by these studies is the effect of the channel spin on light ion reaction mechanisms. Among the systems studied, the choice of $^{10,11}$B nuclei was based on the fact that very high channel spins $^{10}$B(3$^+$) and $^{11}$B(3/2$^+$) are involved when compared to the values of the grazing angular momenta. This has two significant consequences: 1.) the phase space in the exit channel is enlarged and 2.) the composite system angular momentum is increased.

There are, however, experimental difficulties encountered in the study of lighter systems. All of the model calculations require some estimate of the distributions of incident orbital angular momenta contributing to the fully energy damped binary yields. This generally requires a measurement of the fusion cross sections for the reactions—in the fission models, the damped binary yields define the high end of the fusion partial wave distribution whereas, for the orbiting models, the higher fusion partial waves are seen as competing with the orbiting mechanism. Identification of fusion reaction yields involving very light heavy ion reactions is complicated, however, by the difficulty of identifying the corresponding evaporation residues. Frequently, a given element can be produced by nucleon or massive transfer, sequential decay of a compound nucleus or by a binary decay of the composite system. The
production of $^8$Be residues, which subsequently decay by breaking apart into two $\alpha$ particles, may not be negligible. To unfold the different processes it is necessary to look for differences in their kinematics. Here, velocity spectra can be very useful. An example of the unfolding procedure is shown in Fig. 25 for the $^9$Be+ $^{11}$B reaction at $E_{lab}=37$ MeV and $\theta_{lab} = 8^\circ$ [80]. At lower recoil velocities the spectrum is consistent with a statistical model calculation using the code LILITA [81], as shown by the solid curve. The additional component, shown by the dashed curve, can be attributed to a more peripheral reaction mechanism.

Strongly energy damped yields have been investigated in the $^{10,11}$B+ $^{10,11}$B reactions simultaneously with fusion-evaporation residue yields [82]. For the $^{10,11}$B+ $^{11}$B channels, the observed energy spectra and excitation functions of the evaporation residues are consistent with the general fusion systematics in this mass range. However, a significant inhibition of the fusion cross section is observed in the $^{10}$B+ $^{10}$B entrance channel (see Fig. 26). At least part of the missing flux may be directed to strongly energy damped decay yields in the $Z=5$ channel, which are found to be strongly enhanced. These yields demonstrate binary characteristics according to their velocity distributions (which are peaked at higher velocities than expected for evaporation residues) and isotropic angular distributions [82]. A similar enhancement in the $^{11}$B channel is not observed in either the $^{10,11}$B+ $^{11}$B or the $^9$Be+ $^{10,11}$B reactions up to $E_{lab}/A= 4$ MeV. The mechanism by which the very high entrance-channel spin of the $^{10}$B+ $^{10}$B system may play a role in the anomalous behavior observed for this system is not clear. Although higher compound-nucleus spins would be expected to favor binary fission over light particle emission, the behavior is also similar to that observed in somewhat heavier systems (with zero channel spin) and attributed to a dinucleus “orbiting” mechanism.

The experimental situation can be somewhat simpler for reactions involving mass asymmetric entrance channels. Here the use of inverse kinematics can lead to clear identification of the target-like products corresponding to processes that are fully energy damped and emitted at large center-of-mass angles. This approach has been used in an investigation of the $^{16,17,18}$O+ $^{10,11}$B, $^{19}$F + $^9$Be reactions leading to the $^{26-28}$Al compound nuclei [31].
Contributions from binary reaction process were clearly identified in the Li, Be, C, O and F channels. However, only in the target-like particle channels: Li, Be, B, and C, were isotropic distributions of $d\sigma/d\theta_{c.m.}$ observed for all the reactions. Alternatively, the N, O and F products, associated with projectile-like particles, present forward-peaked angular distributions with “life-angles” in the range $25^\circ < \alpha < 50^\circ$ (see Fig. 6), suggesting that a more peripheral reaction mechanism dominates the small-angle yields in these channels. The velocity distributions of the emitted fragments suggest the occurrence of a binary process. This is shown for the $^{18}\text{O}+^{11}\text{B}$ reaction at $E_{lab}=63$ MeV in Fig. 27 from ref. [31]. Although the singles data offer compelling evidence of binary nature of the fully energy-damped yields, the experimental confirmation of such a nature requires the detection of both fragments in coincidence. Such coincidence measurements were performed for the $^{18}\text{O}+^{11}\text{B}$ and $^{17}\text{O}+^{11}\text{B}$ reactions at $E_{lab}=53$ MeV, with the observation that most of the yields correspond to $Z_1 + Z_2 = Z_{CN}$. This indicates that the effect of secondary light-particles emission following (or preceding) scission is negligible for these reactions at the measured energy. Coincidences between heavy fragments and $Z < 3$ particles were associated with evaporation residues.

The degree of inelasticity of the binary yields associated with distributions of constant $d\sigma/d\theta_{c.m.}$ is indicated by the total kinetic energy $< TKE >$ values displayed in Fig. 28 for these yields. Compared to the experimental results are lines showing the expected values in the case of totally relaxed processes in which the outgoing particles carry essentially the barrier energy. Although these results were calculated assuming spherical fragments, similar results are found using the transition-state model for fission where more realistic shapes are assumed for the compound system configuration [31].

Support for the picture of a statistically equilibrated compound nucleus is found in the data obtained for the $^{17}\text{O} + ^{11}\text{B}$, $^{18}\text{O} + ^{10}\text{B}$ and $^{19}\text{F} + ^{9}\text{Be}$ reactions, each of which populates the $^{28}\text{Al}$ compound system. Figure 29 presents excitation functions for intermediate mass fragment cross sections for the three systems. The close agreement among the exit yields for the various entrance channels shows that the Bohr Hypothesis [83] is satisfied. This hypothesis states that the exit channel observables for compound-nucleus reactions should
be independent of the entrance channel except for such conserved quantities as angular momentum and total energy. A similar conclusion is reached by comparing the ratio of yields for different exit channels as a function of the excitation energy of the emitted fragments. Figure 30 presents the ratio \( R = \sigma_C/\sigma_B \) of yield for carbon products (\( \sigma_C \)) compared to the yield for boron (\( \sigma_B \)), for the three entrance channels populating the same compound nucleus. Again, entrance channel independence of the cross section ratios is observed. Although it is not possible, in general, to form a compound nucleus with the same excitation energy and angular momentum distribution using two different entrance channels, the three reactions reaching \( ^{28}\text{Al} \) achieve similar conditions because of the small variation in the entrance channel mass asymmetry.

Predictions of the transition-state model for the fission charge distributions are also compared to the experimental data in Fig. 29. In general, model predictions are found to be satisfactory in reproducing the charge, mass and bombarding energy dependence of the observed yields, thus further supporting the idea that these yields have a fusion-fission origin. It can also be noted that for these reactions, where the statistical fission description seems to work well, the normalized Number of Open Channels (N/F) for the composite system decay are relatively high—some two to four orders of magnitude larger than the ones obtained for the \( ^{12}\text{C} + ^{12}\text{C} \) or \( ^{12}\text{C} + ^{16}\text{O} \) resonant systems, as shown in Fig. 23.

Bhattacharya et al. [73–75] have looked for a possible entrance channel behavior for the fully energy damped yields from the \( ^{31}\text{P} \) compound system as populated through the \( ^{12}\text{C} + ^{19}\text{F}, ^7\text{Li} + ^{nat}\text{Mg}, \) and \( \alpha + ^{27}\text{Al} \) reactions. In this case there is a very large difference in the mass asymmetries of the respective reactions. Again, in a comparison of the damped binary yields for the three systems, no prominent entrance channel behavior is observed beyond what would be expected from the very different partial cross-section distributions. At the respective bombarding energies, the normalized NOC for the grazing partial wave is large for each of these systems.
The first observation of fully energy damped reaction yields in light systems was reported by Shapira et al. [3] in an investigation of \(^{20}\text{Ne} + ^{12}\text{C}\) inelastic scattering at backward angles. Large cross sections were found when summing the yields over many unresolved mutual excitations at high excitation energies. The resulting angular distributions were found to show most of the characteristics, such as a \(d\sigma/d\Omega \propto 1/\sin \theta_{\text{c.m.}}\) angular dependence, of a long-lived, orbiting, \(^{20}\text{Ne} + ^{12}\text{C}\) dinuclear complex. This initial measurement was followed by a very detailed study of the same system [84] where resonant-like behavior was found in the excitation functions for several outgoing channels, reminiscent to that observed for the well-known, resonant, symmetric \(^{16}\text{O} + ^{16}\text{O}\) system. This quasi-molecular resonance behavior extends to \(Q\)-value regions where the total kinetic energy in the exit channel is consistent with an orbiting-type mechanism. It was noted by Shapira et al. [84] that the small number of open reaction channels for \(^{20}\text{Ne} + ^{12}\text{C}\) scattering might be related to the observation of the resonance behavior.

In a study of the \(^{20}\text{Ne} + ^{16}\text{O}\) reaction, Shapira et al. [85] again found evidence of an “orbiting-like” component in the large angle \(^{12}\text{C}\) and \(^{16}\text{O}\) yields. Subsequent to this, the strongly energy damped component in the \(^{24}\text{Mg} + ^{12}\text{C}\) reaction, leading to the same \(^{36}\text{Ar}\) composite system, was investigated by the Munich group through a series of measurements [25,86]. In the study by Glaesner et al. [87], cross section fluctuations for fully damped yields were observed for the first time in such a heavy system, allowing for an Ericson-type fluctuation analysis [88]. Excitation functions were generated for different \(Q\)-value ranges, as shown for the \(Z=6\) channel in Fig. 31, using the data of Ref. [87]. The observed structure is less pronounced than that observed in discrete-level, low \(Q\)-value channels because of the averaging over a large number of states. The coherence width obtained in this measurement of approximately 300-400 keV corresponds to a mean rotation angle for an orbiting-like configuration of 180° to 360°. In further support of an orbiting-like picture, Konnerth et al. [89] have deduced spin alignments for the \(^{24}\text{Mg} + ^{12}\text{C}\) system by measuring the out-of-
plane γ-ray anisotropy. The large positive values of the observed spin alignments suggest the geometry of a sticking dinuclear complex in a stretched configuration.

Perhaps the most striking example of orbiting behavior in a light nuclear system can be seen in the ²⁸Si⁺¹²C reaction yields. This system has been extensively studied over the past two decades for a number of reasons. In addition to showing a very strong orbiting-like behavior [17,61,67,90] (see Fig. 22), it also demonstrates strong resonant structures in its elastic and quasi-elastic yields [91–93]. Fortunately, the reaction is favorable for experimental study since intense ²⁸Si beams are readily available at tandem accelerator facilities and ¹²C makes a very good and relatively contaminant free target.

The energy spectra for the most intense C, N and O fragment exit channels for the ²⁸Si⁺¹²C reaction have been measured at backward angles for a large number of incident energies in the range 29.5 ≤ \(E_{c.m.}\) ≤ 54 MeV. At lower bombarding energies the excitation spectra for the ¹²C fragments are dominated by single and mutual excitations of the ¹²C and ²⁸Si fragments. At higher bombarding energies, however, the dominant strength for all three channels shifts to higher excitation energies [61]. For these higher energy spectra the most probable \(Q\)-values are found to be independent of detection angle. The corresponding, energy-integrated angular distributions are found to follow a \(1/\sin \theta_{c.m.}\) angular dependence near 180° [84]. These characteristics suggest a long lived, orbiting-like mechanism where energy equilibration has been achieved.

Many of the salient features of the orbiting yields, such as their inelasticity and anisotropy, are indistinguishable, however, from those expected for a compound nucleus fusion-fission mechanism. Early on, the fission mechanism was considered as a possible explanation for the energy damped ²⁸Si⁺¹²C yields, but abandoned because the observed cross sections were much greater than model predictions based on the standard rotating liquid drop model. The possibility of a significant fission contribution was again suggested after it was shown that finite-nuclear range effects can lead to significantly reduced fission barriers in lighter systems [39,94,95]. However, as shown in Fig. 22, even though the newer fission calculations may be able to account for the observed cross sections in the nitrogen
and oxygen channels, the calculations significantly understate the cross sections measured in the carbon channel \[39\].

Good agreement with the observed fully damped cross sections, evaporation residue cross sections, and average total kinetic energy values for the damped yields has been obtained using the equilibrium model for fusion and orbiting \[63, 65\], as discussed in Sec. IVB. In particular, the observed saturation trend of the TKE values as a function of the incident energy is well described by this latter model, as shown in Fig. 21. In the equilibrium orbiting model, saturation occurs because a value of the orbital angular momentum is reached, after dissipation, beyond which the formation of a dinuclear complex is not allowed because of the centrifugal repulsion.

Additional studies support the idea that an orbiting-like mechanism dominates that component of the carbon yield characterized by an angular dependence with $d\sigma/d\Omega \propto 1/\sin \theta_{c.m.}$. The entrance-channel dependence of the process was demonstrated by Ray et al. \[26\] by forming the $^{40}$Ca nucleus with both the $^{24}$Mg$^+$+$^{16}$O and $^{28}$Si$^+$+$^{12}$C reactions at closely matched excitation energies and angular momenta. Figure 32 shows the observed ratio of the oxygen to carbon cross section for these reactions as a function of excitation energy. If compound-nucleus fission dominated the cross sections, this ratio would be expected to be very similar for the two reactions. The observation of a strong entrance-channel dependence of the ratios suggests a non-compound mechanism. It is interesting to note that the entrance channel effect becomes smaller at larger excitation energies. This might suggest stronger fission competition for the more strongly damped yields \[90\]. Shiva Kumar et al. \[62\] have extended the entrance channel studies by comparing the carbon to oxygen cross section ratios over an extended range of $^{40}$Ca excitation energies. This study suggests an approach to an equilibrated compound nucleus ratio as the beam energy increases.

In another study that supports an orbiting-like explanation for the less damped yields, the population of magnetic substates of $^{12}$C$(2^+_1)$ and $^{28}$Si states for the $^{12}$C($^{28}$Si, $^{12}$C)$^{28}$Si reaction at 180° has been measured by Ray et al. \[90\] using $\gamma$-ray angular correlation techniques. Qualitatively, the observed selective population of the m=0 magnetic substate with
respect to the beam axis agrees well with a simple dinuclear sticking picture. A subsequent, more complete and detailed experiment has been performed to measure density matrices of the \(^{12}\)C and \(^{28}\)Si excited states \([67]\). The data are found consistent with a dinuclear picture in which bending and wriggling motions are the dominant spin carrying modes. It is interesting to note that these \(\gamma\)-ray angular correlation experiments using the \(^{28}\)Si+ \(^{12}\)C orbiting reaction have been used to illuminate certain conceptual aspects of quantum mechanics \([97]\).

In general, orbiting processes and resonant-like structures have been found to coexist in collisions for which surface transparency is expected based on the small number of open reaction channels \([98]\). The \(^{28}\)Si+\(^{12}\)C and \(^{24}\)Mg+\(^{16}\)O reactions, for example, both show large “orbiting” yields as well as strong resonances at backward angles in their elastic, inelastic \([91,99]\), and transfer exit channels \([99]\). As seen in Fig. 24, the normalized number of open reaction channels for both of these reactions is very small. The mass-symmetric \(^{20}\)Ne+ \(^{20}\)Ne reaction, which leads to the same \(^{40}\)Ca composite system as \(^{28}\)Si+ \(^{12}\)C and \(^{24}\)Mg+ \(^{16}\)O, has also been investigated \([83]\) and found to exhibit strong orbiting-type behavior. Again, this system is found to have a small number of open reaction channels. However, to our knowledge, this is the only “orbiting” system to show almost structureless elastic excitation functions \([100]\).

The \(^{28}\)Si+\(^{14}\)N reaction is an important test case for exploring how surface transparency, as reflected in the number of open channel calculations, is related to the occurrence of orbiting and molecular resonance behavior. Although this system is close in mass to the \(^{28}\)Si+ \(^{12}\)C system, the phase space available to reaction channels is very different for the two: whereas the \(^{28}\)Si+ \(^{12}\)C reaction has only a few exit channels, the \(^{28}\)Si+ \(^{14}\)N reaction is characterized by a large value of N/F (see Fig. 24). The observed orbiting-like cross sections for \(^{28}\)Si+ \(^{14}\)N reaction \([64,101]\) are significantly smaller than for the \(^{28}\)Si+ \(^{12}\)C reaction. The equilibrium model for orbiting \([63]\) has been found to give a reasonably good description \([65]\) of the ensemble of the experimental data \([64,101]\) for this reaction, although fusion-fission calculations performed at \(E_{\text{c.m.}} = 40\,\text{MeV}\) \([39]\) are found to reproduce the overall experimental behavior with comparable success. As a consequence of, or at least coincident
with, the increased reaction phase space, the damped binary breakup yield behave more like "normal" fission.

Pronounced backward angle yields have also been observed in the $^{27}\text{Al}^+$ $^{16}\text{O}$ reaction at several $^{27}\text{Al}$ bombarding energies by Shapira et al. [24]. This is also a system where the number of open reaction channels is large and the observed cross sections for the damped yields are consistent with a fission interpretation.

The symmetric and nearly symmetric mass binary decay of $^{44}\text{Ti}$ has been studied in inclusive and exclusive measurements of the $^{32}\text{S}^+$ $^{12}\text{C}$ reaction at 280 MeV bombarding energy [102]. Although substantial post-scission evaporation occurs at this high energy, it was possible to extract the energy-damped reaction cross sections and $\langle TKE \rangle$ values for this system. The analysis of these data is one of the earlier attempts to describe the damped binary yields in a light system in terms of a fusion followed by fission picture. However, the experimental set-up was designed for the detection of two comparable mass fragments, rather than the unequal mass fragments expected to dominate the fission cross sections for a system of fissility below the Businaro-Gallone point [103]. Similar studies [8] focusing on symmetric mass breakup yields have shown the existence of fission-like yields for three other light systems in this mass region: $^6\text{Li}^+\text{Ca}$, $^9\text{Be}^+\text{Ca}$ and $^{12}\text{C}^+\text{Ca}$, leading to the $^{46}\text{V}$, $^{49}\text{Cr}$ and $^{52}\text{Fe}$ compound nuclei, respectively.

In a study of the $^{28}\text{Si}^+\text{O}$ reaction at $E_{c.m.}=39.1$ and 50.5 MeV, Oliveira et al. [105] found fully energy damped yields which were attributed to a deep inelastic scattering mechanism. These data have also been analyzed in terms of the transition state model and found consistent with a fusion-fission mechanism [106].

In another study of the $^{44}\text{Ti}$ compound system, Barrow et al. [104] have found evidence of correlated resonance phenomena in excitation functions of binary channels from the $^{24}\text{Mg}^+\text{Ne}$ reaction. The data suggest that the observed resonances can be characterized by angular momenta close to that of the grazing angular momentum in the entrance channel. This is taken to suggest a different origin for these structures than the very pronounced resonances seen in elastic and inelastic scattering yields for the $^{24}\text{Mg}^+\text{Mg}$ reaction [7].
which seem to arise from spins higher than the corresponding grazing angular momentum [10]. The $^{24}\text{Mg}^+\ ^{20}\text{Ne}$ study focuses on low-lying excitations and does not address the question of whether this resonance system is also found to exhibit enhanced orbiting-like yields in the more strongly energy-damped channels. A similar resonance behavior to that seen for the $^{24}\text{Mg}^+\ ^{20}\text{Ne}$ reaction is also observed for the $^{28}\text{Si}^+\ ^{20}\text{Ne}$ reaction, as also studied by Barrow et al. [104]. Again, the possibility of an orbiting-like component has not been explored.

\section*{C. $44 < A_{CN} \leq 56$}

For reactions populating compound nuclear masses in the range $44 < A_{CN} \leq 56$ there is relatively little evidence for the pronounced orbiting-like yields observed in some lighter systems. In general, the experimental cross sections for the strongly damped binary yields are in good agreement with expectations based on fission-model calculations. There is still, however, evidence for heavy-ion resonance behavior for some of the systems studied in this mass range.

To study the possible competition between the fission and orbiting mechanisms, the population and decay of the $^{47}\text{V}$ compound system has been extensively studied through three different entrance channels: $^{35}\text{Cl}^+\ ^{12}\text{C}$; $^{31}\text{P}^+\ ^{16}\text{O}$ and $^{23}\text{Na}^+\ ^{24}\text{Mg}$ [29,30,42,107]. These systems cover a wide range of entrance-channel mass asymmetries and therefore allow for a strong test of the decoupling of the observed binary yields from the entrance channel, one of the signatures that can be used to differentiate between the fission and orbiting mechanism.

The binary decay properties of the $^{47}\text{V}$ nucleus, produced in the $^{35}\text{Cl}^+\ ^{12}\text{C}$ reaction, have been investigated between 150 and 280 MeV by means of a kinematics coincidence technique [29,30,42]. The angular distributions of the lightest fragments are found to follow a $1/\sin \theta_{c.m.}$ angular dependence. This is shown in Fig. 33 for fragments with $5 \leq Z \leq 11$ from measurements at $E_{lab} = 180$ MeV and 200 MeV. Distributions of $d\sigma/d\theta_{c.m.}$ are shown.
The distributions are found to be independent of the scattering angle for each exit channels indicating that the lifetime of the dinuclear complex is comparable to or longer than the rotational period.

The binary nature of the reaction products has been clearly established with the coincidence measurement. Complete energy relaxation of the fragments with $5 \leq Z \leq 11$ is evident from the angle independence of their observed TKE values, as shown in Fig. 33 [30]. Although these results are obtained using singles data, equivalent results have been obtained in the coincidence measurements. The averaged TKE values for all detected fragments vary little with incident energy and the TKE value corresponding to a symmetric mass breakup is close to the prediction of the revised Viola systematics [40], as shown in Fig. 8.

To test the entrance-channel independence of the damped reaction yield for the $^{47}$V system, back-angle $^{12}$C and $^{16}$O yields have been measured in the $^{31}$P+ $^{16}$O [108] and $^{35}$Cl+ $^{12}$C reactions [29] at energies leading to the same compound-nucleus excitation energy of $E_{CN}^* = 59.0$ MeV and very comparable angular momenta. The observed $^{12}$C and $^{16}$O cross sections are comparable for the two systems and much smaller than those predicted by the equilibrium orbiting model [63,65]. Also, the ratio of carbon to oxygen cross section, as shown in Fig. 34, has no significant entrance channel effect and is in general agreement with the predictions of the transition-state model calculations [39]. A similar comparison has been done with the $^{35}$Cl+ $^{12}$C and $^{23}$Na+ $^{24}$Mg [30] reactions, populating the $^{47}$V compound nucleus at $E_{CN}^* = 64.1$ MeV. Again, as shown in Fig. 34, the observed behavior is in reasonable agreement with the expectations of the transition-state description of fission [30]. The elemental cross sections for the $^{23}$Na+ $^{24}$Mg reaction are also in agreement with expectations based on the fission picture, as shown in Fig. 19.

One of the most striking phenomena observed in heavy-ion reaction studies is the pronounced resonance structures observed in elastic and inelastic scattering of the $^{24}$Mg+ $^{24}$Mg system [7]. Narrow structures which are correlated in many channels and extending to high excitation energy suggest that a very special configuration of the $^{48}$Cr compound system is formed in this reaction. By measuring the $\gamma$-ray correlations with the $^{24}$Mg fragments, it has
been possible to deduce a resonance spin for at least one of the observed structures that is greater than that of the grazing angular momentum \[10,109\]. This is taken to suggest a very prolate deformed configuration of the compound system leading to the resonance. In earlier measurements of the resonance behavior, peaks were also observed in excitation-energy spectra for the \(^{24}\text{Mg}(^{24}\text{Mg}, {^{24}\text{Mg}}) {^{24}\text{Mg}}\) reaction up to energies where secondary \(\alpha\)-particle evaporation from the fragments obscures any spectroscopic details. This raises the question as to whether the structure observed at higher excitation energies is somehow related to the resonance phenomenon or, instead, is a feature of the fission decay of the compound nucleus.

As discussed in Sec. IV E, a possible ternary fission mode for the \(^{24}\text{Mg}+{^{24}\text{Mg}}\) reaction, as suggested by several model calculations, has also been sought for but not observed.

To explore the relationship of the different reaction mechanisms influencing the binary decay yields of the \(^{48}\text{Cr}\) compound system, the energy-damped yields of the \(^{36}\text{Ar}(E_{\text{lab}}=187.7 \text{ MeV})+{^{12}\text{C}}\ [56], {^{20}\text{Ne}(E_{\text{lab}}=78.0 \text{ MeV})}+{^{28}\text{Si}}\ [56], {^{24}\text{Mg}(E_{\text{lab}}=88.8 \text{ MeV})}+{^{24}\text{Mg}}\ [46]\) reactions have been studied. Each of these reactions populates the \(^{48}\text{Cr}\) compound nucleus at an excitation energy of about 59.5 MeV. In each case, the outgoing fragments were identified by measuring both fragments in a kinematic coincidence arrangement. The calculated mass distribution of the fully energy damped yields with \(6 \leq A \leq 24\) is in excellent agreement with the experimental results for the \(^{24}\text{Mg}+{^{24}\text{Mg}}\) reaction \[46\], with no significant evidence for an excess yield in the entrance channel that might suggest an additional, orbiting mechanism. The agreement is also reasonable good for the \(^{36}\text{Ar}+{^{12}\text{C}}\) entrance channel, although in this case the experimental results show a somewhat greater mass asymmetry of the fission fragments than predicted. The use of the kinematic coincidence technique allows for very good \(Q\)-value resolution in the final channels, as seen in Fig. 35 where the excitation-energy spectra for the \(^{24}\text{Mg}+{^{24}\text{Mg}}\) channel is shown for each of the three entrance channels. The experimental results are indicated by the thick-line histograms. It is evident from this figure that the structure observed at higher excitation energy is correlated for the three entrance channels, making it improbable that this structure is an artifact of the resonance behavior. Rather, the structure seems to be related to the detailed level structure of the final nuclei.
The thin-line histograms in Fig. 35 are obtained using the transition-state model with the saddle-point method and applying the same procedure as discussed for Fig. 16 to associate the flux at the saddle point with specific mutual excitations of the fragments \[ \text{[49,50]} \]. The fission picture can account for most of the observed structures, although with some significant discrepancies observed between the calculated and measured yields to low-lying excitations populated through the \( ^{24}\text{Mg}+\text{Mg} \) and \( ^{20}\text{Ne}+\text{Si} \) channels. This must be expected since both of these reactions show evidence of resonance behavior \[ \text{[7,104]} \] which can not be described by the transition-state picture. The energies corresponding to single and mutual excitations of yrast levels and ground-state band members are shown at the bottom of Fig. 35. Although these excitations are found to contribute to the observed structures, they do not appear to dominate the spectra. Instead, the calculations suggest that random groups of high channel spin excitations account for the general appearance of the spectra.

Instead of using the saddle-point calculation to predict, \textit{a priori}, the excitation energy spectra, Farrar \textit{et al.} \[ \text{[50]} \] have also used this method to explore the compound-nucleus spin distribution leading to the observed fission yields. In this analysis, it is found that the average spin obtained from the fitted distribution is comparable to that obtained from the \textit{a priori} calculation for the \( ^{36}\text{Ar}+\text{C} \) and \( ^{20}\text{Ne}+\text{Si} \) reactions, but is smaller than the systematics would suggest for the \( ^{24}\text{Mg}+\text{Mg} \) entrance channel. The difference in the average fitted and calculated spin values is even greater when a “resonance-subtracted” energy spectrum is used for the \( ^{24}\text{Mg}+\text{Mg} \) reaction. This suggests that there may be direct competition between the heavy-ion resonance and compound-nucleus fission mechanisms for near grazing partial waves of this entrance channel.

The \( ^{56}\text{Ni} \) compound system has also been explored through multiple entrance channels, using the \( ^{16}\text{O}(E_{\text{lab}}=69-87 \text{ MeV})+^{40}\text{Ca} \), \( ^{28}\text{Si}(E_{\text{lab}}=85-150 \text{ MeV})+^{28}\text{Si} \), and \( ^{32}\text{S}(E_{\text{lab}}=121 \text{ MeV and 142 MeV})+^{24}\text{Mg} \) reactions \[ \text{[11]} \]. Excitation functions of the elastic and inelastic excitations of the symmetric \( ^{28}\text{Si}+^{28}\text{Si} \) channel are found to exhibit correlated resonance behavior \[ \text{[4]} \], although somewhat more weakly than seen in the \( ^{24}\text{Mg}+^{24}\text{Mg} \) system. Each of the three entrance channels is found to result in fully energy-damped yields.
that are consistent with a fusion-fission reaction mechanism.

Excitation-energy spectra for the $^{24}\text{Mg}(^{32}\text{S}, ^{28}\text{Si})^{28}\text{Si}$ reaction at $E_{lab}=121$ MeV and 142 MeV [15] are shown in Fig. 17 and are found to be well reproduced by the transition-state model using the extension to the saddle-point method [49] to calculate these spectra. To further confirm the predicted population of final mutual excitation, γ rays were measured in coincidence with the $^{28}\text{Si}$ fission fragments [49] in the excitation energy range $7.6 \leq E_x \leq 16.7$ MeV. In general, the observed and predicted transition rates for specific states in the $^{28}\text{Si}$ fragments were found to be in good agreement. This is shown in Figs. 36 and 37. In Fig. 36 it is seen that the model calculations well reproduce the relative strength of the yrast $2^+ \rightarrow 0^+$ and $4^+ \rightarrow 2^+$ transitions. Since higher spin states tend to feed the $4^+$ level, this agreement suggests that the population of these higher spin states is being reasonable well described. Figure 37 shows the calculated and measured γ-ray spectra on an expanded scale. Again, reasonably good agreement is found between the predicted and observed transition strengths. A quantitative comparison, however, reveals evidence of greater population of members of the $K^{\pi} = 0^+_3$ band in $^{28}\text{Si}$ (taken to include levels at 6691 keV, 7381 keV, 9165 keV, and 11509 keV) than predicted. This band is believed to have a strongly prolate deformed nature [112] and an enhanced population might result from the relatively deformed shapes expected for the nascent fission fragments at the saddle point. It should be noted, however, that there is some debate as to whether the 11509 keV $6^+$ level should be associated with this band [113].

The mass distributions of the fission-like yields for the $^{32}\text{S}+^{24}\text{Mg}$ reaction at $E_{lab}=121$ and 142 MeV [45], obtained by fitting experimental angular distributions assuming a $d\sigma/d\Omega \propto 1/\sin \theta_{c.m.}$ angular dependence, are shown in Fig. 38 by the open histograms. The corresponding predicted mass distributions based on the transition-state model calculations, shown by the solid histograms, are found to be in excellent agreement with the data. One of the results of the model calculations which has yet to be confirmed in any of the systems studied is that significant fission yield is expected in the $^8\text{Be}$ channel. By bridging the light-particle evaporation and fission mass ranges, the predicted strength in the $^8\text{Be}$
channel highlights the idea, as proposed by Moretto [72], that light-particle evaporation and fission yields have a common origin and should be viewed in terms of their respective decay barriers.

In an experiment exploring the energy and spin sharing between fission fragments in the $^{24}\text{Mg}(^{32}\text{S},^{12}\text{C})^{44}\text{Ti}$ reaction at $E_{\text{lab}}=140$ MeV, $\gamma$-ray spectra were obtained in coincidence with the $^{12}\text{C}$ fragments [114]. The results also indicate a statistical decay process consistent with the predictions of the transition-state model. Moreover, no evidence was found for the spin alignment of the $^{12}\text{C}$ fragments, contrary to what might be expected for a deep-inelastic scattering origin of the fully energy-damped yields.

**D. $56 < A \leq 80$**

The reaction products from the $^{35}\text{Cl}+^{24}\text{Mg}$ system have been investigated at a bombarding energy $E = 8$ MeV/nucleon with both inclusive [113] and exclusive measurements [116]. The inclusive data provide information on the properties of both the evaporation residues and the binary-decay fragments. The binary process yields are, for instance, successfully described by statistical models based on either the saddle point picture [39] or the scission point picture [54]. The similar good agreement with theory that is found for the energy spectra, the angular distributions, and the $\langle TKE \rangle$ values makes the hypothesis that fully energy-damped fragments result from a fusion-fission process quite reasonable for the $^{59}\text{Cu}$ compound system, in accordance with findings for other, equivalent systems as shown in this report.

No evidence is seen in the coincidence data for the occurrence of three-body processes in the $^{35}\text{Cl}+^{24}\text{Mg}$ reaction. This result can be contrasted to the situation reported for somewhat heavier mass systems, where significant three-body breakup yields are evident for the $^{32}\text{S}+^{45}\text{Sc}$ [117] and $^{32}\text{S}+^{59}\text{Co}$ [118] reactions, both measured with $E_{\text{lab}}(^{32}\text{S})=180$ MeV (5.6 MeV/u). The nuclear-charge deficits from the compound-nucleus charge found in the $^{35}\text{Cl}+^{24}\text{Mg}$ exclusive measurement, however, can be fully accounted for by the sequential
evaporation of light charge particles (LCP), in agreement with the systematics established for a large number of reactions studied at bombarding energies below 15 MeV/nucleon [119].

The question of whether a small part of the binary reactions come from ternary processes is still an open question and difficult to answer. In general the measured charge-deficit values and other experimental observables (such as cross sections, energy- and angular-distributions or mean TKE values) are very well described by a complete Extended Hauser-Feshbach statistical-model calculation [54] which takes into account the post-scission LCP and neutron evaporation.

Although the fission picture is seen to work well in the $^{35}$Cl+ $^{24}$Mg reaction, a very different conclusion is reached by Yokota et al. [120] in a study of two systems ($^{37}$Cl+ $^{27}$Al and $^{16}$O+ $^{48}$Ti) leading to the somewhat heavier $^{64}$Zn compound system. These reactions populate $^{64}$Zn at comparable excitation energies and spins. The components of the reaction yields corresponding to a $d\sigma/d\Omega \propto 1/\sin \theta_{c.m.}$ angular dependence result in very different $Z$ distributions for the two reactions, contrary to the expectations of the statistical decay of a compound nucleus. It is possible that these systems are again displaying the strong orbiting signature that has been found in several lighter systems. If so, these results could provide an interesting challenge for the number of open channels calculations performed for systems of mass $A_{CN} > 60$.

The transition region where it appears that the asymmetric-mass fission observed in lighter systems may change into the symmetric fission behavior characteristic of heavier systems appears to occur around mass $A \approx 80$. Evans et al. have studied the $^{40}$Ca+ $^{40}$Ca reaction at $E_{c.m.} = 197$ MeV and 231 MeV [121] and the $^{28}$Si+ $^{50}$Cr reaction at $E_{lab}^{(\text{28Sr})} = 150$ MeV [122]. The resulting mass distributions for the lower energy $^{40}$Ca+ $^{40}$Ca reaction and the $^{28}$Si+ $^{50}$Cr reaction are shown in Fig. 39 by the open circles. The mass distributions for the two reactions are found to be quite different, even though the fissility of the two systems is quite similar. This behavior was initially thought to indicate a fast-fission mechanism accounting for the asymmetry dependence of the $^{28}$Si+ $^{50}$Cr yields [122]. However, in exploring the possibility of fission competition in these systems, it has been found that for the
spin values near the critical angular momentum for fusion, where most of the fission yields is expected to originate, the mass asymmetry dependent fission barriers are actually quite different for the two systems. The $^{80}$Zr compound system, populated through the $^{40}$Ca+$^{40}$Ca reaction, is found to have either a very flat distribution of barrier energies as a function of mass asymmetry or slightly lower barriers for the symmetric mass configuration. For the $^{78}$Sr compound system, populated through the $^{28}$Si+$^{50}$Cr reaction, however, the distribution favors asymmetric mass breakup. The bold-line histograms in Fig. 39 show the predicted primary fission mass distributions using the transition-state model and the thin-line histogram show the corresponding mass distributions after secondary light-particle emission from the fission fragments is taken into account. For the two systems, the overall trend of the data seems to be reproduced by the calculations, indicating that these two systems may straddle the Businaro-Gallone [123] transition from asymmetric- to symmetric-mass fission.

VI. OPEN PROBLEMS

A. Time scale

Although the process of binary decay from equilibrated compound nuclei has been clearly identified experimentally and successfully described in terms of phase-space models, more thought is needed on the dynamics through which systems evolve from their entrance channels to deformed and statistically equilibrated compound nuclei that subsequently undergo scission. The occurrence of orbiting and resonance behavior in some systems indicates the superposition of compound nucleus decay products (properly described by the transition state model) and faster direct processes (interpreted on the basis of polarization potentials, entrance channel resonances or DIC orbiting processes). Therefore, the investigation of the dynamics involved in heavy ion collisions leading to totally energy-damped binary exit channels may lead to a better understanding of the competition among the different reaction mechanisms. Within this scenario two questions arise: a) the time scale of the processes
and b) the shape evolution of the system.

It has been suggested by Thoennessen et al. [124] that systems with different entrance channel mass asymmetries may evolve towards their compound nucleus configurations with different time scales such that the most asymmetric one reaches full equilibrium faster. This finding suggests that the mass asymmetry may affect not only the angular momentum distribution but also the competition with faster direct processes. In the case of heavier systems, $\gamma$ rays from the decay of the giant dipole resonance (GDR) built on highly excited compound-nucleus states has been shown to be sensitive (through the shape of the energy spectrum) to the time scale of the process as well as to the deformation of the nuclear system. As we go to lighter systems, where the energy of the GDR is quite high, severe experimental problems are expected with such GDR measurements. However, these measurements should be extended to systems that are as light as possible.

Interferometry measurements based on the detection of emitted pairs of light charged particles has been employed as a technique to probe time scales and nuclear dimensions [125,126]. For heavier systems, these studies have generally involved the use of small angle correlations of protons emitted from a hot source in the determination of emission time scales and sources radii. However, if we go to lighter and equilibrated systems, this technique can be borrowed to obtain estimates of reaction time scales. If a hot composite systems decays into a binary channel and a proton or alpha particle evaporates from one of the fragments, the proximity of the other fragment may distort the kinematics correlation because of the strong Coulomb repulsion. Such a distortion will depend on the time scale for fission and the sequential secondary evaporation.

In cases where there is good $Q$-value resolution, the experimental $Q$-value spectra present a structured behavior even at high excitation energies. This is seen, for example, in Fig. 35 for the three entrance channels populating the $^{48}$Cr compound nucleus. These structures can be associated with selectively populated clusters of high-spin mutual excitations. This situation allows for a fluctuation analysis (see, for example, ref. [87] and Sec. V B) to obtain the coherence width of the intermediate system and, hence, its lifetime (with $\tau = \hbar/\Gamma$). It is
important to assure that the number of levels included in the energy bin is very low, requiring experiments using very thin targets and beams of good energy and spatial resolution.

B. Relationship to heavy-ion resonance behavior-superdeformed minima?

Several of the results presented in this report suggest that a coherent framework may exist which connects the topics of heavy-ion molecular resonances \cite{12, 13}, superdeformation effects as observed in medium mass $\gamma$-ray studies (see the most recent reports quoted in \cite{127}), and fission shape isomerism in the actinides \cite{28}.

The shape of the “normal” saddle-point configuration in light systems is very similar to two, touching, prolate-deformed spheroids in a neck-to-neck configuration. The shape of the system found in a conjectured, secondary well in the potential energy surface is likely to be similar, although involving greater deformation of the nascent fragments.

In calculations of the shape-dependent potential-energy surfaces at high angular momenta (16-40$\hbar$) for the $^{48}$Cr nucleus \cite{128}, a strong superdeformed configuration is predicted that corresponds to an aligned arrangement of two touching and highly deformed $^{24}$Mg nuclei. This superdeformed configuration is a candidate to become yrast at around spin 34$\hbar$, in the high excitation energy region which corresponds to where the quasi-molecular resonances have been observed.

Indeed, from spin alignment measurements \cite{10} of two strong resonances in the $^{24}$Mg+$^{24}$Mg scattering reaction \cite{7}, the deduced spin assignments were found to be comparable to or a few units larger than expected for grazing collisions, leading to the same conclusion that the resonance configurations correspond to a shape of two prolate $^{24}$Mg nuclei placed pole to pole.

This observation has been further supported by theoretical calculations of a molecular model \cite{129} which indicate a dinuclear nature of the observed resonances and suggest the presence of such a stabilized configuration in $^{48}$Cr at high spins. The conjectured isomeric configuration constituting this aligned, pole-to-pole arrangement of two $^{24}$Mg clusters has
a large probability for breakup into two $^{24}$Mg fragments—a situation which is similar to that expected for the symmetric-fission saddle point, suggesting a relationship between the fission mechanism and that responsible for the resonance behavior.

The relative strength of the various statistical and non-statistical processes observed in the binary yields of light systems is found to be related to the number of available open channels for the near-grazing partial waves $^{[18,42]}$. The resonant, non-statistical mode of the $^{24}$Mg+ $^{24}$Mg reaction leading to the $^{48}$Cr compound system emphasizes the dominance of partial waves near or slightly above the grazing angular momentum value $^{[4,7]}$. The fission mechanism has also been found to play a significant role at these spins $^{[46]}$, however, indicating that the nuclear configuration leading to the resonance behavior is only slightly more extended than that expected for the nuclear saddle point.

The coexistence of fission and a separate reaction mechanism corresponding to heavy-ion resonance behavior has been analyzed in detail $^{[46]}$ for the binary breakup of the $^{48}$Cr compound system populated with the $^{24}$Mg+ $^{24}$Mg, $^{20}$Ne+ $^{28}$Si and $^{36}$Ar+ $^{12}$C reactions (see Sec. 5.3). The conclusion drawn from inspection of the energy spectra shown in Fig. 35 was that a significant fraction of the yield observed in the $^{24}$Mg+ $^{24}$Mg exit channel arises from a statistical fission mechanism, with the resonance mechanism primarily influencing the lower excitation energy region of the spectra due to the more symmetric entrance channels.

The influence of the fragment structure and the relationship between the fission mechanism and that responsible for the resonance behavior needs to be investigated further with detailed particle-γ coincidence measurements of the $^{24}$Mg+ $^{24}$Mg system, including excitation functions measurements in the vicinity of the well-known resonance energies.

**VII. CONCLUSIONS**

In this review we have summarized the results and conclusions of many investigators who have studied the fully energy-damped, binary yields arising from reactions involving lighter nuclear systems with $A_{CN} \leq 80$. The experimental and theoretical techniques used in these
investigations have been presented and illustrated with experimental results. The general systematics that have been developed for these yields have been reviewed.

In general, the data lend support to the newer macroscopic energy calculations based on the finite-range, rotating liquid drop model. Fission like yields have been observed in all of the systems studied. Moreover, the experimental systematics support the expectation, based on model calculations, that fission should favor a mass asymmetric breakup of the compound nucleus in these light systems. Further support for the fission picture comes for the measured total kinetic energy values of the fragments which are found to reflect the expected deformation of the compound nucleus at the point of scission.

It is shown that various model calculations that share the premise that the final mass and energy distributions can be described by phase space constraints all lead to comparable predictions of the damped binary yields. These include the transition-state models based on counting the available states at the saddle- or scission-points, the equilibrium orbiting model, and the dynamical breakup model. The strength of the transition-state model using the saddle-point method is found in its ability to describe the general fission behavior over the entire region of mass covered by this report in a relatively “parameter-free” manner. This general success is believed to be related to the ability of the finite-range rotating liquid drop model to correctly calculate the shape and energy of the saddle-point barrier. The similarity of the saddle- and scission-point configuration in these light systems, however, allows for very similar behavior being predicted when the scission point is used as the “transition state” or when equilibrium orbiting is considered.

The general success of the statistical model calculations allows us to now establish a reference for what is the “expected” behavior for the damped binary yields and to search for deviations from this behavior. It has become clear that in some systems there is an additional “orbiting” component that is of much larger cross section than can be accounted for by the fission calculations. Systems where this additional component is present also tend to manifest resonance-like behavior in excitation functions of their elastic, inelastic, and transfer channels. The occurrence “orbiting/resonance” behavior is found to be strongly correlated
with the number of open reaction channels which, in turn, is believed to be associated with the degree of absorption in the grazing partial waves. The precise mechanism(s) involved in the orbiting and resonance behavior is still unknown.

The model calculations also make definite predictions of compound nucleus lifetimes and the shapes corresponding to the fission saddle-point. Measurements aimed at confirming these predictions are likely to require triple coincidences of three outgoing particles—the two resulting heavy fragments from the reaction and either the $\gamma$ ray or light particle emitted from one of the two primary fragments. Such measurements are still in their infancy.

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FIGURES

FIG. 1. Comparison of the fusion-fission (left branch) and dinucleus orbiting (right branch) mechanisms.

FIG. 2. Elastic scattering distribution for the $^{16}\text{O}+^{28}\text{Si}$ reaction showing the “anomalous” large-angle scattering behavior. The dashed curve is the prediction of an optical model calculation. The insert compares a $|P_{L}(\cos\theta)|^2$ angular dependence to the large angle data. (Figure adopted from ref.[16])

FIG. 3. Schematic description of nuclear orbiting in heavy-ion reactions [21].

FIG. 4. Fission-like cross sections for the $^{35}\text{Cl}+^{12}\text{C}$ reaction at $E_{lab}=180$ MeV. This figure is reproduced from ref.[30].

FIG. 5. Angular distribution for the $^{20}\text{Ne}$ channel of the $^{35}\text{Cl}+^{12}\text{C}$ reaction at $E_{lab}=180$ MeV (data taken from ref.[30] together with a $1/\sin\theta$ angular dependence (dashed curve) and the transition-state distribution (solid curve). The curves have been scaled to the data.

FIG. 6. Angular distribution anisotropy $R(\theta)$ as a function of the “life” angle $\alpha$ for $\theta=10^\circ$ and $170^\circ$. The dashed line is the corresponding anisotropy for a $1/\sin\theta$ dependent angular distribution.

FIG. 7. Angular distributions of binary decay channels for the $^{16}\text{O}+^{11}\text{B}$ reaction. An evaporation-residue component has been subtracted to obtain these yields (see ref.[31]). The curves represent fits using Eqn.(2.2) with the indicated “life angles”.

FIG. 8. Most probable TKE release in fission as a function of the parameter $Z^2/A^{1/3}$ of the fissioning nucleus. Open triangles have been taken from previous existing compilations [40,41]. Experimental solid points have been recently compiled in ref.[42]. The dashed line is the result of the Viola systematics [41]. The solid line shows the revised systematics of Tavares and Terranova [42].
FIG. 9. Definition of variables used in determining fragment masses and reaction $Q$-value for a binary reaction using the kinematic coincidence technique.

FIG. 10. Experimental arrangement for studying binary yields from the $^{24}$Mg+$^{24}$Mg reaction [46].

FIG. 11. Schematic of the reaction kinematics for a binary breakup process.

FIG. 12. Comparison of the saddle-point energies deduced from the double spheroid approximation (curves) and the corresponding full macroscopic energy calculations (symbols), at approximately 0.6 and 0.8 times the spin at which the respective fission barriers vanish [39].

FIG. 13. Saddle point shapes for the $^{40}$Ca, $^{56}$Ni, and $^{90}$Zr at the indicated mass asymmetries and spins (solid curves). The corresponding shapes found for the double spheroid approximation discussed in the text are shown by the dashed curves [39].

FIG. 14. Schematic diagram of the energy balance for a fusion-fission reaction.

FIG. 15. Saddle-point energies for the $^{56}$Ni compound nucleus as a function of spin and mass asymmetry. The mass-asymmetry coordinate is given by the final fragment mass assuming fission occurs. Typical saddle-point shapes are also indicated.

FIG. 16. Partial fusion cross sections as a function of compound nucleus spin for the $^{32}$S+$^{24}$Mg reaction at $E_{lab}^{(32S)}=121$ MeV. The shaded region indicates the cross section leading to fission.

FIG. 17. $^{28}$Si+$^{28}$Si excitation-energy spectra for the $^{32}$S+$^{24}$Mg reaction at (a) $E_{c.m.} = 51.0$ MeV and (b) $E_{c.m.} = 54.5$ MeV. The bold-line histograms are the experimental spectra. The lighter curves are the results of model calculations discussed in the text for fission decay to particle-bound states (solid curve) and for all decays (dotted curve). This figure is reproduced from ref.[49].
FIG. 18. Average calculated valued for the compound-nucleus spin $\langle J_{CN} \rangle$, exit-channel orbital angular momentum $\langle \ell_{out} \rangle$, and channel spin $\langle s \rangle$ for the $^{28}Si + ^{28}Si$ fission channel of the $^{32}S + ^{24}Mg$ reaction at $E_{c.m.} = 51.0$ MeV. This figure is reproduced from ref.[49].

FIG. 19. Experimental evaporation-residue and fission cross sections for the $^{35}Cl + ^{12}C$ reaction at $E_{lab} = 200$ MeV and the $^{23}Na + ^{24}Mg$ reaction at $E_{lab} = 89$ MeV (data taken from ref.[60]). The solid-line histograms show the calculated cross sections based on the transition-state model. The dotted-line histograms are the comparable calculations using the Extended Hauser-Feshbach model. The calculated fission cross sections have been corrected for the influence of secondary light-fragment emission from the fragments.

FIG. 20. Experimental values of $\langle TKE \rangle$ for the $^{35}Cl + ^{12}C$ reaction (squares, from ref.[30]) at $E_{lab} = 200$ MeV and the $^{23}Na + ^{24}Mg$ reaction (circles, from ref.[60]) at $E_{lab} = 89$ MeV. The solid- and dashed-line curves show the expected values based on the transition-state model for the two systems, respectively. The dotted-line curve show the expected values based on the Extended Hauser-Feshbach model for the $^{35}Cl + ^{12}C$ reaction.

FIG. 21. Most probable experimental TKE values [17,61] of the orbiting products from the $^{28}Si + ^{12}C$ reaction as compared to the equilibrium model for orbiting [63] (dashed curve) and the transition-state model (solid curves).

FIG. 22. Experimental orbiting cross sections measured in the $^{28}Si + ^{12}C$ reaction [17,61] as compared to the equilibrium model for orbiting [63] (dotted curves) and the transition-state model (solid curves).

FIG. 23. Calculated NOC values as a function of the grazing angular momenta for selected light systems with $A_{CN} < 30$ [31].

FIG. 24. Calculated NOC values as a function of the grazing angular momenta for selected light systems with $36 \leq A_{CN} \leq 48$ [18].
FIG. 25. Experimental velocity spectrum for the boron elements detected from the $^9$Be+$^{11}$B reaction with $E_{lab} = 37$ MeV and $\theta_{lab} = 8^\circ$. The curves are discussed in the text. The figure is from ref.[80].

FIG. 26. Fusion excitation functions for the indicated systems. The dashed curves show Glas and Mosel parameterization of the data. The solid, straight lines are predictions of the total reaction cross sections based on optical model calculations. The solid curves are based on proximity potential fits. This figure is reproduced from ref.[82].

FIG. 27. Velocity plot for the “non-evaporation-residue” components of the $^{18}$O+$^{11}$B reaction at 63 MeV. The circles, centered at the center-of-mass velocity, describe the loci for products with constant $Q$ values. This figure is reproduced from ref.[31].

FIG. 28. Excitation functions for the average total kinetic energies of the indicated systems and charge channels. The lines are based on barrier calculations assuming spherical fragments. This figure is reproduced from ref.[31].

FIG. 29. Fission cross section excitation functions for the indicated systems and charge channels. The three systems populate the common $^{28}$Al compound system. The dashed curves show the predicted cross sections based on the transition-state model of fission. This figure is reproduced from ref.[31].

FIG. 30. Ratio of carbon to boron yields as a function of excitation energy for three different entrance channels populating the common $^{28}$Al compound system. This figure is reproduced from ref.[31].

FIG. 31. Excitation functions for the Z=6 channel of the $^{24}$Mg+$^{12}$C orbiting component at 5 different 1 MeV large $Q$-value windows around a) -12 MeV, b) -13 MeV, c) -14 MeV and d) -15 MeV [87].
FIG. 32. Ratio of the oxygen to carbon cross sections as a function of excitation energy for the $^{28}\text{Si}(E_{\text{lab}}=115 \text{ MeV})+^{12}\text{C}$ and $^{24}\text{Mg}(E_{\text{lab}}=79.5)+^{16}\text{O}$ reactions [26]. The solid line shows the expected ratio for both systems based on the transition-state model [96].

FIG. 33. Angular dependence of the average TKE values measured in the $^{35}\text{Cl}+^{12}\text{C}$ at $E_{\text{lab}}=180 \text{ MeV}$ and 200 MeV. This figure is reproduced from ref.[30].

FIG. 34. Ratio of oxygen to carbon yields for entrance channels populating the common $^{47}\text{V}$ compound nucleus. The top panel shows the ratios for two reactions populating the compound nucleus at an excitation energy of $E_{\text{CN}}^*=59.0 \text{ MeV}$. The reactions shown in the bottom panel populate the compound nucleus at $E_{\text{CN}}^*=64.1 \text{ MeV}$. The dotted lines indicate the predicted ratios based on the transition-state model calculations. The figure is from ref.[60].

FIG. 35. The $^{24}\text{Mg}+^{24}\text{Mg}$ energy spectra for the $^{36}\text{Ar}+^{12}\text{C}$, $^{20}\text{Ne}+^{28}\text{Si}$, and $^{24}\text{Mg}+^{24}\text{Mg}$ reactions at $E_{\text{lab}}=187.7 \text{ MeV}$, 78.0 MeV, and 88.8 MeV, respectively. Spectra derived from experiment are indicated by the thick-line histograms. Spectra obtained from the transition-state model calculation using the saddle-point method are indicated by the thin-line histograms. The vertical lines in (d) mark the mutual excitations below 18 MeV involving the ground-state rotation band and all yrast states, respectively.

FIG. 36. (a) Experimental and (b) calculated $\gamma$-ray spectra for the $^{24}\text{Mg}(^{32}\text{S},^{28}\text{Si})^{28}\text{Si}$ reaction at $E_{\text{c.m.}}$ with $7.6 \text{ MeV} \leq E_x \leq 16.7 \text{ MeV}$. A smooth background has been subtracted from the experimental yields for this comparison. The figure is from ref.[49].

FIG. 37. Same as previous figure but with an expanded scale. The figure is from ref.[49].

FIG. 38. Comparison of the predicted mass distributions using the transition-state model calculations (solid histograms) with the experimental results (open histograms) for the $^{32}\text{S}+^{24}\text{Mg}$ reaction at $E_{\text{lab}}=121 \text{ MeV}$ and 142 MeV. The figure is from ref.[45].
FIG. 39. Differential center-of-mass cross sections (points) as a function of fragment mass for the (a) $^{40}\text{Ca} + ^{40}\text{Ca}$ reaction at $E_{\text{lab}} = 197$ MeV and $\theta_{\text{lab}} = 20^\circ$ [121] and the (b) $^{28}\text{Si} + ^{50}\text{Ca}$ reaction at $E_{\text{lab}} = 150$ MeV and $\theta_{\text{lab}} = 30^\circ$ [122]. The figure is from ref.[39].