I. INTRODUCTION

The time scale of the fission process has been previously addressed using a number of experimental techniques. The largest number of studies have been performed with the “neutron-clock” technique [1] which comprises measurements of the multiplicity of neutrons evaporated by the decaying nucleus before scission occurs. Such measured multiplicities are usually coupled with statistical-model calculations to give a time for fission. Other precission emissions such as light charged particles and giant-dipole-resonance γ rays can be substituted for the neutrons. All of these techniques rely on the accuracy of the statistical-model calculations to give a time for fission. Other prescission multiplicities are usually coupled with statistical-model calculations incorporating simple aspects of the dynamics have enabled us to determine the ranges of fission lifetimes and the contribution of fast fission at different compound-nucleus excitation energies.

Fission lifetime studies are performed using the “neutron-clock” technique associated with statistical and dynamical model calculations. In this framework we have undertaken, at the Louvain-la-Neuve cyclotron facility, the study of 20Ne+159Tb and 20Ne+169Tm induced fission reactions between $E/A = 8$ and 16 MeV. In this work we have determined (a) fusion-evaporation and fusion-fission cross sections; (b) the precission and postscission multiplicities of evaporated light particle (neutron, proton, and alpha) and their energy and angular distributions, and (c) the total energy balance of fission process after taking into account preequilibrium or incomplete-fusion processes. The comparison of the experimental data, multiplicities, and cross sections, with the statistical-model calculations incorporating simple aspects of the dynamics has enabled us to determine the relationship of these extra dynamical times to the total fission time, which also contains contributions from stochastical processes, is complex.

In principle, more direct time scale measurements can be obtained with the crystal blocking technique using a single crystal. The sensitivity of this technique is limited by the velocity of the fissioning system. Early measurements reported a significant tail to the fission time distribution at times greater than 30000 zs [2] for fission induced by the 19F+181Ta fusion reaction. More recent measurement for the $E/A = 24$ MeV $^{238}$U+$^{28}$Si reaction found mean fission lifetimes to be greater than 100 zs for excitation energies up to 250 MeV [3]. The importance of fission events with long time scales ($>1000$ zs) has also been confirmed using $K$ x rays to time the fission of target and projectile-like fragments in the reaction $E/A = 7.5$ MeV $^{238}$U+$^{238}$U [4].

In view of the large range of fission time scales obtained from the different techniques, one must understand exactly what time is being measured by each method and attempt to obtain a global picture of the fission time distribution from all techniques. To this end, this paper will concentrate on the neutron-clock method using recent data obtained from the neutron multidetector DEMON [5]. As one applies the neutron-clock technique using the statistical model to treat the evaporation, it is important to determine the initial excitation energy and spin distributions of the fissioning nuclei.

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For bombarding energies above $E/A = 10$ MeV, preequilibrium (PE) emissions of light particles are expected to remove excitation energy and angular momentum, making it important to perform extensive studies of the evaporation residues and fission fragments to infer these initial quantities. Also at high bombarding energies, even for relatively asymmetric reactions, the maximum spin of the fused system can be quite large, possibly larger than the value $J_{B,F} = 0$ at which the fission barrier vanishes. For such cases, a compound nucleus (CN) will not be formed and the fast-fission mechanism will be observed [6]. To determine the extent of CN fission, the magnitude, if any, of fast fission in the reaction needs to be estimated.

In this paper, we report the results of an extensive set of measurements on the properties of evaporation residues and fission fragments formed in fusionlike reactions of $^{20}$Ne + $^{159}$Tb and $^{20}$Ne + $^{169}$Tm from $E/A = 8$ to 16 MeV. The magnitude of the preequilibrium emission is inferred from the fission-fragment folding angles and the evaporation residue (ER) velocity distributions. From the total fusion cross section, determined from the sum of the fission and ER yields, the maximum $\ell$ waves contributing to fusionlike processes are estimated. With estimates of the angular momentum fraction removed by PE emissions, the intrinsic angular momentum of the composite system is determined and compared to the value where the fission barrier is predicted to vanish in order to explore the possible presence of fast fission.

Prescission and postscission multiplicities of neutrons and light charged particles in coincidence with fission fragments are extracted from the kinetic-energy spectra and their angular distributions using simulations which assume contributions from up to four moving sources. Statistical-model analyses are performed to estimate the dynamical times for fission, both statistical and fast fission and the total fission time scales. The details of the experimental apparatus are described in Sec. II while the results of the experimental measurements are presented in Sec. III. Section IV discusses the analysis of the data including the estimation of fission time scales and the conclusion of this work is contained in Sec. V.

II. EXPERIMENTAL METHOD

Beams of $^{20}$Ne projectiles, extracted from the CYCLONE accelerator at Louvain-la-Neuve, were used to bombard self-supporting $^{159}$Tb and $^{169}$Tm foils of thickness 250 ± 8 $\mu g/cm^2$. Measurements were performed at the bombarding energies of $E/A =$ 8, 10, 13, and 16 MeV. A schematic view of the detection apparatus is shown in Fig. 1. The target was located in the center of a 4-mm-thick Al scattering chamber of 160 cm diameter. The target holder was set to a potential of +18 kV to suppress secondary electron emission. Evaporation residues and fission fragments were detected in two 300-$\mu m$, 600-mm$^2$ Si counters (GJ1 and GJ2). These were placed at forward angles on either side of the beam axis and were moved during the experiment to sample the angular region $8^\circ < \theta_{lab} < 20^\circ$. Secondary electrons liberated during the passage of incident particles through the Au surface layer (500 $\AA$) of each Si detector were accelerated by a 4 kV potential into double-microchannel-plate assemblies mounted in the chevron configuration [7]. Timing signals from these assemblies were used to measure the time of flight of detected particles over their 57 cm flight path from the target with a resolution of 700 ps full width half maximum (FWHM). Energy calibrations of the Si counters were obtained from beams of $^{20}$Ne and $\alpha$ particles elastically scattered off a Au target. For heavy fragments, the energy was corrected for the pulse-height deficit using the formalism of Kaufman et al. [8] fitted to the measured spectra of $^{252}$Cf.

FIG. 1. (Color) Schematic view of the experimental apparatus showing the location of the detectors in the scattering chamber (see text for details).
fission fragments. Particle identification was achieved from energy and time-of-flight information. An example of a bidimensional plot of these two quantities is displayed in Fig. 2. The evaporation residues and fission fragments are well separated from the other reaction products (elastic, quasielastic, and deep inelastic scattering).

Coincident fission fragments were detected in two 20 × 20 cm², X and Y position sensitive, multiwire proportional gas counters (MWPC1 and MWPC2). The counters were filled with a continuous flow of isobutane gas at a constant pressure of 7.5 torr. The emission angles of detected fragments were determined to ±0.4° in both θ and φ, while each counter subtended ±20° in the two directions. The times of flight of detected fragments were measured over the 29.5 cm flight path from the target with a resolution of 500 ps FWHM. The two MWPCs were arranged symmetrically on either side of the beam axis. Their angular positions were adjusted for each beam energy to optimize the coincidence rate and to cover the entire fission-fragment mass distribution, i.e., their central angles varied from 70° to 60° with increasing beam energy. Absolute cross sections were determined from the beam charge collected in the Faraday cup that was held at a potential of −1 kV to suppress secondary electron emission. Two 3-cm-thick CsI counters (CsI1 and CsI2), read by photodiodes, were mounted at θ_{lab} = ±4.1° at 66 cm from the target to detect elastically scattered beam particles. They were used to continuously monitor the beam intensity and its alignment.

Neutrons emitted in coincidence with the fission fragments were detected in the 96 DEMON counters [5]. Each detector, consisting of an active volume of 16 cm diameter by 20 cm thickness, is filled with NE213 liquid scintillator. The detectors were mounted outside the scattering chamber at a distance of 185 cm from the target and were arranged in a 4π geometry as shown in Fig. 3. To minimize the neutron background, the scattering chamber was located at a distance of 5 m above the ground and the beam was stopped in a heavily shielded Faraday cup positioned 6 m from the target. The DEMON detectors were supported by the light-weight Al structure shown in Fig. 3. Separation of detected neutrons and γ rays and the determination of the neutron detection efficiency as a function of energy and detector threshold are discussed in great detail in Ref. [5].

Light charged particles emitted in coincidence with the fission fragments were detected in six triple-Si telescopes (T1–T6). Each telescope consisted of a 85-μm-thick Si front element followed by two 706-μm-thick Si elements. The telescopes were positioned at 19.5 cm from the target at angles of ±115°, ±140°, and ±165° from the beam axis. Excellent particle identification was achieved from the energy-deposition and the energy-loss measurements. Protons, deuterons, tritons, and α particles were well resolved. Only proton and α-particle data will be presented in the remainder of this report as there were very few deuterons and tritons in coincidence with the fission fragments.

III. RESULTS

A. Evaporation residue and fission cross sections

Following Ref. [9], the distribution of residue velocities about the CN recoil velocity V_{CN} is assumed to be Gaussian. In the laboratory reference frame, the distribution is thus

![Color plot of measured energy vs time of flight for heavy fragments detected in the GI counters at θ_{lab} = 9° in 20Ne + 169Tm reaction at E/A = 16 MeV. The locations of the evaporation residues (ER), the fission fragments (Fission), the elastically scattered 20Ne projectiles (ES), and the deep inelastic collisions (DIC) are indicated.](image-url)
where $\sigma_{\text{ER}}$ is the total ER cross section, $S$ is the width of the distribution, and $\theta$ is the recoil angle from the beam axis. The parameters $\sigma_{\text{ER}}, S, V_{\text{CN}}$ were adjusted to obtain the best fits to $\theta_{\text{lab}} = 8^\circ$ data detected with the counters GJ1 and GJ2. Examples of these fits are shown in Fig. 4 for the four reactions on the $^{159}$Tb target. The fitted values of $\sigma_{\text{ER}}$ and $V_{\text{CN}}$ are listed in Tables I and II, respectively. At the lowest bombarding energy, $V_{\text{CN}}$ is consistent with the reaction center-of-mass velocity $V_{\text{c.m.}}$ and thus with complete fusion, but the ratio $V_{\text{CN}}/V_{\text{c.m.}}$ steadily decreases as the bombarding energy is raised, consistent with an increased contribution from incomplete fusion and/or preequilibrium emissions. These experimental velocities are in excellent agreement with the systematics of linear-momentum transfer compiled in Ref. [10].

The mass $M_F$ of a fission fragment detected in the forward counters GJ1 and GJ2 was determined from the measured velocity and kinetic energy. The mean masses $M_F^{\text{exp}}$ (secondary after evaporation) of the measured distributions are listed in Table III. The reaction center-of-mass angular distributions were fitted with the form [13,14]

$$
\frac{d\sigma_F}{d\Omega_{\text{c.m.}}} = \frac{1}{\pi^2 \sin \theta_{\text{c.m.}}} \sigma_F.
$$

where $\sigma_F$ is the total fission cross section and $\theta_{\text{c.m.}}$ is the center-of-mass emission angle of the fragment. This angular
distribution is appropriate for fission of compound nuclei with large angular momentum with $\theta_{\text{c.m.}} \gg 0^\circ$ and $\theta_{\text{c.m.}} \ll 180^\circ$. An example of one of the fits is shown in Fig. 5. The fitted fission cross sections $\sigma_F$ and the sums $\sigma_{\text{ER}} + \sigma_F$, giving the total fusion cross sections $\sigma_{\text{FU}}$, are listed in Table I as a function of the complete-fusion excitation energy $E^*$. The corresponding critical angular momenta have been calculated assuming the sharp cutoff approximation, i.e., $\sigma_{\text{FU}} = \pi \lambda^2 (\ell_{\text{crit}} + 1)^2$. These are listed in Table I and are displayed in Fig. 6 where they are compared to predictions of the complete-fusion models of Wilcke and co-workers [16] and Bass [17] and from the HICOL code of Feldmeier [18]. At the larger bombarding energies, the experimental values of $\ell_{\text{crit}}$ are much larger than these complete-fusion estimates suggesting the possible presence of another reaction mechanism. The values of the ratio $\sigma_{\text{ER}} / \sigma_F$ are also listed in Table I.

Coincident fission fragments detected in the MWPCs were only analyzed when the detected fragment in the MWPC1 was located within $\pm 5^\circ$ both in and out of the reaction plane of the central angle. With this constraint, the complementary fragment detected in MWPC2 is unbiased by that counter’s angular acceptance. From the measured velocity vectors of the two fragments, the mass of each fragment and the total kinetic energy $TKE$ released in fission in the center-of-mass frame can be reconstructed with the assumption that the total momentum in this frame is zero and with an assumed total mass $M_{\text{sc}}$ at scission. This mass is estimated from the multiplicities of coincident neutrons, protons, and $\alpha$ particles (see Sec. IV B). These assumed values of $M_{\text{sc}}$ and the mean total kinetic energies $TKE$ for symmetric mass partition ($\pm 5$ nucleons) are listed in Table III. These $TKE$ values are primary, before postscission evaporation from the fission fragments. This is because the fragment velocities are not affected, on average, by the recoil kicks from these evaporated particles. The deduced $TKE$ values are consistent with the systematics of Viola [15] ($TKE^{\text{Viola}}$ in Table III) to within at most 9 MeV.

The distributions of fission-fragment folding angles $\theta_{12}$ $= \phi_1 + \phi_2$ (sum of the polar angles of the two fragments in laboratory frame) for $|\phi_1 - \phi_2| = 180^\circ \pm 5^\circ$ are shown in Figs. 7 and 8 for both targets. In Fig. 7 the experimental distributions are each fitted with a single Gaussian component indicated by the curves. The folding angle is related to the CN velocity [19] by

$$\tan \left( \frac{\theta_{12}}{2} \right) = \frac{\sqrt{2TKE/M_{\text{sc}}}}{V_{\text{CN}}}. \quad (3)$$

Compound-nucleus velocities $V_{\text{CN}}$ were determined from this equation using the fitted centroids of the $\theta_{12}$ distributions and the mean $TKE$ values of Table III. The ratios $V_{\text{CN}}/V_{\text{c.m.}}$ extracted from this analysis are listed in Table II and compared to the CN velocities obtained from the evaporation-residue velocity distributions. The $V_{\text{CN}}$ values obtained from the ER and fission data need not be identical as these reaction products are expected to be associated with different...
TABLE I. Evolution of evaporation residue $\sigma_{ER}$, fission $\sigma_F$, and total fusion $\sigma_{FU}$ cross sections as functions of the complete-fusion excitation energy $E^\ast$. Also shown are the evaporation and fission cross-section ratios and corresponding critical angular momenta $\ell_{crit}$ derived from the fusion cross sections assuming the sharp cutoff approximation.

<table>
<thead>
<tr>
<th>$E^\ast$ (MeV)</th>
<th>$\sigma_{ER}$ (mb)</th>
<th>$\sigma_F$ (mb)</th>
<th>$\sigma_{FU}$ (mb)</th>
<th>$\sigma_{ER}/\sigma_F$</th>
<th>$\ell_{crit}$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>711±46</td>
<td>641±25</td>
<td>1352±72</td>
<td>1.11±0.08</td>
<td>72±2</td>
</tr>
<tr>
<td>148</td>
<td>743±48</td>
<td>838±38</td>
<td>1581±86</td>
<td>0.89±0.07</td>
<td>87±2</td>
</tr>
<tr>
<td>201</td>
<td>796±45</td>
<td>804±35</td>
<td>1600±80</td>
<td>0.99±0.07</td>
<td>100±2</td>
</tr>
<tr>
<td>254</td>
<td>924±53</td>
<td>759±38</td>
<td>1683±91</td>
<td>1.22±0.09</td>
<td>114±3</td>
</tr>
<tr>
<td>108</td>
<td>351±59</td>
<td>1070±41</td>
<td>1421±100</td>
<td>0.33±0.06</td>
<td>74±3</td>
</tr>
<tr>
<td>144</td>
<td>359±31</td>
<td>1230±54</td>
<td>1589±85</td>
<td>0.29±0.03</td>
<td>88±2</td>
</tr>
<tr>
<td>196</td>
<td>414±25</td>
<td>1210±49</td>
<td>1624±74</td>
<td>0.34±0.02</td>
<td>101±2</td>
</tr>
<tr>
<td>251</td>
<td>478±20</td>
<td>1160±54</td>
<td>1638±74</td>
<td>0.41±0.03</td>
<td>113±3</td>
</tr>
</tbody>
</table>

TABLE II. For each complete-fusion excitation energy $E^\ast$ are listed the experimental mean velocity $V_{CN}$ of the compound nucleus extracted from the ER velocity distributions (ER) and from the fission-fragment folding-angle distributions (fission). The velocity is expressed relative to the reaction center-of-mass velocity $V_{c.m.}$ which is the corresponding complete-fusion value. Also listed are values for the quantity $\xi$ from Ref. [11] giving the ratios of the mean velocity of PE particles to the projectile velocity. The initial CN masses $M_{CN}^{PE}$ from the PE systematics are also listed. In the last two columns are listed the maximum intrinsic angular momenta $J_{\ell=0}$ at which the fission barriers are predicted to vanish in the calculations of Sierk [12].

<table>
<thead>
<tr>
<th>$E^\ast$ (MeV)</th>
<th>$V_{CN}/V_{c.m.}$ ER</th>
<th>$V_{CN}/V_{c.m.}$ fission</th>
<th>$\xi$</th>
<th>$M_{CN}^{PE}$</th>
<th>$J_{\ell=0}^{PE}$ (h)</th>
<th>$J_{\ell=0}^{\ast}$ (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>1.00±0.01</td>
<td>0.97±0.03</td>
<td>0.22±0.21</td>
<td>178±0.3</td>
<td>72</td>
<td>78</td>
</tr>
<tr>
<td>148</td>
<td>0.97±0.02</td>
<td>0.96±0.03</td>
<td>0.61±0.14</td>
<td>178±0.2</td>
<td>84</td>
<td>78</td>
</tr>
<tr>
<td>201</td>
<td>0.94±0.02</td>
<td>0.92±0.02</td>
<td>0.72±0.08</td>
<td>177±0.1</td>
<td>93</td>
<td>78</td>
</tr>
<tr>
<td>254</td>
<td>0.89±0.02</td>
<td>0.89±0.01</td>
<td>0.77±0.05</td>
<td>176±0.2</td>
<td>99</td>
<td>78</td>
</tr>
<tr>
<td>108</td>
<td>1.00±0.01</td>
<td>1.00±0.03</td>
<td>0.11±0.42</td>
<td>188±0.3</td>
<td>74</td>
<td>77</td>
</tr>
<tr>
<td>144</td>
<td>1.00±0.02</td>
<td>0.95±0.03</td>
<td>0.16±0.29</td>
<td>188±0.2</td>
<td>87</td>
<td>77</td>
</tr>
<tr>
<td>197</td>
<td>0.94±0.02</td>
<td>0.91±0.02</td>
<td>0.62±0.13</td>
<td>187±0.1</td>
<td>95</td>
<td>77</td>
</tr>
<tr>
<td>251</td>
<td>0.90±0.02</td>
<td>0.88±0.02</td>
<td>0.69±0.09</td>
<td>186±0.2</td>
<td>100</td>
<td>77</td>
</tr>
</tbody>
</table>

distributions of impact parameter and $\ell$ wave. However, they are consistent with each other, within the experimental uncertainties, for all the reactions studied in this work.

The distributions of fission-fragment folding angles were also analyzed following the method of Ref. [20] where the fusionlike yield is composed of both complete-fusion and incomplete-fusion components, but the incomplete-fusion component is associated purely with a single $\alpha$-particle ejectile from the $^{20}$Ne projectile in the massive transfer description. In this method, folding-angle distributions are fitted by the sum of two Gaussian components; one component for complete fusion with the centroid fixed at the value appropriate for complete fusion $V_{CN}=V_{c.m.}$ and the second Gaussian component with the same width, but a centroid appropriate for the complete fusion of an $^{16}$O projectile at the same $E/A$. Examples of such fits for the $^{20}$Ne+$^{159}$Tm reactions are displayed in Fig. 8. The quality of the fits is inferior to that obtained with a single Gaussian component in Fig. 7 especially in the intermediate region between the two centroids where the fitted yield falls significantly below the experimental data. This implies that incomplete fusion is more complex than a single $\alpha$-particle ejectile. Thus, there must also be fusionlike reactions with one, two, and three nucleons from the projectile that are missing from the final CN. Including these processes will allow for increased yield in this intermediate region and a better agreement with the experimental data. Similar conclusions were also deduced from the $^{20}$Ne+$^{159}$Tb data.

Fission cross sections were also obtained from the MWPC. They are consistent with, but not considered as accurate as, those in Table I due to the uncertainties in establishing the experimental MWPC intrinsic detection efficiency ($\sim 80\%$ on average) over the entire fission-fragment mass distribution.
TABLE III. Mean fission-fragment masses $M_F^{\exp}$ (in nucleons) measured with the GJ1 and GJ2 counters are listed for each bombarding energy $E/A$ and target. These masses are secondary after the evaporation from the fission fragments. Also listed are the assumed masses of fissioning nucleus, $M_{sc}$, in nucleons and the mean total kinetic energy $TKE$ in MeV released in symmetric fission extracted from coincident fission fragments. These are compared to the values from the Viola systematics [15].

<table>
<thead>
<tr>
<th>$E/A$ (MeV)</th>
<th>$M_F^{\exp}$</th>
<th>$M_{sc}$</th>
<th>$TKE$ (MeV)</th>
<th>TKE$^{\exp}$viola (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>$^{20}\text{Ne}+^{159}\text{Tb}$</td>
<td>83.6±5</td>
<td>174.4</td>
<td>125±0.1</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>82.4±5</td>
<td>172.1</td>
<td>136±0.1</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>85.2±5</td>
<td>168.8</td>
<td>126±0.1</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>83.6±5</td>
<td>165.7</td>
<td>121±0.1</td>
</tr>
<tr>
<td>20</td>
<td>$^{20}\text{Ne}+^{169}\text{Tm}$</td>
<td>89.0±5</td>
<td>184.8</td>
<td>129±0.1</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>86.5±5</td>
<td>182.3</td>
<td>146±0.1</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>86.5±5</td>
<td>178.4</td>
<td>142±0.1</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>83.5±5</td>
<td>175.5</td>
<td>138±0.1</td>
</tr>
</tbody>
</table>

B. Neutron multiplicities

Neutrons detected in coincidence with fission fragments are assumed to originate from 4 moving sources. In temporal order, first there are the preequilibrium neutrons with multiplicity $\nu_n^{\text{pe}}$, second are the prescission neutrons evaporated from the compound system before scission ($\nu_n^{\text{pre}}$), and last are postscission neutrons evaporated from the two fission fragments $\nu_n^{\text{F1}}$ and $\nu_n^{\text{F2}}$. The energy spectra of each of these sources are assumed to be thermal-like in their respective reference frames. Based on statistical-model simulations (Sec. IV D), the first-chance emission spectra of neutrons from a compound nucleus are well described by Maxwellian distributions:

$$
\frac{d^2\nu_n}{d\Omega_n dE_n} = \frac{\nu_n}{4\pi T^2} E_n \exp \left(-\frac{E_n}{T}\right),
$$

(4)

where $T$ is the effective nuclear temperature of the emitting source while the solid angle $\Omega_n$ and neutron energy $E_n$ are in the source reference frame. Emissions with this distribution function are often called surface emission. Prescission evaporation from the compound nucleus involves emissions from a number of evaporation steps, but does not contain the very low energy neutrons associated from last-chance decay of a CN just before the excitation energy is exhausted. In statistical-model simulations, these distributions can also be well reproduced by the surface-emission expression [Eq. (4)]. However, the spectra for neutrons emitted from the fission fragments do contain these low-energy last-chance emissions and cannot be fitted with Eq. (4). From many simulations, these spectra were found to be more consistent with a Watt distribution or volume emission spectrum;

$$
\frac{d^2\nu_n}{d\Omega_n dE_n} = \frac{\nu_n}{2(\pi T)^{3/2}} \sqrt{E_n} \exp \left(-\frac{E_n}{T}\right),
$$

(5)

FIG. 5. Measured (data points) and fitted (curve) fission-fragment angular distribution in the reaction center-of-mass frame for the $E/A = 13$ MeV $^{20}\text{Ne}+^{159}\text{Tb}$ reaction. The data were fitted with a $1/\sin \theta_{cm}$ dependence.

FIG. 6. (Color) Experimental data points show the dependence of the critical angular momentum for fusionlike reactions, $\ell_{crit}$, on the complete-fusion excitation energy. These are compared to the predictions of the complete-fusion models of Wilcke and co-workers [16] (solid curves) and Bass [17] (dashed curves). The circular points indicate the critical angular momenta at which a CN is formed in the dynamical code hicol [18].

Rosner et al. [21] came to similar conclusions concerning the shape of the precission and postscission neutron spectra for the $^{38}\text{Ar}+^{169}\text{Tm}$ reaction. Therefore as in Ref. [21], the precission source was assumed to be surface emission [Eq. (4)] and the fission-fragment sources were taken as volume emission [Eq. (5)]. The preequilibrium source was also assumed to exhibit volume emission with a source velocity of half the beam velocity as in Ref. [22]. Note, that in other studies there are a number of other assumptions concerning the shape of the precission and postscission sources; Refs. [20,23,24] assumed both sources are volume emission, while in Ref. [22] both sources are surface emission. Hinde et al. [25] have used sums of Maxwellian distributions for both sources to model the multiple-chance emissions and in Refs.
FIG. 7. Distributions of fission-fragment folding angles $\theta_{12}$ measured for the reactions on the Tb target using coincidence data from the MWPCs. The experimental distributions are displayed by the data points, while the thin solid curves indicate single-component Gaussian fits to these distributions. The vertical lines show the centroids of the Gaussian fits $\theta_{12}^{\text{exp}}$ and the expected mean values for complete fusion $\theta_{12}^{\text{CF}}$.

FIG. 8. (Color) Distributions of fission-fragment folding angles $\theta_{12}$ measured for the reactions on the Tm target. The experimental distributions are displayed by the data points, while the thick solid curves indicate fits to these distributions using the prescription of Ref. [20] consisting of the sum of two Gaussian components associated with complete fusion and incomplete fusion with a single $\alpha$-particle ejectile. The fixed centroids for each component are indicated as $\theta_{12}^{\text{CF}}$ and $\theta_{12}^{\text{CF-1\alpha}}$ and the two Gaussian components are plotted as the thin and dashed curves, respectively.
an iterative procedure which does not rely on assumed shapes for the prescission and postscission spectra was utilized.

To reduce the number of fitting parameters, only events associated with symmetric fission
\[ \text{symmetric mass partition} \]
were fitted, and thus \( T_{F1} = T_{F2} = T_{\text{post}} \) and \( n_{n F1} = n_{n F2} = n_{n \text{post}}/2 \). The neutron multiplicities associated with asymmetric fission have been analyzed
\[ \text{asymmetric mass partition} \]
and \( n_{n \text{pre}} \) and \( n_{n \text{post}} = (n_{n F1} + n_{n F2})/2 \) were not found to have a significant asymmetry dependence, while the individual \( n_{n F1} \) and \( n_{n F2} \) show approximately linear dependencies on the mass of the respective fission fragment as in Ref. [22]

The velocities of the two fission-fragment sources were fixed to the mean fission-fragment velocities measured with MWPC1 and MWPC2 for symmetric mass partition while the CN prescission source was fixed to the value \( V_{\text{CN}} \) from Table II obtained from the residue velocity distributions. Examples of some of the many fitted spectra and angular distributions (both in and out of the reaction plane defined by \( \phi_n = 0^\circ \) and \( 180^\circ \)) are shown in Figs. 9 and 10 for the \( E/A = 13 \text{ MeV} \) reaction on the \(^{159}\text{Tb}\) target. The spectra in Figs. 9(a) and 9(b) are for DEMON detectors directly behind MWPC1 and MWPC2, respectively. Due to the kinematic focusing of the postscission neutrons by the fission fragments, these spectra are dominated by contributions from the respective fission fragments (F1 and F2). The preequilibrium component is constrained mostly from the most forward angle DEMON detectors at 12.5° in Fig. 9(c), and the fitted PE multiplicities \( n_{\text{PE}} \) are listed in Table IV. The spectra for DEMON detectors at backward angles, as in Fig. 9(d), have the largest contributions from the CN source. In Fig. 10, the simultaneous fit to all of the experimental angular distributions both in, and at a number of \( \phi \) angles to, the reaction plane is extremely good, indicating the data are well described by these four moving sources.

The fitted prescission and postscission multiplicities and temperatures from each source are listed in Table IV for symmetric mass partition. The extracted multiplicities do depend on the assumed spectral shapes for the different sources. For example, if volume emission is assumed for the prescission and postscission sources, as in Refs. [20,23], the fits to the kinetic-energy spectra and angular distributions are

\[ \text{FIG. 9. (Color) Examples of some of the multiple-moving-source fits (curves) to experimental neutron kinetic-energy spectra in the laboratory frame for the \( E/A = 13 \text{ MeV} \) \( ^{20}\text{Ne} + ^{159}\text{Tb} \) reaction. The thick solid curves TOT indicate the total contributions from all sources. The contributions from each of the sources are indicated by the labeled curves; CN represents contribution from the prescission CN source, F1 and F2 from the two fission fragments, and PE from preequilibrium emission.} \]

\[ \text{FIG. 10. (Color) Examples of some of the multiple-moving-source fits (curves) to experimental neutron } \theta_n \text{ distributions in the laboratory frame for the \( E/A = 13 \text{ MeV} \) \( ^{20}\text{Ne} + ^{159}\text{Tb} \) reaction. Distributions both in (\( \phi_n = 0^\circ,180^\circ \)) and others at different } \phi_n \text{ angles to the reaction plane are shown. The curves have the same meaning as in Fig. 9 and the fits correspond to the same set of fitted parameters (\( \nu^*, T^* \)) as those in Fig. 9.} \]
TABLE IV. The prescission and postscission neutron multiplicities $n_{pre}$ and $n_{post}$ and corresponding nuclear temperatures $T_{pre}$ and $T_{post}$ deduced from a multiple-moving-source–type analysis of symmetric fission data obtained from the two reactions studied in this work. The experimentally extracted preequilibrium multiplicities $n_{PE}$ are also listed as a function of the complete-fusion excitation energies $E^*$ and compared (in the last column) to $n_{PE}^{sys}$, the estimated PE multiplicities from the systematics of Refs. [20,22,32–34] (see Sec. IV A).

<table>
<thead>
<tr>
<th>$E^*$ (MeV)</th>
<th>$n_{pre}$</th>
<th>$n_{post}/2$</th>
<th>$T_{pre}$ (MeV)</th>
<th>$T_{post}$ (MeV)</th>
<th>$n_{PE}$</th>
<th>$n_{PE}^{sys}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>3.53 ± 0.17</td>
<td>1.96 ± 0.11</td>
<td>1.38 ± 0.07</td>
<td>1.31 ± 0.07</td>
<td>0.23 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>148</td>
<td>4.83 ± 0.09</td>
<td>1.84 ± 0.07</td>
<td>1.75 ± 0.02</td>
<td>1.30 ± 0.04</td>
<td>0.34 ± 0.03</td>
<td></td>
</tr>
<tr>
<td>201</td>
<td>5.91 ± 0.16</td>
<td>2.29 ± 0.12</td>
<td>2.04 ± 0.04</td>
<td>1.41 ± 0.06</td>
<td>0.49 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>254</td>
<td>7.08 ± 0.22</td>
<td>2.51 ± 0.16</td>
<td>2.25 ± 0.07</td>
<td>1.38 ± 0.08</td>
<td>0.88 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>169 Tm</td>
<td>3.22 ± 0.16</td>
<td>2.43 ± 0.10</td>
<td>1.33 ± 0.07</td>
<td>1.35 ± 0.03</td>
<td>0.23 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>108</td>
<td>4.66 ± 0.08</td>
<td>2.22 ± 0.06</td>
<td>1.66 ± 0.02</td>
<td>1.34 ± 0.03</td>
<td>0.32 ± 0.19</td>
<td></td>
</tr>
<tr>
<td>197</td>
<td>6.20 ± 0.13</td>
<td>2.34 ± 0.09</td>
<td>1.93 ± 0.02</td>
<td>1.44 ± 0.05</td>
<td>0.60 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>251</td>
<td>7.08 ± 0.15</td>
<td>2.50 ± 0.10</td>
<td>2.11 ± 0.03</td>
<td>1.46 ± 0.05</td>
<td>0.78 ± 0.04</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 11. Evolution with complete-fusion excitation energy $E^*$ of prescission and postscission neutron multiplicities and the effective nuclear temperatures extracted from the multiple-moving-source fits to the neutron data. Multiplicities are shown for the two targets of this work and for the similar $^{19}$F induced reactions of Ref. [28]. Broken lines are to guide the eye.

of similar quality and the fitted values of $n_{pre}$ are increased by approximately one neutron for all bombarding energies. The evolutions of the multiplicities and effective nuclear temperatures with complete-fusion excitation energy are shown in Fig. 11.

Also plotted in Fig. 11 are neutron multiplicities for the similar reactions $^{19}$F+$^{159}$Tb and $^{19}$F+$^{169}$Tm obtained by Newton et al. [28] using the iterative technique to extract the prescission and postscission multiplicities from the kinetic-energy spectra. These data are associated with lower excitation energies than those of this work, but they match up quite well with the multiplicities we have measured. Our results seem to agree quite well with the published data on $^{20}$Ne+$^{165}$Ho [20] and $^{20}$Ne+$^{168}$Er [25] reactions, considering the different methods of extracting the neutron multiplicities discussed previously. This gives us further confidence in our data and the extracted neutron multiplicities.

C. Charged-particle multiplicities

The $\alpha$ and proton prescission and postscission multiplicities were extracted from fits to the kinetic-energy spectra assuming contributions from three moving sources: one for CN emission and two for the fission fragments. Each source, in its respective moving frame, is described by a Coulomb-shifted Maxwellian spectrum:

$$\frac{d^2\nu_i}{d\Omega dE_s} = \frac{\nu_i}{4\pi T^2} (E_s - B_i) \exp \left( -\frac{E_s - B_i}{T} \right),$$

where $B_i$ is the effective Coulomb barrier. Preequilibrium charged-particle emission could not be experimentally observed in this work because the triple-Si telescopes were only positioned at backward angles. Because of the poor statistics of the data, the prescission nuclear temperatures were fixed to the maximum-allowed temperatures $T_{pre} = E^*/a$ (with $a = A_{CN}/9$ MeV$^{-1}$). For the postscission component, $T_{post}$ was fixed to the experimental value determined for postscission neutrons. Moreover, the effective emission barriers, initially taken from the systematics of Vaz and Alexander [35], had to be decreased by 2–3 MeV, for both prescission and postscission emission, in order to reproduce the experimental data. Such modifications were observed previously [36,37] and were justified by the deformation and the shape oscillations of the hot emitting nuclei. Examples of fitted spectra are shown in Fig. 12 for the $^{169}$Tm target. The
fitted multiplicities are presented in Table V and the evolution of these multiplicities with complete-fusion excitation energy $E^*$ is displayed in Fig. 13. One notable failure of these fits is for $\alpha$ particles at energies near 10 MeV indicated by the arrows in the Fig. 12. We suspect that the reason for this discrepancy is due to the presence of scission $\alpha$ particles emitted during the snapping of the neck at scission or evaporated from the neck region just before or after scission. They

FIG. 12. (Color) Examples of multiple-moving-source fits to the experimental proton and $\alpha$-particle kinetic-energy spectra in the laboratory frame obtained for the $^{20}\text{Ne} + ^{169}\text{Tm}$ reaction. The labeling of the curves is the same as in Fig. 9. The arrows indicate the region of the $\alpha$-particle spectra which cannot be fitted with the three assumed moving sources (see text for details).
TABLE V. Prescission and postscission multiplicities for protons and $\alpha$ particles extracted from multiple-moving-source fits to the measured kinetic-energy spectra are listed for the two reactions studied in this work. The complete-fusion excitation energies $E^*$ are also listed.

<table>
<thead>
<tr>
<th>$E^*$ (MeV)</th>
<th>$\nu_{p}^{\text{pre}}$</th>
<th>$\nu_{p}^{\text{post}/2}$</th>
<th>$\nu_{a}^{\text{pre}}$</th>
<th>$\nu_{a}^{\text{post}/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>0.010$\pm$0.055</td>
<td>0.040$\pm$0.027</td>
<td>0.065$\pm$0.031</td>
<td>0.024$\pm$0.017</td>
</tr>
<tr>
<td>148</td>
<td>0.219$\pm$0.030</td>
<td>0.061$\pm$0.015</td>
<td>0.205$\pm$0.018</td>
<td>0.010$\pm$0.006</td>
</tr>
<tr>
<td>201</td>
<td>0.514$\pm$0.055</td>
<td>0.166$\pm$0.027</td>
<td>0.422$\pm$0.041</td>
<td>0.034$\pm$0.015</td>
</tr>
<tr>
<td>254</td>
<td>0.636$\pm$0.063</td>
<td>0.257$\pm$0.032</td>
<td>0.555$\pm$0.068</td>
<td>0.091$\pm$0.028</td>
</tr>
<tr>
<td>108</td>
<td>0.080$\pm$0.009</td>
<td>0.034$\pm$0.007</td>
<td>0.060$\pm$0.008</td>
<td>0.023$\pm$0.005</td>
</tr>
<tr>
<td>144</td>
<td>0.188$\pm$0.008</td>
<td>0.105$\pm$0.004</td>
<td>0.204$\pm$0.006</td>
<td>0.049$\pm$0.003</td>
</tr>
<tr>
<td>197</td>
<td>0.508$\pm$0.018</td>
<td>0.191$\pm$0.009</td>
<td>0.449$\pm$0.015</td>
<td>0.097$\pm$0.007</td>
</tr>
<tr>
<td>251</td>
<td>0.640$\pm$0.020</td>
<td>0.200$\pm$0.009</td>
<td>0.591$\pm$0.020</td>
<td>0.103$\pm$0.009</td>
</tr>
</tbody>
</table>

have been observed in a number of detailed studies of charged particles accompanying fission [38,37] and are expected to be emitted approximately perpendicular to the fission axis. Our sensitivity to the magnitude of the postscission $\alpha$-particle multiplicity comes only from fitting the spectra in a small range of kinetic energy below the region for these scission particles, and thus can be quite sensitive to the assumed shape for this spectral component in the fits. The uncertainties, listed in Table V, are only the statistical uncertainties obtained from fitting the kinetic-energy spectra. Broken lines are to guide the eye.

FIG. 13. Evolution with complete-fusion excitation energy $E^*$ of the prescission and postscission proton and $\alpha$-particle multiplicities obtained from fitting the kinetic-energy spectra. Broken lines are to guide the eye.

be larger, but are difficult to estimate. These systematic uncertainties are much less of a problem for prescission $\alpha$-particle multiplicities as these particles dominate the fitted spectra at the larger $\alpha$ kinetic energies.

IV. DISCUSSION

A. Preequilibrium emission

For the three highest beam energies, the extracted compound-nucleus velocities in Table II are clearly smaller than the corresponding complete-fusion values indicating the occurrence of preequilibrium emission and/or incomplete fission. As statistical-model analyses of the fission data require a good knowledge of the spin and the initial excitation energy of the CN, it is important to estimate the magnitude of these PE emissions and to determine the angular momenta and excitation energies removed by these particles. As mentioned before, our experimental setup was not adapted for the measurement of the charged-particle contributions to PE emission. To estimate the magnitude of these components, we have used a second-order polynomial interpolation of PE multiplicity systematics of light particles obtained from Refs. [20,22,32–34]. To adjust these multiplicities to our experimental conditions, the reference multiplicities have been scaled by the ratio between our projectile mass and the projectile mass of the reference data. Figure 14 displays the evolution of these expected PE multiplicities as a function of the beam energy per nucleon for neutrons, protons, deuterons, tritons, and $\alpha$ particles. These multiplicities are identical for the two $^{20}$Ne beam induced reactions. Table VI shows the results of the polynomial interpolations for the reactions studied in this work. Note that PE emissions in these systematics are not dominated by $\alpha$ particles. This is consistent with our analysis of the fission-fragment folding-angle distributions in Sec. III A. One must compare the neutron multiplicities $\nu_{n}^{\text{PE (sys)}}$ of Table VI with the experimental values $\nu_{n}^{\text{PE}}$ extracted from the multiple-moving-source fits of the DEMON neutron spectra of Table IV in Sec. III B for the two studied reactions. The agreement between the two sets of
values is good. Total mass ($\Delta m$) and charge ($\Delta z$) losses by PE emission are then calculated as

$$\Delta m = 1 \nu_n^{PE} + 1 \nu_p^{PE} + 2 \nu_d^{PE} + 3 \nu_t^{PE} + 4 \nu_{\alpha}^{PE},$$

$$\Delta z = 1 \nu_n^{PE} + 1 \nu_p^{PE} + 1 \nu_d^{PE} + 2 \nu_{\alpha}^{PE}.$$  

$\Delta m$ and $\Delta z$ are listed in Table VI.

The CN mass after PE emission was expressed as $M_{in}^{PE} = M_{CN}^{PE} - \Delta m$ (Table II). The excitation energy of the CN is estimated using the formalism of Cerruti et al. [11]. The parameter $\xi = V_{PE}/V_p$, giving the ratio of the average velocity of PE emission to the projectile velocity, is obtained by solving Eq. (1) of Ref. [11]. The variation of this parameter with complete-fusion excitation energy is shown in Fig. 15. We have assumed the PE emissions are solely from the projectile ($\tau = 0$ in Ref. [11]) and the mean PE emission angle is zero. The CN excitation energies after PE emission, $E_{in}^{PE}$, deduced from this formalism will be plotted versus the complete-fusion values $E^*$ in Fig. 17. The difference between $E^*$ and $E_{in}^{PE}$ is of course the energy carried away by PE emission.

The intrinsic angular momentum of the CN is assumed to be $J = (\ell - \Delta \ell)$, where $\Delta \ell$ is the angular momentum removed by PE emission. It has been assumed that

\begin{equation}
\Delta \ell = \xi \ell \frac{\Delta m}{M_p},
\end{equation}

where $M_p$ is the initial projectile mass. If $\xi = 1$ ($V_{PE} = V_p$), the angular momentum removed by PE emission is the total initial orbital angular momentum scaled by the fraction of the projectile mass which does not fuse with the target. This is consistent with the simple incomplete-fusion picture where the portion of the projectile, which does not fuse, continues traveling forward with the projectile velocity. However, if this piece of the projectile is slowed down during the incomplete-fusion process, its angular momentum is reduced by the factor $\xi$. The maximum intrinsic angular momenta $J_{\ell_f}^{PE}$ deduced from the $\ell_{crit}$ values of Table I are listed in Table II and compared to the angular momenta $J_B = 0$ for which the fission barriers are predicted to vanish in the calculations of Sierk [12]. These values of $J_B = 0$ are thus exceeded in the fusionlike reactions at the highest bombarding energies. For those impact parameters which lead to $J > J_B = 0$, a compound nucleus cannot be formed as there is no pocket in the potential energy surface into which the system can become trapped. The composite system separates into two approximately equal fragments and the reaction mechanism is generally called “fast fission” as the scission time is expected to be faster than that for the statistical fission which has an important stochastic component. It is experimentally difficult to distinguish from conventional CN-fission reactions if the angular momentum cannot be inferred. Borderie et al. [39] have shown that fast-fission mass distributions are systematically wider than those measured for CN fission. Our data

\begin{table}[h]
\centering
\caption{Preequilibrium multiplicities of light particles ($n$, $p$, $d$, $t$, and $\alpha$) estimated from the systematics of Refs. [20,22,32–34] and the total mass ($\Delta m$) and charge ($\Delta z$) losses from these emissions at each beam energy.}
\begin{tabular}{cccccccc}
\hline
$E/A$ & $v_n^{PE}$(sys) & $v_p^{PE}$(sys) & $v_d^{PE}$(sys) & $v_t^{PE}$(sys) & $v_{\alpha}^{PE}$(sys) & $\Delta m$ & $\Delta z$ \\
\hline
8   & 0.23±0.15 & 0.00±0.03 & 0.00±0.02 & 0.00±0.01 & 0.11±0.02 & 0.67±0.32 & 0.22±0.10 \\
10  & 0.32±0.19 & 0.00±0.02 & 0.00±0.02 & 0.00±0.01 & 0.18±0.02 & 1.06±0.20 & 0.36±0.09 \\
13  & 0.58±0.23 & 0.19±0.01 & 0.07±0.01 & 0.04±0.01 & 0.28±0.01 & 2.06±0.14 & 0.86±0.05 \\
16  & 0.98±0.25 & 0.40±0.01 & 0.17±0.01 & 0.12±0.01 & 0.35±0.01 & 3.38±0.17 & 1.39±0.05 \\
\hline
\end{tabular}
\end{table}

FIG. 14. Evolution of the preequilibrium multiplicities of neutrals [$v_n^{PE}$(sys)] and light charged particles [$v_{\ell}^{PE}$(sys)] for proton, deuteron, triton, and $\alpha$, extracted from the systematics of Refs. [20,22,32–34] as a function of beam energy per nucleon. The curves represent a second-order polynomial interpolation to these systematics.

FIG. 15. Evolution with complete-fusion excitation energy $E^*$ of $\xi$ (the ratios of mean PE velocity to the projectile velocity) as determined for the two reactions studied in this work. $\xi$ is defined following the formalism of Ref. [11]. The lines are to guide the eye.

$$\Delta \ell = \xi \ell \frac{\Delta m}{M_p},$$

where $M_p$ is the initial projectile mass. If $\xi = 1$ ($V_{PE} = V_p$), the angular momentum removed by PE emission is the total initial orbital angular momentum scaled by the fraction of the projectile mass which does not fuse with the target. This is consistent with the simple incomplete-fusion picture where the portion of the projectile, which does not fuse, continues traveling forward with the projectile velocity. However, if this piece of the projectile is slowed down during the incomplete-fusion process, its angular momentum is reduced by the factor $\xi$. The maximum intrinsic angular momenta $J_{\ell_f}^{PE}$ deduced from the $\ell_{crit}$ values of Table I are listed in Table II and compared to the angular momenta $J_B = 0$ for which the fission barriers are predicted to vanish in the calculations of Sierk [12]. These values of $J_B = 0$ are thus exceeded in the fusionlike reactions at the highest bombarding energies. For those impact parameters which lead to $J > J_B = 0$, a compound nucleus cannot be formed as there is no pocket in the potential energy surface into which the system can become trapped. The composite system separates into two approximately equal fragments and the reaction mechanism is generally called “fast fission” as the scission time is expected to be faster than that for the statistical fission which has an important stochastic component. It is experimentally difficult to distinguish from conventional CN-fission reactions if the angular momentum cannot be inferred. Borderie et al. [39] have shown that fast-fission mass distributions are systematically wider than those measured for CN fission. Our data
from both targets show increased widths for the fission-fragment mass distributions at $E/A = 13$ and 16 MeV [29,30], consistent with the systematics of Borderie et al. and thus supporting the presence of fast fission in these reactions.

**B. Mass, charge, and energy balance**

Since the average energies and multiplicities of all the important evaporated particles have been measured, it is possible to reconstruct the excitation energies and masses of the systems formed in different stages of the CN decay. Not only does this allow us to observe the evolution of these quantities with beam energy, it also allows us to check the consistency of the data and see if the estimated initial excitation energies $E^\text{in}$ from the PE systematics are accurate. Let us start first with the mass balance. Using the estimated initial CN masses $M^\text{PE}$ in Sec. IV A, the total mass removed by the prescission, $n\ p$, and $\alpha$ evaporations (determined from the multiplicities listed in Tables IV and V) are subtracted giving the masses of the systems at scission ($M^\text{sc}$). The average mass of the primary fission fragment is half of this value. The final, secondary mass $M_F$ of a fragment is determined by removing the mass loss associated with postscission evaporation again using the multiplicities in Tables IV and V. The curves in Fig. 16 show the evolution of final, secondary mass $M_F$ of the fission fragments (for symmetric fission) with complete-fusion excitation energy $E^*$ for the two studied reactions. The mean values of $M_F$ were directly measured with the GJ1 and GJ2 counters (see Table III) and are indicated by the data points ($M^\text{exp}_F$) in this figure. The agreement between these measured values and the curves inferred by mass balance is extremely good. Using the experimental and predicted light charged particles multiplicities listed in Tables V and VI, a similar procedure was applied to infer the atomic numbers $Z$ of the fission fragments. For example, for the $^{20}\text{Ne} + ^{159}\text{Tb}$ experiment, these $Z_F$ (for symmetric fission) were, respectively, $37.5\pm 0.2$, $37.0\pm 0.3$, $36.5\pm 0.2$, and $36.0\pm 0.2$ for the different excitation energies $E^*$. Unfortunately, $Z^\text{exp}_F$ were not measured experimentally and could not be compared to their corresponding calculated values.

For energy balance, we proceed in a slightly different manner. First, we start with some initial estimate of the initial CN excitation energy $E^\text{in}$ and then remove the energy associated with prescission emission. This is comprised of two components; first is the $Q$-value $Q_1$ and the second is the total kinetic energy $E^\text{kpre}$ of these particles. The average kinetic energy for prescission neutrons is $2T^\text{kpre}$ (surface emis-
TABLE VII. For each complete-fusion excitation energy $E^*$ are listed, for the two studied reactions, the estimated initial CN excitation energies after preequilibrium emission $E^*_{in}$ from PE systematics, as discussed in Sec. IV A, and the results of the energy-balance calculations (see Sec. IV B for details). The initial excitation energy $E^*_{in}$ gives, at the end of the calculations, a residual energy $E^*_{res}$ equal to the energy carried away by $\gamma$-ray emission, $E_{\gamma}$. This latter energy was estimated from the systematics of Refs. [41,42].

<table>
<thead>
<tr>
<th></th>
<th>$E^*_{in}$ (MeV)</th>
<th>$E^*_{in}^{PE}$ (MeV)</th>
<th>$E^*_{in}^{pre}$ (MeV)</th>
<th>$Q_1$ (MeV)</th>
<th>$E^*_{sc}$ (MeV)</th>
<th>$E^*_{res}$ (MeV)</th>
<th>$Q_2$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{20}\text{Ne}+^{159}\text{Tb}$</td>
<td>112</td>
<td>103±3</td>
<td>97±8</td>
<td>12.2</td>
<td>28.9±0.8</td>
<td>56.1±2.4</td>
<td>8.9</td>
</tr>
<tr>
<td></td>
<td>148</td>
<td>133±1</td>
<td>135±4</td>
<td>23.8</td>
<td>40.4±0.4</td>
<td>70.3±1.5</td>
<td>8.4</td>
</tr>
<tr>
<td></td>
<td>201</td>
<td>173±3</td>
<td>170±8</td>
<td>40.3</td>
<td>49.8±1.9</td>
<td>80.1±4.2</td>
<td>12.8</td>
</tr>
<tr>
<td></td>
<td>254</td>
<td>207±6</td>
<td>203±9</td>
<td>53.8</td>
<td>59.5±1.0</td>
<td>89.9±4.4</td>
<td>16.0</td>
</tr>
<tr>
<td></td>
<td>108</td>
<td>99±3</td>
<td>89±8</td>
<td>10.8</td>
<td>26.9±0.8</td>
<td>51.7±2.4</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>144</td>
<td>132±1</td>
<td>134±4</td>
<td>22.4</td>
<td>39.1±0.4</td>
<td>72.2±1.5</td>
<td>11.8</td>
</tr>
<tr>
<td></td>
<td>197</td>
<td>172±3</td>
<td>174±8</td>
<td>42.1</td>
<td>50.4±1.9</td>
<td>82.1±4.2</td>
<td>15.6</td>
</tr>
<tr>
<td></td>
<td>251</td>
<td>211±6</td>
<td>201±9</td>
<td>54.2</td>
<td>58.0±1.0</td>
<td>89.2±4.4</td>
<td>16.9</td>
</tr>
</tbody>
</table>

The $Q$-values were calculated using the mass-deficit table of Ref. [40], with shell and pairing corrections removed for the heavy CN-like systems and experimental mass deficits for the light particles. This prescription was felt appropriate for calculating average $Q$-values as the shell and pairing corrections will vary greatly for each particular event, but are less important for the average. At this point we have determined the excitation energy at scission, $E^*_{sc}$. A second $Q$-value $Q_2$, associated with symmetric fission and the subsequent evaporation of the postscission particles, is now removed as is the kinetic energy of the particles including the average total kinetic energy release in fission, $\overline{TKE}$ (Table III), and the total kinetic energy of postscission particles, $E^*_{post}$. Note that in this step, as the postscission neutrons were fitted with volume-type emission, their average kinetic energy is $(3/2) T^*_{pre}$. The residual energy is thus $E^*_{res} = E^*_{post} - Q_2 - E^*_{k post}$. This residual energy is supposed to be removed by $\gamma$ ray emissions. The total energy of emitted $\gamma$ rays ($E_{\gamma}$) was estimated from the systematics of Refs. [41,42]. The initial excitation energy is then adjusted so as to make $E^*_{res} = E_{\gamma}$ in a second iteration of the energy balance. The initial excitation energies $E^*_{in}$ determined in this manner are compared in Table VII to the values $E^*_{in}^{PE}$ estimated from PE systematics as discussed in Sec. IV A. They are in excellent agreement. Thus both mass and energy balances are shown to provide excellent consistency with the data. The various excitation energies are listed in Table VII and $E^*_{in}$, $E^*_{sc}$, $E^*_{res}$, and $E^*_{in}^{PE}$ are plotted against the complete-fusion values $E^*$ in Fig. 17 for the studied reactions.

An uncertainty in determining mass and energy balance comes from the systematic uncertainties in the postscission $\alpha$ multiplicities due to the difficulties in fitting the postscission component of the $\alpha$-particle kinetic-energy spectra (Sec. III C). However, as $\alpha$-particle emission removes only a small fraction of the initial excitation energy, on average, these uncertainties in $E^*_{in}$ are not too large. For example, if the postscission $\alpha$-particle multiplicities for $E/A = 16$ MeV reactions are increased by a factor of 4, $E^*_{in}$ is only increased by 12 MeV. This uncertainty is even smaller for the lower bombarding energies.

C. Target dependence

The most striking difference in the datasets obtained from the two targets is the ER probability. The smaller ER cross sections for the $^{169}\text{Tm}$ target shown in Table I reflect the fact that the CN is more fissile, having a $J = 0h$ fission barrier $B_F$ which is $\sim 4$ MeV smaller than that for the $^{159}\text{Tb}$ target [12]. The ER yield is predominantly associated with the lower CN spins extending up to the value where $B_F(J)$ is equal to the neutron separation energy. This condition is achieved with a smaller value of $J$ for the more fissile system, and hence the smaller value of $\sigma_{ER}$. However, practically all of the fission yield is expected to come from interactions with low fission barriers, i.e., $B_F(J)$ is smaller than the neutron separation energy or zero in the case of fast fission. Thus the properties of the fission fragments should be very similar for the two targets as they are not that different in mass. This is readily seen in terms of the fitted multiplicities and nuclear temperatures for the prescission and postscission evaporated particles displayed in Figs. 11 and 12. All these quantities show almost the same dependence on bombarding energy for the two targets. Although we have assumed the PE to be identical for the two targets, the deduced values of the excitation energies at scission ($E^*_{sc}$) in Fig. 17 are again similar for the two targets. Therefore in the following, we will only consider the interpretation of the $^{20}\text{Ne}+^{159}\text{Tb}$ reaction.

D. Statistical-model simulations

As the excitation energy at scission ($E^*_{sc}$) increases with bombarding energy (Fig. 17), then the initial excitation energy of the fission fragments must also increase, and consequently the initial CN lifetime of these fragments must decrease. It is not unreasonable that the scission time scale should be commensurate with this fission-fragment CN life-
time, thus suggesting that the time scale for scission is decreasing with increasing bombarding energy. However without some modeling of the fission decay modes, it is difficult to ascertain whether this decrease is simply due to the increasing proportion of fast fission in the total fission yield with beam energy and/or to changes in the statistical fission time scale. To investigate these possibilities, statistical-model simulations incorporating simplistic aspects of the dynamics of fast fission and statistical fission have been performed in this work. The Monte Carlo simulations were based on the statistical-model computer code GEMINI [14,43].

The simulations have to take into account the occurrence of both the preequilibrium and fast-fission processes. We have assumed that the preequilibrium probabilities are independent of impact parameter. This seems quite reasonable as the measured CN velocities determined form ER and fission data, which probe different regions of impact parameter, are consistent within their experimental uncertainties (see Table II). The initial excitation energies \(E_{\text{in}}\) are taken from Table VII. We further assume, as in Eq. (9), the angular momentum removed by PE emission (\(\Delta L\)) is proportional to \(\ell\), the orbital angular momentum of the collision. Thus an initial triangular distribution of \(\ell\) waves for fusionlike reactions maps to a triangular distributions of \(J\). Figure 18 shows some examples of these distributions, the maximum spins \(J_{\text{crit}}\) are taken from Table II. These distributions are subdivided into two regions; the first is region (1) with \(J<J_{\text{BEF}}\) where conventional CN decay is considered to occur, and the second is region (2) where \(J_{\text{BEF}}<J<J_{\text{PE}}\), which is associated with the fast-fission process.

In region (1), a standard statistical decay of the CN is modeled. The partial decay width for light-particle evaporation is calculated with the Hauser-Feshbach formalism using standard spherical transmission coefficients as in Ref. [44]. The fission decay width is calculated from the transition-state formalism using the angular-momentum-dependent fission barriers from Sierk [12]. By treating fission purely statistically, it has generally been found difficult to explain the large experimental prescission multiplicities of light particles in CN decay [1]. Therefore in order to simulate larger prescission emissions, dynamics are often introduced into the simulations. This consists of either a fission delay \(\tau_d^{(1)}\), an initial time period where evaporation is allowed but fission is hindered due to the entrance-channel dynamics and the attainment of a thermal distribution of CN shapes, and/or by particle evaporation during the transition from the saddle point to the scission point. In these simulations we have chosen to model only the first of these and obtain \(\tau_d^{(1)}\) from fitting the experimental data. However, the fitted values of \(\tau_d^{(1)}\) may be interpreted as also including the saddle-to-scission time. As a simplification in the GEMINI simulations, the fission decay width is set to zero up to \(\tau_d^{(1)}\) and then promptly assumes the transition-state value.

In region (2), a full treatment of fast fission would require a dynamical model which considers the variation of the shape of the composite system from the amalgamation of the projectile and target nuclei to the subsequent separation of the fission fragments. During these dynamics, one should also allow for the evaporation of light particles. However, we have followed a simpler scheme which we believe captures the most important aspects of fast fission, which relate to prescission and postscission evaporation. The evaporation from the composite system was treated as being from a deformed system of constant deformation which is meant to represent the mean shape of the system prior to scission. Based on the dynamical code HICOL [18], this shape was taken as prolate (with ratio of major to minor axes of 1.5), rotating about an axis perpendicular to its symmetry axis. Evaporation was considered for a time period of \(\tau_d^{(2)}\), which is meant to represent the duration of the fast-fission interaction. Deformation energies, rotational energies, and transmission coefficients appropriate for the assumed deformation were used in the statistical-model simulations. For both region (1) and (2), the excitation energy at scission is subdivided between the two fission fragments and the postscission evaporation is simulated using spherical transmission coefficients.

As fast fission was not observed in the \(E/A=8\) MeV reaction data, the values of \(\tau_d^{(1)}\) and the level-density parameters \(a_0\) and \(a_F\) for the ground state and saddle-point configurations, respectively, were adjusted to reproduce the prescission and postscission multiplicities of \(n, p,\) and \(\alpha\) particles and the cross section ratio \(\sigma_{\text{ER}}/\sigma_F\) (Table I). These fitted values of the level-density parameters are \(a_0=1/9\) MeV\(^{-1}\) and \(a_F/a_0=1.05\). These values were then assumed independent of excitation energy and used in the simulations for the higher bombarding energies (\(E/A=10, 13,\) and \(16\) MeV). The fitted value of \(\tau_d^{(2)}=45\pm5\) zs at \(E/A=8\) MeV, and its values at the higher bombarding energies were adjusted to fit the experimental cross-section ratios \(\sigma_{\text{ER}}/\sigma_F\). Note, that region (2) is also allowed to contribute to the \(\sigma_{\text{ER}}\). If after the time \(\tau_d^{(2)}\), the angular momentum removed by the evaporated particles is such that the spin of the system is now below \(J_{\text{BEF}}\), then a CN is assumed to be formed and its statistical decay is followed. However, there is only a small yield of ER from such decays and it does not affect \(\sigma_{\text{ER}}\) significantly.

Once \(\tau_d^{(1)}\) is adjusted, the fast-fission time period \(\tau_d^{(2)}\) is then varied in order to fit the multiplicities of all the light particles at the higher bombarding energies. For both prescission and postscission multiplicities, the simulated values are calculated as a weighted average:

\[
\nu_i = \frac{\nu_i^{(1)}(\tau_d^{(1)})\sigma_1^{(1)} + \nu_i^{(2)}(\tau_d^{(2)})\sigma_2^{(2)}}{\sigma_1^{(1)} + \sigma_2^{(2)}},
\]

where \(\nu_i^{(1)}(\tau_d^{(1)})\) and \(\nu_i^{(2)}(\tau_d^{(2)})\) are the simulated values from region (1) and (2), respectively, each is a function of its corresponding dynamical time and \(\sigma_1^{(1)}\) and \(\sigma_2^{(2)}\) are the cross sections associated with the two regions with \(\sigma_{\text{FU}} = \sigma_1^{(1)} + \sigma_2^{(2)}\) being taken from Table I.

Figures 19(a–c) compare the experimental and simulated multiplicities of \(n, p,\) and \(\alpha\) particles, respectively, as functions of \(E/A\). A similar comparison is made for the cross-section ratios \(\sigma_{\text{ER}}/\sigma_F\) in Fig. 19(d). Quite good reproductions of all of the experimental multiplicities are obtained.
FIG. 18. (Color) Examples of the $\ell$ wave and the initial CN spin distributions used for the statistical-model simulations. The maximum values $\ell_{\text{crit}}$ and $J_{\text{crit}}^{\text{PE}}$ are from Tables I and II, respectively. The arrows indicate the angular momenta removed by PE emission. The two regions (1) and (2) of the spin distributions, which are treated differently in the simulations, are indicated. They are separated at the value $J_{B_F=0}$ where the fission barrier is predicted to vanish in the calculations of Sierk [12].
FIG. 19. (Color) For the $^{20}$Ne+$^{159}$Tb reaction, a comparison, as a function of bombarding energy per nucleon $E/A$, of the experimental precission and postscission multiplicities with the simulated values for (a) neutrons, (b) protons, and (c) $\alpha$ particles. The comparison in (d) is for the cross-section ratios $\sigma_{ER}/\sigma_F$. The broken curves are to guide the eye.
with the exception of the postscission $\alpha$ particles where the simulated values are much larger than the experimental values. However, there are large systematic uncertainties in the measured values (which are not included in the error bars in this figure) due to the difficulty in fitting the low-energy portions of the $\alpha$-particle kinetic-energy spectra (Sec. III C). Some of the predicted postscission $\alpha$ particles may even account for some of the experimental scission $\alpha$ particles which were inferred from the kinetic-energy spectra. Apart from this difficulty with the postscission $\alpha$ particles, all the other multiplicities and the cross section ratios are well reproduced by the adjustment of only the two dynamical time scales $\tau_{d}^{(1)}$ and $\tau_{d}^{(2)}$, giving us some confidence in the assumptions of the simulations.

The evolutions of the extracted values of $\tau_{d}^{(1)}$ and $\tau_{d}^{(2)}$ with bombarding energy are shown in Fig. 20. The fission delay $\tau_{d}^{(1)}$ associated with CN fission decreases with bombarding energy from $\sim 45$ zs to approximately $15 \pm 5$ for the two highest bombarding energies. The value of $\tau_{d}^{(1)} \sim 45$ zs for the lowest two bombarding energies agrees quite well with the systematics of Hinde et al. (Fig. 3 in Ref. [22]) for $^{16}$O induced fusion–fission reactions. The agreement is more remarkable because these systematics were based on an analysis of neutron multiplicities only, while $\tau_{d}^{(1)}$, in this work, is determined by fitting $\sigma_{CN}/\sigma_{F}$ and $n, p, \alpha$ multiplicities. The amount of fast fission is quite small at $E/A = 10$ MeV, and thus we should concentrate on the $\tau_{d}^{(2)}$ values extracted from the two highest bombarding energies. They are also approximately $15$ zs, almost equal to the $\tau_{d}^{(1)}$ values. The similarity of the two dynamical time scales suggests that they may have similar origins. For example, the evolution from a compact composite system to a dinuclear shape may be quite similar for conventional and fast fission, similarly the initial entrance-channel dynamics may also be similar. On the other hand, the time scale for shape equilibration is not a consideration for fast fission, and thus it may be a small fraction of the total dynamical time for the $E/A = 13$ and 16 MeV reactions. The larger values of $\tau_{d}^{(1)}$ for the lower two bombarding energies might therefore correspond to an increased importance of the shape equilibrium time or a dependence of the dissipation of temperature. Clearly more detailed simulations of the dynamics are required to investigate these ideas further.
ambiguity in defining a single time to represent a very wide distribution. However, by combining the different techniques, the overall shape of the distribution should become better defined.

V. CONCLUSION

The properties of fission events have been extensively studied in the $^{20}$Ne + $^{150}$Tb and $^{166}$Tm reactions at beam energies of $E/A = 8, 10, 13, 16$ MeV. Measurements of evaporation residues, fission fragments, and the properties of the accompanying light particles have been made. From evaporation-residue velocity distributions and fission-fragment folding angles, the compound-nucleus velocities were found to be less than the complete-fusion values at the highest bombarding energies. This implies the emission of preequilibrium particles, the magnitude of which was estimated from published systematics in a very self-consistent way. The deduced excitation energies of the compound systems ranged from about 100 to 210 MeV. From the measured residue and fission cross sections, the compound-nucleus velocities were constrained only by the data at the lowest bombarding energy where there was no fast-fission component. Subsequently, the data at the higher bombarding energies were each fitted by adjusting just the two dynamical time scales. For $E/A = 13$ and 16 MeV, these extracted dynamical time scales for both statistical fission and fast fission were similar, $\sim 15 \pm 5$ zs, suggesting a common origin. The dynamic time for statistical fission was found to be larger at the lower energies, with the value of $45 \pm 5$ zs at the lowest excitation energy of $\sim 100$ MeV. The total time scale for conventional CN fission can be much larger than the dynamical times, the simulated distribution of scission times extends over many orders of magnitude. However, the median time, the time by which half of the scission events have occurred, is of order similar to the dynamical times and was found to decrease from 115 zs to 40 zs over the range of excitation energies studied.

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[43] R. J. Charity, computer code GEMINI (unpublished); also see http://wnmr.wustl.edu/~rc