Fission Time Scales from Anisotropic In-Plane Distributions in $^{100}\text{Mo}+^{100}\text{Mo}$ and $^{120}\text{Sn}+^{120}\text{Sn}$ Collisions around 20 A MeV

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The characteristics of the fission step following a binary deep-inelastic interaction have been reconstructed for three-body events detected in the reactions $^{100}\text{Mo} + ^{100}\text{Mo}$ at 18.7 A MeV and $^{120}\text{Sn} + ^{120}\text{Sn}$ at 18.4 A MeV. The observed anisotropy of the in-plane angular distributions points to the fast decay of a rotating (and strongly deformed) nuclear object formed at the end of the deep-inelastic interaction. The derived time scale of the process indicates that asymmetric divisions are faster than symmetric ones.

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Interest in nuclear fission in general and particularly in the determination of its characteristic time scale has been revived after a series of recent measurements of pre-scission neutrons (see Ref. [1], and references therein).

As compared to particle emission, nuclear fission is expected to be a slower process, due to the complex change of collective degree of freedom involved in it [2]. Experimentally, this expectation was repeatedly confirmed by the observation of isotropic in-plane angular distributions in a large number of fusion-fission reactions, as well as in the sequential fission decay of heavy reaction products [3]. This fact points to the nucleus undergoing, on the average, at least one full rotation before scission and sets a lower limit of several $10^{-21}$ s for the fission time scale. Recent studies on neutron emission in fusion-fission reactions have argued that the motion towards scission is highly viscous and leads to fission times of the order of $10^{-20}$ s to $10^{-19}$ s [1,4–6]. This time seems to decrease with increasing mass asymmetry, as reported in recent works based on the detection of neutrons [1,7,8] or light charged particles [9] in coincidence with heavy fragments.

Some indications of short time scales ($\approx 10^{-21}$ s) were obtained also from fragment correlations in sequential fissionlike decays following collisions at intermediate bombarding energies [10,11] and from “proximity” modulations of the relative velocity of sequential-fission fragments in the $^{129}\text{Xe}+^{129}\text{Sn}$ collision at 12.5 A MeV [12]. In this latter case, anisotropic in-plane angular distributions were also observed, pointing to three-body events characterized by a preferential collinearity of the three fragments, with the lighter fission fragment roughly located in between the other two.

This Letter presents for the first time evidence that the in-plane angular distribution of a fissionlike decay evolves from a “well behaved” isotropic shape for symmetric splits towards a strong anisotropy for the most asymmetric splits. Moreover, a novel and independent method of estimating the time scale of the process is suggested, based on the analysis of the shape of the in-plane angular distribution.

Two symmetric systems were investigated, namely, $^{100}\text{Mo} + ^{100}\text{Mo}$ at 18.7 A MeV and $^{120}\text{Sn} + ^{120}\text{Sn}$ at 18.4 A MeV. Heavy fragments ($A \geq 20$) were detected with twelve position-sensitive gas detectors covering about 75% of the forward hemisphere [13,14]. From the measured velocity vectors, primary (pre-evaporative) masses, angles, and kinetic energies of the fragments were deduced event by event with an improved version of the kinematic coincidence method [15]. The background of incompletely measured events of higher multiplicity was estimated [15] and subtracted from the data. Extensive Monte Carlo simulations were used to correct the data, taking into account not only the efficiency of the setup, but also additional effects, such as smearing due to sequential evaporation, as well as resolution and possible systematic distortions of the analysis method. Particular care was devoted to the determination [16] of the intrinsic efficiency of the detectors as a function of both atomic number $Z$ and lab velocity of the fragments.

An analysis of how three-body events populate the available phase space proves [14,17] that the reaction mostly proceeds via a sequential two-step mechanism and supports the picture of an initial deep-inelastic interaction followed by the fissionlike decay of one of the deep-inelastic fragments. Indeed the relative velocities of the reconstructed fission fragments are strongly peaked at values close to the Viola systematics [18] and show the expected weak Coulomb-like increase with mass asymmetry. After having identified which pair of fragments originates from this decay, the properties of the second reaction step can be studied. They will be the subject of a forthcoming paper [14], while the present Letter concentrates on the in-plane angular distributions.

We indicate by $\Theta$ the out-of-plane angle between the fission axis and the reaction plane (specified by the beam axis and the separation axis of the deep-inelastic step) and by $\phi$ the in-plane angle between the projection of the fission axis onto the reaction plane and the separa-
tion axis (the latter corresponding to $\Phi=0^\circ$). The angle $\Phi$ is taken positive towards the beam direction. We denote $m_1$, $m_2$ (with $m_1 \geq m_2$) as the masses of the two fragments resulting from the fission of a former deep-inelastic fragment and $m_3$ the mass of the nonfissioning fragment. We choose the fission axis as pointing along the emission direction of $m_1$, so that $\Phi$ always refers to the heavier fission fragment and $-180^\circ \leq \Phi \leq +180^\circ$.

The out-of-plane distributions of the present work show the usual strong preference of the fission axis for the reaction plane and present no significant dependence on the mass asymmetry $\eta = (m_1 - m_2)/(m_1 + m_2)$. Rather surprisingly, the in-plane angular distributions are found to evolve, with increasing $\eta$, from an isotropic to a strongly anisotropic shape. This is clearly seen in Fig. 1, which displays the $\Phi$ distributions for different $\eta$ windows in the reaction $^{100}$Mo $+^{100}$Mo. The selected bin of total kinetic energy loss (TKEL) of the first reaction step, 400–500 MeV, leads to excitation energies of 200–300 MeV in the fissioning nucleus. The solid lines are the result of a fit discussed later. Similar results are obtained for other TKEL bins and for the system $^{120}$Sn $+^{120}$Sn.

The flat in-plane angular distributions found at low $\eta$ values are compatible with the commonly accepted picture of a compound nucleus which loses any memory of its entrance channel and decays simply according to the statistical weights of its open exit channels. In contrast, the observed peaking at small $\Phi$ values in case of asymmetric mass division clearly shows the persistence of some memory of the preceding deep-inelastic step and, in particular, of the direction of its separation axis (the peaked $\Phi$ distribution obviously implies that states with different angular momenta contribute coherently).

Assuming that the in-plane distributions mainly reflect the interplay between rotational frequency (related to the collective angular momentum) of the fissioning system and time scale of the collective motion leading to scission, we tried to fit the data of Fig. 1 with the function

$$f(\Phi) = a + \frac{b}{\sqrt{2\pi}\sigma} \int_{\Phi_0}^{\infty} e^{-(\Phi' - \Phi_0)/\sigma} e^{-(\Phi - \Phi')^2/(2\sigma^2)} d\Phi'$$

which, for $a=0$, represents an exponential decay (of slope given by $\Phi_m$, from $\Phi_0$ onwards) convoluted with a Gaussian of variance $\sigma^2$. For large $\eta$ values one needs to introduce the constant term $a$. The full lines in Fig. 1 show the quality of the fits, corresponding to values of $\chi^2$ per degree of freedom ranging from 1.4 to 2.0. Similar results hold for the system $^{120}$Sn $+^{120}$Sn.

FIG. 1. Experimental in-plane angular distributions of fission fragments from three-body events in the collision $^{100}$Mo $+^{100}$Mo at 18.7 A MeV, for six bins of the mass asymmetry $\eta$. The data refer to TKEL of 400–500 MeV and to reconstructed fissioning masses $90 \leq A \leq 130$. The data are background subtracted and efficiency corrected by means of Monte Carlo simulations. The solid curves correspond to a fit with $f(\Phi)$ taking into account multiple rotations over $\Phi$. For $\eta \geq 0.3$, the following values have been obtained for the parameters $\Phi_m$, $\sigma$, and $a/b$: $39^\circ$, $60^\circ$, $0.11$ ($\eta=0.3$–0.4); $30^\circ$, $50^\circ$, $0.034$ ($0.4$–0.5); $20^\circ$, $26^\circ$, $0.030$ ($0.5$–0.6). For the first three bins the fit is largely unaffected by simultaneous variation of the three parameters. The shown curves correspond to a fit with $a$ fixed to 0, a common value of $\sigma = 77^\circ$, and $\Phi_m = 1200^\circ$, $600^\circ$, $240^\circ$.

In spite of the due caution suggested by the previous considerations, the good agreement with the experimental distributions for all $\eta$ bins is remarkable and makes it rather appealing to look for a more physical interpretation of the crudely guessed function $f(\Phi)$ and of the fitted parameters. To do so, one can find support in the picture proposed recently by Kun [20], who interpreted the fluctuations observed in the cross section of light heavy-ion reactions in terms of the decay of a “quasimolecular” dinuclear system. Also in our case, one can suppose that at the end of the deep-inelastic phase a rotating dinuclear system is formed, which eventually decays via fission with
a lifetime $\tau$. As shown by Kun, the rotation of this dinucleus resembles that of a macroscopic classical object.

In this framework, the exponential in $f(\Phi)$ describes the distribution of asymptotic in-plane angles $\Phi$ (with respect to the direction of the first deep-inelastic scission) at which the second fissionlike scission occurs. The convoluted Gaussian globally takes into account the spread of the initial angle $\Phi_0$, as well as the combined resolution of detectors and analysis method in the determination of the angle $\Phi$. The constant $a$ represents the possible contribution of long-lived (and hence isotropic) fission.

The most interesting physical information resides in the angle $\Phi_m$, which represents the average rotation of the nuclear system from scission to scission and can be related to the dynamics of the process and to its characteristic time scale. In the spirit of Ref. [20], the decaying nucleus is characterized by a collective angular velocity $\omega$ and the average scission-to-scission lifetime can be simply estimated as $\tau = \Phi_m/\omega$. It has to be noted that if the system were allowed to perform large rotations between the two scissions, the angular anisotropy would be washed out. Thus its very observation in the experiment implies rather short scission-to-scission times ($\lesssim 10^{-21}$ s), unless one invokes very small angular momenta, which are at odds not only with the spin values of $40h$–$50h$ estimated from the out-of-plane widths [14] and calculated with transport models [21], but also with the experimental large values of the three-body probability [13,14].

According to refined liquid-drop-model calculations [22], the elongated and necked-in saddle-point shapes of nuclei in this mass region are expected to be very similar to the scission-point shapes, especially for the most asymmetric splits. If the deep-inelastic process produces the fissioning nucleus in some configuration very near to the saddle point, only small changes of the moment of inertia should occur during the motion towards scission. Therefore, neglecting angular momentum losses due to pre-scission particles, $\omega$ is not expected to change appreciably with time. Values of $\omega$ ranging from $0.4 \times 10^{21}$ rad/s (at small $\eta$) to $0.6 \times 10^{21}$ rad/s (for $\eta = 0.5$–0.6) have been obtained using the spin values estimated from the out-of-plane distributions for $\eta \approx 0$ [14] and assuming the rigid rotation of two prolate axisymmetric ellipsoids at contact. The adopted value of 0.6 for the ratio of the axes gives moments of inertia similar to those calculated [23] for the saddle-point shapes of nuclei with fissility $x \approx 0.4$.

The values of the scission-to-scission lifetime $\tau$ obtained in the $^{100}$Mo + $^{100}$Mo and $^{120}$Sn + $^{120}$Sn systems for TKEL in the range 400–500 MeV are shown as a function of $\eta$ in Fig. 2. As mentioned above, for the first $\eta$ bins the values represent lower limits, as indicated by upward arrows. Even with all above-mentioned reservations in mind, Fig. 2 indicates a clear tendency of the second scission process to become faster and faster when going from symmetric to asymmetric splits. At small asymmetries the scission-to-scission lifetimes are compatible with those expected for fission after attainment of global equilibrium, while at high $\eta$ values they become very short and similar to the times characteristic of quasifission [(1–5)$\times10^{-21}$ s], where the heavy intermediate system separates after only a fraction of full rotation [24], without having formed a true compound nucleus.

For comparison, Fig. 2 presents also the fission time scales deduced from pre-scission neutrons [1] in the fission of similar nuclei ($^{126}$Xe) at similar excitation energies ($\approx 250$ MeV) produced by collisions of $^{16}$O on $^{109}$Ag at 288 MeV. In close similarity with our data, the time scale decreases by more than 1 order of magnitude when going from symmetry to $\eta \approx 0.7$. A weaker dependence on the mass asymmetry had been deduced for the much heavier systems $^{32}$S + $^{197}$Au, $^{32}$S + $^{232}$Th at 26 A MeV, where the typical times vary from about $1.5 \times 10^{-20}$ s for symmetric fissions to $7 \times 10^{-21}$ s for asymmetric splits [8].

At high $\eta$ values, Fig. 2 shows that the lifetimes observed in the present work are somewhat shorter than those reported by Hinde et al. [1]. However, it has to be remembered that those times, which are obtained from a completely different observable, refer to fusion-fission reactions and represent the total time from the achievement of the thermal equilibrium to the scission point.

In our case, it may well be that the deep-inelastic interaction leaves a fraction of the produced nuclei (those leading to asymmetric fission) with some degrees of freedom far from complete relaxation, so that they need shorter time to reach the scission point. In particular, the nascent deep-inelastic fragments are expected to be elongated along their separation axis. Possible octupole components at the moment the neck snaps off could even favor the creation of a lighter fragment in a position intermediate between the other two, as observed in the data.
In any case, due to the intrinsically fluctuative character of the deep-inelastic mechanism, the distribution of deformations may be rather broad, with tails extending near or even beyond the saddle-point shape, as expected in the neck rupture model [25].

According to Hinde et al. [5], the motion towards scission seems to be dominated by the fluctuations associated with a large nuclear viscosity and almost independent of the potential energy surface, with the time required to move a certain "distance" (or deformation, in our case) varying as the square of that distance. Therefore, it is not necessary to assume that the nuclei are produced with deformation larger than the saddle point, as the time for fission can be greatly reduced already if the system starts with even a moderate deformation. In qualitative agreement with the findings of Fig. 2, one expects this reduction of the time scale to be more effective for the more asymmetric scissions, which are predicted to present more compact saddle and scission shapes [22]. Such a description of fission is still partly based on equilibrium statistics, as the system is pushed over its saddle-point configuration by thermally induced shape fluctuations, while the initial deformation is still governed by dynamics. This may explain the statistical features of the fission step reported in Ref. [13].

To make all qualitative arguments presented above more quantitative, a reliable theory is strongly needed. However, to our knowledge, none of the currently available models can be successfully used for calculating mass and angular correlations of the three-body events studied in this work, the main difficulty residing in a realistic description of dissipation and fluctuation of a dynamic system evolving towards equilibrium.

In conclusion, the anisotropic in-plane angular distributions observed in three-body events point to the presence of some nonequilibrium effect at the end of the deep-inelastic phase. They hint at a rather stretched configuration formed by three almost collinear fragments, with the lighter fission fragment preferentially located in between the other two "bodies."

A new method is proposed to deduce scission-to-scission time scales as a function of the mass asymmetry. In qualitative agreement with previous results, the most asymmetric divisions are characterized by time scales significantly shorter (of the order of $10^{-21}$ s) than those deduced for the symmetric splits. It is suggested that nonequilibrium in some degrees of freedom, in particular in the shape degrees of freedom, may play a major role in the processes studied in this work, either through the creation of fragments directly beyond the saddle-point deformation, or via strong shape fluctuations. The real nature of these phenomena is, however, rather speculative and not yet clearly established. A better understanding of these three-body processes and of the associated time scales could be quite relevant also for the formation time of intermediate mass fragments produced in multi-fragmentation processes at higher bombarding energies.

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[14] A. A. Stefanini et al. (to be published).