Experimental Studies of Quasi-fission Reactions

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ABSTRACT

A large number of recent experimental studies have shown that a substantial fraction of the total reaction cross section in heavy-ion reactions is found in fission-like processes, which do not result from the fission decay of a completely fused system. Following the suggestion of Swiatecki1) such processes, which represents a complete relaxation of the relative kinetic energy and a substantial amount of net mass transfer between the two fragments, are denoted quasi-fission reactions. They are distinct from compound fission reactions by bypassing the stage of a completely fused system. This typically means that they are associated with short reaction times, which results in several measurable characteristics such as broken forward-backward symmetries, large anisotropies of the angular distributions and increased widths of the fragment mass distributions. The distinction between quasi-fission and deep inelastic reactions is less stringent and has the character of a gradual evolution from one reaction type to the other, as found also as quasi-elastic reaction evolves into deeply inelastic processes as a function of the total kinetic energy loss. In the present paper some of the experimental data characterizing quasi-fission reactions are reviewed and discussed.

1. Introduction

Complete fusion and deep inelastic scattering are well known processes in heavy-ion reaction studies. Conceptually there is a rather clear distinction between the two processes. In complete fusion the two interaction partners amalgamate to form a highly excited system, which may subsequently decay by fission or particle emission, the latter of which has been used extensively in spectroscopic studies of high spin states in neutron deficient nuclei. The deeply inelastic scattering processes, however, evolve as a natural extension of quasi-elastic reactions2) to larger energy losses and particle exchanges between the two reaction partners. The energy loss incurred in deeply inelastic processes range down to the extreme limit where all the relative kinetic energy between the two fragments is damped away and the fragments are emitted with only the Coulomb repulsion energy at the scission configuration. This corresponds roughly to two-thirds of the Coulomb barrier energy in the entrance channel.

In reactions with lighter projectiles, e.g. ^{16}O, there is also experimentally a clear distinction between compound fission and deep inelastic scattering simply by way of the mass of the reaction products. For heavier projectiles, e.g. ^{40}Ca, there is substantially more cross section between the scattering processes centered at the projectile mass and the symmetric fission mass. In fact, in the latter case there is an almost flat mass distribution between the projectile and target masses indicating that the quasi-fission process contributes significantly to the total reaction cross section in this case. In the following we will discuss the experimental signatures of the quasi-fission process and how the study of these processes may add a new dimension to the study of the dynamics of nuclear systems. This is based mainly on the fact that quasi-fission processes often proceed on a time-scale comparable with the rotational period of the system, which gives a quite reliable measure of the reaction time.

2. Angular Distributions

Important clues to the presence of quasi-fission reactions may be obtained from the angular distributions of the fission-like fragments, when interpreted within the concept of the independence of formation and decay of a compound nucleus. The standard theory[3,4] for fission fragment angular distributions is based on the assumption that the fission axis is frozen in during the passage over the saddle point and that the descent from saddle to scission is sufficiently rapid such that this fission axis is unchanged under this process. A large number of experimental data[5] with beams of mass up to A~20 as well as theoretical models[6] describing the excitation of the tilting mode on the basis of nucleon exchange between the two fragments lend support to this picture.

For heavier projectiles, a substantial deviation from this description is observed[7-11]. There are essentially two possible explanations for this observed discrepancy for the heavier projectiles. It has been suggested[12] that the standard theory breaks down for the high angular momenta obtained in compound nuclei formed by heavy ion bombardment. Eventually, at the point where the fission barrier vanishes (or becomes lower than the nuclear temperature[13]), this point of view must prevail. The second possibility is that the observed fission-like fragments do not originate from the fission decay of a compound system, but that they are the result of a more direct type of reaction where transfer of mass from the heavy to the light partner and complete damping of the relative kinetic energy occurs without having gone through a stage of compound nucleus formation[8,11].

In both cases we may describe the mass integrated angular distribution in terms of the following equation, namely

$$W(\theta) \simeq \sum_{I=0}^{\infty} (2I+1)\ P(I) \sum_{K=-I}^{I} \frac{1}{2}\ (2I+1)\rho(K)\ |d^{I}_{0,K}(\theta)|^{2}, \qquad (1)$$

where P(I) is the distribution of partial waves leading to fission-like reactions, $\rho(K)$ is the K-distribution (K is the axial component of the total spin I) and $d^{I}_{0,K}(\theta)$ is the θ-dependent part of the symmetric top wave function. The partial wave distribution P(I) may be taken from model calculations, which reproduce the near-, and sub-barrier cross section10).

The K-distribution is in both the saddle point and the scission point model represented by a Gaussian of the form

$$\rho(K) = N \exp(-K^{2}/2K_{0}^{2}), \qquad (2)$$

where N is a normalization factor and

$$K_{0}^{2} = T\,\hbar^{2}/J_{eff} \quad ; \quad \frac{1}{J_{eff}} = \frac{1}{J_{\parallel}} - \frac{1}{J_{\perp}} . \qquad (3)$$

In this equation T is the nuclear temperature at the point, where the K-distribution is frozen in (saddle or scission point), and $J_{\parallel}$ and $J_{\perp}$ are the corresponding axial and transverse moments of inertia.

Experimental fission angular distributions may be reproduced by the functional form given in Eq. 1 by varying the value of K_0^2. The resulting values of K_0^2, which provide the optimum fit to the angular distributions are plotted (solid points) as a function of the compound nucleus excitation energy in Fig. 1, for a wide range of experimental data10). We note that the K_0^2-values corresponding to the fission saddle point, as given by the rotating liquid drop model14) (solid curve) give a good representation of the data for the $^{19}F+^{208}Pb$, $^{16}O+^{232}Th$, and $^{16}O+^{238}U$ reactions, whereas the K_0^2-values corresponding to the scission point model as represented by two coaxial spheroids in rigid rotation (dashed curves), severely underpredict the data. For these reactions it therefore appears that the K-values selected at the saddle point are preserved during the descent from saddle to scission, as assumed in the standard theory.

For heavier projectiles, i.e. ^{24}Mg, ^{28}Si, and ^{32}S, we see that the experimental K_0^2-values are generally lower than the predictions of the saddle point model, and approach the scission point values, without, however, reaching these values. The fact that very similar composite systems (in terms of saddle point shape, temperature and angular momentum) are formed in the $^{16}O+^{232}Th$ and $^{28}Si+^{208}Pb$, as well as in the $^{16}O+^{238}U$ and $^{32}S+^{208}Pb$ reactions, strongly suggests that the failure of the saddle point model to reproduce the data for the heavy projectiles is connected with an entrance channel effect, and not to a break-down of the saddle point model. This discrepancy for the heavy projectiles therefore points to a strong contribution of quasi-fission reactions in which the apparent mass drift toward mass symmetry takes place without having gone through a stage of compound nucleus formation.

For even heavier projectiles we observe an even more indisputable effect in the angular distribution, which clearly excludes the possibility that these fission-like fragments comes from compound reactions. This is based on the fact that a complete fusion reaction followed by a subsequent fission decay <u>must</u> display certain characteristics, namely a forward-backward symmetry in the angular distribution for any particular mass of the fission-like process. In studies of the $^{50}Ti+^{208}Pb$ reaction using chemical separation and off-line counting techniques, Lützenkirchen et al.$^{15)}$ have found strong forward-backward asymmetries in the angular distributions of the non-symmetric fission-like products. These angular distributions clearly have the characteristics of a more direct reaction with a reaction time, which is comparable to the rotational period of the composite system.

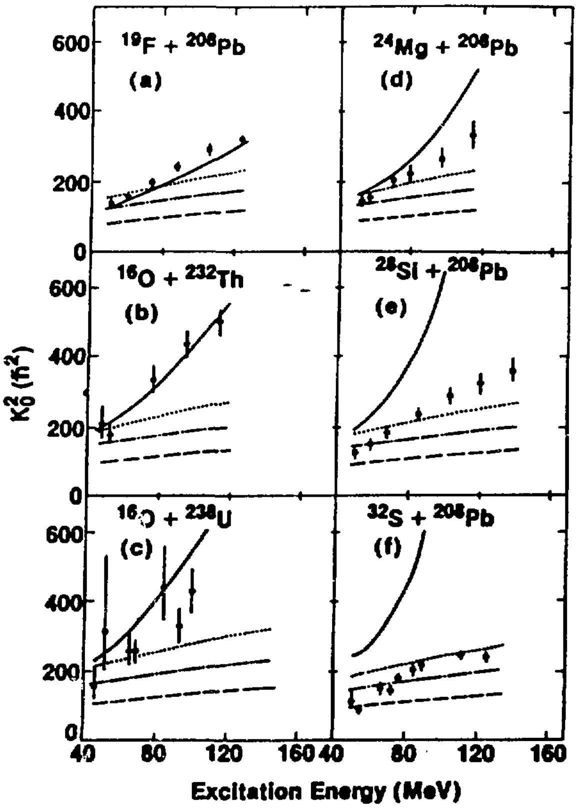

Fig. 1: Comparison of K_0^3 values derived from the analysis of experimental fission anisotropies with the prediction of the saddle point model (solid curves) and the rigid coaxial spheroids scission point model (dashed curves) as a function of the excitation energy of the fissioning system.

Similar results have been found in a recent study of the $^{60}Ni+^{154}Sm$ reaction carried out at the ATLAS accelerator at Argonne National Laboratory, as shown in Fig. 2. As required by the characteristics of two-body reactions, we see that the angular distributions for mass symmetric products are perfectly forward-backward symmetric for all three bombarding energies measured. For lighter masses we see, however, an increasing angular asymmetry, with the light mass fragments being emitted with highest probability in the forward angle.

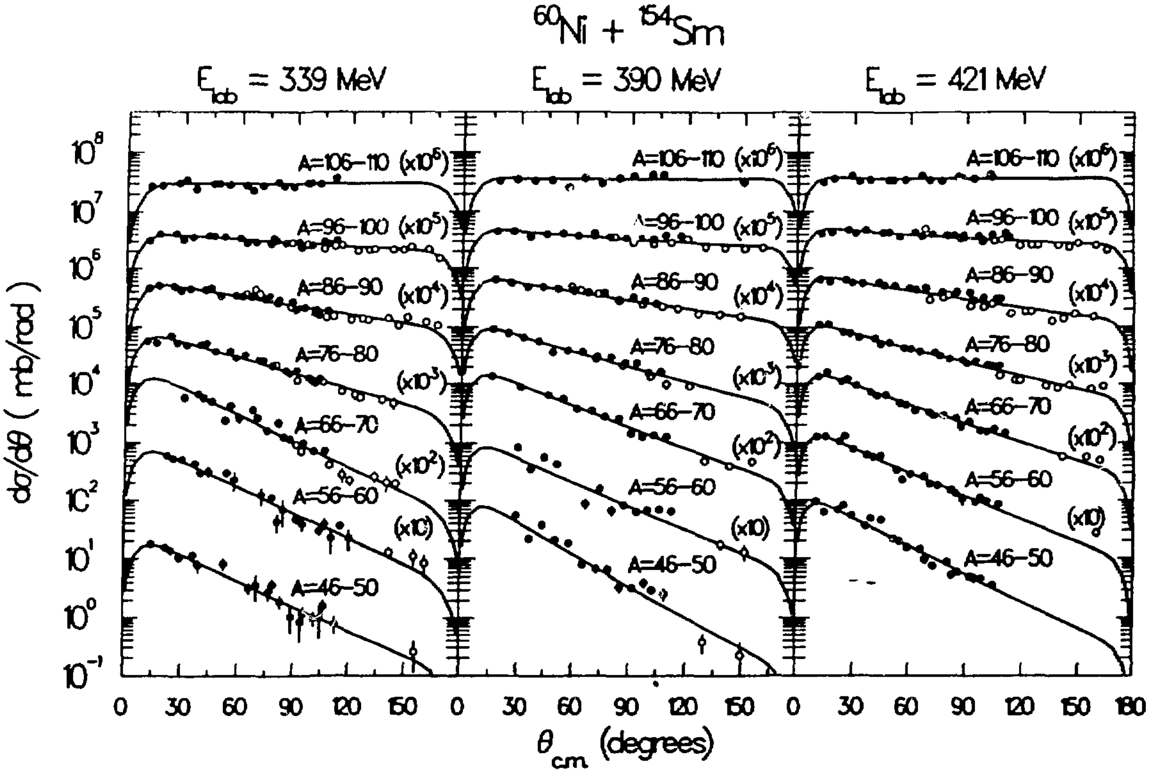

Fig. 2: Angular distributions for fragments falling into different mass bins are shown for the $^{60}Ni+^{154}Sm$ reaction at E_{lab} = 339, 390, and 421 MeV. The solid points are data for the mass bin indicated in the figure. Open circles correspond to the complementary fragment plotted at the supplementary angle.

The solid curves are calculated on the basis of the standard formalism for fission angular distributions, Eq. 1. The angular asymmetry is achieved by multiplying the standard expression with an exponential function such that the full expression is

$$W(\theta) \simeq \sum_{I=0}^{\infty}(2I+1)\ P(I)\ \exp[\beta(\theta - \frac{\pi}{2})] \sum_{K=-I}^{I} \frac{1}{2}\ (2I+1)\rho(K)\ |d^{I}_{0,K}(\theta)|^2, \qquad (4)$$

where β is a parameter controlling the angular asymmetry. As in the analysis of the mass integrated angular distributions the wave distribution P(I) is taken from model calculations, which reproduce the near barrier fission-like excitation function.

3. Mass Distributions

The first indications of the quasi-fission reaction were found in the width of the mass distributions of fission-like fragments[16,17]. This is illustrated in Fig.

3, where the fractional width (FWHM) of the mass distribution is plotted as a function of the maximum partial wave in the reaction relative to the ℓ-value for which the fission barrier vanishes, $\ell(B_f=0)$. One observes a rather sharp increase in the mass width for reactions for which the maximum ℓ-value for fission-like reactions exceed the ℓ-value for which the fission barrier vanishes. Although the disappearance of the fission barrier surely prevents the formation of a compound nucleus and therefore compound fission reactions, it has later been shown[11] that quasi-fission occurs also for systems with an intact fission barrier. One must therefore conclude that the occurence of quasi-fission more closely reflect the dynamical characteristics of the system (as suggested by Swiatecki[1] on the basis of dynamical model calculations) than the static properties of the fused system.

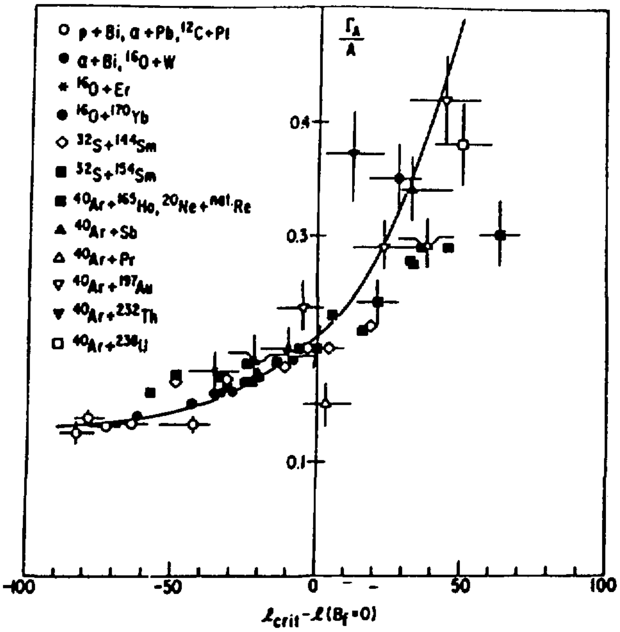

Fig. 3: The normalised mass width Γ_A/A is plotted as a function of critical angular momentum for fusion relative to the angular momentum for which the fission barrier vanishes, $\ell(B_f=0)$. The data are taken from references cited in Ref. 16,17 and from Ref. 18.

4. Time Scales

One of the most interesting properties of the quasi-fission process is the fact that the reaction time scale in many cases is comparable to the rotational period of the system. This is very important in providing a way of measuring the reaction time by means of the rotation angle during contact. The reaction time is related to the angle of rotation, $\Delta\theta$, and the average angular velocity of the system, $\langle\omega\rangle$, simply by the relation

$$\tau_{reac} = \Delta\theta/\langle\omega\rangle. \tag{5}$$

The angle of rotation $\Delta\theta$ of the complex during the reaction is approximated by $\Delta\theta = \pi - \theta_i - \theta_f - \theta$, where θ_i and θ_f are one-half of the computed Coulomb deflection angles of initial and final trajectories and θ is the observed scattering angle.

The average angular velocity is given by $<\omega> = \ell/<J>$, where ℓ is the average angular momentum, and $<J>$ is the average moment of inertia of the system during the rotation. In order to extract reaction times from the data it is necessary to decompose the partial wave distribution into three partially overlapping angular momentum bins, each containing one-third of the total fission-like cross sections and associate each bin with a certain degree of mass drift toward symmetry, in the direction of which the potential tends to drive the system[19].

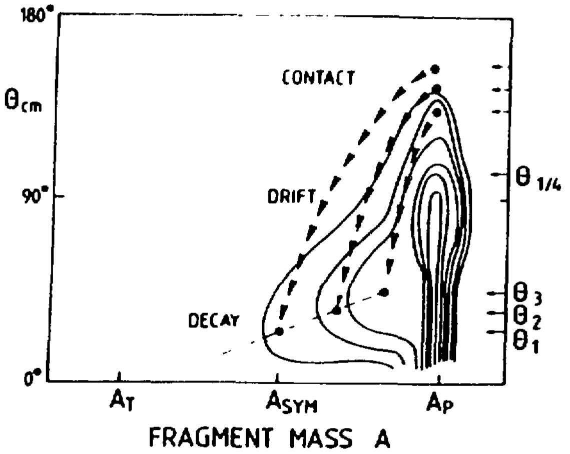

Fig. 4: Schematic illustration of the correspondence between mass drift and angle of rotation on quasi-fission reactions. The final mean emission angles θ_1, θ_2, θ_3 for three different mass regions are marked.

The average angular momentum for each bin is calculated and used in the estimate of the reaction time. It is assumed that the smallest partial waves are associated with the largest mass drifts as a consequence of the larger radial energies available in this case, see Fig. 4. In pure Coulomb trajectories, these partial waves would also lead to the largest scattering angles. The moment of inertia of the composite system is taken as $<J> = 1.4\ J_{sph}$, where J_{sph} is the rigid moment of inertia of the spherical compound nucleus using a radius parameter of $r_0=1.16$ fm.

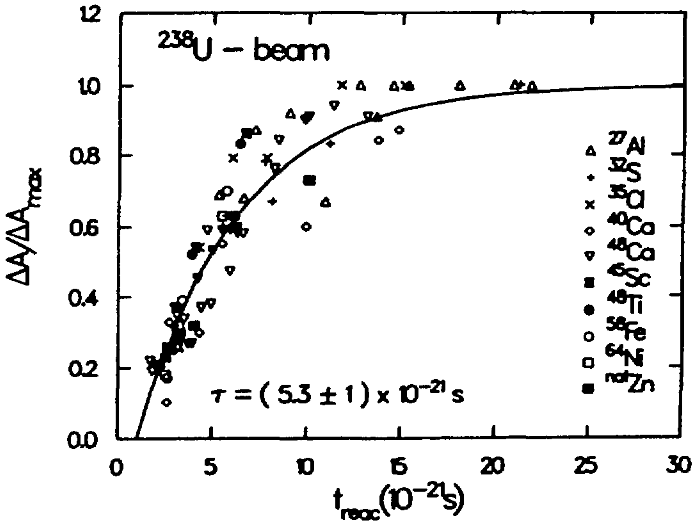

Fig. 5: Normalised mass drift $\Delta A/\Delta A_{max}$ as a function of the reaction time. The solid curve represents the best fit to the data using Eq. 5.

The correlation between the reaction times, extracted in the manner described above from the ^{238}U induced data of Shen et al.[20,21] and Tōke et al.[19], and the associated normalized mass drift toward symmetry, $\Delta A/\Delta A_{max}$, is shown in Fig. 5. The parameter describing the degree of mass drift toward symmetry appears to proceed after a short delay of $t_o \sim 10^{-21}$ s, which is interpreted as the time it takes to establish the neck connecting the two reacting nuclei and allow for the nucleon flow from the heavy nucleus to the lighter nucleus to take place. Following this delay the mass drift toward symmetry is seen to take place within ~ 10-15 x 10^{-21} s. The solid curve in Fig. 5 is computed on the basis of the equation

$$\Delta A/\Delta A_{max} = 1 - \exp[- (t-t_o) / \tau] \qquad (5)$$

which describes an overdamped motion in a harmonic potential. The value of the characteristic time for mass drift, τ, is found to be $\tau = 5.3 \times 10^{-21}$ s. This correlation between mass drift and reaction time as well as the numerical value of the characteristic time constant, τ, gives important clues about the nature of the nuclear dissipation, which will be discussed in the following section.

5. Dissipation Mechanisms

A central issue in the study of fission and heavy ion dynamics is the question of dissipation forces, which resist the shape changes of the nuclear system. Within the framework of macroscopic dynamical models two different dissipation mechanisms have been considered. One such mechanism is one-body dissipation, which arises from the energy loss in collisions of individual nucleons with the moving nuclear surface. It is expected that this dissipation mechanism will dominate if the mean free path of nucleons inside the nuclear medium is longer than the nuclear dimensions, such that there is little chance of scattering off another nucleon in between interactions with the surface. The other proposed dissipation mechanism, two-body dissipation, arises from such nucleon-nucleon collisions, which gives rise to a dissipation resembling the well known viscosity of macroscopic liquids.

The study of quasi-fission reactions provides new and important information relating to the relative importance of these two dissipation mechanisms. It is a characteristic of the two-body viscosity-type dissipation that it decreases with temperature. As a Fermi liquid, the dissipation properties of nuclear matter may be compared to those of liquid ^{3}He. In this latter case it has been observed that the viscosity is inversely proportional to the temperature, $\eta \sim 1/T^2$, as expected from a two-body dissipation mechanism in the framework of the general Landau theory$^{22)}$.

In Fig. 6 we plot the data presented in Fig. 5, but divided into three different bins of excitation energy, namely $E^* = 0 - 40$ MeV, $E^* = 40 - 80$

MeV and E^* = 80 - 120 MeV. The solid curves are identical to the one shown in Fig. 5. It is apparent that the same curve gives a good representation of the data in each excitation energy bin, leading to the conclusion that the characteristic time, τ, is essentially independent of the excitation energy, as expected for the one-body dissipation mechanism. We therefore view this result as a strong indication that the dissipation mechanism associated with the shape changes in nuclei, at least in the relatively low temperatures investigated in the presently cited work, has the character of one-body dissipation.

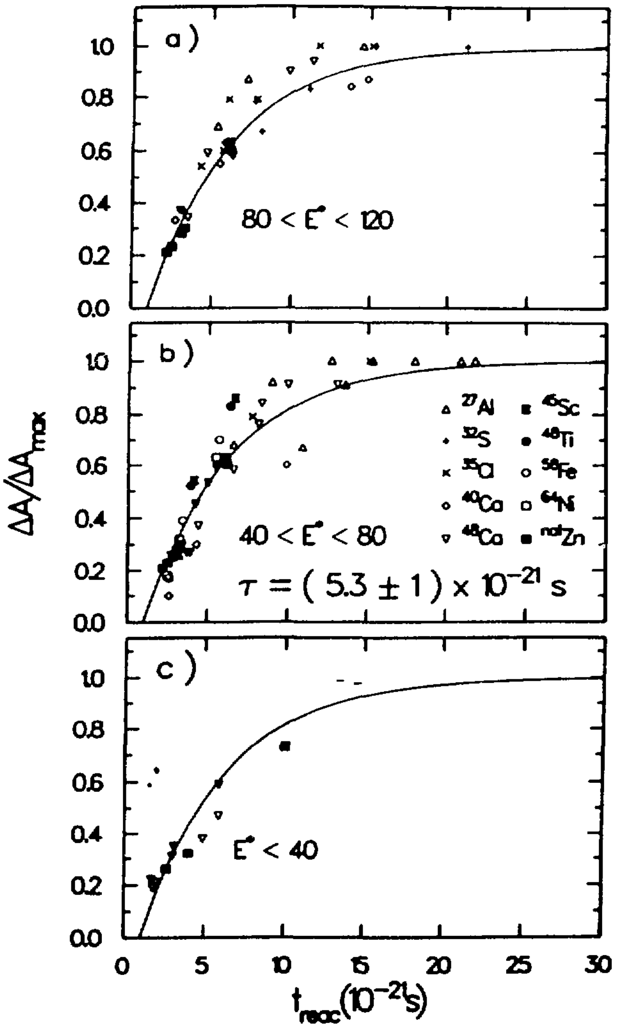

Fig. 6: Illustration of the temperature independence of the time constant for mass drift toward symmetry.

This result relies on the fact that it has been possible to measure the time evolution of the nuclear shapes in quasi-fission reactions. Although the question of the nuclear dissipation mechanism has been studied for many years in the fission process, it has been difficult to come to definite conclusions about its nature due to a lack of direct experimental information on the time scales involved. These questions can now finally be addressed thanks to the discovery of the quasi-fission process and the fact that the reaction time scale in many cases is comparable to the rotational period of the composite system, thus providing the necessary clock for measuring the reaction time.

6. Conclusion

We have seen that the quasi-fission reaction provides a natural link between deeply inelastic scattering and complete fusion reactions and that it may indeed be viewed as a completely damped reaction with substantial net transfer of mass between the two intracting ions. A central point in the study of these reactions is the fact that the reaction time often is comparable with the rotational period of the scattering complex. This provides us with a rather unique opportunity to measure the time evolution of the shape changes and the associated energy dissipation, which are taking place during the scattering process. Studies of the dissipation as a function of excitation energy of the system has lead to the fundamental result that the one-body dissipation mechanism seems to prevail, at least at the range of temperatures studied.

Although some of the basic features of the quasi-fission reactions seem to agree rather well with present theories of nuclear dynamics, it is evident that a wealth of detail remains to be studied experimentally. In quasi-fission reactions we now have the time as an experimental variable to be used in the study of the dynamics of nuclear shape changes which the classical fission reactions did not provide.

7. Acknowledgements

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