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NUCLEON EXCHANGE IN DAMPED NUCLEAR REACTIONS

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NUCLEON EXCHANGE IN DAMPED NUCLEAR REACTIONS

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Abstract Starting from the general context of one-body nuclear dynamics, the nucleon-exchange mechanism in damped nuclear reactions is discussed. Some of its characteristic effects on various dinuclear observables are highlighted and a few recent advances are described.

INTRODUCTION

This Symposium marks the 65th anniversary of the birth of John Huizenga. Through the last dozen years or so, John and his group have contributed significantly to the exploration and clarification of low-energy nuclear dynamics. A recurring theme in this endeavour has been the role of the nucleon exchange mechanism in damped nuclear reactions. It therefore appears especially appropriate to review this topic on the present occasion.

Low-energy nuclear dynamics seeks to describe nuclear systems in which the excitation energy is relatively low, i.e. the excitation energy per nucleon, or the equivalent temperature τ, is small in comparison with the typical kinetic energy of the nucleons, which is characterized by a Fermi kinetic energy of $T_F \approx 37$ MeV. Thus we are concerned with systems in which the temerature ranges from a fraction of an MeV to several MeV. In this regime, the

nuclear system can be approximately described as a Fermi gas of nucleons. Since the temperature τ is much smaller than the Fermi kinetic energy, $\tau << T_F$, the nucleon gas is highly degenerate and, consequently, the phase space for two-body collisions is largely blocked. Therefore, the nucleons move nearly independently in the one-body mean field.

The above description remains valid when the mean field develops slowly in time, as in fission or damped reactions. Therefore, at low energy where the macroscopic nuclear motion is slow, the predominant mechanism for dissipating energy from the macroscopic to the microscopic degrees of freedom is expected to be the coupling between the nearly independent nucleons and the slowly evolving one-body mean field. This "one-body nuclear dissipation" mechanism has received much attention through the past decade.*

As can readily be seen, it is a general characteristic of one-body dissipation that it is (nearly) independent of temperature, in sharp contrast to the ordinary viscosity-generated dissipation associated with common fluids. Early evidence in support of the dominance of one-body dissipation was provided by the fact that the observed kinetic energies of fragments resulting from induced

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*The condition of slow motion can be expressed as $U << V_F$, where U is the characteristic macroscopic speed (e.g. the typical speed of a surface element of a deforming nucleus or the relative speed of two reacting nuclides) and V_F is the Fermi speed of the nucleons. Typically, the idealization of slow motion is of the same quality as the much exploited <u>leptodermous</u> idealization of a thin surface, $b << R$. Indeed, for $\frac{m}{2} U^2 \approx 2$ MeV we have $U/V_F \approx 0.2$, while $b/R \approx 0.2$ for medium-heavy nuclei ($A \approx 100$).

fission are rather independent of the energy of the incident particle, and hence of the temperatures prevailing in the fissioning system.[1] More recent evidence is the fact that the relaxation times for the mass asymmetry evolution determined in quasi-fission reactions appears to be temperature-independent.[2]

Furthermore, the one-body mechanism is expected to produce a generally relatively strong energy dissipation. This is a consequence of the relatively high intrinsic speed of the nucleons. The typical energy associated with a single exciton is then not $\frac{m}{2} U^2$, as one might have expected for a structureless system, but rather $\frac{m}{2} UV_F$, i.e. a factor of V_F/U larger. Indeed, detailed studies indicate that the macroscopic nuclear motion is overdamped under the influence of one-body dissipation. The relative largeness of the elementary exciton energy also suggests that the macroscopic dynamics will be characterized by relatively large fluctuations.

A wealth of theoretical studies have been devoted to the one-body dissipation mechanism. Two simple extremes have received by far the most attention: the mononucleus and the dinucleus. For the mononucleus one considers the dynamics of volume-conserving shape distortions and, under suitable assumptions, the rate of energy dissipation is given by the simple wall formula.[3]

For the dinucleus, the most prominent aspect is the damping of the relative motion. It is instructive to distinguish between two conceptually different one-body damping mechanisms (see Fig. 1). The first consists of particle-hole excitations generated in one nuclide by the time dependence arising from the motion of the reaction

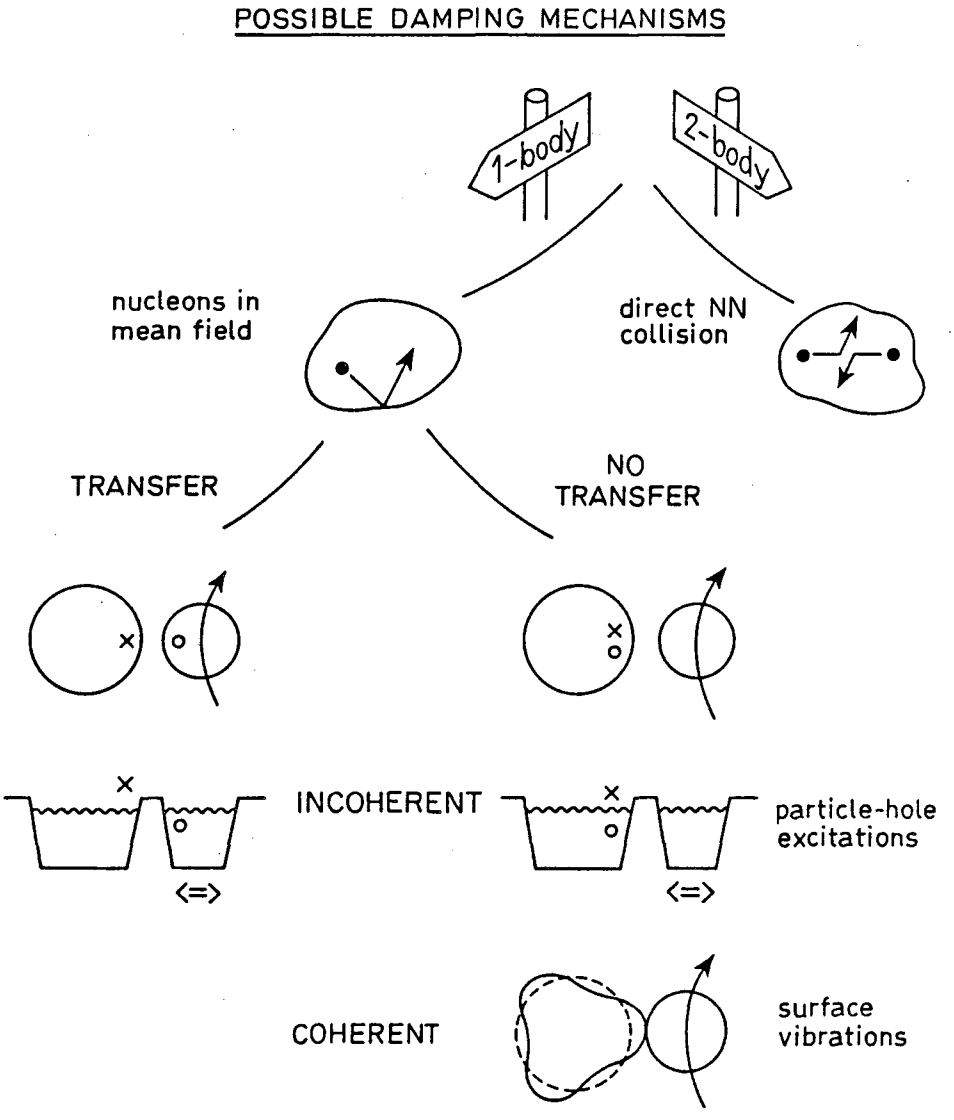

FIGURE 1 Schematic illustration of the conceptual relationship between various types of nuclear dissipation mechanisms.

partner. This mechanism involves no particle transfer and it is expected to dominate at the largest separations, where the transfer form factors fall off rapidly. However, in more intimate configurations, for which the potential is fairly flat, this mechanism becomes less effective.

The second dinuclear one-body dissipation mechanism consists in the transfer of nucleons between the reaction partner.[3] This mechanism is very effective in intimate configurations, where the nucleons can move freely from one dinuclear part to the other through a well-developed window. Since each transferred nucleon carries mass, charge and momentum, this mechanism affects the dinuclear partition of mass and charge, the energy of relative motion, and the relative and intrinsic angular momenta of the two nuclides. In particular, the associated energy dissipation is given by the simple window formula.[3] The simultaneous change in all these dinuclear observables, induced by each individual transfer, gives rise to a rich and intricate dynamical behavior reflecting the unique physical properties of the nuclear many-body system. In the following, a few selected aspects of this many-faceted topic will be briefly discussed.

RELATIONSHIP BETWEEN NUCLEON TRANSFER AND ENERGY LOSS

The essential character of the nucleon-exchange dissipation mechanism can be understood on the basis of two characteristic properties:[4]

- Kinematics of quasi-elastic transfer:

In a quasi-elastic nucleon transfer from nucleus B to nucleus A, the generated intrinsic excitation energy is

$$\omega \approx \left(\frac{m}{2} v_a^2 - \varepsilon_A \right) - \left(\frac{m}{2} v_b^2 - \varepsilon_B \right)$$
$$= (\varepsilon_B - \varepsilon_A) + (\vec{v}_a - \vec{v}_b) \cdot \frac{m}{2} (\overleftarrow{v}_a + \overleftarrow{v}_b) = F - \vec{U} \cdot \overleftarrow{p} \tag{1}$$

Here $F = \varepsilon_B - \varepsilon_A$ is the difference between the two Fermi energies ε_A and ε_B; it is also equal to the difference in the removal energies, $F = S_A - S_B$, and rarely exceeds one MeV. Furthermore, $\vec{v}_a$ is the velocity of the nucleon as seen from the donor nucleus A, and $\vec{v}_b$ is its velocity seen from the receptor nucleus B. The mean value of these two quantities gives the momentum $\vec{p} = \frac{m}{2} (\vec{v}_a + \vec{v}_b)$, and the difference is the relative nuclear velocity $\vec{U} = \vec{v}_b - \vec{v}_a$.

- Fermi-Dirac statistics:

Due to the Pauli exclusion principle, most of the desirable final orbitals are blocked so that only orbitals near the Fermi surface participate in the transfer process, i.e. $p \approx P_F$. Indeed, the transfer probability is modulated by the factor $\bar{f}^A f^B$ where f^B is the occupancy of the donor level and $\bar{f}^A = 1 - f^A$ is the availability of the receptor level.

It follows from the above two features that a typical exciton energy is $\omega_{aye} \approx \frac{1}{2} UP_F$ (which is ≈8 MeV for a typical value of $\frac{m}{2} U^2 = 2$ MeV). Since $U << V_F$, this is considerably more than $\frac{m}{2} U^2$, the amount expected for transfer of matter devoid of prior intrinsic motion. Thus the basic quantal nature of nuclei is reflected in an enhanced dissipation efficiency. It should also be noted that the large intrinsic speed makes the dynamical term $-\vec{U} \cdot \overleftarrow{p}$ in (1) dominate over the static term F, so that transfers are nearly equally likely in either direction. The ensuing back-and-forth ("diffusion-dominated")

character of the multiple transfer process makes it appropriate to adopt the word "exchange" to describe the mechanism.

It is obviously of central interest to test this characteristic feature expected for the nuclear dissipaton mechanism. A pioneering contribution to this was made by John Huizenga and his collaborators seven years ago.[5] They extracted the energy dissipated per nucleon transfer from the growth of the charge variance with energy loss. Assuming that the mass variance $\sigma_A^2 \approx \frac{A}{N}\sigma_Z^2$ measures the integrated number of individual nucleon transfers, the energy dissipated by the last nucleon can be extracted as $dTKE/d\sigma_A^2$ and therefore the coefficient

$$\alpha \equiv \left(\frac{m}{2} U^2 \frac{d\sigma_A^2}{dTKE}\right)^{-1} \tag{2}$$

indicates the factor by which the exciton energy exceeds the nominal expectation of $\frac{m}{2} U^2$. It follows from the previous remarks that one would expect $\alpha \approx V_F/U$ for nuclei. The results were in qualitative agreement with this simple estimate (and in quantitative agreement with detailed dynamical calculations), and they very convincingly demonstrated that the nuclear friction is different from that expected in analogous classical systems.

MASS AND CHARGE PARTITION

The partition of mass and charge among the two nuclides represent two important macroscopic degrees of freedom in the dinucleus and much work has been devoted to exploring the associated dynamical properties. John has played an especially active role in this effort and thanks in large

part to the efforts of him and his group we have made great progress in our understanding of the phenomenon. Much of this work will be reviewed by Udo Schröder in the subsequent presentation so it suffices to briefly summarize the current status:

The evolution of the dinucleus in the N-Z plane can be understood as a diffusion process in which the elementary step is the transfer of a single nucleon. The driving force is given by the corresponding exciton energy $\omega \approx F - \vec{U} \cdot \overleftarrow{p}$. The sign of the static contribution F depends on the direction of transfer while the dynamical contribution $-\vec{U} \cdot \overleftarrow{p}$ is independent of that. As noted above, the fact that usually $|\vec{U} \cdot \overleftarrow{p}| >> |F|$ makes the transfer process diffusion dominated, with predominantly back-and-forth transfers and relatively little average change. Consequently, the resulting mass and charge partitions exhibit small drifts but large variances. The detailed development of the mean values $\langle N \rangle$ and $\langle Z \rangle$ as well as the (co)variances σ_{NN}, σ_{NZ}, σ_{ZZ} can be understood on the basis of the underlying potential-energy surface. An important and characteristic ingredient in this picture is the fact that the effective temperature associated with this transport process is given by the quantity

$$\tau^* = \left\langle \frac{\omega}{2} \cosh \frac{\omega}{2\tau} \right\rangle \tag{3}$$

which deviates significantly from the ordinary temperature τ, particularly at early times when the relative velocity is still important. It is the presence of the above effective temperature that represents the essential difference between an ordinary (classical) diffusion

process and the dinuclear diffusion phenomenon.

Yet, more research on this topic is desirable, both experimentally and theoretically. Although a good overall understanding has been achieved, the correspondence between calculation and data is not perfect. The detailed interplay between isospin and mass relaxation is not yet universally understood. In this connection, it would be interesting to employ nuclei far from stability so that the static deriving force $\vec{F}$ can be varied over a larger domain of values. Moreoever, the nucleon-exchange transport theory has so far relied entirely on macroscopic nuclear models. For a finer reproduction of the data, the microscopic structure of nuclei may be important. For example, the inclusion of individual (shell-corrected) ground-state masses and specific level structure may be called for and will add new richness to the topic.

TANGENTIAL FRICTION

Since each transferred nucleon carries an angular momentum which is typically $\approx \frac{1}{2} RP_F \approx 4\hbar$, the dinuclear rotational modes are substantially affected by the exchange process.

The most significant ingredient in the angular-momentum dynamics is the tangential friction, which acts to reduce the relative sliding of the two nuclear surfaces and thereby reduces the orbital angular momentum of the reacting system. New insight into the dynamics of this process has recently been gained on the basis of Time-Dependent Hartree Fock calculations of the reaction 280 MeV/N $^{40}Ca + ^{40}Ca$.[6]

The numerical solution of the TDHF equations yield the

dinuclear density distribution as a function of time, thus allowing the extraction of the center separation $R(t) = \vec{R}^A(t) - \vec{R}^B(t)$ and an effective neck radius $c_{eff}(t)$ (where the exact definition is fairly immaterial). In terms of these shape parameters the time-dependent current of exchanged nucleons is given as $N(t) = \frac{1}{4} \rho\bar{v}\, \sigma_{eff}(t)$ where the effective neck area is $\sigma_{eff} = \pi c^2_{eff}$. This quantity determines the overall strength of the tangential friction induced by the exchange of nucleons and the associated transport equation for the average orbital angular momentum L(t) can then be solved. In this manner, it is possible to make direct comparisons between the self-consistent, microscopic, one-body TDHF calculation and the corresponding transport model. These studies have been very instructive for understanding the similarities and differences between the two models. The most significant differences are associated with the high degree of dynamical preservation of symmetries in the TDHF model and the finite size of the intrinsic relaxation time. This latter feature is a specific example of nuclear elasto-plasticity, the topic discussed by Nörenberg in his contribution to this Symposium.

OTHER DINCULEAR ROTATIONAL MODES

The systematic study of the rotational modes in the dinucleus is still in its infancy. In the disphere, there are six normal modes of rotation, as compared with two normal modes characterizing the mass and charge partition. The richness of the associated dynamics can be appreciated by noting that while two mean values and three (co)variances suffice to describe the dinuclear distribution in the

N-Z plane, the corresponding description of the angular momentum distribution for the disphere requires two mean values and no less than thirteen (co)variances.

The six normal modes of rotation in the disphere can be grouped into positive and negative modes. The most important are the two wriggling modes, corresponding to depositions of parallel angular momenta in the two nuclei in a direction perpendicular to the dinuclear axis $\hat{R}$. This is the type of excitation responsible for the initial braking of the sliding between the two nuclear surfaces and, if acting long enough, it will lead to a rolling situation. The dissipation of the rolling motion is caused by bending-type excitations in which antiparallel angular momenta are deposited in the nuclei perpendicular to $\hat{R}$. Since such negative modes have generally longer relaxation times, the transition from rolling to sticking happens on a considerably longer time scale (and is most often not quite completed).

Perhaps the most intriguing dinuclear rotational mode is the tilting mode whose relaxation time is the longest (and most complicated) of all. Apart from recoil contributions, the exchange of nucleons can not directly excite the tilting mode so it owes primarily its excitation to the dynamical (Coriolis) feeding from the in-plane wriggling modes, caused by the overall rotation of the dinuclear axis. Since the angle turned by the dinuclear axis provides a means for measuring the reaction time, it is possible to achieve fairly direct information on the dynamics of the tilting mode. This method has not yet been fully exploited. It was pioneered by Lüzenkirschen et al. who measured the angular distribution near the beam as a function of the fragment mass in quasi-fission reactions

where the slow mass drift permits a distinction between different angular sheets (e.g. $\theta \approx \pi$ and $\theta \approx 3\pi$.)[7] The widths of the dip in the angular distribution near the beam is directly related to the degree of tilting excitation (see Fig. 2).

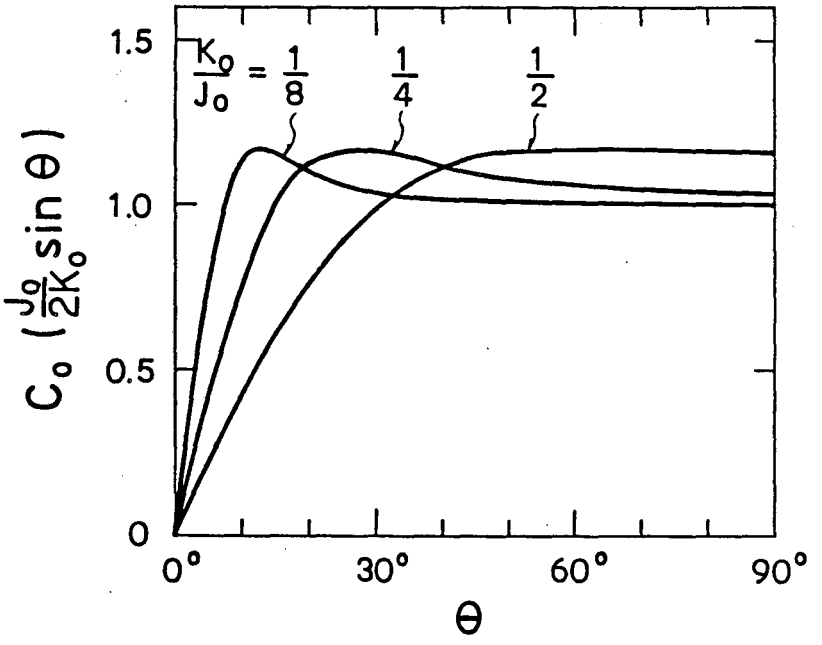

FIGURE 2 The tilting correction factor $C_0(J_0/2K_0 \cdot \sin\theta)$ by which the uncorrected differential cross section $d\sigma/d\theta$ should be multiplied near the beam.[8]

The intricate dynamical evolution of the angular momentum variables can be understood semiquantitatively on the basis of the relaxation times for the six normal modes of rotation in the disphere. An exmaple of calculated relaxation times is shown in Fig. 3. This degree of detail presents a formidable challenge to the experimentalists.

TRANSITION FROM DINUCLEUS TO MONONUCLEUS

As mentioned in the introduction, studies of the one-body dissipation mechanism have been mostly confined to the

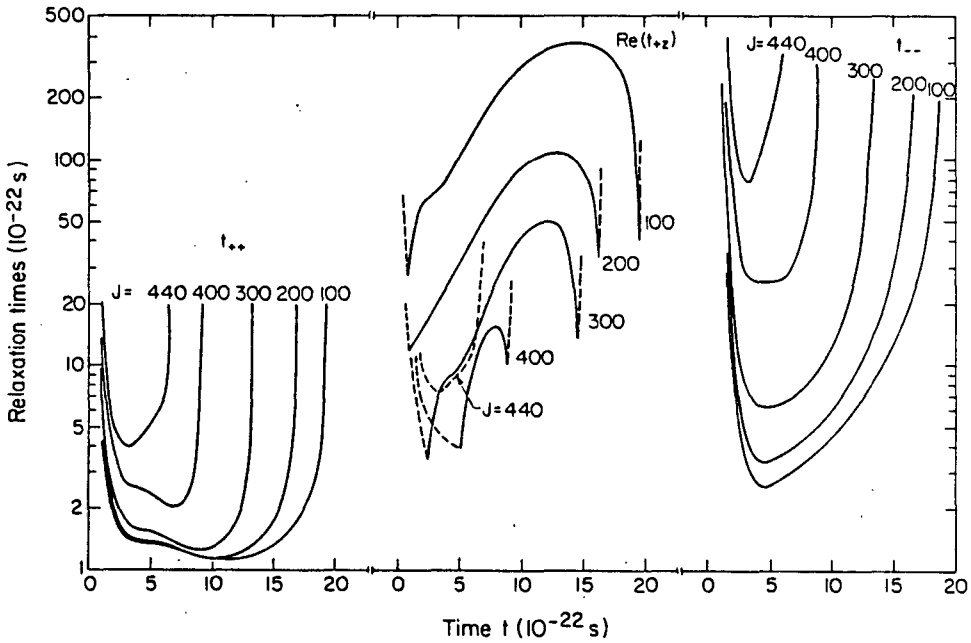

FIGURE 3 Calculated instantaneous relaxation times for the reaction 1400 MeV ^{165}Ho + ^{165}Ho for various values for the total angular momentum J. The relaxation times for the two positive transverse modes (wriggling) are denoted by t_{++}, while that for the positive lngitudinal mode (tilting) is denoted t_{+z}. The (common) relaxation time for the three negative modes (bending and twisting) is denoted t_{--}.[8]

simple extremes of either a mononucleus or a dinucleus. The recently discovered class of quasi-fission reactions are believed to proceed via mononuclei having a well-defined mass asymmetry. Such realizations of the nuclear many-body system are intermediate between mononuclei and dinuclei and the development of the one-body dissipation theory for these systems represents an exciting challenge.

Some, so far only relatively modest, progress in this direction has recently been made.[10] This work is based on the general classical theory of one-body dissipation developed by Koonin et al.[11] In this theory, the energy

dissipation rate has the form of a double surface integral,

$$\dot{Q} = \int d^2a \int d^2b \; u(a) \; \gamma(a,b) \; u(b) \tag{4}$$

as must be the case in a leptodermous system. The two points on the nuclear surface are denoted by a and b and u(a) and u(b) are the corresponding normal velocities of the local surface elements. The physical character of the dissipation is expressed in the dissipation kernel $\gamma(a,b)$ which depends on the two surface locations. In Ref. 11 it was shown that γ can be decomposed in a local and a non-local part, $\gamma = \gamma_{local} + \gamma_{non-local}$, where

$$\gamma_{local}(a,b) = m\rho\bar{v} \; \delta^2(a - b) \tag{5}$$

Here m is the mass of the nucleon, $\rho \approx 0.17/fm^3$ is the nucleon bulk density, and $\bar{v}$ is the mean nucleon speed. The non-local part of γ depends in a complicated way on the symmetries of the shape and its velocity field u(a). When these features are sufficiently irregular the non-local contribution becomes negligible and the general formula (4) reduces to the well-known simple wall formula for a mononucleus:[3]

$$\dot{Q}_{wall} = m\rho\bar{v} \oint d^2a \; u(a)^2 \tag{6}$$

The above result holds for a (sufficiently irregular) mononucleus. It has long been expected that the application of the same general theory to a (sufficiently irregular) dinucleus should lead to the corresponding window formula:

$$\dot{Q}_{window} = \frac{1}{4} m\rho\bar{v} \int d^2c \; \vec{u}(c) \cdot (\overleftrightarrow{I} + \overleftarrow{n}\,\overrightarrow{n}) \cdot u(\overleftarrow{c}) \tag{7}$$

Here the integration is over the (small) window whose normal vector is $\hat{n}$, and the local relative nuclear velocity is denoted by $\vec{u}(c)$. This expectation has recently been borne out.[10]

With this result we can now be confident that we have a theoretical basis which spans the entire domain from the compact mononucleus to the well-developed dinucleus, and thus a framework which is suitable for addressing the much more complicated intermediate regime. This work is presently underway and the progress so far holds promise that a quantitative description of transitional configurations will be established. This will be a very exciting phase of the development of nuclear dynamical theory as the number and character of the macroscopic degrees of freedom are themselves subject to dynamical change in the transitional regime.

CONCLUDING REMARKS

The study of dynamical properties of moderately excited nuclear systems is at a very exciting stage. The ever improving data, and correspondingly more refined theories, steadily advance our understanding of the topic. Not only has our quantitative understanding of the long-known damped reactions become much better, but the broader subject of low-energy nuclear dynamics has received new impetus from the discovery and exploration of the quasi-fission reaction class. At the same time, advances in accelerator capability have permitted us to extend our studies to higher energies where the simple one-body dominated dynamics is expected to gradually give way to more complicated processes.

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