Nucleus-Nucleus Collisions: A Laboratory for Studying Equilibration Phenomena

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The concept of dynamic equilibrium represents a cornerstone underlying our understanding of the gross behavior of chemical systems. Fundamental to the description of the equilibium state is the assumption that microscopic collisions between the components of a given system can be related to the macroscopic observables of that system via statistical methods. Through this approach classical thermodynamics and statistical mechanics have achieved remarkable success in accounting for fully equilibrated systems.

In recent years the major thrust of investigations into the nature of the equilibration process has shifted to nonequilibrium phenomena. Specifically, one wishes to understand the path followed by a reacting system as it evolves from some initial ordered state to the chaotic equilibrium condition. Fulfillment of this goal presents a complex theoretical and experimental challenge. It requires not only an extensive knowledge of collision dynamics, but also depends sensitively on the energy dissipation mechanism associated with two systems when they come in contact. For example, one can consider the different final states that result from the three types of collision possibilities presented by droplets of water and silly putty. At a low relative velocity two water droplets might readily coalescence into a single spherical droplet, whereas two balls of silly putty might simply stick together to form a dumbbell-shaped object; for a water droplet colliding with silly putty one might observe the flow of the water across the surface of the silly putty. In each case the dissipative forces produce a distinctly different final state. Further, by increasing the relative velocity of the collision, one can imagine quite different results might ensue.

For interacting fluids composed of atoms and/or molecules, detailed studies of nonequilibrium phenomena are complicated by the large number of particles present ($\approx 10^{10}$–10^{20}) and the experimental difficulties associated with characterization of the participants at the microscopic level. Collisions between complex nuclei, on the other hand, afford a particularly fertile environment for exploring these complex processes.[1] Nuclear matter can be viewed as a charged, quantal fluid composed of at most a few hundred fermions (neutrons and protons). Given these properties, one expects both mean-field and particle–particle collision effects to manifest themselves in nucleus–nucleus interactions. Since the first excited state in most nuclei corresponds to a temperature of $T \geqslant 10^9$ K, the initial condition for all reactants is that of the ground state. Further, by choosing reactants with different neutron/proton ratios, one can achieve a systematic variation in the chemical potential of the reacting system.

From an experimental point of view, collisions between complex nuclei also offer many advantages in characterizing the development of equilibrium conditions. First, because of the final state energies involved, complete definition of all reactants and products can be achieved, including information on mass, charge, kinetic energy, emission angle, and (in principle) final state multiplicities. This information is critical to definition of the thermal excitation (temperature) and degree of equilibration attained during the collision stage. Second, nature has provided us with a wide variety of nuclear species that can serve as target–projectile combinations, thus creating the possibility of studying reactions governed by many different potential energy surfaces. And finally, modern accelerator technology permits us to adjust the relative collision energy from the reaction threshold to relativistic energies for all projectile–target combinations. Thus, nuclear reactions afford the flexibility to study the role of energy dissipation in the equilibration process over a wide range of conditions, extending from soft encounters near the reaction barrier (controlled by the mutual Coulomb field) to violent conditions which occur at high bombarding energies. Clearly, the latter, if they can achieve equilibrium, hold the promise of forming very hot matter—comparable to the highest temperatures in the present universe.

In Figure 1 the major processes which characterize the final states in strong interactions between complex nuclei are schematically outlined. At low energies near the Coulomb barrier ($\approx$5 MeV per projectile nucleon or $E/A = 5$ MeV for heavy targets), relatively light projectiles ($A \leqslant 20$) lead primarily to complete fusion of the reactants. In contrast, heavy projectiles ($A \geqslant 60$) lead to the formation of short-lived dinuclear species, or damped collisions. Projectile masses between these extremes yield a mixture of both phenomena. As the projectile energy increases, one begins to observe evidence for precompound processes, i.e., decay of the system prior to reaching full statistical equilibrium. These nonequilibrium events first become evident at incident energies of $E/A \approx 10$ MeV, beyond which they grow in importance until they dominate the collision process in the vicinity of the Fermi energy in nuclear matter ($E/A \approx 35$ MeV). Finally, at energies near the total binding energy of the composite projectile–nucleus system ($E \approx 1$–2 GeV) multiple fragmentation events become dominant, indicative of reaching the instanta-

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(1) Schröder, W. U.; Huizenga, J. R. *Treatise on Heavy-Ion Science*; Bromley, D. A., Ed.; Plenum: New York, 1984, Vol. 2, p 115.

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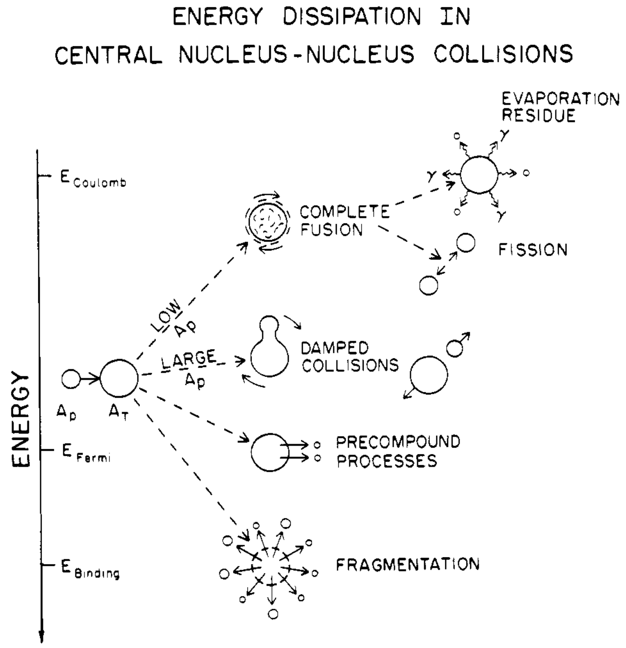

Figure 1. Evolution of collision mechanisms as a function of increasing projectile energy.

neous vaporization limit. In the subsequent discussion we examine these processes in greater depth.

Complete Fusion

When two charged fluids collide, the second simplest thing that can happen is complete fusion (elastic scattering being the simplest).[2] The complete fusion mechanism results in conversion of all of the energy of relative motion into internal excitation of the composite product or into collective degrees of freedom (e.g., rotation). In this sense it is an ideal case for the study of fully equilibrated phenomena since a distribution of final states is formed for which the temperature and angular momentum can be well-defined. Hence, these processes are amenable to relatively straightforward experimental and theoretical analysis.

In order to test experimentally for the complete fusion of target and projectile, one must first demonstrate that the full linear momentum of the projectile has been transferred to the composite system formed in the interaction. In these discussions we will deal primarily with very heavy target nuclei (e.g., uranium) in order to emphasize the statistical aspects of the collision relative to quantal properties. This choice also minimizes perturbation due to the diffuse surface of nuclei, which become increasingly important for lighter nuclei.[3]

For the heaviest target nuclei such as uranium, complete momentum transfer and subsequent mass equilibration can be confirmed via the nuclear fission process.[4] Kinematic constraints provide a convenient confirmation of full momentum transfer since the laboratory angle between the two separating fission fragments, θ_{AB}, is directly related to the linear momentum transferred from the beam to the fissioning system (see Figure 2).

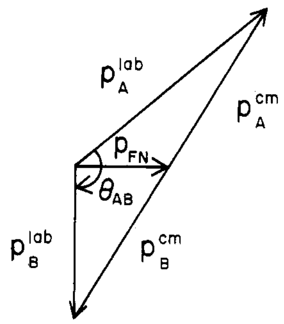

Figure 2. Linear momentum vector diagram for a fissioning nucleus with laboratory momentum p_{FN} which produces fission fragments A and B, separated by a folding angle θ_{AB}. The laboratory and center-of-mass momenta of each fragment are given by p^{lab} and p^{cm}, respectively.

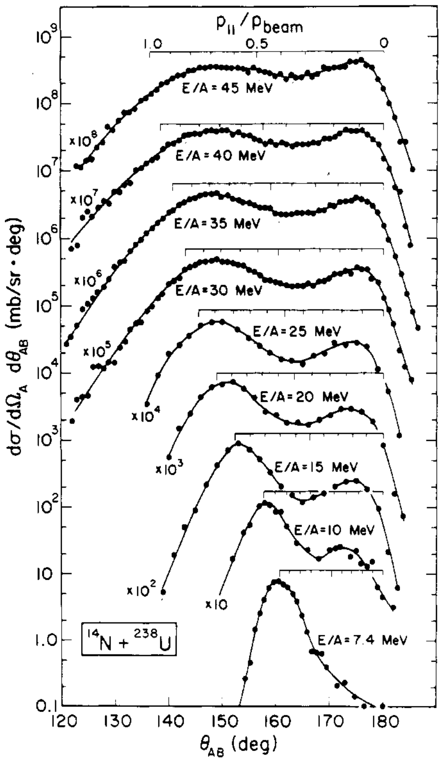

Figure 3. Fission-fragment folding-angle distributions for the $^{14}N + ^{238}U$ reaction. For each measurement a linear momentum transfer scale, $p_{\parallel}/p_{beam}$, is shown immediately above the data. Reproduced with permission from ref 5. Copyright 1985, American Institute of Physics.

In Figure 3 an example of such data for reactions between ^{14}N ions and ^{238}U is shown for several bombarding energies.[5] Here the probability for fission is plotted as a function of the measured angle between binary fission fragments. For each energy, the angle scale is also transformed into the ratio of transferred longitudinal momentum, $p_{\parallel}$, to the momentum of the beam, p_{beam}. Hence, complete fusion corresponds to $p_{\parallel}/p_{beam} = 1.0$. Because the hot fission fragments that are formed in these reactions subsequently cool by light particle evaporation, a dispersion is introduced into these experimental data. However, the average angle of separation is not distorted due to this effect.

For the lowest energies in Figure 3 ($E/A \leq 10$ MeV), one finds that the criterion of complete momentum transfer is satisfied for most of the observed events. It

(2) Koonin, S. E. Presented at the Symposium on the Many Facets of Heavy-Ion Fusion Reactions, Argonne, IL, March 1986, to be published.

(3) Morgenstern, H.; et al. *Phys. Lett. B* **1982**, *113B*, 463.

(4) Sikkeland, T.; et al. *Phys. Rev.* **1962**, *125*, 1350. Sikkeland, T.; Viola, V. E. *Proceedings Conference on Reactions between Complex Nuclei, 3rd*; University Caifornia: Berkeley, 1963; p 232.

(5) Fatyga, M. *Phys. Rev. Lett.* **1985**, *55*, 1376.

is also apparent that a component is present in the data corresponding to lower momentum transfers (approaching $p_{\parallel}/p_{\text{beam}} \approx 0$). These events have been shown to originate from large impact parameter, or peripheral, collision trajectories.[6] They are strongly influenced by the transfer of substructures of the projectile (e.g., ^{1}H, ^{1}n, ^{4}He, etc.), for which the quantal properties of the system are quite important.

From data such as Figure 3, it is possible to determine probabilities for complete fusion as a function of projectile energy for comparison with theoretical predictions. This dependence provides an important source of information about the nature of the mean-field potential which is fundamental to any description of the energy dissipation and equilibration process. Characterization of the mean-field potential is most sensitive to data at the lowest collision energies. Here the relative velocity of the projectile is much less than the Fermi velocities of the individual nucleons in the colliding nuclei. Hence, one-body energy dissipation predominates; i.e., each nucleon interacts primarily with the mean nuclear field created by the ensemble of nucleons in the composite system. Reactions in this energy regime experience a strong driving force toward the equilibrium state, since individual nucleon–nucleon collisions are not sufficiently energetic to escape the mean field. Thus, the total interaction potential for nucleus–nucleus collisions is given by

$$V = V_N + V_C + V_l \qquad (1)$$

where V_N, V_C, and V_l represent the nuclear, Coulomb, and centrifugal potentials, respectively.

At low energies predictions of complete fusion probabilities based on one-body dissipation mechanisms,[7,8] are quite satisfactory, a situation which now exists for a large body of data.[9] At higher energies, angular momentum limits for a rotating liquid drop and more complicated processes cause the fusion probability to decrease, qualitatively consistent with the data. Thus, while many problems remain, the mean-field description of energy dissipation at low energies appears to be relatively well in hand at present.[9]

Damped Collisions

Whereas for relatively light projectiles the attractive nuclear term dominates the interaction potential (eq 1), with increasing projectile mass and charge the repulsive Coulomb and centrifugal forces assume increasing importance. For very heavy projectiles, these terms become dominant and complete fusion disappears. Instead one observes the development of a new mechanism in which the energy of the projectile nucleus is strongly damped but the system is unable to fuse. These "damped collisions" represent one of nature's most dramatic energy dissipation processes, providing a rich source of information about the evolution toward equilibrium.[1]

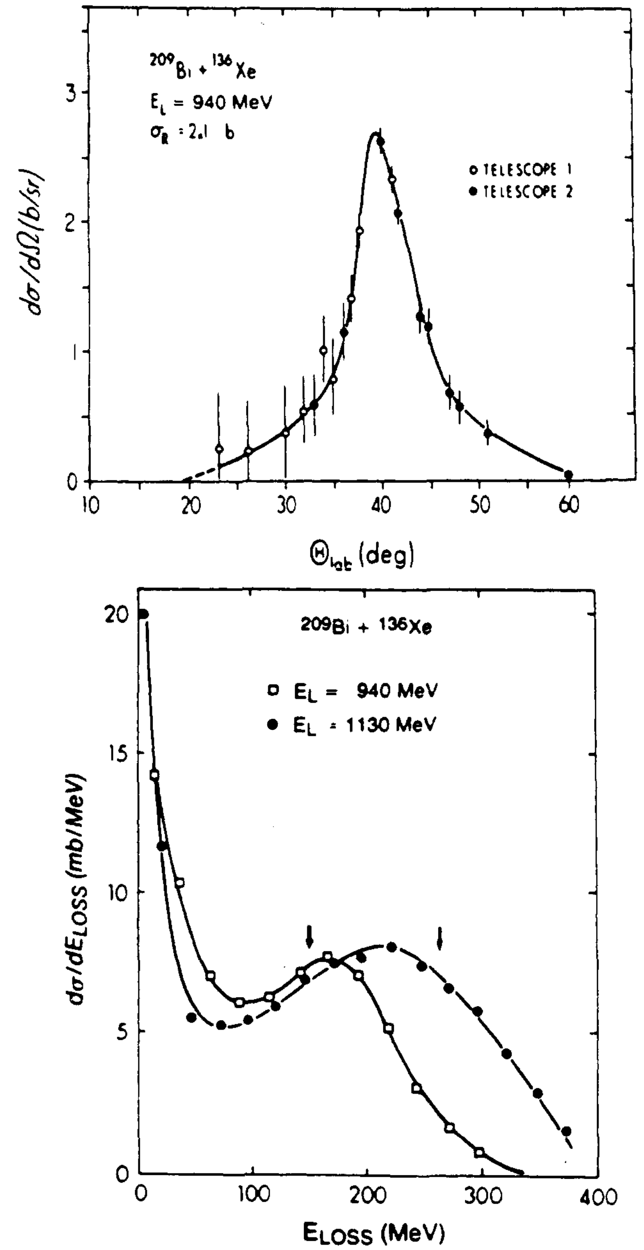

Figure 4. (a) Laboratory angular distribution of the light, Xe-like reaction products observed in the reaction of 940-MeV ^{136}Xe ions with ^{209}Bi. The curve is to guide the eye. (b) The energy-loss spectrum of the ^{209}Bi + ^{136}Xe reaction for 940- and 1130-MeV bombarding energy. The energy loss E_{loss} is defined as the difference between the center-of-mass asymptotic kinetic energies in the entrance and exit channels. The arrows indicate the available kinetic energy in the entrance channel. Data from ref 10.

As depicted in Figure 1, the damped collision mechanism involves the formation of a short-lived rotating dinuclear complex which breaks apart under the influence of Coulomb and centrifugal repulsion after a typical rotation angle of the order of $\pi/2$ (depending on impact parameter). Peripheral (large) impact parameters involve small rotation angles while more central collision trajectories lead to large rotation angles. The net result is that virtually the entire reaction cross section is focused into a small angular range,[10] as shown in Figure 4a. This angular focussing permits one to assign a time scale for the lifetime of these processes,[11] which is about 10^{-21} s (compared to a collision time of about 10^{-22} s). During this short time span, very large amounts of relative collision energy are dissipated into internal degrees of excitation of the two fragments.

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(6) Wilczyński, J.; et al. *Nucl. Phys. A* **1982**, *373*, 109.
(7) Błocki, J.; et al. *Ann. Phys.* (*N.Y.*) **1977**, *105*, 427.
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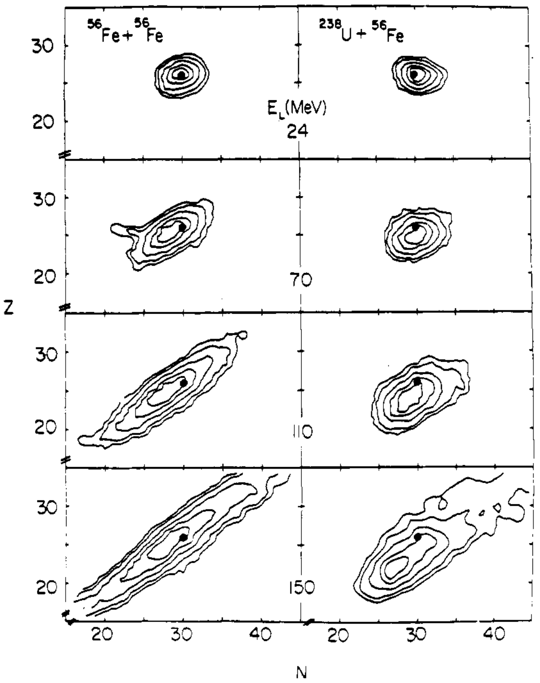

Figure 5. Contour lines of measured cross section in the N–Z plane obtained in the ^{56}Fe + ^{56}Fe reaction at 8° and the ^{238}U + ^{56}Fe reaction at 45° for energy losses E_L of 24 ± 2, 70 ± 5, 110 ± 5, and 150 ± 5 MeV. The contour lines represent 75%, 50%, 25%, 10%, and 5% of the maximum cross section of each distribution. The full circle indicates the location of the projectile ^{56}Fe. Data are from ref 12.

This dissipated energy is observed in the form of energy lost by the projectile (E_{loss}), as shown in Figure 4b.

The principal mechanism of energy loss in damped collisions can be accounted for in terms of nucleon exchange between the projectilelike and targetlike fragments. Because these reactions occur at relatively low velocities, one-body dissipation dominates the reaction dynamics, and nucleons cannot escape from the collision region. Instead, they diffuse randomly across the target–projectile interface, carrying with them momentum and creating particle–hole excitations, which serve as the vehicles of energy transfer.

On the average the net nucleon exchange between the two fragments is near zero, depending on the dinuclear potential energy surface and chemical potential effects associated with the neutron/proton ratio of each. However, the widths of the mass and charge distributions increase systematically with increasing energy dissipation—a strong indication that one is dealing with a classical diffusion process. This is illustrated in Figure 5 for the ^{56}Fe + ^{56}Fe and ^{56}Fe + ^{238}U reactions where discrete charge and mass measurements have been performed on the projectilelike products as a function of energy dissipation.[12] Lines of constant probability for production of a given proton and neutron number are shown for various energy dissipation bins. For small energy losses the contours are quite tight, indicating only a few nucleons have been exchanged. As the energy loss increases, the widths of the distributions broaden systematically and their orientation in the N–Z plane translates in the direction of the valley of β stability—i.e., toward the minimum in the N–Z potential energy surface.

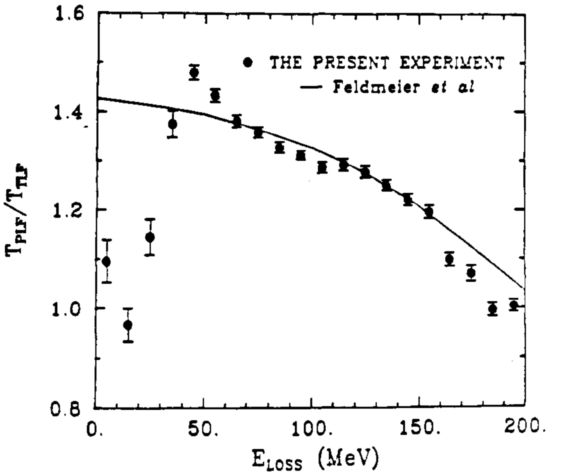

Figure 6. The ratio of projectilelike fragment temperature to targetlike fragment temperature as a function of kinetic energy loss is compared for the present data[15] and the nucleon exchange model of Feldmeier.[16]

The theoretical analysis of damped collisions has relied heavily on theoretical guidance from nonequilibrium transport theories.[13,14] Classical Coulomb trajectory calculations and the proximity potential[8] serve to define the collision dynamics, followed by the use of a Fokker–Planck equation (or similar approximations) for the treatment of nucleon transport probabilities:

$$\frac{\partial}{\partial t} P(x,t) = -\sum_i \frac{\partial}{\partial x_i}[v_i(x,t)P(x,t)] + \sum_{ij} \frac{\partial^2}{\partial x_i \partial x_j}[D_{ij}(x,t)P(x,t)] \quad (2)$$

where v_i is a drift velocity and D_{ij} is a diffusion coefficient. This approach has provided an encouraging first-order description of the damped collision mechanism.

One of the fundamental tests of this theory is its ability to predict the evolution of the system towards thermal equilibrium. For small amounts of dissipated energy the system breaks apart before the diffusion process has had time to reach full equilibration. In this case the nuclei separate with roughly equal amounts of internal excitation energy, E^*, which translates into a higher temperature for the smaller projectilelike fragment (recalling that for a Fermi gas, $T \propto (E^*/A)^{1/2}$). For large values of energy dissipation, i.e., processes where the dinucleus has remained intact for a relatively long time, one expects full equilibrium to develop. Thus, the temperature of the two fragments should be equal. In Figure 6 this dependence is demonstrated for measurements of the ^{56}Fe + ^{165}Ho reaction in a plot of the temperature ratio for the projectilelike and targetlike fragments as a function of energy dissipation.[15] Also shown are theoretical predictions based on the trajectory–diffusion model described above.[16] The success is strikingly good. However, few such comparisons of data with theory exist at present, and

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[16] Feldmeier, H.; Spangenberger, H. *Nucl. Phys. A* **1984**, *428*, 223c.

whether or not this agreement is general or specific remains to be established.

Preequilibrium Processes near the Fermi Energy

The existence of observable nonequilibrium phenomena in damped collisions finds its origin in the delicate balance between the attractive nuclear force and repulsive Coulomb and centrifugal forces associated with collisions between heavy nuclei. Thus, depending on impact parameter, the system can break apart prior to the attainment of full statistical equilibrium, interrupting the equilibration process and permitting the experimentalist to sample the system as a function of time. In the context of the subsequent discussion it is important to stress that damped collisions occur at low relative velocities, where mean-field effects and one-body energy dissipation are dominant and lead to a two-body final state.

By increasing the projectile bombarding energy, one would hope to pump increasing amounts of excitation energy into the nucleus, thereby allowing investigation of thermal properties of nuclear matter all the way to the boiling point. However, as the projectile energy increases, the relatively simple complete fusion and damped collision mechanism become complicated by the growing influence of individual nucleon–nucleon collisions within the interacting nuclear fluid. The coupling of the relative nucleon motion with Fermi motion enhances the importance of two-body energy dissipation mechanisms. These microscopic collisions are capable of producing energetic species at early stages in the time evolution of the reaction. These can escape the mean field of the composite system, removing energy and momentum from the subsequent macroscopic development of the system. At relative collision velocities in the vicinity of the Fermi velocity of nucleons in nuclear matter ($E/A \approx 35$ MeV), the probability for these preequilibrium events increases rapidly. An inherent experimental difficulty accompanies these processes in the form of multibody ($n > 2$) final states.

While the onset of two-body dissipative forces complicates the formation and study of very hot nuclear matter, it affords the opportunity to examine a rich new set of variables related to nonequilibrium phenomena. For example, the combined effects of one- and two-body dissipation may produce very hot localized regions of excitation (or hot spots) at the interface between the reactants at very early collision times.[17] This region can be assigned an instantaneous "temperature", which decays to the fully thermalized limit as the reaction evolves and energy equilibrates throughout the system. The emission of energetic ejectiles (both nucleons and more complex species) from these hot regions provides a mechanism whereby we can study the decay of the system as a function of time, enriching our knowledge of the equilibration process under the influence of two-body dissipative forces.

The transition from the mean-field to nucleon–nucleon regime can be investigated by examining the systematic development of linear momentum transfer with increasing energy,[5] shown in Figure 3. As noted previously, at low energies the reactions are well described by the complete fusion mechanism. With increasing projectile energy, however, two trends in the data become obvious. First, low-momentum-transfer events with $p_{\parallel}/p_{\text{beam}} \approx 0$ are seen to grow rapidly with energy to the point where they become the most probable events at the highest energies. This component of the reaction cross section has its origin in large impact parameter collisions in which the diffuse nuclear surface regions of the participants overlap.[18] While highly interesting in a different context, these reactions will not be examined further here.

More relevant to discussion of equilibration phenomena are the systematic trends in Figure 3 associated with large linear momentum transfers. It is observed that as the bombarding energy increases, the most probable linear momentum transfer no longer corresponds to that expected for complete fusion. Above energies of $E/A \approx$ 10–15 MeV this deviation systematically increases. Beyond the Fermi energy for nuclear matter ($E/A \approx 35$ MeV) the probability for complete momentum transfer decreases to a negligible level. This signals the disappearance of complete fusion as a significant reaction mechanism and the onset of more complex multibody final states.

In order to locate the source of missing linear momentum in these "fusion-like" reactions (implying large momentum transfer but not complete fusion), coincidence experiments have been performed in which an array of detectors is employed to detect the type, energy, and angular dependence of particles emitted in coincidence with angle-correlated binary fission events. Three-body coincidence studies of this type have demonstrated[19,20] that the missing linear momentum in central collisions ($p_{\parallel}/p_{\text{beam}} \geq 0.5$) is carried off primarily by energetic nucleons, and to a lesser extent by helium ions. These are focussed strongly in the direction of the beam axis, implying that they retain a memory of the beam direction and therefore are of a precompound origin. Further, the energy spectra of these ejectiles exhibit properties that are inconsistent with a thermal source.

In Figure 7 the spectra for protons emitted at various angles are shown for the reaction[18] of $E/A = 20$ MeV ^{16}O ions with ^{238}U. For this system the average number of emitted protons is approximately unity and the kinetic energy spectra are well-described by a functional form,

$$N(E) \propto E \exp[-E/T] \tag{3}$$

Hence, the experimental results resemble a Maxwellian distribution for emission of a single particle of energy E from the surface of a thermal source of temperature T. However, the values of T which best describe the spectra are found to be significantly larger than values expected for a fully equilibrated compound nucleus. In addition these (apparent) spectral temperatures are found to be angle dependent, with values of T decreasing from a maximum at the forward most angles to values much closer to that expected for a fully equilibrated system at far backward angles. However, even at the most backward angles, full equilibration is

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(17) Friedmann, W. A.; Lynch, W. G. *Phys. Rev. C* **1983**, *28*, 16; *Phys. Rev. C* **1983**, *28*, 950.

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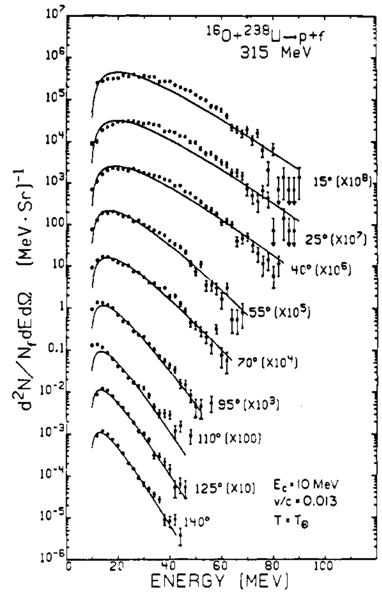

Figure 7. Energy spectra of protons observed in the reaction of 315-MeV ^{16}O ions with ^{238}U. The spectra are labeled by the detection angle of the protons in coincidence with angle-correlated fission fragments. Solid lines are Maxwellian fits assuming the compound nucleus velocity, a Coulomb barrier of 10 MeV for proton emission, and a variable source temperature, T_θ. Values of kT_θ range from 4.0 MeV at backward angles to 9.0 MeV in the forward direction. The fully equilibrated temperature is kT = 3.0 MeV.

not achieved.[18,21] This is a general phenomenon observed in reactions near the Fermi energy and has served as the basis for suggestions that these particles are emitted from a dynamic, localized region of excitation, or "hot spot", on the nuclear surface.[17,19] In this context the angle and energy of the emitted particles serve as a thermometer/clock for varying degrees of equilibration in these reactions.

The systematic increase in linear momentum loss with energy shown in Figure 3 is explained in terms of a growth in the multiplicity of preequilibrium ejectiles. These multibody events ($n > 2$) introduce the experimental necessity of constructing large detector arrays in order to account for the many-body final states which become possible at higher energies. Comparable theoretical complexity is also introduced. The observation of energetic nucleons emitted prior to equilibration strongly suggests that two-body dissipative forces play an important role in these reactions. On the other hand, while the mean field is unable to assimilate the full beam momentum, it is effective in trapping a large fraction of the incoming mass and energy.

The development of theories capable of incorporating both mean-field and nucleon–nucleon degrees of freedom has been an important recent contribution to this field. A macroscopic Boltzmann master equation approach[22] has found success in describing several important features of intermediate energy collisions. More recently, the role of preequilibrium and quantal effects in fast nucleus–nucleus collisions has been explored in terms of a microscopic Boltzmann–Uehling–Uhlenbeck approach.[23] This ambitious theory follows the series of nucleon–nucleon collisions through the time sequence of the reaction while simultaneously tracing the evolution of the mean field and including Pauli blocking effects. Thus, both one- and two-body dissipation mechanisms are accounted for. The extensive theoretical activity in this direction promises to provide a greatly enhanced understanding of fast equilibration processes in the not-too-distant future.[24,25]

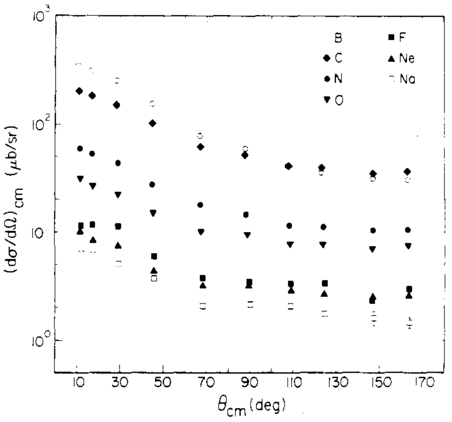

Figure 8. Angular distribution for intermediate-mass fragments in the reaction of 200 MeV ^3He with silver.[30] Symbols for each atomic number are indicated on plot.

While nucleons account for the majority of preequilibrium ejectiles from reactions near and above the Fermi energy, a great deal of recent interest has been generated by the observation of energetic complex fragments among the spectrum of reaction products.[26–31] These "intermediate-mass fragments" include nuclei with atomic numbers $3 \leqslant Z \lesssim 15$, with yields decreasing strongly as a function of increasing Z. Because these fragments are produced only at rather high excitation energies and presumably on short time scales, they may provide a sensitive probe of very hot nuclear matter, such as liquid–gas-phase transitions or localized regions of excitation.

In many respects the properties of intermediate-mass fragments resemble those of nucleons emitted from both equilibrated and nonequilibrated sources. For example, Figure 8 shows angular distributions for fragments emitted in the reaction of 200-MeV ^3He ions with silver nuclei.[30] At angles greater than 90 degrees, the angular distributions are isotropic and yield slope temperatures (eq 3) consistent with values expected for the fully equilibrated compound nucleus, suggesting true statistical equilibrium. In contrast, at forward angles a sharp increase in yield is observed; the corresponding energy spectra yield slope temperatures significantly higher than the full equilibrium value. These properties strongly support a nonequilibrium origin for fragments at forward angles, with the angle of emission providing a potential clock/thermometer with which the path to equilibrium can be followed. An additional intriguing possibility afforded by the emission of com-

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(27) Jacak, B. V.; et al. *Phys. Rev. Lett.* **1983**, *51*, 1846.
(28) Sobotka, L. G.; et al. *Phys. Rev. Lett.* **1983**, *51*, 2187.
(29) Fields, D. J.; et al. *Phys. Rev. C* **1984**, *30*, 1912.
(30) Kwiatkowski, K.; et al. *Phys. Lett.* **1986**, *171*, 41.
(31) Finn, J. E.; et al. *Phys. Rev. Lett.* **1982**, *49*, 1321. Minich, R. W.; et al. *Phys. Lett. B* **1982**, *118*, 458.

plex fragments is the determination of source temperatures from their excited state population ratios.[32,33]

The intermediate-mass fragments pose many challenging problems to our understanding of the microscopic-macroscopic relationships of complex matter. While primarily a high-energy phenomenon, they are also a rare mode of radioactive decay.[34] Even for such a simple process as first-order decay, both the quantal properties of the system and the shape degrees of freedom (e.g. effects of neck formation on the potential energy surface) play important roles. At higher energies one is faced with the situation of describing two systems which begin in their gound states, develop a high degree of chaos, and then form an entirely different ordered system—all on a time scale of 10^{-22}–10^{-21} s.[35] Among these final states are highly unusual products which cannot be explained by conventional mechanisms. For example, in the ^{3}He-induced reaction shown in Figure 8 one observes carbon fragments with over 50% more momentum than that of the beam—implying some energetic material must be moving backwards.[30] At much higher energies, the multifragmentation of nuclei also becomes observable.[36] Explanation of all of these phenomena promises to place strong demands on both experimentalist and theorist over the next several years.

Concluding Remarks

In summary, this discussion has attempted to illustrate the manner in which reactions between complex nuclei can serve to expand our understanding of the pathway from the injection of energy into a system to the attainment of full statistical equilibrium. Both one-body and two-body dissipative forces play important roles in this process, depending on energy. In the mean-field regime complete fusion permits the study of fully equilibrated systems, whereas damped collisions provide a source of nonequilibrium phenomena under conditions where one-body dissipation dominates. At higher energies, preequilibrium processes in which two-body dissipation influences the reaction dynamics strongly can be studied via the emission of energetic nucleons and intermediate-mass fragments. The quantum-statistical interpretation of these experimental phenomena has proven to be a powerful tool in explaining the low-energy behavior of nuclear matter. At higher energies the difficulties magnify significantly due to the combined influence of both one-body and two-body dissipative forces. Still, recent developments, such as the BUU theory,[23-25] have demonstrated important progress in our ability to describe highly complex interactions of nuclear matter.

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