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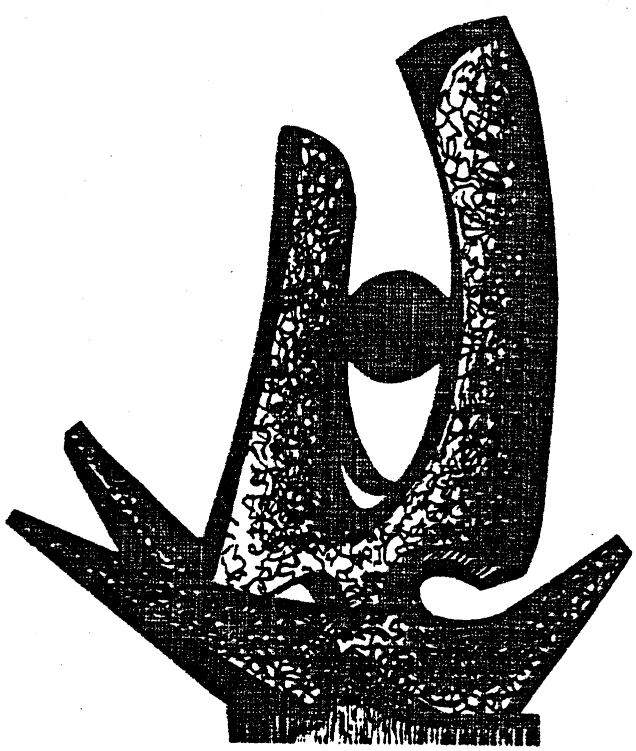
Talk presented at the Symposium "Heavy Ion 84", Mt. Fuji, August 27-31, 1984



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HEAVY-ION DYNAMICS IN A TDHF-BASED CLASSICAL DESCRIPTION

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Abstract:

We present a simple classical model based on the mean-field theory. This model is in reasonable agreement with trends in fusion cross-sections for heavy nuclei, including the barrier to fusion at high Z^2/A. A critical value of the interaction time, which leads to fast fission, is estimated from the reaction $^{238}U+^{89}Y$ at E_{lab}=6 MeV/u. Finally, we estimate the equilibration time for energy by comparing the TDHF-based classical model with recent-experimental data.

1. Introduction

In this contribution we investigate low-energy heavy-ion collisions using a simple classical model. This model is based on the dynamics of Time-Dependent Hartree-Fock (TDHF) theory which at present seems to be the best theory at the microscopic level. Unfortunately, the TDHF theory presents serious computational difficulties and sometimes the results are in disagreement with experimental data.[5] Our purpose is to reduce the mean-field theory to classical equations of motion, which can be easily solved.

This work is organized in the following way. In section 2 we discuss the equations of motions. In section 3 the results are compared with experimental data on fusion and deep inelastic scattering. Collision times are calculated for a variety of reactions and we estimate a critical value for the interaction time which leads to fast fission and is common to all systems.[4] Also, Comparison with the results of a recent experiment[6] suggests that the equilibration time for energy lies between 50 fm/c and 250 fm/c. We summarize our main results in section 4.

2. Equations of Motion

A convenient way to reduce the TDHF system to a classical form is by taking its Wigner Transform. In the limit $\hbar \to 0$, this gives the Vlasov equation

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$$\frac{d}{dt} f(\vec{r},\vec{p},t) = \{h(\vec{r},\vec{p},t);f(\vec{r},\vec{p},t)\} , \tag{1}$$

where $h(\vec{r},\vec{p},t)= \frac{p^2}{2m} + w(\vec{r})$ is the Wigner transform of the self-consistent HF hamiltonian and $f(\vec{r},\vec{p},t)$ is the phase-space distribution. The curly brackets indicate Poisson brackets.

Classically, the most important degrees of freedom are the conjugate variables $\vec{r}$ and $\vec{p}$ describing the relative motion of the two nuclei. We define these quantities as

$$\begin{pmatrix} \vec{r} \\ \vec{p} \end{pmatrix} = \int_A d\vec{r}d\vec{p} \begin{pmatrix} \vec{r} \\ \vec{p} \end{pmatrix} f(\vec{r},\vec{p},t) - \int_B d\vec{r}d\vec{p} \begin{pmatrix} \vec{r} \\ \vec{p} \end{pmatrix} f(\vec{r},\vec{p},t) , \tag{2}$$

where A and B refer to the two colliding nuclei. The Hamilton equations of motion of nucleus A, say, are found by taking the time derivative of eq.(2). Using eq.(1), and after some algebra, we obtain

$$\frac{d}{dt} \vec{r}_A = \frac{\vec{p}_A}{m} \tag{3}$$

and

$$\frac{d}{dt} \vec{p}_A = \pi r_N^2 \, \hat{n}\cdot[\tilde{\tilde{\tau}} + \tilde{1}\left(\rho\frac{\partial U}{\partial \rho} - U\right)]_{NM} + 2\pi\sigma r_N \, \hat{n} + \text{Coulomb term} ,$$

where r_N is the radius of the neck[3] formed during the reaction, σ is the surface energy[2], and we assume that $U(\vec{r}) \equiv \int d\vec{p} w(\vec{r}) f(\vec{r},\vec{p},t)$ is a local function of the density. The subscript NM denotes a nuclear-matter approximation. The particle-flux tensor $\tilde{\tilde{\tau}}$ was evaluated by Randrup.[7] We modify his prescription by introducing a time delay in the damping term.[3]

Before the nuclei touch the dynamics is well described by potential models and we shall use the Bass potential in calculations.[8]

Finally, we shall assume that the two nuclei separate into two fragments again in the rebounding phase if r_N<1 fm or a critical velocity for neck snap is exceeded[1].

3. A Comparison with the Experimental Data

For light nuclei, the reaction cross-section at energies just above the Coulomb barrier is dominated by the fusion cross-section. For very heavy

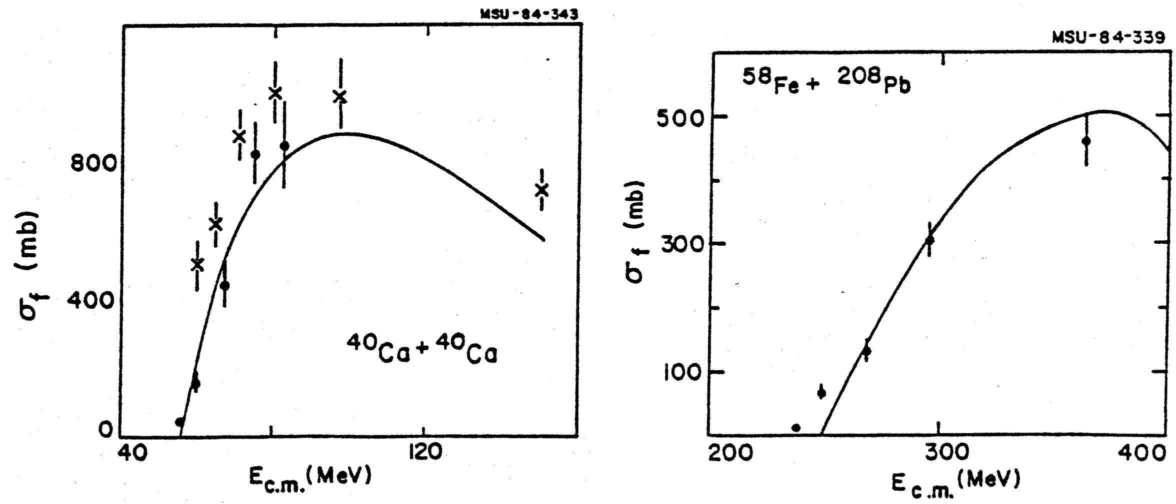

Fig.1. Fusion cross-section versus energy in the C.M. for the systems $^{40}Ca+^{40}Ca$ [10] and $^{208}Pb+^{58}Fe$.[11]

systems, on the other hand, the Coulomb repulsion is very strong, and the condition that the nuclei touch is not sufficient to cause fusion. Thus, an extra injection energy[9] is needed in order to produce fusion. These features are well reproduced by our model.[3] In fig.1 we show how our model compares with experimental data on fusion cross-sections for the systems $^{40}Ca+^{40}Ca$ [10] and $^{58}Fe+^{208}Pb$.[11] A more detailed comparison with data on fusion cross-sections for several different systems is given in ref.3.

Recently an interesting new phenomenon, called fast-fission, has been observed. Its characteristics are intermediate between fusion and deep inelastic collisions. In this case the binary fragmentation of the intermediate composite system is similar to the fission following complete fusion but with a shorter interaction time.

We estimate a critical value for the interaction time for fast fission[4] by comparing our model with the recent experimental data obtained at G.S.I. using a ^{238}U beam[12] incident on several different targets, ranging from ^{16}O to ^{89}Y.

For heavy systems the fusion cross-section is defined as

$$\sigma_{fusion} \equiv \sigma_{compound\ nucleus} + \sigma_{fast\ fission} . \tag{4}$$

For the system $^{89}Y+^{238}U$ at energy E_{lab}=6 MeV/u, the experimental fusion cross-section is less than 60 mb. Our classical model gives no contribution from compound-nucleus formation. If we assume that interaction times larger than

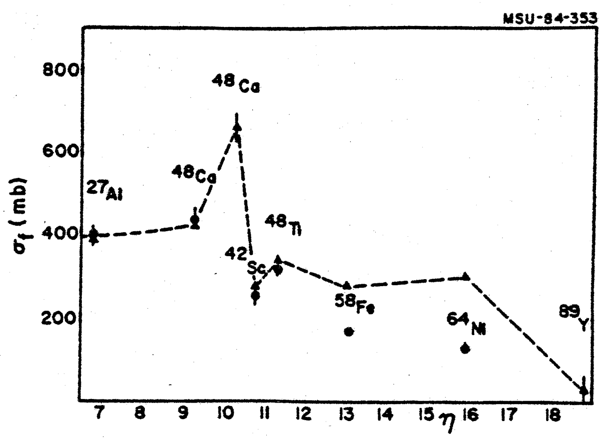

Fig.2. Theoretical fusion cross-section (triangles) versus $\eta=(Z_T^2/A_T)E_{cm}/V_B$ (see text). The different targets are explicitly indicated. The experimental data is from ref.12. The dashed lines are drawn in order to guide the eye.

8×10^{-22}sec lead to fast fission, then we obtain a value for the fusion cross-section in agreement with the observed value. This critical value of the interaction time is independent of the system involved, as we show in fig.2 where the fusion cross-section versus the quantity $\eta=(Z_T^2/A_T)E_{cm}/V_B$ is plotted. Z_T and A_T refer to the charge and the mass of the target, respectively, and V_B is the Coulomb barrier. A comparison of our classical model with other experimental data provides further evidence for the existence of a critical interaction time for fast fission.[4)]

The dominant process at higher energies is the deep inelastic scattering. As an example of this type of reactions, we discuss the result of a recent experiment on the systems $^{58}Ni+^{58}Ni$ and $^{58}Ni+^{197}Au$, at 15 MeV/u.[6)] The purpose of this experiment was to see if thermal equilibrium is attained during the reaction. If this is true, then we expect the available excitation energy to be shared between the two nuclei in proportion to the masses of the projectile and the target. The experimental values of the distributions of charge and mass, however, are in agreement with a calculation performed assuming that the energy is shared equally between the two fragments.

One possible explanation of the non-thermal partitioning of excitation energy is that at high bombarding energy, the system has too little time to reach thermal equilibrium.[3] In fig.3 we show how the interaction time and the energy loss vary with impact parameter. The maximum value for the energy loss agrees with the experimental observation. The interaction time is very short, of the order of 10^{-22}s.

The same considerations can be applied to the system $^{56}Fe+^{165}Ho$ at 8.5 MeV/u. At this lower energy, the experimental values on charge and mass distributions agree with calculations performed assuming thermal equilibrium.

In fig. 4 we plot the interaction time and energy loss versus impact parameter. For b less than 4.6 fm we see fusion. For higher impact parameters, the system has an interaction time of the order of 10^{-21}s, and it can

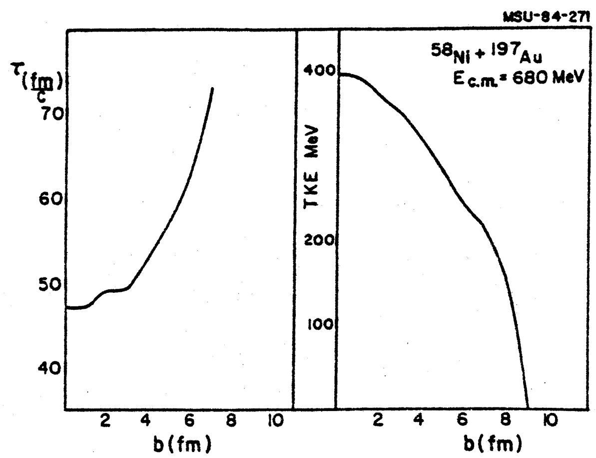

Fig.3. Interaction time and energy loss versus impact parameter for the system $^{58}Ni+^{197}Au$.[6]

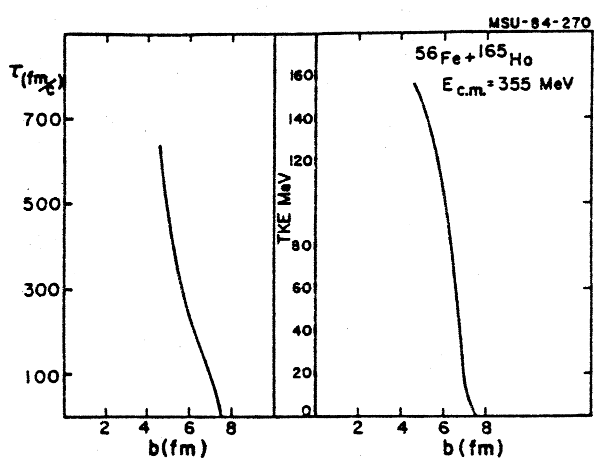

Fig.4. As fig.3 for the system $^{56}Fe+^{165}Ho$.

attain thermal equilibrium. The above results suggest that the time required by the system to reach thermal equilibrium lies in the range 50 fm/c to 250 fm/c. Bertsch[13)] has determined the time to reach local equilibrium, by considering the equilibration of a quadrupole deformation of the Fermi sphere within the Fermi-gas approximation. Our estimate is in good agreement with his numerical result.

4. Summary

In this contribution we have presented a simple classical model based on one-body dissipation. We assumed that during the reaction a neck is formed and we parametrized the radius of the neck by referring to the TDHF calculations.[2-3)] An interesting feature of this model is the delayed-damping term. During the first stage, after neck formation, this implies that the motion is superfluid, while in the second stage a strong dissipation occurs arising from one-body dissipation (superviscosity).

Our model is in good agreement with experimental data on fusion cross-sections and the barrier to fusion at high Z^2/A is reproduced as well. Fast fission occurs in our model if a critical value of the interaction time is exceeded. Such a value is common to all systems.

Finally, the equilibration time for energy was estimated by referring to an experiment at 15 MeV/u .

We plan to extend the model by including fast-particle emissions in the early stage of the reaction and stochastic processes in deep inelastic scattering.

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