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ABSTRACT

The lack of mass drift towards symmetry observed in many Kr-induced reactions, and the excessive mass drift towards larger asymmetry in Ne,Ar-induced reactons, is explained in terms of a dynamical driving force towards larger mass asymmetries due to the attempt of the smaller fragment to contain its temperature gradient with respect to the heavy fragment.

INTRODUCTION

Two striking, apparently unrelated open problems in our understanding of deep inelastic processes are the anomalous drift in mass asymmetry on one hand, and the unexpected thermal partition of the energy between fragments even at small Q-values on the other.

The former effect can be observed in the reluctance of the Kr-like fragment in reactions such as Kr + Er, Kr + Au, etc.[1] to drift toward symmetry as suggested by the potential energy surface, except at the largest energy losses. The counterpart of this effect is the overeagerness of more asymmetric systems to drift towards greater mass asymmetries well above the expectation from potential energy considerations, as observed in reactions like Ne, Ar, + Au, etc.[1] Such experimental facts seem to suggest that the evolution along the mass asymmetry coordinate is controlled by something beyond the relevant static potentials, most likely by dynamical effects. The latter effect is the surprising interfragment thermal equilibration which is observed even at small Q-values, i.e., at short interaction times, as experimentally found, for instance, from the number of neutrons emitted by each fragment.[2-4] This surprise arises from two sources: the short interaction time on the one hand, and the straightforward prediction on the other that just about any mechanism responsible for the energy dissipation tends to deposit approximately equal energy on both fragments, thus leading to a non-thermal distribution.

While these two features seem to be unrelated at first glance, they may well be connected at a deeper level as we intend to show.

THEORETICAL CONSIDERATIONS AND A SIMPLE MODEL

One could make a qualitative argument as follows. Let us assume that particle exchange is the primary means of energy dissipation. It follows that initially, the nearly equal amounts of energy given to both fragments will create a temperature imbalance in favor of the light fragment which in turn will grow hotter. Let us further assume that the one-sided particle flux depends on the temperature of the sending fragment. This would be the case for an ideal classical gas and could be the case for a Fermi gas where particles must overcome a sizable barrier. In this way, an imbalance is created in the two flows, the light fragment sending more particles, and of higher energy, than it receives. This response of the system has two effects. On the one hand, it tends to contain the temperature gradient by forcing higher energy particles into the heavy fragment and, much more important, by forcing a greater energy deposition on the heavy fragment through the flux imbalance. On the other hand, it inevitably forces the light fragment to become progressively lighter. In other words, the light fragment fights the temperature gradient at the expense of its own mass.

In order to illustrate this effect, a simple model can be set up which captures the flavor of the physics although it does not have any pretense to be realistic. The model is the following: Let us consider two containers, A, very large, and B, very small, in order to simulate an asymmetric system. They both contain the same ideal classical gas at the initial temperature T_0. The containers are connected through a small hole and B moves with initial velocity V with respect to A.

Let us calculate for B the particle number N, the velocity V, and the temperature T as a function of the time t. Assuming unity for the particle masses and neglecting the form-factor associated with the size of the hole, one obtains for N:

$$\frac{dN}{dt} = \sqrt{\frac{T_o}{2\pi}} - \sqrt{\frac{T}{2\pi}} \quad . \tag{1}$$

Similarly, for the momentum loss one has:

$$\frac{dP}{dt} = \frac{d(NV)}{dt} = -V\sqrt{\frac{T}{2\pi}} = V\frac{dN}{dt} + N\frac{dV}{dt} \tag{2}$$

or using (1):

$$\frac{d\ln V}{dt} = -\frac{1}{N}\sqrt{\frac{T_o}{2\pi}} \quad . \tag{3}$$

For the energy one obtains:

$$\frac{dE}{dt} = 2\left(\sqrt{\frac{T_o}{2\pi}}\,T_o - \sqrt{\frac{T}{2\pi}}\,T\right) + \frac{1}{2}\sqrt{\frac{T_o}{2\pi}}\,V^2 \quad . \tag{4}$$

Notice that the factor of two preceding the first term arises from the average energy flow 2T or $2T_o$. For the temperature, one obtains simply:

$$\frac{2}{3N}\left[2\sqrt{\frac{T_o}{2\pi}}\,T_o - \left(\frac{3}{2}\sqrt{\frac{T_o}{2\pi}} + \frac{1}{2}\sqrt{\frac{T}{2\pi}}\right)T + \frac{1}{2}\sqrt{\frac{T_o}{2\pi}}\,V^2\right] \quad . \tag{5}$$

We can now define the natural units of the problem:

$$n = \frac{N}{N_o} \; ; \qquad \tau = t\sqrt{\frac{T_o}{2\pi}} \; ; \qquad v = \frac{V}{\sqrt{T_o}}$$

$$T^* = \frac{T}{T_o}$$

In these units, the three differential equations read:

$$\frac{dn}{d\tau} = 1 - \sqrt{T^*} \tag{6}$$

$$\frac{d\ln v}{d\tau} = -\frac{1}{n} \tag{7}$$

$$\frac{dT^*}{d\tau} = \frac{2}{3n}\left[2 - T^*\left(\frac{3}{2} + \frac{1}{2}\sqrt{T^*}\right) + \frac{1}{2}v^2\right] \tag{8}$$

Equation (8) shows that, early in the collision, the temperature of B must increase ($T^*>1$). Thus, Eq. (6) implies that the number of particles n in B must decrease. The rise in temperature is checked by the first term in the right-hand side of Eq. (8) which tends to drive the system towards thermal equilibrium, still at the expense of n.

The full solutions of Eqs. (6), (7), and (8) are shown in Figs. 1, 2, and 3 for various values of the initial velocity. Figure 1 shows that the fragment B experiences a temperature pulse, which is of course larger for larger values of initial velocity, and which decays almost completely within one relaxation time for the velocity. Conversely, Fig. 2 shows a dramatic drop in particle number as a function of time, again the effect being stronger at larger initial velocities. Figure 3 shows the time dependence of the velocity. Notice, especially for the larger initial velocities, that its decay is not rigorously exponential.

CONCLUSIONS

As qualitatively expected, the model shows that: 1) the small fragment becomes hotter than the heavy fragment (in this case the heavy fragment, being infinitely massive, does not warm-up); 2) the temperature increase occurs early in time and is quickly checked and reduced by a diffusion imbalance; 3) the temperature containment is achieved at the expense of the particle number of the small fragment. In other words, the model predicts a driving force of dynamical origin towards larger asymmetries. Obviously, this model strives for simplicity at the expense of realism and it should be considered but an analogue, or perhaps just a metaphor, of what really may go on in a nuclear collision. Yet, the flavor of the physics may encourage those who deal and have dealt extensively with one-body dissipation and transfer to see whether such ideas may find a natural application in their treatment. One might expect this effect to be relevant especially in the quasi-elastic region where the marginal overlap of the two nuclear surfaces does create a barrier that the nucleons must negotiate in order to go from one nucleus to the other.

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FIGURE CAPTIONS

Fig. 1. Dependence of the temperature of container B upon time for different initial velocities.

Fig. 2. Dependence of the number of particles in B upon time for different initial velocities.

Fig. 3. Dependence of the velocity of B upon time for different initial velocities.

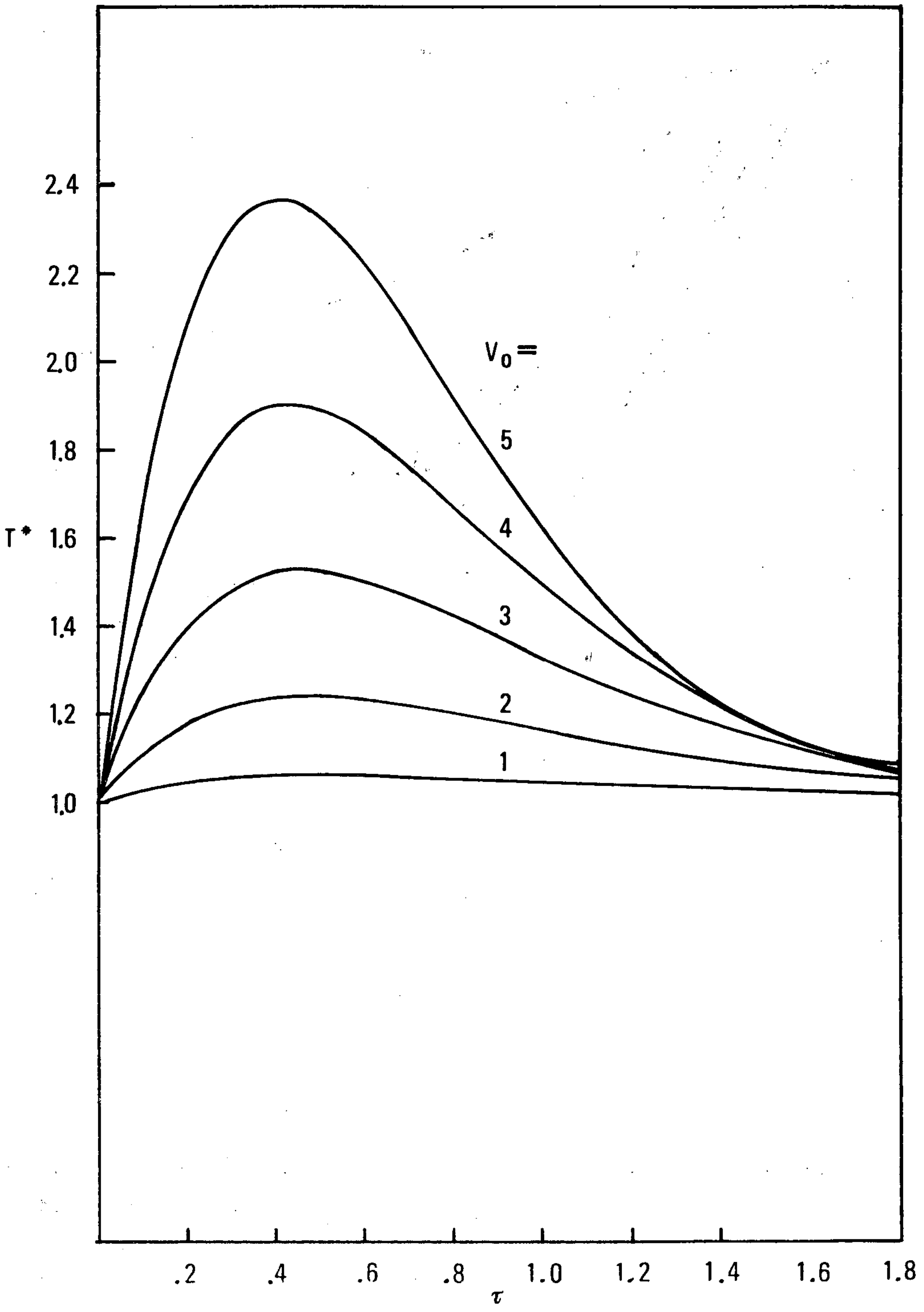

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Fig. 1

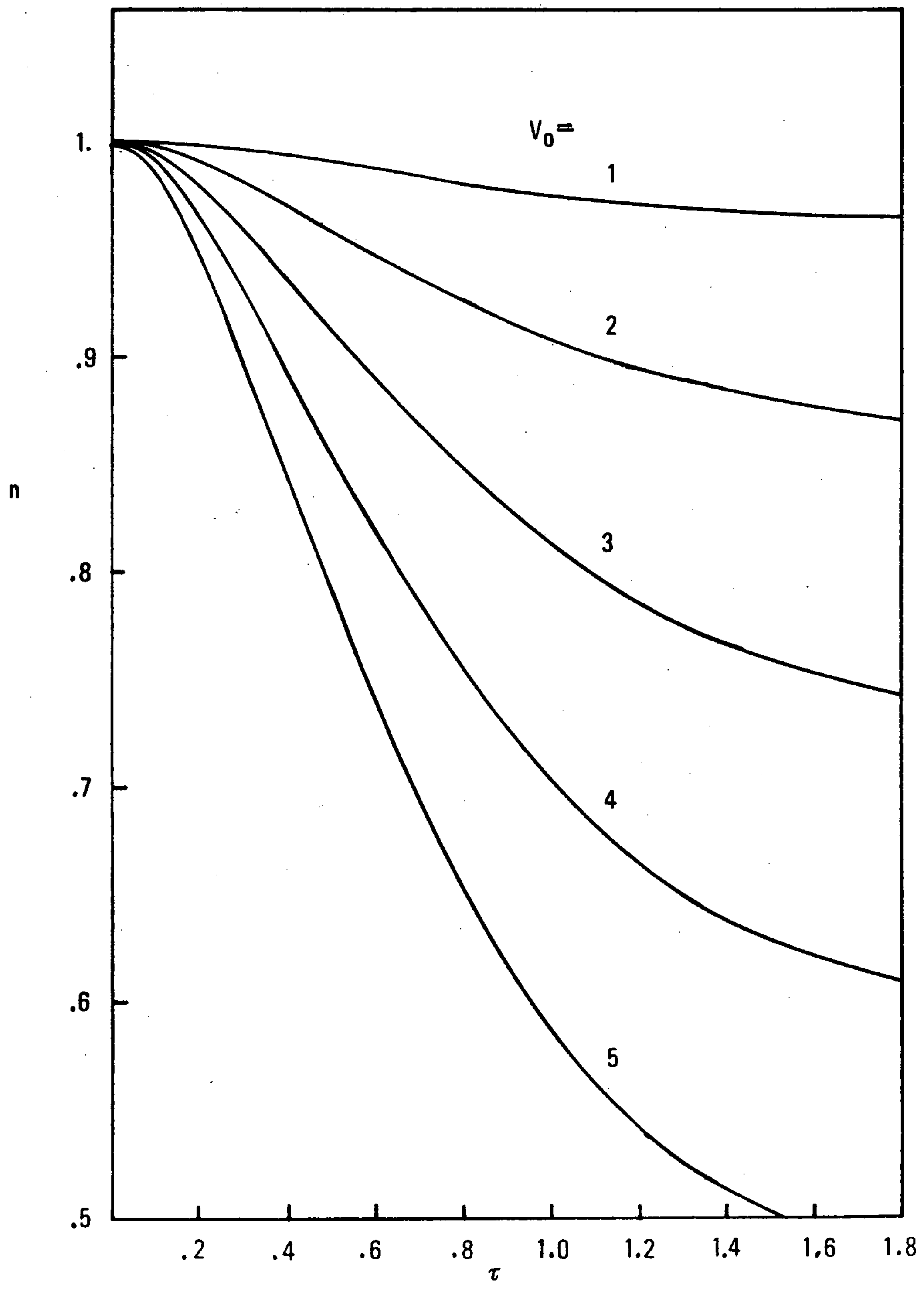

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Fig. 2

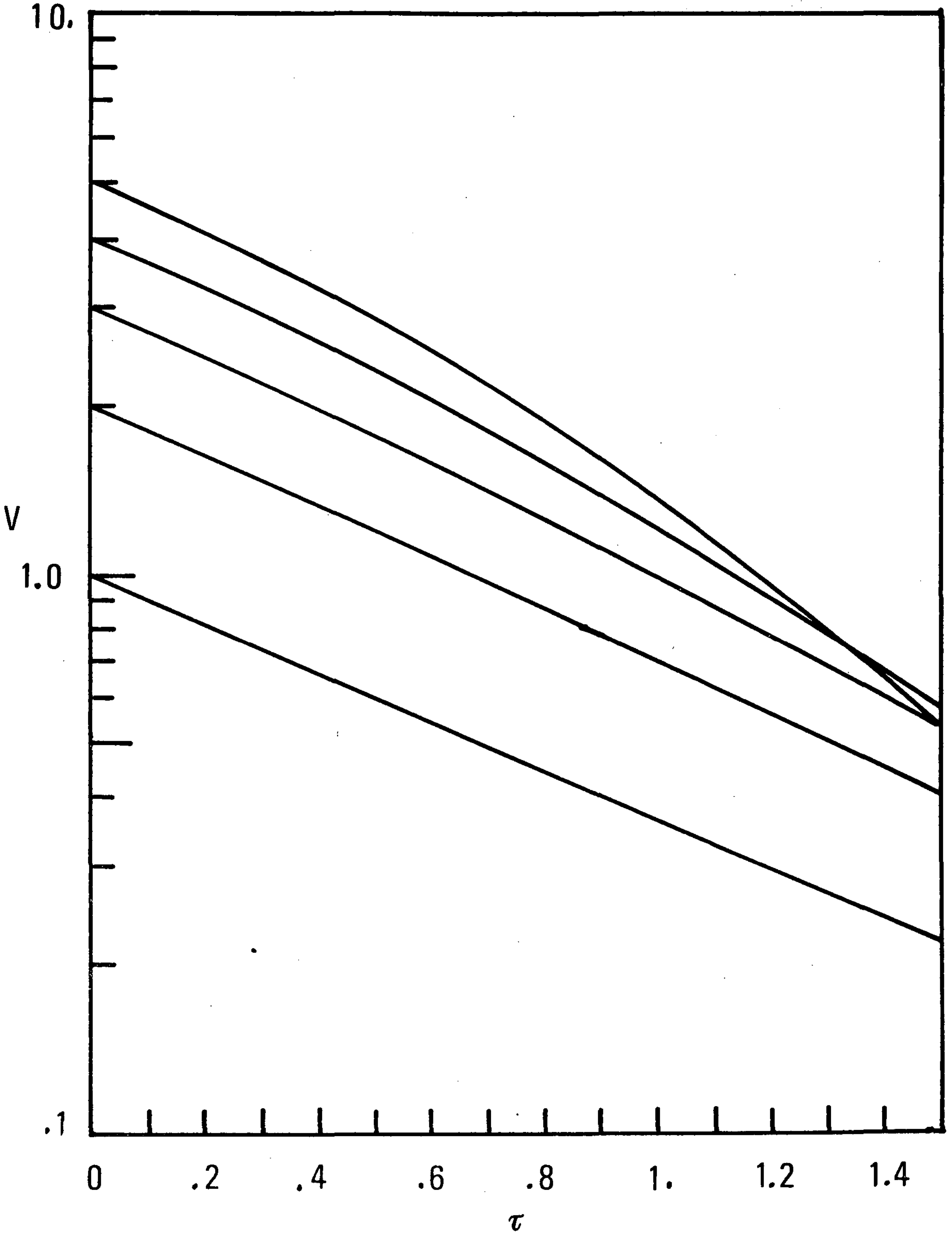

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Fig. 3

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