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Authors

Moretto, L.G.
Babinet, R.P.
Galin, J.
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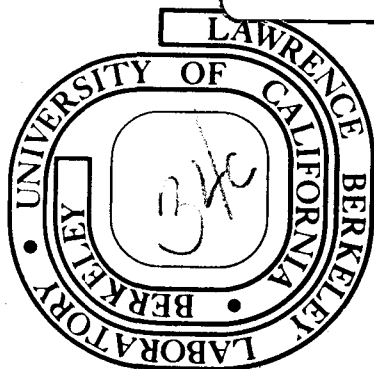
L. G. Moretto, R. P. Babinet, J. Galin, and S. G. Thompson

November 1974

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EXPERIMENTAL EVIDENCE OF A DIFFUSION PROCESS
ASSOCIATED WITH THE MASS ASYMMETRY DEGREE
OF FREEDOM IN HEAVY ION REACTIONS[*]

L. G. Moretto,[†] R. P. Babinet,[‡] J. Galin,[§] and S. G. Thompson

Chemistry Department and
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

Abstract: Dramatic changes of fragment angular distributions over a large range of atomic numbers in the reactions induced by ^{14}N, ^{20}Ne, and ^{40}Ar on natural Ag targets are interpreted as evidence of a diffusion-controlled evolution of an intermediate complex along the mass asymmetry degree of freedom.

The reactions Ag + 160 MeV ^{14}N,[1] Ag + 252 MeV ^{20}Ne,[2] and Ag + 288 MeV ^{40}Ar [3-5]) studied by our group have shown that, invariably, a broad distribution of products is observed, their atomic numbers ranging from one to the sum of the atomic numbers of target and projectile. A large fraction of the cross section for these products is associated with "relaxed" kinetic energy distributions which center at energies close to the Coulomb barrier of the two complementary fragments in contact and whose width is more or less consistent with complete thermalization of the initial kinetic energy.

Insofar as their kinetic energy spectra are concerned, these components of the cross section could be easily interpreted as compound nucleus decay products, and therefore may be confused, on the one hand, with evaporation components in the case of light particle emission, or on the other hand, with fission products in the case of the emission of sizable fragments.

Indications that a different reaction mechanism other than the compound nucleus process is involved can be found in the charge out/or mass distribution of the products as well as in their angular distributions.

The analysis of the charge or mass distribution could in principle establish whether the mass (charge) asymmetry degree of freedom is in fact equilibrated. It is easy to show that the expected equilibrium distribution should be approximately given by:

$$P(Z) = K(Z, T) \exp[-V(Z)/T] \quad ,$$

where the "ridge line" potential energy $V(Z)$ is that of a saddle point constrained to the asymmetry defined by the atomic number Z of one

of the two fragments and $K(Z, T)$ is a factor slowly varying with Z and T; T is the saddle point temperature. Implicit in all the above is the assumption, valid for most combined systems with $A < 200$, that saddle and scission configurations are sufficiently close to prevent any substantial change of asymmetry in the evolution from saddle to scission (or infinity). Calculated ridge lines for the three systems mentioned above are shown in figure 1.

In practice the reliability of the potential energies calculated from the liquid drop model is somewhat uncertain. Therefore the analysis of a single experimental charge or mass distribution, which is broad and does not show a peak centered at the projectile (and target) charge or mass may be inconclusive.

A comparison of the charge or mass yields for similar combined systems with different initial asymmetries is more fruitful.

In our data (^{14}N + Ag, ^{20}Ne + Ag, ^{40}Ar + Ag) there appears to be some evidence that the charge distributions depend upon the initial asymmetries (fig. 2). The cross sections appear to be enhanced in the Z region below the projectile for ^{14}N + Ag, in the Z region above the projectile for ^{40}Ar + Ag and appear to be rather constant and intermediate between the two previous cases for ^{20}Ne + Ag.

An inspection of the corresponding potential energies shows that whatever the angular moments involved, the initial asymmetry or injection point for ^{14}N + Ag definitely lies to the left of the potential energy maximum, on a very steep potential energy slope. If an intermediate complex were to be formed at this particular asymmetry, the potential energy should drive the system towards extreme asymmetries and very small atomic numbers, as observed.

In the ^{40}Ar + Ag system the injection point is to the right of the maximum on a gentle slope leading to the minimum at symmetry. The experimental cross sections indeed appear to increase monotonically towards symmetry.

In the system ^{20}Ne + Ag the injection point is very close to the maximum, perhaps slightly to the left, thus making this system more similar to ^{14}N + Ag than to ^{40}Ar + Ag. The experimental cross sections appear to be leveled with some tendency to increase towards both the large asymmetry and the symmetry region.

This pattern of non-equilibrium distribution does not appear to be consistent with a hydrodynamical evolution of systems with small viscosity. The kinetic energies associated with the emitted particles appear to be completely thermalized, as observed above. In the limiting case of a low viscosity hydrodynamical regime, one should expect to find a sizable fraction of the kinetic energy in a few collective modes of the system, resulting in larger values of the final kinetic energies of the products.

Another limiting possibility which we are proposing here postulates that the time evolution of the intermediate comples (two touching fragments) occurs by diffusion of nucleons between the two fragments. The two fragments are assumed to be in thermal equilibrium within themselves and with each other at any stage of the diffusion insofar as all the degrees of freedom are concerned, with the exclusion of the asymmetry mode. In other words, the asymmetry mode appears to be the slowest mode, its evolution being so slow that, for each value of the asymmetry, all the other modes have time to attain statistical equilibrium.

The evidence of incomplete equilibrium in the mass asymmetry coordinate presented so far may be considered doubtful because of the uncertainty in the potential energies and in the range of angular momentum. Fortunately, a striking evidence for the occurrence of relaxation along the mass (charge) asymmetry mode can be obtained from the angular distributions of the various particles, shown in fig. 3.

All the angular distributions in the center-of-mass are forward peaked to a variable extent and show also a much less pronounced backward peaking. This asymmetry in the forward-backward peaking is a strong indication that decay is occurring in a time either comparable to, or shorter than, the mean rotational period. If the decay were to occur on a time scale much larger than the rotational period, then the angular distributions would be symmetric about 90° and in the limit of high angular momenta they would be proportional to $1/\sin\theta$.

Since the rotational periods for the l waves which are most likely involved in the cross sections in question are of the order of 10^{-20} sec., it follows that the systems decay in a comparable time.

A further conclusion can be drawn from the observation that the kinetic energy spectra at all angles are essentially relaxed (thermalized). This means that the dissipation of the initial kinetic energy into the thermal degrees of freedom occurs on a time scale shorter than the mean rotational period.

However, the most interesting conclusion to be drawn from the angular distributions arise from the variations in the forward peaking from one atomic number to the other. These variations appear to be directly associated with various stages of diffusion of the intermediate

complex along the asymmetry mode. This can be seen best by considering simultaneously the experimental angular distributions shown in fig. 3 and the potential energies shown in fig. 1.

The angular distributions associated with the reaction ^{14}N + Ag vary dramatically as one moves from atomic numbers smaller than the projectile to atomic numbers larger than the projectile and closer to symmetric division. The particles with atomic number lower than the projectile appear to be highly forward peaked. As one goes beyond the atomic number of the projectile and moves towards higher atomic numbers, the forward peaking decreases rapidly until for $Z \geqslant 12$ the angular distributions follow essentially a $1/\sin\theta$ dependence.

This pattern can be qualitatively explained in terms of the diffusion hypothesis. The injection point in the asymmetry parameter is to the left of a potential energy peak on a very steep hill. The "drift" component of the diffusion process tends to follow the potential and quickly populates all the atomic numbers below 7 which can also decay quickly and thus generate a substantial forward peaking. The cross section for higher atomic numbers must arise from the spreading associated with the diffusion which must also deal with a rising potential energy. Therefore the particles with $Z > 7$ are populated on a longer time scale and with a larger time spread. This is more evident the farther the particle is removed in Z from the projectile. Particles with atomic number larger than the projectile should then show a forward peaking decreasing with increasing Z.

The same pattern can be observed for the angular distributions associated with the reaction ^{20}Ne + Ag. Again the angular distributions

for atomic numbers smaller than the projectile are very forward peaked while those associated with particles with Z above the projectile quickly become symmetric with increasing Z. As in the previous case, the injection point is somewhat to the left of the maximum in the potential energy, thus leading to the same qualitative features.

Quite an opposite pattern can be observed in the angular distributions associated with the reactions ^{40}Ar + Ag. The forward peaking never becomes as large as in some of the previous cases. Furthermore it shows a slight decrease as one moves from the Z of the projectile to lower Z's.

An inspection of the potential energy shows that the injection point is now somewhat to the right of the maximum. Cross sections for the lower Z can only arise from the spreading associated with the diffusion. A slight uphill potential appears to be delaying the systems moving towards lower atomic numbers and thus reducing the overall forward peaking. Furthermore the lower Z particles are farther removed from the projectile and are reached by diffusion on the average at a later time. This is consistent with a decreasing forward peaking with decreasing Z.

If the above interpretation is correct, it appears possible to study relaxation phenomena in nuclear systems on a time scale of the order of 10^{-20} sec. A very extensive experimental investigation is being carried out for various combinations of targets and projectiles at various bombarding energies in order to obtain a general overview of this new kind of phenomena.

Furthermore initial theoretical studies on the detailed aspects

of the diffusion process seems to yield satisfactory agreement with the available experimental data.

In general the diffusion hypothesis predicts that a $1/\sin\theta$ angular distribution should be expected for fragments with atomic numbers far removed from the projectile. Therefore it follows that symmetry about 90° is <u>not</u> a sufficient condition for compound nucleus decay.
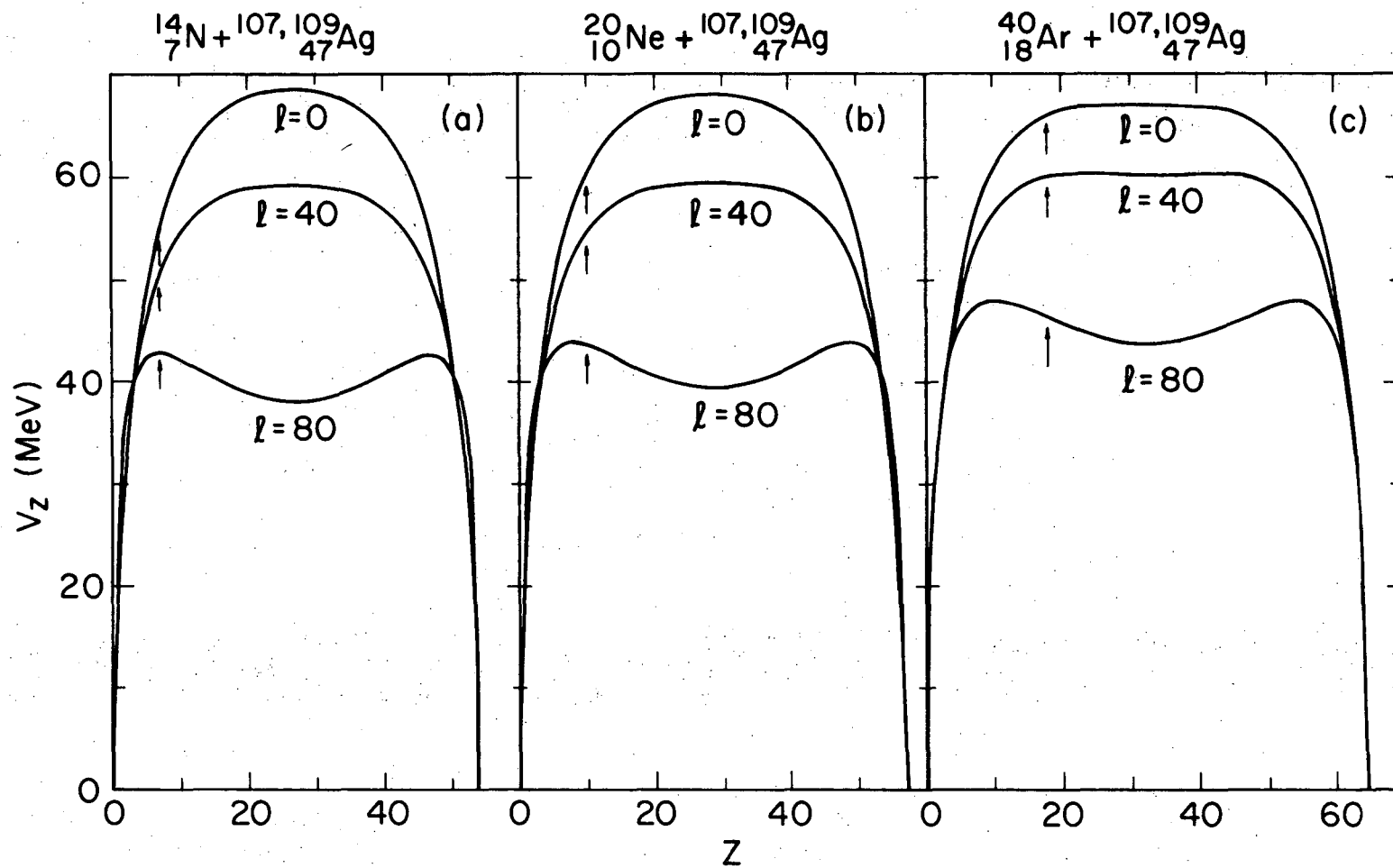
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FIGURE CAPTIONS

Fig. 1.　Potential energies of the intermediate complex vs. asymmetry (expressed by the Z of one of the fragments). The label on each curve refers to the angular momentum of the system. The calculation has been performed for two touching spheres.

Fig. 2.　Cross sections for the production of particles as a function of atomic number at various laboratory angles.

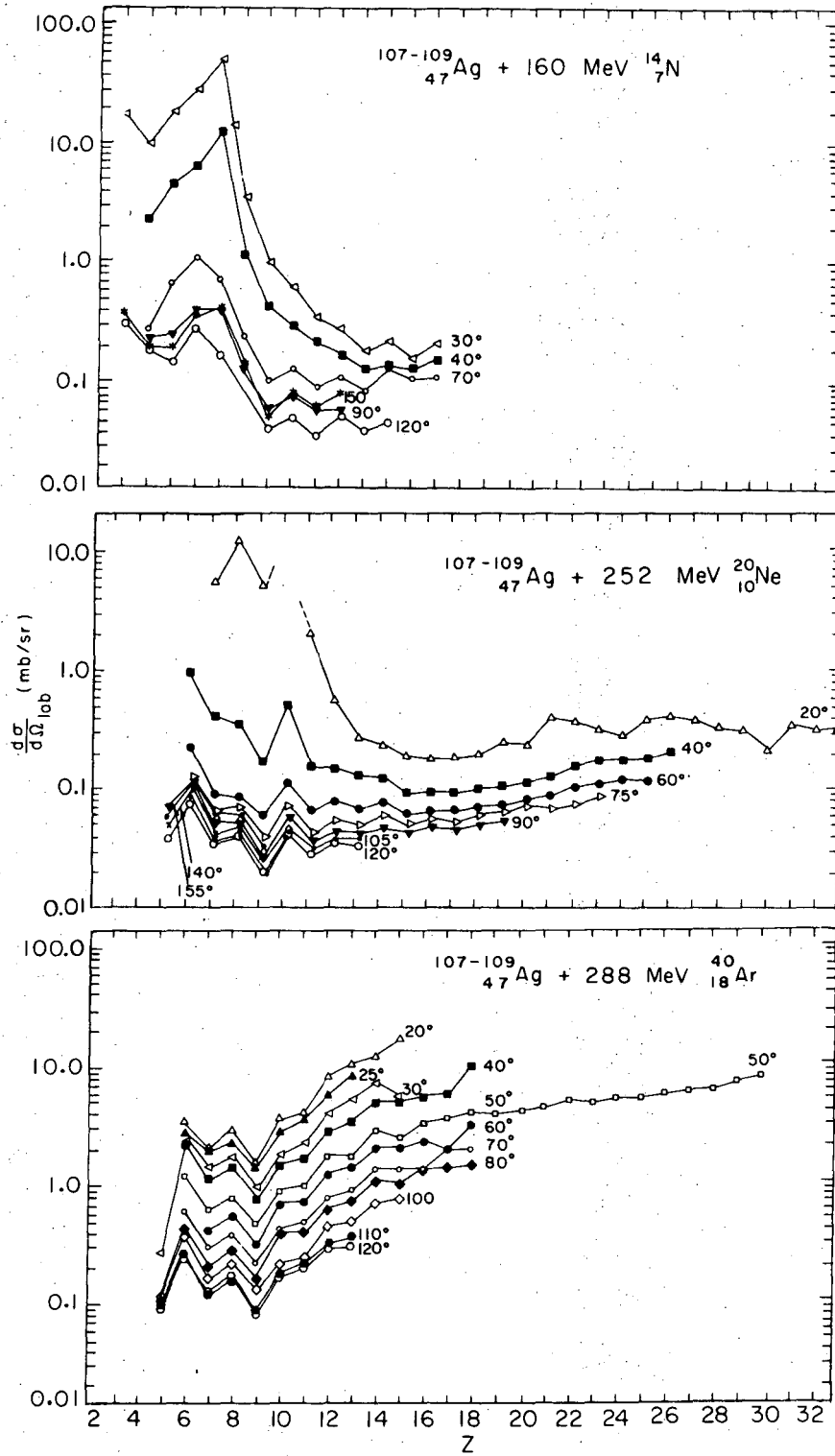Fig. 3.　Center-of-mass angular distributions for various fragments.
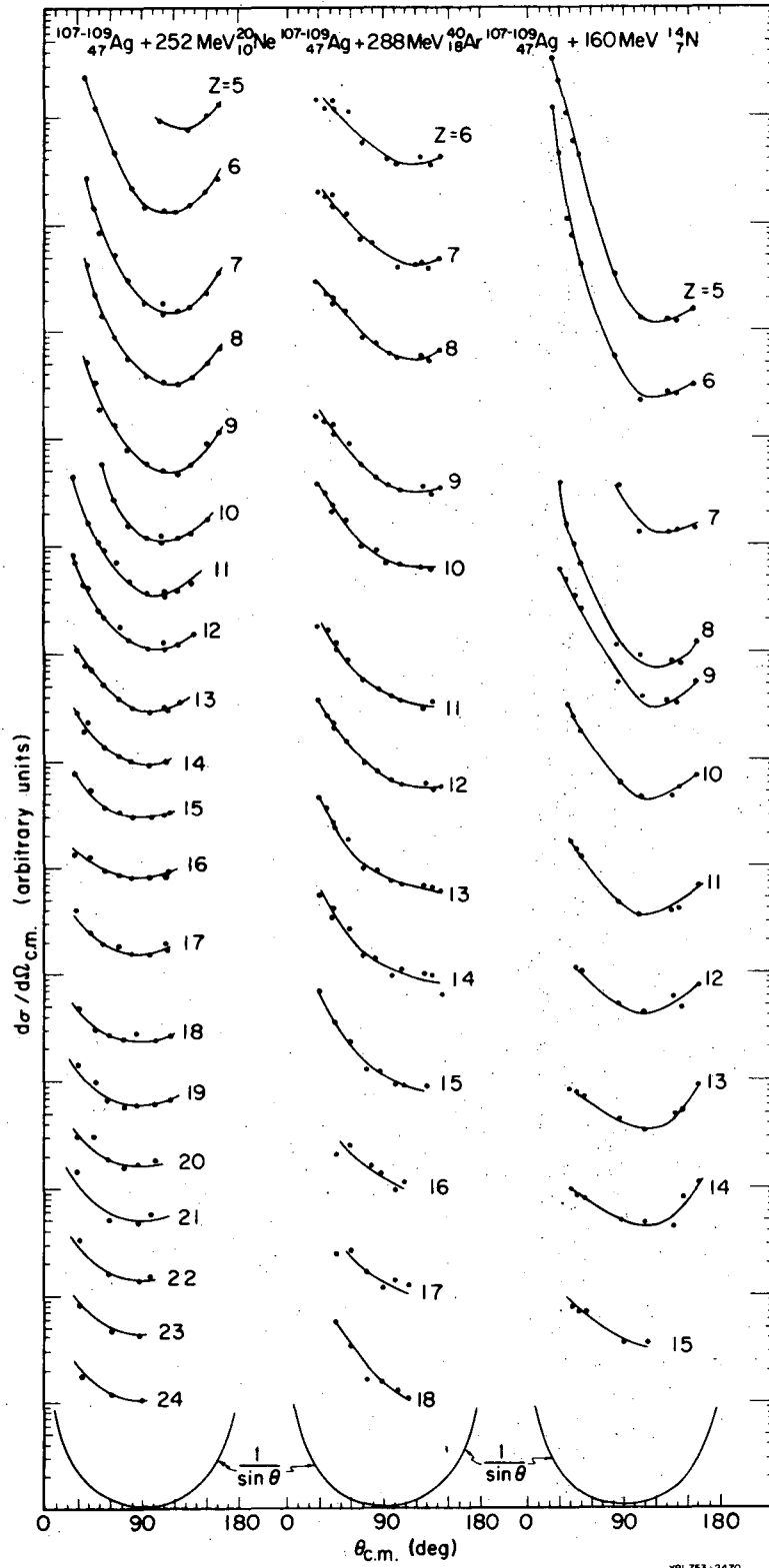
Fig. 1

XBL753-2474

Fig. 2

XBL7411-8216

Fig. 3