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DIFFUSION MODEL PREDICTIONS FOR HEAVIER SYSTEMS: THE REACTION ^{197}Au + 620 MeV ^{86}Kr

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Diffusion Model Predictions for Heavier Systems: The Reaction ^{197}Au + 620 MeV ^{86}Kr *

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ABSTRACT

The cross sections and angular distributions for fragments emitted in the reaction 620 MeV ^{86}Kr + ^{197}Au have been calculated using the Diffusion Model to describe the approach to equilibrium of the reaction system along the mass-asymmetry coordinate. The calculated quantities are compared with experimental results, and extensions of the theory are discussed.

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In the reactions of relatively "light" target-projectile systems (Ar + Ag[2], Ne + Ag[3], Ar + Au[4], Kr + Ag[5]), the measured angular distributions for the relaxed (deep-inelastic, strongly-damped) component of the reaction products exhibit a striking feature, common to all systems: the forward peaking of the distributions is Z-dependent, with the forward peaking largest for the projectile Z and diminishing as the product Z is farther removed from the projectile Z. This general feature is explained by following the approach to equilibrium of the "intermediate complex" (formed in these reactions) along the mass-asymmetry collective coordinate using the Diffusion Model [1]. The diffusion process, as described by the master equation, introduces a progressively longer time-delay in the population of configurations farther removed in Z from the projectile Z. This allows the complex to rotate for a longer time and to generate an angular distribution more symmetric about 90°.

Recent experiments performed by our group have shown a Z-dependent side peaking of the angular distributions for particles emitted in the reactions of "heavy" target-projectile systems (Kr + Au[6], Kr + Ta[7], Xe + Au[8]). This side peak is largest for the projectile Z, diminishes to a shoulder for Z's removed on either side of the projectile, and eventually becomes a forward peak for Z's sufficiently removed from the projectile (see fig. 2a). This pattern of increasing equilibration of the angular distributions as the system is farther removed from the initial configuration is analogous to that seen for "light" systems and should be predicted by the Diffusion Model. The shapes of the angular distributions differ from "light" to "heavy" systems because of differences in the average lifetime of the complex as compared to the average rotational period. For the "light" systems, the relatively small Coulomb field and small moment of inertia of the complex make the lifetime of the complex long enough compared to the rotational period to allow partial orbiting, resulting in forward peaked angular distributions [9]. The larger Coulomb field and larger moment of inertia for the "heavy" systems combine to make the lifetime of the complex too short to allow partial orbiting and leads to side peaked angular distributions.

In addition to the features described above, the width of the Z distribution for a given center-of-mass angle increases as the center-of-mass angle is farther removed from the angle corresponding to the side peak in the angular distributions (see fig. 3a).

As in the previous paper [1], we have used the Master Equation to follow the time-dependent population $\phi_Z(t)$ of systems whose mass-asymmetry is characterized by the atomic number Z of one of the fragments. We have assumed an equilibrated neutron to proton ratio, as shown to be true by Galin, et. al. [10]. The potential energies used are those for two touching spherical fragments as in ref. [1]. A plot of a typical potential energy curve vs. asymmetry can be seen in fig. 1a.

The time dependence of the populations ϕ_Z is given by:

$$\dot{\phi}_Z = \sum_{Z' \neq Z} \lambda_{ZZ'} [\phi_{Z'}\rho_Z - \phi_Z\rho_{Z'}] \qquad (1)$$

where $\lambda_{ZZ'} = \lambda_{Z'Z}$ is the microscopic transition probability between systems specified by the asymmetries Z and Z', and ρ_Z is the level density of the system specified by Z. The level densities can be written in terms of the potential energy of the intermediate complex V_Z, discussed above, measured with respect to the rotating ground state, as $\rho_Z = \rho(E - V_Z)$. The $\lambda_{ZZ'}$ are the product of a diffusion constant κ and a normalized form factor [1]. We have assumed that the high nuclear temperatures involved (2-3 MeV) eliminate correlations between nucleons, so that, in the limit of the independent particle model, the sum in eq. (1) is restricted to $Z' = Z \pm 1$.

The system of equations in eq. (1) can be solved by standard matrix techniques to give the time-dependent populations $\phi_Z(t)$ (normalized to 1). Fig. 1b is a map of contours of constant probability, calculated for the potential energy given in fig. 1a, plotted as a function of mass-asymmetry Z and the time t (in units of 10^{-22} seconds). Note that the drift and spread of the distribution can be easily discerned for short times, and the equilibration of the distribution can be seen for long times.

With the $\phi_Z(t)$'s, we can calculate the differential cross sections as:

$$\frac{d\sigma_Z}{d\Omega}(\Theta) = \int_0^\infty dt \left\{ \sum_b \frac{bP(b)}{\sin\theta \left|\frac{d\Theta}{db}\right|} \phi_Z(b,t)\, \Pi(t;b) \right\} \qquad (2)$$

where P(b) is the probability that a collision at impact parameter b leads to a deep inelastic reaction. For this calculation, P(b) = 1 for all impact parameters $b \leqslant b_{lim}$, and P(b) = 0 for $b > b_{lim}$. The quantity b_{lim} is such that the cross section resulting from collisions at impact parameters in the range $b_{lim} \leqslant b \leqslant b_{max}$ (b_{max} corresponds to a grazing collision) is equal to the quasi-elastic cross section measured for Z's near the projectile Z at lab angles near the grazing angle. The sum in eq.(2) is carried over all impact parameters b which result in a particle Z being emitted at the angle θ after the complex has lived a time t. The quantity Π(t;b) is the probability that the complex formed by a collision at impact parameter b will live a time t. In the previous work, we have assumed $\Pi(t;b) = \frac{1}{\tau} e^{-t/\tau}$, independent of b with τ being the average lifetime of the intermediate complex. Moretto, et. al. [6], have shown that the variation in the width of the Z distributions with angle can be explained by an average lifetime for the complex which decreases with increasing b. In the light of these results, these calculations have been performed with:

$$\Pi(t;b) = \frac{1}{N(b)} \exp\left[-\left(t - \tau(b)\right)^2/\sigma^2(b)\right] \qquad (3)$$

where N(b) is a normalization factor and $\tau(b) = \tau(0)\ (1-b/b_{max})$. This linear form for τ(b) is the simplest that such a decreasing lifetime can take, and trajectory calculations using a volume-type friction in the radial coordinate (similar to the calculation performed by Tsang [11]). have yielded a τ(b) similar to the linear form used. Since the dispersion in any random walk process varies linearly with the elapsed time [12], we have assumed that $\sigma^2(b) = \sigma^2(0)\ (1-b/b_{max})$. The quantity τ(b) represents the average lifetime of the complex formed at impact parameter b, and $\sigma^2(b)$ represents the dispersion of the distribution of lifetimes about this average value. For these calculations, the values of $\sigma^2(0)$ and τ(0) are parameters but can in principle be determined from trajectory calculations.

The parameters used were: $\kappa = 0.25 \times 10^{21}$ sec^{-1} fm^{-2}, $\tau(0) = 3.5 \times 10^{-21}$ sec, and $\sigma(0) = 1.0 \times 10^{-21}$ sec. The calculations have not been optimized with respect to the value of κ, and the value used was chosen because of the success of the previous work on light systems. The position and width of the side peak depends very strongly upon $\tau(0)$ and $\sigma^2(0)$, as one might expect. The position of the side peak in the experimental angular distribution determines $\tau(0)$ very uniquely, and $\sigma^2(0)$ has the effect of making the side peak broader or narrower. The value of $\tau(0)$ should be compared with the rotational period of 8.6×10^{-21} seconds for the average ℓ-value of 185. The value of $\sigma(0)$ would seem to indicate a very strong coupling of intrinsic modes to the collective motion during the collision.

The angular distributions measured recently by our group [6] for 620 MeV $^{86}Kr + {}^{197}Au$ are displayed in fig. 2(a). The general features discussed above, such as the Z dependent side peaking, can be seen quite clearly as one scans Z's both above and below Z = 36. Figure 2(b) shows the angular distributions calculated for this system using the model described above. Note that the magnitude of the side peaking is greatest for Z = 36 and decreases on either side of the projectile. The gradual disappearance of the side peak for Z's above the projectile almost exactly parrots the experimental distributions. The distributions for Z's below the projectile follow a similar pattern, but the side peaking disappears too quickly (after too few Z's). This seems to be due to the assumption of two touching spheres for the shape of the intermediate complex.

Figure 3(a) shows the experimental Z-distributions for constant center-of-mass angles measured by our group. Note the increasing width of the distributions around Z = 36 as one moves both forward and backward in the center-of-mass with respect to 60^0. As mentioned previously, this has been attributed to a decreasing lifetime for the intermediate complex with increasing impact parameter [6]. Figure 3(b) is an analogous plot of the calculated values. The lack of shift of the most probable value in the experimental results is probably due to the difficulty of separating the relaxed component from the quasi-elastic component near the grazing angle.

The absolute cross sections for Z's above the projectile are in agreement within a factor of 2, but the cross sections for Z's below the projectile are in error by much more. The large difference between the experimental and theoretical cross sections seen for Z's much below 36 can again be attributed to our assumption concerning the shape of the complex. Relaxation in the shape of the two touching fragments should allow the Z's below 36 to be populated on a much larger scale.

In conclusion, the Diffusion Model is able to duplicate the qualitative experimental features of the relaxed component observed in the reactions of "heavy" systems like $^{86}Kr + ^{197}Au$. Calculations are currently being performed in which the time-dependence of the kinetic energy of the relative motion of the projectile and target is explicitly followed, thereby generating kinetic energy distributions as well as Z distribution. Such an approach should describe the features of both relaxed and quasi elastic components in a continuous manner.

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FIGURE CAPTIONS

Figure 1. (a) Potential energy of the intermediate complex as a function of Z for $\ell = 50$.

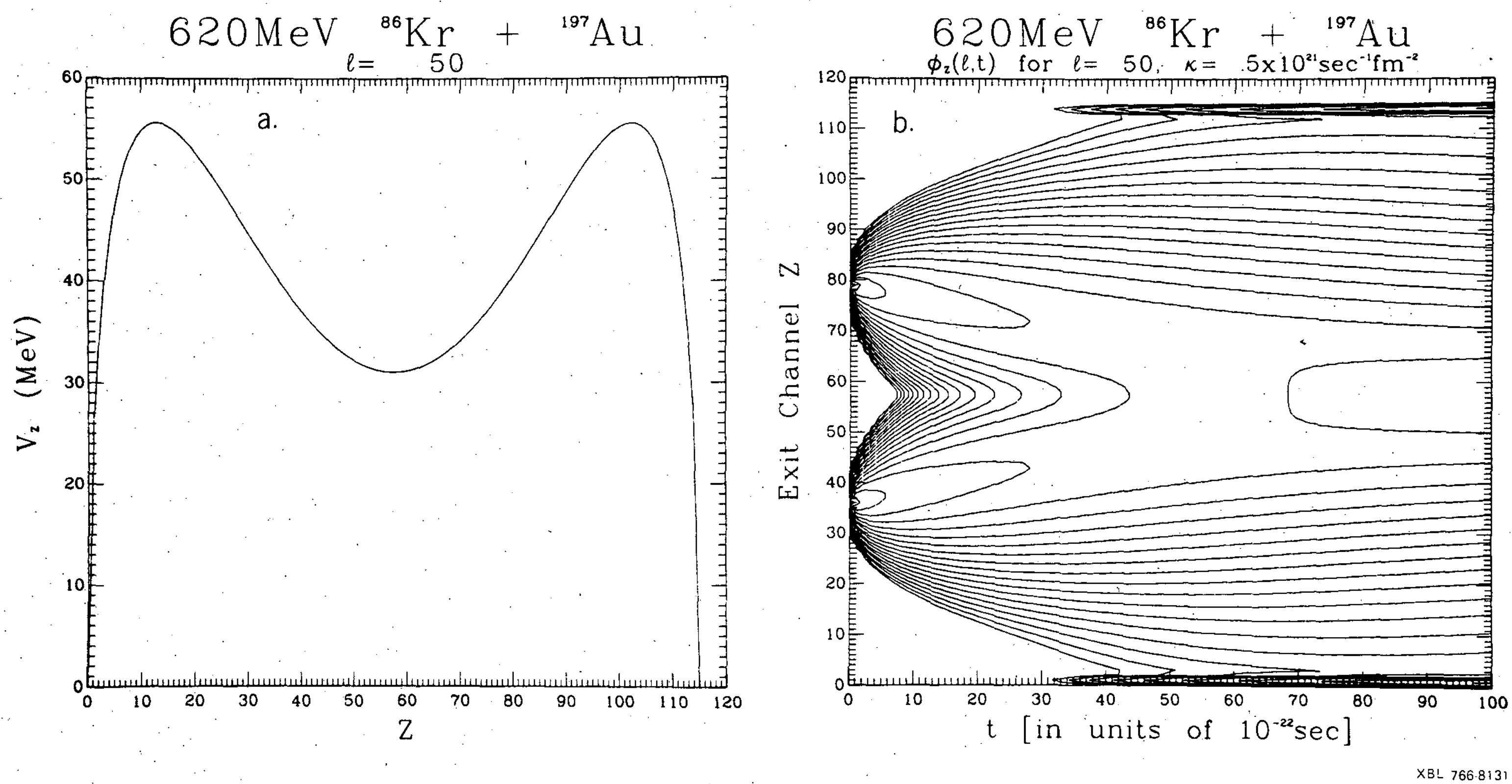
(b) Probability distributions along the mass-asymmetry coordinate as a function of time calculated for $\ell = 50$.

Figure 2. (a) Experimental center-of-mass angular distributions for the reaction ^{197}Au + 620 MeV ^{86}Kr.

(b) Theoretical center-of-mass angular distributions for the same reaction using model described in the text.

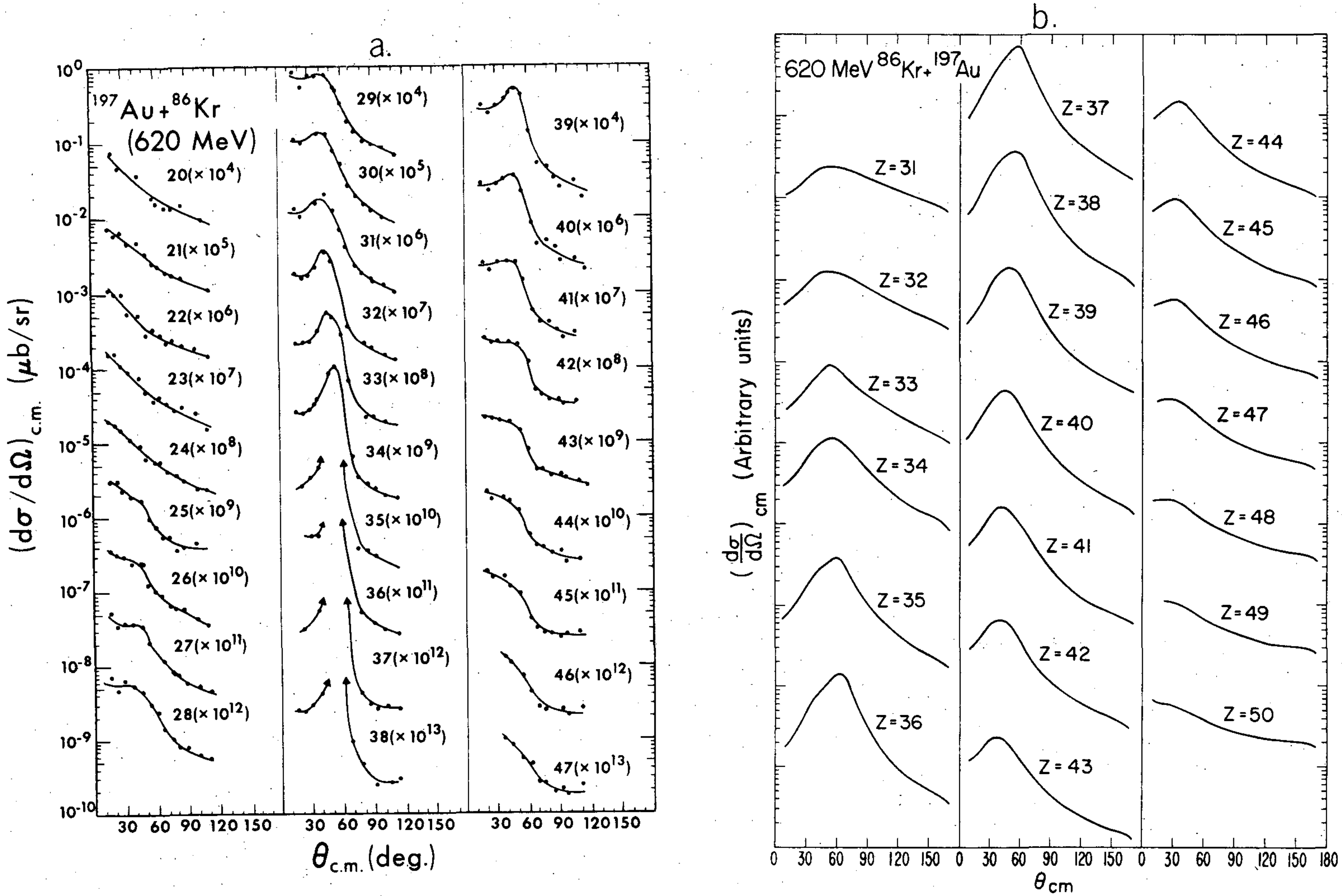
Figure 3. (a) Experimental change of distributions for fixed center-of-mass angle for 620 MeV ^{86}Kr + ^{197}Au.

(b) Theoretical charge distributions for the same reaction using model described in the text.



620MeV 86Kr + 197Au
ℓ= 50
a.
Vz (MeV)
Z
620MeV 86Kr + 197Au
φz(ℓ,t) for ℓ= 50, κ= .5x10²¹sec⁻¹fm⁻²
b.
Exit Channel Z
t [in units of 10⁻²²sec]
XBL 766-8131

Fig. 1



XBL 766-2905A

Fig. 2

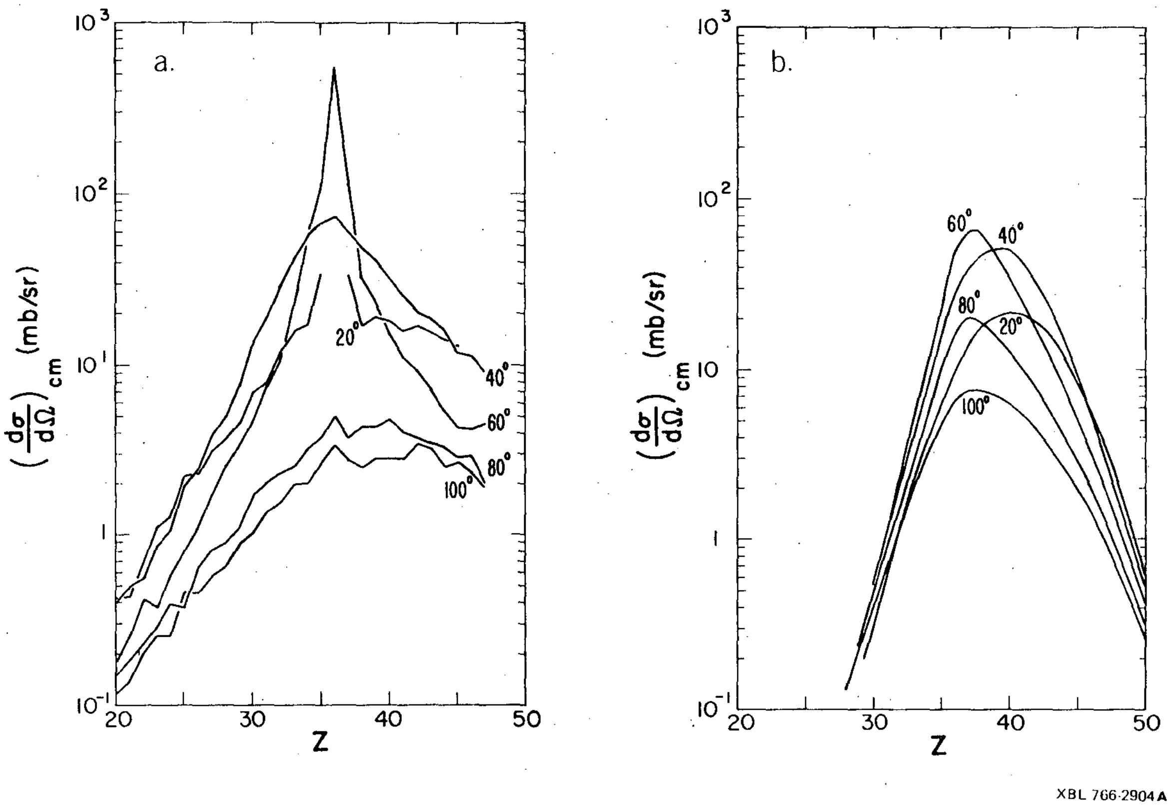

a.
b.
10^3
10^2
10^1
1
10^{-1}
20
30
40
50
Z
$\left(\frac{d\sigma}{d\Omega}\right)_{cm}$ (mb/sr)
20°
40°
60°
80°
100°
10
XBL 766-2904 A

Fig. 3

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