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THEORETICAL CORRELATION BETWEEN ENERGY DISSIPATION, ANGULAR MOMENTUM TRANSFER AND CHARGE DIFFUSION IN DEEP INELASTIC REACTIONS

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ABSTRACT:

The Z-dependence of the transferred orbital angular momentum into the intrinsic spins of deep inelastic collision partners is studied. The correlation between energy loss and nucleon transfer calculated by the present method is compared with that derived by previously proposed empirical methods. The currently used empirical approaches appear to be subject to serious systematic errors.

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A central problem in the analysis of deep inelastic reactions is the determination of mass, charge and angular distributions for individual angular momentum bins.[1,2,3] In principle, distributions can be derived by plotting the cross section $\partial^2\sigma/\partial Z\partial[\mathrm{TKE}]$ in the charge vs. total kinetic energy (Z-TKE) plane and drawing lines on this map corresponding to constant entrance channel angular momenta (ℓ). The resulting distributions as a function of ℓ-bin can then shed light on quantities such as the Fokker-Planck coefficients for describing the time-dependence of the charge-asymmetry degree of freedom.[1] Two different empirical prescriptions for drawing the lines of constant ℓ have been suggested. The first prescription[1,3] calls for the lines to be drawn at constant TKE, parallel to the Z-axis. No physical reason has been given as to why the lines of constant ℓ in this plane should exhibit such behavior. It is certainly not correct for the lowest ℓ-waves, where the TKE of the fragments is expected to be dominated by the Coulomb energy of two touching fragments. This prescription has been widely used, perhaps because of its simplicity. In the second infrequently used prescription,[2] the lines of constant ℓ are drawn parallel to the Coulomb energy of two touching fragments. While the latter prescription accounts for the Q-value associated with mass transfer to some extent, and is probably adequate for the lowest ℓ-waves due to the prevailing Coulomb effects mentioned previously, it is most likely not correct for the highest ℓ-waves. It is therefore essential to determine the correct constant angular momentum contour lines in order to assess the possible systematic errors introduced by the empirical prescriptions.

This problem is of great actual interest. For instance, analyses of the kind mentioned above, employing the first prescription, have been used to determine diffusion coefficients and to evaluate the energy loss per exchanged particle in some heavy ion reactions.[1,3] In particular, the results of the latter estimate seem to indicate an energy loss per exchanged particle much larger than that expected from a 1-body dissipation mechanism.[4] Due to the great interest in this mechanism and its apparent success in describing the energy dissipation observed in spontaneous fission,[4] it is necessary to verify the soundness of the of the empirical procedure before concluding that the observed energy dissipation from such a mechanism is too small. This letter reports on a first attempt to calculate the correct lines of constant ℓ in the Z-TKE plane in a consistent and justifiable way.

In the limit of infinite radial friction (the relevance of which is discussed in a later section of this letter), there are two limiting patterns these lines should display, corresponding to the two extreme regimes associated with the rotational degrees of freedom of the intermediate complex. In the first limiting case the reaction occurs with no transfer of angular momentum from orbital motion to intrinsic spin. In this case, the angular momentum of relative motion as a function of Z, $\ell_{rel}(Z,\ell)$, is a constant independent of Z and equal to ℓ. The total kinetic energy can be calculated as

$$\mathrm{TKE}(Z,\ell) = V_{Coul}(Z) + \frac{\hbar^2 [\ell_{rel}(Z,\ell)]^2}{2\mu_z d_Z^2} \qquad (1)$$

where μ_Z and d_Z are the reduced mass and the distance between centers for the charge-asymmetry specified by Z. The curves in Fig. 1a show examples for this case assuming the shape of the complex to be two touching spheres.

In the second limiting case the complex is rotating as a rigid body at the time of scission, regardless of the impact parameter (ℓ-wave). (Such an assumption was used by Moretto and Sventek[5] in their diffusion model description of deep-inelastic reactions.) In this case, the relative angular momentum is Z-dependent, and given by

$$\ell_{rel}(Z,\ell) = \frac{\mu_Z\, d_Z^2}{\mu_Z\, d_Z^2 + I(Z) + I(Z_T - Z)} \cdot \ell \qquad (2)$$

where I(Z) is the moment of inertia of a fragment with charge Z about its own axis and Z_T is the total charge in the composite system. This expression can be substituted in Eq. (1) to calculate the lines of constant ℓ for this case. The curves in Fig. 1b show examples of this behavior for the same ℓ-waves as for the previous case.

These two cases may be considered as the regimes prevailing at short and long interaction times, respectively. For short interaction times, as in nearly grazing trajectories, the first mechanism is expected to be relevant for Z's close to the projectile. If angular momentum transfer (from orbital to intrinsic spin) is mediated by nucleon exchange between the reaction partners, the amount of ℓ-transfer must be a function of the number of nucleon exchanges, which is directly related to the interaction time. Even though the average lifetime of the complex may be short, the fragments with Z's far removed from the projectile are associated with systems which have survived the longest. Thus, one would expect the ℓ-transfer for that particular asymmetry to be very large. Qualitatively, one would expect the correct curve for near grazing ℓ-waves to look like the dotted curve in Fig. 1c. For ℓ-waves associated with longer interaction times, one would expect the ℓ-transfer to be almost complete, even for Z's near the projectile, since many nuclear exchanges will have occurred during the time of interaction, although the net exchange may be small. Therefore, one would expect the curves to look like those in Fig. 1b. A more reliable conclusion on the qualitative and quantitative aspects of this problem can be obtained from a model calculation.

Consistent with experiment, it is assumed that the radial kinetic energy is dissipated immediately at the interaction radius. (For the lowest ℓ-waves, the interaction times appear to be long compared to the relaxation time of the radial kinetic energy, and for the highest ℓ-waves, even though the interaction times are short, very little of the kinetic energy is in the radial coordinate.) The analysis is restricted to a system of two spheres separated by an ℓ-dependent distance $d(\ell)$ dynamically determined as described farther on in the text. We need to calculate how the orbital angular momentum (ℓ_{rel}) is transferred into the spins of the nuclei (ℓ_1, ℓ_2) and the functional dependence of ℓ_1 and ℓ_2 on the asymmetry of the complex (Z). This calculation may be performed in two steps:

1) The complex, initially at asymmetry Z_p, is assumed to live a time t and to decay with asymmetry Z. The average rate of change of the charge of nucleus 1 is $\dot{Z}_1 = (Z-Z_p)/t$. Since the charge-to-mass ratio has been shown experimentally to equilibrate on a much faster time scale than the charge-asymmetry mode,[6] one may write

$$\dot{A}_1 = (Z-Z_p)\,\alpha/t \qquad (3)$$

where A_1 is the mass of nucleus 1 and α is the A/Z ratio for the composite system. The average rate of nucleon transfer from one nucleus to the other is given by $n_o\sigma$, where n_o is the bulk flux of nuclear matter and σ is the effective window between the nuclei.[7] By forcing the system to arrive at asymmetry Z at time t, we impose an asymmetry on the right (r_{12}) and left (r_{21}) nucleon transfer rates, which can be written as:

$$r_{12} = n_o\sigma - \frac{1}{2}\dot{A}_1$$
$$r_{21} = n_o\sigma + \frac{1}{2}\dot{A}_1 \quad . \qquad (4)$$

Knowing these transfer rates, we can write the following system of coupled differential equations for the spins and the orbital angular momenta:

$$\dot{\ell}_1 = d_1 \, [r_{12} \, d_1(\dot{\theta} - \dot{\theta}_1) + r_{21} \, d_2(\dot{\theta} - \dot{\theta}_2)]/\hbar$$
$$\dot{\ell}_2 = d_2 \, [r_{12} \, d_1(\dot{\theta} - \dot{\theta}_1) + r_{21} \, d_2(\dot{\theta} - \dot{\theta}_2)]/\hbar \qquad (5)$$
$$\dot{\ell}_{rel} = -(\dot{\ell}_1 + \dot{\ell}_2)$$

where d_1 and d_2 are the distances of the nuclear centers from the window and $\dot{\theta}$, $\dot{\theta}_1$, $\dot{\theta}_2$ are the rotational frequencies for the orbital motion, spin 1 and spin 2, respectively. By integrating the Eqs. (5) and (3), subject to the proper initial conditions, we arrive at values for ℓ_1 (Z, ℓ, t) and ℓ_2 (Z, ℓ, t).

2) The functions $\ell_1(Z,\ell)$, $\ell_2(Z,\ell)$ are obtained by integrating out the time dependence. The average lifetime of the complex for a given ℓ-wave is approximated as the time necessary for the dynamical system with no mass transfer to return to the strong absorption radius under the influence of Coulomb plus Proximity potentials and subject to Proximity friction.[7] A gaussian lifetime

distribution $\Pi(t)$ about this average value is used[8] with a variance given by $\sigma^2(\ell) = 1.5\ \tau(\ell)$. The quantity $d(\ell)$ (mentioned earlier) is the average value of the distance between centers along the trajectory using the Proximity Flux function $\Psi\ (r)$[7] for the probability weight function. It is also necessary to weight the $\ell_i(Z,\ell,t)$ by the probability for forming the system Z at time t. This function, $\phi(Z,t)$, can be obtained by solving a Master Equation[5] or an associated Fokker-Planck equation.[9,2]

Figure 2a shows the predictions of the model for the system 1156 MeV $^{136}Xe + {}^{197}Au$. Each pair of adjacent lines brackets 5% of the reaction cross section. The qualitative behavior predicted above is now very apparent. Figure 2b shows the upper portion of Fig. 2a, with contours of constant cross section (as calculated by the Fokker-Planck equation) drawn in. The horizontal lines divide the data into 10 bins, 30 MeV wide. (Only every other line is shown for ease of viewing.) The lines of constant ℓ calculated by the model are chosen to coincide with the parallel lines at the Z of the projectile. Figure 3 is a plot of the ratio of the variance predicted by the present model and the variance derived from the parallel cuts. Note the large difference for the first few bins. It is exactly in this energy region that the previously mentioned discrepancy between experiment and theory was found. The empirical analyses seemed to indicate that the experimental energy loss per particle, calculated as

$$\varepsilon = (E_{cm} - TKE_{bin})/[\sigma_Z^2 \cdot \alpha] \qquad (6)$$

was between two and three times larger than that expected from a 1-body dissipation mechanism. If the empirical variances are in error by as much as is indicated by the present work (see Fig. 3), then the discrepancy between experiment and theory disappears. This result does not confirm or disprove any mechanism for energy dissipation. Rather, it shows the possibility of serious systematic errors in the empirical methods discussed above. However, it seems safe to conclude that the 1-body mechanism is quite capable of dissipating much more of the entrance channel kinetic energy than estimated from the empirical analyses. It should be noted that the above conclusions are not strongly model dependent, since they are based upon the inevitable transfer of angular momentum from orbital to intrinsic rotation accompanying particle transfer.

The present treatment of the angular momentum transfer is being extended to describe the γ-multiplicity data being collected.

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FIGURE CAPTIONS

Fig. 1 (a) Lines of constant total angular momentum (ℓ) in the Z-TKE plane if no transfer to spin occurs. (b) Same quantities if complex rotates rigidly at scission. (c) Qualitative expectations for correct lines of constant ℓ.

Fig. 2 (a) Lines of constant ℓ calculated for 1156 MeV $^{136}Xe + ^{197}Au$ using the present model. (b) Contours of constant $\partial^2\sigma/\partial Z\partial[TKE]$ for the same reaction with parallel cuts and calculated cuts drawn in.

Fig. 3 Ratio of σ_Z^2 from calculated lines and empirical lines vs. bin number. The bin number may be related to TKE loss by the following relation: TKE loss = $30\cdot(\text{Bin number} - \frac{1}{2})$ MeV.

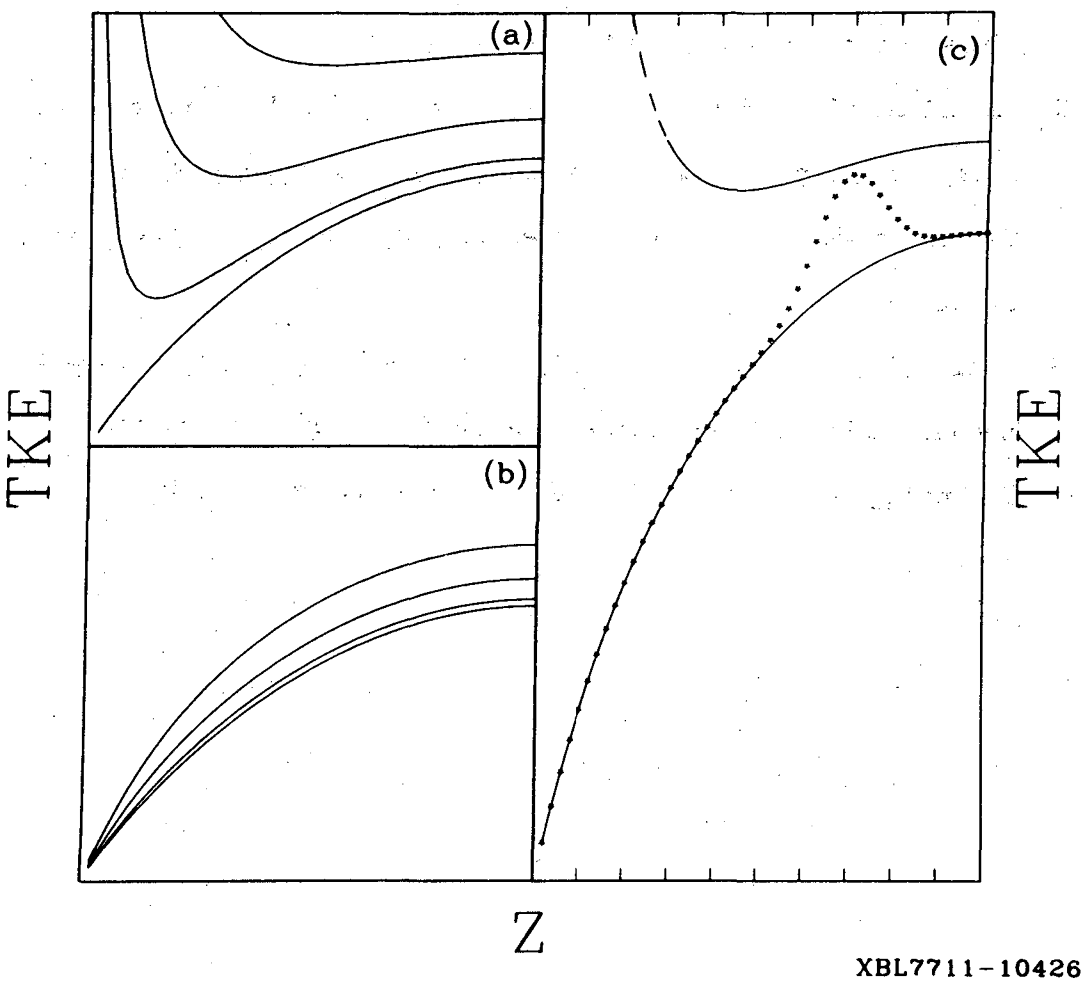

Fig. 1

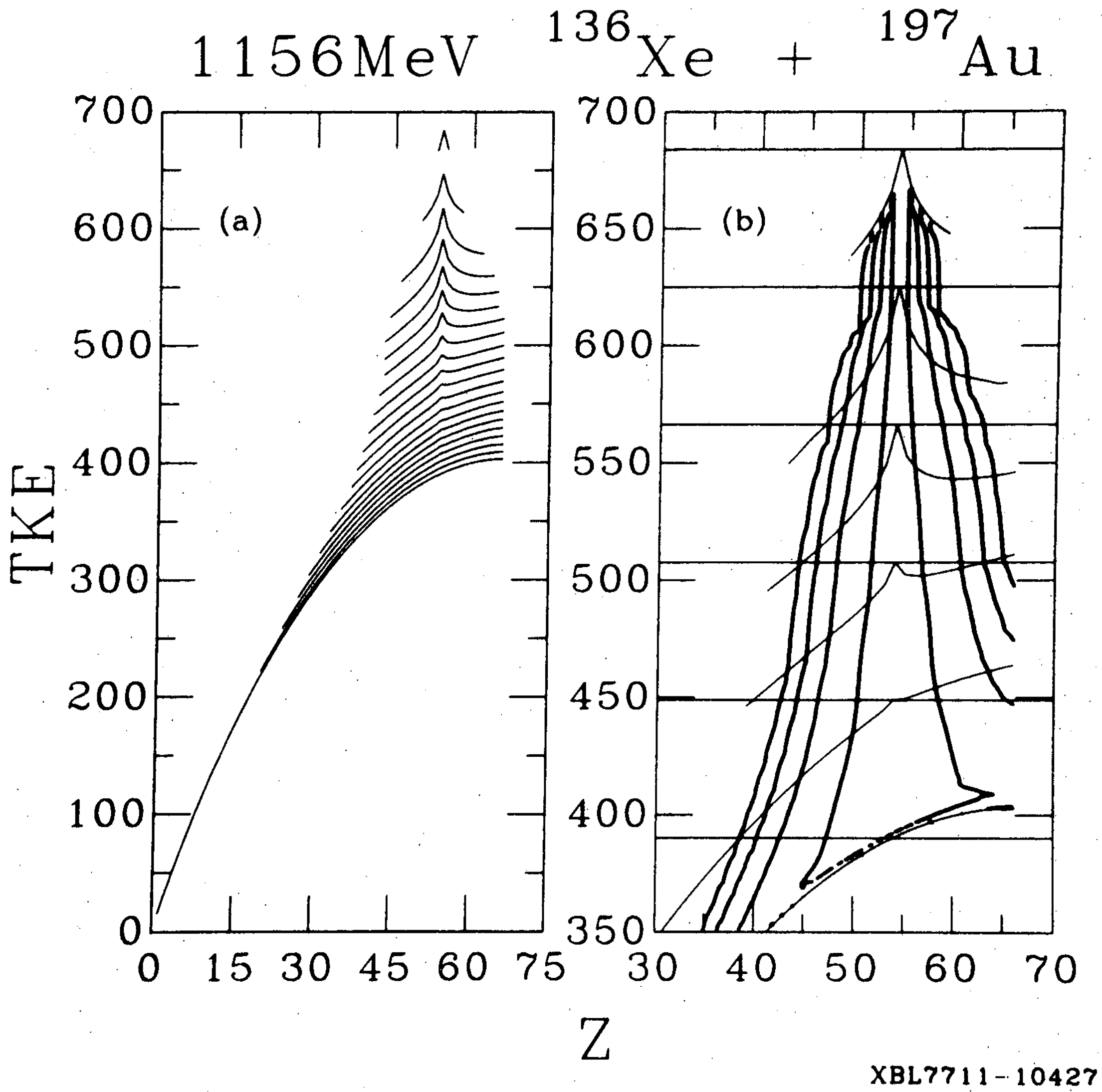
1156MeV ^{136}Xe + ^{197}Au
TKE
Z
(a)
(b)
0
100
200
300
400
500
600
700
350
400
450
500
550
600
650
700
0 15 30 45 60 75
30 40 50 60 70
XBL7711-10427

Fig. 2

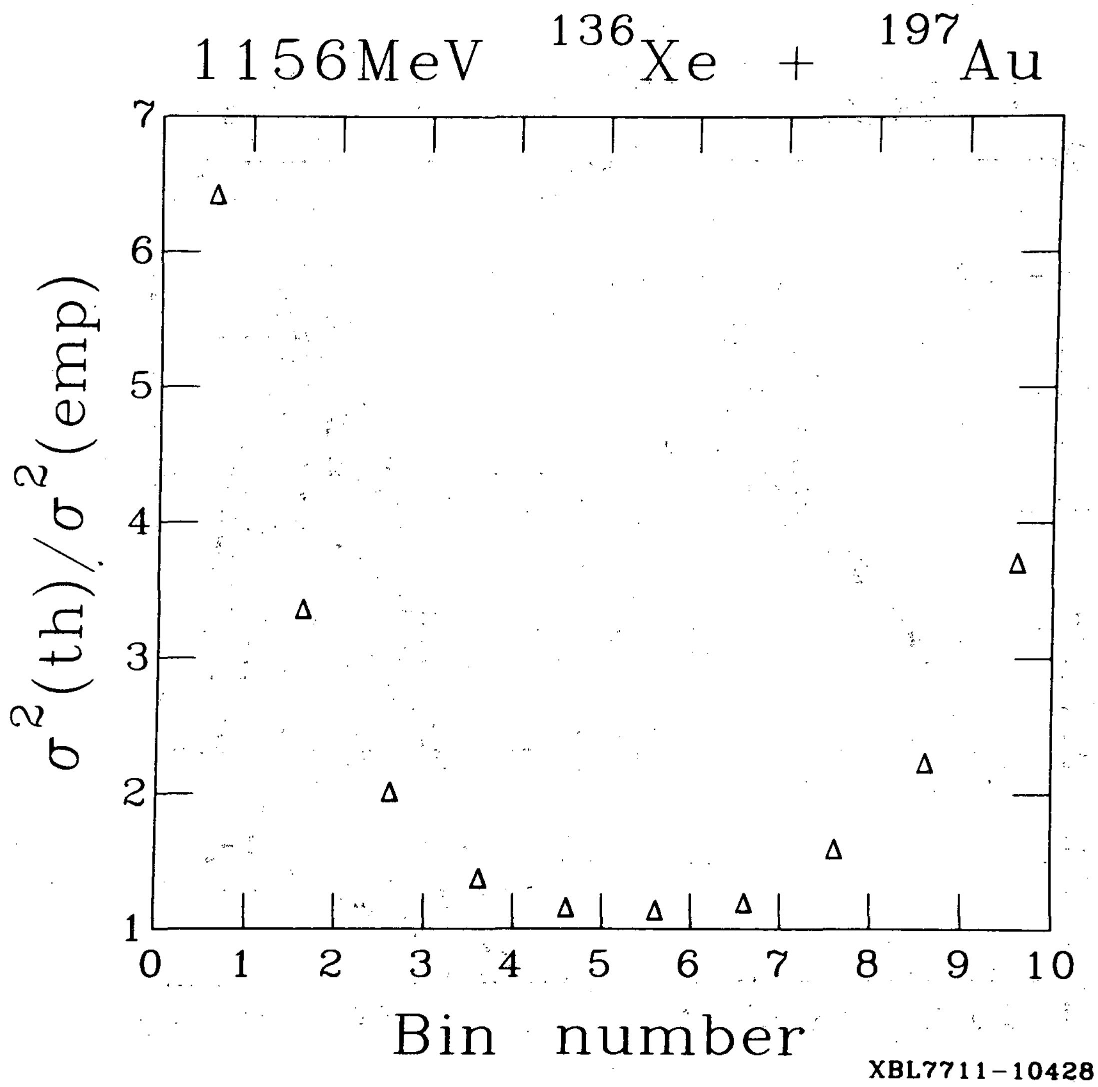
1156MeV ^{136}Xe + ^{197}Au
$\sigma^2(th)/\sigma^2(emp)$
1
2
3
4
5
6
7
0
1
2
3
4
5
6
7
8
9
10
Bin number
XBL7711-10428

Fig. 3

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