information about the basic hadronic interactions.

The authors have benefitted from discussions on this and other related topics with C. B. Chiu, A. Dar, D. H. E. Gross, H. H. Gutbrod, and R. Stock.

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[11]Another example is the pion bremsstrahlung of effective projectile and target in gentle hadron-nucleus and nucleus-nucleus collisions (see Ref. 10).

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[14]See, e.g., F. K. Loebinger, in *Proceedings of the Seventeenth International Conference on High-Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1974), p. I 71.

[15]$\eta \equiv -\ln(\tan\theta_{\rm lab}/2)$, where $\theta_{\rm lab}$ is the production angle. $\bar{\nu} \equiv A\sigma_{hp}/\sigma_{hA}$, where σ_{hA} is the total inelastic cross section between a hadron and a nucleus (of mass number A), and σ_{hp} is that between the same hadron and a proton. In first-order approximation, the nucleons can be considered as homogeneously distributed in the nucleus, the volume of which is proportional to its mass number A. At high energies, viewed from the projectile hadron, the nucleus is a thin slab. The area perpendicular to the incident axis is approximately σ_{hA}, where the cross section of the effective target in the h-A collision is σ_{hp}. Hence, $\bar{\nu}$ is proportional to the average number of nucleons along the incident axis.

[16]See, e.g., R. Hagedorn, *Relativistic Kinematics* (Benjamin, New York, 1963), p. 46.

[17]The existence of friction in heavy-ion reactions has been discussed in the literature; see, e.g., D. H. Gross *et al.*, in *Proceedings of the International Conference on Nuclear Physics, München, Germany, 1973,* edited by J. de Boer and H. J. Mong (North-Holland, Amsterdam, 1973), pp. 1, 394; A. Abul-Madg *et al.*, Phys. Lett. 60B, 327 (1976), and Z. Phys. A277, 379 (1976).

[18]To illustrate the basic ideas, we consider the following simple example: an object of finite size moving with a given velocity v ($<<c$) through a medium, the thickness of which is comparable to that of the moving object. The longitudinal momentum transfer $\Delta P_\parallel$ which causes this object to slow down is $f\Delta t$. Here, f is the frictional force and Δt is the time interval for the moving object to pass the medium. Since $t \propto 1/v$, we see that $\Delta P_\parallel$ is independent of the incident kinetic energy, provided that $f \propto v$.

γ-Ray Multiplicities from a Diffusion Model Incorporating One-Body Dissipation

R. Regimbart,[a] A. N. Behkami,[b] G. L. Wozniak, R. P. Schmitt, J. S. Sventek, and L. G. Moretto
Nuclear Science Division, Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

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γ-ray multiplicities as a function of energy dissipation and mass asymmetry have been calculated from a diffusion model which simultaneously treats energy dissipation and angular momentum transfer on the basis of particle transfer. The good agreement obtained between the model calculations and the experimental multiplicities for ^{86}Kr-induced reactions on ^{107,109}Ag, ^{165}Ho, and ^{197}Au targets lends credence to the one-body dissipation mechanism and l fraction along the mass-asymmetry coordinate.

Recently a good deal of attention has been devoted to the experimental study of γ-ray multiplicities[1-5] in deep inelastic processes. The motivation for this study is twofold. On the one hand, one would like to clarify the mechanism of angular momentum transfer and its relation to energy transfer. There is at present an open discussion[6,7] on the relative contribution of particle transfer and phonon excitation to the energy and the angular momentum transfer. On the other hand, an adequate understanding of the angular momentum transfer mechanism may lead to a determination of the angular momentum fractionation[3] along the mass-asymmetry coordinate and thus to a strict verification of current diffusion models.

Two key quantities must be determined experimentally in order to shed some light on the above problems, namely, the energy (Q value) dependence of the γ-ray multiplicities (and possibly of their second moments) and the dependence of the γ-ray multiplicities upon exit-channel asymmetry (i.e., the fragment charge or mass.) A large body of experimental data is now available, yet no attempt has been made so far to interpret these data in terms of a comprehensive theoretical model. In this Letter we report on a first attempt to explain the experimental data on the basis of a simple diffusion model in which the energy and angular momentum are equilibrated exclusively through particle transfer. This model has already been quite successful[8] in accurately reproducing the Z distributions and the angular distributions for individual Z values. The most recent modification of the model, to include the energy and angular momentum transfer mediated by particle exchange, has been described in detail elsewhere.[6,8] Therefore, only a brief outline of it will be given before comparing its predictions with experiment.

A deeply inelastic collision can be characterized by the entrance asymmetry Z_p, by a total angular momentum l, and by the interaction time t. This time is estimated to be the time necessary for the system with no mass transfer to return to the strong-absorption radius under the influence of the Coulomb and proximity force. The requirement that the system decays with a given exit-channel mass asymmetry determines the left and right mass transfer rates. These transfer rates can be used to write a system of coupled differential equations for the fragments spins $I_i(l,Z,t)$ which can be integrated numerically. The fragment spins are then weighted over the probability $\varphi(Z,l,t)$ that the system with angular momentum l has diffused to the asymmetry Z in a time t. The final result is obtained as the average fragment spins $I_1(Z,E_k)$ and $I_2(Z,E_k)$ as a function of the exit-channel asymmetry Z and kinetic energy E_k.

The transformation from the calculated fragment spins to the γ-ray multiplicity produced by the γ de-excitation of the two fragments is based upon the assumption that most of the fragment angular momentum is removed by stretched $E2$ decays. More specifically we use the following transformation:

$$M_\gamma = \tfrac{1}{2}[I_1(Z_1,E_k)+I_2(Z_1,E_k)]+2\alpha, \qquad (1)$$

where I_1 and I_2 are the fragment spins, M_γ is the γ-ray multiplicity, and α is the number of statistical γ rays emitted by each fragment. Compound-nucleus studies[9,10] with heavy-ion reactions indicate that α ranges from 2.5 to 4 depending upon the nucleus. Because of this uncertainty, caution must be exercised in comparing the absolute values of the calculated and measured multiplicities.

The kinetic-energy dependence of the γ ray multiplicities will be considered first. In Fig. 1 the γ-ray multiplicity M_γ, associated with both frag-

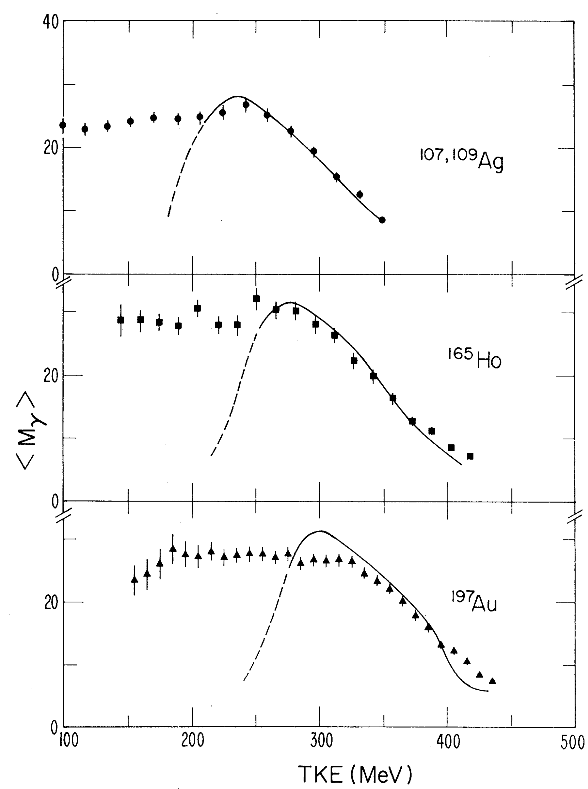

FIG. 1. M_γ vs total kinetic energy (TKE) for the reactions ^{86}Kr(618 MeV) + ^{197}Au, ^{165}Ho, ^{107,109}Ag. The experimental data (solid symbols) have been averaged over 10 Z values (Z_3 = 30–39) near the projectile Z, and the experimental TKE have been corrected for neutron evaporation. The theoretical curves (solid and dashed lines) have been calculated as described in the text. Only relative errors are shown for the data points.

ments from the reactions ^{197}Au, ^{165}Ho, ^{107,109}Ag + ^{86}Kr(618 MeV), is plotted as a function of the exit-channel total kinetic energy (TKE). Both the experimental and the theoretical γ-ray multiplicities have been integrated over a range of exit-channel asymmetries ($Z_3 = 30-39$). The number of statistical γ rays per fragment α was taken to be 3.

The first observation to be made concerns the comparison between experiment and calculation. At the highest kinetic energies both the calculated and experimental multiplicities are low and increase rapidly with decreasing TKE. The agreement between theory and experiment is excellent in this region. At the lowest kinetic energies the experimental multiplicities reach a plateau and then slightly decrease again. The calculated multiplicities on the other hand reach a maximum and then decrease quite rapidly with the decreasing kinetic energy.

The early rapid increase of M_γ with decreasing kinetic energy is due to the rapid transfer of angular momentum associated with the particle transfer which occurs as the energy of relative motion is being equilibrated. The plateau in the experimental multiplicities and the maximum in the calculated multiplicities corresponds to a regime very close to rigid rotation. The drop in the calculations (dashed curve) at lower kinetic energies is due to the effect of the Coulomb energy (which in the model is taken to be that of two touching spheres) and to the fact that lower angular momenta, in the limit of rigidly rotating touching spheres, are associated with lower kinetic energies. The experimental values do not show a drop in multiplicity as large as the theory does because the exit-channel configuration is not constrained to that of two touching spheres. Thus the deep-inelastic component is spread over an energy range extending well below the Coulomb barrier. Furthermore, fluctuations in shape and the statistical excitation of bending and wriggling modes in the exit channel[11] may destroy the simple correlation between kinetic energy and angular momentum predicted by our model at these low energies. One should also note that M_γ is not weighted by the cross section so that regions in phase space which are marginally populated appear with the same weight as the most probable ones. Therefore, the discrepancy in Fig. 1, which involves a relatively small fraction of the cross section associated with very-low-l waves, is effectively magnified.

A second point of comparison is the Z dependence of M_γ in the quasielastic region. Examples of data and calculations are shown in Fig. 2. The characteristic V-shaped pattern visible in the data (open symbols) is very nicely reproduced by the calculations. The qualitative explanation of this pattern is again rather simple. Fragments with Z close to that of the projectile and with substantial kinetic energy have exchanged, on the average, fewer nucleons than fragments farther removed from the projectile Z. Thus less angular momentum is transferred to the former than to the latter fragments, giving rise to the rapid increase of the γ-ray multiplicity as one moves away from the projectile in either direction. Such good agreement is consistent with the agreement observed between experiment and theory in Fig. 1 at the highest kinetic energies. From both of these figures one is tempted to conclude that particle exchange is sufficient to explain quantitatively the dependence of the angular momentum

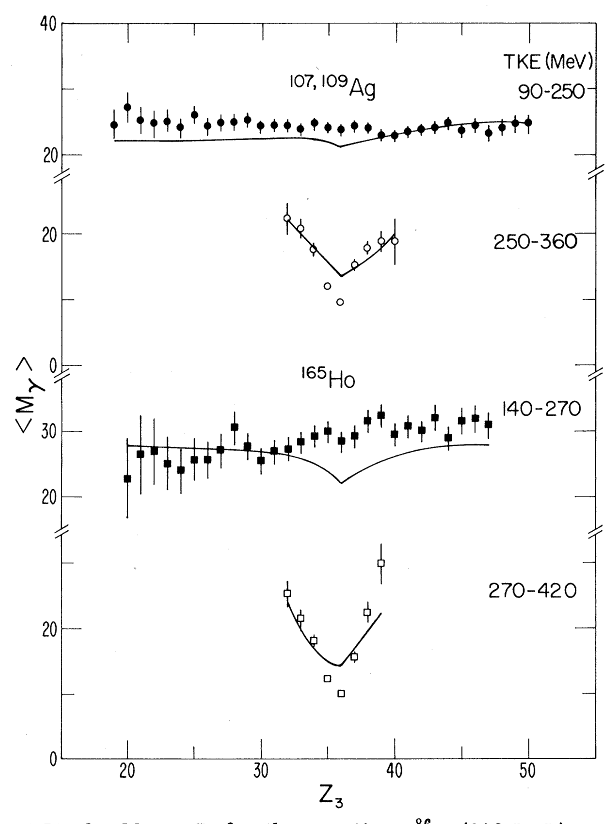

FIG. 2. M_γ vs Z_3 for the reactions ^{86}Kr(618 MeV) + ^{165}Ho, ^{107,109}Ag. A comparison between experiment (symbols) and theory (curves) is made for both the deep-inelastic (solid symbols) and quasielastic (open symbols) components observed in the reactions. The cuts in TKE corresponding to these two components are given in the far right of the figure.

transfer upon kinetic energy loss without invoking the excitation of giant collective modes.[7] To conclude definitely whether this is the case or not, additional evidence is required. Nonetheless, one should note that the same one-body model which reproduces both the Z distributions and the angular distributions as a function of Z quite satisfactorily[8] also handles the energy and angular momentum transfer more than adequately.

The final aspect to be considered is the Z dependence of the γ-ray multiplicity in the deep-inelastic region. Examples of data and calculations are also given in Fig. 2. (The case of $^{197}Au + ^{86}Kr$, which is marred by sequential fission[11] at large Q values is not shown.) Again the experimental data are reproduced quite well. Consistent with remarks made above, when the multiplicity is averaged over the deep-inelastic components, good agreement is achieved with the data. It must be emphasized that in this energy region the calculation predicts near rigid rotation throughout the Z range. Yet the rise of M_γ with decreasing Z, commonly considered as a fingerprint of rigid rotation,[2-4] is conspicuously absent. The reason for this behavior is to be found in the angular momentum fractionation along the mass-asymmetry coordinate as first inferred elsewhere.[3] The main cause for this angular momentum fractionation is the dependence of the interaction time upon l. The high-l waves are characterized by a short interaction time and cannot spread too far away from the entrance-channel asymmetry. The low-l waves are characterized by longer interaction times and can populate asymmetries farther removed from the entrance channel. Consequently, as one moves towards more extreme asymmetries one selects progressively lower l waves.

Furthermore, at high angular momentum, the driving force is strongly directed towards higher Z values and inhibits[8] any diffusion towards lower Z values. As the angular momentum decreases, the driving force also diminishes and may even reverse its sign, thus allowing for a substantial diffusion to occur in the direction of the low atomic numbers. Consequently, the Z values below the projectile Z are selectively populated by lower than average l waves, and hence the lack of rise in the γ-ray multiplicity with decreasing Z.

Recently, fairly large second moments of the γ-ray multiplicities have been reported.[5] The present model can account for about 60 to 70% of the measured values. However, the statistical excitation of bending and wriggling modes in the exit channel, postulated by some of us[11] to understand both the sequential fission and the γ-ray angular distributions, generates a randomly oriented component of angular momentum (13 $\hbar$ to 16 $\hbar$ per fragment), which adequately provides the missing part of the second moments without substantially changing the first moments.

In conclusion, it appears that both the magnitude and the shape of the experimental data can be adequately reproduced by our model. The quality of the agreement lends credibility to the one-body dissipation mechanism. Furthermore, the angular momentum fractionation qualitatively inferred[3] from the experimental data finds quantitative support here.

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[(a)]Present address: Laboratoire de Physique Corpusculaire, Université de Caen, 14000 Caen, France.

[(b)]Present address: Physics Department, Pahlavi University, Shiraz, Iran.

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