Multiplicity of γ Rays in the Reactions ^{86}Kr-^{120}Sn and ^{86}Kr-^{166}Er

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The average γ-ray multiplicity M has been measured as a function of the scattering angle, energy loss, and nuclear charge of the projectile fragment produced in the ^{86}Kr-^{120}Sn and ^{86}Kr-^{166}Er reactions at a bombarding energy of 5.99 MeV/N. M increases steeply as a function of energy loss for the partly damped collisions but remains nearly constant for the fully damped events. M appears to depend mainly on energy loss rather than on mass transfer. The results are discussed in terms of a classical sticking model for the reaction mechanism.

Collisions between very heavy ions are characterized by a continuous dependence of the cross section on deflection angle, energy loss, and mass transfer. This can be ascribed to a smooth dependence on the impact parameter, starting from quasielastic peripheral collisions down to completely damped central interactions. In the present measurements an additional observable, the average γ-multiplicity M, is used to determine the amount of angular momentum introduced into internal rotation of the fragments over the full range of impact parameters. These measurements provide an important test of the validity of different theoretical concepts.

Projectiles of ^{86}Kr delivered from the Unilac accelerator at an energy of 5.99 MeV/N were used to bombard ^{166}Er- and ^{120}Sn-target nuclei. In both cases the grazing angular momentum 1_{gr} is about $210\hbar$. The target and projectile were chosen from a mass region in which the excited products decay predominantly by neutron and γ emission, such that most of the angular momentum is carried away by γ rays. The γ rays were detected in coincidence with the projectilelike fragments. These particles were identified in a large position-sensitive ionization chamber[1] centered around the grazing angle; the γ rays were detected by three NaI crystals (3 in. × 3 in.) mounted in the backward hemisphere at 45° out of the reaction plane. The position-sensitive ionization chamber enabled the continuous determination of M as a function of scattering angle, particle energy, and proton number Z. The corresponding center-of-mass scattering angle $\theta_{c.m.}$ and total kinetic energy (TKE) were calculated event by event. (The correction for neutron evaporation could be neglected at this relatively low bombarding energy.)

At 5.99 MeV/N the Coulomb barrier is exceeded by factors of 1.5 and 1.3 for the Kr-Sn and Kr-Er reactions, respectively. Thus, as is generally observed in deep inelastic reactions,[2] only the Kr-Sn case displays a fully relaxed orbiting component [Fig. 1(a)]. For this reason we shall first use the Kr-Sn system to investigate the angular dependence of the γ multiplicity. The energy-loss and impact-parameter dependence of M is best revealed in the Kr-Er reaction, where the yield is concentrated near the grazing angle, thus allowing a more complete measurement over the full range of the total reaction cross section.

Figure 1(a) shows, for the Kr-Sn system, the dependence of the laboratory energy of the detected particles on the scattering angle measured for one setting of the position-sensitive detector. Three separate areas labeled A, B, and C are defined and correspond, respectively, to elastic (or quasielastic), partly damped, and strongly damped collisions. Figure 1(b) shows the angular dependence of $M(\theta)$ for each of these three branches. The multiplicity increases slowly with angle in the elastic branch A and then changes dramatically with scattering angle in the partly damped region (B). The completely relaxed events in region C show a nearly constant multiplicity at a maximum value of about 20. This behavior of the fully relaxed orbiting component is difficult to understand. In a Wilczyński repre-

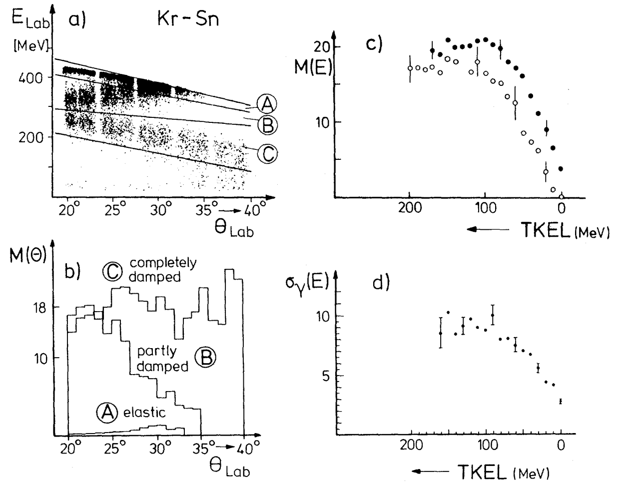

FIG. 1. (a) Scatter plot of the Wilczyński diagram obtained with the position-sensitive ionization chamber. The discontinuity in the data along the abscissa are due to the window supports of the gas counter. (b) Average γ multiplicity of the Kr-Sn reaction as a function of the laboratory scattering angle for the three branches of the upper figure: the elastic A, the partly damped B, and the fully relaxed component C. (c) Dependence of M on the energy dissipation for the Kr-Sn (open circles) and the Kr-Er reaction (full dots). (d) Standard deviation of the multiplicity distributions for the Kr-Er reaction as a function of the TKEL.

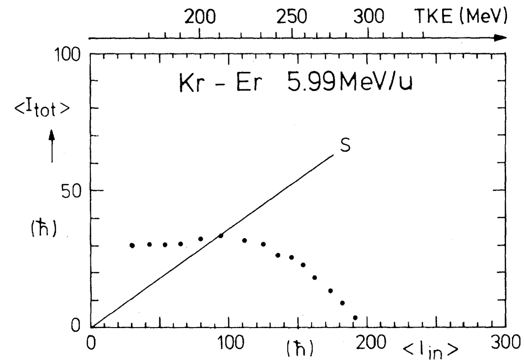

FIG. 2. Internal spin of the fragments as a function of the ingoing angular momentum. The derivation of the quantities is described in the text. The relation between TKE and l_{in} can be directly observed by comparing the upper and lower scale on the abscissa. The straight line indicates the sticking limit of two spheres for the Kr-Er fragmentation.

sentation,[3] the orbiting component corresponds to negative scattering angles where an increase in the deflection angle is associated with a decreasing impact parameter and decreasing initial angular momentum l_{in}. In a classical rolling or sticking case, the total internal spin of the fragments is expected to be proportional to l_{in}; therefore $M(\theta)$ should decrease for increasing laboratory scattering angles in region C. This is not observed in the experimental data for the Kr-Sn system. We shall pursue this point further by considering the multiplicity as a function of energy loss.

Figure 1(c) shows $M(E)$, the dependence of M on the total-kinetic-energy loss (TKEL) for both the Kr-Sn and Kr-Er systems. The data are integrated over scattering angle and fragment charge. As is observed with $M(\theta)$ for the Kr-Sn reaction [Fig. 1(b)], $M(E)$ rises steeply in the region of the partly damped collisions and reaches a plateau at large energy loss. At small values of TKEL the observed value of $M(E)$ is larger in the Kr-Er case by about 4 units, but the general behavior is the same for both reactions. We concentrate in the following on the Kr-Er reaction.

In order to compare the results of these measurements with theoretical predictions we have transformed the dependence of $M(E)$ on TKEL into a relation between internal spin of both fragments (I_{tot}) and the ingoing angular momentum (l_{in}). The ingoing angular momentum has been reconstructed, following the procedure suggested by Schröder and Huizenga,[4] integrating the observed inelastic cross section over the TKE. The validity of such a prescription is based on the existence of a sharp correspondence between l_{in} and TKEL; this correspondence is still a matter of discussion since it is affected by the strength of fluctuations in the energy-loss mechanism. However, we shall show in a separate publication[5] that energy fluctuations should be sufficiently reduced at the point of scission so as not to present a problem for the present analysis.

The internal angular momenta have been approximately deduced from $I_{tot} = 2(M - 5)$, which is based on compound-nucleus–decay studies.[6,7] The results are displayed as full dots in Fig. 2. Under the assumptions contained in the derivations the average spin value $\langle I_{tot} \rangle$ for the fully relaxed component is much higher than expected from the classical sticking condition. This experimental result, however, is well described by the diffusion model of Wolschin and Nörenberg.[8] In their work the large spin values at low impact parameters are ascribed to the fluctuations of the angular momentum distribution. This is due to the quantum-statistical transfer of angular momentum and to the intrinsic motion of the nucleons in the colliding nuclei. On the basis of this explanation, it is also possible to understand the failure of the classical model for the angular dependence $M(\theta)$ for the Kr-Sn system shown in Fig. 1(b).

The standard deviation of the multiplicity distribution σ_γ is shown as function of TKEL in Fig. 1(d) for the Kr-Er system. The increase of $\sigma_\gamma(E)$ with TKEL is in qualitative agreement with a diffusion model for the angular momentum transfer mechanism. Assuming, however, that the variance of the transferred angular momentum σ_I^2 is given by $(2\sigma_\gamma)^2$, the deduced value of σ_I exceeds the predicted values by a factor of 2. The possible contributions of neutron and statistical γ-ray decay to the measured value of σ_γ are currently being investigated. Nevertheless, this rather large discrepancy for σ_I may suggest the presence of additional mechanisms for the introduction of angular momentum at scission.[9,10] Very recent measurements for the Kr + ^{144}Sm reaction also reveal surprisingly large values of σ_γ.[11]

Thus far we have considered the dependence of $M(\theta)$ and $M(E)$ obtained by integration over all the reaction products. In Fig. 3 the multiplicity $M_{\Delta E}(Z,E)$ is shown as a function of the nuclear charge for different bins of the TKEL, each bin having a width $\Delta E = 20$ MeV. Note the surpressed zeros on the ordinate for TKEL > 10 MeV. We observe a slight dependence of $M_{\Delta E}(Z,E)$ on Z for quasielastic events with a minimum at the Z of the projectile, whereas for increasing energy damping $M_{\Delta E}(Z,E)$ tends to be independent of Z. A strong dependence of $M_{\Delta E}(Z,E)$ on Z has been recently observed by different authors[12,13] when the energy bin ΔE constitutes a broad quasielastic region. This effect was interpreted on the basis of a direct dependence of the transferred angular momentum on the net mass transfer. On the other hand, the diffusion model, which assumes that the angular momentum transfer is determined by the total number of nucleonic exchanges during the collision (as opposed to the net mass transfer), describes the energy-integrated Z distributions quite well.[14] Therefore, we have studied the influence of the finite width of the TKE bins on the apparent Z dependence of $M(Z,E)$. Using (i) the measured[15] double-differential cross section $d\sigma^2(Z,E)/dE\,dZ$, (ii) the measured dependence of $M(E)$ on TKE [Fig. 1(b)] which is integrated over all Z, and (iii) the assumption that *M is independent of Z* [i.e., $M(Z,E) = M(E)$], we are able to predict the value of $M_{\Delta E}(Z,E)$, which should be observed for TKEL bins having a finite width ($\Delta E = 20$ MeV). This is done using the relation

$$M_{\Delta E}(Z,E) = \left(\int_E^{E+\Delta E} \frac{d^2\sigma}{dE\,dZ}\, M(E)\right)\left(\int_E^{E+\Delta E} \frac{d^2\sigma}{dE\,dZ}\right)^{-1}.$$

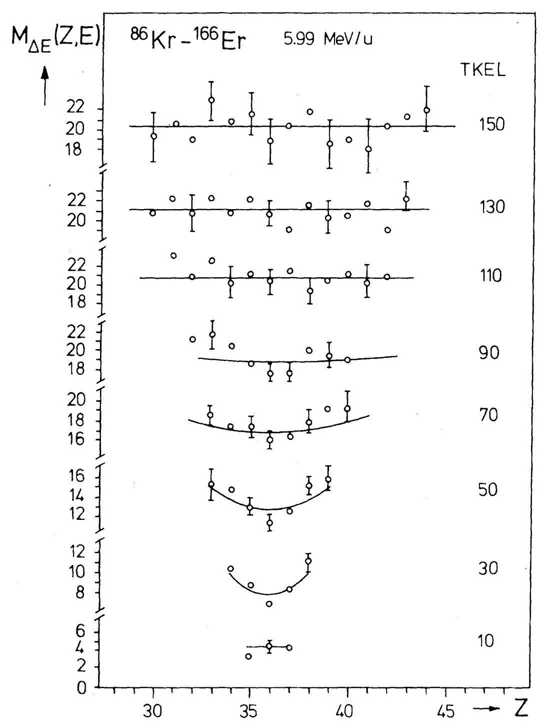

FIG. 3. Element distribution of the γ multiplicity for contiguous bins of the total-kinetic-energy loss.

The results are given by the full curves displayed in Fig. 3. This comparison shows that the apparent Z dependence can, to a large extent, be explained by the finite width of the TKE bins. As a consequence we deduce that the angular momentum dissipation is rather strongly correlated with the energy dissipation and only weakly dependent on the *net* mass transfer. Similarly, we have examined the dependence of $M(\theta, E)$ on the center-of-mass scattering angle for a given energy bin and find a constant distribution within the statistical errors. This is additional evidence that energy loss is the most important parameter governing the γ multiplicity.

The above conclusions are of a different nature than those found in Ref. 12 for Kr bombardment of ^{165}Ho. This difference does not necessarily imply a discrepancy in the experimental data (which were obtained at different bombarding energies). Rather, the main difference in the interpretation of the experimental data most likely originates with the fact that the present experimental data reveal the detailed dependence of the multiplicity simultaneously on Z *and* on energy loss.

In summary, we have measured the dependence of the γ multiplicity on energy loss, scattering angle, and on fragment charge for the Kr-Sn and Kr-Er reaction products. The energy loss, as opposed to scattering angle or net mass transfer, appears to be the basic quantity determining M and hence the transfer of angular momentum for these reactions. Our results for M, which indicate quantitative discrepancies with a classical picture of the reaction mechanism, are well explained by a diffusion model.

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Angular-Momentum Dissipation in Heavy-Ion Collisions

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The angular-momentum dissipation in deeply inelastic heavy-ion collisions is described as a transport process. Using transport coefficients which have been evaluated within a single-particle model, mean value and variance of the intrinsic angular momenta of the fragments are calculated. The fluctuations become important already for initial relative angular momenta $l \lesssim \frac{1}{2} l_{\mathrm{grazing}}$. Excellent agreement with γ-multiplicity data for the reaction ^{86}Kr(5.99 MeV/nucleon) + ^{166}Er is obtained.

The dissipation of relative angular momentum into intrinsic angular momentum of the fragments is one of the most interesting relaxation phenomena in reactions between heavy nuclei.[1-9] Experimental information on angular-momentum dissipation has been obtained from γ rays[1-7] and light particles[8] emitted by the fragments and, in addition, from sequential fission of the heavy

