Angular Momentum Transfer in Deep-Inelastic Reactions as Inferred from Angular Distributions of Sequential-Fission Fragments

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Theoretical results of a model of heavy-ion collisions in terms of elementary modes of excitation are presented for the reaction Kr + Pb at 610 MeV with special emphasis on the transfer of angular momentum. The angular distributions of the fragments resulting from the sequential fission of the heavy reaction partner are calculated in a semiclassical model. Conflicting experimental results reported for similar reactions are discussed and the still rather open range of possibilities in the analysis of the data is stressed.

A large fraction of the deep-inelastic events in reactions like, for example, ^{86}Kr + ^{208}Pb leads to the fission of the heavy partner. The angular distribution of the corresponding sequential-fission fragments contains information about the angular momentum which was absorbed by the heavy reaction partner (cf. Dyer *et al.*,[1] Back and Bjørnholm,[2] Specht,[3] and Wozniak *et al.*[4]).

In the present Letter we analyze the reaction ^{86}Kr + ^{208}Pb at 610 MeV, in the framework of the model of heavy-ion reactions proposed by Broglia, Dasso, and Winther[5] and further developed by Broglia and co-workers.[6,7]

The spectrum of collective and noncollective surface vibrations and of damped giant resonances is the same as that utilized in Refs. 5 and 6. Particle transfer is treated as a diffusion process according to the proximity approximation (cf. Randrup[8]). The quantal fluctuations in energy loss, scattering angle, and angular momentum loss, due to the excitation of surface modes, are taken into account by utilizing a distribution of shapes, representing the zero-point fluctuations as initial conditions.[9] Thus, the trajectory of relative motion is not constrained to remain on a plane. The model incorporates fluctuations due to mass transfer to the extent that this process has been included in the ensemble calculations. Fluctuations due to the statistical nature of the one-body dissipation mechanism are not included.

The equations to be solved for each initial condition are (4)–(9) of Ref. 5, generalized to include the equations for the coordinate of relative motion θ and its conjugate momentum P_θ. The numerical calculations are carried out in the center-of-mass system in a reference frame oriented with the x axis parallel to the beam and with the z axis along the initial relative angular momentum. However, the components of angular momentum quoted below are given in a rotated frame defined so as to have the x axis along the laboratory recoil direction of the target and the z axis perpendicular to the "plane" containing the beam and the asymptotic recoil velocity.

In Fig. 1(a) we show the predictions of the model for the total angular momentum $J_{\rm Pb} = (J_x^2 + J_y^2 + J_z^2)_{\rm Pb}^{1/2}$ transferred to the target as a function of impact parameter. The "error bars" given to the points indicate the standard deviation associated with fluctuations in $J_{\rm Pb}$ generated by the zero-point motion. In Fig. 1(b) the component of angular momentum perpendicular to the reaction plane is shown as a function of the energy loss integrated over scattering angle. As before, the bars represent the effect of the quantal fluctuations in the excitation of the surface modes.

The model of Ref. 5, being essentially a coupled-channels scheme, produces for each impact parameter the probabilities of feeding the different reaction channels. As all partial waves may in principle contribute to the population of a wide range of states, a characteristic feature of these results is the lack of correlation between impact parameter and the final value of dynamical quantities. Note, for example, the size of the fluctuations in Fig. 1(a) for the case of angular momentum. This in turn explains the spread in the angular momentum for high Q values in Fig. 1(b), as large energy losses result from a range of partial waves extending from zero up to nearly the grazing value.

We show in Fig. 1(c) the distribution of components J_x and J_y for the same conditions as in Fig. 1(b) and for a Q value of -150 MeV. We

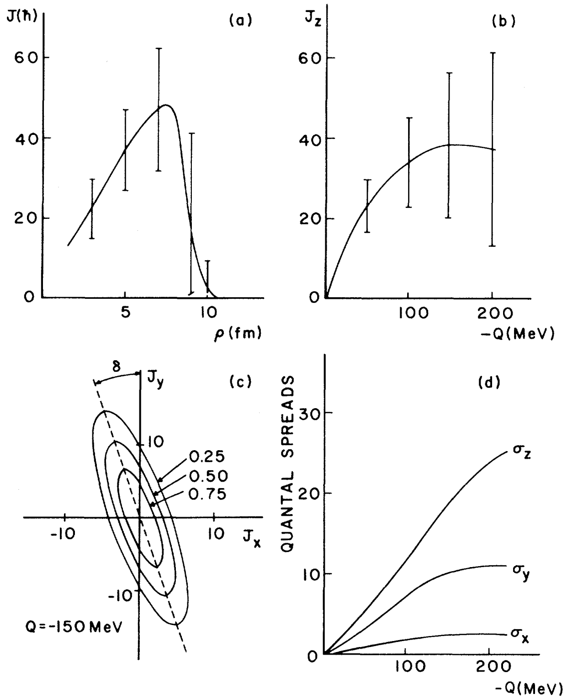

FIG. 1. Distribution of angular momentum and its fluctuation. In (a) we plot the magnitude of the angular momentum absorbed by Pb as function of impact parameter. In (b) and (d) we display the z component and the spreads as functions of the Q value. In (c) the distribution of angular momentum on the reaction plane is shown for $Q = -150$ MeV.

notice a pronounced alignment of the in-plane components of angular momentum in a direction nearly perpendicular to the target recoil direction but actually tilted an angle δ. The main features of this figure are well understood (cf., e.g., Alder and Winther[10]). Note, however, that the angle δ, mostly determined by Q-value effects, is slightly increased by deformations in the exit channel.

The analysis of the distribution of angular momentum in the reaction plane allows us to identify the principal axis of the distribution and to evaluate the corresponding standard deviations. These are indicated as a function of Q value in Fig. 1(d). Irregularities in these curves due to relatively poor statistics (440 trajectories in total) were smoothed out.

In the following we produce the angular distribution of the fission fragments of the Pb-like nucleus as it results from the theoretical model. We use a simple estimate for the case of a fissioning nucleus with a Gaussian distribution of angular momentum ($0 \pm \sigma_x$, $0 \pm \sigma_y$, $J_z \pm \sigma_z$). The fact that low values of total angular momentum may not necessarily lead to fission is neglected. The angular distribution $W(\theta,\varphi)$ of the fission fragments results from the contributions of the different orientations and magnitudes of $\vec{J}$. For a given $\vec{J}$ we use

$$\delta W(\theta,\varphi) \sim \exp\{-[\vec{J}\cdot\hat{n}(\theta,\varphi)]^2/2K_0^2\}, \tag{1}$$

where $\hat{n}(\theta,\varphi)$ is the unit vector with polar angles θ and φ.

The expression (1) is consistent with the usual treatment of fission-fragment angular distributions, the width parameter K_0 being related to the effective moment of inertia of the nucleus at the saddle point.[11] In fact, integrating (1) over all orientations of $\vec{J}$ perpendicular to a beam axis, one obtains the standard formula[11] for compound nuclei:

$$W(\theta) \sim \exp\left(-\frac{J^2\sin^2\theta}{4K_0^2}\right) J_0\left(i\,\frac{J^2\sin^2\theta}{4K_0^2}\right), \tag{2}$$

where θ is the angle measured with respect to the beam axis and J_0 is the Bessel function of order zero. If we ignore the normalization factor, expression (1) can be folded analytically with the Gaussian distribution for $\vec{J}$ to yield

$$W(\theta,\varphi) \sim \frac{\exp\{-\frac{1}{2}[J_z\cos\theta/S(\theta,\varphi)]^2\}}{S(\theta,\varphi)}, \tag{3}$$

where $S^2(\theta,\varphi) = K_0^2 + (\sigma_x^2\cos^2\varphi + \sigma_y^2\sin^2\varphi)\sin^2\theta + \sigma_z^2\cos^2\theta$.

The in- and out-of-plane angular distributions resulting from the values quoted in Figs. 1(b) and 1(d) are shown in Figs. 2(a) and 2(b), respectively for two Q values. The in-plane angle φ is defined with respect to the target-recoil direction. The out-of-plane angular distribution is indicated with a dashed line near the polar axis where the formula is not accurate. Outside this range the expression (3) reproduces well the results obtained with the formalism of Ref. 2.

There are published reports on two experiments which are conflicting in their results although concerning quite similar reactions.[1,3] A 2:1 anisotropy in the in plane was interpreted in Ref. 1 as implying the transferred angular momentum to be mostly orthogonal to the recoil direction. On the other hand, a rather flat rms value of the out-of-plane angular distribution for different azimuthal angles was taken in Ref. 3 as evidence of an isotropic distribution of components of angular momentum in the reaction plane. An ensuing debate has centered on this

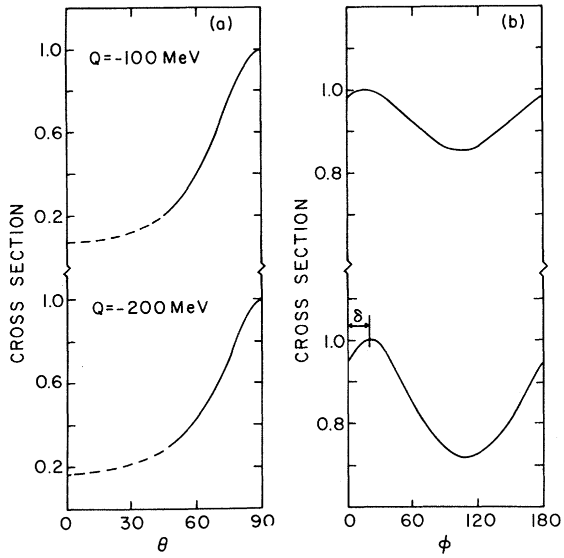

FIG. 2. In-plane and out-of-plane angular distributions. A value (Ref. 3) of $\kappa_0=11$ was used.

question.

As our calculations and expression (3) show, however, these experiments do not directly measure the isotropy (or anisotropy) of the in-plane distribution of angular momentum. In fact, the distribution of fission fragments depends not only on the ratio of the spreads of the components along the principal axes but also rather strongly on their absolute magnitude. It is only when σ_x and σ_y become comparable to or larger than κ_0 that their values may reflect in the resulting angular distributions.

Even acknowledging the limitations of the simple formulation (3) one can rather safely make the following observations. In addition to a direct measurement of the maximum and minimum counting rates in the reaction plane, a way of detecting in-plane anisotropies is by studying the variation of the half-width ($\theta'=\frac{1}{2}\pi-\theta$) of the out-of-plane angular distribution. This is a far more sensitive quantity than the rms value reported in Ref. 3. On the other hand, the rms average of θ' (or θ) seems to be more sensitive to the extent of fluctuations in the aligned component of angular momentum and thus can be useful to learn about σ_z.

In any case it is clear that measurements of the in-plane and average out-of-plane angular distributions will not uniquely determine the four quantities (J_z, σ_x, σ_y, and σ_z) that came out from the model calculation but rather define a range of possibilities. In particular one should be careful to extract quantities such as the alignment (P_{zz}) from the experimental data. Its sensitivity to the measured angular distributions is low, thus requiring very good statistics.

We find that the model of Ref. 5 accounts for many of the observed features of sequential fission induced in heavy-ion collisions. The theoretical results of Figs. 1(b) and 1(d) are in general good agreement with both experiments for the out-of-plane angular distributions. Note, however, that fluctuations due to particle transfer have been poorly treated. As far as the in-plane angular distributions are concerned they are closer to the findings of Ref. 3. The larger anisotropies reported in Ref. 1 would require the x and y components of angular momentum to be about twice as large as currently obtained.

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