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Angular Momentum Transfer in Deeply Inelastic Collisions from Exclusive Sequential-Fission Experiments

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Kinematically complete experiments have been performed on the three-body exit channels in 7.5 MeV/amu ^{208}Pb and ^{238}U on ^{58}Ni and ^{90}Zr. The bulk of the events (>99%) can be interpreted as sequential fission following deeply inelastic collisions. From the angular correlations, oriented-spin values up to $45\hbar$ are deduced for the heavy fissioning fragment. Their constancy at large energy losses points to strong fluctuations in the correlation between energy loss and angular momentum.

One of the outstanding problems in the mechanism of deeply inelastic heavy-ion collisions is associated with the angular momentum transferred from orbital to intrinsic rotation. Besides γ and light-particle emission, sequential fission has already proven a useful probe sensitive both to the magnitude and orientation of the spin transfer.[1-4] We report in this Letter results from the first exclusive experiments in this field.[5,6] By use of heavy-particle beams and large-area detectors, the two- and three-body exit channels in the reactions ^{208}Pb, ^{238}U $\to$ ^{58}Ni, ^{90}Zr have been investigated in a way which is complete both kinematically and in the total phase-space distribution of the events, including all correlations between the observables. We show that the bulk of the three-particle data can, in fact, be interpreted as sequential fission following quasielastic and deeply inelastic collisions. From the fission-fragment angular correlations, oriented-spin values up to $45\hbar$ and rather isotropically distributed nonoriented components of $(10-15)\hbar$ are deduced for the heavy fissioning nucleus. Following an initial rise, the former are observed to remain constant up to the largest energy losses, possibly indicating strong fluctuations in the correlation between energy loss and angular momentum.

Ni and Zr targets of 100–200 μg/cm^2 were bombarded with Pb and U beams of 7.5 MeV/amu from the UNILAC at Gesellschaft für Schwerionenforschung. The targetlike fragments were analyzed in a 40×12 cm^2 position-sensitive ΔE-E gas ionization chamber.[7] A lab acceptance angle of $\sim30°$ in the reaction plane together with the kinematic concentration for forward c.m. angles and the focusing property of the deeply inelastic reaction allowed us to measure the major part of the cross section with one angle setting for each system. The beamlike surviving fragment or its two fission products were detected in coincidence in a 1×1 m^2 position-sensitive parallel-plate avalanche counter[8] with an overall time-of-flight resolution (in connection with the bunched beam) of <0.5 ns. Because of the "inverse" kinematics with the laboratory velocity of the fissioning nucleus being large compared to the velocity of the fission fragments in its rest frame, the possible laboratory directions of the fragments are compressed into a narrow cone of 45°–50° opening angle. Thus, one angle setting of the detector again was sufficient to cover the entire cone, resulting in a 4π efficiency for the investigation of the various fission observables. For a certain fraction of the events, only one fragment was detected because of losses on the support structure of the counter window and on an adjustable beam stop located in front of the detector, shielding it against small-angle (<5°) Rutherford scattering. In the off-line analysis, a step-wise procedure on the basis of the ionization-chamber data was employed, yielding the charge Z and mass M of the targetlike fragment as well as the Q value and c.m. angle of the first binary-reaction step. With the data from the other detector, the fission direction in the frame of the fissioning nucleus can then unambiguously be evaluated even in the case where only one fragment has been observed. With the detection of both, the full information including the total fission kinetic energy and fragment mass ratio is obtained.

The distribution of the vector difference $|\vec{v}_R| = |\vec{v}_1 - \vec{v}_2|$ of the fission-fragment laboratory velocities, integrated over all other observables, is shown in Fig. 1 for two representative examples. It clearly demonstrates the existence of an intermediate fissioning system as a "resonance." The quantity v_R essentially determines the total fission-fragment kinetic energy $E_K = 1/2\, \mu v_R^2$, μ being the reduced mass of the two fragments. The average values $\langle E_K\rangle = 145$ MeV (Pb) and 172 MeV (U) deduced from these distributions are consistent with data on both low- and high-energy–induced fission in this region,[9,10] and also in their systematic dependence on the nuclear charge of the fissioning nucleus[6] (measured via the charge of the targetlike particle). The standard deviations $\sigma_E = 16$ MeV (Pb) and 19 MeV (U) are larger than those found in low-energy fission,[9] but close to the values observed in heavy-ion fusion-fission reactions at excitations greater than 100 MeV.[10] It should be especially emphasized that, within our present limits of accuracy, these velocity distributions are essentially independent of the fission direction and the Q value of the first reaction step, whereas Coulomb-force influences by the targetlike nucleus would have been expected in a truly fast process. We thus conclude that, apart from tails (<1%) of possibly instrumental origin, the bulk of the three-particle events can be interpreted as sequential fission following quasielastic and deeply inelastic collisions.

The overall fission-fragment angular correlations for the four reactions are given in Fig. 2. Spherical coordinates in the frame of the fissioning beamlike particles are used with the normal to the reaction plane of the first step chosen as the quantization (z) axis.[1,3] Thus the equator $\theta_{\text{c.m.}}^F = 90°$ corresponds to that plane; the azimuth angle $\varphi_{\text{c.m.}}^F$ is measured relative to the laboratory recoil direction of the targetlike particles (approximately equivalent to the angle bisector of the c.m. scattering angle). The out-of-plane distributions in the upper part, integrated over all azimuth angles, exhibit a pronounced tendency of the three-body events towards coplanarity immediately indicative of a considerable spin align-

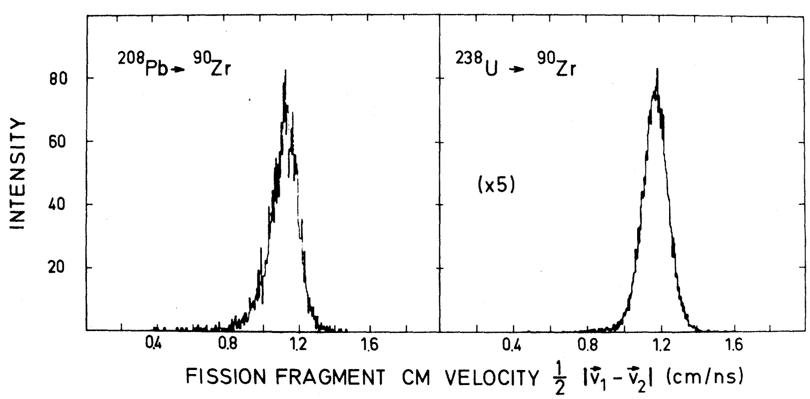

FIG. 1. Distribution of the vector difference $|\vec{v}_1 - \vec{v}_2|$ of the fission-fragment laboratory velocities, integrated over all other observables.

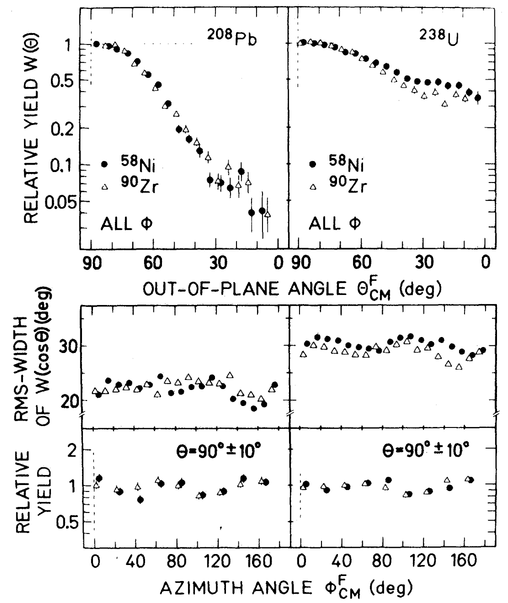

FIG. 2. Overall fission-fragment angular correlations. The polar distributions (upper part) are integrated over all azimuth angles $\varphi_{c.m.}{}^F$. The in-plane distributions (lower part) represent a cut close to the equator. The rms width (center part) is evaluated from the individual polar distributions for each $\varphi_{c.m.}{}^F$.

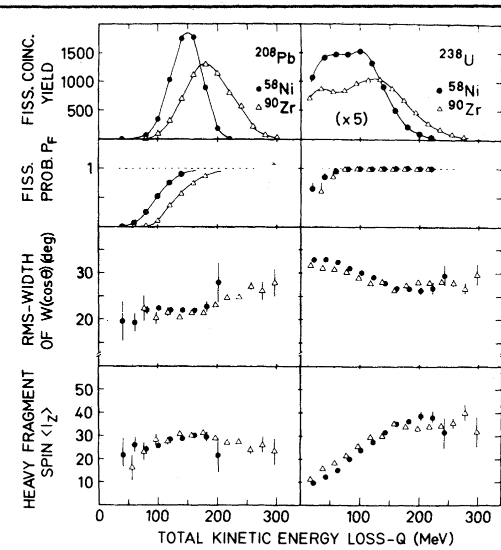

FIG. 3. Fission coincidence yield, fission probabilities (ratio of ternaries to total), rms angles of the polar distributions (integrated over $\varphi_{c.m.}{}^F$), and a lower limit for the average oriented part $\langle I_Z\rangle$ of the heavy-fragment spin (assuming complete alignment).

ment along the z direction (see below). The 90° to 0° ratio is found to be ~25 for the Pb reactions, in quantitative agreement with the result[1] from ^{86}Kr + ^{209}Bi for the specific azimuth angle $\varphi_{c.m.}{}^F = 0$. The smaller value of only ~3 for the U reactions is mainly due to the strong contribution from quasielastic events (compare Fig. 3). The target independence of the distributions (also supported by preliminary data on Pb → Pb and U → U) may, to first order, be explained by an approximate cancellation between the target-mass dependences of the orbital angular momentum brought in by the entrance channel, and that fraction of it transferred to the heavy fissioning fragment in the sticking limit.[6]

The in-plane distributions in the lower part of Fig. 2, defined by the polar-angle selection $\theta_{c.m.}{}^F = 90° \pm 10°$ close to the equator, are rather isotropic for all four systems, consistent with the nearly constant rms width $\theta_{rms} = \sin^{-1}\langle\cos^2\theta\rangle^{1/2}$ of the individual out-of-plane distributions $W(\cos\theta)$ for each $\varphi_{c.m.}{}^F$ (center part), but seemingly inconsistent with the 2:1 enhancement at $\varphi_{c.m.}{}^F = 0$ reported for ^{86}Kr + ^{209}Bi.[1] The slight nonstatistical variations can essentially be traced back to regions with a small chance of losing both fission fragments. A least-squares fit to the data points assuming the form $W(\varphi) \sim (1 + C\cos^2\varphi)$ yields $W(0°)/W(90°)$ values of 1.11 ± 0.29 (Ni), 1.07 ± 0.21 (Zr) for the Pb reactions, and 1.07 ± 0.18 (Ni), 1.13 ± 0.23 (Zr) for the U reactions, whereas a similar fit to the more accurate rms angles results in $\theta_{rms}(0°)/\theta_{rms}(90°)$ ratios of 0.93 ± 0.02, 0.90 ± 0.06, 0.98 ± 0.01, and 0.96 ± 0.01, respectively. We therefore conclude that any random, depolarizing spin components perpendicular to the z axis[1-3] are distributed rather isotropically (see also below).

The more detailed dependences of various quantities on the Q value of the first binary-reaction step are finally contained in Fig. 3—from top to bottom the fission coincidence yield, the fission probability (ratio of ternaries to total), the rms angle of the out-of-plane distribution $W(\cos\theta)$, and a lower limit for the average *oriented* part $\langle I_Z\rangle$ of the heavy-fragment spin. The differences between the Pb and U reactions mentioned above are immediately recognized, the more quasielastic region for the former being cut off by the rapidly decreasing fission probability (the apparent target dependence is trivially due to the plotting versus Q value rather than excitation energy in the Pb-like particles, assuming a sharing proportional to mass). Briefly, the conversion of the rms width θ_{rms} into spin involves the formulation of the fragment angular correlation in terms of $D_{MK}{}^I$ functions,[1-6] properly weighted with the usual Gaussian distribution[3,9] of the spin projection K on the symmetry axis of the fission saddlepoint configuration. Relying on empirical values for the standard deviation K_0 of these distributions[3,9] of $11\hbar$ (Pb-like) and $17\hbar$ (U-like) at an excitation energy E^* of 100 MeV together with a $\sim E^{*1/4}$ dependence, and finally assuming complete alignment, i.e., $I = I_Z = M_Z$ ($\equiv M$), the lower limit for $\langle I_Z \rangle$ shown in Fig. 3 is obtained.

In the U case, the transferred angular momentum is seen to rise gradually with increasing energy loss, reflecting—within the framework of the diffusion model[11]—the rising spin diffusion with increasing (partial-wave-dependent) contact time. For the Pb reactions, this region corresponds to fission probabilities $\ll 1$ where fission mainly occurs via reduction of the fission barrier by rotation, leading to a selection of only the largest spin values I not representative for the true average $\langle I \rangle$. Qualitatively similar in both cases, however, a rather constant behavior is observed in the deeply inelastic region up to the largest energy losses. Such a plateau has also been found in γ-ray multiplicity experiments[12,13] sensitive to $\langle |I_1| + |I_2| \rangle$. It has there been interpreted[11] to arise from a cancellation between a decreasing oriented spin and an increasing statistical, randomly distributed contribution, but is—according to Fig. 3—obviously visible in the oriented part alone. We consider this to be evidence for much stronger fluctuations[14] in the correlation between energy loss and angular momentum than usually assumed, and have therefore chosen to not convert the Q scale into a scale of initial orbital angular momentum.

Because of the existence of random contributions, the absolute size of $\langle I_Z \rangle$ in Fig. 3 is underestimated. Unfortunately, the fragment angular correlation alone cannot, without arbitrary assumptions,[1] uniquely determine all spin components at the same time.[3,5,6] We have made a preliminary attempt, based on the statistical model for the spin-dependent fission probability Γ_f/Γ_{tot},[9] to extract the necessary additional information from the dependence of the observed probabilities on energy loss and charge transfer. In the deeply inelastic region ($-Q > 150$ MeV), internal consistency is obtained for oriented values $\langle I_Z \rangle \approx 40\hbar - 45\hbar$ and in-plane components $\langle M_{x,y}{}^2 \rangle^{1/2} \approx 10\hbar - 15\hbar$, assuming $\langle M_x{}^2 \rangle \approx \langle M_y{}^2 \rangle$. Denoting the recoil direction as the y axis,[3] the observed upper limit 1.2 (1σ) of the in-plane anisotropy averaged over the four reactions would then lead to $\langle M_x{}^2 \rangle^{1/2} \leq 12\hbar - 17\hbar$ and $\langle M_y{}^2 \rangle^{1/2} \geq 8\hbar - 13\hbar$. These numbers are considerably smaller than suggested for $^{86}Kr + ^{209}Bi$,[3] but surprisingly close to the asymptotical result from the diffusion model.[11] They correspond to a spin alignment of $P_{ZZ} = (3\langle I_Z{}^2 \rangle / 2\langle I^2 \rangle - \frac{1}{2}) \approx 0.8$. Solely on the basis of the out-of-plane anisotropies, the considerable alignment of the heavy-fragment spin is illustrated by the limits $1 \geq P_{ZZ} \geq 0.5$ for $0 \leq \langle M_{x,y}{}^2 \rangle < \infty$ (which also demonstrates the insensitivity of P_{ZZ}).

In summary, we have verified the sequential pattern of fission in deeply inelastic collisions, and established some systematics for the magnitude and the alignment of the angular momentum transfer. In particular, evidence has been found for strong fluctuations in the correlation between energy loss and angular momentum, presenting some challenge to current theoretical models.

We are indebted to H. Gemmeke, U. Lynen, B. Martin, A. Olmi, D. Pelte, H. J. Sann, and H. Stelzer for their contributions in various early stages of the program, and to C. H. Dasso, T. Døssing, and G. Wolschin for valuable discussions.

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Multiplicity of K X Rays Emitted in (^{6}Li,xn) Reactions

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Measurement of x-ray–x-ray and x-ray–γ-ray coincidence yields indicates that two to three K x rays are emitted, on the average, during the deexcitation of neutron-poor Tl and Pb isotopes populated by (^{6}Li,xn) reactions. Experimental constraints suggest that approximately two x rays arise from a narrow region of spin ($12 \lesssim J \lesssim 20$) dominated by low-energy $M1$ transitions. Measurement of the singles yield as well as the mean multiplicity of the K x rays provides a useful new method for determining absolute evaporation-residue cross sections.

The emission of K x rays following the formation of compound nuclei was first reported, for α-induced reactions, by Deconninck and Longequeue.[1] The x-ray yields observed were too large by several orders of magnitude to be explained by atomic-collision or electron-shakeoff processes, and so were attributed to internal conversion during the γ cascades deexciting (α, xn) residues. Comparison of measured x-ray yields with total (α, xn) cross sections suggested that significantly more than one K x ray might be emitted per residual nucleus produced.[2] Repeated K-shell conversion (hence, multiple K x-ray emission) is possible during a γ cascade beacuse K-vacancy lifetimes for heavy atoms[3] (~ 10^{-17} sec) are much shorter than typical nuclear transition lifetimes.

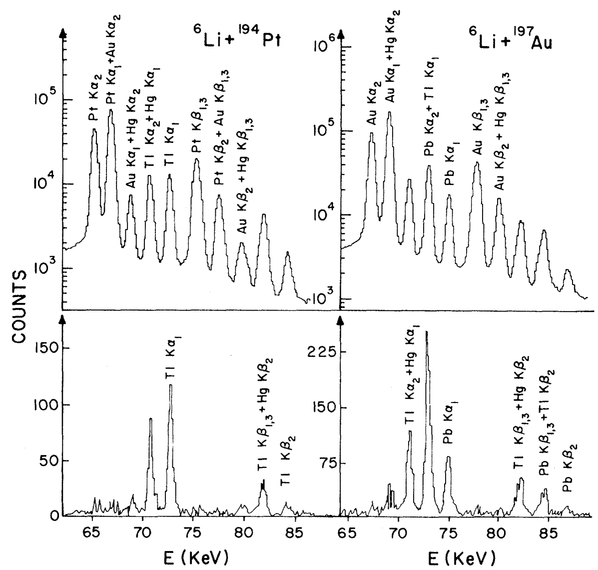

FIG. 1. Representative singles (top) and coincidence (bottom) spectra of K x rays from 95-MeV ^{6}Li bombardment. The bottom spectra were obtained in prompt coincidence with a $K\alpha$ x ray in a second Ge detector, after subtraction of backgrounds from accidental coincidences and from coincidences with Compton-scattered γ rays in the second detector. The multiplicity $\langle M_K \rangle$ was determined from the ratio of coincidence-to-singles events in the compound-nucleus $K\alpha_1$ peak, which has no contribution from other elements or from β activity.

In the present Letter we report the first *direct* measurements of K x-ray multiplicities following fusion reactions. We show that such measurements provide an important new tool in (1) the determination of absolute evaporation-residue cross sections and (2) the investigation of nuclear transition multipolarities in high-multiplicity γ-cascades.

The mean K x-ray multiplicity $\langle M_K \rangle$ has been measured for (^{6}Li,xn) reactions induced on ^{181}Ta, ^{194,198}Pt, ^{197}Au, and ^{208}Pb at bombarding energies of 75, 85, and 95 MeV, using beams from the In-

