# Gamma-Ray Multiplicity Moments from Deeply Inelastic Collisions of $^{86}$Kr and $^{144}$Sm

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First, second, and third moments of gamma-ray multiplicity distributions from deeply inelastic collisions have been measured for the system $^{86}$Kr on $^{144}$Sm at 490-MeV Kr energy. The average gamma-ray multiplicities are $\approx 21$, independent of reaction angle and fragment charge. The multiplicity distributions are broad, with standard deviations of $v \approx 10$, and they have a negative skewness.

Deeply inelastic collisions (DIC) are a characteristic feature of heavy-ion reactions at energies above the Coulomb barrier and extensive data on the energy and mass transfer in DIC have been published.[1] We report here on measurements of gamma-ray multiplicity distributions (first, second, and third moments) from DIC at 5.70 MeV/nucleon of $^{86}$Kr on $^{144}$Sm as a means of obtaining detailed information on the angular momentum transfers accompanying the energy and mass transport. It will be shown that the average gamma-ray multiplicities are compatible with the sticking limit for DIC while the magnitudes of the second moments of the multiplicity distributions provide a severe challenge for such a simple description of the angular momentum transfer.

Previous related publications encompass the fission angular correlations in the $^{86}$Kr + $^{209}$Bi system[2] at 7.1 MeV/nucleon and the measurements of average gamma-ray multiplicities (first moments) of Aleonard *et al.*[3] ($^{86}$Kr + Ag, Ho, Au at 7.2 MeV/nucleon), of Glassel *et al.*[4] ($^{20}$Ne + Ag at 8.75 MeV/nucleon), and of Sann *et al.*[5] ($^{86}$Kr + $^{166}$Er at 5.9 MeV/nucleon). Second and third moments of gamma-ray multiplicity distributions from DIC have not been reported previously.

The $^{86}$Kr beam was provided by the Gesellschaft für Schwerionenforschung UNILAC. The charged-particle reaction products were detected in a $\Delta E$-$E$ telescope with a solid angle of 12.5 msr. The $\Delta E$ measurement was made with a gas ($CH_4$) ionization chamber and the residual energy was obtained from a semiconductor counter. The $\Delta E$-$E$ information was transformed to element ($Z$) and energy information and the resulting $Z$ resolution was $Z/\Delta Z \simeq 50$. Gamma rays were counted in seven 5-cm by 5-cm-diam NaI(Tl) detectors placed in the hemisphere below the scattering chamber at a distance of 12 cm from the target.

For each charged-particle event recorded the gamma-ray detectors which fired were recorded; their trigger levels were at $\approx 100$ keV. From the counting rates in the zeroth, first, second, etc. fold coincidences between the particle telescope and the gamma counters, the gamma-ray multiplicity information was deduced[6] as a function of the fragment energy and $Z$. Measurements were made at particle-detector angles of 25, 30, 35, 43 (grazing), 50, and 55 degrees with respect to the beam axis.

Representative results are shown in Figs. 1 and 2. Figure 1 depicts results as a function of $Z$ for $Q \leq -20$ MeV, where $Q$ is the $Q$ value assuming binary kinematics and fragment mass/charge ratios equal to that of the target plus projectile system. The top part shows the $Z$ spectrum at 35° lab. angle. The lower parts of the figure demonstrate the average multiplicity $\langle M \rangle$ and standard deviation $v = (\langle M^2 \rangle - \langle M \rangle^2)^{1/2}$ of the gamma-ray multiplicity distribution for particle-detector angles of 30, 35, 43, and 50 degrees. At each angle $\langle M \rangle$ reaches a flat level of $\approx 21$ (saturation value) at the extreme $Z$, while it dips near the projectile $Z$. The standard deviations $v$ are quite constant at approximately half the saturation value of $\langle M \rangle$. The 25° and 55° data are similar to those shown.

 

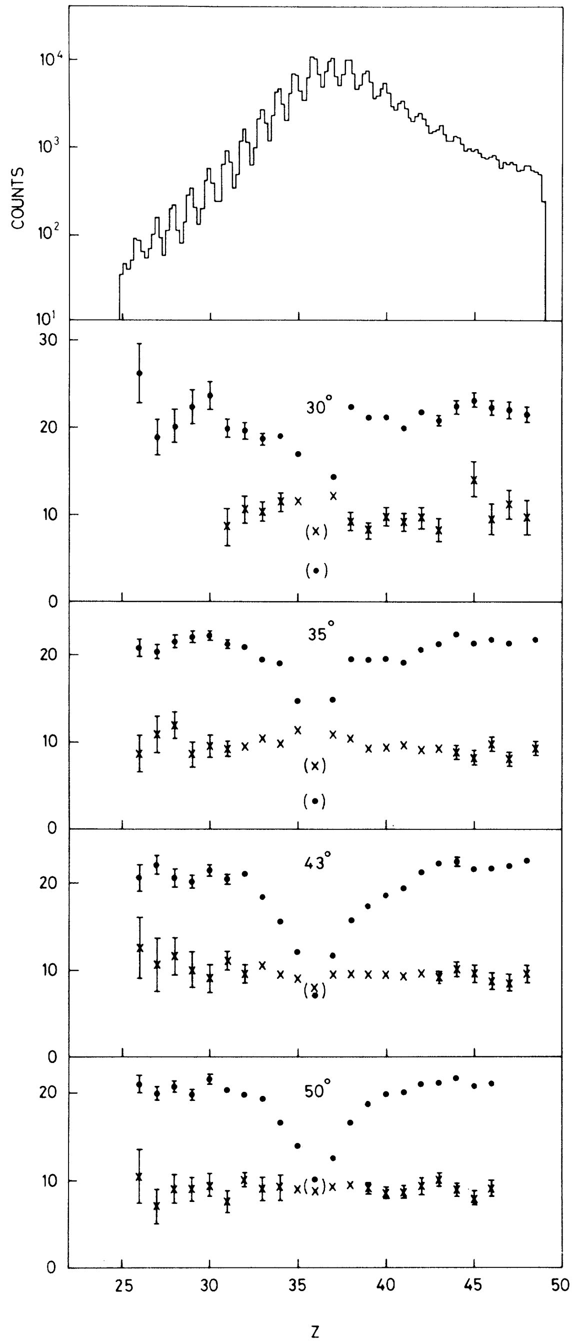


FIG. 1. Top: Yield vs $Z$ summed over coincidence folds 1 through 5 for the DIC region. The particle detector angle was 35° (lab). Lower four frames: $\langle M \rangle$ (filled circles) and $v$ (crosses) as a function of $Z$ (see also the text). The multiplicity formalism used (Ref. 6) may produce asymmetric statistical error bars. Systematic errors from angular distribution effects, neutron background, mathematical convergence, and uncertainties in the gamma-detector efficiencies have not been corrected for. Each effect has been studied by appropriate measurements, and it is concluded that $\langle M \rangle$ suffers by < 5% and $v$ by < 10% from these error sources.

The gamma-ray multiplicity moments obtained after summing the fold count rates over $Z$ (omitting $Z = 36$) are plotted versus $Q$ in Fig. 2. The $\langle M \rangle$ shown in the upper part of the figure for 30, 43, and 50 degrees develops from small values at $Q \approx 0$ towards the saturation value, which is attained for $Q < -90$ MeV. The standard deviations exhibit a similar trend. The very small values of $\langle M \rangle$ in the upper two $Q$ bins at 30° are due to tails from the dominant elastic peak in $Z = 36$.

Inspection of the original, detailed data demonstrates that the dip around $Z = 36$ in the multiplicities of Fig. 1 is associated with the $Q$-value range from $-20$ to $-60$ MeV (see also Fig. 2) where reactions with low $\langle M \rangle$ values occur with substantial cross sections; the low multiplicities are thus tied to the quasielastic reactions.

The lower part of Fig. 2 shows the skewness, $\langle (M - \langle M \rangle)^3 \rangle / v^3$, for the particle-detector angles of 43° and 50°. For $Q$ values close to zero the skewness is positive, while in the $Q$ range below $-60$ MeV it becomes negative. Thus, in the quasielastic region there is an overweight of low-$M$ events, while in the DIC region high-$M$ events dominate.

The gamma-multiplicity distributions in the deep inelastic region thus are characterized by $\langle M \rangle = 21$ and $v = 10$ independent of $Z$ and reaction angle and a negative skewness.[7] Measurements on the system $^{86}$Kr + $^{154}$Sm at 5.70 MeV/nucleon gave similar results.

In order to interpret these results we shall assume that the DIC derive from the incident partial waves from $l_i = 0$ up to $l_i = l_0$ and that the partial waves from $l_0$ up to $l_i = l_{max}$ give rise to the quasielastic reactions (QER). The DIC and QER are supposed to exhaust the classical reaction sum rule. From the measured elastic scattering we find for $^{86}$Kr + $^{144}$Sm at 5.7 MeV/nucleon a quarter-point angle at 82.5° (c.m.) corresponding to $l_{max} = 167$ and a total reaction cross section of 1100 mb. Dividing between QER and DIC at $Q = -60$ MeV we further derive from the particle spectra $\sigma_{DIC} = 740$ mb and $\sigma_{QER} = 360$ mb and thus $l_0 = 137$. The incident angular momentum distribution for the DIC is thus characterized by[7] $\langle l \rangle = 91$, $v = 32$ and a skewness of $-0.57$.

The classical sticking limit[8] has met with some success in predicting the average angular momentum transfers in DIC (see e.g. Refs. 2–4). If we adapt the sticking limit and assume that any given fragment pair $(Z_1, Z_2)$ has received contributions to its production cross section from the entire triangular $l_i$ distribution, the fragment spin $(j_1$

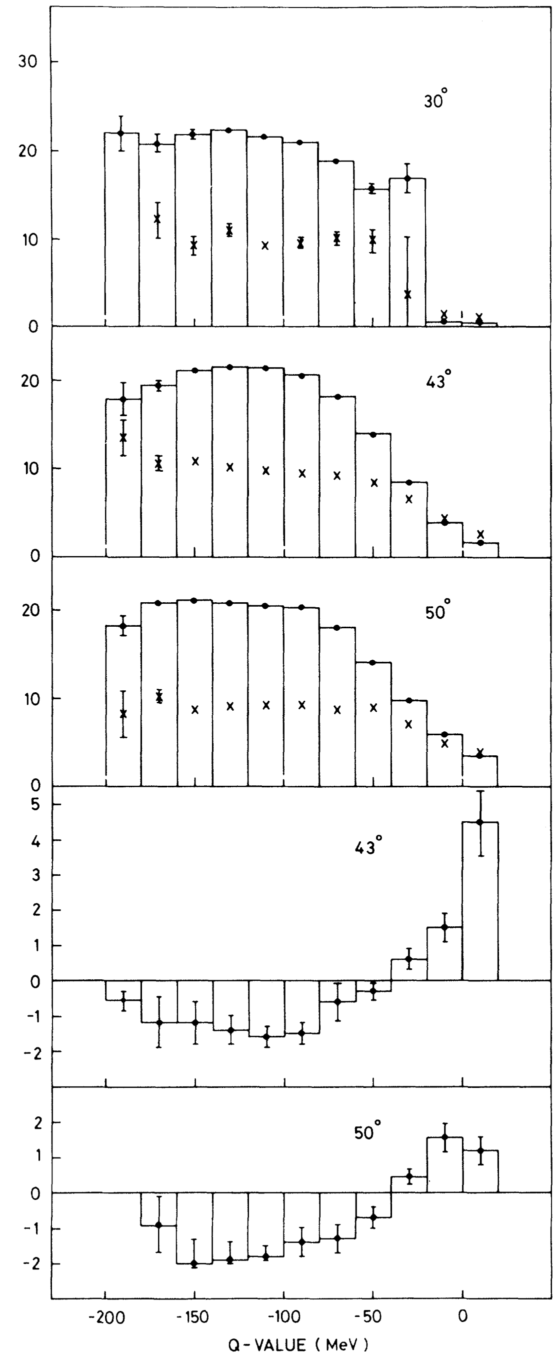


FIG. 2. Top three frames: $\langle M\rangle$ and $v$ vs $Q$ value; the fold count rates have been summed over $Z$ (see also text). Because of significant slit scattering in the beam the projectile $Z$ of 36 was excluded from the data. Lower two parts: Skewness as function of $Q$ value. The skewness is more susceptible to systematic errors than $\langle M\rangle$ and $v$, and the values may be too low by as much as one-half unit.

and $j_2$) distributions are then obtained by scaling the $l_i$ distribution.[8] The fragments then undergo particle decay, which according to statistical-model calculations[9] is dominated by neutron evaporation. (This statement is supported by the data of Ref. 3.) The calculations show that the initial $j$ distributions are moved by the particle decay towards lower $j$ values with little change of shape.

The estimated $j_1+j_2$ distributions after the last particle decay are characterized by values of $\langle j_1\rangle+\langle j_2\rangle$ varying from $19\hbar$ ($Z_1=49$) over $21\hbar$ ($Z_1=36$) to $27\hbar$ ($Z_1=28$) with variances of $v^2=44\hbar^2$, $57\hbar^2$, and $91\hbar^2$, respectively. The skewness is near $-0.6$ in all cases.

These $j_1+j_2$ distributions are difficult to reconcile with the results in Figs. 1 and 2. If, following Refs. 3 and 4, we assume stretched $\lambda=2$ gamma decays, the multiplicities as well as the variances become far too low ($\langle M\rangle\approx 10$ and $v^2\approx 14$ for $Z_1\geq 36$ as compared to the observed values of 21 and 100, respectively).

Another extreme assumption would be stretched $\lambda=1$ decays, which lead to reasonable agreement for $\langle M\rangle$ in the $Z_1\geq 36$ region, but with variances too small be a factor of 2. For the low $Z_1$ values $\langle M\rangle$ becomes too high while $v^2$ is about right.

If we assume the decay model from compound-nucleus experiments,[10-13] a number of gamma rays, $k$, which do not carry away any angular momentum, precede a stretched $E2$ cascade. For a sticking limit with all incident $l_i\leq l_0$ contributing at all $Z$'s the $\langle M\rangle$ data imply $k\approx 12$ ($Z_1=43$) and $k\approx 8$ ($Z_1=28$). Taking into account the change in distributions due to neutron and gamma-ray emission results in an estimate of $v^2<40$ which is in substantial disagreement with the experimental values. The observed constancy of $\langle M\rangle$ with $Z_1$ can also be reproduced by relaxing the assumption of all $l_i$ contributing at all $Z_1$, as suggested by Aleonard *et al.*,[3] but this will not change the discrepancy in the variances. The $l_i$ distribution may be broader than the assumed triangle, but within the confines of the measured $\sigma_{\text{reac}}$, $\sigma_{\text{DIC}}$, and $\sigma_{\text{QER}}$ only an insignificant increase in $v$ is possible. A significant high-angular-momentum tail is improbable also in view of the negative skewnesses.

While the sticking limit cannot be claimed to disagree with the observed $\langle M\rangle$ values (see also Ref. 3), difficulties exist with regard to the multiplicity variances, implying that one needs an angular-momentum dissipation scheme that incorporates fluctuations around the average. One such scheme has been suggested by Ayik, Wolschin, and Nörenberg.[14]

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[7]A. triangular distribution starting at zero for $M=0$ and increasing to $M=M_{\max}$ has $\langle M\rangle = 2/3\, M_{\max}$, $v = 0.35 \times \langle M\rangle$ and skewness $-0.57$.

[8]In the sticking limit $j_1$ and $j_2$ result from rigid rotation of two spheres sticking together. The radii are taken to be proportional to the cubic root of the mass. See also J. P. Bondorf, *Nuclear Spectroscopy and Nuclear Reactions with Heavy Ions* (Editrice Compositori, Bologna, 1976), p. 221.

[9]The statistical-model calculations indicate that an average of eight neutrons are emitted from the two reaction fragments, carrying away on the average a total of 7 units of angular momentum and $\approx 100$ MeV of excitation energy when averaged over a triangular spin distribution.

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# Fission of $^{24}$Mg Following $E0$ and $E2$ Excitation

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We report the electron-induced fission of $^{24}$Mg into two ground-state $^{12}$C nuclei following monopole excitation at energies between 20 and 22 MeV. The observed cross section exhausts at least $(8\pm 2)\%$ of the linear energy-weighted monopole sum rule $S(E0)$ and may form a part of the giant monopole resonance. In addition, we have observed a peak in the $\theta_{^{12}\mathrm{C}} = 45°$ excitation function between 22.0 and 23.5 MeV with a width (full width at half-maximum) < 1 MeV and a $^{12}$C angular distribution, $\sin^2(2\theta_{\mathrm{c.m.}})$, indicating $J^\pi = 2^+$.

Microscopic models that describe nuclear fission are hindered by the large number of nucleons that are usually involved. Studies of the breakup of small nuclear systems such as $^{24}$Mg permit detailed calculations and may suggest general mechanisms for fission. We have observed the fission of $^{24}$Mg into two $^{12}$C nuclei, following electric monopole ($E0$) and quadrupole ($E2$) excitations, induced by inelastic electron scattering at incident energies between 21 and 32 MeV. The bulk of these investigations was carried out at the University of Toronto Electron Linear Accelerator Facility. Polycarbonate films (5-$\mu$m-thick Makrofol, type $KG$, available from Bayers Dyestuffs) were used to detect the fission fragments. The development of these foils, by chemically etching the molecular damage created along the tracks of the heavy ions, is described elsewhere.[1,2] Initial observations of the electrofission of $^{24}$Mg following $E2$ absorption were reported by Chung *et al.*,[3] who used 6-$\mu$m-thick Makrofol with a $^{12}$C detection threshold near 5 MeV. This restricted the