Neutron Emission in Strongly Damped Collisions of ^{86}Kr on ^{166}Er at 602 MeV

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The neutron multiplicity was measured in coincidence with both binary products of the strongly damped collisions of ^{86}Kr on ^{166}Kr at 602-MeV beam energy. The measured ratio of the neutron multiplicities for the light and heavy fragments is in good agreement with the corresponding mass ratio for all mass divisions. The observed multiplicities as well as velocity and angular distributions of the neutrons are consistent with statistical-model calculations assuming isotropic evaporation of neutrons from fully accelerated, unpolarized fragments.

The purpose of this Letter is to present first results of a measurement of neutrons emitted during strongly damped collisions (SDC) of ^{86}Kr on ^{186}Er, which includes determination of the angular distribution of the neutrons and of the neutron multiplicity as a function of excitation energy and mass division. Such measurements provide information on the time scale of energy equilibration, the sharing of excitation energy between the fragments, and the de-excitation process of the fragments. Probable indication of nonequilibrium processes have been recently reported in similar studies.[1,2] The division of the excitation energy between the fragments has also been recently studied using different experimental approaches.[3] Our results show that (1) the excitation energy is shared between the fragments in proportion to their mass, indicating energy equilibration in the composite system; (2) the neutron multiplicity, energy, and angular distribution are in agreement with statistical-model calculations assuming isotropic neutron emission from the fully accelerated fragments. We find no evidence for pre-equilibrium effects or for alignment of the fragments.

The experiments were performed using a 602-MeV beam of ^{86}Kr at the Gesellschaft für Schwerionenforschung Unilac in Darmstadt, impinging on a 250-μg/cm^2 target of ^{166}Er. The two binary products were detected in a pair of two-dimensional position-sensitive parallel-plate avalanche counters (PSPP).[4] The right (R) PSPP was positioned near the grazing angle for projectilelike fragments ($\theta_{\rm gr} \simeq 37°$) with its center at 36° to the beam on the right-hand side of the beam line. Its in-plane acceptance angle was ± 11° and the out-of-plane acceptance approximately ± 2°. The left (L) PSPP was positioned around 46° on the left-hand side of the beam; its in-plane acceptance was ± 12° and its out-of-plane acceptance ± 10°. We made use of the bunched-beam facility of the Unilac which yielded 250-ps-wide beam pulses at 37-ns intervals.

The PSPP were mounted in a thin-walled (3-mm-thick) dome-shaped aluminum scattering chamber, especially desinged to minimize neutron scattering. Eight neutron detectors employing 5-cm-thick NE-213 scintillators of 11.3 and 12.6 cm diam (covered in front and at the circumference by 3-mm-thick lead shields to reduce the γ background) were placed outside the chamber at a distance of ~ 75 cm from the target: Two detectors labeled L and R were placed in the direction of the detected fragments, the detectors FL and FR were placed at forward angles, the detectors BL and BR at backward angles, and the detectors OL and OR out-of-plane with respect to the direction of the two fragments. Details of the exact locations are presented in Table I.

The primary (pre-evaporation) masses and kinetic energies of the fragments were determined event by event from the measured scattering angles of the two fragments and their time of flight (TOF). We estimate the mass resulution to be ~ 10 amu full width at half-maximum (FWHM), and the kinetic energy resolution ~ 50 MeV FWHM.

Each coincident event between the two fragment detectors and at least one neutron counter was recorded by an on-line data acquisition system.[5] The velocity of the neutrons was measured by the TOF method, relative to the 250-ps-wide bunched beam. The overall time resolution was about 1 ns. A pulse-shape-analyzer pulse, characteristic of the rise time of the signal, was recorded with each TOF pulse, together with the amplitude of the pulse-height signal from the photomultiplier. The pulse-height signal was used off line to set the lower discrimination level of the laboratory neutron spectra at 1.6 MeV. All our results pertain to neutrons above this discrimination level. The efficiency of the neutron counter was determined using the method of Drosg.[6] The amount of random coincidences in the TOF spectra was negligible. We measured the neutron absorption by the PSPP's in a separate experiment which utilized neutrons of 3 and 8 MeV from the reaction $^7\mathrm{Li}(p,n)$. The absorption was found to be $<8\%$ except for the counter labeled BR which was not considered in the present analysis.

Velocity spectra of six neutron counters are shown (open circles) in Fig. 1. The error bars reflect only the uncertainty of the threshold determination, which is the main source of error in our results. An additional source of error is our reliance on the general efficiency curve of Drosg.[6] Different counters may deviate by $<\pm 5\%$ from the above curve. The large focusing effect of the fragment motion on the angular distribution of the neutrons permits the determination of the number of neutrons emitted by each fragment by a method similar to that of Fraenkel *et al.*[7]: Neutron counters L and R (approximately in the direction of the fragments) were employed as "primary" counters to determine the multiplicity and velocity spectrum of neutrons evaporated from the fragments. We assumed that all neutrons detected in these two counters are evaporated isotropically in the c.m. system of the fragments. We further assumed that the neutrons detected in counter L come from the left fragment and those detected in counter R from the right fragment, but corrected these distributions to first order for the contribution of each fragment to the *opposite* neutron counter. These corrections were less than 5%. These corrected distributions were used to calculate the final neutron multiplicities and velocity spectra.

In order to check the accuracy of the results[8] a Monte Carlo simulation code was written. The code simulates (1) strongly damped collisions of the primary two-body fragments, (ii) neutron emission by the fully accelerated fragments, and

TABLE I. Positions of the eight neutron counters. The angle θ is measured with respect to the beam axis. φ is the azimuthal angle measured clockwise from the left-hand side of the reaction plane. All counters labeled with R were on the right-hand side of the beam line and those labeled L on the left-hand side of the beam line. Ω is the solid angle.

Counter label	θ (deg)	φ (deg)	Ω (msr)
FL	13	0	18
FR	13	180	19
BL	82	0	23
BR	62	180	25
OL	58	50	23
OR	55	123	25
L	55	0	18
R	43	180	19

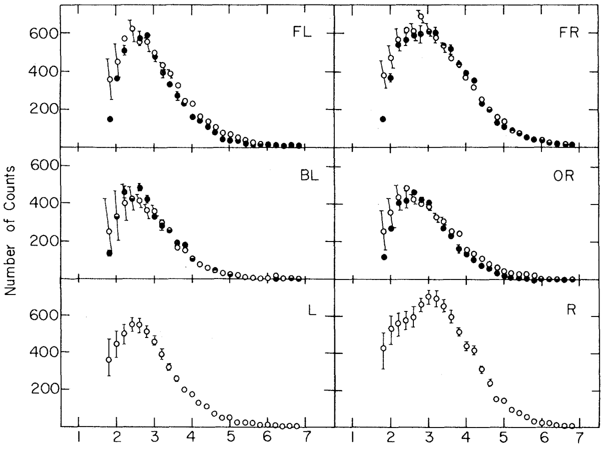

FIG. 1. Measured neutron velocity spectra (open circles) for fragment masses between 68 and 186 and $160 < E_{k,\mathrm{tot}} < 260$ MeV. The full points were calculated from spectra of counters L and R assuming isotropic emission in the c.m. system of the fragments.

(iii) neutron detection. By comparing the number of neutrons determined from the measurements with the numbers given as input to the Monte Carlo code, we determined the accuracy of the extracted values for the two fragments to be ~ 5%.

In Fig. 2 we present the average neutron multiplicity $\bar{\nu}(A)$ as a function of the fragment mass A. $\bar{\nu}(A)$ was averaged over the c.m. total kinetic energy interval of $160 \leqslant E_{k,\mathrm{tot}} \leqslant 260$ MeV (corresponding to the fully relaxed component) and over the complete angular range of the PSPP's. The points were determined using counters L and R. The total number of neutrons, $\bar{\nu}_T(A) = \bar{\nu}(A) + \bar{\nu}(252 - A)$, is also presented as a function of A. The errors shown are due to the uncertainty in the discrimination levels of the neutron counters, as in Fig. 1. We also present in Fig. 2 the multiplicity ratio between the heavy and light fragments ν_H/ν_L as a function of the heavy fragment mass. It is seen that this ratio follows closely the mass ratio M_H/M_L (dashed line).

The average (pre-evaporation) mass of the light fragment is 96.4 amu and that of the heavy fragment 155.6 amu ($\overline{M}_H/\overline{M}_L = 1.61$). The average numbers of neutrons emitted from the light fragment and from the heavy fragment are, respectively, 5.17 ± 0.52 and 9.03 ± 0.90 ($\nu_H/\nu_L = 1.75 \pm 0.35$). From Fig. 2 we conclude that over the total mass range the number of emitted neutrons is divided proportionally to the fragment masses. On the assumption that no charged particles are emitted by the fragments (this assumption is supported by the evaporation calculations) this result indicates that the excitation energy is shared between the fragments proportionally to their masses. The same conclusion has been obtained in entirely different experiments.[3]

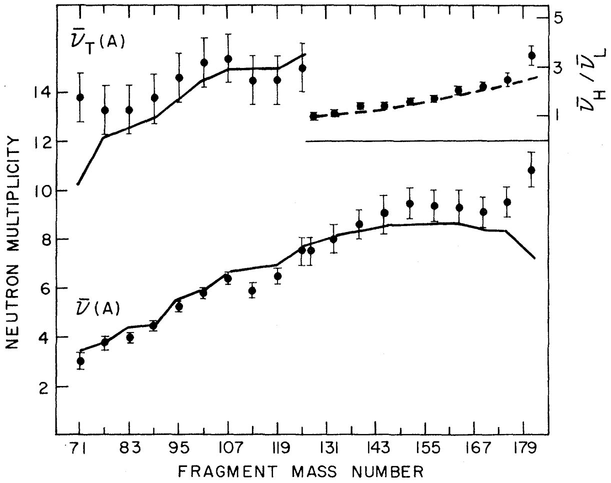

FIG 2. The neutron multiplicity as function of mass $\nu(A)$ averaged over the c.m. kinetic energy interval $160 \leqslant E_{\mathrm{c.m.}} \leqslant 260$ MeV and the complete angular range of the PSPP's. The points were obtained with counters L and R. $\nu_T(A)$ represents the total number of neutrons of both fragments. The solid lines are results of evaporation calculations. The upper right-hand side shows the heavy/light multiplicity ratio and the dashed curve the fragment mass ratio.

The solid lines in Fig. 2 show the calculated neutron multiplicity as obtained from statistical-model calculations.[9] The total excitation energy of the system was assumed to be $\overline{E}_x = E_0 - \overline{E}_{k,\mathrm{tot}} - Q_{gg}$, where E_0 is the incident c.m. energy, $\overline{E}_{k,\mathrm{tot}}$ the mean kinetic energy of the outgoing fragments averaged over a mass bin of 6 amu, and Q_{gg} the average ground-state Q value of the reaction assuming the charge/mass ratio of the fragments to be equal to that of the composite system. The calculation assumes the excitation energy to be divided in proportion to the fragment masses. The initial spins were calculated according to the sticking model.[10] It takes into account the excitation energy dissipated by charged-particle and γ-ray emission and uses the level density formalism of Gilbert and Cameron.[11] It is seen that the calculation reproduces the general trend of the measured multiplicities. The average total number of neutrons is 14.2 ± 1.4; the calculated number is 13.7. It should be pointed out that a total neutron multiplicity of 11.0 ± 2.2 was obtained[2] for the system $^{132}\mathrm{Xe} + {}^{197}\mathrm{Au}$, approximately 25% less than the corresponding calculated multiplicity. This was interpreted in the less complete experiment of Ref. 2 as probable indication for nonequilibrium processes. Neglecting possible differences between the two systems, we note that this interpretation is not supported by the present results.

Figure 3 compares the measured neutron spectra in the c.m. system of each fragment with the evaporation calculations.[9] The calculated spectra are for ^{86}Kr ($E_x = 66$ MeV) and ^{166}Er ($E_x = 132$ MeV) and are in good agreement with the experimental data. We see that in the experimental spectra there is no high-energy component that can be attributed to "pre-equilibrium" emission.

We consider next the angular distribution of the neutrons in the laboratory system: The neutron spectra in counters FR, FL, BL, and OR are compared in Fig. 1 to the calculated spectra based on counters L and R assuming isotropic emission in the fragment c.m. system. Within the systematic and statistical error, the meas-

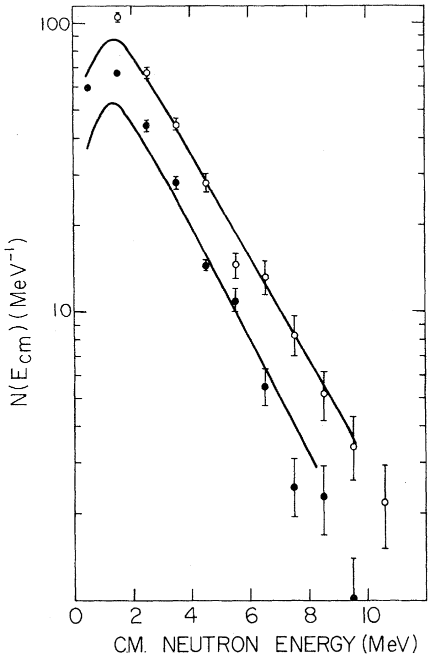

FIG. 3. The neutron energy spectrum in the fragment c.m. system as obtained from neutron counters L and R compared with the calculated spectrum arbitarily normalized. Full circles, light fragment; open circles, heavy fragment.

ured spectra in the forward direction (counters FL and FR), backward direction (counter BL), and out of plane (counters OL and OR) agree with the assumption of isotropic evaporation from the fully accelerated fragments. We see no evidence for the alignment of the fragment spins perpendicular to the reaction plane. (Evaporation calculations predict a ~20% reduction in the number of neutrons in counters OL and OR for fully aligned fragments.) This observation is consistent with the γ-multiplicity measurements of this same reaction.[12]

In conclusion, our results indicate that for the fully relaxed component of the strongly damped collisions, at the end of the interaction, the system is close to thermal equilibrium.

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