Nonequilibrium Neutron Emission in Deep-Inelastic Collisions of ^{86}Kr on ^{166}Er at 1.02 GeV

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(Received 4 May 1981)

Neutrons were measured in coincidence with both fragments of the deep-inelastic collisions of ^{85}Kr on ^{166}Er at 11.9 MeV/amu. The velocity and angular distributions of the neutrons cannot be explained by assuming only statistical neutron evaporation from the fully accelerated fragments.

PACS numbers: 25.70.Bc

The emission of nonequilibrium light particles in deep-inelastic collisions has attracted a large interest both theoretically[1-3] and experimentally[4-12] in recent years. Detailed studies of the neutron emission in heavy systems (mass of the composite system larger than 220), at energies up to 3.5 MeV/amu, have shown that the dissipated energy is uniformly distributed over the composite system before the fragments separate and that the neutrons are statistically evaporated from the fully accelerated fragments.[4-7] The situation is less clear in light systems, where a strong peaking of α particles is observed at forward angles.[9-11] This has been interpreted as evidence of nonequilibrium α emission. However, this interpretation seems now doubtful; simple kinematic effects can reproduce the observed forward peaking of α particles and the experimental results could be consistent with the evaporation hypothesis mentioned above.[13-15]

In this Letter we present results of a measurement of the neutron emission in deep-inelastic collisions of ^{86}Kr on ^{166}Er at 11.9 MeV/amu. This is an extension of our previous work on the same system at lower incident energies. The main aim was to see whether nonequilibrium effects appear at this higher energy. We show that the energy and angular distributions of the neutrons cannot be explained by a simple evaporation hypothesis; there is a clear indication of nonequilibrium neutron emission. Contrary to what is generally believed, the nonequilibrium neutrons are not emitted symmetrically around the beam direction.

The experiments were performed at the Unilac accelerator, Gesellschaft für Schwerionenforschung, Darmstadt with use of a pulsed (27-MHz, 250-ps-wide) beam of ^{86}Kr. We used targets of 50 and 100 $\mu g/cm^2$ of enriched ^{166}Er on thin C backing. The reaction channel was identified with use of a kinematical coincidence technique where the light (L) and the heavy (H) fragments were measured in coincidence with use of position-sensitive parallel-plate avalanche counters. The counters were very similar to those described by Eyal and Stelzer.[16] Each counter consisted of a pair of two identical detectors (each with a sensitive area of 10×8 cm^2) located one above the other symmetrically with respect to the equatorial plane. This double counter arrangement was intended to yield information about the fragmentation of the L fragment.[17] This aspect of the experiment will not be discussed in this paper. The present analysis is restricted to binary events only. This was ensured by accepting only twofold coincidence events with one fragment detected by the left counter and the other one by the right counter, and requiring that the fragment directions were coplanar with the beam axis.

A schematic view of the experimental setup is shown in Fig. 1. The left counter was centered at $\theta = 14°-20°$, i.e., near the grazing angle ($\theta_g = 17°$), and covered an angular range of 15° in plane and 23° out of plane. In order to achieve a complete kinematic overlap between the L and H fragments it was necessary to perform measurements with the right counter centered at $\theta_{lab} = 71°$, 50°, and 29°. These settings selected quasielas-

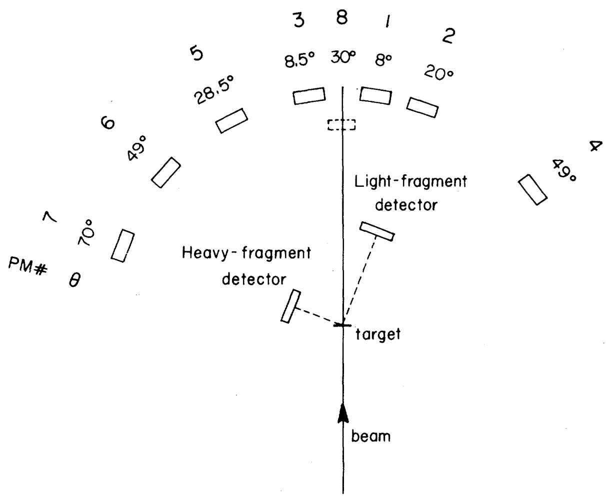

FIG. 1. Schematic view of the experimental setup. PM No. 8 was located in the vertical plane defined by the beam axis at an angle of 30° with respect to the beam. The other seven neutron counters were located in the equatorial plane.

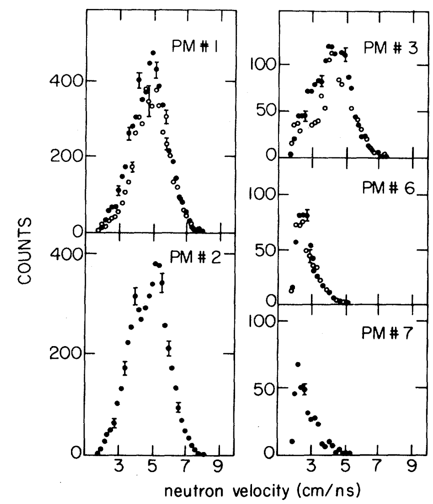

FIG. 2. The closed circles show the measured neutron laboratory velocity spectra in different neutron counters for quasielastic events with TKE > 560 MeV. The open circles represent the calculated velocity distributions based on the reference counters PM No. 2 and PM No. 7.

tic, damped, and strongly damped events, respectively. At each angular setting the right detector covered 26° in plane and 38° out of plane. The detectors were placed inside a spherical scattering chamber of 1 m diameter made of 3-mm-thick aluminum which was designed to minimize neutron scattering. The position signals x,y of the two fragments and the time-of-flight (TOF) signal of the faster fragment were used to reconstruct the event kinematics. The mass and energy resolutions were determined by the spread in velocity and angle imparted to the fragments by particle emission, rather than by the intrinsic resolution of the detectors. They became worse with decreasing total kinetic energy (TKE).

Neutrons were detected in coincidence with the fragments in eight neutron detectors, 5-cm-thick 213NE liquid scintillators of 11.3 cm diameter, placed at 90 cm from the target. The locations of the neutron counters are indicated in Fig. 1. The scintillators were covered with a 3-mm-thick shield to reduce the γ-ray background. Three signals were derived for each particle detected in the neutron counters: (i) a TOF signal relative to the 250-ps-wide bunched beam, (ii) the pulse-height amplitude in the photomultiplier (PM), and (iii) a pulse-shape signal which, together with the TOF signal, allowed a clean separation of neutrons and γ rays. The neutron absorption produced by the fragment detector was measured with use of a ^{252}Cf source. This absorption was always less than 15%. The absolute efficiency of the neutron counters was determined with use of the method of Drosg.[18] A 1.2-MeV neutron-energy threshold level was set off line on the pulse-height signal.

The results were analyzed event by event with use of a procedure very similar to the one used in Ref. 4, and only a short description will be given here. A detailed account will be presented in a later paper.[19] It was assumed that all neutrons are evaporated from fully accelerated fragments, i.e., they are isotropically emitted in the center of mass (c.m.) of the L or the H fragment. Hence two neutron counters suffice to calculate, to first approximation, the c.m. energy spectrum of neutrons emitted by the L and the H fragments.[20] In this analysis PM No. 2 and PM No. 7 were used as reference counters for the L and the H fragments, respectively. An iterative procedure was used to correct for possible neutrons detected in PM No. 2 (7) which were emitted by the H (L) fragment.[21] This iterative correction is important for low-TKE events. The c.m. spectra were then transformed back into the laboratory system and compared with the measured velocity spectra in the other neutron counters.

The results were analyzed as function of the TKE which is generally believed to be the best measure of the interaction time. A sample of the

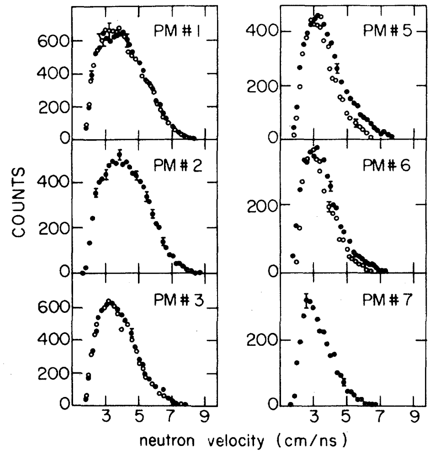

FIG. 3. Same as Fig. 2 for strongly damped events with 200 < TKE < 330 MeV.

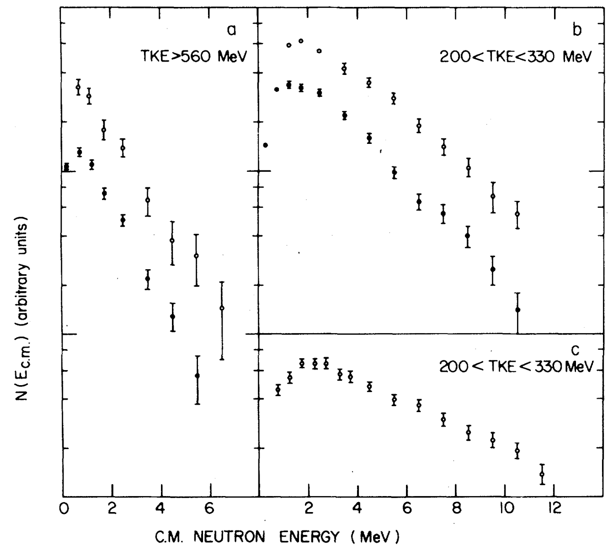

FIG. 4. c.m. energy spectra of the neutrons emitted by the L (closed circles) and the H (open circles) fragments (a) for quasielastic events and (b) for strongly damped events as obtained from the reference counters PM No. 2 and PM No. 7. (c) The c.m. energy spectrum of neutrons emitted by the H fragment in strongly damped events obtained from PM No. 5.

results showing the most interesting features is presented in Figs. 2 and 3. The measured neutron velocity spectra (closed circles) are compared to the projected ones (open circles) for quasielastic events with TKE > 560 MeV (Fig. 2) and for strongly damped events with 200 < TKE < 330 MeV (Fig. 3). PM No. 2 and PM No. 7 are the reference counters on which the analysis was based, and only their measured spectra are presented.

For quasielastic events, most of the neutrons (~ 90%) measured in the forward direction are emitted by the L fragment. The two peaks observed in the measured velocity spectra in PM No. 1 and PM No. 2 correspond to forward and backward emission of neutrons in the c.m. of the L fragment, which has a velocity nearly equal to the magnitude of the beam velocity $v_0 = 4.6$ cm/ns. The double structure disappears with decreasing TKE as seen in Fig. 3 because of the large spread in velocity and angle of the L fragment. A clear discrepancy is observed in Fig. 2 at low neutron laboratory velocities v_n, i.e., for $v_n < v_0$ in PM No. 1 and to a lesser extent also in PM No. 3, the measured spectra being larger than the projected ones. For quasielastic events we therefore identify a small component of nonequilibrium neutrons emitted close to the L fragment direction and extending towards (and beyond) the beam direction. These neutrons may have small velocities $v_n < v_0$ as suggested by Fig. 2 or they may have a broad velocity distribution centered around v_0 (the nonequilibrium neutrons with $v_n > v_0$ cannot be seen in Fig. 2 because of the limitations of our analysis[20]).

The effect seen in Fig. 2 quickly disappears with decreasing TKE and very good agreement is obtained between measured and projected spectra in PM No. 1 and PM No. 3 as can be seen in Fig. 3 for strongly damped events. It should be noted that the nonequilibrium neutrons could also be present in the forward neutron counters at lower TKE but could not be seen because of the analysis procedure.

With decreasing TKE another effect becomes apparent; the neutron counters PM No. 5 and PM No. 6, which are located near the recoil direction of the H fragment, show a high-velocity tail which is not reproduced by the projected spectra. This is clearly seen in Fig. 3 for strongly damped events where it is most prominent. Here the results indicate that there is a component of nonequilibrium neutrons with a broad velocity distribution centered around the beam velocity v_0.

In Fig. 4 we show the c.m. energy spectrum of neutrons emitted by the L and the H fragment for quasielastic [Fig. 4(a)] and strongly damped events [Fig. 4(b)] as obtained from the reference counters PM No. 2 and PM No. 7. The spectra have a nearly exponential falloff with increasing neutron energy; the equal slopes (equal temperatures of the two sources) indicate that the excitation energy is shared between the fragments in proportion to their masses, i.e., the composite system is thermalized prior to the separation of the fragments. Figure 4(c) shows the c.m. energy spectrum of neutrons emitted by the H fragment taking PM No. 5 as reference counter. A much higher temperature is obtained as compared with Fig. 4(b), reflecting the effect of the relatively high-energy nonequilibrium neutrons present in PM No. 5.

To conclude, we have shown that the neutron emission in deep-inelastic collisions of ^{86}Kr on ^{166}Er at 12 MeV/amu cannot be accounted for by assuming only isotropic evaporation by fully accelerated fragments. The experimental analysis shows the presence of a nonequilibrium component of neutrons emitted mainly on the side of the L fragment in quasielastic events, and on the side of the H fragment in strongly damped events. In both cases the results are consistent with a broad velocity distribution centered around the beam velocity. Yet our results clearly indicate (see, for example, the spectra of PM No. 3, Fig. 2) that the nonequilibrium neutrons do not have an angular distribution which is symmetric around the beam direction.

We thank Dr. U. Lynen for helping us with the on-line data acquisition.

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U(6/4) Dynamical Supersymmetry in Nuclei

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(Received 9 March 1981)

We suggest that a supersymmetry scheme based on the supergroup U(6/4) may be useful in describing many properties of nuclei in the Os–Pt region. The bosons and fermions in the fundamental representation of U(6/4) are the low-lying collective (bosonic) and single-particle (fermionic) degrees of freedom. Experimental evidence indicates that the scheme applies to several nuclei in the region within ≈30%. This appears to be the first observed example of a supersymmetry.

PACS numbers: 21.60.Fw, 27.80.+w

Recently, one of us[1] has suggested that dynamical supersymmetries may be present in the spectra of complex nuclei. This suggestion was based on the comparison of the excitation energies of a pair of nuclei in the Os–Pt region. However, it was neither clear which supergroup was relevant to the problem, if any, nor the extent to which the supersymmetry was experimentally present. We have, therefore, performed a more detailed investigation of the problem and in this Letter we