Neutron Emission in Deep-Inelastic Collisions of ^{16}O on ^{93}Nb at 204 MeV

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Spectra and angular distributions of neutrons in coincidence with light fragments produced in deep-inelastic collisions of ^{16}O on ^{93}Nb at 204 MeV have been measured. A significant number of neutrons are emitted in the forward direction with beamlike velocities. Fits of detailed spectra and angular distributions were not possible if one assumed evaporation from accelerated fragments. This presents the first direct evidence for nonequilibrium neutron emission in deep-inelastic reactions.

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Neutron emission in deep-inelastic collisions (DIC) has been measured for several systems.[1-5] The results can be interpreted by assuming that the neutrons are evaporated from fully accelerated fragments. For projectiles with mass above 60 amu and energies below 10 MeV/u, the excitation energy is shared between the fragments in proportion to their mass.[1-4] For lighter projectiles, the excitation energy can be determined only if both light charged particles and neutrons are measured. We present here, for the first time, results of neutron emission in DIC for a system ($^{16}O + ^{93}Nb$ at 204 MeV) in which charged-particle emission has also been measured, thus providing detailed information about the excitation energy dissipation. The α-particle spectra and angular distributions were presented[6] and were interpreted as resulting from fully accelerated fragments with the excitation energy shared in proportion to the fragment masses. However, these conditions do not seem to apply to spectra and angular distributions of neutrons in coincidence with the projectilelike fragment (PLF). A large fraction of the fast neutrons are emitted independently of the PLF final mass and kinetic energy and in addition, the angular distribution is different from that expected from evaporation. We conclude that excitation energy dissipation at beam energies above about 8 MeV/u above the Coulomb barrier can be understood only if all light particles are measured, since different particles are sensitive to different aspects of the dissipation process.

A ^{16}O beam at 204 MeV produced by the Oak Ridge Isochronous Cyclotron was used to bombard a 1-mg/cm^2-thick target of ^{93}Nb. A heavy-ion ΔE-E silicon surface-barrier detector telescope was placed at 22° with respect to the beam. Neutrons in coincidence with the PLF were detected in eight NE-213 liquid scintillators coupled to RCA No. 4522 photomultipliers positioned approximately 70 cm from the target. The neutrons were identified both on the basis of their time-of-flight and pulse-shape characteristics. The overall time resolution was 3.0 ns full width at half maximum (FWHM). This is equivalent to 1 MeV FWHM at 4 MeV and 9 MeV FWHM at 18 MeV. The effect of the finite resolution was included in our subsequent calculations and analysis. Details of the detector geometry are given in Table I. A 1-mm-thick plastic scintillator "paddle" was placed in front of each neutron detector to detect high-energy charged particles that penetrated the 3-mm-thick aluminum wall of the scattering chamber. For each coincident event, the heavy-ion E and ΔE signals were recorded together with the neutron parameters. The neutron detection efficiency at any given neutron energy

TABLE I. Detector geometry. O+Nb experiment; particle telescope at +22°. θ is the angle with respect to beam axis; ψ, the angle with respect to reaction plane.

	A	*B*	*C*	*D*	*E*	*F*	*G*	*H*
θ	−46°	−24°	−11°	14°	28°	63°	66°	143°
ψ	0°	0°	0°	0°	0°	0°	59°	0°

was obtained from the data of Drosg[7] and Anghinolfi.[8] The absolute normalization of the efficiencies was determined by using a ^{252}Cf source facing a surface-barrier detector in 2π geometry.

Neutron spectra in six of the detectors are presented in Fig. 1. These spectra are in coincidence with PLF having charges of 6, 7, and 8 and c.m. kinetic energies ($E_{c.m.}$) between 30 and 160 MeV. Detector *D* (see Table I and Fig. 1), which is close to the direction of the detected PLF, has a large high-energy component in the neutron spectrum, which is expected if one assumes that the neutrons are evaporated from the two fragments: Neutrons emitted by the PLF are highly focused in the direction of the PLF's velocity and thus have a high energy. Detector *H*, which is placed in a backward direction relative to the direction of the PLF, detects neutrons originating almost entirely from the targetlike fragment (TLF) which has an average velocity of 0.5 cm/ns; the laboratory angular distribution of neutrons emitted from this fragment has a low anisotropy, and the average neutron energy should exhibit only small variations with detector angle. By using both this assumption and assumptions stated above about excitation energy sharing[1-4] and by using spin values taken from sticking-model calculations, we have calculated the neutron spectrum in detector *H* with use of a modified version of the statistical-model code JULIAN.[9] The normalization obtained by fitting our calculation to the experimental results below 12 MeV enables us to subtract the calculated contribution of neutrons emitted by the TLF from the neutron spectra in other detectors. Above 12 MeV an additional fast-neutron component is visible in detector *H*, but its magnitude is such as to have a negligible effect on the subtraction procedure described above. In ascribing the origin of all the low-energy neutrons in detector *H* to the TLF, we obtain an effective upper limit of 1.0 ± 0.1 neutrons for the multiplicity associated with the TLF. Results after subtraction are presented in Fig. 2.

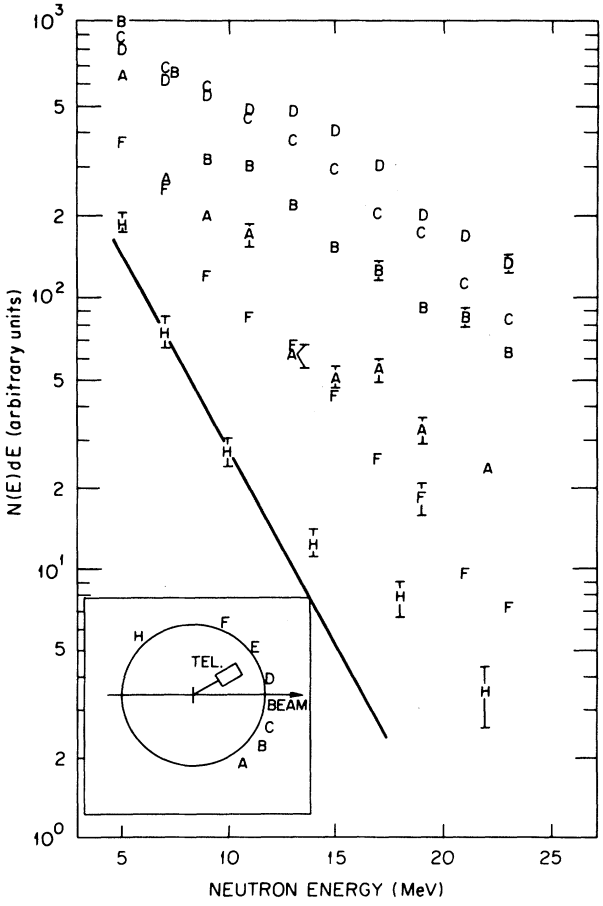

FIG. 1. Neutron spectra in detectors *A*, *B*, *C*, *D*, *F*, and *H* in coincidence with the heavy-ion telescope. The deployment of detectors is indicated in the inset, and the letters used to indicate individual data points indicate the detector from which they originate. The line is the calculated spectrum in detector *H* if we assume evaporation from the TLF only. Spectra from detectors *E* and *G* were omitted to maintain the clarity of the figure. Some typical statistical errors are indicated.

We now compare these residual spectra to spectra obtained by a simulation calculation in which we assume that these neutrons are emitted only from the PLF. The c.m. evaporation spectrum was taken to be identical to that of the TLF—this identity is expected if the two fragments have equal temperatures. The calculation includes the effect of the PLF angular distribution,[6] charge distribution, and kinetic-energy distribution, which were measured separately.[10] The lines in Fig. 2 show the results of the calculation; evidently, the calculated spectra decrease in overall magnitude much more rapidly than the experi-

mental results as a function of the angular separation from the PLF direction. Use of different temperatures for the emission from the PLF does not improve the fit. We conclude that we cannot interpret the spectra as resulting entirely from neutron evaporation from fully accelerated fragments. A better agreement with the experimental results can be obtained (see Fig. 3) if we assume the existence of an arbitrary additional source of neutrons with a temperature of 1.5 MeV moving along the beam axis with a velocity of 3.3 cm/ns and emitting neutrons isotropically. While the speed of this source is similar to that of the average PLF, its different direction accounts for fast neutrons on the opposite side of the beam from the PLF, thus resulting in the improved fit. Similar parametrization of fast particle emission in terms of a moving source has been suggested previously by Symons *et al.*[11] In our case we find the best agreement when we assume equal multiplicities from the PLF and the additional source.

Two additional facts corroborate our conclusion that some of the fast neutrons are due to nonequilibrium emission: (1) The neutron spectra and angular distributions are identical in different energy loss bins. For $E_{c.m.} \geq 120$ MeV, one would expect the anisotropy between neutron spectra obtained in the forward and backward directions to double (based on simulation calculations), compared to $E_{c.m.} \leq 70$ MeV. Experimentally, we find no significant difference between the anisotropies

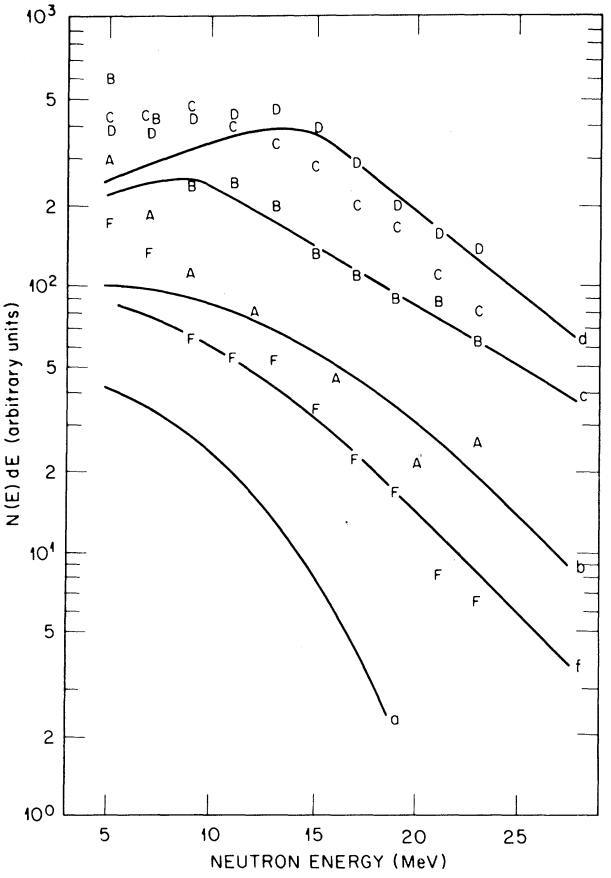

FIG. 2. The neutron spectra of Fig. 1 with the calculated contribution of neutrons evaporated from the TLF subtracted. The lines (labeled with script letters) are results of simulation calculations, when the residual spectra are assumed to result from evaporation by the PLF. There is a correspondence between the script letters labeling the calculated curves and the capital letters depicting the data points (for example, the curve labeled *c* should be compared with data points *C*). Above 10 MeV, some data points have been redistributed in larger bins to facilitate the comparison.

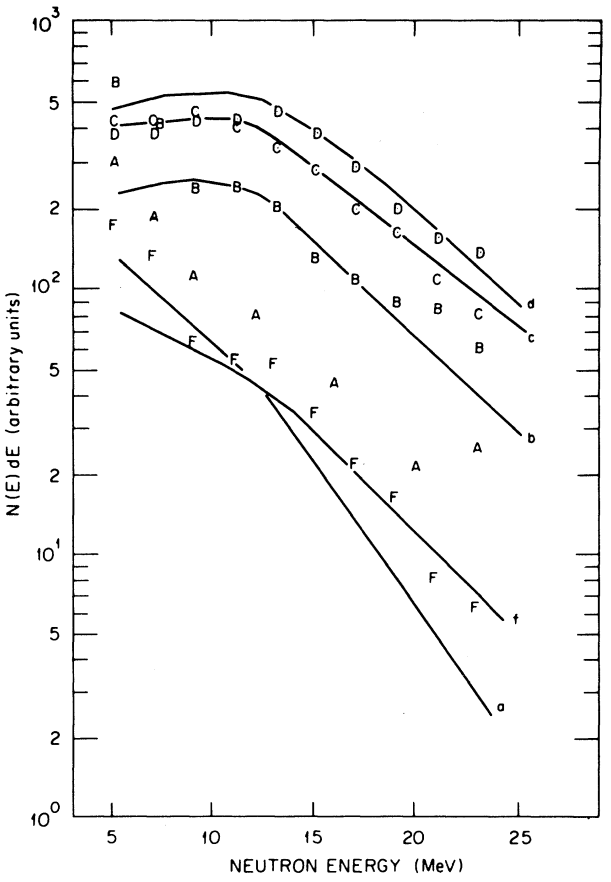

FIG. 3. Same as Fig. 2. The simulation calculation contains an additional neutron source moving along the beam axis with a velocity of 3.3 cm/ns and having a temperature of 1.5 MeV. The letter designations have the same significance as those of Fig. 2. Above 10 MeV, some data points have been redistributed in larger bins to facilitate the comparison.

in the two energy bins. It is therefore unlikely that more than 25% of the fast neutrons are indeed evaporated from the PLF. (2) The average neutron multiplicity of the heavy fragment (obtained from detector H) is low relative to the value obtained from statistical-model calculations.[9] If we assume excitation-energy sharing proportional to the mass and a spin value of 37 units obtained from the sticking model, the statistical-model calculation gives a neutron multiplicity of approximately 2, compared to the experimental value of 1.0 ± 0.1. This implies that a significant fraction of the excitation energy is removed prior to being shared between the fragments.

To summarize, the neutron multiplicities necessary to reproduce the data are (1) 0.15 ± 0.05 neutrons from the PLF; (2) 1.0 ± 0.1 neutrons from the TLF; and (3) 0.15 ± 0.05 neutrons emitted by a source with a temperature of 1.5 MeV and a velocity of 3.3 cm/ns. The emission from the PLF in the simulation does not necessarily imply that the experimental results indicate emission from the fully accelerated PLF—the independence of $E_{c.m.}$ indicates the contrary. Multiplicities (1) and (3) can be viewed as one of several ways the simulation can be tailored to fit the data. We deduce a range of 0.15 ± 0.05 to 0.3 ± 0.1 fast neutrons which are *not* emitted from the PLF after its acceleration. Our results do not seem to be compatible with hot-spot calculations[12,13] because of the low temperatures and the strong forward peaking involved. More likely, an incomplete-fusion mechanism in which neutrons are emitted close to beam velocities accounts for the fast neutrons.[14] Our results could be interpreted as implying that a significant fraction of the fragments (up to 0.3 ± 0.1) are actually emitted together with neutrons. The exact time at which the fast neutrons are produced is not determined, but it is clear that a sizable fraction of these neutrons are not emitted from the accelerated fragments.

Finally, with regard to the compatibility of these conclusions with results of α-particle emission, if we assume an upper limit of 0.3 nonequilibrium neutrons emitted from PLF with an energy of 12 MeV and a binding energy of approximately 8 MeV, the neutrons account for a total of 6 MeV excitation energy. This results in a small decrease in the α-particle emission from the TLF, but the agreement between the simulation calculations and the experimental results of Ref. 6 are still within the limits of the errors. Thus the conclusions of Ref. 6 with respect to energy sharing are unaffected.

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