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NEUTRON EMISSION IN DEEPLY INELASTIC AND FUSION-
EVAPORATION REACTIONS OF 208-MeV 160 WITH ^{93}Nb

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Neutrons emitted in coincidence with deeply inelastic fragments or with evaporation residues have been measured in the 208-MeV 160 on ^{93}Nb reaction. A significant fraction of the neutrons associated with deeply inelastic reactions and emitted in the forward direction cannot be attributed to evaporation from fully accelerated fragments and must be due to nonequilibrium neutron emission mechanisms. Nonequilibrium neutron emission is considerably less important in the fusion reaction.

Neutron emission in deeply inelastic (DI) reactions has been studied by a number of groups.¹⁻³ General conclusions from these works are: (1) The neutrons are evaporated from fully accelerated fragments, and (2) the excitation energy is partitioned between the fragments in proportion to their masses^{1,2} with a possible exception at low excitation energies.³ Our measurement was performed with 208-MeV 160 on ^{93}Nb , which corresponds to a higher bombarding energy per nucleon than those of previous experiments.

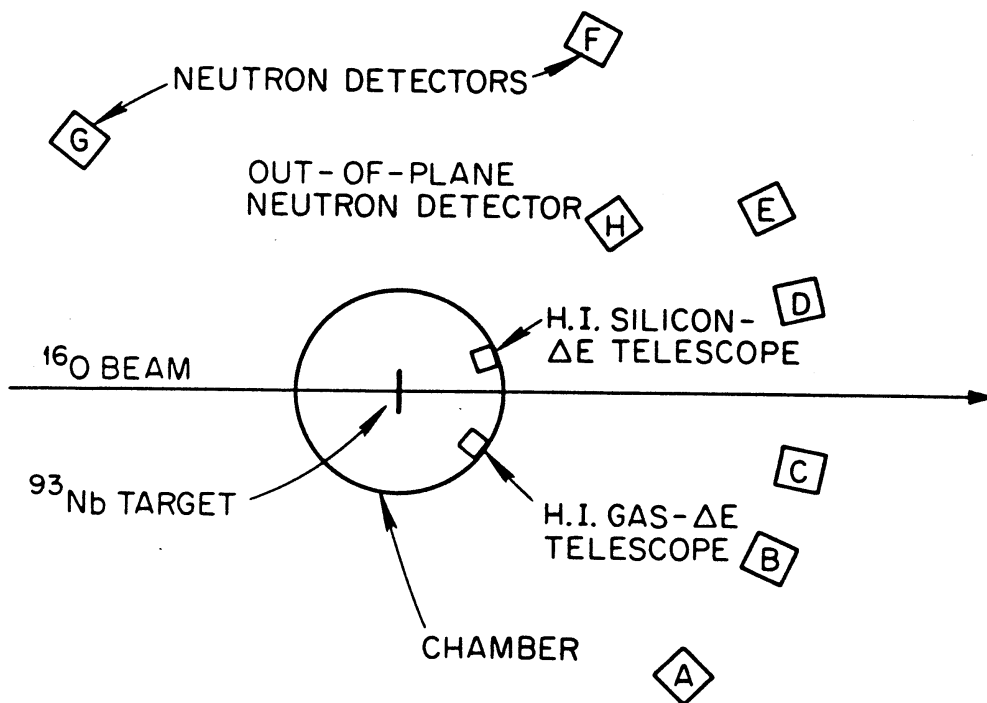


FIGURE 1 Schematic arrangement of detectors. All detectors are shown at their correct in-plane angle. Detector H was located at 59° above the reaction plane.

The arrangement of the detectors is presented in Fig. 1. Heavy ions were detected using ΔE -E counter telescopes on either side of the beam. One telescope had a silicon ΔE detector and was positioned at 22° relative to the beam axis, while the other, located at 27° , had a gas ionization ΔE detector. The latter was used to detect evaporation residues (ER) in addition to DI fragments. The eight neutron detectors were composed of NE 213 scintillators, 5.1 cm thick by 11.8 cm in diameter coupled to RCA 4522 photomultipliers. A 1-mm thick plastic scintillator "paddle" was placed in front of

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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 detected in a scintillator, time-of-flight, pulse-height, and pulse-shape information was recorded.

If the neutron emission in this system were to have general features similar to those deduced for the systems studied in Refs. 1-3, then the bulk of the neutrons would be emitted by the target-like (TL) fragments. In particular, considering the isotopic distribution of the projectile-like (PL) fragments and charged particle emission competition during their deexcitation, we expect that they will emit no more than 5% of the total number of neutrons. Such neutrons will be confined to a cone subtending an angle of $\sim \pm 30^\circ$ around the PL-fragment direction for the angles at which PL fragments were detected in this experiment. Neutrons emitted by the TL fragments will not undergo significant kinematic focussing due to the low TL-fragment velocities ($V_{\text{LAB}} \sim 0.5$ cm/nsec). (Neutrons emitted from ER will have a larger laboratory anisotropy due to the larger source velocity: $V_{\text{LAB}} = 0.9$ cm/nsec.) These considerations lead us to expect that neutrons observed in detectors A or G which are in coincidence with PL fragments observed in the silicon- ΔE telescope are emitted from the TL fragments only.

Thus, we assumed for the purpose of the preliminary analysis presented here that all neutrons detected in detector A in coincidence with PL fragments detected in the silicon ΔE heavy ion telescope were produced by evaporation from the TL fragment. Each event in which a neutron was detected in detector A was transformed to the TL CM system. Assuming isotropic emission in this system, the event was then transformed back to the lab system in the direction of each of the other neutron detectors. Thus calculated spectra were produced for detectors B-H which could be compared with the measured spectrum in each detector. Figure 2(a) presents the sum of these calculated spectra for detectors C and D and the sum of the measured spectra. For neutrons with velocities above 3 cm/nsec (4.7 MeV), the calculated spectra fall below the measured spectra. Figure 2(b) shows the difference between the measured and calculated spectra for the four forward detectors. The spectra peak at velocities close to the beam velocity of 5.0 cm/nsec. The calculated spectrum is found to fit the measured spectrum in detector F and to exceed the measured spectrum in detector G. The fact that this procedure overestimates the number of detected neutrons in

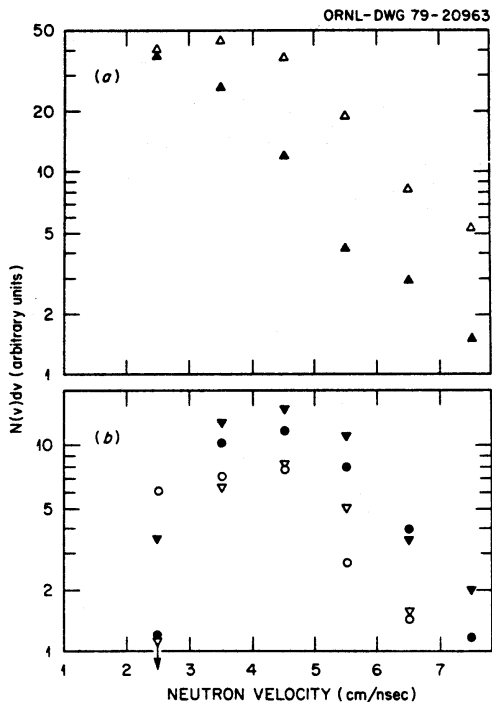


FIGURE 2 (a) Measured (open triangles) and calculated (closed triangles) velocity spectra of neutrons associated with DI reactions averaged for detectors C and D (see Figure 1). The method used for obtaining the calculated spectrum is described in the text. (b) Differences between measured and calculated neutron velocity spectra for detectors B (open circles), C (open triangles), D (closed triangles) and E (closed circles).

detector G implies that detector A also is receiving a non-negligible contribution from sources other than evaporation from the TL fragment, contrary to our initial assumption. The preliminary analysis described above was carried out for events in which PL fragments were detected in the silicon heavy ion detector. Results from an analysis for PL fragments measured in the gas ΔE telescope are similar to those presented here.

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The excess in the measured spectra in the forward detectors is not due to evaporation from the PL fragments for the following reasons: (1) Such an excess should be distributed symmetrically around the heavy ion telescope (Si- ΔE), i.e., since detector C exhibits an excess, detector F should exhibit a similar excess. (2) The excess should fall off rapidly when going from detector D to C to B. (3) The average velocity of neutrons emitted from the PL fragment should be 5.5-6.0 cm/nsec, dropping below 4 cm/nsec in detector B. None of these effects are observed. We conclude, therefore, that a large fraction ($\sim 50\%$) of the neutrons emitted into the forward hemisphere are not due to evaporation from fully accelerated fragments.

Various models predict such nonequilibrium emission: Projectile breakup (note the similarity between the beam velocity and the most probable neutron velocity in the difference spectra), Fermi jets and hot-spot models. The predictions of the various models are not specific enough to allow us to choose between them based on the data presented here. Empirically, we find that the forward-backward anisotropy and neutron energy spectra can be fitted by assuming that 40% of emitted neutrons are due to evaporation from a source moving with half the beam velocity, with the remainder emitted by the fully accelerated TL fragments.

Figure 3 presents two spectra of neutrons in coincidence with ER. The first shows the average of the spectra of the two most forward detectors C and D, and the second is the spectrum of detector G (the most backward). The solid curves are results of evaporation calculations for the compound system from a modified version of the code JULIAN.⁴ For energies below 15 MeV, good agreement is obtained both in the slopes of the energy spectra and in the relative yield at the two angles. At higher energies, the measured neutron spectrum in the forward detectors (C and D) falls off more slowly than the calculated spectrum, indicating the existence of a component with a higher temperature, similar to that measured by Westerberg et al.⁵ Such a tail in the spectrum could also be due to the possibility that TL fragments were included with ER in the analysis. The TL fragments are difficult to exclude due to the near-equality of charge and due to small differences in the kinetic energies. The overall agreement between spectra determined by evaporation calculations, and our experimental data, gives added confidence to the accuracy of our results.

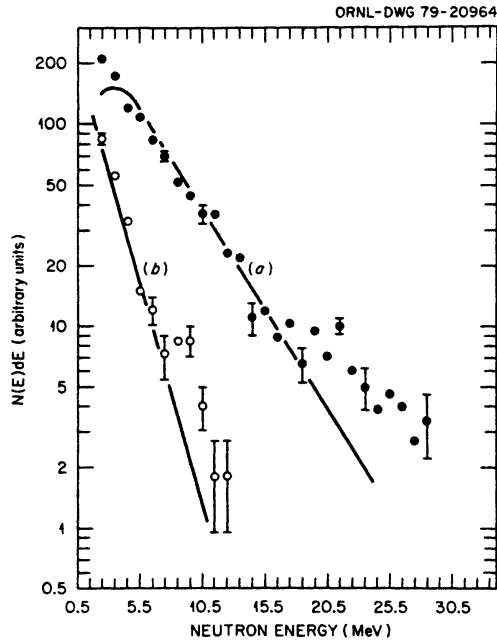


FIGURE 3 Measured (circles) and calculated (lines) energy spectra for neutrons associated with ER. Spectrum (a) is averaged for detectors C and D, and spectrum (b) is for detector G (see Figure 1). Calculated spectra were obtained by means of a modified version of the code JULIAN.⁴

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