Measurement of the Inclusive Neutron Production by Relativistic Neon Ions on Uranium

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Inclusive double-differential cross sections for neutron production were measured at 337 MeV/nucleon in the reaction Ne + U $\rightarrow n + X$. Neutrons were detected with energies between ~ 12 and ~ 600 MeV at laboratory angles of 30°, 45°, 60°, and 90°. The neutron spectra above ~ 30 MeV are comparable with the predictions of a "firestreak" calculation. The neutron spectra differ from proton spectra reported for U and Pb.

We measured the double-differential cross sections for neutron production by 337-MeV/nucleon neon ions interacting in uranium targets. The experiment was carried out at the Bevalac accelerator of the Lawrence Berkeley Laboratory (LBL).

Figure 1 is a scale drawing of the experimental cave. The beam traversed a scintillation-counter telescope consisting of a 20×20-cm² detector S_0 (not shown in Fig. 1), positioned ~ 10 m upstream of the target T, and a 7.6×7.6-cm² scintillator S_1 located next to the target. After traversing the target, the beam continued to a 30.5-cm-diam, 1.2-m-deep beam dump. The depleted ^{238}U targets had an area of 10×10 cm² and were positioned at 45° to the beam axis. One of the targets used was 5.60 g/cm² thick, while the other one was 1.86 g/cm² thick.

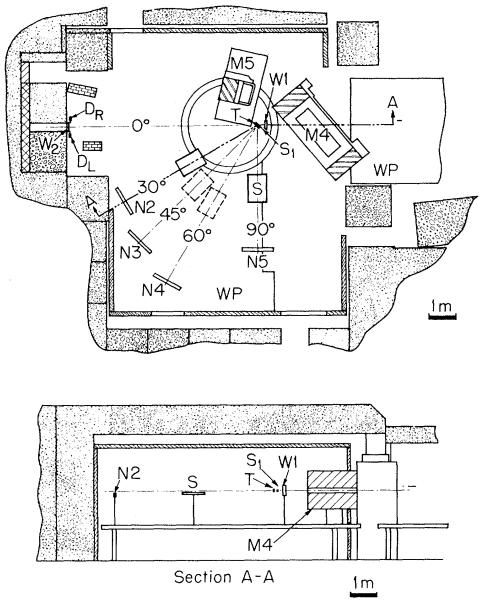

FIG. 1. Scale drawing of the experimental arrangements. S_1, scintillation counter; T, target; N_2 –N_5, neutron detectors; S, shadow bar in position; D_R and D_L, scintillation counters for monitoring beam position; WP, wooden platform. The beam positioning wire chambers $W1$ and $W2$ were removed for data taking. Magnets $M4$ and $M5$ were not used but are shown as possible sources of background.

Neutrons were detected by four 101.6-cm-wide, 10.2-cm-thick scintillation counters made of NE-102 plastic and positioned at 30°, 45°, 60°, and 90°, with flight paths of 5.1, 5.6, 6.0, and 4.2 m, respectively. The 30° and 45° detectors were 12.7 cm high. The 60° and 90° counters were 25.4 cm high. Charged particles incident on the detectors were vetoed with 6-mm-thick plastic scintillators in front of each counter.

The background originating in the material around and upstream of the target was determined by taking data with a dummy target holder in place. Target-correlated background was determined from measurements with and without the shadow bars shown in Fig. 1. The shadow bars consisted of 91.5-cm-thick and 60-cm-wide assemblies of lead bricks, located halfway between the target and a detector. A 12.5-cm-high shadow bar was used at 30° and 45°; at 60° and 90°, the shadow bar was 20 cm high. The shadow bars attenuated neutrons by a factor > 100 at all energies.

The kinetic energy of each detected neutron was obtained from the measured time of flight (TOF) between S_0 and any of the detectors. The neutron detection time was determined by mean timing of signals from both ends of each counter.[1] The light output of each detector was measured separately as the sum of signal amplitudes from the two photomultipliers. The neutron-detector efficiencies were calculated with a Monte Carlo code estimated to be accurate to ~ 5% (excluding

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threshold uncertainties), on the basis of comparisons with available experimental data.[2] An unambiguous determination of TOF required that one, and only one, beam particle be incident on the target during the 200-nsec sampling time; therefore, pileup circuitry rejected beam pulses in S_0 which were accompanied by a second pulse within ± 200 nsec. Use of high-current, high-counting-rate photomultiplier bases[3] allowed a beam counting rate of ~ 5×10^5 per pulse with a rejection ratio of 30–40 %.

Figure 2 is a plot of the double-differential cross sections $d^2\sigma/dTd\Omega$ as a function of neutron energy. The solid curves are the results of a firestreak calculation (neglecting Coulomb effects) by Westfall.[4] Errors include statistics and small effects of uncertainties in the time calibration. The error bars are generally smaller than the size of the symbols. The principal sources of systematic errors are detector efficiencies, target thickness, and beam normalization. The uncertainties in the threshold increase the uncertainties in the efficiencies from ~ 5% above 18 MeV to ~ 10% at 12 MeV. The overall systematic error is estimated to be ~ 10%.

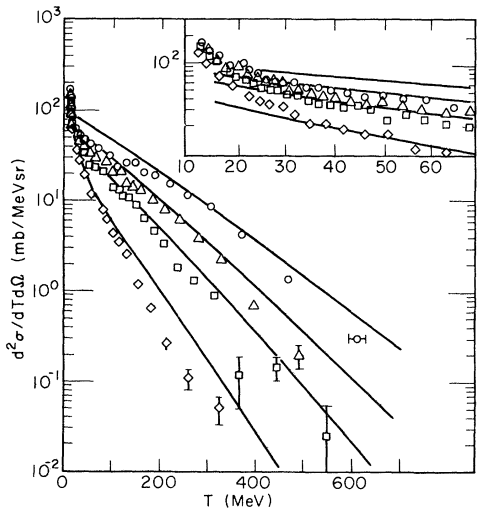

FIG. 2. Measured double-differential cross sections for Ne + U → n + X at a mean incident energy of 337 MeV/nucleon, as a function of neutron energy (circles, 30°; triangles, 45°; squares, 60°; lozenges, 90°), and results of a firestreak calculation (solid curves). Inset: Expanded view of the low-energy portion of the spectra. Errors include statistics and small effects of uncertainties in the time calibration on the width of the energy bin, and on the mean energy of each point. Error bars are generally smaller than the symbol sizes.

The cross sections for different angles approach similar values below 20 MeV, as expected for isotropic neutron evaporation from the target. The neutron spectra at higher energies can be considered as the combination of a broad peak and an approximately exponential spectrum predicted by the firestreak model. Such an interpretation is suggested by the prominent shoulder in the 30° spectrum. The maxima obtained by decomposing the spectra in this manner are at ~ 250, ~ 200, and ~ 130 MeV at 30°, 45°, and 60°, respectively. The large angles and the energies at which shoulders are seen exclude the projectile as a source. It seems more likely that these shoulders are due to a nucleon-nucleon knockout component. The residual portions of the spectra are then found to agree with the firestreak model within a factor of ~ 2.

The cross sections integrated between 12 and 600 MeV at the four laboratory angles are 9.2, 6.3, 4.4, and 2.2 b/sr. The total angle-integrated cross section in the forward hemisphere is ~ 37 b. Based on a reaction cross section of 4.0 b,[5] the average neutron multiplicity in the forward hemisphere is ~ 9. This is comparable to reported proton multiplicities.[6]

Figures 3(a)–(d) are plats of the ratio of the measured neutron production cross section to that for the production of protons in similar reactions as a function of energy. The closed circles refer to proton data[6] from 393-MeV/nucleon Ne + U, and the open circles refer to proton data[7] from 385-MeV/nucleon Ne + Pb. The slightly higher ratios obtained for the latter are due to the smaller cross section in Pb. The solid and dashed curves are the n/p cross-section ratios expected from firestreak calculations (without Coulomb effects)[4] for the appropriate combinations of target and beam energy. Different numbers of neutrons and protons contribute to the projectile-target interaction at different impact parameters. The cross-section ratios given by the firestreak calculations provide a scaling factor for comparison with the experimental data.

The firestreak calculations predict a moderate decrease in the n/p ratio, varying between ~ 1.7 at 20 MeV and ~ 0.9 at 600 MeV. The data differ significantly from this expectation, especially at low energies, where the measured ratio is ~ 2 times the predicted value. The measured n/p ratios decrease with energy much more rapidly than predicted.

Since fragments with $A > 5$ are not considered by the present firestreak calculations, a possible

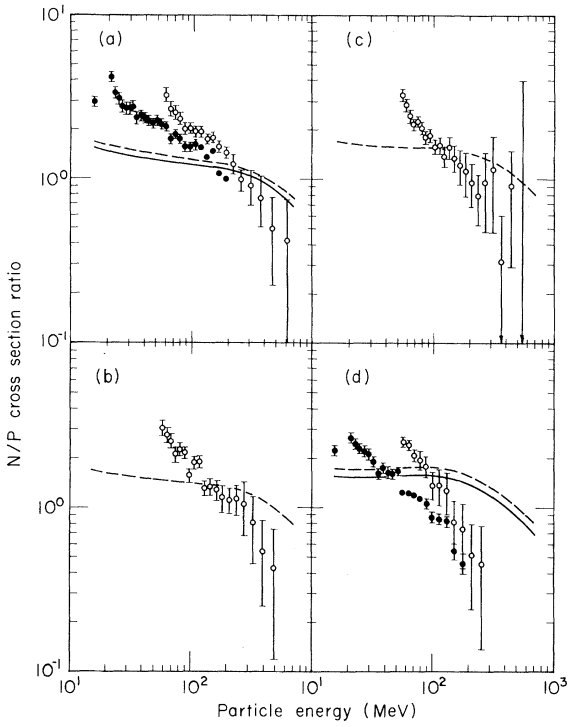

FIG. 3. Neutron to proton cross-section ratios as a function of neutron energy at (a) 30°, (b) 45°, (c) 60°, and (d) 90°. Two sets of ratios are plotted: (I) (Ne + U$\rightarrow n + X$ at 337 MeV/nucleon)/(Ne + U$\rightarrow p + X$ at 393 MeV/nucleon), see Ref. 6; and (II) (Ne + U$\rightarrow n + X$ at 337 MeV/nucleon)/(Ne + Pb$\rightarrow p + X$ at 385 MeV/nucleon), see Ref. 7. Full circles: experimental results for I. Open circles: experimental results for II. Solid curve: firestreak calculation for I. Broken curve: firestreak calculation for II.

mechanism for producing an observed neutron excess at low energies is neutron evaporation from excited, neutron-rich fragments. The existence of such fragments would be expected in the absence of equilibrium, when the projectile energy has not been distributed uniformly among the projectile plus target nucleons.

Preliminary results of some recent calculations[8,9] indicate that Coulomb effects suppress the proton yield at low energies and shift the high-energy part of the proton spectrum toward higher energies. The Coulomb effects seem to be sufficiently large to explain most of the observed results, but a final conclusion will have to await the results of ongoing theoretical work.

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