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LITTLE BOY NEUTRON SPECTRUM BELOW 1 MeV

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ABSTRACT

A high-resolution ^{3}He ionization chamber of the type developed by Cuttler and Shalev was used to study the neutron spectrum from the Little Boy mockup. Measurements were made at distances of 0.75 and 2.0 m and at angles of 0°, 45°, and 90° with respect to the axis of the assembly, which was operated at power levels from 8.6 to 450 mW. Detector efficiency as a function of energy as well as parameters for correction of pulse-height distributions for proton-recoil and wall effects were determined from a set of response functions for monoenergetic neutrons measured at the Los Alamos 3.75-MeV Van de Graaff Accelerator Facility. Pulse-shape discrimination was used to separate ^{3}He-recoil pulses from the pulse-height distribution. The spectrum was found to be highly structured, with peaks corresponding to minima in the total neutron cross section of iron. In particular, 15% of the neutrons above the epithermal peak in energy were found to be in the 24-keV iron window. Lesser peaks out to 700 keV are also attributable to filtering action of the weapon's heavy iron casing. Data taken using experimental proton-recoil proportional counters are compared with the high-resolution spectra.

INTRODUCTION

Data relating to the survivors of nuclear weapon explosions are important in the formulation of radiation protection standards. The biological data are, however, of limited use unless the nature and intensity of radiation from the explosions are well characterized. Although the radiations from the Nagasaki explosion are reasonably well understood, the data from Hiroshima are not. Little Boy, the Hiroshima bomb, was a unique weapon with a radiation output considerably different from that of Fat Man, which was exploded over Nagasaki. Furthermore, the Little Boy design was never tested in the field. All that is known about its radiation output has been determined from calculations and indirect evidence.

Recently at Los Alamos a replica of Little Boy was built with which one could characterize the radiation produced by the explosion. This replica, built as a critical assembly, was identical in every way to the original device except that the explosive assembly system was replaced by a precision linear actuator and the mass of ^{235}U was reduced to a point where the critical system could be safely operated as a low-power steady-state reactor. Measurements of neutron and gamma-ray spectra and dose rates have been made of the radiation output of the replica by many laboratories. This paper discusses measurement of the neutron spectrum from 0.02 to 3 MeV, with principal emphasis on that portion of the spectrum below 1 MeV.

^{3}He Spectrometer Measurements

Two instruments were used to measure low-energy leakage neutron spectra from the Little Boy replica. A high-resolution gridded ^{3}He ionization chamber of the type built by Cuttler and Shalev (Cuttler, Shalev, and Dagan 1969) was used to obtain spectra in the energy range from 20 to 3000 keV. Subsequently, information from 150 to 900 kV was obtained using a proton-recoil gas proportional counter that we are developing.

The gridded ^{3}He ionization chamber has a sensitive volume 5 cm in diameter by 15 cm long filled with 5 atm of ^{3}He, 2 atm of argon, and a small amount of methane. The stainless steel counter tube is surrounded by a thermal-neutron shield consisting of 2 mm of pressed boron nitride sandwiched between two 0.5-mm sheets of cadmium. A heatable calcium purifying cell and an integral low-noise preamplifier complete the assembly. We found that the chamber-preamplifier package was very susceptible to electromagnetic noise pickup; hence, we placed the entire assembly inside a 1-mm-thick aluminum can, which markedly reduced noise. The detector is also very microphonic; interference from vibration of the hydraulic pump of the critical assembly was a serious problem, and we often had to stop taking data outdoors because of high winds.

A typical pulse-height response from this detector is shown in Figure 1 for 1-MeV neutrons. Most neutrons in this energy range react with ^{3}He in the exothermic reaction $^{3}He(n,p)^{3}H$. The energetic charged reaction products produce a charge in the chamber proportional to E_n + 765 keV, where E_n is the neutron energy and 765 keV is the Q-value of the $^{3}He(n,p)$ reaction. Reactions that occur near the walls or ends of the sensitive volume can produce pulses corresponding to less than the full energy due to ions leaving the sensitive volume before depositing all of their energy. This produces a continuum of pulses from full energy down to zero energy (wall effect). Another source of continuum pulses can be seen in the figure; the shelf ending near channel 350 is from proton recoils due to the methane in the counter. The thermal-neutron peak is ubiquitous in the response of these counters, due to the 5000-barn $^{3}He(n,p)$ thermal-neutron cross section.

The potentially most serious impediment to good spectroscopy with this instrument is ^{3}He recoils, which produce a continuum of pulses corresponding to up to three-fourths of the neutron energy. When the neutron spectrum has an appreciable flux above 1 MeV, recoil pulses will override full-energy pulses from lower-energy neutrons. However, these pulses have a considerably shorter risetime than those from the (n,p) reaction, so they may be eliminated from the pulse distribution by pulse-shape discrimination (PSD) (Evans and Brandenberger 1979). Pulse-shape discrimination can also improve the quality of the measured spectrum by

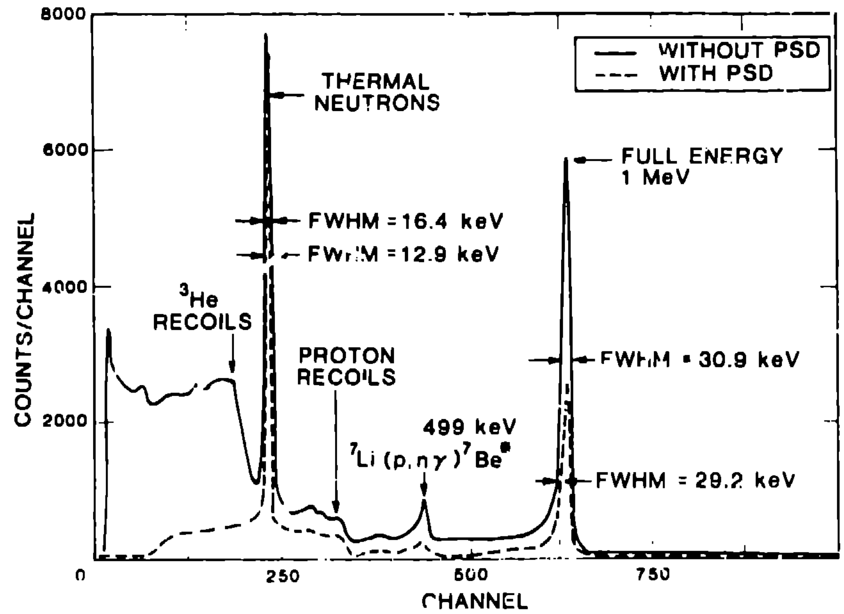

Figure 1. Pulse-height response of the ^{3}He spectrometer to 1-MeV neutrons.

eliminating pulses distorted by pile-up or other electrical interference. However, one pays a price for pulse-shape discrimination. Risetime distributions for ^{3}He(n,p) events and for ^{3}He-recoils overlap considerably, so that it is necessary to discard many desired events to eliminate an appreciable quantity of unwanted events. Thus, counting statistics are adversely affected. For the Little Boy measurements it was found that pulse-shape discrimination was not always necessary because these neutron spectra were sufficiently soft that there were relatively few interfering ^{3}He-recoil pulses.

Data are taken in such a manner that one can use either the whole pulse-height distribution or a portion of the distribution corresponding mainly to ^{3}He(n,p) pulses. Pulses selected as being within appropriate limits of risetime are routed into the first half of the 2048-channel memory, while rejected pulses go to the second half of the memory. A simple summing operation is performed by the analyzer to produce a total pulse-height distribution when desired. A pileup-rejection circuit was found to be essential for these measurements.

The spectrometer was calibrated using monoenergetic neutrons from the ^{7}Li(p,n)^{7}Be reaction at the Los Alamos 3.75-MeV Van de Graaff. From a set of response functions for neutrons of energies from 100 to 1200 keV, the full-energy-peak efficiency was obtained as a function of energy, as were coefficients for stripping out wall-effect and proton-recoil contributions to the pulse-height distribution. The peak-efficiency curve was extrapolated below 100 keV using the inverse-velocity dependency of the ^{3}He(n,p) cross section. The efficiency above 1 MeV was obtained from a previous calibration.

In Figure 2, we display total and pulse-shape-selected pulse distributions for a typical spectrum. For this measurement, the Little Boy replica was pointed upwards (i.e., upside down) inside a concrete building with its active core centered about 2 m above the floor. The nearest wall or ceiling was 4 m distant. The spectrometer tube was located at 90° to the axis of the assembly, at a distance of 0.75 m from the active center. There is little difference except in magnitude between the total and risetime-selected distributions at energies higher than the epithermal peak. Pulses in the total distribution at energies lower than the epithermal peak are due mostly to ^{3}He recoils; pulse-shape selection effectively removes most of these. A slight improvement in energy resolution of the pulse-shape-selected distribution can also be detected.

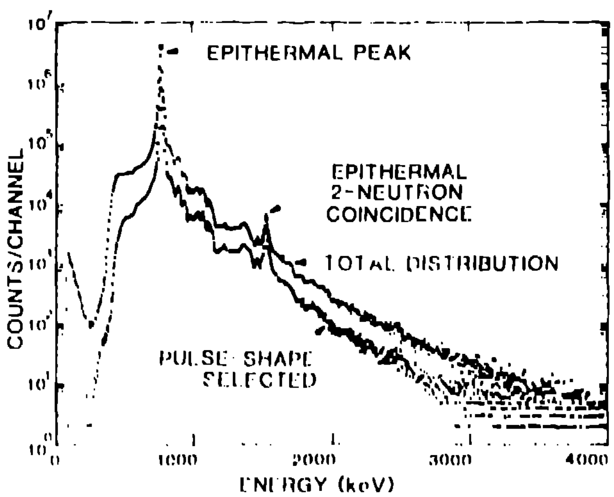

Figure 2. Typical total and pulse-shape-selected ^{3}He pulse-height distributions for Little Boy neutrons.

The sharp peak at 1528 keV is due to accidental coincidence detection of two epithermal neutrons. This was determined by noting the count-rate dependence in this peak relative to the rest of the pulse-height spectrum. The room-scattered background for this measurement was determined by moving the detector to a distance of 2.0 m from the assembly and accumulating spectra with and without an 0.86-m-thick concrete block between the assembly and the spectrometer. We determined that the epithermal coincidence peak was due almost entirely to room-scattered neutrons. The continuum of pulses in the background between the epithermal single and coincidence peaks is attributable almost entirely to unsuppressed pileup and to wall effect from the coincident neutrons. Therefore, the background spectrum measured at 2 m was normalized to completely remove the coincidence peak from the 0.75-m spectrum. This made very little difference in the shape of the spectrum except in the vicinities of these two peaks. After subtraction of background, the data were corrected for wall-effect and proton-recoil distributions. The resultant pulse-height distribution was divided by the measured energy-dependent pulse-shape-selected full-energy-peak efficiency and shifted in energy by the Q-value of the $^3He(n,p)^3H$ reaction to produce the finished spectrum. A FLEXTRAN™ program has been written to permit execution of these calculations within the TN-4000[a] multichannel-analyzer system.

In Figure 3, the spectrum from 0 to 1 MeV is shown. Also shown in the figure is the ENDF/B-V total neutron

(a) FLEXTRAN is a programming language copywrited by Tracor-Northern, Inc., of Middleton, Wisconsin.

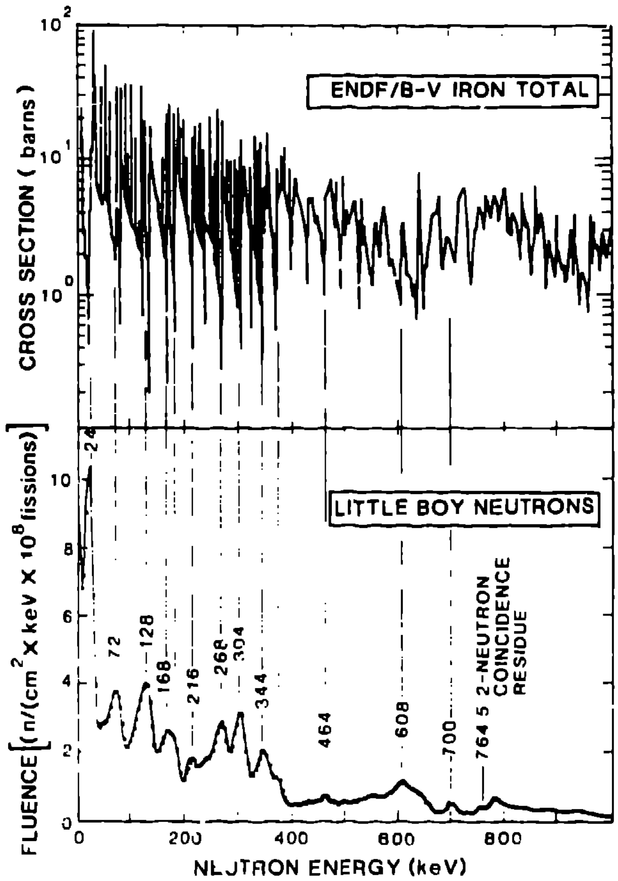

Figure 3. Spectrum 0- to 1-MeV compared with the ENDF/B-V total cross-section for iron.

cross-section for iron. All of the indicated peaks in the spectrum correspond to prominent minima in the iron cross-section. In particular, approximately 15% of the neutrons above the epithermal peak are to be found in the 24-keV iron window, which is often used to produce a nearly monoenergetic 24-keV neutron beam at reactor facilities. The results are consistent with the length of iron that the neutrons penetrate.

Spectra were also measured at the outdoor installation of the replica at distances of 0.75 and 2.0 m and at

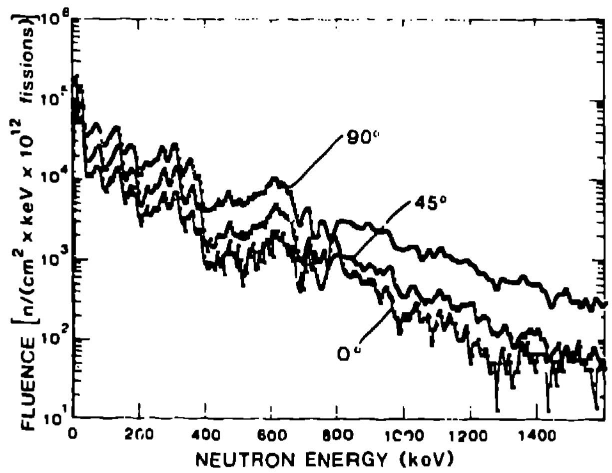

Figure 4. Neutron spectra at 0.75 m.

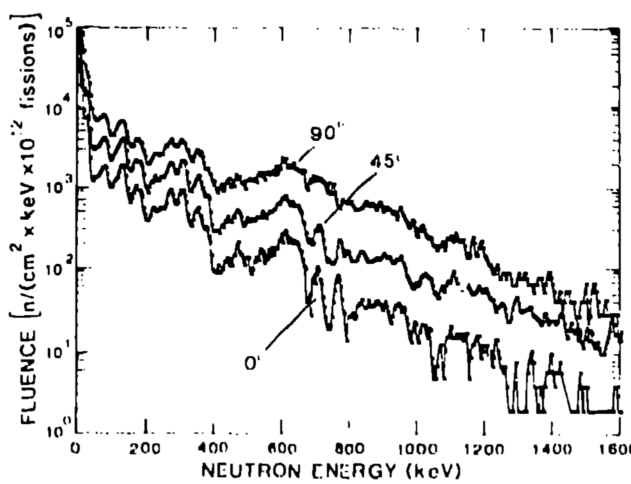

Figure 5. Neutron spectra at 2.0 m.

angles of 0°, 45°, and 90° with respect to the assembly axis. These spectra are shown in Figures 4 and 5. There is a slight hardening of the 90° spectra compared to spectra on axis and, of course, a large difference in total magnitude due to the increased path length through iron in the forward direction as compared to the side. The only background subtracted from these spectra was a reconstruction of the 2-neutron coincidence peak and its associated wall effect produced by taking the difference of two spectra of the same source measured at different counting rates. There are some irregularities in the spectra in the vicinity of 765 keV due to count-rate-dependent gain and resolution shifts of the synthesized background peak.

Proton-Recoil Counter Measurements

As a part of our program to measure intrinsic radiation spectra from weapons, we have been developing a line of proton-recoil proportional counters to measure neutron spectra below 1 MeV. These counters, patterned after a suggestion of Verbinski and Giovannini (1974) are cylindrical chambers 7.5 cm in diameter by 30 cm long, with hemispherical ends. Anode, guard-tube, and insulator dimensions are proportioned according to Benjamin et al. (1968) to minimize end effects. The counter was filled to a pressure of 800 mm of mercury with 80% H_2, 18.4% xenon, 1.5% methane, and 0.1% ^{3}He. The energy scale and resolution of the spectrometer system were determined from the position and width of the ^{3}He peak when the detector was irradiated with thermal neutrons. It was found that the detector resolution was only about 20%, not really state of the art for these detectors, but still useful for dosimetry measurements.

A set of response functions were measured, using monoenergetic neutrons at the Los Alamos 3 75-MeV Van de Graaff. A program was written to strip these response functions, starting with the highest energy response, from an experimental pulse-height distribution to produce a spectrum with resolution characteristic of the detector. Because of the long high-energy tails on the response functions, the stripping process had to be done iteratively, removing only about one-half the calculated fraction of each response corresponding to the experimental curve, then operating with a reduced fraction on the residual. After each iteration, the program calculates the quantity

$$\chi^2 = \sum_{i=1}^{n} \delta_i^2/\varepsilon_i^2 \quad ,$$

where δ_i is the residual in channel i and ε_i is the error determined from counting statistics and estimated errors in measuring the response function. The iteration stops when χ^2 reaches a minimum, which should be close to n, the number of channels over which the data are fit.

In Figure 6, a pulse-height distribution from Little Boy has been fit by a sum of response functions. The solid line is the experimental pulse-height distribution. The areas

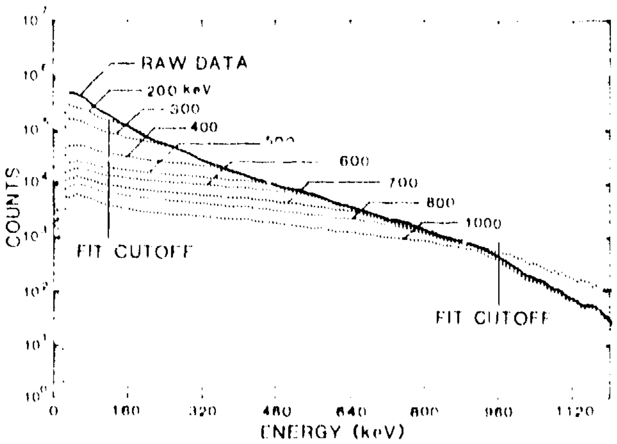

Figure 6. Little Boy proton-recoil spectrum fit with response functions for monoenergetic neutrons.

between curves are the contributions to the distribution of each of the monoenergetic responses. Points below 136 keV were eliminated from the fit because 150- and 100-keV responses were not sufficiently resolved in shape from the 200-keV response. Counting statistics were too poor above 960 keV, and the number of events above this energy was too small to materially affect results at lower energies.

Figures 7-9 show the results of measurements of the Little Boy neutron spectra at 0°, 45°, and 90° from the axis at a distance of 0.75 m. The spectra show the same gross features as the ^{3}He spectra, in particular, a slight hardening at 90° with respect to the on-axis spectrum. The maximum at 600 keV corresponds to a broad peak observed in the ^{3}He counter spectra. In these same three figures, ^{3}He-spectrometer results have been binned into the same energy intervals as the proton-recoil spectra for comparison. The proton-recoil data serve as qualitative confirmation of the ^{3}He spectrometer data, although there is some evidence of spectral shifting.

CONCLUSION

In addition to the work described in this paper, Robitaille and Hoffarth (1983) measured Little Boy neutron

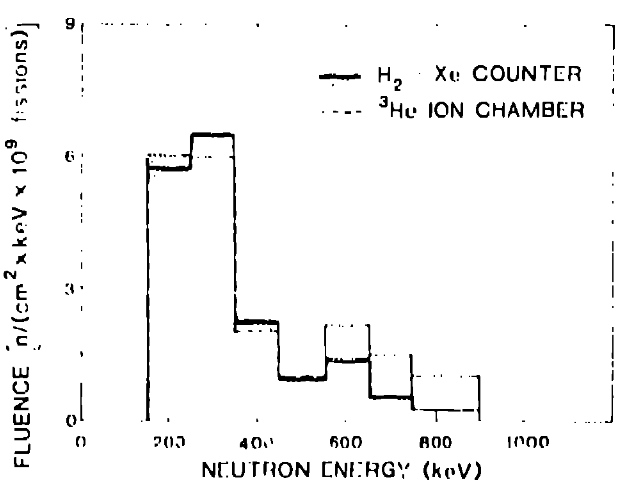

Figure 7. Proton-recoil spectrometry results for neutrons at 0°, 0.75 m from Little Boy, compared with binned results from ^{3}He spectrometry.

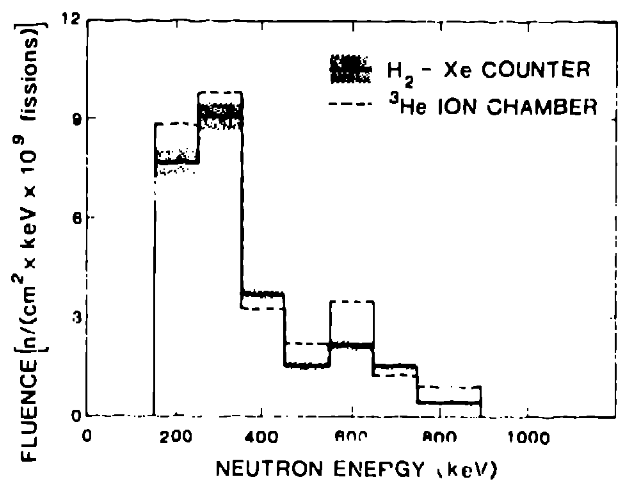

Figure 8. Proton-recoil and ^{3}He-spectrometer results at 45°, 0.75 m.

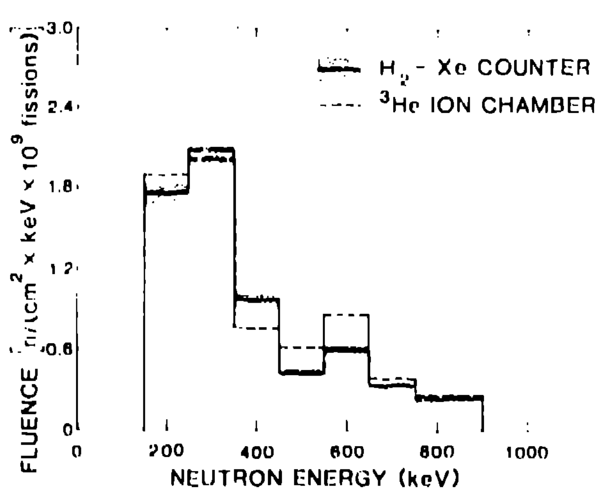

Figure 9. Proton-recoil and ^{3}He-spectrometer results at 90°, 0.75 m.

spectra from 600 keV to 10 MeV using NE213 liquid scintillators, and E. F. Bennett and T. F. Yule of Argonne National Laboratory measured spectra from 1 keV to 3 MeV using proton-recoil proportional counters. There were also measurements using Bonner spheres and track-etch techniques. The intercomparison of all these measurements is now in progress. It can be hoped that the task of intercomparison will yield not only a well-characterized source spectrum for the calculation of Little Boy dose measurements, but also a valuable intercomparison of different techniques and different laboratories of neutron spectrometry.

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