A STUDY OF CYLINDRICAL, ENERGY-PROPORTIONAL PULSE-HEIGHT DETECTORS FOR MEASURING MICRODOSIMETRIC QUANTITIES*

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Abstract. A study has been carried out on the use of cylindrical, energy-proportional pulse-height detectors for determining microdosimetric quantities. In this paper we report the results of using a Hurst chamber to obtain neutron LET spectra and a commercial CH_4 chamber to obtain neutron energy spectra. This work represents an extension of our earlier application of Monte Carlo techniques to the unfolding of LET spectra. The method depends on knowledge of the track-length distribution of charged particles in the chambers, coupled with the measured pulse-height spectra. By several examples it is shown that LET spectra inferred from measurements with the Hurst chamber do not depend critically on the track-length distribution. Calculations for monoenergetic neutrons incident in the CH_4 chamber show that it provides a good energy resolution up to ~2 MeV. Comparisons are made of the effects of different assumptions about the direction of the incident neutrons on the unfolded energy spectrum. Results are presented of neutron energy spectra unfolded from measurements made with the CH_4 chamber exposed to neutrons from the Health Physics Research Reactor.

1. Introduction

A number of investigators have been concerned with obtaining information on neutron LET and energy spectra from measurements made with proportional counters. Rossi developed the use of tissue-equivalent spherical counters for determining LET spectra.[1] As reviewed in Ref. 2, other authors have used particle-recoil chambers (principally recoil protons) for obtaining neutron energy spectra. Some years ago we investigated the use of Monte Carlo unfolding techniques in obtaining neutron LET spectra from measurements made with cylindrical, energy-proportional

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pulse-height detectors.[3,4] We have taken up this problem again and have also applied the Monte Carlo method to unfolding neutron energy spectra. In the next two sections we discuss, respectively, the unfolding methods for obtaining neutron LET and energy spectra, concentrating on the influence of different assumed track-length distributions on the inferred results. In Section 4 we analyze some measurements made at the Health Physics Research Reactor (HPRR).

2. Use of the Hurst Chamber for Obtaining Neutron LET Spectra

To obtain an LET spectrum from a measured pulse-height spectrum, one must know the distribution of recoil-particle track lengths in the sensitive volume of the counter. Ideally, the detector should be operated at low pressure, so that the energy of the recoil particle does not change appreciably as it traverses the sensitive volume. The energy deposited in a pulse can then be related to the LET and the chord length if there are no delta rays and if energy straggling is neglected. In the work reported here, the chord-length distributions are obtained theoretically. The main emphasis of this study is to determine the extent to which inferred LET spectra might generally depend upon the specific distributions assumed. It is suggested that, with optimum chamber design, the role of the track-length distributions is not critical for obtaining LET information with reasonable accuracy.

Figure 1 shows a schematic diagram of the Hurst proportional counter used in this work.[5,6] The counter is lined with polyethylene and filled with cyclopropane. The wall is made thicker than the range of a 20 MeV proton. The device satisfies the requirements of the Bragg-Gray principle. The sensitive volume is a right circular cylinder with height and diameter equal to 4.28 cm. The mean length of isotropic chords in this "square" cylinder is equal to the mean length of isotropic chords in the inscribed sphere.[3] Track-length distributions in the square cylinder of the Hurst chamber thus bear at least this relationship with those in a sphere. This fact makes knowledge of the exact geometric track-length distribution in a square cylinder less critical in unfolding LET spectra than it would be, for example, in an elongated cylinder.

As an example, Fig. 2 shows the calculated pulse-height spectrum H(h) from a broad, parallel beam of 1-MeV neutrons incident laterally on the chamber in a direction perpendicular to its axis. We considered only recoil protons that were generated in the polyethylene walls. A proton entering the gas was assumed, as discussed above, to traverse the gas under such conditions that the energy deposited is given by $h = \varepsilon x$, where ε is the LET (or mass stopping power) and x is the chord length. Detailed transport calculations of the recoil protons were carried out. (It was assumed that an incident neutron produced no more than one recoil proton.) For a large number of incident neutrons we compiled the actual LET distribution $L(\varepsilon)$ and chord length distribution $P(x)$ that gave $H(h)$.

Given the pulse-height spectrum shown in Fig. 2, how critically does the unfolded LET spectrum depend on exact knowledge of the actual chord-length distribution? To investigate this question, we considered the two normalized chord-length distributions shown in Fig. 3. $P_0(x)$ is the actual distribution derived from the detailed calculations for the parallel neutron beam and compiled in obtaining Fig. 2; $P_1(x)$ is the distribution of isotropic chords through the sensitive volume. It is seen that these two functions do not differ markedly. The peak occurs where x has the same value as the height and diameter.[3]

To obtain an LET spectrum by our method,[4] we sample a large number of times (e.g., 10^4) from a given $P(x)$ and an arbitrary (e.g., flat) trial LET distribution, $L(\varepsilon)$. We multiply the selected values in pairs, $x_i \varepsilon_i = h_i$, and compare the resulting trial pulse-height spectrum with the given spectrum $H(h)$ in Fig. 2. We then multiply each of the values ε_i that occur in a given pulse-height interval Δh by the ratio of the given and the trial pulse-height spectra in that interval. This gives a new trial LET distribution, which we then use to repeat the procedure, recalculating $H(h)$. Practice has shown that, after about ten iterations, the LET distribution stabilizes and the calculated and given pulse-height spectra agree to within statistical fluctuations. The function $L(\varepsilon)$, which no longer changes significantly with continued iterations, is the unfolded LET spectrum.

Figure 4 compares the normalized LET spectra $L_0(\varepsilon)$ and $L_1(\varepsilon)$, unfolded by using 30,000 histories each with $P_0(x)$ and $P_1(x)$, respectively. Both spectra were obtained by starting with a flat trial LET function and iterating 20 times. The precise normalized LET spectrum $L(\varepsilon)$, used to calculate Fig. 2, is also shown for comparison. The two unfolded spectra are similar, as expected. Peaks occur around $\varepsilon \sim 950$ MeV cm^2/g and $\varepsilon \sim 450$ MeV cm^2/g. These values correspond to the proton Bragg peak and to the stopping power of 0.5 MeV protons, the average recoil energy. The resolution in the unfolded spectra could be improved by using a larger number of histories in the Monte Carlo calculations. As is, however, this example illustrates that the unfolded spectrum $L_1(\varepsilon)$, based on the assumption of isotropic chords, gives a reasonably close representation of $L_0(\varepsilon)$. This result suggests that, when neutron directions are unknown, use of a "square" cylinder detector and the assumption of isotropic chords will permit obtaining a useful approximation to an unfolded LET spectrum based on more precise knowledge of the track-length distribution.

3. Use of CH_4 Chamber for Obtaining Neutron Energy Spectra

In this study we employed a CH_4 gas counter having a cylindrical volume 2 in. in diameter and 10 in. in length. The gas at 1.25 atm was enclosed in a thin (0.032 in) stainless-steel wall. In contrast to the Hurst chamber, in which the bulk of the neutron interactions occur in the wall, virtually all of the reactions here occur in the chamber gas. We explicitly treat starters and stoppers as well as the continuous loss of energy of recoil particles as they slow down in the gas.

As in the last section, we made detailed calculations for neutrons incident on the cylinder in various geometries. The ranges of the carbon recoil nuclei were neglected in comparison with the chamber dimensions, but the transport of hydrogen recoils, including stoppers and those escaping, was treated explicitly. A pulse-height spectrum was computed and then used to unfold the incident neutron energy spectrum N(E). To do the unfolding, we sampled from an initially flat trial neutron spectrum and computed a trial pulse-height spectrum. In an analogous manner as before, we multipled all of the neutron energies that contributed pulses in a given interval Δh by the ratio of the observed and trial pulse-height spectra in that interval. This procedure gave a new trial neutron spectrum, and the iterative procedure was continued.

As an example, a pulse-height spectrum was calculated for a broad beam of 1-MeV neutrons incident laterally on the CH_4 chamber in a direction perpendicular to its cylindrical axis. Using this pulse-height spectrum, we first unfolded the neutron energy spectrum, assuming only that their direction of incidence was the correct one, side-on. The resulting spectrum obtained with 25,000 histories and 80 iterations is shown by the curve $N_S(E)$ in Fig. 5. One finds a sharp peak at 1 MeV. The same pulse-height spectrum was unfolded by assuming (incorrectly) that the neutrons were incident isotropically. The resulting unfolded spectrum is shown by the curve $N_I(E)$ in Fig. 5. Although the neutrons were parallel and incident laterally, the isotropic analysis still gave a strong peak at the correct energy of 1 MeV. This result is probably due to the relatively large fraction ($\sim$3/4) of recoil protons that stop in the chamber, giving up their entire initial energy in the gas. The curve $N_E(E)$ results when the same side-on pulse-height spectrum is analyzed assuming that the neutrons are incident end-on. Again, a peak occurs at 1 MeV. In this case, however, the analysis "thinks" that the stopping protons result, on the average, from collisions that are more nearly head-on than in the other two cases. Therefore, it assigns many pulses to neutrons of lower energies, resulting in the distinct skewing of $N_E(E)$ toward lower neutron energies. For laterally incident 5-MeV neutrons, only about one-fourth of the recoil protons are stoppers, and so the analysis does not resolve the spectrum as it did at 1 MeV. A chamber of "more square" proportions and higher pressure would be better at the higher neutron energies.

Preliminary calculations and measurements with a ^{4}He chamber at 20 atm pressure indicate that neutron energies can be resolved by this procedure in the range 5-10 MeV. Apart from the higher pressure, the ^{4}He detector offers an additional advantage over the CH_4 counter in that all pulses are due to recoil particles of the same kind. Neutron energy unfolding with the CH_4 device is obscured somewhat by having to assign a given pulse to an H or C recoil particle.

4. Neutron Energy Spectral Measurements at the Health Physics Research Reactor (HPRR)

The CH_4 proportional counter was exposed laterally and end-on with no shielding to neutrons from the bare HPRR.[7] Measurements were made at a point 1 m above the floor and 3 m from the center of the reactor, with its center also 1 m above the floor. The incident neutrons are thus parallel when they reach the chamber. Convenient count rates and exposure times were realized with the reactor running at a steady power of 1 watt.

The neutron energy spectrum at this reference position of the detectors is known from detailed calculations.[8] The gamma-to-neutron dose rate there is about 1/10.

The neutron energy spectra obtained from analyses of the data from the CH_4 chamber are shown in Fig. 6 together with the known spectrum,[8] all curves being normalized to unit area. One of the unfolded spectra was obtained from the pulse-height spectrum measured with the CH_4 chamber exposed side-on and the other from measurements made end-on. The three curves, which are subject to some uncertainties, agree reasonably well. With respect to the measurements, the value of the gas amplification is uncertain to perhaps ±10% and the gamma build-up was not assessed. The latter may be responsible, in part, for the higher values of the unfolded curves at the lower neutron energies. Of the two unfolded curves, one might expect the end-on to yield more accurate results, especially for the higher neutron energies, because of the relatively larger number of stoppers. The stopping recoil protons would be in the forward direction, nearly approximating the energy spectrum of the incident neutrons.

5. Conclusions

These initial studies demonstrate the usefulness of cylindrical proportional counters in obtaining information about neutron LET and energy spectra. Our analyses indicate that use of a "square" cylinder with assumed isotropic chords for iterative unfolding can give useful information about neutron LET spectra under the conditions studied here. Similarly, neutron energy spectral data can be inferred from measurements with a cylindrical chamber, even when the direction of the incident neutrons is not known explicitly.

Acknowledgement

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References

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2. G. Grosshoeg, *Nucl. Instr. Meth.* 162, 125 (1979).

Figure Captions

Fig. 1. Hurst proportional counter. Operation is described in Refs. 5 and 6.

Fig. 2. Calculated pulse-height spectrum for Hurst chamber exposed laterally to broad, parallel beam of 1-MeV neutrons.

Fig. 3. Calculated chord-length distributions of recoil protons in the Hurst chamber. $P_0(x)$ is the actual distribution from a laterally incident parallel beam of 1-MeV neutrons. $P_1(x)$ is the distribution of isotropic chords in the chamber.

Fig. 4. LET spectra for the Hurst chamber with 1-MeV neutrons. $L_0(\varepsilon)$ and $L_1(\varepsilon)$ were found by unfolding H(h) from Fig. 2 with $P_0(x)$ and $P_1(x)$, respectively, from Fig. 3. The "actual" spectrum $L(\varepsilon)$ was used to generate H(h).

Fig. 5. Unfolded energy spectra for 1-MeV neutron beam incident laterally on CH_4 chamber. The same pulse-height spectrum was unfolded using three different assumptions about the geometry of the incident neutrons. The curve $N_S(E)$ was obtained from the correct assumption that the neutrons were incident side-on; $N_E(E)$ assumed end-on incidence and $N_I(E)$ isotropic incidence. All curves were calculated with 25,000 histories and 80 iterations.

Fig. 6. Comparison of known and unfolded neutron energy spectra from HPRR. $N_0(E)$ is the known spectrum; $N_S(E)$ and $N_E(E)$ are the spectra unfolded from side-on and end-on irradiations.

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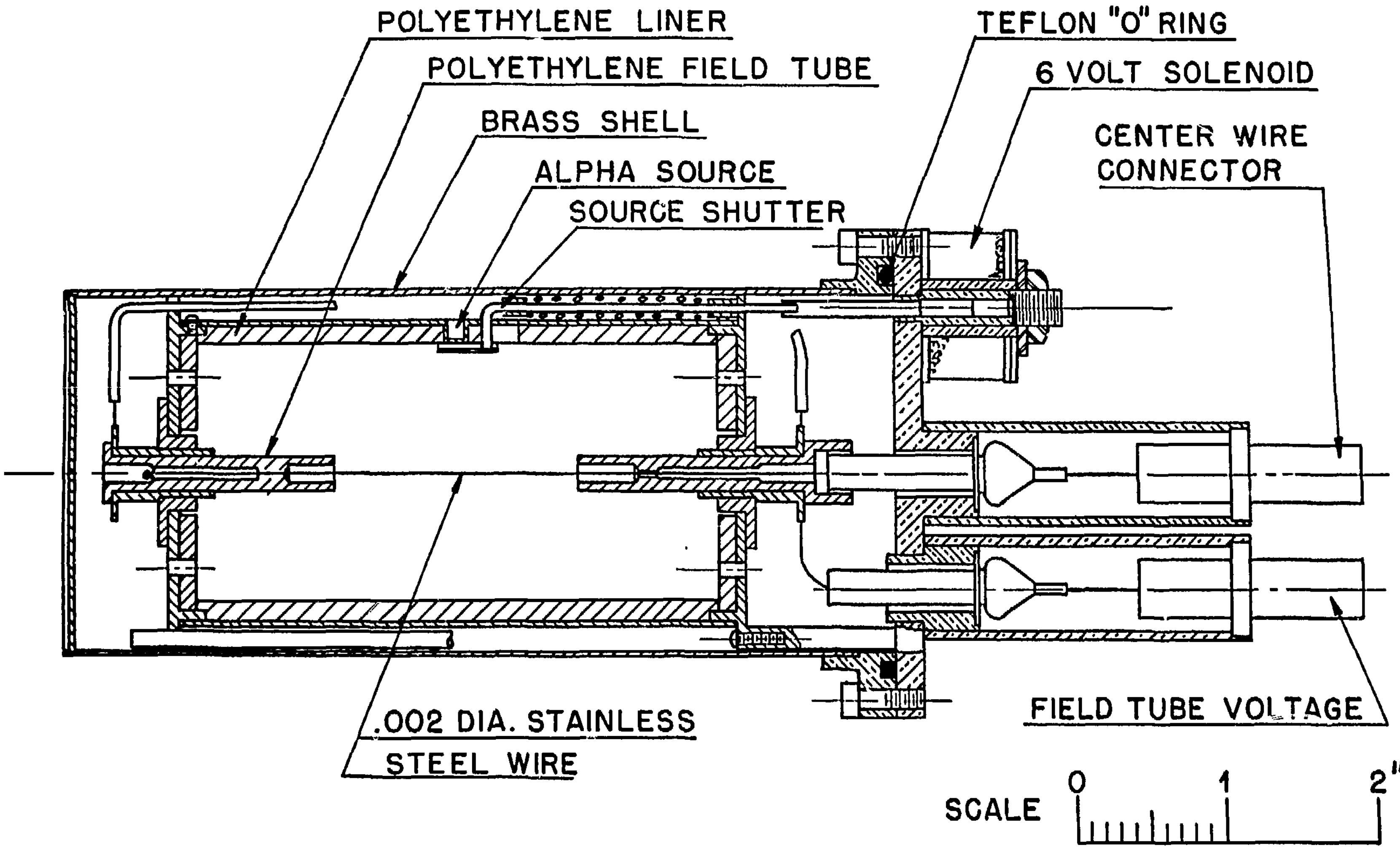


ABSOLUTE FAST NEUTRON DOSIMETER

Figure 1

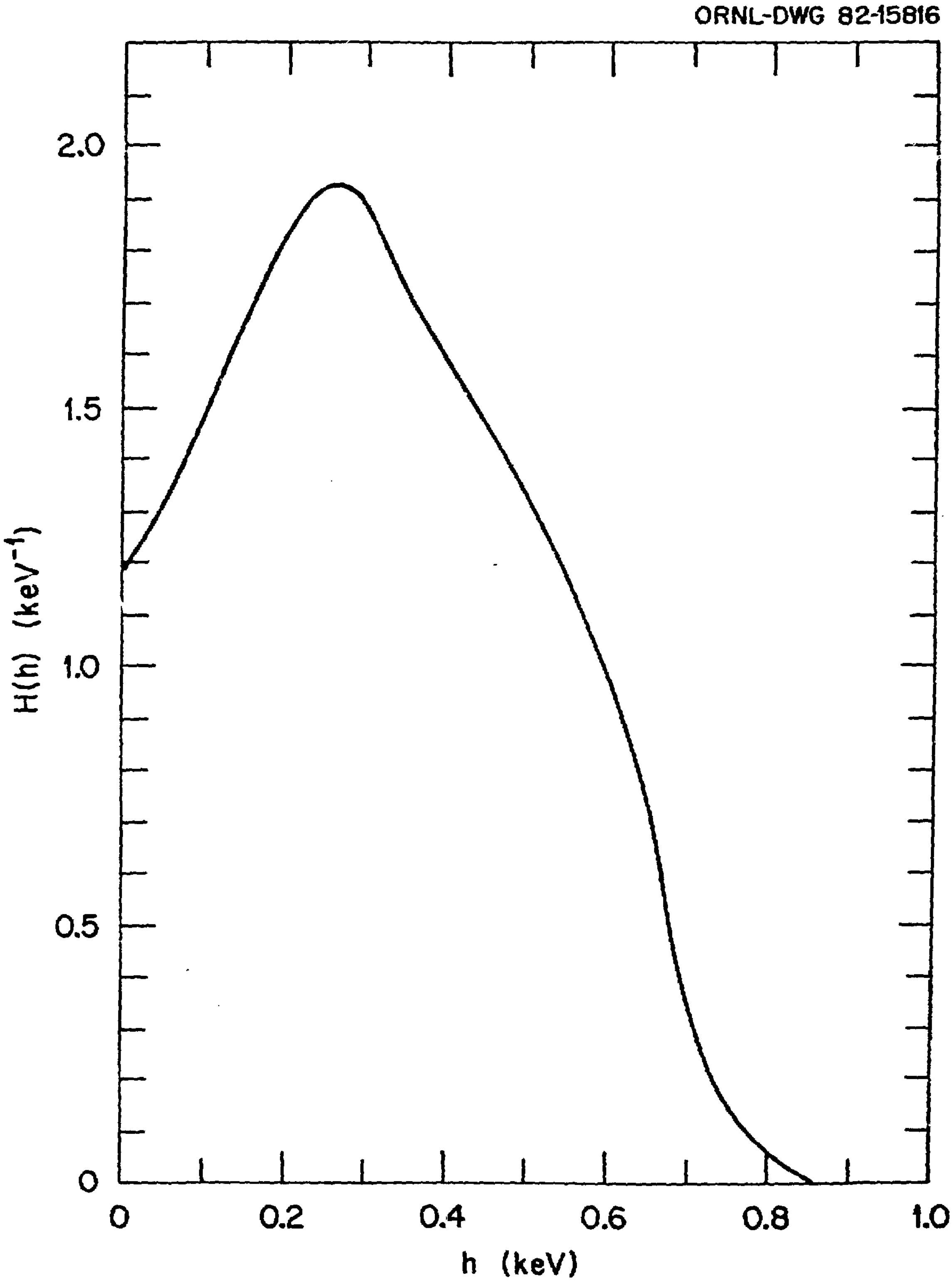
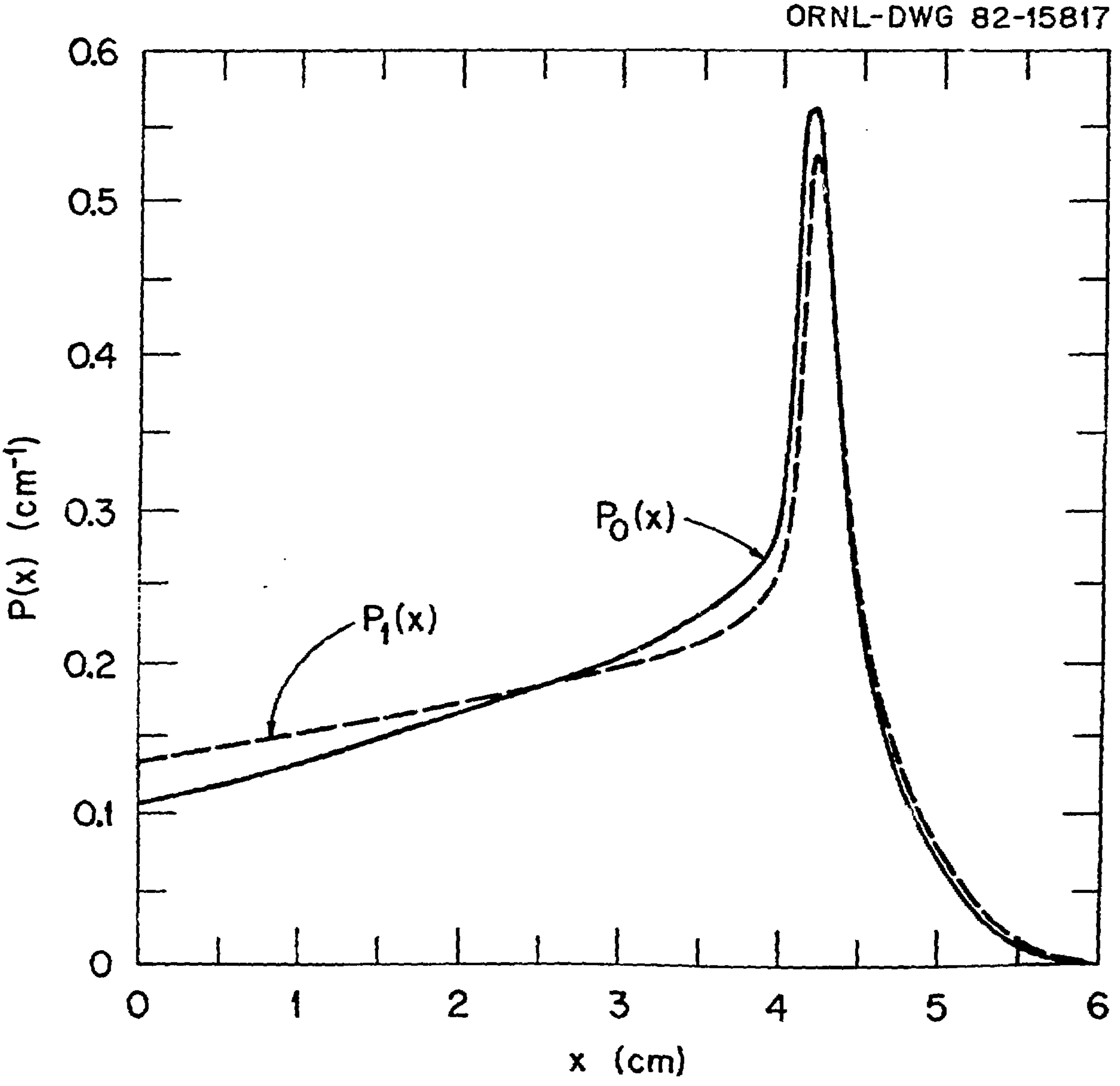


Figure 2



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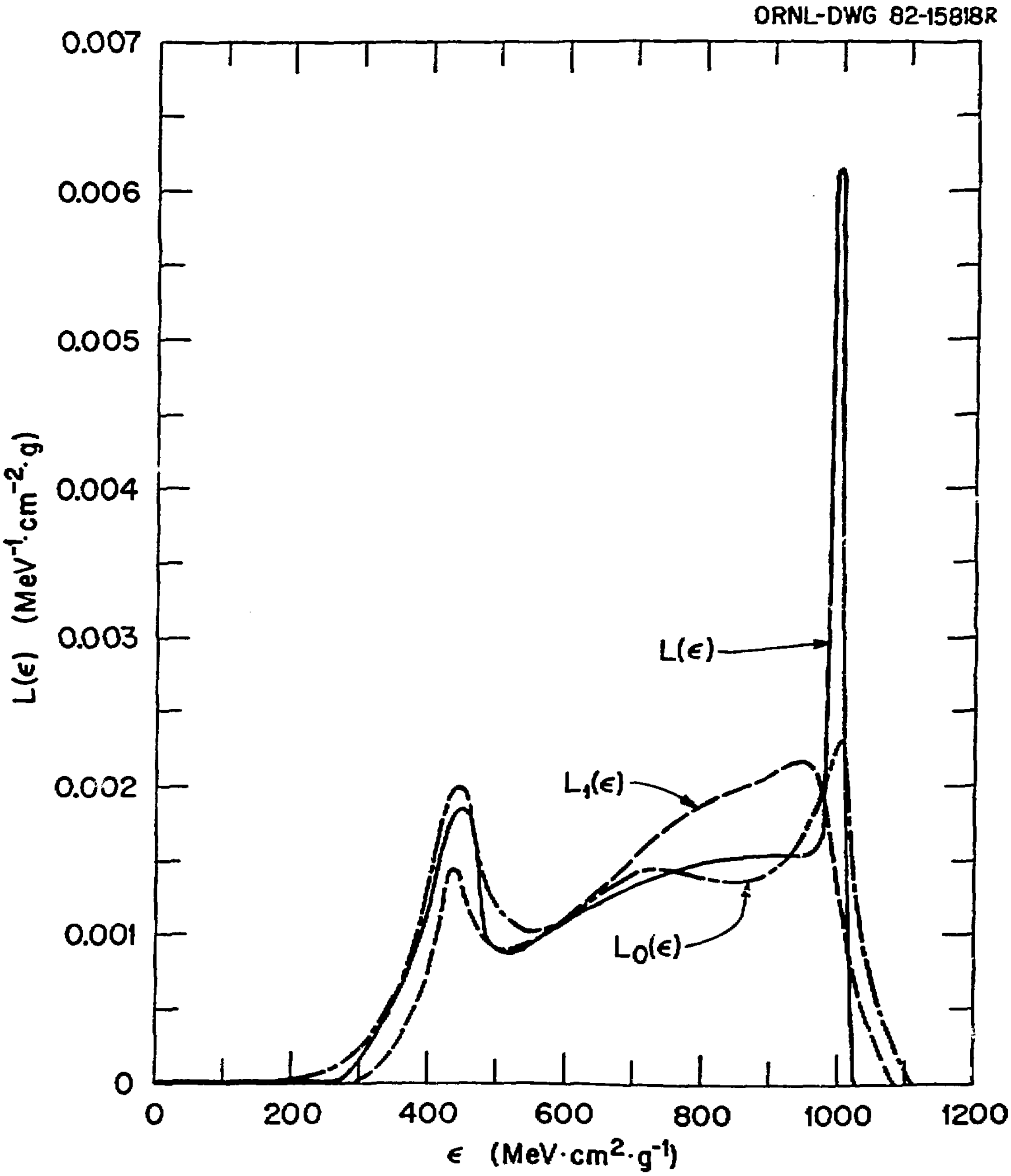
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ϵ (MeV·cm²·g⁻¹)

Figure 4

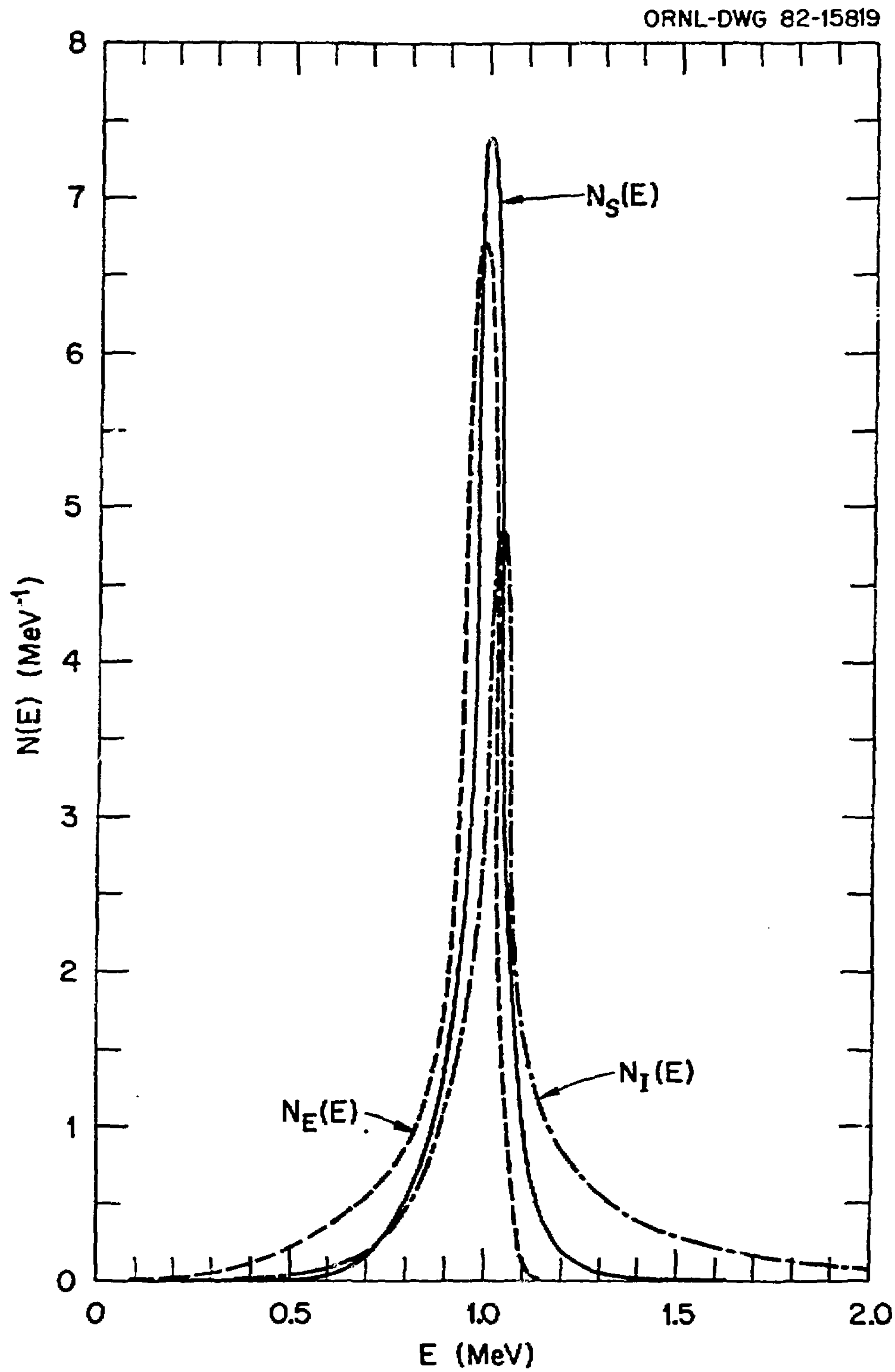
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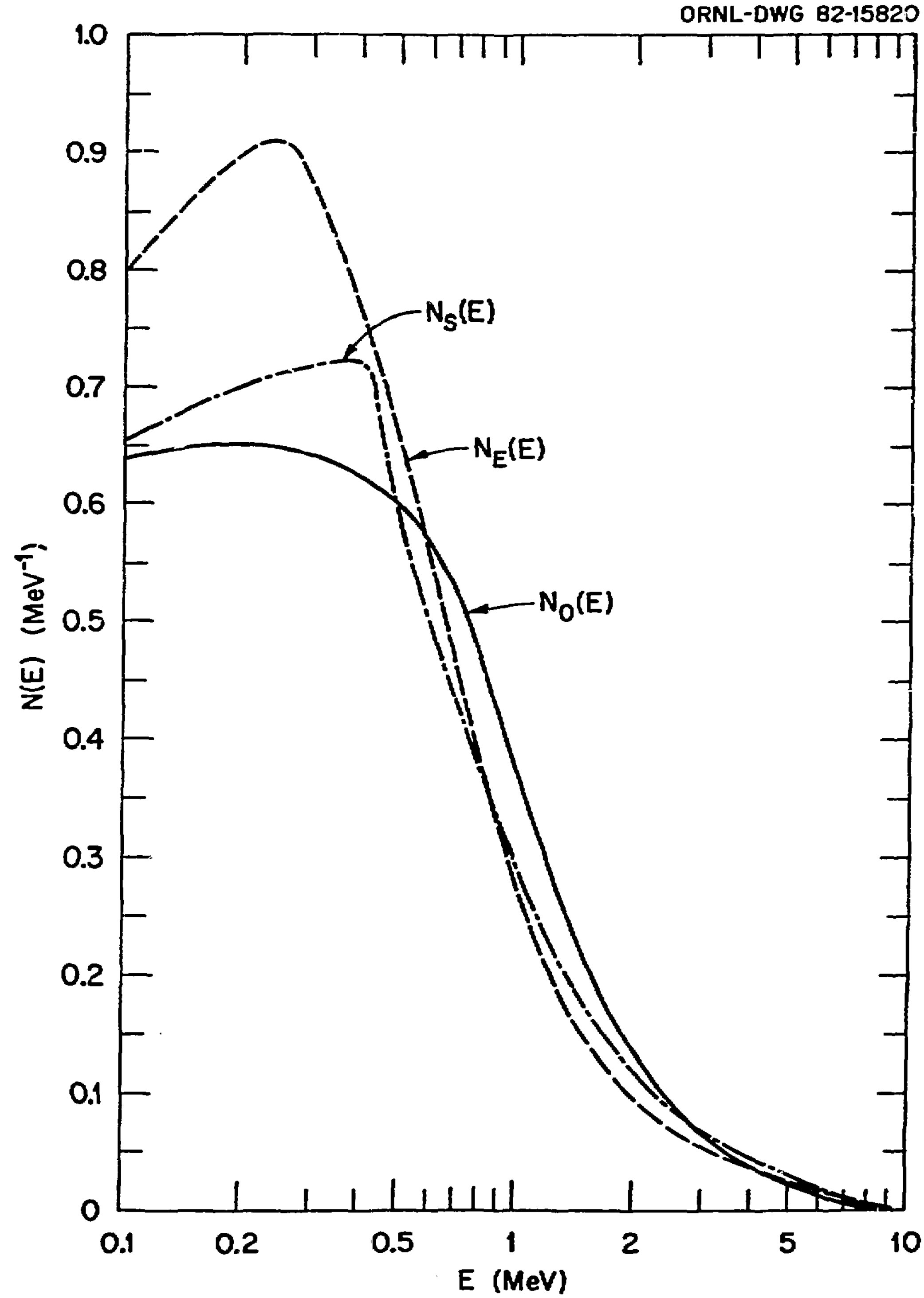
Figure 5



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E (MeV)

Figure 6