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**ENERGY AND TIME DEPENDENCE OF
DELAYED GAMMAS FROM FISSION**

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Printed in USA Price \$ 1.00. Available from the
Office of Technical Services
U. S. Department of Commerce
Washington 25, D. C.

LAMS-2642
PHYSICS
(TID-4500, 17th Ed.)

LOS ALAMOS SCIENTIFIC LABORATORY
OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

REPORT WRITTEN: January 1962

REPORT DISTRIBUTED: July 6, 1962

**ENERGY AND TIME DEPENDENCE OF
DELAYED GAMMAS FROM FISSION**

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Contract W-7405-ENG. 36 with the U. S. Atomic Energy Commission

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ABSTRACT

This report contains some results of an experiment designed to measure the energy and time dependence of the gammas emitted after effectively instantaneous neutron-induced fission of Th^{232} , U^{233} , U^{235} , U^{238} , and Pu^{239} . Seventeen-bin distributions of the absolute number of photons/fission-sec-Mev and intercomparisons and integrations over energy and time of these distributions are given. Gammas having energies between 0.12 and 6.5 Mev were detected during five short time intervals between 0.2 sec and 45 sec after fission occurred.



TABLE OF CONTENTS

	Page
ABSTRACT	3
INTRODUCTION	9
REFERENCES	12

TABLES

1. Bin Widths and Midpoints in Mev for Photon Spectra	13
2. Distribution of Photons/Fission-sec-Mev for the Different Time Intervals Following Th^{232} Fission	15
3. Distribution of Photons/Fission-sec-Mev for the Different Time Intervals Following U^{233} Fission	19
4. Distribution of Photons/Fission-sec-Mev for the Different Time Intervals Following U^{235} Fission	23
5. Distribution of Photons/Fission-sec-Mev for the Different Time Intervals Following U^{238} Fission	27

TABLES (Continued)

		Page
6.	Distribution of Photons/Fission-sec-Mev for the Different Time Intervals Following Pu ²³⁹ Fission	31
7.	Results of Delayed Gamma Spectra Integrated over Energy for Different Time Intervals after Fission	39
8.	Results of Delayed Gamma Spectra Integrated over Energy and Time from 0.20 to 45.0 sec after Fission	41

FIGURES

1.	Pulse height distribution of gammas for different time intervals following Th ²³² fission	14
2.	Photon spectra of gammas for different time intervals following Th ²³² fission	16
3.	Ratios of Th ²³² photon spectra at all time intervals	17
4.	Pulse height distribution of gammas for different time intervals following U ²³³ fission	18
5.	Photon spectra of gammas for different time intervals following U ²³³ fission	20

FIGURES (Continued)

	Page
6. Ratios of U^{233} photon spectra at all time intervals	21
7. Pulse height distribution of gammas for different time intervals following U^{235} fission	22
8. Photon spectra of gammas for different time intervals following U^{235} fission	24
9. Ratios of U^{235} photon spectra at all time intervals	25
10. Pulse height distribution of gammas for different time intervals following U^{238} fission	26
11. Photon spectra of gammas for different time intervals following U^{238} fission	28
12. Ratios of U^{238} photon spectra at all time intervals	29
13. Pulse height distribution of gammas for different time intervals following Pu^{239} fission	30
14. Photon spectra of gammas for different time intervals following Pu^{239} fission	32
15. Ratios of Pu^{239} photon spectra at all time intervals	33
16. Ratios of photon spectra for all isotopes at 0.2 to 0.5 sec interval	34

FIGURES (Continued)

	Page
17. Ratios of photon spectra for all isotopes at 1.0 to 2.0 sec interval	35
18. Ratios of photon spectra for all isotopes at 4.0 to 5.5 sec interval	36
19. Ratios of photon spectra for all isotopes at 10.0 to 13.0 sec interval	37
20. Ratios of photon spectra for all isotopes at 35.0 to 45.0 sec interval	38
21. Comparison of photon spectra integrated over energy for the different time intervals after fission	40

INTRODUCTION

The purpose of this report is to make available information derived from delayed gamma measurements. Results are presented as the energy dependence of gammas in several time intervals following the fission of various isotopes. The comments and explanations pertaining to experimental procedures and to analysis of data, from which these results were obtained, will appear later in several detailed articles. Integrated results will be extended to about 250 seconds after fission, representing 200 sec of data which do not appear in this report.

In the experiment, a sample of material was placed near the center of the Godiva II critical assembly. Following irradiation by a less than 0.05-sec-long burst of fission spectrum neutrons, the sample was pneumatically transferred to a counting geometry containing a 4 in. x 4 in. NaI crystal. The pulses from the crystal were recorded in a 100-channel analyzer for time intervals of 0.2 to 0.5, 1 to 2, 4 to 5.5, 10 to 13, and 35 to 45 sec after fission. Overlapping sets of pulse-height-analyzer data were used to suitably cover the large range of

counting rates present in a given photon spectrum. In addition to these energy spectra, the time decay of gammas above several fixed pulse-height biases was followed from 0.3 sec to 300 sec after fission. However, no time decay data are given in this report.

Normalization of the 100-channel data was accomplished by radiochemical determination of the absolute number of fissions responsible for a measured number of counts in a given pulse-height interval during a given time interval after fission. A seventeen-bin NaI crystal response function was constructed from the results of gamma measurements made from radioactive sources of known strength and from several $(p,\alpha\gamma)$ reactions. Photon spectra were derived by applying this crystal-response function to the pulse-height data.

The figures and tables grouped together at the end of this report consist of data related to the various photon spectra measured. Table 1 lists the parameters for the seventeen-bin photon intervals. The original pulse height distributions for the isotopes Th^{232} , U^{233} , U^{235} , U^{238} , and Pu^{239} are given in Figures 1, 4, 7, 10, and 13, respectively. Tabular and graphical results for the distribution of photons/fission-sec-Mev with time are given in Tables 2 through 6 and Figures 2, 5, 8, 11, and 14. The relative

hardness of a given isotope's spectra at different times is shown in Figures 3, 6, 9, 12, and 15. These ratios were obtained by dividing the spectrum for a given time interval by the spectrum for the 0.2 to 0.5 sec interval.

Comparison of the spectra for different isotopes at a given time interval after fission appear in Figures 16, 17, 18, 19, and 20. The results for spectra integrated over energy appear in Table 7. Table 8 lists both the total delayed-gamma energy per fission and the total number of delayed gammas per fission emitted by the different isotopes. As mentioned earlier, only photons having energies greater than 0.12 Mev were measured. Sufficient time decay data exist to allow calculation of the total number of photons emitted between 0.2 sec and about 250 sec after fission. However, the results in Table 8 apply only to those photons emitted between 0.2 sec and 45 sec after fission.

Only qualitative estimates for the experimental error have been computed. These estimates indicate a maximum standard deviation of $\pm 15\%$ for all but the Pu^{239} numbers, to which a value of $\pm 25\%$ applies.

A few further details concerning this experiment can be obtained by consulting the references.

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- P. C. Fisher, L. B. Engle, Delayed Gammas from Fission I, Bull. Am. Phys. Soc. Ser. II, 6, 307, 1961.
- L. B. Engle, P. C. Fisher, Delayed Gammas from Fission II, Bull. Am. Phys. Soc. Ser. II, 6, 308, 1961.

Table 1

Bin Widths and Midpoints in Mev for Photon Spectra

<u>Bin</u>	<u>ΔE (Mev)</u>	<u>Midpoint (Mev)</u>
1	0.137 - 0.213	0.175
2	0.213 - 0.309	0.261
3	0.309 - 0.428	0.369
4	0.428 - 0.575	0.502
5	0.575 - 0.749	0.662
6	0.749 - 0.954	0.852
7	0.954 - 1.195	1.075
8	1.195 - 1.478	1.337
9	1.478 - 1.808	1.643
10	1.808 - 2.189	1.998
11	2.189 - 2.620	2.405
12	2.620 - 3.110	2.865
13	3.110 - 3.655	3.383
14	3.655 - 4.257	3.956
15	4.257 - 4.918	4.587
16	4.918 - 5.636	5.277
17	5.636 - 6.419	6.028

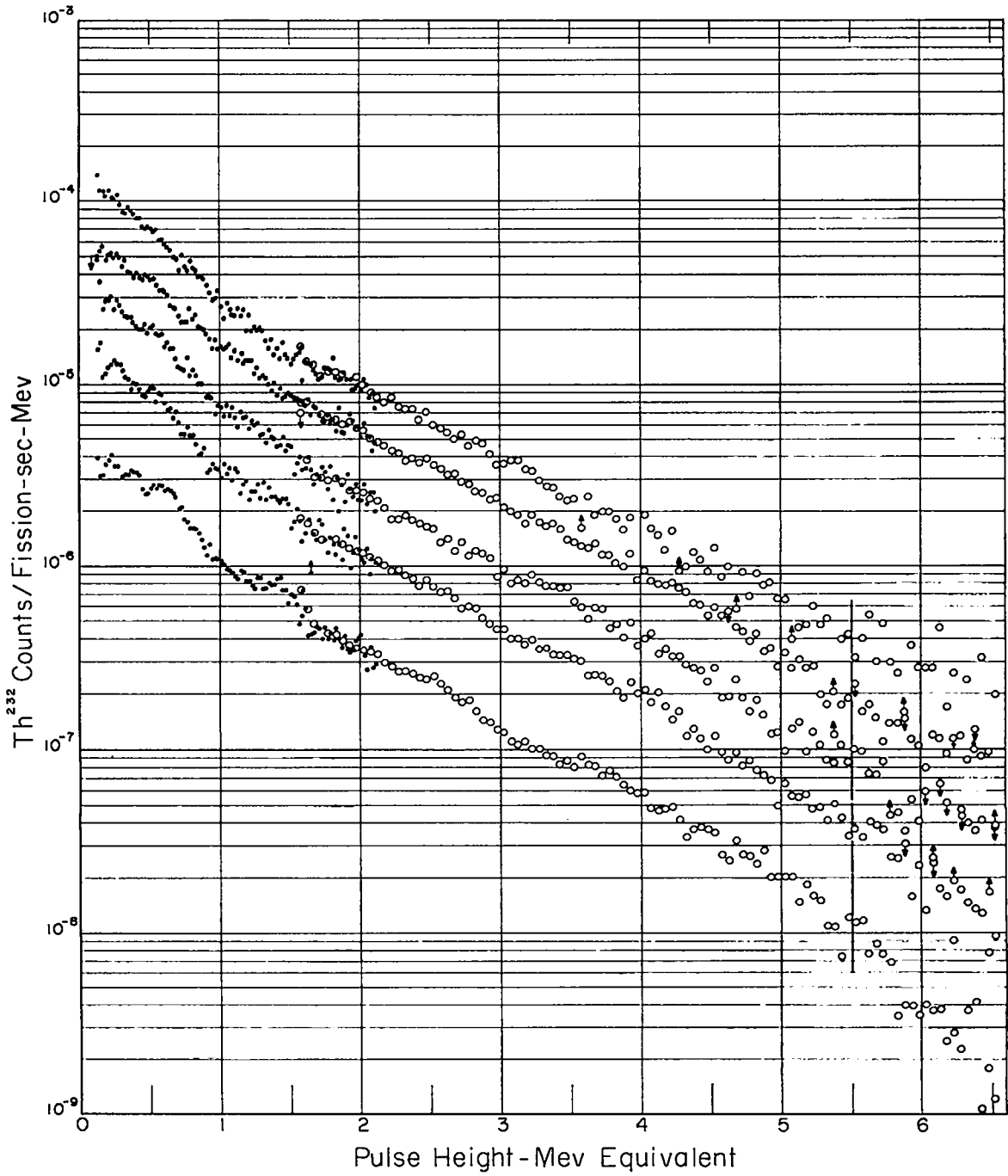


Figure 1. Pulse height distribution of gammas for different time intervals following Th^{232} fission

Table 2

Distribution of Photons/Fission-sec-Mev for the
Different Time Intervals Following Th²³² Fission

Interval Midpoint (Mev)	0.2 - 0.5 sec	1.0 - 2.0 sec	4.0 - 5.5 sec	10.0 - 13.0 sec	35.0 - 45.0 sec
0.175	2.32×10^0	9.79×10^{-1}	6.52×10^{-1}	2.54×10^{-1}	5.53×10^{-2}
0.261	1.19×10^0	5.49×10^{-1}	3.20×10^{-1}	1.51×10^{-1}	3.77×10^{-2}
0.369	8.05×10^{-1}	3.59×10^{-1}	2.20×10^{-1}	9.15×10^{-2}	2.80×10^{-2}
0.502	6.51×10^{-1}	3.40×10^{-1}	1.88×10^{-1}	8.39×10^{-2}	2.35×10^{-2}
0.662	5.04×10^{-1}	2.49×10^{-1}	1.52×10^{-1}	7.19×10^{-2}	2.63×10^{-2}
0.852	4.19×10^{-1}	2.11×10^{-1}	1.05×10^{-1}	4.43×10^{-2}	1.49×10^{-2}
1.075	2.85×10^{-1}	1.66×10^{-1}	7.31×10^{-2}	3.35×10^{-2}	9.66×10^{-3}
1.337	1.90×10^{-1}	1.15×10^{-1}	5.95×10^{-2}	2.82×10^{-2}	9.14×10^{-3}
1.643	1.30×10^{-1}	7.88×10^{-2}	4.12×10^{-2}	1.67×10^{-2}	5.95×10^{-3}
1.998	1.06×10^{-1}	5.91×10^{-2}	2.74×10^{-2}	1.26×10^{-2}	3.72×10^{-3}
2.405	7.82×10^{-2}	4.23×10^{-2}	1.90×10^{-2}	9.57×10^{-3}	3.03×10^{-3}
2.865	5.36×10^{-2}	3.07×10^{-2}	1.24×10^{-2}	6.34×10^{-3}	1.88×10^{-3}
3.383	3.13×10^{-2}	1.82×10^{-2}	8.83×10^{-3}	3.84×10^{-3}	1.03×10^{-3}
3.956	1.91×10^{-2}	1.17×10^{-2}	5.31×10^{-3}	2.66×10^{-3}	7.59×10^{-4}
4.587	1.35×10^{-2}	7.78×10^{-3}	3.21×10^{-3}	1.43×10^{-3}	4.23×10^{-4}
5.277	4.24×10^{-3}	2.70×10^{-3}	1.23×10^{-3}	5.71×10^{-4}	2.18×10^{-4}
6.028	5.88×10^{-3}	2.41×10^{-3}	1.03×10^{-3}	4.61×10^{-4}	9.18×10^{-5}

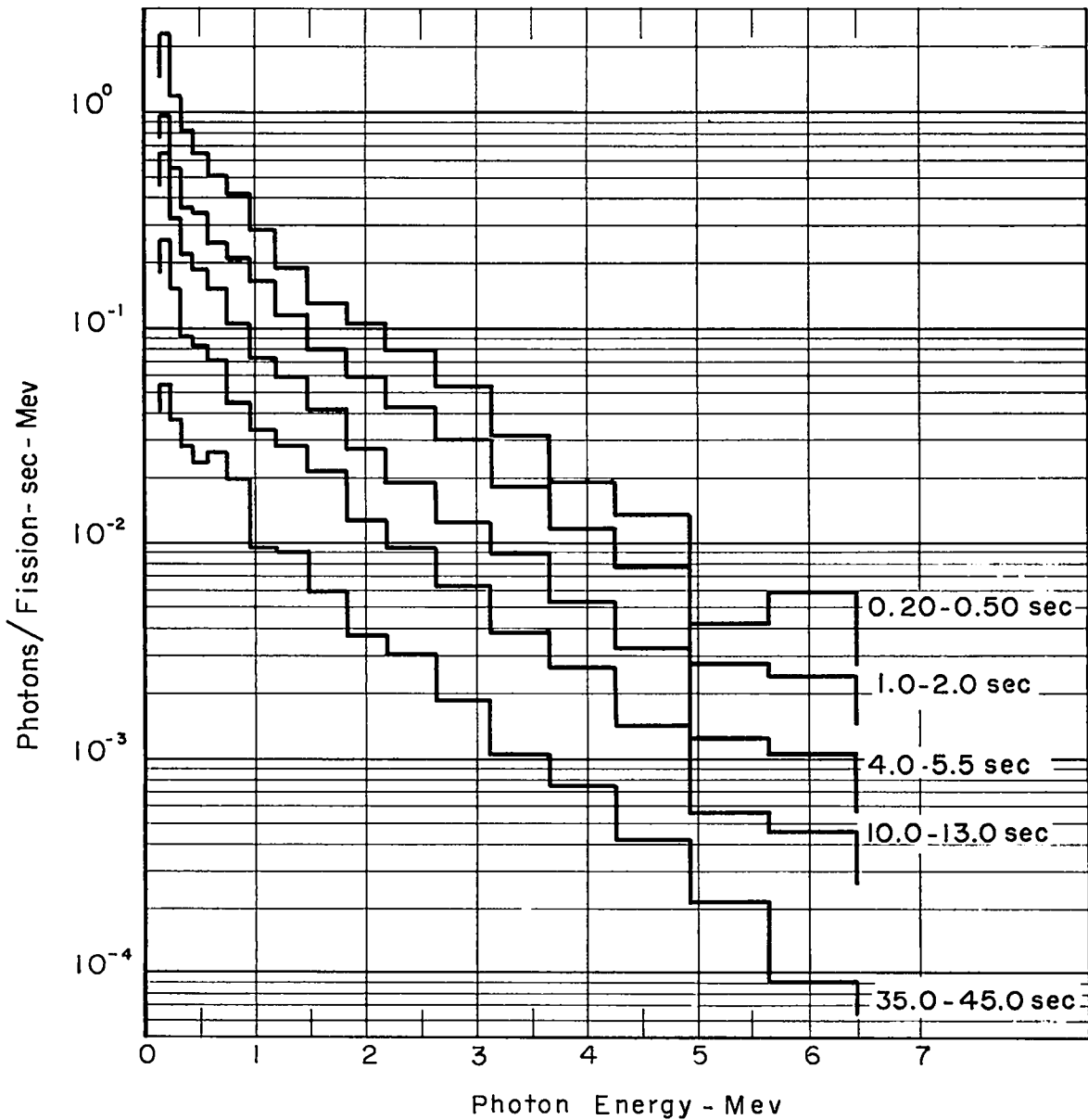


Figure 2. Photon spectra of gammas for different time intervals following Th^{232} fission

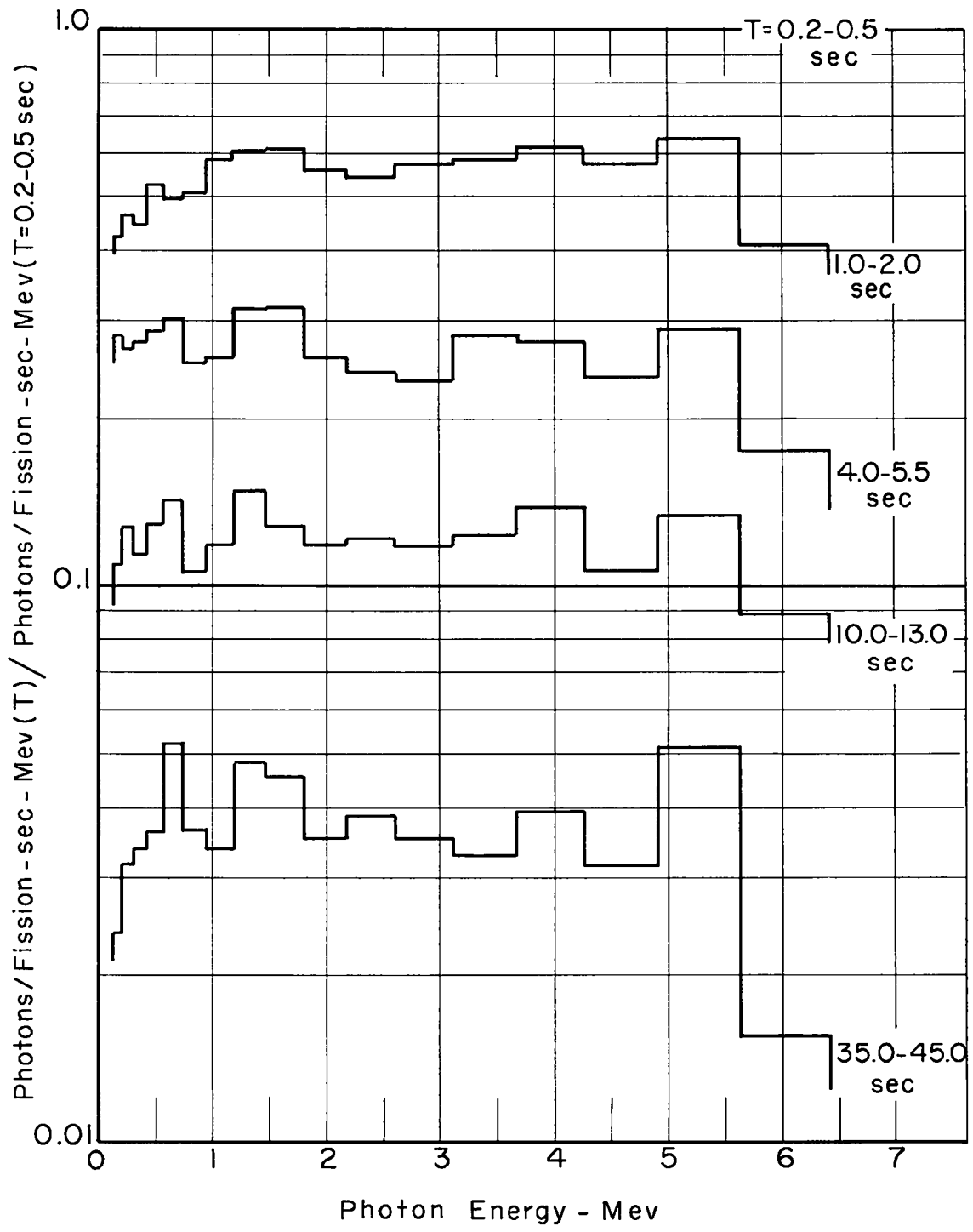


Figure 3. Ratios of Th^{232} photon spectra at all time intervals

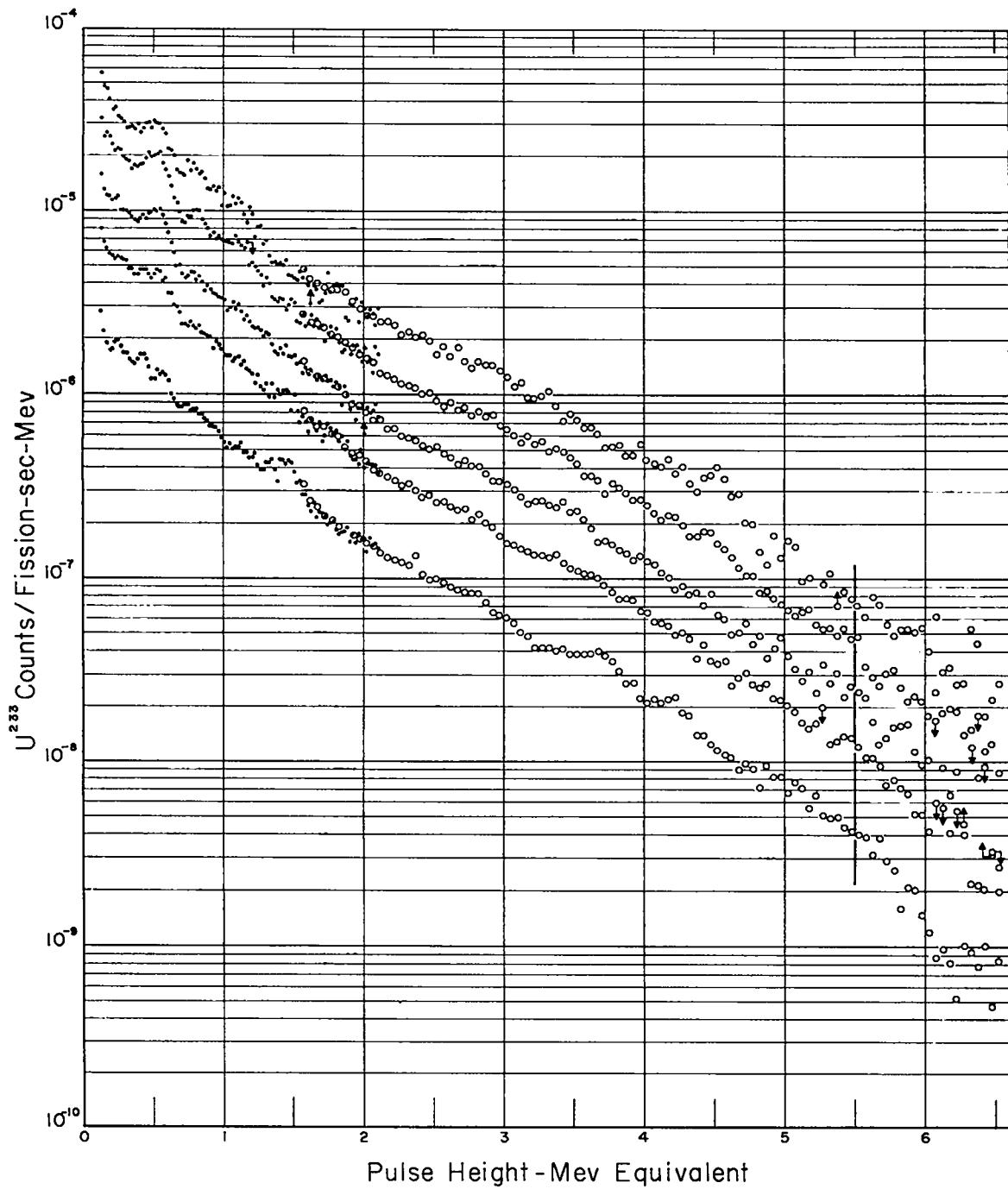


Figure 4. Pulse height distribution of gammas for different time intervals following U^{233} fission

Table 3

Distribution of Photons/Fission-sec-Mev for the
Different Time Intervals Following U²³³ Fission

Interval Midpoint (Mev)	0.2 - 0.5 sec	1.0 - 2.0 sec	4.0 - 5.5 sec	10.0 - 13.0 sec	35.0 - 45.0 sec
0.175	6.20×10^{-1}	3.37×10^{-1}	1.77×10^{-1}	8.86×10^{-2}	2.67×10^{-2}
0.261	2.77×10^{-1}	1.81×10^{-1}	9.96×10^{-2}	5.17×10^{-2}	1.75×10^{-2}
0.369	2.03×10^{-1}	1.27×10^{-1}	7.14×10^{-2}	3.77×10^{-2}	1.28×10^{-2}
0.502	2.78×10^{-1}	1.99×10^{-1}	1.01×10^{-2}	4.37×10^{-2}	1.19×10^{-2}
0.662	1.73×10^{-1}	1.09×10^{-1}	5.72×10^{-2}	2.92×10^{-2}	8.73×10^{-3}
0.852	1.62×10^{-1}	8.91×10^{-2}	3.90×10^{-2}	2.16×10^{-2}	7.45×10^{-3}
1.075	1.35×10^{-1}	8.12×10^{-2}	3.38×10^{-2}	1.77×10^{-2}	5.49×10^{-3}
1.337	7.22×10^{-2}	4.47×10^{-2}	2.25×10^{-2}	1.26×10^{-2}	5.06×10^{-3}
1.643	4.20×10^{-2}	2.72×10^{-2}	1.53×10^{-2}	8.24×10^{-3}	3.23×10^{-3}
1.998	3.18×10^{-2}	1.82×10^{-2}	9.41×10^{-3}	5.02×10^{-3}	1.72×10^{-3}
2.405	2.09×10^{-2}	1.10×10^{-2}	6.01×10^{-3}	3.24×10^{-3}	1.18×10^{-3}
2.865	1.72×10^{-2}	8.62×10^{-3}	4.30×10^{-3}	2.34×10^{-3}	9.38×10^{-4}
3.383	1.08×10^{-2}	5.99×10^{-3}	3.01×10^{-3}	1.49×10^{-3}	4.42×10^{-4}
3.956	5.13×10^{-3}	3.30×10^{-3}	1.68×10^{-3}	9.40×10^{-4}	3.84×10^{-4}
4.587	4.54×10^{-3}	2.06×10^{-3}	8.53×10^{-4}	4.65×10^{-4}	1.52×10^{-4}
5.277	1.16×10^{-3}	7.27×10^{-4}	3.88×10^{-4}	2.18×10^{-4}	8.63×10^{-5}
6.028	9.91×10^{-4}	4.57×10^{-4}	2.43×10^{-4}	1.17×10^{-4}	3.36×10^{-5}

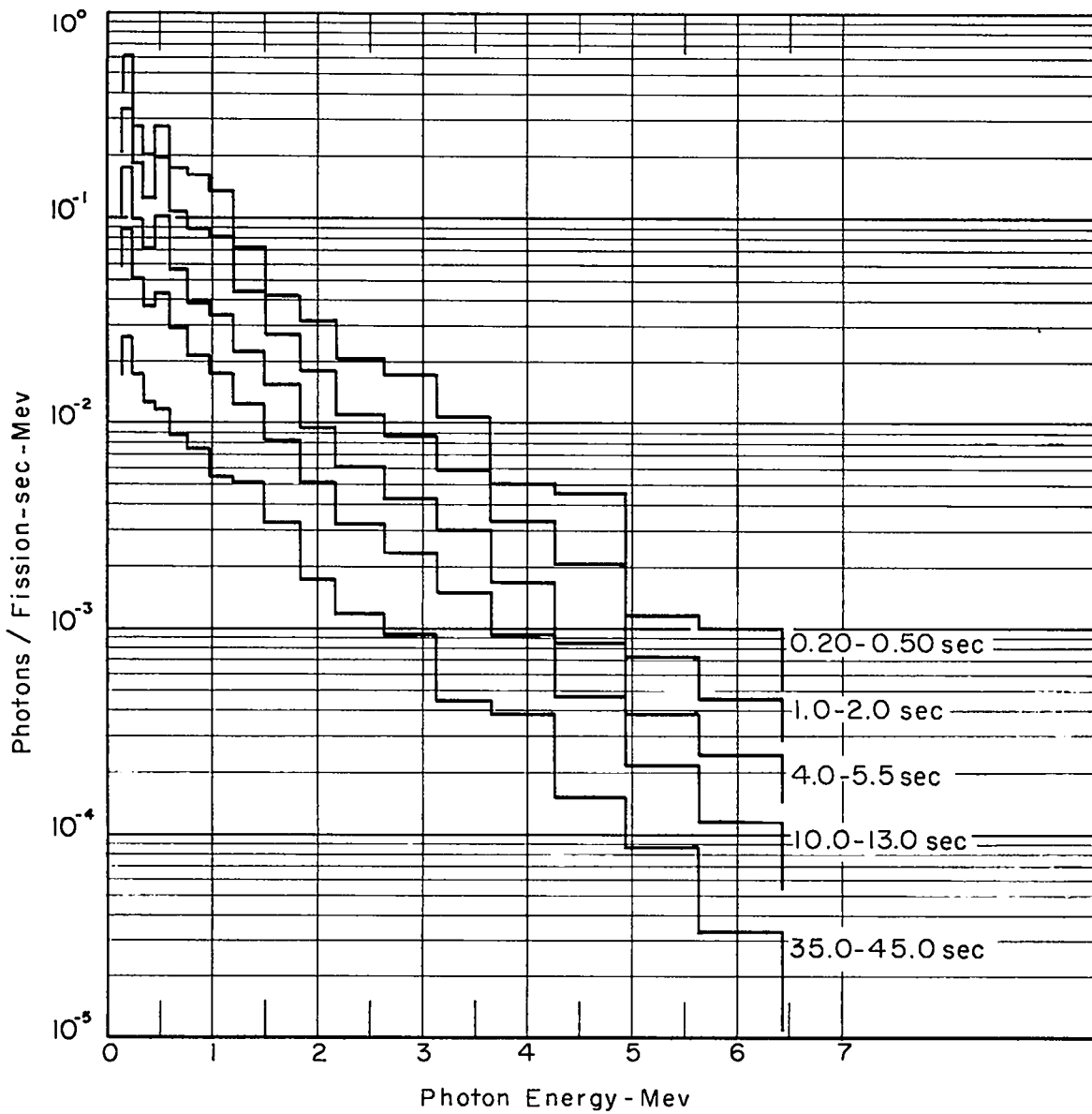


Figure 5. Photon spectra of gammas for different time intervals following U^{233} fission

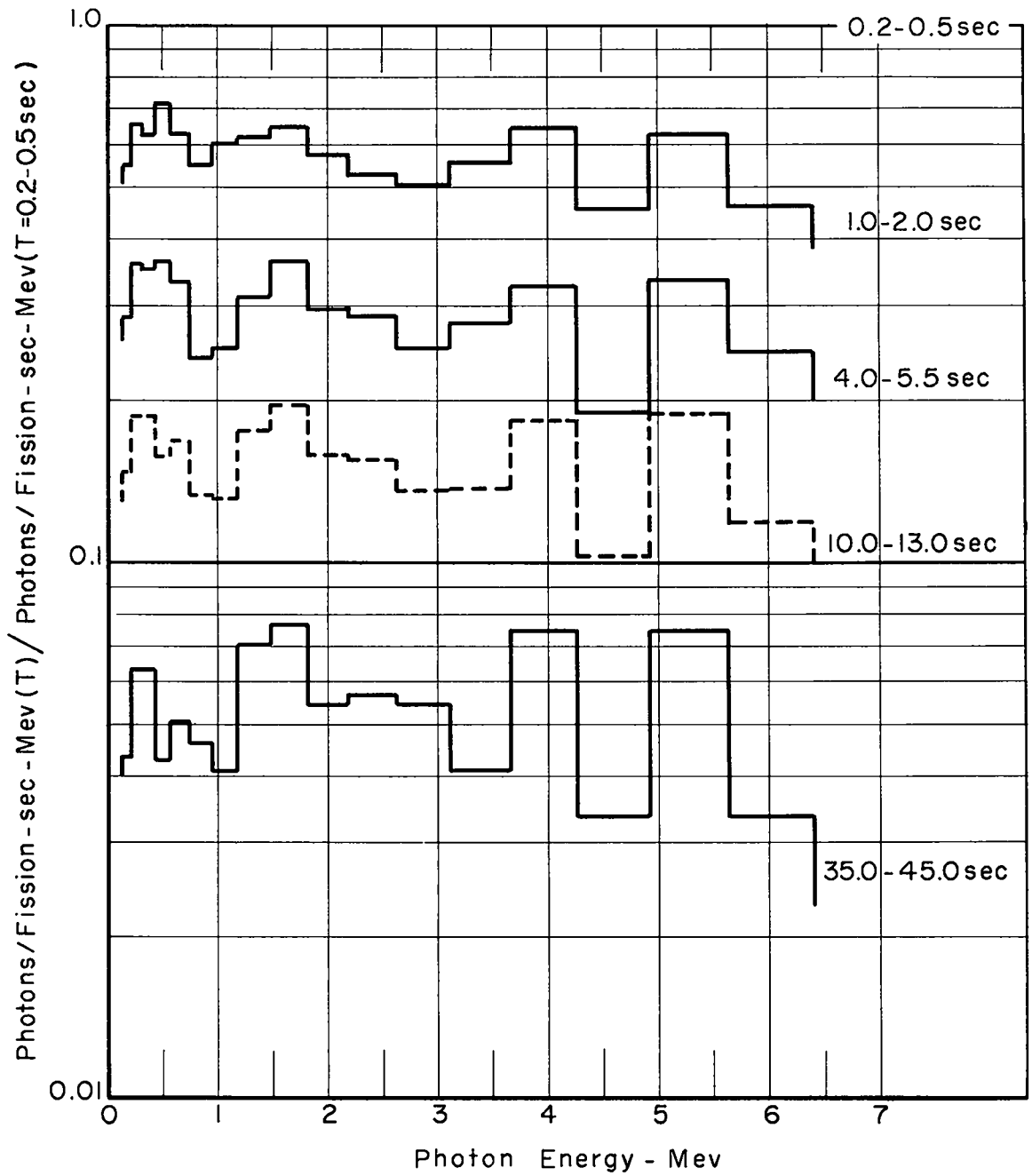


Figure 6. Ratios of U²³³ photon spectra at all time intervals

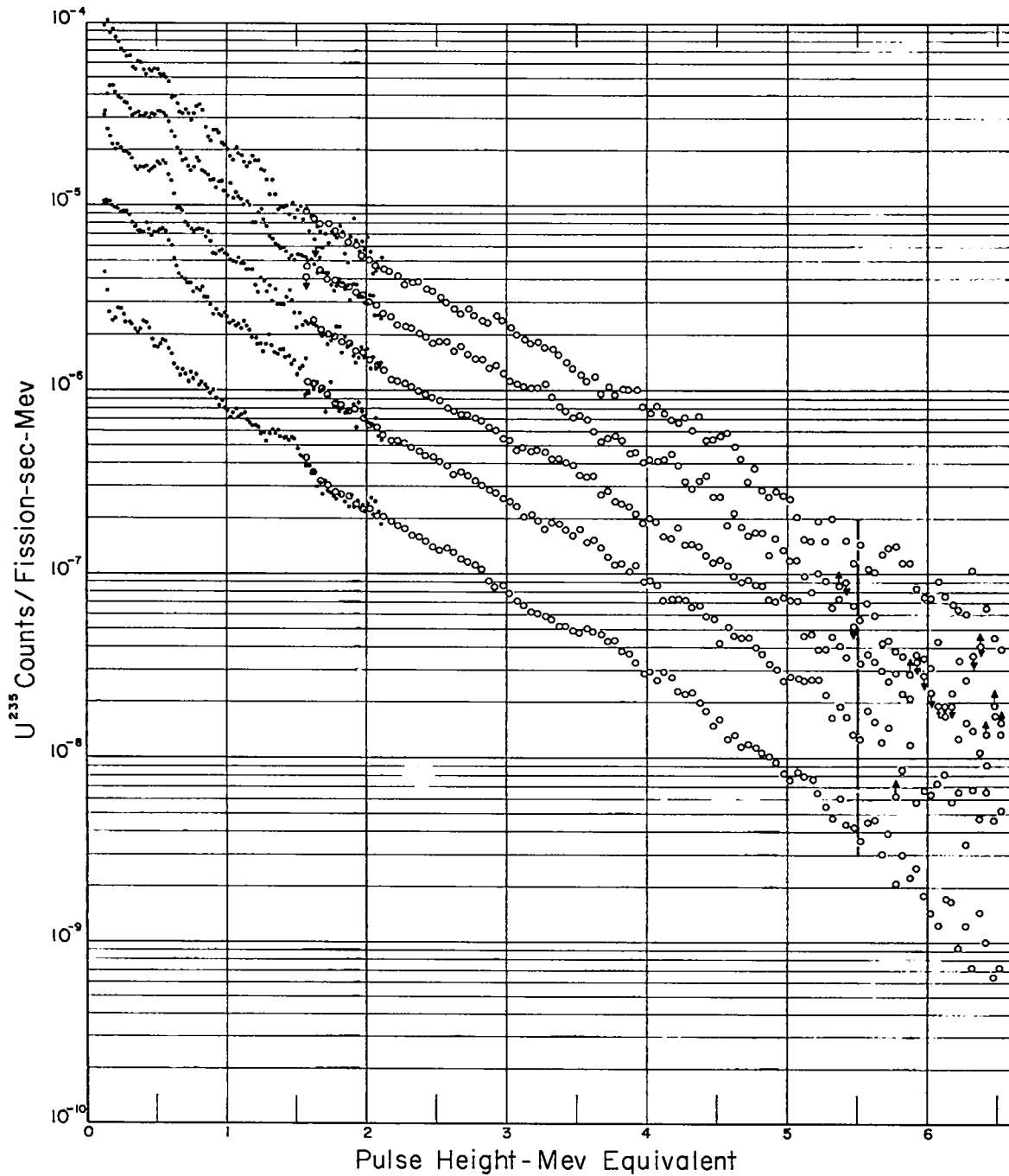


Figure 7. Pulse height distribution of gammas for different time intervals following U^{235} fission

Table 4

Distribution of Photons/Fission-sec-Mev for the
Different Time Intervals Following U²³⁵ Fission

Interval Midpoint (Mev)	0.2 - 0.5 sec	1.0 - 2.0 sec	4.0 - 5.5 sec	10 - 13 sec	35 - 45 sec
0.175	1.33×10^0	5.37×10^{-1}	3.20×10^{-1}	1.45×10^{-1}	3.85×10^{-2}
0.261	6.87×10^{-1}	3.37×10^{-1}	1.95×10^{-1}	9.30×10^{-2}	2.48×10^{-2}
0.369	4.60×10^{-1}	2.35×10^{-1}	1.31×10^{-1}	6.17×10^{-2}	1.86×10^{-2}
0.502	4.92×10^{-1}	2.98×10^{-1}	1.65×10^{-1}	7.19×10^{-2}	1.67×10^{-2}
0.662	3.28×10^{-1}	1.94×10^{-1}	1.03×10^{-1}	4.66×10^{-2}	1.19×10^{-2}
0.852	3.00×10^{-1}	1.53×10^{-1}	6.50×10^{-2}	3.10×10^{-2}	1.03×10^{-2}
1.075	2.18×10^{-1}	1.33×10^{-1}	5.62×10^{-2}	2.55×10^{-2}	7.91×10^{-3}
1.337	1.45×10^{-1}	7.72×10^{-2}	3.73×10^{-2}	1.95×10^{-2}	6.84×10^{-3}
1.643	8.68×10^{-2}	5.06×10^{-2}	2.66×10^{-2}	1.20×10^{-2}	4.06×10^{-3}
1.998	6.17×10^{-2}	3.46×10^{-2}	1.69×10^{-2}	7.56×10^{-3}	2.47×10^{-3}
2.405	3.86×10^{-2}	2.17×10^{-2}	1.09×10^{-2}	5.12×10^{-3}	1.78×10^{-3}
2.865	2.87×10^{-2}	1.62×10^{-2}	7.12×10^{-3}	3.51×10^{-3}	1.26×10^{-3}
3.383	1.85×10^{-2}	1.07×10^{-2}	5.29×10^{-3}	2.19×10^{-3}	6.10×10^{-4}
3.956	9.71×10^{-3}	5.74×10^{-3}	2.64×10^{-3}	1.24×10^{-3}	4.60×10^{-4}
4.587	7.96×10^{-3}	3.37×10^{-3}	1.55×10^{-3}	7.12×10^{-4}	2.12×10^{-4}
5.277	1.67×10^{-3}	1.21×10^{-3}	5.86×10^{-4}	2.94×10^{-4}	8.95×10^{-5}
6.028	1.94×10^{-3}	7.20×10^{-4}	4.54×10^{-4}	1.65×10^{-4}	4.16×10^{-5}

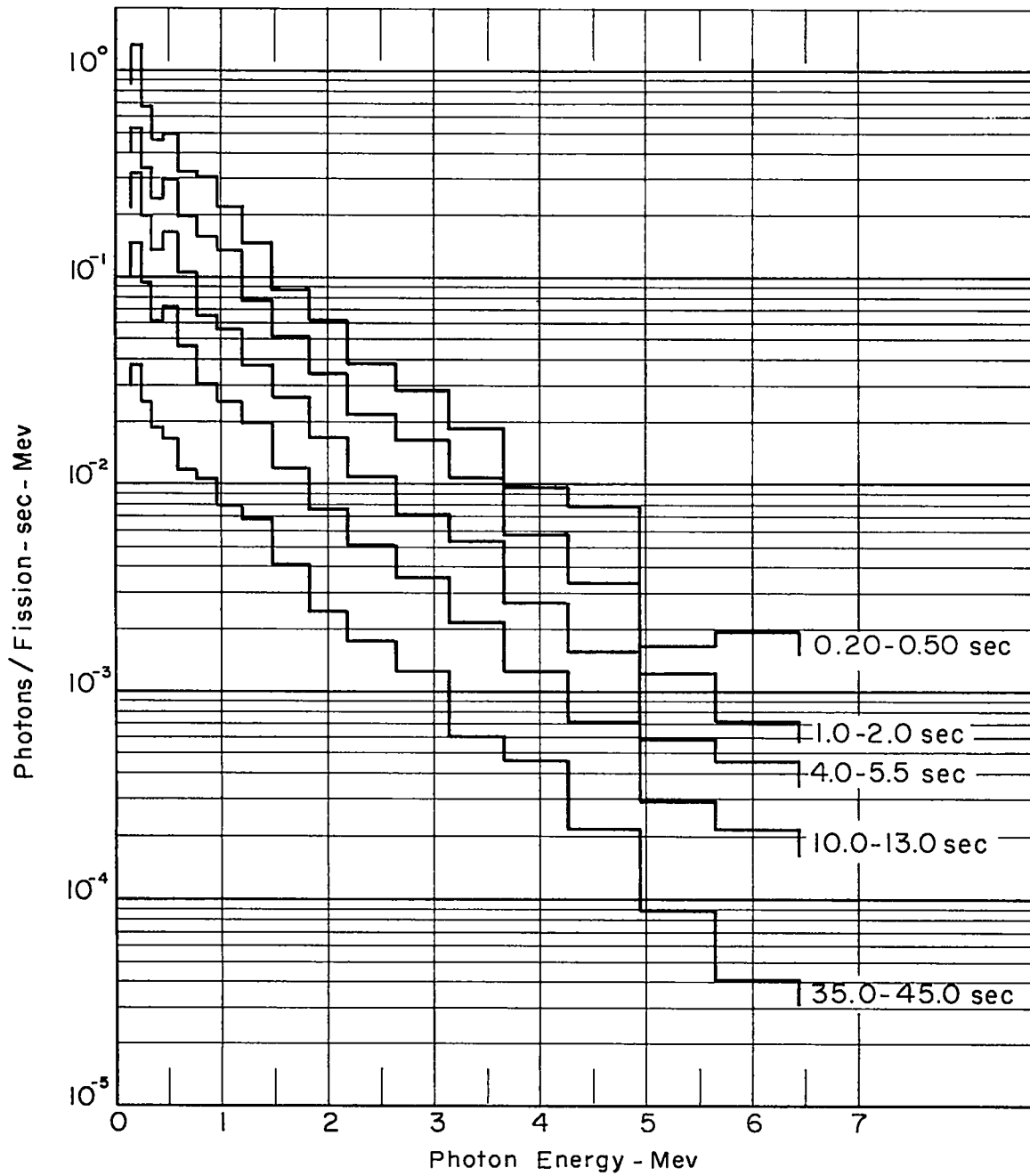


Figure 8. Photon spectra of gammas for different time intervals following U^{235} fission

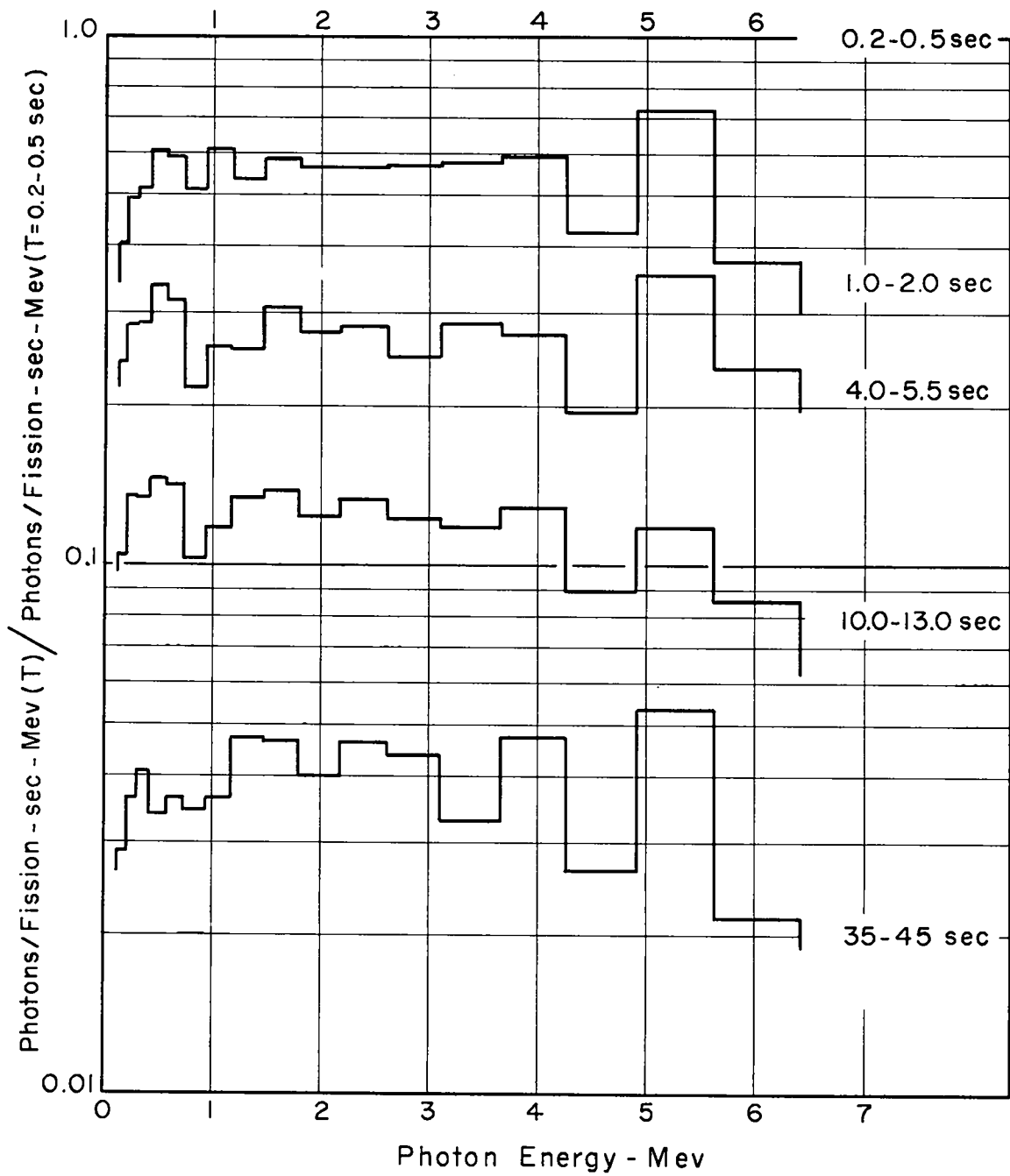


Figure 9. Ratios of U²³⁵ photon spectra at all time intervals

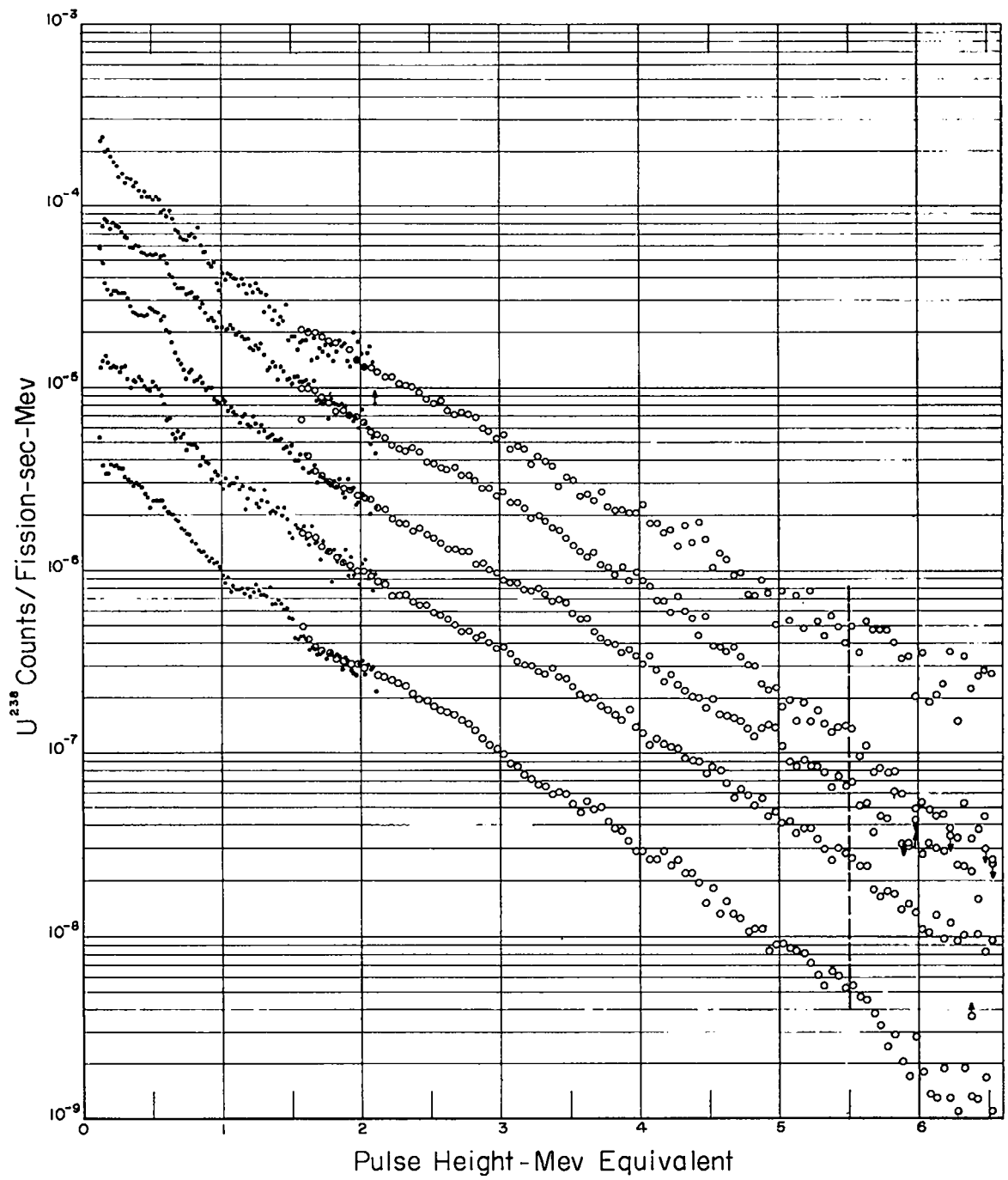


Figure 10. Pulse height distribution of gammas for different time intervals following U^{238} fission

Table 5

Distribution of Photons/Fission-sec-Mev for the
Different Time Intervals Following U²³⁸ Fission

Interval Midpoint (Mev)	0.2 - 0.5 sec	1 - 2 sec	4.0 - 5.5 sec	10.0 - 13.0 sec	35.0 - 45.0 sec
0.175	3.45×10^0	1.08×10^0	6.66×10^{-1}	2.18×10^{-1}	5.28×10^{-2}
0.261	1.61×10^0	7.62×10^{-1}	3.52×10^{-1}	1.33×10^{-1}	3.86×10^{-2}
0.369	1.14×10^0	4.93×10^{-1}	2.35×10^{-1}	9.93×10^{-2}	2.65×10^{-2}
0.502	9.86×10^{-1}	4.77×10^{-1}	2.59×10^{-1}	1.04×10^{-1}	2.21×10^{-2}
0.662	7.39×10^{-1}	3.80×10^{-1}	1.75×10^{-1}	5.91×10^{-2}	1.90×10^{-2}
0.852	6.27×10^{-1}	2.83×10^{-1}	1.08×10^{-1}	4.18×10^{-2}	1.33×10^{-2}
1.075	4.26×10^{-1}	2.33×10^{-1}	8.10×10^{-2}	3.00×10^{-2}	9.05×10^{-3}
1.337	3.32×10^{-1}	1.59×10^{-1}	6.26×10^{-2}	2.65×10^{-2}	8.71×10^{-3}
1.643	1.80×10^{-1}	1.09×10^{-1}	4.41×10^{-2}	1.62×10^{-2}	4.40×10^{-3}
1.998	1.59×10^{-1}	7.16×10^{-2}	2.82×10^{-2}	1.12×10^{-2}	3.11×10^{-3}
2.405	1.08×10^{-1}	4.60×10^{-2}	1.86×10^{-2}	7.43×10^{-3}	2.47×10^{-3}
2.865	7.76×10^{-2}	3.70×10^{-2}	1.24×10^{-2}	5.07×10^{-3}	1.69×10^{-3}
3.383	4.33×10^{-2}	2.15×10^{-2}	8.98×10^{-3}	3.29×10^{-3}	7.70×10^{-4}
3.956	2.30×10^{-2}	1.19×10^{-2}	4.52×10^{-3}	1.83×10^{-3}	4.58×10^{-4}
4.587	1.76×10^{-2}	6.32×10^{-3}	2.35×10^{-3}	1.03×10^{-3}	2.21×10^{-4}
5.277	4.98×10^{-3}	2.20×10^{-3}	1.04×10^{-3}	4.50×10^{-4}	1.02×10^{-4}
6.028	6.79×10^{-3}	1.16×10^{-3}	7.59×10^{-4}	2.73×10^{-4}	4.44×10^{-5}

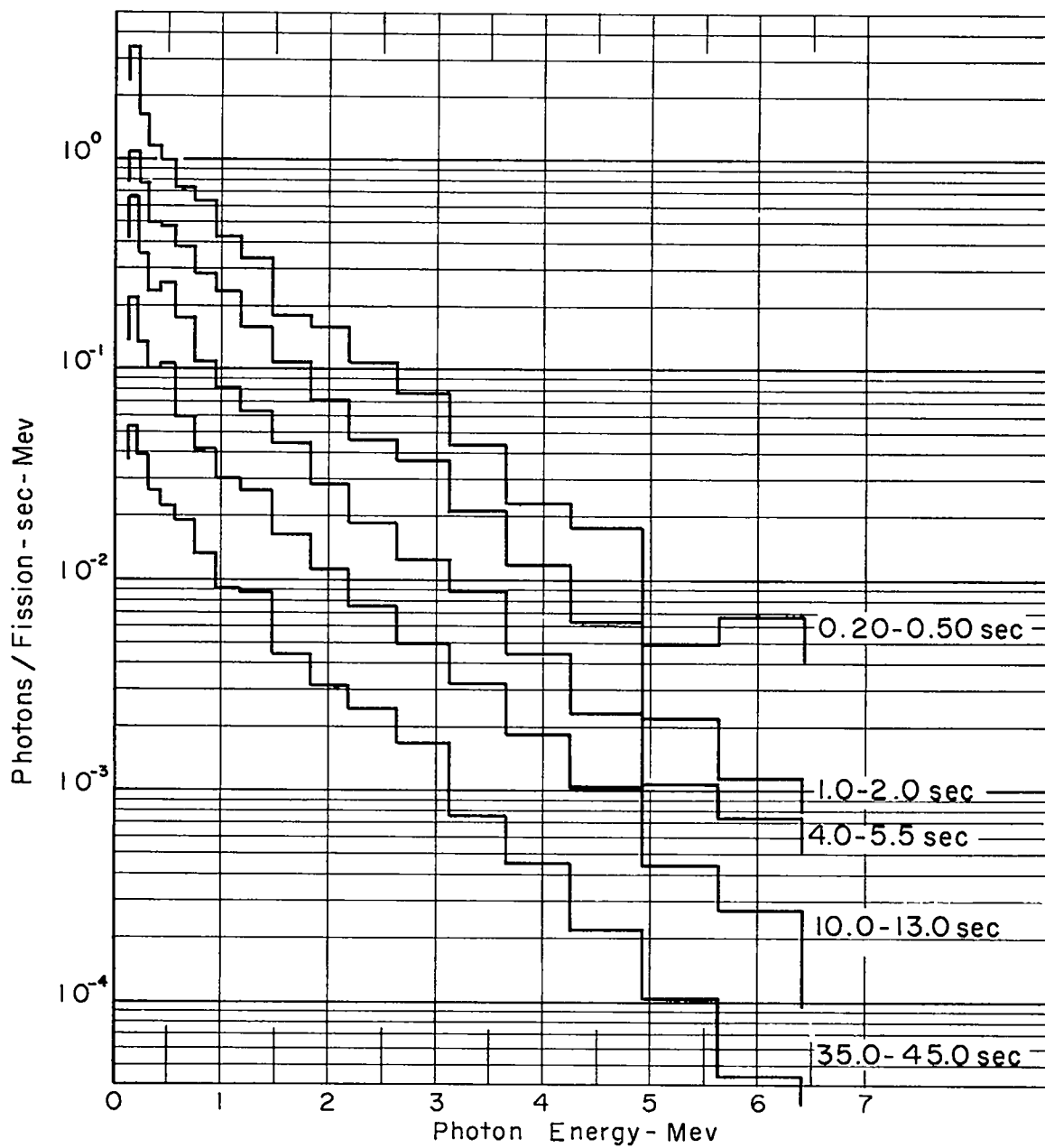


Figure 11. Photon spectra of gammas for different time intervals following U^{238} fission

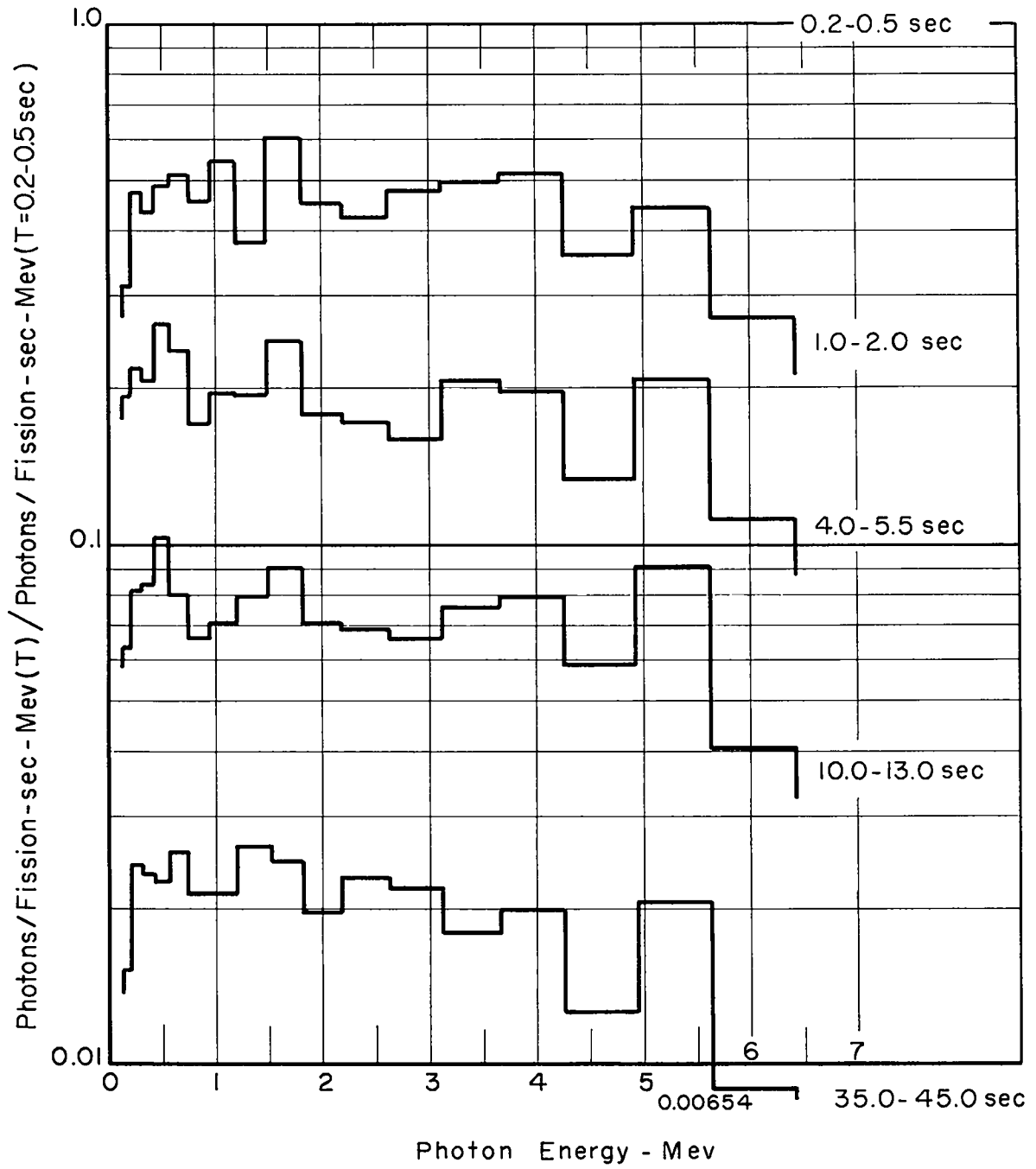


Figure 12. Ratios of U^{238} photon spectra at all time intervals

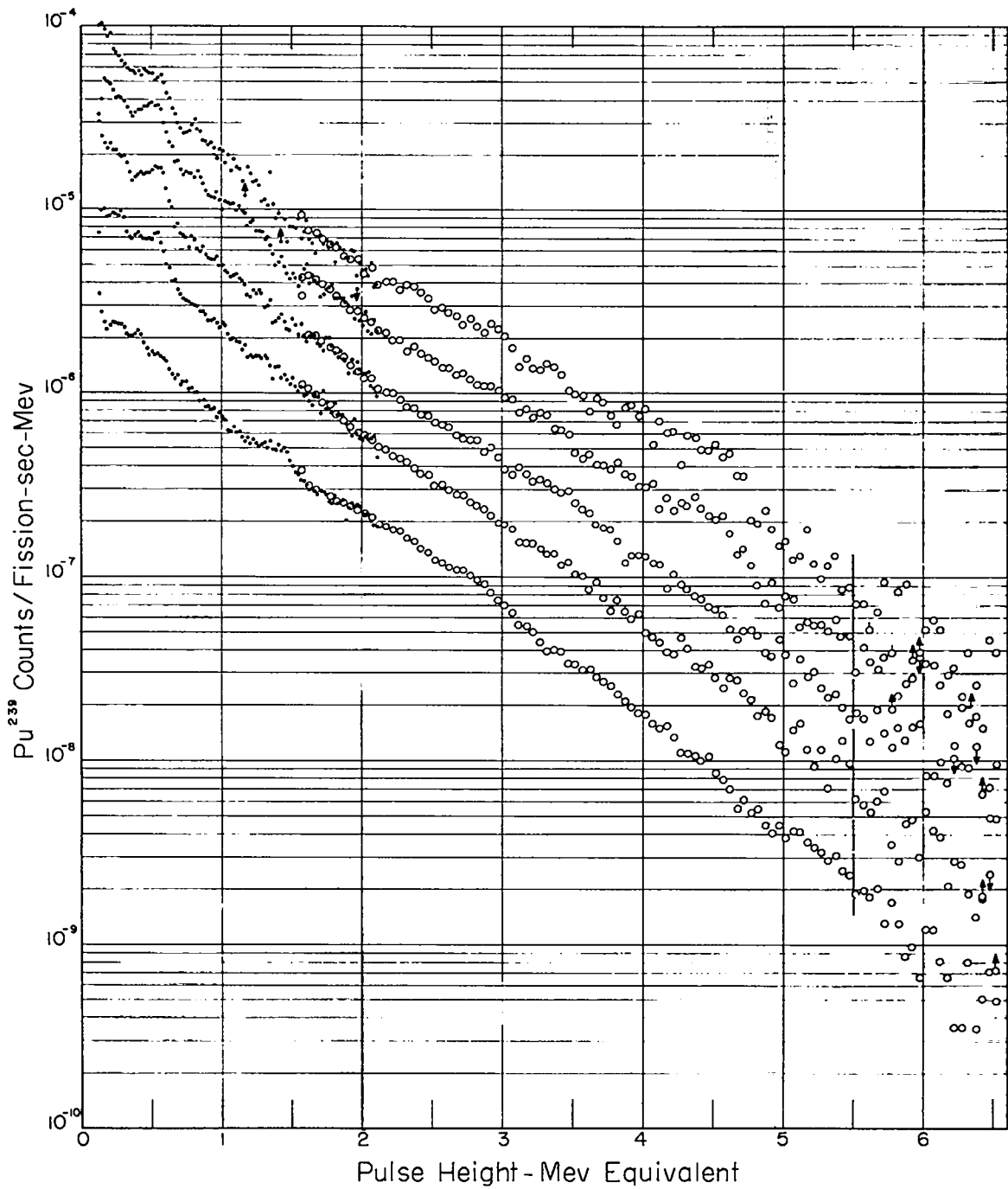


Figure 13. Pulse height distribution of gammas for different time intervals following Pu^{239} fission

Table 6

Distribution of Photons/Fission-sec-Mev for the
Different Time Intervals Following Pu²³⁹ Fission

Interval Midpoint (Mev)	0.2 - 0.5 sec	1.0 - 2.0 sec	4.0 - 5.5 sec	10.0 - 13.0 sec	35.0 - 45.0 sec
0.175	1.43×10^0	6.02×10^{-1}	3.45×10^{-1}	1.43×10^{-1}	3.56×10^{-2}
0.261	6.84×10^{-1}	3.97×10^{-1}	2.10×10^{-1}	1.05×10^{-1}	2.38×10^{-2}
0.369	4.60×10^{-1}	2.72×10^{-1}	1.33×10^{-1}	6.50×10^{-2}	1.87×10^{-2}
0.502	5.35×10^{-1}	3.91×10^{-1}	1.75×10^{-1}	7.38×10^{-2}	1.54×10^{-2}
0.662	3.42×10^{-1}	2.10×10^{-1}	1.07×10^{-1}	4.28×10^{-2}	1.20×10^{-2}
0.852	2.75×10^{-1}	1.45×10^{-1}	6.17×10^{-2}	2.83×10^{-2}	9.30×10^{-3}
1.075	2.12×10^{-1}	1.27×10^{-1}	5.11×10^{-2}	2.30×10^{-2}	6.79×10^{-3}
1.337	1.23×10^{-1}	7.71×10^{-2}	3.28×10^{-2}	1.64×10^{-2}	6.03×10^{-3}
1.643	8.13×10^{-2}	4.60×10^{-2}	2.56×10^{-2}	1.15×10^{-2}	3.50×10^{-3}
1.998	5.28×10^{-2}	3.10×10^{-2}	1.53×10^{-2}	7.02×10^{-3}	2.47×10^{-3}
2.405	3.89×10^{-2}	1.87×10^{-2}	9.28×10^{-3}	4.46×10^{-3}	1.74×10^{-3}
2.865	2.97×10^{-2}	1.37×10^{-2}	5.93×10^{-3}	2.96×10^{-3}	1.25×10^{-3}
3.383	1.46×10^{-2}	8.40×10^{-3}	4.10×10^{-3}	1.69×10^{-3}	5.28×10^{-4}
3.956	8.37×10^{-3}	3.79×10^{-3}	1.81×10^{-3}	7.60×10^{-4}	2.85×10^{-4}
4.587	6.77×10^{-3}	2.95×10^{-3}	9.10×10^{-4}	4.30×10^{-4}	1.14×10^{-4}
5.277	1.42×10^{-3}	6.54×10^{-4}	3.14×10^{-4}	1.47×10^{-4}	4.62×10^{-5}
6.028	1.04×10^{-3}	5.36×10^{-4}	2.47×10^{-4}	7.88×10^{-5}	2.07×10^{-5}

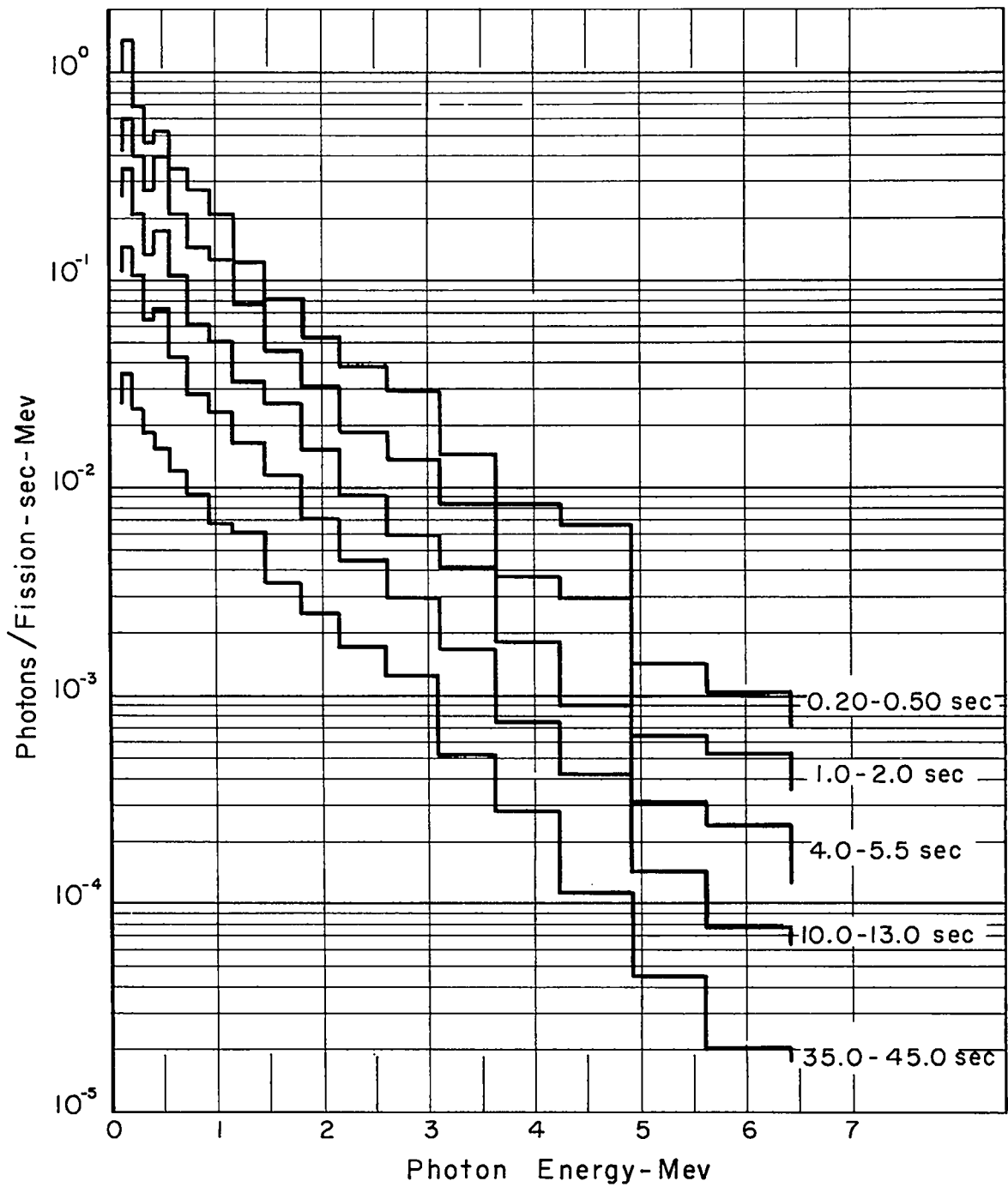


Figure 14. Photon spectra of gammas for different time intervals following Pu^{239} fission

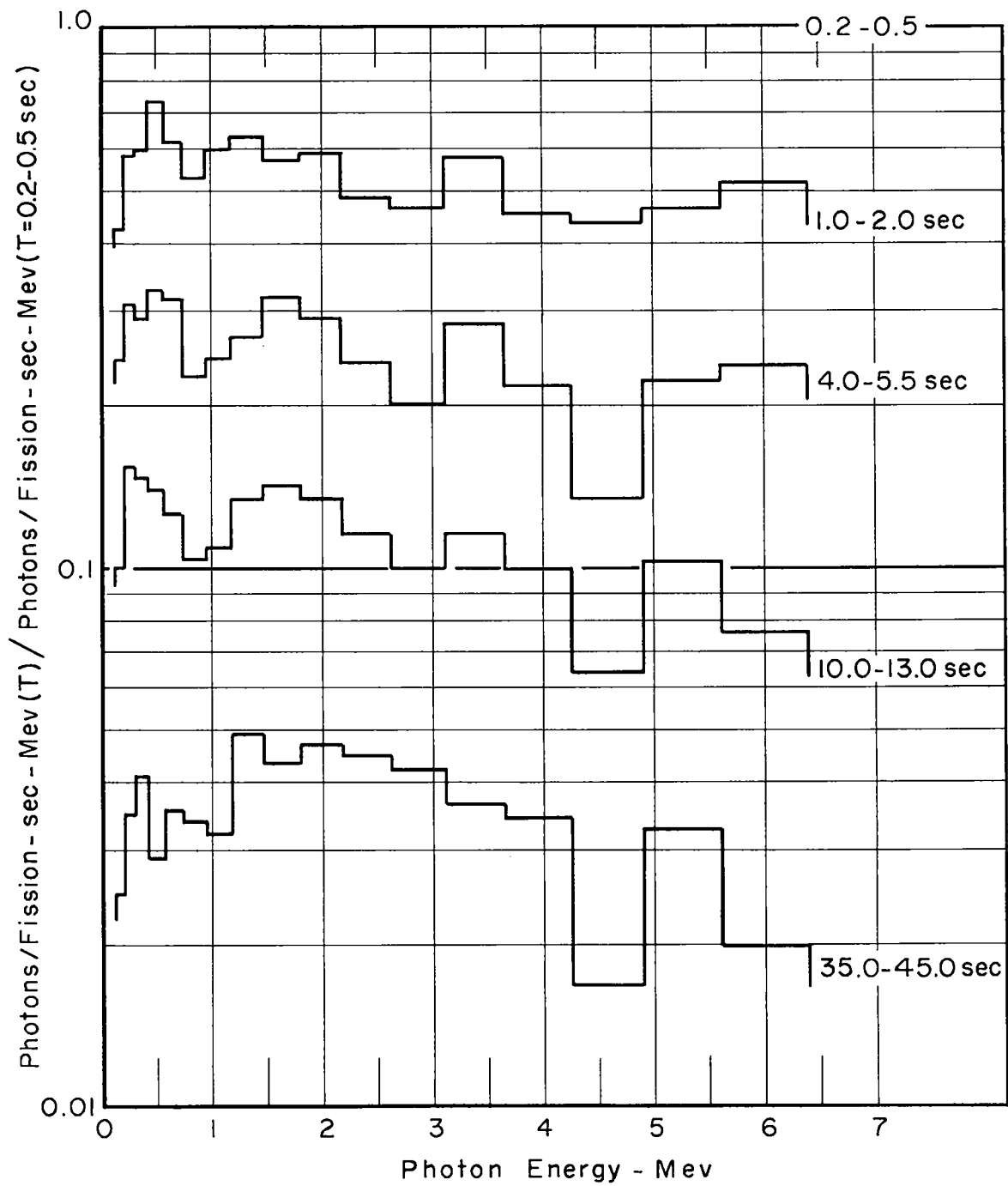


Figure 15. Ratios of Pu^{239} photon spectra at all time intervals

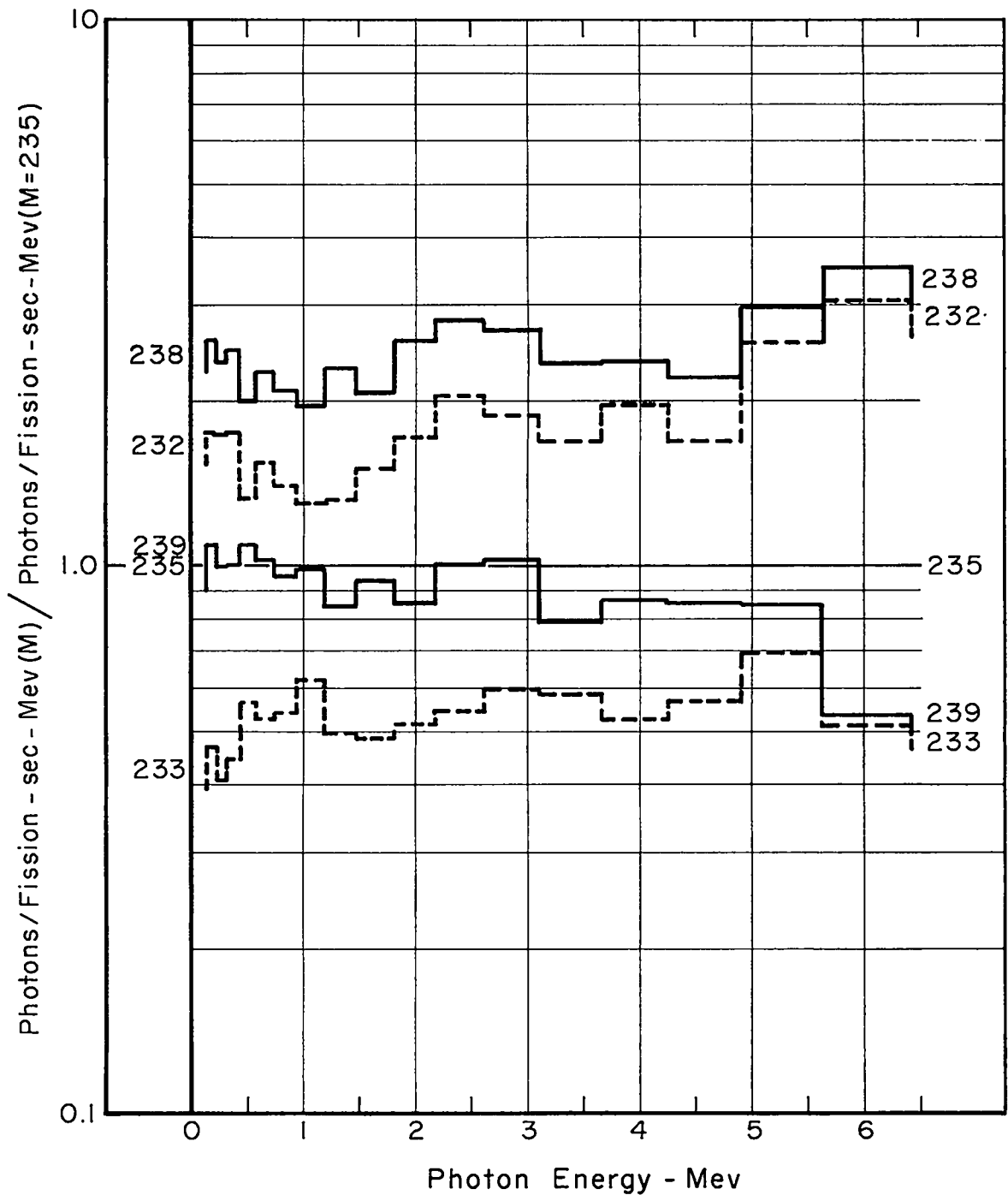


Figure 16. Ratios of photon spectra for all isotopes at 0.2 to 0.5 sec interval

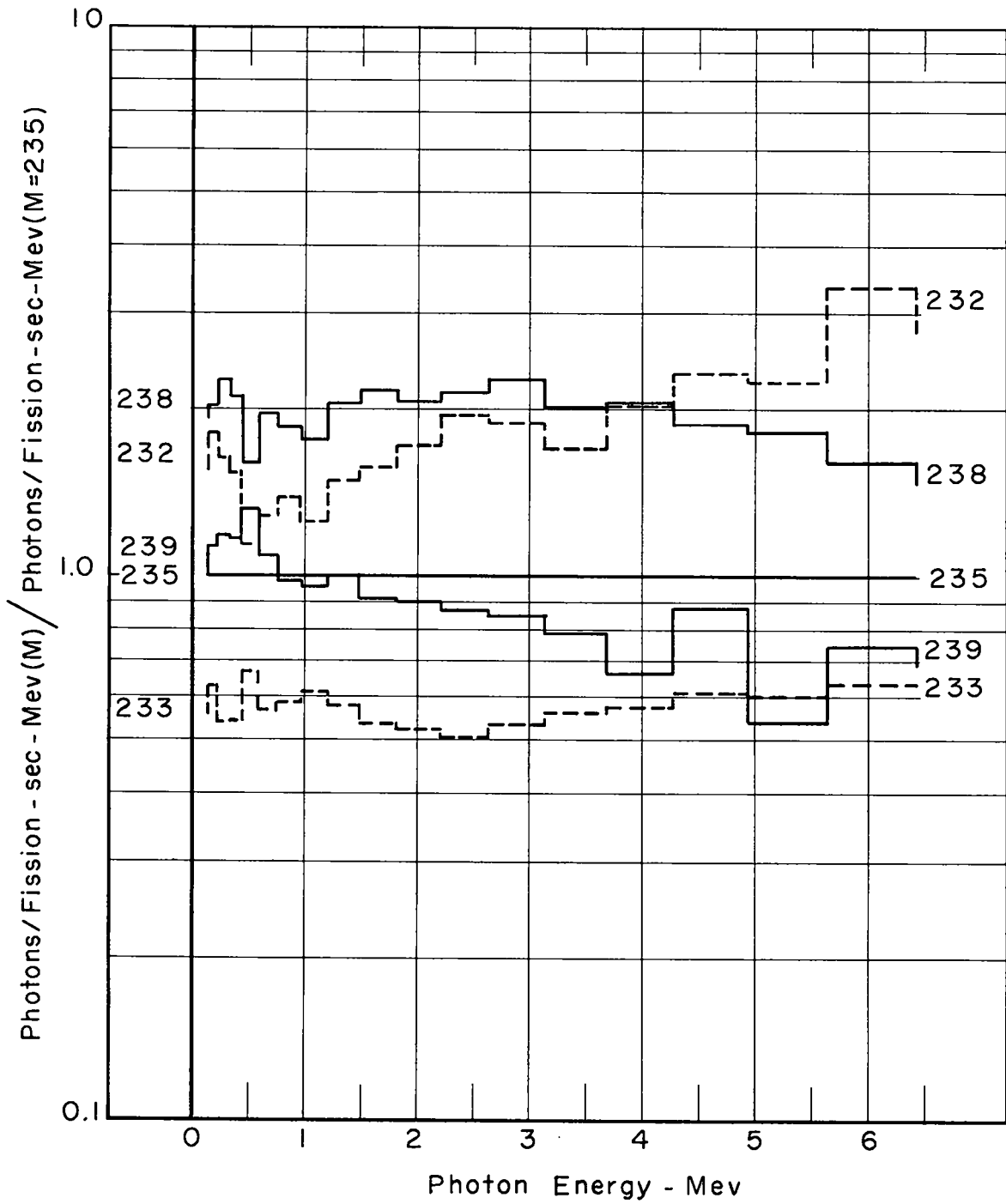


Figure 17. Ratios of photon spectra for all isotopes at 1.0 to 2.0 sec interval

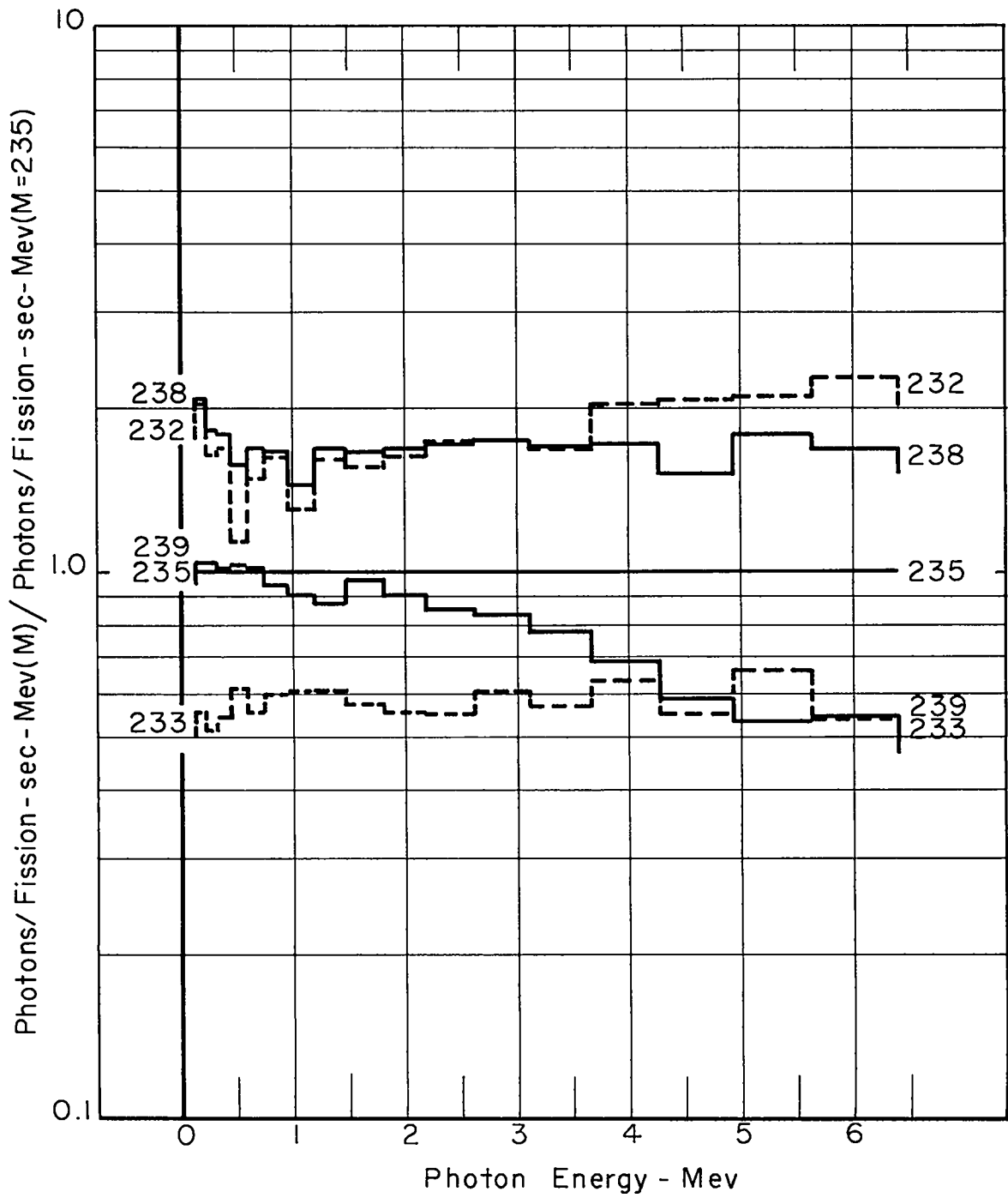


Figure 18. Ratios of photon spectra for all isotopes at 4.0 to 5.5 sec interval

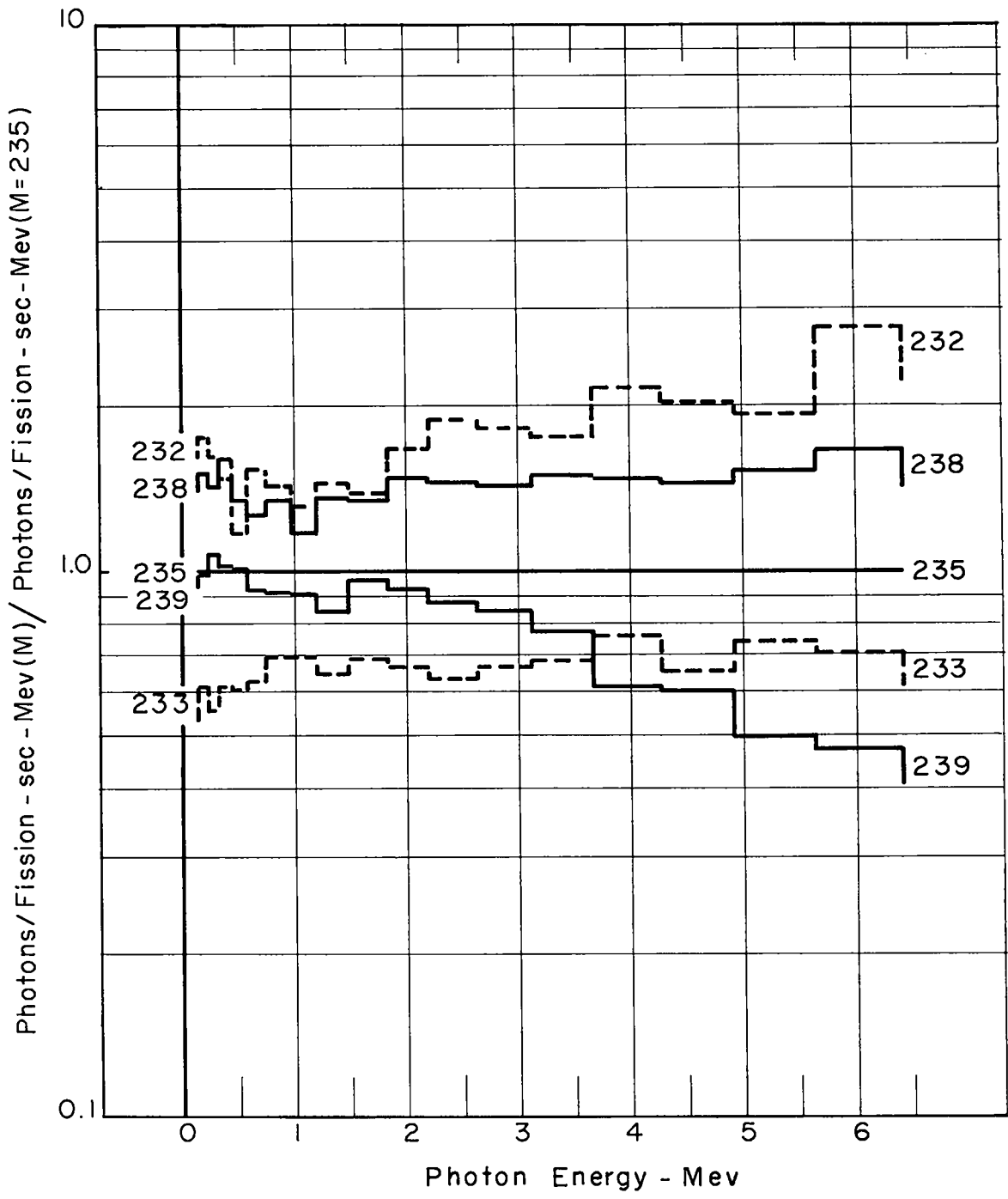


Figure 19. Ratios of photon spectra for all isotopes at 10.0 to 13.0 sec interval

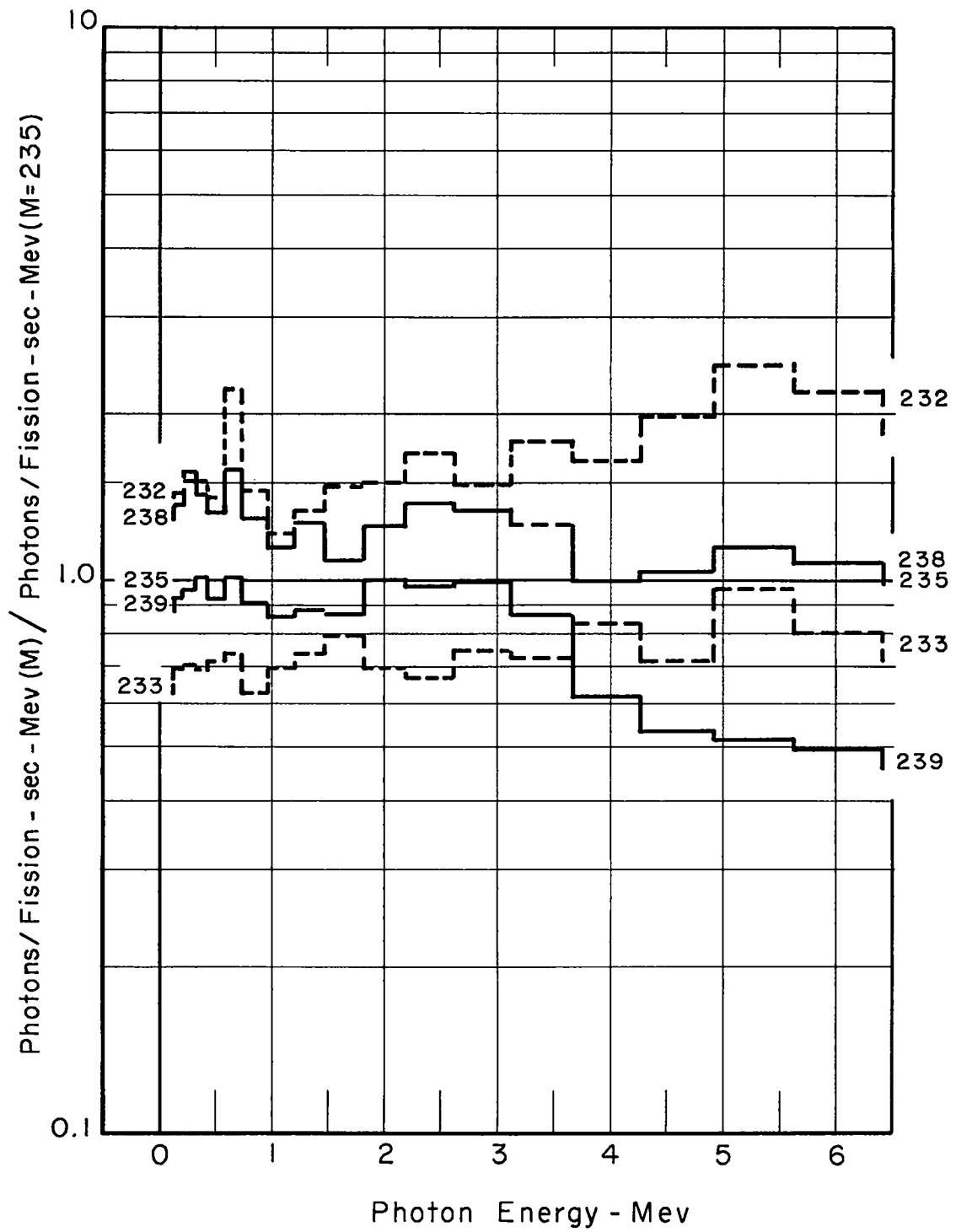


Figure 20. Ratios of photon spectra for all isotopes at 35.0 to 45.0 sec interval

Table 7

Results of Delayed Gamma Spectra Integrated
over Energy for Different Time Intervals
after Fission

<u>Isotope</u>	<u>Time Interval</u>	<u>Photons/ Fission-Sec</u>	<u>Mev/ Fission-Sec</u>	<u>Mev/ Photon</u>
232	0.2-0.5 sec	0.966	0.916	0.948
	1.0-2.0 sec	0.487	0.501	1.029
	4.0-5.5 sec	0.267	0.246	0.921
	10.0-13.0 sec	0.118	0.112	0.949
	35.0-45.0 sec	0.0343	0.0343	1.000
233	0.2-0.5 sec	0.312	0.303	0.971
	1.0-2.0 sec	0.189	0.177	0.937
	4.0-5.5 sec	0.0958	0.0885	0.924
	10.0-13.0 sec	0.0490	0.0465	0.949
	35.0-45.0 sec	0.0161	0.0161	1.000
235	0.2-0.5 sec	0.613	0.564	0.920
	1.0-2.0 sec	0.324	0.311	0.960
	4.0-5.5 sec	0.169	0.153	0.905
	10.0-13.0 sec	0.0775	0.0706	0.911
	35.0-45.0 sec	0.0225	0.0221	0.982
238	0.2-0.5 sec	1.42	1.32	0.930
	1.0-2.0 sec	0.636	0.618	0.972
	4.0-5.5 sec	0.289	0.255	0.882
	10.0-13.0 sec	0.110	0.0988	0.898
	35.0-45.0 sec	0.0303	0.0281	0.927
239	0.2-0.5 sec	0.608	0.529	0.870
	1.0-2.0 sec	0.344	0.296	0.860
	4.0-5.5 sec	0.166	0.138	0.831
	10.0-13.0 sec	0.0746	0.0624	0.836
	35.0-45.0 sec	0.0209	0.0197	0.943

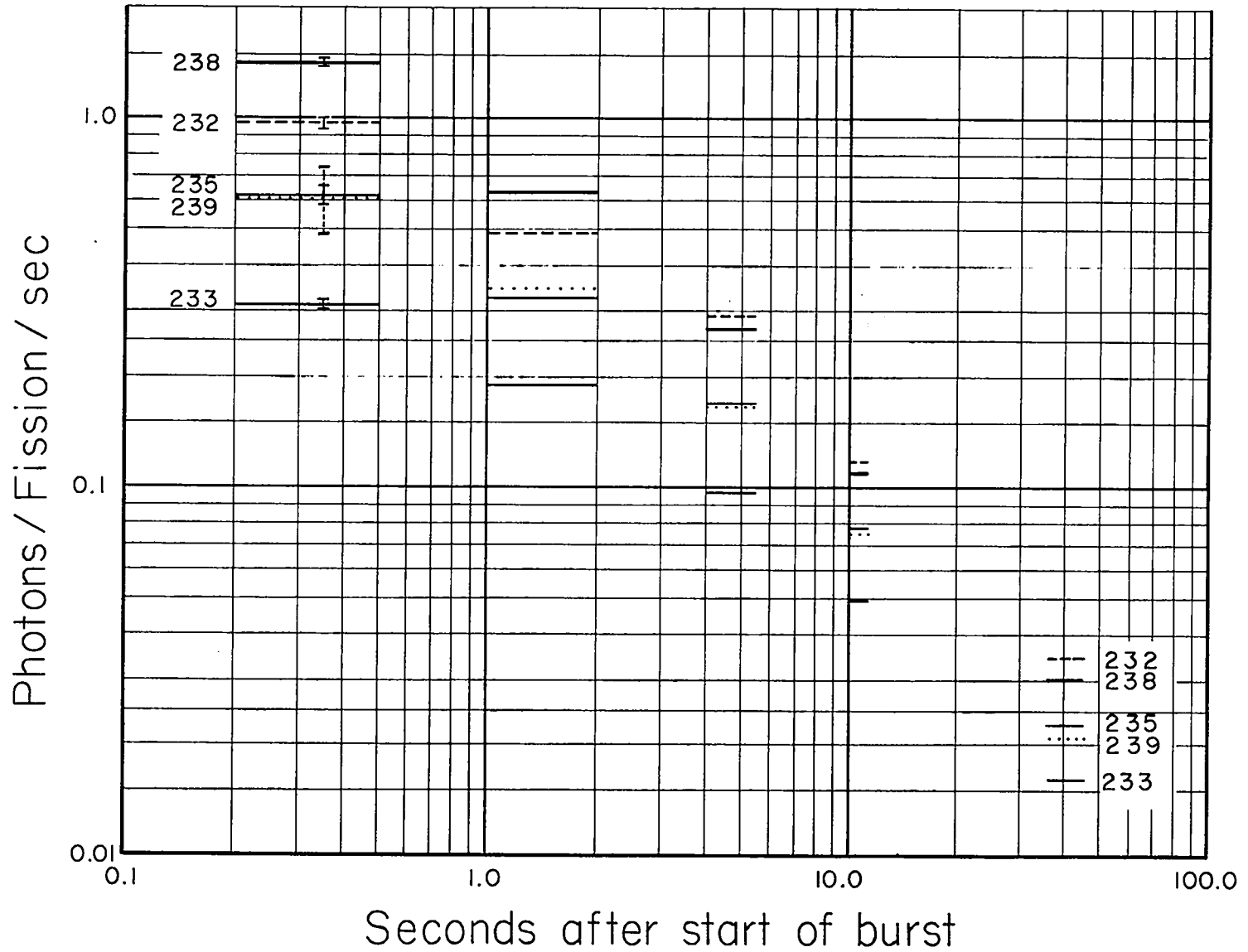


Figure 21. Comparison of photon spectra integrated over energy for the different time intervals after fission

Table 8

Results of Delayed Gamma Spectra Integrated over
Energy and Time from 0.20 to 45.0 sec after Fission

<u>Isotope</u>	<u>Photons/Fission</u>	<u>Mev/Fission</u>	<u>Mev/Photon</u>
232	5.07	5.04	0.994
233	2.02	1.97	0.975
235	3.31	3.18	0.961
238	5.50	5.08	0.924
239	3.26	2.86	0.877