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THE ABSOLUTE SPECTRUM OF PHOTONS EMITTED IN
COINCIDENCE WITH THERMAL-NEUTRON
FISSION OF URANIUM-235*

R. W. Peelle and F. C. Maienschein[†]

*Analysis supported by the Los Alamos Scientific Laboratory.

[†]Joined by T. A. Love particularly for the experimental work,
by R. O. Chester for characterization of the response func-
tions, and by W. Zobel for the spectrum unscrambling.

OAK RIDGE NATIONAL LABORATORY

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Neutron Physics Division

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APRIL 1970

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THE ABSOLUTE SPECTRUM OF PHOTONS EMITTED IN COINCIDENCE
WITH THERMAL-NEUTRON FISSION OF URANIUM-235

ABSTRACT

Data obtained earlier have been fully analyzed to yield the absolute energy spectrum of prompt photons emitted from the fission of ^{235}U by thermal neutrons. In the measurement, each of three types of NaI(Tl) scintillation spectrometers (single-crystal, Compton, and pair) was operated in coincidence with a fission chamber exposed to thermal neutrons from the Oak Ridge Graphite Reactor or the Bulk Shielding Reactor at the Oak Ridge National Laboratory. The effective coincidence resolving time was ≤ 69 nsec. Detailed and careful construction of the response functions of the spectrometer was based on their exposure to radioactive sources of known disintegration rates. These data were used to "unfold" the measured pulse-height spectra to give the absolute differential energy spectrum and uncertainty. The average number of photons per fission was 8.13 ± 0.35 and the energy release per fission was 7.25 ± 0.26 MeV, both over the energy region from 10 keV to 10.5 MeV. Output spectra are given with an effective resolution only slightly broader than the inherent energy resolution of the spectrometers except at energies above 5 MeV, where the raw pulse-height bins were made wider than the spectrometer resolution to reduce statistical uncertainties. Combinations of the data into four sets of coarser energy groups are also included to simplify use of these data in computations. The results obtained here are in approximate agreement with the measurement of Verbinski et al. in the energy region above 100 keV. From 1.5 to 4 MeV the calculation of Zommer et al. gives results which are surprisingly close to the measurements. The observed total energy release in photon emission per fission is predicted reasonably closely by the Thomas and Grover calculation which takes into account the large angular momentum of the fission fragments.

I. INTRODUCTION

The fission process is accompanied by photon emission on many time scales. Approximately one-half of the energy carried away by the photons is emitted promptly after scission (parting of the fragments) occurs. Conceptually, photon emission could occur before scission but there is no evidence for this.¹ Since the "prompt" photon emission occurs with a delay too short to measure, the definition of prompt has depended on the equipment used in measurements. It has usually varied from a few nsec to a few tens of nsec, but at least one measurement has established an upper limit of 0.05 nsec.² On a time scale of tens of nsec to tens of μ sec, photon emission arises from isomeric transitions in the fission fragments.³⁻⁵ The energy emitted in the isomeric transitions amounts to only a few percent of the total. Finally, for times greater than about one sec, beta decay of the fission fragments leads to the so-called fission-product gamma rays.⁶ In the measurement described in this report, we have attempted to determine the absolute yield of the photons emitted promptly after the fission of ^{235}U by thermal neutrons. Prompt was defined for our spectrometer systems by coincidence resolving times in the range of 50-70 nsec.

The motivation for this measurement originally followed from the importance of the fission gamma rays as a source which must be shielded against in reactor design. For this application, the high-energy portion of the gamma-ray spectrum is of most significance due to greater penetration through the reactor shield.⁷ For heating of reactor components by

¹V. Stavinsky and M. O. Shaker, Nucl. Phys. 62, 667 (1965).

²G. V. Val'skii et al., At. Energ. 18, 223 (1965).

³L. Bridwell, M. E. Wyman, and B. W. Wehring, Phys. Rev. 145, 463 (1966).

⁴R. E. Sund and R. B. Walton, Phys. Rev. 146, 824 (1966).

⁵S. A. E. Johansson, Nucl. Phys. 64, 147 (1965).

⁶F. C. Maienschein, Engineering Compendium on Radiation Shielding, Vol. 1, p. 77 (1968), Springer-Verlag New York, Inc.

⁷H. Goldstein, Fundamental Aspects of Reactor Shielding, Addison-Wesley Publishing Company, Reading, Mass. (1959).

the fission gamma rays, on the other hand, the low-energy portion of the spectrum dominates due to higher peak heat deposition rates.⁸ The other major application of fission, to nuclear explosives, also may lead to interest in the fission gamma-ray spectrum.⁹

The theories of fission, which are highly developed in many respects, have not attempted (with one exception¹⁰) to predict in detail the energy distribution of prompt photon emission. Until recently the predictions of total photon energy release per fission fell short of the observations by up to a factor of two.¹¹⁻¹³ This difficulty may have been resolved by considering the inhibition of neutron emission by the large angular momentum of the fission fragments.¹⁴

We have much earlier published a preliminary analysis of part of the data which are reexamined in this paper.^{15,16} The earlier analysis was preliminary in the sense that further spectrometer calibrations and response functions have now been obtained, more detailed background corrections have been made, and the effects of nonunique spectrometer responses have now been unfolded correctly. Also, a large amount of additional data for $E_\gamma < 5$ MeV has now been included. The preliminary (1962) value for the prompt photon energy release per fission was 7.2 ± 0.8 MeV for $E > 0.3$ MeV.

Previous to the publication of the preliminary analysis of our data,¹⁵ a thesis publication of a measurement at ORNL gave the best indication of the prompt-fission gamma-ray spectrum, with a total prompt photon energy release per fission of about 7.5 MeV.¹⁷ That measurement, however,

⁸H. C. Claiborne, "Survey of Methods for Calculating Gamma-Ray Heating," ORNL-RSIC-8 (June, 1965).

⁹S. Glasstone, The Effects of Nuclear Weapons, USAEC (1964).

¹⁰V. P. Zommer et al., Sov. J. Atomic Energy, 19, 1004 (1965).

¹¹R. B. Leachman, Phys. Rev. 101, 1005 (1956).

¹²J. Terrell, Phys. Rev. 113, 527 (1959).

¹³J. M. Ferguson and P. A. Read, Phys. Rev. 139, B56 (1965).

¹⁴T. D. Thomas and J. R. Grover, Phys. Rev. 159, 980 (1967).

¹⁵F. C. Maienschein et al., Proc. U.N. International Conf. on Peaceful Uses of Atomic Energy, Second Geneva Conference, 15, 366 (1958).

¹⁶R. W. Peelle et al., Pile Neutron Research in Physics, International Atomic Energy Agency, Vienna, p. 273, 1962.

¹⁷R. L. Gamble, Dissertation, University of Texas, 1955.

suffered from uncertainty due to background effects of fission neutrons in the scintillation crystal, and from the requirement to unfold the pulse-height spectrum measured with a single-crystal spectrometer. A more recent absolute measurement was made by Rau,¹⁸ also using a single-crystal spectrometer, to study the energy spectrum between ~ 0.1 and 2.5 MeV. He obtained a prompt photon energy release per fission of 9.51 ± 0.23 MeV for $E > 0.1$ MeV by combining his data with our higher energy data.

As suggested above, the object of the measurement reported here was to determine the absolute spectral yield of prompt photons released in the thermal-neutron-induced fission of ^{235}U . Emphasis was placed on the absolute yield rather than on good energy resolution since sharp lines in the spectrum would tend in any event to be smeared by Doppler broadening ($\sim 4\%$) due to the motion of the emitting fission fragments. An attempt was also made to cover the widest practical energy range in one set of measurements. For these reasons, the present results may remain of interest even after parts of the spectrum, such as the x-ray region below ~ 40 keV, have been remeasured with much narrower energy resolution. The object of the reanalysis has been to include additional data, to extend the energy range, to improve upon the accuracy of our preliminary analysis, and especially to provide a more definitive determination of errors. To describe the reanalysis, this report includes a reasonably detailed description of the experimental apparatus, its calibration, the methods of treating the experimental data including the unfolding process, and the results which were obtained.

¹⁸V. F. E. W. Rau, *Annalen der Phys.* 10, 252 (1963).

II. METHOD AND APPARATUS

In order to distinguish those gamma rays emitted "promptly" in the fission process, each of three gamma-ray spectrometers was operated in coincidence with a fission chamber containing ^{235}U . Thermal neutrons from a reactor caused fissions that were identified by pulses from the fission chamber. The resolving time of the coincidence circuit operated by the fission chamber and the gamma-ray spectrometer (50-70 nsec) provided a definition of "prompt" gamma-ray emission. Two sets of equipment were used: one for gamma-ray energies below 700 keV and another for energies above 500 keV.

A. SPECTROMETER CONFIGURATIONS

At High Energies. Since the initial impetus for these measurements arose from reactor shielding needs, the higher energy region of the spectrum was studied first. Multiple-crystal scintillation spectrometers¹⁹ were used to provide a good peak-to-total ratio in the spectrometer response for gamma-ray energies up to ~ 8 MeV. The low efficiency of this spectrometer type required a variable high-intensity thermal-neutron flux (to $7 \times 10^7 \text{ n}\cdot\text{cm}^{-2}\cdot\text{sec}^{-1}$) incident on the fission chamber. This flux was obtained at the ORNL-BSF thermal column²⁰ with negligible fast-neutron background (see Fig. 1). The poor collimation of the "beam" from this thermal column required the widespread use of lithium shielding to absorb unwanted thermal neutrons without producing secondary gamma rays. Gamma rays from the fission chamber passed through the collimator to the (smaller) "center" crystal of the Compton spectrometer shown in Fig. 1 or to the center crystal of the pair spectrometer. A description of these spectrometers is given in Section II-C. One layer of lithium metal (~ 1 in. thick, contained between 1/16 in. stainless-steel walls) completely

¹⁹T. H. Braid, Scintillation Spectroscopy of Gamma Radiation, S. M. Shafroth Ed., Chapt. V., "Compton Spectrometers," Gordon and Breach, N. Y., 1967; S. A. E. Johansson, *Nature* **166**, 794 (1960); J. K. Bair and F. C. Maienschein, *Rev. Sci. Instr.* **22**, 343 (1951).

²⁰E. G. Silver, "Measurements of the Thermal-Neutron Flux from the BSF Thermal Column," in ORNL-2018, p. 39-42 (Sept. 10, 1956).

Fig. 1. Apparatus for High-Energy Gamma-Ray Measurements. The Compton spectrometer is shown in place. The pair spectrometer is shown in the insert.

surrounded the spectrometer and thus the gamma rays had to pass through it. All response functions measured with monoenergetic gamma-ray sources (see Section III) also included this lithium, so it had no net effect on the measured gamma-ray spectrum from fission.

At Low Energies. For energies below 700 keV, a single-crystal scintillation spectrometer was used since the peak-to-total ratio was adequate (> 0.5 for energies < 500 keV). The greater efficiency of this type of spectrometer allowed the use of time-of-flight rejection of backgrounds due to fission neutrons over a flight path of 3.42 m (see Fig. 2). Even with this large fission-chamber-to-spectrometer separation, it was possible to use a lower intensity (10^6 n·cm⁻²·sec⁻¹) but well-collimated neutron beam (No. 57N) from the ORNL Graphite Reactor to induce fissions in a fission chamber.

In order to measure gamma rays with energies as low as 10 keV, the mass of materials between the fission chamber and spectrometer was minimized and carefully determined. In addition to 55.5 mg/cm² of He, foils of Mylar (7.4 mg/cm²) and Al (28.7 mg/cm²) and ~ 23 mg/cm² of MgO reflective coating for the NaI crystal were in the gamma-ray path. Corrections were made for absorption in these materials as well as for the components of the fission chamber. (See Section III-B.)

The lead and lithiated paraffin shielding indicated in Fig. 2 reduced the room background to an unimportant level.

B. FISSION-CHAMBER SYSTEMS

For the high-energy measurements, a spiral fission chamber²¹ containing 230 mg of 99.4% ²³⁵U was used. The cylindrical active volume was ~ 1 -cm diam by 1-cm high. The fission counting rates varied from 33,000 to 94,000 cts·sec⁻¹.

The active portion of the fission chamber for the low-energy measurements consisted of 3 parallel aluminum plates of 5.1-cm diam coated

²¹B. Rossi and H. H. Staub, Ionization Chambers and Counters, McGraw-Hill, New York (1949), p. 210, and ORNL design Q-1534.

Fig. 2. Apparatus for Low-Energy Gamma-Ray Measurements.

on both sides over an area of 3.80×1.33 cm with ~ 0.65 mg/cm² of 95% ²³⁵U. The total ²³⁵U content was 19.2 mg. The counting rate in this chamber was $\sim 24,000$ cts.sec⁻¹. The neutron beam was uniform across the three plates to within 5% as determined by counting of the ¹³⁷Cs fission product in 1969 (10 years after irradiation).

Electronics. A block diagram of the electronic components is shown in Fig. 3. Channel D, the fission-chamber channel, included a high-gain preamplifier²² mounted within a few cm of the fission chamber and a DD-2 type²³ amplifier driving a differential pulse-height analyzer (ORNL-Q-1192 type) and a crossover pickoff timing circuit.²⁴ The crossover pick-off method of fast timing was first developed for this experiment.

For the high-energy experiments, the RG-71 or RG-62 cable length between preamplifier and amplifier was ~ 50 ft. For the low-energy measurements, it was ~ 500 ft since the electronics remained at the BSF for the measurements at the nearby Graphite Reactor. Other features of the circuitry are described in Section II-D.

Fission-Fragment Anisotropy. After completion of our fission gamma-ray measurements, correlations were discovered²⁵ between the directions of gamma-ray and fragment emission which varied as much as 7% from isotropy. For the low-energy measurements, our parallel-plate fission chamber discriminated against fragments which were emitted along the plate (or nearly at right angles to the direction of gamma-ray emission). Since the relative intensity of gamma-ray emission at 90° is a minimum,²⁵ our observed gamma-ray yield is too high by an amount estimated to be $(1 \pm 1)\%$. This estimate is based on the expected chance of escape, as a function of angle, of the fragments (with range of $\sim 8 - 12$ mg/cm²) from the plate of thickness 0.6 mg/cm². A correction for this effect is discussed in IV-C.

²²T. A. Love, R. W. Peelle, and F. C. Maienschein, "Electronic Instrumentation for a Multiple-Crystal Gamma-Ray Scintillation Spectrometer," ORNL-1929, p. 24 (Oct. 1955).

²³E. Fairstein, Rev. Sci. Instr. 27, 475 (1956).

²⁴R. W. Peelle and T. A. Love, "Pulse-Amplitude-Independent Timing Circuits for Driving an Intermediate-Speed Coincidence Unit from the Output of a Double-Line Pulse Amplifier," in ORNL-2389, p. 249 (Sept. 1957).

²⁵M. Hoffman, Phys. Rev. 133, B714 (1964), S. S. Kapoor, Phys. Rev. 133, B598 (1964), and S. Desi et al., Phys. Letters 3, 343 (1963).

Fig. 3. Block Diagram of Electronic Components. The circuit shown is for the Compton spectrometer. An additional crystal channel like B was added for the pair spectrometer and the A crystal replaced. Channel B was deleted for the single-crystal spectrometer.

The high-energy measurements should be less biased since the gamma rays from the spiral fission chamber are seen at a variety of angles with respect to the tangent plane to the fission foil.

C. GAMMA-RAY SPECTROMETER SYSTEMS

The gamma-ray spectrometers consisted of NaI(Tl) crystals mounted on DuMont 6292 photomultipliers, except that the A channel (center crystal) for the high-energy measurements used a DuMont 6291 photomultiplier. The single crystal for the low-energy measurements was a 2.54-cm-high by 4.45-cm-diam cylinder.

For the Compton spectrometer geometry shown in Fig. 1 the crystals were "slabs" cut from right equilateral cylinders of 2.22-cm and 3.83-cm diam by the Harshaw Chemical Company. The slab thicknesses were 0.95 cm and 2.54 cm. This crystal shape was used to reduce the neutron response of the scintillators, which is proportional to their volume, while maintaining a high probability of detecting a photon which was Compton-scattered toward the side crystal. The crystal center-to-center distance was 4.7 cm.

For gamma-ray energies well above the pair-production threshold, better spectrometer response (larger peak-to-total ratio) can be obtained by detecting, in coincidence with the pulse in the center crystal, the two annihilation quanta in separate side crystals. For this purpose two side crystals 5.1 cm in diam and 5.1 cm high were used as shown in the insert in Fig. 1. The B-C center-to-center distance was 10.2 cm. The A crystal was a slab of 1.90 cm cut from a right equilateral cylinder of 2.50-cm diam. The A-B center-to-center distance was 5.2 cm. The gamma-ray energy was then equal to the electron-plus-positron energy (measured in the center crystal if no electron or bremsstrahlung losses occur) plus $2 m_0 c^2 = 1.022$ MeV.

The relationship between the gamma-ray energy and the measured electron energy for the Compton spectrometer depends upon the average angle of scattering for detected events. This relationship was determined by repeatedly observing the electron energy at the peak of the pulse-height distribution, F (in MeV) for 18 sources of known gamma-ray energy,

E (in MeV). Applying least-squares fits to the resulting data gave:

$$E = \frac{F}{2} \left(1 + \sqrt{1 + 4b/F} \right) \quad (2.1)$$

where $b = (0.3236 \pm 0.0016) + (0.0038 \pm 0.0006/F)$.

Electronics. The electronics for the three spectrometers used differed primarily in the number of channels (see Fig. 3). In addition to the fission-chamber channel, D, the low-energy spectrometer had one channel, A; the Compton spectrometer, A and B as shown in Fig. 3; and the pair spectrometer, A, B, and C. The C channel was identical to B. The DD-2 amplifiers²³ drove crossover timing units²⁴ as for channel D. Channel A pulses were analyzed in a 256-channel pulse-height analyzer.²⁶ Pulse-height bands were selected from B and C channels by differential pulse-height analyzers (ORNL-Q-1192 type). The fast-slow coincidence circuit²⁷ permitted use of this pulse-height selection on the side channels, B and C, together with a short (50-70 nsec) resolving time.

Other electronics included high- and low-voltage power supplies with their monitors, a 4-channel pulser, and a count-rate monitoring circuit which maintained cognizance of individual channels during the long (~ 20 hr) data runs.

Electronics Adjustment. The 4-channel pulser served to check the linearities and zero intercepts of the pulse-height analyzer. Gains, the relationships between pulse heights and gamma-ray energies, were determined by exposing the spectrometers to monoenergetic sources of gamma rays. Sources used for this calibration with energies shown in keV are listed in Table II-1. The energies assigned reflect the information available circa 1959.

For the Compton spectrometer the channel B (side crystal) single-channel analyzer (SCA) was set to cover the energy range 150-400 keV. For

²⁶R. W. Schumann and J. P. McMahon, Rev. Sci. Instr. 27, 675 (1956).

²⁷See Ref. 22, p. 11.

Table II-1. Sources Used for Energy Calibration
of Gamma-Ray Spectrometers

Low-Energy Spectrometers		Compton and Pair Spectrometers	
Source	Energy (keV)	Source	Energy (keV)
^{181}Hf	8.8, 57.9	^{203}Hg	279
^{203}Hg	10.3, 73.0, and 279	^{113}Sn	393
^{103}Ru	20. 5	^{85}Kr	517
^{109}Cd	22.5, 88.0	^{137}Cs	662
^{113}Sn	24.6	^{54}Mn	835
^{137}Cs	32.6, 662	^{88}Y	899, 1840
^{147}Nd	39.3, 91.2	^{65}Zn	1114
^{181}Hf	57.9, 136	^{60}Co	1173, 1332
^{51}Cr	323	^{22}Na	1276, 511
^{198}Au	412	^{38}Cl	1600, 2600
^{103}Ru	498	^{24}Na	1368, 2754
^{60}Co	1173, 1332	^{12}C (Po-Be)	4433
^{24}Na	1368, 2754	^{16}N	6135, 7121

the pair spectrometer the B- and C-channel SCA's were set to cover the range 420-600 keV.

The relative times of arrival of pulses in different channels due to a single event were determined by varying the delays shown in Fig. 3, in steps of a few nsec. The prompt-fission gamma rays were necessarily used as a source for adjusting the relative AD delay. Sources giving a high coincidence rate, such as ^{22}Na , were used for adjusting the relative delays AB and AC. The overall average resolving times and uncertainties for each spectrometer are given in Table II-2.

Table II-2. Resolving Times of Gamma-Ray Spectrometers

<u>Spectrometer</u>	<u>Channels</u>	<u>Resolving Time (nsec)</u>
Single-Crystal	A x D	69.0 ± 1.0
Compton	AB x D	56.0 ± 1.5
Pair	ABC x D	56.4 ± 2.3

In order to detect possible changes in the efficiencies of the spectrometers for counting gamma rays, sources were exposed in reproducible positions and the counting rates determined. These sources were selected from those listed in Table II-1.

In general, gain and timing tests were made before and after each individual measurement of fission gamma rays.

III. SPECTROMETER RESPONSE FUNCTIONS

A. PROBLEM DEFINITION

If $\Gamma(E)$ is the desired photon energy spectrum from fission, and if C_k^s are the number of counts per fission observed in pulse-height bins k of spectrometer system s and S_k^s are the corresponding statistical uncertainties, the bin response functions $R_k^s(E)$ are defined by

$$\int_E R_k^s(E) \Gamma(E) dE = \hat{C}_k^s \cong C_k^s \pm S_k^s, \quad (3.1)$$

where $\hat{C}_k^s$ is the expectation value of the binned count C_k^s .

Though pointwise numerical approximations may be employed to invert or "unscramble" Eq. 3.1 to find $\Gamma(E)$, the bin response functions $R_k^s(E)$ are each dependent on the continuous energy variable E and the discrete bin number variable k . As seen in Eq. 3.1, $R_k^s(E)$ is the average probability that a fission gamma ray of energy E will be counted in pulse-height bin k of spectrometer s . It was impractical to perform the calibration process using the unequal and rather broad pulse-height bins employed for the fission data, so our analysis was first made in terms of response functions $R^s(E, p)$ which are the average probability that a fission gamma ray of energy E will produce a count per unit pulse height at p in spectrometer system s . As will be seen in Section V, these response functions are simply integrated over successive pulse-height bins to produce the bin response functions $R_k^s(E)$ of Eq. 3.1.

In the present work the spectrometer responses observed for a series of energies E_i were fit in both energy and pulse-height variables using nonlinear least-squares analyses, and the resulting approximate responses were used in the unscrambling. The dependence on gamma-ray energy was based upon the use of calibration sources of known disintegration rate. The functional forms of the responses were chosen to match the observed behavior of the spectrometers.

B. CALIBRATION OF SOURCE STRENGTHS

Pulse-height spectra were obtained for each spectrometer from a series of sources of known intensity mounted in geometries similar to that of the fission chambers described in Section II. Fission chamber size, shape, and self-absorption were duplicated in the encapsulation of some sources while for others these effects were compensated by calculation. Since the spectrometers had low absolute efficiency measured at the source position, sources convenient for response calibration (10^7 dis/sec) were too intense for direct applications of absolute counting techniques. Most of the source strengths were therefore established using calibrated 4π ionization chambers, while for gamma rays above 3 MeV special procedures were required.

Ion Chamber Calibration - The two chambers used were 10-in. right circular hollow cylinders of iron filled with 40 atm of argon, and each has a reentrant tube along its symmetry axis to hold the source near the center.²⁸⁻²⁹ The average ionization current was estimated using a null method employing a vibrating reed electrometer, a set of high-value resistors, and a laboratory potentiometer. A complete memorandum covering our use and calibration of these chambers is available.³⁰

Though the ion chamber method was chosen for its stability and simplicity, it was necessary to subject output voltage readings to considerable analysis to attain the desired precision. The high-value resistors were carefully calibrated to allow conversion to ionization current, and detailed linearity corrections were made to compensate ion recombination for

²⁸Chamber design based on J. W. Jones and R. T. Overman, "The Use and Calibration of a 100% Geometry Ion Chamber," MONC-399 (AECD-2367) (March 1948).

²⁹The chambers used were under the care of W. S. Lyon and H. Parker and were built essentially according to Oak Ridge National Laboratory drawings Q-884-2 through 4, and Q-1232-9, -10.

³⁰R. W. Peelle, ORNL Memorandum CF-61-4-32, "Use of 4π High-Pressure Ionization Chambers as Secondary Standards for Calibration of Gamma-Ray Sources," April 17, 1961.

the stronger sources. The latter corrections were based on the work of W. S. Lyon and coworkers³¹ using aliquots from a standardized ^{60}Co solution, and they were checked using decay of a (radiochemically) pure ^{198}Au source which decayed throughout the 10^3 range of currents required. Long-term drifts of the instruments were compensated by corrections of up to 5% based on readings from slowly decaying sources.

Once " ^{60}Co -equivalent" disintegration rates were obtained by the process suggested above, it was essential to calibrate the variation of the chamber's efficiency with gamma-ray energy. Since the chambers are "thin" to the gamma rays but not to the secondary electrons, the shape of the efficiency curve is insensitive to filling pressure and depends primarily upon the gamma-ray cross sections of argon modified by corrections for lack of electron equilibrium between the walls and the gas, by attenuation in the central thimble surrounding the source, and by backscatter from the outer chamber wall. Figure 4 shows points on a chamber efficiency curve computed on this basis. This computed efficiency was multiplied by a second-order polynomial correction factor with coefficients fitted to a series of observations with sources calibrated by absolute β - γ and γ - γ coincidence-counting techniques.³²⁻³⁵ The evaluation of the correction polynomial correctly handled the various decay schemes although the figure cannot illustrate this. Of the absolute disintegration rates measured, only that for the 393-keV decay observed from a source of ^{113}Sn had an estimated standard error greater than 1.5%. Unfortunately, the low-energy peak (at ~ 80 keV), which is strongly influenced by attenuation, is not very well tested by the absolute data. Except for this low-energy region and for sources with uncertain decay schemes, the final ion chamber

³¹W. S. Lyon, Oak Ridge National Laboratory, private communication (1959).

³²F. C. Maienschein and R. W. Peelle, "The Spectrum of Prompt Gamma Rays from ^{235}U Fission," in ORNL-3016, p. 82 (Sept. 1960).

³³R. W. Peelle and F. C. Maienschein, "Gamma-Gamma Coincidence Standardization of Sources, with Application to the $\text{B}^{11}(\text{p},\gamma)\text{C}^{12}$ Reaction," in ORNL-3016, p. 96 (Sept. 1960).

³⁴L. P. Remsberg, "Determination of Absolute Disintegration Rates by Coincidence Methods," p. 369ff in Annual Reviews of Nuclear Science 17 (1967), Annual Reviews, Inc. (1967).

³⁵K. P. Meyer, P. Schmid, and P. Huber, *Helva. Phys. Acta* 32, 423 (1959).

Fig. 4. Predicted, Experimental, and Interpolated Energy Dependence of the Fractional Energy Absorption in the Ion Chambers. The line with flagged errors is interpolated from experimental data which are represented by the circles. (A decay-scheme uncertainty probably explains the discrepancy at 0.39 MeV.)

efficiencies for the sources employed in the fission experiment are believed accurate to no worse than 1.5%.

The source capsules employed were thick enough to scatter many gamma rays. Since the Compton-scattered gamma rays often had higher ion-chamber efficiencies than the original gamma rays, the effective absorptions had to be carefully calculated. The effective transmission factors numerically averaged over solid angle ranged from 0.93 to 1.0. (Another set of transmission factors, discussed below, is required to compensate attenuation as observed in the spectrometers.)

Final errors on the strengths of sources calibrated using the ion chambers ranged from 1.5 to 3%, except for one case with badly inconsistent readings and two for which decay schemes were poorly known.

Direct Absolute Calibration - At energies above 2.75 MeV (^{24}Na), calibration of sources using the ion chambers was impossible. In the case of the calibration of the pair spectrometer with ^{24}Na , the same source used for response-function studies was calibrated by absolute coincidence counting after several decay periods (with a well-known half life). For this case the decay rate uncertainty was only 1%. For 6- and 7-MeV gamma rays from 7-sec ^{16}N and for 4.4- and 11.8-MeV gamma rays from the $^{11}\text{B}(p,\gamma)$ reaction (200-keV protons), special complex procedures were required.

The 4.4- and 11.8-MeV gamma rays are a cascade in the ^{12}C nucleus, accompanied by a roughly 3% crossover. In this case the $\gamma\gamma$ absolute counting took place simultaneously with the observation of the pair spectrum and used the center spectrometer crystal for one of the counters. The analysis was complicated by the angular distributions relative to the proton beam but was not disturbed by the spatial and time variation of the source strength in the thick ^{11}B target. The source strength in a very long run (terminated by accelerator breakdown) was obtained to 1.5%,³⁶ but the estimated uncertainty of the resulting efficiency measurement for the 4.4-MeV gamma ray is about 5% because of the very small number of

³⁶See Ref. 33, p. 104-9.

coincidence counts obtained in the pair spectrometer. This calibration dominates our knowledge of the efficiency of the pair spectrometer for energies above ~ 3 MeV.

A lengthy "absolute" experiment was performed to determine the pair spectrometer efficiency at the 6.1-MeV gamma ray in the decay of 7-sec ^{16}N .³⁷ Water was pumped from a reactor irradiation cell through a source volume at the fission-chamber position and through a 4π beta-ray counter consisting of a plastic scintillator with a finely divided internal source volume. Beta-gamma absolute counting was performed using an adjacent scintillator for gamma-ray detection, and then the gamma-ray counter was used as a monitor at the higher reactor power used for determining pulse-height spectra in the pair spectrometer. Turbulent flow was assumed between the beta counter and the source cell, and it was assumed that no significant decay occurred in either location. The final estimated uncertainty was only 4.5%, but the result was seemingly inconsistent with our other measurements by about one third, so these absolute data were finally abandoned. The assumptions of turbulent flow and of proper filling of the passages in the plastic scintillator are the most likely sources of error.

Absorption of Gamma Rays in the Source Capsules - Precise matching of the gamma-ray absorption properties of the fission chambers and the calibration sources could not be accomplished. Therefore, corrections had to be entered so that the final spectrometer response functions compensate for differences between absorption effects (largely Compton scattering except at low energies) for the calibration sources and for the fission chambers.

For the low-energy measurements with the single-crystal spectrometer, absorption by the uranium dominates, and for energies below about 50 keV uncertainties are introduced due to imperfect knowledge of the thicknesses of the chamber plates, and perhaps of the gamma-ray cross sections.³⁸ Measurements using x-ray sources of various energies were made in a dummy

³⁷See Ref. 32, p. 84.

³⁸The gamma-ray cross sections were obtained from NBS Circular 583 by G. W. Grodstein, April, 1957 except for uranium where data were taken from R. B. Roof, Jr., Phys. Rev. 113, 822 (1959).

chamber presumably identical to the counter used, but this did not remove all uncertainty since some of the sources had poorly defined areas. Figure 5 illustrates the estimated mean fission chamber self-absorption for the low-energy measurements combined with the absorption in the spectrometer (see Section II-A). The errors in the calculated photon transmissions were judged to be $< 1\%$ for photon energies > 50 keV, $< 4\%$ for photon energies > 33 keV, and $< 20\%$ for photon energies > 10 keV. In this case the spectrometer response was established first using sources in the correct geometry but without the fission chamber, and then the resulting functions were renormalized on the basis of chamber self-absorption. For this spectrometer, Compton scattering in the fission chamber was considered unimportant ($\leq 2\%$), so the shape of the response function was assumed independent of the self-absorption. (The response function was based on pulse-height spectra measured with the source placed in the center of a fission-chamber mockup.)

For the pair and Compton spectrometers the most frequently used sources were mixed with graphite and aluminum powder and canned with the same brass cans used for the fission chambers in an effort to make scattering and self-absorption effects cancel between source and chamber. Since the mock-up was imperfect, in practice we carried out numerical integrations over the source volumes to estimate attenuation along the line to the crystal from each element of source or fission chamber and corrected the observed efficiency to compensate for any discrepancy. We assumed that scattering differences did not produce any change in the shape of the observed pulse-height spectra. The transmissions for the sources on which the pair and Compton response functions dominantly depend are given in Table III-1. The ratios of transmissions, which are used in calculating the fission photon yield, are all known to within 1%.

C. PULSE-HEIGHT RESPONSE MEASUREMENTS

Figures 6-8 illustrate observed pulse-height spectra from the spectrometer systems for monoenergetic incident gamma rays. These curves are not normalized to give the correct relative efficiencies. The pair and Compton spectrometers usefully overlap in the region 1.6 to 2.4 MeV, while

Fig. 5. Transmission of Photons Through Fission Chamber and Spectrometer for Low-Energy Measurements. The discontinuities are due to x-ray absorption edges.

Table III-1. Transmission of Photons Through the Sources Used for
Calibrating the Pair and Compton Spectrometers and
Through the Fission Chamber

Source	Gamma-Ray Energy (keV)	Transmission Through Source Container	Transmission Through Fission Chamber
^{203}Hg	279	$.845 \pm .011$	$.773 \pm .018$
^{113}Sn	393	$.831 \pm .015$	$.829 \pm .015$
^{85}K	517	$.833 \pm .013$	$.834 \pm .013$
^{137}Cs	662	$.844 \pm .012$	$.850 \pm .012$
^{65}Zn	1114	$.867 \pm .009$	$.875 \pm .009$
^{22}Na	1276	$.871 \pm .009$	$.880 \pm .009$
^{88}Y	1840	$.883 \pm .008$	$.895 \pm .008$
^{24}Na	2754	$.968 \pm .006$	$.908 \pm .007$
^{16}N	6135	$.923 \pm .005$	$.923 \pm .005$
^{12}C	4433	$.987 \pm .005$	$.914 \pm .006$
^{12}C	11,810	$.990 \pm .004$	$.909 \pm .006$

Fig. 6. Pulse-Height Spectra from Monoenergetic Gamma Rays for the Pair Scintillation Spectrometer.

Fig. 7. Pulse-Height Spectra from Monoenergetic Gamma Rays for the Compton Scintillation Spectrometer.

Fig. 8. Pulse-Height Spectra for Monoenergetic Gamma Rays for the Single-Crystal Scintillation Spectrometer.

the Compton and single-crystal spectrometers overlap from 0.4 to 0.8 MeV. The spectrometers intended for use at lower energies respond to higher energy gamma rays, of course, and thereby present an analysis problem. The uniqueness of the pair spectrometer response deteriorates between 7 and 11 MeV because of electron and bremsstrahlung escape from the center crystal.

Complex spectrometer systems can suffer from time drift of their efficiencies. For the pair and Compton systems, both bias settings and geometry changes could cause efficiency and shape shifts. For gamma rays of less than 50 keV in the single-crystal spectrometer, drifts could occur in the coincidence efficiency factor and in the fission chamber self-absorption factor. Daily measurements during the extended high- and low-gain pair spectrometer runs, using the 2.75-MeV gamma rays of ^{24}Na , showed 2.3 and 4% rms fluctuations respectively, largely explained by known statistical fluctuations in the source strength measurements and in the number of observed counts. A similar series of measurements was made using the Compton spectrometer to observe the 1.27-MeV gamma rays from ^{22}Na . The observed rms fluctuation in this case was 4%, compared to the 3% expected on the basis of estimated uncertainties. For the single-crystal spectrometer, internal consistency was established within the rather small statistical errors of the set of runs representing coincident fission data.

D. CHARACTERIZATION OF THE RESPONSE FUNCTIONS

For each spectrometer system (s) an attempt was made to find parameters d_{ij} to represent within experimental uncertainty the response $R^S(E,p)$ as a function of gamma-ray energy (E) and pulse height (p).

Unfortunately, only certain gamma-ray energies E_k were available for study of the responses and often two energies were coupled in a single source. Therefore, the modified Gauss-Seidel nonlinear least-squares fitting procedures,^{39, 40} used to determine the parameters of empirical fitting functions, had to take into account two source energies simultaneously. For Compton and pair response determinations, each calibration spectrum (45 and 20 cases, respectively) was fitted in terms of 9-11 parameters $P_i(E_k)$ for each source gamma ray, and then the variation of these parameters with gamma-ray energy was fitted in a separate procedure to give the needed d_{ij} . A similar procedure was used for the low-energy spectrometer.

The detailed form of the response function for each of the three spectrometers is given explicitly in Appendix II. Numerical values used to match the experimental data are tabulated.

Form of Functions Used to Fit Pulse-Height Spectra. In devising suitable functions for fitting the experimental data from various mono-energetic sources in terms of $P_i(E)$, the following guidelines were used:

1. The expression for $R(E,p)$ should be the sum of terms, each of which represents an obvious shape feature of the observations when plotted as a function of pulse height.
2. Each term in the sum should be a continuous function of pulse height and should have the form of an amplitude coefficient times a shape function having unit area.

³⁹R. O. Chester, R. W. Peelle, and F. C. Maienschein, "Nonlinear Least-Squares Fitting Applied to Gamma-Ray Scintillation Detector Response Functions," in Applications of Computers to Nuclear and Radiochemistry, NAS-NS-3107, pp. 201-212 (1963).

⁴⁰R. W. Peelle, R. O. Chester, and F. C. Maienschein, "The Fitting of Interpolation Functions to Scintillation Spectrometer Pulse-Height Spectra," ORNL-3193, p. 29 (1961).

3. For convenience in combining source-strength information with information from the fits of counts per keV versus pulse height, a single normalizing constant should appear for the entire expression representing either the entire area of the fitted function or that of the peak corresponding to the full gamma-ray energy.
4. Whenever possible, the form should be arranged so that the derivatives of the entire expression with respect to the various parameters are reasonably orthogonal to each other.

Using the above criteria, the general form adopted for the response function was:

$$R(E,p) = (\text{peak efficiency})[(\text{unit area Gaussian for the peak shape}) + (\text{tail magnitude}) (\text{tail shape}) + \text{other localized contributions}].$$

For the pair and Compton spectrometers, the tail shape was a combination of exponential terms. For the Compton spectrometer there were also peaks representing pair production and backscatter, as well as a low-energy rise in the tail which was not exponential. The low-energy spectrometer tail corresponded to the distribution of Compton recoil electrons. Terms were also added to represent a backscatter peak and peaks due to the escape of iodine x-rays (only significant for photon energies between 33 and ~ 150 keV).

Variation of Parameters with Gamma-Ray Energy. In the two-step fitting process used, an attempt was made to ensure that the variations with gamma-ray energy of the parameters $P(E)$ (derived from fitting spectra from monochromatic gamma-ray sources) were physically plausible. For instance, the peak efficiency, P_3 , which determines the magnitude of the response function, should be related to the pertinent cross section in NaI.

For the pair spectrometer, the variation of the peak efficiency with gamma-ray energy is shown in Fig. 9, where the peak efficiency is divided by the Born approximation⁴¹ to the pair cross section. The

⁴¹P. V. C. Hough, Phys. Rev. 73, 266 (1948).

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Fig. 9. Gamma-Ray Energy Dependence of the Peak Efficiency of the Pair Spectrometer Divided by the Hough Formulation of the Born Approximation to the NaI Pair Cross Section. [See P. V. C. Hough, Phys. Rev., 73, 266 (1948).] The efficiency is expressed in terms of photons at the source and thus includes a solid-angle factor. The line was fitted to the experimental points shown.

peak efficiency decreases with increasing gamma-ray energy relative to the pair cross section primarily due to the escape of positrons and due to positron annihilation in flight, both of which remove counts from the spectrum. Bremsstrahlung losses by the electrons and negative electron escape produce smaller pulses which still contribute to the tail. A calculation based on the experimental data in Fig. 9,³² and incorporating a best estimate for each of these effects and for those of absorption in the spectrometer system, gave values of the pair cross section in NaI which were consistent with published data^{42,43} and had comparable estimated uncertainties.

The peak efficiency for the Compton spectrometer is shown in Fig. 10. The efficiency drops rapidly below ~ 300 keV due to the reduced probability of escape from the center crystal and subsequent detection in the side crystal of the scattered photon.

For the single-crystal spectrometer peak efficiency, shown in Fig. 11, the low-energy falloff is due to absorption in the fission chamber and spectrometer system.

The energy resolution or width of the Gaussian peak increased smoothly with energy for all spectrometers. The window functions plotted in Figs. 21 and 22 give a good idea of this variation.

The relative tail magnitude is controlled largely by the parameter P_1 . The smooth variation of this parameter with gamma-ray energy for the pair spectrometer is shown in Fig. 12. For the Compton spectrometer, P_1 is shown in Fig. 13 plotted as a function of the square root of the peak electron energy. (Note in Appendix II a difference in the definition of P_1 evidenced by the $(1-P_1)$ term multiplying the Gaussian peak for the pair spectrometer but not the Compton spectrometer.) The parameters which determine the tail shapes were also made to behave smoothly with energy.

⁴²G. W. Grodstein, "X-Ray Attenuation Coefficients from 10 keV to 11 MeV," NBS Circular 583 (April 30, 1957).

⁴³H. West, Phys. Rev. 101, 915 (1956).

Fig. 10. Peak Efficiency of the Compton Spectrometer as a Function of Gamma-Ray Energy. The efficiency is expressed in terms of photons at the source and thus includes a solid-angle factor. The bars on the labeled vertical lines show the results of individual efficiency measurements. The line represents the result of the fitting process described in the text. The extrapolation shown by the dashed line at higher energies is based upon an estimate of the escape of electrons from the center crystal.

Fig. 11. Peak Efficiency of the Single-Crystal Spectrometer as a Function of Gamma-Ray Energy. The efficiency includes the effects of absorption in the fission chamber and spectrometer system and a solid angle factor which is 1.04×10^{-5} . The measured points represent the weighted averages of several runs. The calculated values were obtained from ORNL Monte Carlo results^a for the total efficiency and peak-to-total ratios of Lazar.^b The discontinuity at 17 keV is due to an L-x-ray absorption edge in uranium, that at 20 keV due to the K-edge in zinc, that at 23 keV due to another L-edge in uranium, that at 33 keV due to iodine K-x-ray escape, which was calculated on the basis of the results of Axel,^c which were unchanged by the observations of Dell and Ebert.^d The dashed extrapolation above 10^3 keV is drawn to pass through the experimental points.

- a. W. E. Mott and R. B. Sutton, Handbuch der Physik, Vol. XLV, p. 124 (1958).
- b. Op. Cit. p. 127.
- c. P. Axel, Rev. Sci. Inst. 25, p. 391 (1954).
- d. J. R. Dell and P. J. Ebert, Nucl. Inst. and Methods, 68, p. 335 (1969).

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Fig. 12. Variation of the Tail Magnitude Parameter, P_1 , for the Pair Spectrometer as a Function of Electron Energy. The points represent the results of fits to pulse-height spectra from individual gamma rays. The line is the fit over energy specified in Appendix II-A. F is taken at the peak of the pulse-height distribution from each gamma-ray source.

Fig. 13. Variation of the Tail Magnitude Parameter, P_1 , for the Compton Spectrometer as a Function of the Square Root of the Electron Energy. The points represent the results of fits to pulse-height spectra from individual gamma rays. The line is the fit over energy specified in Appendix II-B. F is taken at the peak of the pulse-height distribution from each gamma-ray source.

Clearly, some of the parameters have less well-defined variations with gamma-ray energy. The least certain of these were "frozen" during the fitting process and a few are taken to be independent of energy. (See Appendix II for details.)

Some of the features of the response functions, such as the back-scatter peak at ~ 250 keV, are fixed in energy, while others such as the iodine escape peaks and the x-ray peaks, which are composed of many components, may be located in energy only to within the limits of available published data on x-ray transition probabilities.

In all cases the statistical uncertainties in the output parameters were studied. The study was difficult since separate sequential fitting procedures were employed and the correlations between the various P_i parameters had to be recognized in performing the fits as a function of gamma-ray energy to obtain the d_{ij} . This recognition was made possible by employing a nonlinear fitting program with a nondiagonal weighting matrix obtained as the inverse of the variance matrix of the input data. Because of the presence of systematic error in the fits (the empirical formulae could hardly be perfect), many judgments and approximations were required in this weighting procedure.

No problems of nonunique fitting parameters were encountered once plausible functional forms for the response functions were developed.

Examples of Fit Obtained. Illustrations are given to compare the experimental results for individual sources with the pulse-height response predicted by the functions obtained by fitting all data. Figure 14 shows the response of the pair spectrometer to a ^{24}Na source (1.38 and 2.75 MeV gamma rays) with typically good agreement between the overall fit and the individual measurement. The response of the pair spectrometer at high energy, Fig. 15, shows the increase in relative importance of the tail. As is apparent, the statistical accuracy of these particular data is poor (for reasons cited in III-B).

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Fig. 14. Comparison of Pulse-Height Spectrum Measured with the Pair Spectrometer with Predictions from the Response Function of the Form Specified in Appendix II-A. The source is ^{24}Na , emitting photons of 2.75 and 1.38 MeV in equal intensity. The degree of fit is characterized by $\chi^2/\nu = 8.9$.

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Fig. 15. Comparison of Pulse-Height Spectrum Measured with the Pair Spectrometer with Predictions from the Response Function of the Form Specified in Appendix II-A. The source is ^{12}C from $^{11}\text{B}(p,\gamma)$ emitting photons of 4.4 and 11.8 MeV in equal intensity. $\chi^2/\nu = 1.9$; this favorable value is indicative of the poor statistical quality of the experimental data.

The response of the Compton spectrometer to the two gamma rays from ^{24}Na is shown in Fig. 16. The various components of the response function shown may be correlated with the features described in Appendix II-B. The parameters for this plot were based on the data shown rather than on the global fit but the quality of the fit was not significantly different using the global parameters.

The greater abundance of features observed in the low-energy spectrometer made obtaining a good fit for this spectrometer a greater challenge. One of the worst fits for the Compton distribution and backscatter peak is shown in Fig. 17. The response of this spectrometer to two photon groups from a ^{181}Hf source is shown in Fig. 18. The degree of fit obtained is typical for this energy range. In Figs. 17 and 18 the illustrations are based on parameters of the global fits.

Fig. 16. Comparison of Pulse-Height Spectrum Measured with the Compton Spectrometer with Predictions from the Response Function of the Form Specified in Appendix II-B. The source is ^{24}Na , emitting photons of 2.75 and 1.38 MeV in equal intensity. $\chi^2/\nu = 7.1$. The lettered features which combine to give the calculated response are identified in Appendix II-B.

Fig. 17. Comparison of Pulse-Height Spectrum Measured with the Single-Crystal Spectrometer (Histogram) with Predictions from the Response Function of the Form Specified in Appendix II-C (cross-hatched line). The source is ^{137}Cs emitting photons of 662 keV. The Compton distribution and backscatter peak are clearly seen. The degree of fit is typical in the valley just below the Gaussian peak which contains little area, but it is much worse than that obtained for other sources in the Compton distribution and backscatter peak.

Fig. 18. Comparison of Pulse-Height Spectrum Measured with the Single-Crystal Spectrometer with Predictions from the Response Function of the Form Specified in Appendix II-C. The source is ¹⁸¹Hf emitting photons of 134 keV and x-rays which concentrate in two energy regions around 57 and 65 keV. The iodine K-x-ray escape peaks may be clearly seen although those from the 134-keV photon are mixed with a backscatter peak. The degree of fit ($\chi^2/\nu = 4.8$) is typical for this energy region.

IV. TREATMENT OF PULSE-HEIGHT SPECTRA

A. THE ENERGY SCALE FOR PULSE HEIGHTS

Conversion was made from the measured channel number, c , as recorded by the pulse-height analyzer, to energy units, p in MeV, by the equation:

$$p = \frac{1}{h} [c - Q + \Delta c(c) + \delta c(p)] , \quad (4.1)$$

where

- h = gain in ch/MeV,
- Q = zero offset in ch,
- Δc = analyzer nonlinearity correction in ch,
- δc = detector nonlinearity correction in ch.

The gain, h , was determined by exposure of the spectrometer to mono-energetic sources of gamma rays. Typical values of h were 263, 630, and 2400 for 3 sets of low-energy measurements, 56 for the Compton spectrometer, and 24 and 50 for the pair spectrometer, with all values in ch/MeV. The uncertainties in gain determinations, including the effects of drifts, were less than 0.4%.

The zero offset, Q , was also determined from the source measurements with a typical uncertainty of 0.8 ch or less for the low-energy measurements and 0.3 ch or less for the high-energy measurements.

Nonlinear behavior of the pulse-height analyzer was evaluated by the use of a special pulser designed to generate a uniform pulse-height distribution over the range of the analyzer. Periodic measurements (20 overall) with this so-called sliding pulser led to values of Δc which were largest (≤ 3 ch) at the lowest (~ 10) and highest (220) channels used. For channels between 30 and 200, $\Delta c < 1.0$ ch. The uncertainties in Δc were less than 0.5 ch except at the highest channels where they approached 1.0 ch.

For low-energy electrons the light output of NaI(Tl) has been shown to deviate from proportionality with energy absorbed.⁴⁴ From a study of the crystal used for these measurements, the correction for this non-linearity, δ channels, was fitted adequately with the relation:

$$\begin{aligned} \delta c &= 0 & \text{For: } p &> .080 \text{ MeV} \\ &= a[1 - \cos\{20\pi(.080 - p)\}] & .055 < p < .080 \text{ MeV} \\ &= a[1 + 20\pi(.055 - p)] & p < .055 \text{ MeV} . \end{aligned} \quad (4.2)$$

The $\delta c(p)$ term in Eq. 4.1 was actually employed explicitly only for the low-energy data with $h = 630$ ch/MeV, since these data overlapped the 50-80 keV region. Values of a were ~ 1.3 . In all other cases the effect was absorbed into the values of Q (and h , for the runs examining the region below 55 keV).

Uncertainties in the values of p , the pulse-height energies, were calculated from Eq. 4.1. The uncertainties for the gamma-ray energies, E , were equal to those for p for the low-energy and pair spectrometers. For the Compton spectrometer, the effects of error in the constant, b , of Eq. 2.1 must also be taken into account but they are quite small. These uncertainties enter primarily into the bin-width determinations.

B. COMBINATIONS OF PULSE-HEIGHT SPECTRA

The pulse-height data were accumulated in many "runs" of up to one day each, the longest period considered acceptable between calibrations of the equipment.

During the low-energy measurements, 3 gains were used as noted above, and 2 gains used for the pair spectrometer. These gain changes were made to cover the desired energy range with channel widths appropriate to the

⁴⁴R. W. Peelle and T. A. Love, "Establishing an Energy Scale for Pulse-Height Distributions from Gamma-Ray Spectrometers Based on Inorganic Scintillators," ORNL-4118 (Oct. 1967).

local energy resolution. Overall, the measurements extended for 658 hr for the low-energy measurements, including background determinations, for 124 hr for the Compton measurements, and for 685 hr for the pair-spectrometer measurements.

Data from these separate runs were combined to yield the spectra given later. For all combinations, statistical consistency tests were satisfied.

In the data combination, counts were grouped into "bins" which contained a varying number of channels. The bin widths were chosen to improve the statistics within the bins, reduce the numerical difficulty of the unfolding problem, and yet retain most of the inherent energy resolution of the spectrometer. This compromise was easier for the single-crystal spectrometer, where the bin width was between $2/5$ and $3/5$ of the full width at half maximum (fwhm) of the peak due to a monoenergetic gamma ray. For the Compton spectrometer this ratio is about 0.8, and for the pair spectrometer below 5.2 MeV it is about 1. At higher energies (> 5.3 MeV) the bin width became broader than the intrinsic resolution and yet the statistical uncertainties became relatively large due to the small number of high-energy gamma rays.

The bin width, B (in MeV) for the i th bin was therefore taken as

$$B_i = q p_i^{\frac{1}{2}}, \quad (4.3)$$

where p_i is the pulse height at the lower bin edge in MeV, and $q \cong 0.025$ for the low-energy data, 0.1 for the Compton data, 0.08 for the pair data below 5.2 MeV, and 0.16 for the pair data between 5.3 and 7 MeV. The few pair-spectrometer counts above 7 MeV were lumped into two broad bins.

For the Compton spectrometer, it must be noted that the bin width in gamma-ray energy units differs from that given by the above expression in electron energy units. The relationship, derived from Eq. 2.1, is (E and F in MeV)

$$\frac{dE}{dF} = \frac{E + 0.524}{2E - F}. \quad (4.4)$$

Values of dE/dF vary from 1.17 to 1.01 for E between 0.5 and 2.7 MeV.

To perform the combinations of counts into bins, bin edges for each data run were calculated from the gain and zero offset for that run and the bin-width formulas given. Thus the channel number corresponding to the lower edge of bin i or the top edge of bin $i-1$ is given by:

$$c_i = p_i h + Q - \Delta c(c_i) - \delta c(p_i), \quad (4.5)$$

where h , Q , Δc_i , and $\delta c(p_i)$ depend on the experimental run being binned.

Errors in the bin widths are reflected directly in the magnitude of the final gamma-ray spectrum which is given as photons·fission⁻¹·MeV⁻¹. These errors varied from 0.5 to 2.5% including the effects of the dE/dF nonlinearity.

When experimental counts were rebinned, statistical uncertainties were assessed on the basis of the number of counts after rebinning. Thus correlations between adjacent bins need not be considered when a result depends on combinations of adjacent data bins.

C. BACKGROUND CORRECTIONS

Neutron Effects. The efficiency of the time-of-flight discrimination against neutrons for the low-energy experiments was tested by measuring the counting rate in the NaI crystal vs delay time using a shorter resolving time than usual (21.5 nsec). A broad peak at about 150 nsec after the prompt gamma-ray peak could be fit in shape by converting the fission-neutron spectrum to a time scale appropriate to the 342-cm flight path. The calculated time distribution was smeared to account for jitter in the gamma-ray detector and the coincidence resolving time.⁴⁵ Based on these data, the neutron-induced background in the measured low-energy gamma-ray spectrum could not exceed 1 - 2%. Another check was made by measuring the gamma-ray spectrum through 9.0 mm of lead, which preferentially absorbed the gamma rays. These results are consistent, within the considerable uncertainties, with negligible neutron effects.⁴⁵ The estimated uncertainty was $\begin{Bmatrix} +0 \\ -1 \end{Bmatrix}\%$.

⁴⁵T. A. Love, F. C. Maienschein, and R. W. Peelle, "Preliminary Results from a Determination of the Low-Energy Portion of the Gamma-Ray Spectrum Emitted Promptly after Fission of ²³⁵U by Thermal Neutrons," in ORNL-2842, p. 93 (Nov. 1959).

At higher energies, the coincidence requirements of the spectrometer together with the energy selection of the side channel signals minimized the effects of fission neutrons, especially for the pair spectrometer. After a long series of experiments to empirically improve the lead, bismuth and lithium-containing shielding surrounding the spectrometer (see Fig. 1) measurements were made with the Compton spectrometer with lead and polyethylene plugs inserted into the gamma-ray collimator.⁴⁶ The resulting attenuations are consistent with any neutron-induced background of $\leq 15\%$.

The center crystal of the Compton spectrometer was moved back to 48.7 cm from the fission chamber and a measurement made of the time dependence of the counts in this crystal relative to those in the fission chamber. The results show a $(4 \pm 4)\%$ possible effect due to neutrons in the singles spectrum. The coincidence and side-channel pulse height requirements of the Compton and pair spectrometers minimized neutron effects further. The estimated uncertainty was $\{^{+0}_{-4}\%$ for the Compton spectrum and $\{^{+0}_{-2}\%$ for the pair spectrum. If the neutron effects were strongly concentrated at one or a few energies, they could exceed the assumed uncertainties. However, there is no evidence for such concentration in the Compton spectrum observed with the lead plug in place.

To symmetrize the uncertainties from neutron effects and from fission-fragment anisotropy (see Section II-B), otherwise-final pulse-height spectra for all spectrometers were multiplied by 0.985. This compensation led to residual uncertainties for single-crystal, Compton, and pair spectrometers of $(0 \pm 1)\%$, $(-0.5 \pm 2)\%$, and $(+0.5 \pm 1)\%$, respectively.

Random Coincidence Backgrounds. The accidental coincidence in time of signals due to uncorrelated events in the various detectors must be taken into account. The magnitude of these random-coincidence backgrounds depends upon the separate counting rates in each detector and the resolving time of the coincidence circuit. The resolving times, normally 70 nsec at low energy and 56 nsec at high energy, were determined (daily)

⁴⁶F. C. Maienschein, R. W. Peelle, and T. A. Love, "Energy Spectrum of Prompt Gamma Rays Accompanying the Fission of ^{235}U ," in ORNL-2389, p. 99 (Oct. 1957).

by delaying selected signals and analyzing the resulting time-overlap curves to an accuracy of $\leq 4\%$. The single random-coincidence contribution at low energy (AxD), the most important contribution (ABxD) for the Compton spectrometer, and the three most important contributions (ABCxD, ACDxB, and ACxBD) for the pair spectrometer were subtracted bin-by bin. The component lower-order coincidence pulse-height spectra used as input were obtained from experimental observations. Other less-important contributions for the multiple-crystal spectrometers were taken into account by inclusion (as multiplying constants) in the three dominant backgrounds. Random-coincidence backgrounds were kept below 15% of the foreground for gamma-ray energies below ~ 3 MeV but grew to equal the foreground at ~ 6 MeV.

D. COUNT-LOSS CORRECTIONS

The low coincidence counting rates were limited not by the available neutron flux but rather by the loss of counts, primarily in the fission-chamber channel. These losses are of two types as described below. A third and different type of count loss not dependent on counting rate is evaluated at the end of this section.

Single Losses. The rate of fission events was given by the counting rate in the fission-chamber channel after correction for the loss of counts due to the accidental overlap of pulses giving one discriminator output for two or more fissions. This dead time for the amplifier-discriminator circuit was determined by oscilloscope observation to be $(0.90 \pm 0.03 \text{ } \mu\text{sec})$. Even for the maximum counting rate of $94,000 \text{ cts}\cdot\text{sec}^{-1}$, the corresponding error in the counting-rate determination was $< 0.3\%$.

Coincidence Losses. Far more significant losses were caused by the nature of the timing circuits used to establish the coincidence of pulses with a minimum of pulse-height dependence. Accurate timing of the cross-over of the amplifier pulse as examined by the pickoff circuit is dependent upon maintaining the pulse shape. The accidental overlap of two pulses may (and will in general) alter the pulse shape so that the timing requirements are not met and both pulses are "lost" (not counted).

This effect can be evaluated accurately by adding a pulser signal (at 60~ in our case) in addition to the random signals actually used. The deviation from 60~ of the rate of pulses from the coincidence circuit gated with the pulser input gives the loss for one pulse-height setting of the pulser. These individual measurements, made to an accuracy of $\sim 4\%$, could be combined to give an accuracy averaged over all pulse heights of $\sim 8\%$. Corrections of this type, made for each channel, are shown in Table IV-1. As may be seen, most of the large correction is due to losses in the D channel. The overall uncertainty in the loss for the worst case is 2.2%.

Coincidence Circuit Losses. Coincidence counts were also lost due to our desire to use a short resolving time for good neutron separation at low gamma-ray energies where walk and jitter became large. The resolving time was made larger (70 nsec) than for the high-energy measurements (56 nsec), but the probability of recording a true coincidence in the coincidence circuit was still appreciably less than unity for gamma-ray energies below about 50 keV. At 40 keV, it was 0.98; at 30 keV, 0.96; at 20 keV, 0.91; and at 10 keV, 0.77. These quantitative estimates were obtained from a new analysis method developed for this experiment,⁴⁷ and corresponding corrections were introduced into the observed pulse-height spectra. This method also gave error estimates of 1.0% at 40 keV, 1.7% at 30 keV, 3.0% at 20 keV, and 5.0% at 10 keV.

⁴⁷R. W. Peelle, "Determination of Coincidence Circuit Efficiency by Varying the Input Signal Delay," Nucl. Inst. Methods, 29, 293 (1964).

Table IV-1. Correction Factors for Coincidence Counting
Losses (Error is $\sim 8\%$ of Loss)

Measurement	Loss Correction Factor
Low Energy	1.033
Compton	1.069
Pair (Low-Gain)	1.163
Pair (High-Gain)	1.272
Components of Loss by Channel for High-Gain Pair	
D Channel	1.163
A Channel	1.0054
B Channel	1.032
C Channel	1.0175
Background for High-Gain Pair (all channels combined)	1.058

V. CORRECTIONS FOR SPECTROMETER RESPONSE

At the input to the spectrum "unfolding" problem, there was a total of 129 experimental data bins from all three spectrometers, and the formulations described in Section III gave the efficiency and shape of the response of each instrument. The first step in the solution of Eq. 3.1 for the photon spectrum $\Gamma(E)$ was to derive a bin response or sensitivity function for each experimental data bin, i.e.,

$$R_k(E) = \int_{p_k}^{p_{k+1}} R(E,p) dp ,$$

where p_k and p_{k+1} are the pulse heights bounding the k^{th} pulse-height bin. The $R_k(E)$ evidently give the probability that a gamma ray emitted within one of the fission chambers would have been detected in the k^{th} pulse-height bin of the corresponding spectrometer. From these pieces of information and their uncertainties we needed to estimate both the gamma-ray spectrum $\Gamma(E)$ over the whole energy range and the integrals of this spectrum over broad energy regions such as are often required in practical calculations. It is unreasonable to attempt realization of an output spectrum having energy resolution appreciably narrower than that corresponding to the full-energy peak of the spectrometer used, so we decided to let the output energy resolution be based as closely as possible on the intrinsic spectrometer resolution.

The analysis was performed using a subset of the FERD system of W. R. Burrus.⁴⁸ The idea of the system is partly reformulated here to allow a brief description of the unpublished portions of the system and the manner in which we utilized it.

All the quantities g_i for which we desire estimates are weighted integrals over the (unknown!) underlying photon spectrum $\{\Gamma(E)\}$ of the form

⁴⁸W. R. Burrus and V. V. Verbinski, Nucl. Instr. Methods 67, 188 (1969) contains a good description of FERDOR, the predecessor of the FERD system. This reference covers the main numerical methods but not the estimate of the FERD confidence interval.

$$g_i = \int_E W_i(E) \Gamma(E) dE .$$

$W_i(E)$ is an energy-dependent weighting function called a "window." Thus, $W_i(E) = 1$ would be appropriate if g_i is to be the total number of emitted photons/fission; and $W_i(E) = G(E_0)$, a unit-area Gaussian centered at E_0 , would approximate the number of photons·fission⁻¹·MeV⁻¹ at E_0 , subject to the resolution of the Gaussian. The method of Burrus consists in fitting each $W(E)$ with a combination $\sum_k U_k R_k(E)$ of the response functions $R_k(E)$, a combination nearly optimized to minimize the uncertainty in g when g is estimated as follows:

$$\begin{aligned} g &= \int_E \Gamma(E) W(E) dE \cong \int_E \Gamma(E) \left(\sum_k U_k R_k(E) \right) dE \\ &\cong \sum_k U_k \int_E \Gamma(E) R_k(E) dE = \sum_k U_k \hat{C}_k. \end{aligned} \quad (5.1)$$

Equation 3.1, the definition of R_k , has been used in the last step. $\hat{C}_k$ is the expectation value of the binned count in bin k , which we can approximate with the observed C_k within the uncertainty given by its estimated standard error S_k . The U_k form the "combination vector." The main task of the unfolding is to assign values to the U 's for each window.

In forming the synthetic (fitted) window $W'(E) = \sum_k U_k R_k(E)$ to approximate the given $W(E)$, the FERD system takes into account the non-negativity of $\Gamma(E)$ to minimize (approximately) the overall uncertainty in g .^{*} The system recognizes that too close a fit between the synthetic and real windows may lead to successive U_k being large and of alternating sign, in turn leading to excessive statistical uncertainties in g just from propagation of the uncertainties in the binned counts C_k . On the

^{*}The mathematical procedure is that of FERDOR described in Ref. 48, except that the parameter (τ^2/NC) is set equal to unity.

other extreme, a poor match between imposed and synthetic windows leads to the fitting uncertainty described below. For this particular problem, the g 's were good estimates of the center of the output confidence intervals, but the FERD system actually seeks the confidence limits themselves.

Unless there is some a priori smoothness to the underlying spectrum $\Gamma(E)$, a large spike in Γ can occur just at some E' at which the imposed and synthetic windows are not equal. Thus, the confidence interval must be broader than that given by propagation of the counting uncertainties. In FERD the combination vector U is adjusted to obtain the two vectors U_{lo} and U_{up} , such that for every E we have

$$\sum_k U_{lo,k} R_k(E) \leq W(E) \leq \sum_k U_{up,k} R_k(E). * \quad (5.2)$$

The final confidence interval given by FERD, as an estimate of $g = \int \Gamma(E) W(E) dE$, has upper and lower ($\geq 2/3$) confidence limits as follows:

$$\begin{aligned} g_{up} &= \sum_k U_{up,k} C_k + \left(\sum_k U_{up,k}^2 S_k^2 \right)^{1/2} \\ g_{lo} &= \sum_k U_{lo,k} C_k - \left(\sum_k U_{lo,k}^2 S_k^2 \right)^{1/2}, \end{aligned} \quad (5.3)$$

where S_k is the estimated standard counting error in C_k . In general, this system for establishing the output confidence interval has the strength that if the user puts in a $W(E)$ which is an unreasonably sharp function of energy (so that there is difficulty in finding combinations of response functions which nearly match it), he is rewarded with an honest if remarkably broad confidence interval. For the present problem the system has the slight disadvantage that this component of uncertainty is

*The full FERD system accounts for uncertainties in the response function by maintaining these inequalities with whichever confidence limit of the response function leads to a "safer" upper and lower synthetic window. We have taken the upper and lower response matrices as equal, and have chosen to include elsewhere the propagation of systematic uncertainties in the response function.

almost surely overestimated, since both the complexity of the underlying spectrum and its broadening by the Doppler effect limit the error that could be made in the upper (lower) confidence limit if the synthetic window should dip below (rise above) the imposed one at some energy. Further, there is some expectation that a more optimal mathematical method could be chosen to trim the combination vector U to satisfy the synthetic window inequalities (Eq. 5.2).

In order to represent $W(E)$ and $R_k(E)$ in the numerical procedures, a set of "comparison points" must be distributed over the energy region studied. Experience seems to have shown that the output confidence limits become stable if at least three comparison point energies are spaced across each spectrometer resolution width. In this work, below 5 MeV, each pulse-height bin corresponded to no more than one resolution width, and three comparison points were chosen for the energy region corresponding to each pulse-height bin. At higher energies the bins were somewhat broader, so a greater density of points/bin was required. A total of 369 comparison points was chosen to cover the entire spectrum.

The main representation of the output spectrum was based on a choice of 130 quasi-normal window functions, each of which corresponded exactly to the peak part* of an $R_k(E)$, except that each was normalized to unit area. The energy points in the table in Appendix I and in Figs. 19-23 are the mean energies of these numerically derived window functions. This selection of windows was intended to assure that there would be no difficulty in matching these windows with combinations of response functions. The method worked quite well except at the highest energies, where the pulse-height bins were too broad to meet this criterion.

*For each spectrometer the response function contains a normal (or Gaussian) peak of appropriate width. The remainder of the function was set to zero, and the peak part was integrated over the pulse-height bin, just as in the bin response function. Because of the efficiency variation with energy, the resulting function is not necessarily centered at the energy corresponding to the center of the pulse-height bin.

A second set of window functions was employed to obtain the tables of energy-group absolute gamma-ray yields. If E_L and E_U are the two nominal ends of the energy group, then*

$$W(E; E_L, E_U) = \{\text{erf}[E - E_L, P_4(E_L)] - \text{erf}[E - E_U, P_4(E_U)]\} / 2$$

where

$$\text{erf}(x, P_4) \equiv [2 / (P_4 \sqrt{\pi})] \int_0^x \exp\{-\xi^2 / P_4^2\} d\xi.$$

Note that each set of such windows (based on sequences of contiguous energy regions E_L, E_U) for gamma-ray strength adds to unity. To obtain energy yields for each energy group, the above functions were multiplied through by E . Some of the windows for broad energy groups are illustrated in Figs. 19 and 20. The above window shape seemed natural for windows to define group structures, since at least on the low-energy side each window looks just like the sum of response functions for a series of neighboring channels. (In fact, experimental counts within the central region of such windows are weighed about equally in the final result for the corresponding g values.) Some of the narrower groups have seemingly undue sensitivity outside the nominal group limits, but this is the unavoidable consequence of the experimental energy resolution. The sums of neighboring broad-window functions maintain the appropriate (1 or E) sum.

The existence of three independent spectrometer systems was handled by including all of the observed counts in one count vector. It was then necessary to have bin response functions defined at all comparison energies for each of these counting bins. For the spectrometers designed for lower energies, responses were estimated up to 10 MeV. Some experimental data existed to guide these extensions; since the underlying spectrum falls off rapidly with energy, the exact form of the extensions was not critical.

*For each spectrometer system, $P_4(E)$ represents the breadth of the full energy peak in the pulse-height variable. In using this formula, appropriate transformations of variables were performed between pulse height and energy.

Fig. 19. Window Functions Used in the Present Work for Unfolding the Photon Intensity Within Broad Energy Regions. Alternate windows are shown as dashed lines for clarity. Each end of each dash is at a comparison energy used in the standard unfolding scheme. The four sets correspond to our results for the lower energy regions in Tables VI-3 through VI-6.

Fig. 20. Window Functions Used in the Present Work for Unfolding the Photon Intensity Within Broad Energy Regions. Alternate windows are shown as dashed lines for clarity. Each end of each dash is at a comparison energy used in the standard unfolding scheme. The four sets correspond to our results for the higher energy regions in Tables VI-3 through VI-6. Total area windows have the shape shown near their end points but are unity elsewhere.

VI. RESULTS AND CONCLUSIONS

A. GAMMA-RAY SPECTRUM

The photon spectral yield per fission is illustrated in Fig. 21 and tabulated in Appendix I. The low-energy portion of the spectrum is better represented by the linear plot in Fig. 22. In these figures the results are represented by the upper and lower $\geq 2/3$ confidence limits given by the FERD unscrambling program for carefully chosen quasi-normal window functions. These confidence intervals include statistical uncertainties in the data and the difficulties the FERD program has in finding synthetic windows which remain above and below the input window functions.* The intervals do not include the systematic uncertainties discussed in VI-B. Each figure includes a set of typical window shapes; recall that window shapes determine the energy resolution available in the results since the spectral yields approximate the energy integrals of the underlying photon spectrum weighted by these window functions. In Fig. 22 several peaks are apparent in the spectrum with widths comparable to the energy resolution. The lowest peaks at about 15.5 and 31.5 keV are properly placed to be K x-rays from the light and heavy fission fragments, respectively.

The results presented for this x-ray region (11 through 44 keV) were not obtained from the standard FERD analysis using all the count data, but instead from a similar analysis using a count vector obtained by manually subtracting the counts which seem to have arisen from photons of higher energy. In the standard processed pulse-height spectrum (all corrections performed except unscrambling) the lower energy x-ray peak sits atop a background (from spectrometer response "tails") having about three times its area, while the 32-keV peak has an area equal to that of the apparent background. The background number of counts/keV is almost the same in the valley between the peaks as below the lower group and

*Sixty to eighty percent of the confidence interval arose from propagation of statistical counting uncertainties, so $\geq 95\%$ confidence intervals would be 1.6 to 1.8 times as wide as those shown.

Fig. 21. The Energy Spectrum of Gamma Rays Emitted Within 69 nsec After Fission of ^{235}U by Thermal Neutrons. The two lines, which represent the random (largely propagated from counting statistics) $2/3$ confidence limits on the spectrum, are drawn as straight lines between adjacent mean window energies. Systematic uncertainties are given in Fig. 23. The nearly Gaussian shapes shown at the lower left and upper right illustrate typical windows used in unscrambling the result, and therefore indicate the energy resolution available in the result. These windows are drawn as straight lines between successive comparison energies.

Fig. 22. Low Energy Portion of the Energy Spectrum of Gamma Rays Emitted Within 69 nsec After Fission of ^{235}U by Thermal Neutrons. As in Fig. 21, the two lines represent the 2/3 confidence limits based on random uncertainties only. The two lines corresponding to the confidence limits coincide over most of the peaks at 0.016 and 0.031 MeV. The four nearly Gaussian dashed curves at the bottom illustrate the shape of typical window functions used in the unscrambling of the data, and comparisons of these with the data indicate that the observed peaks are only slightly wider than the spectrometer energy resolution. (Zero ordinate is raised for the window illustration.) For comparison, the experimental data of Verbinski et al. are shown with statistical uncertainties. (Private communication from V. V. Verbinski, 1969, of data given in Ref. 50.)

above the upper, so an essentially flat background was chosen to set the altered count spectrum to zero at these three points. We assumed, in essence, that the two apparent peaks are due to K x-ray emission from the light and heavy groups of fission fragments and that no other processes give rise to photons in the energy region 11 to 44 keV. (Our assumption that we have isolated the strengths of these x-ray groups is more defensible than the assumption that the "background" contains no photon continuum.) We chose this treatment of the data because otherwise the unscrambled photon spectrum did not show the lower edge of the lower x-ray group so apparent in the raw data. This difficulty occurs because absorption makes the efficiency at 11 keV quite low and uncertain, and the long tails of our response functions at low pulse heights are imperfectly known. The strengths of the x-ray groups may be obtained by integrating the results in Appendix I, or the same values may be obtained by hand conversion of the numbers of counts in each experimental peak. The results are (0.084 ± 0.018) light-fragment K x-rays per fission and 0.233 ± 0.018 heavy-fragment x-rays per fission.* (See further discussion of integral yields in Section VI-C.)

In the overlap energy regions between the spectrometers used (0.42 to 0.81 MeV and 1.6 to 2.4 MeV), we actually obtained results for a set of quasi-normal windows matching the peaks of the response matrix of each spectrometer. The division points for the published results are at 0.74 and 1.8 MeV. In the low-energy overlap region there is no marked disagreement between the results for the windows of different width, but the broader "Compton" windows average over the structure below 0.65 MeV. Above 0.74 MeV there is no observed structure, and the windows matching the Compton spectrometer response yield a narrower confidence interval. Above 1.8 MeV the broader Compton-spectrometer windows give essentially the same result as the pair-spectrometer windows, but the results for the "pair" windows were used because these windows are so much narrower and

*If the standard count vector were employed, the number of photons/fission in the 21- to 44-keV region would be estimated as 0.28 ± 0.04 . For the 10- to 21-keV region one would obtain about 0.28 ± 0.10 .

the resulting confidence intervals were not much broader. Below 1.7 MeV, the results from the narrower "pair" windows rise above the quoted values until at 1.6 MeV the mean values differ by about twice the linear sum of the quoted uncertainties. These higher values were controlled by the high weights assigned by FERD to the counting results from the pair spectrometer.* We chose the lower values because otherwise a nonphysical discontinuity would result and because the very low efficiency of the pair spectrometer at 1.6 MeV implies that any small undetermined systematic error in the pair-spectrometer pulse-height spectrum would lead to a relatively large error in the output photon spectrum.

Count data for the entire overlap region indicated above were retained and were automatically weighted by FERD into the results for the windows used. It was possible to broaden or narrow the breadth of the data overlap regions, and inclusions of more or less data generally affected the answers in and near the overlap areas. These changes were presumed to reflect the most important of the systematic uncertainties in the experiment, and they appear to be covered by the numerical estimates given below.

B. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties affect the results of Figs. 21 and 22 and Appendix I. The systematic uncertainties are generally a function of photon energy, but they enter in the same sense through a broad energy region or perhaps even the entire spectrum. We have assumed that the various systematic uncertainties are orthogonal and tend to cancel when combined. Tables VI-1 and VI-2 give estimated standard systematic errors for the three spectrometers, and Fig. 23 illustrates the overall result of the analysis. (The uncertainties are shown as errorless, but, in fact, we can only hope that the uncertainty in estimated confidence intervals is as little as 20%.) Our best estimate of the full $2/3$ -confidence interval at any point in the spectrum can be obtained by combining (root sum of squares) the "Total" value from Fig. 23 with the uncertainty tabulated in Appendix I.

*Approaching the pair-production threshold, the energy resolution of the pair spectrometer becomes much narrower than that of the Compton spectrometer. For narrow windows, this led to the high weights.

Table VI-1. Systematic Uncertainties for Single-Crystal Spectrometer

Cause of Error	Photon Energy (keV)						
	10	20	50	100	200	400	700
	Amount of Error (%)						
Peak efficiency ^a	12	5	4	6	5	5	5
Tail fraction ^b	-	-	19	4	3.5	2.2	2
Photon transmission through fission chamber ^a	20	4	2	1	n ^c	n	n
Bin width ^d	2.5	2.5	2.5	2.5	1.0	0.5	0.5
Coincidence circuit Loss ^e	5	3	1	n	n	n	n
Chance coincidence background	0.4	n	n	n	n	n	n
Singles count loss	←————— n —————→						
Coincidence count loss	←————— 0.3 —————→						
Neutron background	←————— 1 —————→						
Fission fragment anisotropy	←————— 1 —————→						
Nonuniform irradiation of uranium foils ^a	4	1.5	0.3	n	n	n	n

^aFigure 23 combines these uncertainties under "peak efficiency."

^bSee text for explanation of the special data treatment below 44 keV. In the 50 to 500 keV region, the % uncertainty fluctuates with energy, but the absolute uncertainty varies smoothly from 0.20 to 0.12 photons.fission⁻¹.Mev⁻¹ through this interval.

^cn = negligible or < 0.3%.

^dError not applicable for sum over all energies.

^eAlready in count vector uncertainties.

Table VI-2. Systematic Uncertainties for Pair and Compton Spectrometers

Cause of Error	Photon Energy (MeV)									
	0.5	1.0	1.5	2	1.6	2	4	6	8	10
	Compton				Pair					
	Amount of Error (%)									
Peak efficiency	5	3.2	2.6	3.0	1.9	2.3	2.3	6	14	50
Spectrometer re- sponse "tail" ^a	0.8	1.2	1.1	1	0.2	0.3	1	2	2	2
Photon transmission ^b through fission chamber	0.9	0.6	0.6	0.6	0.6	0.6	0.4	0.4	0.3	0.3
Bin width ^c	2.0	1.0	0.7	0.5	1.7 ^d	1.3 ^d	0.7 ^d	0.7 ^d	0.7 ^d	0.7 ^d
Chance coincidence background	0.2	0.2	0.2	0.4	0.4	0.4	0.8	4.5	10	?
Singles count loss	← 0.3 →				← 0.5 ^d →					
Coincidence count loss	← 0.6 →				← 1.3 ^d →					
Neutron background	← 2 →				← 1 →					

^aThese are the uncertainties introduced in the overall solution by the tail of the listed spectrometer. In fact, these response tails affect results far outside the energy range of each spectrometer, though not to the extent of dominating the total systematic error there.

^bAlready included in "peak efficiency" uncertainty.

^cError not applicable for sum over all energies.

^dFor low-gain run.

Fig. 23. Systematic or Correlated Uncertainties in the Prompt-Fission Gamma-Ray Spectrum as a Function of Gamma-Ray Energy. The various significant contributions are labeled on the graph. The discontinuity at 1.6 MeV arises because this is the lowest energy at which information from the pair spectrometer is used. The uncertainty due to tail subtraction is shown only at isolated points below 400 keV since it is approximately constant at $\sim 0.10 \text{ photons} \cdot \text{fission}^{-1} \cdot \text{MeV}^{-1}$, and so the percentage uncertainty fluctuates rapidly at low energies in accordance with the peaks and valleys of the gamma-ray spectrum.

The spectrometers were designed so that the relatively easily understood uncertainties in the peak efficiencies would be the most important response function errors. Below 15 keV a large uncertainty is induced by difficulties in estimating or measuring the absorption of materials along the γ -ray flight path, while above 7 MeV the peak efficiency becomes poorly known because the pair spectrometer peak/total ratio was extrapolated into this region. Between these extremes three clues were utilized in estimating the values of the uncertainties: (a) the scatter in measured absolute peak efficiencies around the interpolating line used in the analysis; (b) the output covariance matrix from the least-squares interpolation procedure which used input data having uncertainties propagated from the observed pulse-height spectra;* and (c) in the region (about 0.4 to 2.4 MeV) where the spectrometer systems overlapped, the sensitivity of the result to the size of the overlap region used. Generally, these clues agreed within a factor of two; the tabulated and plotted values reflect a judicious compromise.

Bin-width uncertainties essentially reflect uncertainties in the system nonlinearity; these uncertainties are reduced percentagewise as larger and larger energy intervals are contemplated. These estimates are as large as 2.5% in the low-energy region where the nonlinearity of NaI(Tl) becomes an issue. This uncertainty is relatively most important at 100 keV, but even there it does not have much effect.

Uncertainty in the extent of uncompensated neutron background is discussed in Section IV. It was surely the uncertainty most difficult to estimate. In the restricted range from 0.8 to 1.8 MeV it affects the overall systematic uncertainty.

*If $V(\underline{d})$ is the variance matrix of the interpolation parameters $\underline{d}$ which affect the spectrometer efficiency $P_3(E)$, and if $\underline{h}$ is the vector of derivatives of the fitted efficiency with respect to these same parameters ($h_i = \partial P_3 / \partial d_i$), then the variance of the efficiency at E may be estimated by $V(P_3) = \underline{h}^T V(\underline{d}) \underline{h}$. For this purpose variance matrices based on uncertainties input to the fits were multiplied by the values of chi-square over the number of "degrees of freedom."

A most complex systematic difficulty arises from uncertainties in the response of each spectrometer at low pulse height from photons of higher energy. Indeed, one seldom sees adequate propagated error estimates for this feature of response functions. Since our spectrometers were designed to optimize peak/total ratios, we expected to see large tail effects in the unscrambling only for energies below 1 MeV; this proved to be the case. Using the first two types of clues described under peak efficiency uncertainties, we first obtained an energy-dependent relative uncertainty in the magnitude of each important feature of the spectrometer tail response. (For the single crystal, two examples are the Compton continuum and the backscatter peak.) For each such feature we then generated a perturbed spectrometer response matrix in which that feature was increased by one standard error over the whole range of photon energies; an approximation unless this feature of the spectrum is dominated by a single parameter. The whole spectrum was then unscrambled using the perturbed matrix for that spectrometer and the normal matrix for the other two spectrometers. The overall effect was assessed by observing the shifts in the output estimates. Below 1 MeV, tail-fraction effects were significant; below 400 keV, they were important; and below 70 keV, they became dominant. In the "important" region the uncertainty is not conveniently expressed as a percentage because there is structure in the spectrum and the uncertainty is a smoothly varying number of photons/fission. (The dominant tail uncertainty is the Compton continuum for the single-crystal spectrometer.)

The spectral results above and in Section VI-C were obtained using response matrices and window functions defined at 369 comparison energies, about three per window. To assure ourselves that the mesh fineness was not affecting the results, the unscrambling process was repeated with about 5 comparison energies for each window (585 energies in all). For a large share of the windows the results were unchanged to 0.2%, and in no case was a result shifted by more than 12% of the corresponding FERD confidence interval.

C. INTEGRAL GAMMA-RAY YIELDS

The number of photons·fission⁻¹ emitted over the energy interval from 10 keV to 10.5 MeV within 69 nsec after fission was determined, by integration of the data in Appendix I, to be 8.13 ± 0.35 ; 0.05 of the error arises from the statistical and other random errors and 0.34 from systematic uncertainties. The corresponding energy yield was 7.25 ± 0.26 MeV·fission⁻¹ with 0.03 MeV uncertainty from random and 0.25 MeV from systematic errors.* These results yield an average energy per photon from fission of (0.89 ± 0.05) MeV over the photon energy range from 0.01 to 10.5 MeV.

The energy yield per fission from photons below 10 keV and above 10.5 MeV should be negligible. The number of photons·fission⁻¹ below 10 keV probably does not exceed 0.1 (mostly L-shell x-rays), and none are expected above 10.5 MeV. A small portion (perhaps 10%) of the light-fragment K x-ray yield may have been missed by virtue of our 69 nsec coincidence resolving time since Birdwell and Wyman³ report that 29% of the light-fragment x-rays have an "average" half life of ~ 75 nsec. The "loss" would be 0.008 photons·fission⁻¹ which is negligible compared to our estimated errors.

Combination of the gamma-ray spectral data into wider and fewer bins than those of Appendix I may be useful for computations based on these data. Results are tabulated here since the use of FERD as described in Section V not only simplified the manipulation of the many figures but also gives a more definite answer and a more sensible uncertainty estimate than can be obtained by combining the results from the quasi-normal windows. As illustrated in Figs. 19 and 20, the wider windows approach a rectangular shape with slightly rounded edges, while some of the windows used never attain unit amplitude. The sum obtained by adding the contents of adjacent bins does not have its expectation value affected by this rounding of the edges (see Section V).

*Except for the region below 48 keV, the integral photon and energy yields were determined using FERD with window functions essentially equal to 1 and E; the FERD confidence limits gave the "random uncertainties" referred to in the text. If the integral yields are instead taken from sums over the data in Appendix I, one obtains the negligibly different values 8.16 photons/fission and 7.26 MeV/fission. The systematic components were obtained by averaging over the photon spectrum the appropriate components from Fig. 23.

The first or "narrow" set of 16 bins, shown with photon and energy yields in Table VI-3, gradually increases in width with increasing photon energy. Note that the results in these tables are per bin, not per MeV. The second set of bins, Table VI-4, consists of only eight quite coarse energy groups. The third set, shown in Table VI-5, corresponds to a set of energy intervals which have been used often in calculating gamma-ray attenuations from reactor sources.⁴⁹ Some of these bins are "too narrow," in that the corresponding window shapes in Fig. 20 are not accurately rectangular. Finally, the set of Table VI-6 is shown to allow a comparison with the data of Verbinski et al.⁵⁰ In Tables VI-3 through VI-6 uncertainties shown are estimated for the 2/3 confidence interval and include systematic uncertainties, while the values in parenthesis give the FERD output confidence intervals. The systematic uncertainties dominate except at high energies.

D. COMPARISON WITH OTHER MEASUREMENTS

In Fig. 24 we show a comparison of the gamma-ray spectrum from Fig. 21 with the results of our preliminary analysis of part of the data. The two spectra are remarkably consistent above 0.7 MeV considering the systematic errors in the preliminary analysis. Large changes are seen below 0.7 MeV as we predicted when the low-energy preliminary analysis was published.⁵¹

Figures 22 and 25 show a comparison of our spectrum with the recent results of Verbinski et al.⁵⁰ These authors used a large NaI scintillation spectrometer with an anticoincidence mantle to study fission photons produced in samples of ^{235}U , ^{239}Pu , and ^{252}Cf by thermal neutrons from a reactor. Time of flight was used to exclude neutron backgrounds. Their results for the high-energy region for ^{235}U , shown in Fig. 25, agree rather well in

⁴⁹H. C. Claiborne, private communication. For an example, see H. C. Claiborne and D. K. Trubey, "Dose Rates in a Slab Phantom from Monoenergetic Gamma Rays," ORNL-TM-2574 (April 28, 1969); to be published in Nuclear Applications, May 1970.

⁵⁰V. V. Verbinski et al., "Measurement of Prompt Gamma-Rays from Thermal-Neutron Fission of ^{235}U and ^{239}Pu , and from Spontaneous Fission of ^{252}Cf ," DASA Report No. 2234 (GA-9148) (April 5, 1969).

⁵¹T. A. Love, F. C. Maienschein, and R. W. Peelle, "Preliminary Results from a Determination of the Low-Energy Portion of the Gamma-Ray Spectrum Emitted Promptly After Fission of ^{235}U by Thermal Neutrons," ORNL-2842, p. 93 (1959).

Table VI-3. Photon Yields per Fission

Energy Range (MeV)	Photons·Fission ⁻¹	MeV·Fission ⁻¹
0.010 - 0.021	0.084 ± 0.018 (.005) ^a	0.0013 ± 0.0003(.0001) ^a
0.021 - 0.044	0.233 ± 0.018 (.003)	0.0074 ± 0.0006(.0001)
0.044 - 0.100	0.121 ± 0.012 (.003)	0.010 ± 0.001 (.0002)
0.10 - 0.20	0.651 ± 0.046 (.005)	0.099 ± 0.007 (.001)
0.20 - 0.30	0.548 ± 0.031 (.005)	0.135 ± 0.008 (.001)
0.30 - 0.45	1.033 ± 0.048 (.007)	0.390 ± 0.018 (.003)
0.45 - 0.70	1.710 ± 0.074 (.012)	0.976 ± 0.043 (.007)
0.70 - 1.0	1.305 ± 0.058 (.013)	1.088 ± 0.047 (.012)
1.0 - 1.5	1.170 ± 0.050 (.017)	1.424 ± 0.060 (.020)
1.5 - 2.0	0.535 ± 0.024 (.018)	0.919 ± 0.042 (.032)
2.0 - 2.5	0.316 ± 0.019 (.017)	0.703 ± 0.041 (.036)
2.5 - 3.0	0.189 ± 0.011 (.009)	0.515 ± 0.029 (.025)
3.0 - 4.0	0.159 ± 0.006 (.004)	0.546 ± 0.023 (.015)
4.0 - 5.0	0.057 ± 0.003 (.002)	0.253 ± 0.014 (.010)
5.0 - 6.0	0.0194 ± 0.0025(.0022)	0.106 ± 0.014 (.012)
6.0 - 7.2	0.0093 ± 0.0022(.0020)	0.060 ± 0.013 (.012)
7.2 - 10.5	0.0005 ± 0.0012(.0012)	0.004 ± 0.009 (.009)
0.010 - 10.5	8.13 ± 0.35 (.05)	7.25 ± 0.26 (.03)

^a Contribution due to random uncertainties in parentheses.

Table VI-4. Photon Yields per Fission in Broad Energy Groups

Energy Range (MeV)	Photons·Fission ⁻¹	MeV·Fission ⁻¹
0.021 - 0.100	0.35 ± 0.03 (.02) ^a	0.017 ± 0.002(.001) ^a
0.1 - 0.3	1.20 ± 0.08 (.007)	0.234 ± 0.015(.001)
0.3 - 0.6	2.10 ± 0.10 (.010)	0.952 ± 0.044(.005)
0.6 - 1.0	1.95 ± 0.09 (.016)	1.50 ± 0.07 (.013)
1.0 - 1.8	1.52 ± 0.06 (.022)	2.00 ± 0.08 (.030)
1.8 - 3.0	0.689 ± 0.025(.012)	1.57 ± 0.05 (.026)
3.0 - 5.0	0.217 ± 0.008(.004)	0.799 ± 0.031(.016)
5.0 - 7.2	0.029 ± 0.003(.0019)	0.166 ± 0.018(.011)
0.021 - 7.2	8.05 ± 0.34 (.050)	7.23 ± 0.26 (.027)

^aContribution due to random uncertainties in parentheses.

Table VI-5. Photon Yields per Fission for Energy Groups as Shown^a

Energy Range (MeV)	Photons·Fission ⁻¹	MeV·Fission ⁻¹
0.021 - 0.200	1.00 ± 0.07 (.02) ^b	0.116 ± 0.008(.001) ^b
0.20 - 0.40	1.24 ± 0.06 (.007)	0.381 ± 0.019(.002)
0.40 - 0.60	1.41 ± 0.06 (.008)	0.706 ± 0.031(.004)
0.60 - 0.90	1.60 ± 0.07 (.016)	1.17 ± 0.05 (.012)
0.90 - 1.35	1.28 ± 0.05 (.019)	1.41 ± 0.06 (.023)
1.35 - 1.80	0.593 ± 0.027 (.018)	0.910 ± 0.041(.028)
1.8 - 2.2	0.331 ± 0.014 (.011)	0.655 ± 0.028(.021)
2.2 - 2.6	0.215 ± 0.011 (.009)	0.513 ± 0.028(.024)
2.6 - 3.0	0.144 ± 0.010 (.009)	0.398 ± 0.027(.025)
3.0 - 3.5	0.097 ± 0.005 (.0045)	0.314 ± 0.017(.015)
3.5 - 4.0	0.0623 ± 0.0039(.0034)	0.233 ± 0.015(.013)
4.0 - 4.5	0.0393 ± 0.0029(.0025)	0.166 ± 0.013(.011)
4.5 - 5.0	0.0186 ± 0.0020(.0018)	0.087 ± 0.009(.008)
5.0 - 5.5	0.0117 ± 0.0040(.0040)	0.061 ± 0.021(.021)
5.5 - 6.0	0.0079 ± 0.0045(.0045)	0.045 ± 0.025(.025)
6.0 - 6.5	0.0052 ± 0.0023(.0023)	0.032 ± 0.014(.014)
6.5 - 7.0	0.0035 ± 0.0023(.0023)	0.023 ± 0.015(.015)
7.0 - 8.0	0.0009 ± 0.0018(.0018)	0.006 ± 0.014(.014)
8.0 - 10.0	0.0005 ± 0.0007(.0007)	0.005 ± 0.006(.006)

^aUsed in Ref. 49, for example.^bContribution due to random uncertainties in parentheses.

Table VI-6. Comparison of Photon Yields per Fission

Energy Range (MeV)	Photons·Fission ⁻¹		MeV·Fission ⁻¹	
	ORNL	GA ^a	ORNL	GA ^a
0.14 - 0.30	0.95 ± 0.06 (.006) ^b	0.83	0.203 ± 0.012(.001) ^b	0.181
0.3 - 0.5	1.41 ± 0.07 (.008)	1.32	0.569 ± 0.026(.003)	0.53
0.5 - 0.7	1.33 ± 0.06 (.011)	1.18	0.797 ± 0.036(.007)	0.71
0.7 - 1.0	1.30 ± 0.06 (.013)	1.19	1.088 ± 0.049(.012)	1.02
1.0 - 1.5	1.170 ± 0.050(.017)	1.07	1.424 ± 0.059(.020)	1.34
1.5 - 2.0	0.535 ± 0.024(.018)	0.46	0.919 ± 0.042(.032)	0.80
2.0 - 2.5	0.316 ± 0.019(.017)	0.26	0.703 ± 0.041(.036)	0.58
2.5 - 3.0	0.189 ± 0.010(.009)	0.16	0.515 ± 0.029(.025)	0.43
3.0 - 4.0	0.159 ± 0.006(.004)	0.143	0.546 ± 0.022(.015)	0.49
4.0 - 5.0	0.058 ± 0.003(.002)	0.050	0.252 ± 0.014(.010)	0.22
5.0 - 6.0	0.019 ± 0.003(.002)	0.021	0.106 ± 0.014(.012)	0.116
6.0 - 7.0	0.009 ± 0.003(.003)	0.0098	0.055 ± 0.017(.016)	0.064
7.0 - 10.0	0.001 ± 0.002(.002)	0.0027	0.010 ± 0.015(.015)	0.019
0.14 - 10.0	7.45 ± 0.32 (.02)	6.69±0.3	7.18 ± 0.26 (.03)	6.51±0.3

^aV. V. Verbinski et al., "Measurement of Prompt Gamma Rays from Thermal-Neutron Fission of ²³⁵U and ²³⁹Pu, and from Spontaneous Fission of ²⁵²Cf," DASA Report No. 2234 (GA-9148) (April 5, 1969).

^bContribution due to random uncertainties in parentheses.

Fig. 24. Comparison of the 1958 Preliminary Analysis with Final Results for the Energy Spectrum of Gamma Rays Emitted Within 69 nsec After Fission of ^{235}U by Thermal Neutrons. The final data are taken from Fig. 21, while the crosses give the 1958 results. The straight lines illustrate a piecewise exponential approximation to the spectrum (see section VI-F).

Fig. 25. Comparison of Results of this Paper with the Experiment of Verbinski *et al.* and the Calculations of Zommer *et al.* The present results are taken from Fig. 21. For comparison, the experimental data of Verbinski *et al.* are shown with statistical uncertainties. (Private communication from V. V. Verbinski, 1969, of data given in Ref. 50.) The dashed curve is the prediction of Zommer based on statistical theory.

shape with ours. The largest disagreements appear in the 1.7- to 2.7-MeV region. The low-energy part of the spectrum shown in Fig. 22 contains, except at ~ 150 keV, the same peaks as our spectrum though the magnitudes differ. The data for the energy regions shown in Table VI-6 allow a numerical comparison which indicates that our results are typically about 10% higher than those of Verbinski et al. A most probable cause of this disagreement, which is barely significant, is the determination of the response functions and subsequent unscrambling for the two experiments. At low energies the shorter time intervals included by Verbinski et al. could have excluded some slightly delayed radiations.

Some idea of the detail in the low-energy part of the spectrum may be gained from the measurements of Horsch and Michaelis.⁵² Their spectrum was determined by a Ge(Li) detector operated in coincidence with the signals from two solid-state fission detectors which served to define the mass of the fission fragments producing the photons and to reduce Doppler broadening. These fragment-dependent spectra show ~ 35 gamma rays below 600 keV. The yields were not determined. The peaks in our spectra, which include all angles between photon and fragment directions, would be Doppler broadened by an amount about one-half of the energy resolution. Even taking into account our broader energy resolution, correlations with the Horsch spectra are very evident only near 200 and near 600 keV.

The spectra of Rau,¹⁸ obtained with two different upper energy limits, are not shown since they are not internally consistent.

The integral yields of photons per fission and the energy releases per fission are summarized in Table VI-7. Our results are consistent within error with our preliminary analysis, but results of the reanalysis reported here should be used. The General Atomic yields are lower than ours.* Rau's photon energy release per fission appears quite high and his error assessment is surely too low.

⁵²F. Horsch and W. Michaelis, "Prompt Gamma Rays Emitted from Individual Fragments in Neutron-Induced Fission," SM-122/44, International Atomic Energy Agency Second Symposium on the Physics and Chemistry of Fission, Vienna, 28 July - 1 August 1969.

*If the stated uncertainties are taken to reflect normal error distributions, there would be a 10% chance of a difference in results being at least this large.

Table VI-7. Integral Yields of Photons
and Photon Energy per Fission

Energy Range (MeV)	Photons·Fission ⁻¹	MeV·Fission ⁻¹	Reference
0.010 - 10.5	8.13 ± 0.35	7.25 ± 0.26	This work
0.14 - 10.0	7.45 ± 0.32	7.18 ± 0.26	This work
0.14 - 10.0	6.69 ± 0.3	6.51 ± 0.3	a
0.1 - 10.0	7.95 ± 0.25	9.51 ± 0.23	b
0.1 - 7.6	7.5	7.5	c
0.3 - 10.5	7.4 ± 0.8	7.2 ± 0.8	d

^aV. V. Verbinski et al., "Measurement of Prompt Gamma-Rays from Thermal-Neutron Fission of ²³⁵U and ²³⁹Pu, and from Spontaneous Fission of ²⁵²Cf," DASA Report No. 2234 (GA-9148) (April 5, 1969).

^bV. F. E. W. Rau, *Annalen der Phys.* 10, 252 (1963).

^cR. L. Gamble, Dissertation, University of Texas, 1955.

^dF. C. Maienschein et al., *Proc. U.N. International Conf. on Peaceful Uses of Atomic Energy*, Second Geneva Conference, 15, 366 (1958); R. W. Peelle et al., *Pile Neutron Research in Physics*, International Energy Agency, Vienna, p. 273, 1962.

Our x-ray yields are compared in Table VI-8 with those of other investigators which were summarized by Kapoor.⁵³ Our yields lie below the average of the other widely discrepant values. Uncertainties introduced by incorrectly assessed backgrounds due to fission neutrons and higher energy photons and due to photon absorptions may account for failure of the various results to agree within the quoted standard errors. A comparison of the x-ray yields with what might be expected from the observed gamma-ray spectrum shows only that all the transitions cannot be electric dipole, since under an E1 assumption only half as many x-rays would occur. Essentially all the predicted yield results from transitions of less than 200 keV.

E. COMPARISON WITH THEORY

Historically, as the theory of fission has developed, more energy emission in the form of electromagnetic radiation has been predicted.

Leachmann, in 1956, on the basis of a simple neutron evaporation model predicted $3.8 \text{ MeV} \cdot \text{fission}^{-1}$ as the residual photon energy after neutron emission.¹¹ His approach was generalized by Terrell, who predicted $4.9 \text{ MeV} \cdot \text{fission}^{-1}$ in 1959.¹² Both of these calculations gave predictions of the neutron spectrum in good agreement with measurements.

Zommer et al., in 1965, attempted a calculation of the gamma-ray spectrum from thermal-neutron-induced fission of ^{235}U using statistical theory to account for the neutron evaporation.¹⁰ They assumed all electric dipole transitions, identical radial matrix elements for all states of a given nucleus together with plausible values for the fragment binding energies, mass and charge distributions, nuclear level densities, and radiation widths. They obtained $\sim 6.2 \text{ MeV}$ per fission and a spectrum which is exponential to $\sim 4 \text{ MeV}$ and then drops much more rapidly with increasing energy as is illustrated in Fig. 25. The agreement of the predicted spectrum with our measurement below 4 MeV is quite remarkable. Zommer et al. attributed the failure of their calculations to predict

⁵³S. S. Kapoor, V. S. Ramamurthy, and R. Zaghoul, "Yield of K X-Rays Emitted from ^{236}U Fragments," Bhabha Atomic Research Centre, Bombay, India (B.A.R.C.-363) (1968).

Table VI-8. K-Shell X-Ray Yield from Thermal-Neutron Induced Fission of ^{235}U

Yield of K X-Ray per Fission		
From Light Fragments	From Heavy Fragments	Reference
0.084 ± 0.018	0.233 ± 0.018	this work
$0.043 \pm (0.011)$	$0.12 \pm (0.03)$	a
0.12 ± 0.03	0.20 ± 0.05	b
0.17 ± 0.02	0.43 ± 0.04	c
0.10 ± 0.03	0.42 ± 0.12	d
0.18 ± 0.06	0.34 ± 0.09	e
0.08 ± 0.01	0.30 ± 0.02	f

^aL. E. Glendenin, H. C. Griffin, W. Reisdorf, and J. P. Unik, "High-Resolution Studies of K X-Ray Emission and the Distribution of Mass and Nuclear Charge in the Thermal-Neutron-Induced Fission of ^{233}U , ^{235}U and ^{239}Pu ," Second IAEA Symposium on Physics and Chemistry of Fission Proceedings, Vienna, 28 July-1 August 1969 (IAEA-SM-122/114). The effective time of observation for this measurement was only $\sim$ one nsec. Errors estimated by us on the basis of the description in the reference. The later values in the table come from experiments with increasingly longer resolving times.

^bB. W. Wehring and M. E. Wyman, *Phys. Rev.* 157, 1803 (1967).

^cL. Bridwell, M. E. Wyman, and B. W. Wehring, *Phys. Rev.* 145, 463 (1966).

^dV. V. Sklyarevskii, E. P. Stepanov, and B. A. Medvedev, *JETP* 9, 225 (1959).

^eV. P. Eismont and Yurgenson, *Soviet Journal of Nucl. Phys.* 5, 852 (1967).

^fS. S. Kapoor, V. S. Ramamurthy and R. Zaghoul, "Yield of K X-Rays Emitted from ^{235}U Fragments," Bhabha Atomic Research Centre, Bombay, India (B.A.R.C.-363) (1968).

enough total energy emission to the inclusion of too many levels near the ground states of the fragment nuclei, and thus to too low an average excitation energy of the fragments just prior to gamma-ray emission. They also recognize the possible increase in gamma-ray energy emission due to the high angular momenta of the fragments.

Thomas and Grover¹⁴ in 1967 made calculations to test this hypothesis that photon emission is enhanced in fission-fragment deexcitation due to the large angular momenta of the fragments. For fragment nuclei with excitation energies above the neutron-separation energy, neutron emission may be inhibited by the requirement to carry away a large orbital angular momentum. Thomas and Grover emphasize the partition of energy between neutrons and photons. Their result, ignoring the angular momentum effects, is < 5 MeV; but including it, they obtain 7.1 MeV/fission, in agreement with our measured value.

In an evaluation by Monte Carlo of the energy balance in the fission of ^{235}U , Gordan and Aras obtained 7.66 MeV/fission for the sum of all photon emission prior to beta decay.⁵⁴ They attribute the good agreement with the results of this experiment to the use of the pairing-energy correction in the level density formula as a change in the effective Q -value for neutron emission.

F. APPROXIMATIONS TO THE GAMMA-RAY SPECTRUM

For use of the prompt-fission gamma-ray spectrum in reactor shielding or other calculations, a simple analytical approximation may be adequate. A segmented exponential fit to our earlier results^{7,8} gives a total energy within a few percent of that indicated by the final analysis of the experimental data. Especially in the energy region near 1.2 MeV, a better fit to our final gamma-ray spectrum, $\Gamma(E)$ (in photons·fission⁻¹·MeV⁻¹), is given by:

⁵⁴G. E. Gordon and N. K. Aras, "The Energy Balance in Fission and Monte Carlo Calculations on Prompt-Neutron Emission," Physics and Chemistry of Fission, Vol. II, Proceedings of the Symposium on Physics and Chemistry of Fission, Salzburg, 22-26 March 1965, International Atomic Energy Agency, Vienna, Paper No. SM-60/48.

$$\Gamma(E) = \begin{cases} 6.6 & 0.1 < E < 0.6 \text{ MeV} \\ 20.2 e^{-1.78E} & 0.6 < E < 1.5 \text{ MeV} \\ 7.2 e^{-1.09E} & 1.5 < E < 10.5 \text{ MeV} \end{cases} \quad (6.1)$$

These equations are illustrated in Fig. 24. The table below shows close agreement between Eq. 6.1 and the experimental results.

Energy Range MeV	Photons/Fission		MeV/Fission	
	Eq. 6.1	Experiment	Eq. 6.1	Experiment
0.1 - 0.6	3.30	3.30	1.16	1.19
0.6 - 1.5	3.11	3.12	2.91	2.92
1.5 - 10.5	1.29	1.29	3.11	3.11

Equation 6.1 agrees with the experimental spectrum plus uncertainty to within 10% from 0.6 to 7.5 MeV except at 1.2 and ~ 5.0 MeV, where it deviates about 16%. The constant yield agrees with experiment from 0.1 to 0.6 MeV to within ~ 20% except at 0.26 MeV.

To correspond to a compromise between our spectrum and that of Verbinski et al., Eq. (6.1) was modified as follows:

$$\Gamma(E) = \begin{cases} 6.3 & 0.1 < E < 0.6 \text{ MeV}, \\ 17.1 e^{-1.67E} & 0.6 < E < 1.7 \text{ MeV}, \\ 5.87 e^{-1.04E} & 1.7 < E < 10 \text{ MeV}. \end{cases} \quad (6.2)$$

An approximation for the energy region below 0.6 MeV (0.01 to 0.6 MeV), which may be adequate for shielding calculations, is the emission of 3.74 photons/fission of average energy 0.324 MeV.

VII. ACKNOWLEDGMENTS

The authors of this report wish to acknowledge the essential contributions of the associated authors. T. A. Love participated in all aspects of instrument development, source-strength determinations, and in obtaining the experimental data. R. O. Chester played a leading role in developing the nonlinear fitting programs used to parameterize the spectrometer responses, and, more important, in finding suitable fitting functions and applying these to the calibration data. W. Zobel used his expert knowledge of spectrum unscrambling to carry out the actual spectrometer response-function generation and spectral data unfolding.

K. M. Henry, R. G. Cochran, E. B. Johnson, and J. D. Flynn aided in providing neutrons from the Bulk Shielding Reactor and sometimes in watching the spectrometer system during long runs. The late J. D. Kington set up the low-voltage accelerator used in the $^{11}\text{B}(\text{p},\gamma)$ calibration. R. K. Abele and his group provided fission chambers and advice on their use, while the spectrometer mechanical designs were furnished by H. J. Strippling, R. L. Simpson, T. F. Sliski, and the late F. R. Duncan. W. S. Lyon provided chemical analyses of the contents of the fission chambers as well as consultation concerning the ionization chambers used in source-strength determinations. The unfolding was made possible by use of the FERD method of W. R. Burrus, who freely gave advice concerning its wise use. H. Weaver, O. W. Christian, and others aided in many ways the experimental effort.

The final analysis was made possible by the interest of John Malik and the Los Alamos Scientific Laboratory.

APPENDIX I.
MEASURED PHOTON YIELDS PER FISSION IN QUASI-NORMAL WINDOWS

The mean energy of each window is shown in the first column below. The windows for energies through 0.74 MeV match the shapes of the peaks of the single-crystal spectrometer response functions. From 0.74 through 1.8 MeV, the window shapes match the response of the Compton spectrometer. Above 1.8 MeV, the window shape matches that of the pair spectrometer, except that above 5.3 MeV the effective resolution is markedly broadened by the relatively wide pulse-height bins used.

The second column gives the photon yield per fission and per MeV. The 2/3 confidence limits shown do not include systematic uncertainties. Systematic uncertainties are included in the results given for wider windows in Table VI-3 through VI-6 and are displayed in Fig. 23.

For energies ≥ 0.049 MeV, the results were obtained from a simultaneous analysis of all of the available data. For energies below 0.049 MeV, the results were obtained from pulse-height data by assuming a flat tail in this energy region due to higher energy gamma rays.

Average Window Energy (MeV)	Photon Yield (photons·fis- sion ⁻¹ ·MeV ⁻¹)	Average Window Energy (MeV)	Photon Yield (photons·fis- sion ⁻¹ ·MeV ⁻¹)
0.0117	5.1 ± 9.9	0.054	1.07 ± 0.32
0.0133	13.2 ± 2.4	0.060	1.42 ± 0.20
0.0155	12.9 ± 1.5	0.066	1.58 ± 0.13
0.018	7.1 ± 1.0	0.073	1.57 ± 0.16
0.021	0.9 ± 0.8	0.080	2.30 ± 0.17
0.025	5.7 ± 0.6	0.087	2.51 ± 0.17
0.029	19.4 ± 0.6	0.094	4.13 ± 0.17
0.033	20.8 ± 0.6	0.102	5.03 ± 0.16
0.038	7.2 ± 0.5	0.111	5.53 ± 0.17
0.043	0.4 ± 0.4	0.119	6.77 ± 0.16
0.049	1.0 ± 0.4	0.127	7.00 ± 0.16

Average Window Energy (MeV)	Photon Yield (photons·fission ⁻¹ ·MeV ⁻¹)	Average Window Energy (MeV)	Photon Yield (photons·fission ⁻¹ ·MeV ⁻¹)
0.136	6.76 ± 0.15	0.593	8.18 ± 0.22
0.146	7.58 ± 0.15	0.613	7.56 ± 0.22
0.156	7.24 ± 0.15	0.633	6.36 ± 0.23
0.166	6.57 ± 0.15	0.653	5.90 ± 0.23
0.176	5.43 ± 0.15	0.673	6.02 ± 0.31
0.185	5.63 ± 0.16	0.693	5.77 ± 0.28
0.196	7.27 ± 0.15	0.715	5.98 ± 0.28
0.208	8.31 ± 0.15	0.737	5.67 ± 0.39
0.220	7.06 ± 0.15	0.754	5.30 ± 0.08
0.232	5.06 ± 0.14	0.83	4.58 ± 0.13
0.244	4.70 ± 0.10	0.91	3.75 ± 0.15
0.256	4.15 ± 0.10	0.99	3.21 ± 0.14
0.268	4.12 ± 0.10	1.07	2.85 ± 0.14
0.282	4.93 ± 0.10	1.16	2.58 ± 0.16
0.296	5.77 ± 0.11	1.26	2.61 ± 0.11
0.310	5.41 ± 0.11	1.37	1.94 ± 0.08
0.324	5.65 ± 0.12	1.47	1.44 ± 0.07
0.338	7.01 ± 0.16	1.58	1.21 ± 0.06
0.352	8.22 ± 0.17	1.69	1.04 ± 0.06
0.368	8.23 ± 0.18	1.80	1.07 ± 0.04
0.383	7.37 ± 0.18	1.84	1.03 ± 0.06
0.400	6.72 ± 0.18	1.92	0.87 ± 0.05
0.416	6.48 ± 0.18	1.99	0.871 ± 0.044
0.432	6.66 ± 0.18	2.07	0.717 ± 0.040
0.448	6.77 ± 0.19	2.16	0.647 ± 0.035
0.465	7.63 ± 0.19	2.24	0.638 ± 0.032
0.483	8.18 ± 0.19	2.33	0.563 ± 0.030
0.501	7.48 ± 0.20	2.42	0.510 ± 0.026
0.519	6.30 ± 0.20	2.52	0.486 ± 0.024
0.537	5.78 ± 0.20	2.62	0.456 ± 0.021
0.555	6.44 ± 0.20	2.72	0.408 ± 0.020
0.573	7.51 ± 0.20	2.82	0.351 ± 0.018

Average Window Energy (MeV)	Photon Yield (photons·fis- sion ⁻¹ ·MeV ⁻¹)	Average Window Energy (MeV)	Photon Yield (photons·fis- sion ⁻¹ ·MeV ⁻¹)
2.93	0.268 ± 0.016	4.64	0.048 ± 0.005
3.04	0.234 ± 0.014	4.79	0.032 ± 0.005
3.16	0.196 ± 0.013	4.95	0.024 ± 0.005
3.28	0.193 ± 0.012	5.11	0.022 ± 0.005
3.40	0.182 ± 0.011	5.27	0.026 ± 0.005
3.53	0.132 ± 0.010	5.52	0.020 ± 0.004
3.66	0.127 ± 0.009	5.86	0.0136 ± 0.0033
3.79	0.132 ± 0.009	6.22	0.0107 ± 0.0029
3.92	0.111 ± 0.008	6.59	0.0069 ± 0.0025
4.06	0.103 ± 0.008	6.97	0.0061 ± 0.0022
4.20	0.081 ± 0.007	7.57	-0.0001 ± 0.0014
4.34	0.071 ± 0.007	8.41	0.0002 ± 0.0008
4.49	0.053 ± 0.006	9.68	0.0004 ± 0.0003

APPENDIX II. FORMULAE AND PARAMETERS FOR RESPONSE-FUNCTION GENERATION

A. PAIR SPECTROMETER

For the pair spectrometer the response per unit pulse height $p(\text{keV})$ at gamma-ray energy, E , was written in terms of parameters $P_i(E)$ as

$$R(E, p) = P_3 \left\{ [1 - P_1] G(p; P_4, P_5) + P_1 T(p; P_2, P_6, P_7, P_9) \right\},$$

where

$$\begin{aligned} G(p; P_4, P_5) &= \left\{ \exp[(p - P_5)^2 / P_4^2] \right\} / (P_4 \sqrt{\pi}), \\ T(p; P_2, P_6, P_7, P_9) &= 0, & p \geq P_7, \\ &= A \left\{ 1 - \exp[P_6(p - P_7)] \right\}^2 \times \\ &\quad \left\{ 0.9 \exp[P_2(p - P_7)] + 0.1 \exp(P_9 p) \right\}, & p < P_7. \end{aligned}$$

A is a normalization parameter which maintains unit area for $T(p; P)$ for all E .

$$\begin{aligned} 1/A &= 0.9 \left\{ [1 - \exp(-P_2 P_7)] / P_2 - 2[1 - \exp(-P_7 P_2 - P_6 P_7)] / [P_2 + P_6] \right. \\ &\quad \left. + [1 - \exp(-P_2 P_7 - 2P_6 P_7)] / [P_2 + 2P_6] \right\} \\ &\quad + 0.1 \left\{ [\exp(P_9 P_7) - 1] / P_9 - 2[\exp(P_9 P_7) - \exp(-P_6 P_7)] / [P_6 + P_9] \right. \\ &\quad \left. + [\exp(P_9 P_7) - \exp(-2P_6 P_7)] / [2P_6 + P_9] \right\}. \end{aligned}$$

The equations below give the E dependence of each P_i . Table A-2 gives the interpolation parameters, uncertainties, and the local correlation matrix for each case.* Correlation matrix elements between parameters underlying different P_i were less than 0.12 in all cases. Although some of the complexity of the formulae originated in efforts to foster orthogonality, it can be seen that correlations between output parameters are important.

*These local correlation matrices are typical of those also obtained for the other spectrometer systems.

$$P_1 = d_{11} + d_{12}(x + 0.06) + d_{13}(x^2 + 0.17x - 0.2) \\ + d_{14}(x^4 - 0.55x^2 + 0.35x + 0.15), \quad x = \ln(P_5/1500).$$

$$P_2 = d_{21} \exp\{-d_{22}[(\ln P_5 - d_{23})^2 - 0.16]\}, \quad P_5 > 3294 \\ = P_9, \quad P_5 \leq 3294$$

$$P_3 = [\text{Hough}(E/511)]^2 \exp[d_{31} + d_{32}x + d_{33}(x^2 - 0.8) \\ + d_{34}(x^3 - 1.2x)], \quad x = \ln(P_5/1636).$$

$$P_4 = d_{41}(P_5/1500)^{d_{42}}.$$

$$P_5 = F = E(\text{keV}) - 2m_0c^2 = E - 1022.$$

$$P_6 = 1.316 P_5^{-0.45}.$$

$$P_7 = \begin{cases} P_5 - 0.2023 P_5^{0.824}, & P_5 < 1732. \\ P_5 - 23.212 P_5^{0.188}, & P_5 \geq 1732. \end{cases}$$

$$P_9 = 0.001 \exp[d_{91} + d_{92} \ln(P_5/800)] \\ - 0.001 \exp\{3.091 + d_{93}(1.15 + \ln[P_5/800])\}$$

^aThe Hough formulation of the Born approximation pair cross section,
P. V. C. Hough, Phys. Rev. 73, 266 (1948).

Table A2. Pair Spectrometer Interpolation Parameters

The χ^2/ν value for the final fit leading to all these results was ~ 8 , and no "error expansion" has been performed to force this toward unity. (The local correlation matrix and the standard errors are based on input uncertainties through first-order error theory.)

d_{ij} Parameter Number ^a	Value	Standard Error	Local Correlation Matrix ^b			
11	0.1788	0.0008	1.00	0.46	0.60	-0.64
12	0.1504	0.0020		1.00	0.73	-0.72
13	0.1170	0.0041			1.00	-0.96
14	-0.0072	0.0016				1.00
21	1.95×10^{-3}	0.21×10^{-3}	1.00	0.23	0.24	
22	3.43	0.68		1.00	-0.15	
23	8.787	0.034			1.00	
31	-15.831	0.011	1.00	0.37	0.41	-0.29
32	-0.153	0.015		1.00	0.60	-0.78
33	-0.0377	0.0063			1.00	-0.19
34	-0.0283	0.0083				1.00
41	60.68	0.25	1.00	0.40		
42	0.5808	0.0040		1.00		
91	1.547	0.014	1.00	0.95	0.96	
92	-1.344	0.012		1.00	0.95	
93	-2.58	0.13			1.00	

^aIndex ij refers to the j th parameter employed to fit $P_i(E)$.

^bThe subdiagonal terms of these symmetric matrices have been omitted. If $V_{\alpha\beta}$ are the elements of the parameter covariance matrix propagated from the input data, the elements $\rho_{\alpha\beta}$ of the correlation matrix are: $\rho_{\alpha\beta} = V_{\alpha\beta} (V_{\alpha\alpha} V_{\beta\beta})^{-1/2}$.

B. COMPTON SPECTROMETER

The response per unit pulse height $p(\text{keV})$ of the Compton spectrometer for a photon energy $E(\text{keV})$ was:

$$R(E, p) = P_3 \left\{ G(p; P_4, P_5) + P_1 T(p; P_2, P_6, P_7) + P_8 R(p; P_{12}) + P_{11} [E_s(p; P_9, P_{10}) + 0.25 Z(p)] \right\}.$$

Many of the formulae are in terms of the electron energy F at the peak of the pulse-height distribution for a given E , defined by Eq. 2.1 in Section II-C and below.

$$G(p; P_4, P_5) = \exp[-(p - P_5)^2 / P_4^2] / [P_4 \sqrt{\pi}].$$

$$T(p; P_2, P_6, P_7) = 0, \quad p \geq P_7,$$

$$= A \left(\left\{ 1 - \exp[P_6(p - P_7)] \right\}^2 \exp[P_2(p - P_7)] \right), \quad p < P_7,$$

where

$$1/A = \left\{ 1 - \exp[-P_2, P_7] \right\} / P_2$$

$$+ 2 \left\{ \exp[-P_7(P_2 + P_6)] - 1 \right\} / (P_2 + P_6)$$

$$+ \left\{ 1 - \exp[-P_7(P_2 + 2P_6)] \right\} / (P_2 + 2P_6).$$

$$R(p; P_{12}) = 0, \quad p \geq P_{12},$$

$$= 2(P_{12} - p) / P_{12}^2, \quad p < P_{12}.$$

$$E_s(p; P_9, P_{10}) = \left\{ \exp[-\{(p - P_{10}) / P_9\}^2] \right\} / [P_9 \sqrt{\pi}].$$

$$Z(P) = \left\{ \exp[-\{(p - 308.3) / 38.4\}^2] \right\} / [38.4 \sqrt{\pi}].$$

G represents the Gaussian peak response and T , the "tail." Other localized features of the response functions are: R , which corresponds to a rise in response at the low-energy end which is approximately independent of gamma-ray energy; E_s , which represents the escape peak; and Z , which corresponds to "backscatter" radiation at approximately 511 keV.

The equations for the parameters, P_i , are:

$$\begin{aligned}
P_1 &= \exp[d_{11} + d_{12}x - 1.262 \times 10^{-5}(x^2 - 250)], & x &= \sqrt{F} - 28. \\
P_2 &= \exp[d_{21} + d_{22}y + d_{23}(y^2 - 0.7)], & y &= \ln(F/1665.1) \\
P_3 &= 10^{-6} \left\{ d_{31} + d_{32} \ln(F/1200) + 0.5 d_{33} \right. \\
&\quad \left. - \exp[d_{33} + d_{34} \{2.079 + \ln(F/1200)\}] \right\} & F &< 3000.* \\
P_4 &= d_{41} + d_{42}x + d_{43}(x^2 - 100) + d_{44}x^3, & x &= \sqrt{F} - 28. \\
P_5 &= F = (E^2 - d_{52})/(E + d_{51}). \\
P_6 &= 0.115 \exp[-F^2/(1.41 \times 10^6)], & F &< 790, \\
&= 0.1 \exp[(520 - F)/894], & F &\geq 790. \\
P_7 &= F - 4.15(\sqrt{F} - 8) + 0.0013 (\sqrt{F} - 8)^3, & \sqrt{F} &< 43, \\
&= F - 89.4, & \sqrt{F} &\geq 43. \\
P_8 &= 2.473 \times 10^{-7} F^{1.977}, \text{ but } P_8 \geq 0. \\
P_9 &= 0, & E &\leq 1022, \\
&= 19.46 \exp(5.16 \times 10^{-4}E), & E &> 1022. \\
P_{10} &= E - 1022. \\
P_{11} &= d_{111} + d_{112}z + d_{113}z^3, & z &= (F - 1700)/1000. \\
P_{12} &= 0, & F &\leq 450, \\
&= 264 + 0.195 F & F &\geq 450.
\end{aligned}$$

The interpolation parameters, d_{ij} , for the Compton spectrometer and their errors are given in Table A-3. They were obtained in a fit having $\chi^2/\nu = 2.9$.

*See Fig. 10 for values used in the extrapolation region.

Table A-3. Compton Spectrometer Interpolation Parameters

<u>d_{ij} Parameter Number</u>	<u>Value</u>	<u>Standard Error</u>
11	-0.6308	0.0025
12	0.06959	0.00027
21	-6.370	0.012
22	-1.278	0.013
23	0.303	0.014
31	0.741	0.011
32	-0.724	0.028
33	0.443	0.059
34	-1.441	0.093
41	66.54	0.12
42	2.758	0.018
43	0.0098	0.0012
44	2.72×10^{-4}	0.72×10^{-4}
51	323.6	1.6
52	3821.	590.
81	0.2385	0.0044
82	0.345	0.012
83	1.559	0.039
84	0.783	0.073
111	0.0848	0.0012
112	0.1298	0.0061
113	0.077	0.015

C. SINGLE-CRYSTAL SPECTROMETER

The expression below is used to describe the response function for the single-crystal spectrometer:

$$R(E,p) = (\text{photopeak efficiency}) [(\text{Gaussian photopeak}) + (\text{relative backscatter area})(\text{Gaussian backscatter peak}) + (\text{Compton distribution}) + (\text{iodine x-ray escape peaks})],$$

where $R(E,p)$ is the number of counts/keV from one photon emitted in the fission chamber. The photopeak efficiency was interpolated from the data in Fig. 11. The subsections below detail the parts of this expression.

1. The Photopeak

The Gaussian photopeak is given by

$$\frac{\exp\{ -[(p - E)/\text{width}(E)]^2 \}}{\sqrt{\pi} \text{width}(E)},$$

where p is the pulse height in keV, E the gamma-ray energy and the peak position in keV, and $\text{width}(E)$ is half the width in keV of the photopeak at $\exp(-1)$ of its full amplitude. $\text{width}(E)$ is given by the piecewise expression:

$$\begin{aligned} \text{width}(E) &= -5.527 + 1.4287\sqrt{E} - 0.0043E, & E \geq E_0, \\ &= \text{width}(E_0) - (E_0 - E) [0.7143(E_0)^{-1/2} - 0.0043 \\ &\quad + 0.0007147(E_0 - E)/(2\sqrt{E_0})], & E < E_0, \\ E_0 &= 134.3 \text{ keV}. \end{aligned}$$

$\text{width}(E)$ and $d(\text{width})/dE$ at E_0 are equal for the above expressions.

2. The Backscatter Peaks

The relative backscatter peak area is:

$$0.0295 \exp\left\{ \ln(E/135.1) [0.532 \ln(1256.5/E) + 0.521 \ln(E/321.1)] \right\}.$$

The Gaussian backscatter peak shape is

$$(\sqrt{\pi} \text{WBKSK})^{-1} \exp\left\{-\left[\left(p - \text{EBKSK}(E)\right)/\text{WBKSK}(E)\right]^2\right\},$$

where

$$\text{WBKSK}(E) = 0.94 \text{ width}(E), \text{ and}$$

$$\text{EBKSK}(E) = m_0 c^2 E / (2E + m_0 c^2) + 13.4 \exp\left\{-2.16 [\ln(E/532)]^2\right\}.$$

Note that $\text{EBKSK}(E)$ approximates the energy of 180-degree scattered gamma rays. $m_0 c^2$ is the rest energy of the electron = 511 keV.

3. The Compton Distribution

So long as $\text{complevel}(E)$ is positive, the Compton distribution is given by the expression:

$$\text{complevel}(E) \left[\frac{1 + B(E)^2 Z(p, E)}{Z(p, E) + [1 - B(E) Z(p, E)]^2} \right]^{1/2} + 0.00185 \exp\{-0.0343p/E^{.3165}\},$$

$E > E_1$

while below the energy E_1 ($E_1 \cong 199.5$ keV), where $\text{complevel}(E_1) = 0$, the Compton distribution is given by

$$\text{CVE}(E) \exp\left\{-0.03436[p - (1/2) \text{ecomp}(E)]/E^{.3165}\right\},$$

$E \leq E_1.$

In the above expressions,

$$B(E) = \frac{R(R + \sqrt{R^2 - 1})}{1 + [2R(R + \sqrt{R^2 - 1})]^{1/2}},$$

$$R = 1.1447 + \exp(-0.002485 E),$$

$$Z(p, E) = \exp\left\{[p - \text{compedge}(E)]/\text{width}[\text{compedge}(E)]\right\},$$

$$\text{compedge}(E) = \text{ecomp}(E) - 0.003879 \cdot E \cdot \text{width}[\text{compedge}(E)] \times \exp\left\{-5.9126 [\ln(E/468.1)]^2\right\},$$

$$2\epsilon \equiv \text{ecomp}(E) = 2E^2/(2E + m_0 c^2).$$

Compedge(E) is the position of the upper edge of the Compton distribution, located roughly at the maximum energy of electrons from single Compton scattering. Using the definition of ϵ just above, the formula for the amplitude complevel(E) used above 199.5 keV is:

$$\text{complevel}(E) = \frac{\text{CVE}(E) - 0.00185 \exp(-0.03436\epsilon/E^{.3165})}{\left\{ [1 + B(E)^2 \cdot Z(\epsilon, E)] / [Z(\epsilon, E) + \{1 - B(E) \cdot Z(\epsilon, E)\}^2] \right\}^{1/2}} .$$

All that remains is the definition of CVE(E):

$$\text{CVE}(E) = 0.00749 \text{ width}(E)/E^{.633}, \quad E > 570,$$

$$\text{CVE}(E) = (10^{-5}) \text{ width}(E) \left\{ Z_0 + (YF - Z_0) \exp[\text{ARG}] \right\}, \quad E \leq 570,$$

where

$$\begin{aligned} \text{ARG} = \ln(570/E) \left\{ 9.49 \ln(E/570) \ln \left[\frac{YF - Z_0}{13.273 - Z_0} \right] \right. \\ \left. + \frac{26.4}{(YF - Z_0)} \ln(E/412.1) \right\} \end{aligned}$$

$$YF = 13.525$$

$$Z_0 = 9.571, \quad E > 150,$$

$$= 9.571E(2 - E/150)/150, \quad E \leq 150.$$

4. Iodine X-ray Escape

The iodine x-ray escape peaks are represented by:

$$\begin{aligned} \text{SMRT}(E) \left[0.81 \exp \left\{ -[(p - E + 28.51)/\text{width}(E - 28.51)]^2 \right\} \right. \\ \left. + 0.19 \exp \left\{ -[(p - E + 32.41)/\text{width}(E - 32.41)]^2 \right\} \right], \end{aligned}$$

where

$$\begin{aligned} \text{SMRT}(E) &= 0.519 \exp \left\{ -0.6375 [\ln(E/13.52)]^2 \right\}, & 33.23 < E < 500, \\ &= 0, & E \text{ otherwise.} \end{aligned}$$

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