Photofission cross sections of 238U and 235U from 5.0 MeV to 8.0 MeV

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Photofission cross sections of $^{238}\text{U}$ and $^{235}\text{U}$
from 5.0 MeV to 8.0 MeV

by

Robert Andrew Anderl

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I. INTRODUCTION

A. Background

Nuclear fission is a process by which a nucleus splits into two or more lighter nuclides either spontaneously or after the original nucleus is excited by an external source of energy. Spontaneous fission is observed only in nuclei for which the proton number is greater than 89. Observed half-lives for spontaneous fission range from $10^{18}$ years for thorium ($Z=90$) to $10^2$ years for californium ($Z=98$). Fission induced by various nuclear reactions is observed to be prompt with half-lives less than $10^{-14}$ sec and can occur for nuclei with $Z$ much less than 90 as well as for $Z$ above 90. The probability for induced fission has an observed "threshold" and generally increases rapidly with excitation energy above the threshold. These phenomena suggest that the fission process is characterized by a fission barrier which governs the rate of spontaneous and induced fission.

In measurements of the fission probability (cross section) and angular distribution of fission fragments as a function of excitation energy of the fissioning nucleus, above-threshold phenomena have been observed which suggest specific channels through which the nucleus can fission. In recent years, isomeric states of some heavy nuclei have been observed for which the predominant mode of decay is spontaneous fission with millisecond half-lives. Also, in recent years, pronounced structure has been observed in subbarrier cross section measurements for some heavy nuclei.

The above are only some of the phenomena which are known to characterize the fission process and which, over the past thirty years,
have stimulated considerable theoretical effort to explain the process of
fission. Our understanding of the fission process has been marked by
three major theoretical developments: the application by N. Bohr and
J. A. Wheeler (1) of the liquid drop model of the nucleus to fission; the
proposal by A. Bohr (2) of a discrete fission channel spectrum through
which the nucleus proceeds to fission; and, most recently, the formulation
by Strutinsky (3) of a double-humped barrier to characterize the potential
energy of deformation of a fissionable nucleus.

The development of the liquid drop model of fission by Bohr and
Wheeler hinged on the fact that for heavy nuclei, the long-range re-
pulsive Coulombic forces between the protons cancel, to a large extent,
the attractive short range forces between the nucleons. They showed that
as a heavy nucleus is deformed, the increase in energy due to the nuclear
forces (which act in a manner analogous to surface tension and oppose a
change of shape of the nucleus) is initially greater than the decrease in
Coulombic energy. At some finite distortion, designated as the saddle
point deformation, the decrease in Coulomb energy equals the increase in
surface energy. For distortions beyond this point the Coulomb forces
cause the nucleus to fission. The lowest energy required to reach this
saddle shape is defined as the critical deformation energy, or fission
barrier, and the nucleus at the saddle point deformation is designated
as the transition state nucleus. This description of the mechanism of
fission quite adequately explains some of the gross features of nuclear
fission presented in the first paragraph.

To explain the channel structure observed in the near threshold cross
section measurements, A. Bohr (2) proposed the concept of "fission channels" of the transition state nucleus. Qualitatively, this is understood as follows. When a heavy nucleus captures a particle or absorbs a high energy photon a compound nucleus is formed in which the excitation energy is distributed among a large number of degrees of freedom of the nucleus. The resulting complex state of motion can be described in terms of collective nuclear vibrations and rotations coupled to the motion of the individual nucleons (4). For excitation energies not too far above the fission threshold, a major part of this excitation energy is concentrated in potential energy of deformation as the nucleus proceeds to pass over the saddle point deformation. Bohr (2) proposed that the quantum states available to the nucleus at the saddle point of the "fission channels" are then widely separated, and represent relatively simple types of motion of the nucleus. He suggested that these channels would form a spectrum similar to the observed low energy excitations of the nucleus in its ground state deformation.

In more recent years, the phenomena of spontaneously fissioning isomers and the observed structure in the subbarrier fission cross section have been explained in the framework of the double-humped potential barrier developed by Strutinsky (3,5). Strutinsky noted that while the liquid drop model gives a reasonable phenomenological description of the average properties of the fission process and nuclear masses, it ignores fluctuation effects due to shells. Noting that the presence of shells at different deformations in deformed nuclei, as well as in spherical nuclei, are important for the stability of particular nuclear shapes, Strutinsky incorporated a shell correction factor with a liquid
drop term in the calculation of the deformation energy. The shell correction term effectively modulates the smooth liquid drop term resulting in a potential energy of deformation which has two minima, hence two barriers at different deformations. Provided that the second well is deep enough, there can then be two distinct equilibrium states in the same nucleus at different deformations, one characterizing the stable nucleus and the other characterizing an isomeric state which can easily decay by spontaneous fission.

The focus of much experimental work on fission, in recent years, has been to determine the characteristics of the fission barrier, as complicated as it appears. To this end, systematic measurements of the "fission channel" spectra for the heavy nuclei and measurements of the subbarrier phenomena described earlier have been undertaken. In principle, the energies and fission widths of the transition states can be obtained from cross section measurements of the fissioning nucleus as a function of excitation energy. The angular momentum and parity quantum numbers of the transition states can be determined by measurements of the angular distribution as a function of excitation energy.

The usual methods for experimentally studying the low-lying transition states have been neutron induced fission, (d,pf) and (t,pf) stripping reactions, (α,α'f) inelastic scattering and (γ,f) photofission. Low energy neutron induced fission of even-even target nuclei has been one of the most widely used methods for determining the transition state spectra of even-odd compound nuclei for which the fission threshold exceeds the neutron binding energy. The (d,pf) reaction has been most successfully
used in studies of even-odd compound nuclei, for which the neutron binding energy greatly exceeds the fission threshold, and in studies for which greater amounts of angular momentum transfer are desired. The \((t, pf)\) and \((\alpha, \alpha'f)\) reactions are most often used to study the transition states of even-even systems. They have the advantage, in principle, that at a single bombarding energy, a large range of angular momentum transfer is possible, and information is simultaneously obtained over the entire energy range from the fission threshold to the excitation energy determined by the energy of the stripped proton or inelastic alpha particle. The major disadvantages of the \((d, pf)\), \((t, pf)\) and \((\alpha, \alpha'f)\) reactions are their experimental difficulty and the extremely complex and approximate procedures for analyzing the measured angular distribution information. Although in principle these methods allow several transition states to be populated and identified, the large range of angular momentum transfers creates the extreme difficulties associated with the analysis procedures.

It then seems that photofission cross section and angular distribution measurements are a most simple means of unraveling some of the unknowns in the transition state spectrum. In photofission, dipole and quadrupole absorption dominate the excitation of the compound nucleus. Hence, fission can take place only through a select few fission channels of the transition nucleus. Also, the use of photofission is not limited to studying only even-even or even-odd systems as are some of the direct reactions. Photofission was used in the present work to study the transition spectra of \(^{238}\text{U}\) and \(^{235}\text{U}\).
B. Previous Photofission Measurements

Near-threshold cross sections for photofission of $^{238}$U have been determined from measurements which employed very different sources of photons. Bremsstrahlung has been used by several experimenters (6,7,8,9, 10,11) in measurements of activation functions (6,7,8) and yield curves (9,10,11) from which the cross sections were extracted by differential analysis. Discrete gamma rays, produced by neutron capture in suitable targets, have been used to measure values of the $^{238}$U cross section by other experimenters (12,13,14). Khan and Knowles (15) used Compton scattered gamma rays in their photofission yield measurements, from which the cross section was obtained by an unfolding procedure.

Limited by poor experimental resolution, the average cross sections obtained in the bremsstrahlung experiments have generally showed a plateau, or hint of structure only, near 6.0 MeV. On the other hand, the cross sections obtained with monoenergetic neutron capture gamma rays have been characterized by large fluctuations which limit a meaningful interpretation for resonance structure in the photofission cross sections. Only the work of Khan and Knowles (15) has indicated pronounced structure in the $^{238}$U($\gamma$,f) cross section at 6.2 MeV with a width of approximately 200 keV.Hints of structure were also observed at 5.2 MeV, 5.7 MeV, 7.1 MeV and 7.8 MeV in the cross section reported in Reference (15). Clearly, a need exists for more reliable photofission cross section measurements to determine the energies and widths of the transition states in the fissioning $^{238}$U nucleus.

The angular distribution of the $^{238}$U photofission fragments as a
function of excitation energy has been more extensively investigated. 
The results of such experiments reported in references (6,16,17,18,19) 
were obtained from measurements made with bremsstrahlung (end-point 
energies > 6.0 MeV) or with the gamma rays with an average energy of 7.0 
MeV obtained by the $^{19}$F(p,αγ)$^{16}$O reaction. These experiments indicate 
that the angular distribution is of a predominantly dipole character 
near 6.0 MeV and become more isotropic with increasing excitation energy. 
There are, however, some discrepancies among these early measurements re­
garding the quadrupole contribution near 6.0 MeV. 

A more recent series of angular distribution measurements, with the 
bremsstrahlung end-point energy extended down to 5.0 MeV, Is reported in 
References (20,21,22,23). The qualitative behavior of the angular distri­
butions from these measurements indicates: a large quadrupole contribu­
tion from 5.0 MeV to 5.5 MeV, with approximately 45% of the photofission 
cross section at 5.2 MeV due to quadrupole fission; a dipole contribution 
which is dominant near 5.5 MeV and decreases with increasing end-point 
energy; and, an isotropic contribution of nearly zero at 5.0 MeV, but in­
creasing with energy to become the dominant component at 8.0 MeV. The 
analysis of the relative contributions of quadrupole, dipole and isotropic 
components indicates a structure of "fission channels" compatible with 
that predicted by Bohr's fission channel theory (2). 

The results of the angular distribution measurements reported in 
references (20-23) are summarized in reference (10) and an interpretation 
of the combined results in the framework of the double-humped potential 
barrier is presented. Reference (11), which reported the most recent
bremsstrahlung photofission cross section determined over an energy range of 4.63 MeV to 7.5 MeV, also included new angular distribution measurements over the same energy range. The interpretation of these results was also presented in the framework of the double-humped potential barrier. The conclusions drawn from references (10,11) are considered further in Chapter 6, which includes the interpretation of the cross section derived from present work.

Neutron capture gamma rays, with energies ranging from 5.6 MeV to 9.0 MeV, were used in angular distribution measurements reported in references (24,25,26). The qualitative behavior of the isotropic, dipole and quadrupole contributions were consistent with those from references (20-23). The angular distributions measured by Manfredini et al. (25) and Dowdy and Krysniski (26) were analyzed by the authors in the framework of Bohr's fission channel theory (2). Their conclusions are considered in the interpretation of the cross section measured in this work.

Knowles et al. (27) reported a measurement of the differential photofission cross section of $^{238}$U made with Compton scattered photons. His results indicate: a smooth isotropic contribution which increases from zero at 5.0 MeV to become the major contribution at 8.3 MeV; a dipole contribution which exhibits a well-defined peak at 6.2 MeV with a width of 200 keV; and a small fluctuating quadrupole contribution over the entire energy range. These results, analyzed by the authors in terms of the fission channel theory, are also used in the interpretation of the present cross section results in Chapter 6.

There is very little published literature on either the cross section
or the angular distributions in the photofission of $^{235}\text{U}$. Winhold and Halpern (6) and Bowman et al. (28) used bremsstrahlung to induce fission in targets of $^{235}\text{U}$. The cross section reported in reference (6), was extracted from the measured activation function by differential analysis. No structure was indicated from 5.0 MeV to 10.0 MeV. On the other hand, the cross section reported between 6.0 MeV and 8.5 MeV in reference (28) exhibited a plateau from 6.5 to 7.0 MeV followed by a dip at 7.5 MeV. The results of Khan and Knowles (15) showed hints of structure but, because of data fluctuations, no structure was identified as a resonance.

Only two angular distribution measurements by Winhold and Halpern (6) and Baerg et al. (17) have been reported in the literature. No anisotropy was observed in either measurement.

C. Scope and Objectives of this Work

At the time this work was begun, the photofission cross section data of Khan and Knowles (15) were not yet published. The experimental situation indicated the need for photofission cross section measurements which could resolve the structure in the transition state spectra of $^{238}\text{U}$ and $^{235}\text{U}$. Such measurements correlated with the multitude of angular distribution data can unambiguously identify the characteristics of some of the states in the transition state spectra of the two nuclei and aid in a better understanding of the potential barrier in the fission process.

The primary purpose of the present work, then, was to measure reliable high resolution ($\gamma,f$) cross sections for $^{238}\text{U}$ and $^{235}\text{U}$ from 5.0 MeV to 8.0 MeV. This work was begun at the same time as a similar set of measurements in $^{232}\text{Th}$ and $^{236}\text{U}$ was started by Yester (29) with the same
apparatus. Hence, an additional objective of this work was a systematic comparison of the near threshold cross sections for the three uranium nuclei. The third objective was to interpret the structure in the measured cross sections by applying the results of the angular distribution measurements and theoretical predictions.

The experiments presented here were performed at the Ames Laboratory Compton scattering facility (30,31), which provides a variable energy beam of photons with energies ranging from 8.0 MeV to 3.0 MeV. Photofission yield curves were measured with surface barrier detectors as a function of incident photon energy. The yield curves were then analyzed by a suitable unfolding procedure to obtain photofission cross sections from 5.0 MeV to 8.0 MeV. An earlier attempt at these measurements was made by Hall (32).

The organization of this dissertation is as follows. Chapter 2 deals with some of the theoretical aspects of the fission process necessary for a meaningful interpretation of the present cross sections. Chapter 3 deals with the experimental apparatus used. In Chapter 4, the experimental procedures for these measurements are described. The present experimental results on the photofission cross sections of $^{238}\text{U}$ and $^{235}\text{U}$ are presented in Chapter 5 along with a comparison to cross section measurements by other experimenters. Chapter 6 deals with a discussion and interpretation of the present results. This chapter is concluded with suggestions for future work and some remarks concerning photofission measurements made with the Ames Laboratory Compton scattering facility.
II. THEORY

The purpose of this chapter is to present some of the theoretical concepts necessary for interpreting the structure of the transition state nucleus as determined by cross section and angular distribution measurements. Bohr's "fission channel" theory (2) which was qualitatively described in the introduction, is discussed in more detail, and the implications of a double-humped potential barrier (3) for the fission channel picture are presented. More detailed discussions of the transition state nucleus and the concept of "fission channels" are found in references (2,33,34,35).

Figure 1 illustrates the basic ideas postulated by Bohr to explain the structure in the transition state nucleus at the saddle point. A heavy nucleus undergoes an excitation, \( E_x \), and can decay from its compound state by neutron emission, radiation, or fission. Fission occurs if a sufficient fraction of the energy becomes potential energy of deformation to enable the nucleus to pass over the highly deformed saddle point shape of the transition nucleus. Bohr postulated that for excitation energies not too far above the barrier, fission occurs only through quantum states ("fission channels") which are widely separated and represent simple types of collective motion of the nucleus (rotation and vibration) (2). He suggested that the transition state spectrum should resemble the low-lying excited states of the nucleus at its ground state deformation.

Figure 1 illustrates some collective band structure for an even-even transition nucleus with a stable quadrupole deformation. The transition
Figure 1. Schematic representation of the levels of an even-even compound nucleus and transition state nucleus in Bohr's "fission channel" theory.
states are characterized by the quantum numbers $I$, $K$, $M$ and $\pi$, where: $I$ is the total angular momentum of the nucleus; $M$ is the projection of $I$ on the space fixed axis; $K$ is the projection of $I$ on the symmetry axis of the nucleus; and $\pi$ is the parity. The quantum numbers $I$ and $M$ are conserved as the nucleus undergoes deformation from the initial compound state to the transition state. However, the $K$ quantum number is not conserved in the deformation process to scission, and the $K$ values for the transition state nucleus are unrelated to the initial values of the compound nucleus. But, assuming the transition nucleus to be axially symmetric, $K$ again becomes a good quantum number as the nucleus proceeds from its transition state to the configuration of separated fragments. The sequence of bands of the transition state nucleus are identified as the ground state band, the mass asymmetry band, the bending mode band, the gamma vibrational band and a band constructed from a combination of mass asymmetry and bending (36). Apart from these states the even-even nucleus possesses higher-lying intrinsic states which involve the excitation of a nucleonic configuration. With each intrinsic excitation, characterized by a nonzero $K$, there is associated a rotational band with $I = K, K + 1, K + 2, \ldots$ and both parities.

The transition band spectrum is radically changed if the nucleus has a stable octupole deformation at the saddle. All of the bands characterized by a $K$ quantum number then contain both positive and negative parity levels, and the number of low-lying negative parity levels is greatly increased. In particular, a $1^-$ level would be expected below
and close to the $2^+$ level in the ground state $K = 0$ band. This situation is discussed in references (18,35,37).

The low-lying levels above the threshold for an odd $A$ transition state nucleus are quite different from those in an even-even nucleus. These transition state spectra consist of intrinsic excitations with collective rotational bands having $I = K, K + 1, K + 2, \ldots$ and both parities, built upon them. The spacing between sequential $K$ bands is approximately 250 keV.

Guidelines for the application of the "fission channel" theory to cross section and angular distribution measurements for photofission, neutron-induced fission, and fission induced by the $(d,p)$ reaction are found in references (36,38,39,40). Central to these procedures is the assumption that the fission barrier for each fission channel has a single hump and can be represented by an inverted parabola parameterized by a height and width (36). From the work of Strutinsky (3), we know that this is much too simple an assumption for the shape of the fission barrier. However, in several cases the procedures are still valid.

A suitable qualitative discussion of how the double-humped potential barrier for fission arises for the actinide nuclei was given in Chapter 1. The details of the development of this representation of the fission barrier are found in references (3,5,41,42,43). References (41, 42,43) are excellent review articles which treat the concept of the double-humped barrier in some detail.
For purposes of discussion here, only the effect of a double-humped barrier in the "fission channel" theory is considered. A representation of the double-humped barrier with the states involved in fission is illustrated in Figure 2. Changes in Bohr's model for the channel effects in fission result from the fact that the nucleus stays long enough in the second well to "forget" the specific properties of the channel states which it had when passing over the first barrier A in Figure 2. In particular, this is true for the K quantum number which determines the angular distribution of the fission fragments with respect to the nuclear symmetry axis. In such a case the observed channel structure should correspond to the second barrier B. If this barrier is higher than the first (A), the familiar picture of channel structure in near barrier fission should be valid. In this case it is the second barrier that corresponds to the effective energy threshold. However, if the barrier B is one or two MeV lower than the first, no pronounced structure in the angular distribution is observed because many channels with different K quantum numbers are available. For this latter case, the cross section measured as a function of excitation energy may still exhibit structure associated with the transition state channels at the first barrier. From this discussion, one can conclude that, only for the case of barrier B higher than barrier A, will a correlation of the angular distribution measurements and cross section as a function of excitation energy give an unambiguous interpretation of the transition state spectra at B. On the other hand, for either case, such a correlation of measurements will give information on the relative heights of the barriers for a particular nucleus.
Figure 2. Schematic representation of Strutinsky's double-humped potential barrier
III. EXPERIMENTAL APPARATUS

A. Compton Scattering Facility

The primary photon beam used in this work was obtained from the Compton scattering facility at the 5 MW Ames Laboratory Research Reactor. This novel instrument for producing photons of continuously variable energy from 3.0 MeV to 8.0 MeV has been described in detail in an unpublished report by Hall et al. (30) and in a publication by Anderl et al. (31). The original version of the facility is discussed in reference (30) and the present version which incorporated improved shielding and collimation is described in reference (31). For completeness of this dissertation, the design, construction and operational details of the facility, as well as a detailed discussion of the shielding and collimation are excerpted from reference (31) and included here as Appendix A.

To provide continuity, a brief description of the Compton scattering system is presented here. A description of the photon beam, which was measured directly, is deferred to Chapter IV.

Figure 3 shows the entire Compton scattering facility, with the direct beam section and the scattered beam section shown separately for clarity. Gamma rays produced by neutron capture in the nickel plate are first collimated by the series of direct beam collimators and then Compton scattered from the curved aluminum plate which is external to the reactor. Neutron shielding between the gamma collimators is used to remove neutrons from the direct beam. By means of the series of shadow shields and scattered beam collimators, photons, scattered through a predetermined angle from the aluminum plate, are selected at the target position.
Figure 3. Scale drawing of the ALRR Compton scattering facility showing a horizontal plane through the center of the gamma ray beam.
This angle is determined by the arc of a circle with the source and the target at its extremities. The energy of the photons scattered through this predetermined angle toward the target position is then given by the Compton scattering energy relation (44). The energy is easily varied by rotating and bending the scattering plate, and by moving the target chamber so that a new arc, hence a new scattering angle, is defined by the nickel source, the aluminum scatterer and the target.

A Si(Li) detector viewing gamma rays scattered at 90 degrees from the curved aluminum plate provides an adequate beam monitor of the total photon flux in the direct beam for normalization between runs. Appendix B presents more of the details of this monitor system, especially with regard to its use in the data analysis procedures.

B. Fission Fragment Detection and Counting System

The apparatus used for photofission yield measurements with the Compton scattering facility is shown in detail in Figures 4, 5 and 6. The system included a vacuum chamber with mounting assemblies for surface barrier detectors and for a cylindrical foil target, as well as standard electronics for handling the detector pulses signifying fission and monitor events.

1. Vacuum chamber and refrigeration system

Two different vacuum chambers were used in these measurements. A chamber equipped for cooling the detectors to near 0°C was used in the yield measurements for $^{235}$U. Cooling was necessary to counteract the increase of the detector leakage current which accompanies the radiation
damage in the crystal due to the high alpha flux from the $^{235}$U target. For the $^{238}$U measurement, which was completed first, cooled detectors were not necessary and no significant increase in the leakage current was observed during the course of the experiment.

The vacuum chamber, with the associated detector and target mounting assemblies and with the cooling apparatus used for the $^{235}$U experiment, is shown in Figure 4. Both the chamber for cooling the detectors and the chamber for room temperature operation used the same base and detector-target mounting arrangement. For room temperature operation the chamber walls were one piece, constructed from a 5.50 in. section of 6.125 in. ID by 0.25 in. aluminum pipe to which were welded a 0.375 in. aluminum top and a 0.375 in. bottom flange for bolting to the chamber base. The beam entrance area was thinned down to 0.05 in. for minimal attenuation (< 1%) of the incident photon beam.

As illustrated in Figure 4 the vacuum chamber equipped with the refrigerator was constructed from a 9.50 in. section of pipe with the same wall dimensions as for the smaller chamber. Flanges were welded to the bottom and top of the walls for bolting to the chamber base and for replacement of the two removable brass lids which seal the chamber. The freon expansion chamber was silver-soldered to the lower brass lid as was a feed-through receptacle for bringing copper-constantin thermocouple wires into the chamber. The top provided access for maintenance of the detectors and replacement of targets. The vacuum chamber base was machined and built to provide for a pumping port, eight BNC bulkhead receptacles, the target rotation assembly and holes for centering the
Figure 4. Scale drawing of the vacuum chamber, detector and target mounting assemblies, and cooling apparatus used in the photofission measurements.
vacuum chamber in the facility target chamber. O-ring seals were used on all flanges where necessary. A vacuum of less than $10^{-2}$ torr was maintained in the chamber by means of a cold-trapped pumping station.

The refrigeration system consisted of a freon expansion chamber mounted inside the vacuum chamber and a compressor to which the expansion chamber was attached by means of the high pressure and low pressure lines. Freon-12 was pumped through the system with a pressure of 136 lbs/in.$^2$. In the high pressure line, allowed to expand in the 36 cubic inch expansion chamber and return to the compressor at a pressure of 19.7 lbs/in.$^2$. This simple method for cooling lowered the temperature of the expansion chamber to $-8^\circ$C. Each of the detectors was then cooled by heat conduction to the expansion chamber wall through the copper plate and copper braid as shown in Figure 4. With this arrangement the detectors were cooled to about $0^\circ$C at thermal equilibrium.

The freon expansion chamber was constructed from thin-walled stainless steel, and, as shown in Figure 4, was silver soldered to the brass lid by means of dual thin-walled stainless tubes. This type of arrangement gave adequate thermal isolation of the cold expansion chamber from the room-temperature brass lid.

2. Detector and target assemblies

Four ORTEC heavy ion surface barrier detectors were used for each photofission experiment. Each detector had an active circular area of 600 sq mm and an active depth of 155 microns.

Both of the targets used in this work were fabricated by the Isotope Target Laboratory of Oak Ridge National Laboratory. $^{238}$U (enriched to
99.97\% and $^{235}$U (enriched to 97.68\%) were rolled into rectangular metal foils with dimensions, 5.08 cm by 6.98 cm by 7.77 mg/cm$^2$ and 7.25 mg/cm$^2$, respectively. Each of the rectangular metal foils was then epoxied to a lucite target support cylinder for mounting in the vacuum chamber. These cylindrical foil targets were 5.08 cm high with a diameter of 2.22 cm. Both targets were shipped and stored in glass bottles containing an inert gas atmosphere to prevent oxidation of the metal.

The detector mounting assembly positioned on the vacuum chamber base is shown in Figure 4. The assembly consists of a lucite hub centered about the rotation shaft flange, four lucite rods which serve as radial arms extending 1.75 in. from the hub, and lucite detector holders which slide on the radius arms. Holes for inserting the arms were made in the hub at 0°, 30°, 60° and 90° in two quadrants and 0°, 45° and 90° in the other two quadrants. Set screws rigidly fixed the hub to the centering post.

Each detector holder consisted of a lucite mount which fixed the distance of the detector from the target and centered the detector about the vertical dimensions of the target. The detectors were fixed in the vertical holders by the attached microdot connectors. Leads from the microdot cables were soldered to the bulkhead receptacles to pass the signals to the preamps outside the vacuum chamber.

As shown in Figure 4, the target mounting assembly consisted of the lucite target support cylinder, a lucite target holder and a stainless steel shaft coupled to a 23 rpm electric motor\(^1\) for target rotation. The

\(^1\)Honeywell, Brown Instruments Division.
target rotation feature was incorporated in the design to ensure uniform
target density at all angles for angular distribution measurements. This
feature was, however, not essential for average cross section experiments,
and its use was discontinued in the $^{235}$U experiment when difficulties
developed with the vacuum seal around the steel shaft.

The detector and target mounting assemblies were designed to offer
the flexibility needed for performing both total cross section and angular
distribution measurements for photofission. However, both types of
measurements are not easily done simultaneously with the Compton scattering
facility. The combination of a low intensity gamma beam and the strict
requirements for both a narrow target and narrow angular definition for
the detectors in an angular distribution measurement make the data
collection times extremely lengthy and yield data of questionable value
for such experiments. For this reason the detector and target mounting
assemblies were used in a configuration which optimized the detection
efficiency for an average cross section experiment.

A top view of the detector-target arrangement in the target chamber
is shown in Figure 5. The four detectors were mounted at 45° and
135° with respect to the incident photon beam, with the front surfaces
of the 45° detectors fixed at 1.0 in. from the target cylinder axis, and
1.5 in., for the 135° detectors.

The chamber base to which the detector and target mounting assemblies
were fixed was rigidly attached to a support stand by three centering
bolts. Two of the centering bolts are shown in Figure 5 and the third is
below the last section of the collimator nearest the vacuum chamber. The
Figure 5. Top view of the detector-target arrangement in the facility target chamber
dimensions of the support stand, the target chamber base and the mounting assemblies were chosen so that the cylindrical foil target was exactly fixed at each target position of the Compton scattering facility, and was centered both vertically and horizontally in the photon beam. At the target position the beam, with horizontal and vertical dimensions of 2.54 cm by 5.08 cm, completely overlapped the target foil.

3. **Counting system electronics**

A block diagram of the electronics used is shown in Figure 6. High voltage supplies maintained the fission detectors at +130 volts or +60 volts and the monitor detector at +155 volts for these measurements. Pulses from the fission fragment detectors, F1, F2, F3, F4, and from the beam monitor, M, were amplified by charge sensitive preamps and linear amplifiers. The charge sensitivity of the preamps used in the fission channels was modified from the original design to prevent saturation in the preamp and amplifier by the large fission pulses. With the fission detectors operated at +130 volts the preamp output was about 6.0 millivolts per MeV and the amplifier output was about 0.1 volts per MeV. For an operating detector bias of +60 volts the preamp output was about 5.0 millivolts per MeV and the amplifier output was about 0.09 volts per MeV.

---

1. ORTEC Model 210, for the fission detectors. ORTEC Model 211, for the monitor detectors.

2. ORTEC Model 485 and 410, for the fission chains. Hammer Model NA12, for the monitor chain.
Figure 6. Block diagram of the electronics used for the photofission yield measurements.
Following amplification, pulse height discrimination\(^1\) was used to block the passage of noise and alpha signals in the fission channels and noise signals in the monitor channel. Discriminator levels for each counting chain were established with a calibrated pulser as described in Chapter IV. The signals from the discriminators were then split for two modes of storage of the events in the five counting chains. Scalers\(^2\) in each of the fission channels counted the number of pulses passing through the discriminators for a fixed number of monitor events accumulated in the monitor scaler\(^2\). The discriminator signals were also summed in the sum amplifier\(^3\), which generated a single pulse train composed of pulses of five different fixed amplitudes corresponding to events from each of the five input channels. The sum amplifier output was then processed and stored in 1024 channels of a multichannel pulse-height analyzer\(^4\). Every 2000 sec. the memory was written on magnetic tape\(^5\). The information on the magnetic tape was easily retrieved with a computer procedure. This backup system proved to be invaluable for those data runs in which the scaler information was lost because of electrical power failure.

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\(^1\)Tennelec Model TC400 and Canberra Inst. Model C11430, for the fission chains. ORTEC Model 413, for the monitor chain.

\(^2\)ALRR 602, designed and built in the Ames Laboratory.

\(^3\)ALRR 111, designed and built in the Ames Laboratory.

\(^4\)Nuclear Data Model 2200.

\(^5\)Kennedy Model 1600 tape recorder interfaced to the analyzer.
Overflow from the monitor scaler was counted in the master control unit\(^1\). This scaler timer, modified for handling the overflow, also gated the counting system off after a fixed number of monitor events. The timer recorded the total run time for each yield point.

A mercury switch pulser\(^2\) was used to check the linearity, the stability and the gain characteristics of the entire counting system. Pulser input to the system was through the test input of the preamps, as shown in Figure 6. After energy calibration with a \(^{238}\)Th alpha source, the pulser was used to set the fission channel discriminator levels and check the stability of those settings from run to run. Similarly, the pulser was used to check the level stability of the monitor discriminator. The procedures for these linearity, stability and gain checks are discussed in Chapter IV.

\(^1\)ALRR 003, designed and built in the Ames Laboratory.

\(^2\)Hammar Model NP-10.
IV. EXPERIMENTAL PROCEDURES

A. Measurement of the Scattered Beam Spectra and Intensities

Of fundamental importance for accurate cross section determinations from measured photonuclear yield curves, is an accurate description of the spectra and intensities of the photon beam striking the target. For this reason, the scattered beam spectra and intensities were directly measured, for end-point energies\(^1\) ranging from 3.0 MeV to 8.0 MeV in 100 keV increments, with a NaI-Ge(Li)-NaI pair spectrometer set up at the target position. This corresponds to 51 scattering angle configurations ranging from 27.6° to 6.8°. Yester (29) has described in some detail the experimental aspects of these measurements, as well as the analysis procedures that were used to reduce the raw data. Only a brief summary of these procedures are presented here.

The raw spectra obtained with the pair spectrometer were corrected for the relative efficiency of the spectrometer, for the effect of lead absorbers in the beam during the measurements, and for the effect of paraffin absorbers in the beam for the photofission measurements. These corrected spectra were then summed over 100 keV bins. Representative scattered beam spectra are illustrated in Figure 7 for four scattering angle configurations of the Compton scattering system.

The spectrum of photons in the direct beam, as measured with the same pair spectrometer, is shown in Figure 8. The broad peaks in the scattered spectra are easily correlated with the lines in the direct beam, and the \(^1\)End-point energy: here this term is defined to be the energy of the scattered 8.999 MeV Nickel line for a given scattering angle.
Figure 7. Representative scattered beam spectra at the target position for four scattering angle configurations of the Compton scattering system.
Figure 8. Spectrum of photons in the direct beam as measured with a pair spectrometer. The unlabelled lines are from the nickel source.
only surprising feature of the scattered beam spectra is the relatively large number of photons in the low energy region.

To see if the low energy tail was real, Yester (29) investigated possible sources of systematic error associated with the energy dependent corrections applied to the raw pair spectrometer data. He also checked for systematic errors in the raw data itself by comparing spectra taken of the direct beam and of a $^{56}$Co source. His studies resulted in the conclusion that the real beam spectra are in fact as illustrated in Figure 7, with the large low energy tail produced by secondary scattering in the beam collimators.

In Figure 9, the number of photons striking the 1 in. by 2 in. target spot in $4 \times 10^6$ monitor counts is plotted as a function of end-point energy. Each of the points was determined by: first, calculating the area from 5.0 MeV to 8.6 MeV under each of the scattered beam spectra and, second, correcting for the absolute efficiency of the pair spectrometer. The dips in the photon number at 7.3 MeV and 7.6 MeV result from the use of the shadow shields which prevent some of the gamma rays, scattered from the aluminum plate, from reaching the target. The normalization of this photon number for correspondence with the photofission yield data is discussed in Appendix B.

B. Calibration of the Electronics

Reliability of the photofission yield measurements with the electronic system described in Chapter III depended on several factors: a knowledge of the contributions of noise, alpha and fission pulses to the pulse height distribution from each detector for each target; a technique for
Figure 9. Plot of the end-point energy dependence of the number of photons, with energies between 5.0 MeV and 8.6 MeV, striking the target area in $4 \times 10^6$ monitor counts.
discriminating the noise and alpha pulses from the fission pulses; a procedure for accurately monitoring amplifier gain shifts and discriminator level instabilities throughout the long term experiments (approximately forty days per target); and, finally, a method for determining the efficiency for counting fission events. The first three factors are treated in this section and a detailed efficiency calculation is deferred to Appendix C.

Pulse-height spectra for each detector and target were measured with the target chamber moved into the direct beam. A typical spectrum for one detector and the $^{235}$U target is shown on a logarithmic scale in Figure 10. The spectra for the other detectors, and those from the $^{238}$U target, were nearly identical.

The high peak near channel 50 is due to the large number of alpha particles emitted from the target. As determined in a separate alpha background measurement, the high-energy side of this peak drops rapidly to zero and gives no contribution to the pulse-height spectrum beyond channel 160. The long tail extending out to channel 1024 is attributed to the detection of fission fragments produced in the target. It is important to note that the fission fragment pulse-height distribution is continuous and not separated from the alpha distribution at low energies. The fragment distribution is expected to continue back to zero pulse height because the effective thickness of the target foil is greater than the range of lower-energy fission fragments. The contribution of noise signals to the overall pulse-height distribution is not observed in the spectrum because the lower level discriminator on the analyzer prevented
Figure 10. A typical pulse-height spectrum of alpha particles and fission fragments from the $^{235}$U target for one of the surface barrier detectors.
storage of those pulses.

Because the fission fragment pulse height distribution was not separated from the alpha distribution, it was necessary to develop reliable procedures for establishing and maintaining discriminator levels to prevent the alpha pulses from being counted. Furthermore this feature had to be considered in the calculation of the counting system efficiency which is treated in Appendix C.

A precision pulser, calibrated using alpha particles of known energy, was used to establish suitable discriminator levels and to check on the gain stability of the electronics during the course of the photofission yield measurements.

Alpha spectra from each of the detectors, at biases of +130 volts and +60 volts, were stored in a multichannel analyzer. For these measurements it was necessary to increase the amplifier gains above those used in the photofission experiments so that the amplifier output signals of about 0.9 volts/MeV were spread across the 1024 channels.

A typical spectrum which includes four pulser peaks and six alpha groups from a $^{228}$Th source is shown in Figure 11. The alpha groups are identified as the most intense alphas produced in the decay of $^{228}$Th on through all of its radioactive daughters to stable $^{208}$Pb. The labelled energies and radioactive nuclei were obtained from Lederer et al. (45). Because the 5.67 MeV and 6.06 MeV peaks were not well resolved for each detector, these energies were not used to calibrate the pulser.

A linear function, relating pulser setting to alpha energy, was then obtained for each detector by combining the results of linear least-squares
Figure 11. A typical pulse-height spectrum of alpha particle from a $^{228}$Th calibration source and pulser signals for one of the surface barrier detectors.
fits to plots of alpha energy versus channel number and pulser setting versus channel number.

For the $^{238}$U experiment adequate discrimination of the alpha pulses was achieved with the discriminator levels set at 15 MeV. Suitable discrimination of the alphas was achieved in the $^{235}$U experiment with the discriminators set at 20 MeV. In Figure 10, the 20 MeV alpha energy setting is indicated by the vertical arrow near channel 180. The higher discriminator setting was necessary for the $^{235}$U experiment because the much larger alpha activity of the target caused significantly more pile-up counts for a lower discriminator setting.

C. Acquisition of the Yield Data

For each target, total photofission yields and background yields were measured for selected end-point energies ranging from 5.0 MeV to 8.0 MeV. The beam gates (see Appendix A), which were lifted for the photofission measurements, were lowered for the background yield measurements to attenuate the photon intensity at the target by a factor of $10^6$. No significant change in the neutron background at the target was observed with the beam gates in either configuration. Therefore, it was assumed that the background yield was composed of events due to neutron-induced fission and alpha pile-up only. Hence the difference between these two yield measurements, normalized to the same number of monitor counts, gave the net photofission yield curve to be used for the cross section analysis.

The total photofission yield points were measured in 0.1 MeV increments of the end-point energy. To minimize systematic error, half the yield points were taken every 0.2 MeV from 8.0 MeV to 5.0 MeV and the
complementary half were taken every 0.2 MeV from 4.9 MeV to 7.9 MeV.

Because the background was a smooth, slowly-varying function over the entire end-point energy range, background yield points were measured approximately every 0.5 MeV only. The background yield, for those end-point energies at which no measurements were made, was then estimated from a smooth curve drawn through the measured points.

For both the total photofission yield and the background yield data, some measurements were repeated as a check on reproducibility. In addition, the gain stability of the electronics was checked frequently with the calibrated pulser between yield point runs. Throughout these measurements the discriminator levels did not change by more than 5%.

D. Analysis of the Yield Data

A net photofission yield curve was obtained by normalization of the raw yield data, followed by background subtraction from the total photofission yield. The average photofission cross section was then determined by unfolding the beam spectra from the net photofission yield curve.

1. Calculation of the net photofission yield curve

The raw yield data, for both the photofission and background runs, were in terms of yield per counting chain for a recorded number of monitor events. These data per counting chain were summed to give the total photofission and background yield curves. To make these total yield data compatible with the matrix representation of the incident beam, they were normalized as discussed in Appendix B. This normalization procedure generated total photofission and background yield data normalized to a
fixed number of photons emerging from the reactor.

To obtain the net photofission yield curve, the background yield curve, estimated by a smooth curve drawn through the background yield points, was subtracted from the total photofission yield curve.

The statistical errors assigned to the net photofission yield points were calculated by the standard error propagation formula which combines quadratically the statistical error in the total photofission yield point with the statistical error in the background yield point. The statistical error for each total photofission yield point was calculated as discussed in Appendix B. For the background data a uniform statistical error was assigned to be the square root of the variance calculated between the smooth curve and the measured data points.

2. Calculation of the photofission cross section

For an end-point energy, $E_p$, and for a number of monitor events, $MF$, as defined in Appendix B, the number of fission events detected, $Y(E_p)$, is given by:

$$Y(E_p) = K \times \int_{E_t}^{E_m} I(E_p, E) \sigma(E) dE$$

where

$$K = \text{constant containing target and counting efficiency factors;}$$

$$I(E_p, E) = \frac{\text{number of photons}}{cm^2 \text{ - MeV}}$$

striking the target with energies between $E$ and $E + dE$, for an end-point energy, $E_p$, and for a number of monitor events, $MF;$
\[ \sigma(E) = \text{photofission cross section per nucleus per photon of energy, } E; \]

\[ E_m = \text{maximum photon energy in the incident spectrum for an end-point energy, } E_p; \]

\[ E_t = \text{minimum photon energy in the incident spectrum for an end-point energy, } E_p. \]

The usual approach to solving Equation 3.1 is to express the integral equation in matrix form. This involves: dividing the region of integration into \( n \) bins each of width \( \Delta \), where \( \Delta = (E_m - E_t)/(n - 1) \) and assuming that \( \Xi(E_p, E) \) is a slowly varying function across the bin width and can thus be approximated by an average value \( \Xi'_{pl} \). If \( \sigma_i \) is then defined to be the average value of the cross section at an energy \( E_i \), and \( Y(E_p) \) is replaced by simply \( Y_p \), then Equation 3.1 can be written in the form:

\[
Y_p = K \times \sum_{i=1}^{n} (\Xi'_{pl} \cdot \Delta) \cdot \sigma_i ; p=1, np
\]  

(3.2)

where:

\[ np = \text{number of yield points measured.} \]

Equation 3.2 is reduced further to the form used for unfolding the photofission yield data by relating \( \Xi'_{pl} \cdot \Delta \) to the matrix representation of the beam, \( N_{pl} \), constructed from the measured beam spectra (see Chapter III). The relation between \( \Xi'_{pl} \cdot \Delta \) and \( N_{pl} \) is given by:

\[
\Xi'_{pl} \cdot \Delta = N_{pl} \cdot \left( \frac{1}{TA \cdot B_i} \right) \cdot \frac{MF}{MB}
\]  

(3.3)
where:

\[ N_{pi} = \text{number of photons through a cross sectional area, } TA, \]

that are detected by the pair spectrometer with energies between \( E_i - \Delta/2 \) and \( E_i + \Delta/2 \), for an end-point energy, \( E_p \), and for a number of monitor events, \( MB \);

\[ B_i \] - absolute efficiency correction factor which converts the number of photons detected by the pair spectrometer system to the number in the beam.

Hence, \( E_m \) and \( E_t \) were chosen to give \( \Delta = 0.1 \text{ MeV} \) for \( n = 37 \). The value of np was 31. The matrix, \( N \), was then an np by n matrix whose rows were the measured beam spectra presented in Chapter III.

Upon substituting Equation 3.3 into Equation 3.2, rearranging terms, the equation for \( Y_p \) becomes:

\[ Y_p = \sum_{i=1}^{n} N_{pi} \cdot s_i \quad p=1, np \quad (3.4) \]

where

\[ s_i = \text{reduced average cross section defined by Equation 3.5.} \]

\[ s_i = \left( \frac{K \cdot \frac{1}{TA} \cdot \frac{MF}{MB}}{B_i} \right) \cdot \bar{\sigma}_i \quad (3.5) \]

The numerical solution of Equation 3.4 by straight inversion is in general not successful. Because of the singular nature of the matrix \( N \), the errors in the measured yield points \( Y_p \) are magnified and cause large oscillations to occur in the solution vector \( \bar{Y} \).
Cook (46) and others (47, 48) have developed techniques for incorporating a controlled smoothing function in the inversion process to obtain physical, non-oscillating, solutions for $\lambda$. Yester (29) has described in some detail modifications in this technique for application to photofission data obtained from the Compton scattering facility. Appendix D of this dissertation contains a discussion of the resolution function which gives a measure of the experimental resolution determined in this analysis method. The interpretation of cross sections obtained by this technique is also discussed in Appendix D.

The absolute average cross section $\bar{\sigma}_1$ for an excitation energy $E_1$ is obtained from the reduced cross section $s_1$ by:

$$\bar{\sigma}_1 = (NF \cdot V \cdot \epsilon \cdot \frac{1}{TA \cdot B_1} \cdot \frac{NF}{MB})^{-1} \cdot s_1$$

(3.6)

where:

- $NF$ = number of fissionable nuclei per cm$^3$,
- $V$ = volume of the target foil in cm$^3$,
- $\epsilon$ = efficiency of the counting system, (defined here as the ratio of the number of fission events counted per unit monitor response to the total number of fission events which occur in the target per unit monitor response).

The factor $\epsilon$ was determined for each target as discussed in Appendix C. The other factors in the expression were calculated as discussed in other parts of this section.
V. EXPERIMENTAL RESULTS

A. Photofission of $^{238}\text{U}$

1. Yield data

The total photofission yield and background yield data for $^{238}\text{U}$ are presented in Figure 12. Each yield point is normalized, as described in the previous chapter, to a fixed number of photons emerging from the reactor. Seventeen of the ($\gamma$,f) yield points are average values of repeated yield measurements. The vertical error bars represent the statistical uncertainty in each point. For these data the statistical accuracy in the total ($\gamma$,f) yield ranges from 15.0% at 5.0 MeV to 3.0% at 8.0 MeV.

As expected, the background yield was relatively small and constant over the entire range of end-point energies. A measurement of the background yield with the reactor at zero power indicated that the background count rate at the geometry corresponding to 5.0 MeV was entirely due to alpha pile-up pulses. At the 8.0 MeV position the background consisted of 70% alpha pile-up and the remaining 30% were due to neutron-induced fission.

The net photofission yield curve was calculated by subtracting the background yield, approximated by the straight line shown in Figure 12, from the total yield. The statistical accuracy in the net yield points ranges from 11% at 6.0 MeV to 3% at 8.0 MeV.
Figure 12. The measured photofission yield and background yield data for $^{238}$U. Vertical error bars indicate statistical uncertainty only. The net photofission yield curve was calculated by subtracting the straight line through the background yield points from the total yield.
2. Cross section

The cross section extracted from the net photofission yield data is shown in Figure 13 and is presented in tabular form in Table 1. In Figure 13 the vertical error bars represent uncertainty in the relative cross section, due to the propagation of the yield point statistical errors through the unfolding equations. They do not include a 30% uncertainty associated with the absolute value of the cross section. The horizontal error bars indicate the experimental resolution as determined by the analysis procedure. Thresholds for competing photonic reactions are indicated by the vertical arrows at 6.18 MeV for the \((\gamma,n)\) process and at 7.67 MeV for the \((\gamma,p)\) process (49).

Pronounced structure is seen in the \(^{238}\text{U} (\gamma,f)\) cross section at 6.2 MeV and 7.6 MeV. There are indications of unresolved structure near 5.5 MeV and 7.0 MeV. From the analysis procedure the experimental resolution was determined to be 400 keV at 5.5 MeV and 500 keV at 7.6 MeV with an average resolution of 460 keV over the entire energy range.

It is interesting to note that the qualitative appearance of the yield curve (see Figure 12) between 5.4 MeV to 5.8 MeV clearly indicated the presence of a resonance near 5.5 MeV.

The negative cross section below 5.4 MeV results from large relative uncertainties in background subtraction in the region of very small foreground yields.
Figure 13. $^{238}\text{U}(\gamma,f)$ photofission cross section. Vertical error bars indicate uncertainty in the relative cross section. Horizontal error bars indicate the experimental resolution and represent the widths that would be observed for delta-function resonances. Vertical arrows near the abscissa indicate the threshold for competing reactions.
Table 1. Photofission cross sections of $^{238}\text{U}$ and $^{235}\text{U}$

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$^{238}\text{U}$ Cross section (millibarns)</th>
<th>$^{235}\text{U}$ Cross section (millibarns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>$-0.8 \pm 0.6^a$</td>
<td>$-0.4 \pm 1.9^a$</td>
</tr>
<tr>
<td>5.1</td>
<td>$-0.9 \pm 0.5$</td>
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<td>5.5</td>
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</table>

$^a$These are the relative errors only. The ± 30% error in the absolute scale has not been included.
3. **Comparison to other cross section measurements**

While many measurements of the $^{238}$U photofission cross section have been reported, only the most recently published results of Khan and Knowles (15), Rabotnov et al. (10), Mafra et al. (14), and Manfredini et al. (13) are compared to the photofission cross section derived from the present work.

In Figure 14 the $^{238}$U ($\gamma$,f) cross section is compared to the results obtained by Khan and Knowles (15). Their data show pronounced peaks at 6.2 MeV and 7.8 MeV and less resolved structure at 5.2 MeV, 5.7 MeV and 7.1 MeV. There is excellent agreement between the two measurements up to an excitation energy of 6.8 MeV. As seen in Figure 14, however, there are puzzling differences between the two measurements above this energy. Where we see a broad peak at 7.6 MeV, Khan and Knowles find evidence of two peaks at 7.1 MeV and 7.8 MeV, both with considerably more strength than found in our measurement.

Such a large discrepancy is surprising since Khan and Knowles used a Compton scattering facility (50) similar to that used in this work. However, the analysis procedures used in the two experiments were quite different and very likely constitute the major source of the discrepancies between the two measurements.

Khan and Knowles, in their analysis procedure, assumed the spectrum of photons for each scattering angle to consist of discrete lines with: energies given by the Compton formula applied to the lines in the direct beam; relative intensities the same as for the direct beam lines; and
Figure 14. Comparison of the $^{238}\text{U}$ photofission cross section from this work with that from Khan and Knowles (15).
line shapes given by a measurement of the intensity distribution of a single scattered line. The spectra constructed in this way differed substantially in the lower energy regions from the scattered beam spectra measured in the present work. Where a significant number of photons was observed in the low energy regions of the measured spectra, the constructed spectra showed few photons.

To see if this difference could account for the discrepancies between the two cross sections, a test run with a modified beam matrix was made in the analysis of the $^{238}$U net photofission yield data of the present work. The modified beam matrix was constructed from the measured photon spectra, with the number of photons in the low energy regions reduced, to simulate the spectra of Khan and Knowles. The resultant cross section did in fact show closer agreement with the cross section of Khan and Knowles at the high energy end. Furthermore, the region of the cross section below 6.6 MeV remained unchanged from that shown in Figure 13. Hence, the difference in the representations of the photon spectra can indeed account for the differences in the reported cross sections.

Since no errors can be found in the photon spectra used in this analysis, we conclude that the cross section in Figure 13 is a correct representation of the photofission cross section of $^{238}$U.

In Figure 15, the cross section obtained by Rabotnov et al. (10) is compared to that of the present work. The average cross section from reference (10), which was extracted from a bremsstrahlung produced yield curve, does not resolve the structure at 6.2 MeV, and the minimum at 6.5 MeV is also much less pronounced.
Figure 15. Comparison of the $^{238}$U photofission cross section from this work with that from Rabotnov et al. (10)
A more recent measurement of the $^{238}$U($\gamma$,f) cross section by Ignatyuk et al. (11), who also used bremsstrahlung as the photon source, agrees well with that of Rabotnov et al. (10) and is therefore, not directly compared to the present results.

The cross sections derived from measurements with neutron capture gamma lines from several discrete sources are compared to the present results in Figures 16 and 17. In Figure 16, the cross section points from Mafra et al. (14) are plotted as open circles. With the exception of the high cross section values at 6.73 MeV and 7.91 MeV, the measurements of Mafra et al. are consistent with those of this work.

Care, however, must be taken in the interpretation of the cross sections measured with the narrow discrete gamma lines, especially when compared to cross sections derived from measurements made with continuous photon spectra. The discrete gamma lines have widths of a few ev and may be on or off resonance with levels in the compound nucleus for which the level spacing is of the order of 10 ev at excitation energies of 7 MeV (36). It is obvious that the photon source used in the present work is broad enough to average over the continuum microstructure.

In Figure 17, the cross section values from Manfredini et al. (13) are compared to this work. With the exception of the cross section values at 6.75 MeV and 7.91 MeV, the results of Manfredini et al. are consistent with the present work. Again the caution expressed in the previous paragraph must be considered in the comparison of these two measurements in Figure 17.
Figure 16. Comparison of the $^{238}$U photofission cross section from this work with that from Mafra et al. (14)
Figure 17. Comparison of the $^{238}\text{U}$ photofission cross section from this work with that from Manfredini et al. (13)
B. Photofission of $^{235}\text{U}$

1. Yield data

The total photofission and background yield data, normalized to a fixed number of photons emerging from the reactor, are shown in Figure 18. Six of the $(\gamma,f)$ yield points are average values of repeated yield measurements. The vertical error bars represent the statistical uncertainty in each measured yield point. For these data, the statistical uncertainty in the total $(\gamma,f)$ yield ranged from 4.7% at 5.0 MeV to 2.0% at 8.0 MeV.

Because the cross section for thermal neutron induced fission of $^{235}\text{U}$ is several orders of magnitude greater than the photofission cross section, neutron-induced fission events represented a sizable contribution to the total number of fission events detected. As shown in Figure 18 the total photofission to background ratio was at best 2:1 at 8.0 MeV. Fortunately, the background yield, as shown by the open circles, was a relatively smooth function of end-point energy and could be approximated by the smooth curve over the entire range of end-point energies. A background yield measurement, with the reactor at zero power, indicated that the higher discriminator settings for this experiment effectively blocked all pulses due to alpha pile-up. The background yield was entirely due to neutron-induced fission. The increase in the background yield with increasing end-point energy (decreasing scattering angle) was consistent with a neutron survey meter map of the
Figure 18. The measured photofission yield and background yield data for $^{235}$U. Vertical error bars indicate statistical uncertainty only. The net photofission yield curve was calculated by subtracting the smooth curve through the background points from the total yield.
fast and thermal neutron background at target positions ranging from 0° to 17.3°.

The net photofission yield curve was calculated by subtracting the background yield, approximated by the smooth curve, from the total photofission yield. As expected, the large background subtraction from the total yield significantly increased the errors associated with the net photofission yield data. These errors ranged from 25% at 6.0 MeV to 4.6% at 8.0 MeV.

2. Cross section

The cross section extracted from the net photofission yield data is shown in Figure 19, and is also presented in Table 1. In Figure 19, the vertical error bars represent uncertainty in the relative cross section, due to the propagation of the yield point statistical errors through the unfolding equations. They do not include the 30% uncertainty associated with the absolute value of the cross section. The horizontal error bars indicate the experimental resolution as determined by the analysis procedure. Thresholds for competing photonuclear reactions are indicated by the vertical arrows at 5.30 MeV for the (γ,n) process and at 6.74 MeV for the (γ,p) process (49).

Prominent structure is observed in the $^{235}\text{U} (\gamma,f)$ cross section at 5.9 MeV, 6.6 MeV and 7.5 MeV. There is also an indication of unresolved structure near 5.4 MeV.

From the analysis, the average experimental resolution was determined to be 580 keV, as compared to 460 keV for the $^{238}\text{U}$ measurement. As
Figure 19. $^{235}\text{U}$ photofission cross section. Vertical error bars indicate uncertainty in the relative cross section. Horizontal error bars indicate the experimental resolution and represent the widths that would be observed for delta-function resonances. Vertical arrows near the abscissa indicate the threshold for competing reactions.
discussed in Appendix D, this is not surprising since the experimental resolution is very dependent on the statistical quality of the net yield data. It is interesting to note, however, that although the experimental resolution is not as good in the $^{235}U$ experiment as in the $^{238}U$ experiment, the observed structure in the $^{235}U$ cross section is narrower than that seen in $^{238}U$. This indicates that the resonance structure in the true $^{235}U$ cross section is narrower than in the $^{238}U$ cross section.

3. **Comparison to other cross section measurements**

In the case of $^{235}U$, very little photofission data has been reported. The only previous comparable measurement is that of Khan and Knowles (15), and the two measurements are compared in Figure 20.

Both measurements clearly show a resonance near 6.6 MeV. At energies both above and below this value, however, the general agreement is not good. Khan and Knowles do see a hint of structure near 5.8 MeV but at nowhere near the cross section strengths we have seen at that energy. The large fluctuations in their cross section above 7.0 MeV do not really allow a meaningful comparison of the two measurements. However, the observed behavior between 7.5 MeV and 8.0 MeV appears to be qualitatively different.

It is important to note that Khan and Knowles used a target which was enriched to 46% $^{235}U$ with 54% $^{238}U$. To obtain the $^{235}U(\gamma,f)$ cross section, they had to subtract a large $^{238}U$ contribution from the cross section derived from their curve. For the present work a target enriched
Figure 20. Comparison of the $^{235}\text{U}$ photofission cross section from this work with that from Khan and Knowles (15)
to 97.7% $^{235}\text{U}$ was used. These facts coupled with the earlier discussion of an analysis procedures used by Khan and Knowles lead us to conclude that the cross section derived from the present work is the more reliable of the two.
VI. DISCUSSION AND CONCLUSIONS

A. General Remarks

To establish proper perspective for the interpretation of the measured \((\gamma,f)\) cross sections, some preliminary remarks are in order. The first concerns the relation of the \((\gamma,f)\) cross section, \(\sigma_f(E)\), to the total photon absorption cross section, \(\sigma_a(E)\), given by:

\[
\sigma_f(E) = \frac{\Gamma_f(E)}{\Gamma_t(E)} \cdot \sigma_a(E)
\]

where \(\Gamma_f(E)\) is the decay width or probability for fission associated with the compound nuclear state having a total decay width, \(\Gamma_t(E)\). \(\Gamma_t(E)\) is just the sum of the decay probabilities for the different de-excitation modes of the compound state. These are \(\Gamma_f\) for fission, \(\Gamma_n\) for neutron emission and \(\Gamma_\gamma\) for radiation. De-excitation by charged particles here can be neglected because of its large inhibition by coulomb forces in heavy nuclei.

Structure can appear in \(\sigma_f(E)\) if \(\sigma_a(E)\) and \(\sigma_t(E)\) are smoothly varying functions of \(E\) but \(\Gamma_f(E)\) is not. For this case the structure in \(\sigma_f(E)\) would correspond to channels in the transition state spectrum if the excitation energy were near the barrier. Structure can also appear in \(\sigma_f(E)\) if \(\Gamma_f(E)\) and \(\Gamma_t(E)\) are smoothly varying but \(\sigma_a(E)\) is not. Likewise, if \(\Gamma_f(E)\) and \(\sigma_a(E)\) are smoothly varying, but \(\Gamma_t(E)\) is not because of a fluctuating decay probability for neutron emission or radiation, then structure is also evident in \(\sigma_f(E)\). Clearly then, only if \(\sigma_a(E)\), \(\Gamma_n(E)\) and \(\Gamma_\gamma(E)\) are known, can a realistic interpretation of the structure in
the photofission cross section be made.

Information on the energy dependence of the total photon absorption cross section for heavy elements is very sparse for excitation energies near the fission threshold (5.0 MeV to 8.0 MeV). Generally, the dipole absorption cross section, which dominates quadrupole absorption by a factor of 20 at these energies, is approximated by extrapolating the low-energy tail of the giant dipole resonance to threshold (36).

There is likewise little experimental information on the energy dependence of the neutron widths and radiation widths of the compound states. Generally, these de-excitation modes are included as model dependent factors in the channel analysis of fission cross sections (40).

In the interpretation of the photofission cross section data here, we will assume that $\sigma_a(E)$ and $\Gamma_+(E)$ are smoothly varying functions of excitation energy. The observed structure can then be interpreted as resulting from individual channels in the transition state spectra of the fissioning nucleus.

The second remark concerns the correlation of cross section data with measured angular distributions of fission fragments in the photofission process. For even-even nuclei, the transition state spectrum is postulated to include three well-separated low-lying levels, with quantum numbers $(K, l^+) = (0, 2^+), (0, 1^-)$ and $(1, 1^-)$, through which the nucleus can fission after photon absorption (see Figure 1). Because the levels are well separated, a photofission cross section experiment should, in principle, exhibit structure corresponding to these states, subject to experimental resolution.
The angular distributions of fragments from these states are very different and are given by Huizenga (36) as:

\[ W(\theta) = \frac{5}{8} (\sin^2 \theta + \frac{1}{4} \sin^2 2\theta) \quad \text{for} \ (K, l^\Pi) = (0, 2^+), \]

\[ W(\theta) = \frac{3}{4} \sin^2 \theta \quad \text{for} \ (K, l^\Pi) = (0, 1^-), \]

\[ W(\theta) = \frac{3}{4} (1 - \frac{1}{2} \sin^2 \theta) \quad \text{for} \ (K, l^\Pi) = (1, 1^-). \]

Generally, the function \( W(\theta) = a + b \sin^2 \theta + c \sin^2 2\theta \) is fit to the fragment angular distributions measured as a function of excitation energy. The coefficients \( a, b \) and \( c \) are then representative of the contribution to fission from each of the three states at a selected energy and identify the quantum numbers of the states involved in fission at that energy.

Note that for dominant dipole absorption and fission through both the \((K, l^\Pi) = (0, 1^-)\) and \((1, 1^-)\) channels, the angular distribution becomes isotropic.

For odd mass nuclei, the transition state spectra are more closely spaced and a high resolution photofission cross section measurement is necessary to resolve the corresponding structure. To make matters worse, the angular distribution is not expected to exhibit much anisotropy, especially for unoriented nuclei with high spin ground states (38). This follows because the distributions of compound nuclear spins resulting from photon absorption are not anisotropic (due to several \( M \) values for a given \( l \)), and the maximum fragment anisotropy is correspondingly small.

Angular distribution measurements from polarized targets would be of great
help here. To attempt an interpretation of the quantum characteristics of the structure in the photofission cross section data for even-odd systems, it may be possible to use the results of \((n,f)\) and \((d,pf)\) studies where applicable.

B. Interpretation of the \(^{238}\text{U}(\gamma,f)\) Cross Section

For the \(^{238}\text{U}(\gamma,f)\) cross section derived from the present work, prominent structure is observed at 6.2 MeV and 7.6 MeV with indications of weaker peaks at 5.5 MeV and 7.0 MeV. The qualitative behavior seen in the angular distribution measurements of references \((20,21,22,23,25,26)\) for photofission of \(^{238}\text{U}\) indicates a large quadrupole contribution from 5.0 MeV to 5.5 MeV; a dipole contribution which is dominant near 5.5 MeV and which decreases with increasing excitation energy; and an isotropic contribution of nearly zero at 5.0 MeV, but increasing with energy to become the dominant component at 8.0 MeV. In the framework of Bohr's "fission channel" theory \((2)\), the angular distribution measurements suggest the opening of the following channels characterized by \((K, l^\pi)\):

\begin{align*}
(0, 2^+) & \text{ between 5.0 MeV and 5.5 MeV,} \\
(0, 1^-) & \text{ between 5.5 MeV and 6.0 MeV,} \\
(1, 1^-) & \text{ above 6.0 MeV.}
\end{align*}

The opening of additional channels with \(l^\pi = 1^-\) above this are also expected. It seems reasonable, then, to interpret the structure at 6.2 MeV as the \((K, l^\pi) = (0, 1^-)\) transition state in \(^{238}\text{U}\). The rise in the cross section at 6.6 MeV and the hint of structure at 7.0 MeV can then be interpreted as the opening of a \((K, l^\pi) = (1, 1^-)\) fission channel. The prominent peak at 7.6 MeV is in the transition state region in which
intrinsic excitations dominate and the K values are statistically dis-
tributed.

These interpretations are consistent with the work of Dowdy and
Krysinski (26) and Manfredini et al. (25) who have estimated the thresh-
olds for the two fission channels from channel analysis of their angular
distributions. Dowdy and Krysinski calculated the thresholds for the
\((0,1^-)\) and \((1,1^-)\) fission channels to be 5.98 MeV and 6.63 MeV, respec-
tively. Manfredini et al. obtained 5.60 MeV and 6.54 MeV for the two
thresholds.

The differential cross section measurements by Knowles et al. (27)
show definitely that the peak at 6.2 MeV is due to dipole absorption and
may be classified as the \((0,1^-)\) channel. Khan and Knowles (15) interpret
the smooth region of their cross section above 6.2 MeV as the opening of
the \((1,1^-)\) fission channel. These interpretations are also consistent
with the present one.

Although Rabotnov et al. (10) and Ignatyuk et al. (11) have reported
photofission cross section and angular distribution measurements up to
7.5 MeV, the focus of their analysis and discussion is on the subbarrier
region. Their major objective was to determine the characteristic param-
eters of the double-humped barrier from the photofission measurements.
Only qualitative conclusions are made in these papers concerning the
effect of the double-humped barrier on fission. In an earlier publica-
tion of their angular distribution measurements, Rabotnov et al. (20)
applied "fission channel" analysis to their data and conclude that the
thresholds for the \((K,l^\pi) = (0,1^-)\) and \((1,1^-)\) transition states are
5.7 MeV and 7.0 MeV respectively. These results are in agreement with the present interpretation.

These interpretations are consistent with a double-humped barrier for which the second peak is higher than the first. Welgmann and Theobald (51) have calculated the barrier heights using a combined analysis of data from narrow intermediate structure in near barrier fission cross sections and from shape isomer half-lives. For $^{238}$U, the inner barrier height is estimated to be 5.78 MeV and the outer, 5.90 MeV. These values have an uncertainty of at least 0.3 MeV. In Bohr's "fission channel" theory the $(K,l^m) = (0,0^+)$ transition state would then correspond to an excitation energy of 5.90 MeV. This means that the $(0,1^-)$ channel is 0.4 MeV above the lowest barrier and the $(1,1^-)$ level is 0.7 MeV to 1.1 MeV above the barrier. The peak associated with intrinsic particle excitation is then 1.7 MeV above the barrier.

The transition state spectrum of $^{238}$U has also been studied by inelastic $\alpha$-particle scattering (52,53) and by the $(t,\alpha f)$ stripping reaction (54). However, Hulzenga et al. (52) have made no $K$ assignments. The results of Britt and Plasil (53) indicate the presence of the following rotational bands in the transition state: one $K = 0^+$ band and one $K = 1^-$ band from fission threshold to 0.7 MeV; a $K = 2^+$ or a combination of a $K = 3^-$ and an additional $K = 1$ band from 0.7 MeV to 1.6 MeV; either two $K = 4$ bands and an additional $K = 1$ band or an additional $K = 3$ band only at approximately 1.6 MeV. Only states in the first two bands are excited to an appreciable extent by photofission. The interpretation of the present photofission measurements is consistent with the presence of the
K = 1− band. However, the peak at 6.2 MeV in the photofission cross section has been identified as due to the \( l = 1^- \) state in the \( K = 0^- \) band. Britt and Plasil were not able to fit their results when this band was included in their analysis. A discrepancy then exists between the assignments from the photofission measurements and the \((\alpha,\alpha')\) measurements.

The angular correlation measurements by Cramer and Britt (54), who studied the transition states of \(^{238}\text{U}\), via the \(^{236}\text{U}(t,pf)\) stripping reaction, indicate that \( K = 0^\pm \) bands are present in the transition state spectra just above threshold. They also indicate that \( K \geq 2 \) bands become available for excitation energies between 6.0 MeV and 6.5 MeV. The present cross section interpretation is consistent with the \( K = 0^- \) band just above threshold.

In summary, the present \(^{238}\text{U}(\gamma,f)\) cross section measurement, as correlated with the existing \((\gamma,f)\) angular distribution, indicates the presence of \( K = 0^- \) and \( K = 1^- \) bands in the low lying transition state spectra. The \((K,l^\pi) = (0,1^-)\) and \((1,1^-)\) states are identified at excitation energies of 6.2 MeV and at 6.6 to 7.0 MeV respectively. A prominent peak at 7.6 MeV is seen in the transition state region where intrinsic excitations dominate. Total photon absorption measurements and \((\gamma,n)\) measurements in the energy range, 5.0 MeV to 8.0 MeV, are needed to unambiguously confirm the interpretation of the present \(^{238}\text{U}(\gamma,f)\) cross section.
C. Interpretation of the \(^{235}\text{U}(\gamma, f)\) Cross Section

Prominent structure in the \(^{235}\text{U}(\gamma, f)\) cross section is observed at 5.9 MeV, 6.6 MeV and 7.5 MeV with a hint of structure at 5.4 MeV. Because of the high spin (7/2\(^-\)) of the \(^{235}\text{U}\) ground state, photofission angular distribution measurements show no anisotropy and cannot be used for the interpretation of the structure in the \(^{235}\text{U}(\gamma, f)\) cross section. Photofission angular distribution measurements with a polarized target would aid in the interpretation of these data. In the absence of such data, studies of the transition state spectra of \(^{235}\text{U}\) via (n,f) and (d,pf) reactions have been investigated. The object of this search was to see if fission channels identified by these methods could also correspond to channels through which the \(^{235}\text{U}\) nucleus fissions after photon absorption.

First, consider the different \(K\) bands through which the \(^{235}\text{U}\) transition state nucleus can fission after a compound state is formed by dipole absorption. The compound states formed following electric dipole absorption have total angular momenta of \(9/2^+, 7/2^+\) and \(5/2^+\). Since for an even-odd nucleus the members of a rotational band with quantum number \(K\) have total angular momenta \(I = K, K + 1, K + 2, \ldots\), the possible \(K\) bands through which the \(^{235}\text{U}\) nucleus can fission are \(K = 1/2^+, 3/2^+, 5/2^+, 7/2^+, 9/2^+\).

The transition state spectrum of \(^{235}\text{U}\) has been investigated experimentally in the \(^{234}\text{U} (n,f)\) reaction by Lamphere (55,56) and by Behkami \textit{et al.} (57). Lamphere measured the fission cross section and angular anisotropy as functions of neutron energy from 0.2 MeV to 4 MeV.
(excitation energies in the compound nucleus of 5.5 MeV to 9.5 MeV).
The observed cross section exhibits a prominent peak at an excitation
energy of approximately 6.1 MeV. The angular anisotropy shows structure
at approximately 5.5 and 6.1 MeV. Lamphere suggests a K band sequence
of 1/2^+, 3/2^-, 1/2^- for excitation energies between 5.5 MeV and 6.4 MeV.
He associates the prominent peak at 6.1 MeV with the K = 1/2^- band.

Behkami et al. (57) measured the fission fragment angular distribu-
tions as a function of neutron energy from 0.2 MeV to 1.2 MeV (excitation
energies of 5.5 MeV to 6.5 MeV). An analysis of their angular distri-
bution, combined with Lamphere's (55) cross section, indicates the
following sequence of accessible states in the transition nucleus:
K^T = 1/2^+, 3/2^+, 3/2^- for excitation energies between 5.5 MeV and 5.8 MeV;
and at least one or more states with K = 1/2^- for excitation energies
between 5.9 MeV and 6.5 MeV. Vandenbösčh et al. (58) measured the
angular anisotropy of fission fragments from the reaction ^234U (d,pf)
for excitation energies from 5.3 MeV to 7.3 MeV. Their data indicate
that, on the average, approximately eight fission channels open every
250 keV over this energy range. Because of the higher angular momentum
transfer with this reaction than with the neutron induced fission of ^234U,
some of the channels are expected to have K quantum numbers > 3/2.

These data do not allow a meaningful interpretation of the structure
in the ^235U (γ,f) cross section. Rather they demonstrate the complexity
of the transition state spectrum in ^235U. Much additional information is
necessary before the cross section from the present work can be related
unambiguously to the transition state spectrum of ^235U. Also, the remarks
made in section A of this chapter surely have a bearing on the inter-
pretation of the results.

D. Comparison of the (γ,f) Cross Sections of

\[ ^{238}\text{U}, \; ^{236}\text{U} \text{ and } ^{235}\text{U} \]

In Figure 21 the (γ,f) cross sections for \(^{238}\text{U}\) and \(^{235}\text{U}\) from this work are compared to the (γ,f) cross section for \(^{236}\text{U}\) measured by Yester (29). Because the total photon absorption cross section and the widths for the competing reactions are not known, the comparison of these three cross sections is somewhat open-ended. There are, however, some systematic features worth pointing out. The first is the systematic appearance of the prominent peak near 7.5 MeV in all these cross sections. The second feature concerns the width of structure observed in the three measurements. Although the experimental resolution for the \(^{235}\text{U} (γ,f)\) measurement was not as good as for either the \(^{236}\text{U} (γ,f)\) or \(^{238}\text{U} (γ,f)\) measurements, the structure in the \(^{235}\text{U} (γ,f)\) cross section appears to be narrower. Another feature is the systematic shift to lower energy, of the first prominent peak, with decreasing neutron number.

E. Concluding Remarks

The photofission cross sections for \(^{238}\text{U}\) and \(^{235}\text{U}\) from 5.0 MeV to 8.0 MeV have been deduced from yield curve measurements. Structure is observed in both cross sections. For \(^{238}\text{U}\) some of the structure can be associated with specific transition states of the nucleus. The interpretation of the structure, however, is somewhat open-ended because of the lack of certain experimental information.
(γ,f) CROSS SECTIONS FOR THREE URANIUM ISOTOPES

- 238U THIS WORK
- 236U YESTER
- 235U THIS WORK

Figure 21. Comparison of the photofission cross sections of 238U and 235U from this work with that of 236U from Yester (29)
In order to assess each cross section properly, measurements of the total photon absorption cross sections and the cross sections for competing modes of de-excitation of the compound nucleus are necessary. At the present time the photon absorption cross section is generally assumed to be a smooth function of excitation energy. The effects of competing modes of decay, if considered, are incorporated in a theoretical manner. As pointed out in section A of this chapter, neglect of these two features can lead to structure in the measured photofission cross section which is not due to resonance phenomena in the fission channels.

An interpretation of the structure in the $^{235}\text{U} \,(\gamma,f)$ cross section is essentially impossible due to lack of suitable angular distribution experiments. As discussed previously, photofission angular distributions from unpolarized targets, for which the ground state spin is greater than one, is isotropic because of the several possible orientations of the total angular momentum with respect to the Z axis. Angular distribution measurements with polarized $^{235}\text{U}$ targets might yield some information which would help to interpret the $(\gamma,f)$ cross section.

The systematic appearance of the peak at 7.5 MeV in the cross sections measured in this work, and those obtained by Yester (29), is puzzling, but believed to be real and not the result of systematic error. A measurement of the photofission cross sections to higher energy would help resolve this puzzling feature.

In conclusion, some final remarks concerning photofission experiments with the Compton facility are in order. Two of the major limiting features of the facility which affect the reliability of the measured
cross section are: its marginal photon beam intensity, and its complex scattered photon spectrum which must be precisely known for cross section extraction. The photon spectrum is especially complex because of the presence of rather intense background lines from iron and aluminum in the reactor. If these could be eliminated and, at the same time, the source intensity could be increased by increasing the size of the nickel plate, a more "monochromatic" photon source would be developed.

Long counting times were required for the photofission experiments because of the combination of low intensity beam and rather inefficient fragment detection system (~3%). An increase of detection efficiency by a factor of ten would enable high quality yield data to be obtained from which a more reliable cross section could be extracted.
VII. BIBLIOGRAPHY


VIII. ACKNOWLEDGMENTS

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IX. APPENDIX A: THE ALRR COMPTON SCATTERING FACILITY

It is the purpose of this appendix to discuss in more detail the design, construction and operational details unique to this reactor-based facility at the Ames Laboratory. Much of the information presented here was excerpted from reference (31).

Of particular importance in this appendix are the discussions on the shielding and collimation used with the present facility. Past experience (32) has shown that inadequate shielding and collimation limit seriously the usefulness of a reactor-based Compton scattering system for photonuclear studies.

A. Principles of Operation

The fundamental principle for design of a Compton scattering device was suggested by Cormack (59) and is illustrated in Figure 22. If the source, scattering material, and target are made to lie on the circumference of the same focal circle, all source photons which are scattered in the direction of the target have scattered through the same angle. Thus, from the properties of the Compton effect (44), which relates the scattered photon energy, $E$, to the incident photon energy, $E_0$, the scattering angle, $\theta$, and the rest mass of an electron, $m_0c^2$, by the equation

$$ E = E_0 \left[ 1 + E_0 (1 - \cos \theta) / (m_0c^2) \right], $$

all photons of energy $E_0$, after being scattered through the same angle $\theta$,
Figure 22. Focusing principle of a Compton scattering system
have the same energy E. By then moving the target or the source along the focal circle, the scattering angle, hence the energy of the photons striking the target, is varied.

In practice the above principle is used in three geometrical scattering configurations: a plane circular geometry, a cylindrical geometry and a surface of revolution geometry. A point source, point target and a scatterer with limited vertical extent are used in the plane circular geometry for which Figure 22 represents the actual scattering configuration. Extending the figure in the vertical direction (perpendicular to the plane of the page) gives rise to the cylindrical scattering geometry in which a line source, a line target and a cylindrical scattering shell are used. The third scattering configuration is achieved by requiring the scattering material to lie on a surface of revolution defined by rotating the focal circle about the axis joining the source to the target. For this latter application both a point source and a point target are used. A suitable geometry is selected to optimize either the scattered photon energy resolution, the scattered photon intensity, or the feasibility for varying the scattered photon energy for a single primary source.

8. Description of the ALRR Facility

1. **General design features**

   The design of this facility is illustrated in Figures 23, 24 and 25. Figure 23 shows a horizontal projection of the cylindrical scattering geometry used at the ALRR experiment. The specific instrument
Figure 23. Horizontal projection of the cylindrical scattering geometry used at the ALRR Compton scattering facility.

\[
\tan \alpha = \frac{\sin \theta}{r/c + \cos \theta}
\]
parameters, as displayed in Figure 23, are defined as follows:

Source - Ni(n,\gamma) source inside the reactor near the core,

Pivot - fixed point about which the aluminum scatter rotates,

Target - focal point for gamma rays scattered from the aluminum plate through an angle \( \Theta \),

\( c \) - fixed distance of 157.5 in. from the source to the pivot,

\( r \) - fixed radial distance of 84.0 in. from the pivot to the target for each scattering configuration,

\( \Theta \) - angle through which the "focused" gamma rays scatter,

\( \alpha \) - angle through which the scattering plate is rotated about the pivot for a scattering angle \( \Theta \),

\( R \) - the radius of the focal circle defined by the source, pivot and target positions for a scattering angle \( \Theta \).

The simple geometrical configuration follows the basic design of Figure 22 and lends itself to a very simple method of operation. The scattering configuration for gamma rays scattered through an angle \( \Theta \) to be focused at the target is achieved by: (i) moving the target about the pivot until \( r \) makes an angle \( \Theta \) with \( c \), (ii) rotating the aluminum plate about the pivot so that the tangent to the plate at the pivot makes an angle \( \alpha \) with \( c \), and (iii) curving the scattering plate so that it lies on the focal circle defined by the source, pivot and target.

A pictorial representation of the facility is given in Figure 24. This picture, which simulates the actual installation, shows a gamma ray beam emanating from a nickel source placed inside a tangential access tube of the ALRR, scattering from a curved aluminum plate, and coming to focus on a target placed inside the target chamber. Further reference to this figure is made in a later section.
Figure 24. Pictorial simulation of the complete ALRR Compton scattering facility
The entire facility, shown in detail in Figure 25, is divided for clarity into the direct beam section and the scattered beam section. This drawing shows the top view of a horizontal plane through the center of the gamma ray beam. In this figure the target chamber and scattering plate are positioned for focusing of gamma rays scattered through 20°. A more detailed description of the facility now follows.

2. Source and scattering plate details

A 1 kg plate of natural nickel, 4 in. x 4 in. x 0.5 in., is used as the neutron capture gamma source. Nickel was chosen because it emits a simple gamma spectrum with intense high energy photons and, in its metal form, it can withstand the gamma heating near the reactor core. The nickel plate is positioned near the center of the 247 in. long, 6 in. diameter, tangential tube of the 5 MW ALRR by a removable source assembly and it is so mounted, as shown in Figure 25, that it can be rotated to change the effective width of the "line" source. At the source position gamma heating of the nickel is approximately 0.2 watts per gram, hence the source assembly near the nickel plate is cooled with circulating cooling water. A thermal neutron flux of $3 \times 10^{13}$ neutrons $1/cm^2$-sec at the nickel position produces a $2.14 \times 10^4$ Ci gamma source.

A uniquely designed scattering plate assembly is used in this facility. The aluminum plate with dimensions, 0.75 in. thick, 15 in. high at its center, and 89 in. long, is bent into a cylindrical shell by applying a "column loading"-type force to each end and is rotated by turning a vertical pivot post to which the plate is attached. As shown in Figure 24 the "column loading" force is applied to each end of the
Figure 25. Scale drawing of the ALRR Compton scattering facility showing a horizontal plane through the center of the gamma ray beam.
plate with two rods whose lengths are varied by means of a screw, chain drive and motor assembly. The peculiar plate shape insures that the plate will bend into a cylindrical shell when the "column loading" force is applied. Since the radius of curvature of the plate is directly related to the length of the connecting rods which form a chord of the focal circle, the curvature can be determined by monitoring the number of revolutions of the drive motor. This is accomplished by means of a 10,000 ohm helipot potentiometer which is attached to one end of the curvature drive motor shaft. As the chord length, hence the curvature, is changed by the drive motor, the potentiometer resistance is measured and displayed by a digital ohmmeter. A calibration curve is used to relate this resistance value to the curvature calculated for a specific scattering configuration. In a similar way, the rotation of the plate is monitored with a potentiometer attached to the pivot post drive motor shaft. Very simply then, the scattering plate is made to lie on the focal circle defined by the source, pivot and target by adjusting its curvature and rotation.

3. Beam collimation and shielding

Proper design of beam collimation and shielding presents a major problem in the construction of a reactor-based facility such as this. Since the primary beam itself is Compton-scattered, any scattering material in the beam in addition to the curved plate will add substantial contamination to the beam. In particular, beam collimators must be very carefully designed in order that they be effective in defining beam geometry without contributing scattered gamma rays to the primary beam.
In addition to the scattering problem, the reactor and its shielding are intense sources of both gamma rays and neutrons. This will produce contamination of the primary beam before scattering, and will also result in general background radiation at the experimental target. The first of these just increases the complexity of the final beam; the second, however, contributes to a general background which can vary with target position in a complex way.

Figure 25 shows the shielding and collimation system which has been successfully used with the Ames facility. In general, the system must fulfill three separate basic functions:

1) minimize the flux of gamma rays from all sources other than the Nickel target,

2) eliminate gamma rays scattered from all surfaces other than the scattering plate,

3) shield the experimental target and counters from stray gamma and neutron background radiation.

The first of these is accomplished by locating the nickel target in a beam tube which is tangent to the reactor core, with the lead and bismuth collimators in the beam tube as shown in Figure 25. This system of collimators effectively prevents gammas from the core itself, and from the reactor shielding wall, from entering the primary beam. The resulting beam from the reactor exit port has a vertical spread of 6.6 degrees, with 2 degrees in the horizontal plane. The dimensions and location of the collimator sections have been carefully chosen to minimize
scattering into the beam from both the beam tube walls and from the collimator surfaces themselves.

The second objective is met by this system of collimators plus the system of moveable "shadow shields" shown in Figure 25. The latter shield the target chamber from gammas scattered by the walls of the beam tube and the collimators near the reactor exit port. Experience has shown these to be very important in reducing beam contamination. These shields can be moved vertically in and out of the beam plane by means of remote-controlled pneumatic lifts. The fact that both the plate and target chamber must be moved to change the energy of the scattered beam prevents the use of more conventional types of collimation of the scattered beam.

Removal of neutrons from the direct beam is accomplished with appropriately positioned filters of paraffin, paraffin loaded with boron carbide, boral and cadmium. The positioning of these filters between the sections of the direct beam collimators helps to reduce contamination due to photoneutron production in the collimator materials as well as the neutrons diffusing out from the core area. Neutron filters, not shown in Figure 25 are a 0.25 in. boral disc separating the last 2 in. section of the masonite collimator from the other 10 in. part, a 0.375 in. boral disc following the middle borated paraffin plug, and a 0.03 in. cadmium sheet which covers the exit port of the beam tube. This combination of filters amounts to 30 in. of neutron moderating material in the path of the direct beam.
Three collimators comprise the collimation assembly for the scattered beam. These are: a vertical defining collimator (not shown in Figure 25) which is positioned in the shielding wall between the scattering and target chambers, a horizontal defining collimator which is installed in the entrance hole of the target chamber shielding wall, and a final beam size collimator which is installed just inside the target chamber. These collimators define scattered beam horizontal and vertical acceptance angles which are compatible with the beam divergence angles at the reactor exit port and define a 2 in. high by 1 in. wide beam spot at the target position. 6.75 in. of borated paraffin is used in the middle collimator to reduce the fast neutron and thermal neutron background at the target.

The target chamber is a hollow cylinder with an inner diameter of 22.0 in., a height of 24 in., and 8.0 in. thick walls of concrete. It is mounted on a platform which is moved along a curved track by means of a drive motor. A calibrated scale inscribed along the curved track is used to position the target chamber in the proper scattering configuration. Access to the chamber is through doors in the walls of the chamber or through the top if a lid is removed.

Neutron and gamma background in the experimental area is reduced to acceptable levels with the use of the concrete shielding walls surrounding the scattering plate, concrete filled lids over the top of the scattering plate assembly, a concrete, paraffin and lead beam stop in line with the reactor beam tube. The curved front shielding face is filled with concrete to a height of 24 in. and with lead the rest of the
way. It also incorporates a series of 11 lead beam gates and a removable lead plug at 0°. Up to three lead filled scattered beam gates are lifted pneumatically to pass the scattered beam into the target for a given scattering angle. The removable plug at 0° provides access to the direct beam. This facility is limited to scattering angles between 0° and 30° with the present shielding design.
X. APPENDIX B: BEAM MONITOR AND DATA NORMALIZATION

In Chapter III the beam monitor system was very briefly described. It is the purpose of this appendix to show how this monitor system was used for normalization of the photofission yield data to the measured photon spectra for the scattered beam.

The primary objective of an ideal photon beam monitor in a photonic yield experiment is to measure the total number of photons striking the target; some of which produce the measured yield. This number combined with knowledge of the photon spectrum, the number of target nuclei per cm$^3$, and the efficiency for counting the photonuclear events, allows the extraction of an absolute reaction cross section in mb per nucleus per photon.

In practice, however, there is no detector suitable for directly measuring the total number of photons striking the target. Rather, most experimenters obtain a relative measure of this photon number by placing a monitor detector in front of or behind the irradiated target. Using detector efficiency curves and accounting for beam degradation due to scattering or absorption in the monitor and in the target, the total number of photons is estimated by correcting the monitor count rate. Other limitations due to beam size, intensity and energy further complicate and make this correction procedure difficult and inaccurate.

The beam monitor system used with the Compton scattering facility consisted of a Si(Li) detector which detected gamma rays scattered at 90° from the aluminum scattering plate, and the appropriate electronics.
for counting a relative number of the photons detected. This system provided a relative measure of the number of photons emerging from the reactor during a data run, hence a relative measure of the number of photons striking the target.

As described in Chapter IV, the absolute number and energy spectrum of photons striking the target area were measured as a function of end-point energy for a fixed number of monitor counts. Likewise, the yield data were measured as a function of monitor counts with the same monitor system. The yield data were then easily normalized to the photon number measurements via a comparison of the relative monitor events accumulated.

The approach to data normalization for these experiments was to normalize all yield points and all corresponding beam measurements to a fixed number of photons emerging from the reactor. This effectively removed any time-dependent effects from the measured yields.

To accomplish this with the data from the monitor system, the dependence of the monitor count rate on the aluminum scattering plate configuration was determined. This dependence was measured several times as a function of end-point energy over a time period in which the reactor operating conditions were constant. The dependence of the relative monitor count rate for a fixed number of photons emerging from the reactor, is shown in Figure 26. The data points were calculated by normalizing all of the measured count rates to that for an end-point energy of 5.0 MeV. The smooth curve drawn through the data points was used in the normalization procedure for the photofission and beam data.
Figure 26. Dependence of the beam monitor count rate on the aluminum scattering plate configuration (hence, dependence as a function of end-point energy)
The photofission and background fission yield data were then normalized to a constant number of photons emerging from the reactor, using:

\[ Y(E_p) = Y'(E_p) \cdot \left( \frac{M'(E_p)}{M(E_p) \cdot MF} \right) \]  

(9.1)

where:

- \( Y'(E_p) \) = total fission yield measured for an end-point energy \( E_p \),
- \( M'(E_p) \) = accumulated monitor counts for the measurement of \( Y'(E_p) \),
- \( M(E_p) \) = relative monitor count-rate factor obtained from Figure 26,
- \( MF \) = fixed number of monitor events for an end-point energy of 5.0 MeV,
- \( Y(E_p) \) = total fission yield normalized to a constant number of photons emerging from the reactor as represented by \( MF \).

Statistical errors \( DY(E_p) \) for each of the normalized yield points, \( Y(E_p) \), were calculated by:

\[ DY(E_p) = DY'(E_p) \cdot \left( \frac{M'(E_p)}{M(E_p) \cdot MF} \right) \]  

(9.2)

where \( DY'(E_p) \) is the square root of \( Y'(E_p) \) and the normalization factor in paranthesis is identical to that in equation 9.1.

In a similar way the beam spectra were normalized for a fixed number of monitor events, \( MB \).

The values for \( MB \) and \( MF \) were chosen in accordance with the differences in data collection times between the beam measurements and the
fission experiments. For the beam measurements MB was selected to be \(4 \times 10^6\) events and for the photofission measurements, MF was selected to be \(14 \times 10^6\) events and \(13 \times 10^6\) events for the \(^{238}\text{U}\) and the \(^{235}\text{U}\) experiments, respectively.
XI. APPENDIX C: EFFICIENCY OF THE COUNTING SYSTEM

The purpose of this appendix is to show how the efficiency, $e$, of the fission fragment detection and counting system was determined. This factor is used in the calculation of the absolute cross sections discussed in Chapter IV.

The overall efficiency for each detector is the product of a solid angle factor, $G'$, a correction, $F$, for fragment absorption in the target, and a correction, $L$, for the lower level discriminator. This quantity is then summed for the four detectors to give $e$. If $f'(\theta)$ is the angular distribution of the fission fragments and $\Omega$ is the solid angle subtended by the detector, then:

$$G' = \int_{\Omega} \frac{f'(\theta) d\Omega}{4\pi}.$$ 

For each target and each detector the factors $F$, $G'$ and $L$ were calculated as follows.

The threshold factor, $L$, was calculated from the pulse-height spectrum of fission fragments, measured with the target chamber moved into the direct beam. A typical spectrum of fragments from $^{235}\text{U}$ is shown on a logarithmic scale in Figure 27. The spectra for the other detectors and for the $^{238}\text{U}$ target were nearly identical. The large peak near channel 50 is due to alphas from the target, and the tail, extending out to channel 1024, is attributed to the fission fragments emitted from the target. In the figure DL1 denotes the discriminator level setting for the photofission yield measurements. All fission pulses with pulse
Figure 27. A typical pulse-height spectrum of alpha particles and fission fragments from the $^{235}$U target for one of the surface barrier detectors.
heights less than that corresponding to channel DL1 were not counted in the yield measurements.

To obtain an estimate of the ratio of events recorded to the events detected, the spectrum of fission fragments was extrapolated to zero pulse height. This region of the fission pulse-height spectrum was approximated by fitting a straight line to the logarithm of the data between DL1 and DL2 and then using the fit parameters to extend the distribution to zero pulse height as indicated in Figure 27.

L was then calculated as the ratio of the area under the fragment pulse-height spectrum from channel DL1 to channel 1024 to the area under the extended spectrum from channel zero to channel 1024. The results of this calculation for each detector and each target are given in Table 2.

Table 2. Threshold correction factors, for each detector and target, for the counting efficiency calculation

<table>
<thead>
<tr>
<th>Detector</th>
<th>$^{238}$U target</th>
<th>$^{235}$U target</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>0.627</td>
<td>0.573</td>
</tr>
<tr>
<td>F2</td>
<td>0.602</td>
<td>0.542</td>
</tr>
<tr>
<td>F3</td>
<td>0.593</td>
<td>0.592</td>
</tr>
<tr>
<td>F4</td>
<td>0.654</td>
<td>0.525</td>
</tr>
</tbody>
</table>

Measurements of the pulse-height spectra for alpha particles from $^{238}$U, along with a calculation of the loss of particles in the target foil, were necessary for evaluation of the factors G' and F.
For each detector, the number of alpha particles detected per unit time, \( C \), is the product of a solid angle factor, \( G \); a correction factor, \( A \), for particle absorption in the target; and the rate, \( R \), at which alpha particles are produced in the target. If \( f(\theta) \) is the angular distribution of the alpha particles and \( \Omega \) is the solid angle subtended by the detector, then:

\[
G = \frac{\int_{\Omega} f(\theta) d\Omega}{4\pi}.
\]

Assuming that the angular distributions for alpha emission and fragment emission are approximately the same, \( G' \) equals \( G \), and the factor, \( F \cdot G' \), can be calculated with the expression:

\[
F \cdot G' = \left( \frac{F}{A} \right) \cdot \left( \frac{C}{R} \right).
\]

\( C \) was calculated from the measured alpha pulse-height spectrum. A typical spectrum is shown in Figure 28. The peak at low channel number is due to noise and masks the alpha spectrum in that region. The smeared out distribution extending from channel 700 down to the noise contribution is due to the alpha particles. It was necessary to extend the alpha distribution to zero pulse height for the calculation of \( C \). This was accomplished, in an approximate manner, by calculating an average count per channel over a ten channel region in the vicinity of the minimum of the distribution between the noise and alpha peaks. Then, this average value was assigned at all channel locations less than that labelling the minimum. \( C \) was calculated as the area under the extended alpha pulse-height spectrum from channel zero to channel 750.
Figure 28. A typical pulse-height spectrum of alpha particles from the $^{238}$U target for one of the surface barrier detectors. The peak at low channel number is due to noise.
R was calculated by multiplying the specific activity for $^{238}\text{U}$, which is $2.01 \times 10^5$ dpm/mg (60), by the mass of the target foil (272 mg for $^{238}\text{U}$). The factors, $C/R$, calculated for detectors, F1, F2, F3 and F4, are 0.010, 0.019, 0.020 and 0.011 respectively.

The calculation of the factors $F$ and $A$, which account for fragment and alpha particle loss in the target foil, is best explained with the aid of Figure 29. This figure is a cross sectional view (the $Z = 0$ plane in cylindrical coordinates) of the cylindrical target foil, with inside radius, $R$, and thickness, $T$, and a detector at a distance, $D$, from the axis, $C$, of the target. The cylindrical coordinates, $r$ and $\theta$, define each point in the target foil at which a particle (fragment or alpha) is produced, and $p$ refers to the path length in the foil of the particle on a trajectory toward $C'$, the center of the detector. $\theta_m$ is the value of $\theta$ for which $r$, $(r = R + T)$, is perpendicular to the tangent line drawn from $C'$ to the foil surface. $\Omega$ is the solid angle subtended by the target at $C'$.

The shaded area in the figure corresponds to that region of the target foil for which particles, having a range equal to $T$, have path lengths, $p$, which are less than or equal to $T$. Particles produced in this region and emitted into the solid angle, $\Omega$, will be detected at $C'$. Particles produced in the unshaded foil region between $\theta_m$ and $-\theta_m$ have path lengths greater than the foil thickness and are absorbed in the foil. For particles with range equal to the foil thickness, the correction factor for absorption in the foil is then approximated by the shaded area divided by the total foil area between $\theta_m$ and $-\theta_m$. 
Target 29. Illustration of the geometrical considerations for calculation of the correction factors which account for particle loss in the target foil
A computer program was written to treat the calculation of the absorption correction factors in three dimensions; that is, to include the vertical extend of the target above and below the \( Z = 0 \) plane. This involved calculating the surface \((r, \theta, z)\), for which the path length, \( p \), for particles on a trajectory to \( C' \), was equal to the range of the particle. Given this surface, the quantity \( V_S/V_T \), where \( V_S \) is the volume of foil material for \( p \) less than the particle range and \( V_T \) is the total volume between \( \theta_m \) and \( -\theta_m \), was calculated as a function of \( D \), particle range and location \( C' \) on the detector surface. This volume factor was then used as a reasonable approximation to the fractional number of particles emitted into the solid angle \( \Omega \) and detected at \( C' \).

To calculate the value of \( F \) used here, it was necessary to consider the mass yield distribution and the range of kinetic energies of the fragments produced in photofission. Fragments with masses ranging from 70 amu to 160 amu are produced in fission with kinetic energies ranging from 100 MeV to 40 MeV (61). These fragments have relative probabilities for production as given by a measured mass-yield distribution (62) and have ranges in uranium metal foil from 13 mg/cm\(^2\) to 7 mg/cm\(^2\) (63).

The upshot of these facts is that for each fragment produced at a point \((r, \theta, z)\) in the foil and detected at \( C' \), there is a unique volume, \( V_S \), from which it can come. For the more energetic light fragments, \( V_S \) is greater than the corresponding volume for the heavy, less-energetic fragments. The volume factor ratio used to approximate \( F \) has to account for these volume differences as well as the differences in yield production.
An average volume, $\overline{VS}$, was calculated for the fission fragment emission as follows. Values of $VS$ were calculated for 28 fission products, with mass numbers ranging from 77 to 156 and with corresponding ranges, as measured in uranium metal foil by Niday (63). The average volume $\overline{VS}$ was then calculated by taking the weighted sum of the 28 $VS$ values, where the weighting factors were given by the percentage mass yields as measured by Katcoff (62). $F$ was then approximated by $\overline{VS}/VT$.

Because there are only two intense alpha groups from the radioactive decay of $^{238}\text{U}$ with energies and relative intensities of (4.20 MeV, 77%) and (4.15 MeV, 23%), the value for $A$ was well approximated by the volume $VS$, calculated for alpha particles with energy 4.20 MeV divided by $VT$. The range for this energy alpha was interpolated from the range-energy tables of Northcliffe and Schilling (64).

For detectors F1 and F4, for which $D$ equals 1.0 in., $F/A$ was calculated to be 0.79. The corresponding quantity for detectors F2 and F3, for which $D = 1.5$ in., was 0.84.

The fragment absorption and solid angle factor, $F \cdot G'$, calculated from the values for $F/A$ and $C/A$, are given in Table 3.

Table 3. Fragment absorption and solid angle factors, $F \cdot G'$, for each detector and both the $^{238}\text{U}$ and $^{235}\text{U}$ targets, for the counting efficiency calculation

<table>
<thead>
<tr>
<th>Detector</th>
<th>$F \cdot G'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>0.008</td>
</tr>
<tr>
<td>F2</td>
<td>0.016</td>
</tr>
<tr>
<td>F3</td>
<td>0.017</td>
</tr>
<tr>
<td>F4</td>
<td>0.009</td>
</tr>
</tbody>
</table>
Although the calculation of the $F \cdot G'$ factors were made for the $^{238}\text{U}$ target only, they are also applicable for the $^{235}\text{U}$ target, because of nearly identical target foil characteristics and nearly identical mass yields and kinetic energies of the fission fragments.

Combining the factors from Tables 2 and 3, the efficiency, $\epsilon$, of the counting system was calculated to be:

- 0.030 for the $^{238}\text{U}$ target
- 0.027 for the $^{235}\text{U}$ target.
XII. APPENDIX D: INTERPRETATION OF EXPERIMENTAL RESOLUTION

The purpose of this appendix is to present a discussion which will give some insight into the interpretation if the cross sections obtained from the photofission yield data by the method of Cook (46). Most of the material in this appendix was excerpted from Yester (29) who modified Cook's method for solving Equation 3.4 of this dissertation.

As explained by Yester (29) the solution that is obtained for Equation 3.4 is a smoothed representation of the true solution $s$. As derived by Yester, the smoothed solution, $s'$, is obtained from:

$$\mathbf{N}^T \cdot \mathbf{W} \cdot \mathbf{V} = (\mathbf{N}^T \cdot \mathbf{W} \cdot \mathbf{N} + \lambda \mathbf{S}) \cdot \bar{s}$$  (12.1)

where: $\mathbf{N}$ is the matrix representation of the photon beam, $\mathbf{N}^T$ is the transpose of $\mathbf{N}$, $\mathbf{W}$ is a diagonal weighting matrix, $\mathbf{V}$ is the measured yield data, $\mathbf{S}$ is the smoothing matrix, and $\lambda$ is a scale factor which determines how much smoothing is applied.

The smoothed solution, $s'$, is related to the true solution, $\bar{s}$, by:

$$\bar{s}' = \mathbf{R} \cdot \bar{s}$$   (12.2)

where: $\mathbf{R}$ is called the resolution function. An expression for $\mathbf{R}$, as derived by Yester, is given by:

$$\mathbf{R} = (\mathbf{N}^T \cdot \mathbf{W} \cdot \mathbf{N} + \lambda \mathbf{S})^{-1} \cdot \mathbf{N}^T \cdot \mathbf{W}$$  (12.3)

$\mathbf{R}$ is called the resolution function because it is a measure of the minimum separation in energy of structure in a cross section that can be seen as separate peaks in the solution to the yield equation. Ideally,
one would like the resolution function, \( R(E_i, E_j) \), to be a delta function of unit amplitude that peaks at an energy \( E_j = E_i \). In actuality, \( R \) is Gaussian in shape and is characterized by some full-width-at-half-maximum. The value of this full-width-at-half-maximum is quoted in the text of this dissertation as a measure of the overall experimental resolution for the cross sections obtained.

A test case illustrating the meaning of the resolution function and its dependence on the statistical quality of the data was investigated. A cross section, with a functional form of two Gaussians added together, was constructed. From this assumed cross section, the values of the average cross section \( \bar{s} \), were calculated at 100 keV intervals. The yield, \( \bar{Y} \), for the above cross section was obtained by multiplying the beam matrix and \( \bar{s} \) together. A yield, \( \bar{Y} \), with statistical fluctuations was then obtained from the relation:

\[
Y_i = Y'_i + r\sqrt{y'_i} \tag{12.4}
\]

The random number \( r \) was generated from a Gaussian distribution of unit amplitude, zero mean and unit standard deviation. A second test yield was formed from the same average cross section, but the statistical errors used were smaller by a factor of \( \sqrt{10} \). That is,

\[
Y_i = Y'_i + r\frac{\sqrt{y'_i}}{\sqrt{10}} \tag{12.5}
\]

for the second case.
The solutions to the test yields are shown in Figure 30 along with the assumed cross section. Since the solutions are smoothed and averaged, they are represented as smooth curves even though information is obtained at 100-keV intervals. The length of the horizontal error bars represents the full-width-at-half-maximum of the resolution function at that energy. In test case #1 the widths of the resolution function at the energies of the two peaks overlap, and the solution appears as one large broad peak with only a hint that the peak is a doublet. In test case #2, however, the resolution is better, and two peaks are observed in the solution. The vertical error bars represent the propagation of the errors in the yield data through the defining equation (equation 12.1) for $s_i$. Thus, although the overall resolution is limited by the intrinsic resolution of the photon beam, this value is approached by minimizing the statistical error in the yield data.

From the above test and many others, it was found that good solutions to the yield equation could be obtained.
Figure 30. Test cases illustrating the dependence of the resolution of the analysis procedure on the statistical quality of the yield data.