

COMPTON EFFECT

INTRODUCTION

Arthur Holly Compton quantitatively established the Compton effect in 1923 when he published careful spectroscopic measurements of X-rays scattered at various angles by light elements. He found that X-rays scattered at larger angles had systematically longer wavelengths. He discovered that the observations were accounted for by considering the scattering as a collision between a single photon and a single electron in which energy and momentum are conserved. The Compton effect demonstrates the apparent duality of waves and particles in an especially clear way; the photon/electron collision can be treated as a billiard-ball collision in which energy and momentum is conserved, yet the scattering of X-rays from a crystal reveals wave-like properties as is evidenced by their constructive and destructive interference. Compton was awarded the Nobel Prize in 1927 for his work.¹

EXPERIMENTAL PROCEDURE

The main objectives of the experiment are:

- to investigate the energy shift of a photon scattered by a free electron (the Compton effect) as a function of incident energy and scattering angle
- to observe and measure the angular distribution of the differential cross section for the scattering of γ -rays from electrons (verification of the Klein-Nishina formula)

The simple theory leading to the Compton energy shift treats the scattering material as a gas of free electrons. This approximation (known as the "impulse approximation") begins to fail in high-Z scattering materials and/or low energy (compared to the binding energy of the electron) incident photons. This leads us to the third objective:

- a study of the failure of the impulse approximation as evidenced by
 - (i) broadening of the $h\nu'$ peak
 - (ii) reduction of scattered intensity by the competing photo absorption in the scatterer
 - (iii) appearance of a subsidiary peak of elastically scattered photons²

¹ The 1927 Nobel Prize in Physics was divided equally between Compton and Charles Thomson Wilson (Great Britain) for his method of making the paths of electrically charged particles visible by condensation of vapour (i.e., the cloud chamber).

² See graphs of such spectra in "Use of Asymptotically Correct Wave Function for Three-Body Raleigh-Ritz Calculations" by M. Rotenberg and J. Stein, Phys Rev **182**, 1 (1969), pp 9-10.

The resolution of the Ge detector is good enough to study the Compton line shape, or profile. Thus, time permitting (and this may take quite a bit of time), it is possible to launch

- an investigation of electron momentum distributions: By measuring the doppler shift of gamma rays scattered by moving electrons, Compton scattering can be used to study the motion (velocities) of electrons in atoms. This technique does not measure a specific physical parameter but, in yielding the 1-dimensional momentum distribution, it provides information on the electron wave function. Such information is basic to an understanding of all the properties of a physical system.

APPARATUS AND INSTRUMENTATION

γ sources: ^{137}Cs (662 keV), ^{60}Co (1.17 and 1.33 MeV), and ^{241}Am (59.6 keV)

aluminum, copper, lead, and plastic targets

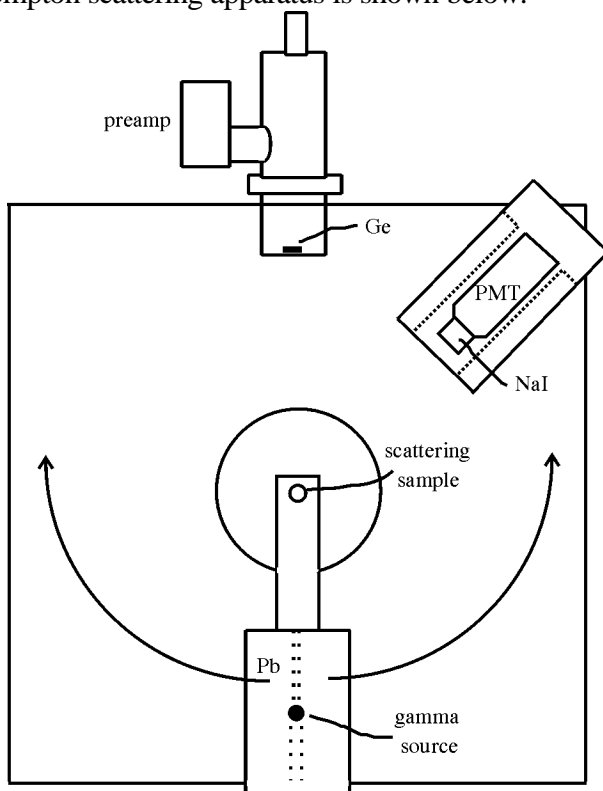
scattering apparatus (see figure)

NaI(Tl) scintillation detector

Planar pure Ge detector with cryostat

gamma ray spectrometer (HVPS, preamp, spectroscopy amp, MCA)

A schematic of the Compton scattering apparatus is shown below.



The experimental setup consists of a γ source in a lead shield/collimator, a scattering target, two types of detectors (only one used at a time) and all the electronics necessary for pulse height

analysis (PHA) to obtain an energy spectrum of the scattered radiation. Each of these is described in more detail below. At low energies the Compton energy shift is relatively small necessitating the use of a high-resolution detector, namely the "intrinsic" germanium detector. However, its efficiency (2% for energies less than 100 keV) drops precipitously at higher energies (down to 0.02% at 1 MeV), making it impractical for use at energies >100 keV. For the higher energies, the NaI(Tl) scintillation detector is used.

γ -ray sources and scattering targets:

Three radioactive sources are used to vary the incident photon energy. These are $^{137}_{55}\text{Cs}$ (662 keV), $^{60}_{27}\text{Co}$ (1.17 and 1.33 MeV), and $^{241}_{95}\text{Am}$ (59.6 keV). All are stored in the "radiation closet" when not in use; source strengths are posted on the door of the closet. Have one of the faculty or staff show you how to hold, move, and install the source in its lead shield/collimator. **Know your safety precautions for handling radioactive materials.** (Review pp 6-8 in the Introduction of this Manual.) Check the gamma radiation near the source as well as the areas you work in and plan out what precautions and safety measures you must make during the course of your experiment. It is assumed that you have attended the "Radiation Safety Lecture" given at the beginning of the semester. Wear the ionization pen personal dosimeters and record your dose at the end of every laboratory session in the logbook near the dosimeter charger. There are plenty of lead bricks to shield you (and the detector) from unwanted radiation. **Be very careful in moving any of the lead bricks.** The bricks weigh 25 lbs and could do quite a bit of damage if dropped on your foot. Furthermore, they are quite malleable and care should be taken to set them down gingerly - otherwise they become dented and won't set straight.

The scattering angle is varied by rotating the radiation source around the scatterer; the detectors remain fixed. The source shield/collimator is a 5" dia x 8" long lead cylinder (in a copper housing) that sits on a rotatable arm. A hole runs down the length of its axis. The γ source/holder should be inserted all the way in the $\frac{1}{2}$ " dia hole so that the source is in the middle of the cylinder (remove the brass sleeve to accommodate the physically larger Am-241 source). The $\frac{1}{4}$ " dia hole collimates the radiation.

Many scattering targets (in cylindrical and thin plate form) are available. The cylindrical targets are held by a $\frac{3}{16}$ " dia post positioned at the center of rotation of the source. Other targets (different materials and/or thickness) can be fabricated if desired. Lead bricks may be used as "slits" in front of the detector to cut down on the acceptance angle and confine the scattering angle to a smaller range.

Scintillation detector:

The detector consists of a cylindrical thallium doped sodium iodide scintillation crystal³ coupled to a photomultiplier tube⁴ (PMT), sealed in an aluminum container. When gamma rays enter the scintillation crystal, they lose energy in the crystals via Compton scattering and the photoelectric process. The resulting energetic electrons cause ionization or excitation of the phosphor. The excitations decay by emitting visible light, which is detected by the PMT.⁵ The K shell electrons of iodine are responsible for most of the absorptions and the thallium for most of the visible light emission. The PMT is biased **positively (+1.0 kV maximum)** with a high-voltage supply (HVPS).⁶ The detector is shielded from background radiation by a lead cylinder (1" wall thickness) and magnetically by a mu-metal shield.

Planar pure Ge detector with cryostat:

Germanium detectors are semiconductor diodes having a P-I-N structure in which the intrinsic (I) region is sensitive to ionizing radiation. When photons interact with the material in the depleted region (I), holes and electrons are produced and are swept by the electric field to the N and P electrodes, respectively. This charge pulse is converted into a voltage pulse by a capacitor and integral charge sensitive preamplifier. The preamplifier uses a "pulsed optical reset" to periodically discharge the capacitor.

Because germanium has a relatively low band gap, the detector must be cooled in order to reduce the thermal generation of charge carriers (leakage current) to an acceptable level. Otherwise, leakage current induced noise would destroy the energy resolution of the detector. The detector is mounted in a vacuum chamber which is inserted into a 30 liter LN₂ dewar. The sensitive detector surfaces are thus protected from moisture and condensable contaminants. Our detector type is a "Planar" -- consult *Bench Notes* for details.⁷

It takes a full afternoon to cool the detector to operating temperature. Therefore, inform the staff at least one day before you intend to use it. We will worry about keeping it cooled for the duration of your experiments. **Warning: Before applying the high voltage bias (-1500 volts) the detector MUST be cooled at least 4 hrs; also, the detector should not be allowed to warm up with the bias voltage applied. To do otherwise can destroy the detector and preamplifier (replacement cost = \$12,000).** A LN₂ monitor⁸ has been

³ The crystal diameter is 2" and the length is 2".

⁴ Electron Tubes Ltd., Type 9266KFLB04.

⁵ See Birks (1964) or Curran (1953) for details of scintillation detection.

⁶ Ortec/EG&G model 556 (0-3 kV, 0-10 mA)

⁷ Canberra detector model 7120010E, cryostat model 7600, and Pulsed Optical (PO) Preamp model 2008

⁸ Canberra model 1786

interlocked with the HVPS⁹ to help protect against such a catastrophe. Also note that the end-cap of the detector housing is equipped with a very thin beryllium window. **Caution: The Be window is very fragile. Do not allow anything to touch it. Do not remove the protective plastic cover.**

Multichannel analyzer (MCA)¹⁰:

The detector output consists of pulses of variable amplitude, the amplitude being proportional to the energy of the radiation. The distribution of pulse heights can be analyzed and stored by a pulse height analyzer (PHA). The acronyms MCA and PHA will be used interchangeably. In short, a PHA stores a histogram of the number of pulses applied to its input versus the voltage of the pulses that in this case, is equivalent to the energy of the radiation, which caused the pulse. The histogram is thus an energy spectrum (number of counts vs. energy). The detector H.V. bias, amplifier gain and analog-to-digital converter (ADC) settings all determine the energy scale of the spectrum. Refer to the manuals with the *Bench Notes*. Note that once an energy calibration is performed, none of the above settings can be changed without a recalibration. In fact, it is best to leave *all* the electronics on (for the entire duration of your experiments) to minimize drifts caused by instrument warm-up. ***An important note regarding energy calibration:*** For the NaI detector, special care should be taken to avoid count rates greater than typical Compton scattering count rates, which are on the order of 50 - 100 counts per second. The gain of the phototube varies with count rate and recovery from a blast of light can take several hours. As a starting point, position a 10 μ Ci calibration source 20 - 30 cm from the detector.

The MCA has been configured to operate in its anticoincidence mode. This means that the ADC will process pulses *unless* the GATE input is active ($\approx 2.5V$). When using the Ge detector, the INHIBIT OUT of the preamp should be connected to the GATE input of the MCA. The INHIBIT OUT goes high for the duration of the preamp optical reset pulse (during which time one does not want to analyze).

The software that controls the MCA is called MAESTRO. Double-click on the MAESTRO icon in the Program Manager to start the MCA. To export data from the MCA software, print the data to a file. A text file will be generated with columns of data. The default file format is in thirteen columns: the first column contains every twelfth channel number and the remaining columns contain the number of counts in the respective channels. A C program called *compton.c* is available for converting this file to two-column format, which can be imported into

⁹ Canberra model 3102

¹⁰ EG&G Ortec TRUMP-2k, a computer-based MCA.

plotting programs. Run this program using LabWindows CVI. A shortcut should be present on the desktop.

Please save all your data files in a separate data folder in c:\students. At the end of the experiment, remember to delete all data files and folders that you create.

Begin by reading the instruction manuals for the instrumentation. Observe the output pulses directly from the detectors with an oscilloscope before using the MCA. Familiarize yourself with the MCA next. Using the radioisotope calibration sources (ask staff), learn how to perform a pulse height analysis and energy calibration. This will take at least one lab period. You're then ready for the Compton effect.

REFERENCES

- A.H. Compton, "A Quantum Theory of the Scattering of X-Rays by Light Elements," Phys Rev **21**, 483-502, (1923).
- O. Klein and Y. Nishina, "über die Streuung von Strahlung durch freie Elektronen nach der neuen relativistischen Quantendynamik von Dirac," Zs. f. Phys. **52**, 853-864 (1929); Y. Nishina, "Die Polarisation der Comptonstreuung nach der Diracschen Theorie des Elektrons," Zs. f. Phys. **52**, 869-877 (1929)

For historical background, you may wish to look at the following:

- A. Compton, "The Scattering of X Rays as Particles", Am J Phys **29**, 817 (1961). Compton reviews the experimental evidence and the theoretical considerations that led to the discovery and interpretation of x-rays acting as particles.
- A.A. Bartlett, "Compton Effect: Historical Background", Am J Phys **32**, 120-127 (1964). A historical review of the experiments that were later explained by Compton's discovery of the Compton effect.

The mathematical treatment of Compton scattering is given in many texts such as:

- R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles*, 2nd ed, (John Wiley, NY, 1985). The photoelectric effect, Compton scattering, and pair production and pair annihilation are treated in Chapt 2. Selection rules for γ decay are discussed on pp 578-584. Cabot QC174.12.E34
- A.C. Melissinos, *Experiments in Modern Physics*, (Academic Press, N.Y., 1966). Cabot: QC33.M52
- *Compton Scattering*, edited by B. Williams, (McGraw-Hill, London, 1977). Physics Research QC794.6.S3

- W. Heitler, *The Quantum Theory of Radiation*, 3rd ed, (Clarendon, Oxford, 1954). Cabot QC475.H43

Experimental information you might need can be found in the following references:

- C. Lederer and V. Shirley, *Table of Isotopes*, 7th ed, (Wiley, NY, 1978). The decay of radionuclides is given in detail. Cabot REF QD466.L37
- A.T. Helms, *Graphs of the Compton Energy-Angle Relationship and the Klein Nishina Formula from 10 keV to 500 MeV*, N.B.S. Circular No. 542, (U.S. Dept of Commerce, 1953).
- *X-ray Attenuation Coefficients from 10 keV to 100 MeV*, N.B.S. Circular No. 583.
- J. Birks, *The Theory and Practice of Scintillation Counting*, (Pergamon, NY, 1964). Physics Research QC787.C6 B53. An empirical formula for the fraction of counts in the photopeak is given on p488.
- P. Ouseph, *Introduction to Nuclear Radiation Detectors*, (Plenum, NY, 1975).
- K. Siegbahn, *Alpha-, Beta-, and Gamma-ray Spectroscopy*, (North Holland Publ Co, Amsterdam, 1965), Vol 1 & 2. For scintillation spectrometry, see J.H. Neiler and P.R. Bell's Chapter V, Vol 1. Cabot QC771.S5

Inelastic x-ray scattering, a developing field made possible by the synchrotron, is described in this article:

- E. Isaacs and P. Platzman, "Inelastic X-Ray Scattering in Condensed Matter Systems," *Physics Today* **49** no. 2, 40-45. (Feb. 1996).

One final note:

After he received his Nobel Prize in 1927, Arthur Compton was very much in demand as a speaker at universities and conferences. He wasn't really very interested in public speaking, so he developed a standard speech which he repeated whenever necessary. To make these public speaking obligations more tolerable to Compton, he was provided with a chauffeur who drove him to the site and who then sat in the back of the hall until the speech was over. One night on the way to a talk, Compton was complaining about having to deliver the speech again. The chauffeur responded, "If you think it's boring giving that speech over and over, think of how boring it is for me having to listen to it. I think I know the whole speech word for word."

Well, that got Compton thinking. It occurred to him that nobody at the lecture hall knew what he looked like. He arranged to trade clothes with the chauffeur and let him give the speech. Compton took a seat at the back of the hall as the chauffeur began to speak. The speech was given flawlessly. Thunderous applause followed. The master of ceremonies then called the speaker back for a short question-and-answer session. The first question was on the kinetic energy of the recoiling electron in X-ray scattering experiments. The chauffeur listened carefully to the question and then responded, "That is a really dumb question. In fact, that question is so dumb, I think I'll have my chauffeur answer it."