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COMPUTER SIMULATION OF THE RICE UNIVERSITY GAMMA RAY TELESCOPE

by

Bhaswar Sen

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE

MASTER OF SCIENCE

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HOUSTON, TEXAS
MARCH 1988
Abstract

COMPUTER SIMULATION OF THE RICE UNIVERSITY GAMMA RAY TELESCOPE

Bhaswar Sen

Calculations have been made of the new Rice University gamma ray astronomical telescope, over the energy interval 0.1 MeV - 5.0MeV. A computer program, ACCEPT, was used and simulations performed on the Rice University's AS-9000 mainframe. For gamma ray fluxes at 3.5 g cm$^{-2}$ atmospheric depth over Palestine, Texas, efficiency curves for the principal detector have been obtained. Energy deposition profiles have been calculated and compared to previous simulations and observations. The study shows the simulation code ACCEPT to be more machine dependent than previously believed.
Acknowledgment

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Chapter I Introduction

A beam of gamma radiation, or any electromagnetic radiation, exhibits a characteristic exponential absorption in matter. The reason is that, in the processes of absorption or scattering which remove monoenergetic gamma ray photons from an incident beam, each photon is removed individually in a single event. To detect photons, one therefore measures the product of the photons' interaction with matter. These products are the electrons in the matter.

There are three main processes which contribute to the total absorption of a gamma ray photon [Evans1972]. These are (i) photoelectric absorption; (ii) Compton scattering by the electrons in an atom; and (iii) production by the gamma ray of a positron-electron pair in the electric field of the atom or nucleus.

In the photoelectric process all the energy of the incident photon is transferred to a bound electron which is then emitted from the atom. The kinetic energy of the emitted electron is the difference between the energy of the photon and the binding energy of the particular atomic shell it is ejected from. The excess momentum in the process is balanced by the recoil of the nucleus. The photoelectric effect for a given shell in the atom is largest at photon energies close to the ionization potential for the shell and falls off rapidly with increasing photon energy above the ionization potential. At low energies, below 0.2 MeV for NaI and 20 keV for plastic, the photoelectric effect is the principal mechanism of absorption. As the energy increases, the photoelectric effect loses in importance compared to Compton scattering as the primary mechanism for removing photons from the initial beam. In this latter process the incident photon is scattered by the electron in the atom rather than absorbed. One of the atomic electrons makes a transition to an ionized state, and the incident photon is scattered with reduced energy. In the energy region where this type of scattering gives the main contribution to the absorption, i.e. between 0.2 MeV and 8 MeV for NaI and from 18 keV and greater for plastic, the energy of the
incident photon is large compared to the binding energy of the atomic electrons. The process may therefore be considered to be the scattering of photons by free electrons initially at rest.

At sufficiently high energies photoelectric absorption and Compton scattering become unimportant compared to the process of pair production. In this phenomenon a gamma ray of sufficient energy, in the presence of the Coulomb field of the nucleus, disappears by creating an positron-electron pair. In order for this process to occur the gamma ray energy must exceed $2m_ec^2$ or 1.02 MeV. Since energy and momentum cannot both be conserved if a positron-electron pair is created in free space, the process can only take place when the gamma ray passes through matter. The excess momentum is then absorbed by the nucleus, which is so massive that the energy of its recoil may be neglected.

All gamma ray detectors rely on a measurement of the electron which is ejected when a gamma ray interacts with matter. One important method of measuring the energy of gamma ray photons is by using a scintillation counter. The basic components of a scintillation counter are a scintillator, which converts into light a fraction of the energy lost by a charged particle as ionization, and a photoelectric device which converts the light into an electrical signal. However the design and fabrication of such a detector requires an indepth knowledge of its response to gamma ray photons. The problem of determining the response of a scintillation counter to gamma rays is basically one of calculating the transport of that radiation through the scintillation detector. The quantity that must be calculated in order to determine the response of the counter is the total energy deposited in the detector; therefore the amount of energy carried off by the source radiation and secondary radiation that escapes has to be determined. The only practical way of obtaining a solution to this complicated transport problem is by utilizing Monte Carlo methods programmed for calculation on high-speed computers.
The Monte Carlo method is a numerical method of solving mathematical problems by means of random sampling. Two distinctive features of the Monte Carlo method are (i) the independent random-sampling structure of the computational algorithm; and (ii) the error of calculation is proportional to the inverse square root of the number of trials.

In many experimental situations, it is impossible to use calibrated sources covering the whole relevant energy range. With the Monte Carlo method one can hope to reproduce in a flexible way any experimental physical situation. For example, it is not difficult to treat cases in which the gamma ray source has a non-negligible energy width, or a complex energy spectrum. Sizes, shapes and the geometrical configuration of the sources and the detectors can be easily reproduced to fit different cases. The technique has previously been applied to calculate the behavior of unshielded NaI(Tl) detectors to gamma rays [Capponi et al. 1982], and calculations show a good agreement with experimental data at low energies and for small detectors [Saito et al. 1984]. Results for other detectors are discussed below. Monte Carlo simulation has also been used to calculate the response of other detector materials [Rogers 1982] to gamma radiation.

Almost all studies mentioned above used simplified radiation transport models. Simplifications included (i) ignoring transport of charged particles; (ii) radiation losses by these charged particles; and (iii) using simple analytic expressions for interaction cross sections. In the cases already mentioned the authors required the particles to deposit the entire kinetic energy at their point of creation, to avoid encoding complex scattering theories. Not surprisingly, these theoretical works were in good agreement with experimental data at low energies. For energies above a few MeV it is necessary to treat primary/secondary particle transport and consider bremsstrahlung effects. The importance of these effects is dependent on the size of the detector; larger detectors give a smaller effect.

A number of Monte Carlo codes [Colbert 1973; Guber et al. 1967; Halbleib 1979;
Jordan 1971; Straker et al. 1972] has been developed for describing the generation and transport of electron/photon cascades in multimaterial configuration. The cross section and sampling procedures are essentially the same for all members of the group. The largest difference between the codes is the use of combinatorial geometry [Guber et al. 1967; Halbleib 1979; Straker et al. 1972], as opposed to a system of paraxial quadratic surfaces and cartesian planes [Colbert 1973; Jordan 1971].

Overview of the thesis

This work describes the result of one of the Monte Carlo codes, ACCEPT [Halbleib 1979], which was used to simulate the Rice University gamma ray telescope. ACCEPT is a three-dimensional, multimaterial coupled electron/photon Monte Carlo transport code. For the present study, a section of code was added to ACCEPT, so that the simulation could be confined to only a particular preset time span and studied as a function of the given interval. This change was required due to a serious limitation in financial and computational support. The telescope simulated is a simplified version of the instrument presently under construction.

An outline of the physical processes involved when a high energy photon (1.0 GeV to 0.1 MeV) loses its energy in any scintillator is discussed. For completeness, both electron and photon transport mechanisms are discussed. A brief explanation of the code is then presented outlining its operation. The logic of the code, the approximations involved and their statistical accuracies are discussed.

Samples of our simulations are provided, and results of early tests performed on the detectors (inorganic crystal NaI and organic CH) included. Detector response to gamma radiation coming from extended sources of any size, having energies included in the range 5.0 MeV - 0.1 MeV is discussed and compared to those obtained elsewhere [Capponi et al. 1983].
Chapter II Gamma Ray Telescope

The modified Rice University telescope [Fitch 1986] will be used to detect gamma ray background and astronomical sources in the energy range a hundred keV to 10 MeV. It will be made up of an array of one hundred and twenty one NaI crystals surrounded by an anti-coincidence shield. The shield defines the field of view of the array and ensures total absorption of the gamma ray in the NaI array.

The anti-coincidence shield will simultaneously be viewed by thirty photomultiplier tubes connected in parallel. All the electrical signals will then be added for pulse analysis, to achieve a fairly good timing and positioning system for detection of photon interactions. The NaI crystals may be viewed by a position sensitive detector and a large photomultiplier tube (PMT) or by one hundred and twenty one separate PMT's, providing good energy and position resolution. Each of the one hundred and twenty one NaI crystals is individually packed in a protective, reflective and light opaque shield. Calibrated response functions of each crystal will be used to find the energy of the gamma ray with a sharply improved sensitivity over previously available instruments. The new system will reject activation background, which provided the chief limit on sensitivity of earlier gamma ray astronomical telescopes.

Another new feature of the Rice University gamma ray telescope will be its active coded mask aperture. Extensively simulated [Fenimore et al. 1978; Crannell et al. 1985] for improving signal-to-noise ratio of detectors for low-intensity sources (particularly X-ray sources) while maintaining high angular resolution, it has not yet found wide use in gamma ray astronomy. It is designed to produce a unique image of the source, through an analysis of the gamma ray shadow pattern and location, as cast upon the detector plane by the coded mask. The system should provide excellent angular resolution. Since the positions and sizes of gamma ray sources are known to no better than a few degrees, the
coded mask system will be designed to (i) improve angular resolution; and (ii) reduce present inaccuracies.

Operating principles

A photon of energy $E_\gamma$ makes an interaction with the NaI crystal and deposits energy $E_e$ in the detector. The interaction is considered "bad" and rejected if the detector and the anti-coincidence indicate energy deposition in the shield by the high energy photon. All signals from the NaI crystal not accompanied by a simultaneous signal from the anti-coincidence are treated as "good" events and counted.

The Monte Carlo code was used to simulate the physical processes involved in the detection of a gamma photon. In these simulations the array was approximated by a single large NaI crystal placed in its well-shaped anti-coincidence shield. Organic CH was used to approximate the plastic comprising the anti-coincidence shield.

In the simulation performed, an ambient gamma ray spectrum [Gehrels 1985] was assumed and the unscattered flux through the anti-coincidence shield determined. This flux was then used as the primary spectral input for the Monte Carlo simulation of the NaI crystal and its energy deposition spectrum computed. An event was termed "complete deposition" if $E_e = E_\gamma$, and called "partial deposition" if $E_e \neq E_\gamma$. The total detection efficiency of the telescope was calculated. All calculations were performed to the one standard deviation confidence level.

Figure II(1) is a cartoon of the Rice University gamma ray telescope presently under construction. Figure II(2) shows the dimensions of the simplified telescope and the cartesian coordinate system used in the simulations.
Chapter III  Physical Processes

A. Photon Interaction

A flux of gamma photons of a given energy is incident on the telescope. The points at which each of the photons impinges are chosen at random. The photon is described by six parameters in the program data array. These parameters are,

E  energy of the photon
X  shown in Fig.II(1)
Y  shown in Fig.II(1)
Z  shown in Fig.II(1)
Θ  shown in Fig.III(1)
Φ  shown in Fig.III(1)

As mentioned in section I, there are a number of ways by which MeV gamma rays can be scattered or absorbed. A catalog of the possible processes by which the photons may interact with matter has been put in a systematic form [Evans 1972] as given below:

Kinds of Interaction
1. Interaction with atomic electrons.
2. Interaction with nucleons.
3. Interaction with the electric field surrounding nuclei or electrons.
4. Interaction with the meson field surrounding nucleons.

Effects of Interaction
a. Complete scattering.
b. Elastic scattering (coherent).
c. Inelastic scattering (incoherent).
d. Production of positron-electron pairs.
   e. Absorption.

The relative importance of the photoelectric effect, Compton scattering and pair production is shown graphically in figure III(2). Photoelectric collisions are important only for low energy and small atomic number (Z). Pair production is of major importance only for large energy and large Z. Compton collisions predominate in the
entire domain of intermediate energy, for all $Z$. Described here are the three interactions and the approximations which have been made in the program.

I. Compton scattering

When the incident photon has an energy $h\nu_0$ which cannot be neglected in comparison with the rest energy of an electron $m_0c^2$, the relativistic effects in the theory of scattering become significant. This phenomenon, Compton scattering, takes into account the conservation of photon momentum, $h\nu_0/c$. Barring the trivial case of zero scattering angle, which is equivalent to unscattered radiation, the theory developed by Klein and Nishina (1929) correctly predicts the energy and the momentum of the scattered photon and the struck electron. Though strictly valid for unbound electrons at rest, the theory also holds when the atomic binding energy of the struck electron is small compared to $h\nu_0$. This latter situation obtains in the case of scintillation phosphors used to measure gamma rays.

In the Monte Carlo simulation of the scattering, the angle of scattering of the unpolarized photon is determined randomly using the normalized Klein-Nishina cross section [Evans 1972]

$$d(\sigma^e) = \frac{r_e^2}{2} d\Omega \left( \frac{\nu'}{\nu_0} \right)^2 \left( \frac{\nu_0}{\nu'} + \frac{\nu'}{\nu_0} \sin^2 \theta \right)$$

$\text{cm}^2/\text{electron}$

where $r_e$ is the classical radius of an electron, $e^2/m_0c^2$; $\nu_0$ is the frequency of the incident photon; $\nu'$ is the frequency of the scattered photon; $\theta$ is its angle of scattering with respect to the incident direction; and $d\Omega$ is the solid angle into which the photon is scattered. The energies of the scattered photon and the struck electron and the angle of scattering of the electron are determined from the principle of conservation of energy.

The azimuthal angles, $\Phi$, for the scattered photon and electron are assumed to be isotropically distributed in the interaction system. In the Monte Carlo procedure, $\Phi$,
chosen randomly. Euler transformations are performed to obtain the spherical coordinates in the detectors cartesian system.

2. Photoelectric effect

For energies of less than $\sim 0.5$ MeV the predominant mode of gamma ray interaction in all medium and high Z absorbers is the photoelectric effect. This mode of interaction only occurs for bound electrons where the recoil of the entire atom accounts for the momentum conservation. On absorbing a photon of energy $h\nu_o$ an electron is ejected from the atom with an energy [Evans 1972];

$$E = h\nu_o - B_e$$

where $B_e$ is the binding energy of the ejected electron. The remainder of the energy appears as characteristic X-rays (especially from high Z elements) or Auger electrons (low Z elements) as a result of the filling of the vacancy created in the inner atomic shell.

The first major approximation in the program arises from the fact that the photoelectric cross sections for atomic levels other than the K-shell are poorly known [Evans 1972]. Experimental determinations of cross sections of L- and higher shells have not been done with sufficient accuracy. When the energy of the photon is greater than the binding energy of K-shell electrons $B_{elr}$, ejected photoelectrons are always from this level. If the photon energy is less than $B_{elr}$, the entire energy is transferred to a single electron. For every K-shell photoelectron there is an eighty percent probability that the binding energy appears as a resonant fluorescent $K_{\alpha}$ X-ray. The rest of the time an Auger electron from the L-shell is ejected. To reduce the "run time" on the computer the program produces the photoelectrons and the X-rays for the highest Z element of each material only. In our case these are iodine and carbon, for the array and shield respectively. We therefore have a $K_{\alpha}$ X-ray of energy 29.2 KeV (iodine) and a 0.28 KeV K edge (carbon) [Harshaw 1984].
The angle of emission of the photoelectrons is determined from a set of normalized cross section formulae [Heitler 1954] that are valid for the atomic K-level. The cross section formulae cover (i) non-relativistic photons ejecting two K-shell electrons; (ii) photons with energy near the K-shell absorption edge; and (iii) relativistic photons ejecting K-shell electrons and Kα X-rays. Respectively, they are given by the formulae,

\[
(\tau) = \sigma_T \alpha^4 Z^5 2^{5/2} \left( \frac{m_e c^2}{\hbar \nu_o} \right) \text{ cm}^2/\text{atom}
\]

\[
(\bar{\tau}) = \sigma_T 8\pi \alpha^5 Z^6 \left( \frac{m_e c^2}{\hbar \nu_o} \right) \frac{e^{-\xi} \coth \xi}{1-e^{-2\pi \xi}} \text{ cm}^2/\text{atom}
\]

\[
(\bar{\tau}) = \sigma_T \frac{3}{2} \alpha^4 Z^5 \left( \frac{m_e c^2}{\hbar \nu_o} \right) e^{-\pi \beta + 2 \beta^2 (1-\log \beta)} \text{ cm}^2/\text{atom}
\]

where \(\sigma_T\) is the Thomson scattering cross section, \(8\pi/3 \left( e^2/m_o c^2 \right)^2\); \(\alpha\) is the fine structure constant; \(m_o\) is the rest mass of the electron; \(\xi = (Z e^2/\hbar \nu_o)\); and \(\beta = (\alpha Z)\). Approximate theories of L-shell ejection have only been worked out in the non-relativistic case. Poor experimental knowledge of the cross sections for the electrons in the L- or higher shells is accounted for by an increase of the K-shell cross sections by a constant factor, in order to compensate for relatively infrequent interactions with these electronic levels [Evans 1972].

The remaining angles for the photoelectrons and the X-ray photons are randomly chosen assuming an isotropic distribution in the interaction system. Euler transformation to the detectors coordinate system is then performed.

3. Pair production

In the electromagnetic field of a charged particle, an incident photon of energy \(\hbar \nu_o\) (greater than 1.02 MeV), can be completely absorbed to produce an electron-positron
pair. The total kinetic energy of the electron-positron pair is given by:

$$T = h\nu - 2m_{\text{o}}^2 c^2$$

The positron energy, $E_+$, is determined from the normalized cross section [Evans 1972];

$$d(\chi) = \frac{\sigma}{h\nu - 2m_{\text{o}}^2 c^2} dE_+ \quad \text{cm}^2/\text{nucleus}$$

where

$$\sigma = \alpha r_{\text{e}}^2 = \frac{1}{137} \frac{e^2}{m_{\text{o}}^2 c^4}$$

and $P$ is a dimensionless function of $h\nu$ and $E_+$ whose value varies from 0 when $h\nu_o = 2m_{\text{o}}^2 c^2$ to ~20 when $h\nu_o \to \infty$. The measured quantity is the electron energy, which is then given by:

$$E_- = h\nu - 2m_{\text{o}}^2 c^2 - E_+$$

The average angle of emission between the incident photon and the created particles, for $E >> m_{\text{o}} c^2$, is given by:

$$<\theta_\pm> = \frac{m_{\text{o}} c^2}{E_\pm}$$

The azimuthal angles are isotropic and $180^\circ$ apart; and are chosen randomly. The usual Euler transformations are then performed.

**B. Electron Interaction**

Electrons lose their energy in matter by two primary processes

(i) ionization or

(ii) radiative bremsstrahlung emission.

For electrons with energies around $2m_{\text{o}} c^2$ the excitation or ionization of atoms (inelastic collision) is the principal mechanism of energy loss. For higher energies bremsstrahlung
gives rise to an increased rate of energy loss, outweighing the losses due to the inelastic collisions.

An important feature of ACCEPT, missing from almost all previous electron/photon transport codes, is its handling of multiple scattering of both primary and secondary electrons. By tracking multiple scattering events down to the cutoff energy, ACCEPT gives better results than most codes which do consider this process [Mitchell 1977; Rogers 1982]. The coding of multiple scattering is based entirely on the works of Goudsmit and Saunderson and (i) applies to all angular deflections without restriction on the values of their magnitudes; and (ii) can be evaluated for any desired single scattering cross section. Detailed multiple scattering Monte Carlo simulations [Berger 1963; Wilson 1951] show a range reduction of 0.65 radiation lengths (i.e., the distance over which the electron has its energy reduced by a factor of e) compared to that of a singly scattered electron. The result has been incorporated into ACCEPT in its electron transport code. In ACCEPT, the energy deposited by an electron traversing a distance d in the scintillator is given by:

\[ E_{\text{dep}} = E_e \ln 2 \left[ e^{-(R-d)/X_0 \ln 2} - 1 \right] \]

where \( R \) is the range for a single scatter; and \( X_0 \) is the radiation length in the material.

C. Interaction cross section

As noted in the Introduction, the intensity of monoenergetic photons, \( I \), through a scintillator decreases exponentially;

\[ I = I_0 e^{-\mu x} \]

where \( I_0 \) is the initial intensity of the photons; \( \mu \) is the total linear attenuation coefficient expressed in inverse centimeters; and \( x \) is the distance traversed in centimeters. The total numerical value of the attenuation coefficient is given by:
\[ \mu = \sigma + \tau + \kappa \]

Figures III(3) and III(4) show the dependence of attenuation coefficient on photon energy for Compton scattering (\(\sigma\)); photoelectric effect (\(\tau\)); pair production (\(\kappa\)); and total coefficient (\(\mu\)) for NaI and the CH [Harshaw 1984].

The probability for a collision to occur within a distance \(x\) is given by:

\[ P(x) = 1 - e^{-\mu x} \]

The Monte Carlo determination of distance \(x\) from an arbitrary point of departure to the first collision must be,

\[ x = -\frac{1}{\mu} \ln (1 - r) \]

where

\[ r = P(x) = 1 - e^{-\mu x} \]

and where \(r\) is a random number between 0 and 1. Since (1-\(r\)) is equidistributed on \(0 \leq r \leq 1\) if \(r\) is, the above relation may be modified to read;

\[ x = -\frac{1}{\mu} \ln (r) \]

If the randomly determined path is longer than the physical size of the telescope, the photon is considered to have escaped unscattered. The Monte Carlo method is always concerned with the distance \(x\) from the point of departure to collision, and only in case of collision turns to a consideration of the nature of target hit, and the type of processes involved. Figure III(5) shows in a block diagram the interaction of gamma ray photons with matter.
Chapter IV ACCEPT

A. Monte Carlo code

ACCEPT [Halbleib 1979] is a three dimensional, multimaterial coupled electron/photon transport code. It combines a condensed-history* electron Monte Carlo technique with a conventional single scattering photon Monte Carlo technique to simulate the transport of all generation of cascade particles over the large energy range from 10 keV up to 1.0 GeV for electrons and photons. For electron transport, processes such as production of knock-on electrons, continuous bremsstrahlung, characteristic K, L and M X-ray production, production and scattering/absorption of annihilation radiation, energy-loss straggling and multiple elastic scattering are all included. The photon transport code allows photoelectric, Compton, pair production interaction and possible subsequent generation and transport of corresponding secondary particles. Detailed transport of electrons is carried out to preset cutoffs. Then they are transported out along a straight-line trajectory.

The ACCEPT code consists of two permanent files, EZPXSEC and EZEXSEC, and an executable disk file named ACCEPT which is partitioned into three sections called PGEN, DATAPAC and ACCEPT. As far as electron transport is concerned, the code uses the algorithm written for the charged particle transport code ETRAN [Berger 1963]. As noted in the section on Physical Processes, the photon transport uses the logic of a single-scattering process.

*A condensed-history substep of an electron is a random walk in which each step, from state n to n+1, takes into account the combined effect of many collisions. The transition probabilities for each step are determined from the appropriate multiple scattering theories. A discrete set of such substeps provides the history of the electron which can be used for the solution of the problem.
1. EZPXSEC

EZPXSEC, the photon cross section library, uses the results of two analyses performed at Sandia laboratory. Analyses provide much of the data for the (i) characteristic X-rays; (ii) Auger electrons; and (iii) total pair production. Cross section data for photoelectric and Compton interactions are compiled from previous works done by the author of ACCEPT.

2. EZEXSEC

EZEXSEC, the electron cross section library, is taken directly from the data compiled at the National Bureau of Standards (NBS) for their ETRAN [Berger 1963] code. An advantage of these data over any analytic approximations, is that empirical corrections to the bremsstrahlung cross section are based on experimental results. The cross sections for other processes are determined from previous works at NBS [Berger 1963].

3. PGEN

PGEN is the first section of the ACCEPT file. This routine prepares the photon sampling distribution required by the Monte Carlo routine, using the file EZPXSEC and the users input of (i) the geometry of the detector; and (ii) the constituent materials of the detector with their atomic numbers and their weight fractions. The distribution covers an energy range from 1000 MeV down to 100 keV. The routine also uses experimental data for the average K-fluorescence energy. As mentioned earlier, the production of fluorescence and Auger electrons is allowed for the highest atomic element of each material, regardless of its weight fraction.

4. DATAPAC

The second section of ACCEPT prepares the electron sampling distribution for the
Monte Carlo routine. It uses the EZEXSEC file along with the user defined (i) maximum energy of the source radiation; (ii) density of each target material; (iii) "state" (solid, liquid or gas) of each target material; and (iv) geometry data transferred from the PGEN file.

5. ACCEPT

ACCEPT is the last of the three sections that make up the ACCEPT file. It was obtained by amalgamating sections of two widely used codes, CYLTRAN [Halbleib 1977] and MORSE [Straker et al. 1972]. The former is a particle transport code for two dimensional materials having cylindrical symmetry. The code however required that particle trajectories be described in all three dimensions. The MORSE coupled neutron/gamma transport code employed a combinatorial geometry scheme for the description of the target material. The ACCEPT subprogram was obtained by replacing the geometrical structure of the Monte Carlo routine of CYLTRAN by a modified version of the combinatorial scheme employed in the MORSE code. Additional requirements for adapting this system to the peculiar characteristics of condensed-history Monte Carlo were then provided by Halbleib.

Discussed below are the important features and subsections of the ACCEPT subprogram.

5a. Trajectories

ACCEPT uses a full three dimensional description of particle trajectories; particle (i.e., photon and/or electron) position is specified in cartesian coordinates, and particle direction is described by the appropriate spherical polar angles.

Particle histories are followed until they either escape or their energies fall below the chosen cutoff. In the latter case for photons, the residual energy is deposited on the spot, whereas a more elaborate terminal approximation procedure is employed for the deposition of the residual energy and charge of electrons.
5b. Boundary crossing

Photon transport in the ACCEPT code is accomplished via conventional microscopic Monte Carlo methods where particle trajectories which cross boundaries pose no problems. However, when the condensed-history electron Monte Carlo substep crosses a material boundary, certain approximations are invoked.

When a material is finely zoned for a high resolution deposition profile, the inaccuracies of the boundary-crossing approximations are compounded many times. The logic of ACCEPT code was constructed to distinguish between those boundaries that are material boundaries and those that are not. In the latter case the boundary-crossing approximations are avoided.

5c. Combinatorial-geometry routines

A brief description of those combinatorial-geometry routines which are required to process the body and input zone data and to track the electron/photon cascade through the specified configuration follows.

i. Subroutine INPUT reads the combinatorial geometry data; writes the necessary body and input zone data to an internal unit for subsequent access by the routine JOGEN; determines the starting addresses of the various types of data to be stored in the body/input zone array; and calls the subroutine JOGEN.

ii. Subroutine JOGEN reads the body and input zone data provided by INPUT; close packs the body/input zone array with the data required in the Monte Carlo calculations; executes the option selected for specifying the volumes of the input zones; and prints the combinatorial geometry specification of the problem configuration.

iii. Subroutine ZONEA, through calls to subroutine GG, determines the input
zone of material corresponding to the sampled source position; determines
the uncollided distance to escape from this input zone using the sampled
source position and direction; and dynamically stores source zone
information in order to more efficiently determine the source zone of
subsequent primary particles. Much of the coding in ZONEA is the same as
that in the second half of the subroutine DISTA (see below).

iv. Subroutine PR is called by subroutine ZONEA, GG (see below) and
DISTA. When the debug parameter in ACCEPT, is left non-blank, it prints
the combinatorial tracking logic for debugging purposes. This subroutine
requires care in its use as it can be expensive both in terms of "execution
time" and "computer printouts."

v. Subroutine GG is one of the essential parts of the combinatorial-geometry
routines. For a given particle position and direction, and a given body as
defined by the combinatorial geometry data, GG employs the appropriate
vector-analytic geometry to determine the uncollided distance to exit the
body, surface of entry and surface of exit. The logic includes a check on the
possibility that these data have already been determined on a previous call,
in which case they are retrieved from storage and control is returned to the
calling routines (ZONEA, DISTA, ANGLE).

vi. Subroutine DISTA is the primary tracking routine of the ACCEPT code.
For a particle at a given position with a given direction in a given input
zone, DISTA calculates the distance to escape from this zone and compares
the distance with either the coupled interaction distance in the case of a
photon, or the condensed-history substep in the case of an electron. If the
distance to escape is greater than either the coupled interaction distance or
the condensed-history substep, control is returned to the calling routines (either EHIST or PHIST). Otherwise DISTA determines the new input zone encountered upon escape from the given input zone. The utility routine, GG, described earlier is an essential element of the tracking procedure. A very important feature of the method is its dynamic character, according to which the number of a zone being entered upon exit from the given zone is stored in order to improve the efficiency of the search upon subsequent exits from the given zone. It is important to note that this dynamic storage can result in substantial reduction of user input and time required to execute the program. Subroutine DISTA was generalized so as to apply to both condensed-history electron transport and single scattering photon transport. A special feature of the former is the a posteriori sampling of secondary production along the condensed-history substep of an electron. DISTA linearly apportions a substep which lies within more than one input zone of the same material in order to permit subsequent sampling of secondary events at random positions along that substep. Also, since escape of scattered photons is generally not so important in three dimensional applications of ACCEPT, the next event estimator for photon escape, which is very time consuming especially when used with combinatorial geometry, is eliminated in DISTA.

vii. Subroutine ZONE uses the data describing the apportionment of an electron condensed-history substep among more than one input zone of the same material, as determined in subroutine DISTA, in order to determine the input zone in which a randomly sampled secondary event occurs.

viii. Subroutine ANGLE deals specifically with electron transport. When a
condensed-history substep is truncated at a material boundary, ANGLE uses geometry data from the most recent call to DISTA from EHIST in order to sample from the truncated multiple scattering distribution.

ix. Subroutine ZONEC also deals significantly with electron transport. It is a generalization to combinatorial geometry of the variance reduction option for trapped electrons. For an electron having energy between trapping threshold and cutoff, and located in a given code zone consisting of an arbitrary combination of body types, subroutine ZONEC determines the minimum distance to the surface of that code zone and compares this distance with the residual continuous-slowing-down-approximation range of the electron.

5d. Void zones

The logic required to accommodate void zones is considerable and is very frequently simulated with very low density gases. ACCEPT however allows void zones in the target geometry configuration. Halbleib gives three reasons for his encoding of the logic for void zones. First, a faster code results because void transport bypasses many collisional algorithms. Second, a more accurate code results because void transport is rigorous, whereas condensed-history electron transport through small-areal density simulated voids involves a number of approximations. Finally, a substantial amount of memory is required to store the cross section data of the simulated gas. By allowing actual voids ACCEPT easily uses it as the escape zone for all particles.

5e. Shell effects

The treatment of ionization and relaxation effects within stopping media is not very detailed in the ACCEPT code. Photoionization and electron-impact ionization, as well as relaxation by fluorescent and Auger processes, are considered only in the case of K-shell of the highest atomic number element of a given material. Photon transport below 10 keV
is not allowed. Detailed interest in shell ionization and relaxation is neither feasible nor preferable with ACCEPT. There are however other codes like CYLTRAN [Halbleib et al. 1977] which are better suited to do the shell calculations precisely and accurately.

5f. Statistics

Under the normal, or default option, the histories of primary photon are run in 10 equal batches. The output routine is called at the end of each batch. Immediately before each write statement, a call is made to subroutine STATS. This routine recalls the statistical variables corresponding to the output quantities about to be written, computes the estimate of the standard error (in percent) based on the number of batches that have been run, and transfers the statistical parameters required for the subsequent batch to storage. Unless modified, only the final results based on the total number of batches are printed out. The user may specify a number of batches other than 10 by inserting the desired number in the input subroutine INPUT.

Incorporated is a feature that prevents the user from exceeding the computational time limit. Before beginning to process a new batch, the remaining portion of the time requested for the job is compared with an estimate of the time per batch. If this estimate is larger than the time remaining, results based on the number of completed batches-including estimates of the statistical errors-are printed out and the run is terminated. This feature, though built into the logic of the ACCEPT code, is machine dependent and was modified at Rice to allow the user to study the program as a function of the preset time so as to optimize the entire operation.

Under normal operation, virtually every Monte Carlo output quantity is followed by a one or two digit integer from 0 through 99 (estimates greater than 99 are shown as 99) that is the best estimate of the statistical standard error expressed as a percent of the final
value:

\[(S.E.)_N = \frac{100}{|<\chi_N>|} \left\{ \left| \frac{<\chi_N^2> - <\chi_N>^2}{N-1} \right| \right\}^{1/2}\]

where

\[<\chi_N> = \frac{1}{N} \sum_{i=1}^{N} x_i\]

and

\[<\chi_N^2> = \frac{1}{N} \sum_{i=1}^{N} x_i^2\]

The \(x_i\)'s are the values of the quantity obtained from each batch, and \(N\) is the total number of completed batches (usually 10).
Chapter V Results and their Significance

1. Background components

Due to the intense radiation environment at the balloon altitudes and the weak fluxes from astronomical objects at gamma ray energies, spectroscopic observations have always been background dominated in this energy range. One of the major challenges in designing new instruments is to find the optimum detector and shield configuration and to make the right material choices to achieve minimum background. In general, the background in a balloon-borne gamma ray spectrometer is made up of discrete lines superimposed on a continuum. The lines originate from the (i) natural radioactivity of the material in the instrument; (ii) activation of the instrument materials by atmospheric protons and neutrons; and (iii) the annihilation of positrons produced in the instrument and the atmosphere by atmospheric radiations. The origin of the continuum is (i) atmospheric and cosmic gamma rays that enter the instrument through its aperture or penetrate its shield and (ii) activation of the instrument by atmospheric neutrons and protons.

Figure V(1) shows a measured background, by the Low Energy Gamma Ray Spectrometer [Gehrels 1985], at Palestine, Texas. The spectrometer was a cooled Ge detector flown at an atmospheric depth of 3.5 g cm$^{-2}$. The data include only those events for which there were no simultaneous shield veto, since events with vetos are excluded from source observations and therefore do not contribute to the background for the source measurements.

At low energies ($\leq$150 keV), a major source of background is atmospheric and cosmic gamma rays that enter the instrument through its aperture and interact in the detector. The low energy background gamma ray flux is approximately independent of angles between 0° and 70° [Gehrels 1985]; the cosmic flux obeys a secant law.

High energy gamma radiation in the atmosphere is mainly produced by the decay of
π⁰-mesons produced in the nuclear collisions of cosmic ray particles in the air or by bremsstrahlung of relativistic primary and secondary electrons [Schönfelder et al. 1977]. At the top of the atmosphere the first process is dominant at energies above about 50 MeV. Below that energy, atmospheric gamma rays are produced more and more via bremsstrahlung of electrons; below 10 MeV, the π⁰-decay is negligible. The electrons that contribute to the background are either produced within the atmosphere (real atmospheric components), or they enter the atmosphere from outside. Above the cutoff, the latter kind of component consists of primary electrons; below the cutoff, it consists of reentrant electrons that were originally produced in the atmosphere.

The major background component due to high energy gamma rays is the leakage without detection through the shield. That is, the background is caused by the fraction of atmospheric gamma rays that manage to leak through the shield without being detected and then interact with the detector. Earlier flights of gamma ray detectors [Schönfelder et al. 1977] have shown the zenith angle distribution of the total gamma ray flux at MeV energies in the atmosphere to be essentially flat between 0° and 70°, rising by a factor of ~4 to a peak at 110°, and then falling by a factor of ~2 to a plateau between 130° and 180°.

The research reported herein was a calculation of the shield leakage in the Rice University gamma ray telescope. The study used an ambient gamma ray flux measured in the past by experimental flights [Schönfelder et al. 1977; Gehrels 1985] and theoretical studies. The differential energy spectrum (ph cm⁻² sr⁻¹ s⁻¹ MeV⁻¹) used in various angular regions at 3.5 g cm⁻² were 0.052E⁻¹.81 for 0° to 65°; 0.085E⁻¹.66 for 65° to 95°; 0.14E⁻¹.50 for 95° to 130°; and 0.047E⁻¹.45 for 130° to 180°. Figure V(2) shows the total downward gamma ray flux at 5.0 g cm⁻² over Palestine, Texas.

There are several uncertainties in these spectra. They were measured only in the 10.0-1.5 MeV energy range, while the power-law forms given above were assumed in
our analysis to apply over the energy range 5.0-0.1 MeV. However, at 0.5 MeV and below, the direct leakage of atmospheric gamma ray photons is cut off by the increasing cross section of the shield. Below 0.5 MeV the dominant shield leakage background is from high energy photons that are scattered in materials near the detector. Also the original measurements, which were made at 2.5 g cm\(^{-2}\) atmospheric depth, were corrected to 3.5 g cm\(^{-2}\) using a theoretically calculated depth dependence.

In this study, the simplifying assumption was made that the instrument pointed straight upward throughout the simulation. A tilt of the instrument would have increased the shield leakage through one side as the slightly thinner upper section moved between 90\(^\circ\) and 110\(^\circ\), but at the same time a decrease would be noticed as the thick lower section moved to 90\(^\circ\).

2. Program verification and application

To verify a program of the complexity and versatility of ACCEPT is very difficult. Only one previous use of the code was found in the literature, and that for a completely different application. However, results from earlier generations of electron/photon Monte Carlo codes were found and compared with those obtained by using ACCEPT. Results from the ETRAN [Berger 1963] (see section IV) are compared with the present calculations. Discussed later are some minor problems on the use of ACCEPT at Rice University.

The simulation of the Rice University gamma ray telescope was performed in two parts. In the first part an ambient flux between 14\(^\circ\)\(^*\) and 180\(^\circ\) was determined for the plastic anti-coincidence shield. The calculation of the flux required a prior estimation of the areal dependence of the shield with the zenith angle. This dependence was determined

\(^*\)The aperture of our telescope is 14x14 squared degrees. The anti-coincidence shield therefore screens the NaI detector from the ambient radiation between 14\(^\circ\) and 180\(^\circ\).
using a simple analytic expression. Figures V(3) and V(4) show the relation between area and zenith angles for plastic and NaI respectively. A problem with flux calculations centered around the energy width at each primary energy: the width should be small enough for statistical accuracy but large enough to keep computation time within reasonable limits. A compromise of 0.1 MeV at 1.0 MeV was achieved and the widths were then scaled as the square root of the ratio of the primary energy to 1.0 MeV. The instrumental energy resolution has been measured to have these same characteristics. Seven primary energies were selected (0.1, 0.5, 0.75, 1.0, 2.0, 3.5, 5.0 MeV) to cover the entire operating range of the telescope. Figures V(5 a-d) show the primary flux used for the simulation of the Rice University gamma ray telescope.

In addition to NaI, the extensive cross section library of ACCEPT allowed the simulation of the plastic anti-coincidence shield. Extended sources at large distances from the target allowed illumination of all six surfaces of the shield. However, limitations on the memory allocation and computation time at the Rice mainframe did not allow simulation of broad parallel beams of photons. A thousand histories in ten batches were used in eleven different angular orientations to determine the response of the plastic shield. A resulting variation in the estimation of the standard errors, by ACCEPT, was noticed and reduced to less than 1% by increasing the number of trials and batches by a factor of ten. This section of the simulation allowed the estimation of the fraction of unscattered primary photons through the plastic shield. In Tables 1(a-d) the primary energies, the primary flux and the unscattered flux for the plastic shield are listed. Also listed are the standard errors based on the general methods of their propagation [Bevington 1969] using the 1σ errors listed by the subroutine STATS (see section IV) of the ACCEPT code.

The simulation of the bare 15 x 15 cm² NaI crystal constituted the second part of this study of the Rice University gamma ray telescope. Using the unscattered flux through the
plastic shield and the ratios of the projected NaI to plastic areas, an incident flux for the NaI crystal was tabulated. Also tabulated was the calculated flux incident on the bare NaI crystal at angles between 0° and 14°. Table 2 lists these quantities for the NaI as a function of angular range. Simulation in one hundred batches of a thousand histories each were performed and the results tabulated. Sixteen independent orientations were selected between 0° and 180° to determine the response of the NaI crystal. Tables of the (i) fraction of unscattered photons through the NaI crystal; and (ii) energy deposited per incident scattered photon were constructed to determine the energy deposition profile of the detector.

Problems in reducing calculations in sixteen independent angular intervals to the four allowed by the selected ambient spectrum proved more difficult than expected. Various methods of averaging (normal, weighted) proved inconclusive and unsatisfactory. On the advice of a colleague, Kurt Lifman, polynomial fits were made to the two quantities (unscattered fraction; energy deposition fraction) and the area under the curves determined by simple integration. A very simple non-linear polynomial fit program [Bevington 1969] provided the (i) coefficients of the polynomial fit; (ii) minimum chi-squared; and (iii) maximum coefficient of correlation for the different points in the angular bins required. Small number of events in each bin (~4) proved to be a problem while trying to minimize chi-square and will be discussed later.

Results of these calculations thus provided the number of unscattered photons, with errors, through the NaI crystal. A product of the scattered fraction with the energy deposition fraction provides the final product of this study: the energy deposition profile or the response function of the NaI detector.

3. Response function of the NaI detector

Table 3 lists the energy deposited (MeV s⁻¹ MeV⁻¹) for the seven primary energies and the total efficiency of the NaI for a unidirectional beam of photons incident through
the aperture. The total efficiency is defined as the ratio of scattered photons to the total incident flux which would strike the sensitive detectors front face where there is no cladding. Figure V(6) shows the energy deposition profile of the NaI detector simulated in this study.

Figure V(7) lists the total efficiency for a 8 x 8 cm² NaI crystal determined using the codes ETRAN and EGS. Compared with Table 3, the results obtained using the codes with our results within the limited statistical accuracy. The systematic difference, though small, can be explained by the larger size of our detector, though no effort has been made to confirm it with some other code. However, from a practical point of view this difference is not important for NaI detectors since efficiencies for detection above a certain threshold are important, and on this point the three results appear to agree.

An attempt at determining the total efficiency of our detector for omnidirectional gamma ray flux, for the angular distribution given by Gehrels, was made and is shown in figure V(8). This efficiency is well below the efficiency of the detector for the flux through the aperture as shown in Table 3. The background that leaks through is small compared with the aperture radiation, assuming Gehrels, 1985, flux in both cases and a vertically upward orientation of the detector. Table 4 shows the ratio of the energy deposited by the aperture flux (0° - 14°) to that deposited by the background flux (14° - 180°).

Statistical accuracy of this quantity proved harder to determine than expected and no attempts were made to be calculate it. However, compared with figure V(9) the agreement seems quite satisfactory. Figure V(9) is the total efficiency is for a point source lying on the detector axis for a 5 x 5 inches NaI detector. While no errors are shown in figure V(9), the MES code [Caponi 1983] ignores electron transport and multiple scattering and thus is probably less accurate than our study.

There have been a wide variety of NaI response function measurements reported
[Rogers 1982]. Detailed comparison between theory and experiment is often difficult because the experimental conditions are not completely specified (sources of scattering; shield thickness, etc.). The only photofraction (measured and calculated) found in the literature is shown in figure V(10). It is for a 8x8 cm² bare NaI detector. Compared with figure V(8) of our study the agreement may well be called reasonably good.

4. Significance

This detailed study of the shield leakage and the response function of our gamma ray telescope led to a better understanding of the detector and to specific recommended techniques for reducing the background in future instruments designed at Rice University.

Detailed comparison with a variety of codes calculating NaI response functions verifies the accuracy of our use of ACCEPT. One major advance of this study has been the study of the effect of the detector's shield on the response function. ACCEPT quantitatively explained the response function of clad NaI detectors and qualitatively explained the efficiency of plastic as an anti-coincidence shield. A few persistent discrepancies at high energy (~ 5.0 MeV) require further study of our detector with other codes.

This study also demonstrated the problems in executing a program written for a machine not available at Rice University. Developed for a 60-bit CDC machine and run on a 16-bit AS 9000, ACCEPT often terminated simulations without providing any traceback information. Extensive reprogramming of the timing and debugging subroutines of the ACCEPT helped but the latter never worked satisfactorily. Certain features of ACCEPT could never be accessed (void zone calculations; enclosed sources, etc.), which resulted in a few approximations in the final results. Lack of information about previous use of ACCEPT both in literature and from the author of the code combined with a poorly written user's manual, made the installation of the program and
its use difficult. The structure of the code is poorly designed and excessive time is lost in searching for encoded information.

An important problem in this study was the determination of errors in results obtained with a small number of events. Since a Gaussian approximation for the data distribution is no longer valid, the correct determination of errors is not easy. When the probability distribution of the quantity is not symmetrical, the smallest and the central confidence interval are not the same. From physical reasoning the smallest confidence interval is recommended but it is usually more convenient to use the central interval. More likely than not the asymmetric distribution is approximately Poisson and tabulated limits of confidence intervals can be used for calculating errors. Where the probability distribution of the small number of events is not Poisson, estimation of errors becomes harder and Monte Carlo simulation using Bayesian statistics is required. Some codes are available [Helene 1984] that give a fairly good estimates of the errors. In this study the distribution of events was assumed to be Gaussian and therefore normal formulae were used to estimate errors in such cases. Using techniques already in the literature [Bevington 1969] the standard errors give the central and the smallest confidence interval. Problems arose at very low energies but a Gaussian distribution was retained to avoid unnecessary complications.
References


Fitch, J.E.: Private communication (1986).


Guber, W., Nagel, R., Goldstein, R., Mettelman, S., Kalos, M.H.: A geometric description technique suitable for computer analysis of both the nuclear and conventional vulnerability of armored military vehicles. MAGI-6701, Mathematical Applications Group, Inc. (1967).

Halbleib, J.A., Sr., Vandevender, W.H., Jr.: Coupled electron photon collisional


Harshaw Radiation Detectors Catalog. Ohio: 1984

Helene, O.: Errors in experiments with small number of events. Nucl. Instr. and Meth. 288 (1984) 120.


Appendix I Electron Transport

For electrons of relatively low energy the loss of energy in matter is due to excitation and ionization of the bound electrons in the stopping substance. For high energies, however, the energy loss of the electron is due to an entirely different mechanism, namely loss by the emission of electromagnetic radiation in the electric field of the nuclei of the stopping material. The radiation, bremsstrahlung, is the dominant factor in the energy loss of fast electrons (i.e., \( E \geq 2.0 \text{ MeV} \)).

1. Average energy loss by inelastic collisions

In this process energy is transferred to the atomic electrons by raising them to higher energy levels including the continuum. Electrons with energies large compared to the ionization energy of the bound electrons, in most cases transfer only a few times the binding energy. Inelastic collision is an efficient process only at low energies and even then multiple scattering accounts for the total energy loss.

The basic formula for the energy lost per centimeter by an electron, travelling with velocity \( \beta \) (i.e., the ratio \( v/c \)), is [Bethe et al. 1953]:

\[
-(\frac{dE}{dx})_{\text{ion}} = \frac{2\pi r_0^2}{\beta^2} N Z \left[ \ln \frac{\beta (E-1)}{2 I (1 - \beta^2)} \right] \left( 2 \sqrt{1 - \beta^2} - 1 + \beta^2 \right) \ln 2 + 1 - \beta^2 + \frac{1}{8} \left( 1 - \beta^2 \right)^2
\]

where \( r_0 \) is the classical radius of an electron; \( N \) is the number of atoms per cubic centimeter of the matter; \( E \) is the total kinetic energy of the electron; \( Z \) is the atomic number of the matter and \( I \) is the mean geometric ionization potential of the absorbing atom. First given by Møller, in 1932, this gives the energy lost in a single scatter. Detailed multiple scattering theory, as used in the program, will be discussed later in this section. The energy loss is large for small velocities and decreases as \( 1/v^2 \), where \( v \) is the particle speed. It reaches a minimum when the kinetic energy, \( E \), is of the same order of the rest energy of an electron. For \( E \) greater than \( 2m_0c^2 \), the inelastic collision loss is
almost negligible compared with the other loss modes.

The average energy loss is also a measure of the average primary ionization of the atom. The fractional number of cases in which a collision with an atom results in ionization rather than excitation is almost independent of the energy of the primary electron. The number of primary ion pairs per centimeter path is inferred from the fact that about one pair is formed for every 30 eV lost by the electron. Since the recombination of these ion pairs powers the scintillator's emission of light, the number is an important indicator of the electron's energy.

2. Radiative bremsstrahlung loss

The second way in which an electron loses energy in passing through matter is by emission of electromagnetic radiation. The average energy loss per centimeter is given by [Bethe et al. 1953]:

\[- \frac{dE}{dx} \text{rad} = N E \sigma \text{rad}\]

where

\[\sigma \text{rad} = \int_{0}^{\nu_{0}} \frac{\hbar \nu}{E} \sigma(E, \nu) \, d\nu\]

where $N$ is the atoms per cubic centimeter of the absorber; $E$ is the electron kinetic energy; and $\sigma(E, \nu)$ is the Bethe-Heitler approximation to the bremsstrahlung cross section. Due to a $Z^2$ dependence in $\sigma(E, \nu)$, the relative importance of bremsstrahlung loss in heavy elements is more than that in light elements. The bremsstrahlung radiation is independent of the electron energy, to first order, and is thus not a good measure of the particle's initial energy.

The total energy loss per centimeter is given by the sum
\[- \frac{dE}{dx} = (\frac{dE}{dx})_{\text{ion}} + (\frac{dE}{dx})_{\text{rad}}\]

The point of emission of the photon occurs randomly along the path of the electron. The number of photons produced inside the scintillator is reduced according to the distance traversed inside and outside the detector, if the electron escapes. The average distance travelled (range), by an electron of energy $E$ is given by [Wilson 1951]:

$$R(E) = \int_{m_e c^2}^{E} \frac{dE}{-dE/dx}$$

The average range is roughly half the energy (MeV) if the distance is measured in gm/cm².

The angle of emission $\theta$, is chosen randomly, according to the theory of Goudsmitt and Saunderson [Berger 1963]. The cross section used to determine the angle is analytically determined. The azimuthal angle $\Phi$, is considered symmetrically distributed in the interaction system and chosen randomly. Euler transformations are then performed to the detectors coordinate system.

3. Multiple scattering

For condensed materials and for electrons of medium (~10 MeV) or low energy (<1 MeV), the measurements of energy loss are made very complicated by the cumulative effect of a large number of scatterings of the electron by the atoms of the stopping material. The small mass of the electron makes its range at these energies very much larger, with the result that the total number of scattering processes which accompany a given energy loss is much greater. As far as the energy loss of the electron is concerned, it has the effect of considerably increasing the total path length taken by an electron in passing through a material of given thickness and correspondingly increasing the energy loss. The approximate range, $r$ (in radiation length units), of an electron of energy $E$ due
to single scattering is given by [Wilson 1951]:

\[ r = \frac{R}{X_0} = \ln 2 \cdot \ln \left(1 + \frac{E}{E_c \cdot \ln 2}\right) \]

where \(X_0\) is the radiation length and \(E_c\) is the critical energy at which an inelastic collision energy transfer to atomic electrons is comparable to the radiative bremsstrahlung loss.

Multiple scattering is taken into account by dividing the electron path into two parts: (i) a straight line along the direction in which the electron is produced by the gamma photon; and (ii) essentially a diffusive path, chosen randomly and symmetrically. The energy at which an essentially straight path gives way to random diffusion has been worked out [Bethe et al. 1953; Wilson 1951] and is given by:

\[ E'_r = E_r \left(1 - e^{-\frac{E_E}{r}}\right) \]

where

\[ E'_r = 22 \cdot E^{-1/2} \]
Appendix II CDC Update Emulator

The ACCEPT Monte Carlo program is written for a CDC-7600 machine, which does not exist at Rice University. Therefore an emulator is required so that Rice's mainframe may access most of that machine's functions. Provided by the Oak Ridge group together with the ACCEPT code the emulator, UPEML [Mehlhorn et al. 1984], is a machine portable program written in FORTRAN 77. The program facilitates the use of CDC based scientific packages on alternate computer systems.

UPEML makes extensive use of the conditional file structure of the CDC, to combine several geometry problem options into a single program file. The emulator does not emulate every command recognized by a CDC processor. The syntax of the UPEML execution-control statements also differ in scope and sophistication. Therefore a detailed study of the emulator package and familiarization with the specific syntax of the commands is an important part of working with the ACCEPT code on an IBM-like mainframe.

UPEML is required for maintaining and manipulating library files that contain the equivalent of the ACCEPT source files. UPEML can perform the following three functions

(i) it can generate a program library from an input source file (called a "creation run");
(ii) it can manipulate the contents of an existing program library (called a "correction run"); and
(iii) it can regenerate a set of sequential source files from the program library.

In addition to this list of individual tasks UPEML can perform combinations of these tasks. Quite frequently, UPEML generates a new program file during a correction run that modifies the old program library. UPEML is controlled through two separate mechanisms:

(i) the execution control input line specifies the purpose of the UPEML run and
input/output instructions; and

(ii) the file control directives specify the manipulation to be performed by UPEML on
the program library.

Detailed instructions on the operation of the emulator are given in the reference mentioned
above.
Figure II(1) The Rice University gamma ray telescope
Plastic
\[-37.465 \leq X \leq 37.465 \text{ (cm)}\]
\[-37.465 \leq Y \leq 37.465 \text{ (cm)}\]
\[-30.480 \leq Z \leq 30.480 \text{ (cm)}\]

NaI(Tl)
\[-6.985 \leq X \leq 6.985 \text{ (cm)}\]
\[-6.985 \leq Y \leq 6.985 \text{ (cm)}\]
\[0.000 \leq Z \leq 5.080 \text{ (cm)}\]

Figure III(2) The simulated telescope and its cartesian coordinates
Figure III(1) The photon's reference coordinate system
Figure III(2) Relative importance of three major types of gamma ray interactions
Figure III(3) Linear attenuation coefficient for NaI
Figure III(4) Linear attenuation coefficient for plastic
Figure III(5) Block diagram of the interaction of the photon with matter
Figure V(1) Gamma ray components over Palestine, Texas
Figure V(2) Measured downward gamma ray flux over Palestine, Texas
Figure V(3) Projected area of the plastic
Figure V(4) Projected area of the NaI
Figure V(5a) Photon flux on plastic (14° - 65°)
Figure V(5b) Photon flux on plastic (65° - 95°)
Figure V(5c) Photon flux on plastic (95° - 130°)
Figure V(5d) Photon flux on plastic (130° - 180°)
Table 1(a) \[ N = 0.052E^{-1.81} \text{ (ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}) \] (14°-65°)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Primary Flux (ph/s/MeV)</th>
<th>Unscattered Flux (ph/s/MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>16.84</td>
<td>1.88 (2)</td>
</tr>
<tr>
<td>3.5</td>
<td>26.30</td>
<td>1.93 (3)</td>
</tr>
<tr>
<td>2.0</td>
<td>56.43</td>
<td>0.50 (5)</td>
</tr>
<tr>
<td>1.0</td>
<td>141.97</td>
<td>0.98 (11)</td>
</tr>
<tr>
<td>0.75</td>
<td>191.39</td>
<td>0.82 (13)</td>
</tr>
<tr>
<td>0.5</td>
<td>351.34</td>
<td>0.64 (21)</td>
</tr>
<tr>
<td>0.1</td>
<td>2953.29</td>
<td>0.00 (99)</td>
</tr>
</tbody>
</table>

Table 1(b) \[ N = 0.085E^{-1.66} \text{ (ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ MeV}^{-1}) \] (65°-95°)

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Primary Flux (ph/s/MeV)</th>
<th>Unscattered Flux (ph/s/MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>27.77</td>
<td>0.72 (3)</td>
</tr>
<tr>
<td>3.5</td>
<td>41.1</td>
<td>0.63 (3)</td>
</tr>
<tr>
<td>2.0</td>
<td>81.01</td>
<td>0.43 (6)</td>
</tr>
<tr>
<td>1.0</td>
<td>183.7</td>
<td>0.21 (13)</td>
</tr>
<tr>
<td>0.75</td>
<td>237.16</td>
<td>0.01 (24)</td>
</tr>
<tr>
<td>0.5</td>
<td>409.29</td>
<td>0.05 (41)</td>
</tr>
<tr>
<td>0.1</td>
<td>2679.93</td>
<td>0.00 (99)</td>
</tr>
<tr>
<td>Energy (MeV)</td>
<td>Primary Flux (ph/s/MeV)</td>
<td>Unscattered Flux (ph/s/MeV)</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>5.0</td>
<td>67.47</td>
<td>2.07 (3)</td>
</tr>
<tr>
<td>3.5</td>
<td>94.3</td>
<td>1.89 (3)</td>
</tr>
<tr>
<td>2.0</td>
<td>170.04</td>
<td>1.37 (6)</td>
</tr>
<tr>
<td>1.0</td>
<td>344.64</td>
<td>0.65 (12)</td>
</tr>
<tr>
<td>0.75</td>
<td>424.86</td>
<td>0.43 (17)</td>
</tr>
<tr>
<td>0.5</td>
<td>686.53</td>
<td>0.31 (26)</td>
</tr>
<tr>
<td>0.1</td>
<td>3445.96</td>
<td>0.00 (99)</td>
</tr>
</tbody>
</table>

Table 1(d) $N = 0.047E^{-1.45}$ (ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ MeV$^{-1}$) (130°-180°)
<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Flux (ph/s/MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(0°-14°)</td>
</tr>
<tr>
<td>5.0</td>
<td>0.04</td>
</tr>
<tr>
<td>3.5</td>
<td>0.06</td>
</tr>
<tr>
<td>2.0</td>
<td>0.14</td>
</tr>
<tr>
<td>1.0</td>
<td>0.36</td>
</tr>
<tr>
<td>0.75</td>
<td>0.49</td>
</tr>
<tr>
<td>0.5</td>
<td>0.89</td>
</tr>
<tr>
<td>0.1</td>
<td>7.54</td>
</tr>
</tbody>
</table>
Table 3  NaI detector characteristics for aperture-only gamma radiation, using the background given by Gehrels (1985), and a telescope pointed vertically upwards

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Energy deposited (MeV/s/MeV)</th>
<th>Total Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.488 (31)</td>
<td>0.72 (3)</td>
</tr>
<tr>
<td>3.5</td>
<td>0.436 (41)</td>
<td>0.74 (4)</td>
</tr>
<tr>
<td>2.0</td>
<td>0.333 (83)</td>
<td>0.83 (4)</td>
</tr>
<tr>
<td>1.0</td>
<td>0.24 (57)</td>
<td>0.90 (4)</td>
</tr>
<tr>
<td>0.75</td>
<td>0.345 (66)</td>
<td>0.93 (3)</td>
</tr>
<tr>
<td>0.5</td>
<td>0.515 (85)</td>
<td>0.95 (5)</td>
</tr>
<tr>
<td>0.1</td>
<td>0.85 (99)</td>
<td>1.00 (99)</td>
</tr>
</tbody>
</table>

Table 4  Ratio of energy deposited by aperture flux to background flux

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Ratio (aperture energy/background energy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.0</td>
<td>0.075 (31)</td>
</tr>
<tr>
<td>3.5</td>
<td>0.09 (41)</td>
</tr>
<tr>
<td>2.0</td>
<td>0.27 (71)</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0 (57)</td>
</tr>
<tr>
<td>0.75</td>
<td>3.00 (67)</td>
</tr>
<tr>
<td>0.5</td>
<td>6.8 (84)</td>
</tr>
<tr>
<td>0.1</td>
<td>(\infty) (99)</td>
</tr>
</tbody>
</table>
Figure V(6) Energy deposited in the NaI for the aperture gamma radiation
<table>
<thead>
<tr>
<th>( \epsilon_0 ) (MeV)</th>
<th>( \epsilon^\prime )</th>
<th>( \epsilon^\prime\prime )</th>
<th>( \epsilon_{\text{net}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ETRAN</td>
<td>EGS</td>
<td>ETRAN</td>
</tr>
<tr>
<td>0.3</td>
<td>0.875</td>
<td>0.879</td>
<td>0.0056</td>
</tr>
<tr>
<td>0.5</td>
<td>0.707</td>
<td>0.700</td>
<td>0.0234</td>
</tr>
<tr>
<td>0.8</td>
<td>0.524</td>
<td>0.519</td>
<td>0.0643</td>
</tr>
<tr>
<td>1.0</td>
<td>0.471</td>
<td>0.459</td>
<td>0.0979</td>
</tr>
<tr>
<td>1.5</td>
<td>0.370</td>
<td>0.358</td>
<td>0.114</td>
</tr>
<tr>
<td>2.0</td>
<td>0.304</td>
<td>0.304</td>
<td>0.119</td>
</tr>
<tr>
<td>3.0</td>
<td>0.225</td>
<td>0.218</td>
<td>0.112</td>
</tr>
<tr>
<td>4.0</td>
<td>0.178</td>
<td>0.168</td>
<td>0.114</td>
</tr>
<tr>
<td>5.0</td>
<td>0.143</td>
<td>0.138</td>
<td>0.119</td>
</tr>
<tr>
<td>6.0</td>
<td>0.117</td>
<td>0.114</td>
<td>0.112</td>
</tr>
<tr>
<td>8.0</td>
<td>0.0793</td>
<td>0.070</td>
<td>0.0951</td>
</tr>
<tr>
<td>10.0</td>
<td>0.0567</td>
<td>0.056</td>
<td>0.0720</td>
</tr>
<tr>
<td>12.0</td>
<td>0.0425</td>
<td>0.040</td>
<td>0.0444</td>
</tr>
<tr>
<td>15.0</td>
<td>0.0259</td>
<td>0.021</td>
<td>0.0198</td>
</tr>
<tr>
<td>20.0</td>
<td>0.0092</td>
<td>0.009</td>
<td>0.0198</td>
</tr>
</tbody>
</table>

Figure V(7) Detector efficiency for broad parallel beam of photons (Roger, 1982)
Figure V(8) Total efficiency of NaI detector (omnidirectional)
Figure V(9) Total efficiency for a point source (Capponi, 1983)

<table>
<thead>
<tr>
<th>$E_\gamma$ (MeV)</th>
<th>Expt Heath c)</th>
<th>EGS Bare</th>
<th>EGS Clad a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.320</td>
<td>0.820</td>
<td>0.836(3)</td>
<td>0.826(3)</td>
</tr>
<tr>
<td>0.662</td>
<td>0.536</td>
<td>0.566(3)</td>
<td>0.559(2)</td>
</tr>
<tr>
<td>0.835</td>
<td>0.474</td>
<td>0.498(2)</td>
<td>0.492(2)</td>
</tr>
<tr>
<td>1.33</td>
<td>0.357 b)</td>
<td>0.366(5)</td>
<td>0.361(5)</td>
</tr>
<tr>
<td>1.78</td>
<td>0.290</td>
<td>0.319(2)</td>
<td>0.315(3)</td>
</tr>
<tr>
<td>2.75</td>
<td>0.225 b)</td>
<td>0.227(3)</td>
<td>0.224(2)</td>
</tr>
<tr>
<td>3.13</td>
<td>0.207 b)</td>
<td>0.209(4)</td>
<td>0.206(4)</td>
</tr>
</tbody>
</table>

Figure V(10) Photofraction calculations and observations for isotropic source (Roger, 1982)