ABSORPTION OF BETA AND GAMMA RADIATION

The purpose of this experiment is to understand the interaction of radiation and matter, and the application to radiation detection and shielding

Apparatus: ^{137}Cs source, ^{137}Ba source, Geiger counter in stand, aluminum and lead absorbers, electronic counter, Lab Pro hardware interface, Logger pro data acquisition software

References: Physics: **Cutnell & Johnson**, 5th: Chapters 31, 32
Physics: **Serway & Beichner**: 5th, v2, Chapter 45

Introduction The natural environment involves nuclear radiation. Mankind has added to this by production of power and by application of "artificial" radiation to medical and other uses. Detection provides information about the radiation environment; shielding involves protection by confinement of radiation or of vulnerable objects. Both involve crucially the specific interaction with matter of various common radiation types.

Nature already provides essential shielding. The atmosphere and the earth's dipole magnetic field protect us from external solar and galactic cosmic rays. The earth's matter contains most of the natural radiation which provides significant heating of the interior. "Artificial" radiation (lifetimes short compared to that of the earth) tend to be concentrated, and to require careful attention to containment by shielding. Examples include fission power generation, medical radioisotope use for diagnosis or treatment, X-radiation etc.

Common radioactive emission particles

Different radiations have different properties, as summarized below:

Radiation	***Type of Radiation***	***Mass (AMU)***	***Charge***	***Shielding material***
Alpha	Particle	4	+2	Paper, skin, clothes
Beta	Particle	1/1836	±1	Plastic, glass, light metals
Gamma	Electromagnetic Wave	0	0	Dense metal, concrete, Earth
Neutrons	Particle	1	0	Water,concrete, polyethylene, oil

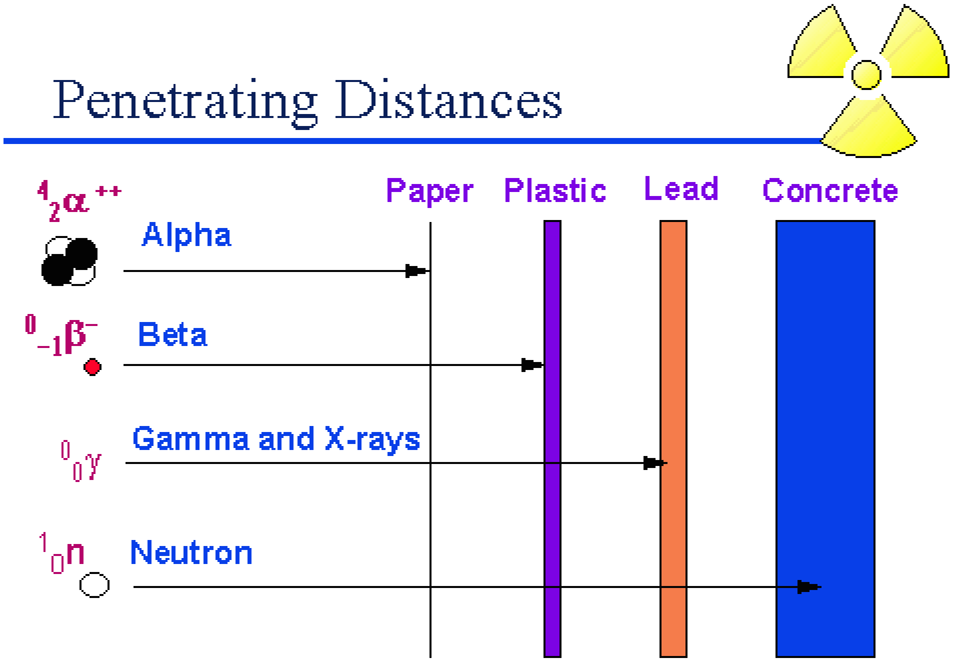


Figure 1 **Effective Shielding Materials for Various Radiation Types**

The diagram above shows the important qualitative difference in material penetration between charged (alpha and beta) and uncharged (gamma and neutron) particles, and also that slow-moving charged particles (alpha) lose energy much more rapidly than fast (beta). More detailed discussion is needed to understand origin of the various radiation types and the important variation of their interaction rate with energy and with absorber element.

Alphas (α) radiation of natural origin is emitted from heavy, unstable nuclei in a transmutation, with conservation of total charge Z and mass number A (but not mass – some is converted into the decay kinetic energy). (The nucleus of the abundant helium isotope ^{4}He is an alpha particle – 2 protons and 2 neutrons.) While easily absorbed themselves, their emission (usually in a radioactive decay chain terminating in a lead isotope) is frequently accompanied by more penetrating betas, and by still more penetrating gammas.

Betas (β) also involve nuclear transmutation. They are identical to atomic electrons, but were not pre-existing before emission. Their appearance is accompanied by that of an electron anti-neutrino (or electron neutrino, if a positive electron (positron) is emitted).

Gammas (γ) do not involve nuclear transmutation, but a change in state like that involving atomic photon emission, with the high energy nuclear photon emission maintaining the total energy balance.

Neutrons (n) are nuclear constituents (with quark substructure). They are produced sometimes by natural alpha bombardment of another nucleus and also, very copiously, in nuclear fission reactors where they make the "chain reaction" chain (being able easily to enter a fissionable nucleus (235 uranium or 239 plutonium) by virtue of lack of charge).

The radioactive source for this experiment is $^{137}{}_{55}\mathrm{Cs}_{82}$ (Cesium 137)**.** It emits both beta and gamma radiation. (Actually, daughter $^{137}\mathrm{Ba}^{*}$ emits the γ ' s.) Its half-life is about 30 years.

All cesium nuclei contain 55 protons, but the neutron number varies among Cs "isotopes". The ^{137}Cs isotope has (137 - 55) = 82 neutrons. It is unstable, and beta decays (β^-) to the A = 137 isotope of barium: $^{137}{}_{56}\mathrm{Ba}_{81}$ (56 protons and 81 neutrons. Note **a)** overall charge conservation, **b)** conservation of (n + p) total (baryon (heavy particle) conservation.)

In beta decay, there is a single nucleus which decays, resulting in three final particles: a beta (electron) particle, an accompanying (unobservable in this experiment) electrically neutral anti-neutrino, "ν bar", and a new chemically different nucleus with Z' = Z + 1 (in our case: 56 (Ba) = 55 (Cs) +1 proton). The kinetic energy released corresponds to the difference between total nuclear rest mass in the initial and final situations, and is shared among the three final particles. Because the beta and neutrino are very light compared to the final nucleus, energy and momentum conservation dictate that the new nucleus gets very little energy though it carries much linear momentum. However, the other two (β^- and ν) share the momentum and energy in various ways. Thus, **there is not a single β kinetic energy, but a range from zero to a unique maximum.**

In gamma decay, the final nucleus is the same as the initial one. It has the same A (atomic number), Z (proton number), and N (neutron number), but in a lower energy state. A = N + Z. The γ-ray, a high-energy photon, carries off some mass-converted energy.

Shielding The goal of shielding is confinement, with eventual conversion of radioactive energy to heat which can be dissipated by cooling (air, water, etc.). As we will see, the primary radioactivity particle may sometimes induce secondary energetic particles by basic interaction processes, and they in turn produce tertiary particles etc. It is necessary to study the dependence of various fundamental interaction processes on particle energy and on absorber atomic number Z, to understand these cascade processes in a quantitative way. Depending on primary energy and type, various shielding methods illustrated schematically above will be appropriate. Sometimes a combination is employed, layered to deal with the successive cascade particles.

Detection The goal is usually to obtain electrical signals, which can be sorted by size or timing for analysis. A charged particle is necessary to interact with the detector matter, which may produce ionization (as with the Geiger counter shown above, or a spark chamber, or a cloud chamber, or a bubble chamber), UV photons (as with a NaI scintillating crystal or a liquid or solid plastic scintillator coupled to a multi stage photomultiplier tube), electron-hole pairs (as with a single crystal Si or Ge detector). If the primary radiation is not charged (neutron, gamma), detection depends on interaction first to produce a moving charged particle, which will then generate the signal – no primary interaction, no signal.

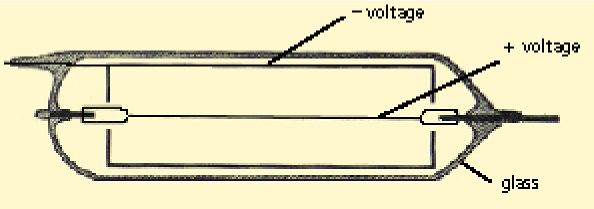


Figure 2 A Geiger tube detector. The center wire operates at + voltage, attracting primary electrons released in the counter gas. For high enough voltage, a very strong field near the wire accelerates electrons to produce secondaries, resulting in an avalanche and a large voltage pulse, independent of initiating electron number.

Radiation Detectors

Radiation detectors are used extensively in medical imaging (CAT, PET scanning etc), prospecting, research, radiation safety monitoring, etc. Commercial devices of great sophistication are readily available, owing to intense interest in nuclear energy release for peaceful and warlike purposes, and to scientific interest in the structure of nuclei and in the characteristics and interactions of elementary particles.

Canberra is one major manufacturer of modern radiation detectors. General information about radiation detectors may be found on their web site:

http://www.canberra.com/products/449.asp

Information on photomultipliers, X-ray imaging etc. may be found at

http://usa.hamamatsu.com/

Solid state detectors

Surface Barrier detectors used mainly for the detection of alpha and beta radiation.

Cooled Germanium detectors. This type of detector is used for the detection of gamma-rays and offers very high spectral resolution.

Gas filled detectors

Geiger counters. These are gas filled counting devices that, unlike gas filled proportional chambers, provide no spectral resolution. They are used mainly for particle detection. The complete electron avalanche near the wire reduces or eliminates the need for external amplification. A high voltage supply is needed.

Photomultiplier tubes (PMTs). An incoming photon knocks an electron out of the photocathode, which is then *multiplied* by each of a chain of dynodes to generate a readable current pulse at the anode. A high voltage supply is needed.

Scintillators

Inorganic scintillators. The most common scintillation crystal used as a radiation detector is NaI(Tl). They are used for the detection of x-ray and gamma-ray radiation with medium resolution. Photoelectric absorption or Compton scattering in the crystal leads to scintillation light that is usually converted to an electrical pulse by a photomultiplier tube.

Organic (plastic) scintillators. These low mass detectors are used for the detection of many types of radiation with generally low energy resolution. They are often used in coincidence systems where a particle or gamma-ray loses a small part of its energy to the detector. The scintillation light is usually converted to an electrical pulse by a photomultiplier tube.

http://www.dur.ac.uk/j.l.osborne/nplab/RadnDet.html

Interactions with matter

β ' s and γ' s It makes sense to consider these together, though one is charged and the other not, because each can release the other type in a cascade or shower involving more and more entities at lower and lower energies. This is because both interact electromagnetically. In these processes it is important to realize that electrons are forever for our purposes (conservation of leptons, light elementary particles) , but photons may come and go. Electrons freed by gammas were previously bound to atoms or molecules, whereas new photons can be created (or old ones vanish).

(We will need to distinguish between betas and electrons, though betas are identically non pre-existing electrons produced in nuclear decay. Betas always involve a range of energies, up to some maximum, and absorption of betas assumes a range of energies. Electrons of a single energy have a pretty well defined range; we would need an accelerator to produce them.) But, surprisingly, the range of mono energetic electrons, all with the same initial kinetic energy K_e ,is about the same as that of a continuous beta energy distribution with the same maximum energy ("end point") K_e.

The gamma ray photon (energy related to frequency by Planck's constant: $E = h\,\nu$) has three fundamental interactions, successively dominant as photon energy increases in the order:

a) photoelectric effect with atomic electron – all photon energy transferred to electron, primary photon disappears,

b) Compton effect – photon interacts with free electron – primary photon disappears and secondary photon appears (lower energy), electron recoils with remaining energy,

c) pair production – photon interacts with positively charged nucleus - primary photon disappears and non-pre existing positron-electron pair (charge conserving) appear with kinetic energy equal to excess over pair rest mass energy (1.02 MeV). Positron eventually finds a different (atomic) electron and annihilates with emission of two gamma rays photons, each with 0.511 MeV energy (conserving the rest mass energy of the annihilated e^+ - e^- pair).

An energetic electron can scatter easily from a nucleus, because it is so light, losing energy by radiation (accelerated charged particles radiate). The radiation appears in a secondary "bremsstrahlung" (braking radiation) photon. This process can be used to generate continuous energy-spectrum X-rays. Also present would be atomic transition photons of definite energy characteristic of the impacted material, typical refractory such as tungsten (W) or tantalum (Ta).

In a series of such interactions involving electrons and photons, a single primary entity of either type may thus produce multiple secondary (tertiary, etc.) entities of lower and lower individual energy. A spectacular example is the air shower produced by a very energetic cosmic ray proton, which involves electrons and photons in increasing numbers and decreasing energies, spreading by scattering to cover many square miles at ground level, where they can be detected as arising from a single primary by their coincident arrival at widely separated plastic scintillation – photomultiplier detectors.

The net result, for betas and gammas, is pretty closely exponential absorption, with the coefficient depending on absorber material.

α ' s and n 's These are discussed together only for convenience. Again there is a charged and an uncharged particle, but without shower interchange as above. The alpha loses energy by electromagnetic interaction with atomic electrons with little deflection (little acceleration), because the α is so much heavier than an electron. Thus negligible bremsstrahlung is emitted. The alpha sails along with little deviation to a pretty definite range, which depends on its energy.

The neutron (though it has charged quark sub structure) does not interact electromagnetically, for our purposes. It may scatter from a proton with transfer of partial energy to the charged recoil proton, which then interacts electromagnetically. At sufficiently low energies, a neutron may be captured efficiently by cadmium or boron, with subsequent emission of a gamma ray, which leads us back to the gamma shielding problem. Neutrons are the agents of a chain fission reactor (because uncharged, and strongly interacting with fissile nuclei such as ^{235} U or ^{239} Pu). Thus neutron shielding is a major concern in nuclear power reactors. However, it is of less concern in natural radioactivity or spent reactor fuel, though some neutrons may be emitted.

Procedure

The ^{137} Cs source

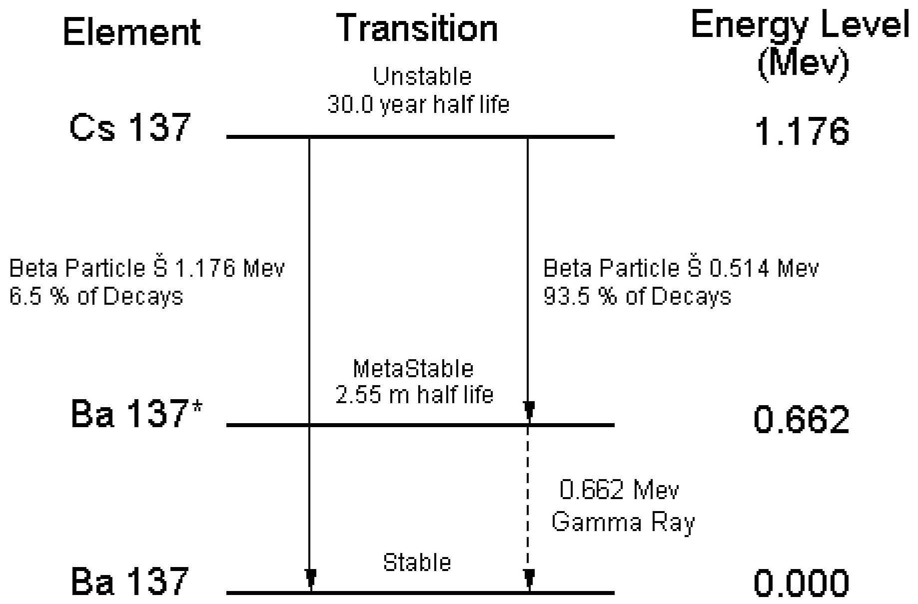
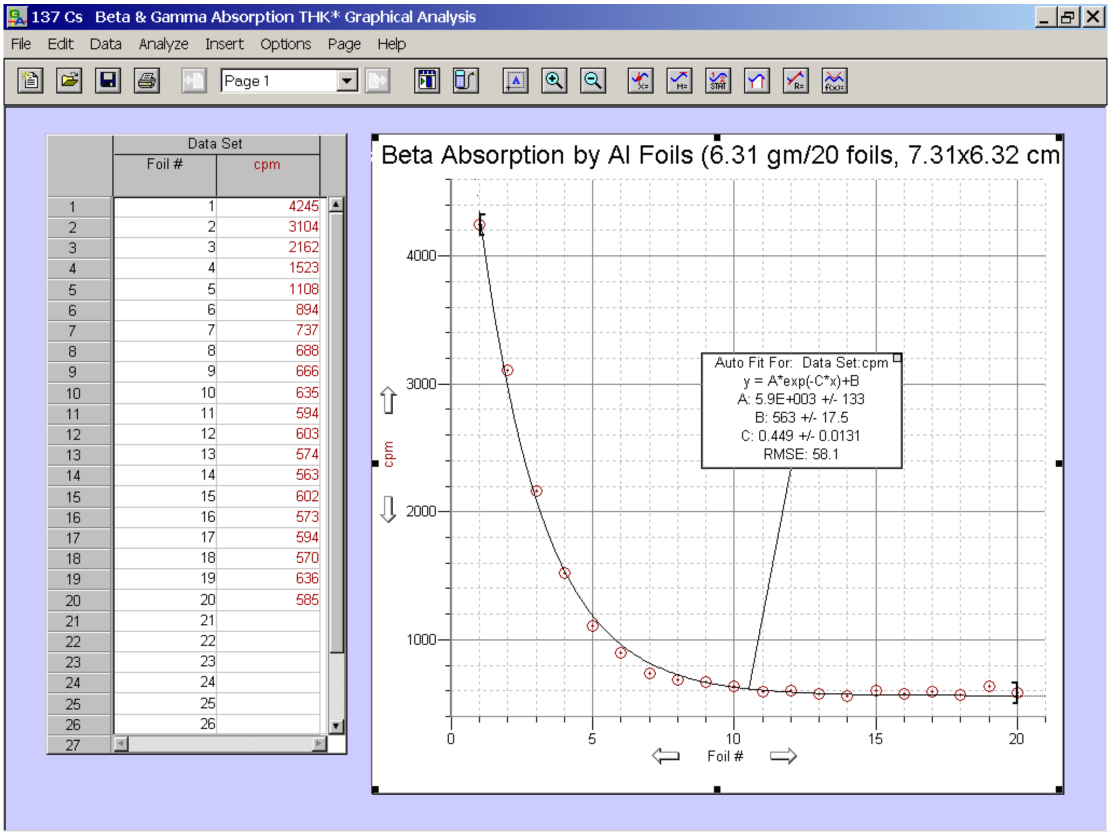


Figure 3 A = 137 Decay Schematic 94 % follow the Parent (^{137} Cs) – Daughter (^{137} Ba *) - Grandaughter (^{137} Ba ground state) Route

The (somewhat unconventional) diagram above shows the decay energetics. (Conventionally, the ^{137}Cs would be offset to the left, showing the difference in charge between the Cs and Ba nuclei. The ^{137}Cs can decay via two routes to ^{137}Ba . Almost 94% of the decays go through a two-step process. A beta particle with a limiting energy of 0.514 MeV yields metastable ^{137}Ba * with a shorter life, which eventually emits a gamma ray with 0.662 MeV energy. About 7% of the decays of ^{137}Cs can directly yield stable ^{137}Ba ("lowest or "ground" state), emitting a beta with a limiting energy of 1.176 MeV, with no subsequent gamma.

Note well: The beta(s) are emitted in a nuclear transmutation (^{137}Cs --> ^{137}Ba) (Rutherford), the gamma transition does not involve a transmutation, but rather a change of state within the ^{137}Ba system.

Beta absorption



	Data Set	
	Foil #	cpm
1	1	4245
2	2	3104
3	3	2162
4	4	1523
5	5	1108
6	6	894
7	7	737
8	8	688
9	9	666
10	10	635
11	11	594
12	12	603
13	13	574
14	14	563
15	15	602
16	16	573
17	17	594
18	18	570
19	19	636
20	20	585
21	21	
22	22	
23	23	
24	24	
25	25	
26	26	
27		

Auto Fit For: Data Set:cpm
y = A*exp(-C*x)+B
A: 5.9E+003 +/- 133
B: 563 +/- 17.5
C: 0.449 +/- 0.0131
RMSE: 58.1

Figure 4 Beta Absorption in Al Foils (The element does not matter much.)

Familiarize yourself with the counting equipment. It consists of a gas-filled Geiger tube with high voltage supply and a stand, which can hold trays for the radioactive source and the absorbers. The amplified output of the Geiger tube (a short electrical voltage pulse for each beta or gamma detected) is counted by the Lab Pro interface and displayed in a Logger Pro 3 file. Count interval and total counting time are specified in the Experiment menu (Data Collection).

Open the Logger Pro 3 file **Radiation Detection and Shielding.xmbl**.

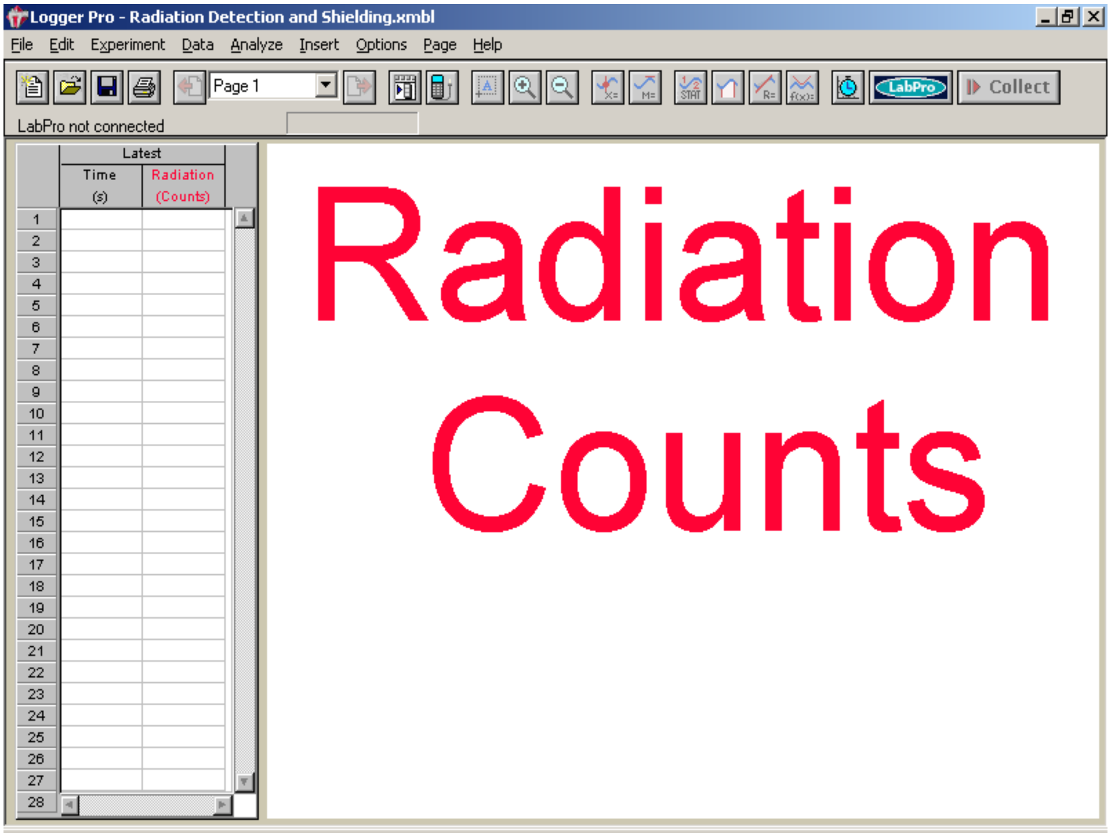


Figure 5 Logger Pro 3 Data Acquisition Program

In Experiment: Data Collection, set for one sample. Set the Length and Sample Collection Time to be equal. The number of samples should read 1.

You should allot more run time as the rate falls, to maintain statistics. At the end of each run, record in Graphical Analysis or on paper the counting rate, the total absorber thickness and the counts. The first two data columns will clear when you begin another data run.

Begin by counting the background for one minute to check that the equipment operates properly. The background is partly from cosmic rays and partly from radioactive materials, which are normally present in the ground and in building materials.

Get the radioactive disk source from the instructor. It consists of a small, safe amount of cesium 137, covered and sealed in plastic, which emits observable beta particles and gamma rays. Put the source top-side up in a tray on the bottom shelf of the stand. Count for one minute.

Put one of the thin aluminum absorbers (made of four ply aluminum foil on a tray between the counter and the source. Count for one minute. Add more of the thin aluminum absorbers and determine the counting rate each time, until the counting rate becomes approximately constant. Continue, to establish this background constant counting rate accurately. Plot rate vs. total foil thickness (mm) and fit with Graphical Analysis.

> *(Determining the thichness of a foil would be difficult. Instead, one would weigh and measure several (for greater precision). Then the thickness of one foil in centimeters is* $\{W/(N\text{x}A)\}$ *(*g/cm^2*) /* ρ *(*mg/cm^3*):* $\rho_{Al} = 2.666\ g/cm^3$ *.})*
>
> *You may use 0.0713 mm per 4-ply aluminum foil.*

The counting rate vs. absorber thickness seems to fall off exponentially, eventually leaving a background due mainly to ^{137} Ba gammas which are little affected by the thin aluminum absorber. The exponential recipe predicts that there will always be some betas. In fact, the recipe will fail at some point.

The “stopping distance” in the curve below is ambiguous, for exponential behavior. We can make an arbitrary, but reasonable, definition of stopping distance: for example, the absorber thickness at which the total count is 5% above the background. In terms of a fit formula: Fit = A*exp(-C*x)+B, this would be:

Fit(x) = 1.05 B. For your fit background B, find some close curve value of x for the 1.05*B fit value, convert x into mm and read the beta ray “end point” (i.e. maximum) energy.

There is then another ambiguity – in the decay scheme shown above are, not one, but two beta decay possibilities, each with its own energy-conserving end point. It is reasonable to compare your chart beta energy with that for the most abundant branch (94%), for which the maximum beta energy is 514 keV. **Report** your absorption curve beta end point energy (1.05*B recipe) determined from the absorption curve of Figure 6 below, and the ratio of that to the accepted 514 keV.

> (**Remember:** Beta particles are produced in a three-body decay and, therefore, have various energies, depending on the share taken by the associated anti-neutrino and the share (quite small) teken by the recoiling daughter nucleus. So the total energy is conserved, but the partition varies. The maximum beta energy is called the “end point” energy.)

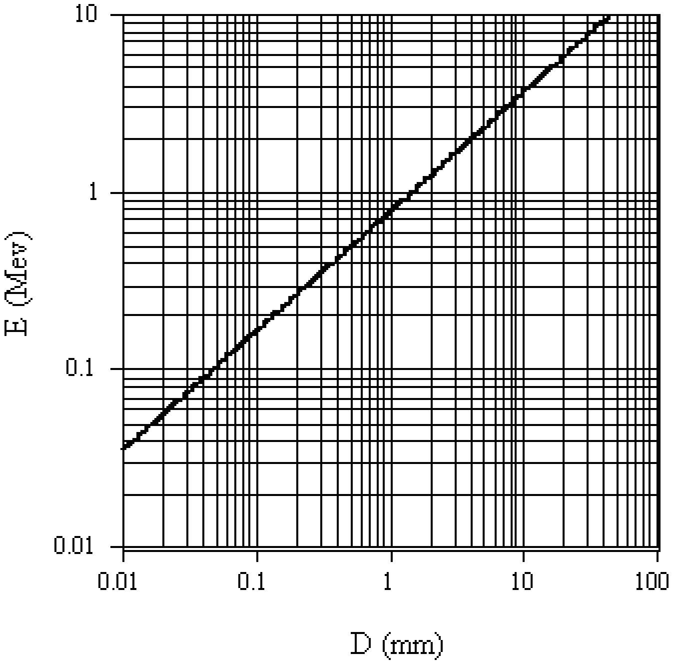
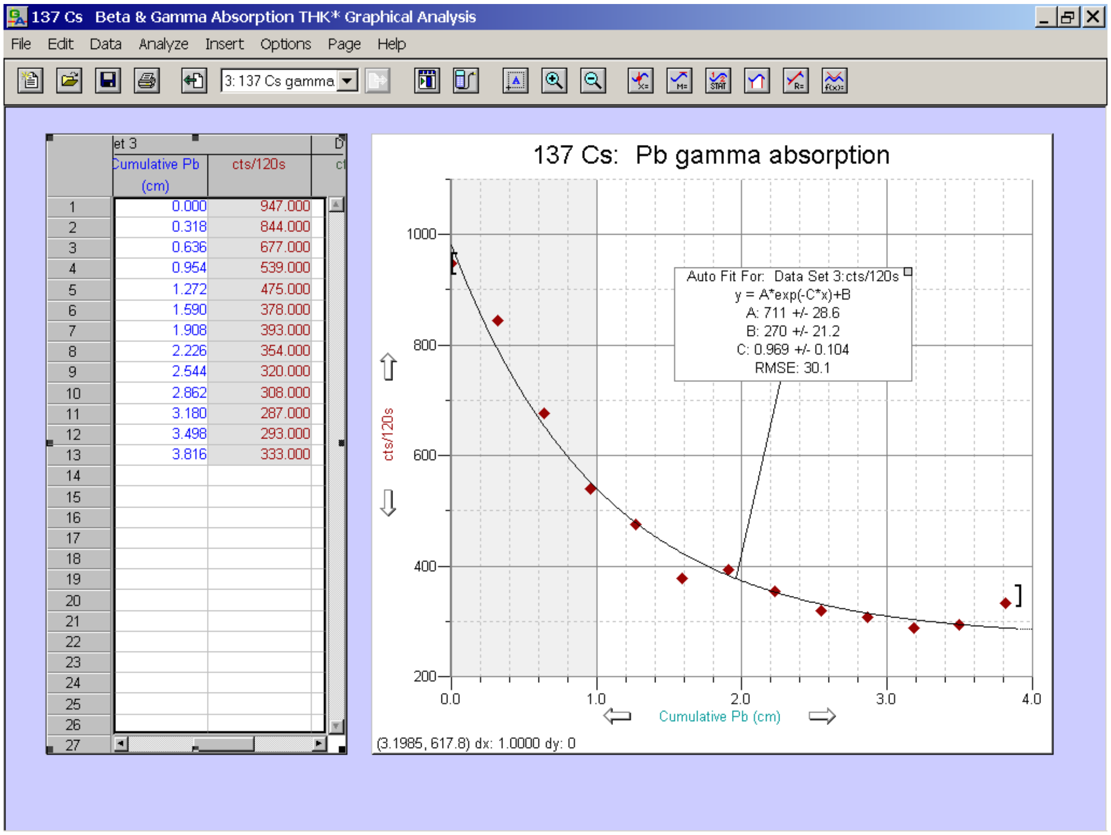


Figure 6 **Beta Ray (β) End Point Energy (MeV) vs. Range (mm) in Al**

Gamma ray absorption



	Cumulative Pb (cm)	cts/120s
1	0.000	947.000
2	0.318	844.000
3	0.636	677.000
4	0.954	539.000
5	1.272	475.000
6	1.590	378.000
7	1.908	393.000
8	2.226	354.000
9	2.544	320.000
10	2.862	308.000
11	3.180	287.000
12	3.498	293.000
13	3.816	333.000

Auto Fit For: Data Set 3:cts/120s
y = A*exp(-C*x)+B
A: 711 +/- 28.6
B: 270 +/- 21.2
C: 0.969 +/- 0.104
RMSE: 30.1

(3.1985, 617.8) dx: 1.0000 dy: 0

Figure 7 Absorption of ^{137}Cs Gammas (γ) in Pb

Turn the source over so that the aluminum holder is between the counter and the source. The aluminum holder will absorb most of the beta particles and pass most of the gamma rays. Count for two minutes. Record thickness and cts/120 seconds.

Add lead absorbers one at a time (plate thickness 1.27 mm or 3.18 mm – use thicker). Count for two minutes each. Cumulate the thickness of Pb absorbers and plot your counting rate vs. cumulated Pb thickness in a GA file. Fit an exponential + background, and record fit parameters. If the automatic fitting program is balky, select the data points on the graph. You may well need to do a manual fit to provide the auto program with suitable starting parameters for its search.

Repeat with the thick (1/4 inch) aluminum absorbers (thickness 6.430 mm) in place of the lead absorbers. This time there will be room for only a few absorbers. Fit the Al absorption and record, as for the Pb absorption.

Remember: For gammas, absorber atomic number Z is very important, with different X and gamma energy dependence for each of the various interactions. Higher energy gamma interactions with matter typically produce a secondary gamma of lower energy. Only for the photoelectric effect does the primary disapper with no secondary, and this process dominates at lower energies only. Thus, the measurement involves a compound process, with a different mix of primaries and secondaries at each "slice" of absorber.

For compactness, higher density ρ is helpful. Lead is the most effective gamma shielding material, both for high Z and for density. Of course, "heavy" concrete (made with metal bearing sands) may be cheaper. Heavy concrete can also be quite effective for shielding MeV neutrons.)

WASH YOUR HANDS WHEN FINISHED WITH Pb