# *Radiation*: quantization, emission and … Absorption!

Prologue for this week:

Is *everything* quantized?!??

Well, is *everything* quantized? – Somehow, that seems to be the (incorrect!) impression that a lot of students come away with, from earlier coursework. The best answer I can give is **NO**. Yet many students come in thinking (incorrectly) that electrons (for example) can only take on discrete values of allowed energies, and that *any* time light is emitted from something that only a discrete set of allowed frequencies would be allowed (with those frequencies corresponding to transitions between the discrete, allowed energy states, as seen in the *emission spectra* of isolated atoms). That much is very clearly wrong, in general.

While we can easily observe that *some* types of emitted light are clearly quantized (for example, *again*, the characteristic radiation emitted by excited gases of isolated atoms), you can *also* easily see in the lab that other types of emitted light appear to be associated with a continuous spectrum (like the **thermal radiation** associated with an incandescent lightbulb), and we should note that sometimes (as when we look at the spectra emitted by stars) the spectra that we observe contain *both* - discrete, characteristic spectra superimposed on a continuous background.
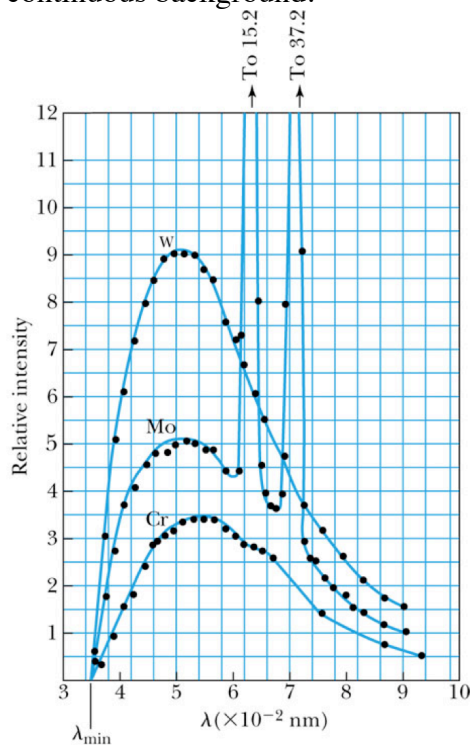
Fig. 1. [Taken from a Modern Physics text written by one of our IWU grads, Andy Rex, and his friend Steve Thornton] Radiation emitted when electrons, after acceleration through 35 kV, slam into various targets: tungsten (W), molybdenum (Mo), chrome (Cr). Note that the minimum emitted wavelength is identical in each case, but that for a molybdenum target there are sharp "characteristic lines" observed. Similar characteristic lines would be observed for the other targets if we looked over a different energy range.

Those of you who took PHYS 106 at IWU did a lab where you worked with "electron guns." In particular, you accelerated electrons by applying a voltage difference between the cathode (where the electrons were thermally emitted) and the accelerator plate. Because of accumulated negative charge on a surrounding cylinder, the electron *beam* was fairly reasonably focused along the optic axis. Any electrons making it through the aperture in the accelerator plate went on until slamming into the (fluorescently coated) glass plate on the face of the tube. When accelerated electrons slam into an obstacle (like the glass plate), this must initiate outward-traveling waves in the *fields* associated with that electron ("braking radiation").

> **Any time a charged particle is accelerated (or decelerated), this instigates outward-traveling waves in the *fields* associated with that particle (*i.e.*, radiation).**

95% of radiation treatment in the US currently makes use of electron guns of the sort you used in that first lab. (Luckily, the glass enclosure was thick enough to absorb the soft *x rays* produced, since we were using relatively low accelerating voltages.) Still, this sort of treatment eventually touches everyone (either personally or because of a friend or family member), and is also an essential component of many industrial processes, such as in quality control of "cling film" plastics (*e.g.*, Seran™ wrap), so today we will think a bit more about how radiation is *absorbed*.

For now, the key point is that this *example* serves to de-bunk the misconception noted at the outset of this document: students often believe that electrons (for example) can only take on discrete values of allowed energies, and that *any* time light is emitted from something that only a discrete set of allowed frequencies would be allowed (with those frequencies corresponding to transitions between the discrete, allowed energy states). *Why* is that wrong? – Well, for starters, in the PHYS 106 lab that you did, you could give the electrons *any* energy you wanted, just by turning the knob that controls the accelerating voltage. That means that there simply are *not* a limited, discrete set of "allowed" energies available to *these* (free, unbound) electrons.

Moreover, even if we keep the accelerating voltage (and therefore the electron energy) *fixed* the "braking radiation" associated with the electrons slamming into a target is NOT quantized! Figure 1 shows the (*x ray* portion of the) spectrum of the light emitted in this way (commonly referred to by a German word for "braking radiation," *bremsstrahlung*). Although the electrons were all accelerated through a fixed voltage of 35 kV, the emitted electromagnetic radiation is characterized by a continuous spectrum (though, depending on the target and the range of energies examined, we can *also* see a discrete set of allowed frequencies, which *do* correspond to transitions between the discrete, allowed energy states associated with core electrons *bound* in atoms in the target).

> **_Free_ electrons can have any energy we choose to give them, but electrons _bound_ in an atom are constrained to a discrete set of allowed energies.**

So, where *does* quantization come from? Hopefully, this answer will be significantly clarified in PHYS 207, but … essentially, bound electrons act like standing waves, which means that only certain wavelengths lead to stable "bound states." – Importantly, this result is not just true for electrons; it's true for, …well, anything! For example, protons and neutrons, when **confined** (via the strong and electroweak nuclear forces) to the nucleus do, indeed, have *only* discrete values of allowed energies, and so *emissions* (light or not) coming from the nucleus are characterized by discrete energies.

Long before people figured out what the various kinds of emissions coming from the nucleus *were*, they simply labeled them according to the first three letters of the Greek alphabet: alpha, beta and gamma emissions. These really correspond to three modes of radioactive decay (from high-energy states to lower-energy states). We now know that in gamma decay, a high-energy photon is emitted (and even if its wavelength corresponds to the x-ray portion of the electromagnetic spectrum, we still refer to it as a gamma ray, to denote its nuclear origin). In alpha decay, an isotope decays by the emission of a helium nucleus (which is, itself, a relatively stable "bit" that can fly off of an otherwise unstable, larger nucleus). In beta decay (which is what we study right now), an electron is emitted, but it does *not* come from the set of electrons that are originally part of the atom: instead, the expelled electron is actually **_created_** (inside the nucleus) at the moment of decay.

The nucleus of an atom is composed of two types of nuclides: protons and neutrons. The number of nucleons define the isotope of an element, often denoted by the symbol $^A_Z X$, where A is the nuclide number, Z is the number of protons in the nucleus and X is the chemical symbol for the element. Many of the isotopes that exist, whether they are naturally occurring or man-made, are unstable and decay radioactively until they reach a stable isotope. In this lab, we will examine the *absorption* (*e.g.*, in your skin) of beta particles that were emitted when a $^{36}_{17}Cl$ (*i.e.*, **chlorine-36) isotope** decays by emission of a beta particle and an anti-neutrino, in the process given by Equation (1).

$$^{36}_{17}Cl \rightarrow ^{36}_{18}Ar + e^- + \overline{v} \tag{1}$$

In a later lab, you may use a mass spectrometer to independently show that the emitted beta particles do indeed have a fairly well defined energy, and yet what you will study for now is simply the *absorption* of these energetic particles. Here, it helps to think back to what we just noted about bremsstrahlung: even when we kept the accelerating voltage (and therefore the electron energy) *fixed* the "braking radiation" associated with *absorption* of the electrons into a target is NOT quantized! So, too, in today's experiment you will find that absorption of beta particles is really a *random process*.

> **Tell me of a pithy remark I might insert here about *random processes*.**
> (Hey, I just wrote this. We're still in *beta*!)

In this experiment, an absorbing material (aluminum foil) of thickness x is placed between the radioactive source and a detector (a Geiger counter).

Because the absorption process is *random*, we expect the observed rate of detected beta particles [called the *apparent* activity, $A(x)$], will be an *exponential* function of the absorber thickness. That is, $A(x)$ will be given by:

$$A(x) = A_0 e^{-\mu x} \tag{1}$$

where A_0 is the regular rate of beta emission by the source when _no_ absorber is in place.

Fair enough, … but **_why_** did we write that **_because_** the absorption process is *random*, we expect the detected count rate will be an *exponential* function of the absorber thickness??? – What does the *exponential* function have to do with randomness?

Suppose that, in a large class, at the end of each line of text in this document, everyone flips a coin, to determine whether or not they will read any further. In that case, the number of readers remaining after each line can be plotted using Igor Pro:

$N = N_0 * \exp[\mu * \text{linenumber}]$
Best fit: $\mu = 0.69315$
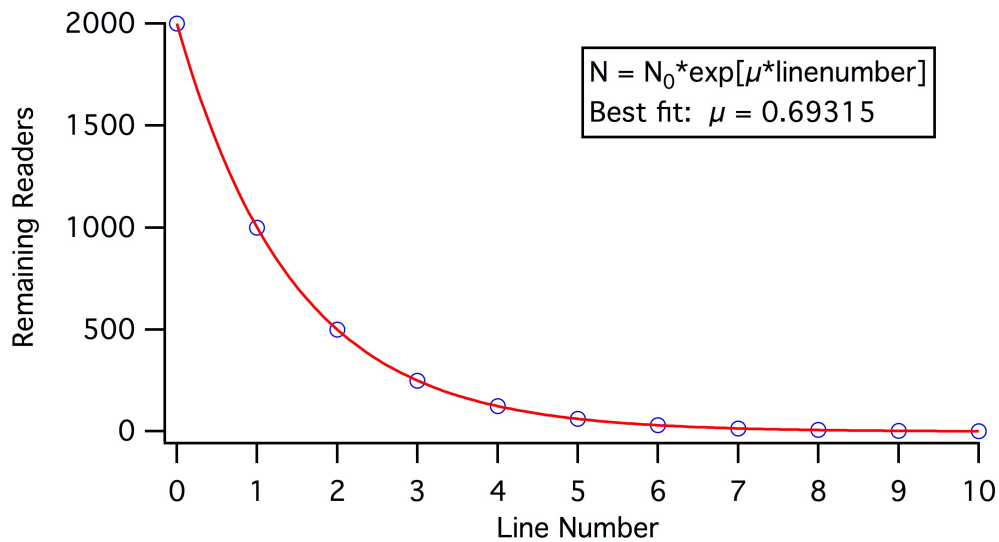
The blue circles show the data; the red line is a fit to the (exponential) form shown in the box. Note, first, that this really is well described by the exponential function. Also note that *even though this example has nothing to do with radioactivity*, this situation is characterized by a "half-life" (namely, the average time required to read one line of text). We can speak of the "half-life" of (non-radioactive) substances you ingest or of (non-radioactive) drug dosages you might deliver to a patient. The decay process in Equation (1), which happens to be radioactive, occurs *randomly*, with a half-life of 3×10^5 years.
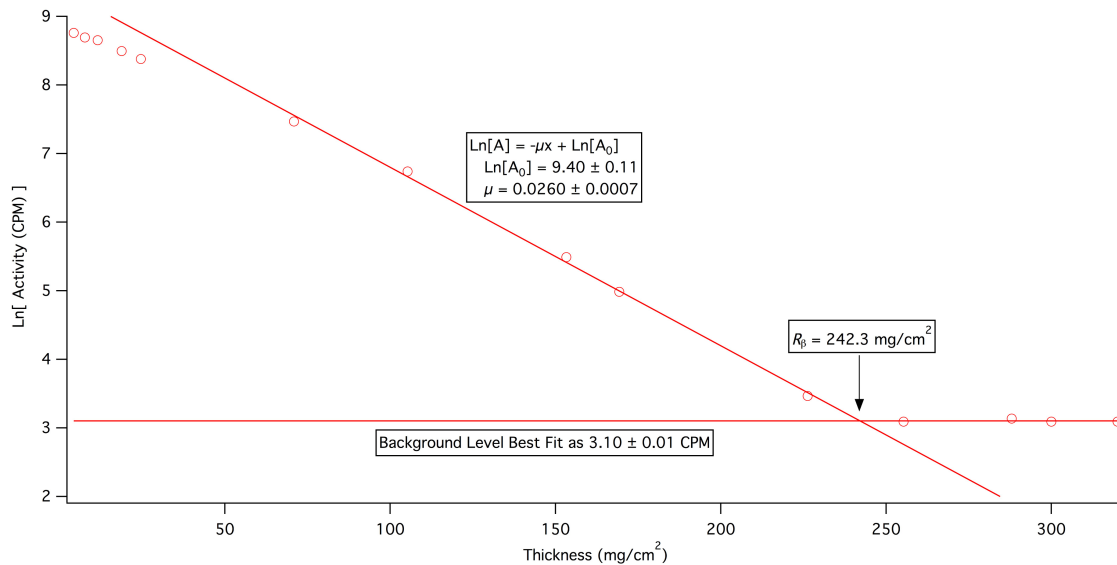
Interestingly, an inspection of Equation (1) will show that the statistically *predicted* count rate (or the amount of whatever food was ingested or the amount of medicine remaining in a patients system) *never* actually reaches zero. In other words, no matter how thick a piece of aluminum foil we place between the chlorine source and the Geiger tube, there will *always* be the chance that some electron will happen to get through. After all, matter (including aluminum) is mostly made up of empty space: whether or not a particular beta particle happens to run into something that will completely halt its progress through is, after all, something that is *random*.

There *is* an absorber thickness, however, which stops a good majority of the beta particles; we know that we have reached this effective maximum "**RANGE**" for the electrons when the number of counts registered by the detector is close to that due to the background radiation alone. A good chunk of that background radiation is due to atomic particles from outer space called cosmic rays, or from secondary particles.

Taking the natural logarithm of Eq. (1) yields an equation of the form:

$$\ln(A) = -\mu x + \ln(A_0) \qquad (2)$$

which tells us that we should get a simple straight-line graph if we make a plot of the logarithm of the count rate versus absorber thickness. Example (student) data is shown in the next graph:

Ln[A] = -μx + Ln[A₀]
Ln[A₀] = 9.40 ± 0.11
μ = 0.0260 ± 0.0007

$R_\beta = 242.3 \text{ mg/cm}^2$

Background Level Best Fit as 3.10 ± 0.01 CPM

Ln[Activity (CPM)]

Thickness (mg/cm²)

In practice, the curve shows some deviation from linearity, but if we focus our attention on the straight *part* of the curve and extrapolate to find where it intersects the background activity, then this point of intersection gives the absorber thickness corresponding to the effective maximum "range" for the electrons emitted from our source. This is called, R_β, the maximum particle range. You will determine R_β of these beta particles in aluminum. Then, from a Range *vs*. Energy graph, which will be supplied to you in lab, you will be able to determine the energy possessed by the beta particles emitted in the chlorine-36 decay.

Note the odd-looking units we associate with thickness here. Clearly they do *not* have the dimensions of a length; however, these units have great utility in discussions relating to the absorption of radiation: they allow us to quickly find how much shielding to use.

> Note: To convert an absorber thickness given in mg/cm²
> into an actual thickness (in centimeters),
> divide by the **density** of the absorber material.

Remember, because matter (including aluminum) is mostly made up of empty space: whether or not a particular beta particle happens to run into something that will completely halt its progress through is, after all, something that is *random*. In such a process, the *density* of an absorber is clearly as important as its thickness - and the use of the units shown above *reflects* this fact. Moreover, if we express the particle range, R_β, in these units, we can simply divide by the density of any material (*e.g.*, air) to find out how much of that substance will be required for shielding. (Think about that as you consider how far away from the source you've been sitting throughout this lab.)

Corrections: The apparatus is such that one can never have "zero" absorber thickness between the source and the counting system. There are always present in the system:
- the Geiger tube's end window, which is equivalent to about 1 mg/cm² of absorber;
- the source cover which is equivalent to about 1 mg/cm²; and
- the intervening air, which amounts to about 1mg/cm² per centimeter of thickness.

The air thickness must be measured and corrections for these three things taken into account. Although the tables we supply for this lab make it easy, *it should be clear in your records what is raw data and where corrections have been introduced.*

Note also that, in Equation (1), the units of both $A(x)$ and of A_0 are "counts per minute" (CPM). That means that the units associated with the factor μ (called the *absorption coefficient*) must be the *inverse* of the units we associated with the thickness, x.

ABSORPTION DATA

[Take as much, or as little, data as you feel you need. -- Always extend any data table as needed!]

Data for the graph can be collected by recording the count rates, which correspond to different thicknesses of aluminum absorbers. The absorbers are of such varying thicknesses that changes of total absorber thickness of practically any size can be effected by judiciously picking and **combining** the absorbers during the experiment. Intervals of about 50 mg/cm² would be appropriate at first, <u>with smaller intervals near the end point</u>.

	Aluminum Absorber Thickness (mg/cm²)	"Corrected" Absorber Thickness (mg/cm²)	C.P.M.	Estimated Uncertainty
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				
12.				
13.				
14.				
15.				

Source distance d _____ cm   Background = _____ cpm
Geiger tube radius _____ cm

Method of Analysis: Clearly state the corrections made for the end window, the source cover, and air.

If your measured range for the beta particles, after corrections, turns out to be less than 1200 mg/cm², then an **empirical** relation you can use is:

Energy = Exp[6.63 – 3.2376 Sqrt[10.2146 – Log[MeasuredRange]]]

where MeasuredRange is the value of your measured range based on the CORRECTED total absorber thickness, in mg/cm², and the result will be the energy in MeV

Beta Particle Radiation (from Chlorine-36)

Range: R_β = _____ mg/cm²   Experimental Energy: $E =$ _____ MeV
Range *in aluminum* = _____ cm   Actual Energy: $E =$ ___0.7___ MeV
Range *in air* = _____ cm   % error   = _____ %

Questions:

1. How far should **you** have been sitting from the source?

2. What is your experimental result for the absorption coefficient for aluminum?
   [Use your graph to determine an experimental result for μ,
   along with a <u>quantitative</u> measure of your *confidence* in
   this. Express your answer in units consistent with Eq. (1)]

<u>Use this space for a compelling display of initiative and insight</u>:

Write Specific Conclusions and Critical Analysis!!