Some Handy Facts About Radiation,
or,
How Not To Get Cooked

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This document is meant to give you a brief introduction to some of the practical issues associated with radiation, its interaction with the human body, and how not to get killed or seriously injured when dealing with it. It is *not* meant to replace a standard radiation safety handbook; this is a supplement, for informational purposes. To be perfectly honest, it's a compilation of common sense and interesting facts about radioactives.

> *"A day without radiation would be like night."*
> —Anon.

By and large, radioactives are fairly safe to work with, so long as you obey some simple precautions. In most radiation labs, the most significant health hazard comes from the lead bricks used as shielding; heavy metal poisoning is a constant risk. However, it is quite possible to have some extremely nasty things happen to you as a result of carelessness with radioactive sources. The only thing which can prevent this is continuous vigilance and attentiveness to safety procedures.[1]

"Radiation" in general refers to energetic particles, typically emitted from nuclear processes. Not all radiation is harmful; as the quote at the beginning should remind you, *sunlight* is radiation too. The primary danger of radioactivity of all sorts is the disruption of cellular function by the impact of these energetic particles. At low levels, this can lead to flawed cell replication and cancers; at higher levels, it can directly interfere with biological function, and be rapidly lethal.

The purpose of this file is twofold: First, to give a brief overview of the types of radiation, their sources and effects, and how they can be safely handled; second, to give some general survival tips for being in a radioactives lab.

One thing to keep in mind to begin with is the half-life of a radioactive substance, this being the average time it takes for half of any sample to decay. Nuclei in a sample decay more or less independently, with a fixed probability per unit time; thus the total number of nuclei which have not decayed decreases exponentially, $N = N_0 e^{-t/\tau}$. The half-life is $\tau \log 2$. The shorter the half-life of a substance, the more quickly one is rid of it, but on the other hand the faster it must emit its radiation before vanishing.

Another thing to notice is that nuclear processes typically involve things happening at a wide variety of energy scales. The same decay chain may involve a series of events with energies ranging from the keV to the MeV, with intermediate states as heavy as the GeV, and half-lives ranging from milliseconds to gigayears. Therefore, keep a close eye on the SI prefices, and do not assume something is a typo because it involves very disjoint scales.

Much of the material in this document comes from *The Nuclear Weapons FAQ*, by Carey Sublette. This (very interesting) document is available on the Net at *http://www.milnet.com/milnet/nukeweap/Nfaq0.html*

THE TYPES OF RADIATION

The primary types of radiation are α particles, β particles, γ rays, neutrons, and radioisotopes.

α particles

What they are: α particles are ^{4}He nuclei (two protons and two neutrons) emitted typically by the decay of unstable nuclei. On emission, they typically have a kinetic energy on the order of a few MeV.

Sources: α particles are typically emitted by the decay of unstable nuclei and by fusion reactions. Check the notes on any particular source to see if it is an α emitter.

How they are produced: Since an α particle is essentially a small nucleus in itself, an α–emitting nucleus can be thought of as an unstable bound state of two nuclei. The potential for such a bound state goes to zero at infinity, then increases to approximately 10MeV at a distance of a few fermi due to electrostatic repulsion. Below this distance, the strong force takes over and the potential drops precipitously, down to a minimum (at zero distance) where the energy is still *positive*, of order 5MeV. Because this energy is greater than the energy at infinite separation, this is not a true "bound state" – the system can decrease its energy by releasing the α particle. Classically, the potential barrier would prevent this, but quantum-mechanically this barrier can be penetrated.

α particles are also directly produced in fusion reactions, by the combination of lighter isotopes such as two deuterons. (A deuteron is a bound state of a proton and a neutron; the energy of a single α particle is lower than the total energy of two deuterons, so if the Coulomb potential barrier can be surpassed this is an energetically favorable process.)

Primary dangers: Because of their large mass and the relatively high cross-section for complete nuclei to interact with matter, α particles are capable of doing a great deal of damage to the human body, more so than any other form of radiation. However, their high cross-section makes them easy to block; most α radiation will be stopped by clothing or a reasonably thick sheet of paper.

The primary risk with α emitters, therefore, is getting an α source either onto your skin or (worst of all) inside your body. Make sure never to touch a source directly, to avoid small grains of it ending up on your skin. This also leads to

Survival Rule #1: *Never* touch your mouth after being in a radiation lab without first washing your hands *thoroughly* with soap and water. The act of abrasion will get most of these sources off you quickly.

Strong α sources are potentially more dangerous, and should be shielded using precautions similar to those for γ sources.

β particles

What they are: β particles are energetic electrons and positrons emitted by nuclei.

Sources: β particles are created by the decay of unstable nuclei, and by virtually all nuclear processes, including both fission and fusion.

How they are produced: The basic nuclear β process is

$$n \rightarrow p + e^- + \bar{\nu}_e \tag{1}$$

This increases the atomic number by one ($n \rightarrow p$) and emits a fast electron. The antineutrino leaves rapidly and is essentially noninteracting; it is not interesting for our purposes. This reaction is energetically favorable, meaning that a bare neutron is actually an unstable particle with a half-life of approximately 900sec; nuclear forces may moderate this or make it unfavorable, depending on the system. However, this process must go through an intermediate state, $p + W^+$, which is an effective "potential barrier" almost 85GeV high; because this is so large, the quantum process is very slow, and so most β decays are fairly gradual.

Primary dangers: β particles have a lower interaction cross-section with matter than α particles. On the one hand, this makes them somewhat less damaging; on the other hand, it makes them more difficult to block. The difficulty of blocking a source depends greatly on the strength of the source, and particularly on the kinetic energy of the emitted β particles. (This energy can vary widely between different sources)

As a practical matter, strong β sources should be treated using the same precautions as γ sources.

γ rays

What they are: γ rays are energetic photons (tens of keV up to several MeV) emitted by nuclear processes. (X-rays are simply the lower end of the γ ray spectrum)

Sources: Again, these are created by pretty much every nuclear process. In particular, many unstable nuclei emit such particles. When an isotope is γ-active, in fact, the frequency spectrum of photons it emits is a unique fingerprint of the isotope; this is a handy way to identify the isotopic composition of an unknown substance, even from a distance.

How they are produced: γ rays are produced in virtually any transition between unstable states. However, they do not change quantum numbers such as the number of protons and neutrons, and so typically cannot "stabilize" an unstable nucleus. The most common way in which these are naturally produced is when an unstable nucleus decays

by other means (often β decay) to a highly unstable intermediate state, which then cools down to a more stable nucleus by γ emission. γ rays are also the primary mechanism of energy release when nuclei are broken up (fission) or more stable nuclei are assembled. (Fusion)

Primary dangers: γ rays are, in many ways, one of the most dangerous types of radiation. The high energy of the individual particles guarantees a great deal of damage to any molecule they strike. Most materials are fairly transparent to light at such high frequencies, and so a good deal of shielding material is often needed. However, when interacting with a human body, the sheer quantity of both γ photons and of body is enough to make up for this transparency; γ rays can do significant harm, both to surface layers and deeper in the body.

The best material for absorbing γ rays is ^{207}Pb, which is both a highly stable isotope and optically very dense. As a result, you will often find many lead bricks in a radiation lab.

Survival Rule #2: Always keep the source inside shielding when it is not actively in use. If your source is shaped, (many lab sources are in the form of a radioisotope built into a shaped radiation shield) never point it at a person. (The "safe distance" depends on the strength of the source) Keep the sources pointed at the floor.

Unfortunately, lead provides its own dangers, namely heavy metal poisoning; ingesting it can lead to organ damage and brain damage. Therefore, see rule 1 with particular emphasis.

Neutrons

What they are: Neutrons are, well, neutrons, emitted at high energy.

Sources: There are two basic sources of neutrons: Radioisotopes and fission reactions. Check your source information to see whether a given substance is a neutron source; typically strong neutron sources are also fissile materials.

Fission reactions work by virtue of the fact that a large, just-barely-stable nucleus being hit by an energetic neutron will break apart, releasing lighter nuclei, a good deal of energy (typically in the form of γ rays), and energetic neutrons. By placing a sufficient amount of fissile material in one place, a "chain reaction" can be triggered by having these emitted neutrons trigger further fissions.

Neutrons come in two forms, slow and fast. Fast neutrons (typically emitted only by fission reactions) have very high kinetic energies and are potentially extremely hazardous. In a typical nuclear power plant, the core is surrounded by a large buffer (such as heavy water) designed to kinetically slow these neutrons until they are easier to manage. Slow neutrons are the product of this, and are also emitted by various radioisotopes.

How they are produced: Neutrons are created by decays and by fission. In decays, they are produced in much the same way as α particles, but since they are electrically neutral the potential barrier (and thus the emission energy) is not very high. In fission, a large nucleus breaks into two smaller nuclei, as well as some leftover neutrons. (Larger nuclei have more neutrons per proton than smaller ones) The excess energy is released in the form of γ rays and neutron kinetic energy.

Primary dangers: There are several kinds of dangers posed by neutrons. The first danger is that they behave much like α particles, since both are types of nuclear (rather than leptonic or photonic) matter and have fairly high interaction cross-sections. This means that they can do a great deal of damage to the body. Their lower mass and the fact that they are electrically neutral means that they are significantly harder to block, however; for these purposes, treat them like strong γ sources. Lead is effective, but so is a large enough tank of water. The extent of shielding required depends on the source.

The second danger is more subtle and insidious. Many stable nuclei, including those in your favorite shielding materials, absorb neutrons fairly readily. (That's why they're shielding materials) In doing so, they are transmuted to heavier and heavier isotopes. A nucleus with too many neutrons will often emit a β particle to transform a neutron into a proton.

Over a period of time, this can transform shielding material into radioactive substances! This is called "secondary radiation" and means that material used to shield radiation sources itself becomes low-level radioactive waste after a time, and must be treated (and disposed of) accordingly. While all forms of radiation do this, neutrons are particularly bad offenders since they are relatively easily absorbed by nuclei.

Survival Rule #3: Anything in a radiation lab is suspect and may be hazardous. Sweep your radiation lab with a Geiger counter on a regular basis. Check your lead bricks. Oh yes, and neutrons don't show up well on standard Geiger counters; if you have any neutron sources in your lab, make sure you have a detector that can handle them.

Important note: Secondary radioactivity can be produced only by particles that can change the atomic number of a nucleus, specifically α particles and neutrons. γ rays do not cause this, and β particles do so sufficiently weakly

that for practical purposes they do not either.

Radioisotopes

Finally, we come to radioisotopes in general: Those wonderful, beneficial and baneful substances which emit the above types of radiation naturally. Radioisotopes all have various chemical properties in addition to their radioactivity which require special attention. They can be produced naturally, synthetically, or accidentally by means of secondary radiation. Also, the smaller nuclei produced in fission reactions are typically radioactive as well; these get into everything and are the primary hazard of nuclear weapons. (Well, apart from getting blown up)

When working with a new radioisotope, always read up ahead of time on its particular properties. Good things to check are the table of nuclides (see footnote below) for the decay processes, and the Materials Safety Data Sheets.

Sample isotope: ^{90}Sr

For example, ^{90}Sr is a β emitter with a half-life of 29.1 years, produced primarily in Uranium fission. Its decay pattern is[2]

$$^{90}Sr \longrightarrow_{29.1yr} \beta(546keV) + {}^{90}Y \longrightarrow_{2.67d} \beta(2.28MeV) + {}^{90}Zr \ , \tag{2}$$
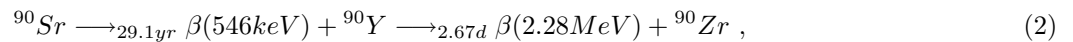
the last of which is stable.[3] Chemically, it is similar to Calcium, and as a result approximately 10% of the amount ingested is absorbed into the bone, with a biological half-life of 50 years. (Meaning the amount of time it takes to flush the Strontium out of the body) This substance was one of the worst things emitted by the Chernobyl disaster.

In the lab, it is a mid-range β source and should be kept well-shielded, with particular emphasis on avoiding any ingestion.

Sample isotope: ^{137}Cs

^{137}Cs is one of the most common radioisotopes. It is a standard laboratory γ source, as well as a significant by-product of nuclear reactions. It has extensive medical uses, especially in the treatment of cancer by radiation therapy. It is often used as an indicator for oil pipe leaks or as a filler, since its γ spectrum is well-known and it does not produce secondary radiation in exposed materials.

The decay pattern of ^{137}Cs is twofold; approximately 92% of the time it decays to the excited state ^{137}Ba*, whereas the rest of the time it decays directly to ordinary ^{137}Ba. Both decays have a half-life of approximately 30.07yr. The decay pattern of interest to us is

$$^{137}Cs \longrightarrow_{30.07yr} \beta(1.176MeV) + {}^{137}Ba^\star \longrightarrow_{2.56m} \gamma(0.662MeV) + {}^{137}Ba \tag{3}$$
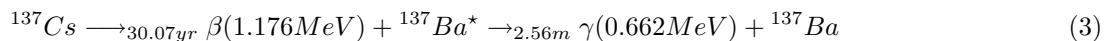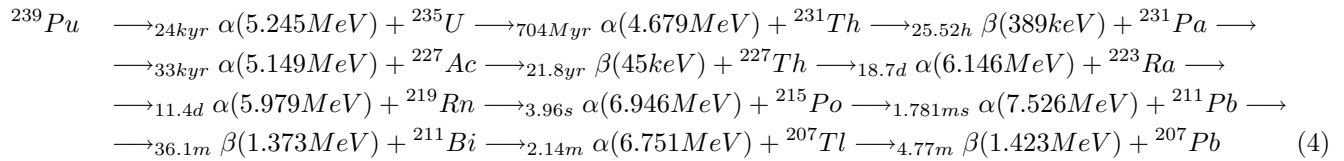
The second decay is so much faster than the first decay that it can be treated as effectively instantaneous. (The appendix, however, contains a detailed calculation of the rate of this process; it's a good sample calculation for how to study multi-stage decays) This is a hybrid β/γ source, but in practice one is only interested in the γ's; therefore a typical laboratory source is covered in a thin layer of some metal which absorbs the β radiation almost completely.

From a safety perspective, apart from the usual "don't eat that!" rule, this is a γ source and should be kept within lead shielding whenever it is not actively in use. When handling it, keep it as far from your body as possible, and if it is a shaped source be careful where you point it. If your experimental apparatus requires the use of such a γ source over a prolonged period of time, make certain that wherever the source sits is heavily shielded (again, using lead), leaving only your detectors exposed directly.

Sample isotope: ^{239}Pu

Although we will not be using it in this lab, it is worth discussing Plutonium, both since it is of great practical interest to anyone living in the modern age, and to try to clarify some myths about it. Unlike most other radioactives, there's really little way to pretty this one up: Plutonium is bloody dangerous. However, most of its dangers come from chemistry rather than physics.

The primary decay pattern of Plutonium is: (note that the half-lives listed vary widely, from 1.781 milliseconds for Polonium-215 up to 704 million years for Uranium-235)

$$
\begin{aligned}
^{239}Pu \quad &\longrightarrow_{24kyr} \alpha(5.245MeV) + {}^{235}U \longrightarrow_{704Myr} \alpha(4.679MeV) + {}^{231}Th \longrightarrow_{25.52h} \beta(389keV) + {}^{231}Pa \longrightarrow \\
&\longrightarrow_{33kyr} \alpha(5.149MeV) + {}^{227}Ac \longrightarrow_{21.8yr} \beta(45keV) + {}^{227}Th \longrightarrow_{18.7d} \alpha(6.146MeV) + {}^{223}Ra \longrightarrow \\
&\longrightarrow_{11.4d} \alpha(5.979MeV) + {}^{219}Rn \longrightarrow_{3.96s} \alpha(6.946MeV) + {}^{215}Po \longrightarrow_{1.781ms} \alpha(7.526MeV) + {}^{211}Pb \longrightarrow \\
&\longrightarrow_{36.1m} \beta(1.373MeV) + {}^{211}Bi \longrightarrow_{2.14m} \alpha(6.751MeV) + {}^{207}Tl \longrightarrow_{4.77m} \beta(1.423MeV) + {}^{207}Pb \quad (4)
\end{aligned}
$$

Note that once it passes the initial threshold of decaying to ^{231}Th, the rest of the decay is fairly rapid. A single atom of ^{239}Pu will, over its lifetime, emit eight α particles and four β particles, with a total energy of 51.6MeV. It is therefore a mixed α/β source, and in a laboratory setting should be treated as a strong α emitter.

The more serious threats from Plutonium, however, are chemical. There are two issues. First, Plutonium is chemically similar to Iron, having a valence-4 state and a similar atomic radius. It is highly electronegative. There is a favorable reaction in which a Plutonium atom displaces the Iron atom at the center of a hemoglobin molecule, at which point your circulatory system helpfully transports Plutonium throughout the body, especially to the liver and the bone marrow. This makes Plutonium a particularly deadly thing to ingest.

The second danger is that it is pyrophoric; when exposed to air, it forms the oxide PuO_2. This substance is both highly flammable and an oxidizer; like magnesium, it provides its own oxygen for combustion. This combustion releases further amounts of Plutonium soot into the air, which (guess what?) then forms more oxides. Fighting Plutonium fires is therefore particularly amusing. Fortunately, in the absence of water the oxide layer on the surface of a piece of Plutonium acts as an effective buffer against further oxidization, so this effect is normally significant only when either very small particles are present (as, for example, when machining the metal) or when moisture is present. (Water releases the PuO_2 layer and allows more oxidization to take place)

There are several other interesting facts about Plutonium, but in the interest of space I'll refer the interested reader to section 6.2.2 of Sublette.

GLOWING AND GETTING HOT

Popular culture has associated glowing and getting hot with radioactivity. Both of these have some basis in fact, although the large majority of sources do neither. It is, however, worth looking at the origin of these two behaviors.

A typical radioisotope which glows (quite visibly, mostly in greenish light) is Tritium, an unstable isotope of Hydrogen. (T=^{3}H) Its decay pattern is

$$
^3H \longrightarrow_{12.33yr} \beta(19keV) + {}^3He \quad (5)
$$

The mass of Tritium is 3.016u;[4] thus a gram of Tritium contains approximately $2 \cdot 10^{23}$ atoms, half of which will decay in 12.33 years. Since these decays occur at a constant rate, this means that there are an average of $2.57 \cdot 10^{14}$ electrons are emitted per second. As these electrons try to move through the Tritium, they scatter off other atoms and emit most of their kinetic energy as heat and light; any emitted photons which are above the frequency at which Tritium becomes opaque are absorbed and reemitted at lower frequencies. The total radiant energy may be calculated from the number of electrons and their kinetic energy; it is approximately 0.78 Watts per gram of Tritium. Most of this is emitted in the form of infrared light (heat), but some comes out in the form of visible light. In terms of the radiation effects discussed in the next section, for a 75kg-human this would be a dose of approximately 1rem/second if it were purely in the form of β radiation; however, most of it is emitted in the form of relatively harmless light, and the actual radiation dose from this is in the millirem range.

Some important things to note from this calculation: First, even something not very radioactive like Tritium can produce a significant number of particles. Glowing is a mechanism by which effective radioactivity is decreased, so most things which are glowing are not hazardous to be around; but don't ingest them! (That would quickly end the glowing and damping effect, and replace it with a fairly bright β source inside your body) Also, the fact that any visible light at all was emitted is because the emitted β particles had the relatively low energy of 19keV apiece; only β decays ever produce energies this low. Other sources typically emit particles with enough kinetic energy that visible light is not formed by the time it reaches your body. Therefore, glowing is a symptom of a fairly soft β source; the most dangerous things are the ones that don't glow!

Referring to sources as "hot" has a more important basis in fact: All sources emit a considerable amount of energy, and ultimately (if you don't get hit by them first) this energy is converted by scattering off ambient objects into heat.

A good rule of thumb is that, if you can feel appreciable heat coming from any radioactive source, you have probably just received a lethal or nearly lethal dose.

Survival Rule #4: If you see something that glows, it's probably a low-energy but high-intensity β source. (Few keV per particle, lots of particles) If you see something that's hot enough for you to feel its temperature, get medical attention *quickly.*

THE EFFECTS OF RADIATION ON THE BODY

Much of this section comes from section 5.6.3 of Sublette.

The basic units of radiation are *Roentgens*, *rads*, and *rems*. Roentgens measure the amount of ionizing energy available in the radiation. Rads factor in absorption, and therefore measure the amount of ionization taking place. One rad is defined as the absorption of 100 ergs per gram of tissue, or 0.01J/kg. Rems (short for *R*adiation *E*quivalent in *M*an) factors in the different biological effects of different types of radiation, and is therefore very useful when dealing with radiation safety.

Rems are calculated from rads by multiplying by a "radiation biological effect" (RBE) constant which is different for each type of radiation. For γ and β radiation the RBE is 1; for α particles, it is between 10 and 20, depending on the energy.[5] For neutrons, different RBE's are used depending on which biological effect is under consideration. For *immediate effects* (such as radiation sickness) the RBE is 1; for the delayed formation of cataracts (neutrons do subtle damage to eyes) the RBE is 4-6; for causing general systemic cancers, the RBE is 10; for causing leukemia in particular the RBE is 20.

As you can see, α particles and neutrons bear particular watching over. Some typical numbers involving rems are:

Typical background radiation	100mrem/yr[6]
Diagnostic X-rays	40-120mrem[7]
Flying from New York to Hong Kong	10mrem[8]
Radon exposure	Up to 100rem/yr[9]
Occupational safety limit	0.3rem/wk
	5rem/yr[10]
	1.5rem/yr (for pregnant women)
Lifetime safety limit	200 rems

A dose of 100rem/yr is a safety risk comparable to (very) heavy smoking, and is almost certain to lead to cancer sooner or later. For higher exposure risks, consult the "acute exposure" table in Sublette. Note that the doses listed in this table correspond to exposure of several hundred or thousand rems in a *single incident*; for the purposes of chronic rather than acute exposure, the effective dosage is

$$R_{eff} = R_{tot}t^{-0.26} \ , \tag{6}$$

where R_{tot} is the total exposure over time and t is the time in weeks.

For R_{eff} up to 25 rems of whole-body dosage, the primary health risk is the development of cancers, especially leukemia. Above this point acute effects begin to set in; the leading effect is a drop in white blood cell, lymphocyte, and platelet counts, impairing overall immune function. Sperm counts become significantly depressed starting at approximately 20 rems, with 80-rem doses causing temporary sterility about 50% of the time.

Beyond this point, acute symptoms set in. The first symptom of acute radiation injury is typically nausea; if you ever experience such a symptom in a laboratory environment, seek medical attention immediately.

The effects of radiation are cumulative over time, and there is no "threshold exposure" below which the risk is zero.

THE GOOD NEWS

After all of this rather frightening stuff, here's the good news: Really, it takes a good deal of work to get yourself exposed that seriously. If you are only working with pre-made sources, your risks are minimal so long as you assudiously obey ordinary safety precautions, with particular attention to the ones noted above. Do not spend more time than you need to among radioactives; keep sources shielded whenever possible; and make sure nothing gets into your body. As long as you follow these simple rules, your interactions with radiation should be safe and enjoyable.[11]

APPENDIX: HOW TO CALCULATE LIFETIMES FOR MULTI-STAGE DECAYS

The decay of ^{137}Cs is a good place to give an example of how to work out the lifetime of a multi-step process. The three numbers for which we wish to solve are N_{Cs}, $N_{Ba^\star}$, and N_{Ba}. First of all, the Cesium decays at a constant rate τ_{Cs}, (n.b. this is the lifetime, not the half-life; they differ by $\log 2$) and so

$$\dot{N}_{Cs} = -\frac{1}{\tau_{Cs}}N_{Cs} \ . \tag{7}$$

Now, if all the Cesium were to decay into excited Barium, and all of the excited Barium were to decay into stable Barium, the next equation would read

$$\dot{N}_{Ba^\star} = +\frac{1}{\tau_{Cs}}N_{Cs} - \frac{1}{\tau_{Ba^\star}}N_{Ba^\star} \ ;$$

the first term is the formation of Barium from Cesium, the second is its decay into stable Barium. But actually, only 0.92 atoms of excited Barium are formed from each atom of Cesium, so the equation is

$$\dot{N}_{Ba^\star} = 0.92\frac{1}{\tau_{Cs}}N_{Cs} - \frac{1}{\tau_{Ba^\star}}N_{Ba^\star} \ . \tag{8}$$

Finally, each decaying Cesium atom forms 0.08 atoms of stable Barium, and each decaying excited Barium forms one stable Barium atom. Thus

$$\dot{N}_{Ba} = \frac{1}{\tau_{Ba^\star}}N_{Ba^\star} + 0.08\frac{1}{\tau_{Cs}}N_{Cs} \ . \tag{9}$$

Combining these equations into a single matrix equation for the vector $N = (N_{Cs}, N_{Ba^\star}, N_{Ba})$, gives

$$\dot{N} = AN \ , \tag{10}$$

where

$$A = \begin{pmatrix} -\tau_{Cs}^{-1} & 0 & 0 \\ 0.92\tau_{Cs}^{-1} & -\tau_{Ba^\star}^{-1} & 0 \\ 0.08\tau_{Cs}^{-1} & \tau_{Ba^\star}^{-1} & 0 \end{pmatrix} \ . \tag{11}$$

The solution to this is $N(t) = N(0)e^{At}$, where the exponential of a matrix is defined by its Taylor series.[12] Explicitly, if one starts with an initial amount of pure ^{137}Cs,

$$
\begin{aligned}
N_{Cs}(t) &= N_{Cs}(0)e^{-t/\tau_{Cs}} \\
N_{Ba^\star}(t) &= N_{Cs}(0)\frac{0.92\tau_{Ba^\star}}{\tau_{Ba^\star} - \tau_{Cs}}\left(e^{-t/\tau_{Ba^\star}} - e^{-t/\tau_{Cs}}\right) \\
&\approx N_{Cs}(0)\left(0.92\frac{\tau_{Ba^\star}}{\tau_{Cs}}\right)e^{-t/\tau_{Cs}} \\
N_{Ba}(t) &= N_{Cs}(0)\left(1 + \frac{0.92\tau_{Ba^\star}}{\tau_{Cs} - \tau_{Ba^\star}}e^{-t/\tau_{Ba^\star}} + \frac{0.08\tau_{Ba^\star} - \tau_{Cs}}{\tau_{Cs} - \tau_{Ba^\star}}e^{-t/\tau_{Cs}}\right) \\
&\approx N_{Cs}(0)\left(1 - 0.92\frac{\tau_{Ba^\star}}{\tau_{Cs}}\right)\left(1 - e^{-t/\tau_{Cs}}\right) \ .
\end{aligned}
\tag{12}
$$

The last approximation uses the fact that $\tau_{Cs} = 43.39yr = 2.28 \cdot 10^7 min$, and $\tau_{Ba^\star} = 3.69min$. As a practical matter, this second decay is so much faster than the first decay that it can be treated as practically instantaneous; however, this method can be used correctly even when the decays are all of comparable lengths.

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[1] This document will be absurdly cheerful and somewhat frightening, in keeping with the tradition started by the US government during the Cold War. Nonetheless, the information here is meant to be accurate rather than reassuring – somewhat at variance with the tradition.

[2] Note that each step in the decay chain has its own half-life. To calculate the total time to decay, write (for example) $dN_Y/dt = (1/\tau_{Sr})N_{Sr}$, where τ_{Sr} is the lifetime (not half-life!) of Strontium, and similar equations for all other isotopes involved. The resulting system of linear ODE's can be solved by the usual methods.

[3] This decay pattern was looked up in the table of nuclides at *http://atom.kaeri.re.kr/*

[4] The atomic mass unit is defined so that the mass of ^{12}C is exactly 12u; molar calculations are done in terms of u. For conversion, 1u≈ 0.932GeV.

[5] A new unit, the Sievert, is coming into use which is similar to the rem; one Sievert is roughly 100 rems. Sieverts use a constant factor of 20 for all α particles and 10 for neutrons, however, independent of their energy.

[6] This depends greatly on where you live. At higher altitudes, cosmic ray exposures are higher; in Colorado, for example, a typical annual exposure just from walking around is 250mrem/yr.

[7] Dental X-rays are less, chest X-rays are more; the average person gets approximately 80mrem/year out of this.

[8] Again, due to cosmic rays. This number from the January 2002 Scientific American, p. 22.

[9] No, that's not a typo. Indoor Radon exposure is potentially a very high source of radioactivity. Present American safety standards require essentially no more than 200mrem/yr of exposure in a house before the building is unsafe; many nations have stronger requirements. However, it is possible for a house to have a much higher level. Commercial radon detectors can be purchased at any hardware store, and are a must if you have a basement.

[10] This is the US standard for maximum safe annual exposure for people who work with radiation. If you work at any radiation facility for a length of time, you will be assigned a dosimeter and have your exposures carefully tracked.

[11] Bet you never thought you'd see a sentence like *that*, did you?

[12] For a diagonal matrix, therefore, the matrix exponential is just the matrix whose diagonal elements are the exponentials of the diagonal elements of the original matrix. For a general matrix, one can always write it in the form $A = P^{-1}DP$, where P is orthogonal and D is diagonal. Then $e^A = \sum \frac{1}{n!}A^n = \sum \frac{1}{n!}P^{-1}DPP^{-1}D\cdots P = \sum \frac{1}{n!}P^{-1}D^nP = P^{-1}e^DP$. This allows one to evaluate the exponential of an arbitrary matrix.