Nuclear Decays

The first evidence of radioactivity was a photographic plate, wrapped in black paper and placed under a piece of uranium salt by Henri Becquerel on February 26, 1896. Like many events in science, the discovery was accidental, and it changed the course of history. Since Becquerel's discovery, scientists have studied different types of nuclear decays. By nuclear decay, we mean that an original nucleus emits one or more particles and becomes another nucleus. The decay event is probabilistic, as discussed in Chapter 2, and is characterized by a half-life. In this chapter, we will describe the different types of nuclear decays that can occur. You might be familiar with the main types of nuclear decay: alpha, beta and gamma. We will first review these common decays and discuss other types as well.

For every type of radioactive decay, there are certain quantities that are the same before and after the decay. We call these conserved quantities. Some quantities that are conserved in nuclear decays are: the charge, the total number of neutrons and protons, total energy, the total momentum of the system, and the total lepton number. To determine if a particular decay is possible or not, one often considers these conserved quantities. If one of the conserved quantities listed above cannot remain unchanged, then the decay will not happen.

Alpha Decay

An alpha particle is a He^4 nucleus, that is, it consists of 2 protons and 2 neutrons. It turns out that the combination of 2 protons plus 2 neutrons is very tightly bound. In fact, the He^4 nucleus has the largest binding energy per nucleon of all the nuclei. For some heavy nuclei, this stable combination of neutrons and protons can be ejected from the nucleus. We refer to this decay as alpha decay.

An example alpha decay process is the decay of U^{238}:

$$_{92}U^{238} \rightarrow_{90} Th^{234} +_2 He^4(4.2MeV) \tag{1}$$

In this particular decay, the uranium 238 isotope spontaneously emits an alpha particle. The remaining nucleus is $_{90}Th^{234}$. What was once uranium is now thorium, and an alpha particle is emitted. Since the half-life for this decay is very long, around a billion years, the probability for decay per minute is very small.

One can check that charge is conserved, since the bottom numbers add up to be the same on the left and right side of the equation. That is, 92 is equal to 90 + 2. One can check that the number of protons + neutrons is conserved, since the top numbers add up to be the same on the left and right side of the equation: 238 = 234

+ 4. The 4.2 MeV is the amount of energy released in this particular decay process. This energy is shared between the ${}_{90}Th^{234}$ and the ${}_{2}He^{4}$ nuclei. Since the helium nucleus is much lighter than the thorium nucleus, the helium nucleus (alpha particle) gets essentially all of the kinetic energy.

Having the total momentum of the system conserved leads to an interesting property. Since the initial momentum of the uranium nucleus is zero, the final momentum of the thorium plus alpha particle must also be zero. This means that the alpha particle travels in the opposite direction, with the opposite momentum, as the thorium nucleus. Since the energy released is the same for every decay, the alpha particle will have the same energy for every decay. For example, if we had 10 ${}_{92}U^{238}$ nuclei, and they all decayed. We would then have 10 alpha particles emitted, each with a kinetic energy of around 4.2 MeV. The amount of energy released is the same for each decay, and the two decay products can only share the energy one way. We say that the released alpha particle is mono-energetic.

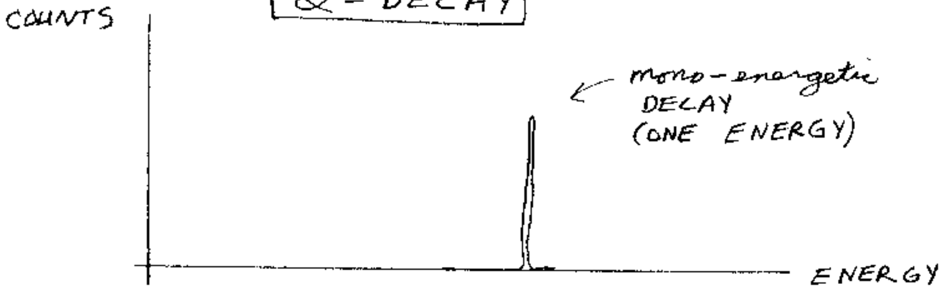
In general, when a single nucleus decays into 2 particles, then the energy of the emitted particles is the same for every decay. The emitted particles are mono-energetic. When we use a detector to detect the alpha particle for the 92U238 decay, we will see a sharp peak in the alpha spectrum at 4.2 MeV. The nice thing about mono-energetic decays, is that by measuring the energy of the emitted particle, we can often identify the decay. Each decay will have its own particular amount of energy released. For example, for the alpha decay of ${}_{86}Rn^{222}$:

$${}_{86}Rn^{222} \rightarrow_{84} Po^{218} +_{2} He^{4}(3.3MeV) \tag{2}$$

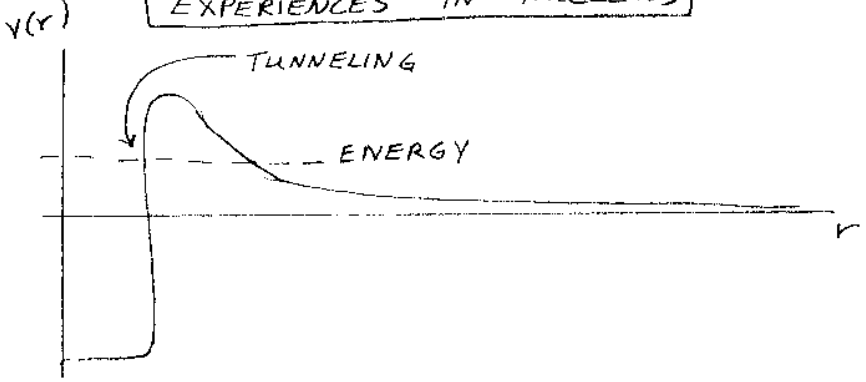
the alpha particle is emitted with only 3.3 MeV of energy. By measuring the energy of the alpha emitted, we can identify which decay process has occurred. An example spectrum for alpha decay might look like the one in the figure.

Alpha decay only takes place in nuclei with large numbers of neutrons and protons. You might be wondering what kind of process causes 2 neutrons and 2 protons to suddenly be thrown out of the nucleus. First of all, the combination of 2 neutrons and 2 protons is the most stable combination of nucleons. It is the most tightly bound system of neutrons and protons. Due to the details of the strong interaction, 2 neutrons and 2 protons are more stable than a bound neutron and proton. A successful model that explains alpha decay quite well is to consider that the alpha particle moves around inside the nucleus. The strong force holds it in the nucleus, but the electrical force tends repels it away. If one makes a graph of the potential that the alpha particle experiences in terms of the distance from the center of the nucleus, it would look like the one shown in the figure.

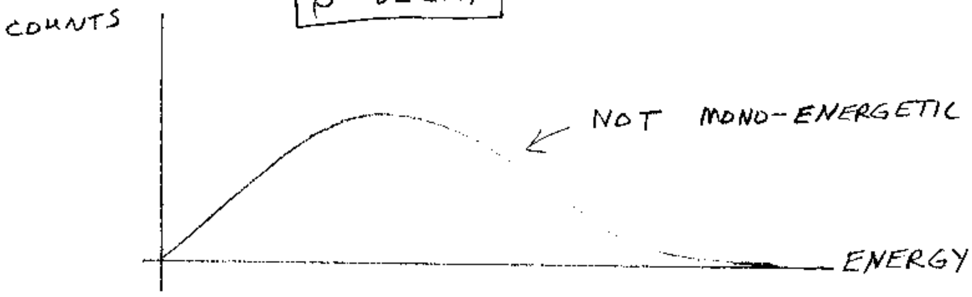
EXAMPLE OF SPECTRUM FOR α-DECAY



POTENTIAL THAT α-PARTICLE EXPERIENCES IN NUCLEUS



EXAMPLE OF SPECTRUM FOR β-DECAY



For short distances, the attractive strong force is the most important. For large distances the electrical repulsion is the most important. The dotted line is the energy of the alpha particle. In a classical picture, the alpha particle will never escape, since it does not have enough energy to "climb over" the potential hill. However, the laws of quantum mechanics allow for the possibility of "tunneling" though the potential barrier and escaping.

We can obtain a qualitative result from this picture: alpha particles that have less energy have a more difficult time to tunnel through the barrier than alpha particles with more energy. That means that decays with alpha particles with low energy will have longer half-lives than decays that emit alpha particles with high energy. Experiments show this to be true. An exact quantum mechanical calculation from the Schroedinger equation was done in 1929 by Condon et. al. They derived an equation which relates the half-life of the alpha decay to the energy of the emitted alpha particle. Experiment matched their calculations very well. The alpha decay calculation was one of the first successes of the Schroedinger equation, and was the first demonstration of quantum mechanical tunneling.

What happens to the emitted alpha particle? It eventually slows down by "bumping" into other nuclei. Then it acquires two electrons and becomes a neutral He atom. In fact, the only way we can obtain He on the earth is via alpha decay. Since there is still a lot of uranium in the earth, He gas can become trapped under ground. The He gas can be collected when mining for natural gas.

Some final notes on alpha decay:

1.The emitted alpha particle is always mono-energetic.
2.The half-lives for alpha decay can be very short, or very long (billions of years).
3.Next time you see a He balloon, think of alpha decay.

Beta Decay

A beta particle, β, is an electron, ${}_{-1}e^0$. When a radioactive nucleus undergoes beta decay, it emits an electron and another particle called an electron anti-neutrino, $\bar{\nu}_e$. Beta decay can occur in nuclei that have an excess of neutrons. In beta decay a neutron in the nucleus changes into a proton and emits an electron and an electron anti-neutrino, $\bar{\nu}_e$. An example of beta decay is given by the decay of Cs^{137}:

$$ {}_{55}Cs^{137} \rightarrow_{56} Ba^{137*} +_{-1} e^0 + \bar{\nu}_e(514MeV) \tag{3} $$

The symbol $_{-1}e^0$ is the symbol for the beta particle, since the electron has a negative charge of e and does not contain any protons or neutrons. The electron on the right side of the equation does not come from one of the orbiting electrons in the atom. It is produced inside the nucleus. The symbol for the neutrino is $\bar{\nu}_e$. The neutrino has no charge, and does not contain any neutrons or protons. In fact it is essentially massless. An unsolved problem in physics was the mass of the neutrino. Recently it has been measured to be very very small. The neutrino also interacts very very weakly with other particles. This is nice for us, since we don't have to worry about the radiation effects it might have on us. In our laboratory experiments we can ignore the neutrinos. They do us no harm, and we don't have the equipment to detect them. The star on the $_{56}Ba^{137*}$ nucleus means that the nucleus is in an excited state.

One should check in the decay equation if charge, the number of protons and neutrons, and lepton number are conserved. Charge is conserved, since the bottom number on the left is equal to the sum of the bottom numbers on the right side of the equation: 55 = 56 -1. Since 137 = 137 + 0, the numbers of protons plus neutrons is conserved. The electron has a +1 lepton number, and the anti-neutrino has a -1 lepton number. Thus lepton number is conserved, since on the right side we have a net total of zero lepton number which is the same that we started with.

The 514 MeV is the energy that is shared among the three decay products: $_{56}Ba^{137*}$,the electron and the neutrino. Since there are now three objects in the final state, the electron does not get the same energy every time a $_{55}Cs^{137}$ nucleus decays. The energy 514 MeV is the total energy emitted in the decay, and is the maximum energy that the beta particle (electron) can obtain. The electron can have any energy from zero to 514 MeV. If we measure the electron's energy (beta particles energy), the spectrum will not show a single peak, as with alpha decay, but will be a continuous range of energies. An example of a beta spectrum is shown in the figure with the alpha spectrum.

The fact that the beta spectrum was not mono-energetic led Pauli to predict the existence of a new particle that shared the energy with the electron. Since the particle was chargeless and nearly massless, the particle was named "little neutral one" or neutrino.

At the nucleon level, the beta decay process is the "decay" of a neutron into a proton, an electron and a neutrino. In fact, a neutron in free space will decay by beta decay with a half-life of around 12 minutes:

$$_0n^1 \rightarrow_1 p^1 +_{-1} e^0 + \bar{\nu}_e \tag{4}$$

This decay is possible in free space because the mass of the neutron is greater than the sum of the masses of the proton, electron and neutrino. The actual physical interaction that is responsible for beta decay is the weak interaction. The weak interaction is much weaker than the strong and the electromagnetic interaction. For beta decay, half-lives vary from as short as a few minutes to tens of years. The half-life depends on how the wave functions of the neutron and proton overlap in the initial and final nucleus, and half-lives can sometime be as long as a billion years.

Notes on beta decay

1.Beta can occur when a nucleus has an excess of neutrons.
2.The energy of the emitted electron is not mono-energetic, but rather continuous. One describes the energy by stating the maximum energy that the electron can have.
3.The interaction involved is the weak interaction.
4.The neutrino is always produced in beta decay and is a) very light (essentially massless), b) chargeless, c) very very weakly interacting.

Gamma Decay

A gamma particle is a photon. Gamma decay in the nucleus is similar to photon decay in atoms. When an electron changes energy levels in an atom, it emits a photon (with energy of order electron volts). For example, in physical chemistry you studied the spectrum of hydrogen. When the electron ”drops” to a lower energy level in hydrogen, a photon is emitted. The energy of the photon equals the energy lost by the electron when it ”dropped” from one energy level to another. Since the allowed energies of the electron orbiting the proton are quantized, photons of only certain frequencies are emitted. The spectrum of hydrogen is characterized by the special set of frequencies of light that are emitted. In atoms with more than one electron, the situation is the same with the valance electrons doing the ”dropping” from one energy level to a lower one. With atoms photon emission occurs because the charge distribution changes (i.e. electrons change their distribution around the nucleus). The physical force involved is the electromagnetic interaction, since charge is the ”source” of the interaction.

A nucleus can also exist with different ”excited” charge distributions. When a nucleus rearranges its charge and changes energy levels from a higher to a lower energy, it gives off a photon, just as atoms do. With atoms, the energies involved are electron volts. With nuclei, the energies involved are thousands (KeV) to millions (MeV) of electron volts. The energy of a photon is related to its frequency:

$$E = h\nu \tag{5}$$

where h is Plank's constant, and ν is the frequency of the photon. If E has energy of electron volts (atomic transition energies), then the frequency of the photon will be in the visible range of the electromagnetic spectrum. Our eyes can detect this radiation (light) well. If E has an energy of between a thousand and 100 thousand of electron volts, then the frequency of the radiation falls in the X-ray region of the electromagnetic spectrum. If E has an energy greater than 100 thousand electron volts, we term this radiation gamma rays or gamma particles, γ. We cannot see this radiation, but can detect it with our laboratory equipment.

The fundamental process for gamma decay is the electromagnetic interaction. The electromagnetic interaction is relatively strong, so the probability for decay is high. This means that half-lives for electromagnetic decays are in general, very short. In atoms, the half-lives for photon decay are usually on the order of nano or pico seconds. In nuclei the half-lives of gamma decay are also short. The actual half-life depends on the angular momentum transfer of the decay and the overlap of the initial and final charge states, but are usually of the order of micro to pico seconds (10^{-6} to 10^{-12} seconds). An example of gamma decay is given by:

$$_{56}Ba^{137*} \rightarrow _{56} Ba^{137} + \gamma(662KeV) \tag{6}$$

The symbol γ refers to the gamma particle (photon), which is chargeless and massless. The gamma emitted has an energy of 662 KeV.

In gamma decay, we have the situation where we start with a single excited nucleus which decays into two particles in the final state. This is the same kinematics as with alpha decay. Since energy and momentum are conserved in the decay, the gamma is emitted with the same energy every time. The emitted gamma particle is mono-energetic. In the laboratory, we have very good detectors for measuring the energy of gamma particles. Since we can measure the energy of gamma particles well, we will be able to identify what type of decays we have in our sample. By calibrating our equipment we will also be able to determine how much of the radioisotopes are present in the sample.

Other Nuclear Decays and Radiation

Positron Decay:

A positron is an anti-electron, the anti-particle of an electron. It has a charge of +e, and has the mass of an electron. Positron decay is the same type of interaction as beta decay. The weak interaction is the physical process in positron decay. In beta decay, a neutron changes into a proton, an electron, and an electron anti-neutrino. In positron decay, a proton changes into a neutron, a positron, and an electron neutrino, ν_e. This decay process can occur when a nucleus has an excess of protons. An example is given by:

$$_{11}Na^{22} \rightarrow_{10} Ne^{22*} +_{+1} e^0 + \nu_e \tag{7}$$

The symbol $_{+1}e^0$ stands for the positron, since it has a charge of +e and does not contain any neutrons or protons. In free space, a proton cannot undergo positron decay, since the mass of a neutron is greater than a proton. However, in nuclei, positron decay can occur, since the final nucleus can have a smaller mass than the initial one. As in beta decay, the energy spectrum of the emitted positron is continuous, since it shares its energy with the neutrino.

The positron does not travel far after it is produced. It quickly interacts with an electron. The two particles then annihilate each other and produce two gammas. In the annihilation process, the sum of the energy of the two gamma particles must equal the energy of the electron and positron. Thus, each of the gamma particles that are produced have an energy of 511 KeV. This type of radiation (the two 511 KeV gammas) is referred to as annihilation radiation. In our laboratory experiments, we don't detect the positron, but rather one of the two 511 KeV gamma particles that are produced when the positron annihilates.

Electron Capture (EC):

In electron capture, an electron from the innermost atomic shell is "captured" by the nucleus. It interacts with a proton in the nucleus, producing a neutron and a neutrino. An example is given by the electron capture that can occur with Na^{22}:

$$_{11}Na^{22} +_{-1} e^0 \rightarrow_{10} Ne^{22*} + \nu_e \tag{8}$$

The electron on the left side of the equation comes from the innermost atomic electron shell. What actually happens in the nucleus is that a proton plus the orbiting electron are converted to a neutron and a neutrino:

$$_{1}p^1 +_{-1} e^0 \rightarrow_{0} n^1 + \nu_e \tag{9}$$

The physical process responsible is the weak interaction. Since the neutrino is the only particle emitted from the atom and is difficult to detect, the electron capture process itself does not cause any damage to living organisms.

After electron capture, the atom can undergo two different types of decays:

a) One possibility is gamma decay, since often the residual nucleus is in an excited state. This is the case for the ${}_{11}Na^{22}$ electron capture. After the electron is captured ${}_{10}Ne^{22}$ is formed in an excited state. From this excited state, ${}_{10}Ne^{22}$ can decay to its ground state via gamma decay.
b) Another possibility is x-ray emission. Since an electron was captured from an inner atomic level, there is a "hole" in this atomic level. Other electrons in the atom can "drop down" to fill the vacancy. When they do, x-rays are emitted.

In both cases, the gamma and the x-ray are mono-energetic.

Isomeric Transitions (IT):

In an isomeric transition, an excited nucleus de-excites to its ground state. In doing so, it can emit either a gamma or an electron (from an atomic orbit). We discuss the two cases below.

a) *Isomeric "Gamma" Transitions*

This is the "standard" gamma decay discussed earlier. The nucleus de-excites via an electromagnetic transition and a high energy photon (gamma) is emitted. The actual process is electromagnetic and involves a redistribution of the charge in the nucleus. It is identical to atomic electron transitions in which electrons "drop" from a higher to a lower atomic orbit and emit a photon. The photons emitted in a nuclear transition have energies that are 100,000 times that of photons emitted in atomic transitions. In both cases the photons emitted are mono-energetic (i.e. have a discrete spectrum). An example equation for gamma decay is given above for the ${}_{56}Ba^{137*}$ decay. For the ${}_{10}Ne^{22*}$ decay we have:

$$ {}_{10}Ne^{22*} \rightarrow_{10} Ne^{22} + \gamma \qquad (10) $$

b) *Isomeric "Internal Conversion" Transitions*

In internal conversion, an electron from an inner atomic shell is emitted when the nucleus de-excites. That is, when the nucleus de-excites from a higher to a lower state, an orbiting electron is ejected instead of a gamma particle. This type of process is much different than beta decay in which an electron is also emitted (along with a neutrino). First, the electron emitted in an internal conversion process is mono-energetic! It has the same energy every time. It has the energy that a gamma particle would have minus the binding energy of the atomic electron. Second, the interaction is electromagnetic and not the weak interaction. There are no neutrinos emitted.

An example of an internal conversion is the de-excitation of Ba^{137}:

$$_{56}Ba^{137*} + (electroninorbit) \rightarrow_{56} Ba^{137} + (electronejectedfromtheatom) \tag{11}$$

After the electron is ejected from its orbit, a "hole" is produced where electron was. Another electron in the atom will "jump" down to fill the vacancy, and an X-ray will be emitted. Thus, when internal conversion takes place, an electron is ejected from the atom and an X-ray is emitted.

Fission:

Fission is a process by which a heavy nucleus splits into two smaller nuclei. Often neutrons are also ejected. An example is the spontaneous fission of Cf^{252}:

$$_{94}Cf^{252} \rightarrow X + Y + neutrons \tag{12}$$

Nuclei X and Y have atomic numbers between 30 and 64. We will not be using any nuclei that undergo fission in our laboratory. Fission decays are important in nuclear reactors and in nuclear bombs.

X-ray production:

X-rays are photons that have energies between 1 and 100 KeV. One categorizes X-rays into two types: characteristic X-rays, which are produced produced from electrons changing from one energy level to another in an atom, and X-rays produced when electrons slow down. Characteristic X-rays are mono-energetic (i.e. they have a specific energy). The process of producing X-rays when electrons slow down is called Bremsstrahlung and emit a continuous spectrum of energies.

Characteristic X-rays:

Characteristic X-rays are produced when electrons close to the nucleus change atomic energy levels. X-ray emission is initiated when an electron from the innermost energy level of the atom is removed by electron capture or isomeric transition. This "hole" is quickly filled by another electron in the atom, and an X-ray photon is emitted. The emitted X-ray is mono-energetic, and depends on the charge of the nucleus. Nuclei with more protons will produce X-rays of higher energy. In fact, the energy of the emitted X-rays is completely characterized by the atomic charge Z of the nucleus. An exact calculation is complicated, but one can obtain a rough estimate of the energies of the X-rays emitted from the formula for the hydrogen spectra:

$$E \approx 13.6Z^2(\frac{1}{n_f^2} - \frac{1}{n_i^2})eV \tag{13}$$

Where Z is the atomic number of the nucleus, i.e. the number of protons in the nucleus. The integers n_f and n_i correspond to the final quantum level (the quantum level of the hole) and the initial quantum level of the electron that does the transition. Note that the X-ray energy has a strong dependence on Z. The main types of transitions that produce X-rays come from values of n_i and n_f equal to 1, 2, or 3. For these transitions we have special names: Transitions from $n_i = 2$ to $n_f = 1$ are termed K_α; Transitions from $n_i = 3$ to $n_f = 2$ are termed L_α; Transitions from $n_i = 3$ to $n_f = 1$ are termed K_β.

Lets see how well the formula for the X-ray energies works with some examples from our laboratory. We will measure the X-ray energies for Barium and Lead. Listed below in the table are the experimental values of X-rays from some common elements along with the estimate of the K_α X-ray energy from the formula above. Columns 3, 4, and 5 list the experimental values of the X-ray energies.

Element	Z	K_α (KeV)	K_β (KeV)	L_α (KeV)	$10.2Z^2$ (KeV)
Fe	26	6.4	7.1	0.7	6.9
Ba	56	32	35	4.4	32
Pb	82	73	84	10	69

The very last column is the estimate for the K_α X-ray. The value of $10.2Z^2$ KeV comes from using $n_f = 1$ and $n_i = 2$, since $13.6(1 - 1/2^2) = 10.2$. It is remarkable how close the energies in the last column are to the K_α energies of the third column.

Notice that the energy of the characteristic X-rays emitted is approximately proportional to Z^2, (the number of protons)^2. If one could "knock out" inner electrons from atoms and measure the X-rays that are emitted as the "holes" are filled, one could identify what elements are in a sample. This is the principle behind X-ray fluorescence. In X-ray fluorescence techniques, innermost electrons are knocked out of the atoms in the sample. The energies of the X-rays emitted are measured, and one can determine what elements are in the sample. We have an X-ray fluorescence machine at Cal Poly Pomona, and we will try to use it to determine the elemental content of various biological samples. X-ray fluorescence works best with heavy nuclei (large Z), since the production of X-rays is greater and the energies are easier to measure.

Bremsstrahlung:

The German translation of bremsstrahlung is breaking radiation. When a charge accelerates or decelerates it can emit photons. If the acceleration is large enough, X-rays can be produced. These X-rays are not mono-energetic, but have a continuous energy spectrum.

Summary

As discussed in this chapter, there are many ways for radioactive nuclei to decay. Sometimes a radioactive isotope can only decay one way, other times there are more than one possibility. Each type of decay has a distinct probability per unit time to occur. Fortunately for us, scientists have measured the decays of many isotopes. In class you will receive a handout which lists the decay possibilities for many isotopes. We will use this information extensively in our classroom work. Lets end the chapter by discussing the decay schemes of three isotopes commonly used in our experiments: Cs^{137}, Na^{22}, and Mn^{54}.

Cs^{137}:

Cs^{137} decays via beta decay. There are two possible final states after the beta decay: the ground state of Ba^{137}, or an excited state of Ba^{137}. The final state is the excited state 99% of the time:

$$_{55}Cs^{137} \rightarrow_{56} Ba^{137*} +_{-1} e^0 + \bar{\nu}_e (99\%) \tag{14}$$

$$_{55}Cs^{137} \rightarrow_{56} Ba^{137} +_{-1} e^0 + \bar{\nu}_e (1\%) \tag{15}$$

The excited state of Ba^{137} can also decay in two different ways: via gamma emission or internal conversion. The gamma decay occurs 85% of the time, and internal conversion happens15% of the time:

$$_{56}Ba^{137*} \rightarrow_{56} Ba^{137} + \gamma(85\%) \tag{16}$$

$$_{56}Ba^{137*} + (electroninorbit) \rightarrow_{56} Ba^{137} + (electronejectedfromtheatom)(15\%) \tag{17}$$

If $_{56}Ba^{137*}$ does undergo internal conversion, a hole is left in the inner electron orbit. Another electron quickly fills the hole and an X-ray is emitted.

Thus for every $_{55}Cs^{137}$ decay, there are a lot of particles that can be emitted. There is an 85% chance that a gamma will be emitted. We call 0.85 the gamma yield factor. There is always an electron emitted in beta decay, and there are also electrons emitted when internal conversion occurs. In addition, characteristic X-rays are emitted.

Na^{22}

The isotope Na^{22} can decay via positron decay or internal conversion. Positron decay is more probable and occurs around 90% of the time:

$$_{11}Na^{22} \rightarrow_{10} Ne^{22*} +_{+1} e^{0} + \nu_e(90\%) \tag{18}$$

$$_{11}Na^{22} +_{-1} e^{0} \rightarrow_{10} Ne^{22*} + \nu_e(10\%) \tag{19}$$

When positron decay occurs, the positron collides with an electron in the sample and produces two gamma particles:

$$_{+1}e^{0} +_{-1} e^{0} \rightarrow \gamma + \gamma \tag{20}$$

where each gamma has an energy of 511 KeV. The excited state of $_{10}Ne^{22*}$ decays to the ground state via gamma decay:

$$_{10}Ne^{22*} \rightarrow_{10} Ne^{22} + \gamma(1275KeV) \tag{21}$$

Thus, for every decay of $_{11}Na^{22}$ a gamma of 1275 KeV is produced, and 90% of the time two gamma's of energy 511 KeV are emitted. The gamma yield factors for the decay is 1.0 for a gamma of energy 1275 KeV, and 1.80 for a gamma of 511 KeV.

Mn^{54}

The isotope Mn^{54} has a particularly simple decay scheme, with only one gamma emitted per decay.