CEM/PHY 327 Modern Physics
Common Radioactive Nuclides — Reading Nuclear Data

Sources of Information:

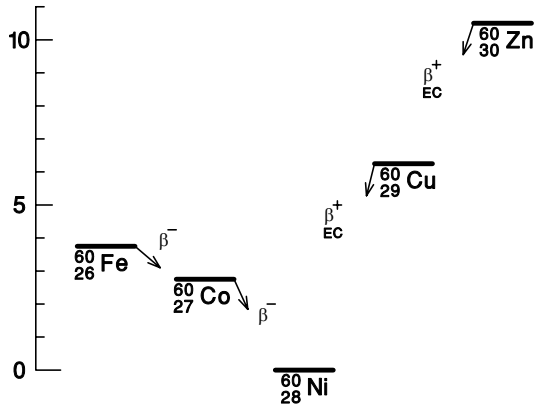
Decay schemes for radioactive nuclides contain a great deal of information which has taken many years (and many dollars) to piece together. The *Table of Isotopes* is the main reference book where all this information is compiled. In the last 20 years the book has almost tripled in size. The wealth of information in the *Table of Isotopes* can make the search for a particular piece of information a daunting experience. The *Chart of Nuclides* contains a small subset of the *Table of Isotopes* data, but it is arranged in a very different way. It presents a good deal of information in a very compact form and actually contains some information about all nuclides on just one piece of poster-sized paper.

The purpose of this document is to summarize the important aspects of the nuclear information contained in the *Table of Isotopes* and the *Chart of Nuclides*. Additionally, commonly-used nuclides have been chosen as examples of using the *Table of Isotopes* and *Chart of Nuclides*; this way the reader can become familiar with these common nuclides.

Note, many people use the words *isotope* and *nuclide* synonymously. This is not correct. When we study a specific nuclear species (a specific Z and N) we should call it a nuclide because we are examining a particular nuclear species. On the other hand, isotope means "same place," a name which comes from the knowledge that isotopes occupy the same place in the periodic table. ^{35}Cl and ^{37}Cl occupy the same place in the periodic table because they have the same chemistry (which is the basis for the periodic table). ^{35}Cl and ^{37}Cl are isotopes of each other. But ^{35}Cl referenced by itself, particularly for its nuclear properties, should be called a nuclide. Clearly when we compare the nuclear properties of nuclei with differing Z, such as ^{35}S and ^{35}Cl, we are comparing nuclides, not isotopes. Incredibly, the *Table of Isotopes* is misnamed; it contains nuclear information grouped by mass number; it is not grouped by chemical periodicity. It is not a comparison of isotopes; it is a compilation of data about nuclides; it should be called the "Table of Nuclides." The *Chart of the Nuclides* is correctly titled.

Beta Decay Basics

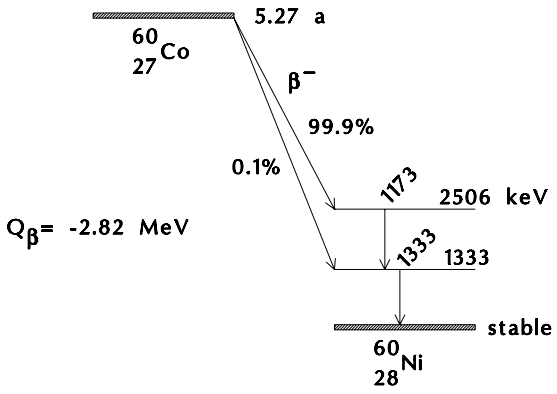
For a given atomic mass number (A), the number of protons (Z) and neutrons (N) can vary. However, of all the combinations of Z and N that add to a particular A, usually one combination (at most three combinations) is stable. For example, if we examine mass 60, the stable combination is 28 protons and 32 neutrons. This corresponds to ^{60}Ni. Any other combination is "less favorable," which essentially means "has higher energy."



The *Table of Isotopes* is arranged by mass number. The figure on the right is the opening information for A = 60. There is an energy scale on the left which is calibrated in Mev. We see that Z=27, N=33 is about 3 Mev less favorable than Z=28, N=32. It is not surprising that Z=26, N=34 is even more energetic. ^{28}Fe can change a neutron into a proton, electron, and antineutrino. After ejecting the electron and antineutrino it becomes ^{27}Co. Likewise, ^{27}Co can convert a neutron to a proton, electron, and antineutrino, eject the electron and antineutrino, and become stable ^{60}Ni. This is beta-minus decay.

A Fairly Normal Beta-Minus Decay

Most beta decays are followed by *prompt* gamma rays. The beta decay populates one or more excited states of the daughter nucleus. The excited states have lifetimes too short to measure so gamma decay of the excited states happens promptly.



To the right is the decay scheme for ^{60}Co. The actual entry in *Table of Isotopes* contains much more information; the figure on the right is accurate but contains only the most important pieces information.

First notice ^{60}Co decays to ^{60}Ni by emitting a beta-minus (β^-). In this particular comparison ^{60}Co is the parent and ^{60}Ni is the daughter. However, not shown is the fact that ^{60}Co can be obtained from the decay of ^{60}Fe. In that case ^{60}Co would be the daughter and ^{60}Fe the parent. So whether ^{60}Co is the parent or the daughter depends on the context in which we are discussing it. But ^{60}Ni will never be a parent because it is *stable*. The word *stable* might be used to indicate a nuclide is stable, or we might note the absence of half-life information and deduce stability from that, or we might make use of more information (not shown in the figure above) that shows ^{60}Ni is at the bottom of the beta-stability energy-parabola for all of mass 60 nuclides.

^{60}Co decays with a half-life of 5.27 years. Some charts list this as 5.27 y whereas others, including the one above, list this as 5.27 a (annus = year). Highly unstable nuclides would decay much quicker, perhaps even within microseconds. More stable nuclides would decay with longer half-lives; some are billions of years.

^{60}Co is unstable toward beta decay because ^{60}Ni has lower energy. The energy difference is called the Q-value. The decay scheme gives the Q-value as −2.82 MeV. This means the transformation of ^{60}Co to ^{60}Ni releases 2.82×10^6 electron-volts of energy. Think of the Q-value as similar to enthalpy (ΔH) in thermodynamics. A negative enthalpy process means an exothermic (energy releasing) process. A negative Q-value means energy is released in the transformation which begins in the ground state of ^{60}Co and ends in the ground state of ^{60}Ni.

The ground state of ^{60}Co is incompatible with beta transition directly to the ground state of ^{60}Ni. This is most likely caused by a large difference in angular momentum between the states. As a result, ^{60}Co decays to an excited level of ^{60}Ni in over 99% of the decays. This excited level has an energy of 2506 keV above the ground state. Therefore the maximum energy carried away by the beta particle would be the Q-value of 2820 keV minus the energy of the excited state (2506 kev) yielding a difference of 314 keV. But in beta decay an antineutrino is also emitted and the nucleus recoils. These both carry away some of the energy. Therefore, if we were detecting beta particles from ^{60}Co, we would occasionally detect a beta with nearly 314 keV of kinetic energy, but on average the beta energy would be much less. In fact its average value will be about half its maximum value; in this case the average beta energy is about 150 keV.

If ^{60}Co decayed to the ground state most of the time, so that on average we would see a 1.4 MeV β^- (half of 2.82 MeV), we would undoubtedly use ^{60}Co as a source of beta particles and we would call ^{60}Co a *beta emitter*. However, since the beta usually has very low energy and gamma rays carry much of the energy away, we usually refer to ^{60}Co as a *gamma emitter* or as a *gamma source*. As described above, the average beta energy is only 150 keV and it is followed by two high-energy gammas. The gamma radiation is the primary way the ^{60}Co energy is released and gamma radiation is the main thing we see. If we want a source

of approximately 1-MeV photons, ^{60}Co would be a good choice; if we want a source of high-energy beta particles ^{60}Co would be a poor choice. In fact, if we package ^{60}Co in a container with any reasonable wall thickness (e.g. a glass vial), these low-energy beta particles will not pass through the container and will not be seen at all.

Notice that the gamma decay does not involve a 2506-keV photon to take the nickel nucleus all the way to the ground state. Instead, two photons come out in sequence. The first has energy of 1173 keV (the upper diagonally-written number in the decay scheme) and brings us down to a 1333-keV level. The 1333 level then decays to the ground state by emitting a 1333-keV photon. Again, angular momentum incompatibility probably prohibits the decay of the 2506 state directly to the ground state.

Note that when the gammas come out, the nucleus has already changed to ^{60}Ni. It would be tempting to identify the gammas as ^{60}Ni gammas. However we do not do this; we call them ^{60}Co gammas. The primary reason for this is they would not be seen if we did not have the ^{60}Co to begin with. Indeed, ^{60}Ni is stable and it would seem weird to say a stable nucleus emits gamma rays. However, it is possible to see these gammas without having ^{60}Co. ^{60}Cu (note copper; not cobalt) also decays to ^{60}Ni via beta-plus. This is one of the things shown in the *Table of Isotopes* but not shown in the decay scheme above. Yet another way to see gamma photons is via *coulomb excitation*. An accelerator shoots a beam of several-MeV protons (or other positive particles) at a nickel target. The projectiles get close enough to the nickel nuclei to transfer energy to the nickel nucleus; but the projectiles do not enter the nickel nucleus. We excite and then see the de-excitation of the 1333-keV level of ^{60}Ni without having either ^{60}Co or ^{60}Cu. Only in this case might we say we are seeing ^{60}Ni gammas.

As mentioned, the gammas are called *prompt gammas* (or *prompt photons*) because there is no measurable time delay between the beta and the gammas. Of course there is a definite ordering of events. The beta occurs first, then the 1173 photon followed by the 1333 photon. But this sequence is extremely fast; probably faster than picoseconds (less than 10^{-12} s). The ^{60}Co is in no big hurry to beta decay (half-life greater than five years), but when it does decay, it gets to the ground state of ^{60}Ni quite quickly.

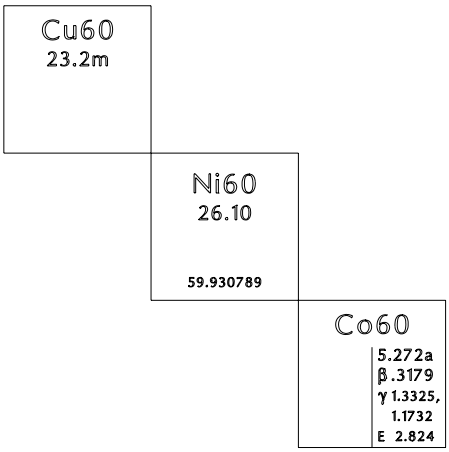
In this particular decay (^{60}Co) the 1173-keV photon is seen 99.88% of the time, but not 100% of the time because the beta might go directly to the 1333 level. In that case the beta takes more energy, and only the 1333 gamma is seen. We would say the 1173 intensity is 99.88% and the 1333 intensity is 100%. This is another reason to call these ^{60}Co gammas. If we had started with ^{60}Cu we would see the 1333-keV photon about 88% of the time and we would see the 1173 about 26% of the time. This is because the beta-plus decay of ^{60}Cu populates the excited states of ^{60}Ni differently than ^{60}Co populates them. In fact, the 1333 level is only populated 5% of the time by the beta-plus decay of ^{60}Cu and the 2506 level not at all. ^{60}Cu mostly populates a 3124 level not shown in the diagram. If we were performing coulomb excitation with an accelerator we would see even a different *photon population*. None of the ^{60}Cu data nor coulomb excitation data are shown in the scheme drawn above.

The point of the previous paragraph is this: One sees a different set of gamma rays and/or a different set of gamma-ray intensities from the nuclear energy levels of ^{60}Ni depending upon how the ^{60}Ni was made or how it was excited. Therefore, when we see an almost-equal mixture of 1173 and 1333-keV gamma rays, it is clear these are being seen because ^{60}Co is β^- decaying to ^{60}Ni.

Also not shown in *Table of Isotopes* decay schemes is the presence of atomic photons. In the beta-decay process it is common for electrons to be knocked out of the atom. This is called *electron shakeoff*. This results in visible, ultraviolet, and x-ray photons when the electrons recombine with the atom and arrange into the electronic ground state of nickel. The visible and UV photons will not be seen by nuclear detectors but the x-rays might be seen. The highest-energy x-rays for ^{60}Co decay would come from the ejection and subsequent re-filling of the 1s electron in ^{60}Ni. The energy of these x-rays is about 8 keV. This is very low

energy as far as nuclear gamma detectors is concerned. For example, a NaI gamma detection system would almost never be used this low so we won't detect x-rays from a ^{60}Co source in a NaI detection system. Incidentally, since x-ray energies are determined by the atomic number (Z) of the atom, and since the x-rays emitted when we have a ^{60}Co source actually come from Ni (Z = 28) rather than Co (Z = 27), we correctly refer to the x-rays as nickel x-rays.

To the right is the information in the *Chart of Nuclides* in the vicinity of ^{60}Co. On the chart, the ^{60}Ni box is colored gray which indicates it is stable. The number right under the Ni60 heading (26.10) is the natural abundance of ^{60}Ni, that is, ^{60}Ni comprises 26.1% of an average piece of nickel found in the earth's crust. The number at the bottom (59.930789) is the exact mass of ^{60}Ni as measured with a mass spectrometer. This is not the average mass of all nickel isotopes; this is the mass of just ^{60}Ni.

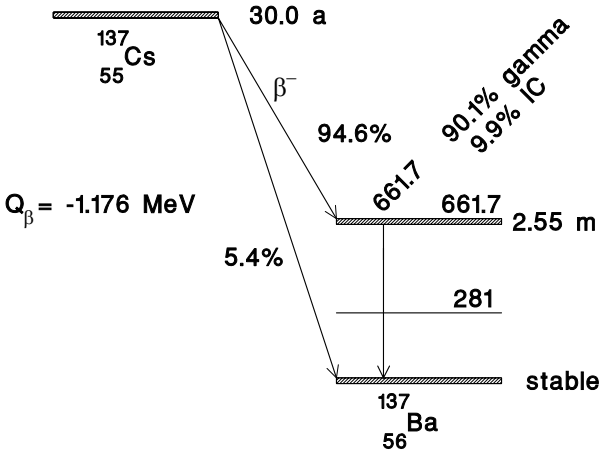


The ^{60}Cu box shows that it is radioactive and has a half life of 23.2 minutes. Since it is not the object of our current discussion, the additional information contained in that box has not been shown.

The ^{60}Co box has been divided in two parts. The part on the right is information about the ground state of ^{60}Co and this is what we are interested in. The left part is not filled in, but on the *Chart of Nuclides* it contains information about an excited state of ^{60}Co. On the right part we see the information we have already learned about ^{60}Co. That is, we see the half life of 5.27 years, the maximum observed beta-decay energy, the energies of the two most prevalent gamma rays, and the Q-value for the beta decay (listed on the chart as an E-value).

An Example With Delayed Gamma Rays

The decay scheme for ^{137}Cs is shown on the right. It has many similarities to ^{60}Co and some differences. First note the obvious: ^{137}Cs has a half life of 30.0 years; it decays by β^- to ^{137}Ba; the total decay energy (Q) is 1.176 MeV.



Now note some differences. The level to which the beta goes is not as consistent. 6.5% of the time the beta goes to the barium ground state; in this case there is no gamma. Also in this case the beta will have significant energy; it probably will make it out of the container and could be detected with a suitable beta detector. However, 93.5% of the time the beta will go to the 661.7-keV excited state. That will be followed by a gamma decay to the ground state, emitting a 661.7-keV gamma ray.

The 661.7-keV level is shown as a bold line and has 2.55 minutes written beside it. This gamma is not prompt. The excited level has a rather significant half-life. This is because the angular momentums of the 661.7 level and the ground state are so different that gamma decay is not easy between the two levels. It is so difficult that it sometimes doesn't even happen; instead, the 661.7-keV of excess energy can be given to

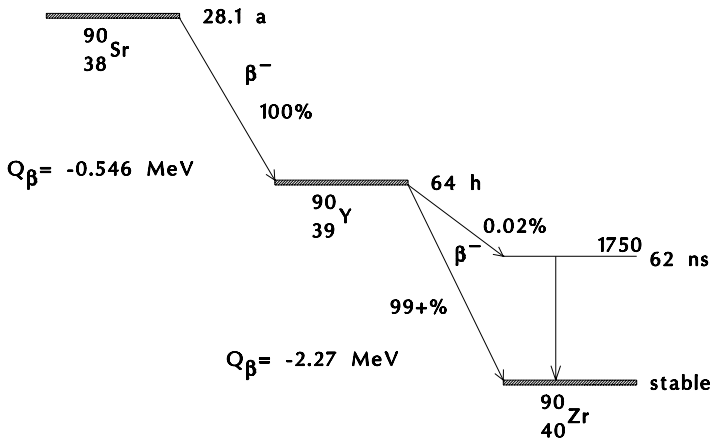
an atomic electron which is then ejected from the atom. This is called *internal conversion* and is labeled IC in the decay scheme. The information above depicts that the 661.7-keV excited state will de-excite (decay) by emitting a gamma ray about 90.1 percent of the time, and it will decay by ejecting an atomic electron (IC) about 9.9 percent of the time. Another term applied to this type of situation is *isomeric transition*. When the decay of a nuclear excited state is angular-momentum inhibited, and therefore the state has a measurable lifetime, it is called an *isomeric state*. When the state finally does de-excite we say we have an isomeric transition. When someone refers to an isomeric transition you can assume the following: it is an abnormally long-lived excited state, probably because its decay is angular-momentum inhibited; it will eventually decay but might do so by ejecting an electron as opposed to emitting a gamma ray; the ratio of IC to gamma is typically higher as the lifetime of the state gets longer.

A 281-keV level is shown in the ^{137}Ba scheme. It is known to exist, probably from coulomb scattering experiments, but it does not become involved in ^{137}Cs decay. The 281 level was included just to help you realize that the *Table of Isotopes* contains as much information as is known about ^{137}Ba. Not all of this information pertains to our current interests.

Again, as is typical, x-rays from the ^{137}Ba are not shown in the decay scheme. There are several barium x-rays with energies very close together. A NaI detector won't resolve the individual energies so they will be seen as one broad peak at about 32.9 keV.

An Beta-Decay Example with No Gamma Rays

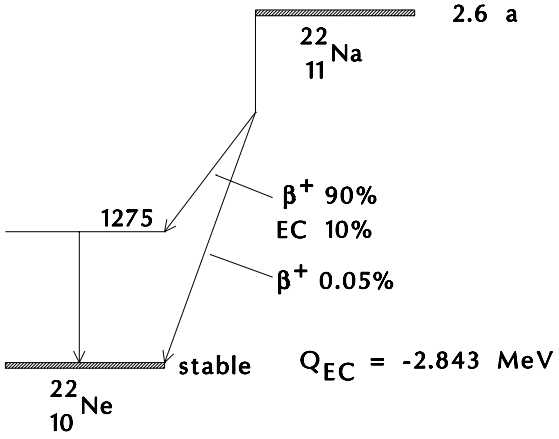
To the right is the decay scheme for ^{90}Sr. In this case the beta-minus is 100% to the ground state; there is no gamma. The daughter (^{90}Y) is also unstable. It decays by beta-minus to ^{90}Zr. Again the decay is almost always to the ground state. Therefore a source made of ^{90}Sr will, after a few weeks, contain a mixture of ^{90}Sr and ^{90}Y and will be emitting almost entirely beta radiation. For obvious reasons we typically call ^{90}Sr a beta source.



A very small percentage of time a gamma is emitted (0.02% of ^{90}Y decays), and when this happens we will have a 1750-keV photon. This is quite high energy and will often be off scale (not seen) with gamma-detection systems. However, a NaI detector system could easily be adjusted to detect this gamma.

There will be x-rays from both ^{90}Y (about 15 keV) and from ^{90}Zr (also about 15 keV). These are not likely to be seen in a NaI detection system.

An Example of Beta-Plus Decay



On the right is the decay scheme for ^{22}Na. This nuclide is quite different from those already studied. This nuclide is proton rich and decays by beta-plus. In beta-plus decay the nucleus must get rid of a proton, or it must convert a proton to a neutron. The latter is what it does, but it needs an electron to do it. One way to get the electron is to capture an orbital electron. This is called *electron capture*. Another way to get an electron is to make one from energy ($E = mc^2$). To conserve charge you can't just make an electron; you have to make both an electron and a positron. This takes 511 keV each for a total of 1022 keV. If the parent nucleus is more energetic than the daughter by at least 1022 keV then it can use some of that energy to make the electron-positron pair. It uses the electron to convert a proton into a neutron. It doesn't use the positron so it spits it out as a β^+.

The Q-value is given as Q_{EC} (electron capture). This means the ^{22}Na parent is 2.843 MeV more energetic than the daughter ^{22}Ne. If it were written as Q_β it might be confusing: has the 1022 keV energy needed to make the e^-e^+ already been subtracted or not? If the Q is given as the electron-capture energy difference it is clear the 1022 keV has not been subtracted.

Thus ^{22}Na is 2.843 MeV above the daughter. In 90% of the decays 1.022 MeV of this energy is used to create the e^-e^+; the electron joins with a proton; the nucleus changes to ^{22}Ne (in an excited state of 1.275 MeV), and the final energy difference of 2.843 – 1.022 – 1.275 = 0.546 MeV ends up in the kinetic energy of the β^+, the recoiling nucleus, and the neutrino which always accompanies β^+ decay. A little of the energy also likely knocks out orbital electrons which will lead to x-rays or light.

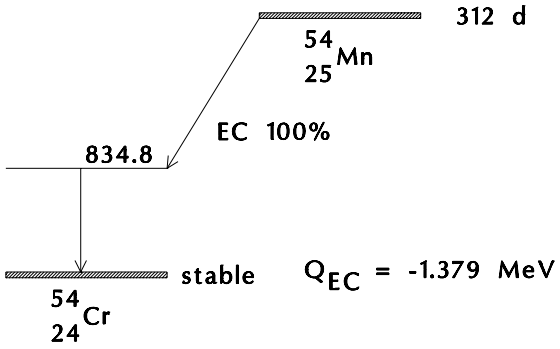
In 10% of the decays the β^+ does not occur; an electron is captured. This leaves 1.568 MeV (2.843 – 1.275) to be distributed between the neutrino and recoiling nucleus (and electron ejection leading to x-rays and light). This decay method also leaves us in the 1.275-MeV excited state so we will see this state decay by a prompt gamma of 1.275 MeV energy no matter whether we got to the state by the β^+ or the EC. Thus we will see the gamma almost 100% of the time. However in 0.05% of the decays the β^+ goes to the ground state. In this case the only radiation we see directly from the ^{22}Na vicinity is the x-rays and light (and a neutrino if we are equipped to see it).

However, there is one last and very important thing not shown in the decay scheme. In fact it is the most plentiful radiation observed with this β^+ source. The β^+ will quickly come to rest, meet an electron and annihilate. This will yield two 511-keV photons going opposite directions. Thus every β^+ decay yields <u>two</u> 511 photons. With 90% of the decays yielding positrons we would say the 511 probability is 180%, a number which at first glance seems strange. To summarize the photons from ^{22}Na we would say we expect to see 1.275 MeV about 100% of the time and we expect to see 0.511 MeV about 180% of the time.

Incidentally, we would call the 1.275 a gamma ray but not the 511 photons. The 511-kev photons do not come from the nucleus and can't be called gammas. Instead we call them annihilation photons and we usually abbreviate them as $\gamma^\pm$. In case the gamma symbol seems to imply gamma ray, remember the gamma symbol is also the generic symbol for photon.

A Nucleus Which only Has Electron Capture

^{54}Mn is a source which does not have enough energy to produce observable β^+. The Q-value is high enough to make the e^-e^+ pair, but apparently not enough would be left over to leave the daughter in any acceptable/existing higher state. The existence of gamma rays and energy levels within the nucleus is of course evidence for quantization of the nuclear energy. It may be there are no levels between the ground state and the 834.7 state. This would make it impossible for β^+ to occur (1022 keV and 834.7 keV add to more than the Q-value). On the other hand, lower levels may exist, but they might have angular momenta which are too different from the ^{54}Mn ground state to allow a transition to them which would conserve angular momentum.



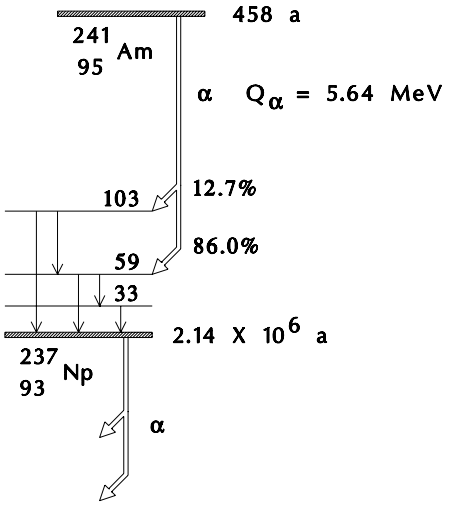
Whatever the reason, the 100% electron capture leads to an excited state which decays via a 834.8-keV gamma. This is a very clean source; aside from a few chromium x-rays, the only thing we see is the 834.8 gamma.

An Example of Alpha Decay

The figure on the right is an example of how we draw the decay scheme for alpha decay. It is very similar to what we have already seen except for the double alpha line coming straight down.

This source, ^{241}Am, is the one used in most household smoke detectors. The alphas are very ionizing and ionize the air in a metallic chamber. This allows a small current to flow between to conductors in the ionized region. When products of combustion enter this region the current changes and the alarm is sounded.

Note that the half-life of ^{241}Am is very long, and the daughter (^{137}Np) is incredibly long. It almost seems worthless to acknowledge ^{137}Np is unstable because we will not witness many decays of it if we have a ^{241}Am source.



The alpha decay populates various levels in the daughter just like beta decay does. We then see gammas as these levels de-excite. In the scheme shown, the percentages do not add up to 100%. This is because there is population of <u>many</u> other levels with small percentages for each. So the given scheme is a simplification. Nonetheless, the gammas shown are the primary gammas and they are fairly low energy. X-rays would also occur. But clearly the emission of a >5-MeV alpha is the major thing observed with this source.

Beyond α, β, γ: Proton or Neutron Emission

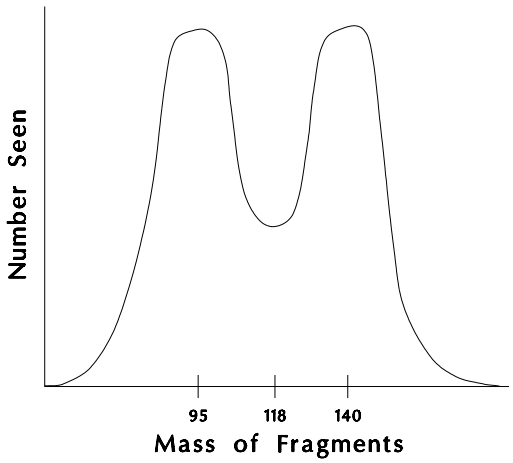
If beta decay occurs because the nucleus is proton rich or neutron rich, can a proton-rich nucleus simply eject a proton, or can a neutron-rich nucleus simply eject a neutron. The answer is "rarely." First, beta decay is much simpler and more efficient. Changing a proton to a neutron does double good. It not only reduces the number of protons, it also increases the number of neutrons. This feature will clearly make beta-plus/electron-capture decay energetically favorable over proton emission in almost all cases. However, at some point another driving force comes into play — mass. If the nucleus is not only proton rich, but also too massive, then proton emission provides a reduction in mass that beta decay does not.

Even so, we do not observe decay by proton or neutron emission all by itself. That is, a proton-rich and heavy nucleus will not, on its own, emit a proton. However, proton/neutron emission can happen following some other event which shakes up the nucleus. One type of shake up is nuclear reactions in which the nucleus is bombarded by particles from an accelerator or with neutrons from a reactor. For example it is very normal for reactions to occur such as (p,2n) which means a proton is jammed into the nucleus and as a result two neutrons are ejected. This, however, is not typically called a decay process. It is called a nuclear reaction.

Another time protons or neutrons might be emitted is following another type of decay such as fission or even beta decay. When a heavy nucleus fissions, neutrons are generally emitted. This is what allows chain reactions to occur in reactors and in nuclear bombs. Also, when we are far from beta stability, emission of a beta (plus or minus) might be followed by emission of a nucleon (proton or neutron). For example ^{100}Rb is far from stability on the neutron rich side, and when it beta-minus decays a neutron is also emitted. We call this process *beta-delayed neutron emission*; we call the emitted neutrons *delayed neutrons.* It turns out that delayed neutrons are important in the control of nuclear reactors. When a large nucleus fissions we get two nuclides which are each neutron rich (read the next section about fission). Therefore each fission product will be a beta-minus emitter and could be a candidate for beta-delayed neutron emission. Some of the neutrons seen in fission are delayed neutrons whereas some are prompt neutrons. If all the neutrons were prompt we could not control a nuclear reactor. We could not replace the control rods fast enough to prevent a chain-reaction explosion once we had removed the rods far enough to start the chain reaction. Apparently the early reactor physicists making the first reactors did not know about delayed neutrons. Lucky for them delayed neutrons exist; otherwise they would have blown themselves up and scattered radioactivity over the countryside.

Beyond α, β, γ: Fission

If a nucleus it too massive, it might simply split in half. This is called fission. Most people have heard about fission because it is the process used in nuclear reactors and also the process used in nuclear weapons (not only atomic bombs, or more accurately, fission bombs, but also as initiators of fusion bombs). An aspect of fission not commonly known is that the nucleus rarely splits exactly in half. It typically splits into a larger nuclide and a smaller nuclide whose sizes are about 3/5 and 2/5 of the original nuclide. The exact way a particular parent nucleus splits is not always the same. One ^{235}U nuclide might fission into pieces of mass 95 and 138 (plus two neutrons) while the next ^{235}U might split into 96 and 136 and three neutrons. The distribution of masses following fission



produces a double-humped graph. This indicates a higher likelihood of nonsymmetrical division as compared to symmetrical division (which would produce a single hump). The graph on the right is the approximate graph for ^{235}U.

It is clear that following fission we will have excess neutrons. The line of stability (on the Chart of Nuclides) tips toward neutrons as we go toward heavy nuclides. So ^{235}U has 92 protons and 143 neutrons. If it splits into mass 95 and mass 138, the most stable configurations are ^{92}Zr (Z=40, N=52) and ^{143}Nd (Z=60 and N=83). This combination has a total of 52+83 = 135 neutrons. The 143 neutrons in ^{235}U are clearly more than can be used by the stable configurations of nuclides in the mass 95 and mass 138 region of the Chart of Nuclides. (Note that ^{235}U cannot fission directly to ^{92}Zr and ^{143}Nd because the number of protons is not correct. These nuclides were chosen as examples to illustrate the neutron-proton ratio in that region of the chart.)

Fission most readily occurs when it is induced by *thermal neutrons*. A thermal neutron is a slow-moving neutron, literally one which is moving with typical thermal energy of about kT. The thermal neutron can slip through the electron cloud and enter the nucleus and cause sufficient disturbance to initiate fission. As described in the preceding paragraph, the fission process will result in excess neutrons. Some of these will be emitted promptly and some will be delayed. (Some will not be emitted because beta-minus decay will change them into protons.) Any emitted neutrons can hit other ^{235}U nuclides and initiate more fission. A chain reaction is possible. But the prompt and delayed neutrons are not very efficient at inducing fission because they are travelling too fast. They must be slowed down (or thermalized) before they are very effective at initiating more fission. That's why nuclear reactors have materials called *moderators* between the fuel assemblies. The moderator material slows down the fast neutrons so they can be more effective at keeping a chain reaction going.

Aside from *induced fission*, it is also possible for a nucleus to fission on its own. This is called *spontaneous fission* and is abbreviated in charts and tables as SF. Spontaneous fission does not occur with sufficient frequency to make it a major mode of radioactive decay, but it does occur in the very heavy nuclides. Often spontaneous fission occurs from an excited state. For example, ^{238}U does not noticeably fission from the ground state, but fissions from a 2559-keV state populated by the beta-minus decay of ^{238}Pa into ^{238}U. In this case the 2559-keV state decays by gamma about 95% of the time and spontaneously fissions about 5% of the time.

In a reactor one produces a certain amount of ^{252}Cf (californium). ^{252}Cf has a half-life of about 2.6 years. It can be separated from the fuel and used as a radioactive source. It decays by alpha emission about 97% of the time and by spontaneous fission about 3% of the time. Even though alpha decay is predominant, ^{252}Cf is generally regarded as a fission source. The need for a fission source generally arises from the desire to have energetic heavy ions. When ^{252}Cf fissions the *fission fragments* fly apart with considerable energy. These fission fragments can be used for a variety of experiments. However fission sources are considered to be fairly dangerous because they are so radioactively *dirty*. That is, they fling fission fragments all over the place and these fission fragments are also radioactive. So a fission source in a container quickly contaminates the whole container with a radioactive hodgepodge. Workers need to follow strict handling procedures to prevent self contamination and lab contamination.