"One of the paradigms of nuclear science since the very early days of its study has been the general understanding that the half-life, or decay constant, of a radioactive substance is independent of extranuclear considerations." (Emery) Like all paradigms, this one is subject to some interpretation. Normal decay of radioactive stuff proceeds via one of four mechanisms:

- **Alpha decay**: the emission of an alpha particle (a helium-4 nucleus) which reduces the number of protons and neutrons present in the parent nucleus by two each;
- **Beta decay**: encompassing several related phenomena in which a neutron in the nucleus is replaced by a proton, or a proton is replaced by a neutron, along with some other things involving electrons, positrons, neutrinos, and antineutrinos. These other things are, as we shall see, at the bottom of several questions involving perturbation of decay rates;
- **Gamma decay**: the emission of one or more gamma rays — very energetic photons — that take a nucleus from an excited state to some other (typically ground) state; some of these photons may be replaced by "conversion electrons", of which more shortly;
- **Spontaneous fission**: in which a sufficiently heavy nucleus simply breaks in half. Most of the discussion about alpha particles will also apply to spontaneous fission.

\(\gamma\) decay often occurs from the daughter nucleus of one of the other decay modes. We neglect very exotic processes like C-14 emission or double beta decay in this analysis.

\(\beta\) decay happens most often to a nucleus with a neutron excess, which decays by converting a neutron into a proton:

\[
\underset{\beta \text{ decay}}{n \rightarrow p^+ + e^- + \bar{\nu}_e} \tag{1}
\]

where

- \((n)\) is a neutron
- \((p)\) is a proton
- \((e^-)\) is an electrons and
- \((\bar{\nu}_e)\) is an antineutron of the electron type.

The type of beta decay that involves destruction of a proton is not familiar to many people, so deserves a little elaboration. Either of two processes may occur when this kind of decay happens:

\[
\underset{\beta \text{ positron emission}}{p^+ \rightarrow n + e^+ + \nu_e} \tag{2}
\]

where \((e^+)\) is a positron (anti-electron) and \((\nu_e)\) is the electron neutrino; or

\[
\underset{\beta \text{ electron capture}}{p^+ + e^- \rightarrow n + \nu_e} \tag{3}
\]

where the electron is captured from the neighborhood of the nucleus undergoing decay. These processes are called "positron emission" and "electron capture" respectively. A given nucleus that has too many protons for stability may undergo beta decay through either, and typically both, of these reactions.

"Conversion electrons" are produced by the process of "internal conversion", whereby the photon that would normally be
emitted in gamma decay is virtual and its energy is absorbed by an atomic electron. The absorbed energy is sufficient to unbind the electron from the nucleus (ignoring a few exceptional cases), and it is ejected from the atom as a result.

Now for the tie-in to decay rates. Both the electron-capture and internal conversion phenomena require an electron somewhere close to the decaying nucleus. In any normal atom, this requirement is satisfied in spades: the innermost electrons are in states such that their probability of being close to the nucleus is both large and insensitive to things in the environment. The decay rate depends only very weakly on the electron wave functions, i.e., on how much of their time the inner electrons spend very near the nucleus. For most nuclides that decay by electron capture or internal conversion, the probability of grabbing or converting an electron is usually also insensitive to the environment, as the innermost electrons are the ones most likely to get grabbed/converted.

Example 1: $\text{^{7}Be}$

However, there are exceptions, the most notable being the astrophysically important isotope beryllium-7. Be-7 decays purely by electron capture (positron emission being impossible because of inadequate decay energy) with a half-life of somewhat over 50 days. It has been shown that differences in chemical environment result in half-life variations of the order of 0.2%, and high pressures produce somewhat similar changes. Also, reference 2 measures a 0.8% reduction in half-life for Be-7 atoms enclosed within carbon-60 cages.

Other cases where known changes in decay rate occur are zirconium-89 and strontium-85, also electron capturers; technetium-99m (*m* implying an excited state), which decays by both beta and gamma emission; and various other "metastable" things that decay by gamma emission with internal conversion. With all of these other cases the magnitude of the effect is less than is typically the case with Be-7.

What makes these cases special? The answer is that one or more of the usual starting assumptions — insensitivity of electrons near the nucleus to external forces, or availability of the innermost electrons for capture/conversion — are not completely valid. Atomic beryllium only has 4 electrons to begin with, so that the "innermost electrons" are also practically the outermost ones and therefore much more sensitive to chemical effects than usual. With most of the other cases, there is so little energy available from the decay (as little as a few electron volts; compare this with most radioactive decays that release hundreds or thousands of kiloelectron volts), courtesy of accidents of nuclear structure, that the innermost electrons cannot undergo internal conversion. Remember that converting an electron requires dumping enough energy into it to expel it from the atom (more or less); "enough energy" is typically some tens of keV, so they do not get converted at all in these cases. Conversion therefore works only on some of the outer electrons, which again are more sensitive to the environment.

Example 2: $\text{^{187}Rh}$

A real anomaly is the beta emitter rhenium-187. Its decay energy is only about 2.6 keV, practically nothing by nuclear standards. "That this decay occurs at all is an example of the effects of the atomic environment on nuclear decay: the bare nucleus rhenium-187 [i.e., stripped of all orbital electrons] is stable against beta decay [but not to bound-state beta decay, in which the outgoing electron is captured by the daughter nucleus into a tightly bound orbital] and it is the difference of 15 keV in the total electronic binding energy of osmium [to which it decays] and rhenium [...] which makes the decay possible" (Emery).

Reference 3 discusses this bound-state decay of bare-nucleus rhenium-187. Whereas neutral rhenium-187 has a half-
life of \((42 \times 10^9)\) years, the authors measured fully ionized rhenium-187 to have a half life of just 33 years! They discuss the cosmological implications of the altered half life of rhenium-187 in various degrees of ionization in stellar interiors, and what that implies for our knowledge of galactic ages.

\(\alpha\) decay and spontaneous fission might also be affected by changes in the electron density near the nucleus, for a different reason. These processes occur as a result of penetration of the "Coulomb barrier" that inhibits emission of charged particles from the nucleus, and their rate is very sensitive to the height of the barrier. Changes in the electron density could, in principle, affect the barrier by some tiny amount. However, calculations show that the magnitude of the effect is very small. For a few \(\alpha\) emitters, the change has been estimated to be of the order of 1 part in \(10^7\) or less, which is unmeasurable given that the \(\alpha\) emitters' half lives are not known to that degree of accuracy to begin with.

Note

All told, the existence of changes in radioactive decay rates due to the environment of the decaying nuclei is on solid grounds both experimentally and theoretically. However, the magnitude of the changes is nothing to get very excited about.

References

1. G. T. Emery, Perturbation of Nuclear Decay Rates, Annual Review of Nuclear Science 22, pg 165 (1972). Papers describing specific experiments are cited in that article, which contains considerable arcane math but also gives a reasonable qualitative feel for what is involved.

2. The recent work on Be-7 enclosed in C-60 cages is in Ohtsuki et al., Enhanced Electron-Capture Decay Rate of Be-7 Encapsulated in C-60 Cages. Phys. Rev. Lett. 93, 112501 (2004).


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