Title
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Introduction

Radioactivity is a property of the atomic nucleus. Many unstable nuclei spontaneously disintegrate, forming different nuclei by emitting some form of matter and energy. When they are sufficiently energy excited, all nuclei can disintegrate, but the term radioactivity is usually reserved for the decay of nuclei with little or no excitation energy. For example, an unexcited nucleus of ^{226}Ra (nuclear charge +88) disintegrates into ^{222}Rn (charge +86) and ^{4}He (charge +2). The ^{4}He nucleus (the α-particle) carries off as kinetic energy nearly all the 5.59 MeV of energy liberated in the decay. There are many other ways, described in what follows, by which unstable nuclei can decay.

Radioactive decay is *spontaneous*. It can occur even when the nucleus is totally isolated from external influences, although the presence of atomic electrons is sometimes required. Unlike most chemical reactions, the decay is not triggered by the absorption of energy from external sources. An unstable nucleus may live for billions of years before it suddenly and spontaneously disintegrates.

Radioactivity was discovered accidentally by Henri Becquerel in 1896 [1]. At that time it was known that x rays cause glass to fluoresce and that they also blacken photographic plates. Becquerel therefore investigated a possible connection between these two effects by placing a fluorescent uranium compound on a sensitive plate. The plate was blackened, but he soon found that even nonfluorescent compounds of uranium produced the same effect but by the emission of radiations capable of penetrating black paper and pieces of silver. Before the invention of particle accelerators, α particles were the only way to investigate the structure of the atom. This method lead Rutherford to the discovery of the atomic nucleus in 1911 [2]. In the following four decades, studies of radioactivity led to the discovery of several new chemical elements (Po, Ra, Rn, Ac, Fr), the production and identification of the neutron, and the discovery of artificially induced nuclear transformations and of nuclear fission.

Radioactive Decay Law

For a given unstable nucleus and a given type of decay to a specific final product, there is a definite probability that the nucleus will disintegrate within a time interval *dt*. Since the decay is a property of the isolated nucleus (or atom), the number *dN* of nuclei disintegrating in a time interval *dt* is proportional only to the number *N* of nuclei present in the sample:

$$dN/dt = \lambda N \, ,$$

where λ is the proportionality constant (decay constant). Integration of this equation gives the number *N* of nuclei remaining at time *t* out of a number N_0 present at $t = 0$:

$$N = N_0 e^{-\lambda t} \, .$$

By setting the remaining number equal to one-half of the initial number, the time $t_{1/2}$ for one-half of the nuclei to decay is obtained:

$$t_{1/2} = (\ln 2)/\lambda = 0.693/\lambda \, .$$

The quantity $t_{1/2}$ is called the *half-life*. Values for known unstable nuclei range from about 10^{-12} s to 10^{20} years, an enormous range. The exponential decay law has been tested out to 45 half-lives by Norman *et al.* [3], at which point only $2.8 \times 10^{-14} N_0$ nuclei remain in the sample.

Because of the statistical nature of the decay process, the number of decays *dN* in time interval *dt* is an average quantity subject to fluctuations resembling those of death rates in a biological population. When sufficiently large numbers *N* of decay events are observed in successive measurements, the fluctuations in *N* obey a Gaussian distribution with standard deviation equal to $\sqrt{N}$.

Types of Radioactive Decay

In addition to the emission of ^{4}He nuclei (α-particles), unstable nuclei may decay in a variety of other ways that can be classified according to the fundamental force that is responsible. The strong nuclear force between the nuclear constituents (neutrons and protons) causes the emission of α-particles. The same force can also bring about other decay modes. For example, nuclei that contain an unusually high ratio of protons to neutrons can, in a few cases, decay by proton emission [4] (e. g., ^{19}Na which contains 11 protons and only 8 neutrons). Nuclei with an unusually high ratio of neutrons to protons sometimes decay by the emission of a neutron (e.g., ^{10}Li which has 7 neutrons and only 3 protons). In rare cases, the emission of heavier fragments is observed. For example, the nucleus ^{223}Ra occasionally decays by emitting a nucleus of ^{14}C rather than the much more probable α-particle [5].

The much weaker *electromagnetic force* can cause an unstable nucleus to emit a photon (γ ray). This can occur, though, only when the nucleus is excited to an energy above its lowest (ground) state. Frequently, a nucleus will decay by particle emission to an excited state of the product nucleus, which in turn will emit a γ ray. Alternatively, the electromagnetic force can cause a nucleus to interact with, and eject, an electron from an atomic orbital as an alternative to the emission of a γ ray. This process is known as *internal conversion* (IC). The Coulomb (electric) part of the electromagnetic force may become so strong in nuclei with many protons that it overcomes the strong force that tends to hold nuclei together. In this case, the heavy nucleus may break into two smaller nuclei of roughly equal mass and charge by a process known as *spontaneous fission* (SF). About 200 MeV of energy is released, mainly as kinetic energy of the two fission fragments.

An extremely weak force (known simply as the *weak force*) causes the emission of either negatively charged electrons (β^- particles) or positively charged electrons (β^+ particles, positrons). In many cases, an unstable nucleus captures an atomic electron as an alternative to emitting a positron. This process is called *electron capture* (EC). EC, β^+ or β^- emission, collectively known as β decay, are accompanied by the emission of a neutrino or an antineutrino, (ν or $\bar{\nu}$), particles with zero electric charge and very small mass. The available kinetic energy is shared by the β particle and the neutrino. Thus, the energy of the β particle covers a broad range of values from near zero to the maximum available energy. The nucleus ^{82}Se has been observed to decay by the simultaneous emission of two β^-particles and two antineutrinos. The half-life for this decay is enormously long – 0.83×10^{20} years. It is theoretically possible for certain nuclei to decay by emitting two β^-particles with no neutrinos. Very recently this type of decay has been claimed to be observed in ^{76}Ge double-β decay [6].

Table l: Summary of the modes of radioactive decay of unstable nuclei with charge Z and mass

Decay mode	Emitted particle	New Z	New A	Force responsible
α decay	α, (^{4}He)	Z - 2	A - 4	Strong
Proton decay	^{1}H; (proton)	Z - 1	A - 1	Strong
Neutron decay	neutron	Z	A - 1	Strong
Fragment Z_l, A_1	e.g., ^{14}C	Z - Z_l	A - A_1	Strong
β^- decay	β^- (electron), $\bar{\nu}$	Z + 1	A	Weak
	β^+ (positron), ν	Z - 1	A	Weak
	ν only (EC)	Z - 1	A	Weak
	$2\beta^-$, $2\bar{\nu}$	Z + 2	A	Weak
	$2\beta^-$, no $\bar{\nu}$?	Z + 2	A	Weak
γ decay	γ (photon)	Z	A	Electromagnetic
	electron (IC)	Z	A	Electromagnetic
Spontaneous fission	Nucleus breaks into two fragments of various sizes	~ Z/2	~ A/2	Coulomb (electromagnetic)

Compared with the time scale of most nuclear events, radioactive decay is an extremely slow process. For the emission of charged nuclear particles such as protons, α-particles, and heavier fragments, and for

SF, the slowness is caused by a Coulomb potential energy barrier that inhibits the separation of the unstable nucleus into two charged fragments. In fact, a11 nuclei with charge greater than about 66 are unstable to α decay, but unless the energy release is greater than 4 MeV, the Coulomb barrier makes the half-life so long that the decay is unobservable.

The processes of β decay and γ decay are slow because the fundamental forces that are responsible are so weak. In no case does the gravitational force play a detectable role. Each type of decay leaves a residual nucleus that is related in a definite way to the atomic number (nuclear charge, Z) and mass number A of the initial unstable nucleus. Table 1 summarizes the various decay modes.

Many radioactive nuclei are unstable with respect to decay by more than one mode. A ^{238}U nucleus, for example, can emit an α particle and produce a nucleus of ^{234}Th. Alternatively, it is also capable of spontaneously fissioning into two roughly equal fragments as a result of the Coulomb forces arising from its high nuclear charge. Each mode of decay has its own characteristic half-life (its partial half-life). For ^{238}U, they are 4.47×10^9 years (α decay) and 8.3×10^{15} years (SF). The α-decay process is thus much more probable in this case. Very often, a nucleus produced by the decay of another is itself unstable. The ^{234} Th produced by the α decay of ^{238}U undergoes β^- decay ($t_{1/2}$= 24.1 days) to form ^{234}Pa, itself unstable. The chain of decays continues until finally the stable nucleus ^{206}Pb is reached. The products of spontaneous fission (as well of those of neutron-induced fission in nuclear power plants) are nearly always unstable. Most of them decay by the β^- process.

Very frequently, the decay of an unstable nucleus leads to the formation of a second nucleus in an energy-excited state. For example, the nucleus ^{56}Co (half-life 77 days) decays by positron emission (β^+ decay) or by electron capture (EC) to one of several excited states of ^{56}Fe, which in turn decays by γ-ray emission or by internal conversion to states of lower energy, and finally to the completely stable lowest-energy state (the ground state) of ^{56}Fe (the main isotopic component of ordinary iron). One of the excited states of ^{56}Fe (0.847 MeV above the ground state) decays to the ground state with a half-life of 6×10^{-12} s. Excited states with longer half-lives are known as isomers (or isomeric states). The γ rays from ^{56}Co decay were observed also from the 1987 supernova explosion SN 1987a. Radioactive decays to excited states have been an important source of information about nuclear spectroscopy and structure.

See also: Alpha Decay; Beta Decay; Gamma Decay; Isomeric Nuclei; Nuclear Properties.

Bibliography

R. D. Evans, *The Atomic Nucleus.* McGraw-Hill, New York, 1955. Particularly useful for statistics of radioactive decay.

B. G. Harvey, *Introduction to Nuclear Physics and Chemistry*, Prentice-Hall, Inc., 1969.

J. K. Tuli, Nuclear Wallet Cards (January 2000). Available from National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973: a pocket-sized compilation of nuclear and radioactivity data.

E. Browne and R. B. Firestone, *Table of Radioactive Isotopes.* Wiley, New York, 1986.

W. M. Cottingham and D. A. Greenwood, *An Introduction to Nuclear Physics.* Cambridge University Press, New York, 1986.

K. S. Krane, *Introductory Nuclear Physics.* Wiley, New York, 1987.

S. B. Patel, *Nuclear Physics: An Introduction.* Wiley, New York, 1988.

References

1. H. Becquerel, Compt. Rend. **122**, 501 (1896).
2. E. Rutherford, Phil. Mag. Ser. 6, **XXI**, 669-688 (1911).
3. E. B. Norman, S. B. Gazes, S. G. Crane, D. A. Bennett, Phys. Rev. Lett. **60**, 2246 (1988).
4. Joseph Cerny, R. A. Mendelson, Jr., G. J. Wozniak, John E. Esterl, and J. C. Hardy, Phys. Rev. Lett. **22**, 612 (1969).
5. H. J. Rose and G. A. Jones, Nature (London) **307**, 245 (1984).

6. H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, A. Dietz, and O. Chkvorets, Phys. Lett. B **586**, 198 (2004).