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Submitted to Encyclopedia of Physics

LBL-5030
Preprint c.1

RADIOACTIVITY

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May 1976

Prepared for the U. S. Energy Research and
Development Administration under Contract W-7405-ENG-48

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Radioactivity

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Radioactivity

INTRODUCTION. Radioactivity is a property of the atomic nucleus. Many unstable nuclei spontaneously disintegrate, forming different nuclei and emitting some form of energy. For example, the nucleus ^{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 4.86 MeV of energy liberated in the decay. There are many other ways, described below, in which unstable nuclei can decay.

Radioactive decay is spontaneous. It occurs 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. 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 non-fluorescent compounds of uranium produce the same result by the emission of radiations capable of penetrating black paper and pieces of silver. In the following four decades, studies of radioactivity led to the discovery of several new chemical elements (Po, Ra, Rn, Ac, Fr), the discovery and investigation of the nucleus, the production and identification of the neutron, the discovery of artificially induced nuclear transformation 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 disintegrating in a time interval dt is proportional to the first power of the number N of nuclei present:

$$\frac{dN}{dt} = \lambda N$$

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

$$N_t = N_o e^{-\lambda t}$$

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} sec to 10^{15} years, an enormous range. The exponential decay law resembles that of first-order reactions in chemical kinetics.

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 birth or 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 RADIOCATIVE 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 (protons and neutrons) causes the emission of α-particles and (rarely) protons. The much weaker electromagnetic force can cause an unstable nucleus to emit energy in the form of a photon (γ-ray). In many cases the electromagnetic force causes an unstable nucleus to interact with, and eject, an electron from an atomic orbital as an alternative to the emission of a photon. This process is known as internal conversion (IC). The Coulomb (electric) part of the electromagnetic force is responsible for the break-up of many heavy nuclei into two much smaller nuclei by a process called spontaneous fission (SF). An extremely weak force (known simply as the weak force) causes the emission of 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 and β^+ or β^- emission, collectively called β-decay, are accompanied by the simultaneous emission of a neutrino (ν), a particle of zero mass and charge.

Compared with the time scale of nuclear events, radioactive decay is an extremely slow process. For α-decay, proton emission and SF, the slowness is caused by a potential energy barrier which inhibits the separation of the unstable nucleus into two parts. The processes of β- and γ-decay are slow because the fundamental forces that are

responsible for the creation of the β-particle and neutrino or of the γ-ray are so weak. In no case does the fundamental 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 I summarizes the various decay modes:

Table I

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
β-decay	β^- (electron), ν	Z+1	A	Weak
	β^+ (positron), ν	Z-1	A	✓
	ν only (EC)	Z-1	A	✓
γ-decay	γ (photon)	Z	A	Electromagnetic
	e^- (electron) (IC)	Z	A	✓
Spontaneous Fission (SF)	Nucleus breaks into two parts of various sizes	∿Z/2	∿A/2	Coulomb (Electromagnetic)

Table I. Summary of the modes of radioactive decay of unstable nuclei. The initial nucleus has atomic number Z and mass number A.

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 parts as a result of

the Coulomb forces arising from its high nuclear charge. Each mode of decay has its own characteristic half-life. For ^{238}U, they are 4.51×10^{9} years (α-decay) and 8.0×10^{15} years (SF). The α-decay process is thus much more probable (for ^{238}U). Very often, a nucleus produced by the decay of another is itself unstable. The ^{234}Th produced by α-decay of ^{238}U β^--decays ($t_{1/2}$ 24.1 days) to form ^{234}Pa, itself unstable. The products of spontaneous fission (as well as 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, a nucleus of ^{56}Co (half-life 77 days) decays by positron emission (β^+-decay) or by electron capture to one of several excited states of ^{56}Fe which in turn decays by γ-ray emission or by internal conversion to lower energy states and finally to the completely stable lowest energy state (the ground state) of ^{56}Fe (the main component of ordinary iron). One of the excited states of ^{56}Fe (0.845 MeV above the ground state) decays to the ground state with a half-life of 6×10^{-12} sec. Excited states with measurable half-lives are known as isomers (or isomeric states). Radioactive decays to excited nuclear states have been an important source of information about nuclear spectroscopy and structure.

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Work performed under the auspices of the U. S. Energy Research and Development Administration.

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