NATURAL AND HUMAN-PRODUCED RADIOACTIVITY

María-Ester Brandan
Physics Institute, Mexico National University UNAM, Mexico

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Summary

The main types of radioactive processes are defined. The sources of natural radioactivity are identified, as well as the human activities that produce radioactive nuclei. Quantities are given for the presence of sources of radioactivity in the Earth, and their impact on the radiation dose received by human population. It is concluded that most of the radioactivity in the planet and the dose received today, are of natural origin.

1. Introduction

Radioactivity is the spontaneous emission of nuclear particles, electrons or electromagnetic radiation, as the consequence of a rearrangement that increases the stability of an atomic nucleus. Since the energies involved in the binding of the nuclear

constituents are of the order of the megaelectronvolts, MeV (10^6 eV), the emitted radioactive particles have kinetic energies which are typically of this magnitude.

In 1896, the French physicist Henri-Antoine Becquerel unexpectedly discovered the emission of invisible, yet highly penetrating radiation, arising from a handful of phosphorescent potassium uranyl disulfate left over photographic film wrapped in thick black paper. In 1898, Maria Sklodowska, a Polish student in Paris, in work shared with her husband Pierre Curie, coined the term radioactivity for the Becquerel radiation, discovered that not only uranium but also thorium was radioactive, and performing an arduous chemical treatment managed to isolate two new elements, polonium and radium, which were also radioactive and present in the pitchblende mineral from where uranium is extracted. The three scientists shared the 1903 Physics Nobel Prize for the discovery and research on the radiation phenomena, and Maria Curie received the 1911 Nobel Prize in Chemistry for her discovery of the new radioactive elements.

The discovery that radioactivity could be produced in the laboratory was an achievement by the same family. Irène Curie, the eldest daughter of Pierre and Maria, was also a physicist, married to Frederic Joliot, a former student of Maria Curie. In 1934 they irradiated stable aluminum with the alpha particles from a radioactive source, and discovered that after removing the source, the aluminum continued emitting radiation for a few minutes. They had transformed normal aluminum into radioactive phosphorus, opening the way to the controlled production of radioactive nuclei. In 1935 Frederic and Irène Joliot-Curie were awarded the Nobel Prize in Chemistry for the synthesis of the radioactive nuclides.

2. Half-life

The radioactive emissions are particles or electromagnetic waves emitted by unstable nuclei which suffer a transmutation (decay) in order to reach a more stable configuration. The intensity of the emissions decreases exponentially with time, having each nucleus a particular rate of decay. This property, which is calculated quantum-mechanically out of the properties of the initial and final nuclei, is represented by the nuclide half-life. The half-life $T_{½}$ is the time necessary for half of the nuclei initially present in a sample to decay. The activity of a sample is the number of decays per unit time, and it also follows the exponential law, decreasing according to the nuclide half-life. If A_0 is the sample's activity at an initial time, after a time equal to $T_{½}$ the activity will be A_0 /2.

The SI unit for the activity is the becquerel (Bq), equal to 1 decay per second. The traditional unit, the curie (Ci), which is equal to 3.7×10^{10} Bq, is still in use.

The studies performed immediately after the discovery of radioactivity identified three types of radioactive emissions, called alpha, beta and gamma rays or particles. These emissions had different electrical properties and their penetration in matter was different: alpha rays could be stopped with a simple sheet of paper, beta particles required a few millimeters of metal to be stopped, while gamma rays could penetrate many centimeters of solid material being only partially attenuated. Today, the

mechanisms leading to these three modes of nuclear decay are well known, and other less common mechanisms to perform a nuclear transmutation have also been identified.

3. Types of Radioactivity

3.1. Alpha Decay

The initial (parent) nucleus emits a helium nucleus, called in this case an alpha-particle, and the final (daughter) nucleus contains two less protons and two less neutrons than the parent. The energy which is released out of the mass difference between initial and final partners, Q, is shared between the alpha-particle and the daughter nucleus in proportions that go as the inverse ratio of their masses. As an example, we consider the decay of the isotope 238 of uranium (^{238}U) into ^{234}Th,

$^{238}\text{U} \rightarrow {}^{234}\text{Th} + {}^{4}\text{He}, \quad Q = 4.27$ MeV.

Alpha-particles are emitted with a kinetic energy equal to 4.19 MeV, and the ^{234}Th nucleus recoils with 0.08 MeV. $T_{1/2}$ for this decay is equal to 4.47×10^{9} years.

3.2. Beta Decay

There are three modes of beta decay, known as beta-minus, beta-plus, and electron capture. Half-lives for beta decay range generally between milliseconds and years.

In beta-minus decay, one of the neutrons in the unstable nucleus transforms itself in a proton and two particles, an electron and an anti-neutrino, are created. For instance, in

$^{32}\text{P} \rightarrow {}^{32}\text{S} + e^{-} + \nu, \quad Q = 1.71$ MeV,

the released energy Q is shared among the three final particles, more than 99% of it being taken by the two light partners, the electron and the anti-neutrino. As a consequence, the electrons (called in this case, beta-particles) are emitted with a continuous energy spectrum which extends from zero up to the Q value, with an average energy equal to 0.69 MeV. Typically, the mean beta particle energy is about 1/3 of the maximum energy. The half-life for this particular decay is equal to 14.3 days.

In beta-plus decay, a proton transforms into a neutron, creating a positron and a neutrino. Consider the decay of ^{19}Ne,

$^{19}\text{Ne} \rightarrow {}^{19}\text{F} + e^{+} + \nu, \quad Q = 2.24$ MeV,

where essentially all of the Q value is shared between the light positron and neutrino, similarly to the situation in beta-minus decay. The value of $T_{½}$ for this case is 17.3 seconds.

Electron capture is a process alternative to beta-plus decay, which permits that a proton turns into a neutron by the capture of an orbital electron. In this case,

$^{101}\text{Rh} + e^{-} \rightarrow {}^{101}\text{Ru} + \nu, \quad Q = 0.541$ MeV,

and $T_{½}$ is 3.3 years. All of the released energy is taken by the emitted neutrino. In cases when beta-plus is not energetically allowed, electron capture becomes the only possible decay mechanism for nuclei having an excess of protons.

3.3. Gamma Decay

The emission of electromagnetic radiation from the nucleus is the most common form of gamma decay. This process permits the release of excitation energy out of a nucleus which is not in its lowest energy state. We can represent the emission of a photon, called in this case a gamma ray γ, as

^{12}C (4.44 MeV) $\rightarrow$ ^{12}C (g.s.) + γ, Q= 4.44 MeV,

where the parent ^{12}C nucleus in its 4.44 MeV excited state, emits a gamma ray. The daughter nucleus is ^{12}C in the ground state, and the energy released, which is carried away by the radiation, is equal to the energy difference between the initial and final nuclear states.

An alternative to the emission of the photon is the process of internal conversion, where the excess nuclear energy is directly transferred to an orbital electron, which is thus liberated. An example is

^{160m}Ho (60 keV) $\rightarrow$ ^{160}Ho (g.s.) + e^-, Q= 60 keV,

and the electron is emitted with the nuclear Q value minus its atomic binding energy.

3.4. Proton Radioactivity

The spontaneous emission of a proton out of a ^{151}Lu nucleus, formed as a product of the reaction between two heavy nuclei, has been observed. This rare form of radioactive decay is represented by

$^{151}Lu \rightarrow {}^{150}Yb + p$, Q= 1.24 MeV.

The half-life has been measured as 85 milliseconds.

3.5. Heavy-nucleus Radioactivity

This type of radioactive process is similar to alpha-decay, the emitted nucleus being heavier than an alpha-particle. The first such decay observed was

$^{223}Ra \rightarrow {}^{14}C + {}^{209}Pb$, Q= 31.8 MeV.

This particular mode of nuclear emission off a radium nucleus is present simultaneously with the alpha-decay, in a relative proportion of only 5×10^{-10}, which makes its detection extremely difficult. The spontaneous emission of other heavy nuclei, including ^{24}Ne, has been reported.

3.6. Spontaneous Fission

Heavy nuclei may gain in energy if they split into two daughter nuclei plus a number of neutrons, this process is called spontaneous fission. An example is the fission of ^{252}Cf, which breaks apart into two heavy fragments and a few neutrons, releasing energies of the order of 200 MeV, with a $T_{½}$ equal to 2.65 years.

4. Natural Radioactivity

The phenomenon of radioactivity was discovered in a sample of uranium salts, that is, in a natural material. In fact, radioactivity is a natural process, and there is no place on Earth where we could escape from the contact with the approximately 60 radioactive nuclides found in nature. Since the universe is radioactive, humans, who inhale and ingest air, food and drink containing atoms from the environment, are naturally radioactive too. Natural radioactivity can be classified as primordial or cosmogenic, depending on the time when the emitting nucleus was formed.

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Bibliography

Susan Quinn (1995) *Marie Curie- A Life*, 509 pp. New York, USA, Simon & Schuster [Biography which provides complete information concerning the Curies family work and discoveries of natural and human-made radioactivity]

United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR (1993) *Sources and Effects of Ionizing Radiation*, 922 pp. New York, USA: United Nations [The most complete evaluation of the sources of ionizing radiation and the effects of exposures to human health]

University of Michigan, Radioactivity in Nature, web page:

http://www.umich.edu/radinfo/introduction/natural.html [Summary of natural and human-produced radioactivity including a list of web references for additional information]

Biographical Sketch

María-Ester Brandan, was born in Santiago, Chile. She received B.Sc. (Physics) from Universidad de Chile, and M.Sc. and Ph..D. (Physics) from University of Wisconsin-Madison, USA. She is a full professor at UNAM, Mexico's National University, Mexico City, since 1991. She was an Invited scientist at Lawrence Berkeley Laboratory, Oak Ridge National Laboratory and Institut des Sciences Nucléaires, Grenoble. She is a Fellow of several Scientific Societies: American Physical Society (Fellow), Mexican Physical Society, Chilean Physical Society. She is a Member of the Mexican Academy of Sciences. Since 1997, she is academic coordinator of the M.Sc. (Medical Physics) program at UNAM. Her main subjects of research include the interaction between light heavy-ions as deduced from elastic scattering data, and the thermo-luminescent response of dosimetric materials to heavy-charged particles.