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Short History of Nuclear Decays Including Nuclear Fission

Dorin N. Poenaru[1], Radu A. Gherghescu[1], Joseph H. Hamilton[2], Horst Stöcker[3]

[1]Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania
[2]Vanderbilt University, Nashville, USA
[3]Frankfurt Institute of Advanced Studies, Frankfurt am Main, Germany
Email: poenaru@nipne.ro, radu@theory.nipne.ro, j.h.hamilton@vanderbilt.edu, Stoecker@fias.uni-frankfurt.de

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Abstract

A short history of the different kinds of nuclear decay modes (α decay, β decay, γ decay, induced fission, spontaneous fission, ternary and multi-cluster fission, fissioning shape isomers, and cluster radioactivities) is presented below, showing how the important research activities at the end of 19th century and the beginning of the 20th one, lead to the discovery of atomic nucleus by Ernest Rutherford in 1911. We shall start with X-rays—a precursor of all these phenomena. The first observation of alpha-, beta-, and gamma radiations was made by Antoine Henri Becquerel in 1896, who observed that beta-rays are deviated by a magnetic field. Marie and Pierre Curie coined the name radioactivity after they produced two new elements: polonium and radium. Alpha particles were first described in the investigations of radioactivity by Ernest Rutherford in 1899, and by 1907 they were identified as He^{2+} ions. In 1928, George Gamow had solved the theory of alpha decay via tunneling through a potential barrier. The alpha particle is trapped in a potential well by the nucleus. According to the principles of quantum mechanics, it has a small probability of tunneling through the barrier and escape from the nucleus. Gamow solved a model potential for the nucleus and derived, from first principles, a relationship between the half-life of the decay, and the energy of the emission, which had been previously discovered empirically, and was known as the Geiger-Nuttall law.

Keywords

Alpha Decay, Heavy Particle Decay, Spontaneous Fission

1. Introduction

In this article we would like to review the history of different nuclear decay modes and the superheavy nuclei, which are intensively studied both experimentally and theoretically, leading to a real progress in our knowledge. The history may help us to understand better the large diversity of phenomena. There are many books and articles about this subject. We give few examples (Loveland, Morrissey, & Seaborg, 2006; Martin, 2011; Rutherford, 1910; Takigawa & Washiyama, 2017).

2. X-Rays

The first Nobel Prize for Physics was granted in 1901 to the mechanical engineer and physicist Wilhelm Conrad Röntgen (1845-1923) born in Lennep, Prussia, German Confederation. In 1874 he became a lecturer at the University of Strasburg and in 1875—professor at the Academy of Agriculture at Hohenheim, Württemberg. He returned to Strasburg as a professor of physics in 1876, and in 1879 he was appointed to the chair of physics at the University of Giessen. In 1888 he obtained the physics chair at the University of Würzburg, and in 1900 at the University of Munich.

His original article *On A New Kind Of Rays* (Röntgen, 1895) was published on 28 December 1895. Other articles followed (Röntgen, 1896; Röntgen, 1897).

X-rays (or Röntgen rays) are electro-magnetic radiations with energies in the range 100 eV to 100 keV. He studied cathode rays from a Crookes tube which he had wrapped in black cardboard so that the visible light from the tube would not interfere, using a fluorescent screen painted with barium platinocyanide.

X-rays are generated in an X-ray tube having a cathode (negative charge) and an anode side (positive electrical charge). An X-ray beam is generated by passing an electron beam through a vacuum between the cathode and the anode. As the electrons collide and interact with the atoms on the anode target, a great amount of energy is produced. Only about 1% of this energy is X-radiation; 99% is a heat which must be removed from the anode. The tube enclosure is shielded and a series of lead shutters allow the diagnostic beam to exit. The cathode consists of a wire filament that emits electrons when heated. The temperature of the filament is controlled by the electric current through the filament; as the current is increased, the temperature of the filament is increased and the filament produces more electrons. The period of time during which the X-rays are permitted to leave the tube is measured in fractions of a second. The mAs thus controls the total number of X-rays produced. The anode is constructed at an angle so that the X-rays produced are directed downward (toward the film) through a window in the metal housing of this tube.

There are many books and articles presenting Röntgen's exceptional achievements e.g. (Novelline, 2019; Trevert, 2018; Agar, 2012; Haase, Landwehr, & Umbach, 1997; Glasser, 1993; Nitske, 1971).

The first use of X-rays in medicine was by John Hall-Edwards in Birmingham, England on 11 January 1896, when he radiographed a needle stuck in the hand of an associate. On February 14, 1896 Hall-Edwards was also the first to use

X-rays in a surgical operation. The first harmful effect of X-rays was published by John Daniel, Vanderbilt in Science, III, No. 67, p 562 (1896) on the depilatory effect of X radiation.

Röntgen is considered the father of diagnostic radiology, the medical speciality which uses imaging to diagnose disease.

Awards: Rumford Medal (1896); Matteucci Medal (1896); Elliott Cresson Medal (1897), and Nobel Prize for Physics (1901).

In 2004 the International Union of Pure and Applied Chemistry (IUPAC) named the element with atomic number $Z = 111$, roentgenium.

3. Alpha Decay

Alpha decay is a type of radioactive decay in which an atomic nucleus emits an alpha particle (helium nucleus) and decays into a different atomic nucleus, with a mass number reduced by four and an atomic number reduced by two. An alpha particle is identical to the nucleus of a helium-4 atom, which consists of two protons and two neutrons. It has a charge of +2e and a mass of 4 u. For example, uranium-238 (^{238}U) decays to form thorium-234 (^{238}Th) (Borzendowski, 2009; Curie & Sheean, 1999).

$$^{238}\mathrm{U} \rightarrow {}^{234}\mathrm{Th} + {}^{4}\mathrm{He}$$

The first observation of alpha-decay was made by Antoine Henri Becquerel (1852-1908) in 1896 (Becquerel, 1896). Becquerel shared the 1903 Nobel Prize for Physics with Marie and Pierre Curie.

Becquerel, engineer and physicist, was born in Paris in a famous family which produced four generations of physicists. He studied engineering at the Ecole Polytechnique and the Ecole des Ponts et Chaussées. The SI unit for radioactivity, the becquerel (Bq), is named after him.

A crater in the moon is named Becquerel (1986).

He became the third in his family to occupy the physics chair at the Museum National d'Histoire Naturelle in 1892. In 1894 he became chief engineer in the Department of Bridges and Highways before he started his early experiments. Learning of Röntgen's discovery of X-rays Becquerel began looking for a connection between the phosphorescence he had already been investigating and the newly discovered X-rays, and thought that phosphorescent materials, such as some uranium salts, might emit penetrating X-ray-like radiation when illuminated by sunlight.

In May 1896, after other experiments involving non-phosphorescent uranium salts, he arrived at the correct explanation: the penetrating radiation came from the uranium itself, without any need for excitation by an external energy source. Followed a period of intense research into radioactivity (e.g. the element thorium is also radioactive and the discovery of additional radioactive elements polonium and radium by Marie and Pierre Curie, elements with a much stronger decay activity). Henri published seven papers on the subject in 1896. He observed that when different radioactive substances were put in the magnetic field, they deflected in different directions or not at all, showing that there were three classes of radioactivity: negative, positive, and electrically neutral.

Maria Salomea Sklodowska (1867-1934) was born in Warszaw, the 6th child of two teachers in Poland Kingdom (then Russian Empire). In 1891, aged 24, she followed her older sister Bronislawa to study in Paris, where she earned higher degrees and conducted scientific work. She was a Polish and naturalized-French physicist and chemist who conducted pioneering research on radioactivity. The first woman to win a Nobel Prize (in Physics 1903, in Chemistry 1911), the first person and only woman to win twice, and the only person to win a Nobel Prize in two different sciences. She was part of the Curie family legacy of five Nobel Prizes. She was also the first woman to become a professor at the University of Paris, and in 1995 became the first woman to be entombed on her own merits in the Pantheon in Paris (The Associated Press, 1995; Curie & Sheean, 1999; Curie, Curie, & Bémont, 1898; D'Arrigo, Eremin, Fazio, Giardina, Glotova, Klochko, Sacchi, & Taccone, 1994). Other Awards: Davy Medal (1903); Matteucci Medal (1904); Elliott Cresson Medal (1909); Albert Medal (1910) and Willard Gibbs Award (1921).

She named the first chemical element she discovered polonium, after her native country. She married Pierre Curie in 1895. They shared two pastimes: long bicycle trips, and journeys abroad, which brought them even closer. In Pierre, Marie had found a new love, a partner, and a scientific collaborator on whom she could depend.

Pierre Curie (1859-1906) was born in Paris. In 1880 Pierre and his brother Jacques (1856-1941) demonstrated that an electric potential was generated when crystals were compressed, i.e. piezoelectricity. To aid this work they invented the piezoelectric quartz electrometer. The following year they demonstrated the reverse effect: crystals could be made to deform when subject to an electric field. Almost all digital electronic circuits now rely on this in the form of crystal oscillators. In subsequent work on magnetism Pierre Curie defined the Curie scale. This work also involved delicate equipment—balances, electrometers, etc. He is known for: Radioactivity; Curie's law; Curie-Weiss law; Curie constant; Curie temperature, and Discovery of piezoelectricity. Awards: Davy Medal (1903); Nobel Prize in Physics (1903); Matteucci Medal (1904), and Elliott Cresson Medal (1909) (Curie, Curie, & Bémont, 1898; Molinié & Boudia, 2009).

Pierre Curie was introduced to Maria Sklodowska by their friend, physicist Jozef Wierusz-Kowalski. Curie took her into his laboratory as his student. His admiration for her grew when he realized that she would not inhibit his research. She agreed to marry him in 1895.

Alpha particles were first described in the investigations of radioactivity by Ernest Rutherford in 1899, and by 1907 they were identified as He^{2+} ions. In 1928, George Gamow had solved the theory of alpha decay via tunneling—the first application of quantum mechanics to a nuclear phenomenon (Gamow, 1928). It is a "*one body model*". Since the neutron has not been known at that time, the α particle has been considered to be formed by four protons and two electrons. In the same year Gurney and Condon published their theory (Gurney & Condon, 1928; Gurney & Condon, 1929). The alpha particle is trapped in a potential well by the nucleus. According to the principles of quantum mechanics, it has a small probability of tunneling through the barrier and escaping from the nucleus. Gamow solved a model potential for the nucleus and derived, from first principles, a relationship between the half-life of the decay, and the energy of the emission, which had been previously discovered empirically, and was known as the Geiger-Nuttall law (Geiger & Nuttal, 1911).

Microscopic theories have been developed (Harada, 1961; Fliessbach & Mang, 1976; Fliessbach & Okabe, 1985; Fröman, 1957; Delion, 2010; Delion, Insolia, & Liotta, 1992a, 1992b, 1992c; Dodig-Crnkovic, Janouch, Liotta, & Sibanda, 1985).

The best agreement with experimental results has been obtained by Varga et al. (Varga, Lovas, & Liotta, 1992) by combining the shell model wave function with a cluster model one.

The time-independent R-matrix theory of nuclear reactions was successfully applied (Fliessbach, 1975; Fliessbach, 1976a; Fliessbach & Mang, 1976; Harada, 1961).

In 1991-1992 Delion et al. (Delion, Insolia, & Liotta, 1992a; Delion, Insolia, & Liotta, 1992b; Insolia, Curutchet, Liotta, & Delion, 1991; Delion, Insolia, & Liotta, 1992c; Delion, 2010) considered deformed parent nuclei (Ra, Rn and Th isotopes). They took a large configuration space, Nilsson + BCS wave functions in a Woods-Saxon potential with parameters introduced by Dudek and Nazarewicz.

Also many-body theory of alpha decay appeared (Lane & Thomas, 1958; Mang, 1957, 1960; Tonozuka & Arima, 1979; Thomas, 1954; Zeh & Mang, 1962; Zeh, 1963).

T. Fliessbach (Fliessbach, 1975; Fliessbach, 1976a; Fliessbach, 1976b; Fliessbach & Manakos, 1977; Fliessbach & Mang, 1976; Fliessbach, Mang, & Rasmussen, 1976; Fliessbach & Okabe, 1985) observed that in a consistent theory one has to introduce a *renormalization* of basis states due to antisymmetrization.

In 1979, Tonozuka and Arima (Tonozuka & Arima, 1979) succeeded to increase the amplitude of α reduced width (parent ^{212}Po) by including higher configuration mixing.

A dynamic theory of the fission process based on Strutinsky macroscopic-microscopic method was successful in getting calculated fission half-lives in agreement with experimental results. As a preliminary step toward a unified description of α-decay, cluster radioactivities and cold fission (Poenaru, Ivaşcu, & Săndulescu, 1979) in 1979 fission theory was extended to the very large asymmetry encountered in α-decay. Then a phenomenological shell correction energy was introduced into three variants of liquid drop models, and in such a way three numerical superasymmetric fission models (NuSAFM), starting from three macroscopic models were found: LDM (Myers & Swiatecki, 1966); FRNFM (Möller, Madland, Sierk, & Iwamoto, 2001), and Y + EM (Krappe & Nix, 1974; Krappe, Nix, & Sierk, 1979). The models were extended to binary systems with different charge densities (Poenaru, Ivaşcu, & Mazilu, 1979; Poenaru, Ivaşcu, & Mazilu, 1980a).

An analytical superasymmetric fission model (ASAFM) and a new semiempirical formula for α-decay half-lives, both developed since 1980, have also been based on these studies.

Alternatively, there were many articles presenting results obtained within the cluster model of Buck, Dover and Vary (Buck & Merchant, 1989; Buck, Merchant, & Perez, 1990; Buck, Merchant, & Perez, 1991a, 1991b; Buck, Merchant, & Perez, 1992a, 1992b; Buck, Merchant, & Perez, 1993).

Alpha-decay of spontaneously fissioning isomers (Poenaru & Ivaşcu, 1981a) has been estimated by us in 1981 in the framework of NuSAFM, by using the parametrization of a spheroid intersected with a sphere.

Many semi-empirical relationships have been derived, e.g. (Geiger & Nuttal, 1911; Viola Jr. & Seaborg, 1966; Poenaru, Ivaşcu, & Mazilu, 1980b; Poenaru & Ivaşcu, 1983; Poenaru & Ivaşcu, 1984; Poenaru, Ivaşcu, & Mazilu, 1982; Poenaru, Plonski, & Greiner, 2006). See also our ASAF (Poenaru & Ivaşcu, 1983; Poenaru & Ivaşcu, 1984; Poenaru & Greiner, 1991a; Poenaru & Greiner, 1991b; Poenaru & Greiner, 1996; Poenaru & Gherghescu, 2021; Akrawy, Poenaru, Ahmed, & Sihver, 2022) and UNIV models (Poenaru, 1996; Poenaru, Gherghescu, & Greiner, 2011a; Gherghescu, Carjan, & Poenaru, 2011; Poenaru, Ivaşcu, & Greiner, 1989; Poenaru, Greiner, Hamilton, & Ramayya, 2001; Poenaru & Gherghescu, 2020; Poenaru, 1977; Poenaru & Gherghescu, 2017; Poenaru & Gherghescu, 2018a, 2018b; Poenaru, Gherghescu, & Greiner, 2011b; Poenaru, Ivaşcu, & Mazilu, 1989; Poenaru & Plonski, 1996).

Among the 18 formulae used to calculate alpha-decay half-lives, a systematic study published in December 2015 (Wang, Wang, Hou, & Gu, 2015) shows that "*SemFIS*2 *formula is the best one to predict the alpha-decay half-lives… In addition, the UNIV*2 *formula with fewest parameters and the VSS, SP and NRDX formulas with fewer parameters work well in prediction on the SHN* α *decay half-lives.*". Both SemFIS2 (semi-empirical formula based on Fission Theory) and UNIV2 (universal curve) have been developed by us.

Bremsstrahlung emission accompanying α decay was observed in 1994 (D'Arrigo, Eremin, Fazio, Giardina, Glotova, Klochko, Sacchi, & Taccone, 1994).

Predicted by V. I. Goldansky (1966) (Ann. Rev. Nucl. Sci. 16), proton radioactivity was discovered experimentally at GSI Darmstadt (Hofmann & Münzenberg, 2000; Hofmann, Reisdorf, Münzenberg, Heßberger, Schneider, & Armbruster, 1982; Hofmann, 1996). Among other many publications we also quote (Delion, 2010).

4. Beta Decay

In β decay (Fermi, 1934; Fermi, 1968) electrons or positrons are emitted from an atomic nucleus. For example, beta decay of a neutron transforms it into a proton by the emission of an electron accompanied by an antineutrino, or conversely a proton is converted into a neutron by the emission of a positron with a neutrino.

The emission is possible if the energy release (Q value) is positive. Beta decay is a consequence of the weak force, which is characterized by relatively lengthy decay times.

In beta minus (β^-) decay, a neutron is converted to a proton, and the process creates an electron and an electron antineutrino. In beta plus (β^+) decay, a proton is converted to a neutron and the process creates a positron and an electron neutrino. β^+ decay is also known as positron emission.

In 1900, Becquerel measured the mass-to-charge ratio (m/e) for beta particles by the method of J. J. Thomson used to study cathode rays and identify the electron. He found that m/e for a beta particle is the same as for Thomson's electron, and therefore suggested that the beta particle is in fact an electron.

In 1899, Ernest Rutherford separated radioactive emissions into two types: alpha and beta (now beta minus), based on penetration of objects and ability to cause ionization.

In 1900, Paul Villard identified a still more penetrating type of radiation, which Rutherford identified as a fundamentally new type in 1903 and termed gamma rays.

In 1901, Rutherford and Frederick Soddy showed that alpha and beta radioactivities involve the transmutation of atoms into atoms of other chemical elements.

Nucleons are composed of up quarks and down quarks, and the weak force allows a quark to change type by the exchange of a W boson and the creation of an electron/antineutrino or positron/neutrino pair. For example, a neutron, composed of two down quarks and an up quark, decays to a proton composed of a down quark and two up quarks.

Electron capture is sometimes included as a type of beta decay, because the basic nuclear process, mediated by the weak force, is the same. In electron capture, an inner atomic electron is captured by a proton in the nucleus, transforming it into a neutron, and an electron neutrino is released.

In 1930, Wolfgang Pauli postulated the existence of the neutrino to explain the continuous distribution of energy of the electrons emitted in beta decay. Only with the emission of a third particle could momentum and energy be conserved. By 1934, Enrico Fermi had developed a theory of beta decay to include the neutrino, presumed to be massless as well as chargeless. The transition rate is proportional to the strength of the coupling between the initial and final states factored by the density of final states available to the system (Fermi, 1932; Fermi, 1934; Fermi, 1968).

Neutrino is an elementary particle fermion (spin 1/2) and a lepton which interacts via weak force, electromagnetic force and gravity. A lepton is an elementary particle with spin 1/2 that does not undergo strong interactions. There are charged leptons (electron-like: electron; muon, and tau) and neutral leptons (electron neutrino; muon neutrino, and tau neutrino). There are six kinds of leptons. First generation are electronic leptons: electron (e^-) and elctron neutrino (ν_e). The 2nd generation are muonic leptons: muon (μ^-) and the muon neutrino (ν_μ). The third one are tauonic leptons: tau (τ^-) and the tau neutrino (ν_τ). Electrons are stable and the most common charged lepton in the universe. Muons and taus can only be produced in high energy collisions (cosmic rays or in particle accelerators).

For every lepton flavor there is a corresponding type of antiparticle, known as an antilepton, that differs from the lepton only in that some of its properties have equal magnitude but opposite sign.

The electron was discovered in 1897 by Sir Joseph John Thomson (1856-1940) born in Cheetham Hill, Manchester, Lancashire, England. He won the Nobel Prize in Physics in 1906 for his work on the conduction of electricity in gases.

The next lepton to be observed was the muon, discovered by Carl David Anderson (1905-1991) in 1936. Anderson was born in New York City, the son of Swedish immigrants. He received the 1936 Nobel Prize in Physics. Only in 1947 was proposed the concept of leptons as a family of particle.

The first neutrino, the electron neutrino, was introduced by Wolfgang Pauli (1900-1958) in 1930 to explain certain characteristics of beta decay. Pauli was born in Vienna and received the Nobel Prize in Physics in 1945 for his decisive contribution through his discovery of a new law of Nature, the exclusion principle or Pauli principle. The discovery involved spin theory, which is the basis theory of the structure of matter.

Electron neutrino was first observed in the Cowan-Reines neutrino experiment conducted by Clyde Cowan (1919-1974) and Frederick Reines (1918-1998) in 1956. Cowan was born in Detroit, Michigan. Frederick Reines received the Nobel Prize in Physics in 1995 in both their names. Reines was born in Paterson, New Jersey.

The muon neutrino was discovered in 1962 by Leon M. Lederman (1922-2018), Melvin Schwartz (1932-2006), and Jack Steinberger (1921-2018), and the tau discovered between 1974 and 1977 by Martin Lewis Perl and his colleagues from the Stanford Linear Accelerator Center and Lawrence Berkeley National Laboratory. They received the Nobel Prize in Physics in 1988. Lederman was born in New York City, New York. Melvin Schwartz was born in New York City, New York. Jack Steinberger was born in the city of Bad Kissingen in Bavaria, Germany. Jack Steinberger was awarded the Nobel Prize in Physics in 1988, for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino. He shared the prize with Leon M. Lederman and Melvin Schwartz. At the time, all three experimenters were at Columbia University.

The tau neutrino remained elusive until July 2000, when the DONUT collaboration from Fermilab announced its discovery.

Example of electron emission (β^- decay):

$$^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + \mathrm{e}^- + \overline{\nu}_e$$

Positron emission (β^+ decay):

$$^{23}\mathrm{Mg} \rightarrow {}^{23}\mathrm{Na} + \mathrm{e}^+ + \nu_\mathrm{e}$$

The beta spectrum energy is continuous.

E.T. Booth J.R. Dunning (Colombia University), and F.G. Slack (Vanderbilt) discovered in 1939 beta-delayed neutron emission, a process esential for control of nuclear power reactors.

The theory of electron capture was first discussed by Gian-Carlo Wick in a 1934 paper, and then developed by Hideki Yukawa and others. K-electron capture was first observed in 1937 by Luis Alvarez, in the nuclide ^{48}V (later won the Nobel Prize in 1968 for particle physics) went on to study electron capture in ^{67}Ga and other nuclides.

Electron capture is a process in which the proton-rich nucleus of an electrically neutral atom absorbs an inner atomic electron, usually from the K or L electron shell. This process changes a nuclear proton to a neutron and simultaneously causes the emission of an electron neutrino.

Example:

$$^{59}\mathrm{Ni} + \mathrm{e}^- \rightarrow {}^{59}\mathrm{Co} + \nu_\mathrm{e}$$

M. Hirsch et al. (Hirsch, Staudt, Muto, & Klapdor-Kleingrothaus, 1993) predicted β^+ *EC*-decay half-lives.

5. Gamma Decay

The γ ray is an electromagnetic radiation with energy much larger than that of X rays (50 KeV to 8 MeV); there are even larger energies, e.g. 100 - 1000 TeV observed from the Cygnus X-3 microquasar (Gamma ray). These rays are produced when an excited nuclear level decays to a lower nuclear level.

Paul Ulrich Villard (1860-1934) a French chemist and physicist, discovered gamma radiation in 1900, while studying radiation emitted from radium. Villard knew that this kind of radiation is more powerful than previously described types of rays from radium (beta rays noted by Henri Becquerel in 1896, and alpha rays, discovered by Rutherford, in 1899). He did not name them as a different fundamental type. In 1903, Villard's radiation was recognized as being of a type fundamentally different from previously named rays by Ernest Rutherford, who named Villard's rays gamma rays by analogy with the beta and alpha rays that Rutherford had differentiated in 1899.

The rays emitted by radioactive elements were named in order of their penetrating power, using the first three letters of the Greek alphabet: alpha rays as the least penetrating, followed by beta rays, followed by gamma rays as the most penetrating. Rutherford also noted that gamma rays were not deflected (or at least, not easily deflected) by a magnetic field, another property making them unlike alpha and beta rays.

Gamma rays were first thought to be particles with mass, like alpha and beta rays. Rutherford initially believed that they might be extremely fast beta particles, but their failure to be deflected by a magnetic field indicated that they had no charge. In 1914, gamma rays were reflected from crystal surfaces, proving that they were electromagnetic radiation. Rutherford and his co-worker Edward Andrade measured the wavelengths of gamma rays from radium, and found that they were similar to X-rays, but with shorter wavelengths and (thus) higher frequency. A gamma decay was then understood to usually emit a gamma photon. Edward Neville da Costa Andrade (1887-1971) was an English physicist, writer, and poet.

Natural sources of gamma rays on Earth include gamma decay from radioisotopes such as potassium-40, and also as a secondary radiation from various atmospheric interactions with cosmic ray particles.

Gamma rays are produced by many astronomical processes in which there are high-energy electrons. Such electrons produce secondary gamma rays by the mechanisms of bremsstrahlung, inverse Compton scattering and synchrotron radiation. A large fraction of such astronomical gamma rays are screened by Earth's atmosphere. Notable artificial sources of gamma rays include fission (in nuclear reactors) as well as high energy physics experiments, such as neutral pion decay and nuclear fusion (See Kantele, Stöffl, Ussery, Decman, Henry, Estep, Hoff, & Mann, 1984; Russo, Pedersen, & Vandenbosch, 1975; Schirmer, Gerl, Habs, & Schwalm, 1989; Singer, Mutterer, Kopach, Klemens, Hotzel, Schwalm, Thirolf, & Hesse, 1997; Butler, Daniel, Irving, Morrison, Nolan, & Metag, 1980).

A sample of gamma ray-emitting material that is used for irradiating or imaging is known as a gamma source. It is also called a radioactive source, isotope source, or radiation source, though these more general terms also apply to alpha-and beta-emitting devices. Gamma sources are usually sealed to prevent radioactive contamination.

The emission of a gamma ray from an excited nucleus typically requires only 10^{-12} seconds. Gamma decay may also follow nuclear reactions such as neutron capture, nuclear fission, or nuclear fusion. When high-energy gamma rays, electrons, or protons bombard materials, the excited atoms emit characteristic secondary gamma rays, which are products of the creation of excited nuclear states in the bombarded atoms. Such transitions form a topic in nuclear physics called gamma spectroscopy, used to identify the composition of a given material.

Example of γ ray production:

$$^{60}\mathrm{Co} \to {}^{60}\mathrm{Ni}^{*} + \mathrm{e}^{-} + \nu_{\mathrm{e}} + \gamma + 1.17\ \mathrm{MeV}$$

$$^{60}\mathrm{Ni}^{*} \to {}^{60}\mathrm{Ni} + \gamma + 1.33\ \mathrm{MeV}$$

Other kind of sources besides radioactive decay: astrophysical sources (electron-positron annihilation, neutral pion decay, bremsstrahlung, inverse Compton scattering, and synchrotron radiation); terrestrial thunderstorms (high intensity static electric fields accelerating electrons, which then produce gamma rays by bremsstrahlung as they collide with and are slowed by atoms in the atmosphere). Gamma rays up to 100 MeV can be emitted by terrestrial thunderstorms); solar flares; cosmic rays (high speed electrons or protons collide with ordinary matter can produce pairs of gamma rays at 511 keV. Bremsstrahlung is produced at energies of tens of MeV or more when cosmic ray electrons interact with nuclei of high atomic number); pulsars and magnetars (pulsars are thought to be neutron stars with magnetic fields that produce focused beams of radiation, and are far less energetic, more common, and much nearer sources than quasars or the rarer gamma-ray burst sources of gamma rays); Quasars and active galaxies (more powerful γ rays from very distant quasars are thought to have a gamma ray production source similar to a particle accelerator), and Gamma-ray bursts (the most intense sources of gamma rays are the long duration bursts over few tens of seconds. By contrast, short gamma-ray bursts of two seconds or less, which are not associated with supernovae, are thought to produce gamma rays during the collision of pairs of neutron stars, or a neutron star and a black hole.

6. Induced Fission

Induced fission is a nuclear reaction in which a particle (for example a neutron) bombards a target nucleus (say ^{235}U). It differs from other types of nuclear reactions: can be amplified via a nuclear chain reaction in which the neutrons released by each fission event can produce more events, which release more neutrons and cause more fission.

The isotopes that can sustain a fission chain reaction are called nuclear fuels, and are said to be fissile (for example ^{235}U and ^{239}Pu). These fuels split into two fragments with atomic masses centering near 95 and 135 u. Most nuclear fuels undergo spontaneous fission only very slowly, decaying instead mainly via an alpha-beta decay chain over periods of millennia. In a nuclear reactor or nuclear weapon, the overwhelming majority of fission events are induced by bombardment with another particle, a neutron, which is itself produced by prior fission events.

Fission in fissile fuels are the result of the nuclear excitation energy produced when a fissile nucleus captures a neutron. This energy, resulting from the neutron capture, is a result of the attractive nuclear force acting between the neutron and nucleus.

The most common fission process is binary fission, and it produces the fission products noted above, at 95 ± 15 and 135 ± 15 u. However, the binary process happens merely because it is the most probable. In about 2 to 4 fissions per 1000 in a nuclear reactor, a process called ternary fission produces three positively charged fragments (plus neutrons) and the smallest of these may range from so small a charge and mass as a proton ($Z = 1$), to as large a fragment as argon ($Z = 18$). The small fragments, are composed of 90% helium-4 nuclei with more energy than alpha particles from alpha decay (so-called long range alphas at 16 MeV), plus helium-6 nuclei, and tritons (tritium). The ternary process ends up producing significant helium-4 and tritium gas buildup in the fuel rods of modern nuclear reactors.

The fission process requires a total input energy of about 7 to 8 MeV to initially overcome the nuclear force which holds the nucleus into a spherical or nearly spherical shape, and deform it into a peanut shape in which the fragments are able to separate. About 6 MeV of the fission energy is supplied by the simple binding of an extra neutron to the heavy nucleus via the strong force. This amount is not enough for fission. The remaining energy can be supplied by other mechanisms: more kinetic energy of the incoming neutron (fast neutrons with energies larger than 1 MeV).

Italian physicists under the famous Enrico Fermi's (1901-1954) leadership performed experiments inducing radioactivity with neutrons. Fermi discovered that slow neutrons were more easily captured by atomic nuclei than fast ones. After bombarding thorium and uranium with slow neutrons, he concluded that he had created new elements, heavier than the targets. Although he was awarded the Nobel Prize for this discovery (1938), the new elements were later revealed to be nuclear fission products (Fermi, 1932). He was called the architect of the nuclear age and the architect of the atomic bomb (due to the important role he played in the Manhattan project). He was one of very few physicists to excel in both theoretical physics and experimental physics. Fermi held several patents related to the use of nuclear power, and was awarded the 1938 Nobel Prize in Physics for his work on induced radioactivity by neutron bombardment and for the discovery of transuranium elements. He made significant contributions to the development of statistical mechanics, quantum theory, and nuclear and particle physics. He left Italy in 1938 to escape new racial laws that affected his Jewish wife, Laura Capon.

He led the team that designed and built Chicago Pile-1, which went critical on 2 December 1942, demonstrating the first human-created, self-sustaining nuclear chain reaction. He was on hand when the X-10 Graphite Reactor at Oak Ridge, Tennessee, went critical in 1943, and when the B Reactor at the Hanford Site did so the next year. At Los Alamos, he headed F Division, part of which worked on Edward Teller's thermonuclear Super bomb. He was present at the Trinity test on 16 July 1945, where he used his Fermi method to estimate the bomb's yield.

Fermi did important work in particle physics, related to pions and muons, and he speculated that cosmic rays arose when material was accelerated by magnetic fields in interstellar space. Many awards, concepts, and institutions are named after Fermi, including the Enrico Fermi Award, the Enrico Fermi Institute, the Fermi National Accelerator Laboratory, the Fermi Gamma-ray Space Telescope, the Enrico Fermi Nuclear Generating Station, and the synthetic element fermium, making him one of 16 scientists who have elements named after them. Other awards: Matteucci Medal (1926); Hughes Medal (1942); Medal for Merit (1946); Franklin Medal (1947); ForMemRS (1950); Barnard Medal for Meritorious Service to Science (1950); Rumford Prize (1953) and Max Planck Medal

(1954).

His former co-worker Edoardo Amaldi (1908-1989) wrote a review article (Amaldi, 1984) in which he gave the details of their experiments and of the other ones which followed. Ida Noddack (1896-1978), was a German chemist and physicist. In 1934 she was the first to mention the idea later named nuclear fission (Noddack-Tacke, 1934). With her husband, Walter Noddack, she discovered element 75, rhenium. Noddack criticized Enrico Fermi's chemical proofs in his 1934 neutron bombardment experiments, from which he claimed that transuranic elements have been produced. Noddack's idea of nuclear fission was not confirmed until much later. Experiments along a similar line to Fermi's, by Irène Joliot-Curie (1897-1956) (Joliot & Curie, 1934; Curie & Joliot, 1934), Frédéric Joliot-Curie (1900-1958) and Pavle Savić (1909-1994) in 1938 raised *interpretational difficulties* when the supposed transuranics exhibited the properties of rare earths rather than those of adjacent elements. Frédéric received (with his wife Irène) the Nobel Prize for Chemistry (1935). Other awards: Hughes Medal (1947) and ForMemRS (1946). In 1959 a stamp with his portrait was issued by Romania, celebrating the 10th anniverssary of mondial Mouvement for Peace.

On December 17, 1938, Otto Hahn (1879-1968) and Friedrich Wilhelm "Fritz" Strassmann (1902-1980) gave the chemical proof that the previously presumed transuranic elements were isotopes of barium, and Hahn wrote these exciting results to his exiled colleague Lise Meitner, explaining the process as a 'bursting' of the uranium nucleus into lighter elements. Meitner and Otto Frisch utilized Fritz Kalckar and Niels Bohr's liquid drop model to provide a first theoretical model and mathematical proof of what Frisch coined nuclear fission. Frisch also experimentally verified the fission reaction by means of a cloud chamber, confirming the energy release. Therefore, Noddack's original hypothesis was finally accepted.

O. Hahnwas born in Frankfurt am Main. He was awarded the Nobel Prize in Chemistry in 1944 for the discovery and the radiochemical proof of nuclear fission. Other awards: Emil Fischer Medal (1919); Cannizzaro Prize (1939); Copernicus Prize (1941); Max Planck Medal (1949); Paracelsus Medal (1952); Henri Becquerel Medal (1952); Pour le Mérite (1952); Faraday Lectureship Prize (1956); ForMemRS (1957); Wilhelm Exner Medal (1958); Hugo Grotius Medal (1958), and Légion d'Honneur (1959).

Fritz Strassmann was born in Boppard, German Empire. He received the Enrico Fermi Award (1966).

Lise Meitner (1878-1968) was born in Vienna, Austria-Hungary. Meitner, Hahn and Frisch understood that the fission process, must be accompanied by an enormous release of energy. She was the first woman to become a full professor of physics in Germany. She lost this position in the 1930s because of the anti-Jewish Nuremberg Laws of Nazi Germany, and in 1938 she fled to Sweden, where she lived for many years, becoming a Swedish citizen. Meitner has received many posthumous honors, including naming chemical element 109 meitnerium in 1992. Awards: Lieben Prize (1925); Max Planck Medal (1949);

Otto Hahn Prize (1955); ForMemRS (1955); Wilhelm Exner Medal (1960), and Enrico Fermi Award (1966).

Her nephew, Otto Robert Frisch (1904-1979) was also born in Vienna, Austria-Hungary. He was Fellow of the Royal Society. In Birmingham with Sir Rudolf Peierls (1907-1995) they wrote the FrischPeierls memorandum at the University of Birmingham, which was the first document to set out a process by which an atomic explosion could be generated. They would use separated uranium-235, which would require a small critical mass and could be made to achieve criticality using conventional explosives to create a powerful detonation. It was the basis of British work on building an atomic device (the Tube Alloys project) and also that of the Manhattan Project on which Frisch worked as part of the British delegation. Rudolf Peierls awards: Commander of the Order of the British Empire (1946); Medal of Freedom (1946); Royal Medal (1959); Lorentz Medal (1962); Max Planck Medal (1963); Knight Bachelor (1968); Enrico Fermi Award (1980); Matteucci Medal (1982), and Copley Medal (1986).

Frisch went to America in 1943. At Los Alamos he was the leader of the Critical Assemblies group. They determined the amount of enriched uranium required to create the critical mass, which would sustain a nuclear chain reaction.

The starting point for the liquid drop model was the Weizsäcker formula. Carl Friedrich Freiherr von Weizsäcker (1912-2007) was a German physicist and philosopher, born in Kiel, Germany. Awards: Max Planck Medal (1957); Goethe Prize (1958), and Templeton Prize (1989).

Niels Henrik David Bohr (1885-1962), (Bohr & Wheeler, 1939) was a Danish physicist who made fundamental contributions to understanding atomic structure and quantum theory, for which he received the Nobel Prize in Physics in 1922. He developed the Bohr model of the atom, in which he proposed that energy levels of electrons are discrete and that the electrons revolve in stable orbits around the atomic nucleus but can jump from one energy level (or orbit) to another.

The discovery of nuclear fission by Otto Hahn in December 1938 (and its theoretical explanation by Lise Meitner) generated intense interest among physicists. Bohr brought the news to the United States where he opened the Fifth Washington Conference on Theoretical Physics with Fermi on 26 January 1939. When Bohr told George Placzek that this resolved all the mysteries of transuranic elements, Placzek told him that one remained: the neutron capture energies of uranium did not match those of its decay. Bohr thought about it for a few minutes and then he announced "I have understood everything". Based on his liquid drop model of the nucleus, Bohr concluded that it was the ^{235}U and not the more abundant ^{238}U. H.L. Anderson, E.T. Booth, J.R. Dunning, E. Fermi, G.N. Glasoe, F.G. Slack (all working at Colombia) published the first verification of Hahn and Strassmann's work and quickly provided experimental evidence that slow neutrons of ^{235}U were responsible for fission. Booth, Dunning and Slack went on to measure the first mass distribution of asymmetric fission. Bohr and Wheeler developed a theoretical treatment which they published in a September 1939 paper (Bohr & Wheeler, 1939).

The liquid drop model of the atomic nucleus predicts equal-sized fission fragments. The nuclear shell model is needed to explain the mass asymmetry. V.I. Strutinsky (1929-1993), born in Odessa, Ukraine, developed his macroscopic-microscopic method (Strutinsky, 1967; Brack, Damgaard, Jensen, Pauli, Strutinsky, & Wong, 1972) used to explain the fission mass asymmetry, e.g. (Pashkevich, 1971; Brosa & Knitter, 1990; Möller, Madland, Sierk, & Iwamoto, 2001; Poenaru, Gherghescu, & Greiner, 2005; Sierk, 1985).

The best asymmetric two-center shell model (Gherghescu, 2003) was developed using the previous model (Maruhn & Greiner, 1972; Rutz, Bender, Bürvenich, Schilling, Reinhard, Maruhn, & Greiner, 1997).

7. Spontaneous Fission

Spontaneous fission was discovered by Soviet physicists Georgy N. Flerov (1913-1990) and Konstantin A. Petrzhak (1907-1998).

Flerov was born in Rostov-on-Don and graduated from the Leningrad Polytechnic Institute (Peter the Great St. Petersburg Polytechnic University) with specialities thermal physics and nuclear physics. He wrote to Stalin in April 1942, while serving as an air force lieutenant, urgings to build the uranium bomb without delay (Flerov & Petrjak, 1940).

In the 1970s he claimed as his discovery two transition metal elements: seaborgium and bohrium. After his death the Nuclear Reaction Laboratory of J.I.N.R. Dubna was named G.N. Flerov Laboratory. He founded this Laboratory in 1957, and was director there until 1989. Also during this period, he chaired the Scientific Council of the USSR Academy of Sciences. Awards: Hero of Socialist Labour (1949); Two Orders of Lenin (1949, 1983); Order of the October Revolution (1973); Order of the Red Banner of Labour, three times (1959, 1963, 1975); Order of the Patriotic War, 1st class (1985); Lenin Prize (1967); Stalin Prize, twice (1946, 1949); USSR State Prize (1975), and Honorary Citizen of Dubna. The element flerovium (atomic number 114) was named after him.

Konstantin Antonovich Petrzhak (1907-1998) was born in Lukow, now in Poland. He was a Russian nuclear physicist of Polish ethnicity, professor of physics at the Saint Petersburg State University. In 1934, Petrzhak joined the Khlopin Radium Institute located in the State University, Saint Petersburg directed by Igor Kurchatov (1903-1960). Awards: 1946 Stalin prize (2nd degree; jointly with Georgy Flyorov for discovery of spontaneous fission; 100,000 Soviet roubles each); 1950 Council of Ministers Prize (for work on fulfillment of governmental tasks); 1953 USSR State Prize (for work on soviet atomic project); 1953 Order of the Red Banner of Labour (for work on soviet atomic project), and 1957 Presidium of Academy of Sciences of USSR Prize. Like Flyorov, he also worked in Russia's atomic bomb project.

The Soviet's nuclear project under Kurchatov happened in three periods. The first phase (1935-1945) stage. Followed the building of the atomic industry and atomic weapons (1946-1949). The third stage (1950-1957) was the progress of the atomic industry, the creation of hydrogen weapons and the birth of the atomic power generation and the atomic fleet in the Soviet Union. The first group of researchers working to build a nuclear-thermonuclear weapon was led by A.D. Sakharov (1921-1989) in 1953: I.E. Tamm, Z.S. Belenky, V.L. Ginzburg, A.D. Sakharov, Yu.A. Romanov, and I.Ya. Pomeranchuk, V.N. Klimov, N.N. Bogolyubov, and D.V. Shirkov. Later, a joint team headed by Khariton discovered the basic physical principle of modern thermonuclear weapons, radiation implosion, and carried out a successful test. In 1955 the team included: Ya.B. Zeldovich, Yu.A. Trutnev, and A.D. Sakharov.

Andrei Dmitrievich Sakharov was born in Moscow. Awards: Hero of Socialist Labor (1953 1955 1962); Stalin Prize (1953); Lenin Prize (1956); Prix mondial Cino Del Duca (1974); Nobel Peace Prize (1975), and Elliott Cresson Medal (1985). The Nobel Committee's: *In a convincing manner Sakharov has emphasised that Man's inviolable rights provide the only safe foundation for genuine and enduring international cooperation*.

As in the previous section, we should stress the important article (Bohr & Wheeler, 1939) who explained many properties of nuclear fission based on the liquid drop model (LDM) and Strutinski's macroscopic-microscopic method (Strutinsky, 1967; Brack, Damgaard, Jensen, Pauli, Strutinsky, & Wong, 1972), allowing to explain fission fragment mass asymmetry. Many other theories have been developed, e.g. (Brosa & Knitter, 1990; Krappe, Nix, & Sierk, 1979; Möller, Madland, Sierk, & Iwamoto, 2001; Pashkevich, 1971; Poenaru, 1996; Poenaru, Gherghescu, & Greiner, 2005; Poenaru, Ivaşcu, & Greiner, 1989; Sierk, 1985; Viola Jr. & Seaborg, 1966; Businaro & Gallone, 1955; Swiatecki, 1955; Michaudon, 1973; Randrup, Tsang, Möller, Nilsson, & Larsson, 1973; Björnholm & Lynn, 1980; Herrmann, 1988, 1989; Nix, 1972, 1989; Poenaru & Ivaşcu, 1989).

Hulet et al. (Hulet et al., 1986) observed for the first time the *bimodal symmetric fission*.

There are many methods used to calculate spontaneous fission half-lives. The simplest ones are semi-empirical relationships (Viola Jr. & Seaborg, 1966; Wang, Wang, Hou, & Gu, 2015; Poenaru, Ivaşcu, & Săndulescu, 1979; Poenaru & Gherghescu, 2016a).

Very frequently used are fission dynamics based on cranking inertia (Poenaru & Gherghescu, 2014; Poenaru & Gherghescu, 2016b; Poenaru, Gherghescu, & Greiner, 2005; Poenaru & Ivaşcu, 1981b).

Other models are Hartree-Fock-Bogoliubov approach with finite-range and density-dependent Gogny force (Michaudon, 1973) and self-consistent symmetry-unrestricted nuclear density functional with Skyrme energy density functional and cranking inertia (Xu, Ren, & Guo, 2008).

The accuracy of these models should be improved because at present a comparison between different results obtained for a given decay mode shows a huge discrepancy (more than 10 orders of magnitude). The results of Robert Smolanczuk et al. (Smolanczuk, Skalski, & Sobiczewski, 1995; Smolanczuk, 1997) are frequently very close to the experimental data.

With the discovery that the new element ^{252}Cf had a spontaneous fission branch, it became a rich source for the studies of the nuclear structure of neutron-rich radioactive nuclei and industrial applications for its compact source of energy and neutrons.

Using ^{252}Cf, B. Musangu and Vanderbilt coworkers [Phys. Rev. C 101, 034610 (2020)] discovered that ^{144}Ba and ^{148}Ce had a second very hot fission mode with 8 - 11 neutrons compared to the normal mode centered around 4 neutron emission. They proposed this was related to their octupole deformed shape at the scission.

All superheavy neutron-rich nuclei produced in reactions $Z \geq 107$ - 118 with ^{48}Ca beams first undergo alpha decay and finally spontaneous fission.

8. Ternary and Multi-Cluster Fission

Ternary fission is a comparatively rare (0.2% to 0.4% of total binary fission events) kind of nuclear fission in which three charged products are produced.

The smallest of the charged products may range from so small a charge and mass as a single proton ($Z = 1$), up to as large a fragment as the nucleus of argon ($Z = 18$), or even larger. The most common small fragment is helium-4 (about 90% of the total yield). It is called long range alpha.

It produces significant helium-4 and tritium gas buildup in the fuel rods of modern nuclear reactors.

The phenomenon was discovered in a Chinese-French cooperation (Tsien, Ho, Vigneron, & Chastel, 1946; Tsien, Ho, Chastel, & Vigneron, 1947; Tsien, Ho, Vigneron, & Chastel, 1947a; Tsien, Ho, Vigneron, & Chastel, 1947b; Wigner & Eisenbud, 1947; Tsien, Ho, Vigneron, & Chastel, 1947c).

Many research works have been performed, e.g. (Vanderbosch & Huizenga, 1973; Diehl & Greiner, 1974; Cârjan, 1976, 1986; Wagemans, 1989; Mutterer & Theobald, 1996; Manimaran & Balasubramaniam, 2009; Ramayya, Hamilton et al., 1998; Poenaru, Greiner, Hamilton, Ramayya, Hourany, & Gherghescu, 1999).

Review articles may be also found (Mutterer & Theobald, 1996; Manimaran & Balasubramaniam, 2009; Poenaru, Greiner, Hamilton, Ramayya, Hourany, & Gherghescu, 1999).

Frankfurt School (Diehl and Greiner, 1974; Hahn, Lustig, & Greiner, 1977) developed theoretical models based on the liquid drop model and the three-center shell-model.

The energy released in ternary fission was calculated (Poenaru, Greiner, & Gherghescu, 1998) and multicluster accompanied fission was predicted (Poenaru, Greiner, Hamilton, Ramayya, Hourany, & Gherghescu, 1999; Poenaru, 2001). Quasi-molecular states in ternary fission have been investigated (Poenaru, Dobrescu, Greiner, Hamilton, & Ramayya, 2000a; Poenaru, Dobrescu, Greiner, Hamilton, & Ramayya, 2000b; Poenaru, Greiner, Hamilton, & Ramayya, 2001; Present, 1959; Vanderbosch & Huizenga, 1973; Ramayya, Hamilton et al., 1998). Ternary fission and cluster radioactivities have been also studied (Poenaru, 2001; Gherghescu, Poenaru, & Greiner, 2008).

True ternary fission (Poenaru, Gherghescu, Greiner, Nagame, Hamilton, & Ramayya, 2003) means a process in which the three fragments are equally sized.

A new microscopic shell model (three center shell model) was developed (Hahn, Lustig, & Greiner, 1977; Manimaran & Balasubramaniam, 2009).

A new kind of ternary fission, collinear cluster tri-partition (Pyatkov et al., 2010) is studied in JINR Dubna.

Quaternary fission, at 1 per 10 million binary fissions, is also known. The most common mode of quaternary fission involves emission of two alpha particles. Experimental results: (Gönnenwein, Jesinger, Mutterer, Trzaska, Petrov, Gagarski, Nesvizhevski, & Geltenbort, 2003).

9. Fissioning Shape Isomers

A nuclear isomer is a metastable state of an atomic nucleus caused by the excitation of one or more of its nucleons (protons or neutrons). The corresponding half-lives are 100 to 1000 times longer than the half-lives of the excited states decaying promptly (the order of 10^{12} seconds). Usually the isomers have half-lives are no longer than 10^{9} s. The first nuclear isomer and decay-daughter system, now known as ^{234m}Pa/^{234}Pa was discovered by Otto Hahn in 1921. Metastable isomers of a particular isotope are usually designated with an m.

Fission isomer or shape isomer, discovered by S.M. Polikanov et al. in JINR Dubna (Polikanov, Druin, Karnaukhov, Mikheev, Pleve, Skobelev, Subotin, Ter-Akopian, & Fomichev, 1962) have been experimentally observed in very heavy nuclei, like ^{241f}Am. The measured fission half-lives may vary from nanoseconds to microseconds. They are denoted with a superscript f. A scientific cooperation with a romanian team (N. Vîlcov et al.) was started in 1964 in order to produce and measure fissioning isomers at the cyclotron in Magurele near Bucharest, e.g. (Flerov, Ivanov, Martalogu, Pleve, Polikanov, Poenaru, & Vilcov, 1965a; Flerov, Ivanov, Martalogu, Pleve, Polikanov, Poenaru, & Vilcov, 1965b; Flerov, Martalogu, Pleve, Polikanov, Poenaru, & Vilcov, 1967b; Flerov, Pleve, Polikanov, Tretyakova, Martalogu, Poenaru, Sezon, Vilcov, & Vilcov, 1967a).

Dr. S.M. Polikanov left Soviet Union and has been working many years at GSI Darmstadt. Consequently, the cooperation with Romania was continued by a team led by Dr. Y.P. Gangrsky, see e.g. (Vilcov, Vilcov, Gangrsky, Marinescu, Pleve, Poenaru, & Kharisov, 1972; Galeriu, Marinescu, Poenaru, Vilcov, Vilcov, Gangrsky, Hien, & Khan, 1974). Experimental studies have been performed by Dr. G. Sletten et al. from Niels Bohr Institute, Riso, Roskilde, Copenhagen, Denmark (Lark, Sletten, Pedersen, & Bjørnholm, 1969; Polikanov & Sletten, 1970), by Dr. H.C. Britt from Lawrence Livermore National Laboratory USA (Burnett, Britt, Erkkila, & Stein, 1970; Britt, Burnett, Erkkila, Lynn, & Stein, 1971; Britt, 1973), by Dr. V. Metag from Justus-Liebig-Universität Giessen, and GSI Darmstadt, Germany (Metag, Repnow, & von Brentano, 1971; Habs, Metag, Specht, & Ulfert, 1977; Metag, Habs, & Specht, 1980), Prof. Dr. P. von Brentano from Köln University (Metag, Repnow, & von Brentano, 1971).

Among theories, we may cite (Metag, Repnow, & von Brentano, 1971), (Specht, Weber, Konecny, & Heunemann, 1972; Specht, 1974; Britt, 1973; Vandenbosch, 1974; Libert, Meyer, & Quentin, 1980; Poenaru & Ivaşcu, 1981a).

In order to explain this newphenomenon, V.M. Strutinsky developed his macroscopic-microscopic method leading to total deformation energy with two minima: the first one the ground-state, and the 2nd one the shape isomeric state at larger deformation (Strutinsky, 1967).

10. Cluster Radioactivities

Cluster decay (heavy particle radioactivity or heavy ion radioactivity) is a kind of nuclear decay in which a nucleus spontaneously emits a small cluster, larger than alpha particle, but smaller than a binary fission fragment The new phenomenon was predicted in 1980 (Sändulescu, Poenaru, & Greiner, 1980).

Four years after, the first successful experiment was reported, in which ^{14}C radioactivity of ^{223}Ra was identified (Rose & Jones, 1984) after about 6 months of measurements with 11 events clearly seen:

$$^{223}\text{Ra} \to {}^{14}\text{C} + {}^{209}\text{Pb}$$

Standard equipment with semiconductor detectors had been used at Oxford University.

In the same year the experiment was confirmed by two different groups. One in Institut de Physique Nucléaire Orsay (Gales, Hourani, Hussonnois, Schapira, Stab, & Vergnes, 1984) used the SOLENO—a superconductor spectrometer with liquid helium. Next year the confirmation came from the Argonne National Laboratory (Kutschera, Ahmad, Armato III, Friedman, Gindler, Henning, Ishii, Paul, & Rehm, 1985) with a magnetic spectrometer. Due to a much higher activity of the source, the 11 events could be obtained in few hours.

None of the experimentalists (Rose & Jones, 1984; Gales, Hourani, Hussonnois, Schapira, Stab, & Vergnes, 1984; Kutschera, Ahmad, Armato III, Friedman, Gindler, Henning, Ishii, Paul, & Rehm, 1985) cited the early theoretical work. Consequently a comment was submitted to the editor of Physical Review Letters (Sändulescu, Poenaru, Greiner, & Hamilton, 1985), mentioning clearly the original work four years before. This article was seriously taken into account, and since then the majority of experimentalists and theoreticians working in the field are citing (Sändulescu, Poenaru, & Greiner, 1980)—which became the most cited article in the field. In 1983-1985 additional articles were published (Poenaru & Ivaşcu, 1983; Poenaru & Ivaşcu, 1984; Poenaru, Ivaşcu, Săndulescu, & Greiner, 1984; Poenaru, Ivaşcu, Săndulescu, & Greiner, 1985; Poenaru, Greiner, Ivaşcu, & Săndulescu, 1985).

Articles with comprehensives tables of calculated half-lives and Q-values followed (Poenaru, Greiner, Depta, Ivaşcu, Mazilu, & Săndulescu, 1985; Poenaru, Schnabel, Greiner, Mazilu, & Gherghescu, 1991).

Up to now the following cluster decay modes have been experimentally confirmed (Bonetti & Guglielmetti, 2007): ^{14}C, ^{20}O, ^{23}F, $^{22,24-26}$Ne, ^{28,30}Mg, ^{32,34}Si with half-lives in good agreement with predicted values within our analytical superasymmetric fission model (ASAF). An important role in experiments on cluster decay modes performed in Berkeley, Orsay, Dubna and Milano played P. Buford Price (Price, 1989), Eid Hourany and Michel Hussonnois (Hourani & Hussonnois, 1989; Hourani, Hussonnois, & Poenaru, 1989), Svetlana Tretyakova (Tretyakova, 1992), and Roberto Bonetti (Bonetti & Guglielmetti, 2007) and their coworkers.

Several review articles and books have been published, for example (Delion, 2010; Bonetti & Guglielmetti, 2007; Price, 1989; Greiner, Ivaşcu, Poenaru, & Săndulescu, 1989; Poenaru, Ivaşcu, & Greiner, 1989; Poenaru & Greiner, 1996; Poenaru & Greiner, 1997; Poenaru & Greiner, 2010).

11. Super Heavy Nuclei

The transuranium elements are the chemical elements with atomic numbers greater than 92 (Warda & Egido, 2012; Warda, Zdeb, & Robledo, 2018). They can be produced via nuclear reactors or particle accelerators.

The liquid drop model fission barrier of the heaviest elements becomes negligible small. In order to survive, the super heavy nuclei (with atomic numbers ≥ 104) must have a finite potential barrier of microscopic shell plus pairing corrections (Strutinsky, 1967) nature.

Many new elements have been were discovered by the Lawrence Berkeley National Laboratory (LBNL), University of California, Berkeley, led by Edwin McMillan, Glenn Seaborg, and Albert Ghiorso, during 1945-1974.

They named $Z = 104$ element rutherfordium (symbol Rf), after Ernest Rutherford. This discovery was also claimed by the JINR Dubna, Russia, led by Georgy N. Flerov [they named the element kurchatovium (Ku)]. IUPAC concluded that credit should be shared.

Similarly for $Z = 105$ dubnium (Db), after the city of Dubna. Originally named hahnium (Ha) in honor of Otto Hahn by the Berkeley group (1970) but renamed by IUPAC (1997). Discovery was also claimed by the JINR, which named it nielsbohrium (Ns) after Niels Bohr. IUPAC concluded that credit should be shared.

$Z = 106$ is named seaborgium (Sg) after Glenn T. Seaborg. Seaborg was still alive, but it became accepted by IUPAC (1974). It was also claimed by the JINR. IUPAC concluded that the Berkeley team had been the first to synthesise the element.

The Gesellschaft für Schwerionenforschung (Heavy Ion Research) in Darmstadt, Germany, led principally by Gottfried Münzenberg, Peter Armbruster, and Sigurd Hofmann, during 1980-2000, are responsible for several other super heavies.

Z = 107 bohrium (Bh), named after the Danish physicist Niels Bohr. This discovery was also claimed by the JINR. IUPAC concluded that the GSI had been the first to synthesise the element.

Z = 108 hassium (Hs), after the Latin form of the name of Hessen, the German Bundesland where this work was performed (1984). This discovery was also claimed by the JINR. IUPAC concluded that the GSI had been the first to synthesise the element, while acknowledging the pioneering work at the JINR.

Z = 109 meitnerium (Mt). Lise Meitner (see above) was an Austrian physicist one of the earliest to study nuclear fission (1982).

Z = 110 darmstadtium (Ds) after Darmstadt, Germany, the city in which this work was performed (1994). It was also claimed by the JINR (the name becquerelium after Henri Becquerel), and by the LBNL (the name hahnium). IUPAC concluded that the GSI had been the first to synthesize the element.

Z = 111 roentgenium (Rg) after Wilhelm Conrad Röntgen, discoverer of X-rays (1994).

Z = 112 copernicium (Cn) after the astronomer Nicolaus Copernicus (1996).

Rikagaku Kenkyusho (RIKEN) in Wako, Saitama, Japan, led by Kosuke Morita: Z = 113 nihonium (Nh). Japan is named Nihon in Japanese (2004). This discovery was also claimed by the JINR. IUPAC concluded that RIKEN had been the first to synthesise the element.

The JINR Dubna, Russia, led by Yuri Ts. Oganessian, in collaboration with Lawrence Livermore National Laboratory (LLNL), since 2000 discovered new elements 114 and 116.

J.H. Hamilton (Vanderbilt), Yu. Ts. Oganessian and J. Roberto (Oak Ridge National Lab) formed a new collaboration with LLNL invited to join. This group was credited with the discovery of new elements 115, 117 and 118.

Z = 114 flerovium (Fl) after Soviet physicist Georgy N. Flyorov, founder of the JINR (2004).

Z = 115 moscovium (Mc) after Moscow Oblast (Region) Russia, where it was discovered.

Z = 116 livermorium (Lv) after the Lawrence Livermore National Laboratory (LNL), a collaborator with JINR (2004).

Z = 117 tennessine (Ts) after the State of Tennessee, where Vanderbilt and ORNL are located.

Z = 118 oganesson (Og) after Yuri Ts. Oganessian, who led the JINR team in its discovery of elements 114 to 118.

Superheavies (SH) have only been made artificially. They have short half-lives (few minutes to just a few milliseconds, except for Db with a half life of over a day), which also makes them extremely difficult to study.

SHs have all been created since the latter half of the 20th century, and are continually produced during the 21st century. Mainly two kinds of fusion reactions have been used to produce them.

1) Cold fusion (GSI, RIKEN), in which the target is usually ^{208}Pb or ^{209}Bi

(Hofmann & Münzenberg, 2000; Hofmann, 1996; Hofmann, Hamilton, & Lane, 1996; Morita et al., 2007). One neutron is evaporated.

2) Hot fusion (JINR Dubna and LNL), with the ^{48}Ca projectile (Oganessian et al., 2010; Oganessian & Utyonkov, 2015).

The first calculations have been reported by H. Meldner (Meldner, 1966). In the same year Walter Greiner (1935-2016) and Ulrich Mosel wrote a memorandum in order to build a new Research Center in Darmstadt, devoted to study Nuclear Physics using reactions with heavy ions (Greiner & Mosel, 1966; Mosel & Greiner, 1969). A. Sobiczewski et al. found the following magic numbers in this new region: $Z = 114$ and $N = 184$ (Sobiczewski, Gareev, & Kalinkin, 1966). Among other theoretical works we can cite (Bohr & Wheeler, 1939; Brack, Damgaard, Jensen, Pauli, Strutinsky, & Wong, 1972; Brosa & Knitter, 1990; Möller, Madland, Sierk, & Iwamoto, 2001; Pashkevich, 1971; Poenaru, 1996; Sierk, 1985; Poenaru, Ivaşcu, & Greiner, 1989).

The chemistry of SHs was studied by B. Fricke and W. Greiner (Fricke and Greiner, 1969).

A possible important contribution was found (Poenaru, Gherghescu, & Greiner, 2011a, 2011b) for cluster decay which may be comparable or even stronger than αdecay for SHs with $Z \geq 121$. See also (Poenaru & Greiner, 1991a; Poenaru & Greiner, 1991b; Poenaru, Ivaşcu, & Greiner, 1989; Poenaru, Ivaşcu, & Mazilu, 1982).

Many other theoretical works have been reported, e.g. (Poenaru, Plonski, & Greiner, 2006; Wang, Wang, Hou, & Gu, 2015; Xu, Ren, & Guo, 2008; Santhosh, Biju, & Sahadevan, 2010; Bao, Zhang, Royer, & Li, 2013; Smolanczuk, Skalski, & Sobiczewski, 1995; Smolanczuk, 1997; Poenaru & Gherghescu, 2014; Poenaru & Gherghescu, 2016a, 2016b; Warda & Egido, 2012).

Review articles or chapters in books, for example: (Warda & Egido, 2012; Staszczak, Baran, & Nazarewicz, 2013; Oganessian & Utyonkov, 2015; Grumann, Mosel, Fink, & Greiner, 1969; Nilsson, Tsang, Sobiczewski, Szymański, Wycech, Gustafson, Lamm, Möller, & Nilsson, 1969; Marinov, Batty, Kilvington, Newton, Robinson, & Hemingway, 1971; Poenaru, Stöcker, & Gherghescu, 2018; Hamilton, Hofmann, & Oganessian, 2013; Kumar, 1989; Greiner & Poenaru, 2010; Oganessian & Utyonkov, 2015; Poenaru & Greiner, 1996; Poenaru, 1996; Krappe & Pomorski, 2012).

12. Conclusion and Outlook

In 10 sections we presented information about X-rays, alpha-decay, beta-decay, gamma-decay, induced fission, spontaneous fission, ternary and multi-cluster fission, shape isomers, cluster radioactivities and superheavy nuclei. All these kinds of nuclear decay modes are very important for basic research as well as for applications, particularly the induced fission used in many nuclear power stations all over the world. We hope that this article will help the experimentalists and theorists to develop new research works leading to new findings in their field of activity.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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