



## Write the difference between lanthanides and actinides

F-block chemical elements Actinides in the periodic table Hydrogen Helium Lithium Beryllium Boron Carbon Nitrogen Oxygen Fluorine Argon Potassium Calcium Scandium Titanium Vanadium Chromium Manganese Iron Cobalt Nickel Copper Zinc Gallium Germanium Arsenic Selenium Bromine Krypton Rubidium Strontium Vttrium Zirconium Niobium Molybdenum Technetium Ruthenium Rhodium Silver Cadmium Indium Tin Antimony Tellurium Iodine Xenon Caesium Barium Lanthanum Cerium Praseodymium Neodymium Promethium Samarium Europium Gadolinium Terbium Dysprosium Holmium Erbium Thulium Ytterbium Lutetium Hafnium Tongsten Rhenium Osmium Iridium Platinum Gold Mercury (element) Thallium Lead Bismuth Polonium Astatine Radon Francium Radium Actinium Thorium Protactinium Uranium Neptunium Plutonium Americium Curium Berkelium Californium Einsteinium Fermium Mendelevium Nobelium Lawrencium Bohrium Hassium Meitnerium Darmstadtium Roentgenium Copernicium Nihonium Flerovium Moscovium Livermorium Tennessine Oganesson Part of a series on the Periodic table forms 18-column · 32-column Alternative & extended forms Periodic table history Dmitri Mendeleev predictions Discovery of elements Naming & etymology for places for people controversies (in East Asia) Systematic element names Sets of elements By periodic table structure Groups (1–18) 1 (alkali metals) 2 (alkaline earth metals) 3 4 5 6 7 8 9 10 11 12 13 14 15 (pnictogens) 17 (halogens) 18 (noble gases) Periods (1–7, ...) 1 2 3 4 5 6 7 8 + Blocks (s, p, d, f, ...) Atomic orbitals Aufbau principle By metallic classification Metals alkali alkaline earth transition post-transition lanthanide actinide (superactinide) Metalloids dividing metals reactive nonmetals noble gases By other characteristics Coinage metals Platinum-group metals Precious metals Refractory metals Heavy metals Light metals Native metals Noble metals Main-group elements Rare-earth elements Transuranium, transplutonium elements Major, minor & trans- actinides Elements by abundance (in human body) by atomic properties by isotope stability by annual production by symbol Properties of elements Atomic weight Crystal structure Electron affinity configuration Electronegativity (Allen, Pauling) Goldschmidt classification Nutrition Valence Data pages for elements Abundance Atomic radius Boiling point Critical point Density Electrical resistivity Electron affinity / configuration Electronegativity Hardness Heat capacity / of fusion / of vaporization lonization energy Melting point Oxidation state Speed of sound Thermal conductivity / expansion coefficient Vapor pressure Category Chemistry Portal vte The actinoid / æktıncıd/ (IUPAC nomenclature, also called actinide[1] / 'æktīnaīd/) series encompasses the 15 metallic chemical elements with atomic numbers from 89 to 103, actinium through lawrencium. The informal chemical symbol An is used in general discussions of actinoid chemistry to refer to any actinoid.[2][3][4] Since "actinoid" means "actinium-like" (cf. humanoid or android), it has been argued for semantic reasons that actinium cannot logically be an actinoid, but IUPAC acknowledges its inclusion based on common usage.[5] All the actinides are f-block elements, except the final one (lawrencium) which is a d-block element. Actinium has sometimes been considered d-block instead of lawrencium, but the classification with lawrencium in the d-block is more often adopted by those who study the matter.[6][7] The series mostly corresponds to the filling of the 5f electron shell, although in the ground state many have anomalous configurations involving the filling of the 6d shell due to interelectronic repulsion. In comparison with the lanthanides, also mostly f-block elements, the actinides show much more variable valence. They all have very large atomic and ionic radii and exhibit an unusually large range of physical properties. While actinium and the late actinides (from americium onwards) behave similarly to the lanthanides, the elements thorium, and uranium are much more similar to transition metals in their chemistry, with neptunium and plutonium occupying an intermediate position. All actinides are radioactive and release energy upon radioactive decay; naturally occurring uranium and thorium, and synthetically produced plutonium are the most abundant actinides on Earth. These are used in nuclear reactors and nuclear weapons. Uranium and thorium also have diverse current or historical uses, and americium is used in the ionization chambers of most modern smoke detectors. Of the actinides, primordial thorium and uranium occur naturally in substantial quantities. The radioactive decay of uranium produces transient amounts of actinium and protactinium, and atoms of neptunium and plutonium are occasionally produced from transmutation reactions in uranium ores. The other actinides are purely synthetic elements. [2][8] Nuclear weapons tests have released at least six actinides heavier than plutonium into the environment; analysis of debris from a 1952 hydrogen bomb explosion showed the presence of americium, curium, berkelium, californium, einsteinium and fermium.[9] In presentations of the periodic table, the f-block elements are customarily shown as two additional rows below the main body of the table.[2] This convention is entirely a matter of aesthetics and formatting practicality; a rarely used wide-formatted periodic table inserts the 4f and 5f series in their proper places, as parts of the table's sixth and seventh rows (periods). vteActinides Actinium89Ac[227] Thorium90Th232.04 Protactinium91Pa231.04 Uranium92U238.03 Neptunium93Np [237] Plutonium94Pu[244] Americium95Am[243] Curium96Cm[247] Berkelium97Bk[247] Californium98Cf[251] Einsteinium99Es[252] Fermium100Fm[257] Mendelevium101Md[258] Nobelium102No[259] Lawrencium103Lr[266] Primordial From decay Synthetic Border shows natural occurrence of the element Discovery, isolation and synthesis Synthesis of transuranium elements[10][11] Element Year Method Neptunium 1940 Bombarding 238U by neutrons Plutonium 1941 Bombarding 238U by deuterons Americium 1944 Bombarding 239Pu by neutrons Curium 1944 Bombarding 239Pu by αparticles Berkelium 1949 Bombarding 241Am by α-particles Californium 1950 Bombarding 242Cm by α-particles Einsteinium 1952 As a product of nuclear explosion Mendelevium 1955 Bombarding 253Es by α-particles Nobelium 1965 Bombarding 243Am by 15N or 238U with 22Ne Lawrencium 1961–1971 Bombarding 252Cf by 10B or 11Band of 243Am with 18O Like the lanthanides, the actinides form a family of elements with similar properties. Within the actinides, there are two overlapping groups: transuranium elements, which follow uranium in the periodic table: and transplutonium elements, which follow plutonium. Compared to the lanthanides, which (except for promethium) are found in nature in appreciable quantities, most actinides are rare. Most do not occur in nature, and of those that do, only thorium and uranium do so in more than trace quantities. The most abundant or easily synthesized actinides are uranium and thorium, followed by plutonium, americium, actinium, neptunium, and curium.[12] The existence of transuranium elements was suggested in 1934 by Enrico Fermi, based on his experiments.[13][14] However, even though four actinides were known by that time, it was not yet understood that they formed a family similar to lanthanides. The prevailing view that dominated early research into transuranics was that they were regular elements in the 7th period, with thorium, protactinium and uranium corresponding to 6th-period hafnium, tantalum and tungsten, respectively. Synthesis of transuranics gradually undermined this point of view. By 1944, an observation that curium failed to exhibit oxidation states above 4 (whereas its supposed 6th period homolog, platinum, can reach oxidation state of 6) prompted Glenn Seaborg to formulate an "actinide hypothesis". Studies of known actinides and discoveries of further transuranic elements provided more data in support of this position, but the phrase "actinide hypothesis" (the implication being that a "hypothesis" is something that has not been decisively proven) remained in active use by scientists through the late 1950s. [15][16] At present, there are two major methods of producing isotopes of transplutonium elements: (1) irradiation of the lighter elements with neutrons; (2) irradiation with accelerated charged particles. The first method is more important for applications, as only neutron irradiation using nuclear reactors allows the production of sizeable amounts of synthetic actinides; however, it is limited to relatively light elements. The advantage of the second method is that elements heavier than plutonium, as well as neutron-deficient isotopes, can be obtained, which are not formed during neutron irradiation.[17] In 1962–1966, there were attempts in the United States to produce transplutonium isotopes using a series of six underground nuclear explosions. Small samples of rock were extracted from the blast area immediately after the test to study the explosion products, but no isotopes with mass number greater than 257 could be detected, despite predictions that such isotopes would have relatively long half-lives of  $\alpha$ -decay. This non-observation was attributed to spontaneous fission owing to the large speed of the products and to other decay. channels, such as neutron emission and nuclear fission.[18] From actinium to uranium Enrico Fermi suggested the existence of transuranium and thorium were the first actinides discovered. Uranium was identified in 1789 by the German chemist Martin Heinrich Klaproth in pitchblende ore. He named it after the planet Uranus,[8] which had been discovered eight years earlier. Klaproth was able to precipitate a yellow compound (likely sodium diuranate) by dissolving pitchblende in nitric acid and neutralizing the solution with sodium hydroxide. He then reduced the obtained yellow powder with charcoal, and extracted
a black substance that he mistook for metal. [19] Sixty years later, the French scientist Eugène-Melchior Péligot identified it as uranium oxide. He also isolated the first sample of uranium metal by heating uranium tetrachloride with metallic potassium. [20] The atomic mass of uranium was then calculated as 120, but Dmitri Mendeleev in 1872 corrected it to 240 using his periodicity laws. This value was confirmed experimentally in 1882 by K. Zimmerman. [21][22] Thorium oxide was discovered by Friedrich Wöhler in the mineral Thorianite, which was found in Norway (1827).[23] Jöns Jacob Berzelius characterized this material in more detail by in 1828. By reduction of thorium tetrachloride with potassium, he isolated the metal and named it thorium after the Norse god of thunder and lightning Thor.[24][25] The same isolation method was later used by Péligot for uranium.[8] Actinium was discovered in 1899 by André-Louis Debierne, an assistant of Marie Curie, in the pitchblende waste left after removal of radium and polonium. He described the substance (in 1899) as similar to titanium[26] and (in 1900) as similar to thorium.[27] The discovery of actinium by Debierne was however questioned in 1971[28] and 2000,[29] arguing that Debierne's publications in 1904 contradicted his earlier work of 1899–1900. This view instead credits the 1902 work of Friedrich Oskar Giesel, who discovered a radioactive element named emanium that behaved similarly to lanthanum. The name actinium comes from the Greek aktis, aktinos (ακτίς, ακτίνος), meaning beam or ray. This metal was discovered not by its own radiation but by the radiation of the daughter products. [30][31] Owing to the close similarity of actinium and lanthanum and low abundance, pure actinium could only be produced in 1950. The term actinide was probably introduced by Victor Goldschmidt in 1937.[32][33] Protactinium was possibly isolated in 1900 by William Crookes.[34] It was first identified in 1913, when Kasimir Fajans and Oswald Helmuth Göhring encountered the short-lived isotope 234mPa (half-life 1.17 minutes) during their studies of the 238U decay. They named the new element brevium (from Latin brevis meaning brief);[35][36] the name was changed to protoactinium (from Greek πρῶτος + ἀκτίς meaning "first beam element") in 1918 when two groups of scientists, led by the Austrian Lise Meitner and Otto Hahn of Germany and Frederick Soddy and John Cranston of Great Britain, independently discovered the much longer-lived 231Pa. The name was shortened to protactinium in 1949. This element was little characterized until 1960, when A. G. Maddock and his co-workers in the U.K. isolated 130 grams of protactinium from 60 tonnes of waste left after extraction of uranium from its ore.[37] Neptunium (named for the planet Neptune, the next planet out from Uranus, after which uranium was named) was discovered by Edwin McMillan and Philip H. Abelson in 1940 in Berkeley, California.[38] They produced the 239Np isotope (half-life = 2.4 days) by bombarding uranium with slow neutrons.[37] It was the first transuranium element produced synthetically.[39] Glenn T. Seaborg and his group at the University of California at Berkeley synthesized Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No and element 106, which was later named seaborgium in his honor while he was still living. They also synthesized more than a hundred actinide isotopes. Transuranium elements do not occur in sizeable quantities in nature and are commonly synthesized via nuclear reactions conducted with nuclear reactors. For example, under irradiation with reactor neutrons, uranium-238 partially converts to plutonium-239: U 92 238 + n 0 1  $\rightarrow$  U 92 239  $\rightarrow$  23.5 min  $\beta$  - Np 93 239  $\rightarrow$  2.3 days  $\beta$  - Pu 94 239 ( $\rightarrow$  2.4  $\cdot$  10 4 years  $\alpha$ ) U 92 235 {\displaystyle {\ce}  ${^239}U + {0}^{1}n - {} {92}^{239}U - [\beta ^{-}][23.5] {\ce {min}}} {93}^{239}Np - [\beta ^{-}][2.3] {\ce {days}}} {94}^{239}Pu} \\eft({\ce {->[\alpha][2.4\cdot 10^{4}] {\ce {years}}}} \\eft({\ce {->[\alpha][2.4\cdot 10^{4}] {\ce {years}}} {10^{4}} {10^{4}} {\ce {years}}} {10^{4}} {10^{4}} {10^{4}} {\ce {years}} {10^{4}} {10^{4}} {\ce {years}} {10^{4}} {10^{4}} {\ce {years}} {10^{4}} {10^{4}} {\ce {years}} {10^{4}} {10$ reactors located at the Hanford Site, which produced significant amounts of plutonium-239 for the nuclear weapons of the Manhattan Project and the United States' post-war nuclear arsenal.[40] Actinides with the highest mass numbers are synthesized by bombarding uranium, plutonium, curium and californium with ions of nitrogen, oxygen, carbon, neon or boron in a particle accelerator. Thus nobelium was produced by bombarding uranium-238 with neon-22 as U 92 238 + Ne 10 22  $\rightarrow$  No 102 256 + 4 0 1 n {\displaystyle {\ce {\_{92}^{238}U + \_{10}^{22}Ne -> \_{102}^{256}No + 4 0^1n}}. The first isotopes of transplutonium elements, americium-241 and curium-242, were synthesized in 1944 by Glenn T. Seaborg, Ralph A. James and Albert Ghiorso. [41] Curium-242 was obtained by bombarding plutonium-239 with 32-MeV  $\alpha$ -particles Pu 94 239 + He 2 4  $\rightarrow$  Cm 96 242 + n 0 1 {\displaystyle {\ce} { {94}^{239}Pu + 2^4He -> {96}^{242}Cm + 0^1n}}. The americium-241 and curium-242 isotopes also were produced by irradiating plutonium in a nuclear reactor. The latter element was named after Marie Curie and her husband Pierre who are noted for discovering radium and for their work in radioactivity.[42] Bombarding curium-242 with α-particles resulted in an isotope of californium 245Cf (1950), and a similar procedure yielded in 1949 berkelium-243 from americium-241.[43] The new elements were named after Berkeley, California, by analogy with its lanthanide homologue terbium, which was named after the village of Ytterby in Sweden.[44] In 1945, B. B. Cunningham obtained the first bulk chemical compound of a transplutonium element, namely americium hydroxide.[45] Over the few years, milligram quantities of americium and microgram amounts of curium were accumulated that allowed production of isotopes of berkelium (Thomson, 1949)[46][47] and californium (Thomson, 1950).[48][49][50] Sizeable amounts of these elements were produced in 1958 (Burris B. Cunningham and Stanley G. Thomson),[51] and the first californium compound (0.3 µg of CfOCI) was obtained in 1960 by B. B. Cunningham and J. C. Wallmann.[52] Einsteinium and fermium were identified in 1952–1953 in the fallout from the "Ivy Mike" nuclear test (1 November 1952), the first successful test of a hydrogen bomb. Instantaneous exposure of uranium-238 to a large neutron flux resulting from the explosion produced heavy isotopes of uranium, including uranium-253 and uranium-255, and their \beta-decay yielded einsteinium-255. The discovery of the new elements and the new data on neutron capture were initially kept secret on the orders of the US military until 1955 due to Cold War tensions.[9][53] Nevertheless, the Berkeley team were able to prepare einsteinium and fermium by civilian means, through the neutron bombardment of plutonium-239, and published this work in 1954 with the disclaimer that it was not the first studies that had been carried out on those elements.[54][55] The "Ivy Mike" studies were declassified and published in 1955.[53] The first significant (submicrograms) amounts of einsteinium were produced in 1961 by Cunningham and colleagues, but this has not been done for fermium yet.[56] The first isotope of mendelevium, 256Md (half-life 87 min), was synthesized by Albert Ghiorso, Glenn T. Seaborg, Gregory R. Choppin, Bernard G. Harvey and Stanley G. Thompson when they bombarded an 253Es target with alpha particles in the 60-inch cyclotron of Berkeley Radiation Laboratory; this was the first isotope of any element to be synthesized one atom at a time.[57] There were several attempts to obtain isotopes of nobelium by Swedish (1957) and American (1958) groups, but the first reliable result was the synthesis of 256No by the Russian group (Georgy Flyorov et al.) in 1965, as acknowledged by the IUPAC in 1992. In their experiments, Flyorov et al. al. bombarded uranium-238 with neon-22.[10] In 1961, Ghiorso et al. obtained the first isotope of lawrencium by irradiating californium-252) with boron-10 and boron-11 ions.[10] The mass number of this isotope
was not clearly established (possibly 258 or 259) at the time. In 1965, 256Lr was synthesized by Flyorov et al. from 243Am and 18O. Thus IUPAC recognized the nuclear physics teams at Dubna and Berkeley as the co-discoverers of lawrencium. Isotopes Nuclear properties of isotopes of the most important transplutonium isotopes [58][59][60] Isotope Half-life Probability of spontaneousfission in % Emission energy(MeV) (yield in %) Specific activity (Bg/kg)[61] of  $\alpha$  y  $\alpha$ ,  $\beta$ -particles fission 241Am 432.2(7) y 4.3(18)×10-10 5.485 (84.8) 5.442 (13.1)5.388 (1.66) 0.059 (35.9)0.026 (2.27) 1.27×1014 546.1 243Am 7.37(4)×103 y 3.7(2)×10-9 5.275 (87.1)5.233 (11.2)5.181 (1.36) 0.074 (67.2) 0.043 (5.9) 7.39×1012 273.3 242Cm 162.8(2) d 6.2(3)×10-6 6.069 (25.92)6.112 (74.08) 0.044 (0.04)0.102 (4×10-3) 1.23×1017 7.6×109 244Cm 18.10(2) y 1.37(3)×10-4 5.762 (23.6)5.804 (76.4) 0.043 (0.02)0.100 (1.5×10-3) 2.96×1015 4.1×109 245Cm 8.5(1)×103 y 6.1(9)×10-7 5.529 (0.58)5.488 (0.83)5.361 (93.2) 0.175 (9.88)0.133 (2.83) 6.35×1012 3.9×104 246Cm 4.76(4)×103 y 0.02615(7) 5.343 (17.8)5.386 (82.2) 0.045 (19) 1.13×1013 2.95×109 247Cm 1.56(5)×107 y - 5.267 (13.8)5.212 (5.7)5.147 (1.2) 0.402 (72)0.278 (3.4) 3.43×109 - 248Cm 3.48(6)×105 y 8.39(16) 5.034 (16.52)5.078 (75) - 1.40×1011 1.29×1010 249Bk 330(4) d 4.7(2)×10-8 5.406 (1×10-3)5.378 (2.6×10-4) 0.32 (5.8×10-5) 5.88×1016 2.76×107 249Cf 351(2) v 5.0(4)×10-7 6.193 (2.46)6.139 (1.33)5.946 (3.33) 0.388 (66)0.333 (14.6) 1.51×1014 7.57×105 250Cf 13.08(9) v 0.077(3) 5.988 (14.99)6.030 (84.6) 0.043 4.04×1015 3.11×1012 251Cf 900(40) y ? 6.078 (2.6)5.567 (0.9)5.569 (0.9) 0.177 (17.3)0.227 (6.8) 5.86×1013 - 252Cf 2.645(8) y 3.092(8) 6.075 (15.2)6.118 (81.6) 0.042 (1.4×10-2)0.100 (1.3×10-2) 1.92×1016 6.14×1014 254Cf 60.5(2) d ≈100 5.834 (0.26)5.792 (5.3×10-2) - 9.75×1014 3.13×1017 253Es 20.47(3) d 8.7(3)×10-6 6.540 (0.85)6.552 (0.71)6.590 (6.6) 0.387 (0.05)0.429 (8×10-3) 9.33×1017 8.12×1010 254Es 275.7(5) d < 3×10-6 6.347 (0.75)6.358 (2.6)6.415 (1.8) 0.042 (100)0.034 (30) 6.9×1016 - 255Es 39.8(12) d 0.0041(2) 6.267 (0.78)6.401 (7) -4.38×1017(β)3.81×1016(α) 1.95×1013 255Fm 20.07(7) h 2.4(10)×10-5 7.022 (93.4)6.963 (5.04)6.892 (0.62) 0.00057 (19.1)0.081 (1) 2.27×1019 5.44×1012 256Fm 157.6(13) min 91.9(3) 6.872 (1.2)6.917 (6.9) - 1.58×1020 1.4×1019 257Fm 100.5(2) d 0.210(4) 6.752 (0.58)6.695 (3.39)6.622 (0.6) 0.241 (11)0.179 (8.7) 1.87×1017 3.93×1014 256Md 77(2) min - 7.142 (1.84)7.206 (5.9) - 3.53×1020 - 257Md 5.52(5) h - 7.074 (14) 0.371 (11.7)0.325 (2.5) 8.17×1019 - 258Md 51.5(3) d - 6.73 - 3.64×1017 - 255No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (3.4) 8.78×1021 - 259No 3.1(2) min - 8.312 (1.16)8.266 (2.6)8.121 (27.8) 0.187 (2.6) (2.6)8.121 (27.8) 0.187 (27.8) 0.187 (27.8) 0.187 (27.8) 0.187 (27.8) 0.187 (27.8) 0.187 (27.8) 0.187 (27.8) 0 58(5) min — 7.455 (9.8)7.500 (29.3)7.533 (17.3) — 4.63×1020 — 256Lr 27(3) s < 0.03 8.319 (5.4)8.390 (16)8.430 (33) — 5.96×1022 — 257Lr 646(25) ms — 8.796 (18)8.861 (82) — 1.54×1024 — Actinides have 89-103 protons and usually 117-159 neutrons. 32 isotopes of actinium and eight excited isomeric states of some of its nuclides were identified by 2016.[58] Three isotopes, 225Ac, 227Ac and 228Ac, were found in nature and the others were produced in the laboratory; only the three natural isotopes are used in applications. Actinium-225 is a member of the radioactive neptunium series;[62] it was first discovered in 1947 as a decay product of uranium-233, it is an α-emitter with a half-life of 10 days. Actinium-225 is less available than actinium-228, but is more promising in radiotracer applications.[31] Actinium-227 (half-life 21.77 years) occurs in all uranium ores, but in small quantities. One gram of uranium (in radioactive equilibrium) contains only 2×10-10 gram of 227Ac.[31][58] Actinium-228 is a member of the radioactive thorium series formed by the decay of 228Ra;[62] it is a β- emitter with a half-life of 6.15 hours. In one tonne of thorium there is 5×10-8 gram of 228Ac. It was discovered by Otto Hahn in 1906.[31] There are 31 known isotopes of thorium ranging in mass number from 208 to 238.[58] Of these, the longest-lived is 232Th, whose half-life of 1.4×1010 years means that it still exists in nature as a primordial nuclide. The next longest-lived is 230Th, an intermediate decay product of 238U with a half-life of 75,400 years. Several other thorium isotopes have half-lives over a day; all of these are also transient in the decay chains of 232Th, 235U, and 238U. 28 isotopes of protactinium are known with mass numbers 212–239[58] as well as three excited isomeric states. Only 231Pa and 234Pa have been found in nature. All the isotopes have short lifetimes, except for protactinium-231 (half-life 32,760 years). The most important isotopes are 231Pa and 233Pa, which is an intermediate product in obtaining uranium-233 and is the most affordable among artificial isotopes of protactinium. 233Pa has convenient half-life and energy of y-radiation, and thus was used in most studies of protactinium chemistry. Protactinium-233 is a β-emitter with a half-life of 26.97 days. [58][63] There are 26 known isotopes of uranium, having mass numbers 215–242 (except 220 and 241). [59] Three of them, 234U, 235U and 238U, are present in appreciable quantities in nature. Among others, the most important is 233U, which is a final product of transformation of 232Th irradiated by slow neutrons. 233U has a much higher fission efficiency by low-energy (thermal) neutrons, compared e.g. with 235U. Most uranium chemistry studies were carried out on uranium-238 owing to its long half-life of 4.4×109 years.[64] There are 24 isotopes of neptunium with mass numbers of 219, 220, and 223–244;[59] they are all highly radioactive. The most popular among scientists are long-lived 237Np (t1/2 = 2.20×106 years) and short-lived 239Np, 238Np (t1/2 ~ 2 days).[39] Eighteen isotopes of americium are known with mass numbers from 229 to 247 (with the exception of 231).[59] The most important are 241Am and 243Am, which are alpha-emitters and also emit soft, but intense y-rays; both of them can be obtained in an isotopically pure form. Chemical properties of americium were first studied with 241Am, but later shifted to 243Am, which is almost 20 times less radioactive. The disadvantage of 243Am is production of the short-lived daughter isotope 239Np, which has to be considered in the data analysis.[65] Among 19 isotopes of curium, ranging in mass number from 233 to 251,[59] the most accessible are 242Cm and 244Cm; they are α-emitters, but with much shorter lifetime than the americium isotopes. These isotopes emit almost no y-radiation, but undergo spontaneous fission with the associated emission of neutrons. More long-lived isotopes of curium (245–248Cm, all  $\alpha$ -emitters) are formed as a mixture during neutron irradiation, this mixture is dominated by 246Cm, and then 248Cm begins to accumulate. Both of these isotopes, especially 248Cm, have a longer half-life (3.48×105 years) and are much more convenient for carrying out chemical research than 242Cm and 244Cm, but they also have a rather high rate of spontaneous fission. 247Cm has the longest lifetime among isotopes of curium (1.56×107 years), but is not formed in large quantities because of the strong fission induced by thermal neutrons. Seventeen isotopes of berkelium were identified with mass numbers 233–234, 236, 238, and 240–252.[59] Only 249Bk is available in large quantities; it has a relatively short half-life of 330 days and emits mostly soft βparticles, which are inconvenient for detection. Its alpha radiation is rather weak (1.45×10-3% with respect to β-radiation), but is sometimes used to detect this isotope. 247Bk is an alpha-emitter with a long half-life of 1,380 years, but it is hard to obtain in appreciable quantities; it is not formed upon neutron irradiation of plutonium because of the  $\beta$ -stability of isotopes of curium isotopes with mass number below 248.[65] The 20 isotopes of californium with mass numbers 237–256 are formed in nuclear reactors;[59] californium-253 is a  $\beta$ -emitter and the rest are  $\alpha$ -emitters. The isotopes with even mass numbers (250Cf, 252Cf and 254Cf) have a high rate of spontaneous fission, especially 254Cf of which 99.7% decays by spontaneous fission. Californium-249 has a relatively long
half-life (352 years), weak spontaneous fission and strong y-emission that facilitates its identification. 249Cf is not formed in large guantities in a nuclear reactor because of the slow \beta-decay of the parent isotope 249Bk and a large cross section of interaction with neutrons, but it can be accumulated in the isotopically pure form as the \beta-decay product of (pre-selected) 249Bk. Californium produced by reactor-irradiation of plutonium mostly consists of 250Cf and 252Cf, the latter being predominant for large neutron fluences, and its study is hindered by the strong neutron radiation.[66] Properties of some transplutonium isotope pairs[67] Parent isotope t1/2 Daughter isotope t1/2 Time to establish radioactive equilibrium 243Am 7370 years 239Np 2.35 days 47.3 days 245Cm 8265 years 241Pu 14 years 129 years 247Cm 1.64×107 years 243Pu 4.95 hours 7.2 days 250Bk 3.2 hours 35.2 hours 35.2 hours 255Es 39.8 days 255Fm 22 hours 5 days 257Fm 79 days 253Cf 17.6 days 49 days Among the 18 known isotopes of einsteinium with mass numbers from 240 to 257,[59] the most affordable is 253Es. It is an  $\alpha$ -emitter with a half-life of 20.47 days, a relatively weak y-emission and small spontaneous fission rate as compared with the isotopes of californium. Prolonged neutron irradiation also produces a longlived isotope 254Es (t1/2 = 275.5 days).[66] Twenty isotopes of fermium are known with mass numbers of 241–260. 254Fm, 255Fm and 256Fm are α-emitters with a short half-life (hours), which can be isolated in significant amounts. 257Fm (t1/2 = 100 days) can accumulate upon prolonged and strong irradiation. All these isotopes are characterized by high rates of spontaneous fission.[66][68] Among the 17 known isotopes of mendelevium (mass numbers from 244 to 260),[59] the most studied is 256Md, which mainly decays through the electron capture (α-radiation is ≈10%) with the half-life of 77 minutes. Another alpha emitter, 258Md, has a half-life of 53 days. Both these isotopes are produced from rare einsteinium (253Es respectively), that therefore limits their availability.[58] Long-lived isotopes of nobelium and isotopes of lawrencium (and of heavier elements) have relatively short half-lives. For nobelium, 11 isotopes are known with mass numbers 250–260 and 262. The chemical properties of nobelium and lawrencium were studied with 255No (t1/2 = 3 min) and 256Lr (t1/2 = 3 s). The longest-lived nobelium isotope, 259No, has a half-life of approximately 1 hour.[58] Lawrencium has 13 known isotopes with mass numbers 251–262 and 266. The most stable of them all is 266Lr with a half life of 11 hours. Among all of these, the only isotopes that occur in sufficient quantities in nature to be detected in anything more than traces and have a measurable contribution to the atomic weights of the actinides are the primordial 232Th, 235U, and 238U, and three long-lived decay products of natural uranium, 230Th, 231Pa, and 234U. Natural thorium consists of 0.02(2)% 230Th and 99.98(2)% 232Th; natural protactinium consists of 100% 231Pa; and natural uranium consists of 0.0054(5)% 234U, 0.7204(6)% 235U, and 99.2742(10)% 238U.[69] Formation in nuclear reactors Table of nuclides: Buildup of actinides in a nuclear reactor, including radioative decay The figure buildup of actinides is a table of nuclides with the number of neutrons on the horizontal axis (isotopes) and the number of protons on the vertical axis (elements). The red dot divides the nuclides in two groups, so the figure is more compact. Each nuclide is represented by a square with the mass number of the element and its half-time.[70] Naturally existing actinide isotopes (Th. U) are marked with a bold border. alpha emitters have a yellow colour, and beta emitters have a blue colour. Pink indicates electron capture (236Np), whereas white stands for a long-lasting metastable state (242Am). The formation of actinide nuclides is primarily characterised by:[71] Neutron capture reactions (n,y), which are represented in the figure by a short right arrow. The (n,2n) reactions and the less frequently occurring (y,n) reactions are also taken into account, both of which are marked by a short left arrow. Even more rarely and only triggered by fast neutrons, the (n,3n) reaction occurs, which is represented in the figure with one example, marked by a long left arrow. In addition to these neutron- or gamma-induced nuclear reactions, the radioactive conversion of actinide nuclides also affects the nuclide inventory in a reactor. These decay types are marked in the figure by diagonal arrows. The beta-minus decay, marked with an arrow pointing up-left, plays a major role for the balance of the particle densities of the nuclides. Nuclides decaying by positron emission (beta-plus decay) or electron capture (c) do not occur in a nuclear reactor except as products of knockout reactions; their decays are marked with arrows pointing downright. Due to the long half-lives of the given nuclides, alpha decay plays almost no role in the formation and decay of the actinides in a power reactor, as the residence time of the nuclear fuel in the reactor core is rather short (a few years). Exceptions are the two relatively short-lived nuclides 242Cm (T1/2 = 163 d) and 236Pu (T1/2 = 2.9 y). Only for these two cases, the α decay is marked on the nuclide map by a long arrow pointing down-left. Distribution in nature Unprocessed uranium ore Thorium and uranium are the most abundant actinides in nature with the respective mass concentrations of 16 ppm and 4 ppm.[72] Uranium mostly occurs in the Earth's crust as a mixture of its oxides in the mineral uraninite, which is also called pitchblende because of its black color. There are several dozens of other uranium minerals such as carnotite (KUO2VO4·3H2O) and autunite (Ca(UO2)2(PO4)2·nH2O) The isotopic composition of natural uranium is 238U (relative abundance 99.2742%), 235U (0.7204%) and 234U (0.0054%); of these 238U has the largest half-life of 4.51×109 years. [73][74] The worldwide production of uranium in 2009 amounted to 50,572 tonnes, of which 27.3% was mined in Kazakhstan. Other important uranium mining countries are Canada (20.1%), Australia (15.7%), Namibia (9.1%), Russia (7.0%), and Niger (6.4%).[75] Content of plutonium in uranium and thorium ores[76] Ore Location Uranium content, % Mass ratio 239Pu/Ore Ratio 239Pu/U (×1012) Uraninite Canada  $13.5 9.1 \times 10 - 12 7.1$  Uraninite Congo  $38 4.8 \times 10 - 12 12$  Uraninite Colorado, US 50  $3.8 \times 10 - 12 7.7$  Monazite Brazil  $0.24 2.1 \times 10 - 14 8.3$  Monazite North Carolina, US  $1.64 5.9 \times 10 - 14 3.6$  Fergusonite - 0.25 [{\ce {>500^{(circ }C}]} U{}+2MgF2}} Among the actinides, thorium and uranium are the easiest to isolate. Thorium is extracted mostly from monazite: thorium pyrophosphate (ThP2O7) is reacted with nitric acid, and the produced thorium nitrate treated with tributyl phosphate. Rare-earth impurities are separated by increasing the pH in sulfate solution.[78] In another extraction method, monazite is decomposed with a 45% aqueous solution of sodium hydroxide at 140 °C. Mixed metal hydroxides are extracted first, filtered at 80 °C, washed with water and dissolved with concentrated hydrochloric acid. Next, the acidic solution is neutralized with hydroxides to pH = 5.8 that results in precipitation of thorium hydroxide (Th(OH)4) contaminated with ~3% of rare-earth hydroxides; the rest of rare-earth hydroxide is dissolved in an inorganic acid and then purified from the rare earth elements. An efficient method is the dissolution of thorium hydroxide in nitric acid, because the resulting solution can be purified by extraction with organic solvents: [78] Separation of uranium and plutonium from nuclear fuel [79] Th(OH)4 + 4 HNO3 - Th(NO3)4 + 4 H2O Metallic thorium is separated from the anhydrous oxide, chloride or fluoride by reacting it with calcium in an inert atmosphere: [80] ThO2 + 2 Ca - 2 CaO + Th Sometimes thorium is extracted by electrolysis of a fluoride in a mixture of sodium and potassium chloride at 700–800 °C in a graphite crucible. Highly pure thorium can be extracted from its iodide with the crystal bar process. [81] Uranium is extracted from its ores in various ways. In one method, the ore is burned and then reacted with nitric acid to convert uranium into a dissolved state. Treating the solution of tributyl phosphate (TBP) in kerosene transforms uranium into a dissolved state. filtered and the uranium is extracted by reaction with hydroxides as (NH4)2U2O7 or with hydrogen peroxide as UO4.2H2O.[78] When the uranium ore is rich in such minerals as dolomite, magnesite, etc., those minerals consume much acid. In this case, the carbonate method is used for uranium extraction. Its main component is an aqueous solution of sodium carbonate, which converts uranium into a complex [UO2(CO3)3]4-, which is stable in aqueous solutions at low concentrations of hydroxide ions. The advantages of the sodium carbonate method are that the chemicals have low corrosivity (compared to nitrates) and that most non-uranium metals precipitate from the solution. The disadvantage is that tetravalent uranium ore is treated with sodium carbonate at elevated temperature and under oxygen pressure: 2 UO2 + O2 + 6 CO2-3 -2 [UO2(CO3)3]4- This equation suggests that the best solvent for the uranium carbonate processing is a mixture of carbonate. At high pH, this results in precipitation of diuranate, which is treated with hydrogen in the presence of nickel yielding an insoluble uranium tetracarbonate. [78] Another separation method uses polymeric resins as a polyelectrolyte. Ion exchange processes in the resins result in separation of uranium. Uranium from resins is washed with a solution of ammonium nitrate or nitric acid that yields uranyl nitrate, UO2(NO3)2.6H2O. When heated, it turns into UO3, which is converted to UO2 with hydrogen: UO3 + H2  $\rightarrow$  UO2 + H2O Reacting uranium dioxide with
hydrofluoric acid changes it to uranium tetrafluoride, which yields uranium metal upon reaction with magnesium metal: [80] 4 HF + UO2  $\rightarrow$  UF4 + 2 H2O To extract plutonium, neutron-irradiated uranium is dissolved in nitric acid, and a reducing agent (FeSO4, or H2O2) is added to the resulting solution. This addition changes the oxidation state of plutonium from +6 to +4, while uranium remains in the form of uranyl nitrate (UO2(NO3)2). The solution is treated with a reducing agent and neutralized with ammonium carbonate to pH = 8 that results in precipitation of Pu4+ compounds.[78] In another method, Pu4+ and UO2+2 are first extracted with hydrazine washing out the recovered plutonium.[78] The major difficulty in separation of actinium is the similarity of its properties with those of lanthanum. Thus actinium is either synthesized in nuclear reactions from isotopes of radium or separated using ion-exchange procedures.[31] Properties Actinides have similar properties to lanthanides. The 6d and 7s electronic shells are filled in actinium and thorium, and the 5f shell is being filled with further increase in atomic number; the 4f shell is filled in the lanthanides. The first experimental evidence for the filling of the 5f shell in actinides was obtained by McMillan and Abelson in 1940.[82] As in lanthanides (see lanthanide contraction), the ionic radius of actinides monotonically decreases with atomic number (see also Aufbau principle).[83] Properties of actinides (the mass of the most long-lived isotope is in square brackets)[74][84] Element Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr Core charge (Z) 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 --- Natural guantity isotopes - 230, 232 231 234, 235, 238 - --- --- --- Longest-lived isotope 227 232 231 238 237 244 243 247 251 252 257 258 259 266 Half-life of the longest-lived isotope 21.8 years 14 billion years 32.500 years 4.47 billion years 2.14 million years 2.14 million years 32.500 years 4.47 billion years 2.14 million years 2.14 million years 32.500 years 4.47 billion years 2.14 million years 2.14 million years 32.500 years 4.47 billion years 2.14 million years 2.14 million years 32.500 years 4.47 billion years 2.14 million years 32.500 years 4.47 billion years 32.500 years 4.47 billion years 2.14 million years 32.500 years 4.47 billion years 32. 80.8 million years 7,370 years 15.6 million years 1,380 years 900 years 1.29 years 100.5 days 52 days 58 min 11 hours Most common isotope 227 232 231 238 237 239 241 244 249 252 253 255 260 Half-life of the most common isotope 21.8 years 14 billion years 32,500 years 4.47 billion years 2.14 million years 24,100 years 433 years 18.1 years 320 days 2.64 years 20.47 days 20.07 hours 78 min 3.1 min 2.7 min Electronic configuration in the ground state (gas phase) 6d17s2 5f26d17s2 5f26d17s2 5f36d17s2 5f46d17s2 5f67s2 5f76d17s2 5f97s2 5f97s2 5f107s2 5f117s2 5f127s2 5f26d17s2 5f 5f147s27p1 Oxidation states 2, 3 2, 3, 4 2, 3, 4 5, 6, 7 3, 4, 5, 6, 7 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 5, 6, 7 2, 3, 4, 2, 3 2, 3 2, 3 3 Metallic radius (nm) 0.203 0.180 0.162 0.153 0.150 0.162 0.173 0.174 0.170 0.186 0.186 ? 0.198 ? 0.198 ? 0.197 ? 0.171 Ionic radius (nm): An4+An3+ 0.126 0.114 - 0.104 0.118 0.103 0.118 0.101 0.116 0.100 0.115 0.099 0.114 0.099 0.112 0.097 0.110 0.096 0.109 0.084 0.091 0.084 0.095 0.083 0.088 Temperature (°C):melting boiling 10503198 18424788 1568? 4027 1132.24131 639? 4174 639.43228 1176? 2607 13403110 9862627 900? 1470 860? 996 1530— 830— 830— 1630— Density, g/cm3 10.07 11.78 15.37 19.06 20.45 19.84 11.7 13.51 14.78 15.1 8.84 ? 9.7 ? 10.3 ? 9.9 ? 14.4 Standard electrode potential (V): E° (An4+/An0)E° (An3+/An0) - -2.13 - 1.83 - -1.47 - -1.38 - 1.66 - 1.30 - 1.79 - 1.25 -2.00 -0.90 -2.07 -0.75 -2.06 -0.55 -1.96 -0.55 -1.96 -0.55 -1.97 -0.36 -1.98 -0.29 -1.96 - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Purple Brown Violet Red Rose Yellow Colorless Beige Yellow-green Green Green Green - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Purple Brown Violet Red Rose Yellow Colorless Beige Yellow-green Green Green Green Green - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Purple Brown Violet Red Rose Yellow Colorless Beige Yellow-green Green Green Green Green - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Purple Brown Violet Red Rose Yellow Colorless Beige Yellow-green Green Green - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Purple Brown Violet Red Rose Yellow Colorless Beige Yellow-green Green Green - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Purple Brown Violet Red Rose Yellow Colorless Beige Yellow-green Green Green - -1.74 - -1.20 - -2.10 Color: [M(H2O)n]3+ - Colorless Blue Yellow Dark blue Green Purple Yellow-green Pur Pink — — — — — — — — Approximate colors of actinide ions in aqueous solutionColors for the actinides 100–103 are unknown as sufficient quantities have not yet been synthesized [87] Actinide (Z) 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 Oxidation state +2 Fm2+ Md2+ No2+ +3 Ac3+ Th3+ Pa3+ U3+ Np3+ Pu3+ Am3+ Cm3+ Bk3+ Cf3+ Es3+ Fm3+ Md3+ No3+ Lr3+ +4 Th4+ Pa4+ U4+ Np4+ Pu4+ Am4+ Cf4+ +5 PaO+2 UO+2 NpO+2 PuO+2 AmO+2 +6 UO2+2 NpO2+2 PuO2+2 AmO2+2 +7 NpO3+2 PuO3+2 AmO3-5 Physical properties Major crystal structures of some actinides vs. temperature Metallic and joinc radii of actinides[84] A pellet of 238PuO2 to be used in a radioisotope thermoelectric generator for either the Cassini or Galileo mission. The pellet produces 62 watts of heat and glows because of the heat generated by the radioactive decay (primarily g). Photo is taken after insulating the pellet under a graphite blanket for minutes and removing the blanket. Californium Actinides are typical metals. All of them are soft and have a silvery color (but tarnish in air),[88] relatively high density and plasticity. Some of them can be cut with a knife. Their electrical resistivity varies between 15 and 150 µOhm cm.[84] The hardness of thorium is similar to that of soft steel, so heated pure thorium can be rolled in sheets and pulled into wire. Thorium is nearly half as dense as uranium and plutonium, but is harder than either of them. All actinides are radioactive, paramagnetic, and, with the exception of actinium, have several crystalline phases: plutonium has seven, and uranium, neptunium and californium three. The crystal structures of protactinium, neptunium and plutonium do not have clear analogs among the lanthanides and are more similar to those of the 3dtransition metals.[74] All actinides are pyrophoric, especially when finely divided, that is, they spontaneously ignite upon reaction with air at room temperature.[88][89] The melting point of actinides does not have a clear dependence on the number of f-electrons. The unusually low melting point of neptunium and plutonium (~640 °C) is explained by hybridization of 5f and 6d orbitals and the formation of directional bonds in these metals.[74] Comparison of ionic radii of lanthanides and actinides[90] Lanthanides Ln3+, Å Actinides An3+, Å An4+, Å Lanthanum 1.061 Actinium 1.11 – Cerium 1.034 Thorium 1.08 0.99 Praseodymium 1.013 Protactinium 1.05 0.93 Neodymium 0.995 Uranium 1.03 0.93 Promethium 0.979 Neptunium 1.00 0.90 Europium 0.950 Americium 0.99 0.89 Gadolinium 0.938 Curium 0.98 0.88 Terbium 0.923 Berkelium – – Dysprosium 0.908 Californium – – Holmium 0.894 Einsteinium – – Erbium 0.881 Fermium – – Thulium 0.869 Mendelevium – – Vtterbium 0.858 Nobelium – – Chemical properties Like the lanthanides, all actinides are highly reactive with halogens and chalcogens; however, the actinides react more easily. Actinides, especially those with a small number of 5f-electrons, are prone to hybridization. This is explained by the similarity of the electron energies at the 5f, 7s and 6d shells. Most actinides exhibit a larger variety of valence states, and the most stable are +6 for uranium, +5 for protactinium and neptunium, +4 for thorium and plutonium and +3 for actinium and other actinides.[91] Actinium is chemically similar to lanthanum, which is explained by their similar ionic radii and electronic structures. Like lanthanum, actinium almost always has an oxidation state of +3 in compounds, but it is less reactive and has more pronounced basic properties. Among other trivalent actinides Ac3+ is least acidic, i.e. has the weakest tendency to hydrolyze in aqueous solutions.[31][74] Thorium is rather active chemically. Owing to lack of electrons on 6d and 5f orbitals, the tetravalent thorium compounds are colorless. At pH < 3, the solutions of thorium salts are dominated by the cations [Th(H2O)8]4+. The Th4+ ion is relatively large, and depending on the coordination number can have a radius between 0.95 and 1.14 Å. As a result, thorium salts have a weak tendency to hydrolyse. The distinctive ability of thorium salts is their high solubility both in water and polar organic solvents.[74] Protactinium exhibits two valence states; the +5 is stable, and the +4 state easily oxidizes to protactinium(V). Thus tetravalent protactinium in solutions is obtained by the action of strong reducing agents in a hydrogen atmosphere. Tetravalent protactinium is chemically similar to uranium(IV) and thorium(IV). Fluorides, phosphates, hypophosphate, iodate and phenylarsonates of protactinium(IV) are insoluble in water and dilute acids. Protactinium forms soluble carbonates. The hydrolytic properties of pentavalent protactinium are close to those of tantalum(V) and niobium(V). The complex chemical behavior of protactinium is a consequence of the start of the filling of the 5f shell in this element.[63] Uranium
has a valence from 3 to 6, the last being most stable. In the hexavalent state, uranium is very similar to the group 6 elements. Many compounds of uranium(IV) and uranium(VI) are non-stoichiometric, i.e. have variable composition. For example, the actual chemical formula of uranium(VI) compounds are weak oxidants. Most of them contain the

linear "uranyl" group, UO2+2. Between 4 and 6 ligands can be accommodated in an equatorial plane perpendicular to the uranyl group acts as a hard acid and forms stronger complexes with oxygen-donor ligands than with nitrogen-donor ligands. NpO2+2 and PuO2+2 are also the common form of Np and Pu in the +6 oxidation state. Uranium(IV) compounds exhibit reducing properties, e.g., they are easily oxidized by atmospheric oxygen. Uranium(III) is a very strong reducing agent. Owing to the presence of d-shell, uranium (as well as many other actinides) forms organometallic compounds, such as UIII(C5H5)3 and UIV(C5H5)4.[74][92] Neptunium has valence states from 3 to 7, which can be simultaneously observed in solutions. The most stable state in solution is +5, but the valence +4 is preferred in solid neptunium compounds. Neptunium metal is very reactive. Ions of neptunium are prone to hydrolysis and formation of coordination compounds.[39] Plutonium also exhibits valence states between 3 and 7 inclusive, and thus is chemically similar to neptunium and uranium. It is highly reactive, and guickly forms an oxide film in air. Plutonium reacts with hydrogen even at temperatures as low as 25-50 °C; it also easily forms halides and intermetallic compounds. Hydrolysis reactions of plutonium(V) can enter polymerization reactions.[93][94] The largest chemical diversity among actinides is observed in americium, which can have valence between 2 and 6. Divalent americium is obtained only in dry compounds and non-aqueous solutions, but also in the solid state. Tetravalent americium forms stable solid compounds (dioxide, fluoride and hydroxide) as well as complexes in aqueous solutions. It was reported that in alkaline solution americium can be oxidized to the heptavalent state, but these data proved erroneous. The most stable valence of americium is 3 in the aqueous solutions and 3 or 4 in solid compounds. [95] Valence 3 is dominant in all subsequent elements up to lawrencium (with the exception of nobelium). Curium can be tetravalent in solids (fluoride, dioxide). Berkelium, along with a valence of +3, also shows the valence of +4, more stable than that of curium; the valence 4 is observed in solid fluoride and dioxide. The stability of Bk4+ in aqueous solution is close to that of Ce4+.[96] Only valence 3 was observed for californium, einsteinium and fermium. The divalent state is proven for mendelevium and nobelium, and in nobelium it is more stable than the trivalent state. Lawrencium shows valence 3 both in solutions and solids.[95] The redox potential E M 4 + AnO 2 2 + {\displaystyle {\ce {\mathit {E}} {\frac {M^{4}+}{AnO2^{2}+}}} increases from -0.32 V in uranium, through 0.34 V (Np) and 1.04 V (Pu) to 1.34 V in americium revealing the increasing reduction ability of the An4+ ion from americium to uranium. All actinides form AnH3 hydrides of black color with salt-like properties. Actinides also produce carbides with the general formula of AnC or AnC2 (U2C3 for uranium) as well as sulfides An2S3 and AnS2.[91] Uranyl nitrate (UO2(NO3)2) Agueous solutions of uranium III, IV, V, VI salts Agueous solutions of uranium III, IV, V, VI salts Agueous solutions of neptunium III, IV, V, VI, VII salts Aqueous solutions of plutonium III, IV, V, VI, VII salts Uranium tetrachloride U3O8 (yellowcake) Compounds Oxides and hydroxides Oxides of actinides[31][39][63][97][98] Compound Color Crystal symmetry, type Lattice constants, Å Density, g/cm3 Temperature, °C a b c Ac2O3 White Hexagonal, La2O3 4.07 - 6.29 9.19 - PaO2 - Cubic, CaF2 5.505 - - - Pa2O5 White cubic, CaF2 Cubic Tetragonal Hexagonal Rhombohedral Orthorhombic 5.446 10.891 5.429 3.817 5.425 6.92 - - - 4.02 - 10.992 5.503 13.22 - 4. 18 - 700 700-1100 1000 1000-1200 1240-1400 - ThO2 Colorless Cubic 5.59 - - 9.87 - UO2 Black-brown Cubic 5.47 - - 10.9 - NpO2 Greenish-brown Cubic, CaF2 5.424 - - 11.1 - PuO Black Cubic, NaCl 4.96 - - 13.9 - PuO2 Olive green Cubic 5.39 - - 11.44 - Am2O3 Red-brown Red-brown Cubic, Mn2O3 Hexagonal, La2O3 11.03 3.817 - - 5.971 10.57 11.7 - AmO2 Black Cubic, CaF2 5.376 - - - Cm2O3 White[99] - - Cubic, Mn2O2 Hexagonal, LaCl3 Monoclinic, Sm2O3 11.01 3.80 14.28 - - 3.65 - 6 8.9 11.7 - CmO2 Black Cubic, CaF2 5.37 - - - Bk2O3 Light brown Cubic, Mn2O3 10.886 - - - BkO2 Red-brown Cubic, CaF2 5.33 - -- - Cf2O3[100] Colorless Yellowish - Cubic, Mn2O3 Monoclinic, Sm2O3 Hexagonal, La2O3 10.79 14.12 3.72 - 3.59 - - 8.80 5.96 - - CfO2 Black Cubic 5.31 - - - Es2O3 - Cubic, Mn2O3 Monoclinic Hexagonal, La2O3 10.07 14.1 3.7 - 3.59 - - 8.80 6 - - Approximate colors of actinide oxides(most stable are bolded)[101] Oxidation state 89 90 91 92 93 94 95 96 97 98 99 +3 Pu2O3 Am2O3 Cm2O3 Bk2O3 Cf2O3 Es2O3 +4 ThO2 PaO2 UO2 NpO2 PuO2 AmO2 CmO2 BkO2 CfO2 +5 Pa2O5 U2O5 Np2O5 +5.+6 U3O8 +6 UO3 Dioxides of some actinides Chemical formula ThO2 PaO2 UO2 NpO2 PuO2 AmO2 CmO2 BkO2 CfO2 CAS-number 1314-20-1 12036-03-2 1344-57-6 12035-79-9 12059-95-9 12005-67-3 12016-67-0 12010-84-3 12015-10-0 Molar mass 264.04 263.035 270.03 269.047 276.063 275.06 270-284\*\* 279.069 283.078 Melting point[102] 3390 °C 2865 °C 2547 °C 2400 °C 2175 °C Crystal structure An4+: / O2-: Space group Fm3m Coordination number An[8], O[4] An – actinide \*\*Depending on the isotopes Some actinides can exist in several oxide forms such as An2O3, AnO2, An2O5 and AnO3. For all actinides, oxides AnO3 are amphoteric and An2O3, AnO2 and An2O5 are basic, they easily react with water, forming bases:[91] An2O3 + 3 H2O  $\rightarrow$  2 An(OH)3. These bases are poorly soluble in water and by their activity are close to the hydroxides of rare-earth metals.[91] Np(OH)3 has not yet been synthesized, Pu(OH)3 has a blue color while Am(OH)3 is pink and curium hydroxide Cm(OH)3 is colorless.[103] Bk(OH)3 and Cf(OH)3 are also known, as are tetravalent hydroxides for Np, Pu and Am and pentavalent for Np and Am.[103] The strongest base is of actinium. All compounds of actinium are colorless, except for black actinium sulfide (Ac2S3).[91] Dioxides of tetravalent actinides crystallize in the cubic system, same as in calcium fluoride. Thorium reacting with oxygen exclusively forms the dioxide: Th + O 2  $\rightarrow$  1000  $\circ$  C ThO 2  $^{\circ}$  Thorium dioxide {\displaystyle {\ce {Th{}+O2->[{\ce {1000^{\circ }C}}]\overbrace {ThO2}  $^{\circ}$  Thorium dioxide {}}} Thorium dioxide is a refractory material with the highest melting point among any known oxide (3390 °C).[101] Adding 0.8-1% ThO2 to tungsten stabilizes its structure, so the doped filaments have better mechanical stability to vibrations. To dissolve ThO2 in acids, it is heated to 500-600 °C; heating above 600 °C produces a very resistant to acids and other reagents form of ThO2. Small addition of fluoride ions catalyses dissolution of thorium dioxide in acids. Two protactinium oxides have been obtained: PaO2 (black) and Pa2O5 (white); the former is isomorphic with ThO2 and the latter is easier to obtain. Both oxides are basic, and Pa(OH)5 is a weak, poorly soluble base.[91] Decomposition of certain salts of uranium, for example UO2(OH)2. Reaction of uranium(VI) oxide with hydrogen results in uranium dioxide, which is similar in its properties with ThO2. This oxide is also basic and corresponds to the uranium hydroxide (U(OH)4).[91] Plutonium, neptunium and americium form two basic oxides: An2O3 and AnO2. Neptunium trioxide is unstable; thus, only Np3O8 could be obtained so far. However, the oxides of plutonium and neptunium with the chemical formula AnO2 and An2O3 are well characterized.[91] Salts Trichlorides of some actinides[104] Chemical formula AcCl3 UCI3 NpCl3 PuCl3 AmCl3 CmCl3 BkCl3 CfCl3 CAS-number 22986-54-5 10025-93-1 20737-06-8 13569-62-5 13464-46-5 13537-20-7 13536-46-4 13536-90-8 Molar mass 333.386 344.387 343.406 350.32 349.42 344-358\*\* 353.428 357.438 Melting point 837 °C 800 °C 767 °C 715 °C 603 °C 545 °C Boiling point 1657 °C 1767 °C 850 °C Crystal structure An3+: / Cl-: Space group P63/m Coordination number An\*[9], Cl [3] Lattice constants a = 762 pm c = 432.8 pm a = 739.4 pm a = 738.2 pm c = 421.4 pm a = 726 pm c = 414 pm a = 738.2 pm c = 412.7 pm a = 738 pm c = 409 pm \*An – actinide \*\*Depending on the isotopes Actinide fluorides[39][63][98][104][105] Compound Color Crystal symmetry, type Lattice constants, Å Density, g/cm3 a b c AcF3 White Hexagonal, LaF3 4.27 - 7.53 7.88 PaF4 Dark brown Monoclinic 12.7 10.7 8.42 – PaF5 Black Tetragonal, β-UF5 11.53 - 5.19 – ThF4 Colorless Monoclinic 13.7 10.99 8.58 5.71 UF3 Reddish-purple Hexagonal 7.18 - 7.34 8.54 UF4 Green Monoclinic 11.27 10.75 8.40 6.72 α-UF5 Bluish Tetragonal 6.52 - 4.47 5.81 β-UF5 Bluish Tetragonal 11.47 - 5.20 6.45 UF6 Yellowish Orthorhombic 9.92 8.95 5.19 5.06 NpF3 Black or purple Hexagonal 7.129 - 7.288 9.12 NpF4 Light green Monoclinic 12.67 10.62 8.41 6.8 NpF6 Orange Orthorhombic 9.91 8.97 5.21 5 PuF3 Violet-blue Trigonal 7.09 - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26
4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Red-brown Orthorhombic 9.95 9.02 3.26 4.86 AmF3 Pink or light beige hexagonal, LaF3 7.04[76][106] - 7.25 9.32 PuF4 Pale brown Monoclinic 12.59 10.57 8.28 6.96 PuF6 Pale brown Monoclinic 12.59 10.57 8.28 PuF6 Pale brown Monoclinic 12.59 10.5 9.53 AmF4 Orange-red Monoclinic 12.53 10.51 8.20 - CmF3 From brown to white Hexagonal 4.041 - 7.179 9.7 CmF4 Yellow Monoclinic, UF4 12.51 10.51 8.20 - BkF3 Yellow-green Trigonal, LaF3 Orthorhombic, YF3 6.97 6.7 - 7.09 7.14 4.41 10.15 9.7 BkF4 - Monoclinic, UF4 12.47 10.58 8.17 - CfF3 -Trigonal, LaF3 Orthorhombic, YF3 6, 94 6.65 - 7.04 7.10 4.39 - CfF4 - - Monoclinic, UF4 Monoclinic, UF4 1.242 1.233 1.047 1.040 8.126 8.113 - Einsteinium trijodide glowing in the dark Actinides easily react with halogens forming salts with the formulas MX3 and MX4 (X = halogen). So the first berkelium compound, BkCl3, was synthesized in 1962 with an amount of 3 nanograms. Like the halogens of rare earth elements, actinide s are insoluble. Uranium easily yields a colorless hexafluoride, which sublimates at a temperature of 56.5 °C: because of its volatility, it is used in the separation of uranium isotopes with gas centrifuge or gaseous diffusion. Actinide hexafluorides, They are very sensitive to moisture and hydrolyze forming AnO2F2.[107] The pentachloride and black hexachloride of uranium were synthesized, but they are both unstable.[91] Action of acids on actinides yields salts, and if the acids are non-oxidizing then the salt is in low-valence state:  $U + 2H2SO4 \rightarrow U(SO4)2 + 2H2 2Pu + 6HCI \rightarrow 2PuCl3 + 3H2$  However, in these reactions the regenerating hydrogen can react with the metal, forming the corresponding hydride. Uranium reacts with acids and water much more easily than thorium.[91] Actinide salts can also be obtained by dissolving the corresponding hydroxides in acids. Nitrates, chlorides, sulfates and perchlorates of actinides are water-soluble. When crystallizing from aqueous solutions, these salts forming a hydrates, such as Th(NO3)4·6H2O, Th(SO4)2·9H2O and Pu2(SO4)3·7H2O. Salts of high-valence actinides easily hydrolyze. So, colorless sulfate, chloride, perchlorate and nitrate of thorium transform into basic salts with formulas Th(OH)2SO4 and Th(OH)3NO3. The solubility and insolubility of trivalent and tetravalent actinides is like that of lanthanide salts. So phosphates, fluorides, oxalates, iodates and carbonates of actinides are weakly soluble in water; they precipitate as hydrates, such as ThF4·3H2O and Th(CrO4)2·3H2O.[91] Actinides with oxidation state +6, except for the AnO22+-type cations, form [AnO4]2-, [An2O7]2- and other complex anions. For example, uranium, neptunium and plutonium form salts of the Na2UO4 (uranate) and (NH4)2U2O7 (diuranate) types. In comparison with lanthanides, actinides more easily form coordination compounds, and this ability increases with the actinide valence. Trivalent actinides do not form fluoride coordination compounds, whereas tetravalent thorium forms K2ThF6, KThF5, and even K5ThF9 complexes. Thorium also forms the corresponding sulfates (for example Na2SO4·Th(SO4)2·5H2O), nitrates and thiocyanates. Salts with the general formula An2Th(NO3)6·nH2O are of coordination number of thorium equal to 12. Even easier is to produce complex salts of pentavalent and hexavalent actinides. The most stable coordination compounds of actinides – tetravalent thorium and uranium – are obtained in reactions with diketones, e.g. acetylacetone.[91] Applications Interior of a smoke detector containing americium-241. While actinides have some established daily-life applications, such as in smoke detectors (americium)[108] [109] and gas mantles (thorium),[80] they are mostly used in nuclear weapons and as fuel in nuclear reactors.[80] The last two areas exploit the property of actinides to release enormous energy in nuclear reactions, which under certain conditions may become self-sustaining chain reactions. Selfillumination of a nuclear reactor by Cherenkov radiation. The most important isotope for nuclear power applications is uranium-235. It is used in the thermal reactor, and its concentration in natural uranium does not exceed 0.72%. This isotope strongly absorbs thermal neutrons releasing much energy. One fission act of 1 gram of 235U converts into about 1 MW day. Of importance, is that 23592U emits more neutrons than it absorbs; [110] upon reaching the critical mass, 23592U enters into a self-sustaining chain reaction. [74] Typically, uranium nucleus is divided into two fragments with the release of 2-3 neutrons, for example: 23592U + 10n  $\rightarrow$  11545Rh + 11847Ag + 310n Other promising actinide isotopes for nuclear power are thorium-232 and its product from the thorium-233. Nuclear reactor[74][111][112] The core of most Generation II nuclear reactors contains a set of hollow metal rods, usually made of zirconium alloys, filled with solid nuclear fuel pellets – mostly oxide, carbide, nitride or monosulfide of uranium, or their mixture (the so-called MOX fuel). The most common fuel is oxide of uranium-235. Fast neutrons are slowed by moderators, which contain water, carbon, deuterium, or beryllium, as thermal neutrons to increase the efficiency of their interaction with uranium-235. The rate of nuclear reaction is controlled by introducing additional rods made of boron or cadmium or a liquid absorbent, usually boric acid. Reactors for plutonium production are called breeder reactor or breeders; they have a different design and use fast neutrons. Emission of neutrons during the nuclear chain reaction, but also for the synthesis of the heavier actinides. Uranium-239 converts via β-decay into plutonium-239, which, like uranium-235, is capable of spontaneous fission. The world's first nuclear reactors were built not for energy, but for producing plutonium-239 for nuclear weapons. About half of the produced thorium is used as the light-emitting material of gas mantles. [80] Thorium is also added into multicomponent alloys of magnesium and zinc. So the Mg-Th alloys are light and strong, but also have high melting point and ductility and thus are widely used in the aviation industry and in the production of missiles. Thorium also has good electron emission properties, with long lifetime and low potential barrier for the emission.[110] The relative content of thorium and uranium isotopes is widely used to estimate the age of various objects, including stars (see radiometric dating).[113] The major application of plutonium has been in nuclear weapons, where the isotope plutonium-239 was a key component due to its ease of fission and availability. Plutonium-based designs allow reducing the critical mass to about a third of that for uranium-235.[114] The "Fat Man"-type plutonium bombs produced during the Manhattan Project used explosive compression of plutonium to obtain significantly higher densities than normal, combined with a central neutron source to begin the reaction and increase efficiency. Thus only 6.2 kg of plutonium was needed for an explosive yield equivalent to 20 kilotons of TNT.[115] (See also Nuclear weapon design.) Hypothetically, as little as 4 kg of plutonium—and maybe even less—could be used to make a single atomic bomb using very sophisticated assembly designs.[116] Plutonium-238 is potentially more efficient isotope for nuclear reactors, since it has smaller critical mass than uranium-235, but it continues to release much thermal energy (0.56 W/g)[109][117] by decay even when the fission chain reaction is stopped by control rods. Its application is limited by its high price (about US\$1000/g). This isotope has been used in thermopiles and water distillation systems of some space satellites and stations. So Galileo and Apollo spacecraft (e.g. Apollo 14[118]) had heaters powered by kilogram quantities of plutonium-238 oxide; this heat is also transformed into electricity with thermopiles. The decay of plutonium-238 produces relatively harmless alpha particles and is not accompanied by gamma-irradiation. Therefore, this isotope (~160 mg) is used as the energy source in heart pacemakers where it lasts about 5 times longer than conventional batteries. [109] Actinium-227 is used as a neutron source. Its high specific energy (14.5 W/g) and the possibility of obtaining significant guantities of thermally stable compounds are attractive for use in long-lasting thermoelectric generators for remote use. 228Ac is used as an indicator of radioactivity in chemical research, as it emits high-energy electrons (2.18 MeV) that can be easily detected. 228Ac-228Ra mixtures are widely used as an intense gamma-source in industry and medicine.[31] Development of selfglowing actinide-doped materials with durable crystalline matrices is a new area of actinide utilization as the addition of alpha-emitting radionuclides to some glasses and crystals may confer luminescence. [119] Toxicity Schematic illustration of penetration of radiation through sheets of paper, aluminium and lead brick Periodic table with elements colored according to the half-life of their most stable isotope. Elements which contain at least one stable isotope. Slightly radioactive elements: the most stable isotope is very long-lived, with a half-life of over two million years. Significantly radioactive elements: the most stable isotope has half-life between 800 and 34,000 years. Radioactive elements: the most stable isotope has half-life between one day and 130 years. Highly radioactive elements: the most stable isotope has
half-life between several minutes and one day. Extremely radioactive elements: the most stable isotope has half-life less than several minutes. Radioactive substances can harm human health via (i) local skin contamination. (ii) internal exposure due to ingestion of radioactive isotopes, and (iii) external overexposure by B-activity and v-radiation. Together with radium and transuranium elements, actinium is one of the most dangerous radioactive poisons with high specific q-activity. The most important feature of actinium is its ability to accumulate and remain in the surface layer of skeletons. At the initial stage of poisoning, actinium accumulates in the liver. Another danger of actinium is that it undergoes radioactive decay faster than being excreted. Adsorption from the digestive tract is much smaller (~0.05%) for actinium in the body tends to accumulate in the kidneys and bones. The maximum safe dose of protactinium in the human body is 0.03 µCi that corresponds to 0.5 micrograms of 231Pa. This isotope, which might be present in the air as aerosol, is 2.5×108 times more toxic than hydrocyanic acid.[63][contradictory] Plutonium, when entering the body through air, food or blood (e.g. a wound), mostly settles in the lungs, liver and bones with only about 10% going to other organs, and remains there for decades. The long residence time of plutonium in the body is partly explained by its poor solubility in water. Some isotopes of plutonium emit ionizing α-radiation, which damages the surrounding cells. The median lethal dose (LD50) for 30 days in dogs after intravenous injection of plutonium is 0.32 milligram per kg of body mass, and thus the lethal dose for humans is approximately 22 mg for a person weighing 70 kg; the amount for respiratory exposure should be approximately four times greater. Another estimate assumes that plutonium is 50 times less toxic than radium, and thus permissible content of plutonium in the body should be 5 µg or 0.3 µCi. Such amount is nearly invisible under microscope. After trials on animals, this maximum permissible dose was reduced to 0.65 µg or 0.04 µCi. Studies on animals also revealed that the most dangerous plutonium exposure route is through inhalation, after which 5-25% of inhaled substances is retained in the body. Depending on the plutonium compounds, plutonium is localized either in the lungs or in the lymphatic system, or is absorbed in the blood and then transported to the liver and bones. Contamination via food is the least likely way. In this case, only about 0.05% of soluble 0.01% insoluble compounds of plutonium absorbs into blood, and the rest is excreted. Exposure of damaged skin to plutonium would retain nearly 100% of it.[93] Using actinides in nuclear fuel, sealed radioactive sources or advanced materials such as self-glowing crystals has many potential benefits. However, a serious concern is the extremely high radiotoxicity of actinides and their migration in the environment.[120] Use of chemically unstable forms of actinides in MOX and sealed radioactive sources is not appropriate by modern safety standards. There is a challenge to develop stable and durable actinide-bearing materials, which provide safe storage, use and final disposal. A key need is application of actinide solid solutions in durable crystalline host phases.[119] Nuclear properties Half-lives and branching fractions for actinides and natural decay products [121] Nuclide Half-life Decay mode Branching fraction Source 20681Tl 4.202 ± 0.011 m  $\beta$ - 1.0 LNHB 20881Tl 3.060 ± 0.008 m  $\beta$ - 1.0 BIPM-5 21082Pb 22.20 ± 0.22 y  $\beta$ - 1.0 ENSDF  $\alpha$  (1.9 ± 0.4) x 10-8 21182Pb 36.1 ± 0.2 m β-1.0 ENSDF 21282Pb 10.64 ± 0.01 h β-1.0 BIPM-5 21482Pb 26.8 ± 0.9 m β-1.0 ENSDF 21183Bi 2.14 ± 0.02 m β-0.00276 ± 0.00004 ENSDF α 0.99724 ± 0.00004 21283Bi 60.54 ± 0.06 m α 0.3593 ± 0.0007 BIPM-5 β-0.6407 ± 0.0007 21483Bi 19.9 ± 0.4 m α 0.00021 ± 0.00001 ENSDF β-0.6407 ± 0.00004 ENSDF α 0.99724 ± 0.00004 ENSDF α 0.99724 ± 0.00004 ENSDF α 0.99724 ± 0.0007 BIPM-5 β-0.6407 ± 0.0007 21483Bi 19.9 ± 0.4 m α 0.00021 ± 0.00001 ENSDF β-0.6407 ± 0.0007 ENSDF α 0.99724 ± 0.997 0.99979 ± 0.00001 21084Po 138.376 ± 0.002 d α 1.0 ENSDF 21986Rn 3.96 ± 0.01 s α 1.0 ENSDF 22086Rn 55.8 ± 0.3 s α 1.0 BIPM-5 22187Fr 4.9 ± 0.2 m β- 0.00003 ENSDF α 0.99995 ± 0.00003 22388Ra 11.43 ± 0.05 d α 1.0 ENSDF 14C (8.9 ± 0.4) x 10-10 22488Ra 3.627 ± 0.007 d α 1.0 BIPM-5 22588Ra 14.9 ± 0.2 d β-1.0 ENSDF 22688Ra (1.600 ± 0.007) x 103 y α 1.0 BIPM-5 22888Ra 5.75 ± 0.03 y β-1.0 ENSDF 22489Ac 2.78 ± 0.17 h α 0.091 +0.020 -0.014 ENSDF EC 0.909 +0.014 -0.020 22589Ac 10.0 ± 0.1 d α 1.0 ENSDF 22789Ac 21.772 ± 0.003 y α 0.01380 ± 0.00004 ENSDF  $\beta$ - 0.98620 ± 0.00004 22889Ac 6.15 ± 0.02 h  $\beta$ - 1.0 ENSDF 22790Th 18.718 ± 0.005 d  $\alpha$  1.0 BIPM-5 22890Th (98.60 ± 0.23 d  $\alpha$  1.0 BIPM-5 22990Th (7.34 ± 0.16) x 103 y  $\alpha$  1.0 ENSDF 23090Th (7.538 ± 0.030) x 104 y  $\alpha$  1.0 ENSDF SF ≤ 4 x 10-13 23190Th 25.52 ± 0.01 h  $\beta$ - 1.0 ENSDF  $\alpha$  $\sim 4 \times 10 - 1323290$ Th (1.405 ± 0.006) × 1010 y  $\alpha$  1.0 ENSDF SF (1.1 ± 0.4) × 10 - 1123390Th 22.15 ± 0.15 m  $\beta$  - 1.0 LNHB 23490Th 24.10 ± 0.03 d  $\beta$  - 1.0 ENSDF 23191Pa (3.276 ± 0.011) × 104 y  $\alpha$  1.0 ENSDF SF  $\leq 3 \times 10 - 1223291$ Pa 1.32 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.02 d EC 0.00003 ± 0.00003 ± 0.00001 ENSDF  $\beta$  - 0.99997 ± 0.  $0.00001 23391Pa 26.98 \pm 0.02 d \beta - 1.0 LNHB 23491Pa 6.70 \pm 0.05 h \beta - 1.0 ENSDF 234m91Pa 1.159 \pm 0.016 m IT 0.0016 \pm 0.0002 IAEA-CRP-XG \beta - 0.9984 \pm 0.0002 23292U 68.9 \pm 0.4 y \alpha 1.0 ENSDF SF 23392U (1.592 \pm 0.002) x 105 y \alpha 1.0 ENSDF SF 23492U (2.455 \pm 0.006) x 105 y \alpha 1.0 ENSDF SF 23492U (2.455$ LNHB SF (1.6 ± 0.2) x 10-11 235m92U 26 ± 1 m IT 1.0 ENSDF 23592U (7.038 ± 0.005) x 108 y  $\alpha$  1.0 ENSDF SF (7 ± 2) x 10-11 23692U (2.342 ± 0.004) x 107 y  $\alpha$  1.0 ENSDF SF (9.4 ± 0.4) x 10-10 23792U 6.749 ± 0.016 d  $\beta$ - 1.0 LNHB 23892U (4.468 ± 0.005) x 109 y  $\alpha$  1.0 LNHB SF (5.45 ± 0.004) x 107 y  $\alpha$  1.0 ENSDF SF (9.4 ± 0.4) x 10-10 23792U 6.749 ± 0.016 d  $\beta$ - 1.0 LNHB 23892U (4.468 ± 0.005) x 109 y  $\alpha$  1.0 LNHB SF (5.45 ± 0.004) x 107 y  $\alpha$  1.0 ENSDF SF (9.4 ± 0.4) x 10-10 23792U 6.749 ± 0.016 d  $\beta$ - 1.0 LNHB 23892U (4.468 ± 0.005) x 109 y  $\alpha$  1.0 LNHB SF (5.45 ± 0.004) x 107 y  $\alpha$  1.0 ENSDF SF (9.4 ± 0.4) x 10-10 23792U 6.749 ± 0.016 d  $\beta$ - 1.0 LNHB 23892U (4.468 ± 0.005) x 109 y  $\alpha$  1.0 LNHB SF (5.45 ± 0.004) x 107 y  $\alpha$  1.0 ENSDF SF (9.4 ± 0.4) x 10-10 23792U 6.749 ± 0.016 d  $\beta$ - 1.0 LNHB 23892U (4.468 ± 0.005) x 109 y  $\alpha$  1.0 LNHB SF (5.45 ± 0.004) x 107 y  $\alpha$  1.0 ENSDF SF (9.4 ± 0.4) x
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