= 365 pm and c =
1182 pm , and four formula units per unit cell . The crystal consists of a double @-@ hexagonal close packing with the layer sequence ABAC and so is isotypic with ? @-@ lanthanum . At pressures above 23 GPa , at room temperature , ? @-@ Cm transforms into ? @-@ Cm , which has a face @-@ centered cubic symmetry , space group Fm3m and the lattice constant a = 493 pm . Upon further compression to 43 GPa , curium transforms to an orthorhombic ? @-@ Cm structure similar to that of ? @-@ uranium , with no further transitions observed up to 52 GPa . These three curium phases are also referred to as Cm I , II and III .

Curium has peculiar magnetic properties . Whereas its neighbor element americium shows no deviation from Curie @-@ Weiss paramagnetism in the entire temperature range , ? @-@ Cm transforms to an antiferromagnetic state upon cooling to 65 ? 52 K , and ? @-@ Cm exhibits a ferrimagnetic transition at about 205 K. Meanwhile , curium pnictides show ferromagnetic transitions upon cooling : 244CmN and 244CmAs at 109 K , 248CmP at 73 K and 248CmSb at 162 K. Similarly , the lanthanide analogue of curium , gadolinium , as well as its pnictides also show magnetic transitions upon cooling , but the transition character is somewhat different : Gd and GdN become ferromagnetic , and GdP , GdAs and GdSb show antiferromagnetic ordering .

In accordance with magnetic data , electrical resistivity of curium increases with temperature ? about twice between 4 and 60 K ? and then remains nearly constant up to room temperature . There is a significant increase in resistivity over time (about 10 µ? · cm / h) due to self @-@ damage of the crystal lattice by alpha radiation . This makes uncertain the absolute resistivity value for curium (about 125 µ? · cm) . The resistivity of curium is similar to that of gadolinium and of the actinides plutonium and neptunium , but is significantly higher than that of americium , uranium , polonium and thorium .

Under ultraviolet illumination , curium (III) ions exhibit strong and stable yellow @-@ orange fluorescence with a maximum in the range about 590 ? 640 nm depending on their environment . The fluorescence originates from the transitions from the first excited state 6D7 / 2 and the ground state 8S7 / 2 . Analysis of this fluorescence allows monitoring interactions between Cm (III) ions in organic and inorganic complexes .

= = = Chemical = = =

Curium ions in solution almost exclusively assume the oxidation state of + 3 , which is the most stable oxidation state for curium . The + 4 oxidation state is observed mainly in a few solid phases , such as CmO2 and CmF4 . Aqueous curium (IV) is only known in the presence of strong oxidizers such as potassium persulfate , and is easily reduced to curium (III) by radiolysis and even by water . The chemical behavior of curium is different from the actinides thorium and uranium , and is similar to that of americium and many lanthanides . In aqueous solution , the Cm3 + ion is colorless to pale green , and Cm4 + ion is pale yellow . The optical absorption of Cm3 + ions contains three sharp peaks at 375 @.@ 4 , 381 @.@ 2 and 396 @.@ 5 nanometers and their strength can be directly converted into the concentration of the ions . The + 6 oxidation state has only been reported once in solution in 1978 , as the curyl ion (CmO2 +
2) : this was prepared from the beta decay of americium @-@ 242 in the americium (V) ion 242AmO +
2 . Failure to obtain Cm (VI) from oxidation of Cm (III) and Cm (IV) may be due to the high Cm4 + / Cm3 + ionization potential and the instability of Cm (V) .

Curium ions are hard Lewis acids and thus form most stable complexes with hard bases . The bonding is mostly ionic , with a small covalent component . Curium in its complexes commonly exhibits a 9 @-@ fold coordination environment , within a tricapped trigonal prismatic geometry .

= = = Isotopes = = =

About 20 radioisotopes and 7 nuclear isomers between 233Cm and 252Cm are known for curium , and no stable isotopes . The longest half @-@ lives have been reported for 247Cm (15 @.@ 6

million years) and 248Cm (348 @,@ 000 years) . Other long @-@ lived isotopes are 245Cm (half @-@ life 8500 years) , 250Cm (8 @,@ 300 years) and 246Cm (4 @,@ 760 years) . Curium @-@ 250 is unusual in that it predominantly (about 86 %) decays via spontaneous fission . The most commonly used curium isotopes are 242Cm and 244Cm with the half @-@ lives of 162 @.@ 8 days and 18 @.@ 1 years , respectively .

 All isotopes between 242Cm and 248Cm , as well as 250Cm , undergo a self @-@ sustaining nuclear chain reaction and thus in principle can act as a nuclear fuel in a reactor . As in most transuranic elements , the nuclear fission cross section is especially high for the odd @-@ mass curium isotopes243Cm , 245Cm and 247Cm . These can be used in thermal @-@ neutron reactors , whereas a mixture of curium isotopes is only suitable for fast breeder reactors since the even @-@ mass isotopes are not fissile in a thermal reactor and accumulate as burn @-@ up increases . The mixed @-@ oxide (MOX) fuel , which is to be used in power reactors , should contain little or no curium because the neutron activation of 248Cm will create californium . This is strong neutron emitter , and would pollute the back end of the fuel cycle and increase the dose to reactor personnel . Hence , if the minor actinides are to be used as fuel in a thermal neutron reactor , the curium should be excluded from the fuel or placed in special fuel rods where it is the only actinide present .

 The table to the right lists the critical masses for curium isotopes for a sphere , without a moderator and reflector . With a metal reflector (30 cm of steel) , the critical masses of the odd isotopes are about 3 ? 4 kg . When using water (thickness ~ 20 ? 30 cm) as the reflector , the critical mass can be as small as 59 gram for 245Cm , 155 gram for 243Cm and 1550 gram for 247Cm . There is a significant uncertainty in these critical mass values . Whereas it is usually of the order 20 % , the values for 242Cm and 246Cm were listed as large as 371 kg and 70 @.@ 1 kg , respectively , by some research groups .

 Currently , curium is not used as a nuclear fuel owing to its low availability and high price . 245Cm and 247Cm have a very small critical mass and therefore could be used in portable nuclear weapons , but none have been reported thus far . Curium @-@ 243 is not suitable for this purpose because of its short half @-@ life and strong ? emission which would result in excessive heat . Curium @-@ 247 would be highly suitable , having a half @-@ life 647 times that of plutonium @-@ 239 .

 = = = Occurrence = = =

 The longest @-@ lived isotope of curium , 247Cm , has a half @-@ life of 15 @.@ 6 million years . Therefore , any primordial curium , that is curium present on the Earth during its formation , should have decayed by now . Curium is produced artificially , in small quantities for research purposes . Furthermore , it occurs in spent nuclear fuel . Curium is present in nature in certain areas used for the atmospheric nuclear weapons tests , which were conducted between 1945 and 1980 . So the analysis of the debris at the testing site of the first U.S. hydrogen bomb , Ivy Mike , (1 November 1952 , Enewetak Atoll) , beside einsteinium , fermium , plutonium and americium also revealed isotopes of berkelium , californium and curium , in particular 245Cm , 246Cm and smaller quantities of 247Cm , 248Cm and 249Cm . For reasons of military secrecy , this result was published only in 1956 .

 Atmospheric curium compounds are poorly soluble in common solvents and mostly adhere to soil particles . Soil analysis revealed about 4 @,@ 000 times higher concentration of curium at the sandy soil particles than in water present in the soil pores . An even higher ratio of about 18 @,@ 000 was measured in loam soils .

 The transuranic elements from americium to fermium , including curium , occurred naturally in the natural nuclear fission reactor at Oklo , but no longer do so . Exceedingly minute amounts of the isotope 244Cm may be produced naturally from the theoretically predicted extremely rare double beta decay of the trace primordial isotope 244Pu , but this has not yet been observed .

 = = Synthesis = =

=== Isotope preparation ===

Curium is produced in small quantities in nuclear reactors , and by now only kilograms of it have been accumulated for the 242Cm and 244Cm and grams or even milligrams for heavier isotopes . This explains the high price of curium , which has been quoted at 160 ? 185 USD per milligram , with a more recent estimate at 2 @,@ 000 USD / g for 242Cm and 170 USD / g for 244Cm . In nuclear reactors , curium is formed from 238U in a series of nuclear reactions . In the first chain , 238U captures a neutron and converts into 239U , which via ? ? decay transforms into 239Np and 239Pu .

Further neutron capture followed by ? ? -decay produces the 241Am isotope of americium which further converts into 242Cm :

For research purposes , curium is obtained by irradiating not uranium but plutonium , which is available in large amounts from spent nuclear fuel . Much higher neutron flux is used for the irradiation that results in a different reaction chain and formation of 244Cm :

Curium @-@ 244 decays into 240Pu by emission of alpha particle , but it also absorbs neutrons resulting in a small amount of heavier curium isotopes . Among those , 247Cm and 248Cm are popular in scientific research because of their long half @-@ lives . However , the production rate of 247Cm in thermal neutron reactors is relatively low because of it is prone to undergo fission induced by thermal neutrons . Synthesis of 250Cm via neutron absorption is also rather unlikely because of the short half @-@ life of the intermediate product 249Cm (64 min) , which converts by ? ? decay to the berkelium isotope 249Bk .

The above cascade of (n , ?) reactions produces a mixture of different curium isotopes . Their post @-@ synthesis separation is cumbersome , and therefore a selective synthesis is desired . Curium @-@ 248 is favored for research purposes because of its long half @-@ life . The most efficient preparation method of this isotope is via ? @-@ decay of the californium isotope 252Cf , which is available in relatively large quantities due to its long half @-@ life (2 @.@ 65 years) . About 35 ? 50 mg of 248Cm is being produced by this method every year . The associated reaction produces 248Cm with isotopic purity of 97 % .

Another interesting for research isotope 245Cm can be obtained from the ? @-@ decay of 249Cf , and the latter isotope is produced in minute quantities from the ? ? -decay of the berkelium isotope 249Bk .

=== Metal preparation ===

Most synthesis routines yield a mixture of different actinide isotopes as oxides , from which a certain isotope of curium needs to be separated . An example procedure could be to dissolve spent reactor fuel (e.g. MOX fuel) in nitric acid , and remove the bulk of the uranium and plutonium using a PUREX (Plutonium ? URanium EXtraction) type extraction with tributyl phosphate in a hydrocarbon . The lanthanides and the remaining actinides are then separated from the aqueous residue (raffinate) by a diamide @-@ based extraction to give , after stripping , a mixture of trivalent actinides and lanthanides . A curium compound is then selectively extracted using multi @-@ step chromatographic and centrifugation techniques with an appropriate reagent . Bis @-@ triazinyl bipyridine complex has been recently proposed as such reagent which is highly selective to curium . Separation of curium from a very similar americium can also be achieved by treating a slurry of their hydroxides in aqueous sodium bicarbonate with ozone at elevated temperature . Both americium and curium are present in solutions mostly in the + 3 valence state ; whereas americium oxidizes to soluble Am (IV) complexes , curium remains unchanged and can thus be isolated by repeated centrifugation .

Metallic curium is obtained by reduction of its compounds . Initially , curium (III) fluoride was used for this purpose . The reaction was conducted in the environment free from water and oxygen , in the apparatus made of tantalum and tungsten , using elemental barium or lithium as reducing agents .

Another possibility is the reduction of curium (IV) oxide using a magnesium @-@ zinc alloy in a melt of magnesium chloride and magnesium fluoride .

== Compounds and reactions ==

=== Oxides ===

Curium readily reacts with oxygen forming mostly Cm2O3 and CmO2 oxides , but the divalent oxide CmO is also known . Black CmO2 can be obtained by burning curium oxalate (Cm2 (C2O4) 3) , nitrate (Cm (NO3) 3) or hydroxide in pure oxygen . Upon heating to 600 ? 650 ° C in vacuum (about 0 @.@ 01 Pa) , it transforms into the whitish Cm2O3 :
<formula> .
Alternatively , Cm2O3 can be obtained by reducing CmO2 with molecular hydrogen :
<formula>
Furthermore , a number of ternary oxides of the type M (II) CmO3 are known , where M stands for a divalent metal , such as barium .
Thermal oxidation of trace quantities of curium hydride (CmH2 ? 3) has been reported to produce a volatile form of CmO2 and the volatile trioxide CmO3 , one of the two known examples of the very rare + 6 state for curium . Another observed species was reported to behave similarly to plutonium tetroxide and was tentatively characterized as CmO4 , with curium in the extremely rare + 8 state ; however , new experiments seem to indicate that CmO4 does not exist .

=== Halides ===

The colorless curium (III) fluoride (CmF3) can be produced by introducing fluoride ions into curium (III) -containing solutions . The brown tetravalent curium (IV) fluoride (CmF4) on the other hand is only obtained by reacting curium (III) fluoride with molecular fluorine :
<formula>
A series of ternary fluorides are known of the form A7Cm6F31 , where A stands for alkali metal .
The colorless curium (III) chloride (CmCl3) is produced in the reaction of curium (III) hydroxide (Cm (OH) 3) with anhydrous hydrogen chloride gas . It can further be converted into other halides , such as curium (III) bromide (colorless to light green) and curium (III) iodide (colorless) , by reacting it with the ammonia salt of the corresponding halide at elevated temperature of about 400 ? 450 ° C :
<formula>
An alternative procedure is heating curium oxide to about 600 ° C with the corresponding acid (such as hydrobromic for curium bromide) . Vapor phase hydrolysis of curium (III) chloride results in curium oxychloride :
<formula>

=== Chalcogenides and pnictides ===

Sulfides , selenides and tellurides of curium have been obtained by treating curium with gaseous sulfur , selenium or tellurium in vacuum at elevated temperature . The pnictides of curium of the type CmX are known for the elements nitrogen , phosphorus , arsenic and antimony . They can be prepared by reacting either curium (III) hydride (CmH3) or metallic curium with these elements at elevated temperatures .

=== Organocurium compounds and biological aspects ===

Organometallic complexes analogous to uranocene are known also for other actinides , such as

thorium , protactinium , neptunium , plutonium and americium . Molecular orbital theory predicts a stable " curocene " complex ($?_8$ @-@ C8H8) 2Cm , but it has not been reported experimentally yet .

Formation of the complexes of the type Cm (n @-@ C3H7 @-@ BTP) 3 , where BTP stands for 2 @,@ 6 @-@ di (1 @,@ 2 @,@ 4 @-@ triazin @-@ 3 @-@ yl) pyridine , in solutions containing n @-@ C3H7 @-@ BTP and Cm3 + ions has been confirmed by EXAFS . Some of these BTP @-@ type complexes selectively interact with curium and therefore are useful in its selective separation from lanthanides and another actinides . Dissolved Cm3 + ions bind with many organic compounds , such as hydroxamic acid , urea , fluorescein and adenosine triphosphate . Many of these compounds are related to biological activity of various microorganisms . The resulting complexes exhibit strong yellow @-@ orange emission under UV light excitation , which is convenient not only for their detection , but also for studying the interactions between the Cm3 + ion and the ligands via changes in the half @-@ life (of the order ~ 0 @.@ 1 ms) and spectrum of the fluorescence .

Curium has no biological significance . There are a few reports on biosorption of Cm3 + by bacteria and archaea , however no evidence for incorporation of curium into them .

= = Applications = =

= = = Radionuclides = = =

Curium is one of the most radioactive isolable elements . Its two most common isotopes 242Cm and 244Cm are strong alpha emitters (energy 6 MeV) ; they have relatively short half @-@ lives of 162 @.@ 8 days and 18 @.@ 1 years , and produce as much as 120 W / g and 3 W / g of thermal energy , respectively . Therefore , curium can be used in its common oxide form in radioisotope thermoelectric generators like those in spacecraft . This application has been studied for the 244Cm isotope , while 242Cm was abandoned due to its prohibitive price of around 2000 USD / g . Curium @-@ 243 with a ~ 30 year half @-@ life and good energy yield of ~ 1 @.@ 6 W / g could make for a suitable fuel , but it produces significant amounts of harmful gamma and beta radiation from radioactive decay products . Though as an ? @-@ emitter , 244Cm requires a much thinner radiation protection shielding , it has a high spontaneous fission rate , and thus the neutron and gamma radiation rate are relatively strong . As compared to a competing thermoelectric generator isotope such as 238Pu , 244Cm emits a 500 time greater fluence of neutrons , and its higher gamma emission requires a shield that is 20 times thicker ? about 2 inches of lead for a 1 kW source , as compared to 0 @.@ 1 in for 238Pu . Therefore , this application of curium is currently considered impractical .

A more promising application of 242Cm is to produce 238Pu , a more suitable radioisotope for thermoelectric generators such as in cardiac pacemakers . The alternative routes to 238Pu use the (n , ?) reaction of 237Np , or the deuteron bombardment of uranium , which both always produce 236Pu as an undesired by @-@ product ? since the latter decays to 232U with strong gamma emission . Curium is also a common starting material for the production of higher transuranic elements and transactinides . Thus , bombardment of 248Cm with oxygen (18O) or magnesium (26Mg) yielded certain isotopes of seaborgium (265Sg) and hassium (269Hs and 270Hs) . Californium was discovered when a microgram @-@ sized target of curium @-@ 242 was irradiated with 35 MeV alpha particles using the 60 @-@ inch (150 cm) cyclotron at Berkeley :

242
96Cm + 4
2He ? 245
98Cf + 1
0n
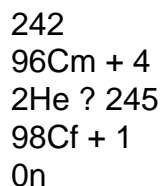
Only about 5 @,@ 000 atoms of californium were produced in this experiment .

= = = X @-@ ray spectrometer = = =

The most practical application of 244Cm ? though rather limited in total volume ? is as ? @-@ particle source in the alpha particle X @-@ ray spectrometers (APXS) . These instruments were installed on the Sojourner , Mars , Mars 96 , Mars Exploration Rovers and Philae comet lander , as well as the Mars Science Laboratory to analyze the composition and structure of the rocks on the surface of planet Mars . APXS was also used in the Surveyor 5 ? 7 moon probes but with a 242Cm source .

An elaborated APXS setup is equipped with a sensor head containing six curium sources having the total radioactive decay rate of several tens of millicuries (roughly a gigabecquerel) . The sources are collimated on the sample , and the energy spectra of the alpha particles and protons scattered from the sample are analyzed (the proton analysis is implemented only in some spectrometers) . These spectra contain quantitative information on all major elements in the samples except for hydrogen , helium and lithium .

= = Safety = =

Owing to its high radioactivity , curium and its compounds must be handled in appropriate laboratories under special arrangements . Whereas curium itself mostly emits ? @-@ particles which are absorbed by thin layers of common materials , some of its decay products emit significant fractions of beta and gamma radiation , which require a more elaborate protection . If consumed , curium is excreted within a few days and only 0 @.@ 05 % is absorbed in the blood . From there , about 45 % goes to the liver , 45 % to the bones , and the remaining 10 % is excreted . In the bone , curium accumulates on the inside of the interfaces to the bone marrow and does not significantly redistribute with time ; its radiation destroys bone marrow and thus stops red blood cell creation . The biological half @-@ life of curium is about 20 years in the liver and 50 years in the bones . Curium is absorbed in the body much more strongly via inhalation , and the allowed total dose of 244Cm in soluble form is 0 @.@ 3 ?C . Intravenous injection of 242Cm and 244Cm containing solutions to rats increased the incidence of bone tumor , and inhalation promoted pulmonary and liver cancer .

Curium isotopes are inevitably present in spent nuclear fuel with a concentration of about 20 g / tonne . Among them , the 245Cm ? 248Cm isotopes have decay times of thousands of years and need to be removed to neutralize the fuel for disposal . The associated procedure involves several steps , where curium is first separated and then converted by neutron bombardment in special reactors to short @-@ lived nuclides . This procedure , nuclear transmutation , while well documented for other elements , is still being developed for curium .