

# Flerovium

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**Flerovium** is a superheavy artificial chemical element with symbol **Fl** and atomic number 114. It is an extremely radioactive synthetic element. The element is named after the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna, Russia, where the element was discovered in 1998. The name of the laboratory, in turn, honours the Russian physicist Georgy Flyorov (Флёров in Cyrillic, hence the transliteration of "yo" to "e"). The name was adopted by IUPAC on 30 May 2012.

In the periodic table of the elements, it is a transactinide element in the p-block. It is a member of the 7th period and is the heaviest known member of the carbon group; it is also the heaviest element whose chemistry is currently known. Initial chemical studies performed in 2007–2008 indicated that flerovium was unexpectedly volatile for a group 14 element;<sup>[10]</sup> in preliminary results it even seemed to exhibit properties similar to those of the noble gases.<sup>[11]</sup> More recent results show that flerovium's reaction with gold is similar to that of copernicium, showing that it is a very volatile element that may even be gaseous at standard temperature and pressure, that it would show metallic properties, consistent with it being the heavier homologue of lead, and that it would be the least reactive metal in group 14.

About 90 atoms of flerovium have been observed: 58 were synthesized directly, and the rest were made from the radioactive decay of heavier elements. All of these flerovium atoms have been shown to have mass numbers from 284 to 289. The most stable known flerovium isotope, flerovium-289, has a half-life of around 2.6 seconds, but it is possible that this isotope may have a nuclear isomer with a longer half-life of 66 seconds; this would be one of the longest half-lives of any isotope of a superheavy element. Flerovium is predicted to be near the centre of the theorized island of stability, and it is expected that heavier flerovium isotopes, especially the possibly doubly magic flerovium-298, may have even longer half-lives.

## Predicted properties

### Flerovium, <sup>114</sup>Fl

General properties	
<b>Name, symbol</b>	flerovium, Fl
Flerovium in the periodic table	
<b>Atomic number</b> ( <i>Z</i> )	114
<b>Group, block</b>	group 14 (carbon group), p-block
<b>Period</b>	period 7
<b>Element category</b>	<span> </span> <span> </span> post-transition metal
<b>Standard atomic weight</b> ( <i>A</i> <sub>r</sub> )	[289]
<b>Electron configuration</b>	[Rn] 5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>2</sup> <i>(predicted)</i> <sup>[2]</sup>
per shell	2, 8, 18, 32, 32, 18, 4 <i>(predicted)</i>
Physical properties	
<b>Phase</b>	solid <i>(predicted)</i> <sup>[2]</sup>
<b>Melting point</b>	340 K (67 °C, 160 °F) <i>(predicted)</i> <sup>[3]</sup>
<b>Boiling point</b>	420 K (147 °C, 297 °F) <i>(predicted)</i> <sup>[3][4][5]</sup>
<b>Density</b> near r.t.	14 g/cm <sup>3</sup> <i>(predicted)</i> <sup>[3]</sup>
<b>Heat of vaporization</b>	38 kJ/mol <i>(predicted)</i> <sup>[3]</sup>
Atomic properties	
<b>Oxidation states</b>	0, 1, <b>2</b> , 4, 6

# Nuclear stability and isotopes

The physical basis of the chemical periodicity governing the periodic table is the electron shell closures at each noble gas (atomic numbers 2, 10, 18, 36, 54, 86, and 118): as any further electrons must enter a new shell with higher energy, closed-shell electron configurations are markedly more stable, leading to the relative inertness of the noble gases.<sup>[3]</sup> Since protons and neutrons are also known to arrange themselves in closed nuclear shells, the same effect happens at nucleon shell closures, which happen at specific nucleon numbers often dubbed "magic numbers". The known magic numbers are 2, 8, 20, 28, 50, and 82 for protons and neutrons, and also 126 for neutrons.<sup>[3]</sup> Nucleons with magic proton and neutron numbers, such as helium-4, oxygen-16, calcium-48, and lead-208, are termed "doubly magic" and are very stable against decay. This property of increased nuclear stability is very important for superheavy elements: without any stabilization, their half-lives would be expected by exponential extrapolation to be in the range of nanoseconds ( $10^{-9}$  s) when element 110 (darmstadtium) is reached, because of the ever-increasing repulsive electromagnetic forces between the positively charged protons that overcome the limited-range strong nuclear force that holds the nucleus together. The next closed nucleon shells and hence magic numbers are thought to be at the centre of the long-sought island of stability, where the half-lives to alpha decay and spontaneous fission lengthen again.<sup>[3]</sup>

Initially, by analogy with the neutron magic number 126, the next proton shell was also expected to occur at element 126, too far away from the synthesis capabilities of the mid-20th century to achieve much theoretical attention. In 1966, new values for the potential and spin-orbit interaction in this region of the periodic table<sup>[28]</sup> contradicted this and predicted that the next proton shell would occur instead at element 114,<sup>[3]</sup> and that nuclides in this region would be as stable against spontaneous fission as many heavy nuclei such as lead-208.<sup>[3]</sup> The expected closed neutron shells in this region were at neutron number 184 or 196, thus making <sup>298</sup>Fl and <sup>310</sup>Fl candidates for being doubly magic.<sup>[3]</sup> 1972 estimates predicted a half-life of about a year for <sup>298</sup>Fl, which was expected to be near a large island of stability with the longest half-life at darmstadtium-294 ( $10^{10}$  years, comparable to that of <sup>232</sup>Th).<sup>[3]</sup> After the synthesis of the first

	(predicted) <sup>[2][3][6]</sup>
<b>Ionization energies</b>	1st: 823.9 kJ/mol (predicted) <sup>[2]</sup> 2nd: 1601.6 kJ/mol (predicted) <sup>[3]</sup> 3rd: 3367.3 kJ/mol (predicted) <sup>[3]</sup> (more)
<b>Atomic radius</b>	empirical: 180 pm (predicted) <sup>[2][3]</sup>
<b>Covalent radius</b>	171–177 pm (extrapolated) <sup>[4]</sup>
<b>Miscellanea</b>	
<b>CAS Number</b>	54085-16-4
<b>History</b>	
<b>Naming</b>	after Flerov Laboratory of Nuclear Reactions (itself named after Georgy Flyorov) <sup>[7]</sup>
<b>Discovery</b>	Joint Institute for Nuclear Research (JINR) and Lawrence Livermore National Laboratory (LLNL) (1999)
<b>Most stable isotopes of flerovium</b>	

isotopes of elements 112 through 118 at the turn of the 21st century, it was found that the synthesized neutron-deficient isotopes were stabilized against fission. In 2008 it was thus hypothesized that the stabilization against fission of these nuclides was due to their being oblate nuclei, and that a region of oblate nuclei was centred on <sup>288</sup>Fl. Additionally, new theoretical models showed that the expected gap in energy between the proton orbitals 2f<sub>7/2</sub> (filled at element 114) and 2f<sub>5/2</sub> (filled at element 120) was smaller than expected, so that element 114 no longer appeared to be a stable spherical closed nuclear shell. The next doubly magic nucleus is now expected to be around <sup>306</sup>Ubb, but the expected low half-life and low production cross section of this nuclide makes its synthesis challenging.<sup>[14]</sup> Nevertheless, the island of stability is still expected to exist in this region of the periodic table, and nearer its centre (which has not been approached closely enough yet) some nuclides, such as <sup>291</sup>Mc and its alpha- and beta-decay daughters,<sup>[a]</sup> may be found to decay by positron emission or electron capture and thus move into the centre of the island.<sup>[29]</sup>

Due to the expected high fission barriers, any nucleus within this island of stability decays exclusively by alpha decay and perhaps some electron capture and beta decay,<sup>[3]</sup> both of which would bring the nuclei closer to the beta stability line where the island is expected to be. Electron capture is needed to reach the island, which is problematic because it is not certain that electron capture becomes a major decay mode in this region of the chart of nuclides.<sup>[29]</sup>

Several experiments have been performed between 2000 and 2004 at the Flerov Laboratory of Nuclear Reactions in Dubna studying the fission characteristics of the compound nucleus <sup>292</sup>Fl by bombarding a plutonium-244 target with accelerated calcium-48 ions.<sup>[30]</sup> A compound nucleus is a loose combination of nucleons that have not yet arranged themselves into nuclear shells. It has no internal structure and is held together only by the collision forces between the target and projectile nuclei.<sup>[31][b]</sup> The results revealed how nuclei such as this fission predominantly by expelling doubly magic or nearly doubly magic fragments such as calcium-40, tin-132, lead-208, or bismuth-209. It was also found that the yield for the fusion-fission pathway was similar between calcium-48 and iron-58 projectiles, indicating a possible future use of iron-58 projectiles in superheavy element formation.<sup>[30]</sup> It has also been suggested that a neutron-rich flerovium isotope can be formed by the quasifission (partial fusion followed by fission) of a massive nucleus.<sup>[32]</sup> Recently it has been shown that the multi-nucleon transfer reactions in collisions of actinide nuclei (such as uranium and curium) might be used to synthesize the neutron-rich superheavy nuclei located at the island of stability,<sup>[32]</sup> although production of neutron-rich nobelium or seaborgium nuclei is more likely.<sup>[29]</sup>

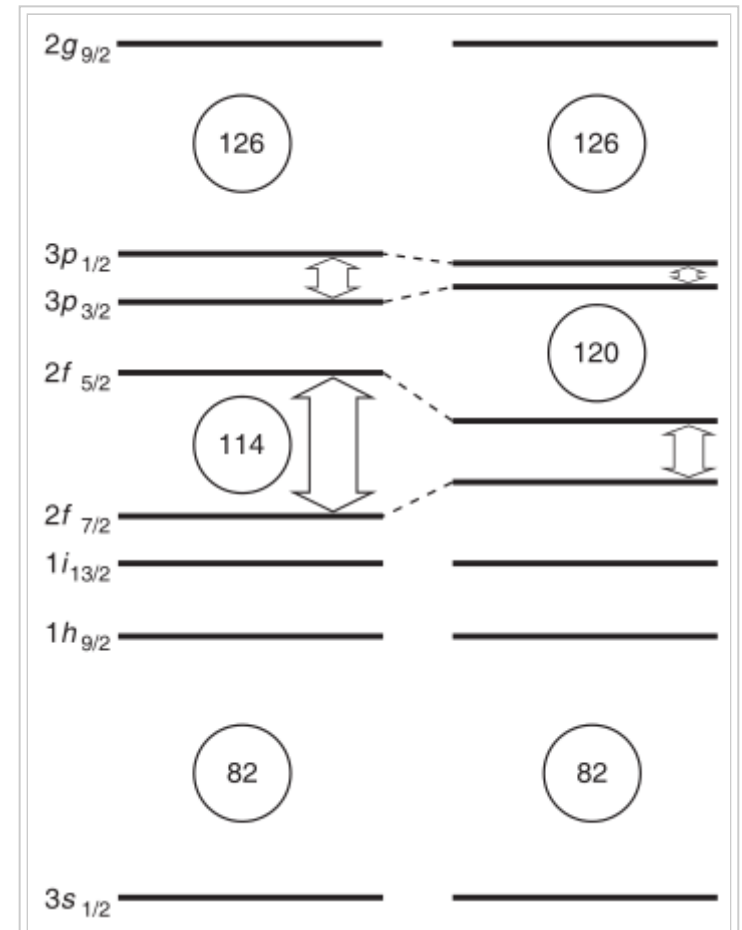
iso	NA	half-life	DM	DE (MeV)	DP
<b>289Fl</b>	syn	2.6 s	α	9.82,9.48	<sup>285</sup> Cn
<b>289mFl ?</b>	syn	2–23 s	α	9.71	<sup>285m</sup> Cn ?
<b>288Fl</b>	syn	0.8 s	α	9.94	<sup>284</sup> Cn
<b>287Fl</b>	syn	0.48 s	α	10.02	<sup>283</sup> Cn
<b>287mFl ?</b>	syn	5.5 s	α	10.29	<sup>283m</sup> Cn ?
<b>286Fl</b>	syn	0.13 s	40% α	10.19	<sup>282</sup> Cn
			60% SF		
<b>285Fl</b> <sup>[8][9]</sup>	syn	125 ms	α	10.41(5)	<sup>281</sup> Cn
<b>284Fl</b> <sup>[8][9]</sup>	syn	2.5 <sup>+1.8</sup> <sub>−0.8</sub> ms	SF		



electrons move faster than in lighter atoms, at velocities comparable to the speed of light.<sup>[37]</sup> In relation to flerovium atoms, it lowers the 7s and the 7p electron energy levels (stabilizing the corresponding electrons), but two of the 7p electron energy levels are stabilized more than the other four.<sup>[38]</sup> The stabilization of the 7s electrons is called the inert pair effect, and the effect "tearing" the 7p subshell into the more stabilized and the less stabilized parts is called subshell splitting. Computation chemists see the split as a change of the second (azimuthal) quantum number  $l$  from 1 to  $\frac{1}{2}$  and  $\frac{3}{2}$  for the more stabilized and less stabilized parts of the 7p subshell, respectively.<sup>[39][c]</sup> For many theoretical purposes, the valence electron configuration may be represented to reflect the 7p subshell split as  $7s^2 7p_{1/2}^2$ .<sup>[2]</sup> These effects cause flerovium's chemistry to be somewhat different from that of its lighter neighbours.

Due to the spin-orbit splitting of the 7p subshell being very large in flerovium, and the fact that both flerovium's filled orbitals in the seventh shell are stabilized relativistically, the valence electron configuration of flerovium may be considered to have a completely filled shell, making flerovium a very noble metal. Its first ionization energy of 8.539 eV (823.9 kJ/mol) should be the highest in group 14.<sup>[2]</sup> The 6d electron levels are also destabilized, and may still be able to participate in chemical reactions in flerovium (but not the later 7p elements), which might allow it to behave in some ways like transition metals and allow higher oxidation states<sup>[3]</sup> such as +4 and +6. They should be less stable than the +2 state, following periodic trends, and may only be stable in flerovium fluorides.<sup>[3]</sup>

The closed-shell electron configuration of flerovium results in the metallic bonding in metallic flerovium being weaker than in the preceding and following elements; thus, flerovium is expected to have a low boiling point,<sup>[2]</sup> and has recently been suggested to be possibly a gaseous metal, similar to the predictions for copernicium, which also has a closed-shell electron configuration.<sup>[14]</sup> The melting and boiling points of flerovium are predicted to be around 70 °C and 150 °C,<sup>[2]</sup> significantly lower than the values for the lighter group 14 elements (those of lead are 327 °C and 1749 °C respectively), and continuing the trend of decreasing boiling points down the group. Although earlier studies predicted a boiling point of ~1000 °C or 2840 °C,<sup>[3]</sup> this is now considered unlikely because of the expected weak metallic bonding in flerovium and that group trends would expect flerovium to have a low sublimation enthalpy.<sup>[2]</sup> In the solid state, flerovium is expected to be a dense metal due to



Orbitals with high azimuthal quantum number are raised in energy, eliminating what would otherwise be a gap in orbital energy corresponding to a closed proton shell at element 114. This raises the next proton shell to the region around element 120.<sup>[14]</sup>

its high atomic weight, with a density variously predicted to be either  $22 \text{ g}\cdot\text{cm}^{-3}$  or  $14 \text{ g}\cdot\text{cm}^{-3}$ .<sup>[2]</sup> The electron of the hydrogen-like flerovium ion (oxidized so that it only has one electron,  $\text{Fl}^{113+}$ ) is expected to move so fast that it has a mass 1.79 times that of a stationary electron, due to relativistic effects. For comparison, the figures for hydrogen-like lead and tin are expected to be 1.25 and 1.073 respectively.<sup>[40]</sup> Flerovium would form weaker metal-metal bonds than lead and would be adsorbed less on surfaces.<sup>[40]</sup>

## Chemical

Flerovium is the heaviest known member of group 14 in the periodic table, below lead, and is projected to be the second member of the 7p series of chemical elements. The first five members of this group show the group oxidation state of +4 and the latter members have an increasingly prominent +2 chemistry due to the onset of the inert pair effect. Tin represents the point at which the stability of the +2 and +4 states are similar, and lead(II) is the most stable of all the chemically well-understood group 14 elements in the +2 oxidation state.<sup>[2]</sup> The 7s orbitals are very highly stabilized in flerovium and thus a very large  $sp^3$  orbital hybridization is required to achieve the +4 oxidation state, so flerovium is expected to be even more stable than lead in its strongly predominant +2 oxidation state and its +4 oxidation state should be highly unstable.<sup>[2]</sup> For example, flerovium dioxide ( $\text{FlO}_2$ ) is expected to be highly unstable to decomposition into its constituent elements (and would not be formed from the direct reaction of flerovium with oxygen),<sup>[2][41]</sup> and flerovane ( $\text{FlH}_4$ ), which should have Fl-H bond lengths of  $1.787 \text{ \AA}$ ,<sup>[6]</sup> is predicted to be more thermodynamically unstable than plumbane, spontaneously decomposing into flerovium(II) hydride ( $\text{FlH}_2$ ) and hydrogen gas.<sup>[42]</sup> The only stable flerovium(IV) compound is expected to be the tetrafluoride,  $\text{FlF}_4$ .<sup>[43]</sup> even this may be due to  $sd$  hybridizations rather than  $sp^3$  hybridization,<sup>[44]</sup> and its decomposition to the difluoride and fluorine gas would be exothermic.<sup>[6]</sup> The gross destabilization of all the tetrahalides (for example,  $\text{FlCl}_4$  is destabilized by about  $400 \text{ kJ/mol}$ ) is unfortunate because otherwise these compounds would be very useful in gas-phase chemical studies of flerovium.<sup>[6]</sup> The corresponding polyfluoride anion  $\text{FlF}_6^{2-}$  should be unstable to hydrolysis in aqueous solution, and flerovium(II) polyhalide anions such as  $\text{FlBr}_3^-$  and  $\text{FlI}_3^-$  are predicted to form preferentially in flerovium-containing solutions.<sup>[2]</sup> The  $sd$  hybridizations might be possible as the 7s and 6d electrons in flerovium share approximately the same energy, perhaps making even higher oxidation states like +6 possible with extremely electronegative elements, such as in flerovium(VI) fluoride ( $\text{FlF}_6$ ).<sup>[3]</sup> In general, the spin-orbit contraction of the  $7p_{1/2}$  orbital should lead to smaller bond lengths and larger bond angles: this has been theoretically confirmed in  $\text{FlH}_2$ .<sup>[6]</sup>

Due to the relativistic stabilization of flerovium's  $7s^2 7p_{1/2}^2$  valence electron configuration, the 0 oxidation state should also be more stable for flerovium than for lead, as the  $7p_{1/2}$  electrons begin to also exhibit a mild inert pair effect:<sup>[2]</sup> this stabilization of the neutral state may bring about some similarities between the behaviour of flerovium and the noble gas radon.<sup>[11]</sup> Due to the



expected relative inertness of flerovium, its diatomic compounds FIH and FIF should have lower energies of dissociation than the corresponding lead compounds PbH and PbF.<sup>[6]</sup> Flerovium(IV) should be even more electronegative than lead(IV);<sup>[43]</sup> lead(IV) has electronegativity 2.33 on the Pauling scale; the lead(II) value is only 1.87.

Flerovium(II) should be more stable than lead(II), and polyhalide ions and compounds of types  $\text{FIX}^+$ ,  $\text{FIX}_2$ ,  $\text{FIX}_3^-$ , and  $\text{FIX}_4^{2-}$  ( $\text{X} = \text{Cl}, \text{Br}, \text{I}$ ) are expected to form readily. Fluorine would be able to also form the unstable flerovium(IV) analogues.<sup>[2]</sup> All the flerovium dihalides are expected to be stable;<sup>[2]</sup> with the difluoride being water-soluble,<sup>[45]</sup> spin-orbit effects would destabilize flerovium dihydride ( $\text{FIH}_2$ ) by almost 2.6 eV (250 kJ/mol).<sup>[41]</sup> In solution, flerovium would also form the oxoanion flerovite ( $\text{FIO}_2^{2-}$ ) in aqueous solution, analogous to plumbite. Flerovium(II) sulfate ( $\text{FISO}_4$ ) and sulfide ( $\text{FIS}$ ) should be very insoluble in water, and flerovium(II) acetate ( $\text{FIC}_2\text{H}_3\text{O}_2$ ) and nitrate ( $\text{FI}(\text{NO}_3)_2$ ) should be quite water-soluble.<sup>[3]</sup> The standard electrode potential for the reduction of  $\text{FI}^{2+}$  ions to metallic flerovium is estimated to be around +0.9 V, confirming the increased stability of flerovium in the neutral state.<sup>[2]</sup> In general, due to the relativistic stabilization of the  $7p_{1/2}$  spinor,  $\text{FI}^{2+}$  is expected to have properties intermediate between those of  $\text{Hg}^{2+}$  or  $\text{Cd}^{2+}$  and its lighter congener  $\text{Pb}^{2+}$ .<sup>[2]</sup> The standard electrode potential for the  $\text{FI}^{2+}/\text{FI}$  couple is predicted to be  $-0.9$  V.<sup>[3]</sup>

## Experimental chemistry

Flerovium is currently the heaviest element to have had its chemistry experimentally investigated. Two experiments were performed in April–May 2007 in a joint FLNR-PSI collaboration aiming to study the chemistry of copernicium. The first experiment involved the reaction  $^{242}\text{Pu}(^{48}\text{Ca},3\text{n})^{287}\text{Fl}$  and the second the reaction  $^{244}\text{Pu}(^{48}\text{Ca},4\text{n})^{288}\text{Fl}$ : these reactions produce short-lived flerovium isotopes whose copernicium daughters would then be studied.<sup>[46]</sup> The adsorption properties of the resultant atoms on a gold surface were compared with those of radon, as it was then expected that copernicium's full-shell electron configuration would lead to noble-gas like behaviour.<sup>[46]</sup> Noble gases interact with metal surfaces very weakly, which is uncharacteristic of metals.<sup>[46]</sup>

The first experiment allowed detection of three atoms of  $^{283}\text{Cn}$  but also seemingly detected 1 atom of  $^{287}\text{Fl}$ . This result was a surprise given the transport time of the product atoms is  $\sim 2$  s, so the flerovium atoms produced should have decayed to copernicium before adsorption. In the second reaction, 2 atoms of  $^{288}\text{Fl}$  and possibly 1 atom of  $^{289}\text{Fl}$  were detected. Two of the three atoms displayed adsorption characteristics associated with a volatile, noble-gas-like element, which has been suggested but is not predicted by more recent calculations. These experiments provided independent confirmation for the discovery of

copernicium, flerovium, and livermorium via comparison with published decay data. Further experiments in 2008 to confirm this important result detected a single atom of  $^{289}\text{Fl}$ , and supported previous data showing flerovium having a noble-gas-like interaction with gold.<sup>[46]</sup>

The experimental support for a noble-gas-like flerovium was soon to weaken abruptly. In 2009 and 2010, the FLNR-PSI collaboration synthesized further atoms of flerovium to follow up their 2007 and 2008 studies. In particular, the first three flerovium atoms synthesized in the 2010 study suggested again a noble-gas-like character, but the complete set taken together resulted in a more ambiguous interpretation, unusual for a metal in the carbon group but not fully like a noble gas in character.<sup>[47]</sup> In their paper, the scientists refrained from calling flerovium's chemical properties "close to those of noble gases", as had previously been done in the 2008 study.<sup>[47]</sup> Flerovium's volatility was again measured through interactions with a gold surface, and provided indications that the volatility of flerovium was comparable to that of mercury, astatine, and the simultaneously investigated copernicium, which had been shown in the study to be a very volatile noble metal, conforming to its being the heaviest group 12 element known.<sup>[47]</sup> Nevertheless, it was pointed out that this volatile behaviour was not expected for a usual group 14 metal.<sup>[47]</sup>

In even later experiments from 2012 at the GSI, the chemical properties of flerovium were revealed to be more metallic than noble-gas-like. Jens Volker Kratz and Christoph Düllmann specifically named copernicium and flerovium as belonging to a new category of "volatile metals"; Kratz even speculated that they might be gaseous at standard temperature and pressure.<sup>[14][48]</sup> These "volatile metals", as a category, were expected to fall between normal metals and noble gases in terms of adsorption properties.<sup>[14]</sup> Contrary to the 2009 and 2010 results, it was shown in the 2012 experiments that the interactions of flerovium and copernicium respectively with gold were about equal.<sup>[49]</sup> Further studies showed that flerovium was more reactive than copernicium, in contradiction to previous experiments and predictions.<sup>[14]</sup>

## Source

- Wikipedia: Flerovium (<https://en.wikipedia.org/wiki/Flerovium>)