Physics of superheavy elements

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- What is nuclear physics?
- What are superheavy elements?
- How to create superheavy elements?
- What are chemical properties of superheavy elements?
Introduction: atoms and atomic nuclei

What would you see if you magnified the dog?

~ 50 cm
Introduction: atoms and atomic nuclei

~ 50 cm

~ μm = 10^{-6} m
Introduction: atoms and atomic nuclei

~ 50 cm

~ \( \mu m = 10^{-6} \) m

~ 10^{-8} m

~ 10^{-10} m

All things are made of atoms.
All things are made of atoms.

- Thales, Democritus (ancient Greek)
- Dalton (chemist, 19th century)
- Boltzmann (19th century)
- Einstein (1905)

STM image
(surface physics group, Tohoku university)

\(~ 10^{-10} \text{ m} \)
Introduction: atoms and atomic nuclei

- ~50 cm
- ~10^{-8} m
- ~10^{-10} m
- ~10^{-15} m
Neutral atoms: \# of protons = \# of electrons

Chemical properties of atoms \rightarrow \# of electrons

\[ M_p \sim M_n \sim 2000 \, M_e \] \rightarrow the mass of atom \sim the mass of nucleus
Periodic table of chemical elements

<table>
<thead>
<tr>
<th>Group</th>
<th>1</th>
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Lanthanides | 57 La | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er |
Actinides    | 89 Ac | 90 Th | 91 Pa | 92 U  | 93 Np | 94 Pu | 95 Am | 96 Cm | 97 Bk | 98 Cf | 99 Es | 100 Fm |

tabular arrangement of chemical elements based on the atomic numbers (\# of electrons = \# of protons)
What are we made of?

- **oxygen**: 43 kg
- **carbon**: 16 kg
- **hydrogen**: 7 kg
- **nitrogen**: 1.8 kg
- **calcium**: 1.0 kg
- **phosphorus**: 780 g
- **potassium**: 140 g
- **sulphur**: 140 g
- **sodium**: 100 g
- **chlorine**: 95 g
- **magnesium**: 19 g
- **iron**: 4.2 g
- **fluorine**: 2.6 g
- **zinc**: 2.3 g
- **silicon**: 1.0 g
- **rubidium**: 0.68 g
- **strontium**: 0.32 g
- **bromine**: 0.26 g
- **lead**: 0.12 g
- **copper**: 72 mg
- **aluminium**: 60 mg
- **cadmium**: 50 mg
- **cerium**: 40 mg
- **barium**: 22 mg
- **iodine**: 20 mg
- **tin**: 20 mg
- **titanium**: 20 mg
- **boron**: 18 mg
- **nickel**: 15 mg
- **selenium**: 15 mg
- **chromium**: 14 mg
- **manganese**: 12 mg
- **arsenic**: 7 mg
- **lithium**: 7 mg
- **caesium**: 6 mg
- **mercury**: 6 mg
- **germanium**: 5 mg
- **molybdenum**: 5 mg
- **cobalt**: 3 mg
- **antimony**: 2 mg
- **silver**: 2 mg
- **niobium**: 1.5 mg
- **zirconium**: 1 mg
- **lanthanum**: 0.8 mg
- **gallium**: 0.7 mg
- **tellurium**: 0.7 mg
- **yttrium**: 0.6 mg
- **yttrium**: 0.6 mg
- **bismuth**: 0.5 mg
- **thallium**: 0.5 mg
- **indium**: 0.4 mg
- **gold**: 0.2 mg
- **scandium**: 0.2 mg
- **tantalum**: 0.2 mg
- **vanadium**: 0.11 mg
- **thorium**: 0.1 mg
- **uranium**: 0.1 mg
- **samarium**: 50 µg
- **beryllium**: 36 µg
- **tungsten**: 20 µg
proton (+e)
neutron (no charge)

Where are neutrons?
Nuclear Chart: 2D map of atomic nuclei

proton number

neutron number
Nuclear Chart: 2D map of atomic nuclei

- Isotopes:
  - $^{16}\text{O}$ ($Z=8$, $N=8$, $A=16$)
  - $^{17}\text{O}$ ($Z=8$, $N=9$, $A=17$)
  - $^{18}\text{O}$ ($Z=8$, $N=10$, $A=18$)

- Proton number $Z$
- Neutron number $N$
- Mass number $A = Z + N$
- Stable nuclei in nature: 287
- Nuclei artificially synthesized: about 3,000
- Nuclei predicted: about 7,000 ~ 10,000

Nuclear Physics: Several static and dynamical properties of those nuclei
Nuclear Chart: 2D map of atomic nuclei

- how many neutrons can be attached?
- what is the shape of nuclei?
- is there any exotic structure?
- what is the heaviest nucleus?
- how do nuclei decay?

….. etc. etc.
An example of what we investigate in nuclear physics

- what is the shape of a nucleus?

Are nuclei all spherical?
Some nuclei are deformed in the ground state! What are combinations of \((Z,N)\) which yield a deformation?

http://t2.lanl.gov/tour/sch001.html
What is the heaviest element?
What is the heaviest element?

natural elements:  \textbf{Pu} (Z=94) \rightarrow \text{a tiny amount in nature}  \\
\textbf{U} (Z=92)  \\

What determines these numbers??
What is the heaviest element?

natural elements:  
Pu (Z=94) → a tiny amount in nature  
U (Z=92)

What determines these numbers??

heavy nuclei → large Coulomb repulsion  
unstable against α decay

\( {}^4 \text{He} \) nucleus  
= α particle

(Z,N)  
(Z-2,N-2)  
(Z=2,N=2)
Decay half-lives of heavy nuclei

\[ T_{1/2} \ (\text{year}) \]

- \( ^{232}\text{Th} \): \( 1.405 \times 10^{10} \) years
- \( ^{238}\text{U} \): \( 4.468 \times 10^9 \) years
- \( ^{244}\text{Pu} \): \( 8.08 \times 10^7 \) years
- \( ^{247}\text{Cm} \): \( 1.56 \times 10^7 \) years

Heavier nuclei: unstable against fission

The age of the universe: 13.7 billion years
The age of the earth: 4.6 billion years
Periodic table of chemical elements

<table>
<thead>
<tr>
<th>Group</th>
<th>Period</th>
<th>Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>H, He</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>Li, Be, B, C, N, O, F, Ne</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Na, Mg, Al, Si, P, S, Cl, Ar</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Rb, Sr, Y, Zr, Nb, Mo, Tc,Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>Fr, Ra, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Uut, Fl, Uup, Lv, Uus, Uuo</td>
</tr>
</tbody>
</table>

**Lanthanides**: 57 La, 58 Ce, 59 Pr, 60 Nd, 61 Pm, 62 Sm, 63 Eu, 64 Gd, 65 Tb, 66 Dy, 67 Ho, 68 Er, 69 Tm, 70 Yb, 71 Lu

**Actinides**: 89 Ac, 90 Th, 91 Pa, 92 U, 93 Np, 94 Pu, 95 Am, 96 Cm, 97 Bk, 98 Cf, 99 Es, 100 Fm, 101 Md, 102 No, 103 Lr

**Artificially synthesized (‘man-made’) elements**: Ds, Rg, Cn, Uut, Fl, Uup, Lv, Uus, Uuo

**Superheavy elements (SHE)**: synthesized through nuclear reactions
Prediction of island of stability: an important motivation of SHE study

Island of stability around $Z=114$, $N=184$

W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)

Modern calculations: $Z=114, 120$, or $126$, $N=184$

E.g., H. Koura et al. (2005)
who is she?

<table>
<thead>
<tr>
<th>Z</th>
<th>Name</th>
<th>Year</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>Darmstadtium (Ds)</td>
<td>1994</td>
<td>Germany</td>
</tr>
<tr>
<td>111</td>
<td>Roentgenium (Rg)</td>
<td>1994</td>
<td>Germany</td>
</tr>
<tr>
<td>112</td>
<td>Copernicium (Cn)</td>
<td>1996</td>
<td>Germany</td>
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<tr>
<td>113</td>
<td>No name yet</td>
<td>2003 Russia / 2004 Japan</td>
<td></td>
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<tr>
<td>114</td>
<td>Flerovium (Fl)</td>
<td>1999</td>
<td>Russia (*)</td>
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<tr>
<td>115</td>
<td>No name yet</td>
<td>2003</td>
<td>Russia</td>
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<tr>
<td>116</td>
<td>Livermorium (Lv)</td>
<td>2000</td>
<td>Russia</td>
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<tr>
<td>117</td>
<td>No name yet</td>
<td>2010</td>
<td>Russia</td>
</tr>
<tr>
<td>118</td>
<td>No name yet</td>
<td>2002</td>
<td>Russia</td>
</tr>
</tbody>
</table>

(*) island of stability: Z=114, N=184
Fl discovered: Z=114, N=174-175
→ island not yet confirmed
How to synthesize SHE?

Nuclear fusion reactions

two positive charges repel each other

cf.

accelerate a projectile nucleus to overcome the barrier

nuclear attractive interaction

compound nucleus

e.g.,

\[ ^{70}\text{Zn} + ^{209}\text{Bi} \rightarrow ^{279}\text{113} \]
CN = compound nucleus
ER = evaporation residue

contact
fusion
evaporation

Quasi-fission cannot distinguish experimentally detected

CN = compound nucleus
ER = evaporation residue
typical values for Ni + Pb reaction

$10^{11} = 100,000,000,000$

$10^6 = 1,000,000$

very rare event !!

CN = compound nucleus
ER = evaporation residue

exponentially detected
Element 113 (RIKEN, K. Morita et al.)

$^{70}\text{Zn} \ (Z=30) + ^{209}\text{Bi} \ (Z=83) \rightarrow ^{278}\text{113} + n$


only 3 events for 553 days experiment
Theoretical treatment

\[ P_{ER} = P_{cap} \cdot P_{CN} \cdot P_{sur} \]

- \( P_{cap} \): contact
- \( P_{CN} \): fusion
- \( P_{sur} \): evaporation

CN = compound nucleus
ER = evaporation residue

CN = compound nucleus
ER = evaporation residue
EPCap: quantum mechanics
energy dissipation
thermal motion
2-body potential
1-body potential
compound nucleus
energy dissipation
\( P_{\text{cap}}: \text{quantum mechanics} \)
\((b)^{86}\text{Kr} + ^{208}\text{Pb}\)
Theory: Langevin approach

multi-dimensional extension of:

\[ m \frac{d^2 q}{dt^2} = -\frac{dV(q)}{dq} - \gamma \frac{dq}{dt} + R(t) \]

- \( q \): internuclear separation,
- \( \gamma \): friction coefficient
- \( R(t) \): random force
- \( \frac{dq}{dt} \): deformation,
- asymmetry of the two fragments

\(^{48}\text{Ca} + ^{244}\text{Pu} \rightarrow ^{292}\text{Ni}

E' = 33 \text{ MeV}
Quasi-fission (QF)

$^{34}\text{S} + ^{238}\text{U}$

Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85(’12)044614
Quasi-fission (QF)

fusion-fission

\[ ^{34}\mathrm{S} + ^{238}\mathrm{U} \]

Y. Aritomo, K.H., K. Nishio, S. Chiba, PRC85(’12)044614
Element 113

- Dubuna
  \[ {^{48}Ca} + {^{243}Am} \rightarrow {^{288}115} + 3n \rightarrow {^{284}113} + \alpha \] (2003)
  \[ {^{48}Ca} + {^{249}Bk} \rightarrow {^{293}117} + 4n \rightarrow {^{189}115} + \alpha \rightarrow {^{285}113} + \alpha \] (2010)
  etc.
- RIKEN
  \[ {^{70}Zn} + {^{209}Bi} \rightarrow {^{278}113} + n \] (2004) Cold Fusion: \(^{208}\text{Pb}\) or \(^{209}\text{Bi}\) target

Hot Fusion: \(^{48}\text{Ca}\) projectile
Flerov Laboratory of Nuclear Reactions, JINR, Dubna, Russia about 120 km north of Moscow

$^{105}$Db (Dubnium)
<table>
<thead>
<tr>
<th></th>
<th>Hot Fusion</th>
<th>Cold Fusion</th>
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<tbody>
<tr>
<td>Example</td>
<td>$^{48}\text{Ca} + ^{243}\text{Am} \rightarrow 4\text{n}$</td>
<td>$^{70}\text{Zn}+^{209}\text{Bi} \rightarrow 1\text{n}$</td>
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<tr>
<td>asymmetry</td>
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<td>Capture</td>
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<td>Survival</td>
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\[ \sigma \sim fb = 10^{-39} \text{ cm}^2 \]

RIKEN
(Cold fusion)

3rd event Aug. 12 2012

Dubna
(Hot fusion)

\[ \sigma \sim pb = 10^{-36} \text{ cm}^2 \]

cf. Cold Fusion:
connected to known nuclei

Hot Fusion:
neutron-richer CN
Naming rights?
Under discussions in the joint IUPAC/IUPAP Joint Working Party

IUPAC = International Union of Pure and Applied Chemistry
IUPAP = International Union of Pure and Applied Physics

- RIKEN (Japan)
  much less ambiguity with cold fusion
- Dubna (Russia)
  much larger number of events
Chemistry of superheavy elements

Are they here in the periodic table?
That is, does e.g., Lv show the same chemical properties as O, S, Se, Te, and Po?
relativistic effect: important for large $Z$

$$E = mc^2$$

Solution of the Dirac equation (relativistic quantum mechanics) for a hydrogen-like atom:

$$E_{1S} = mc^2 \sqrt{1 - (Z\alpha)^2} \sim mc^2 \left(1 - \frac{(Z\alpha)^2}{2} - \frac{(Z\alpha)^4}{8} + \cdots\right)$$

relativistic effect
Famous example of relativistic effects: the color of gold

Gold looked like silver if there was no relativistic effects!
Silver (Ag)  

3.7 eV  

5s  

4d  

Gold (Au)  

2.4 eV  

6s  

5d  

cf. visible spectrum  

2.76 eV  

1.65 eV
Gold (Au) Silver (Ag)

Non-Rel. Non-Rel.

Rel. Non-Rel. Rel.

3.7 eV 2.4 eV

Au blue: absorbed Ag no color absorbed

Silver (Ag) Gold (Au)
Chemistry of superheavy elements

How do the relativistic effects alter the periodic table for SHE?

→ a big open question
Summary

- All things are made from atoms.
- The heaviest natural elements are U/Pu.
- Prediction: the island of stability
- Superheavy elements (SHE) up to Z=118 have been synthesized with nuclear fusion reactions.
- The fusion probability for SHE is extremely small.
- The naming rights for Z=113: RIKEN or Dubna?
- Chemistry of SHE: relativistic effects?
Homework

- Deadline: Wednesday, Nov. 13, 2013
- Submit the homework inside an envelope at #1047 (10th floor, Hagino’s office) in the Science Complex B building or send it by e-mail to hagino@nucl.phys.tohoku.ac.jp.

1. Explain why it is so difficult to synthesize a superheavy element.
2. Write what you thought about the physics and chemistry of superheavy elements and/or your impression on this lecture.