Physics of superheavy elements

What is the heaviest element?
What is the heaviest element? Pu (Z=94) → a tiny amount in nature
U (Z=92)

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

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} = \alpha \text{ particle}

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

- $^{232}\text{Th}$: $1.405 \times 10^{10}$ 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
Periodic table of chemical elements

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</table>

- artificially synthesized (‘man-made’)
- superheavy elements (SHE)

nuclear reactions
Fusion reactions for SHE

the element 113: Nh

November, 2016

Heavy-ion fusion reaction
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)

Yuri Oganessian
Extra binding for $N$ or $Z = 2, 8, 20, 28, 50, 82, 126$ (magic numbers)

$\rightarrow$ Very stable

$^{4}\text{He}_{2}, ^{16}\text{O}_{8}, ^{40}\text{Ca}_{20}, ^{48}\text{Ca}_{28}, ^{208}\text{Pb}_{126}$
Liquid Drop Model (LDM)

fission barrier

LDM+shell correction

Z. Patyk et al., NPA491(‘89) 267
<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Year</th>
<th>Location</th>
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<td>Roentgenium</td>
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<td>1994</td>
<td>Germany</td>
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<td>Cn</td>
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<td>Germany</td>
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</tbody>
</table>

Germany, Japan: cold fusion reactions
Russia: hot fusion reactions
How to synthesize SHE?

Nuclear fusion reactions

- Fusion of medium-heavy systems:

- Fusion of heavy and super-heavy systems:

  re-separation
$Z_1 \times Z_2 = 1296$

$Z_1 \times Z_2 = 2000$

C.-C. Sahm et al.,
Z. Phys. A319('84)113
EPcap: quantum mechanics

thermal fluctuation

2-body potential

1-body potential

compound nucleus

heat up

re-separation

\((b)^{86}\text{Kr} + ^{208}\text{Pb}\)

\(E\)

P\text{\_cap: quantum mechanics}
(note) fission barrier in the liquid drop model

\[ a = R \cdot (1 + \epsilon) \]
\[ b = R \cdot (1 + \epsilon)^{-1/2} \]
\[ ab^2 = R^3 = \text{constant} \]

\[ \Delta E = \Delta E_{\text{Surf}} + \Delta E_{\text{Coul}} \]
\[ = E_S^{(0)} \left\{ \frac{2}{5} (1 - x) \epsilon^2 - \frac{4}{105} (1 + 2x) \epsilon^3 + \ldots \right\} \]

\[ E_S^{(0)} = +a_S A^{2/3} \]

\[ x \equiv \frac{E_C^{(0)}}{2E_S^{(0)}} = \frac{a_C}{2a_S} \cdot \frac{Z^2}{A} \sim 1 \frac{1}{53.3} \cdot \frac{Z^2}{A} \]

\[ E_C^{(0)} = a_C Z(Z - 1)/A^{1/3} \]
fission barrier in the liquid drop model

\[ a = R \cdot (1 + \epsilon) \]
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fission barrier:

\[ \epsilon_B = \frac{21(1 - x)}{3(1 + 2x)} \]
\[ E_B = \frac{98}{15} \cdot \frac{(1 - x)^3}{(1 + 2x)^2} \cdot E_S^{(0)} \]
if two identical nuclei contact:

\[
\frac{a}{b} \sim \frac{2R}{R} = 2 \rightarrow \epsilon \sim 0.587
\]

\[
\begin{align*}
a &= R_0 \cdot (1 + \epsilon) \\
b &= R_0 \cdot (1 + \epsilon)^{-1/2}
\end{align*}
\]

\[
\begin{align*}
40_{20}^{40}\text{Ca} + 40_{20}^{40}\text{Ca} \rightarrow 80_{40}^{80}\text{Zr} \\
120_{50}^{120}\text{Sn} + 120_{50}^{120}\text{Sn} \rightarrow 240_{100}^{240}\text{Fm}
\end{align*}
\]

threshold: $Z_1^*Z_2 = 1600 \sim 1800$

\[
\begin{align*}
a_s &= 16.8 \text{ MeV} \\
a_C &= 0.72 \text{ MeV}
\end{align*}
\]
CN = compound nucleus
ER = evaporation residue

cannot distinguish experimentally
defined transitions

CN = compound nucleus
ER = evaporation residue
experimentally detected

Quasi-fission

fission

cannot distinguish experimentally
defined transitions
typical values for Ni + Pb reaction

\[ 10^{11} = 100,000,000,000 \]

\[ 10^6 = 1,000,000 \]

very rare event !!

experimentally detected

ER = evaporation residue

CN = compound nucleus
typical values for Ni + Pb reaction

\[ 10^{11} = 100,000,000,000 \]

hot fusion: optimizes this process

\[ 10^6 = 1,000,000 \]

very rare event!!

cold fusion: optimizes this process

\[ 99,999,000,000 \]

\[ 999,999 \]

experimentally detected

CN = compound nucleus
ER = evaporation residue
Element 113 (RIKEN, K. Morita et al.)

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


only 3 events for 553 days experiment
CN = compound nucleus
ER = evaporation residue

\[ \sigma_{ER}(E) = \frac{\pi}{k^2} \sum_{l} (2l + 1) T_l(E) P_{CN}(E, l) W_{suv}(E^*, l) \]
Langevin approach

multi-dimensional extension

\( q: \)
- internuclear separation,
- deformation,
- asymmetry of the two fragments

thermal fluctuation

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

\( \gamma: \) friction coefficient

\( R(t): \) random force
Theory: Lagenvin approach

multi-dimensional extension of:

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

\( \gamma \): friction coefficient

\( R(t) \): random force

\(^{48}\text{Ca} + ^{244}\text{Pu} \rightarrow ^{292}\text{114} \)

\( E^* = 33 \text{ MeV} \)
Future directions

Superheavy elements synthesized so far

Towards Z=119 and 120 isotopes

Towards the island of stability

Theoretical issues:

- to understand the reaction dynamics
- to make a reliable theoretical prediction for fusion cross sections
Hot fusion for $Z = 119$ and 120

Towards $Z=119$ and 120 isotopes

hot fusion: $^{48}$Ca + actinide targets

Dubna: $^{48}$Ca + $^{249}$Cf ($\beta_2 = 0.235$) $\rightarrow ^{297-x}$Og ($Z=118$) + $xn$

role of deformation?
Quantum friction?

Hot fusion: $^{48}\text{Ca} + \text{deformed actinide target}$

Effect of deformation

Open problems
- how is the shape evolved to a compound nucleus?
- Deformation: a quantum effect
  - how does the deformation disappear during heat-up?

Quantum friction?
Towards Z=119 and 120 nuclei

Another issue

\[ ^{48}_{20}\text{Ca} + ^{99}_{25}\text{Es} \rightarrow 119 \]
\[ ^{48}_{20}\text{Ca} + ^{100}_{26}\text{Fm} \rightarrow 120 \]

the targets: not available with sufficient amounts

Dubna: \[ ^{48}\text{Ca} + ^{249}_{98}\text{Cf} \rightarrow ^{297-x}\text{Og} (Z=118) + xn \]

\[ ^{249}_{98}\text{Cf} \text{ (351 year)} \]
\[ ^{252}_{99}\text{Es} \text{ (471.7 day)} \]
\[ ^{257}_{100}\text{Fm} \text{ (100.5 day)} \]

\[ ^{48}\text{Ca} \rightarrow ^{50}_{22}\text{Ti}, ^{51}_{23}\text{V}, ^{54}_{24}\text{Cr} \text{ projectiles} \]

cf. \[ ^{46}_{21}\text{Sc}_{25} : \text{relatively small neutron number} \]

how much will fusion cross sections be reduced?
nobody still knows
Towards the island of stability

neutron-rich beams: indispensable

- how to deal with low beam intensity?
- reaction dynamics of neutron-rich beams?
  - capture: role of breakup and (multi-neutron) transfer?
  - diffusion: neutron emission during a shape evolution?
  - survival: validity of the statistical model?

structure of exotic nuclei

more studies are required
Are they here in the periodic table?
Does Nh show the same chemical properties as B, Al, Ga, In, and Tl?
relativistic effect: important for large $Z$

\[ E = mc^2 \]

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

\[ E_{1s} = mc^2 \sqrt{1 - (Z\alpha)^2} \sim mc^2 \left( 1 - \frac{(Z\alpha)^2}{2} - \frac{(Z\alpha)^4}{8} + \ldots \right) \]

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

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

5s → 4d

3.7 eV

Gold (Au):

6s → 5d

2.4 eV

cf. visible spectrum

2.76 eV (Silver) 1.65 eV (Gold)
Silver (Ag)  
Gold (Au)  

3.7 eV  2.76 eV  2.4 eV  1.65 eV

Absorbed (Au)  
Reflected (Au)  
Reflected (Ag)

cf. visible spectrum
How do the relativistic effects alter the periodic table for SHE?  
→ a big open question