DECAY MODES AND A LIMIT OF EXISTENCE OF NUCLEI

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How is the limit of elements?

Chemistry

- In chemical study, elements up to Z~172 have been discussed.
- Are such elements can be existed?
- In other words, does the corresponding nuclei exist in certain half-lives?

P. Pyykko presented a more improved table.
How far does the area of nuclei extend?
- some qualitative estimations-

Lecture Notes in Physics 581, p.317 (Greiner) 2001
also in talks of Kratz and Greiner himself

Some qualitative estimation were studied, but rather quantitative estimation are required.

We estimate decay modes by using the KTUY mass formula.

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Fig. 1. The periodic system of elements as conceived by the Frankfurt school in the late sixties. The islands of superheavy elements ($Z = 114$, $N = 184, 196$ and $Z = 164$, $N = 318$) are shown as dark hatched areas.

On Beyond Uranium, p.66 (S, Hofmann) 2002. Figure was taken from Sobiczewski (1974)
\[ M(Z, N) = M_{\text{gross}}(Z, N) + M_{\text{eo}}(Z, N) + E_{\text{sh}}(Z, N) \]

\[ M_{\text{gross}}(Z, N) : \text{Gross term} \]
\[ A^{-1/3} \text{ expansion term including } |N-Z|, (N-Z)^2 + \text{Coulomb term} \]

\[ E_{\text{sh}}(Z, N) : \text{Shell term} \]

Spherical nuclei: Calculate from a modified Woods-Saxon potential (a function of \( Z, N \)) (NPA671(00)96)

Spherical state of All nuclei are obtained.

Deformed nuclei: Mixing weight of the above spherical shell energies weight : determined by shapes of nuclei (NPA674(00)47)

\[ E_{\text{sh}}(Z, N) = \sum_{\text{def.}} (<E_{\text{sh}}^{\text{sph}}(Z, N)>_{\text{def.}} + \Delta E_S(Z, N) - \Delta E_C(Z, N) - \Delta E_{\text{pro}}(Z, N)) \]

Mass table (Z,N>1, Z<131, N<201) : available from the web site of Nuclear Data Center of JAEA
Results of the KTUY mass formula

1. Nuclear shell energies $E_{sh}(Z, N)$

2. Deformation parameter alpha2 of KUTY

3. RMS dev. from exp. mass

4. KTUY05

5. N-drip line in the light region

- $N=14, 20, 28, 50$ gap -> decreasing

Difference between calc. and exp. masses for 2219 nuclei ($Z, N \geq 2$)

1. Nuclear shell energy
2. Nuclear shape
3. Better mass-reproduction
4. Change of magicities in n-rich
5. Reproduction of n-drip line
6. etc.

Nuclear shell energy
Deformation parameter $\alpha_2$ ($\alpha_4$ and $\alpha_6$ are also obtained)

KUTY05

N-drip line in the light region

KTUY05

N=14, 20, 28, 50 gap -> decreasing

Deformation parameter $\alpha_2$
Reproduction of the KTUY model

RMS deviation from experimental data in keV

<table>
<thead>
<tr>
<th>Mass formulas</th>
<th>Mass</th>
<th>Neutron</th>
<th>Proton</th>
<th>Alpha</th>
<th>Beta</th>
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<tr>
<td></td>
<td>S_n</td>
<td>S_p</td>
<td>Q_α</td>
<td>Q_α &gt; 0</td>
<td>Q_β</td>
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<td>KTUY</td>
<td>653</td>
<td>316</td>
<td>353</td>
<td>517</td>
<td>494</td>
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<td>395</td>
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<td>640</td>
<td>564</td>
<td>593</td>
<td>683</td>
<td>641</td>
</tr>
</tbody>
</table>

Exp. data: AME2003 by Audi et al.

- KTUY gives **Smallest RMS dev.** from exp. derivatives of masses by **10-20%**
α-decay Q-values from GSI and RIKEN related to $^{234}$Bk $^{277}$Cn $^{271}$Ds ($^{275}$Cn)

Experiment: steep at $N \approx 162$, flat at $N \approx 164$

KTUY: smooth property, but deformed shell is not clear

*All predictions are calculated as ground-to-ground-state decays.
Estimation of nuclear decay modes

- Alpha-decay
- Beta-decay
- Proton emission
- Spontaneous fission

Sensitivity

- Q-values from masses
- Single-particle potential
- Potential energy surface plus penetration probability
Alpha and beta decay half lives

**Alpha decay: phenomenological relation between Q\(\alpha\) and \(T^{\alpha}_{1/2}\):**

\[
\log_{10} T_{\alpha}(s) = 1.7195 \sqrt{\frac{A-4}{A} Z_D / \sqrt{Q_{\alpha}(\text{MeV})}} - 1.2901 \sqrt{\frac{A-4}{A} RZ_D} + 0.07466 \sqrt{\frac{A-4}{A} R^{3/2} / Z_D^{1/2}} \cdot Q_{\alpha}(\text{MeV})
\]

\[-\log_{10} N = 0.159175 + h_0 \delta_{eo}.
\]

\[R = r_0 A_0^{1/3} + d_0, \quad r_0 = 1.08 \text{ fm}.
\]

- RMS dev.: **1/10~10 times** in partial half-lives if exp. Q-values are adopted.
- Uncertainty of estimated \(Q_{\alpha}\) is \(\sim\)500 keV. Typically, shift of 300 keV gives a change of \(T^{1/2}_{\alpha}\) in one order of magnitude in the superheavy mass region.
- Totally Uncertainty of \(10^{-3}-10^{3}\) in \(T^{\alpha}_{1/2}\)

**Beta decay: the Gross theory of beta decay**

\[
\lambda_{\alpha} = \lambda_{F} + \lambda_{GT} + \lambda_{1}^{(0)} + \lambda_{1}^{(1)} + \lambda_{1}^{(2)}
\]

\[
\lambda_{F} = \frac{m_e^5 c^4}{2 \pi^3 \hbar^7} |g_{\nu}|^2 \int_{-Q}^{0} |M_{F}(E)|^2 f(-E) dE : \text{Fermi (allowed)}
\]

\[
\lambda_{1}^{(2)} = \frac{m_e^5 c^4}{2 \pi^3 \hbar^7} \left( \frac{m_e c}{\hbar} \right)^2 |g_{\lambda}|^2 \sum_{ij} |M_{ij}(E)|^2 f_1(-E) dE : \text{1st forbidden}
\]

\[
|M_{\Omega}(E)|^2 \approx \int_{\epsilon_{\min}}^{\epsilon_{\max}} D(E, \epsilon) W(E, \epsilon) \frac{d n_{1}}{d \epsilon} d\epsilon
\]

\(D(E, \epsilon)\) : One particle strength function

- Consider sum rules of beta-decay
- Not only allowed but also forbidden transition is treated:
- Averaged even-odd effect is introduced.
Spontaneous Fission half-lives

- **SF-dominant region exists (N≈170)** (in agreement with measured data)
- Fission barrier height based on the KTUY mass calculation.

**Spontaneous fission half-lives**: Penetration probability is calculated with 1-dim. WKB method (mass inertia is adjustable parameter).

- Potential energy surface
- Saddle point
- Ground state
- Energy (MeV)
- Deformation α2
- Deformation
- Fission barrier heights (MeV)
- Neutron number N
- Fission barrier height based on the KTUY mass calculation.

**Decay chains terminate by fission.**

- Decay chains terminate by fission.
- α decay chain
- GSI, RIKEN
- Dubna (1999-

- α decay chain
- N=184
Estimation of Partial half lives

Spontaneous fission

Quite sensitive to the shell closure.

Proton emission

There has rather long partial half lives even outer proton-drip line

α decay

Rather sensitive to the proton shell closure.

+ β-decay by using the gross theory of β-decay + KTUY
Total half-lives ($\alpha, \beta, p, sf$)

- $^{310}{[126]}$ (T$_{1/2} \sim 10^{-7}$ s)
- $^{354}{[126]}_{228}$ (T$_{1/2} \sim 100$ yr)
- $^{298}{[114]}$ (T$_{1/2} \sim 10$ d)
- $^{294}$Ds (T$_{1/2} \sim 300$ yr)

(Long-lived superheavy nuclei distributes near the $\beta$-stability line)
Most dominant decay ($\alpha$, $\beta$, sf, p) ($T_{1/2} \geq 1$ ns)

The bulletin of the Physical Society of Japan (BUTSURI), 60 (2005)
Decay modes in the superheavy region

Periodicity of nuclear closed shell

How far does the area of nuclei extend? (finiteness)

“Peninsula”

N=126 magic

Fission

“Cape”

N=228 magic

N=184

N=228

Z=126

Z=114

Z=101

Z=82

Z=114

Z=101

N=126

N=228

235U

208Pb

an example of r-process path

Only nuclei with >10^{-9}s

sf(more dom. than p)

sf(Sequential alpha decays from hot fusion terminated by fission)

sf(impede to produce \( [114] \) by the r-process)

Shortest: most dominant decay

sf(more dom. than p)
Main decay modes

Spontaneous-fissioning nuclei is the border in the neutron-deficient side. $T_{sf} = 10^{-9}$ s line and neutron-drip line crosses near $N \approx 340$ (cf. fissility line). Islands of stability corresponding $N = 228, 308, Z=164$ magicity appear.
Spherical neutron magic: beyond 184

Neutron: N=164, 184, 228, 308 gap appear clearly.

Calculated with KY potential (Koura et al., NPA671 (2000) 96)

KTUY formula
Spherical
Spherical proton magic: beyond 114 (or 126)

Proton: Z=114, 164 gap exist, but are not so remarkable.
Upper limit of Atomic number with half-lives longer than $10^{-9}$ s:

- $N \approx 184$ region $\Rightarrow Z \approx 136$,
- $N \approx 228$ region $\Rightarrow Z \approx 142$,
- $N \approx 308$ region $\Rightarrow Z \geq 175$.

Uncertainty of half-lives: They may be in 3 order of magnitude. ex. $^{294}$Ds: 0.3 y $\sim$ 0.3 My
Conclusion

- We calculate **nuclear decay modes** and **total half-lives** in the (ultra) superheavy nuclear mass region by using the **KTUY mass model**.
- **Nuclear decay mode of superheavy nuclei**:
- **Other regions of “island of stability of superheavy nuclei”**
  - “Peninsula” near the proton-drip region along $N=126$
  - Next “island (cape) of stability” along $N=228$ (small) and also $N=308$ (large) <- due to the shell closure of the nuclear mean-field potential.
- **Limit of Existence of nuclei**:
- **A finiteness of region of (relatively) long-lived nuclei**
  - Predicted number of nuclei:
    - 11,000 for nuclei with > 1 ns
    - 10,000 for nuclei with > 1 μs
    - 8,000 for nuclei with > 1 ms
    - 4,000 for nuclei with > 1 s
  - Calculation region reaches the limit of macroscopic fissility line.
Спасибо!

Thank you for your attention!