Superallowed alpha decay to doubly-magic $^{100}\text{Sn}$

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Superallowed $\alpha$ Decay to Doubly Magic $^{100}$Sn

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Outline

- Alpha decay, past and present
- Theoretical description of alpha decay
- Observation of the $^{108}\text{Xe}-^{104}\text{Te}-^{100}\text{Sn}$ alpha decay chain
- Discussion of alpha-decay reduced widths
  - $^{208}\text{Pb}$ region vs $^{100}\text{Sn}$ region
  - theoretical calculations for $^{104}\text{Te}$
- Summary and Outlook
Alpha decay - early days

- **Becquerel** discovers first radioactivity (1896)
- **Rutherford** characterizes “alpha rays” (1899)
  - Identification of alpha rays as He ions (1907)
- **Geiger-Nuttall** law (1911)
  - \( \log(T_{1/2}) = AQ_{\alpha}^{-1/2} + B \)
- **Gamow** theory of alpha decay (1928)
  - tunneling through a Coulomb/centrifugal barrier
  - probabilistic interpretation of quantum mechanics
- **Geiger-Marsden** experiment (1909)
  - \( \alpha \) scattering on Au foil
  - Rutherford proposes small/heavy atomic nucleus
- First nuclear reactions with \( \alpha \) particles as beams
  - \( \alpha + ^{14}\text{N}, \) discovery of **proton** (1920)
  - \( \alpha + \text{Be}, \) discovery of **neutron** (1932)
Alpha decay today

Exotic proton-rich nuclei
New isotopes
Super-heavy nuclei
Masses
Structure

There are many formulas for calculating $\alpha$-decay widths but **microscopic description** of $\alpha$ decay remains challenging

$^{238}\text{U} - 4.5 \times 10^9 \text{ a}$
$^{232}\text{Th} - 1.4 \times 10^{10} \text{ a}$
Significance of alpha decay

- Clustering in nuclei
  - Emission of heavy clusters
  - Fission
- Astrophysics
  - $\alpha + \alpha + \alpha \rightarrow ^{12}\text{C}$ creation in stars, Hoyle state
  - $(p, \alpha)$ reactions
  - ($\alpha, n$) reactions
- Applications
  - Targeted radiation therapy
  - Thermo-electric engines
  - Smoke detectors
  - He from $\alpha$ decay of U and Th

$^{20}\text{Ne EDF calculations, Nature 487, 341 (2012)}$
Gamow alpha-decay model

G. Gamow, Z. Phys. 51, 204 (1928)

\[ \lambda = \nu P \]
\[ \Gamma = \hbar \lambda = \hbar \nu P \]

\[ \lambda = \frac{\nu}{2R_0} \exp \left[ -2 \int_{R_1}^{R_2} \frac{2\mu}{\hbar} |Q_\alpha - V(r)| \, dr \right] \]

Can be readily calculated
Very steep function of Q-value

\[ \Gamma = \delta^2 P \]
\[ \delta^2 = \frac{\Gamma_{\text{exp}}}{P_{\text{calc}}} \]

\( \delta^2 \) - \( \alpha \) preformation factor/ reduced \( \alpha \) decay width

\( \lambda \) - decay constant
\( \Gamma \) – decay width
\( \nu \) - assault frequency
\( P \) – penetration probability

Nuclear potential
Coulomb/centrifugal barrier

Nuclear Structure and Dynamics, May 13-17, 2019
R-matrix expression of the alpha-decay width

Decay width:

$$\Gamma_L(R) = 2\gamma_L^2(R) P_L(R)$$

- $P_L(R)$ - penetrability
- $R$ - channel radius (outside of the nucleus)

Reduced width amplitude:

$$\gamma_L(R) = \left(\frac{\hbar^2 R}{2\mu}\right)^{1/2} F_L(R)$$

Formation amplitude:

$$F_L(R) = \int d\xi_\alpha d\xi_D d\hat{R} [\phi_\alpha(\xi_\alpha) \psi_D(\xi_D) Y_L(\hat{R})]^{*}_{\alpha_4,\nu_4} \psi_P(\xi_\alpha \xi_D; R)$$

Overlap between parent nucleus and daughter nucleus + alpha at a distance R outside of nuclear interactions
Challenges of microscopic $\alpha$-decay width calculations

- Microscopic description using the shell model
  - Underestimates experimental values by about 2 orders of magnitude
  - Only Shell Model+Cluster Model reproduces $^{212}\text{Po}$
    
    K. Varga et al., PRL 69, 37 (1992)

- Large configuration space
- Antisymmetrization
- Normalization
- Configuration mixing (nucleon-nucleon residual interaction)
  - pairing, proton-neutron interaction
- Contribution from the continuum

$\alpha$ decay of $^{212}\text{Po}$ to doubly-magic $^{208}\text{Pb}$ is the simplest case and serves as a benchmark for the calculations
\( ^{100}\text{Sn} \) physics

\( ^{104}\text{Te} \) α decays to doubly magic \( ^{100}\text{Sn} \), protons and neutrons occupy the same orbitals.

Self-conjugate 
\( n-p \) \( T=0 \) pairing  
Isospin non-conservation

\( ^{100}\text{Sn} \) physics

Doubly-magic  
Shell model

\( \beta \)-decay

Isomers  
Seniority spin-gap

\( \alpha \)-decay

rp process end point

p, 2p decay

Super-allowed  
\( \beta \)-decay

Super-allowed  
GT \( \beta \)-decay

\( ^{100}\text{Sn} \) rp process end point

\( ^{100}\text{Sn} \) physics

Nuclear Structure and Dynamics, May 13-17, 2019
$^{100}$Sn region experimental status

$\alpha$ and p decay island NE of $^{100}$Sn
Estimated $^{104}$Te lifetime 1-10 ns
$^{108}$Xe-$^{104}$Te chain instead

$^{105}$Te lifetime 1-10 ns
$^{108}$Xe chain instead

$\alpha$ decay
proton decay
$\beta$-delayed protons with sizeable branch
Observed/expected

Nuclear Structure and Dynamics, May 13-17, 2019
Argonne Fragment Mass Analyzer

Nuclear Structure and Dynamics, May 13-17, 2019
Recoil-Decay Correlations

- Implant-decay spatial and time correlations in DSSD
- Digital DAQ to detect PU waveforms
- Si box to catch escaping alphas

$^{58}\text{Ni}(^{54}\text{Fe},4n)^{108}\text{Xe}$ reaction
~5 days, ~30 pnA
FMA set to $A=108$, charge states $Q=+26,+27$
Recoil-decay correlations

TWO fast high energy decay events
Expected 0.09 random events
Both events were in coincidence with the Si box (only 1 out of 400 events were coincidences)
• The same total energy for both events
• Compared to $\alpha$ emitters different energy split
• Estimated cross section $\sim 200 \text{ pb}$ (extrapolated 1-5 nb for $^{100}\text{Sn}$)
Observation of weak proton branch in $^{108}$I

8 events followed by $^{107}$Te decay

$Q_p=597(13)$ keV

$b_p=0.5(3)$%

$T_{1/2}=26.4(8)$ ms

Sn-Sb-Te cycle at the termination of the rp-process
$^{108}\text{Xe}/^{104}\text{Te} \, \alpha$-particle energy determination

- Measured implantation depth and escape angle allow to determine energies of both $\alpha$ particles.
- Sum of energies is much better constrained.

$E_{\alpha}(^{104}\text{Te}) = 4.9(2)$ MeV
$E_{\alpha}(^{108}\text{Xe}) = 4.4(2)$ MeV
$\sum E_{\alpha} = 9.3(1)$ MeV
Alpha-decay Q value systematics

\[ Q_\alpha(^{104}\text{Te}) = 5.1(2) \text{ MeV} \]

\[ Q_\alpha(^{108}\text{Xe}) = 4.6(2) \text{ MeV} \]
Comparison with mass models

Locally adjusted double-folding potential

\[ Q_\alpha(^{104}\text{Te}) = 5.42(0.07) \text{ MeV}, \ T_{1/2}^{^{104}\text{Te}} = 5 \text{ ns (assumed P=10%)} \]
\[ Q_\alpha(^{108}\text{Xe}) = 4.65(0.15), \ T_{1/2}^{^{108}\text{Xe}} = 60 \mu\text{s (assumed P=5%)} \]
DSSD traces for the $^{108}\text{Xe}-^{104}\text{Te}$ pile-up events

Doubly differentiated traces

NO noticeable delay
TWO decays faster than 20 ns each imply $T_{1/2} < 18 \text{ ns}$
$^{108}\text{Xe}-^{104}\text{Te}$ reduced width limits

$W_{\alpha} = \frac{\delta^2}{\delta^2(^{212}\text{Po})}$

$E_{\alpha} = 4.5/4.8 \text{ MeV}$

$T_{1/2}(^{108}\text{Xe}) = 164 \mu s$

$T_{1/2}(^{108}\text{Xe}) = 58 \mu s$

$T_{1/2}(^{108}\text{Xe}) = 35 \mu s$

$W_{\alpha}(^{104}\text{Te})W_{\alpha}(^{108}\text{Xe}) > 25$

At least one $W_{\alpha}$ greater than 5
Reduced $\alpha$-decay widths near $^{100}\text{Sn}$

If $W_\alpha(^{104}\text{Te})/W_\alpha(^{108}\text{Xe}) \sim 2$ as for $^{106}\text{Te}/^{110}\text{Xe}$ pair: $W_\alpha(^{104}\text{Te}) > 6$, $W_\alpha(^{108}\text{Xe}) > 3$
Reduced $\alpha$-decay width global systematics

$^{104}$Te, $W_{\alpha}>5$

$\rho' \sim 50$

$\log_{10}|R F(R)|^2 > -1.3$

$\rho' = \sqrt{A_{\alpha}A Z_{\alpha}Z_{\alpha}(A_{\alpha}^{3/2} + A_{Z}^{3/2})}$

Multistep shell model

Monika Patial, R. J. Liotta, and R. Wyss, Phys. Rev. C 93, 054326 (2016)

R-matrix

$^{212}$Po
Calculated $T_{1/2}=15 \mu s$, experiment 298 ns

$^{104}$Te
Calculated $T_{1/2}=1.5 \mu s$, assuming $Q_\alpha=5.06$ MeV, experiment $T_{1/2}<15$ ns
$\alpha$-particle formation probability **4.85 times larger** in $^{104}$Te compared to $^{212}$Po
Complex-energy shell model


R-matrix

$^{212}\text{Po}$
- Calculated $T_{1/2}$ is 36 times too long (R-matrix)
- Too small configuration space

$^{104}\text{Te}$
- No convergence
- $T_{1/2} < 500$ ns, assuming $Q_{\alpha}=5.15$ MeV
- Need to add proton-neutron interaction
- Better treatment of continuum
Summary and Outlook

- First observation of $^{108}\text{Xe}-^{104}\text{Te}-^{100}\text{Sn}$ chain
  - Enhanced alpha preformation
- Theoretical description of $\alpha$ decay still work in progress
  - $^{104}\text{Te}$, $^{108}\text{Xe}$ important for the role of neutron-proton interaction
- Future measurements (more beam, larger efficiency)
  - $^{104}\text{Te}$ lifetime (~1 ns)
  - more precise $\alpha$-decay widths for $^{108}\text{Xe}$ and other N~Z $\alpha$ emitters
  - $^{112}\text{Ba}$ N=Z $\alpha$ emitter
  - alpha emitters “north-east” $^{100}\text{Sn}$ can be studied at the new generation fragmentation facilities