Alpha decay chains from superheavy nuclei

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Extra-stable Nuclei: Magic N, Z (Closed Shell structure)

N = 2, 8, 20, 28, 50, 82, 126, ?

Theoretical Predictions:

Z = 2, 8, 20, 28, 50, 82, ?

1965: Myers & Swiatecki : Z=114, N= 184 – possibly doubly magic (closed shell)

Report UCRL, 11980 (1965)

1966: Confirmed: Sobiczewski, Gareev, Kikulin,

Phys. Lett. 22, 500 (1966)

1969: Nilson et al. longest fission half life centers symmetrically around Z=114, N=184

S. G. Nilsson et al, N.P.A 131,1 (1969)

1969: Mosel & Greiner: studied: Z=114, Z=164 & alpha-decay estimated.

U. Mosel, W. Greiner, Z. Phys. 222, 261 (1969),

Beyond actinides (Z=89 -103), there exists a region called, “Magic Island”, or, “Island of stability” (250 <A <320) where one can find super heavy elements with large life times.

MAGIC Neutron and Proton numbers

N = 2, 8, 20, 28, 50, 82, 126,(162),184

Z = 2, 8, 20, 28, 50, 82, (108),114

Superheavy Doubly magic nucleus:

^{298}114:

Z=114,
N=184 **Spherical**

Superheavy Doubly magic nucleus:

^{270}Hs:

Z=108
N=162 **Deformed.**

Modern theories predict bound magic SHE with:

Z=120, 124 and 126

N=184

Will survive fission **Spherical**

Questions:

- **Will they live long?**
- **Are they found in nature?**
- **Can we make them in the laboratory?**
- **How do we detect them?**

Can SHE be found in Nature?

None found!!!

- **Search for Superheavy Elements in Nature**
- E. Cheifetz et al., Nuclear Chemistry Div., LBL, Berkeley, California, USA,
- **Phys. Rev. C. 6 (October 1972)**

- **A search for superheavy-element fission-tracks in iron meteorites**
- R. K. Bull, Department of Physics, University of Birmingham, Birmingham, UK
  Nature 282, 393 - 394 (22 November 1979)

- **Search for spontaneous fission emitters in Atlantis II (Part II)**
- T. Lund, R. Brandt, D. Molzahn, G. Tress, P. Vater and A. Marinov,
- Kernchemie, FB 14, Philipps-Universität, Marburg, Federal Republic of Germany,
- GSI, Darmstadt and Hebrew University, Jerusalem, Israel
- **Journal Zeitschrift für Physik A Hadrons and Nuclei, 300, 285 (1981)**

- **Search for spontaneous fission tracks of superheavy nuclei in deep-sea nodule minerals**
- K. Murtazaev, K. ; V.P. Perelygin,
- **Sov. At. Energy (Engl. Translation) Vol/Issue: 63:6; 407- 409(December 1987)**

Finally Found in Nature ?????

Evidence for a long-lived superheavy nucleus with atomic mass number A = 292 and atomic number Z = 122 in natural Th

arXiv:0804.3869v1 [nucl-ex]

A. Marinov[1], I. Rodushkin[2], D. Kolb[3], A. Pape[4], Y. Kashiv[1], R. Brandt[5], R.V. Gentry[6] & H.W. Miller[7]
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[2]Analytica AB, Aurorum 10, S-977 75 Luleå, Sweden
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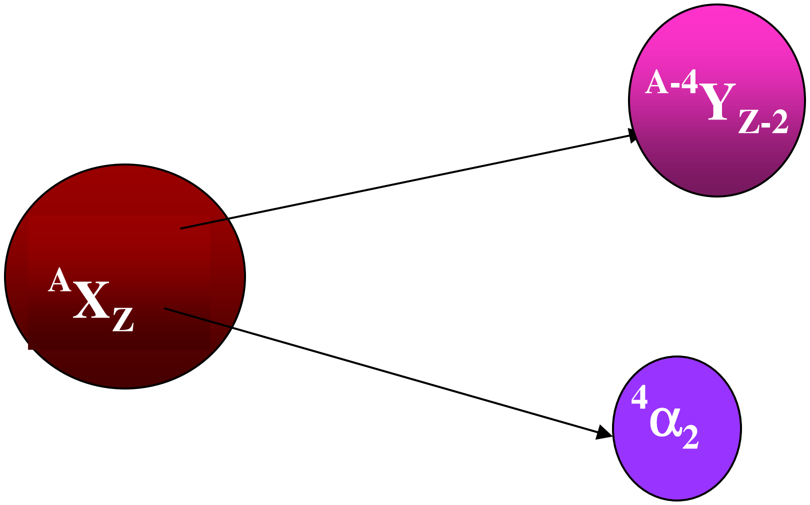
Evidence for the existence of a superheavy nucleus with atomic mass number A=292 and abundance $(1\text{-}10)\times10^{-12}$ relative to ^{232}Th has been **found in a study of natural Th** using inductively coupled plasma-sector field mass spectrometry. The measured mass matches the predictions for the mass of an isotope with atomic number Z=122 or a nearby element. **Its estimated half-life of $t_{1/2} \geq 10^8$ y suggests that a long-lived isomeric state exists in this isotope**. **The possibility that it might belong to a new class of long-lived high spin super- and hyperdformed isomeric states** is discussed.

Not confirmed, as yet!

Alpha-particle Emission from superheavy



The spontaneous emission of alpha- particle from a nucleus is possible if the released energy Q > 0.

$$Q = [\, M(^{A}X_{Z}) - M(^{A-4}Y_{Z-2}) - M(^{4}\alpha_{2}) \,]c^{2} \quad (\text{MeV})$$

To detect a SHE through alpha-particle channel:

✓**SHE should have large alpha-decay half-life (Tα)**

✓**(Tα) should be less than spontaneous fission half-life T(SF) and beta decay half life T(β).**

Theoretical Prediction of α-decay Half-lives

Methodology used by us:

(i) WKB framework for quantum tunneling of alpha-particle from nuclear potential.

(ii) Density-dependent Effective NN interaction of microscopic nature is used to calculate nuclear potential by double folding method.

(iii) Coulomb and centrifugal potential are also added to calculate total interaction energy (E(R)) of alpha-particle inside the parent nucleus.

(iii) Mass formula of **Myers & Swiatecki**, **Muntian–Hofmann–Patyk–Sobiczewski** and **KUTY** have been used to calculate the alpha-decay half lives.

This formalism yields excellent agreement with the experimental data, especially when **experimental Q-values** are used. Different mass formula gives somewhat different results of which the mass formula of **Muntian–Hofmann–Patyk–Sobiczewski** yields the best result.

Finally, existing Fission and Beta-decay half-lives are taken in to consideration to predict the long-lived superheavy nuclei which will decay through alpha channel.

P. Roy Chowdhury, C. Samanta, D.N. Basu, Phys. Rev. C77, 044603 (2008)

Calculation

- Total interaction energy: $\mathbf{E(R) = V_N(R) + V_C(R) + \hbar^2\, l(l+1) / (2\mu R^2)}$
- The WKB action integral from turning points (TP) R_2 to R_3 :

$$K = (2/\hbar) \int [2\mu\, (E(R) - E_v - Q)]^{1/2}\, dR \qquad \ldots\ldots\ldots\ldots\ldots (1)$$

- At the three Turning points (TP) : $\mathbf{E(R_1) = E(R_2) = E_v + Q = E(R_3)}$.

The alpha particle oscillates between 1st and 2nd TP and tunnels through the barrier at 2^{nd} and 3^{rd} TP. μ= reduced mass.

- The zero point vibration energy $\mathbf{E_v \propto Q}$.

$\mathbf{E_v}$=0.1045Q for even Z-even N, 0.0962Q for odd Z-even N, 0.0907Q for even Z–odd N, 0.0767Q for odd -odd parent nuclei (includes pairing and shell effects).

D.N.Poenaru, W. Greiner, Ivascu, Mazilu, Plonski, Z. Phys. A325 (1986) 435

- The decay half life of the parent nucleus:

$$T = [\, h \ln 2 / 2E_v\,].[1+\exp(K)\,] \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

- The half lives are very sensitive to Q, as it goes to the exponential function in eqn. 2 through the action integral (eqn.1).

Double folded nuclear potentials between daughter & emitted nucleus

- $V_N(R) = \int \rho_\alpha (r_1)\, \rho_d (r_2)\;\; v\,(s)\; d^3r_1 d^3r_2$

The density distribution function of α-particle is of Gaussian form:

- $\rho_\alpha (r) = 0.4229 \exp(-0.7024r^2)$
  where $\int \rho_\alpha (r)\, d^3r = \int \rho_\alpha (r)\, 4\pi^2 r dr = A_\alpha =$ mass no. of α-particle.

The matter density distribution for the daughter nucleus can be described by spherically symmetric Fermi function.

- $\rho_d (r)= \rho_0 (r)/[1+\exp\{(r-c)/a\}]$ with half density radius
  $c = r_\rho(1- \pi^2a^2/3r_\rho^{\,2})$,

equivalent sharp radius. $r_\rho = 1.13A_d^{1/3}$, diffuseness $a = 0.54$ fm.

The DDM3Y effective interaction

- The general expression for the density dependent effective M3Y interaction potential v(s) is written as

$$v\,(s,\rho,\varepsilon) = t^{M3Y}(s,\varepsilon\,)\,g(\rho,\varepsilon\,) \qquad (1)$$

- where M3Y effective interaction potential supplemented by a zero range pseudo potential t^{M3Y} (in MeV) is given by

$$t^{M3Y}(s,,\varepsilon\,) = 7999\,\exp(-4s)/(4s) - 2134\,\exp(-2.5s)/(2.5s) + J_{00}(\varepsilon\,)\delta(s) \qquad (2)$$

- where the zero-range pseudo-potential $J_{00}(\varepsilon\,)$ representing single-nucleon exchange term is given by

$$J_{00}(\varepsilon\,) = -276\,(1 - \alpha\,\varepsilon)\ (\mathrm{MeV.fm^3}) \qquad (3)$$

- and the density dependent part is given by

$$g(\,\rho,\varepsilon\,) = C\,(1 - \beta(\varepsilon)\,\rho_d^{\,2/3})\,(1 - \beta(\varepsilon)\,\rho_\alpha^{\,2/3}) \qquad (4)$$

Coulomb Potential

- Assuming spherical charge distribution for residual daughter nucleus and emitted nucleus as a point particle, the Coulomb potential $V_c(R)$ between them is:

$$V_c(R) = Z_\alpha Z_d e^2/(2R_c). [3 - (R/R_c)^2] \quad \text{for } R \le R_c.$$

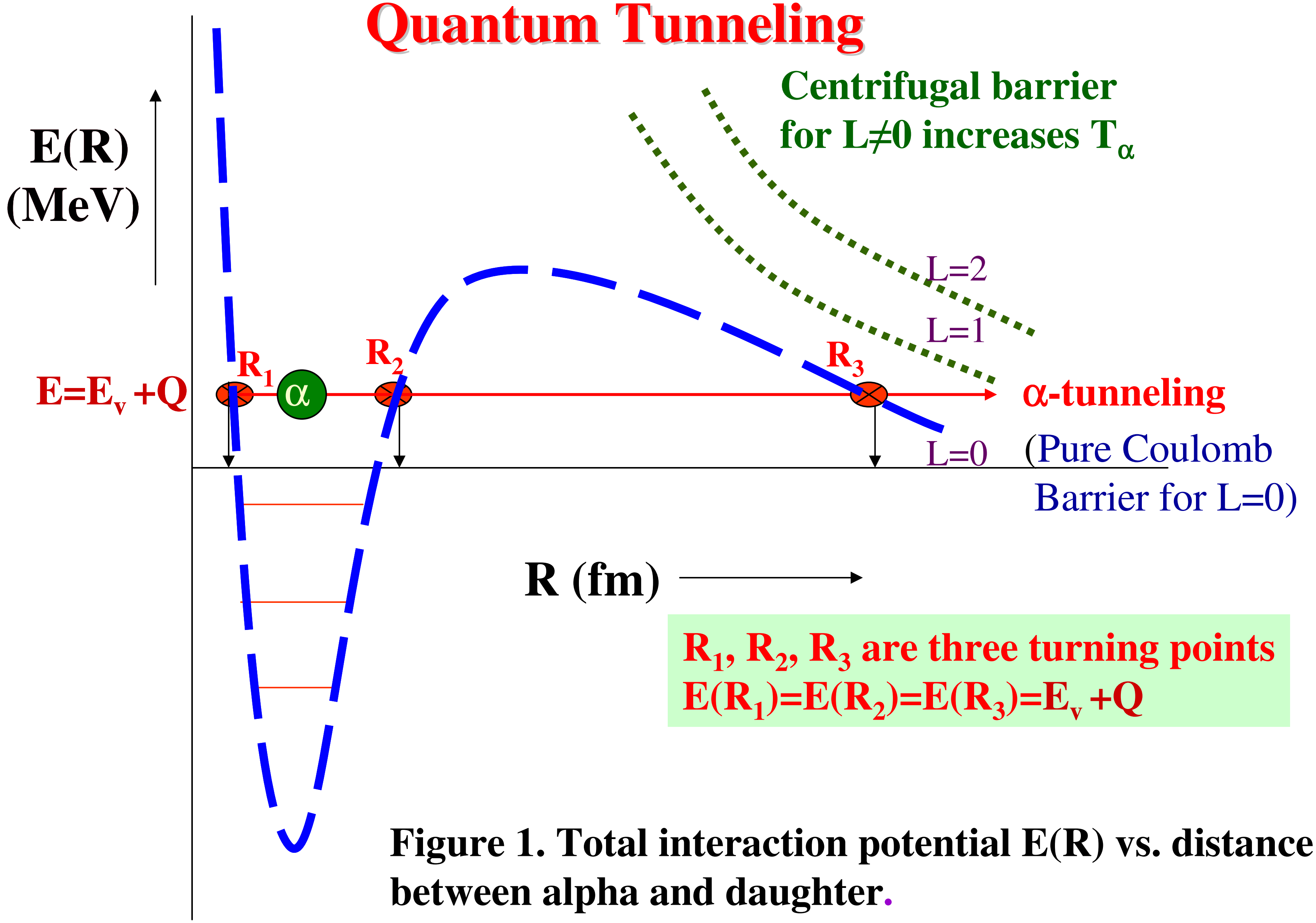
$$= Z_\alpha Z_d e^2/R \quad \text{otherwise}$$

- The touching radial separation R_c between two nuclei is

$$R_c = c_e + c_d$$

and c_e, c_d are half density radii.

Quantum Tunneling



R_1, R_2, R_3 are three turning points

$E(R_1)=E(R_2)=E(R_3)=E_v+Q$

Figure 1. Total interaction potential E(R) vs. distance between alpha and daughter.

Quantum theory of α-decay was established in 1928 by Gamow according to tunneling through a potential barrier.

Q-values, Spontaneous Fission and Beta Decay

Theoretical Q-values are taken from three different mass formulae:

1. Q-MMM: Muntian-Hofmann-Patyk-Sobiczewski (MMM) ,
   Acta. Phys. Pol. B34, 2073 (2003)
2. Q-MS: Myers-Swiatecki (MS) Nucl. Phys. A601, 141 (1996)
3. Q-KUTY: Koura-Uno-Tachibana-Yamada (KUTY)
   Nucl. Phys. A 674, 44 (2000)

❖SF half-lives T(SF), calculated in a dynamical approach using macroscopic microscopic method (MMM) by Smolanczuk et al. are shown in plots.

Smolanczuk et al, Phys. Rev C52, 1871 (1995), PRC56, 812 (1997)

❖Beta-decay half lives (T_β) are taken from:

P. Moller, J. R. Nix, K.-L. Kratz, Atomic Data & Nuclear Data Tables, 66,131 (1997)

Important Experimental Discoveries

In the early 1990s **Peter Armbruster, Sigurd Hofmann, Gottfried Münzenberg** and co-workers at the GSI laboratory in **Darmstadt, Germany,** used cold-fusion reactions to synthesize elements **107-112**.

These data were later confirmed by **Kosuke Morita and co-workers** at the **RIKEN, Japan** who also synthesized elements **110 and 111, 112, 113** in cold-fusion reactions.

Isotopes of the SHE **112, 113, 114, 115, 116** and the element ^{294}**118** have been produced in fusion evaporation reactions at Flerov Laboratory of Nuclear Reactions (FLNR)-Joint Institute for Nuclear Research (JINR), **Dubna, Russia by Yu.Ts. Oganessian and co-workers**.

SHE Z=106, 107, 108, 112 and recently, 114 have been chemically characterized.

Need more such experiments to confirm the properties of heavier elements.

FLNR-JINR Data: Our calculations

P. Roy Chowdhury, C. Samanta and D.N. Basu, Phys. Rev. C 73, 014612(2006)

** Yu. Ts. Oganessian et al., PRC 74 (2006) 044602

[ref] Expt: *Yu. Ts. Oganessian et al., PRC 70 (2004) 064609

Parent Nuclei Z	**A**	**EXPT* Q (MeV)**	**Theory [M-S] Q (MeV)**	**Experiment [ref] $T_{1/2}$**	**This work $T_{1/2}$**
118	294	11.81 ± 0.06	12.51	(-0.31) .89 (+1.07) ms**	**(-0.18) 0.66 (+0.23) ms**
116	290	11.00 ± 0.08	11.34	**(-6.0) 15.0 (+26) ms**	**(-5.2) 13.4 (+7.7) ms**
114	286	10.35 ± 0.06	9.61	**(-0.03) 0.16 (+0.07) s**	**(-0.04) 0.14 (+0.06) s**
112	282	**S.F.**			

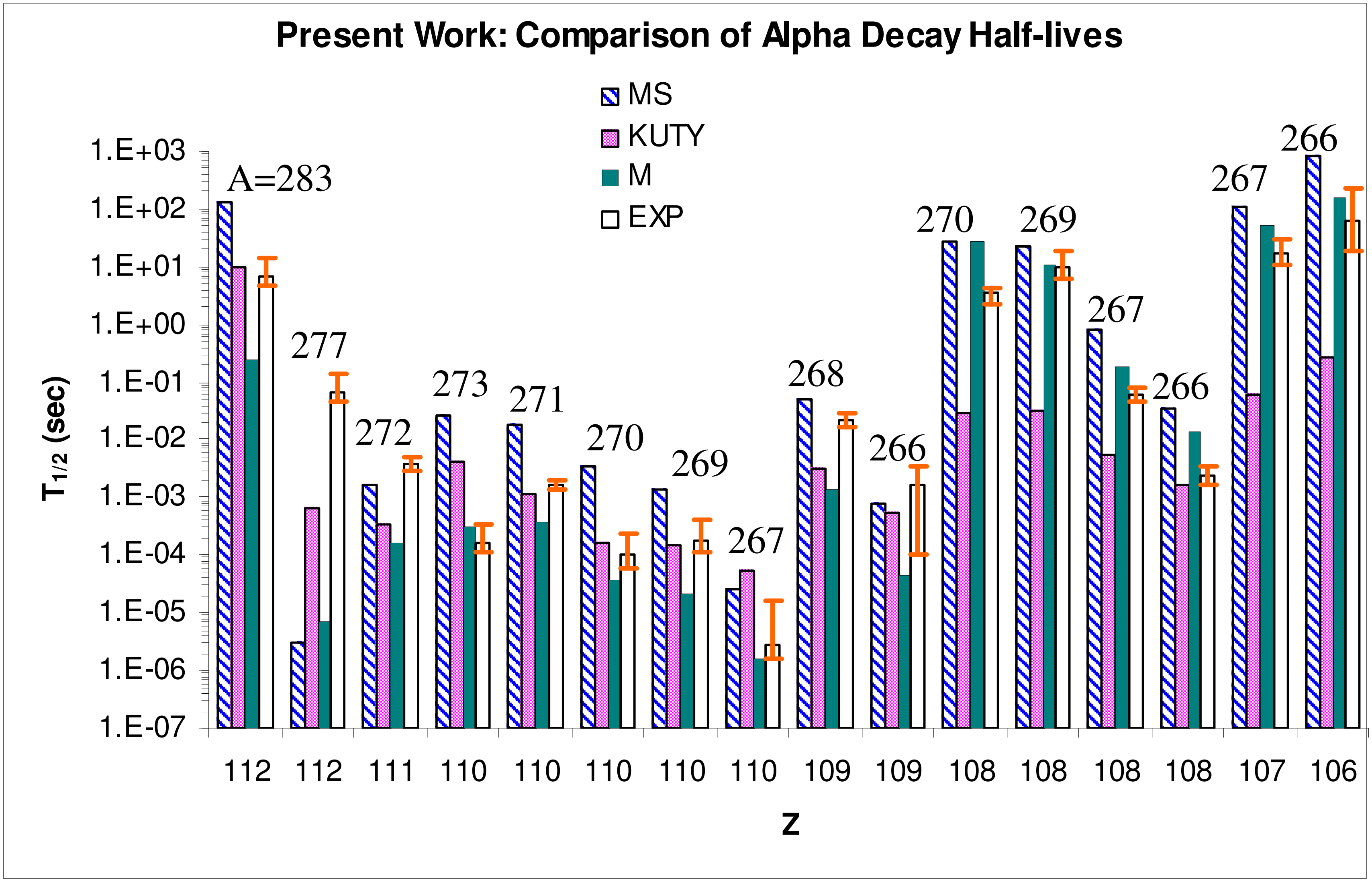
112 ununbium **(Uub) , 114** ununquadium **(Uuq), 116** ununhexium **(Uuh), 118** ununoctium **(Uuo)**

Parent Nuclei Z	**A**	**EXPT* Q (MeV)**	**Theory [M-S] Q (MeV)**	**Experiment [ref] $T_{1/2}$**	**This work $T_{1/2}$**
112	283	9.67 ± 0.06	9.22	**(-0.7) 4.00 (+1.3) s**	**(-2.0) 5.9 (+2.9) s**
110	279	9.84 ± 0.06	9.89	**(-0.03) 0.18 (+0.05) s**	**(-0.13) 0.40 (+0.18) s**
108	275	9.44 ± 0.07	9.58	**(-0.06) 0.15 (+0.27) s**	**(-0.40) 1.09 (+0.73) s**
106	271	8.65 ± 0.08	8.59	**(-1.0) 2.40 (+4.3) min**	**(-0.5) 1.0 (+0.8) min**
104	267	**S.F.**			

104 Rutherfordium **(Rf), 106** Seaborgium **(Sg), 108** Hassium **(Hs), 110** Darmstadtium **(Ds)**

GSI data: Our calculations

P. Roy Chowdhury, C. Samanta, D.N. Basu, Atomic Data & Nuclear Data Tables (in press)



Calculations with Q-MS, Q-MMM and Q-KUTY are shown

RIKEN data : our calculations with Q-experiment

*EXPT: K. Morita et al., Jour. Phys. Soc. of Japan 73 (10): 2593 (2004)

113 Ununtrium (Uut), 111 Roentgenuim (Rg), 109, Meitnerium (Mt), 107 Bohrium (Bh), 105 Dubnium (Db)

Parent Nuclei ^{A}Z	Expt.* E_α (MeV)	**Expt. Q (MeV)**	**Expt. Decay Time(t) T1/2=0.693*t**	**This work** $T_{1/2}$
^{278}113	11.68 ± 0.04	11.90 ± 0.04	**344 µs** **(238 µs)**	**(-18) 101** **(+27) µs**
^{274}111	11.15 ± 0.07	11.36 ± 0.07	**9.26 ms** **(6.41 ms)**	**(-0.12) 0.39** **(+0.18) ms**
^{270}109	10.03 ± 0.07	10.23 ± 0.07	**7.16 ms**** **(4.96ms)**	**(-17.68)** **52.05** **(+27.02) ms**
^{266}107	09.08 ± 0.04	09.26 ± 0.04	**2.47 s** **(1.71 s)**	**(-1.38)** **5.73** **(+1.82) s**
^{262}105		**S.F.**		

** Problem: As Q value decreases, the half life should increase. Deviations to this predominant behavior are observed in the above experimental data (111 and 109).

P. R.Chowdhury, D.N.Basu, C. Samanta, Phys. Rev. C 75, 047306 (2007)

This discrepancy does not exist in repeat experiment: K. Morita et al., J. Phys. Soc. Jpn. 76, 045001 (2007)

Doubly Magic Deformed Superheavy (Z=108, N=162): First Evidence

Phys. Rev. Lett. 97, 242501 (2006)

Doubly Magic Nucleus $^{270}Hs_{162}$

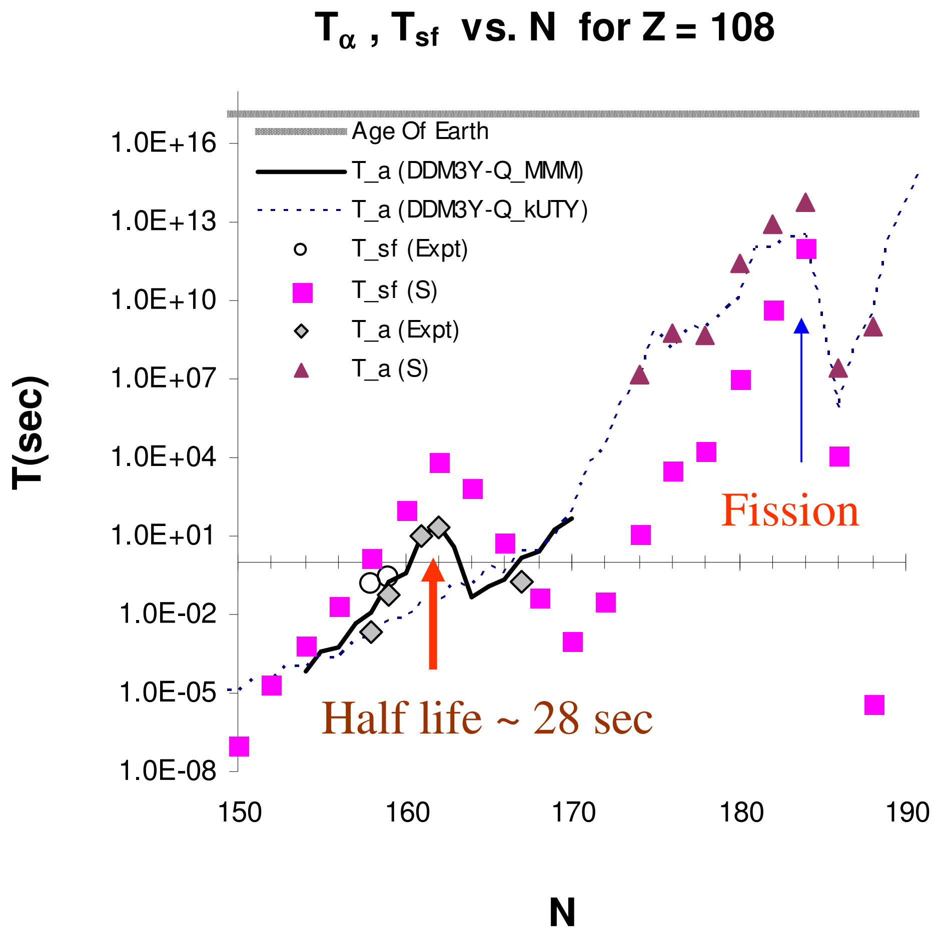
J. Dvorak,1 W. Brüchle,2 M. Chelnokov,3 R. Dressler,4 Ch. E. Düllmann,5,6 K. Eberhardt,7 V. Gorshkov,3 E. Jäger,2 R. Krücken,1 A. Kuznetsov,3 Y. Nagame,8 F. Nebel,1 Z. Novackova,1 Z. Qin,2,9 M. Schädel,2 B. Schausten,2 E. Schimpf,2 A. Semchenkov,1,2 P. Thörle,7 A. Türler,1 M. Wegrzecki,10 B. Wierczinski,1 A. Yakushev,1 and A. Yeremin3

1Technische Universität München, D-85748 Garching, Germany 2Gesellschaft für Schwerionenforschung mbH, D-64291 Darmstadt, Germany 3Joint Institute for Nuclear Research, 141980 Dubna, Russian Federation 4Paul Scherrer Institut, CH-5232 Villigen, Switzerland 5Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA 6University of California, Berkeley, California 94720-1460, USA 7Universität Mainz, D-55128 Mainz, Germany 8Japan Atomic Energy Agency, Tokai-mura, Ibaraki 319-1195, Japan 9Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China 10Institute of Electron Technology, PL-02-668 Warsaw, Poland

Theoretical calculations predict ^{270}Hs (Z=108, N=162) to be a doubly magic deformed nucleus, decaying mainly by α-particle emission. In this work, based on a rapid chemical isolation of Hs isotopes produced in the ^{26}Mg+^{248}Cm reaction, we observed 15 genetically linked nuclear decay chains. Four chains were attributed to the new nuclide ^{270}Hs, which decays by α -particle emission with Q_α=9.02±0.03 MeV to ^{266}Sg which undergoes spontaneous fission with a half-life of 444(+144/-148) ms. A production cross section of about 3 pb was measured for ^{270}Hs. Thus, ^{270}Hs is the first nucleus for which experimental nuclear decay properties have become available for comparison with theoretical predictions of the N=162 shell stability.

Z = 108, 106: Our Calculations

C. Samanta, P. Roy Chowdhury, D.N. Basu, Nucl. Phys. A 789, 142 (2007)

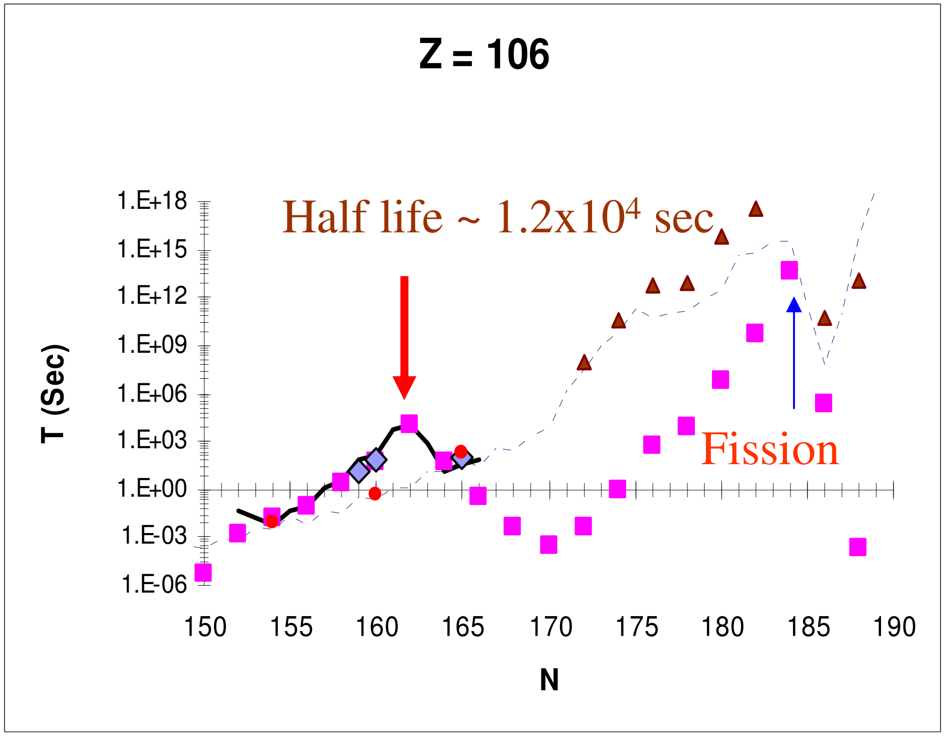


T_{α} , T_{sf} vs. N for Z = 108

Fission

Half life ~ 28 sec

Z=106, N=162 is more stable than doubly magic Z=108, N =162



Z = 106

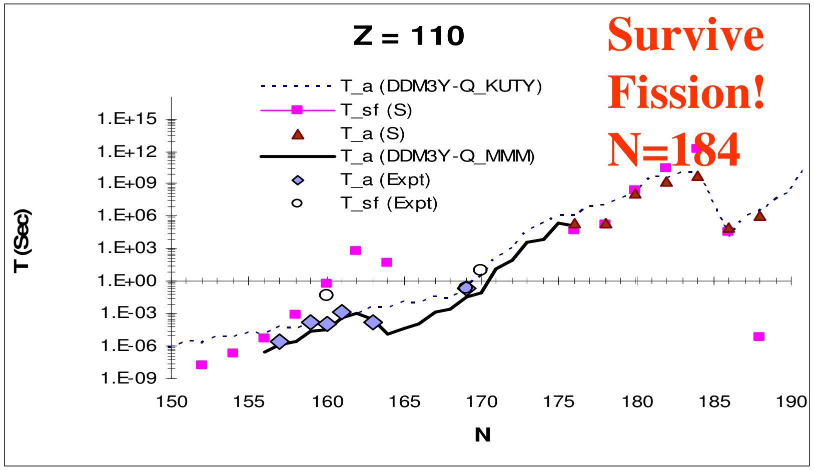
Half life ~ 1.2x10^4 sec

Fission

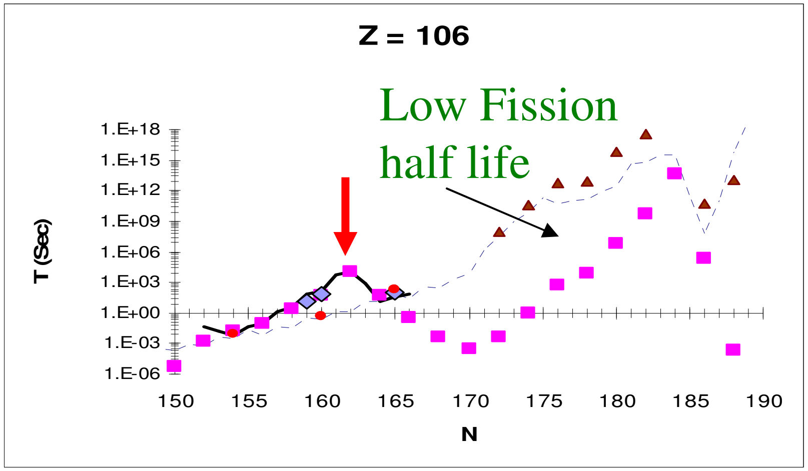
What about the large stability of N=184?

May not survive fission before it can alpha-decay!

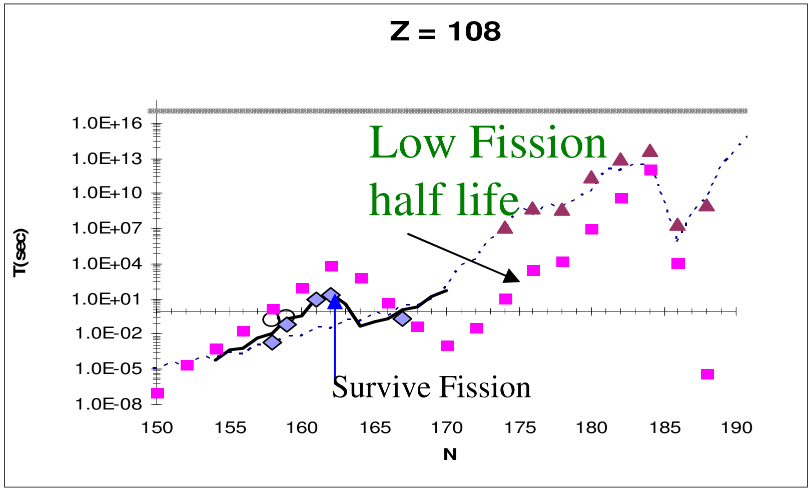
Will all isotopes survive fission? .. No!



Survive Fission! N=184

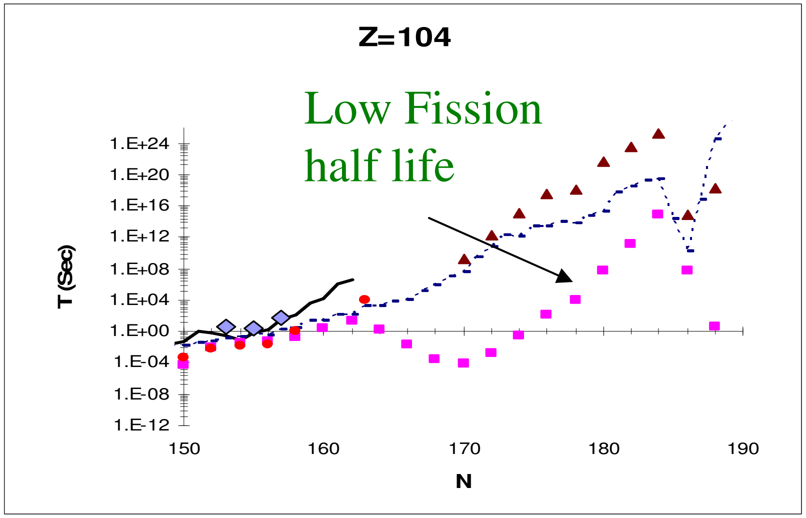


Low Fission half life



Low Fission half life

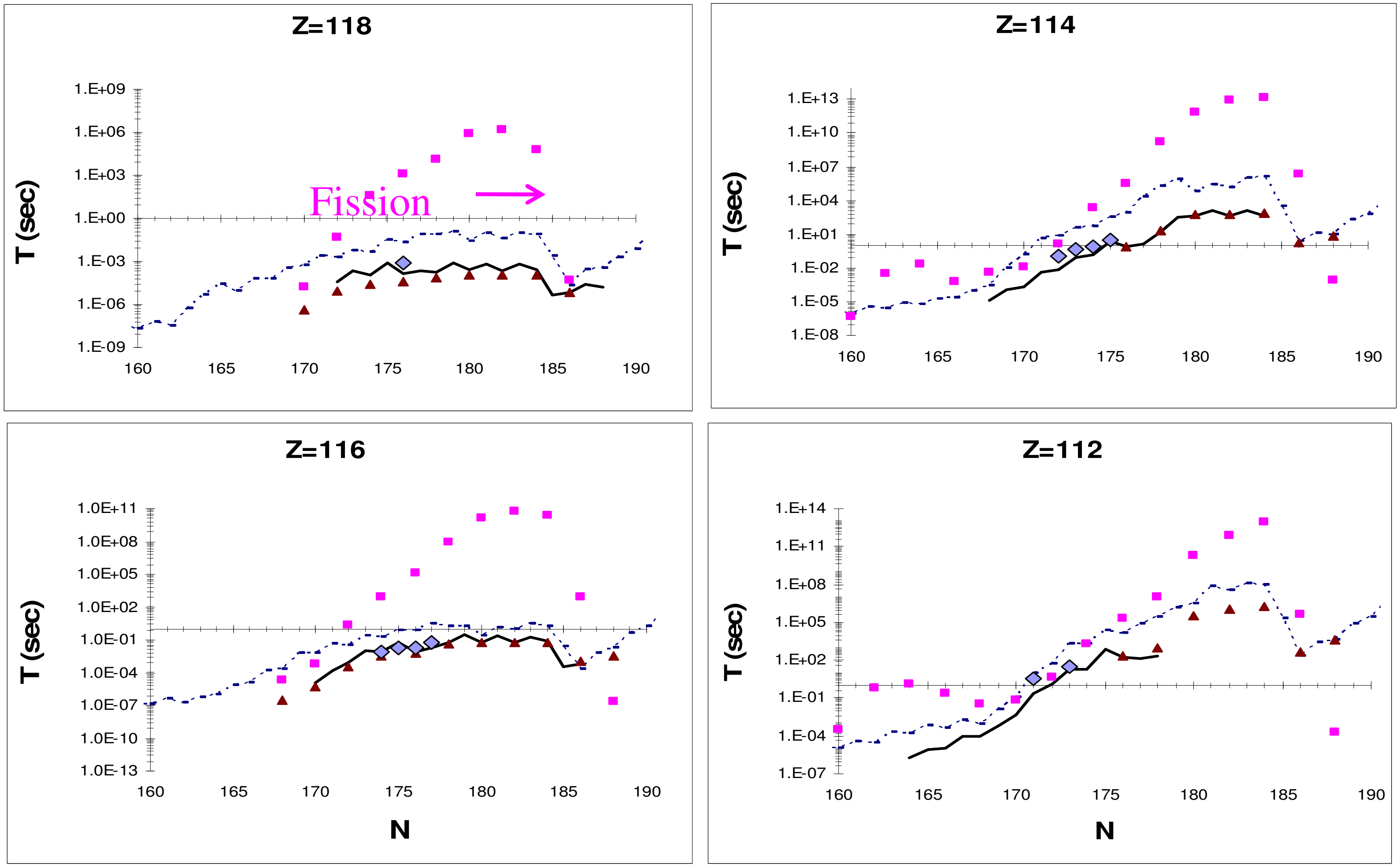
Survive Fission



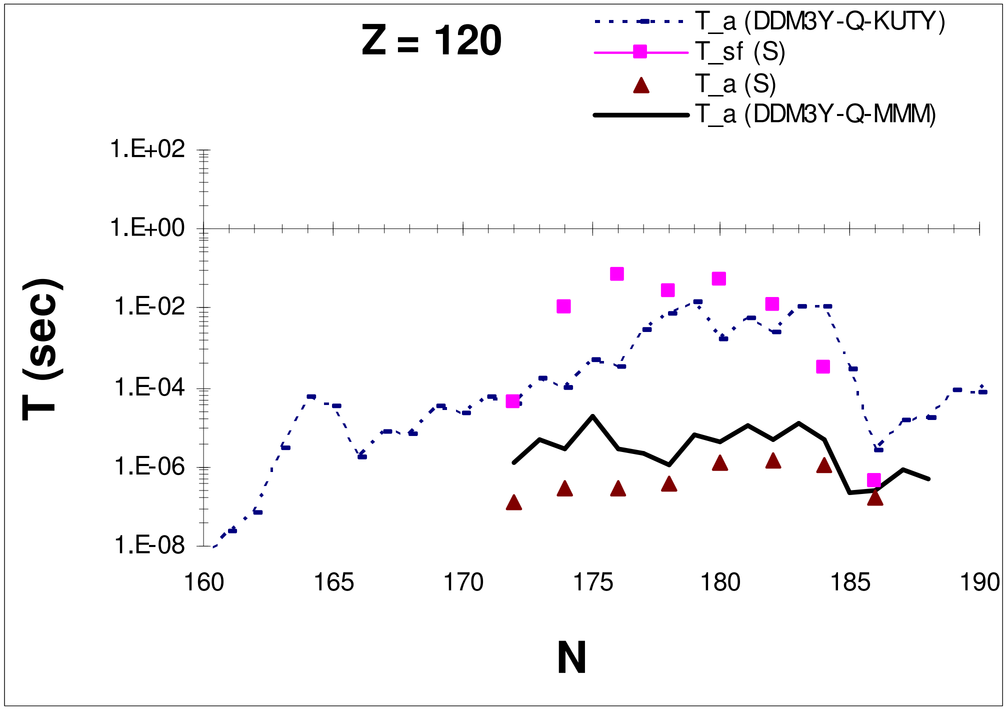
Low Fission half life

Fiset & Nix., NPA 193(1972) 647: Z=110, N=184 $t_{1/2}$ ~ $10^{9.4}$ years (age of the earth ~ 10^9 years) ;
We find T_α ~ 10^9 s.

Higher Z (Heavier Elements):
Large fission half-life, but α-decay half-life decreases



Alpha-decay half-life decreases with increasing Z



Can the element Z=122, A=292 be found in Nature in its ground state?............ No!

Our prediction:

For A = 292, Z ≥122, T_α ~ micro-seconds [mass from KUTY]

"Nuclear Half-lives for a-radioactivity of elements with 100 ≤ Z ≤ 130",
P.Roy Chowdhury, C. Samanta, D.N. Basu, At. Data & Nucl. Data Tables (2008).

^{277}112 and its alpha-decay chain: GSI & RIKEN data

C. Samanta, D.N.Basu, P.R.Chowdhury, Jour. Phys. Soc. Japan , 76, 124201 (2007)

- Observed first four alpha-decay chains of GSI and RIKEN are similar (except the chain 3 of GSI which extends up to ^{257}No).

S. Hofmann et al, EPJA 14, 147 (2002), K. Morita et al, JPSJ 76, 043201 (2007)

- Quantum tunneling model reasonably reproduces the experimental data of α_2 and α_3 decay channels of GSI and RIKEN with l=0.
- For the α_1 decay, l ~ 7 can explain the data.
- But, for the α_4 , α_5 and α_6 decays, the calculated alpha-decay half lives are higher than the experimental ones which can not be explained.

Problem!

Theoretical Q values considered here are for: $(\text{Parent})_{G.S} \Longrightarrow (\text{daughter})_{G.S}$ decays.

But, there is no guarantee that the experimentally observed alpha decay chains proceed from the $(\text{Parent})_{G.S} \Longrightarrow (\text{daughter})_{G.S}$. In fact, transitions to and from excited states are also possible.

D.S. Delion, R.J. Liotta, R. Wyss, Phys. Rev. C76, 044301 (2007)

Where is the Magic Island ?

P. Roy Chowdhury, C. Samanta, D.N. Basu, Phys. Rev. C77, 044603 (2008)

✓Considerably large half- lives for detection of these **SHE.**

Alpha-decay half lives of

- **Z=116, N=184 (~10^{-2} seconds)**
- **Z=114, N=184 (~10^{2} seconds)**
- **Z=110, N=183 (~10^{10} seconds)**
- **Z=108, N=184 (~10^{12} seconds) But, fission half-life is slightly lower.**

❖Nucleus with **Z = 110, N = 183** will be near the center of a **magic island.**

Alpha-decay half lives of

Z=108, N=162 (~30 seconds)

- **Z=106, N=162 (~10^{4} seconds)**
- **Z=104, N=162 (~10^{6} seconds) But, will not survive fission!**

❖Nucleus with **Z = 106, N = 162** will be near the center
of a **small magic island/peninsula**
With half life greater than the (deformed) **doubly magic** Z =108, N =162

Life times of the above SHE would be far less than the age of the earth.

Thank You!