温度効果を考慮した
重い中性子過剰核の核分裂障壁
Thermal effects on the Fission Barrier of neutron-rich nuclei

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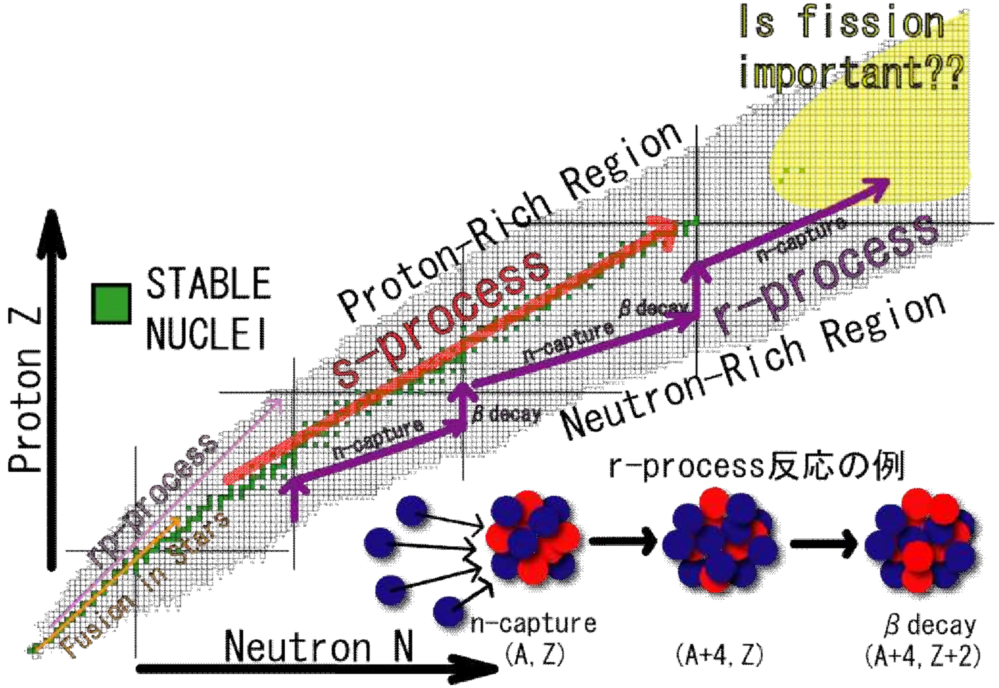
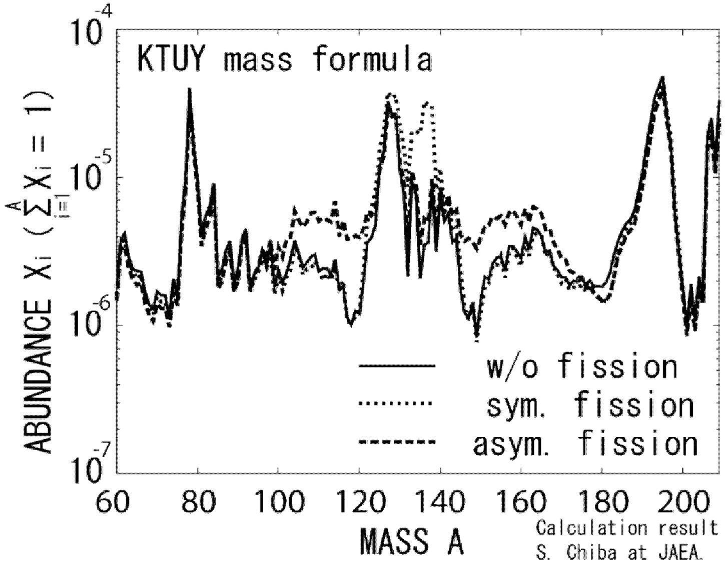
★ 宇宙核物理連絡協議会主催 第1回研究戦略ワークショップ
「核物理から見た宇宙 -rプロセス研究の新時代に向かって」

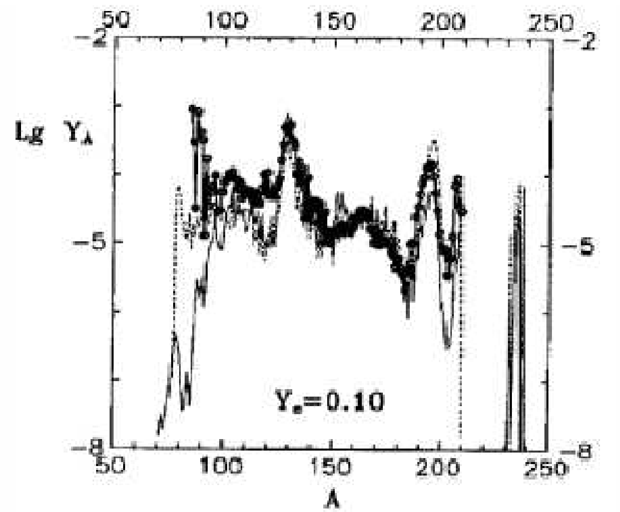
"New Era of Nuclear Physics in the Cosmos -the r-process nucleosynthesis"
日時：2008年9月25,26日
場所：理化学研究所 RIBF棟2階大会議室 (201号室)

INTRODUCTION





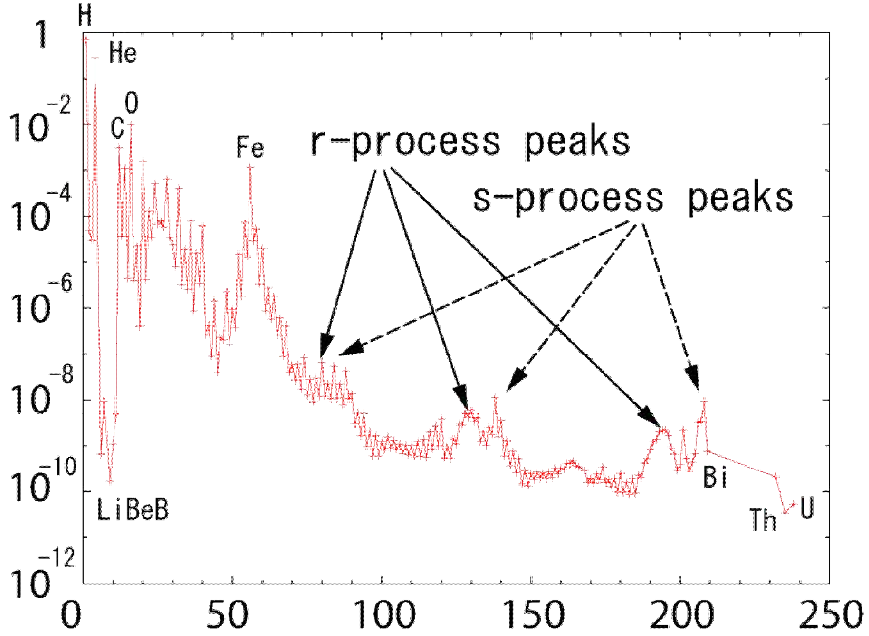
Calculation result from
S. Chiba at JAEA.

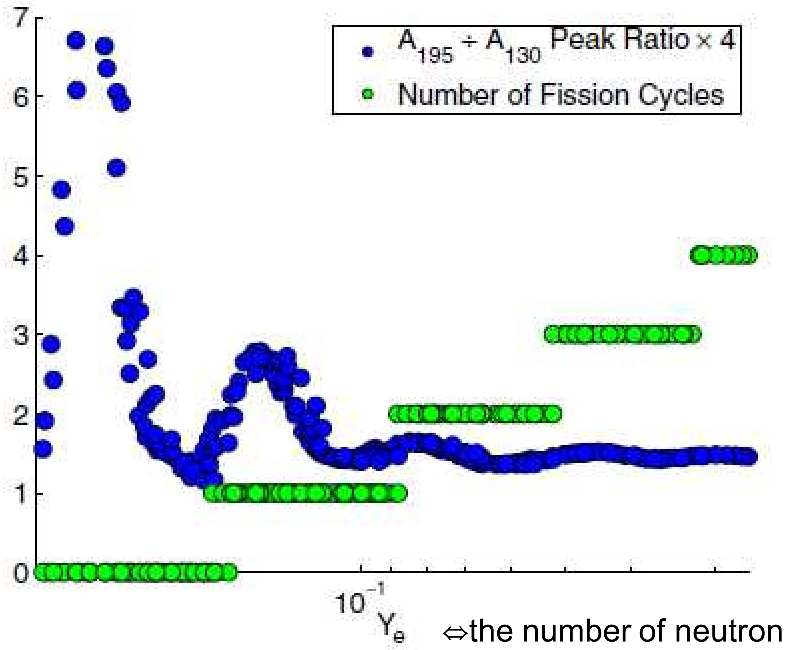


Nucl. Phys. A688, 587, (2001),
I.V. Panov, C. Freiburghaus, F.-K. Thielemann

Circle : solar abundance.
Dashed and solid lines : r-abundance with different mass formulae.

r-process with fission





1. Cosmochronometer

^{238}U : half life = 4.468×10^{9} year,
^{232}Th : half life = 1.405×10^{10} year.

2. Termination of r-process

3. Final dist. of the abundance

4. Fission cycling
(Peak ratio A_{195} / A_{130})

cf. J. Phys. G : Nucl. Part. Phys. 35 (2008) 014059,
R. Surman, J. Beun, G. C. McLaughlin, S Kane, and W. R. Hix

Ambiguities in Fission!!

1. Fission Fragments
2. Fission Barrier height
3. Curvature

MOTIVATION

clarify the role of fission in the r-process

- Fission barriers in r-process have been derived with
    1. ETFSI (Extended Thomas Fermi Strutinsky Integral)
    2. Macroscopic-microscopic model

□ **Heavy Neutron-rich nuclei** (exotic nuclei)

□ **Assumption of Nuclei at <u>Zero temperature</u>**
(Ground-state)

cf. "Effect of beta-decay of excited-state nuclei "
J. Phys. G : Nucl. Part. Phys. **35** (2008) 025203
M. A. Famiano, R. N. Boyd, T. Kajino, K. Otsuki, M. Terasawa, and G. J. Mathews

Influence on abundance of heavy nuclei A>160

<u>Our approach</u>

◆ **Microscopic Model**

Skyrme-Hartree-Fock-Bogoliubov Method (HFB) (symmetric fission)

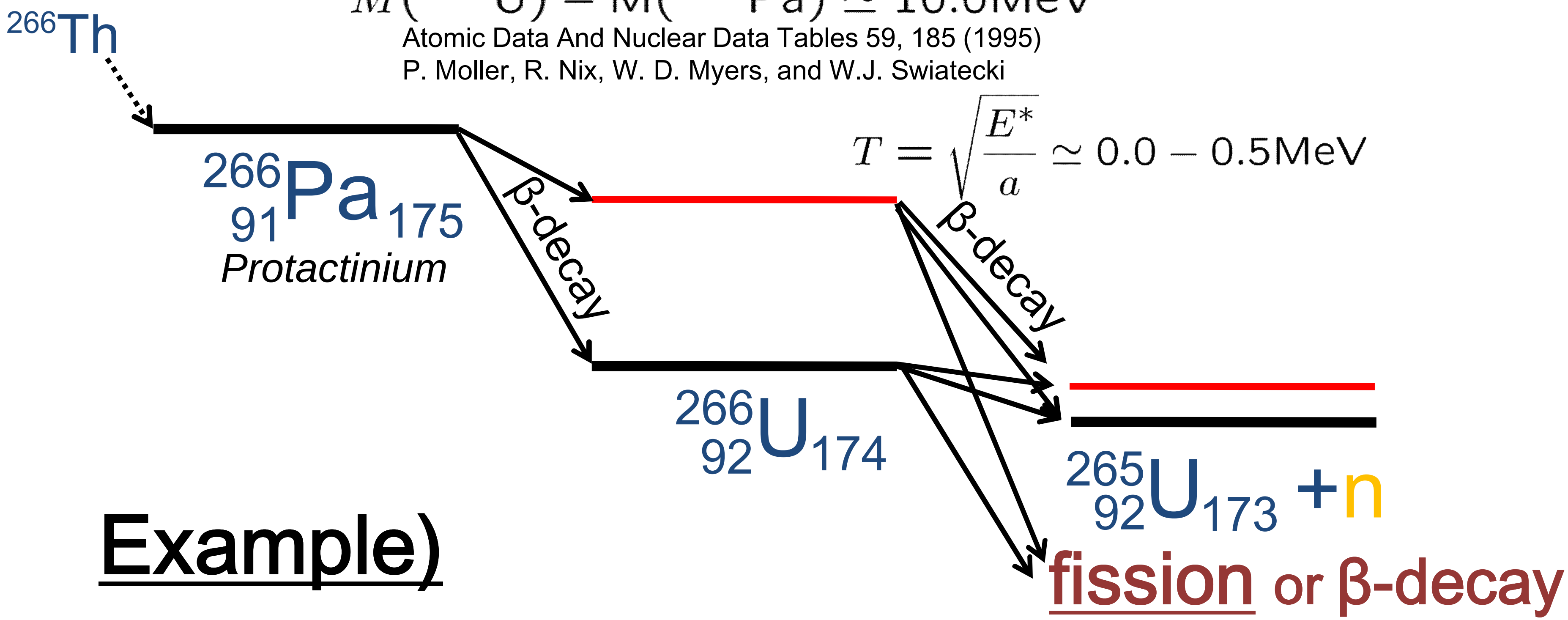
◆ **Thermal effect (Highly Excited State)**

SCENARIO

$$M(^{266}\mathrm{U}) - \mathrm{M}(^{266}\mathrm{Pa}) \simeq 10.0\mathrm{MeV}$$

Atomic Data And Nuclear Data Tables 59, 185 (1995)
P. Moller, R. Nix, W. D. Myers, and W.J. Swiatecki

<u>Example)</u>



The effect of highly excited nucleus

- Pairing phase-transition $\left(T_{\mathrm{crit}} \simeq \frac{\Delta_0}{1.76}\right)$

"Quantum Theory of Many Particle Systems"
Fetter and Walecka, p. 448

$\Delta_0 \simeq 0.6$ MeV (T_{crit}=0.34 MeV) for ^{236}U

Influence → Fission Barrier Height,

Beta-decay, and Neutron Emission

Finite Temperature HFB (THFB)

Nucl. Phys. A**352** (1981) 30,
Alan L. Goodman
Phys. Rev. C70, 025801(2004)
Nicolae Sandulescu

Density operator

$$D_{\text{HFB}} = \frac{\exp(-\beta \sum_i E_i \hat{n}_i)}{Z_{\text{HFB}}} = \prod_i (f_i \hat{n}_i + (1 - f_i)(1 - \hat{n}_i))$$

■Grand Partition Function Z : $Z_{\text{HFB}} = Tr\left(\exp(-\beta \sum_i E_i \hat{n}_i)\right) = \prod_i (1 + e^{-\beta E_i})$

■Expectation value of an operator O : $O = \langle \hat{O} \rangle = Tr(\hat{O} D)$

$$\rho = U^T f U^* + V^\dagger (1 - f) V \qquad \kappa = U^T f V^* + V^\dagger (1 - f) U$$

■Quasi Particle Occupation probability : $f_k = \frac{1}{1 + \exp(\beta E_k)}$

THFB equation from variation $\Omega = E - TS$ E_k:Quasi Particle Energy

$$\begin{pmatrix} h(T) - \lambda & \Delta(T) \\ -\Delta^*(T) & -h^*(T) + \lambda \end{pmatrix} \begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

$$h_{ij}(T) = K_{ij}(T) + \sum_{kl} v_{ikjl} \rho_{lk}(T) \qquad \Delta_{ij}(T) = \frac{1}{2} \sum_{kl} v_{ijkl} \kappa_{kl}(T)$$

CONSTRAINT THFB

■Constraining operator

$$Q = \sum_i r_i^2 Y_{20}(\hat{r}_i) \quad \beta = \sqrt{\frac{5}{16\pi}} \frac{4\pi}{3AR_0^2} \langle Q \rangle$$

■Total Energy and Average Gap Parameter

Average gap delta: $\langle \Delta \rangle = \int dr\, \kappa_T(r) \Delta_T(r) / \int dr\, \kappa_T(r)$

Total Energy: $E = \langle H \rangle$

Barrier height: $V_f = E_{max} - E_{min}$

Parameter set : SLy4

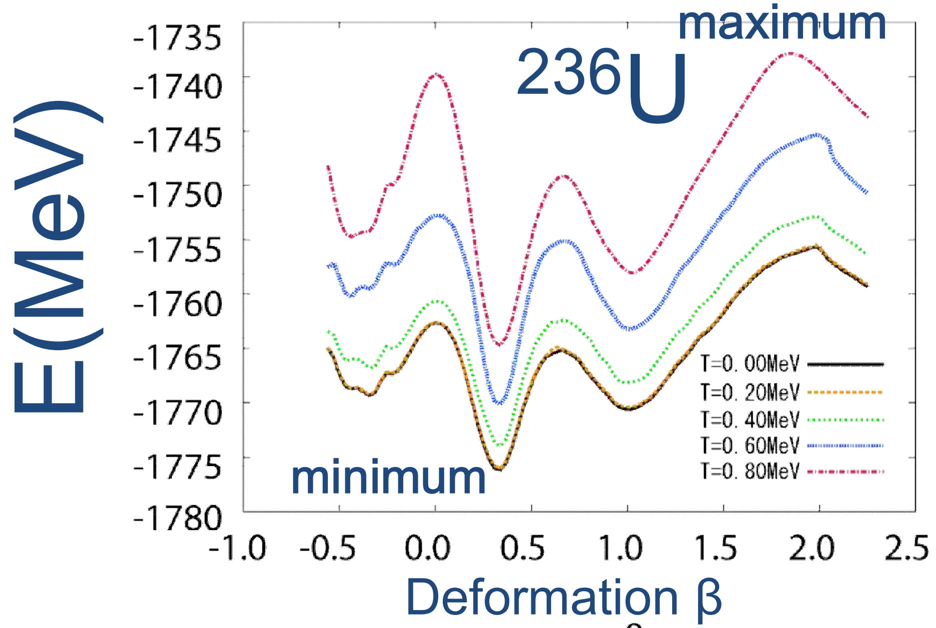
Volume pairing : $V_{vol}^{p} = 295.369$,

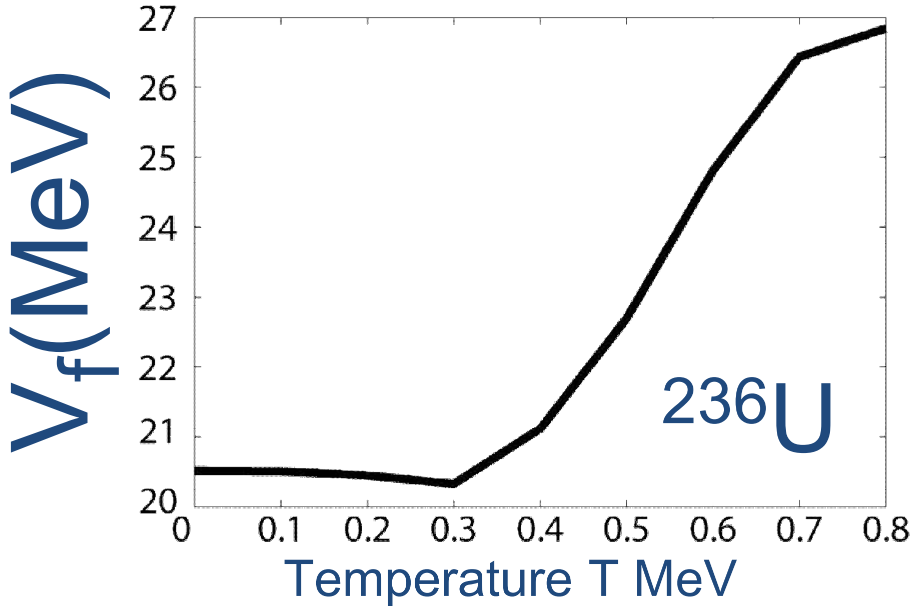
$V_{vol}^{n} = 286.669$ MeV,

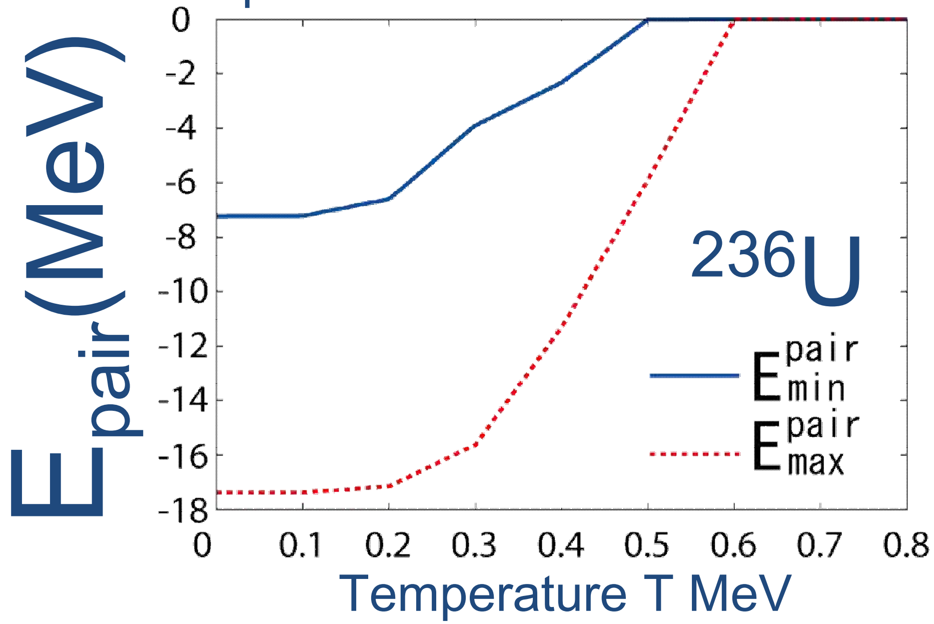
determined so as to reproduce

the gap parameter $\Delta(^{236}U)$

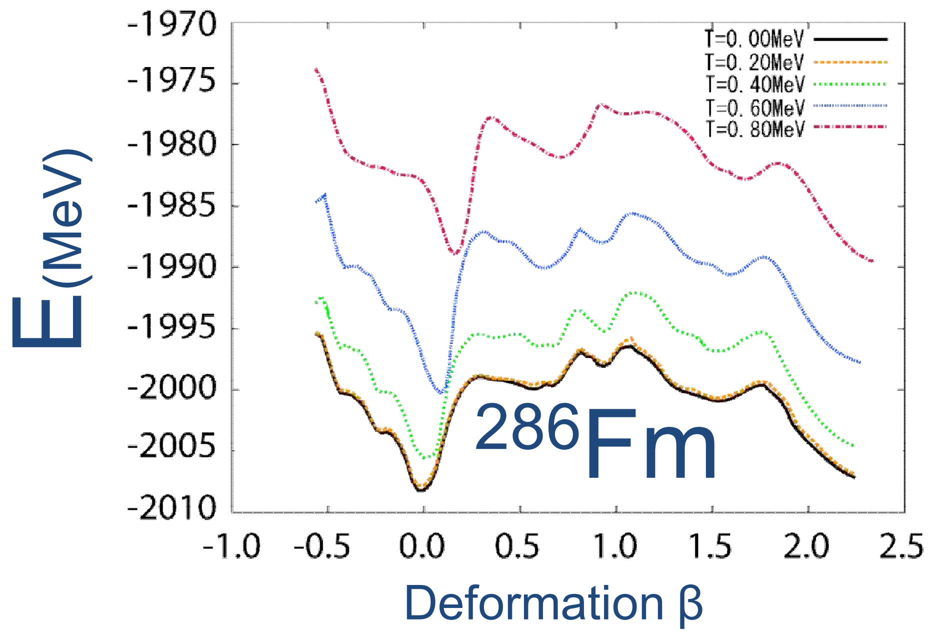
RESULT～^{236}U

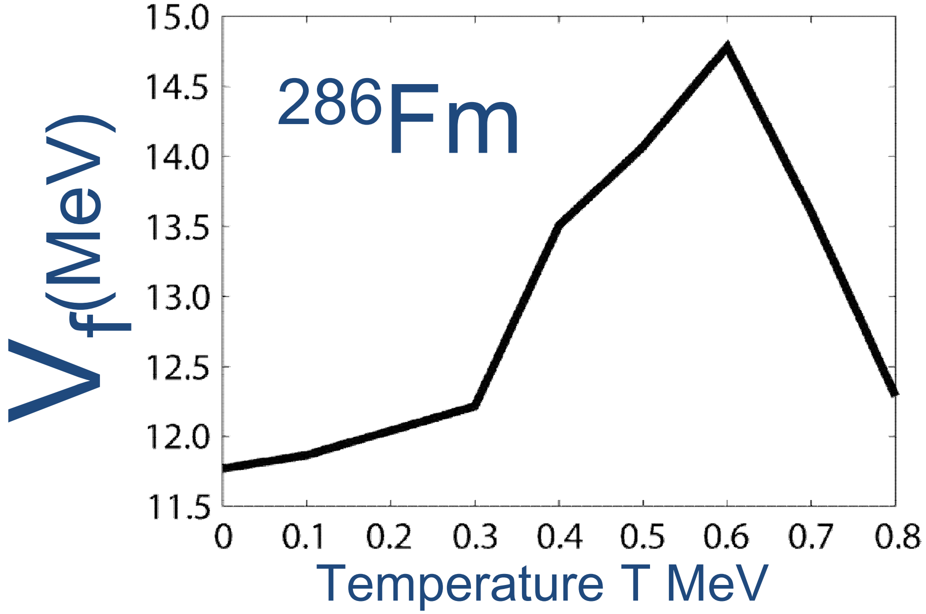

E(MeV)
-1735
-1740
-1745
-1750
-1755
-1760
-1765
-1770
-1775
-1780
236U
maximum
minimum
T=0.00MeV
T=0.20MeV
T=0.40MeV
T=0.60MeV
T=0.80MeV
-1.0 -0.5 0.0 0.5 1.0 1.5 2.0 2.5
Deformation β

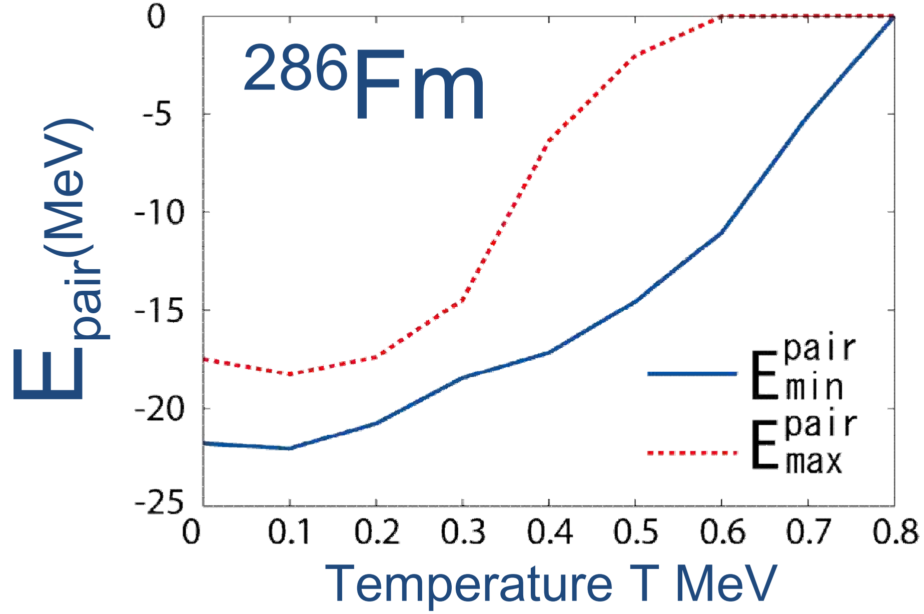

Vf(MeV)
27
26
25
24
23
22
21
20
236U
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Temperature T MeV


Epair(MeV)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
236U
Epair min
Epair max
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
Temperature T MeV

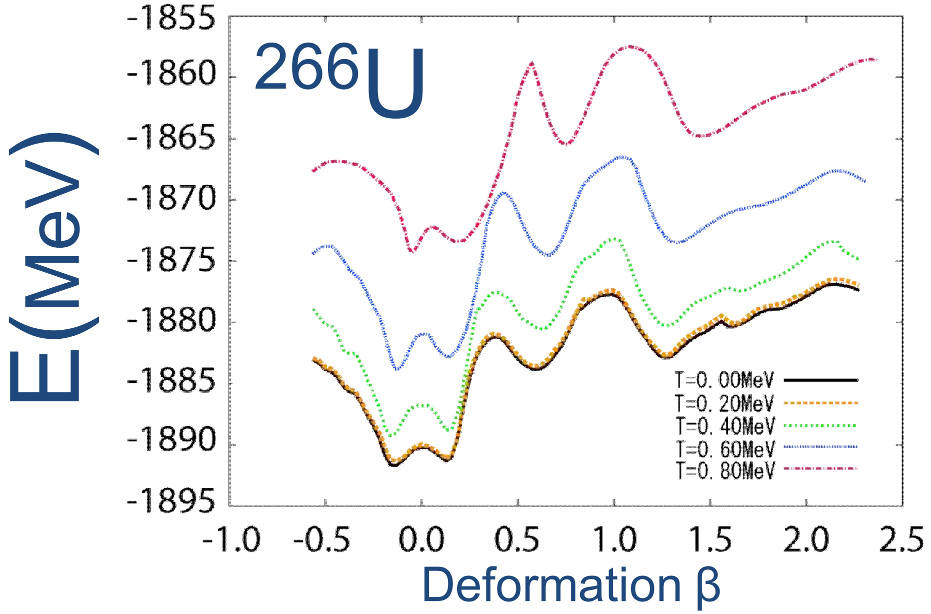
RESULT～^{286}Fm

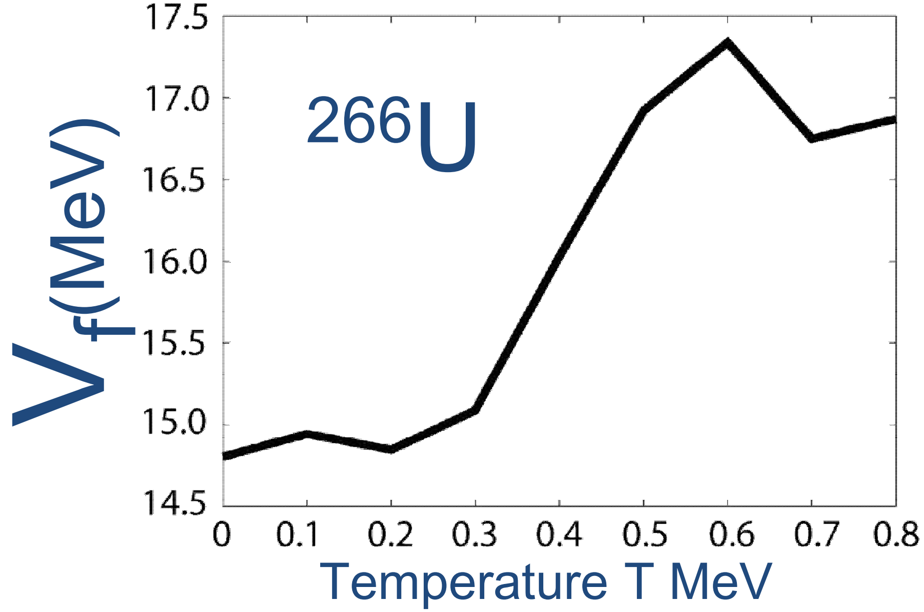


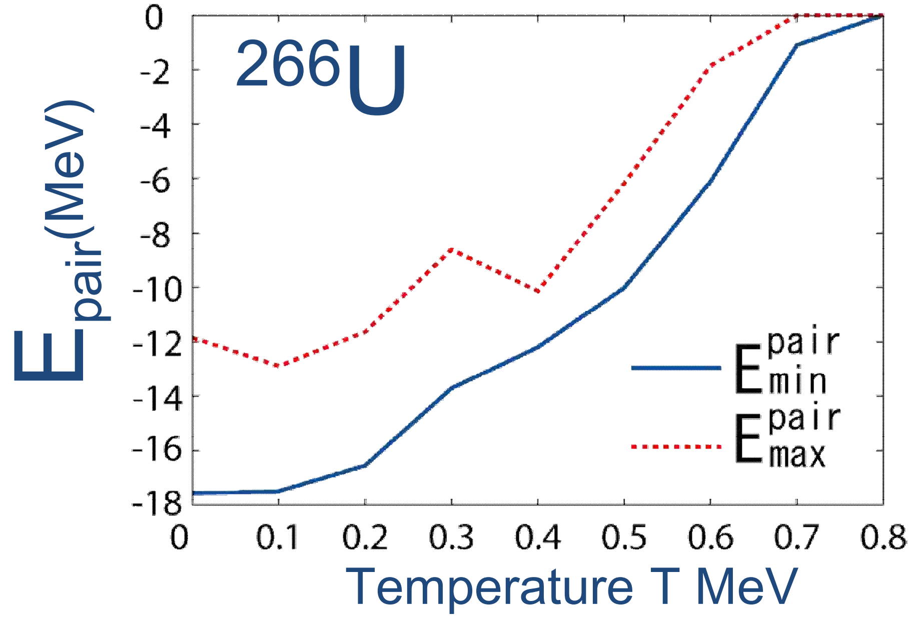




RESULT～^{266}U


266U
E(MeV)
-1855
-1860
-1865
-1870
-1875
-1880
-1885
-1890
-1895
-1.0
-0.5
0.0
0.5
1.0
1.5
2.0
2.5
Deformation β
T=0. 00MeV
T=0. 20MeV
T=0. 40MeV
T=0. 60MeV
T=0. 80MeV


266U
Vf(MeV)
17.5
17.0
16.5
16.0
15.5
15.0
14.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Temperature T MeV


266U
Epair(MeV)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Temperature T MeV
Epair min
Epair max

RESULT～Decay Rate

- Decay width derived from

  Bohr-Wheeler formula

$$\Gamma_f = \frac{\omega_0}{2\pi} e^{-V_b/T}$$

E* is approximated with

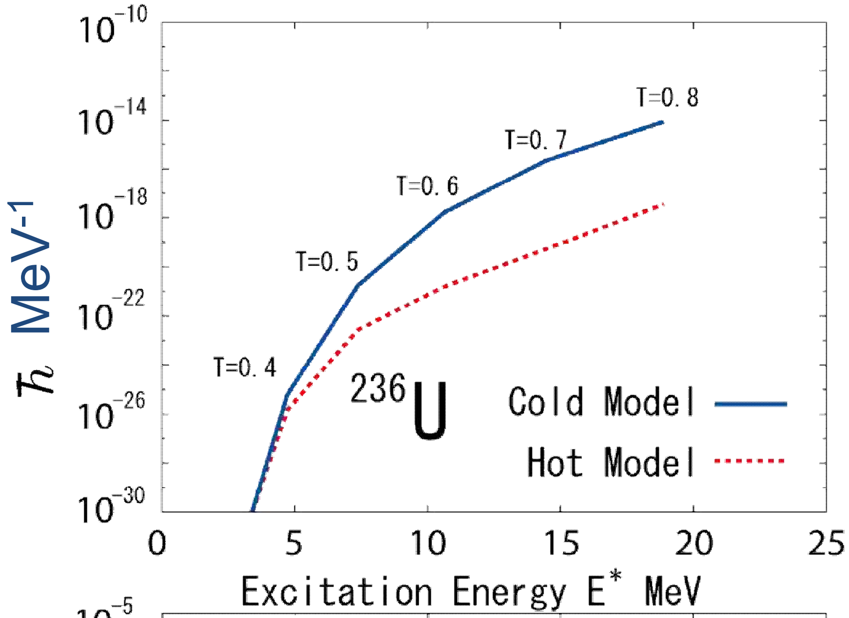
$$E^* = aT^2 \simeq \frac{A}{8}T^2$$

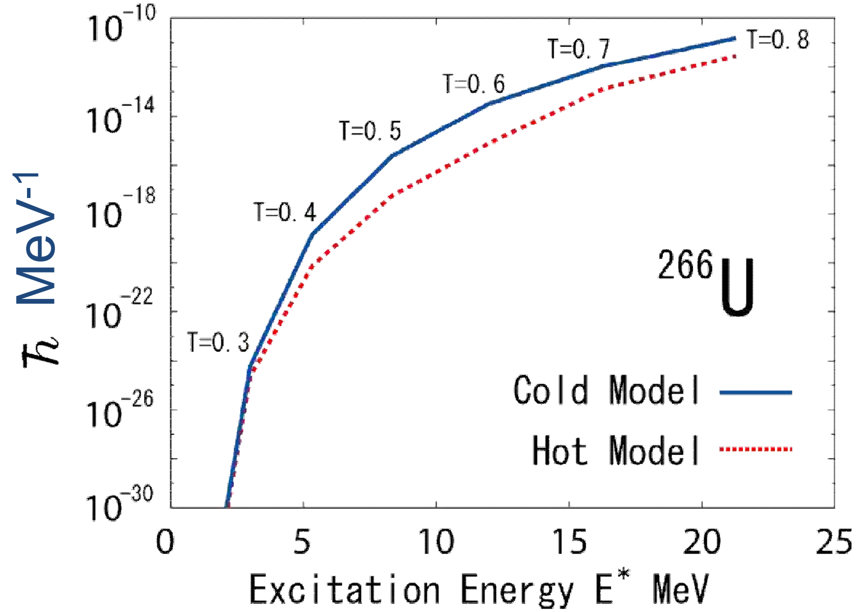
$$M(^{236}\mathrm{U}) - \mathrm{M}(^{236}\mathrm{Pa}) \simeq 3.0\mathrm{MeV}$$

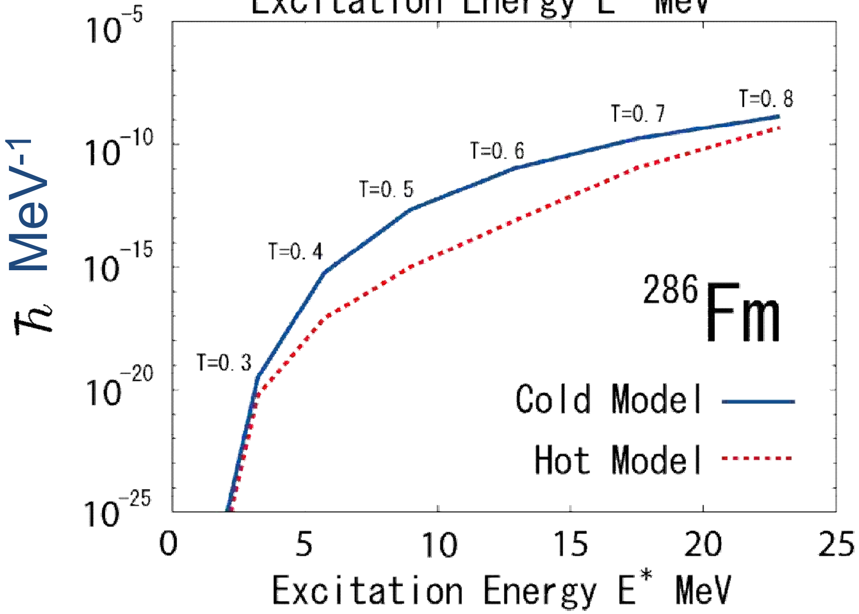
$$M(^{266}\mathrm{U}) - \mathrm{M}(^{266}\mathrm{Pa}) \simeq 10.0\mathrm{MeV}$$

$$M(^{286}\mathrm{Fm}) - \mathrm{M}(^{266}\mathrm{Es}) \simeq 11.1\mathrm{MeV}$$

Atomic Data And Nuclear Data Tables 59, 185 (1995)
P. Moller, R. Nix, W. D. Myers, and W.J. Swiatecki







SUMMARY

Calculate the Fission Barrier Height for neutron-rich nuclei with THFB method

- Pairing Phase transit. leads to important effects on V_f.

  depend on pairing energy at g.s and saddle point.

- Fission rates of hot neutron-rich nuclei are suppresed.

- Fission of hot nuclei is important ?

excitation energy of r-process nuclei(neutron-rich nuclei), mass, pairing strength, level density parameter

---- *Future work* ----

- Asymmetric fission for the practical r-process application
- Correction of Temperature at Saddle point