Interaction dependence of the nuclear level density calculated using Hartree–Fock–Bogoliubov theory

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Introduction

Motivation

Nuclear data needed for developing a nuclear transmutation system for long-lived fission products (LLFPs)

- We are planning nuclear data evaluations for

  4 LLFPs : ^{79}Se, ^{93}Zr, ^{107}Pd, ^{135}Cs

  \+ nuclei produced via the nuclear transmutation of these LLFPs.

  Neutron, proton induced
  0～200 MeV energy range

- The nuclear data evaluation is characterized with,

  ✓ Use of new experimental data to be obtained by other project group

  ✓ Development of theoretical methods appropriate/needed for unstable nuclei

One of the plan is,

Hauser-Feshbach calculation using a nuclear level density (NLD) derived from a microscopic nuclear structure calculation

For nuclear data evaluation,

- ✓ NLD up to 200 MeV
- ✓ NLD of wide mass range of nuclei are needed

➢ A microscopic method can be used for this purpose is,

- Hartree-Fock-bogoliubov (BCS) + combinatorial (statistical) method

P. Demetriou and S.Goriely, Nucl. Phys. A695 (2001) 95

S.Hilaire, J.P.Delaroche and M.Girod, Eur. Phys. J. A 12 (2001) 169

S.Goriely, S.Hilaire and A.J.Koning, Phys. Rev. C 78 (2008) 064307

➢ The microscopic calculation depends on used Hamiltonian

Effective nuclear interaction
Gogny, BSk, MSk …

To investigate how NLD depends on the effective nuclear interaction is an way to know about the reliability of NLD

In this study,

- ✓ NLD were calculated from HFB +statistical method using Skp, SLy4, SkM* Skyrm forces
- ✓ Hauser-Feshbach calculation using these NLD were performed
- ✓ Difference of NLD and resulting (n,2n) cross section are discussed

Framework

- Hartree-Fock-Bogoliubov theory + statistical method

  ✓ Grand partition function

  BCS approximation with constant-G approach

  P. Demetriou and S.Goriely, Nucl. Phys. A695 (2001) 95

$$Z(\alpha_n, \alpha_p, \beta) = \mathrm{Tr}(\mathrm{e}^{-\beta \mathrm{H}+\alpha_\mathrm{p}\hat{\mathrm{N}}_\mathrm{p}+\alpha_\mathrm{n}\hat{\mathrm{N}}_\mathrm{n}})$$
$$= \prod_{i\in q=p,n} \exp\left(-\beta\left[(\epsilon_i - \lambda_q)\rho_i + \frac{1}{2}G\rho_i^2 - \frac{\Delta_q^2}{4E_i} - E_i f_i\right]\right)(1+e^{-\beta E_i})$$

Renormalization term omitted

ϵ_i , λ_q are those obtained from finite temperature HFB calculation

$\Delta_q = G\sum_{i\in q} u_i v_i$ G is determined from HFB pairing energy

$$\alpha_q = \beta\lambda_q$$
$$\beta = 1/T$$
$$f_i = (1+\exp(\beta E_i))^{-1}$$

  ✓ State density

$$\omega(E, N_n, N_p) \sim \frac{1}{(2\pi)^{3/2}}\frac{e^{S(T)}}{(\det D)^{1/2}}$$

entropy

$$S(T) = -\sum_i (f_i \ln f_i + (1-f_i)\ln(1-f_i))$$

  ✓ Thermal excitation energy

$$U(T) = E(T) - E(T=0)$$

E(T): Total energy of the system obtained from the finite temperature HFB calculation

- Effective nuclear interaction

➢ Skyrme forces : Skp, SLy4, SkM*

✓ Pairing force

$$V_{\text{pair}}^{(\text{n,p})}(\boldsymbol{r}) = V_0^{(\text{n,p})}\left(1 - \frac{1}{2}\frac{\rho_0(\boldsymbol{r})}{\rho_c}\right)\delta(\boldsymbol{r}-\boldsymbol{r}')$$

- Surface-volume mix type
- ε_{cut}=60 MeV

✓ Pairing strength parameters

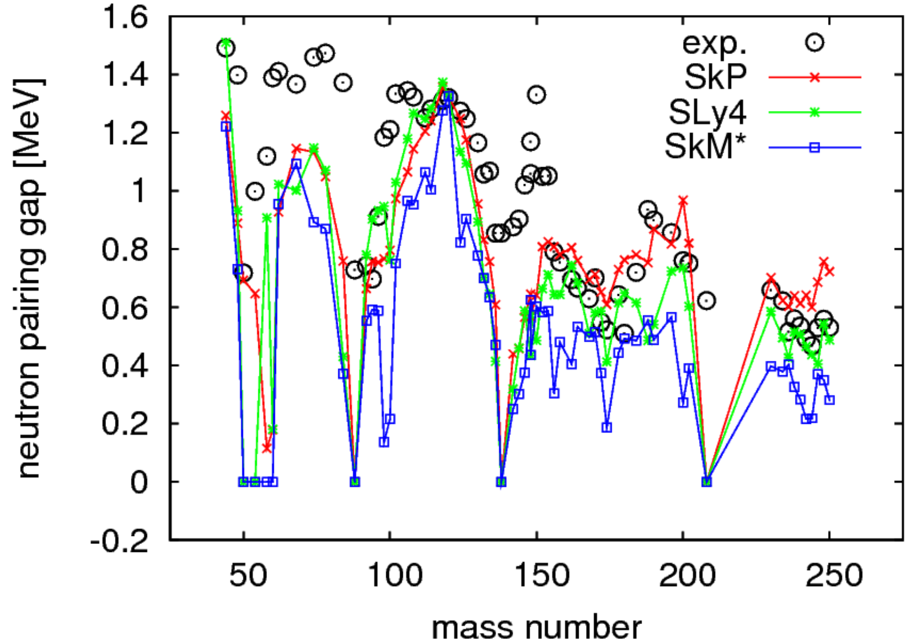
$V_0^{(n)}$ and $V_0^{(p)}$ are determined to reproduce the experimental pairing gaps of ^{120}Sn and ^{138}Ba

Unit : [MeV]

	SkM*	SLy4	SkP
$V_0^{(n)}$	-244	-291	-217
$V_0^{(p)}$	-258	-277	-231

✓ Neutron pairing gaps

66 even-even nuclei
that have experimental values of D_0



Experimental values of the pairing gaps are deduced from the three-point mass differences

$$\Delta^{(3)}(N+1)$$

✓ Level density

$$\rho(U,J) = (1 - f_{dam}(U))K_{vib}(U)\rho_{\rm sph}(U,J) + f_{dam}(U)K_{vib}(U)\rho_{\rm def}(U,J)$$

$$\rho_{\rm sph}(U,J) = \frac{2J+1}{2(2\pi)^{1/2}\sigma^3}\exp\left(-\frac{J(J+1)}{2\sigma^2}\right)\omega(E,N_n,N_p)$$

$$\rho_{\rm def}(U,J) = \frac{1}{2}\sum_{K=-J}^{J}\frac{1}{(2\pi\sigma^2)^{1/2}}\exp\left(-\frac{J(J+1)}{2\sigma_\perp^2} - \frac{K^2}{2}\left(\frac{1}{\sigma^2} - \frac{1}{\sigma_\perp^2}\right)\right)\omega(E,N_n,N_p)$$

$f_{dam}(U)$: damping function for smooth transition between ρ_{sph} and ρ_{def}

✓ Phenomenological vibrational collective enhancement

IAEA-TECDOC-1506: Reference Input Parameter Library-2, IAEA, 2005

$$K_{\rm vib}(E_x) = \exp[\delta S - (\delta U/t)]$$

$$\delta S = \sum_i (2\lambda_i + 1)[(1+n_i)\ln(1+n_i) - n_i \ln n_i]$$

$$\delta U = \sum_i (2\lambda_i + 1)\omega_i n_i,$$

$$n_i = \frac{\exp(-\gamma_i/2\omega_i)}{\exp(\omega_i/t) - 1}$$

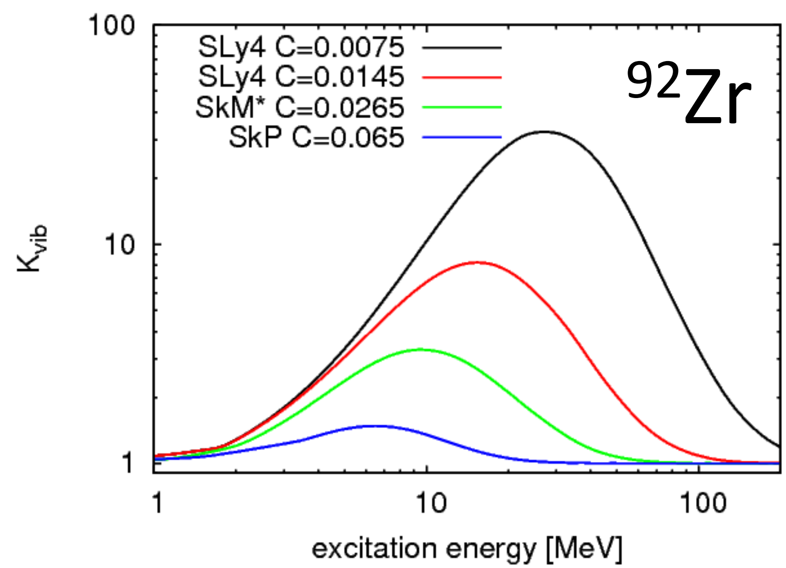
$$\gamma_i = \underline{C}A^{1/3}(\omega_i^2 + 4\pi^2 t^2)$$

damping width parameter

$$\omega_2 = 65A^{-5/6}/(1 + 0.05\delta W)$$

$$\omega_3 = 100A^{-5/6}/(1 + 0.05\delta W)$$

✓ Damping width parameter C of K_{vib} is optimized for each force by fitting D_0 of well deformed nuclei



- Hauser-Feshbach calculation using the microscopic NLD

CCONE code O. Iwamoto, J. Nucl. Sci. and Technol. 44 (2007) 687.

- Hauser-Feshbach statistical model
  - ✓ Optical model potential: Koning-Delaroche
  - ✓ Gamma strength function: Enhanced generalized Lorentzian (EGLO) model
  - ✓ Nuclear level density

Present work

- Hartree-Fock-Bogoliubov theory + statistical method with Skp, SLy4, SkM* forces

For comparison,

- Hartree-Fock-Bogoliubov theory + combinatorial method taken from RIPL-3

  S.Goriely, S.Hilaire and A.J.Koning, Phys. Rev. C 78 (2008) 064307

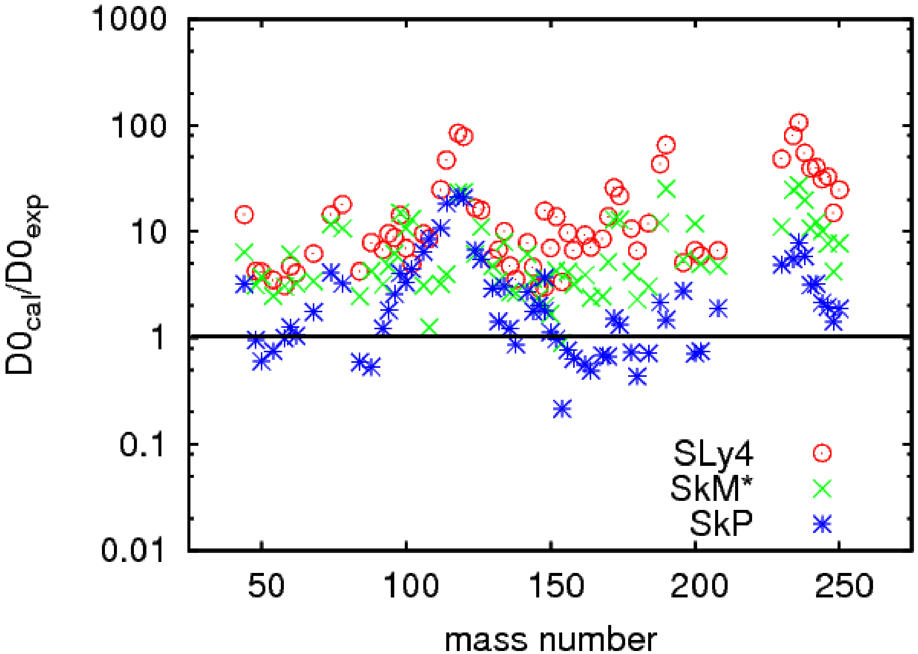
- Fermi Gas model with Mengoni-Nakajima level density parameter

  A.Mengoni, Y.Nakajima, J. Nucl. Sci. Tecnnol. 31 (1994) 152

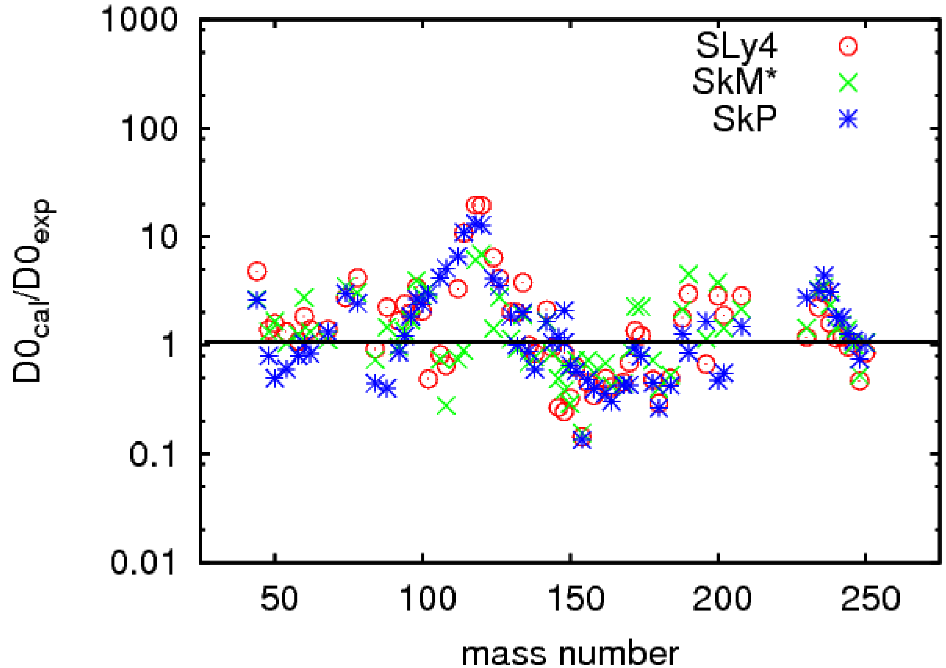
Results

- S-wave neutron resonance spacing D_0 for 66 even-even nuclei

✓ Without K_{vib}



✓ Using K_{vib} with damping width parameter optimized for each force

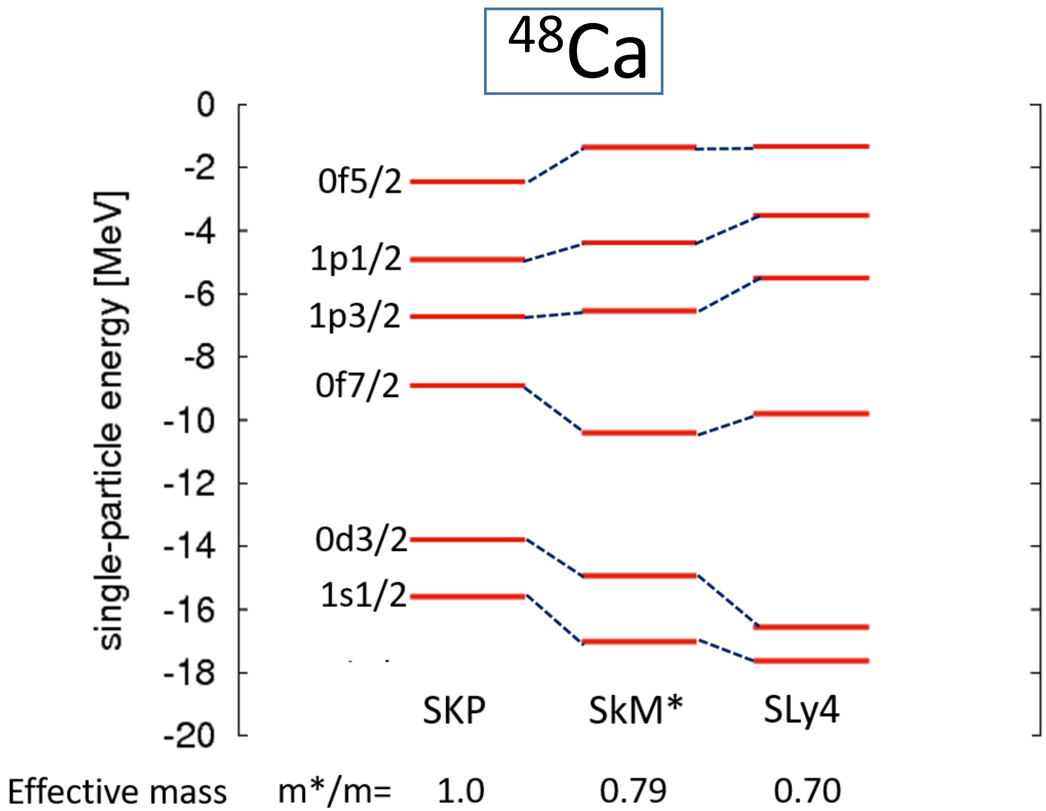


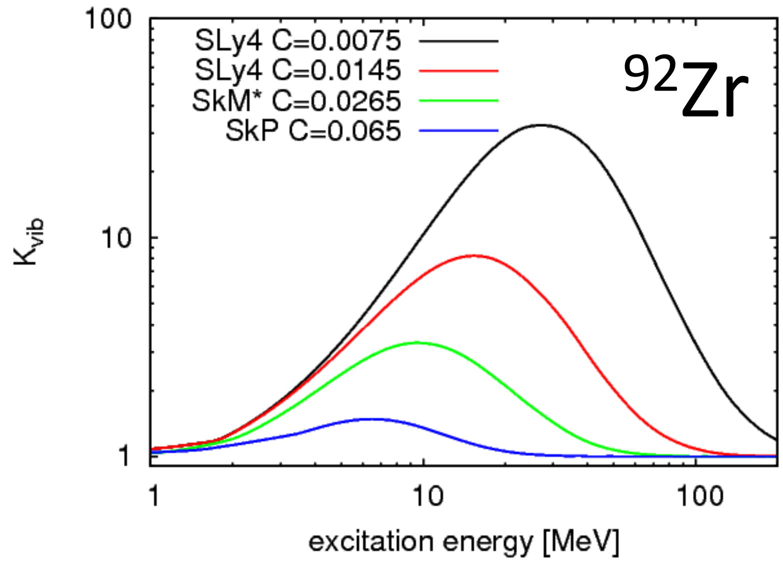
✓ For Skp force, NLD calculated without K_{vib} is not bad compared to SkM* and SLy4

✓ Vibrational collective enhancement is essential for NLDs calculated using SkM* and SLy4

✓ By using the optimized K_{vib}, all forces deduce similar D_0

- Single-particle levels





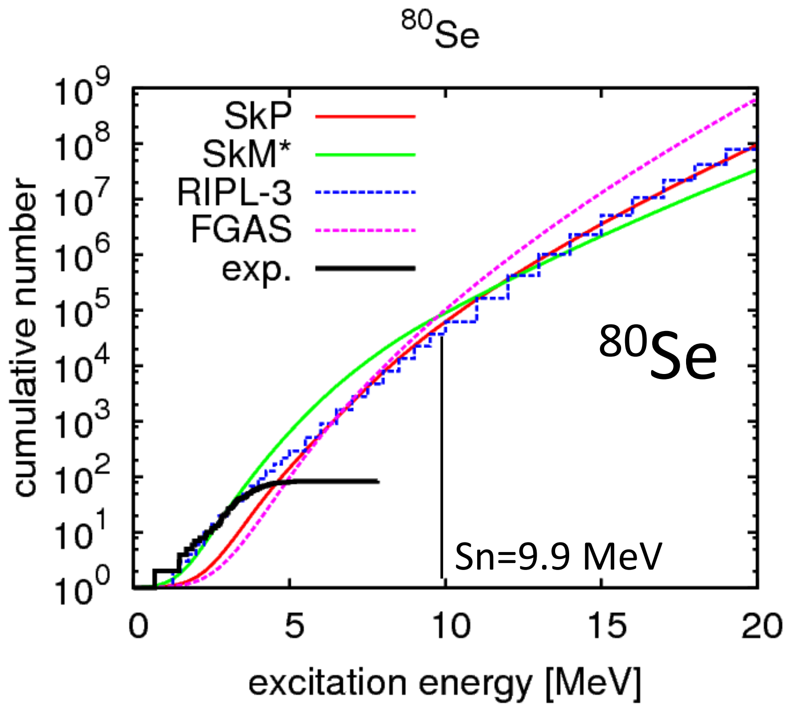
✓ Vibrational collective enhancement should be treated explicitly in NLD calculated using effective mass ∼0.7 Skyrm forces

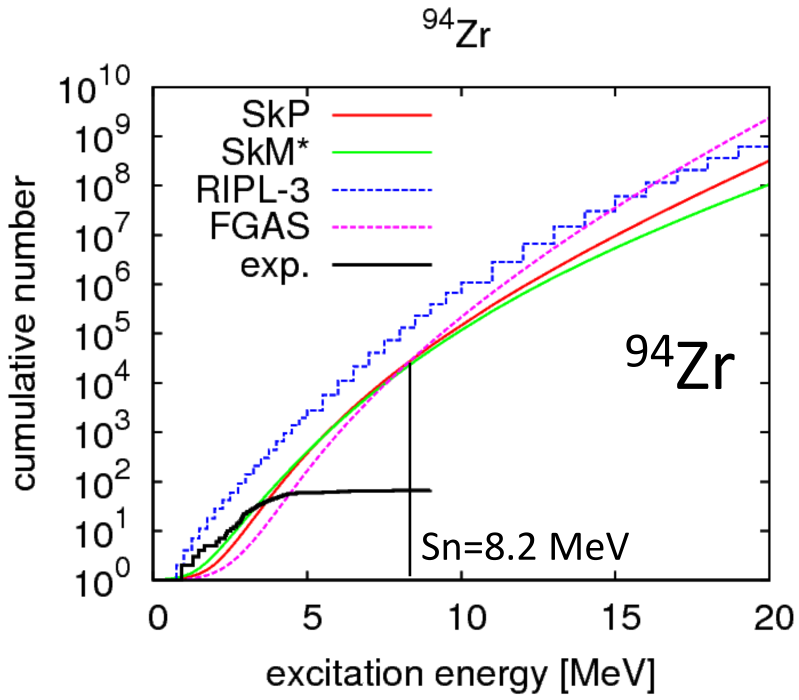
✓ Effect of the vibrational collective enhancement may be implicitly included in effective mass ∼ 1 forces

- Cumulative number of levels

FGAS: Fermi Gas without constant temperature cal.
RIPL-3: S.Goriely, S.Hilaire and A.J.Koning, PRC78 (2008) 064307

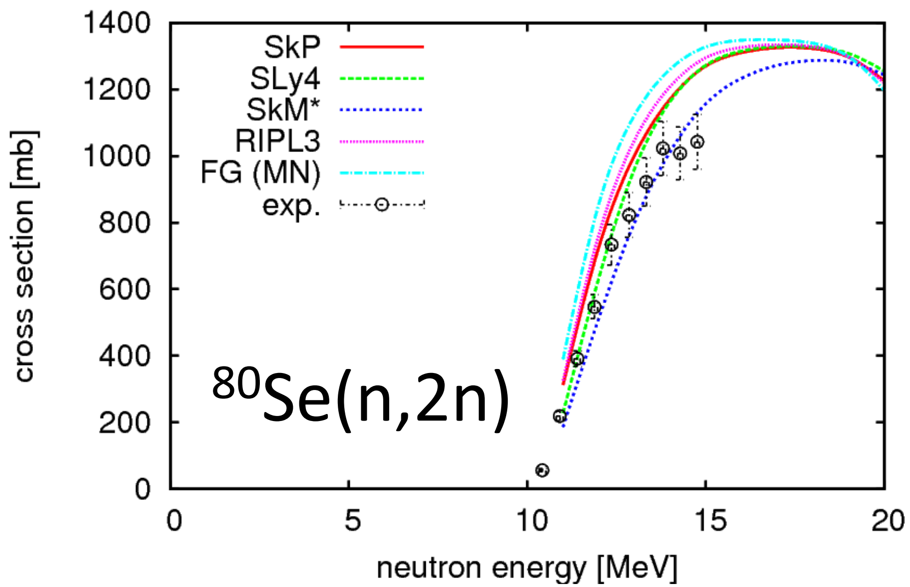
Compound nuclei of LLFPs (^{79}Se, ^{93}Zr)

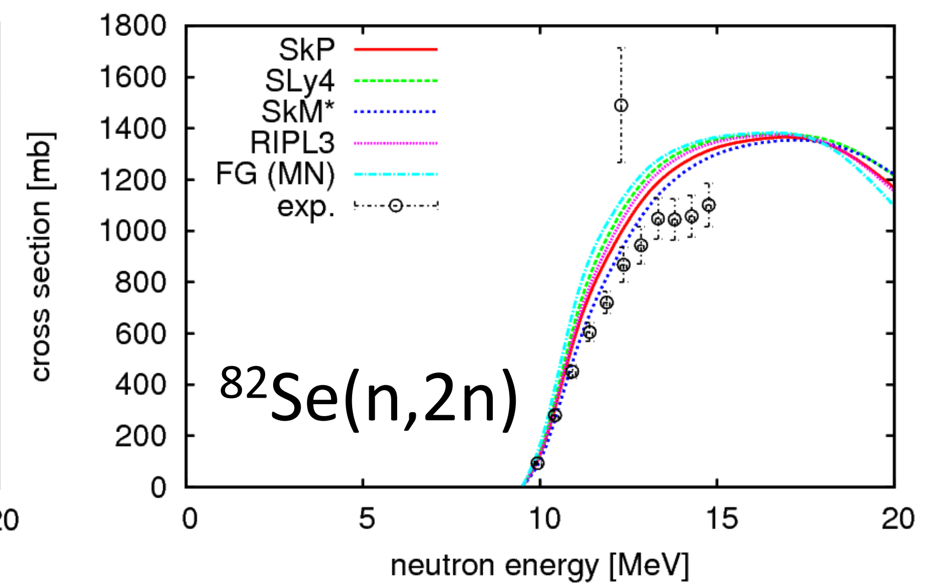


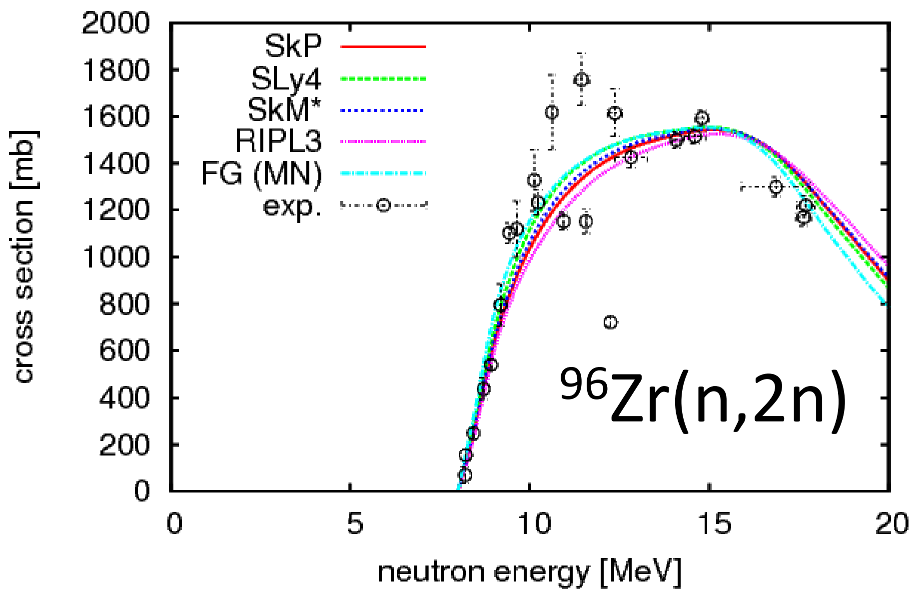


- ✓ NLDs cross around the neutron threshold.
- ✓ NLD around and above neutron threshold are influenced by the disappearance of deformation and vibrational collective enhancement.
- ✓ How these differences affect the cross section calculated using Hauser-Feshbach ?

- Differences in (n,2n) cross section

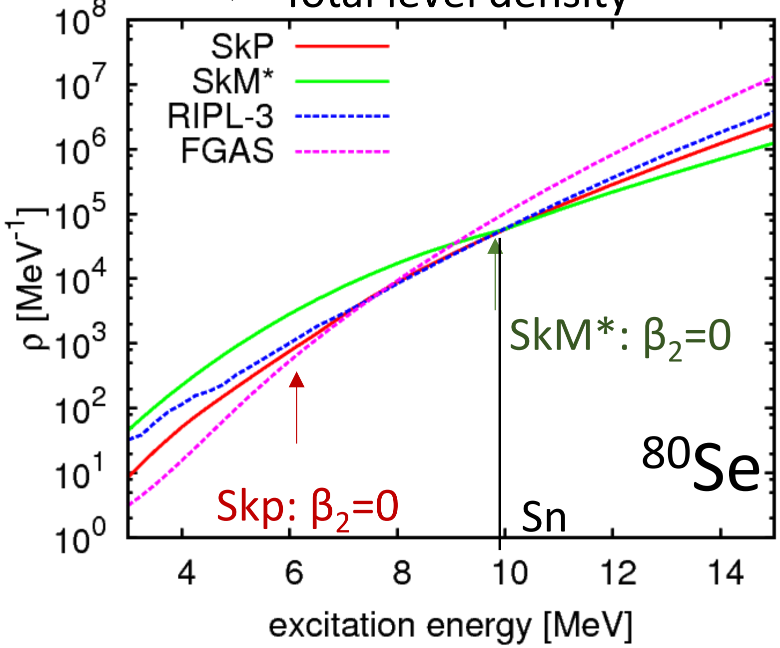




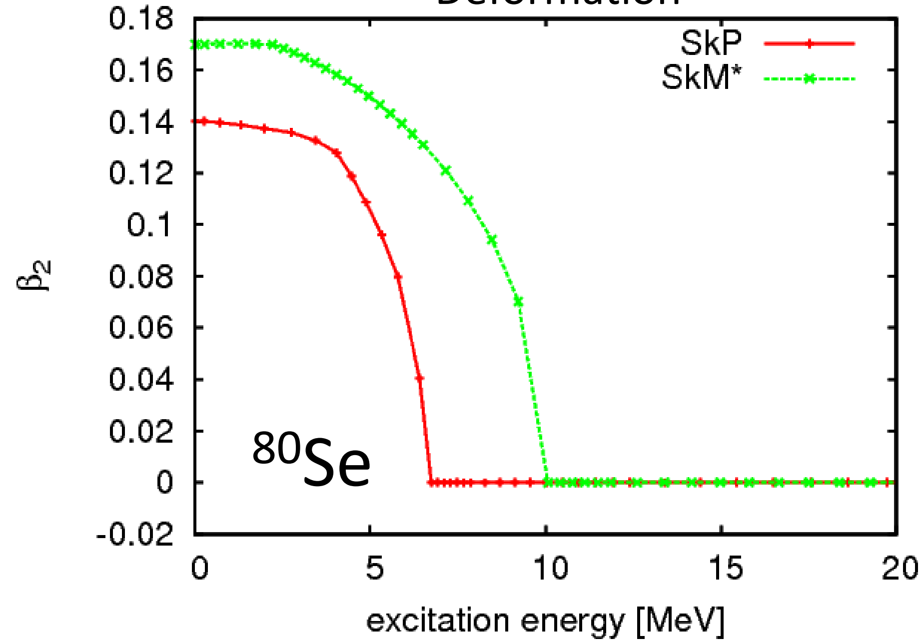


- ✓ (n,2n) cross section even have sensitivity to the difference of NLD
- ✓ Significant difference is found in ^{80}Se
- ✓ What is the reason for this differences ?

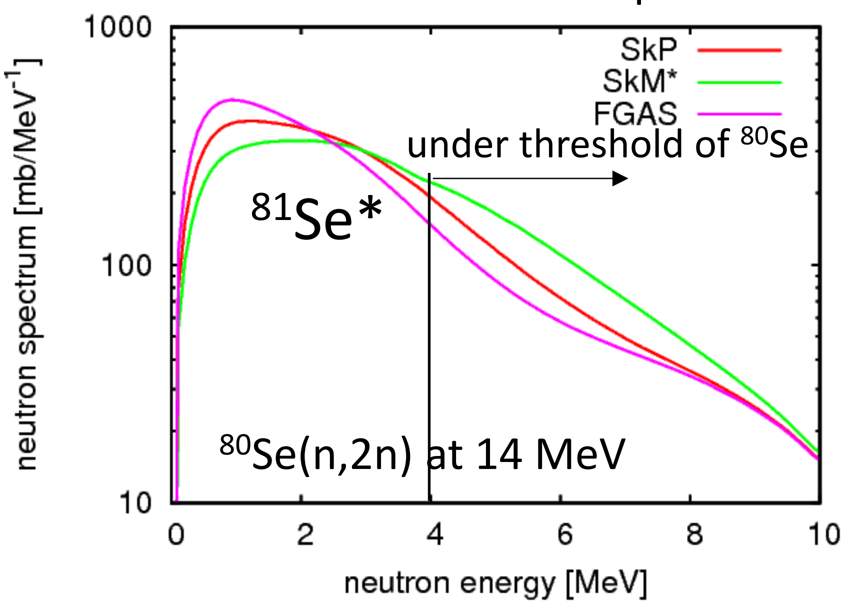
✓ Total level density



✓ Deformation



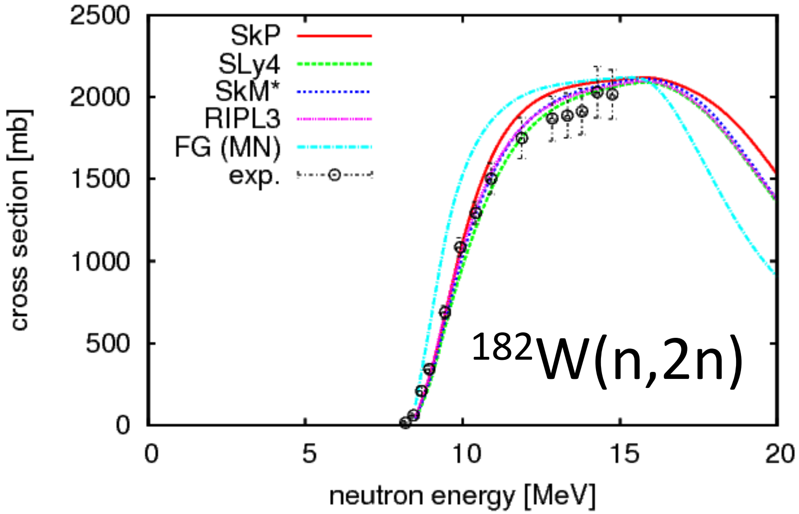
✓ Neutron emission spectrum

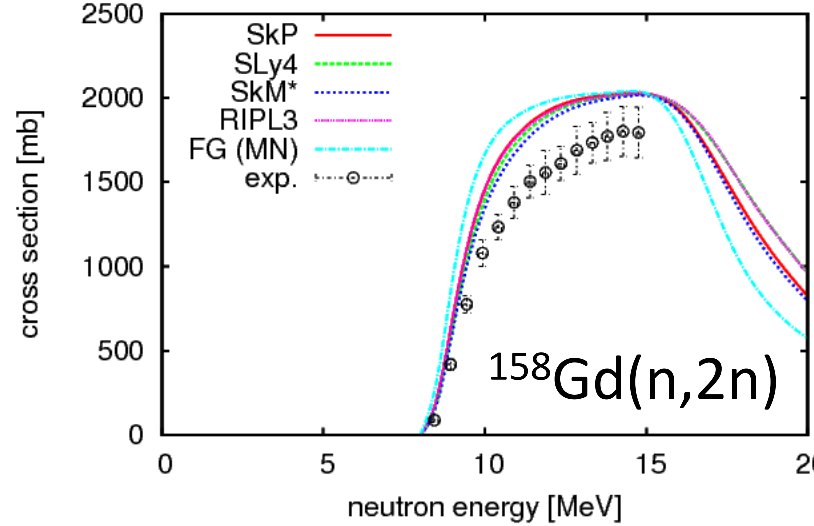


✓ (n,2n) cross section has sensitivity to the slope of the target nucleus NLD

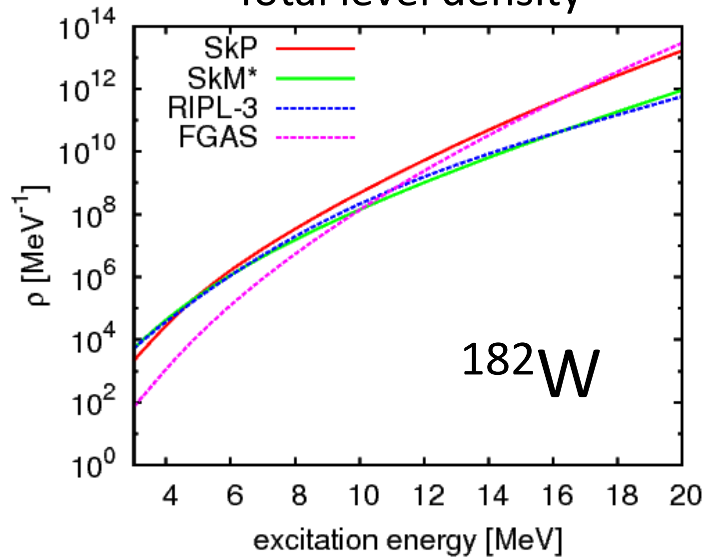
✓ If the deformation change occurs around the neutron threshold, (n,2n) cross section is significantly reduced

- (n,2n) cross section of well deformed nuclei

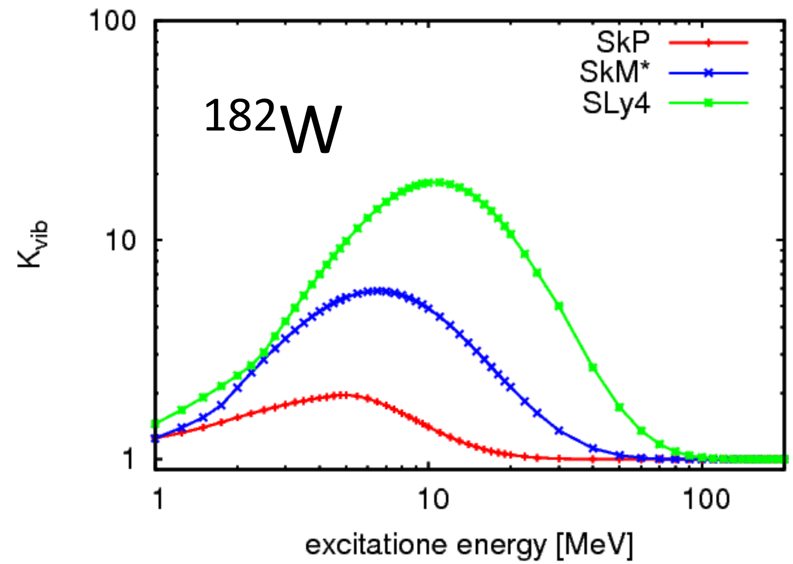




✓ Total level density



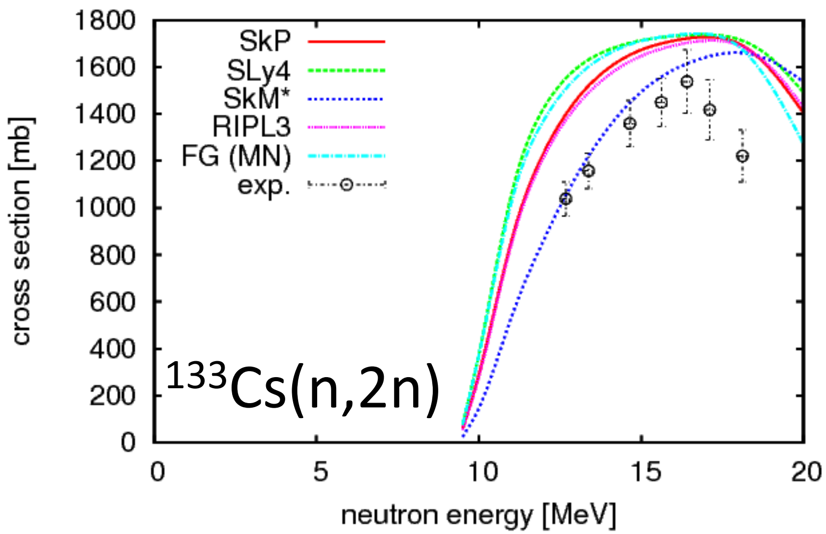
✓ Vibrational collective enhancement

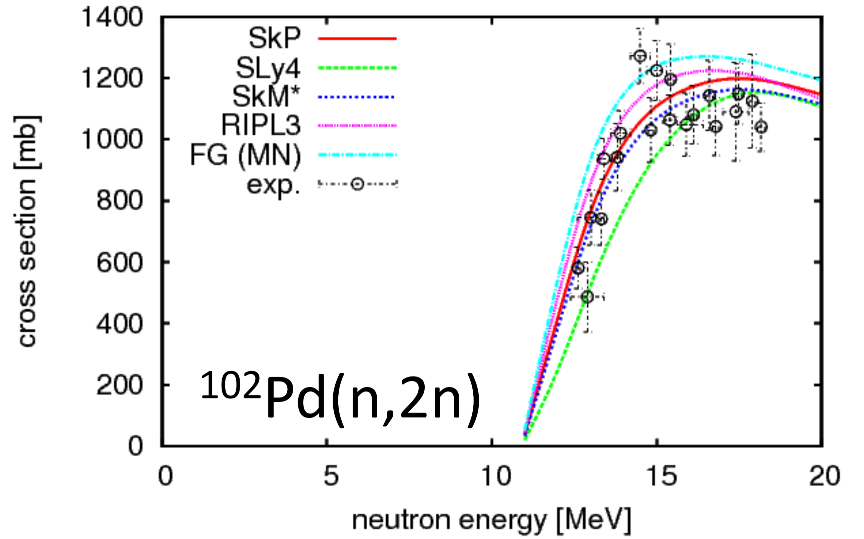


✓ If the deformation does not change below 20 MeV, difference is small

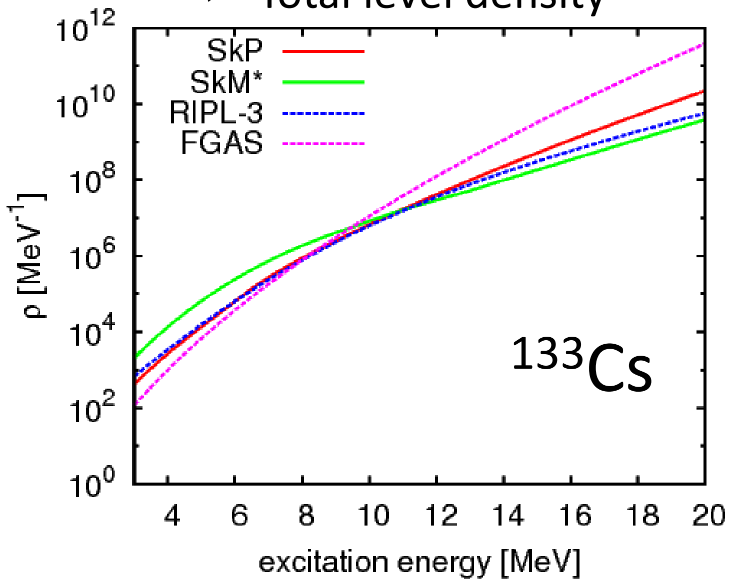
✓ On the other hand, difference in K_{vib} has noticeable effect on (n,2n) cross section

- Differences in (n,2n) cross section of nuclei around LLFPs

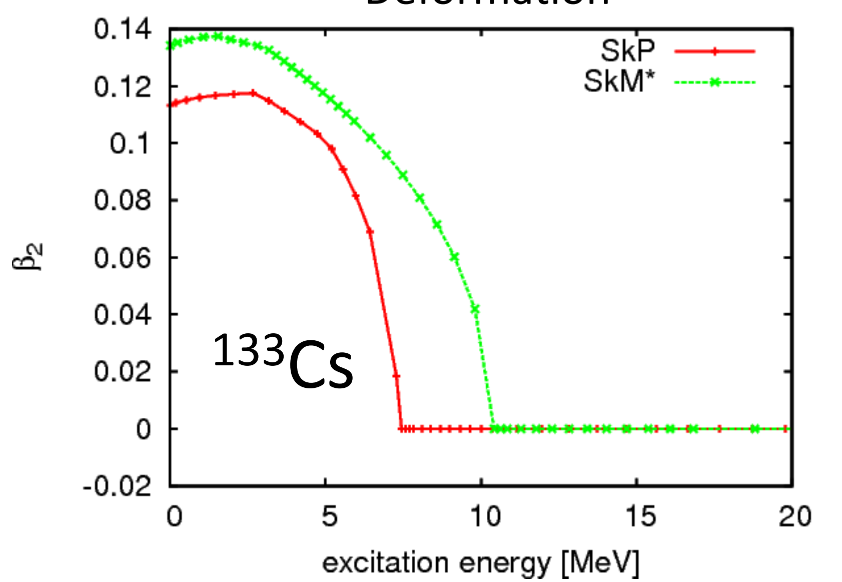




✓ Total level density



✓ Deformation



✓ Difficulty in describing the deformation change is a source of large uncertainty

Summary

- NLD were calculated from HFB +statistical method using Skp, SLy4, SkM* Skyrm forces
  - ✓ The vibrational collective enhancement is essential for effective mass ～0.7 forces
  - ✓ NLD obtained from Skp, SLy4, SkM* forces deduce similar D_0 if the optimized vibrational collective enhancements are combined
- Hauser-Feshbach calculation using these NLD
  - ✓ (n,2n) cross section have sensitivity to the slope of the target nucleus NLD
  - ✓ If the deformation change occurs around the neutron threshold, (n,2n) cross section is significantly reduced
    → Large difference among used forces
  - ✓ Difference in the damping of K_{vib} for each forces is also visible in (n,2n) cross section