Unified approach for multiband optical model in soft deformed even-even and odd-A nuclides

<u>D.Martyanov*</u>, E.Soukhovitskii, R.Capote, J.M.Quesada Molina, S.Chiba

**Joint Institute for Power and Nuclear Research – Sosny, Minsk, Belarus*

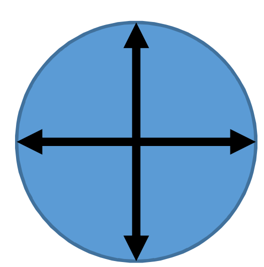
Outline

- Intro
  - General issues on multiband coupling (PRC2016)
  - Effective deformations: fitting params, calc using structure model
  - SRM
- Problem: odd nuclides
- Idea
  - Collectivity – even-even core
  - Spins assignment
- Results
  - XS, total ratios
  - Multiband coupling: CN ratios, direct XS
  - Stretching
  - Volume conservation
- Conclusions

Optical model for soft deformed nuclei

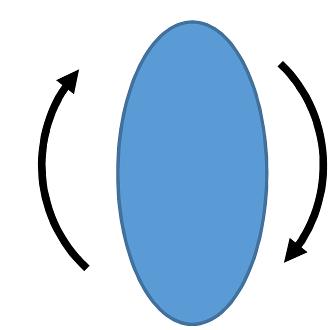
Conventional OMP
$V\big(r, R(\theta', \varphi')\big)$

Soft spherical nucleus
(vibrational excitations)



Tailor expansion near sphere

Rigid deformed nucleus
(rotational excitations)



Static multipolar expansion

But actinides are both considerably deformed in GS and soft for vibrations

Explicit deformations → vibrations
bad convergence for big deformations

Good convergence for big static deformations
no explicit deformations → no vibrations!

Solution: Taylor expansion near axial static form

$$R_i(\theta',\varphi')$$

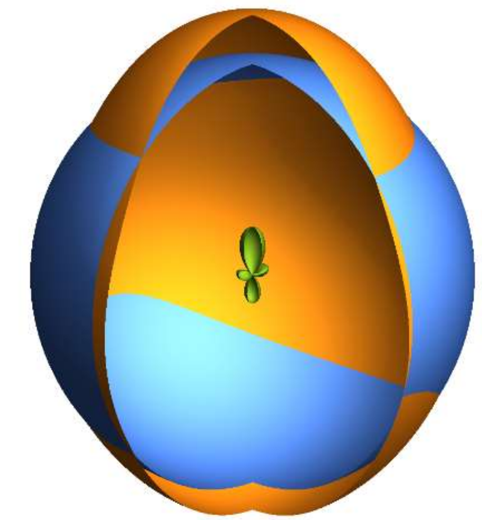
$$= R_{0i}\left\{1 + \sum_{\lambda=2,3;even\ \mu} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta',\varphi') + \sum_{\lambda=4,6} \beta_{\lambda 0} Y_{\lambda 0}(\theta')\right\}$$

$$= R_i^{zero}(\theta') + \delta R_i(\theta',\varphi';\delta\beta_2,\gamma,\beta_3)$$

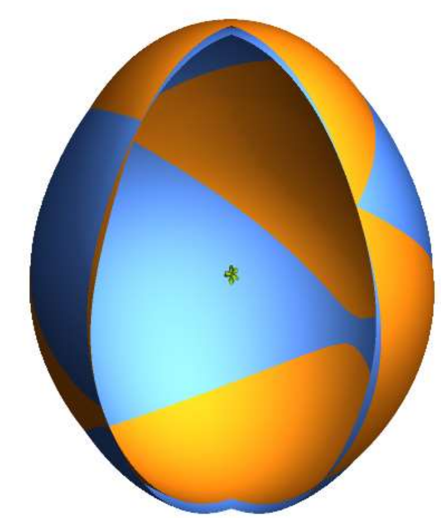
$$= R_{0i}\left\{1 + \sum_{\lambda=2,4,6} \beta_{\lambda 0} Y_{\lambda 0}(\theta')\right\}$$

$$\beta_2 = \beta_{20} + \delta\beta_2$$
$$\langle\delta\beta_2^2\rangle, \langle\gamma^2\rangle, \langle\delta\beta_3^2\rangle \ll \beta_{20}^2$$

$$+R_{0i}\left\{\beta_{20}\left[\frac{\delta\beta_2}{\beta_{20}}\cos\gamma + \cos\gamma - 1\right]Y_{20}(\theta') + \frac{(\beta_{20}+\delta\beta_2)\sin\gamma}{\sqrt{2}}\left[Y_{22}(\theta',\varphi') + Y_{2-2}(\theta',\varphi')\right] + \beta_3 Y_{30}(\theta')\right\}$$



Near sphere



Near axially deformed

Potential expansion near axially deformed shape

$$
\begin{aligned}
&V\big(r, R(\theta', \varphi')\big) \\
&\approx V\big(r, R^{zero}(\theta')\big) + \frac{\partial}{\partial R} V\big(r, R\,(\theta', \varphi')\big)\Big|_{R^{zero}(\theta')} \delta R(\theta', \varphi'; \delta\beta_2, \gamma, \beta_3) \\
&\approx V\big(r, R^{zero}(\theta')\big) + \frac{\nu_2(r)}{R_0 \beta_{20}} \delta R(\theta', \varphi'; \delta\beta_2, \gamma, \beta_3)
\end{aligned}
$$

Rigid rotor

Softness

$$
R_{zero}(\theta') = R_{0i} \left\{ 1 + \sum_{\lambda=2,4,6} \beta_{\lambda 0} Y_{\lambda 0}(\theta') \right\}
$$

$$
\nu_2(r) = 2\pi \int_0^{\pi} V\big(r, R^{zero}(\theta')\big) Y_{20}(\theta') \sin\theta' \, d\theta'
$$

E.S. Soukhovitskiĩ et al, PRC 94 (2016) 64605

Coupled channels matrix elements

Rigid rotor

$$
\begin{aligned}
&\langle i|V(r,\theta,\varphi)|f\rangle \\
&= \sum_K^I \sum_{K'}^{I'} A_K^{I\tau} A_{K'}^{I'\tau'} \Bigg\{ \sum_{\lambda=0,2,4,\ldots} v_\lambda(r) \langle IK || D^\lambda_{;0} || I'K\rangle A\left(ljI;l'j'I';\lambda J\frac{1}{2}\right)\delta_{KK'} \\
&+ v_2(r)\Bigg\{\left[[\boldsymbol{\beta_2}]_{\boldsymbol{eff}} + [\boldsymbol{\gamma_{20}}]_{\boldsymbol{eff}}\right]\langle IK||D^2_{;0}||I'K\rangle A\left(ljI;l'j'I';2J\frac{1}{2}\right)\delta_{KK'} \\
&+ [\boldsymbol{\gamma_{22}}]_{\boldsymbol{eff}}\langle IK||D^2_{;2} + D^2_{;-2}||I'K\rangle A\left(ljI;l'j'I';2J\frac{1}{2}\right) \\
&+ [\boldsymbol{\beta_3}]_{\boldsymbol{eff}}\langle IK||D^3_{;0}||I'K\rangle A\left(ljI;l'j'I';3J\frac{1}{2}\right)\delta_{KK'} \\
&+ [\boldsymbol{\beta_0}]_{\boldsymbol{eff}}\delta_{KK'}\delta_{II'}\delta_{jj'}\delta_{ll'}\Bigg\}\Bigg\}
\end{aligned}
$$

β- and γ-vibrations and stretching

$K = 2$ band coupling

Octupole coupling
(negative parity band)

Volume conservation correction

Effective deformations

$$[\beta_2]_{eff} = \left\langle n_i(\beta_2) \middle| \frac{\delta\beta_2}{\beta_{20}} \middle| n_f(\beta_2) \right\rangle \qquad [\beta_3]_{eff} = \left\langle n_i(\beta_3) \middle| \frac{\beta_3}{\beta_{20}} \middle| n_f(\beta_3) \right\rangle$$

$$[\gamma_{20}]_{eff} = \langle n_i(\gamma) | \cos\gamma - 1 | n_f(\gamma) \rangle \qquad [\gamma_{22}]_{eff} = \left\langle n_i(\gamma) \middle| \frac{\sin\gamma}{\sqrt{2}} \middle| n_f(\gamma) \right\rangle$$

$$[\beta_2^2]_{eff} = \left\langle n_i(\beta_2) \middle| \frac{\delta\beta_2^2}{\beta_{20}^2} \middle| n_f(\beta_2) \right\rangle \qquad [\beta_3^2]_{eff} = \left\langle n_i(\beta_3) \middle| \frac{\beta_3^2}{\beta_{20}^2} \middle| n_f(\beta_3) \right\rangle$$

$$[\beta_0]_{eff} = -\frac{\beta_{20}}{\sqrt{4\pi}} \left[2[\beta_2]_{eff} + [\beta_2^2]_{eff} + [\beta_3^2]_{eff} \right]$$

Softness effects

- Multiband coupling (for bands, corresponding to collective excitations)
- Nucleus stretching due to rotation (centrifugal forces)
- Additional monopole coupling due to account of volume conservation in vibrating nucleus

Approach to effective deformations

Effective deformations as fitting parameters

- Rough model to keep minimal number of parameters, only multiband coupling accounted (rigid rotor coupling within each band)
- No additional knowledge needed

E.S. Soukhovitskiĩ et al, PRC 94 (2016) 64605

Direct calculation

- Nuclear structure model needed
- Gives all model effects

For even-even nuclides using SRM:

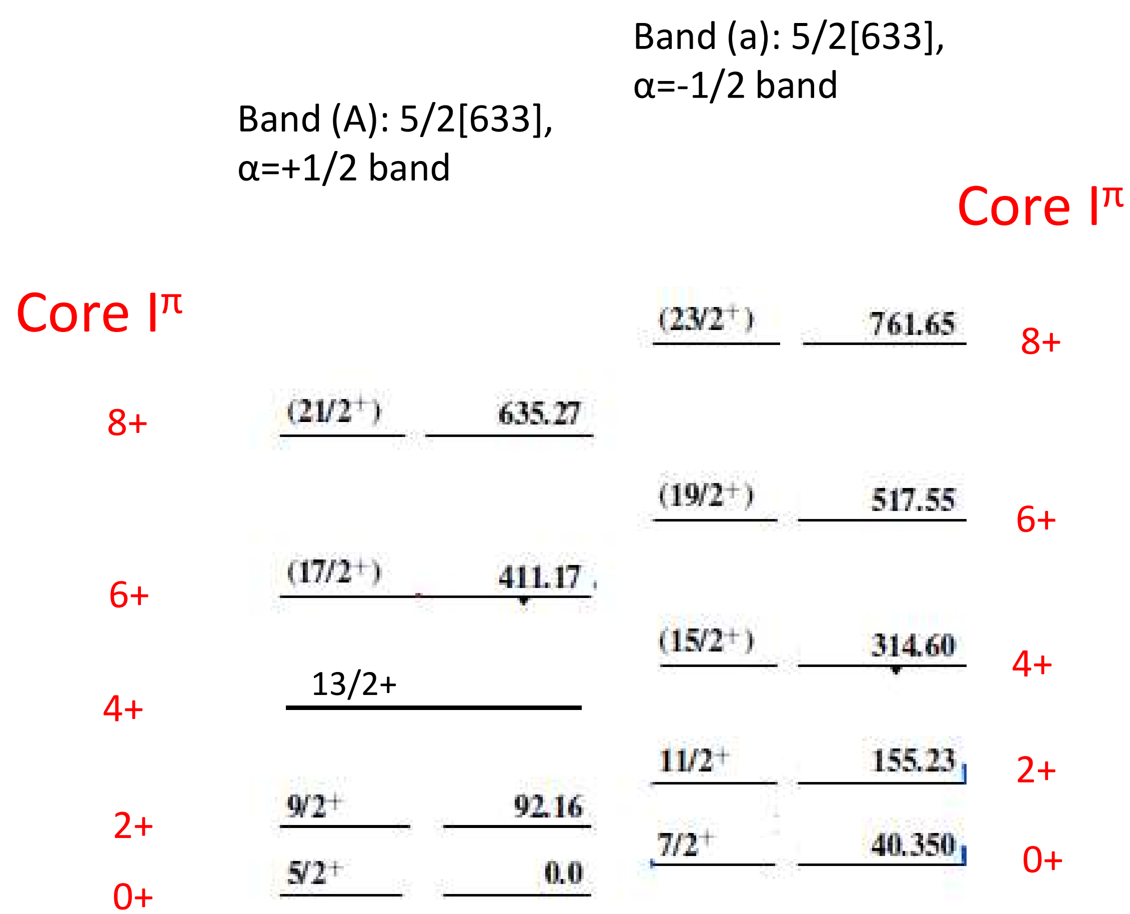
D. Martyanov et al, EPJ Web Conf. 146 (2017) 12031 (ND2016)

Towards odd nuclides

No appropriate nuclear model (describing softness), but…

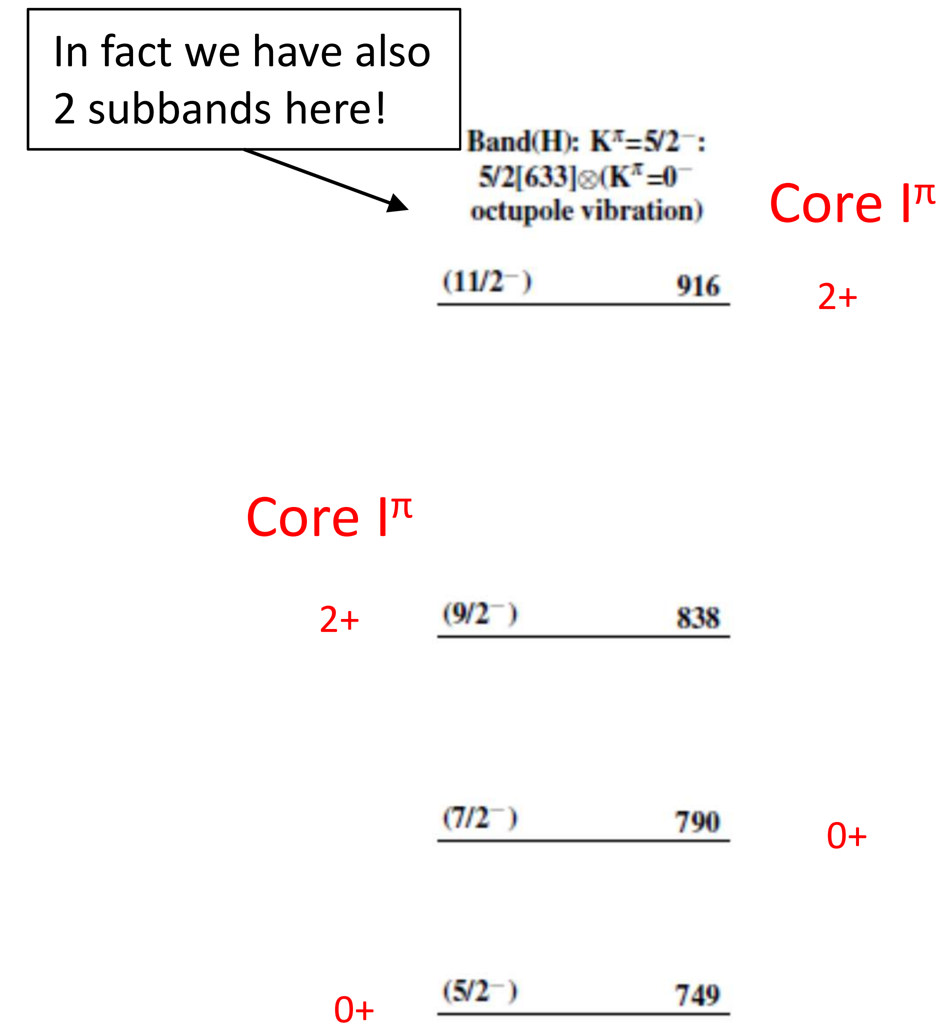
- Nuclear softness – collective effect, determined mainly by the even-even core, and varies smoothly from nucleus to nucleus
- $\langle \psi_{odd} | \beta | \psi_{odd} \rangle \approx \langle \psi_{core} | \beta | \psi_{core} \rangle$
- We may try to couple levels for bands built on single-particle state same as in GS
- We need to build appropriate core states

Core states assignment (^{233}U)



Core state: no vibrational excitation, only rotation

GS band



Core state: first octupole excitation, rotation

Octupole band

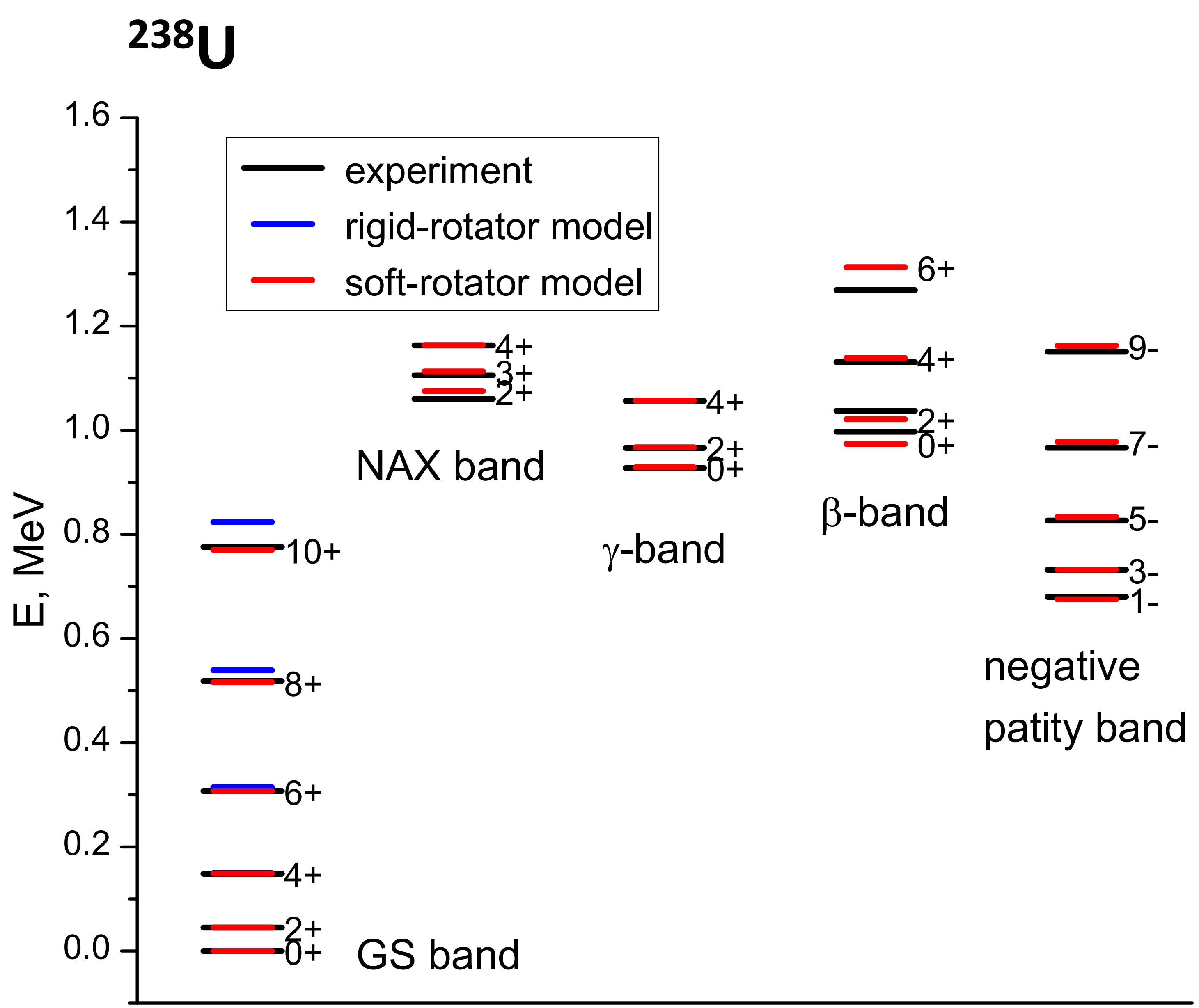
Calculation algorithm

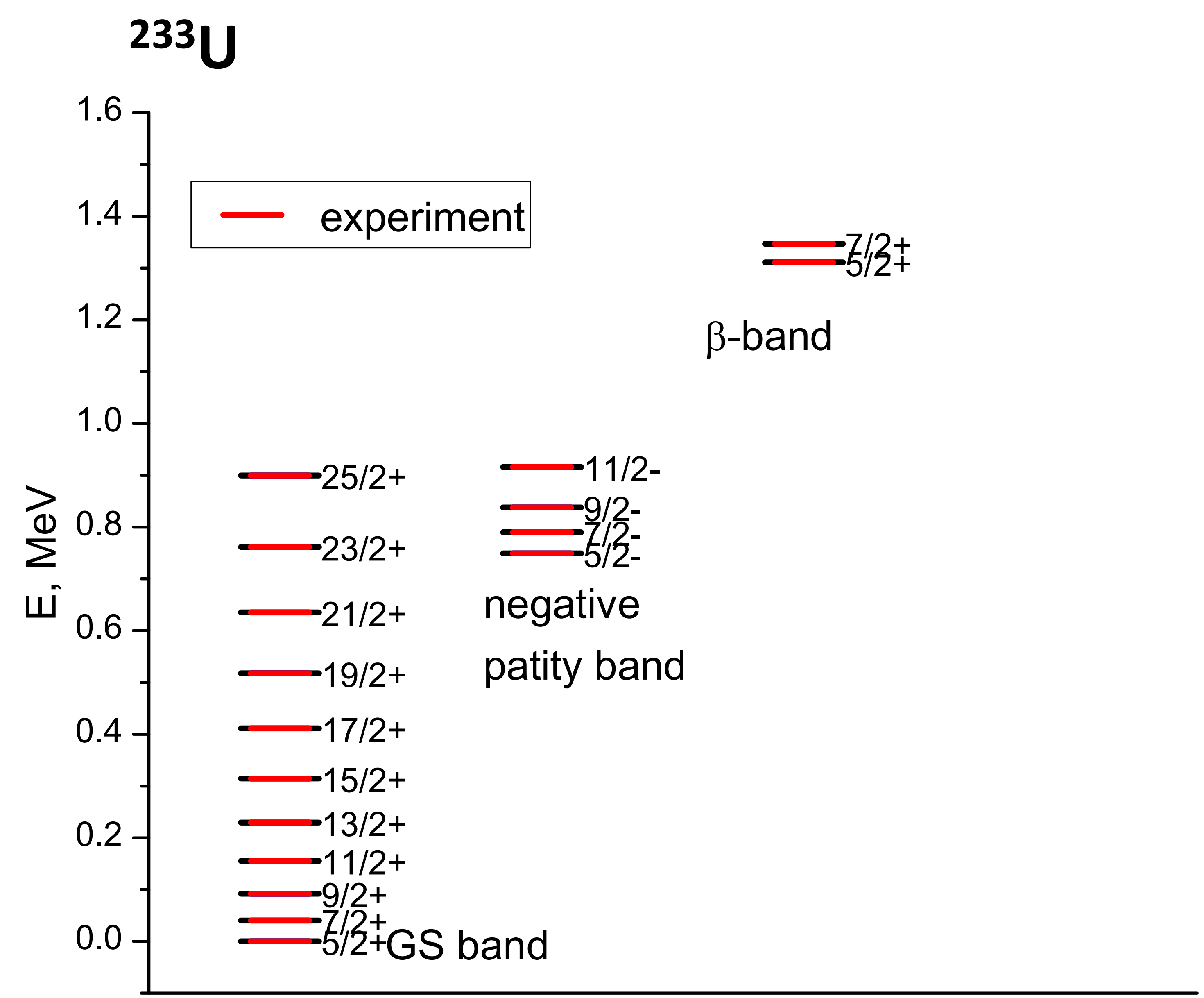
1. Build new regional OMP on ^{238}U and ^{232}Th experimental data

2. Use ^{233}U experimental data to fit its deformations with resulting OMP

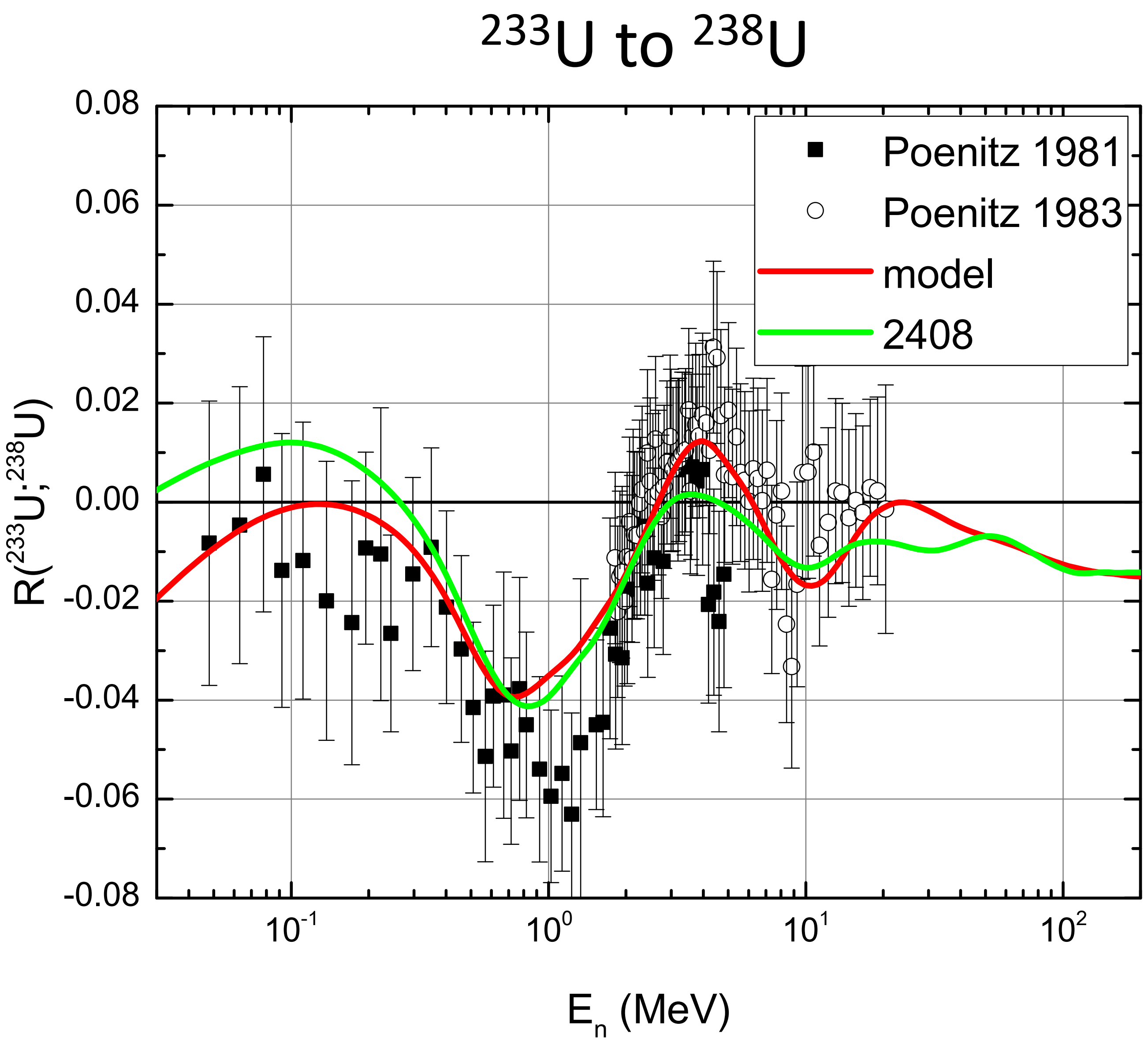
3. Calculate all model predictions for ^{233}U, ^{238}U, and ^{232}Th for full and restricted (some options disabled or truncated coupling scheme) model

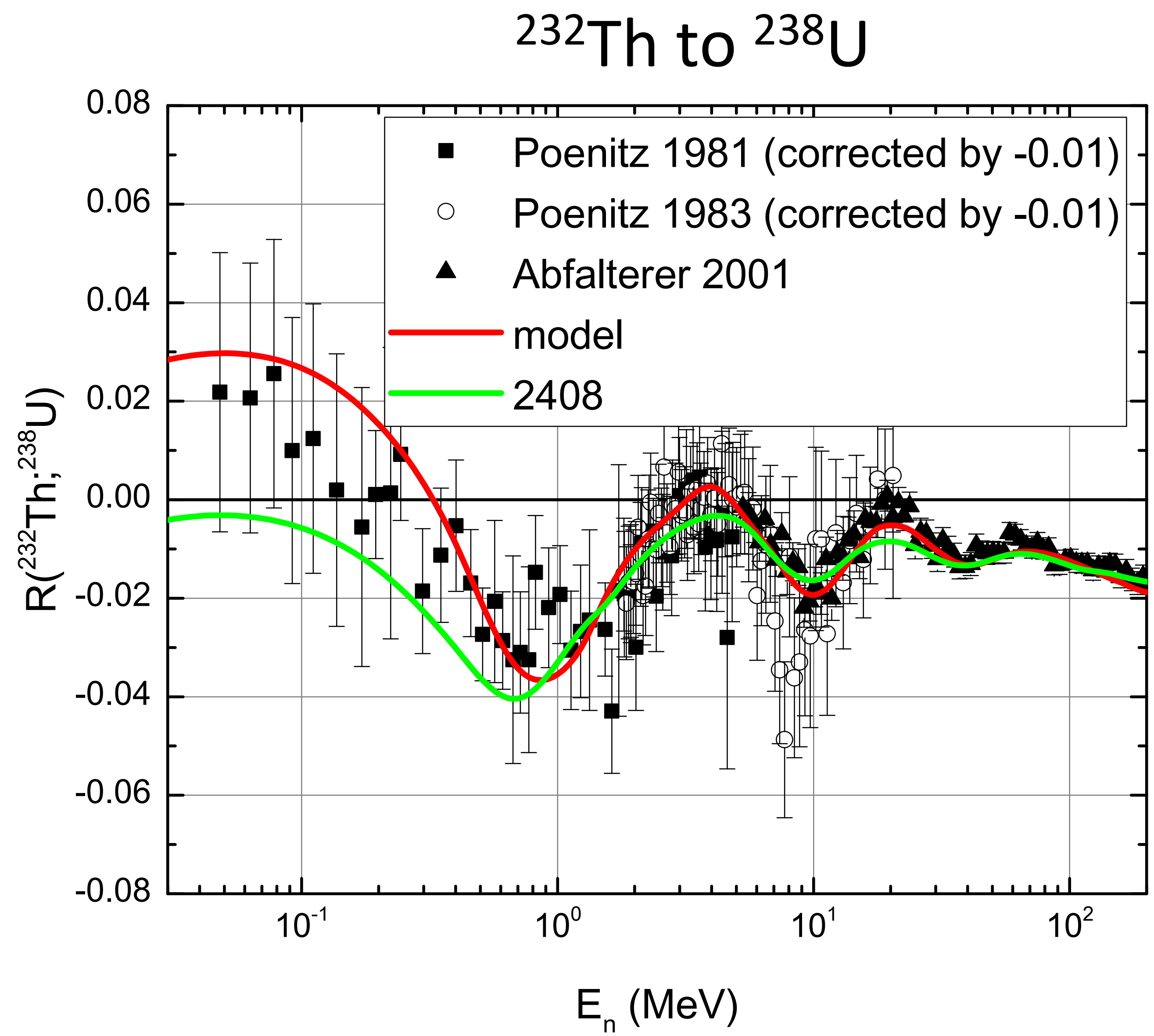
Coupling scheme



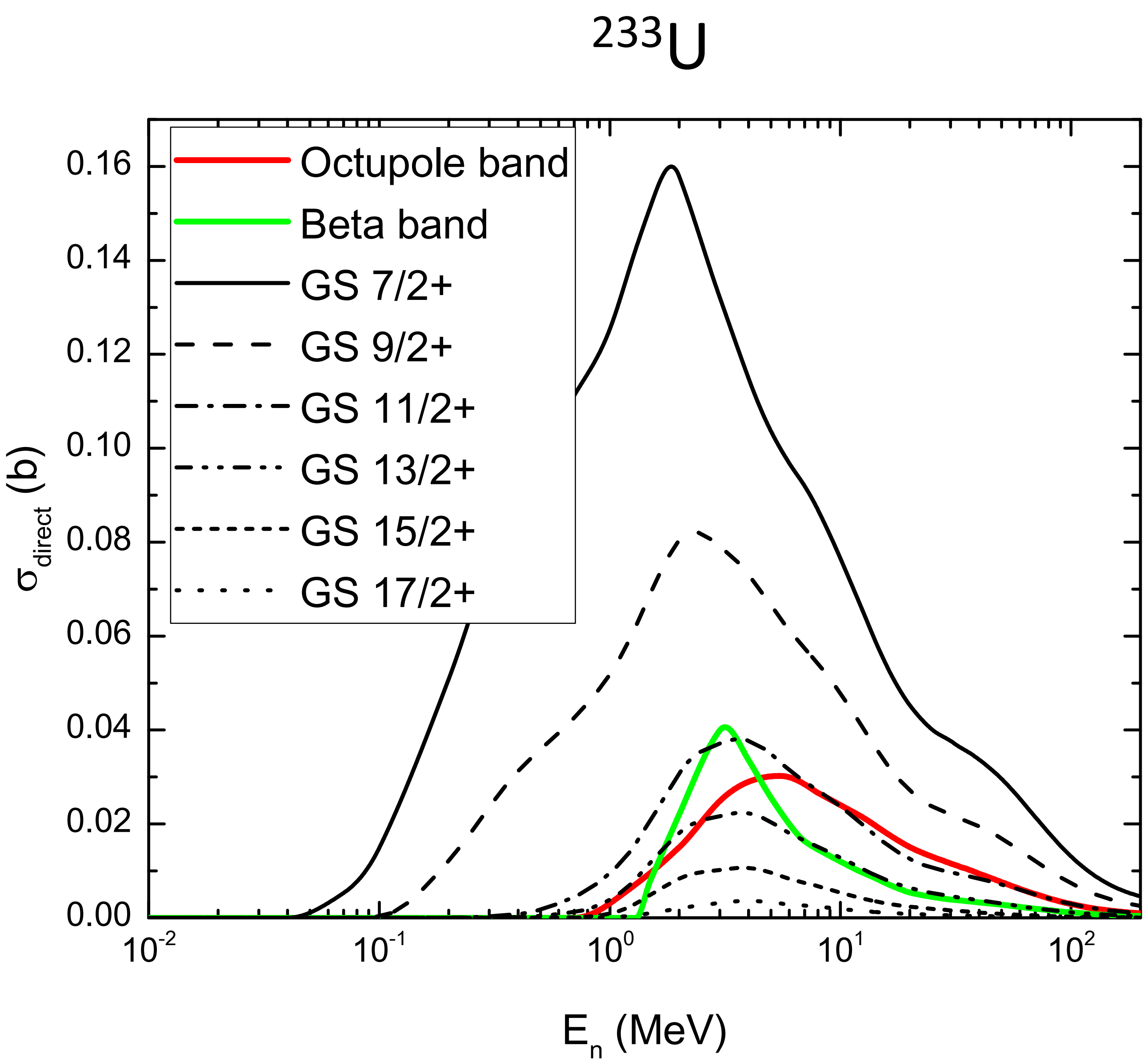


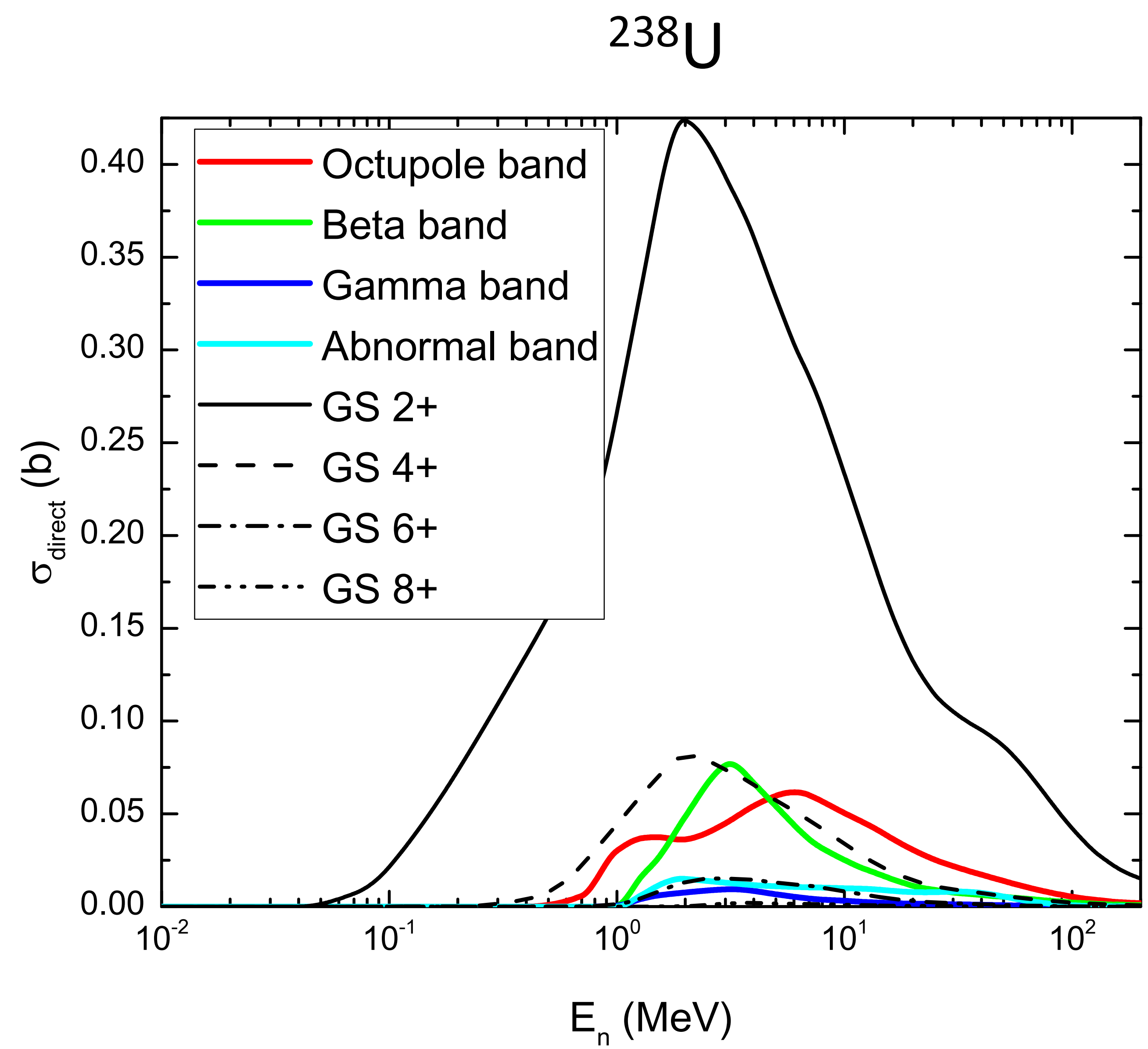
OMP figure of merit: symmetrized total XS ratio for different nuclei $R(A,B) = \frac{1}{2}\frac{\sigma_A - \sigma_B}{\sigma_A + \sigma_B}$



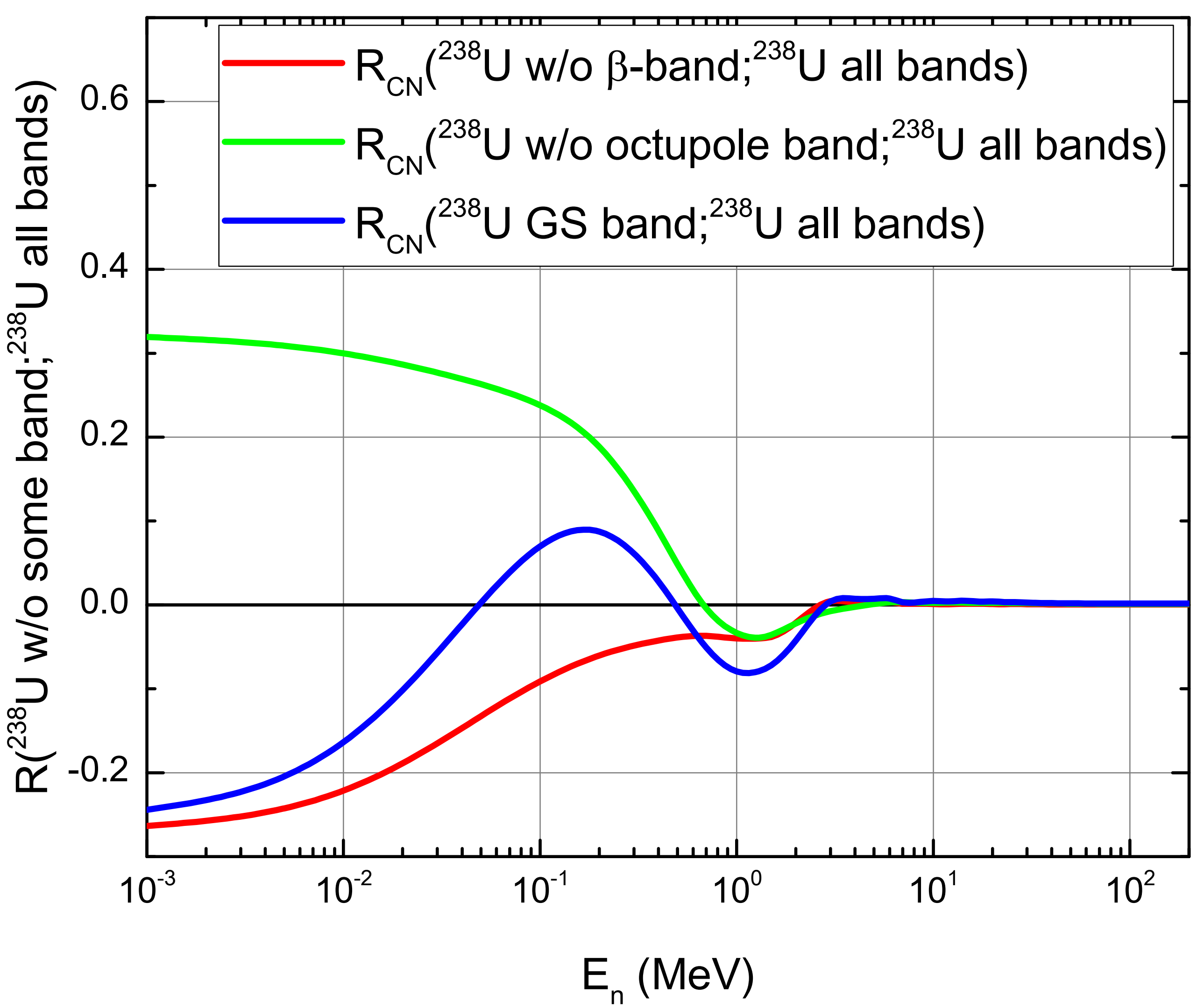


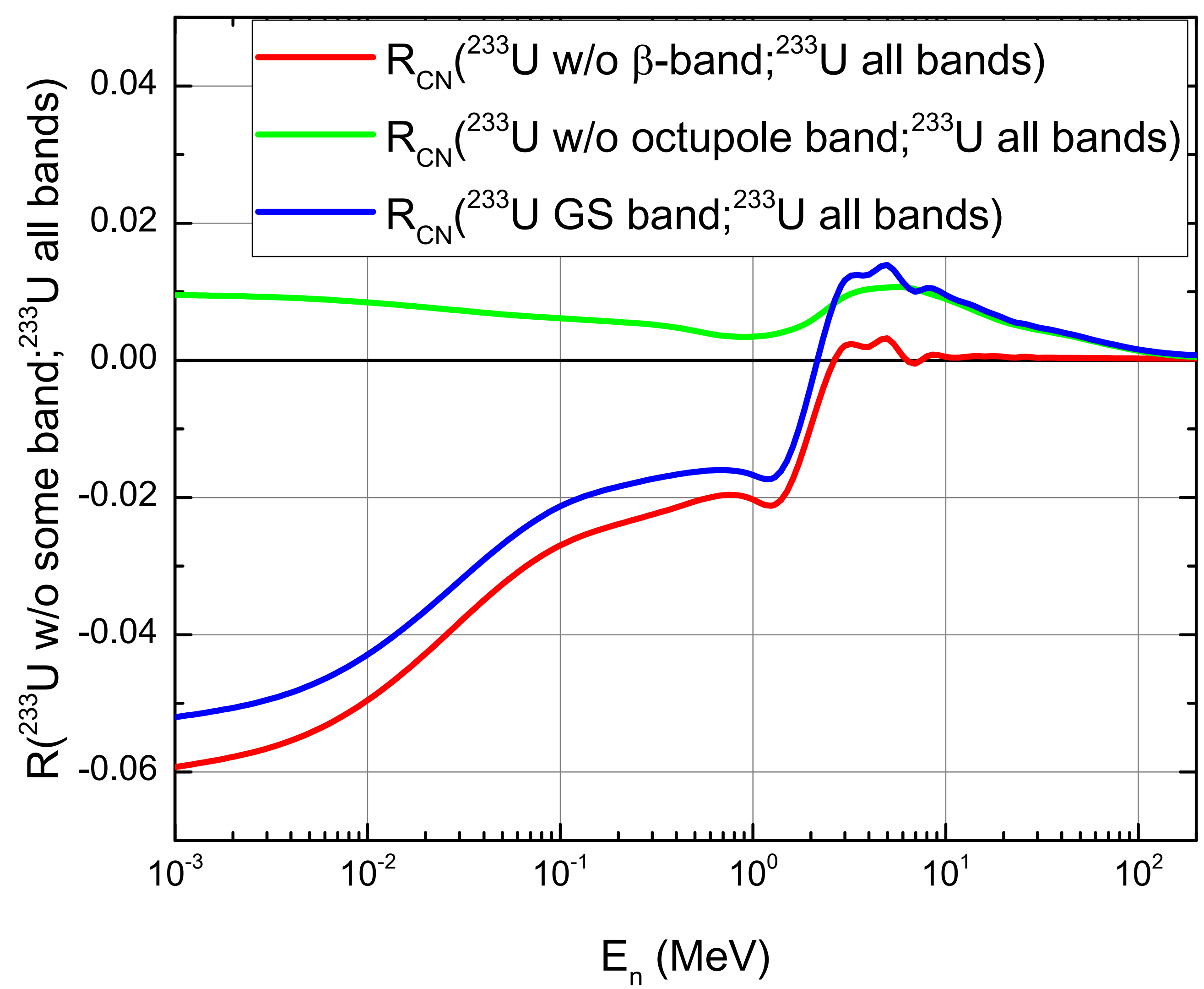
Multiband coupling: Direct level excitation XS



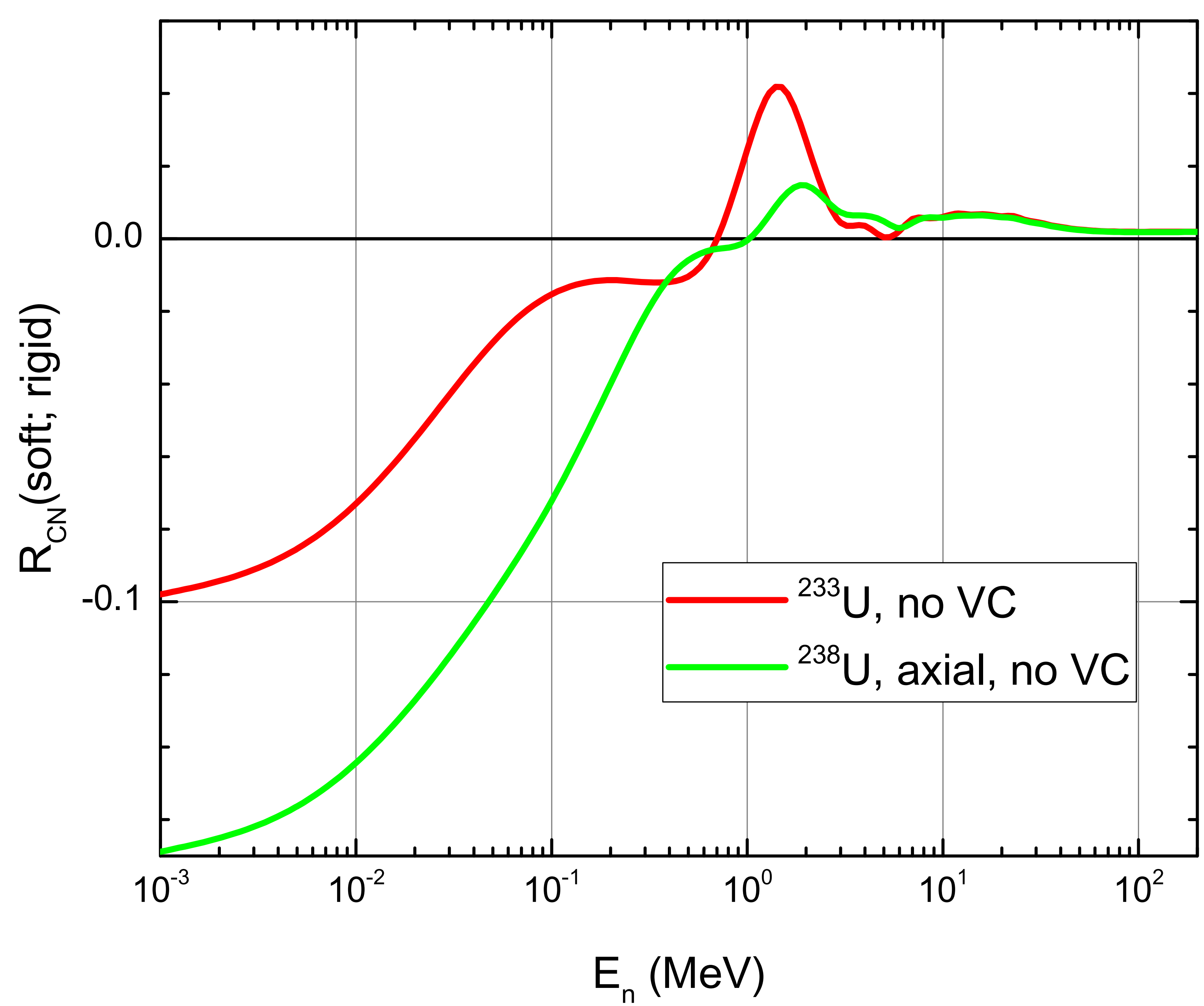


Multiband coupling: CN XS change

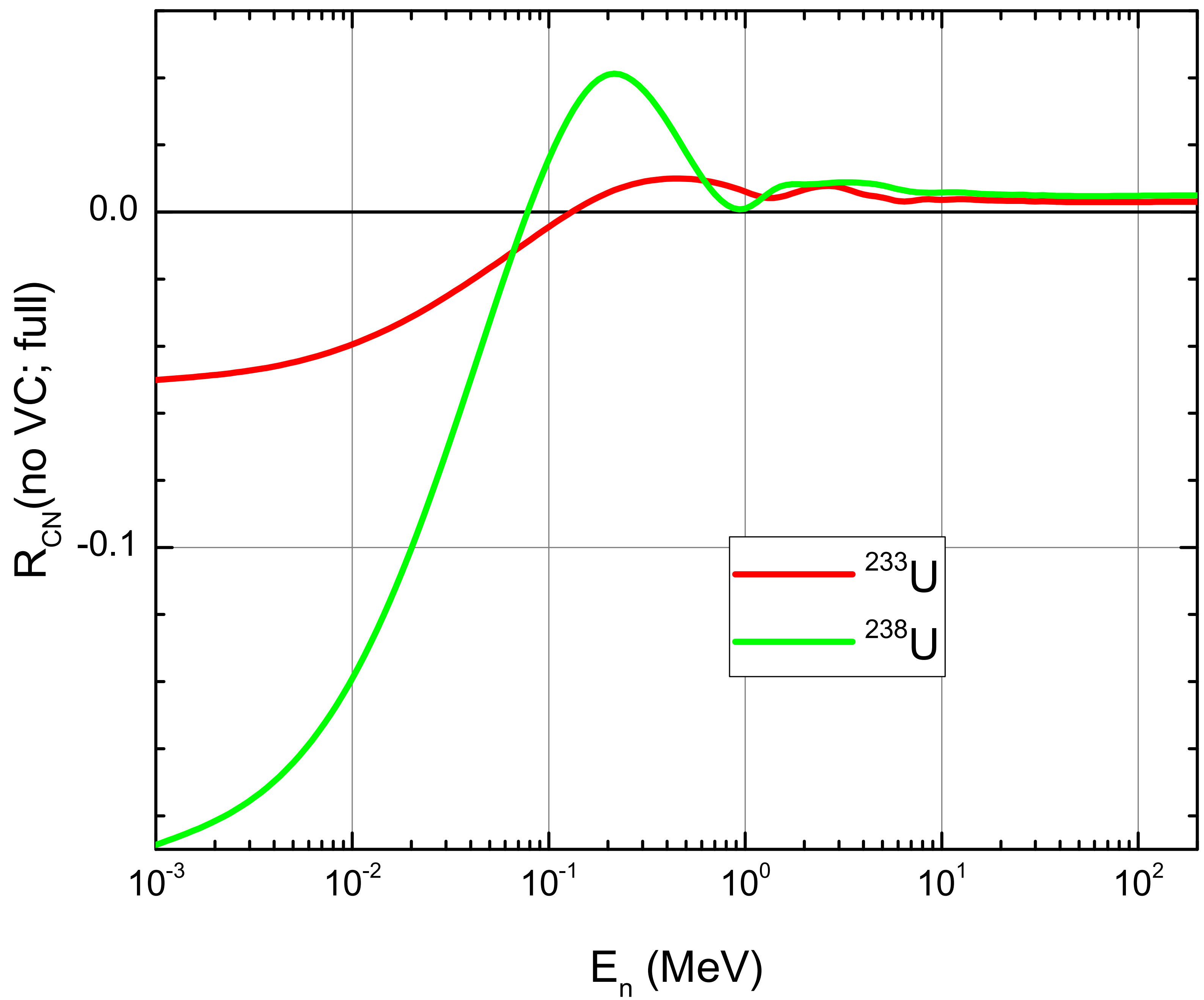




Nucleus stretching: CN XS change



Volume conservation: CN XS change



Summary

- Softness and multiband coupling are important to reach accurate CCOM calculations results for odd nuclides
- We can build and use fully functional regional OMP for actinides, both even-even and odd!
- Have to look thoroughly to band assignment in odd actinides: very few rotational bands built on GS single-particle state + core vibration! (e.g. none for ^{235}U)

Software

All calculations performed by two FORTRAN codes which have been being developed E. Soukhovitskii and coworkers for many years:

- optical model code **OPTMAN** (optical potential fitting, cross-section calculations)
- nuclear structure code **SHEMMAN** (soft-rotator model parameters fitting and levels prediction)

OPTMAN

- recommended to use with latest version of IAEA reference input parameter library (RIPL-3) for nuclear data evaluation
- used with the EMPIRE – nuclear reaction model code, one of the most used tools for basic research and evaluation of nuclear data

RIPL-3: Capote, R. et al., Nucl. Data Sheets 110, 3107–3214 (2009)
OPTMAN and SHEMMAN: E. Sh. Sukhovitski et al., JAERI-Data/Code 2005-002 (2005)

Thank you for the attention!

Comparison with the GS-band-only potential