Multiband coupling and nuclear softness in dispersive Lane-consistent optical model for actinides

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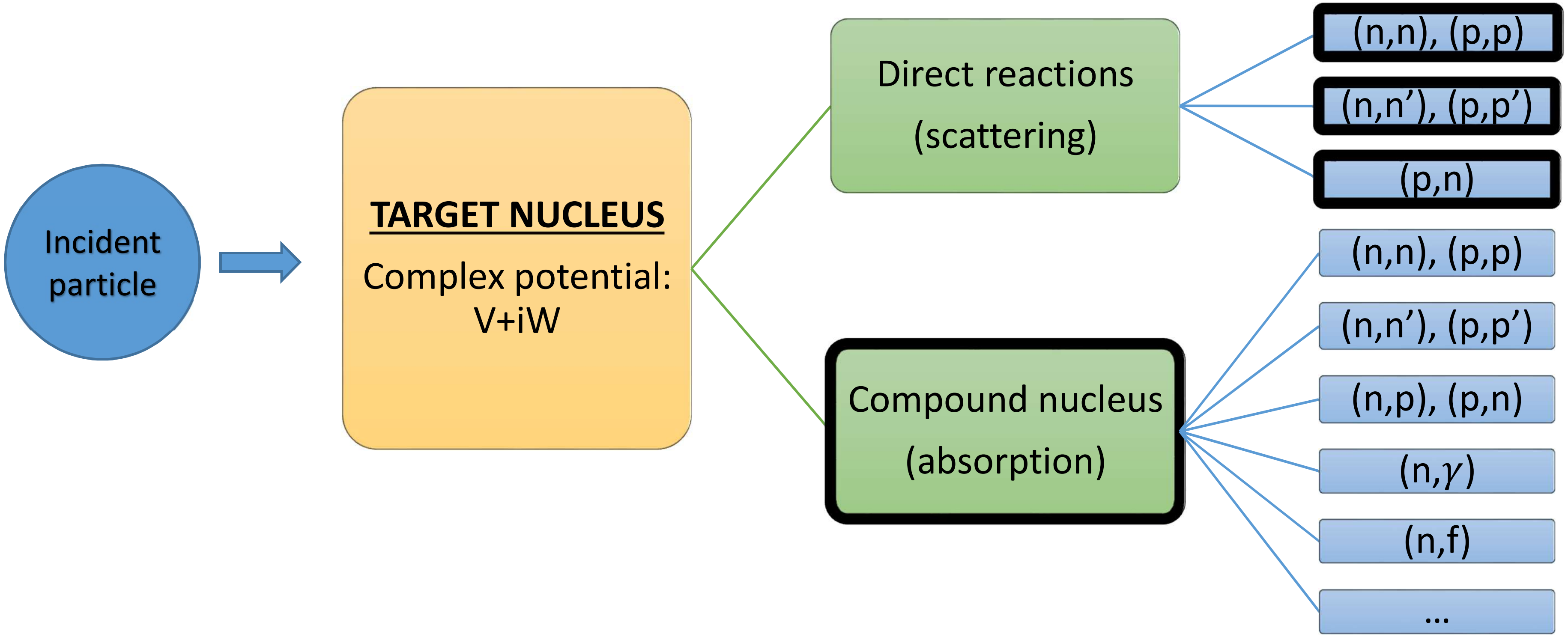
Basics: Optical model



Results:

- total cross section
- direct scattering cross sections, angular dependencies, polarization change
- absorption cross section, nuclear transmission coefficients

Basics: Coupled channels

- Method for exact account of interaction between different reaction channels:
  - ✓Orbital moments
  - ✓Incident particle spins
  - ✓Residual target excitations
  - ✓…
- Solve system of equations describing channels, coupled by optical potential
- Result – scattering matrix

Model feature 1: Dispersive relation

Casuality → Kramers–Kronig relations:

- Energy-dependent imaginary part of the potential yields additional (polarization) term to the real part:

$$\Delta V(E) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty}\frac{W(E')}{E'-E}dE'$$

- Physically realistic and constraint energy dependence of the potential
- Used energy dependence allows analytical expressions for $\Delta V(E)$

Model feature 2: Lane consistency

Isospin-symmetric form of optical potential (only nuclear part without Coulomb):

- $V_{pp} = V_0 + \frac{N-Z}{4A} V_1,$
- $V_{nn} = V_0 - \frac{N-Z}{4A} V_1$
- $V_{pn} = \frac{\sqrt{N-Z}}{2A} V_1$

Allows same parameterization for direct neutron, proton scattering and (p,n)-reactions

Optical potential

Energy and other *Radial profile* *Nucleus shape*

$$V(r,R(\theta,\varphi),E) = -V_{HF}(E) f_{WS}(r,R_{HF}(\theta,\varphi))$$ Main real part

$$-[\boldsymbol{\Delta V_v(E)} + iW_v(E)] f_{WS}(r,R_v(\theta,\varphi))$$ Volume

$$-[\boldsymbol{\Delta V_s(E)} + iW_s(E)] g_{WS}(r,R_s(\theta,\varphi))$$ Surface

$$+V_{Coul}(r,R_c(\theta,\varphi))$$ Coulomb

$$+\left(\frac{\hbar}{m_\pi c}\right)^2 [V_{so}(E) + \boldsymbol{\Delta V_{so}(E)} + iW_{so}(E)] \times \frac{1}{r}\frac{d}{dr} f_{WS}(r,R_{so})(\hat{\boldsymbol{l}}\cdot\hat{\boldsymbol{\sigma}})$$ Spin-orbit

$$\boxed{f_{WS}(r,R) = \frac{1}{1+\exp\left(\frac{r-R}{a}\right)}}$$

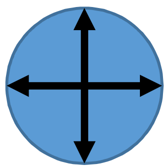
Coulomb correction (allows Lane consistency):

$$\boxed{E = E_{inc} - E_{Coul}}$$

Optical model for soft deformed nuclei

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

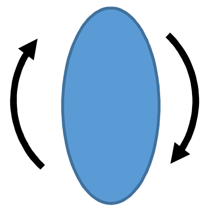
Soft spherical nucleus
(vibrational excitations)



Taylor expansion near sphere

Explicit deformations → vibrations
bad convergence for big deformations

Rigid deformed nucleus
(rotational excitations)



Static multipolar expansion

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

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

Solution: Taylor expansion near axial static form

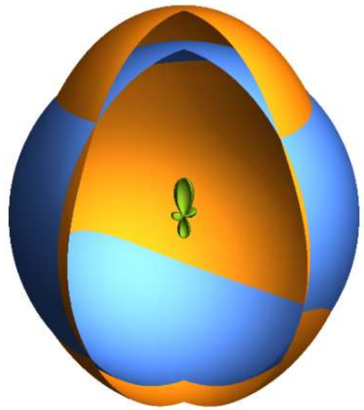
$$R_i(\theta',\varphi') = R_{0i}\left\{1 + \sum_{\lambda=2,3;even\ \mu} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta',\varphi') + \sum_{\lambda=4,6} \beta_{\lambda 0} Y_{\lambda 0}(\theta')\right\}$$

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

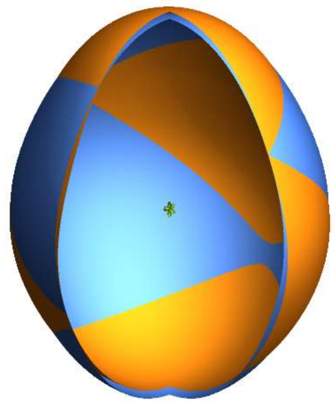
$$\beta_2 = \beta_{20} + \delta\beta_2$$
$$\langle\delta\beta_2\rangle, \langle\beta_{20}\gamma\rangle, \langle\beta_3\rangle, \langle\beta_{00}\rangle \ll \beta_{20}$$

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

$$+R_{0i}\left\{\beta_{20}\left[\frac{\delta\beta_2}{\beta_{20}}\cos\gamma + \cos\gamma - 1\right] Y_{20}(\theta') + \frac{(\beta_{20}+\delta\beta_2)\sin\gamma}{\sqrt{2}}\left[Y_{22}(\theta',\varphi') + Y_{2-2}(\theta',\varphi')\right] + \beta_3 Y_{30}(\theta') + \beta_{00} Y_{00}\right\}$$



Near sphere



Near axially deformed

Potential expansion near axially deformed shape

$$V\left(r, R(\theta', \varphi')\right)$$

$$\approx V\left(r, R^{zero}(\theta')\right) + \frac{\partial}{\partial R} V\left(r, R\ (\theta', \varphi')\right)\Big|_{R^{zero}(\theta')} \delta R(\theta', \varphi'; \delta\beta_2, \gamma, \beta_3)$$

$$\approx \boxed{V\left(r, R^{zero}(\theta')\right)} + \boxed{\frac{\nu_2(r)}{R_0 \beta_{20}} \delta R(\theta', \varphi'; \delta\beta_2, \gamma, \beta_3)}$$

Rigid rotor

Softness

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

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

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Coupled channels matrix elements

$$\langle i|V(r,\theta,\varphi)|f\rangle$$

$$= \sum_{K}^{I}\sum_{K'}^{I'} A_K^{I\tau} A_{K'}^{I'\tau'} \left\{ \sum_{\lambda=0,2,4,\dots} \nu_\lambda(r) \langle IK||D_{;0}^{\lambda}||I'K\rangle A\left(ljI;l'j'I';\lambda J\frac{1}{2}\right)\delta_{KK'}\right.$$

Rigid rotor

$$+\nu_2(r)\left\{\left[[\boldsymbol{\beta_2}]_{\boldsymbol{eff}}+[\boldsymbol{\gamma_{20}}]_{\boldsymbol{eff}}\right]\langle IK||D_{;0}^{2}||I'K\rangle A\left(ljI;l'j'I';2J\frac{1}{2}\right)\delta_{KK'}\right.$$

β- and γ-vibrations and stretching

$$+[\boldsymbol{\gamma_{22}}]_{\boldsymbol{eff}}\langle IK||D_{;2}^{2}+D_{;-2}^{2}||I'K\rangle A\left(ljI;l'j'I';2J\frac{1}{2}\right)$$

$K=2$ band coupling

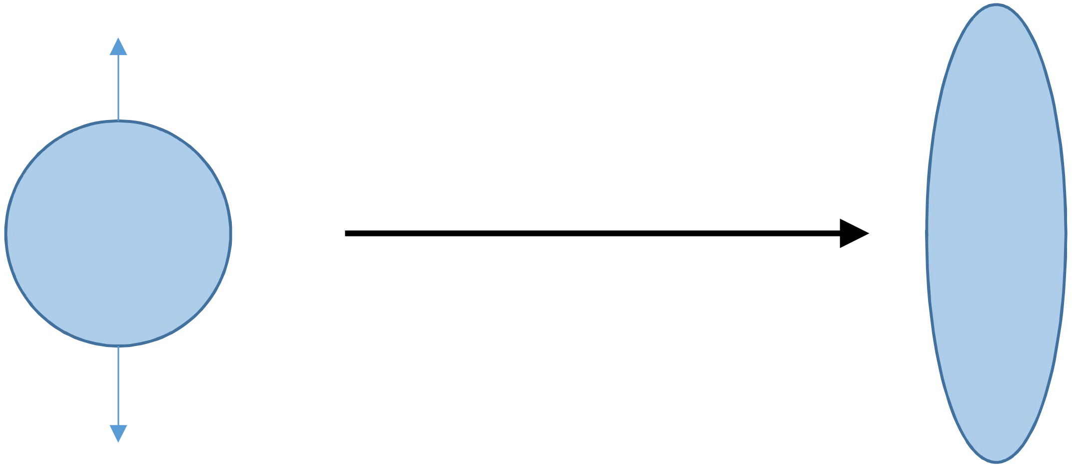
$$+[\boldsymbol{\beta_3}]_{\boldsymbol{eff}}\langle IK||D_{;0}^{3}||I'K\rangle A\left(ljI;l'j'I';3J\frac{1}{2}\right)\delta_{KK'}$$

Octupole coupling (negative parity band)

$$\left.\left.+[\boldsymbol{\beta_0}]_{\boldsymbol{eff}}\delta_{KK'}\delta_{II'}\delta_{jj'}\delta_{ll'}\right\}\right\}$$

Volume conservation correction

Volume conservation term



$$R(\theta,\varphi) = R_0$$

$$R'(\theta,\varphi) = R_0\left\{1 + \boxed{\beta_{00}Y_{00}} + \sum_{\lambda\mu} \beta_{\lambda\mu} Y_{\lambda\mu}(\theta,\varphi)\right\}$$

Compensation term

Incompressible nuclear matter: $V = V'$

$$\boxed{\beta_{00} = -\frac{\sum \beta_\lambda^2}{\sqrt{4\pi}}}$$

Effective deformations

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

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

$$[\gamma_{20}]_{eff} = \langle n_i(\gamma) | \cos\gamma - 1 | n_f(\gamma) \rangle$$

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

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

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

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

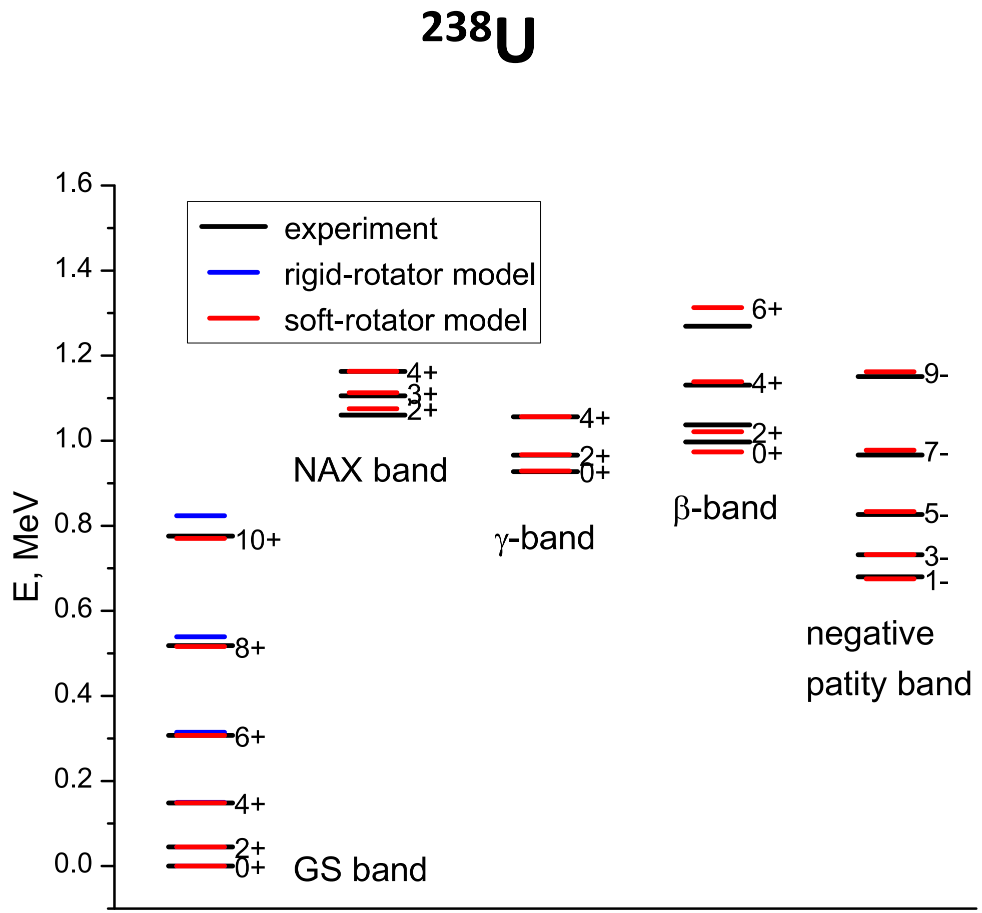
Effective deformations are defined by collective nuclear wavefunctions

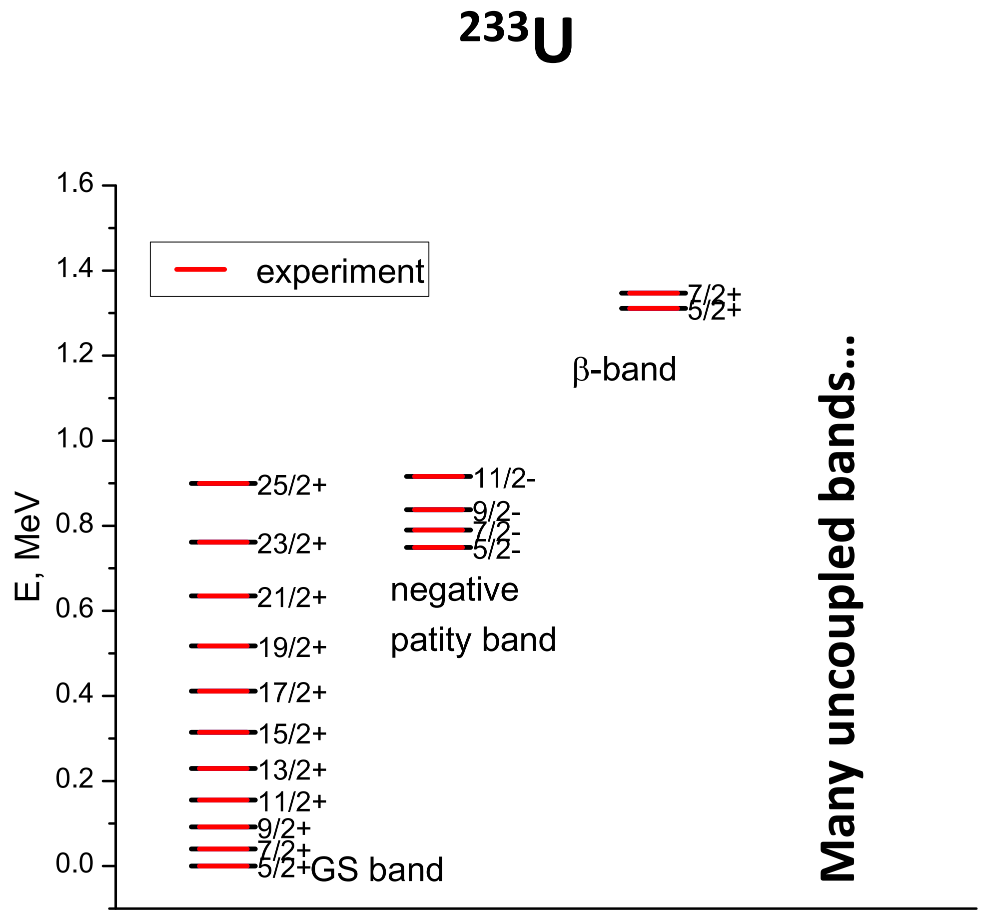
Towards odd nuclides

We have soft-rotator model for even-even actinides, but no appropriate nuclear model (describing softness) for odd-A ones…

- 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

Coupling scheme

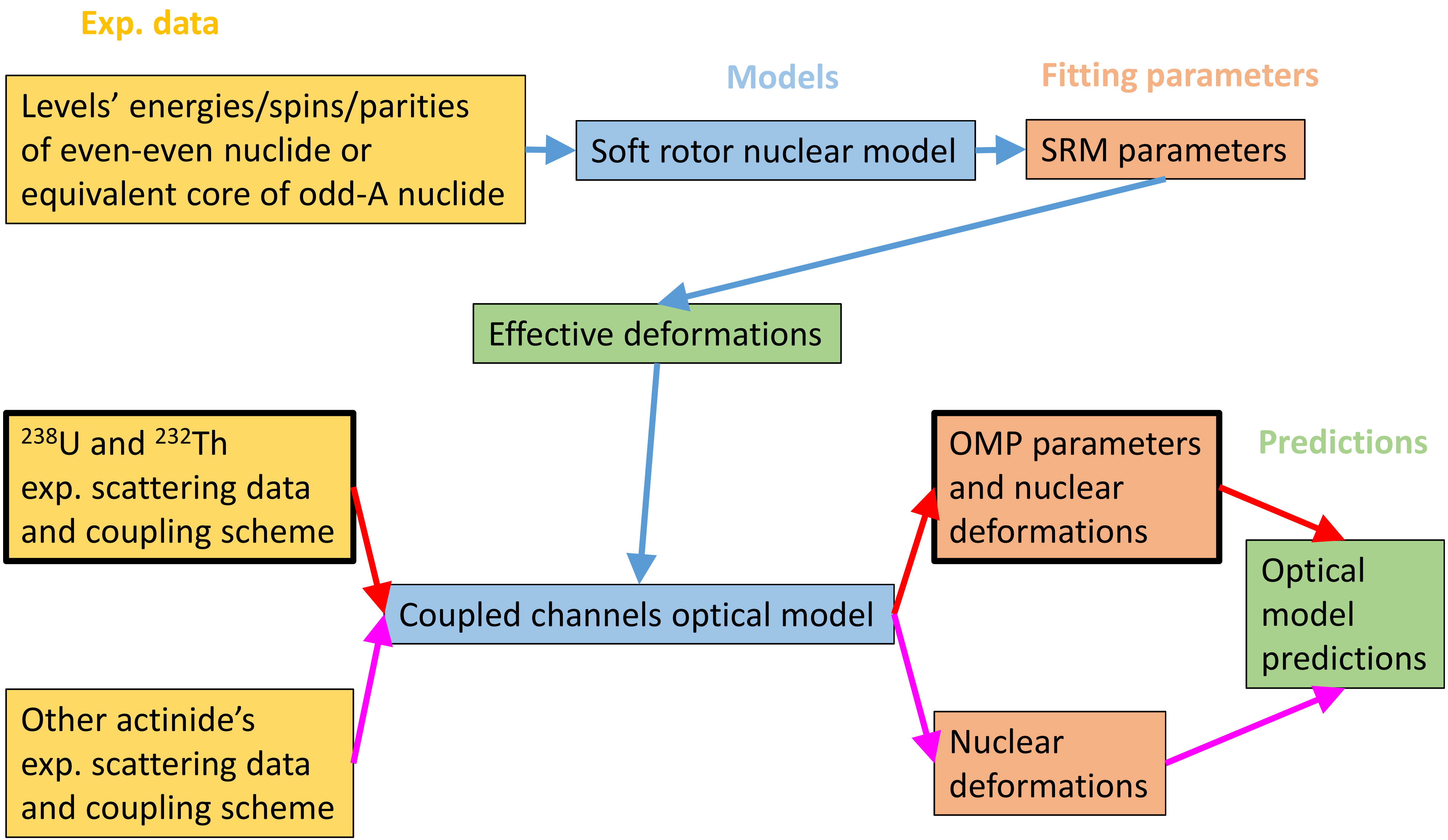




Saturated coupling scheme:
almost all low-lying levels
are coupled (and described by SRM)

Only a few bands coupled: those that
correspond to vibrational excitation of the core
and sp-wavefunction same as in GS (ENDSF)

Regional potential for actinides: calculation algorithm

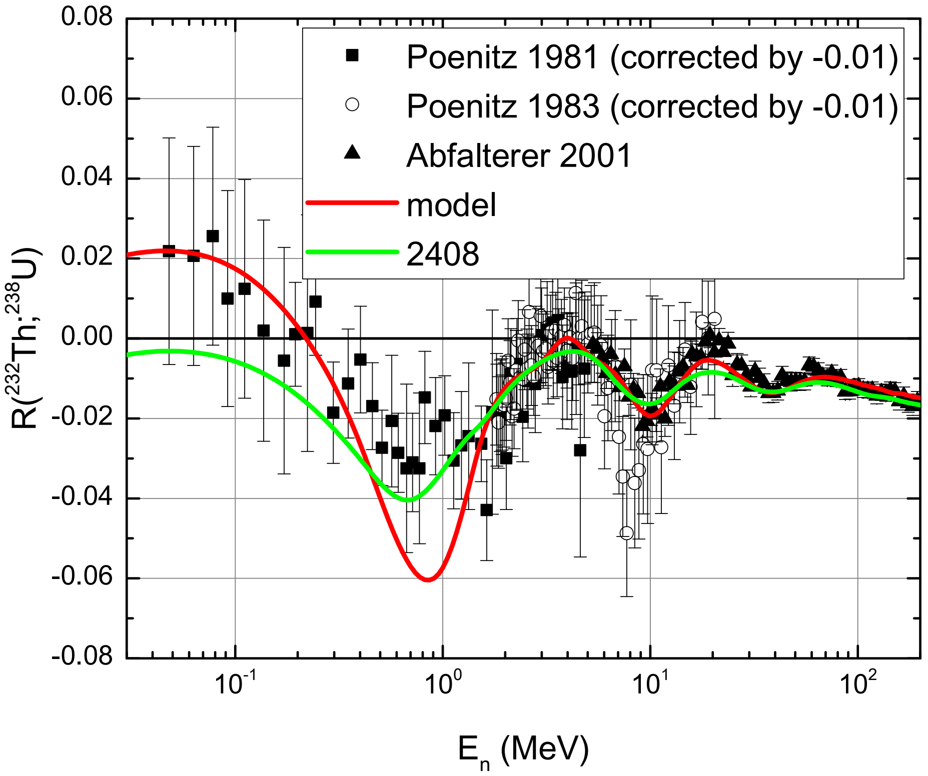


OMP figure of merit: symmetrized total XS ratio for different nuclei

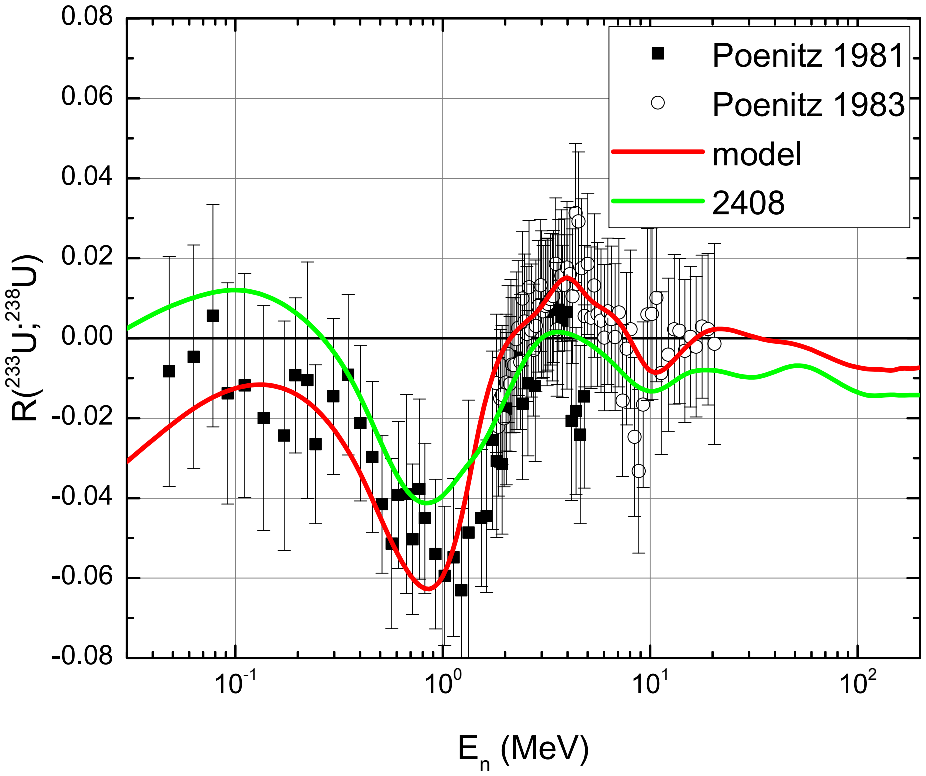
$$R(A,B) = \frac{1}{2}\frac{\sigma_A - \sigma_B}{\sigma_A + \sigma_B}$$

Many other data is fitted: total XS, (in)elastic angular distributions, (p,n), strength functions and scattering radii

^{232}Th to ^{238}U



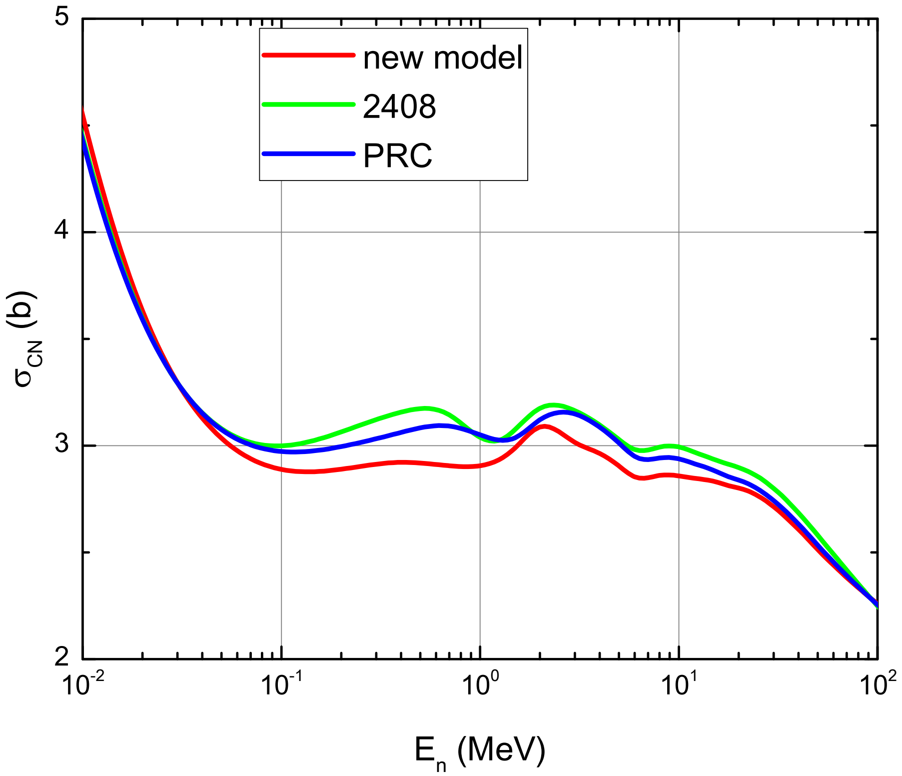
^{233}U to ^{238}U



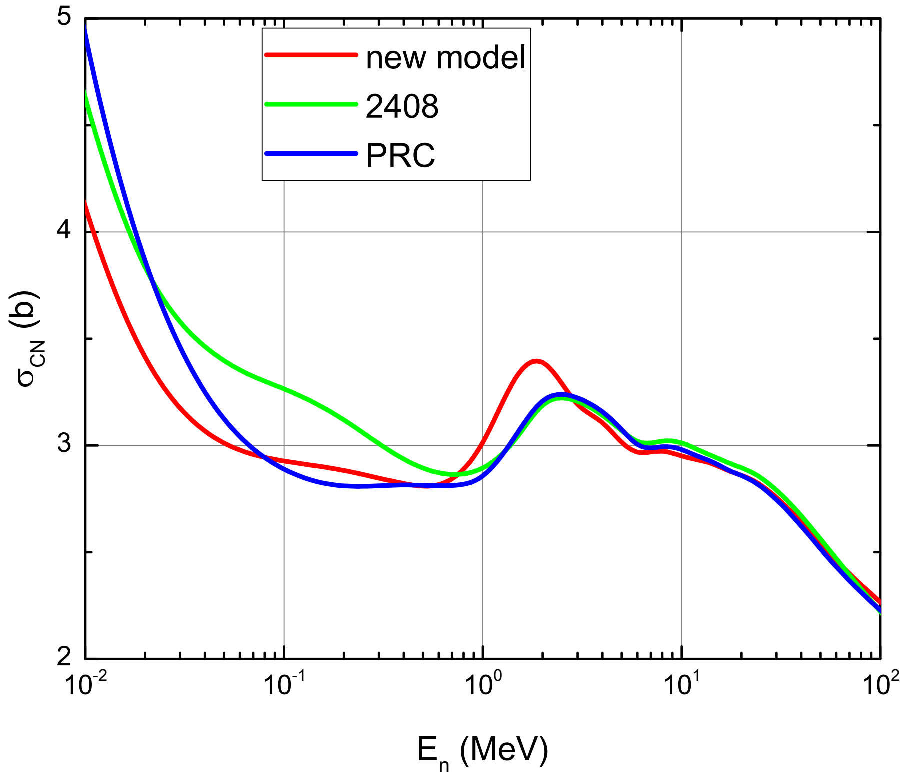
Comparison with other potentials

CN XS changes up to 0.3 barn between models fitted to the same data

^{238}U



^{233}U



Softness effects

- Multiband coupling (for bands, corresponding to collective excitations)

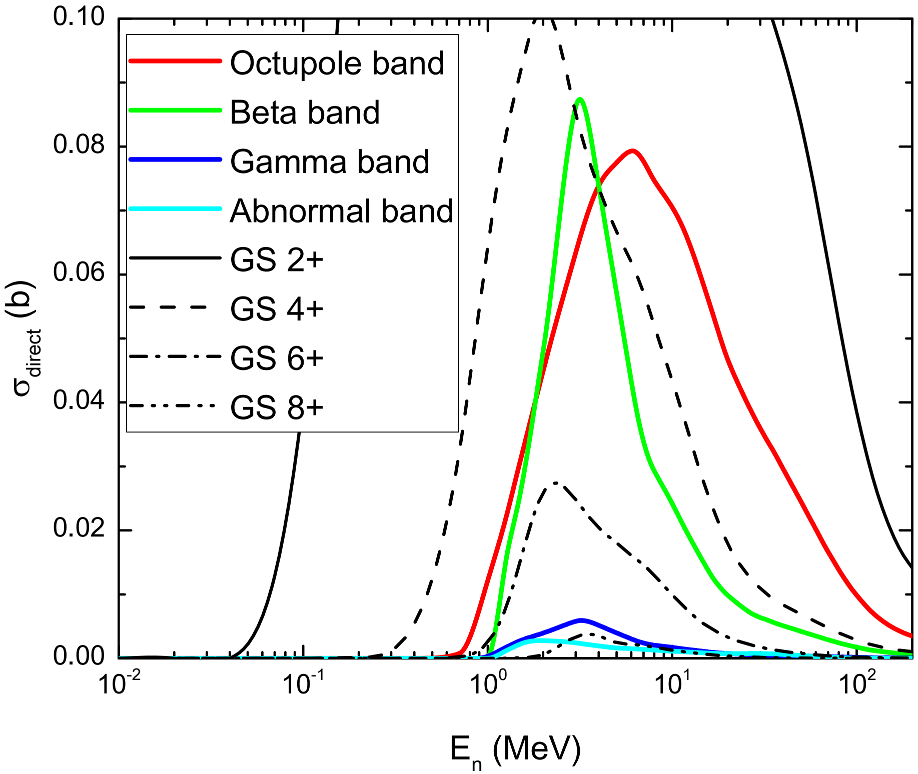
- Nucleus stretching due to rotation (centrifugal forces)

- Additional monopole coupling due to account of volume conservation in vibrating nucleus

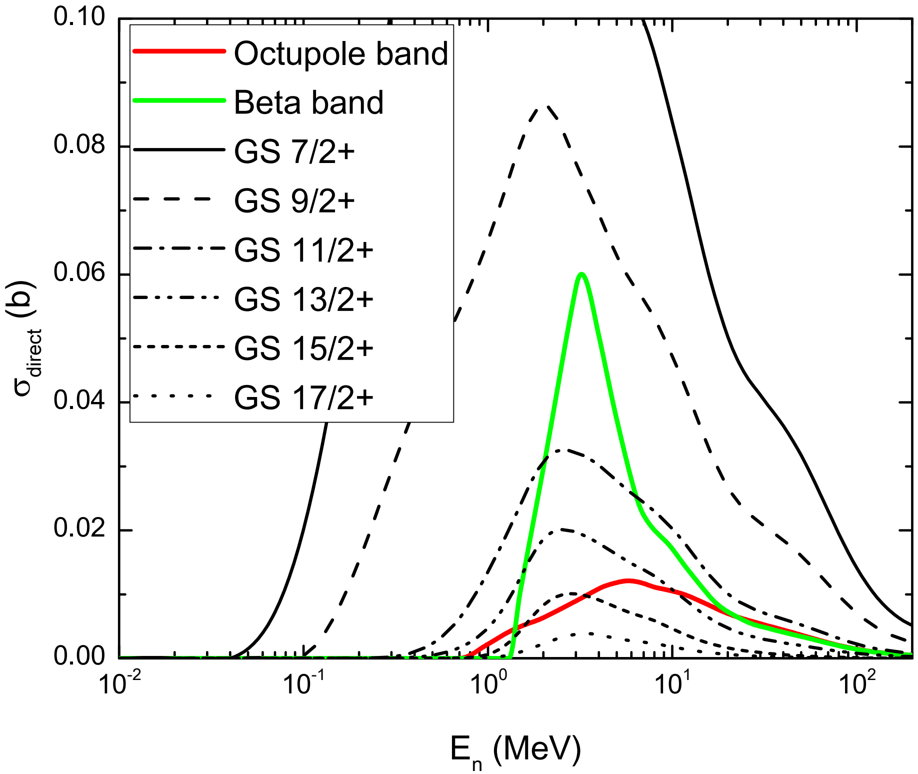
Multiband coupling 1: Direct level excitation XS

Other bands' impact is comparable to one from 2nd/3rd excited GS band level

^{238}U



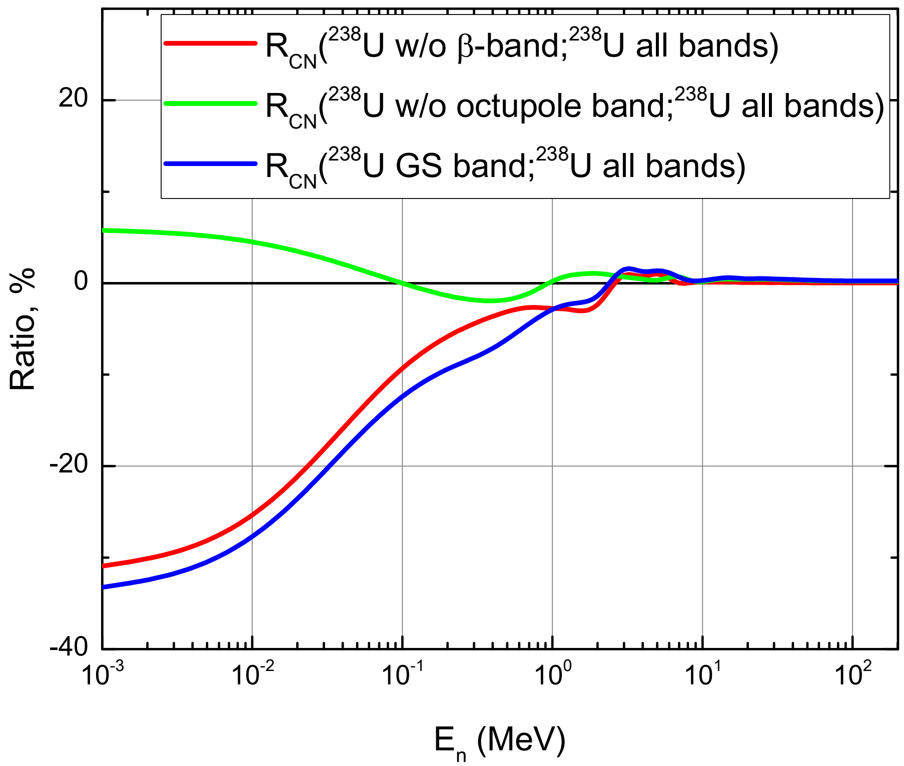
^{233}U



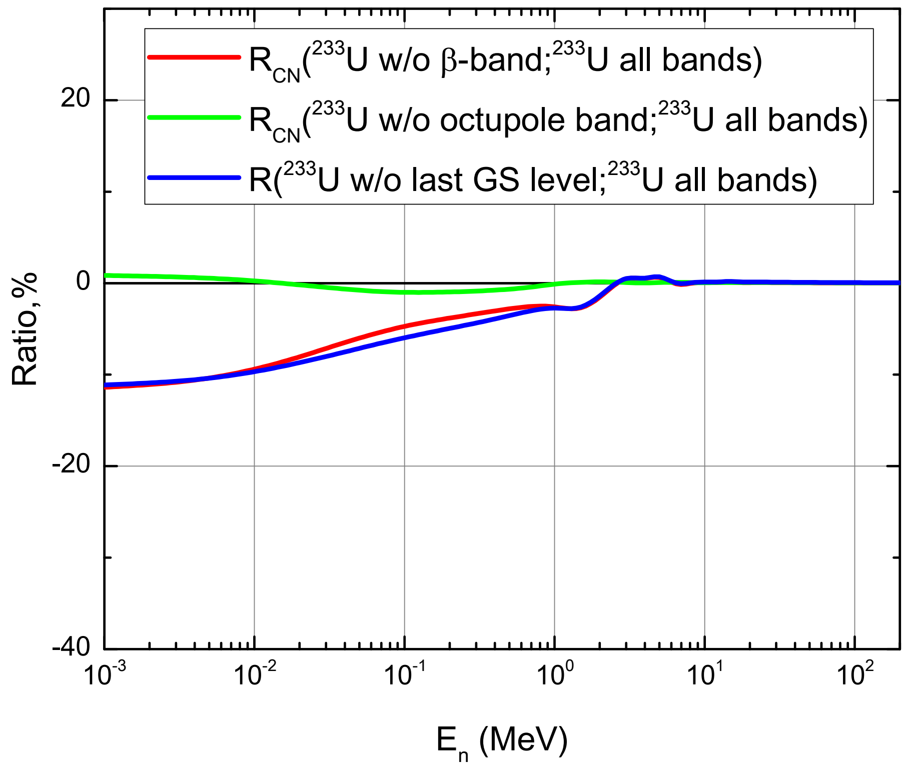
Multiband coupling 2:
CN XS change due to bands removal

Large impact of β-vibrational states in the coupling scheme

^{238}U

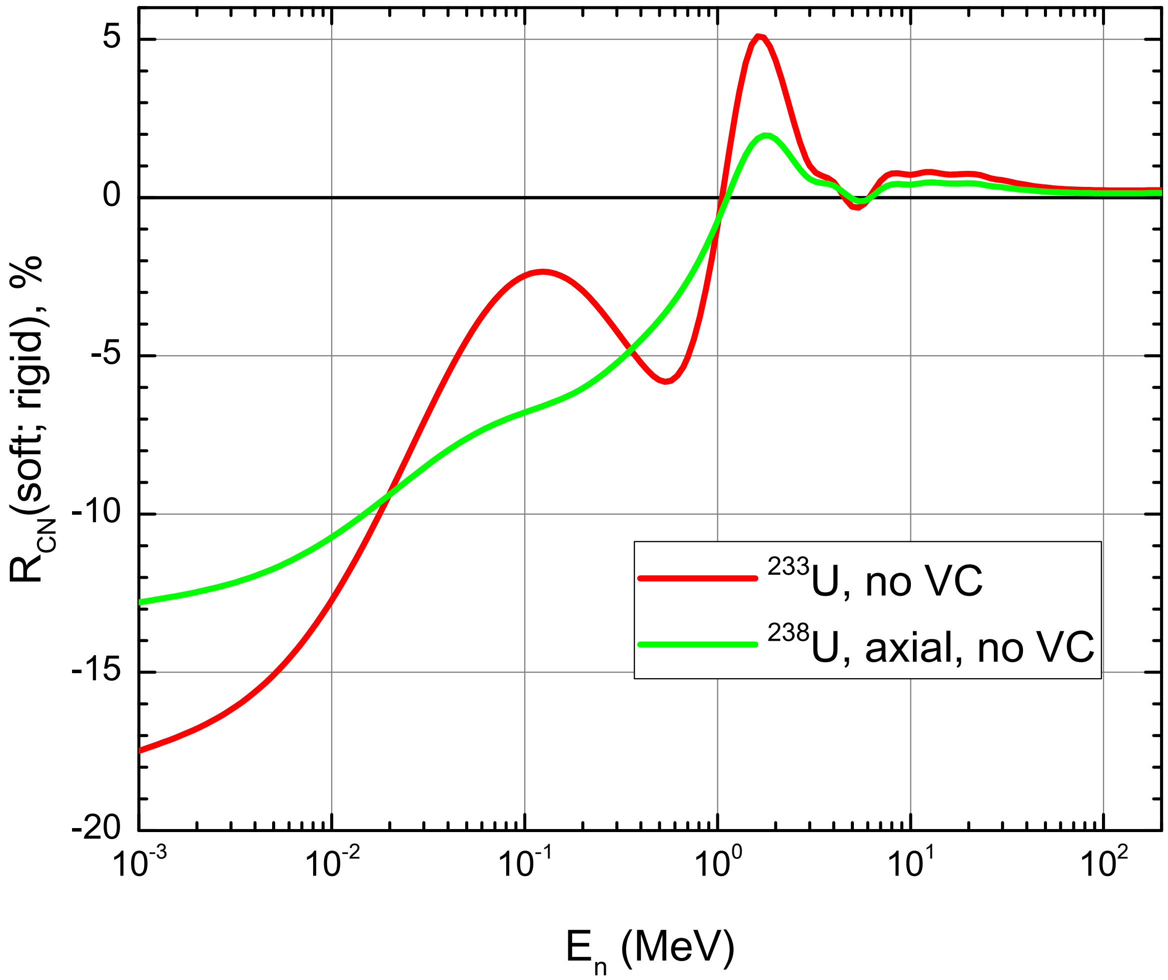


^{233}U



Nucleus stretching: CN XS change

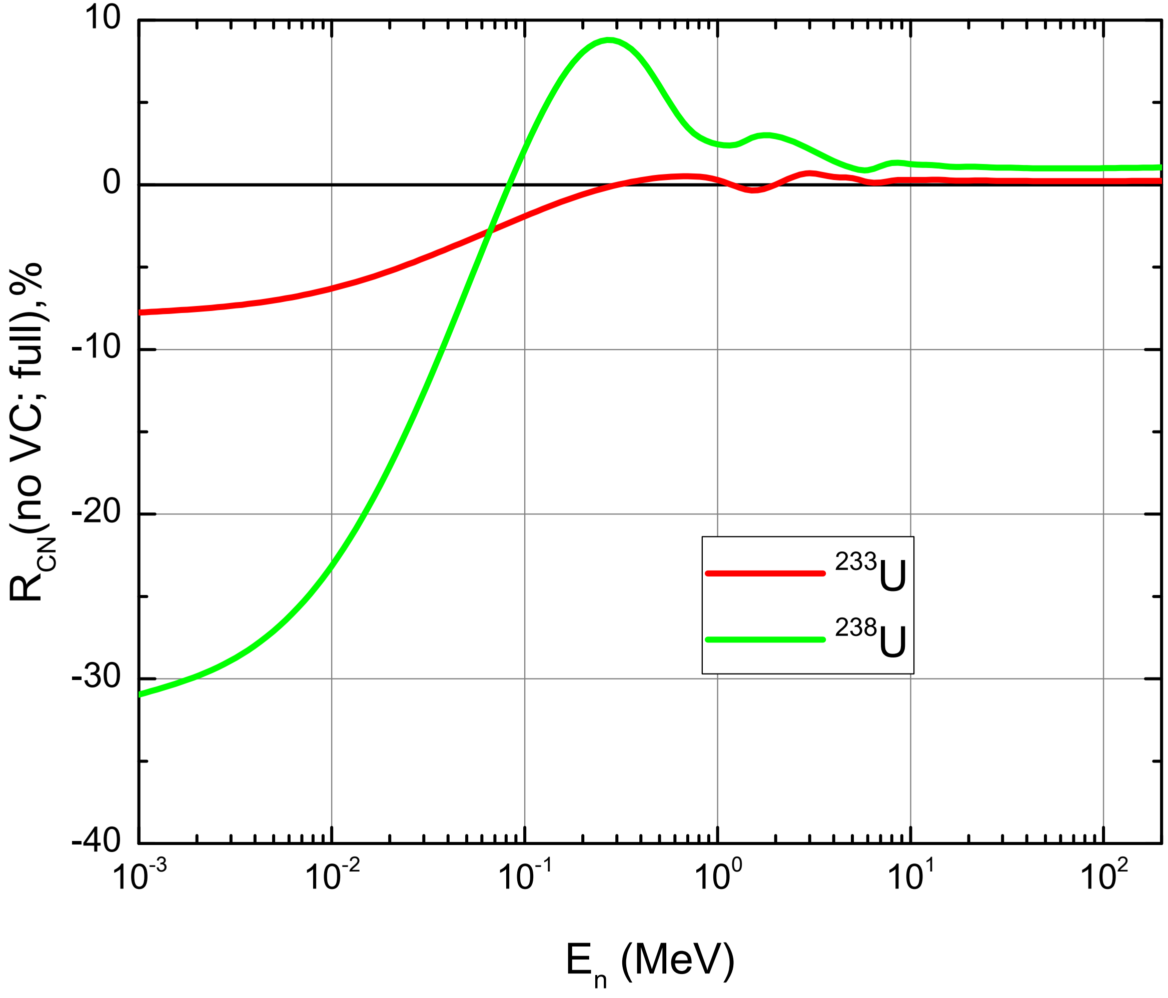
Nucleus stretching gives large impact even then only GS-band levels are coupled



Only GS band is coupled here, no non-axiality or volume conservation is accounted

Volume conservation: CN XS change

Volume conservation effect is also important but static deformations also contribute here



Summary

- Dispersive Lane-consistent coupled channels optical model is taken as a base
- Softness and multiband coupling are important to reach accurate CCOM calculations results for both even-even and odd-A nuclides
- We can build and use fully functional regional OMP for actinides, both even-even and odd!

Software

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

- optical model code **OPTMAN** (optical potential fitting, cross-section calculations) with dispersive corrections as discussed with Quesada, Capote, Chiba et al.
- nuclear structure code **SHEMMAN** (soft-rotator model parameters fitting and levels prediction)

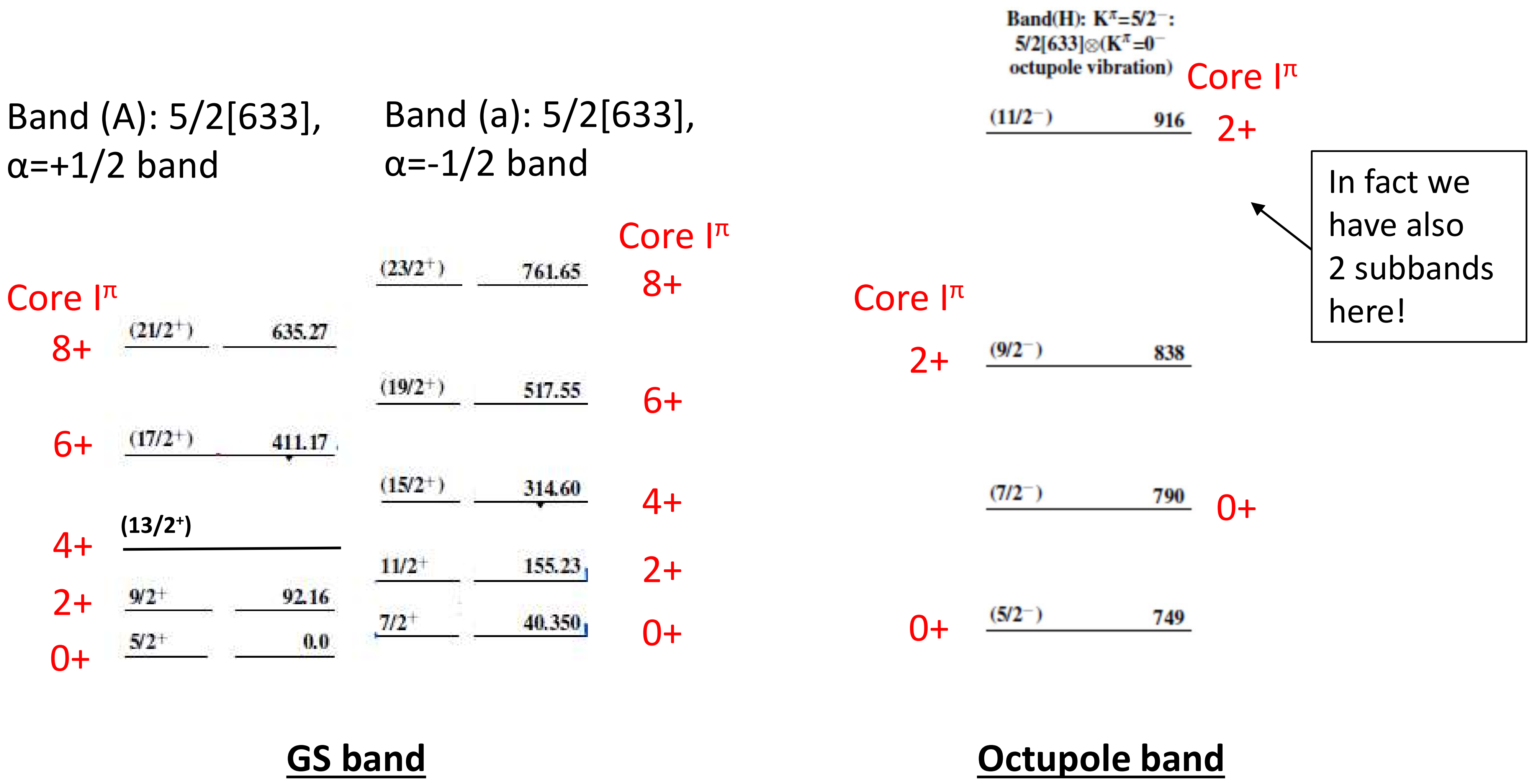
OPTMAN

- recommended to use for SRM potentials compiled in the IAEA reference input parameter library (RIPL-3) for nuclear data evaluation
- used with the EMPIRE nuclear reaction model code for basic research and nuclear data evaluation (e.g. recent Fe-56 CIELO evaluation)

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)
Dispersive corrections: Soukhovitski, E. Sh. et al, JAEA-Data/Code--2008-025 (2008)
Soft description of Fe56: W. Sun et al, Nucl. Data Sheets 118, 191-194 (2014)

Thank you for your attention!

Core states assignment (^{233}U states from ENSDF)



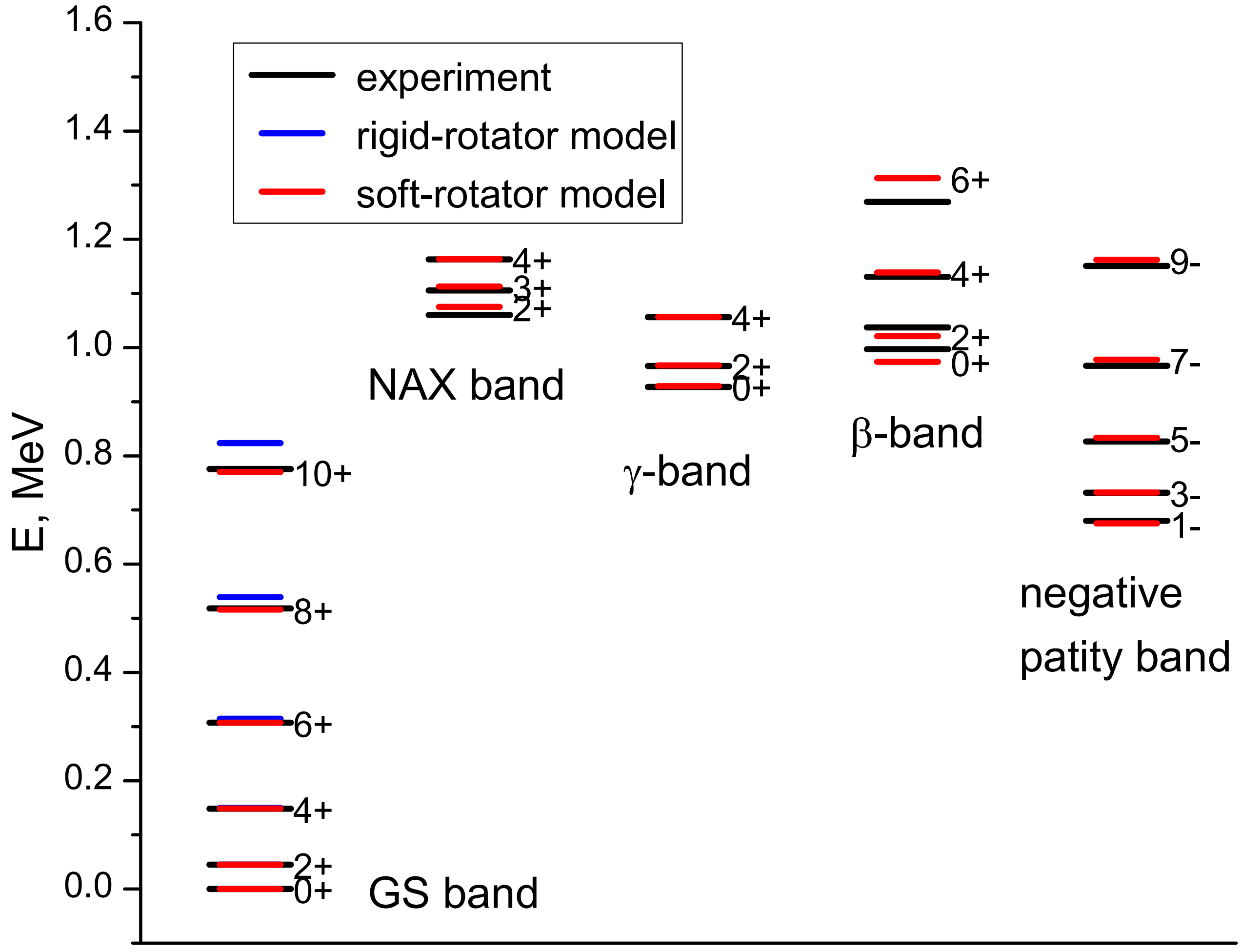
Core state: no vibrational excitation, only rotation

Core state: first octupole excitation, rotation

Is softness important?

GS band levels energies deviate from rigid rotor level sequence for high spins due to nuclear stretching form centrifugal forces.
Soft-rotor model describes experimental energies and other bands as well.

^{238}U



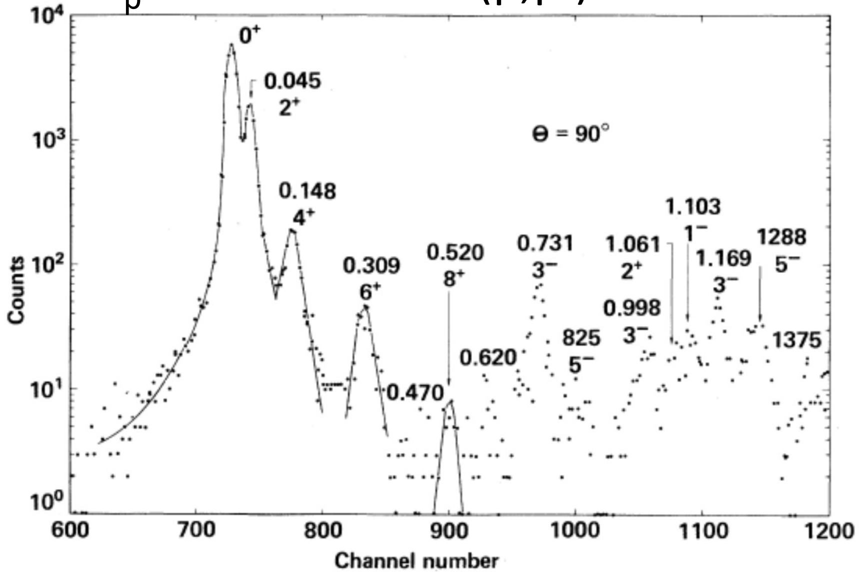
Are other bands important?

No nucleon scattering data for other-than-GS band in EXFOR for actinides

…

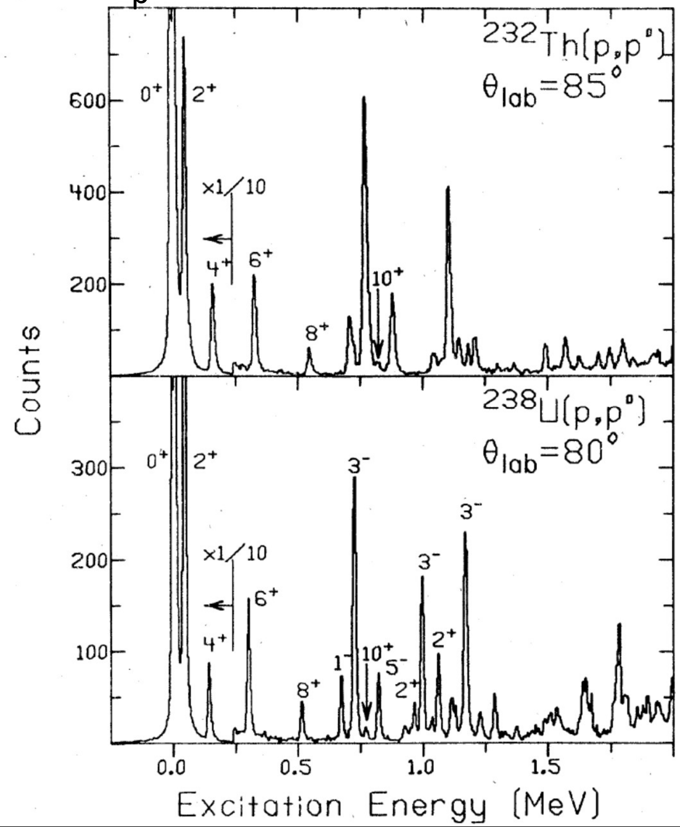
but there are clear evidences of levels from **other bands** in some proton inelastic scattering experimental works

E_p=26 MeV ^{238}U(p,p’)



L. F. Hansen et al, PRC 25 (1982) 189

E_p=35 MeV



C. H. King et al, PRC 20 (1979) 2084

Outline

- Optical model and coupled channels basics
- Dispersion relations
- Lane consistency
- Multiband coupling
- SRM for “effective” deformations
- Odd-A approach
- Regional potential for actinides

Approaches 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)
- Ambiguous description for nuclides with poor experimental data
- No additional knowledge needed

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

Direct calculation

- Nuclear structure model for soft deformed nuclei is needed
- More consistent result
- Gives all model effects

For even-even nuclides using SRM:

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

Recent dispersive OMP development

Dispersive Lane-consistent OMP for deformed nuclei (actinides):

- **2008** – rigid rotor regional potential (RIPL 2408)
- **2015** – parametric multiband coupling, rigid intra-band coupling; good description of even-even, but only sp-excitations were used for odd-A nuclides (PRC 2016)
- **2016** – soft rotor description of even-even nuclei (ND 2016)
- **2019** – approach to soft odd-A nuclides: collective excitation of the core, not sp-states; detailed analysis of softness effects (ND 2019)

Towards other odd-A actinides

How to evaluate many important nuclides with no identified bands built on **<u>only</u>** vibrational excitation of the core (e.g. ^{235}U)?

- Make calculation with only GS band levels coupled, but using soft model – results should be more reliable than for rigid rotor (primary calculations are done for ^{235}U and ^{239}Pu)
- Use more sophisticated nuclear structure models to identify corresponding states
- Construct these states using evaluations of the core (corresponding even-even nucleus) excitations and correct level/spin sequence for an odd-A nuclide