



Role of the tensor force in fission

Asymmetric to symmetric fission transition in neutron-deficient Thorium isotopes

R. Bernard, NP, L.M. Robledo and M. Anguiano, PRC 101, 044615 (2020)

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- I. New fission experimental data @ SOFIA
- II. Asymmetric to symmetric transition in Thoriums: Microscopic analysis
- III. Static evaluation of TKE, TXE and neutron multiplicity
- IV. Conclusions and perspectives

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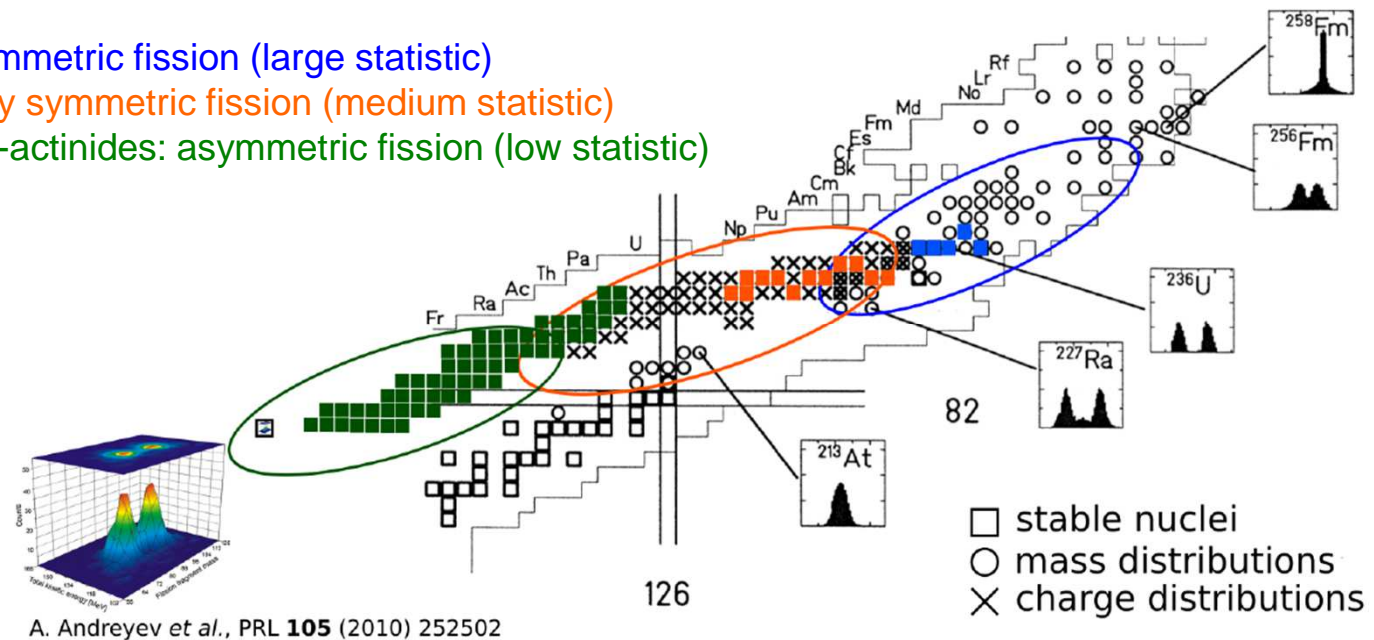
2012 campaign

Complete the **charge** distribution from K.-H. Schmidt *et al.* with the **mass** distribution and **prompt-neutron multiplicity**

⇒ **Characterization of the scission point (deformation)**

SOFIA experiment:

- Heavy actinides: asymmetric fission (large statistic)
- Light actinides: mainly symmetric fission (medium statistic)
- Neutron-deficient pre-actinides: asymmetric fission (low statistic)



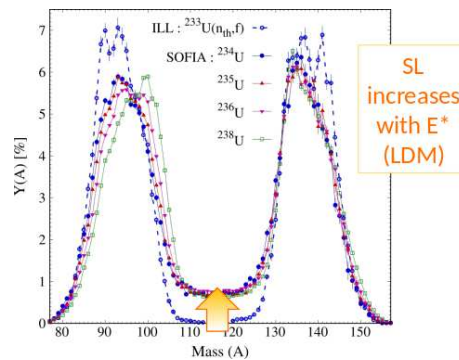
K.-H. Schmidt *et al.*, NPA **665** (2000) 221

2021 campaign

New data focussed on neutron-deficient pre-actinides with a much larger statistic (not yet published)

▪ Charge yields and mean prompt-neutron multiplicity in neutron-deficient Thoriums

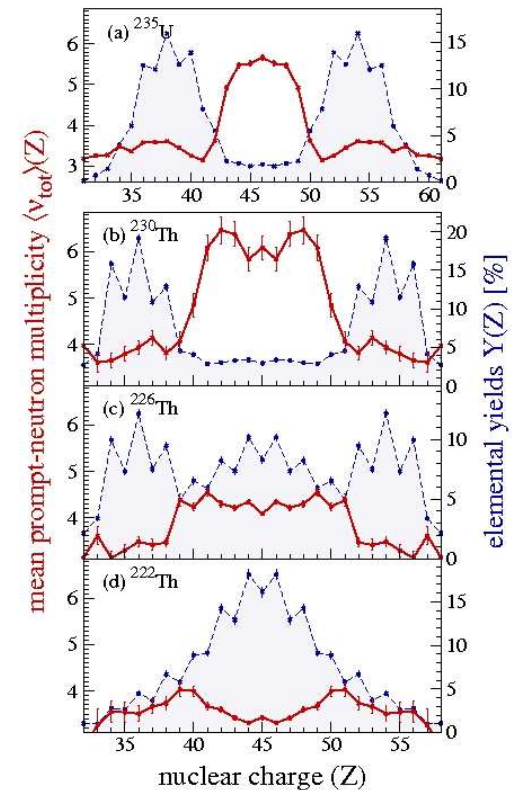
In actinides, asymmetric fission driven by shell effects in heavy fragments



- asymmetric mode: compact, strong TKE, low neutron multiplicity
- symmetric mode: elongated, low TKE, strong neutron multiplicity

Observation of a NEW symmetric compact fission mode in Thoriums

- ^{230}Th isotope: Same behaviour as ^{236}U isotope
- Symmetric fission more and more favoured in the lighter Thoriums
- Prompt neutron multiplicity $\langle v_{\text{tot}} \rangle$ drops at symmetry : Effect of 2.5 neutrons, Difference in $E_{\text{int,FF}} \sim 20\text{MeV}$!
- Drop of $\langle v_{\text{tot}} \rangle$ signs a lower E_{FF} , thus a low Q_{20} deformation



A. Chatillon et al., PRL 124, 202502 (2020)

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- HFB method under particle numbers and deformation constraints

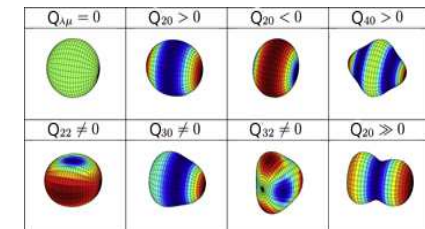
- D1ST2a Gogny interaction

$$V_{12}(\rho) = \sum_{j=1}^2 (W_j + B_j P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau) e^{-\frac{(\mathbf{r}_1 - \mathbf{r}_2)^2}{\mu_j^2}}$$

$$+ t_3 (1 + x_0 P_\sigma) \delta(\mathbf{r}_1 - \mathbf{r}_2) \rho^\alpha \left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right)$$

$$+ i W_{LS} \overleftarrow{\nabla}_{12} \delta(\mathbf{r}_1 - \mathbf{r}_2) \wedge \overrightarrow{\nabla}_{12} (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)$$

$$+ (V_{T1} + V_{T2} P_{12}^\tau) \left[3 \frac{(\vec{\sigma}_1 \cdot \vec{r}_{12})(\vec{\sigma}_2 \cdot \vec{r}_{12})}{|\vec{r}_{12}|^2} - \vec{\sigma}_1 \cdot \vec{\sigma}_2 \right] e^{-(\vec{r}_{12})^2 / \mu_T^2}$$



D1S

Tensor

Determination of V_{T1} , V_{T2} and μ_T

- $1f_{7/2} - 1f_{5/2}$ neutron spin-orbit splitting in ^{48}Ca
- Energy of the first 0^- state in ^{16}O

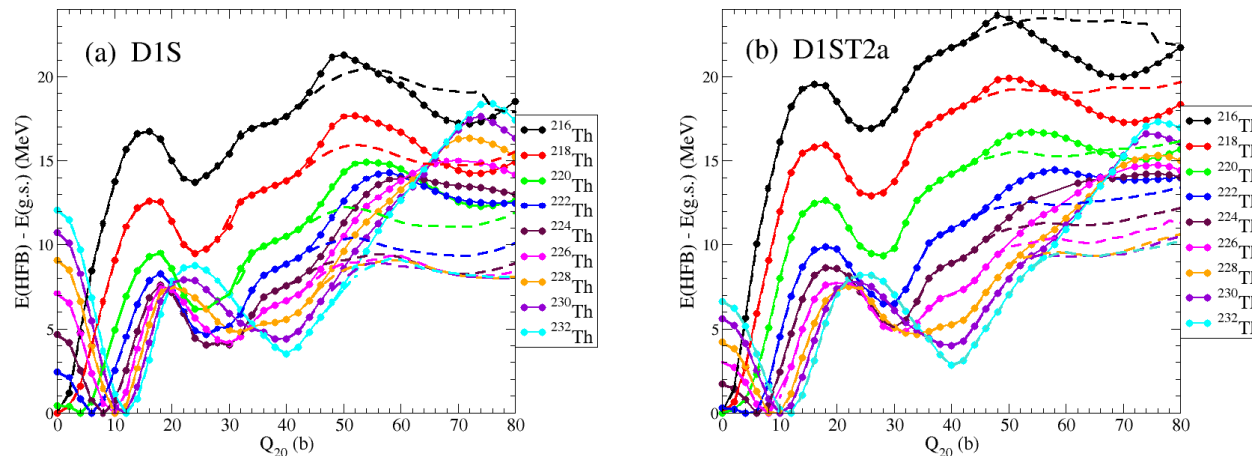
Attractivity / repulsivity of the tensor term

Values of the parameters:

$$V_{T1} = -135\text{MeV} \quad V_{T2} = +115\text{MeV} \quad \mu_T = 1.2\text{fm}$$

- $V_{pn} = 2V_{T2} = +230\text{MeV}$ is repulsive
- $V_{nn} = V_{pp} = V_{T1} - V_{T2} = -20\text{MeV}$ is attractive

- Deformation properties up to the second symmetric/asymmetric barriers in $^{232-216}\text{Th}$ isotopes using $\{Q_{20}, Q_{30}\}$ as collective variables



Symmetric path: Full line
Asymmetric path: Dashed line

With the tensor term :

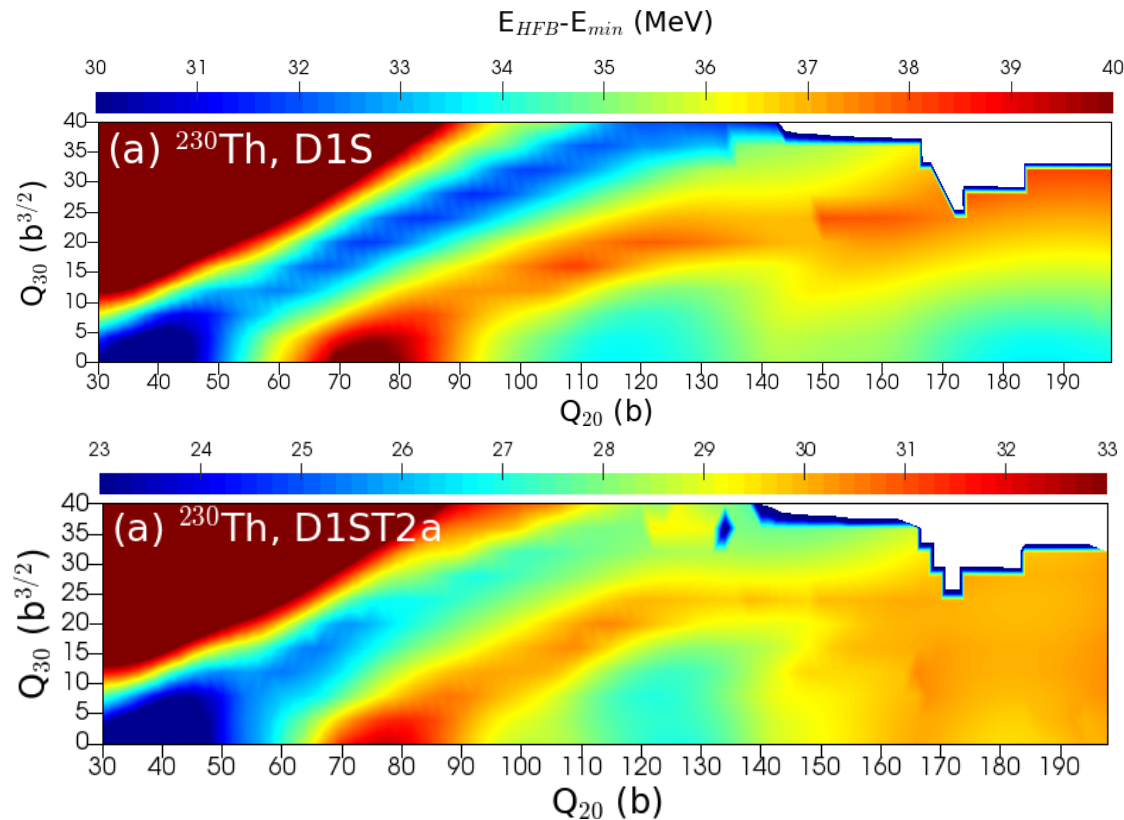
- Strong decreasing of the spherical barrier height in all even-even isotopes
- Rebalancing of the symmetric/asymmetric second barrier heights

In ^{222}Th , $\Delta E(\text{sym/asym}) \approx 4.5\text{MeV}$ with D1S $\rightarrow \Delta E(\text{sym/asym}) \approx 2.0\text{MeV}$ with D1ST2a

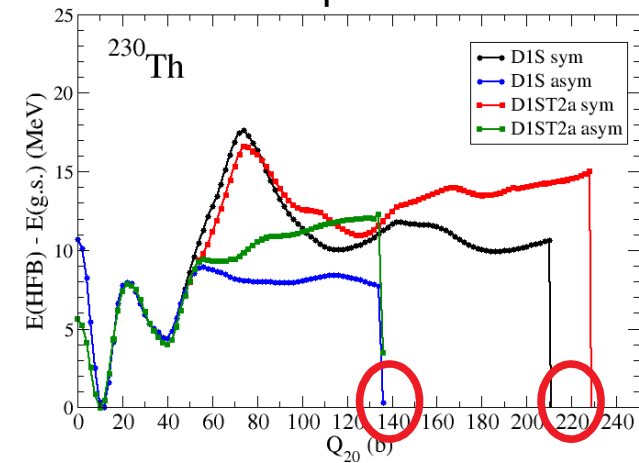
In ^{216}Th , $\Delta E(\text{sym/asym}) \approx 1.5\text{MeV}$ with D1S $\rightarrow \Delta E(\text{sym/asym}) \approx 0.0\text{MeV}$ with D1ST2a

The tensor term tends to favour the symmetric path in light Thorium isotopes

II. Analysis of the asymmetric to symmetric transition in Thoriums

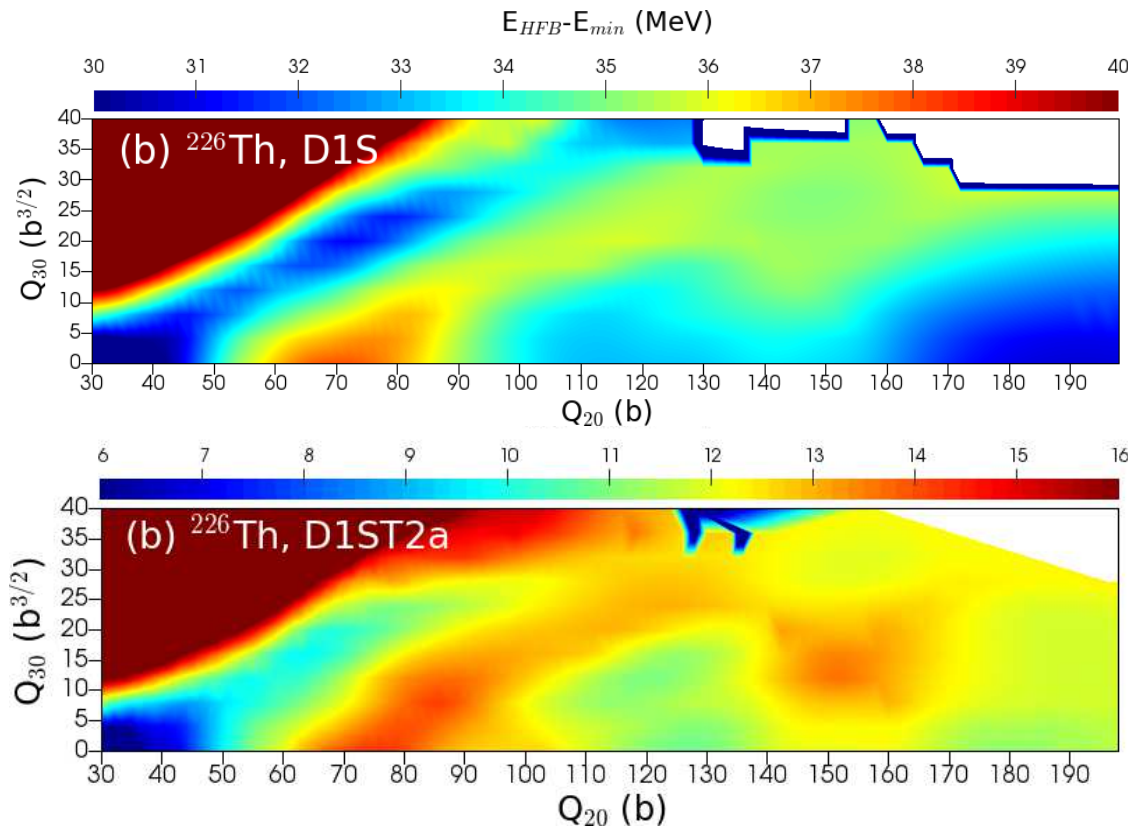


Symmetric and asymmetric
1D paths

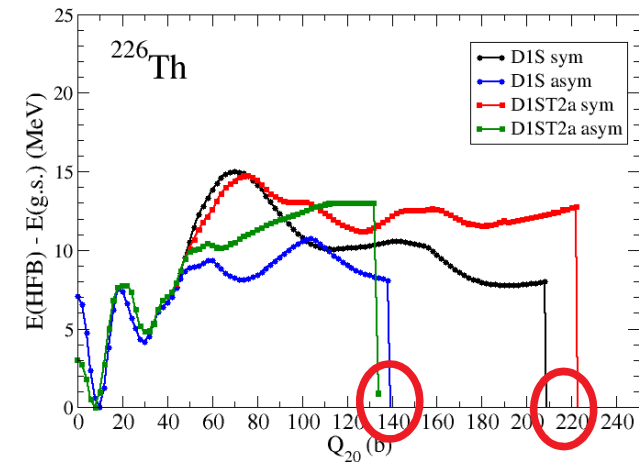


- Asymmetric fission favoured with both D1S and D1ST2a
- Heights of the second humps little modified
- Symmetric fission longer with D1ST2a

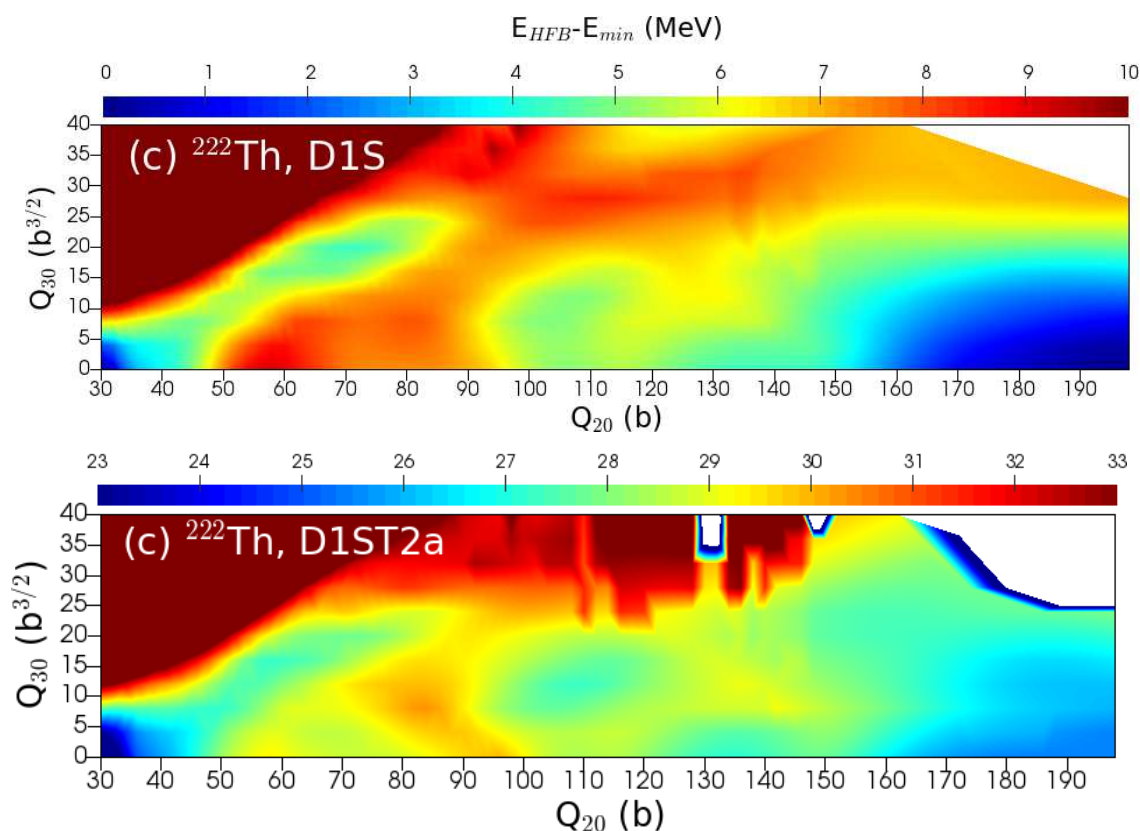
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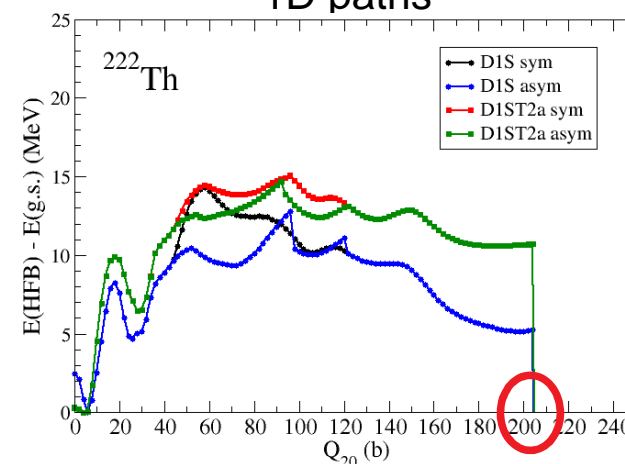
Symmetric and asymmetric 1D paths



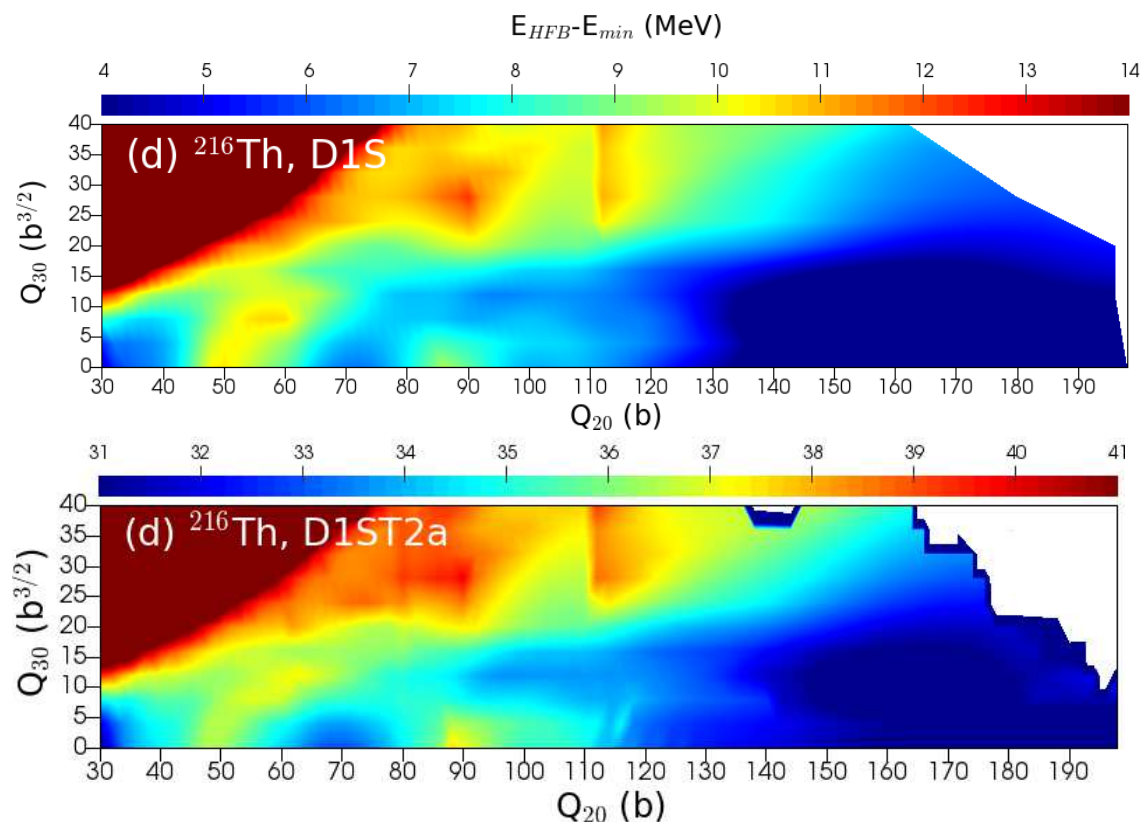
- Asymmetric fission still favoured with both D1S and D1ST2a
- Starting of the rebalancing of symmetric and asymmetric barriers with D1ST2a
- Symmetric fission still longer with D1ST2a



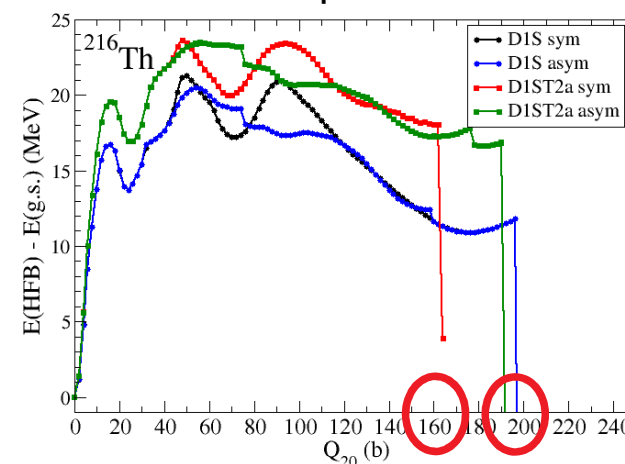
Symmetric and asymmetric 1D paths



- The asymmetric path clogs with both D1S and D1ST2a
- Lowest energy path: a mixed path
- Strong rebalancing between the symmetric and the asymmetric barriers with D1ST2a (difference: 4.5MeV with D1S and 1.5MeV with D1ST2a)



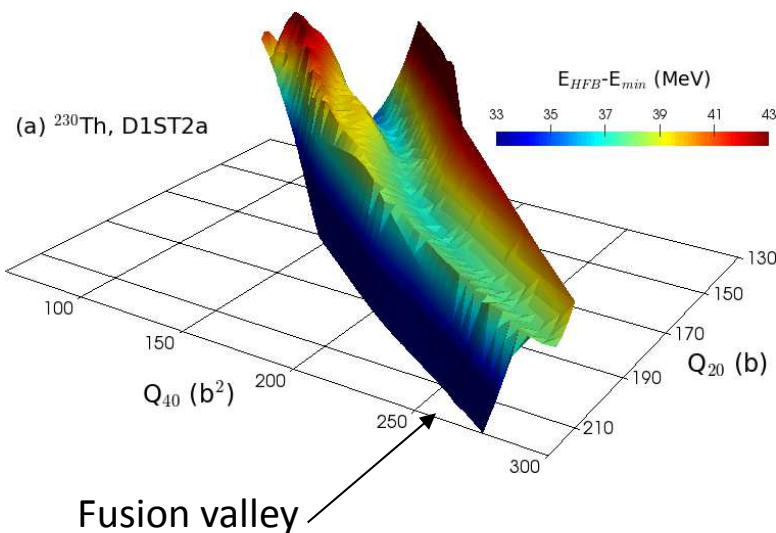
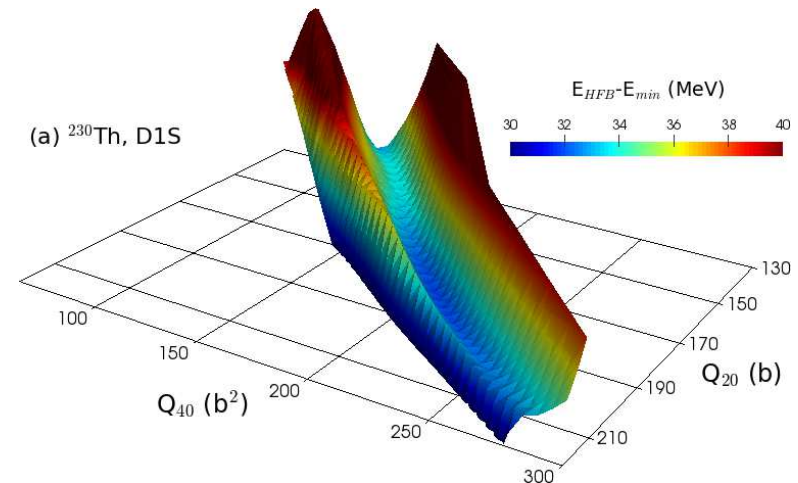
Symmetric and asymmetric 1D paths



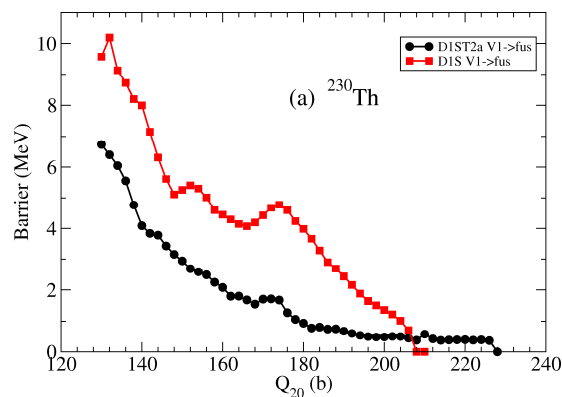
- Mixed path slightly favoured with D1S
- Similar symmetric and mixed barrier heights with D1ST2a
- Appearance of a compact symmetric fission with D1ST2a

Role of the Q_{40} collective variable in the symmetric fission?

- Symmetric compact scission and tensor term effect – Role of the multipole Q_{40}

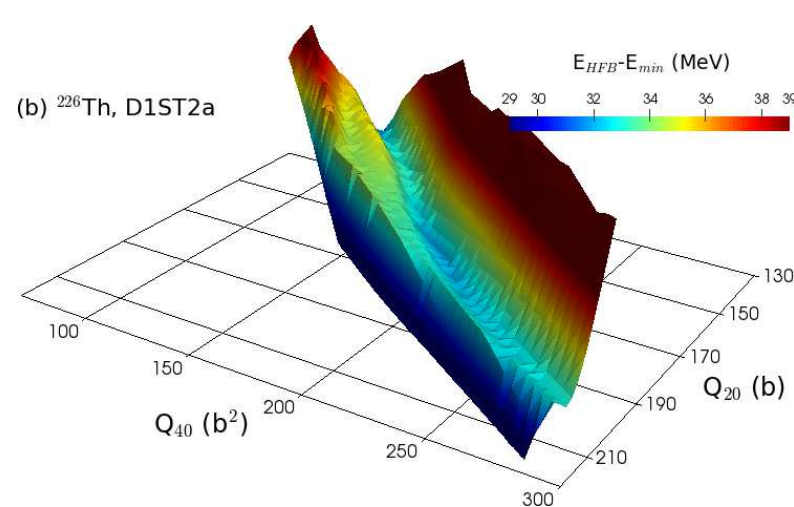
 ^{230}Th 

Transverse barrier heights

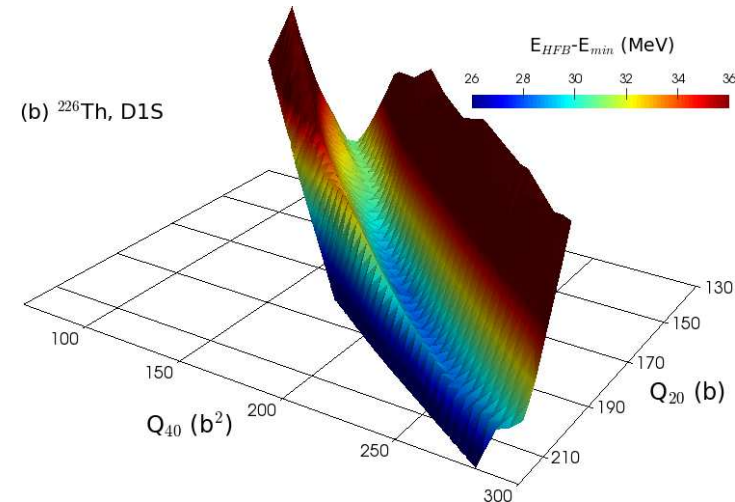


- Existence of a principal valley V1 for both D1S and D1ST2a
- Existence of a plateau with D1ST2a
- Noticeable decrease of the transverse barrier « V1 → fusion » with D1ST2a

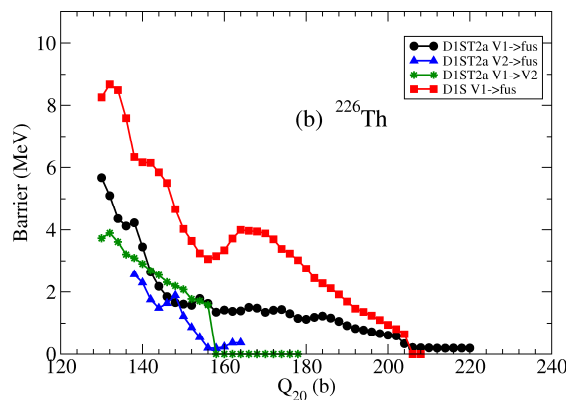
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^{226}Th



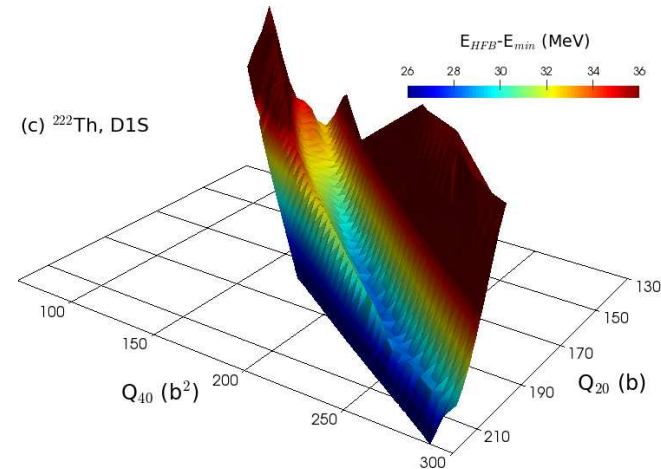
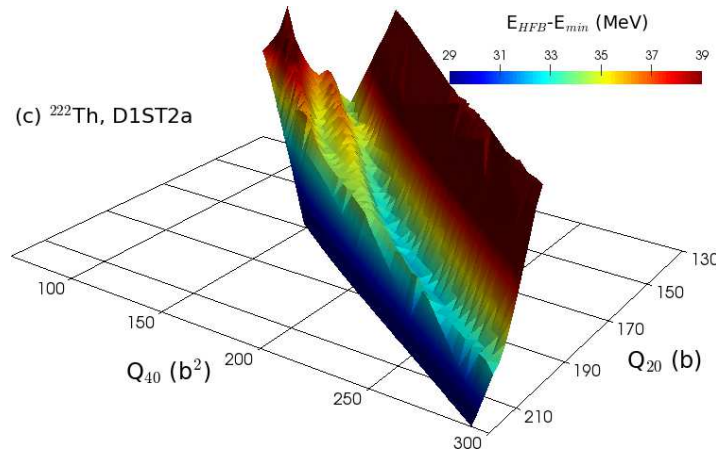
Transverse barrier heights



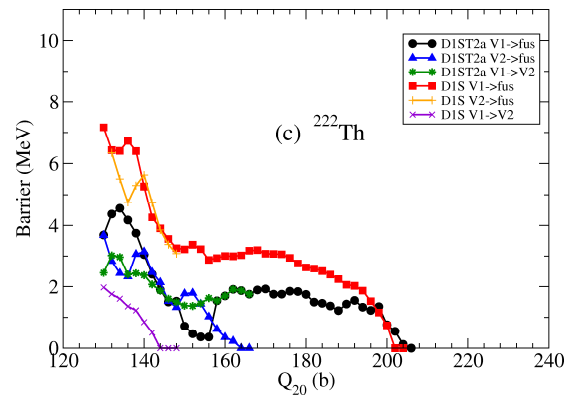
- Existence of a principal valley V1 for both D1S and D1ST2a
- The plateau digs and generates a proto-valley V2 with D1ST2a, located at higher energy [*Cold fission: possible populating by excitation of transverse mode (compatible barrier height in J.-F. Berger et al., Nucl. Phys. A (1989)) * Direct populating of the proto-valley possible with the excitation energy of the fissioning system (SOFIA: ~14MeV)]
- Barrier height « V1 → fusion » still lower with D1ST2a
- The proto-valley V2 leads to a compact fission

II. Analysis of the asymmetric to symmetric transition in Thoriums

^{222}Th



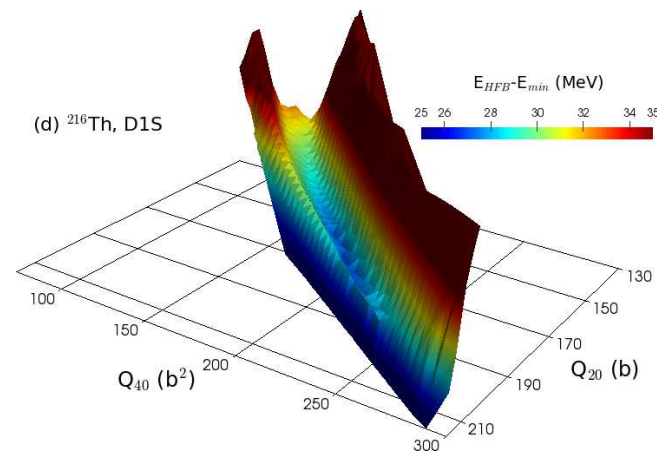
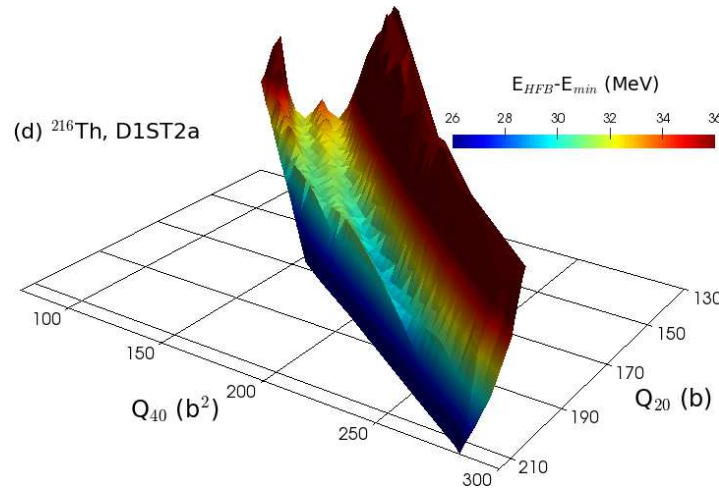
Transverse barrier heights



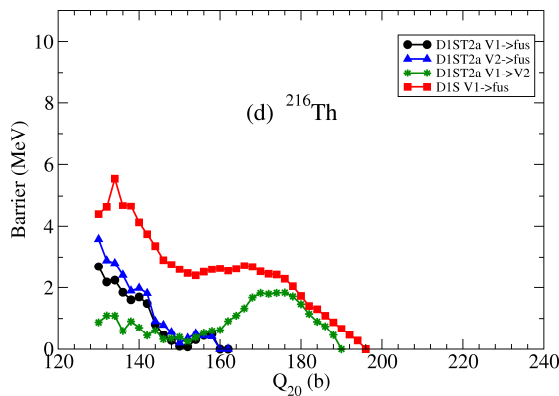
- Existence of a principal valley V1 for both D1S and D1ST2a
- The proto-valley V2 transforms into a genuine secondary valley, still higher in energy than the V1 but more competitive
- Same populating scenarii than those evoked in ^{226}Th
- Barrier height « V1 → fusion » still lower with D1ST2a
- The valley V2 leads to a compact fission

II. Analysis of the asymmetric to symmetric transition in Thoriums

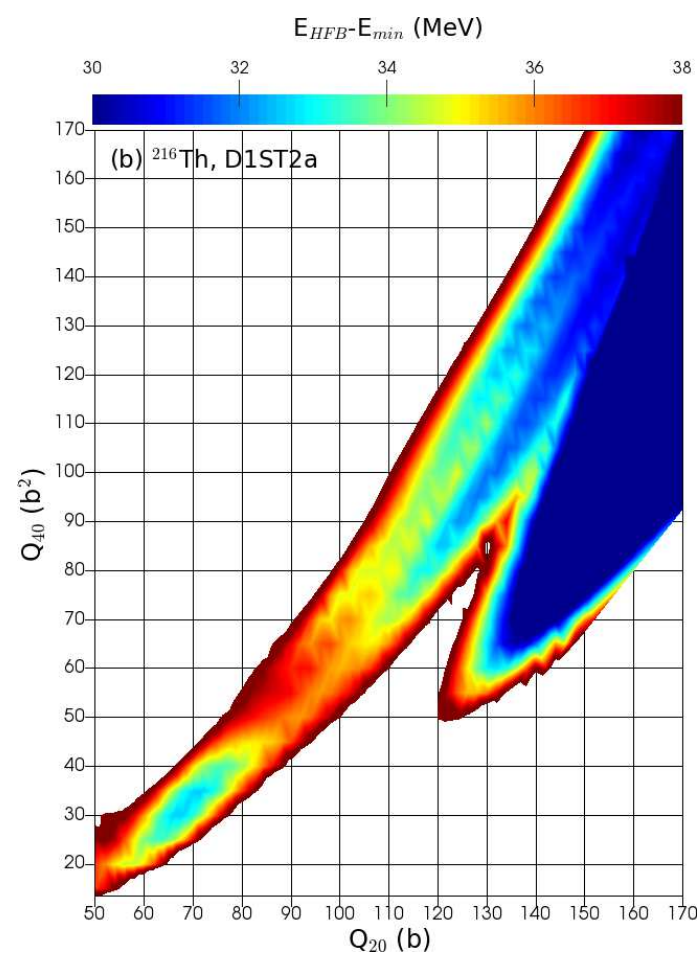
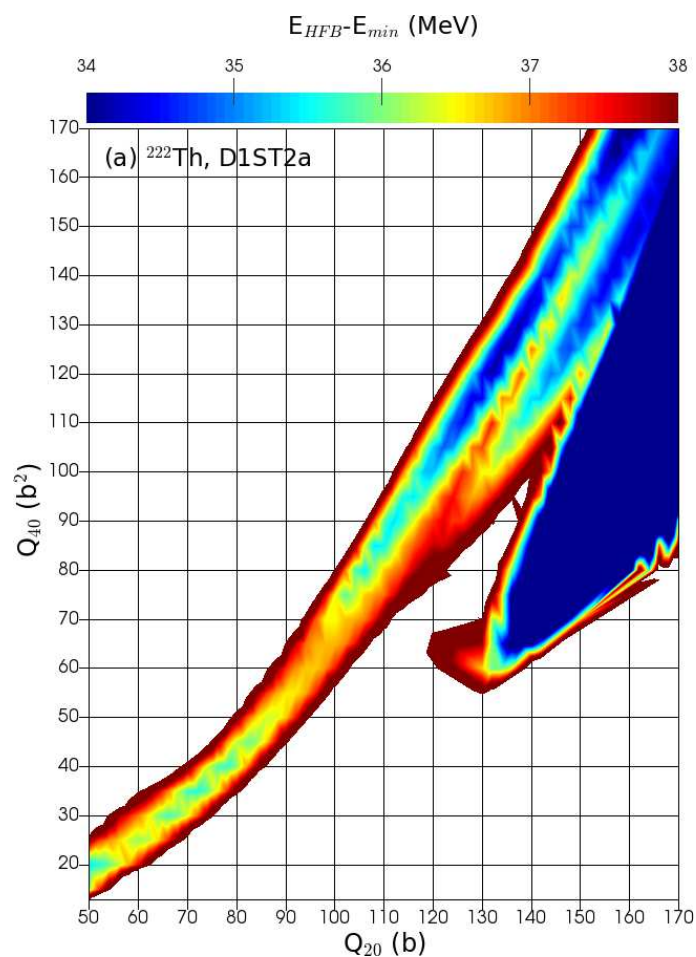
^{216}Th



Transverse barrier heights



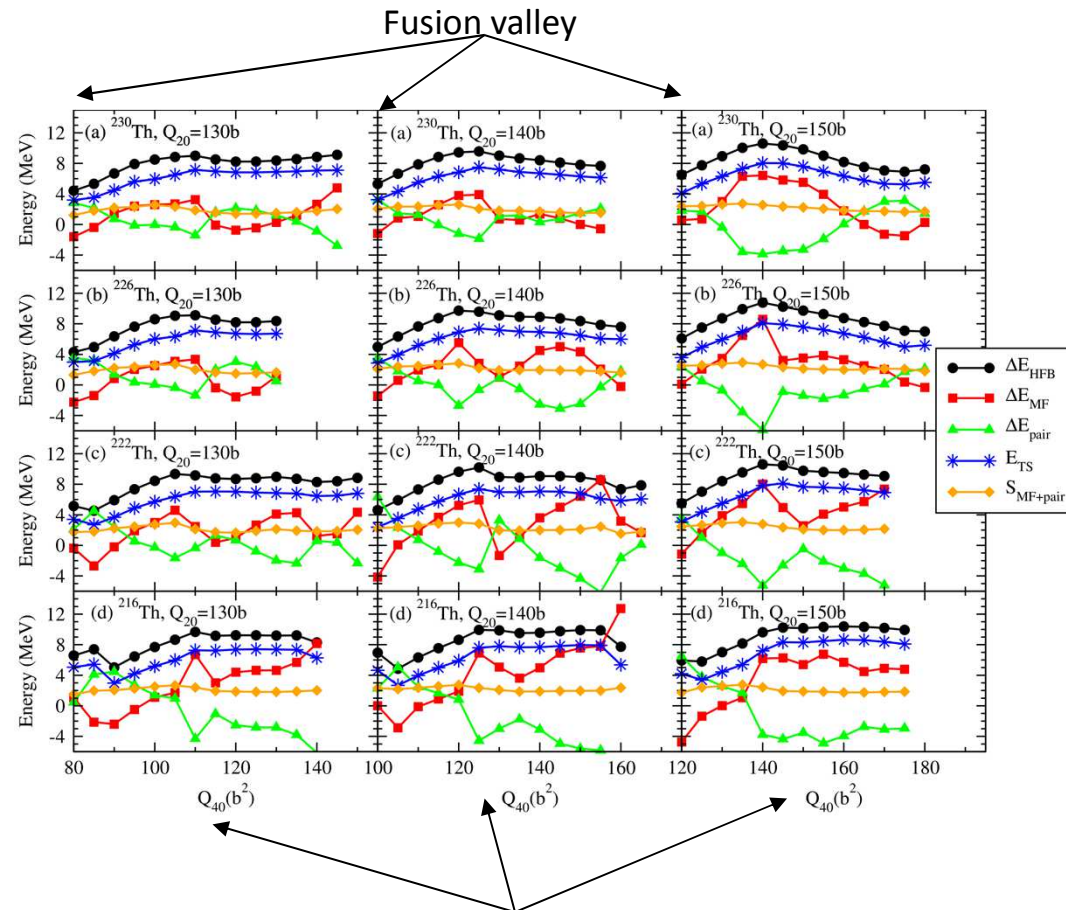
- Existence of a principal valley V1 only for D1S
- The secondary valley V2 becomes the principal valley for D1ST2a, the lowest in energy
- Same populating scenarios than those evoked in ^{226}Th
- Barrier height « V1 → fusion » still lower with D1ST2a
- The valley V2 leads to a compact fission already observed in the previous 1D analysis.

Nascent valleys in ^{222}Th and ^{216}Th 

II. Analysis of the asymmetric to symmetric transition in Thoriums

Analysis of the total HFB energy $E_{\text{HFB}} = E_{\text{MF}} + E_{\text{pair}} (+ E_{\text{TS}})$

$$\Delta E_{\text{HFB}} = E_{\text{HFB}}(\text{D1ST2a}) - E_{\text{HFB}}(\text{D1S}) = \Delta E_{\text{MF}} + \Delta E_{\text{pair}} + E_{\text{TS}}$$

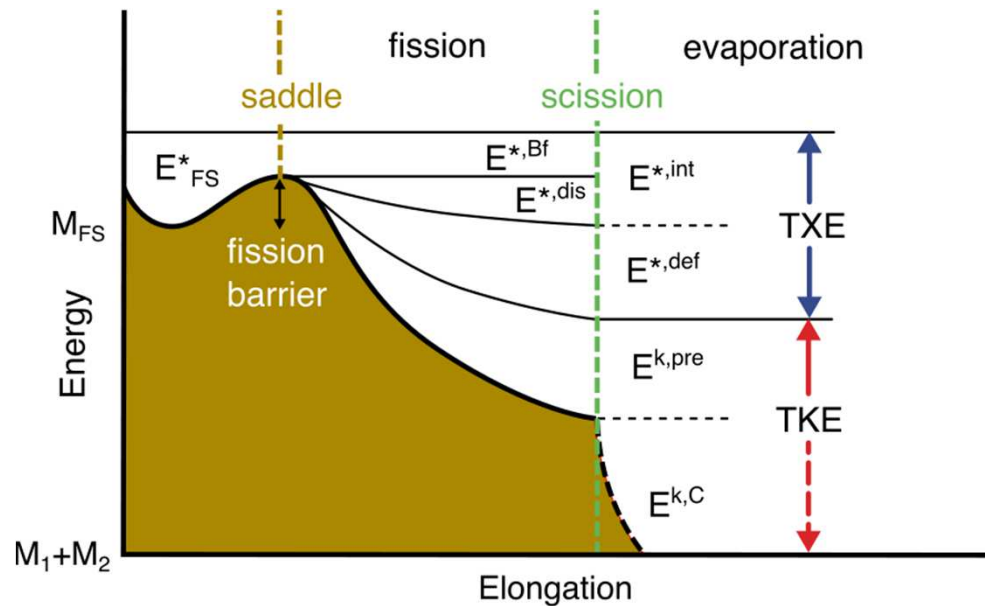


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- **Distribution of the available energy:**

$$E^* = \text{Kinetic energy} + \text{Excitation energy}$$

$$= \text{TKE} + \text{TXE}$$

$$= E^{k,c} + E^{k,pre} + E^{def} + E^{int}$$

- **Experimental measurements :**

$$E^* = \text{TKE} + E_n + E_\gamma$$

- **In our microscopic evaluation, we stand at the barrier :**

- $E^* = E_{HFB}(\text{saddle}) - E_{HFB}(\text{g.s., fragments})$
- $E^{k,c}$ = Coulomb energy
- $E^{def} = E_{HFB}(\text{scission, fragments}) - E_{HFB}(\text{g.s., fragments})$

- **Intrinsic energy of the fragments (need of a non-adiabatic approach !):**

- Microscopic calculation with 2QP excitations (R. Bernard et al., PRC 2011, PhD thesis of P. Carpentier)
- Three phenomenological scenarios
 1. First limit case: $E^{int} = 0 \text{ MeV}$
 2. Usual empirical formula: $E^{int} = 35\% \text{ TXE}$
 3. Second limit case: $E^{k,pre} = 0 \text{ MeV}$

III. Static evaluation of the TKE, TXE and neutron multiplicity

Nucleus	Valley	TKE ₁	TKE ₂	TKE ₃	E _{coul}	TXE ₁	TXE ₂	TXE ₃	E _{def}	ν_1	ν_2	ν_3
²³⁰ Th	1	178.7	170.4	157.8	157.8	15.4	23.6	36.3	15.4	~1	1	2
²²⁶ Th	1	178.0	170.3	157.2	157.2	14.2	21.9	35.0	14.2	0	1	2
²²² Th	1	177.0	169.1	156.5	156.5	14.8	22.8	35.3	14.8	0	1	2
²¹⁶ Th	1	182.3	177.8	157.2	157.2	8.2	12.6	33.3	8.2	0	0	1
D1S, Symmetric path												

To be noticed:

- ν : neutron number by fragment

- S_n for odd and odd-odd fragments calculated at the HFB level with the EF approximation

- Neutron kinetic energy evaluated with GEF

Nucleus	Valley	TKE ₁	TKE ₂	TKE ₃	E _{coul}	TXE ₁	TXE ₂	TXE ₃	E _{def}	ν_1	ν_2	ν_3
²³⁰ Th	1	167.7	153.2	151.3	151.3	26.8	41.3	43.2	26.8	1	2	2
²²⁶ Th	1	171.8	161.0	152.4	152.4	20.0	30.7	39.4	20.0	1	~2	2
	2	186.3	183.3	173.7	173.7	5.4	8.4	18.0	5.4	0	0	1
²²² Th	1	175.1	166.8	156.1	156.1	15.5	23.9	34.5	15.5	0	1	2
	2	187.5	185.7	171.8	171.8	3.2	4.9	18.9	3.2	0	0	1
²¹⁶ Th	1	180.0	174.7	160.8	160.8	9.8	15.1	29.0	9.8	0	~1	1
	2	187.5	186.2	172.1	172.1	2.4	3.7	17.8	2.4	0	0	1
D1ST2a, Symmetric path												

▪ SL symmetric mode (V1 valley)

- D1ST2a produces more deformation energy than D1S
- D1ST2a favours the neutron emission

▪ Compact symmetric mode (V2 valley)

- Significant increase of the TKE (in the 3 scenarii)
- Weak deformation energy
- Mode with a weak emission of neutrons
- Results strongly compatible with the SOFIA data on light Thorium isotopes

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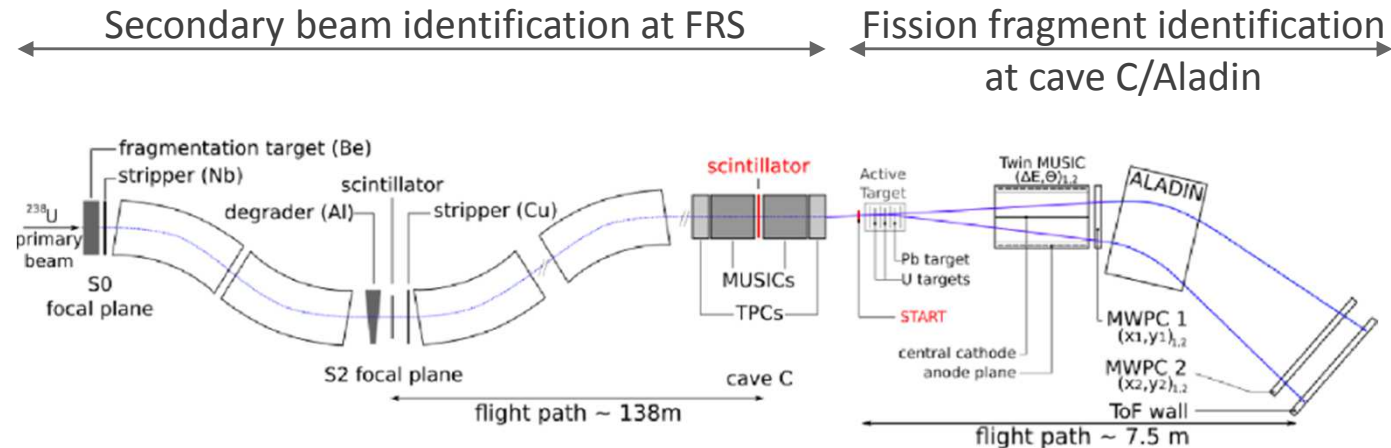
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Conclusions :

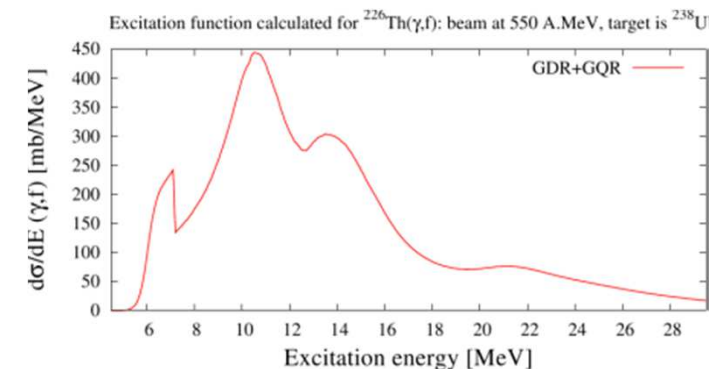
- The tensor term plays a non-negligeable effect on both symmetric and asymmetric barrier heights along the transition
- The present tensor term rebalances the symmetric and the asymmetric barrier heights along the transition
- The asymmetric to symmetric fission transition in light Thorium isotopes finds an explanation in the present analysis of the potential energy surfaces
- The present tensor term makes a « NEW » SYMMETRIC VALLEY appear in (Q_{20}, Q_{40}) collective variables which leads to a COMPACT SYMMETRIC FISSION in the light Thoriums, in agreement with experimental SOFIA data

Perspectives:

- **Dynamical study in the (Q_{20}, Q_{30}, Q_{40}) collective space**
 - Description of the asymmetric to symmetric transition
 - Populating of the SL and compact valley : mixing of modes
 - Calculation of observables (yields, neutron multiplicity...)
- **Full fit of a generalized Gogny interaction (fully finite range with a tensor term)**
 - PhD thesis of Geoffrey Zietek (2021-2023)
 - With a tensor term able to reproduce this new compact mode
 - With a global decrease of the barrier heights
 - Preserving standard properties of the Gogny interaction
- **Treatment of intrinsic excitations (2QP excitations,) allowing the description**
 - PhD thesis of Paul Carpentier (2021-2024)
 - Generalization and application of the SCIM (R. Bernard et al., PRC 2011):
Bogoliubov QP, N dimensions in the deformation space, dynamical treatment

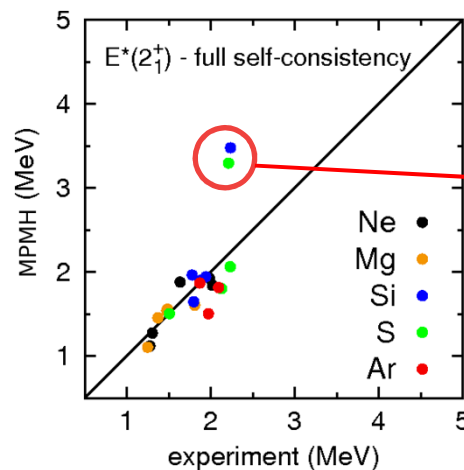


- **Method: Inverse kinematics at relativistic energy**
 - nuclear charge and mass of each fragment,
 - total prompt-neutron multiplicity
- **Electromagnetic induced fission**
 - radioactive beams with broad range of fissioning nuclei
 - low energy fission at relativistic energy
- **Set-up based on the ΔE -Bp-ToF method**
 - ionic charge state obtained from ΔE ;
 - ions fully strip $Q=Z$; $A/Z=Bp/\beta\gamma$
 - applied for the secondary beam and fission fragments



• General context

- Improvement of the Gogny interaction
- Example : MPMH configuration mixing approach



- Monopole shift in ^{30}Si and ^{30}S (C. Robin, N. Pillet et al., PRC95, 044315 (2017))
- Need to improve certain spin-orbit partner splittings, pn pairing...

• Extension of the Gogny force

- First step: Finite range density dependent term \rightarrow D2 (F. Chappert, N. Pillet, M. Girod, J.-F. Berger, PRC91, 034312 (2015))
- Second step : Generalized Gogny interaction (Work in progress, Fully finite range, Adding of a finite range tensor term)

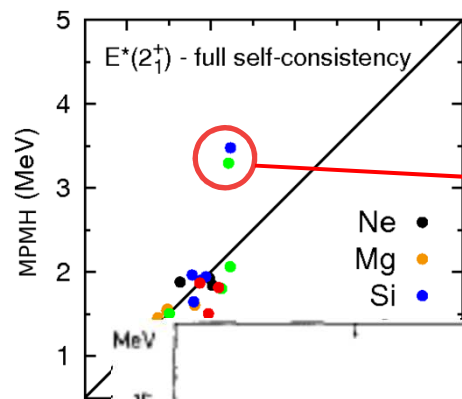
D1-type Gogny force

$$V_{12}(\rho) = \sum_{j=1}^2 (W_j + B_j P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau) e^{-\frac{(\mathbf{r}_1 - \mathbf{r}_2)^2}{\mu_j^2}} + t_3 (1 + x_0 P_\sigma) \delta(\mathbf{r}_1 - \mathbf{r}_2) \rho^\alpha \left(\frac{\mathbf{r}_1 + \mathbf{r}_2}{2} \right) + i W_{LS} \overleftrightarrow{\nabla}_{12} \delta(\mathbf{r}_1 - \mathbf{r}_2) \wedge \overleftrightarrow{\nabla}_{12} (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)$$

$$V_{12}(\rho) = \sum_{j=1}^2 (W_j^c + B_j^c P_\sigma - H_j^c P_\tau - M_j^c P_\sigma P_\tau) e^{-(\vec{r}_1 - \vec{r}_2)^2 / \mu_j^2} + \sum_i (W_i^d + B_i^d P_\sigma - H_i^d P_\tau - M_i^d P_\sigma P_\tau) \frac{e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_i^2}}}{(\mu_i \sqrt{\pi})^3} \frac{\rho^\alpha(\vec{r}_1) + \rho^\alpha(\vec{r}_2)}{2} + \sum_k (W_k^s - H_k^s P_\tau) e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_k^2}} \vec{L} \cdot \vec{S} + \sum_l (W_l^t - H_l^t P_\tau) e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_l^2}} S_{12}$$

- **General context**

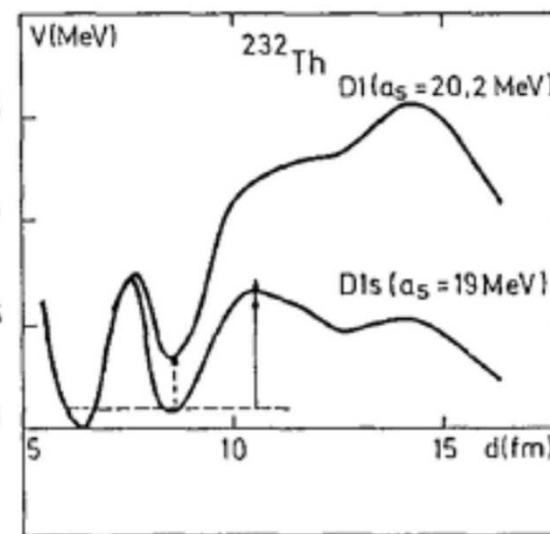
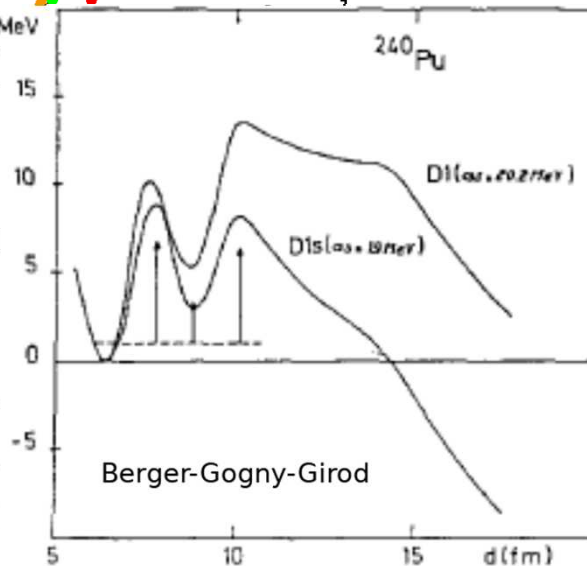
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- Need to improve certain spin-orbit partner splittings, pn pairing...

- **Extension of**

- First step: Fi (F. Chappert, N.
- Second step (Work in prog



$$e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_j^2}} \left(\frac{\rho^\alpha(\vec{r}_1) + \rho^\alpha(\vec{r}_2)}{2} \right)$$

D1-type Gogny force

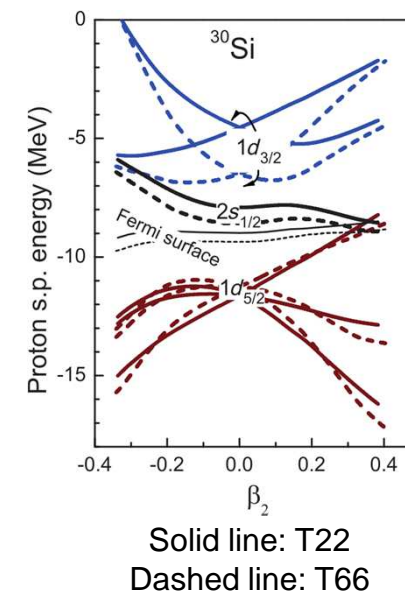
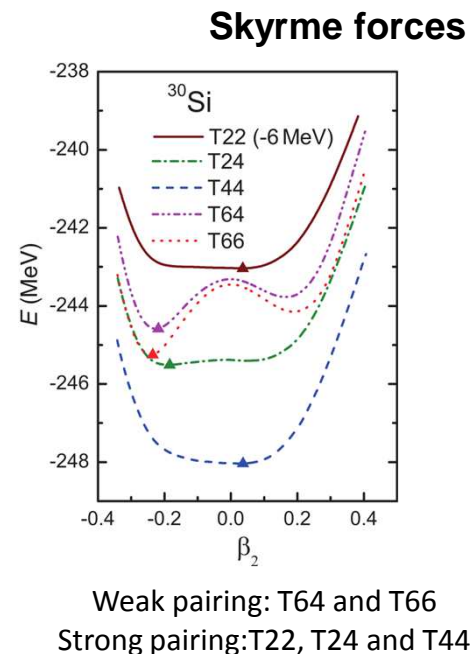
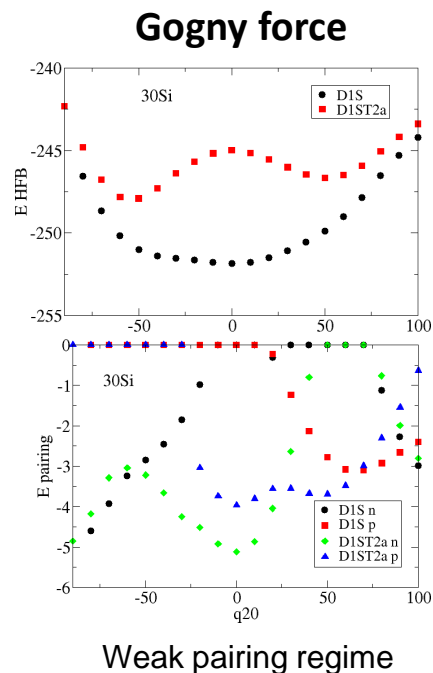
$$V_{12}(\rho) = \sum_{j=1}^2 (W_j + B_j P_\sigma - H_j P_\tau - M_j P_\sigma P_\tau) e^{-\frac{(\vec{r}_1 - \vec{r}_2)^2}{\mu_j^2}} + t_3 (1 + x_0 P_\sigma) \delta(\vec{r}_1 - \vec{r}_2) \rho^\alpha \left(\frac{\vec{r}_1 + \vec{r}_2}{2} \right) + i W_{LS} \vec{\nabla}_{12} \delta(\vec{r}_1 - \vec{r}_2) \wedge \vec{\nabla}_{12} (\vec{\sigma}_1 + \vec{\sigma}_2)$$

Need of new data to constrain the new parameters: **What about new fission data?**

The Gogny force and the tensor term

- (T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005))
- T. Otsuka et al., Phys. Rev. Lett. 97, 162501 (2006) → GT2 force: Full refit of the force at the HF level
- M. Anguiano et al., Phys. Rev. C 86, 054302 (2012) → D1ST2a force: D1S + perturbative tensor
- R. N. Bernard, M. Anguiano, Nucl. Phys. A 953 (2016) 32

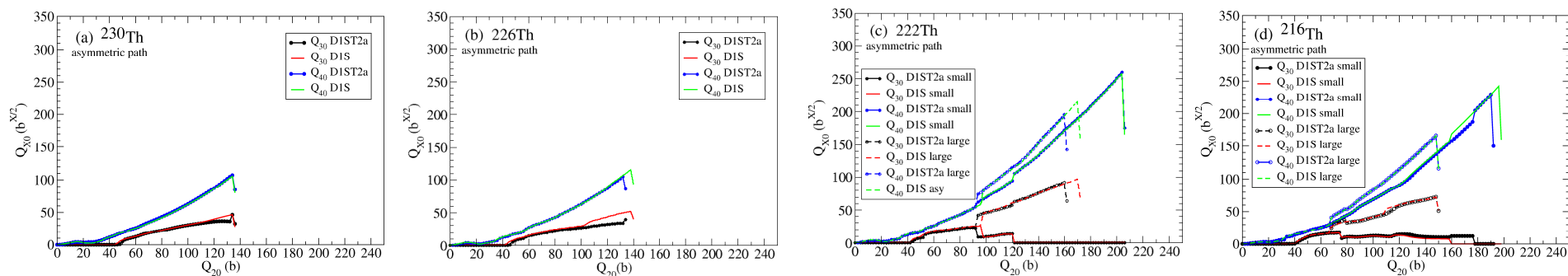
Interplay between tensor force, deformation and pairing correlations



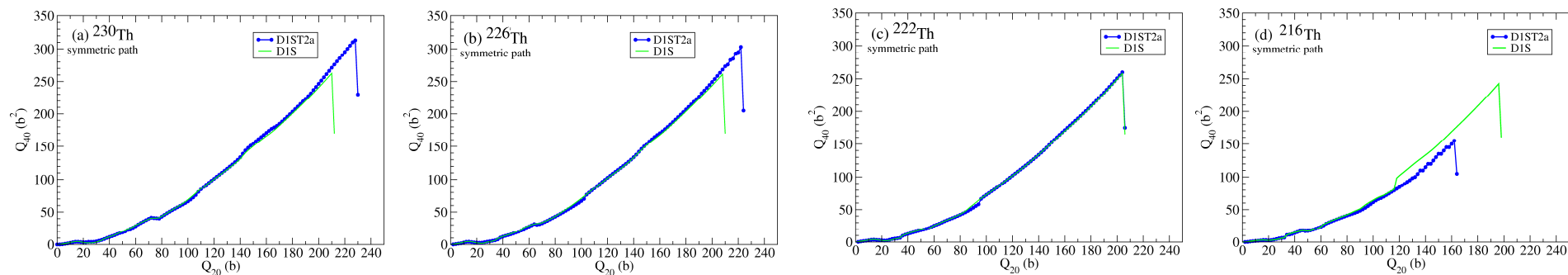
A. Li, X.R. Zhou, and H. Sagawa,
Prog. Theor. Exp. Phys. 2013, 063D03

Evolution of the collective variables along the 1D symmetric and asymmetric paths

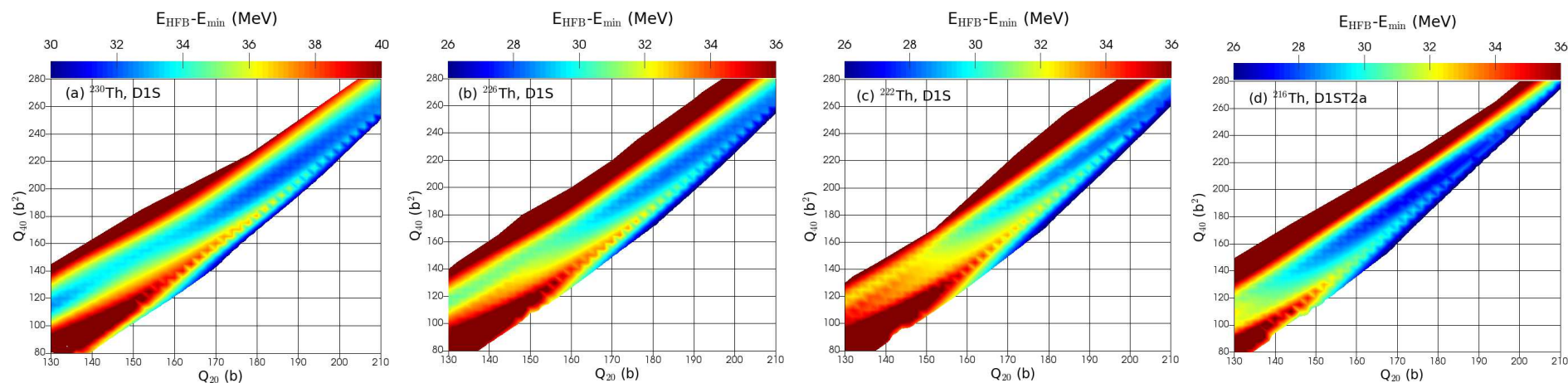
Asymmetric path



Symmetric path



D1S



D1ST2a

