Selected topics in theoretical study of structure & synthesis mechanism of SHN

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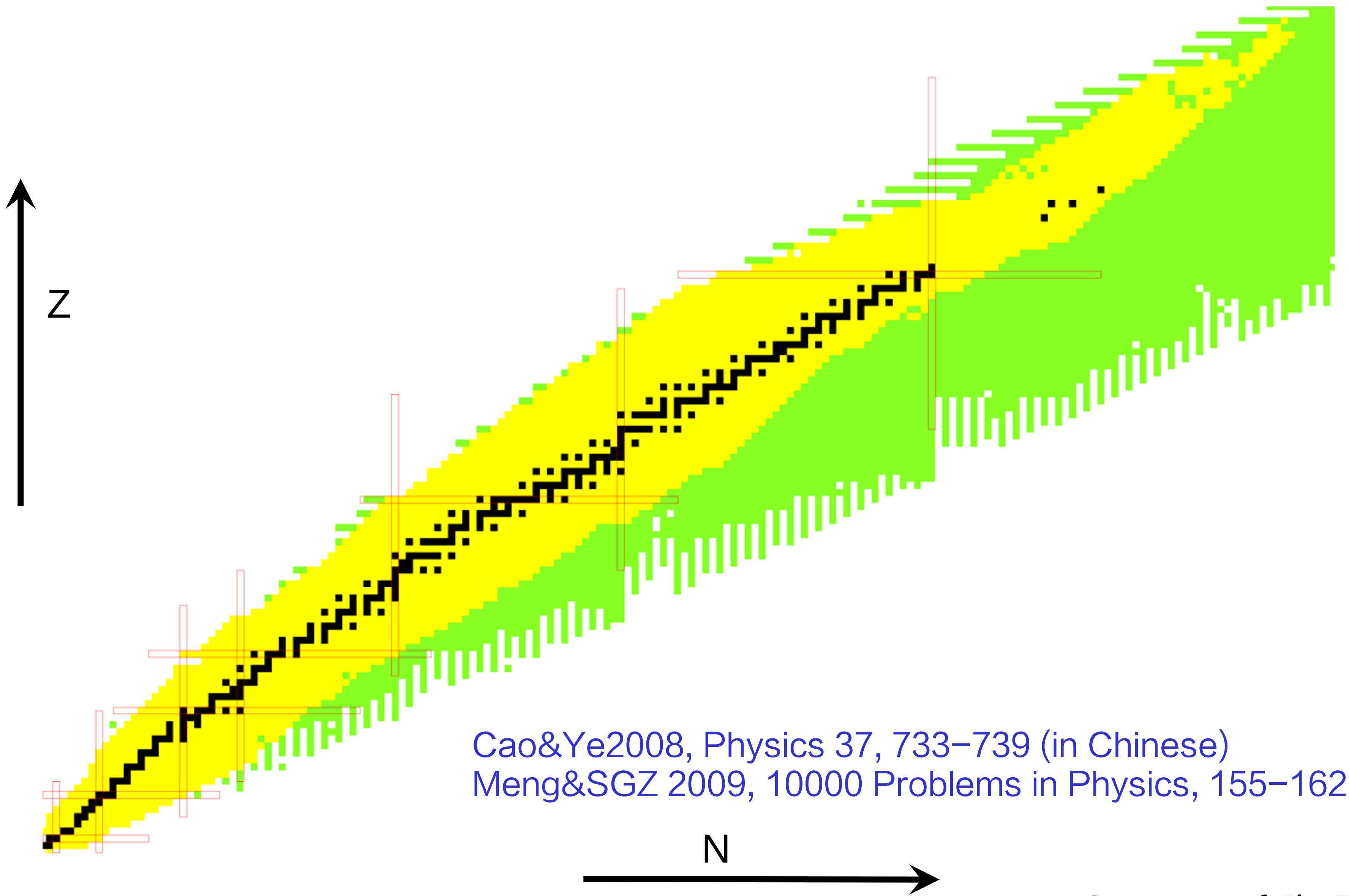
- Introduction
- Selected topics
  - **Low-lying states**
  - **PES & fission barriers**
  - **Evaporation residue cross sections**
- Summary

FUSHE2012, May 13-16, 2012

Erbismuehle - Weilrod

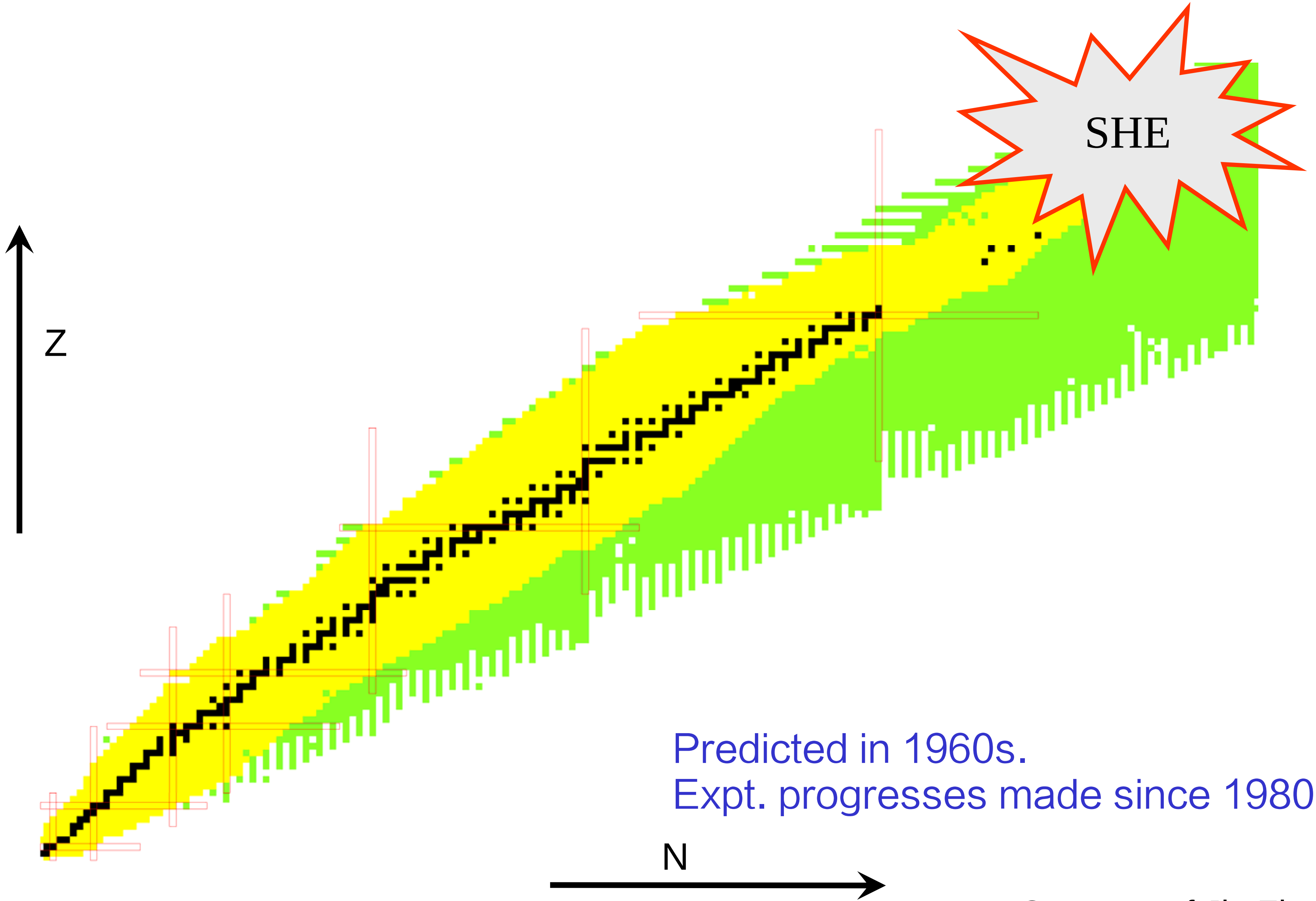
Stable & unstable nuclei



Cao&Ye2008, Physics 37, 733−739 (in Chinese)
Meng&SGZ 2009, 10000 Problems in Physics, 155−162

Courtesy of Jie Zhao

Super heavy nuclei: Charge & mass limits of existence



Predicted in 1960s.
Expt. progresses made since 1980s

Courtesy of Jie Zhao

Table of elements: ends?

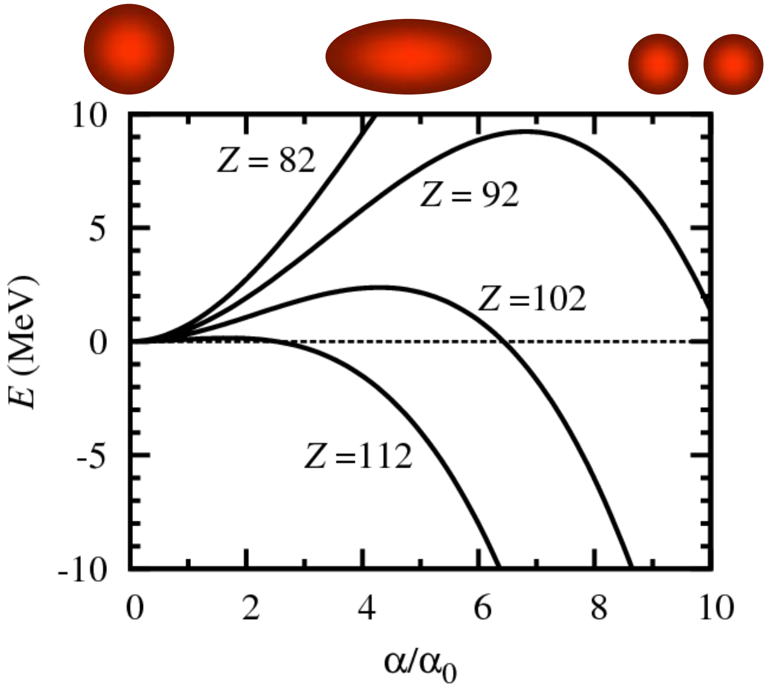
WebElements, Aug. 2011

Group	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period																			
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

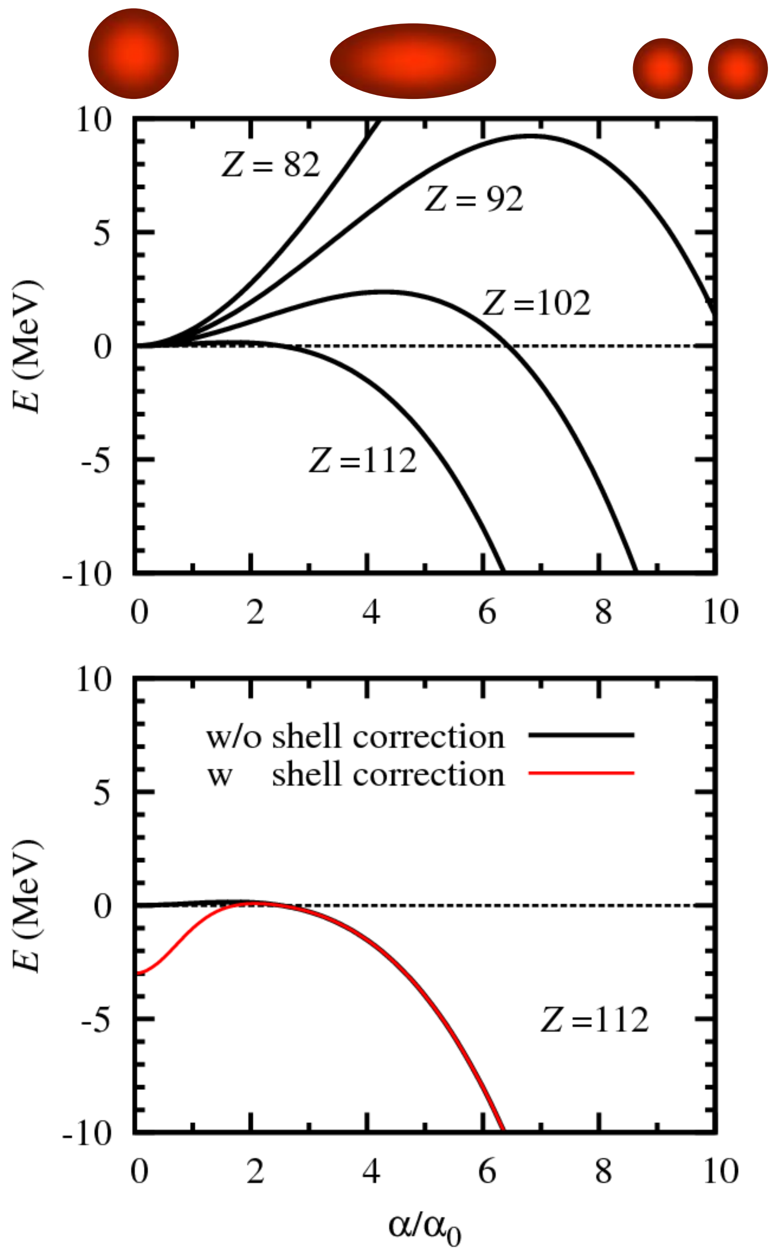
IUPAC/IUPAP Joint Working Party, 2011:

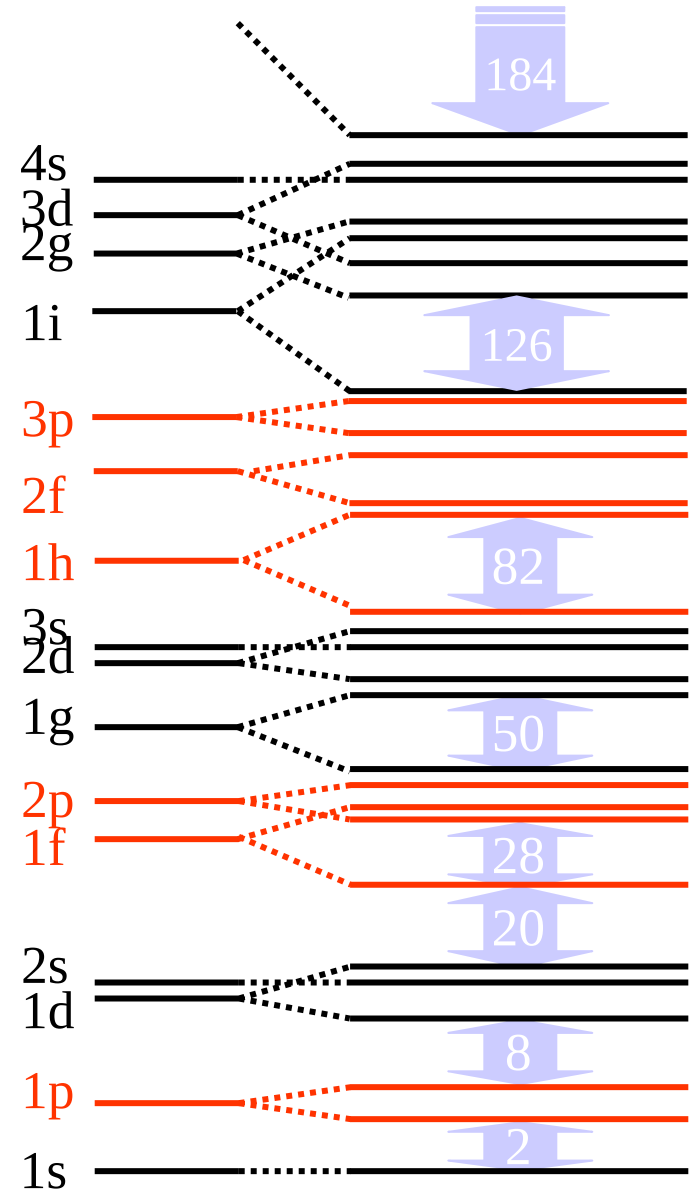
114: flerovium (symbol Fl); 116: livermorium (symbol Lv)

Existence of SHN: Quantum shell effects



Existence of SHN: Quantum shell effects



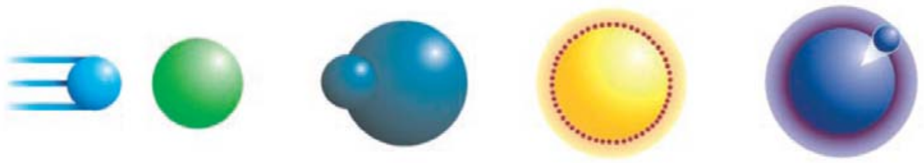


Experimental exploration of the island of stability

- If $T_{1/2}$~10^8 years & produced in the nucleosynthesis
  - **SHN would survive until now**
  - **No confirmed results found in searching for SHE in the Nature**

Herrmann2004

- Synthesis of SHE in laboratories via heavy ion fusions
  - **GSI in Darmstadt, Germany**
  - **Flerov Laboratory of Nuclear Reactions in Dubna, Russia**
  - **Lawrence Berkeley National Laboratory in Berkeley, USA**
  - **RIKEN in Wako, Japan**
  - **GANIL in Caen, France**
  - **HIRFL in Lanzhou, China**



Hofmann_Münzenberg2000_RMP72-733

Morita...2004_JPSJ73-2593

Oganessian...2007_JPG34-R165

Oganessian...2010_PRL104-142502

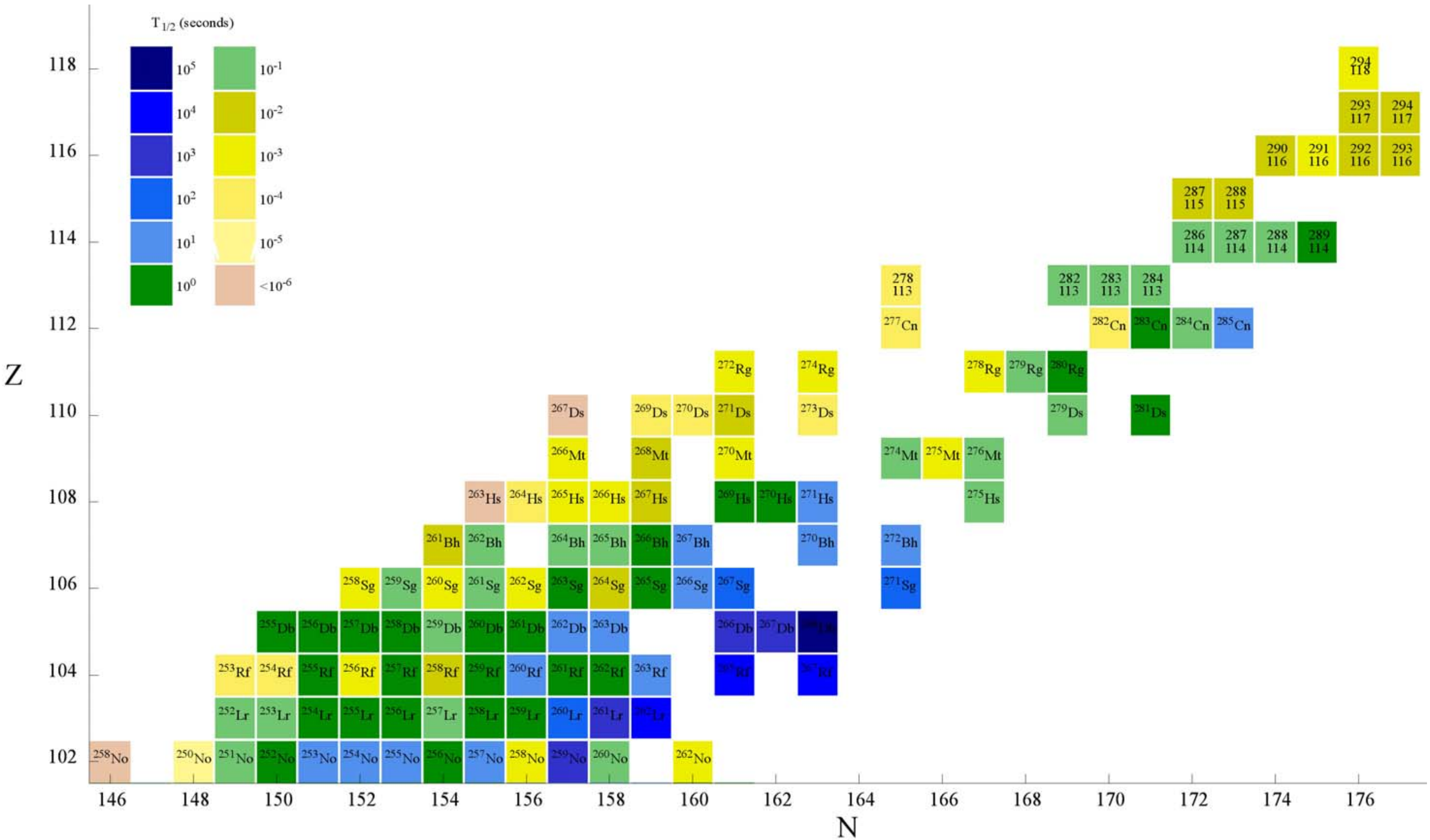
Zhang…2011_ChinPhysLett

Man-made SHN

- Neutron capture followed by beta deca
  - **In reactors: Z=94-100**
  - **In nuclear bomb: Z=98-100**

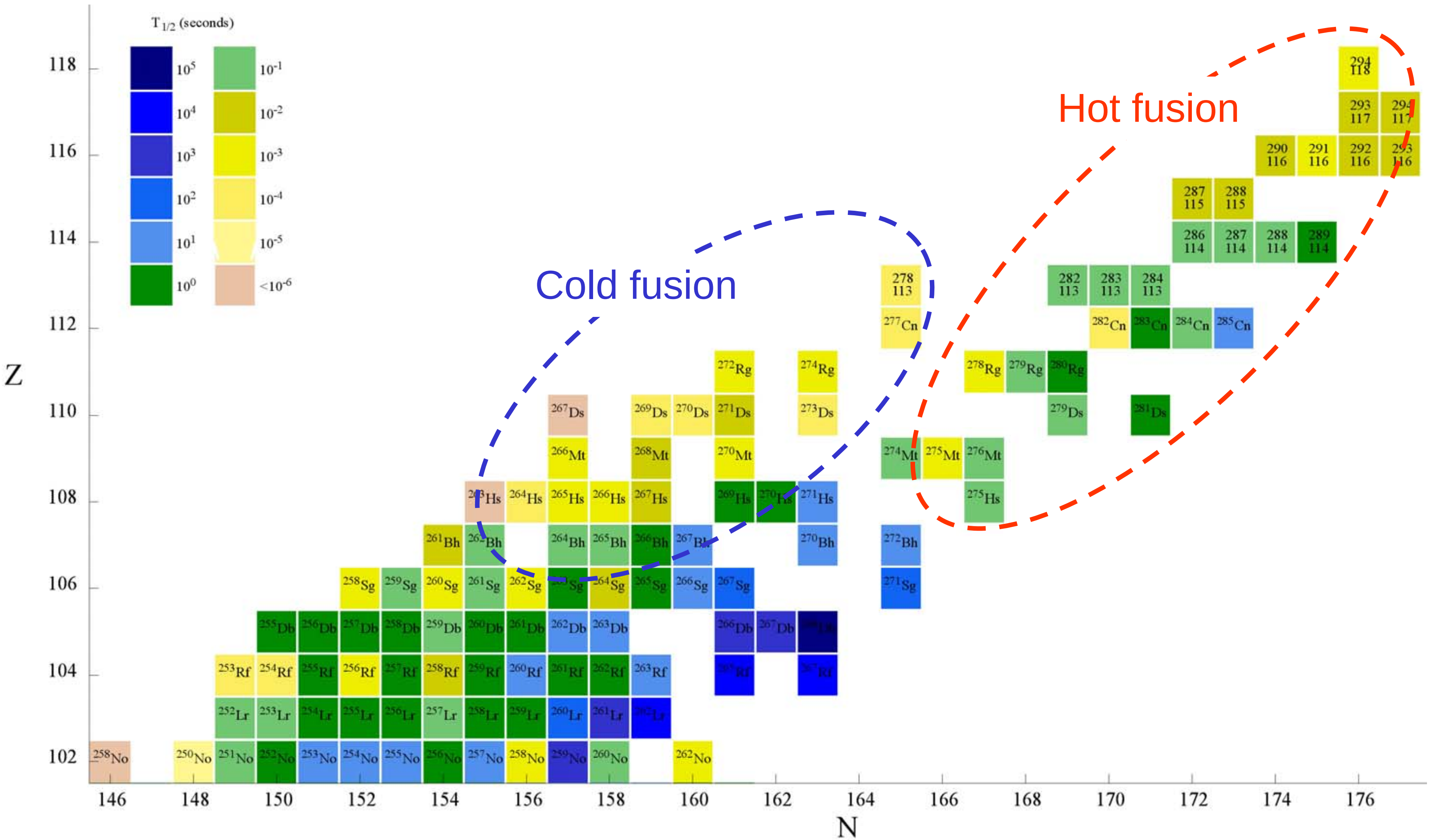
- Light ions as projectiles
  - **Proton, D, T, ^{4}He: up to Z=101**
- Heavy ions as projectiles
  - **Cold fusion: ^{208}Pb or ^{209}Bi as targets, up to Z=113**
  - **Hot fusion: ^{48}Ca as projectiles, up to Z=118**

Experimental progresses



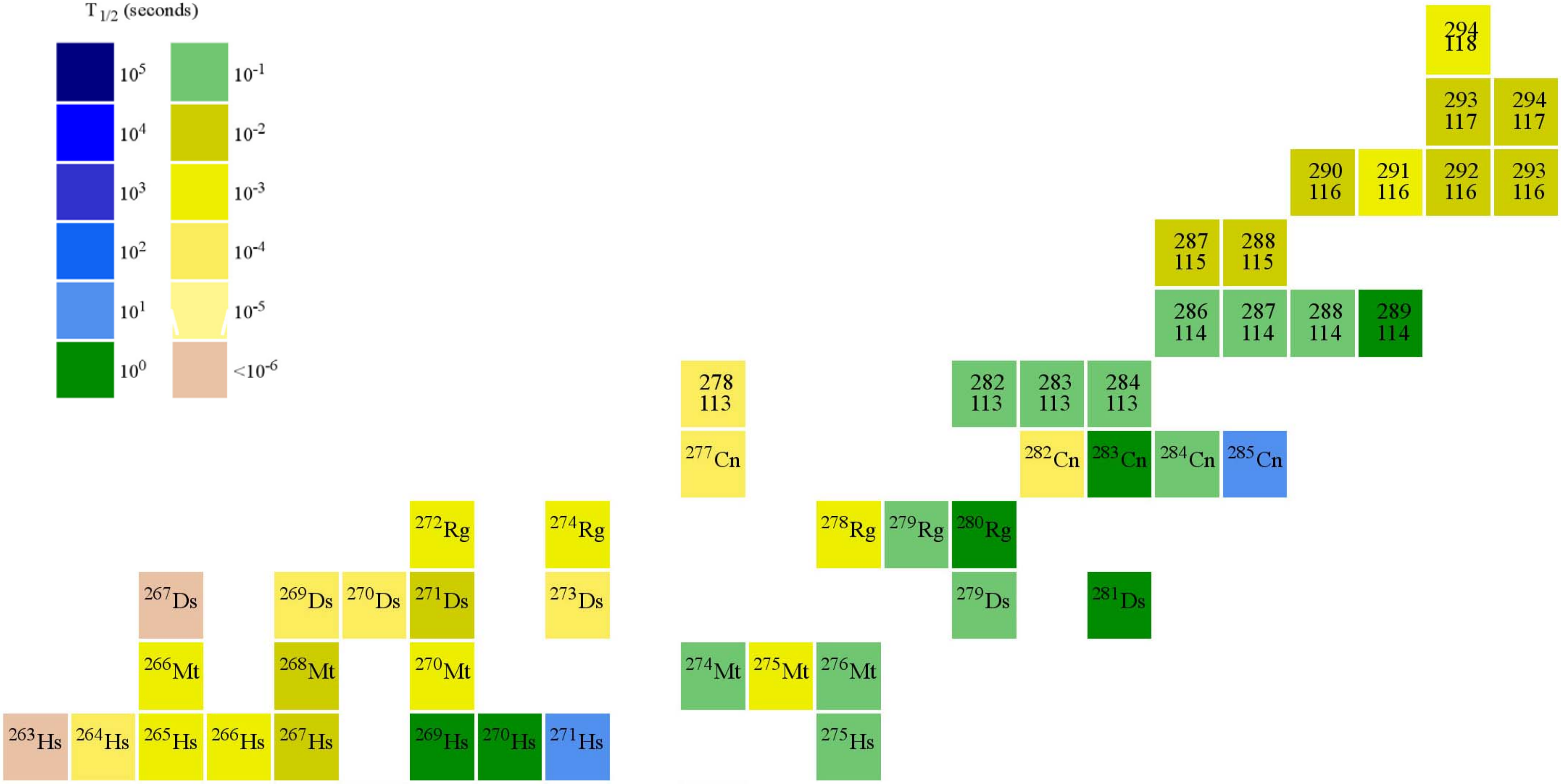
Courtesy of Kai Wen

Experimental progresses



Courtesy of Kai Wen

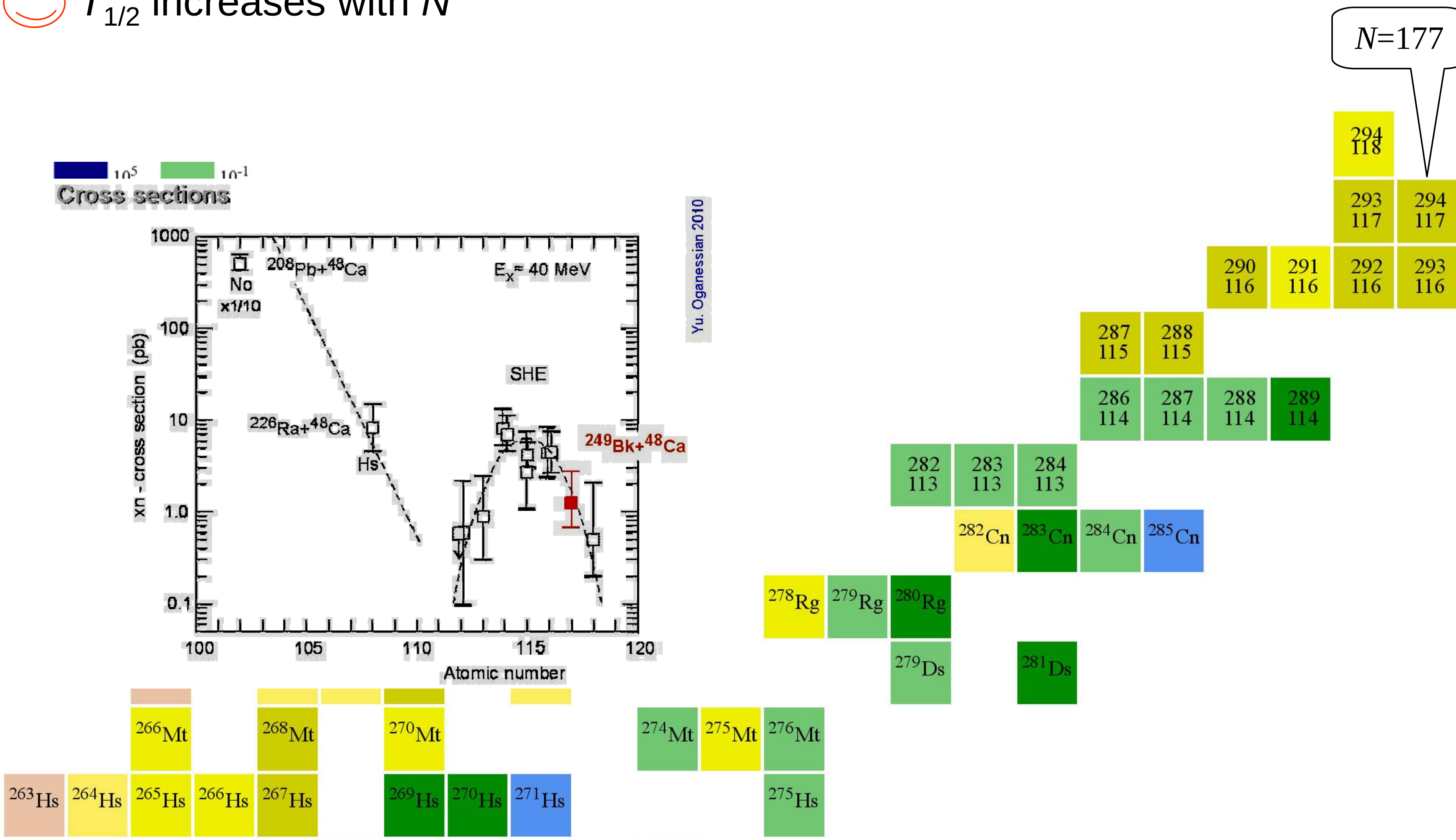
Experimental progresses



Courtesy of Kai Wen

Experimental progresses

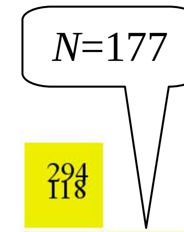
- At least 7 neutrons less than N = 184
- $T_{1/2}$ increases with N

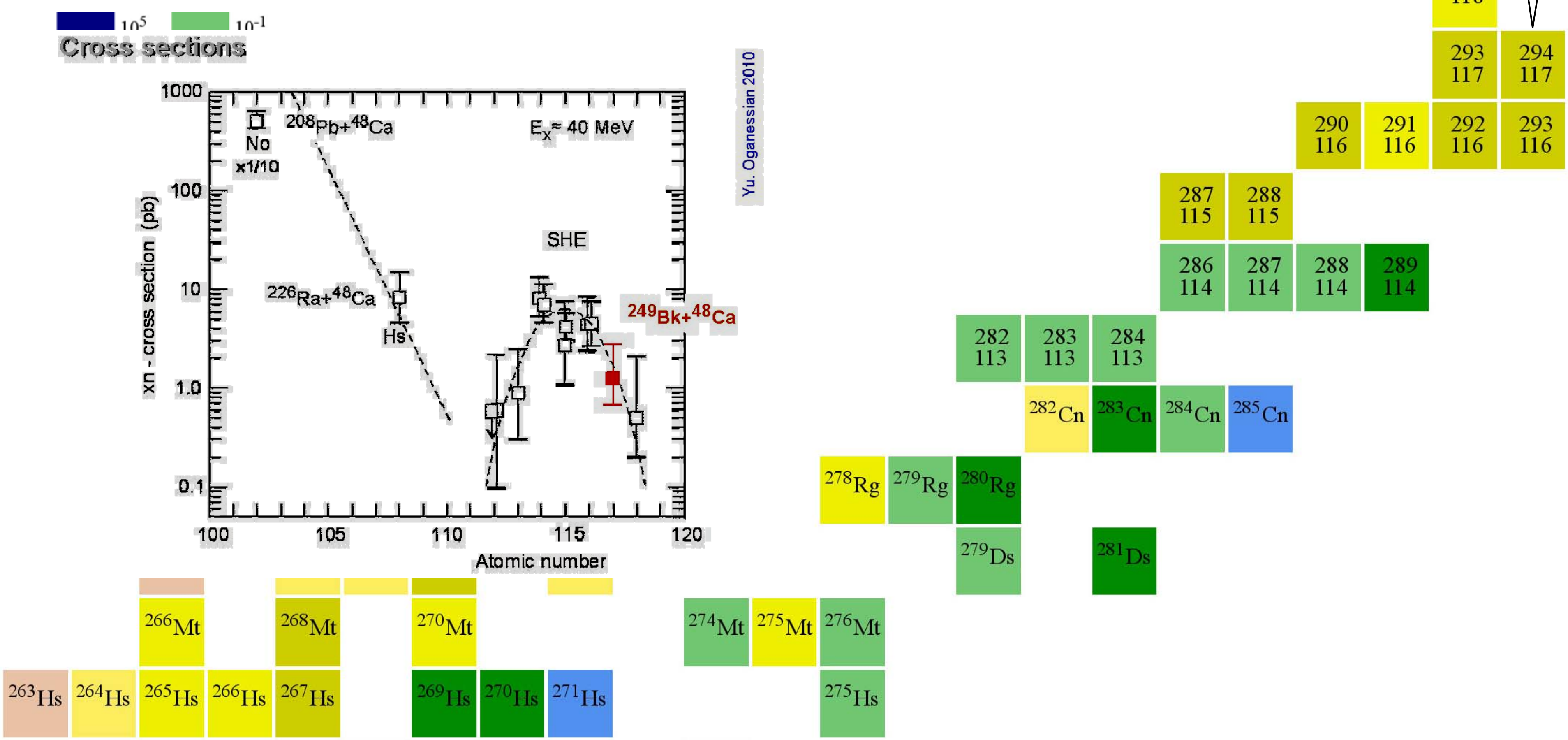


Courtesy of Kai Wen

Experimental progresses

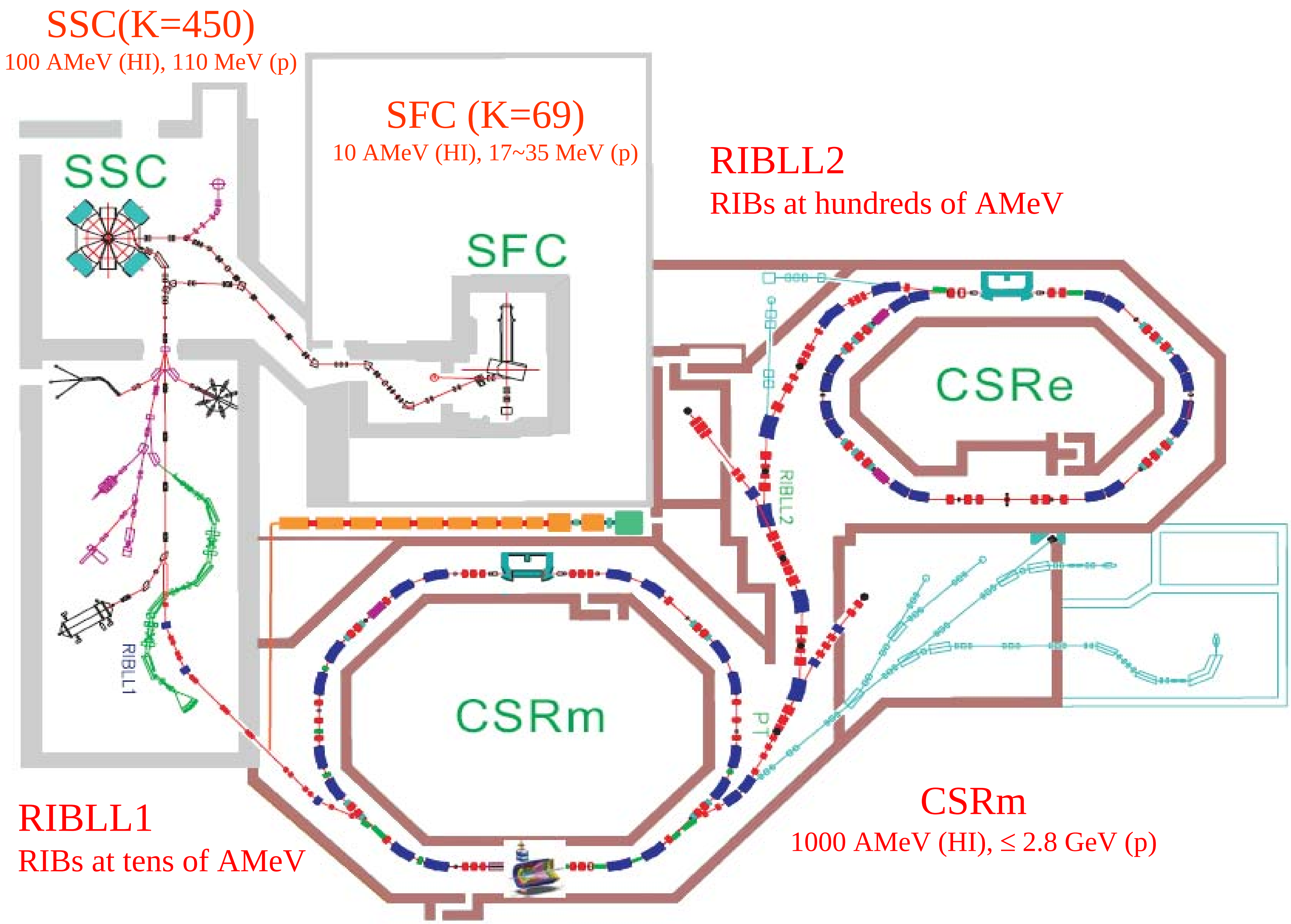
- At least 7 neutrons less than N = 184
- $T_{1/2}$ increases with N
- ? X-section maximal at Z = 114
- Extremely low X-section for even heavier SHE





Courtesy of Kai Wen

Heavy Ion Research Facility in Lanzhou (HIRFL)



Mass measurements w/ CSR

>20 new masses

PRL **106,** 112501 (2011) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2011

Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr and Their Impact on Nucleosynthesis in the *rp* Process

X. L. Tu,[1,2] H. S. Xu,[1,*] M. Wang,[1] Y. H. Zhang,[1] Yu. A. Litvinov,[3,4,1] Y. Sun,[5,1] H. Schatz,[6] X. H. Zhou,[1] Y. J. Yuan,[1] J. W. Xia,[1] G. Audi,[7] K. Blaum,[3] C. M. Du,[1,2] P. Geng,[1,2] Z. G. Hu,[1] W. X. Huang,[1] S. L. Jin,[1,2] L. X. Liu,[1,2] Y. Liu,[1] X. Ma,[1] R. S. Mao,[1] B. Mei,[1] P. Shuai,[8] Z. Y. Sun,[1] H. Suzuki,[9] S. W. Tang,[1,2] J. S. Wang,[1] S. T. Wang,[1,2] G. Q. Xiao,[1] X. Xu,[1,2] T. Yamaguchi,[10] Y. Yamaguchi,[11] X. L. Yan,[1,2] J. C. Yang,[1] R. P. Ye,[1,2] Y. D. Zang,[1,2] H. W. Zhao,[1] T. C. Zhao,[1] X. Y. Zhang,[1] and W. L. Zhan[1]

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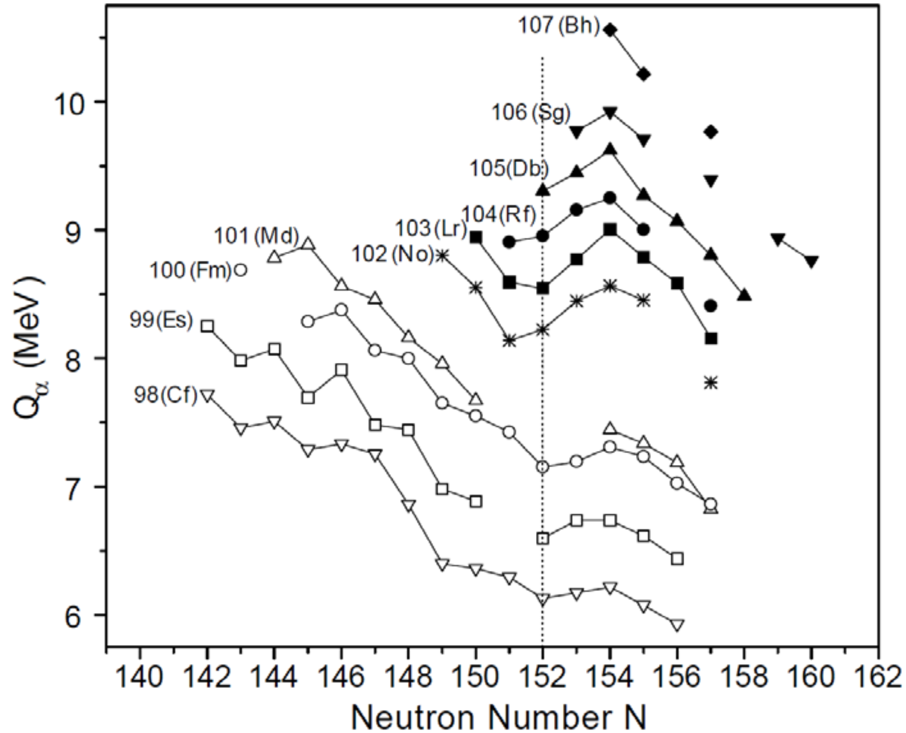
SHE @ HIRFL

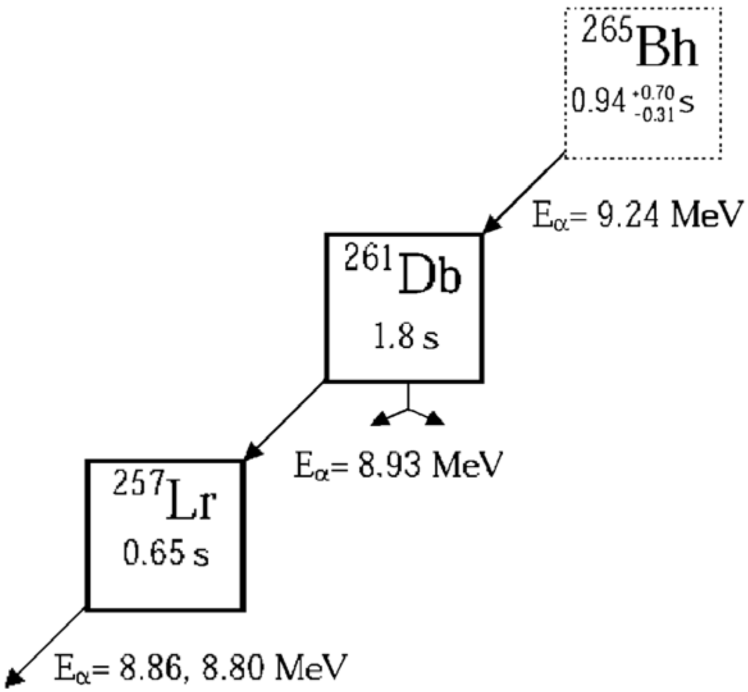
He-jet technique & rotating-wheel

2001: ^{259}Db (Z = 105)



Gan...2001_EPJA10-21

2004: ^{265}Bh (Z = 107)



Gan...2004_EPJA20-385

Nuclear chemistry for SHE

New gas-filled spectrometer @ Lanzhou: ^{271}Ds

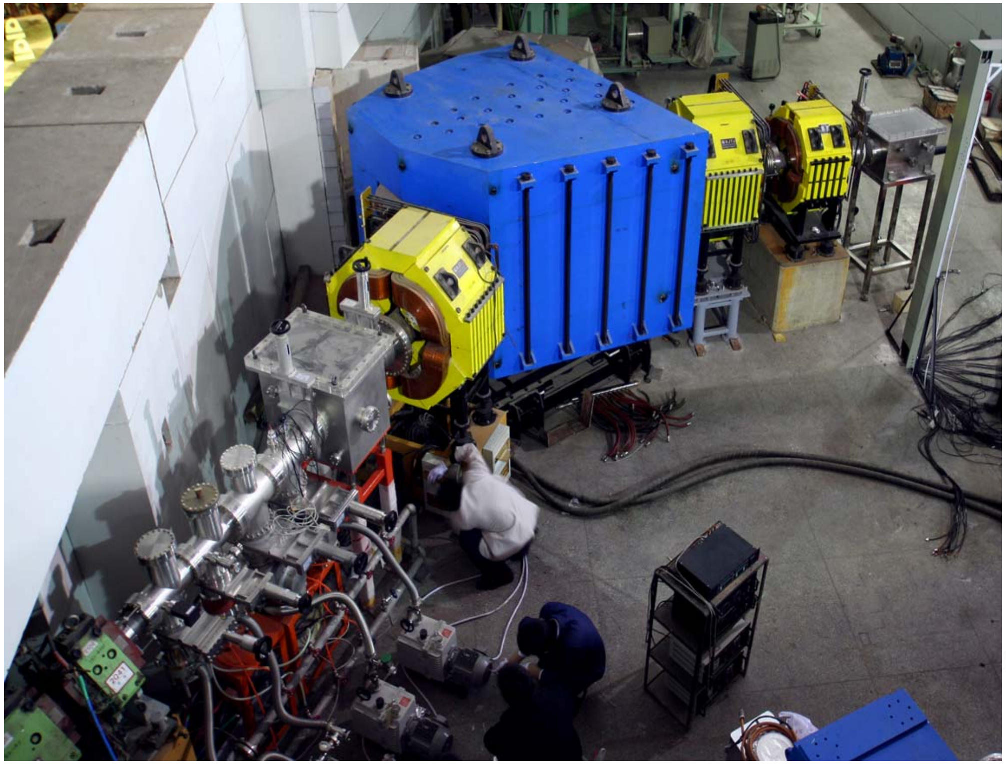
2011.01.15 $^{64}Ni + ^{208}Pb \rightarrow ^{272}Ds^*$ 7 days

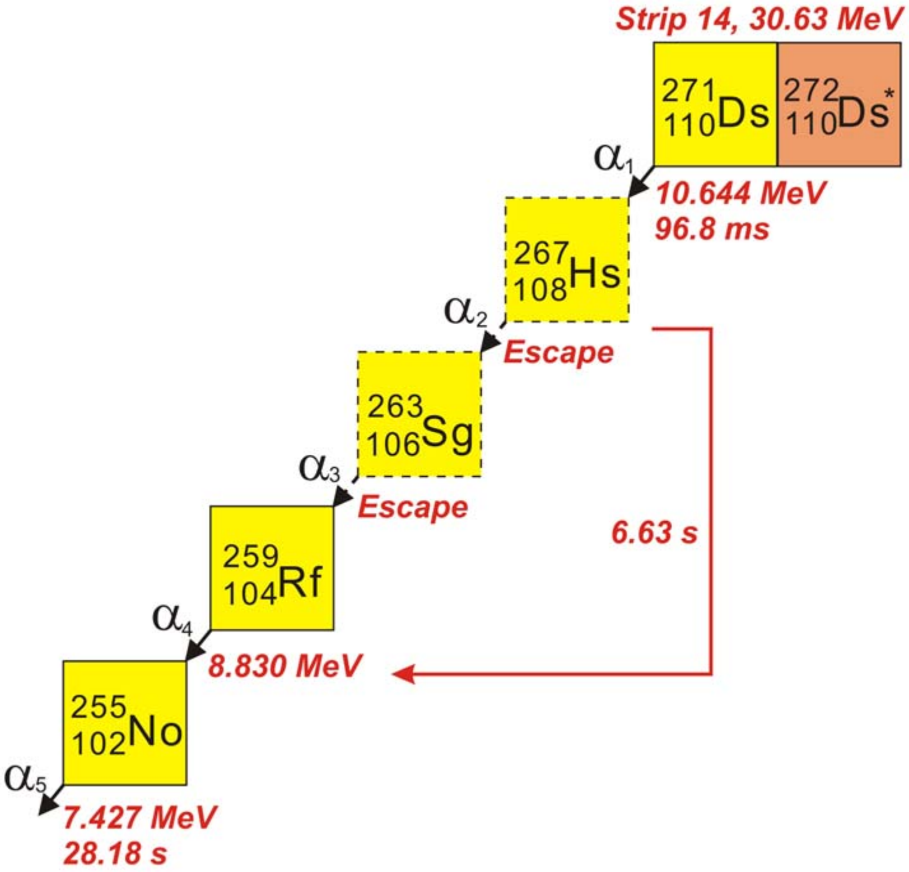
2011.03.15 $^{64}Ni + ^{208}Pb \rightarrow ^{272}Ds^*$ 13 days

IMP/CAS, ITP/CAS

Nanjing Univ, CIAE

Zhang, Gan, Ma …,
Chinese Physics Letters 29 (2012) 012502





Theoretical Study of SHN

- Structure
- Decay & fission
- Synthesis mechanism

Theoretical Study of SHN

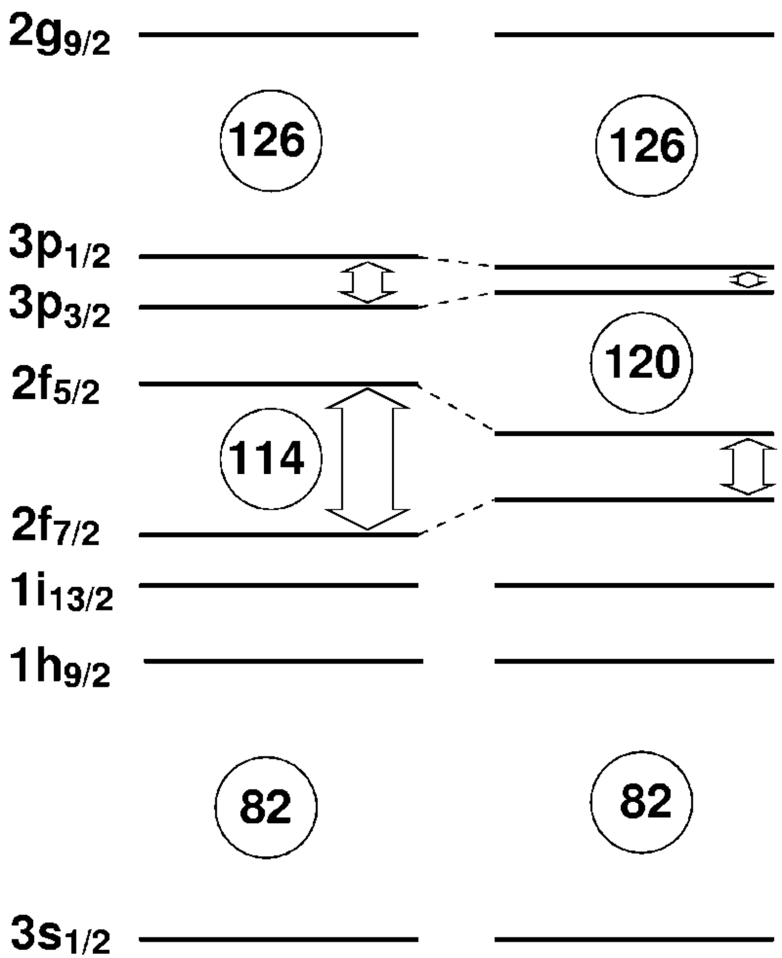
- Structure
  - Ground state properties
    - **Binding energy (separation energy, Q value)**
    - **Deformation; exotic shapes?**
    - **Single particle level (shell) structure ⇒ location of the island**
  - Spectroscopy
  - Saddle point properties
    - **Potential energy surface ⇒ fission path & fission barrier**
    - **Shell structure**
  - Isomeric states
    - **Longer half-life? A step stone toward the island of stability?**
  - Excited compound nucleus
    - **Level density**
    - **Quenching of shell effects w/ temperature**
  - ...

Spectroscopy of nuclei with Z~100

- Synthesis of SHN ⇒ Decay modes & energies; X-sections, ...

- Spectroscopy of SHN
  - **Detailed structure & stability**

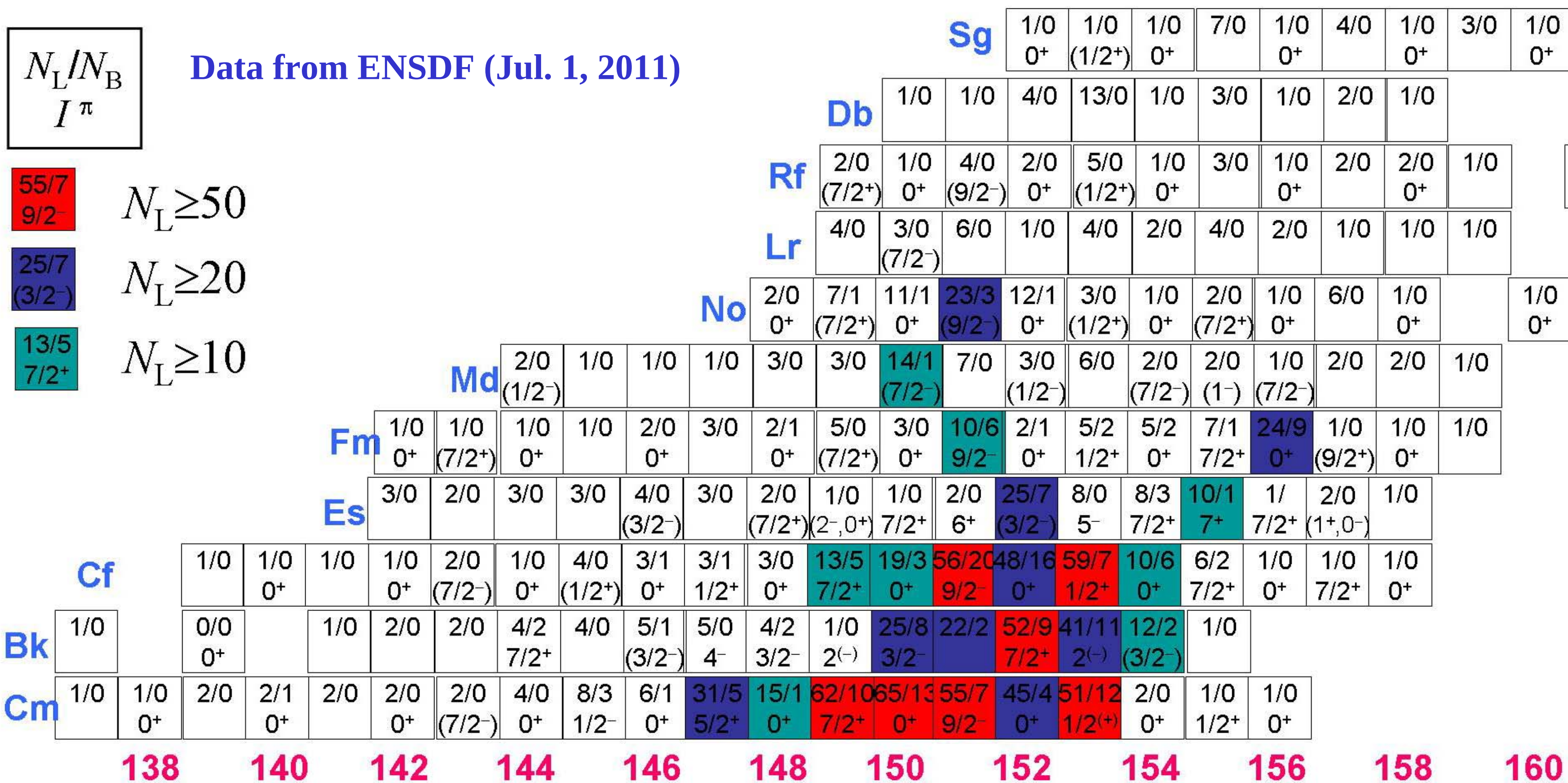
- Spectroscopy of deformed nuclei with Z~100 & N~152
  - **Of interest in itself --- occurrence of deformation & *K*-isomerism**
  - **Orbitals around the Fermi level in these nuclei stem from those connected to the spherical shell gaps in SHN (1/2⁻[521])**



Herzberg_Greenlees_Butler...
2006_Nature442-896

Experimental facilities & status

RITU@JYFL	SHIP@GSI	VASSILISSA@FLNR	FMA@ANL
LISE3@GANIL	RMS@JAEA	HIRFL@IMP	...



Leino_Hessberger2004_ARNPS54-175
Herzberg_Greenlees2008_PPNP61-674

Theoretical study of low-lying spectra

- Self-consistent approaches

Egido_Robledo2000_PRL85-1198
Afanasjev...2003_PRC67-024309
Delaroche...2006_NPA771-103
Bender...2003_NPA723-354
Adamian...2011_PRC

- Macroscopic-Microscopic models

Cwiok...1994_NPA573-356
Muntian...1999_PRC60-041302R
Sobiczewski...2001_PRC63-034306
Parkhomenko_Sobiczewski2004_APPB35-2447
Parkhomenko_Sobiczewski2005_APPB36-3115
Adamian...2011_PRC

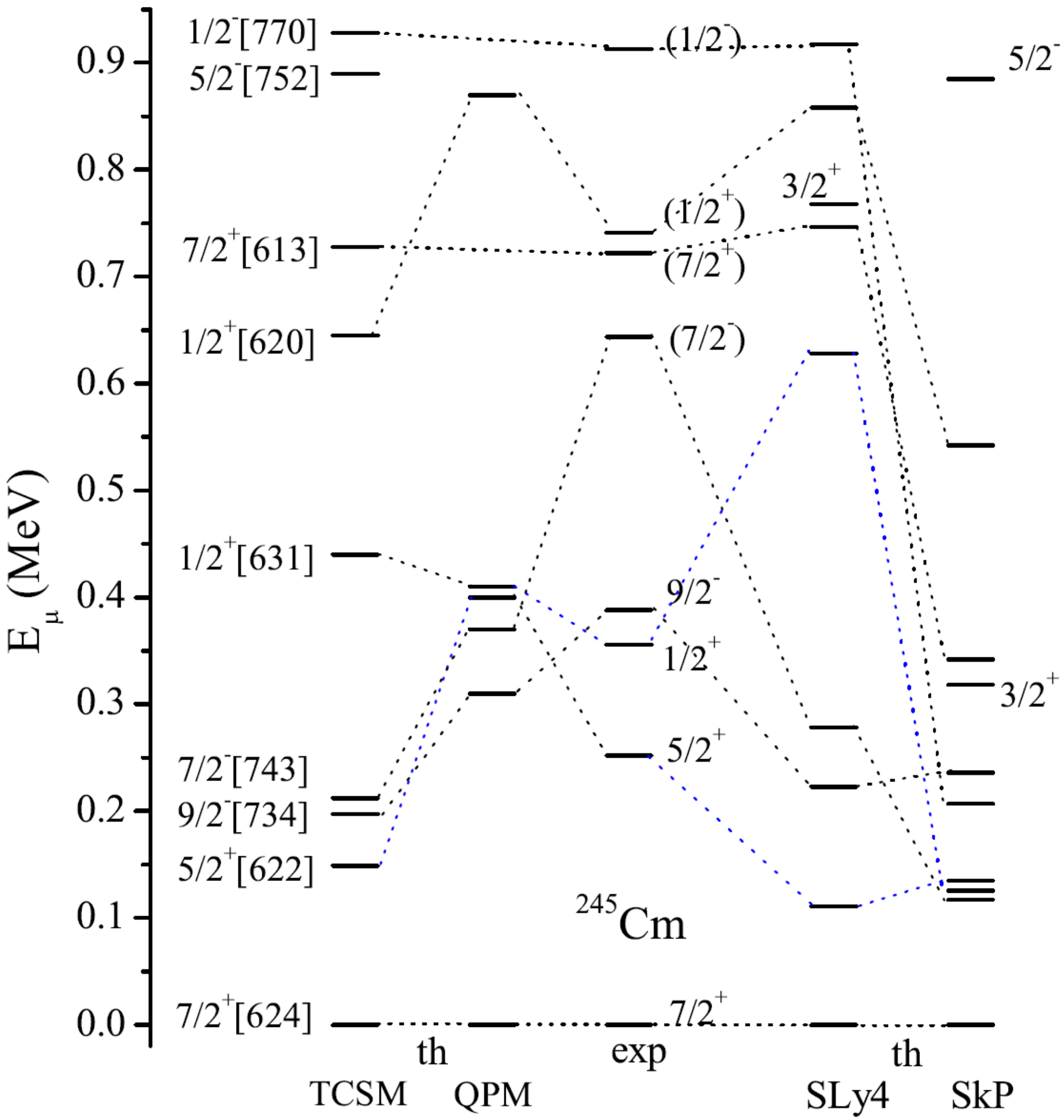
- Projected shell model

Sun...2008_PRC77-044307
Chen...2008_PRC77-061305
Al-Khudair...2009_PRC79-034320

- Cranking shell model

He...2009_NPA817-45
Zhang...2011_PRC83-011304R
Zhang...2012, PRC85_014324
Liu...2012_arxiv1204.5527

One-quasineutron spectra in ^{245}Cm



- An agreement between data & various models
- In some cases, the order is not reproduced

Adamian_Antonenko_Kukulin_Lu_Malov_SGZ2011_PRC84-024324

Cranking Shell Model w/ PNC for pairing

$$H_{\mathrm{CSM}} = H_0 + H_{\mathrm{P}} = H_{\mathrm{Nil}} - \omega J_x + H_{\mathrm{P}}$$

$$|\Psi\rangle = \sum_i C_i \, |i\rangle$$

$$J^{(1)} = \frac{1}{\omega} \langle \Psi | J_x | \Psi \rangle$$

$$n_\mu = \sum_i |C_i|^2 P_{i\mu}$$

- Applications of CSM-PNC
  - **Normally deformed & superdeformed high spin rotational bands of nuclei with A ~ 160, 190, & 250**
  - **Mechanism of identical bands in normally deformed nuclei**
  - **Nonadditivity in moments of inertia of high-K rotational bands**
  - **…**

Zeng...1994_PRC50-746

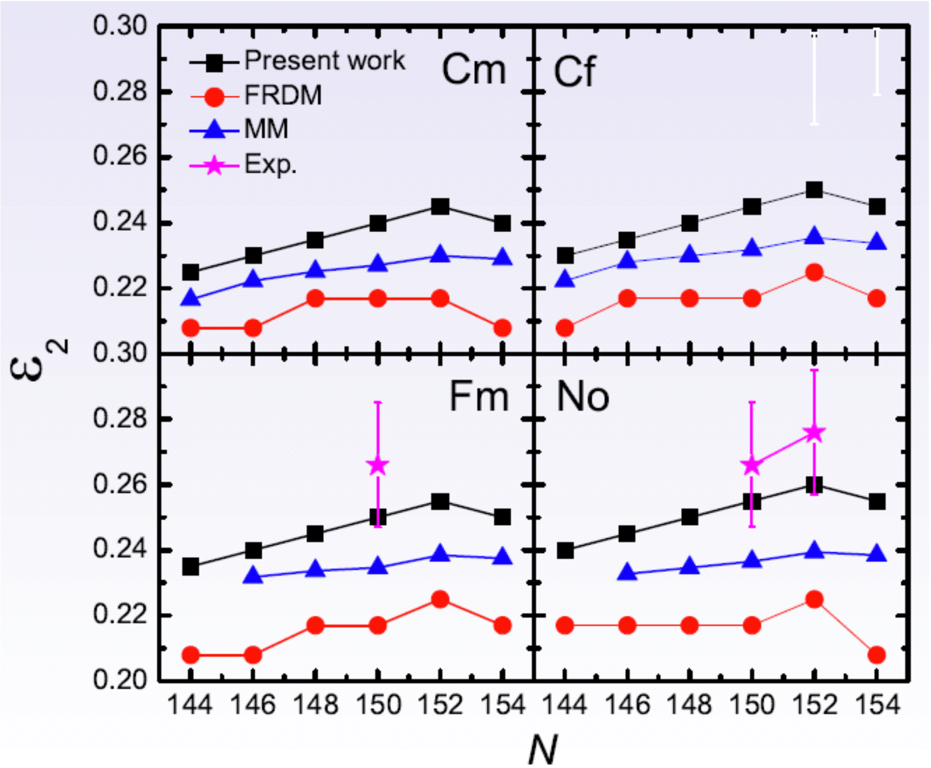
Zeng…1994_PRC50-1388

Nilsson parameters & deformation parameters

N	l	κ_p	μ_p	N	l	κ_n	μ_n
4	0,2,4	0.0670	0.654				
5	1	0.0250	0.710	6	0	0.1600	0.320
	3	0.0570	0.800		2	0.0640	0.200
	5	0.0570	0.710		4,6	0.0680	0.260
6	0,2,4,6	0.0570	0.654	7	1,3,5,7	0.0634	0.318

A new set of Nilsson parameters

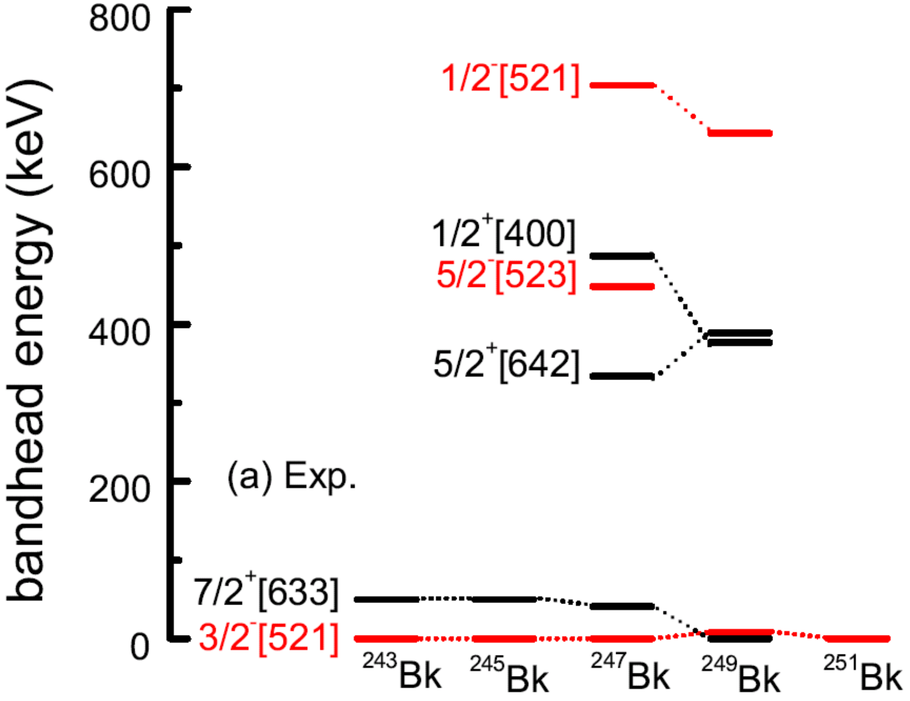
- Reproduce well single particle structure in heavy nuclei

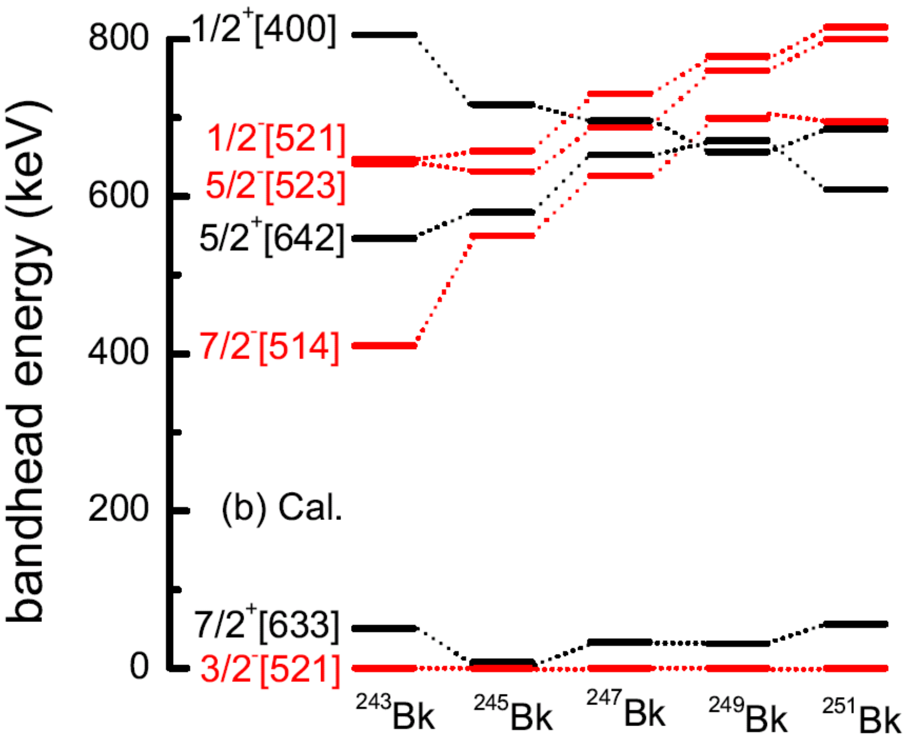


Zhang_Zeng_Zhao_SGZ2011_PRC83-011304R

Zhang_He_Zeng_Zhao_SGZ2012, PRC85_014324

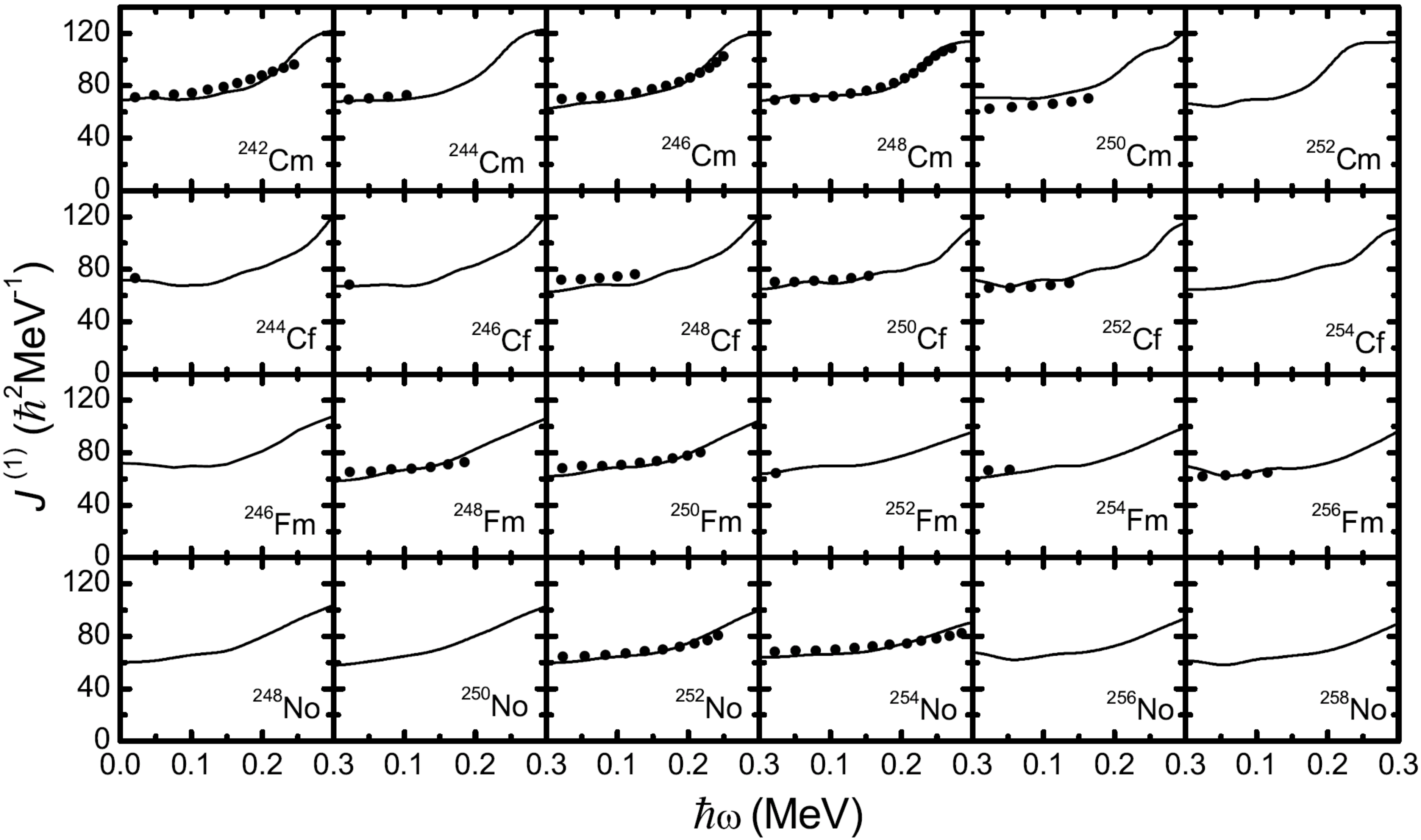
Bandhead energies in Bk (Z=97) isotopes





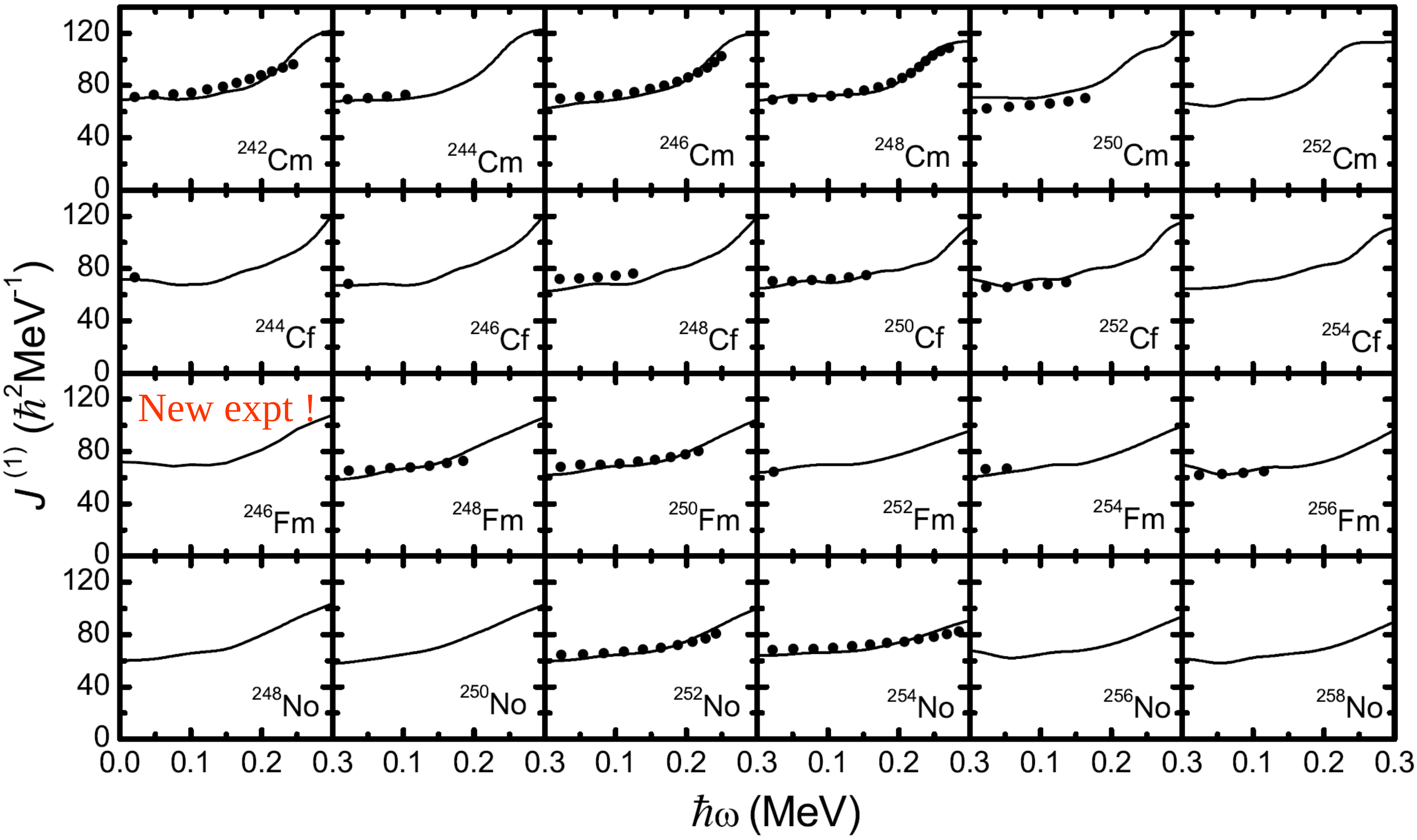
Zhang_He_Zeng_Zhao_SGZ2012, PRC85_014324

Moments of inertia of even-even nuclei



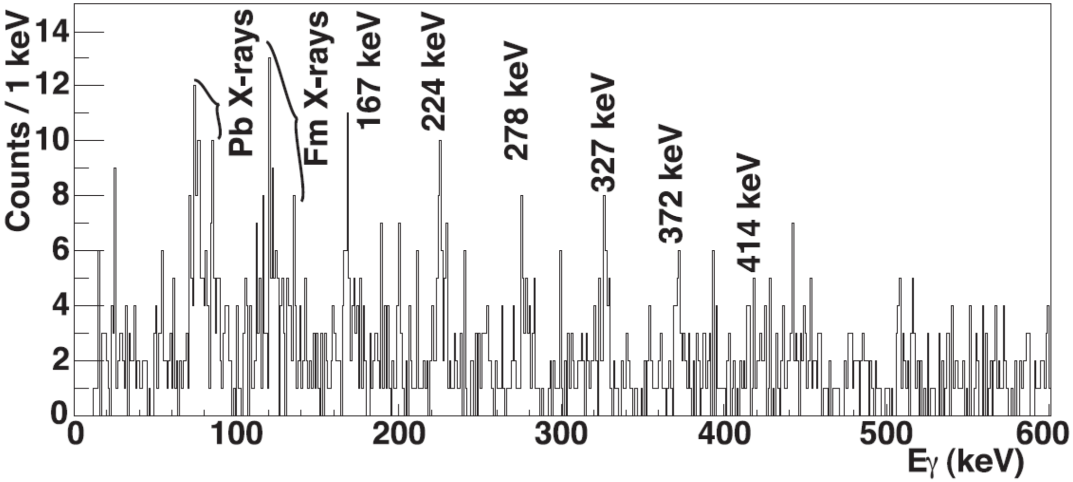
Zhang_He_Zeng_Zhao_SGZ2012, PRC85_014324

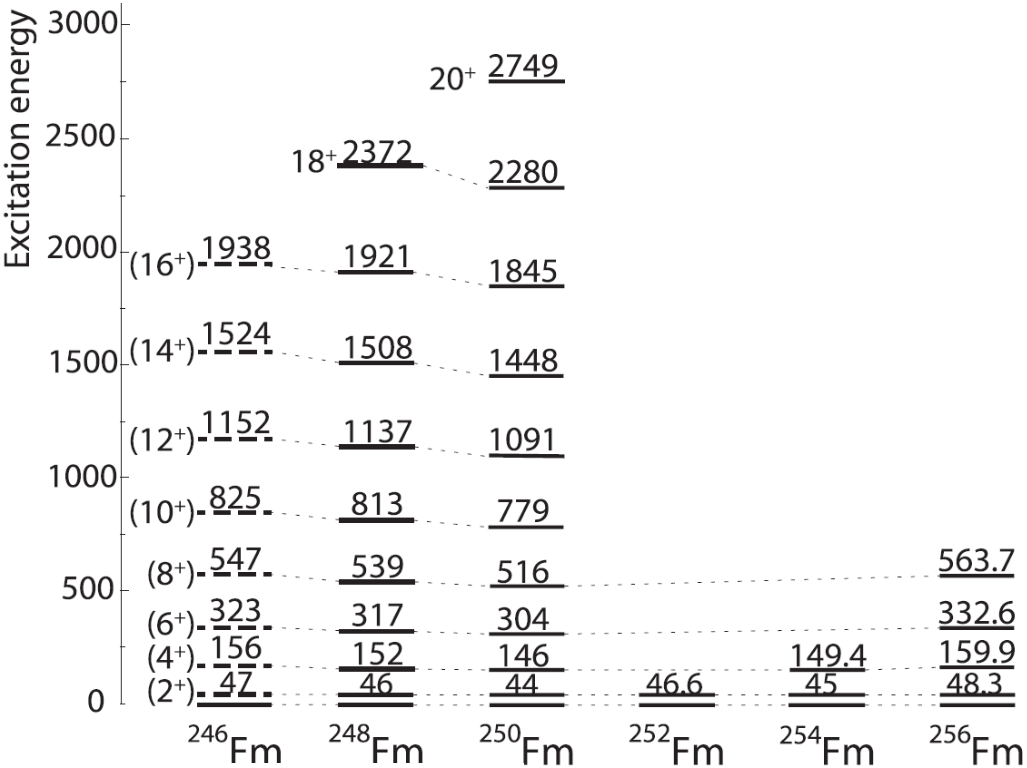
Moments of inertia of even-even nuclei



Zhang_He_Zeng_Zhao_SGZ2012, PRC85_014324

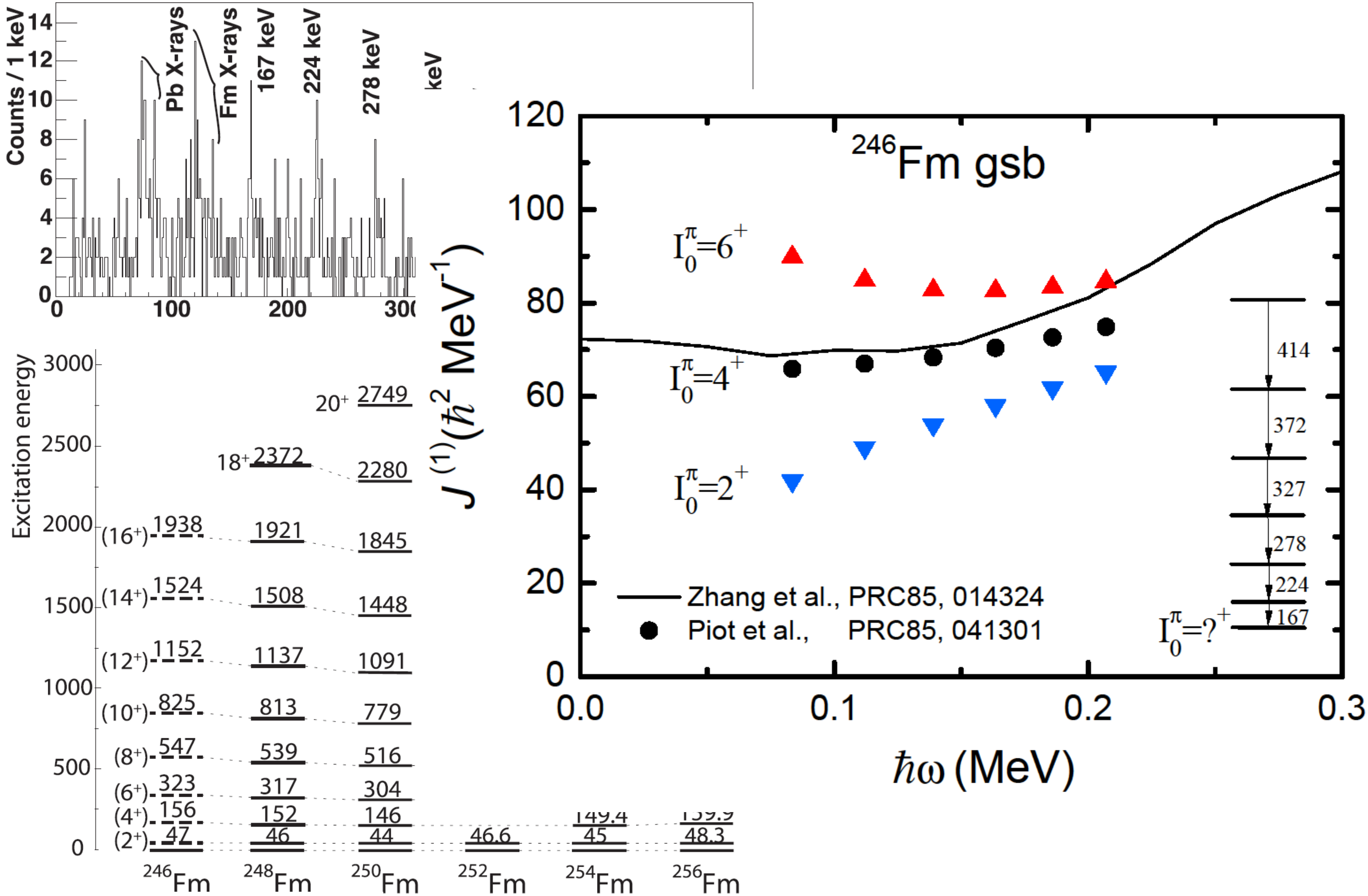
^{246}Fm: ground state band observed @ Jyvaskyla





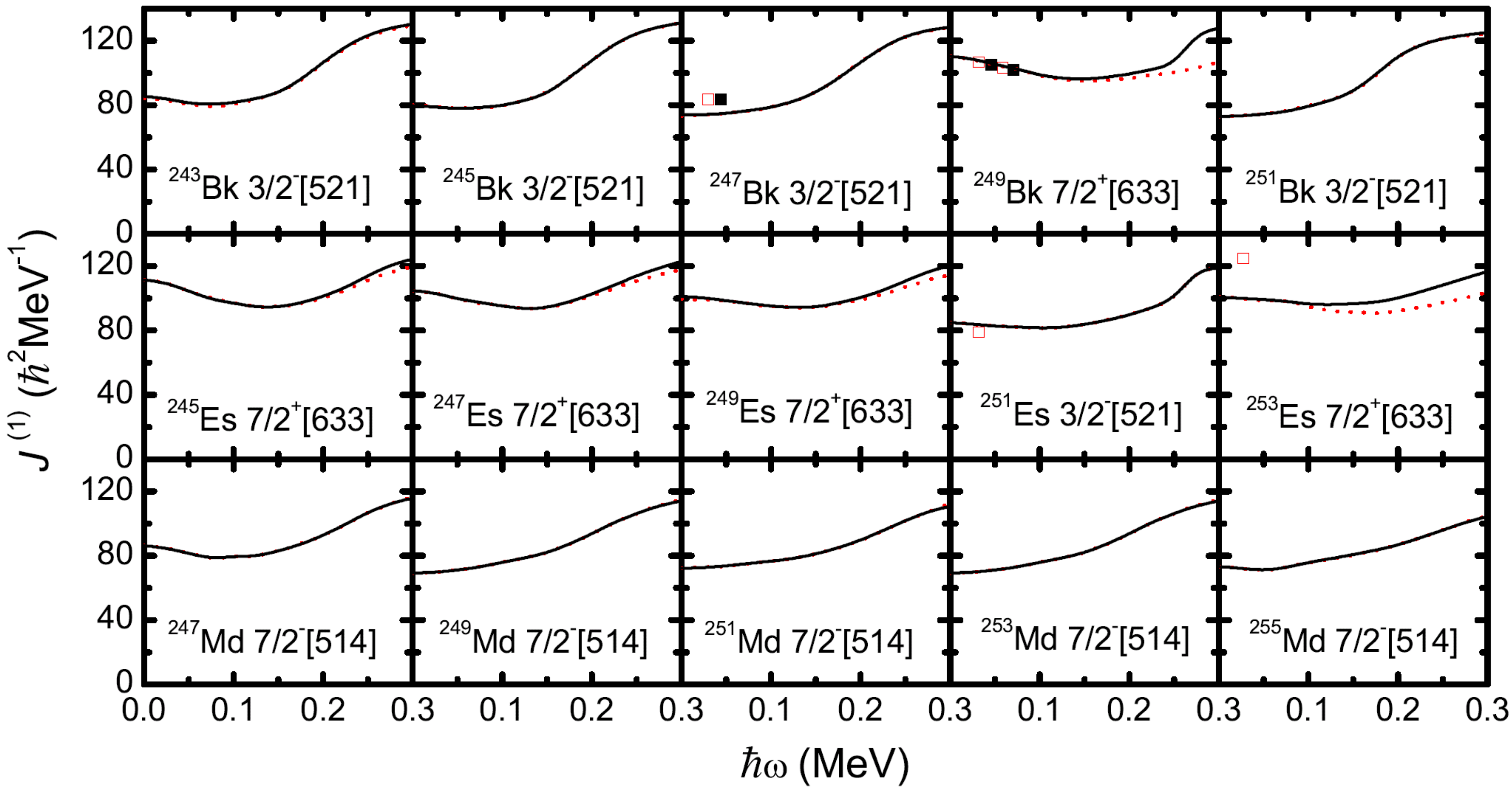
Piot...2012 PRC85_041301R

^{246}Fm: ground state band observed @ Jyvaskyla



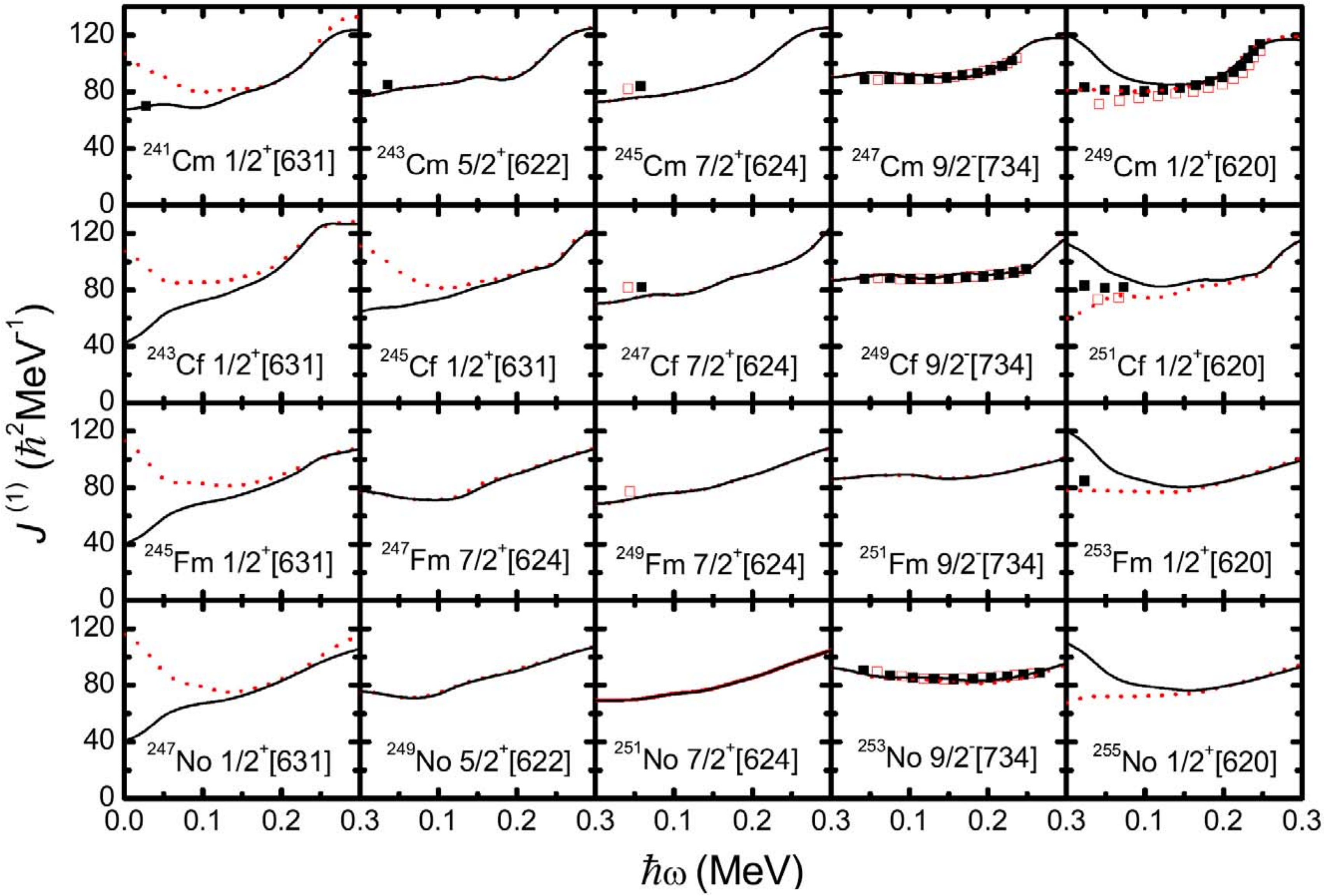
Piot...2012 PRC85_041301R

Moments of inertia of odd-Z nuclei



Zhang_He_Zeng_Zhao_SGZ2012, PRC85_014324

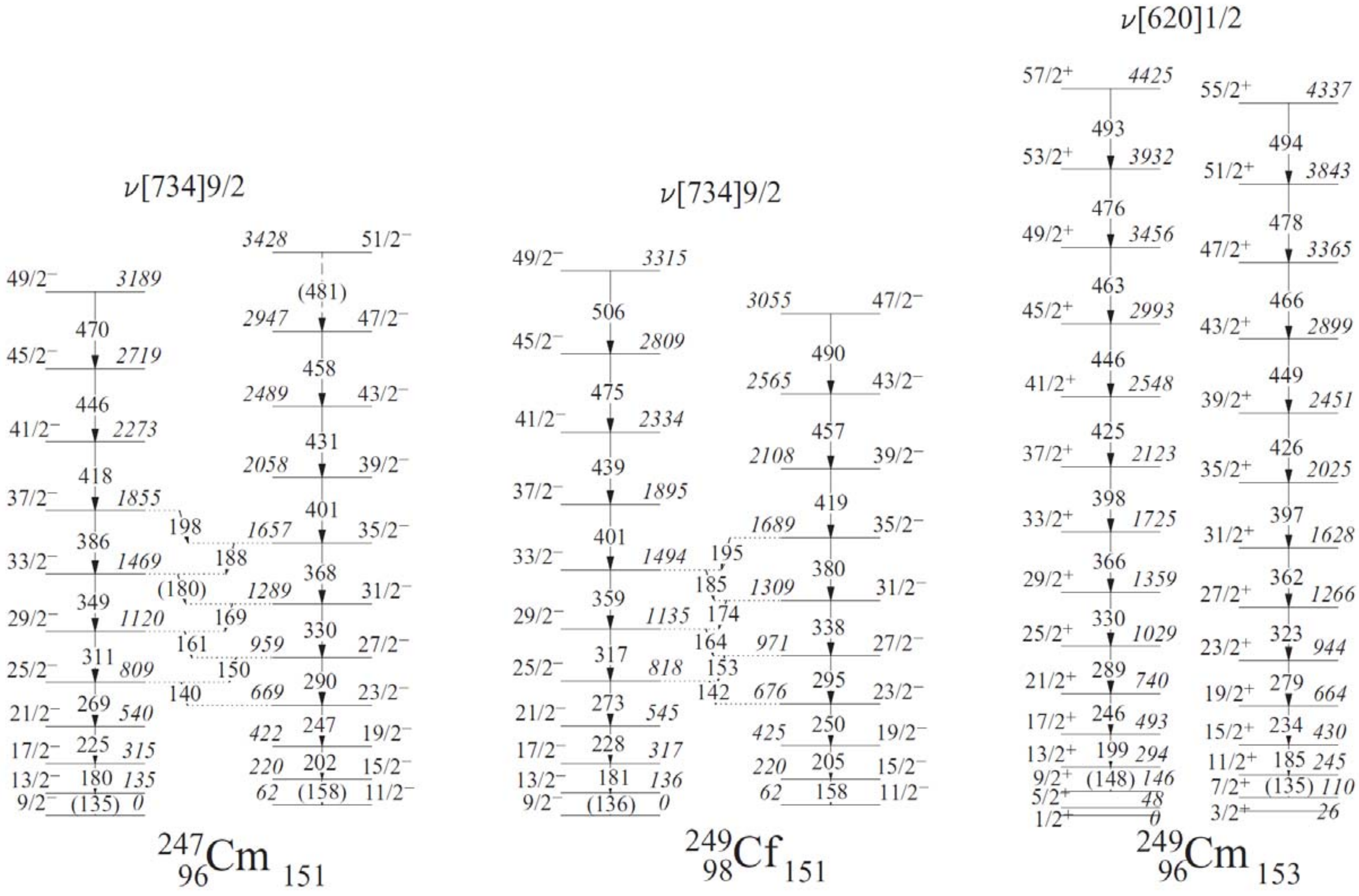
Moments of inertia of odd-N nuclei



Zhang_He_Zeng_Zhao_SGZ2012, PRC85_014324

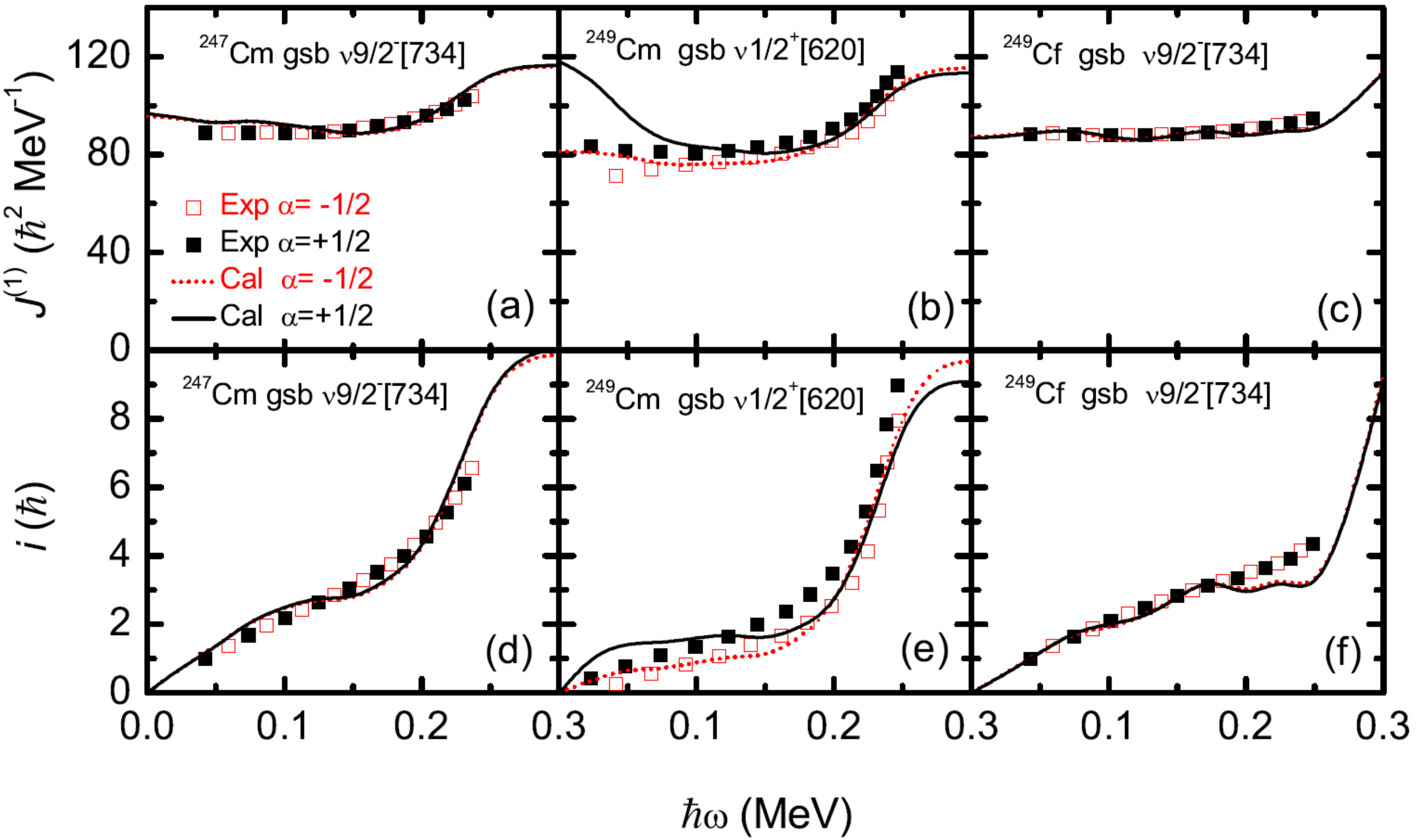
Rotational bands in ^{247,249}Cm & ^{249}Cf: Expt

Tandel...2010_PRC82-021303R



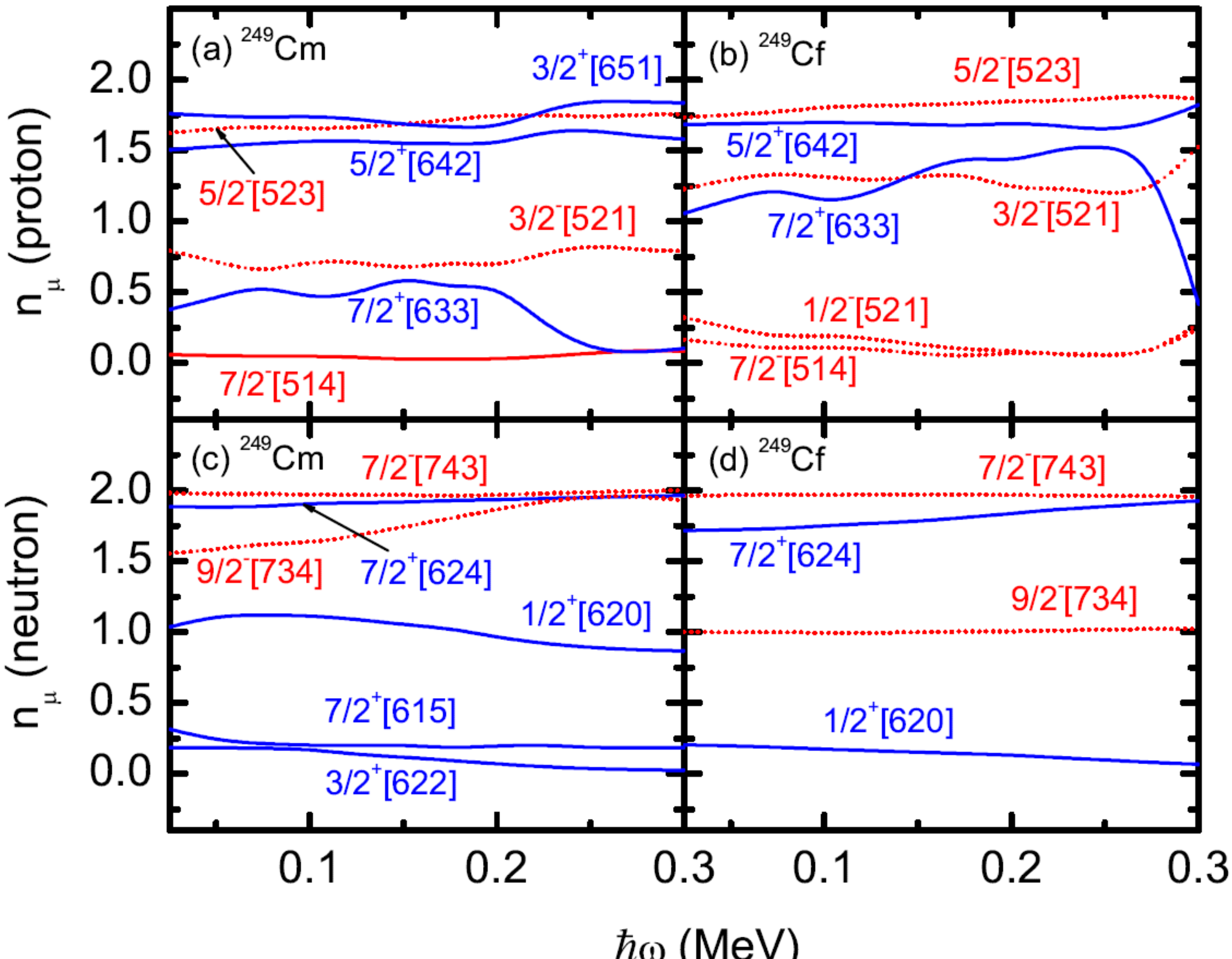
Rotational bands in ^{247,249}Cm & ^{249}Cf: MoI & align.

Zhang_Zeng_Zhao_SGZ2011_PRC83-011304R



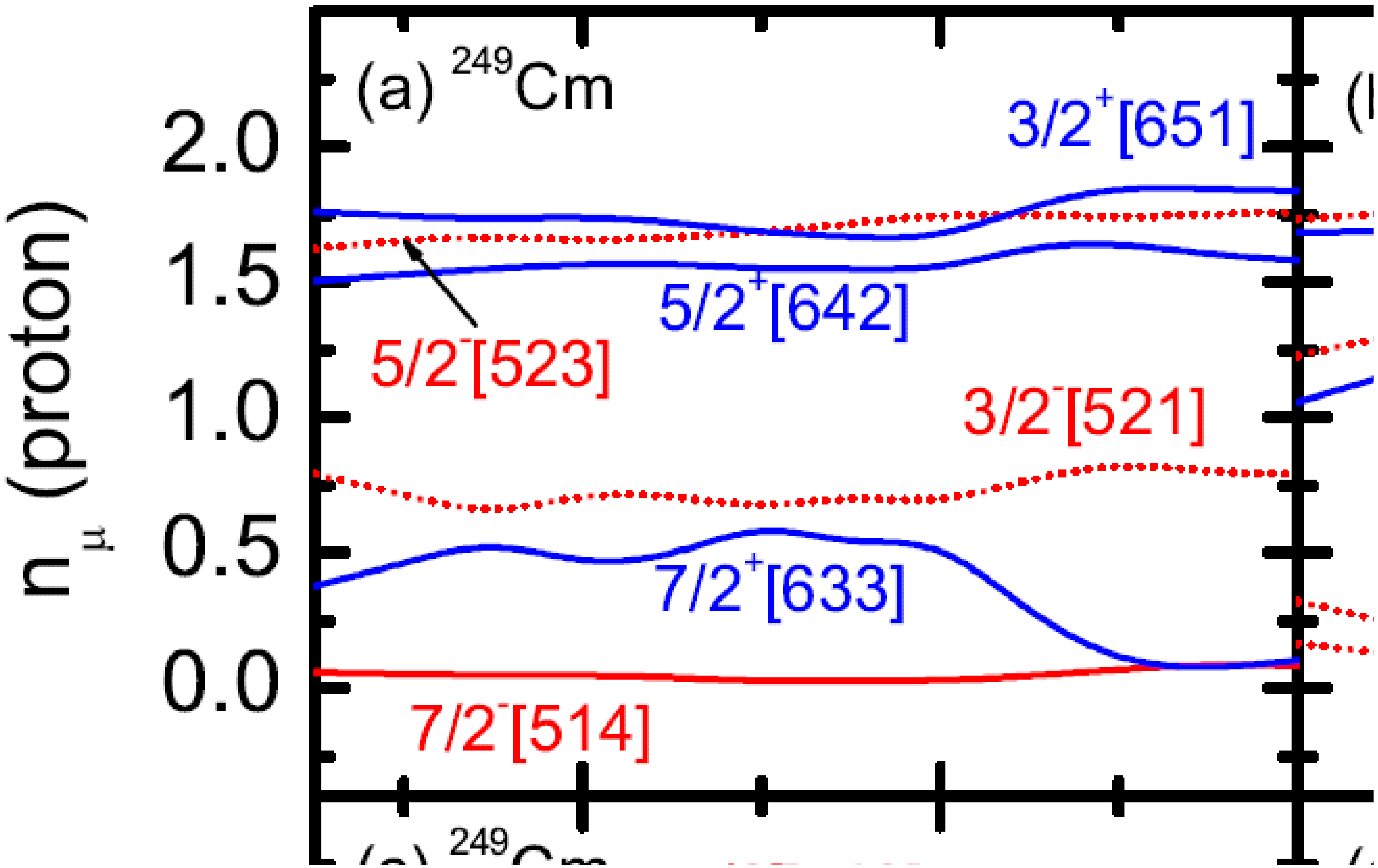
Rotational bands in ^{247,249}Cm & ^{249}Cf: occupations

Zhang_Zeng_Zhao_SGZ2011_PRC83-011304R

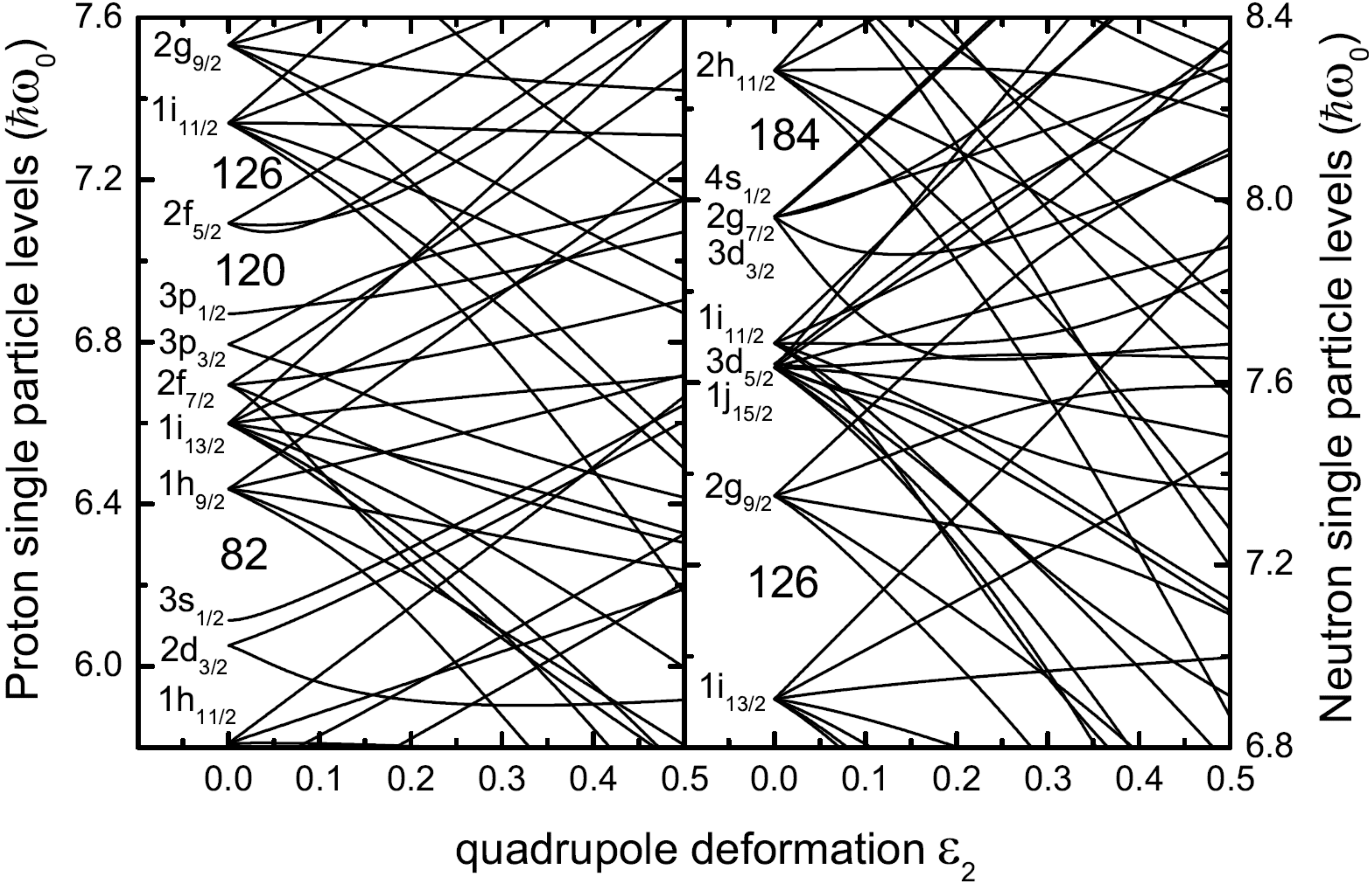


Rotational bands in ^{247,249}Cm & ^{249}Cf: occupations

Zhang_Zeng_Zhao_SGZ2011_PRC83-011304R

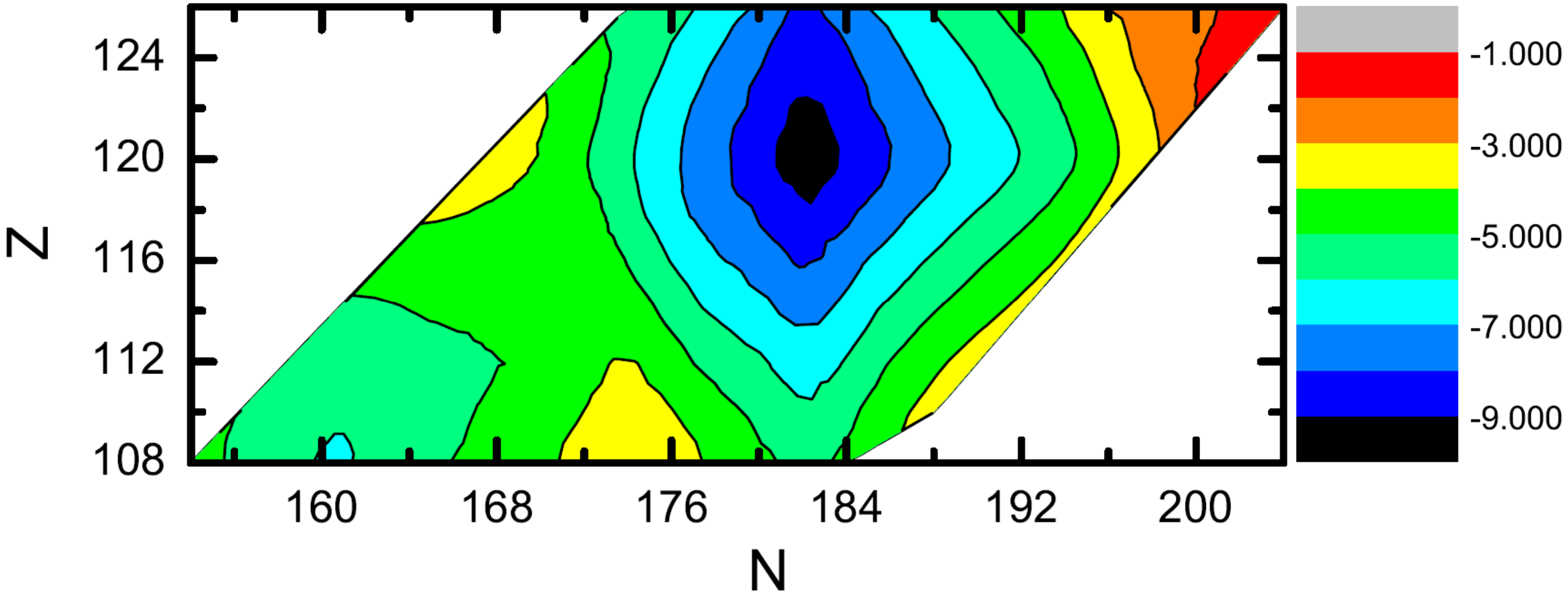


Magicity in SHN with the new Nilsson parameter set



Zhang et al., in preparation

Microscopic correction energy



Zhang et al., in preparation

A multi-dimensional constrained RMF model & PES

- A constraint deformed RMF model for normal & hypernuclei
  - ➢**Deformation space: (β_2, γ, β_3, ⋯)**
  - ➢**An axially deformed harmonic oscillator basis**
- Shapes of hypernuclei

  Lu_Zhao_SGZ2011_PRC84-014328

- Fission barriers of heavy & superheavy nuclei

  Lu_Zhao_SGZ 2012 PRC85_011301R

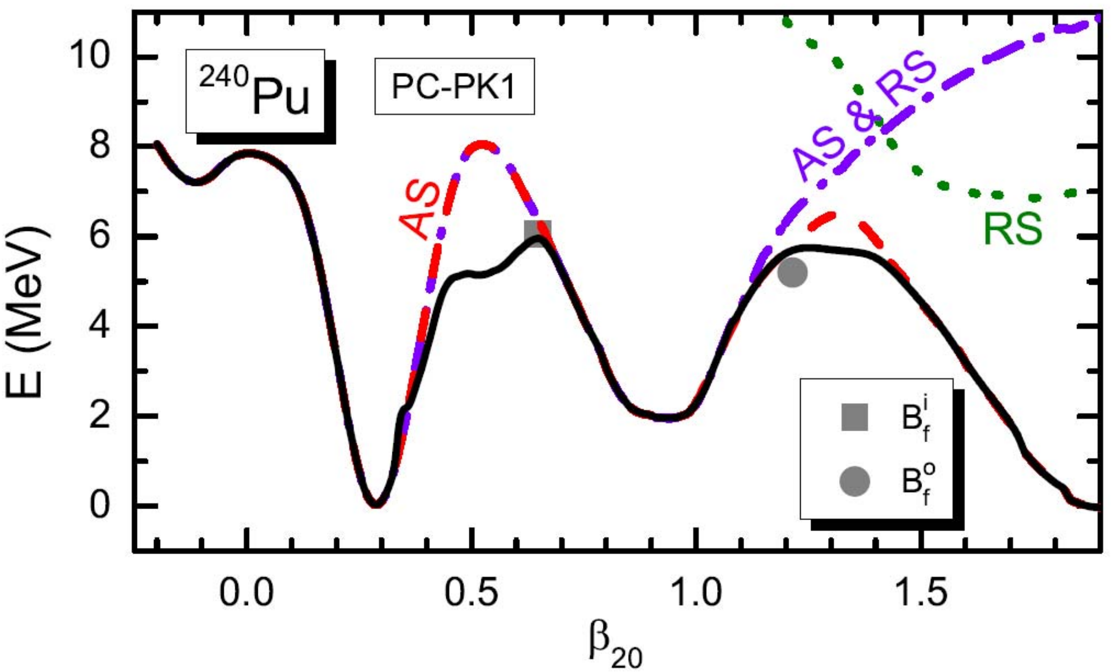
Why multi-dimensional?

- Triaxiality: the 1st barrier

  Abusara…2010_PRC82-044303

- Asymmetry: the 2nd barrier

  Rutz…1995_NPA590-680



Relativistic mean field model

$$
\begin{aligned}
\mathcal{L} = {}& \bar\psi_i \left(i\partial\!\!\!/ - M\right)\psi_i + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - g_\sigma\bar\psi_i\sigma\psi_i \\
& - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - g_\omega\bar\psi_i\omega\!\!\!/\psi_i \\
& - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec\rho_\mu\vec\rho^\mu - g_\rho\bar\psi_i\vec{\rho\!\!\!/}\vec\tau\psi_i \\
& - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - e\bar\psi_i\frac{1-\tau_3}{2}A\!\!\!/\psi_i,
\end{aligned}
$$

Serot_Walecka1986_ANP16-1

Reinhard1989_RPP52-439

Ring1996_PPNP37-193

Vretenar_Afanasjev_Lalazissis_Ring2005_PR409-101

Meng_Toki_SGZ_Zhang_Long_Geng2006_PPNP57-470

A multi-dimensional constrained RMF model

Lu_Zhao_SGZ 2011_PRC84-014328

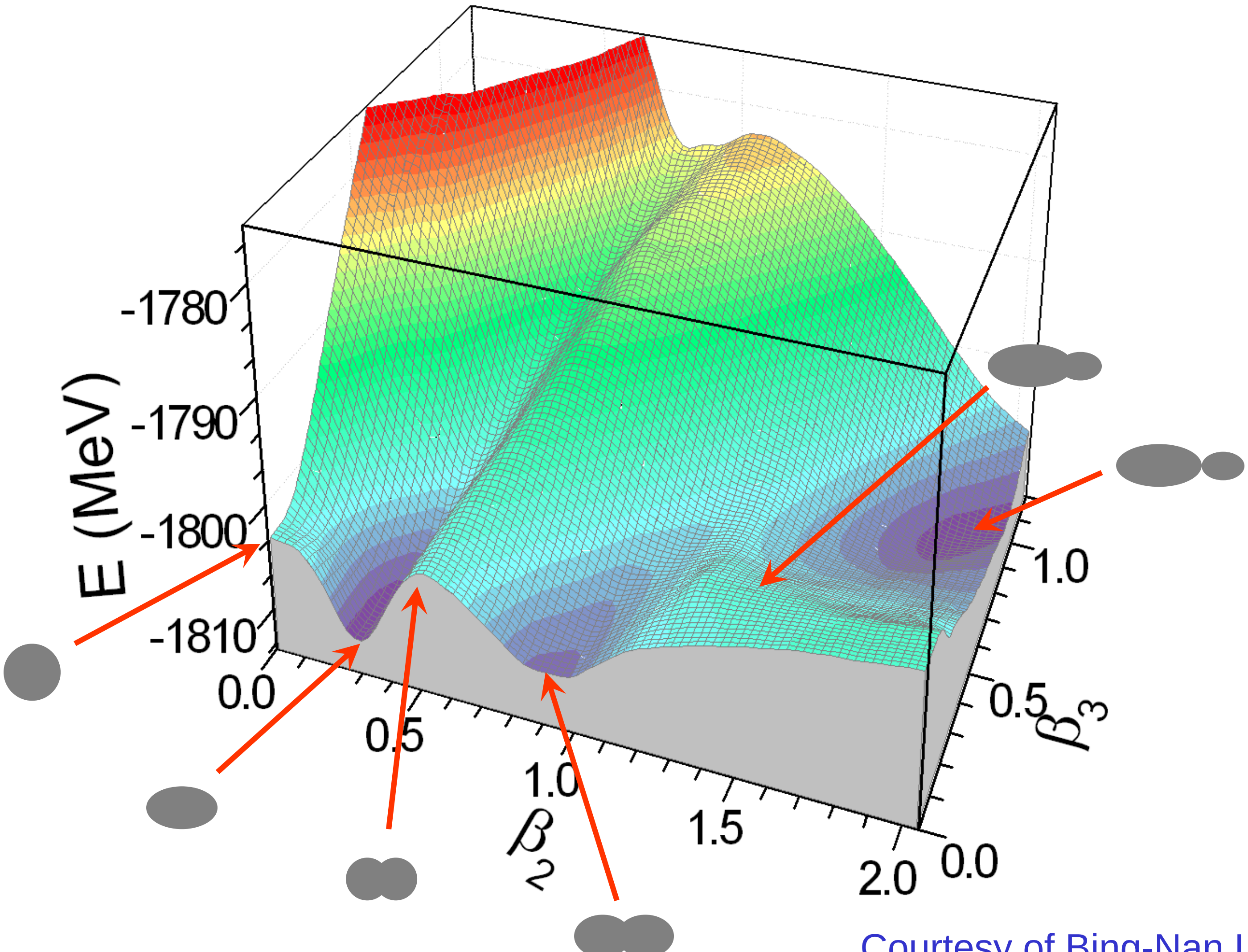
Lu_Zhao_SGZ 2012 PRC85_011301R

Lu_Zhao_SGZ in preparation

	Non-linear	Density-dependent
Meson exchange	**NL3, NL3*, PK1, …**	**DD-ME1, DD-ME2, …**
Point Coupling	**PC-F1, PC-PK1, …**	**DD-PC1, …**

Potential energy surfaces

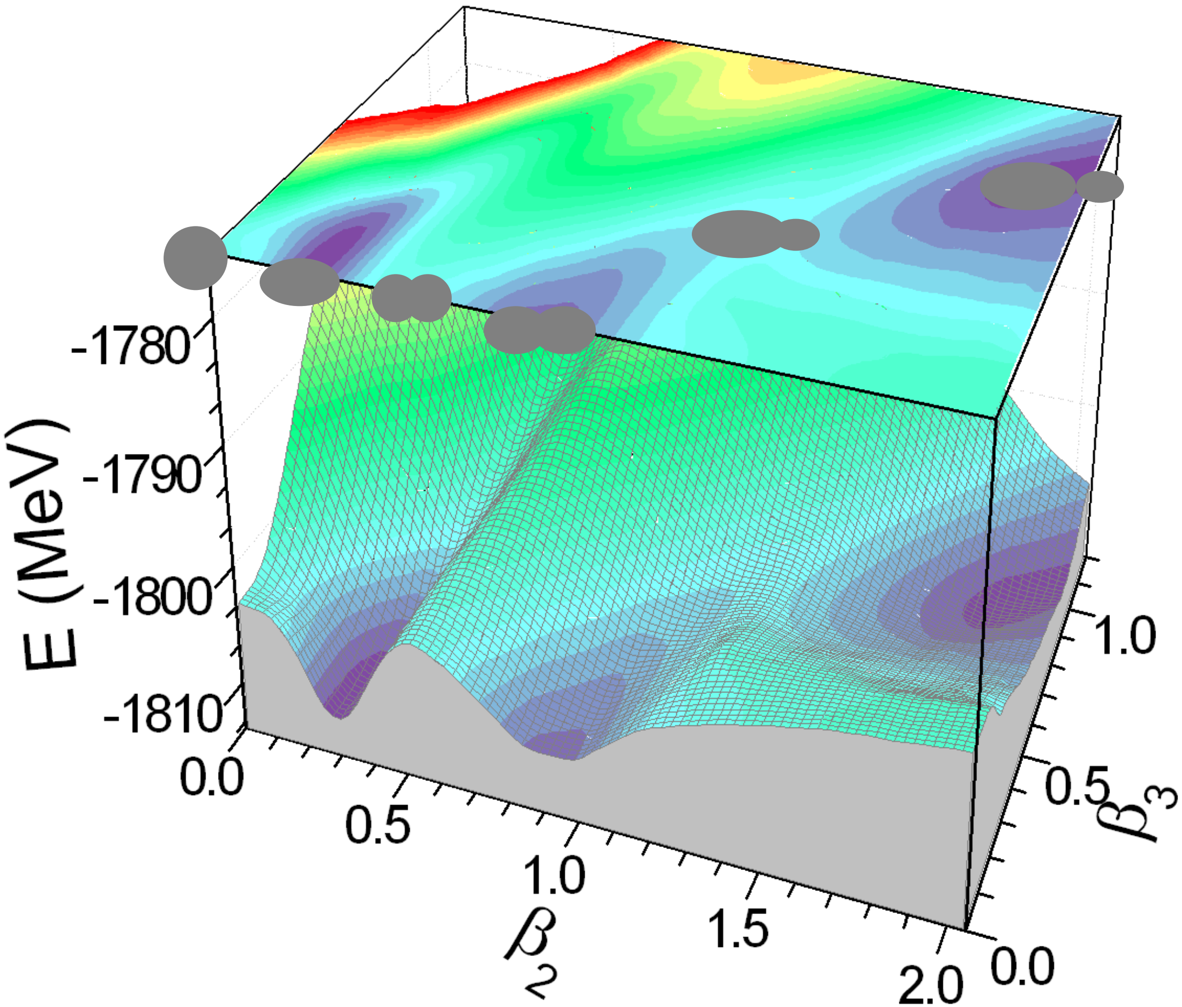
- Mass, shape, & fission



Courtesy of Bing-Nan Lu (吕炳楠)

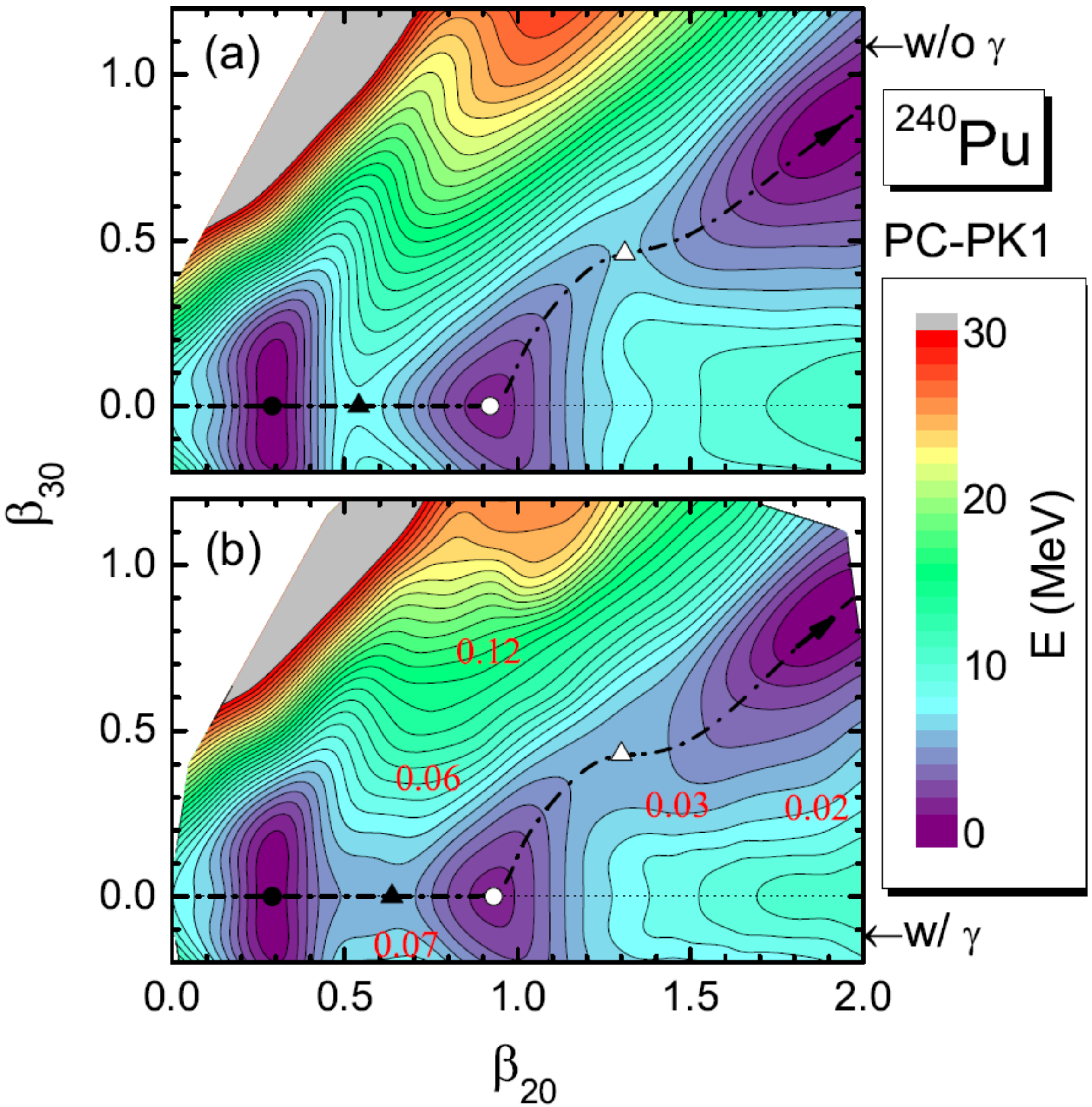
Potential energy surfaces

- Shape, fission path & fission barrier



Courtesy of Bing-Nan Lu (吕炳楠)

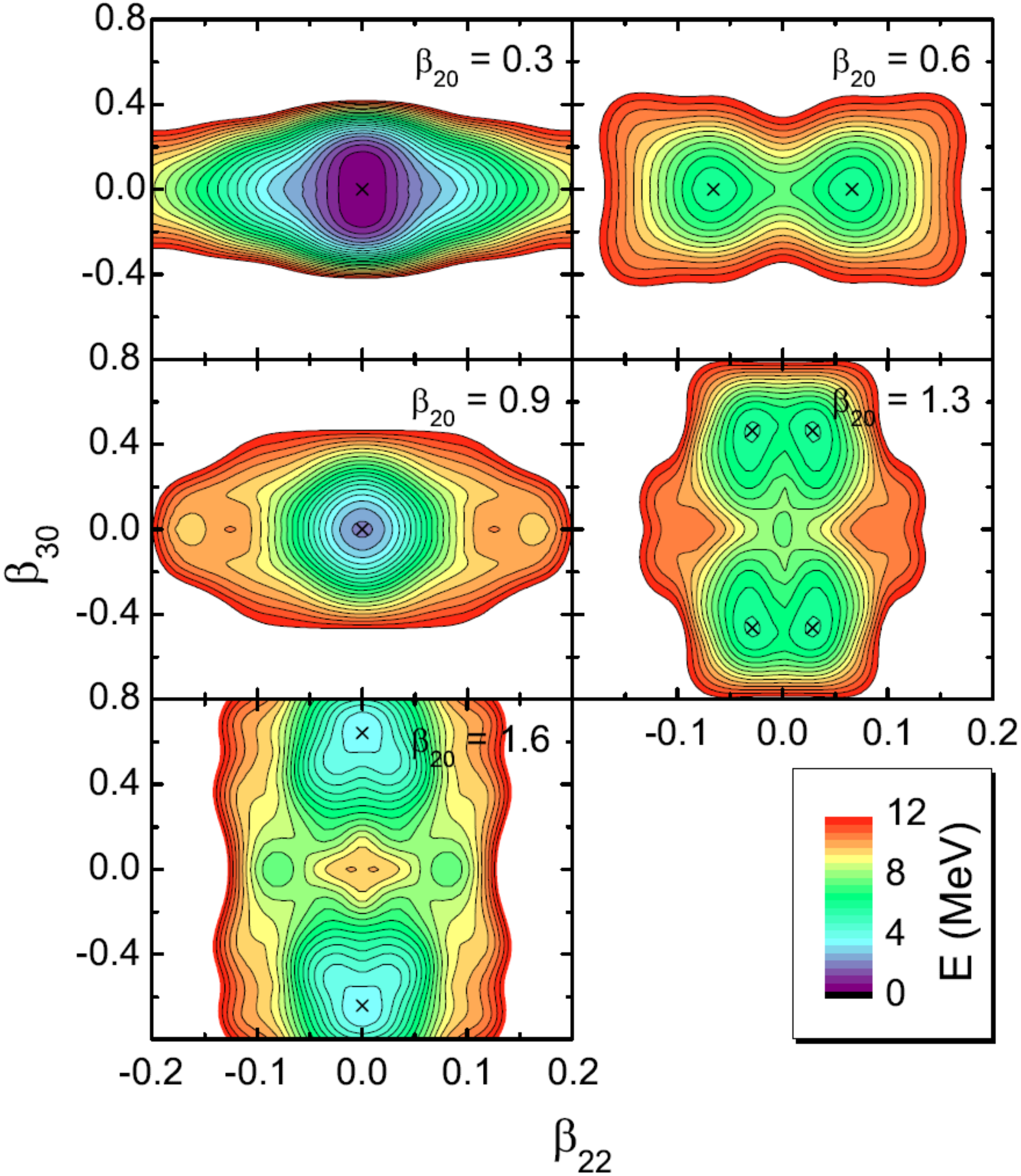
Three-dimensional constraint in the space (β_{20}, β_{22}, β_{30})

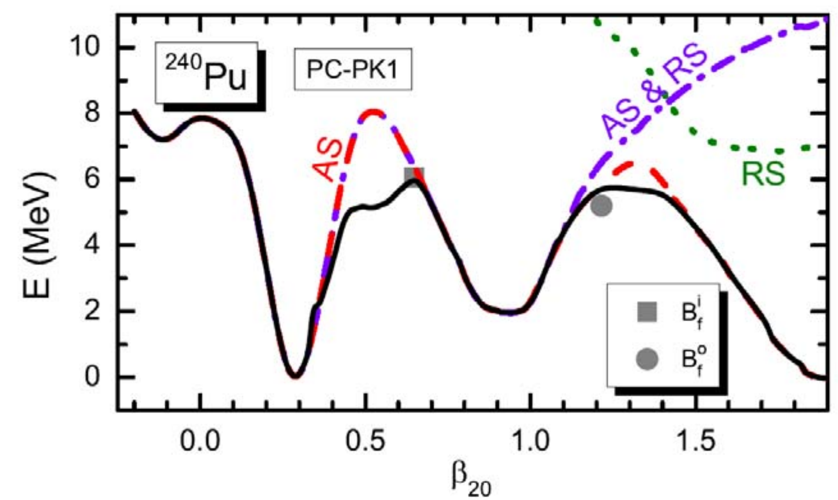


Lu_Zhao_SGZ2012 PRC85_011301R

Three-dimensional constraint in the space (β_{20}, β_{22}, β_{30})

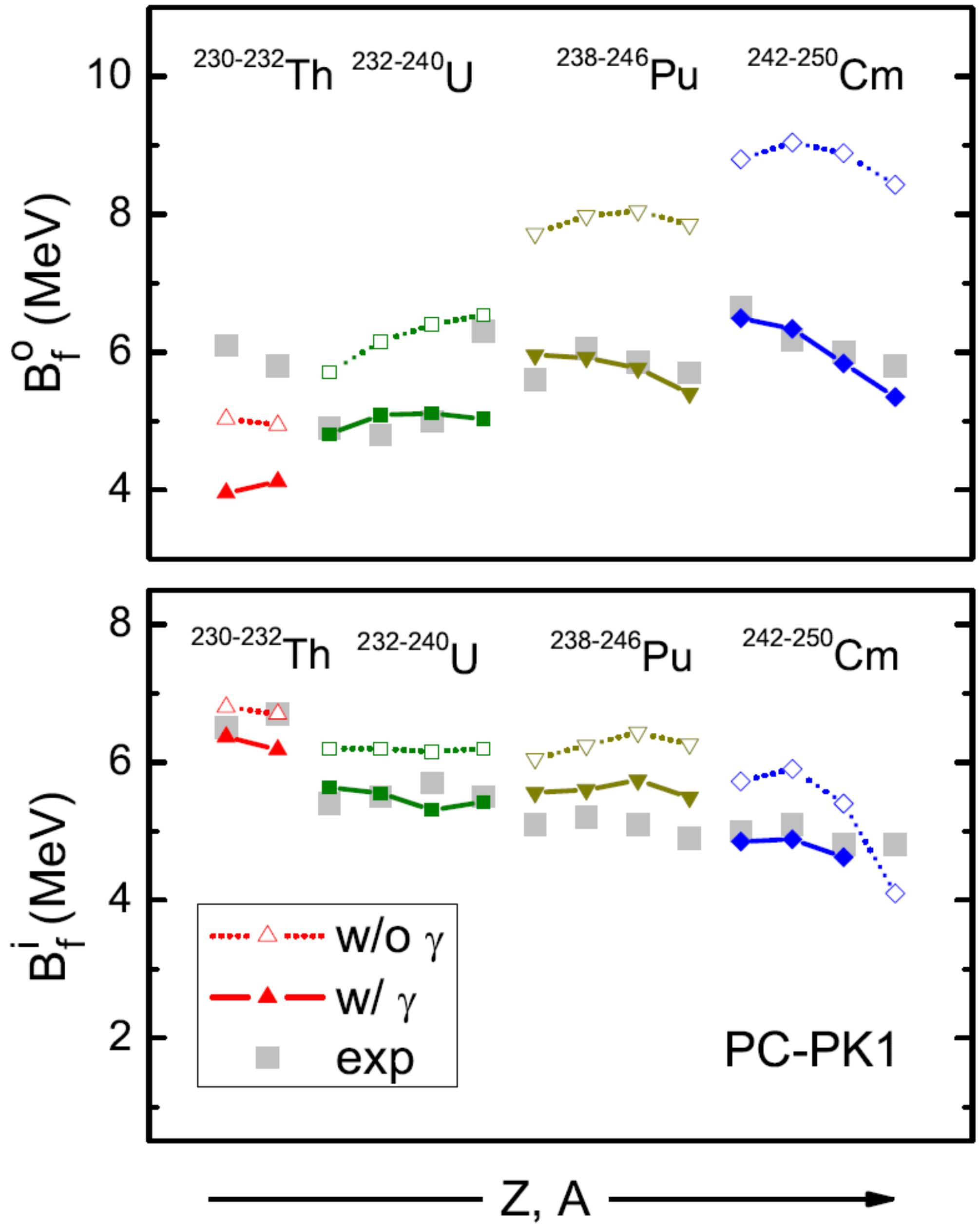
Lu_Zhao_SGZ2012 PRC85_011301R

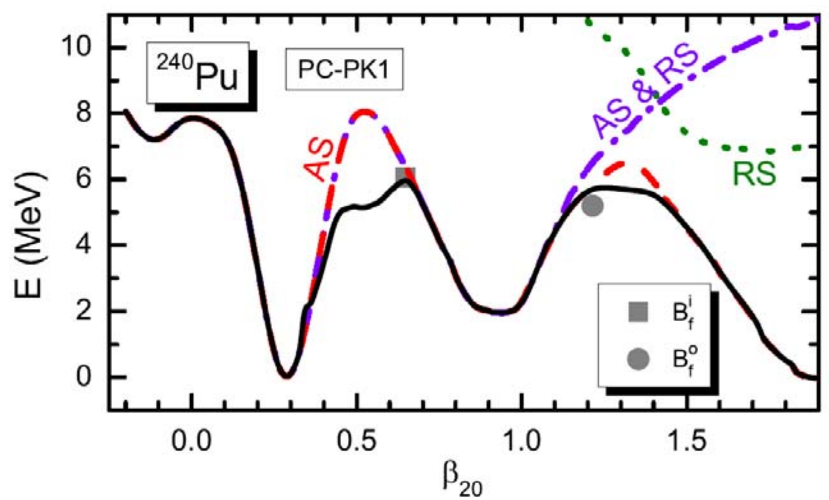




B_f of some even-even actinide nuclei

Lu_Zhao_SGZ2012 PRC85_011301R





Tetrahedral shape in heavy & superheavy nuclei?

PHYSICAL REVIEW C **77**, 061305(R) (2008)

Nonaxial-octupole effect in superheavy nuclei

Y.-S. Chen,[1] Yang Sun,[2,3] and Zao-Chun Gao[1,4]

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[2]*Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China*

[3]*Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA*

[4]*Department of Physics, Central Michigan University, Mount Pleasant, Michigan 48859, USA*

(Received 26 March 2008; published 26 June 2008)

The triaxial-octupole Y_{32} correlation in atomic nuclei has long been expected to exist but experimental evidence has not been clear. We find, in order to explain the very low-lying 2^- bands in the transfermium mass region, that this exotic effect may manifest itself in superheavy elements. Favorable conditions for producing triaxial-octupole correlations are shown to be present in the deformed single-particle spectrum, which is further supported by quantitative Reflection Asymmetric Shell Model calculations. It is predicted that the strong nonaxial-octupole effect may persist up to the element 108. Our result thus represents the first concrete example of spontaneous breaking of both axial and reflection symmetries in the heaviest nuclear systems.

Tetrahedral shape in heavy & superheavy nuclei?

PHYSICAL REVIEW C **77**, 061305(R) (2008)

[1]*China Instit*
[2]*Department of*
[3]*Joint Institute*
[4]*Departme*

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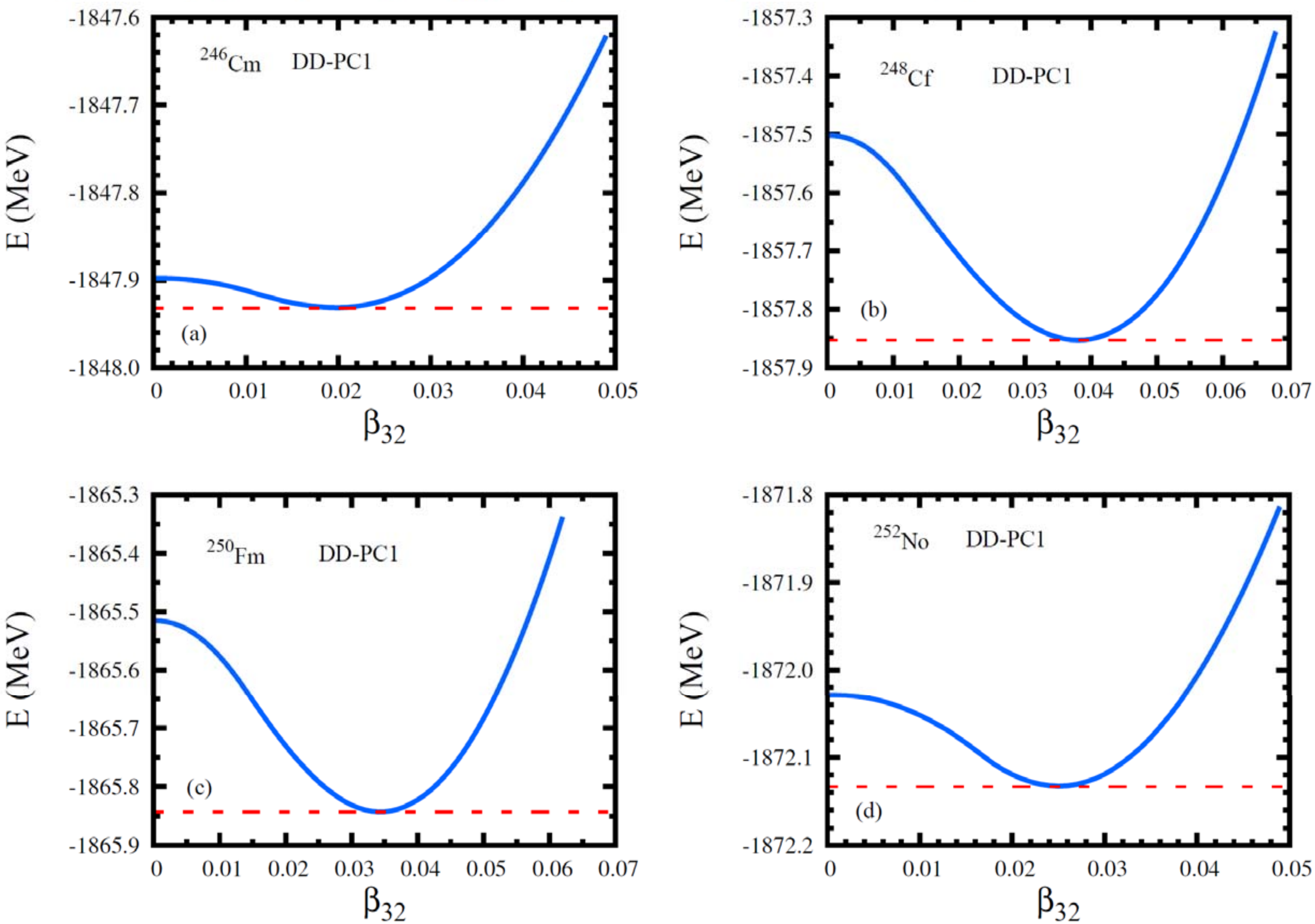
correlations are sho
quantitative Reflect
effect may persist u
breaking of both ax



Zhao_Lu_Zhao_SGZ in preparation

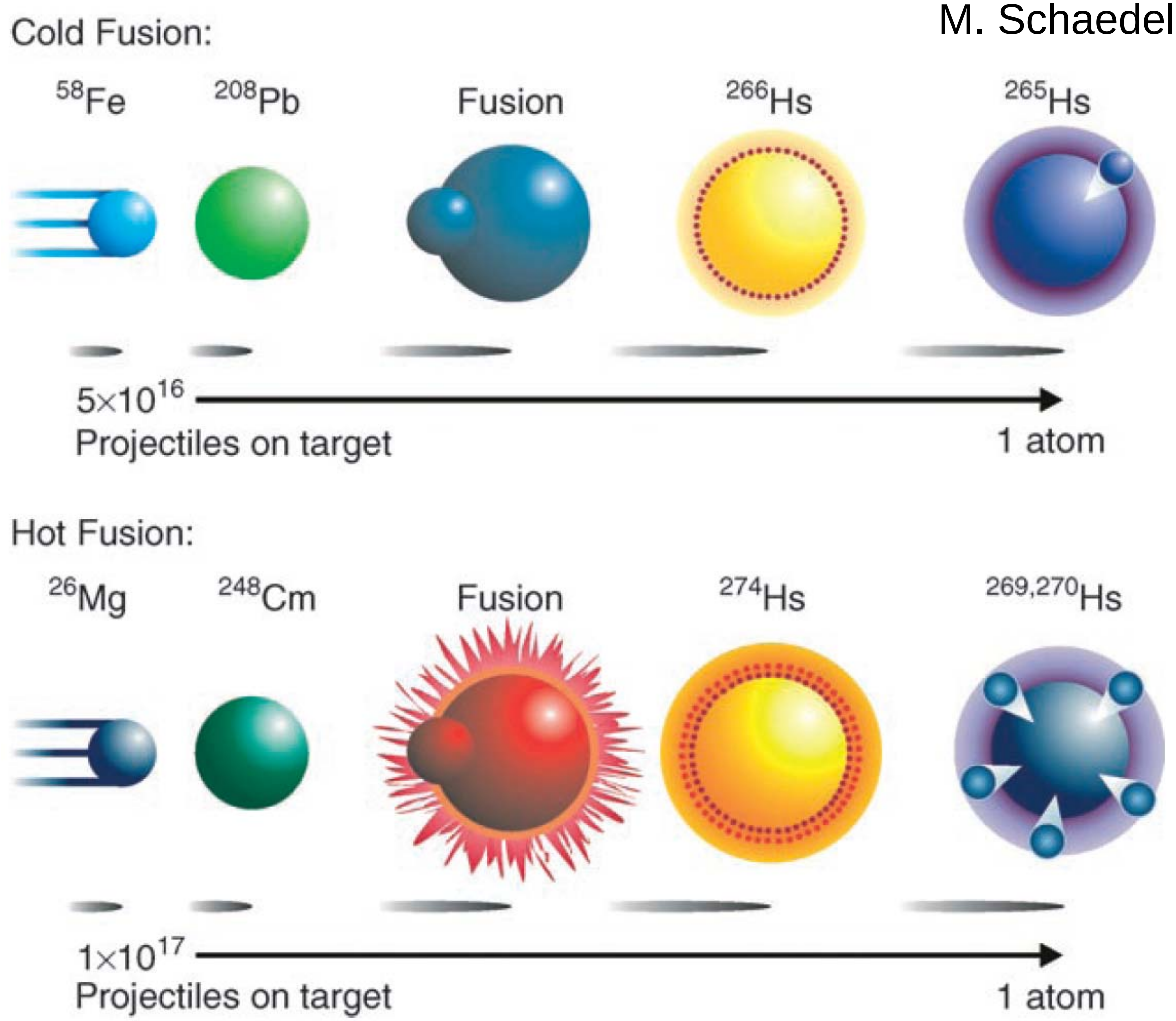
Theoretical Study of SHN

- Structure
- Decay & fission
- Synthesis mechanism

Three-step to a SHN

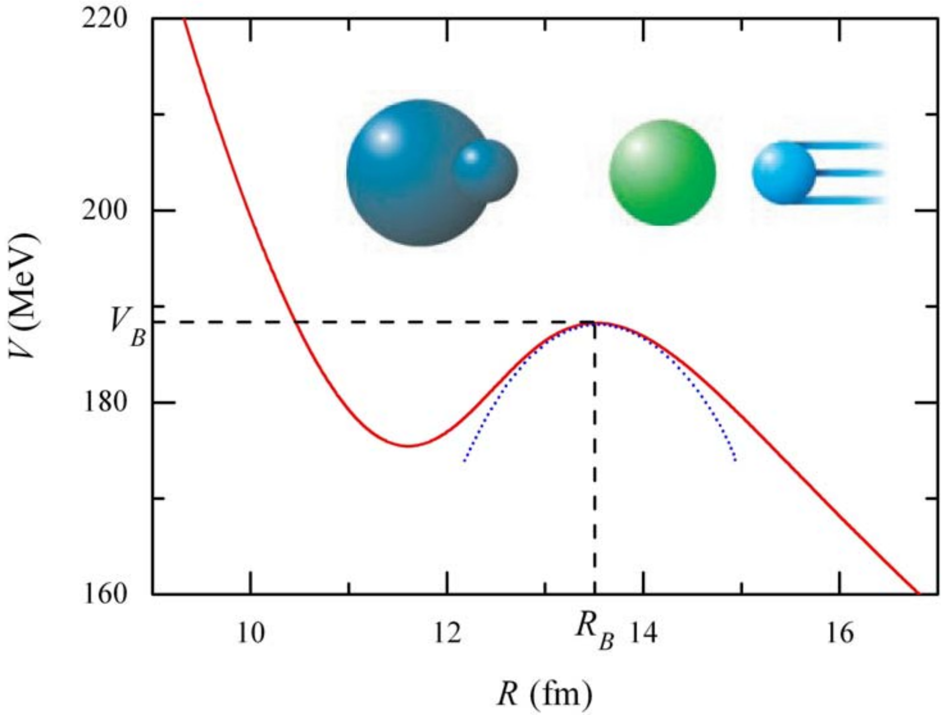
M. Schaedel

- Capture
- Formation of CN
- Deexcitation of CN



$$\sigma_{\mathrm{ER}}(E_{\mathrm{cm}}) = \sum_J \underbrace{\sigma_{\mathrm{cap}}(E_{\mathrm{cm}}, J)}_{\text{Capture}} \underbrace{P_{\mathrm{CN}}(E_{\mathrm{cm}}, J)}_{\text{CN formation}} \underbrace{W_{\mathrm{sur}}(E_{\mathrm{cm}}, J)}_{\text{neutron(s) emission}}$$

Capture process



- **Path integral method**
- **WKB approximation**
- **Hill-Wheeler formula**
- **New formula by Li et al.**
- **...**

$$\sigma_{\text{cap}}(E_{\text{cm}}, J) = \frac{\pi\hbar^2}{2\mu E_{\text{cm}}}(2J+1)\,T(E_{\text{cm}}, J)$$

$$T(E_{\text{cm}}, J) = \left(1 + \exp\left[-\frac{2\pi}{\hbar\omega}(E_{\text{cm}} - E_{\text{rot}} - V_B)\right]\right)^{-1}$$

Hill_Wheeler1953_PR089-1102

Formation of CN

- The macroscopic dynamical model

  Swiatecki1982_NPA376-275

- The fluctuation-dissipation model

  Abe2002_EPJA13-143; Shen...2002_PRC66-061602R

- The nucleon collectivization model

  Zagrebaev2001_PRC64-034606

- The fusion by diffusion models

  Liu_Bao2007_PRC76-034604 Swiatecki...2005_PRC71-014602

- The model based on multi-dimensional Langevin equations

  Zagrebaev_Greiner2005_JPG31-825

- Models based on the di-nuclear system concept

  Adamian...1998_NPA633-409

  Li...2003_EuroPhysLett64-750; Zhao...2008_IJMPE17-1937; Li...2010_NPA834-353c

- ......

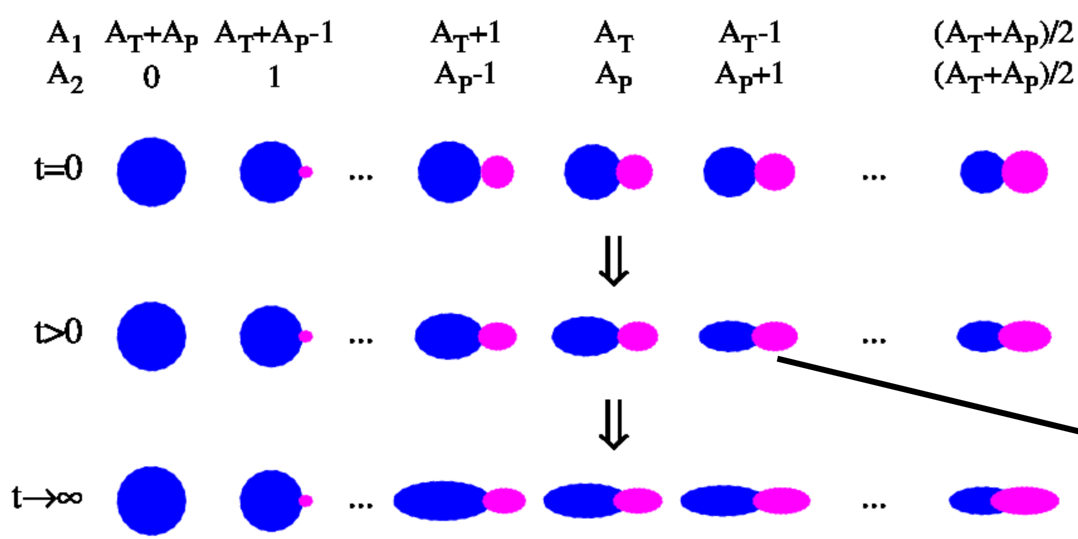
Volkov2004_ActaPhysHungA19-67

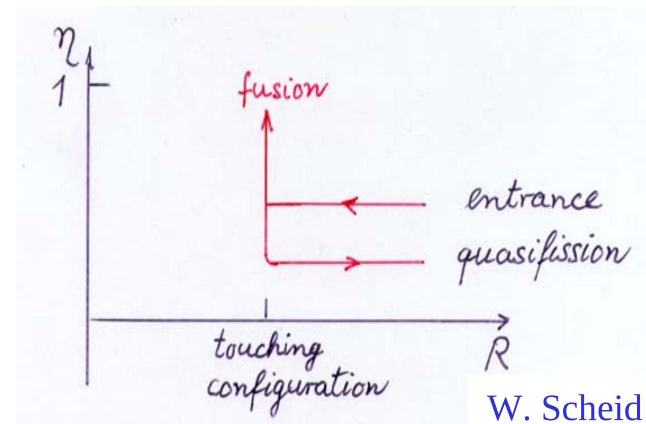
Feng...2011_NuclPhysRev28-1

The DNS models

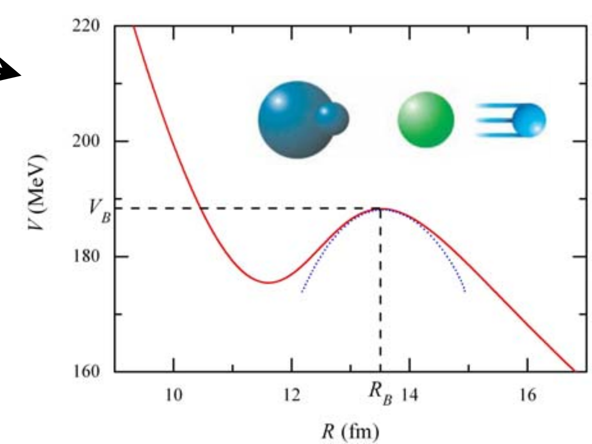
After the capture process, the two colliding nuclei form a di-nuclear system and keep their individualities

- **Exchanges of nucleon between the two nuclei**
- **The DNS may go quasi-fission & the heavier one may fission**
- **Deformations develop in both nuclei**





W. Scheid



The DNS models

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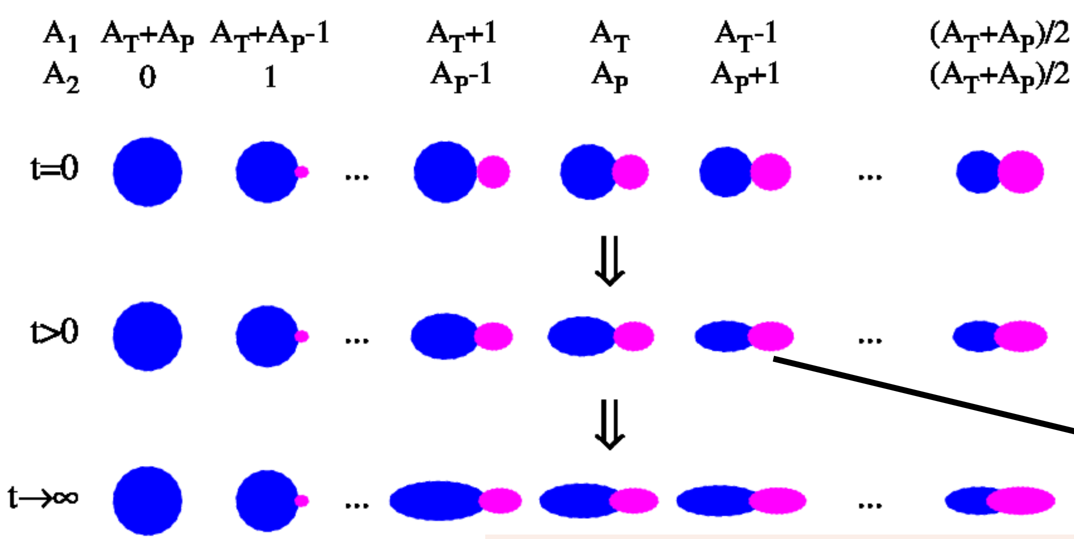
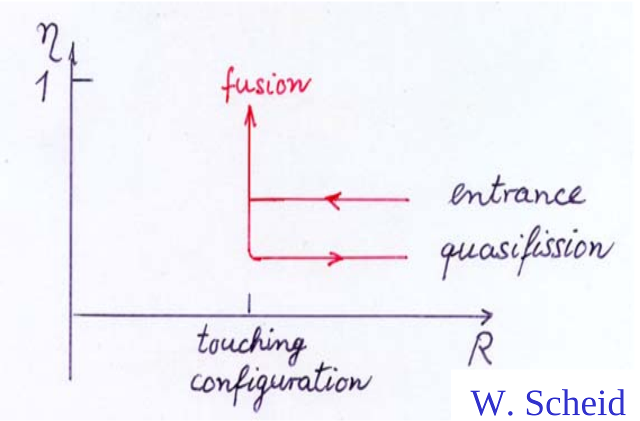
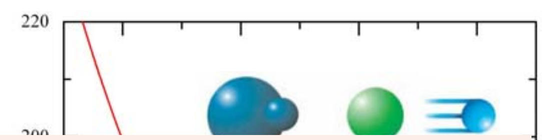




W. Scheid

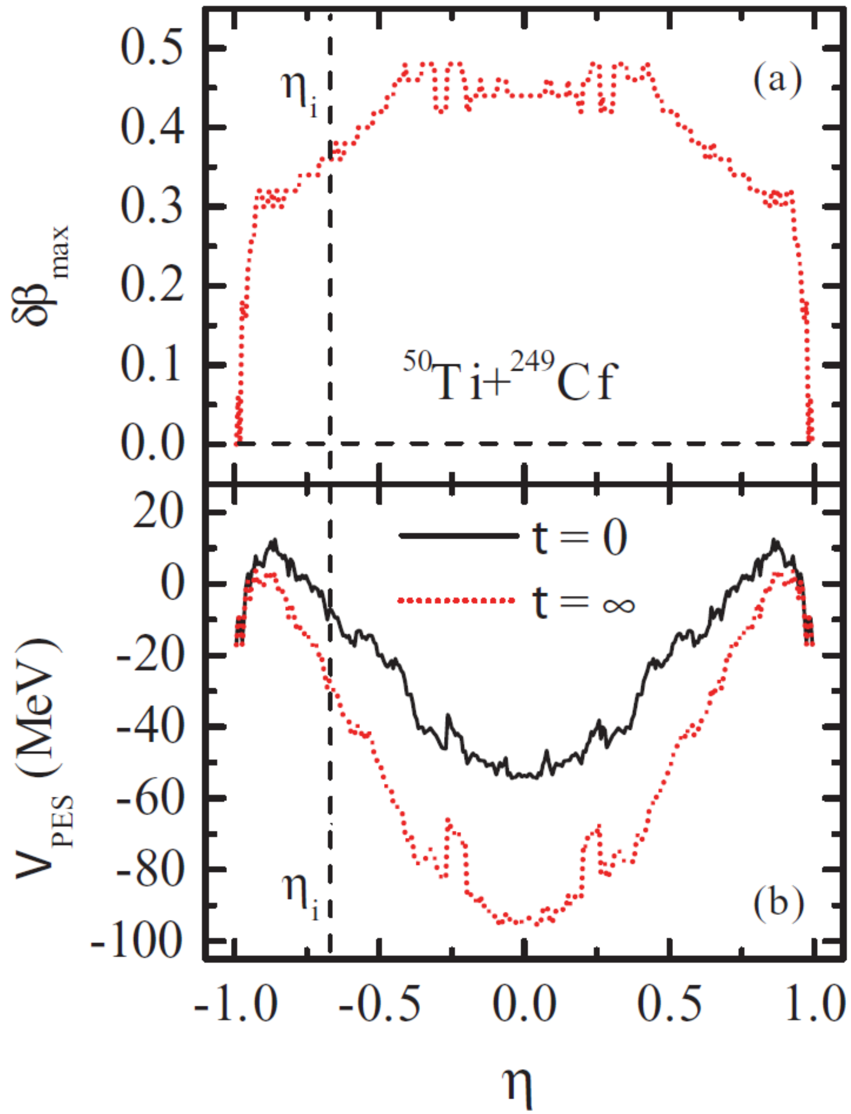


$$P(A_1, t = 0) = \delta_{A_1 A_P}$$

$$\begin{aligned}
\frac{d}{dt}P(A_1,t) &= \sum_{A_1'} W_{A_1'A_1}(t)\, d_{A_1}(t)\, P(A_1',t) && \text{gain}\\
&- \sum_{A_1'} W_{A_1A_1'}(t)\, d_{A_1'}(t)\, P(A_1,t) && \text{loss}\\
&- \Lambda^{\mathrm{qf}}_{A_1}(t)\, P(A_1,t) && \text{leak via quasifission}\\
&- \Lambda^{\mathrm{fis}}_{A_1}(t)\, P(A_1,t) && \text{leak via fission}
\end{aligned}$$

R (fm)

Dynamical PES

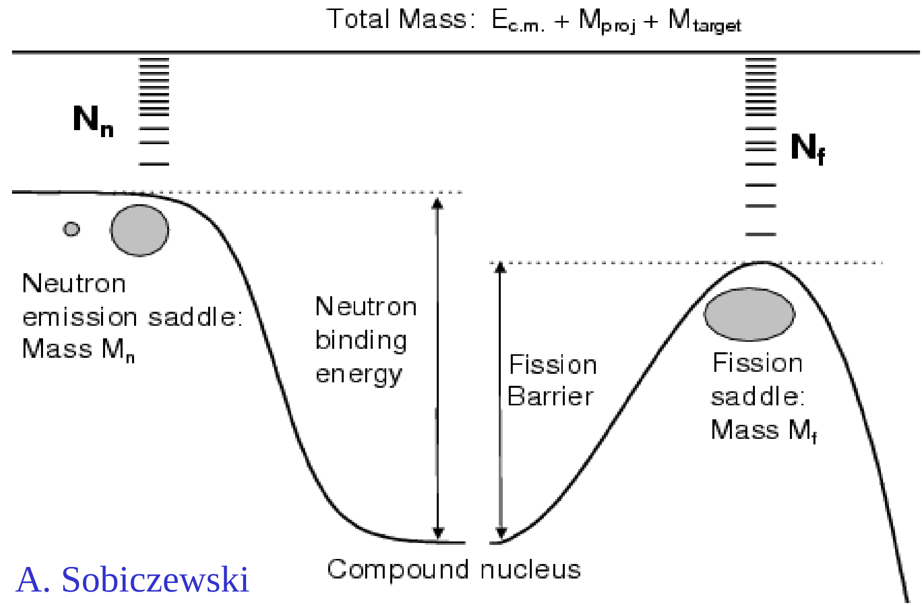


Wang_Zhao_Scheid_SGZ 2012_PRC85-041601R

Survival probability

De-excitation of excited CN:

- Fission
- Neutron emission
- Gamma decay
- Light-charged particle emission



A. Sobiczewski

Survival probability

De-excitation of excited CN:

- Fission
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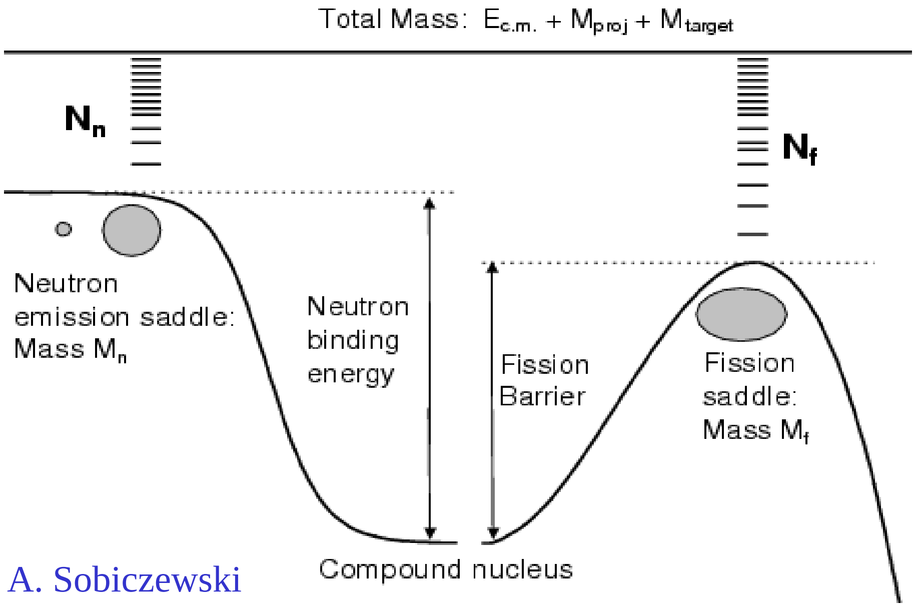


A. Sobiczewski

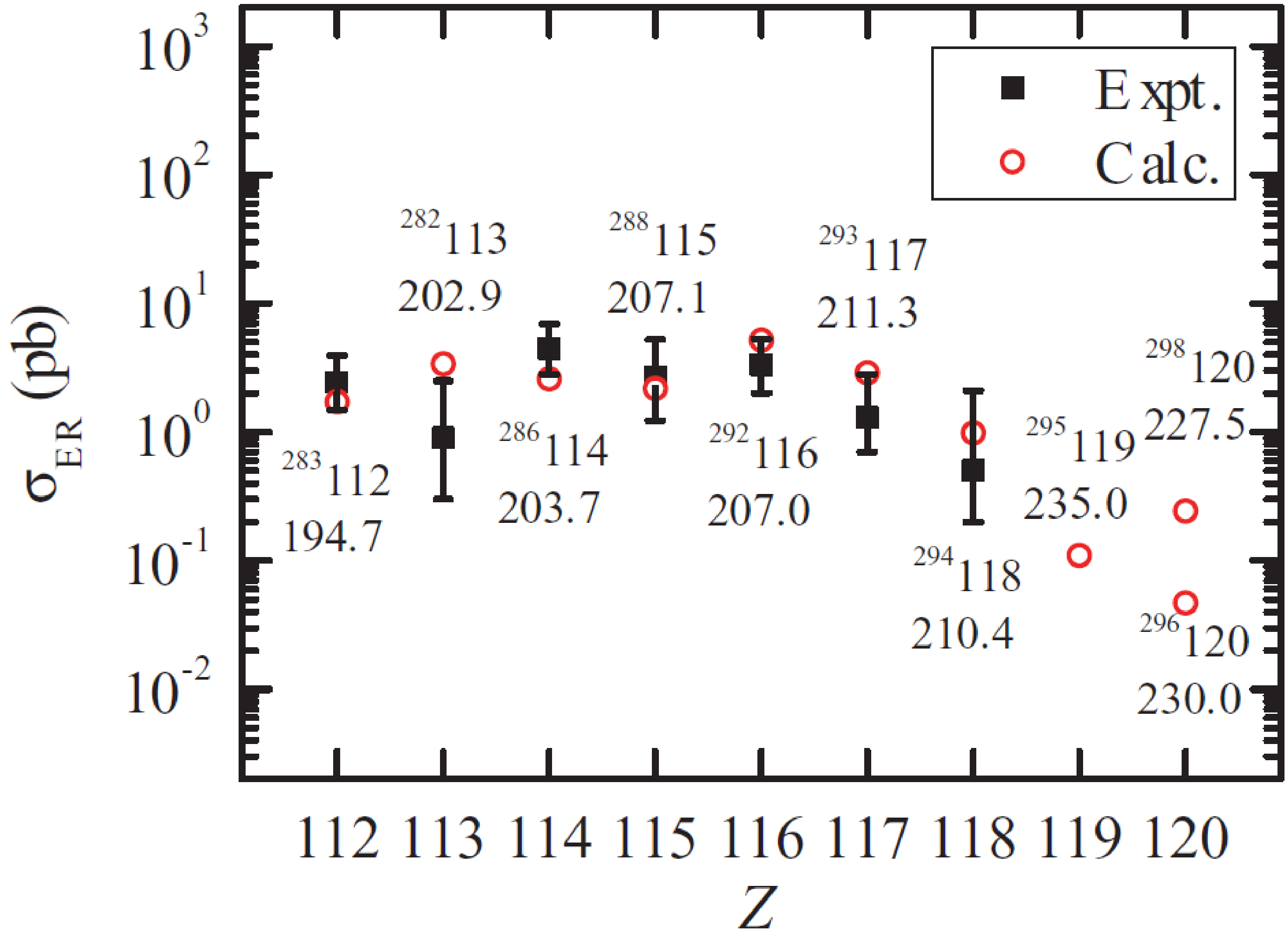
$$W_{\text{sur}}(E^*_{\text{CN}}, m, J) = P_{\text{r.l.}}(E^*_{\text{CN}}, m) \prod_{i=1}^{m} \frac{\Gamma_{\text{n}}(E^*_i, J)}{\Gamma_{\text{n}}(E^*_i, J) + \Gamma_{\text{f}}(E^*_i, J)}$$

Parameters needed:

- Fission barrier
- Neutron separation energy
- Level density
- Light-charged particle emission

X-sections in hot fusion reactions from a DNS model

Wang_Zhao_Scheid_SGZ 2012_PRC85-041601R

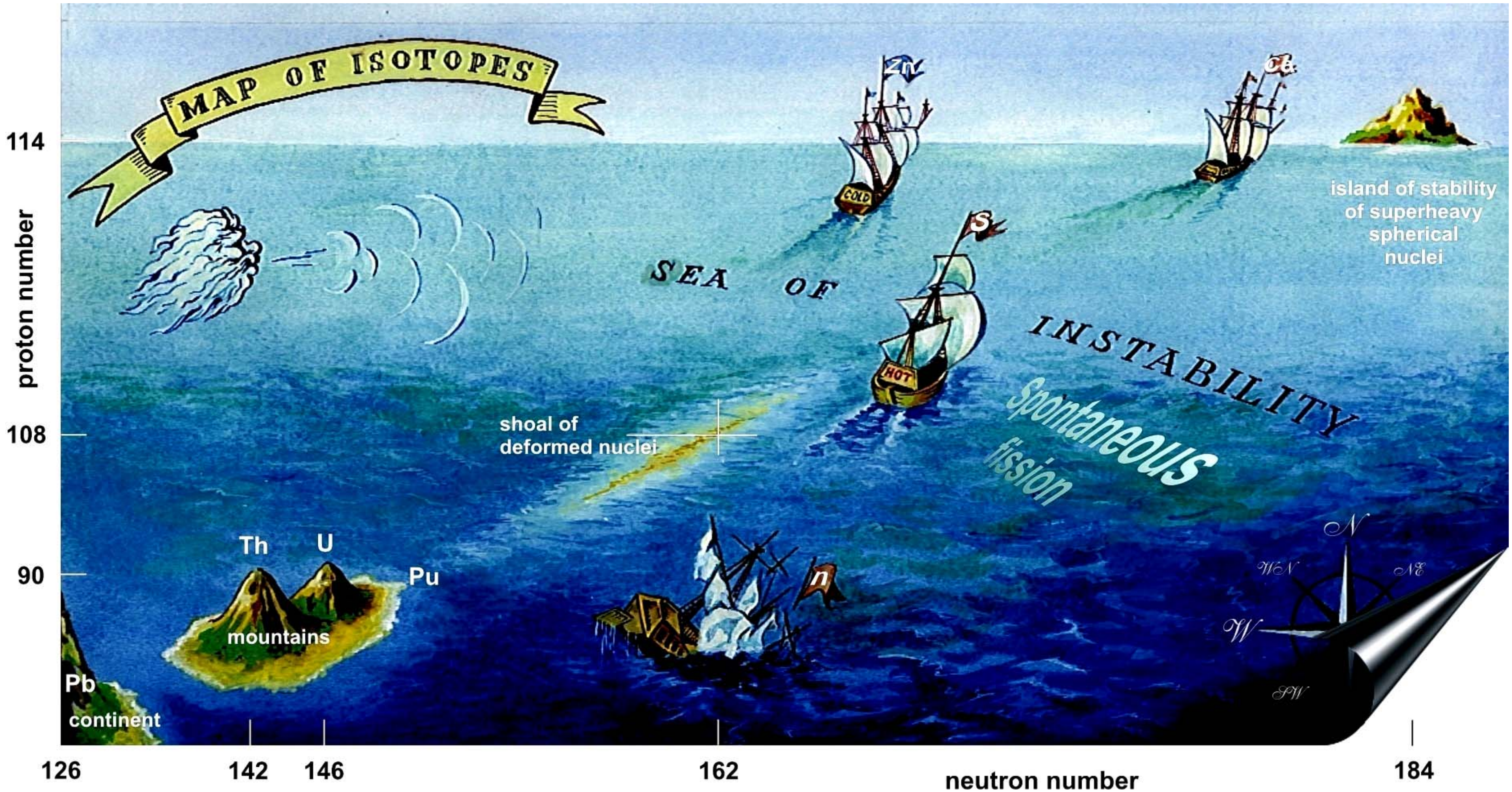


Summary & perspectives

✓Exploration of charge & mass limits

✓Rich of physics
✓Lots of problems

Structure + Reaction; Experiment + Theory

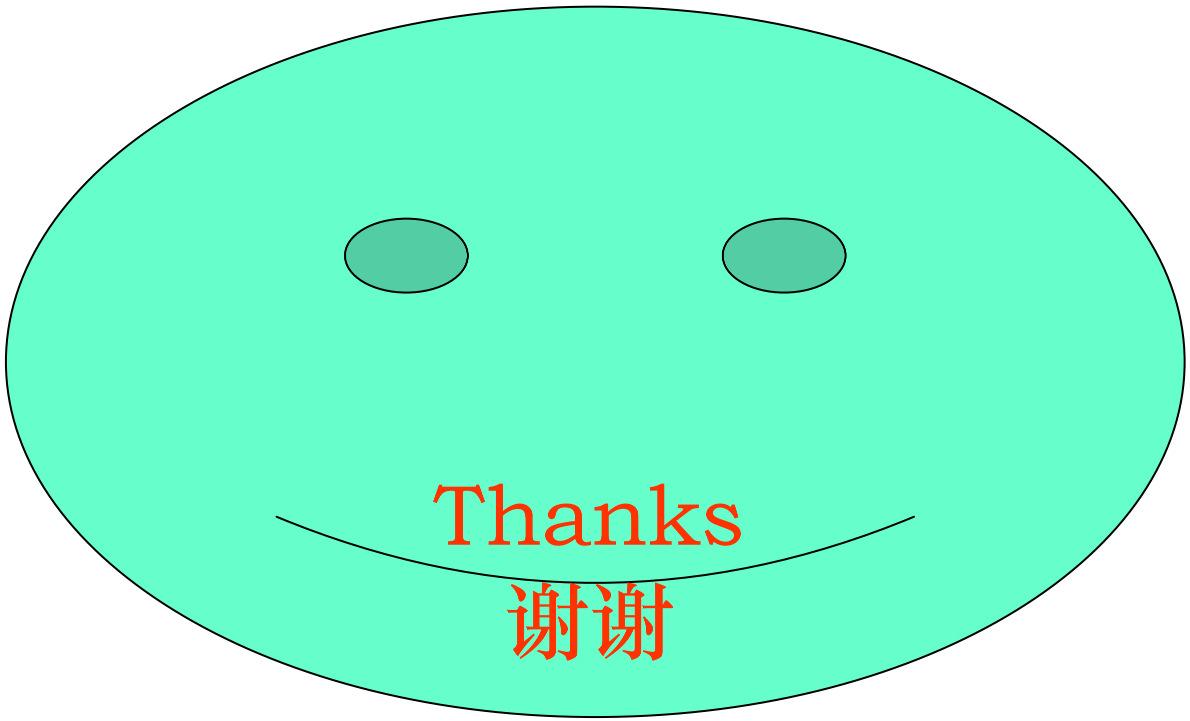


Zhou, Shan-Gui

周 善 贵

ITP/CAS

Beijing



Email: sgzhou@itp.ac.cn

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