The 18th CNS International Summer School (CNSSS19)
Aug 21-27, 2019, Tokyo

Theoretical Study of Superheavy Nuclei

--- Structure Properties & Synthesis Mechanism ---

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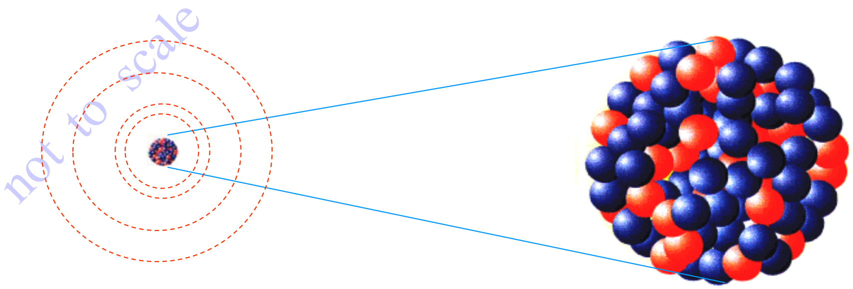
Supported by: NSFC, CAS & MOST
HPC Cluster of KFTP/ITP-CAS
ScGrid of CNIC-CAS

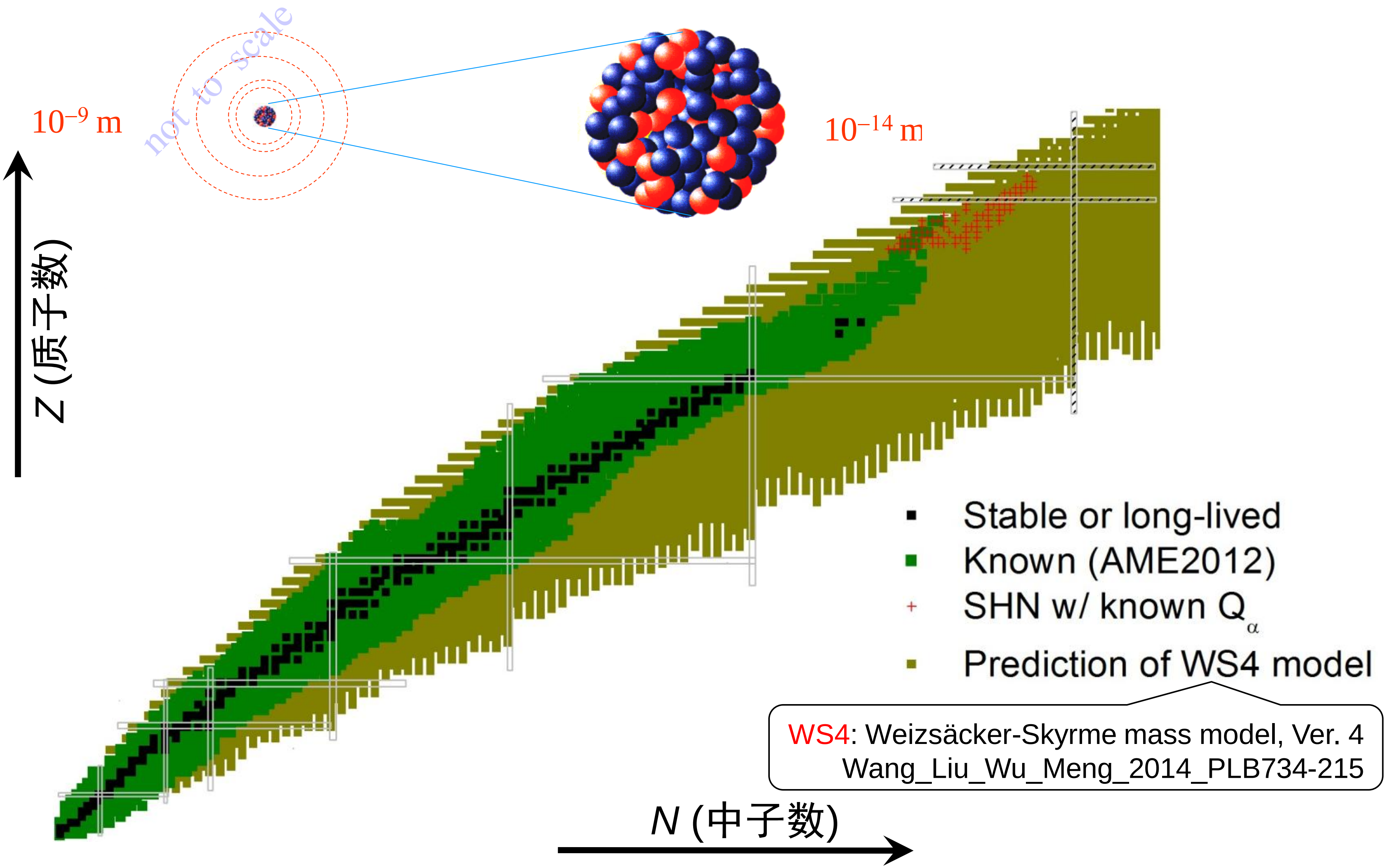
Atomic nucleus & nuclide

10^{-9} m



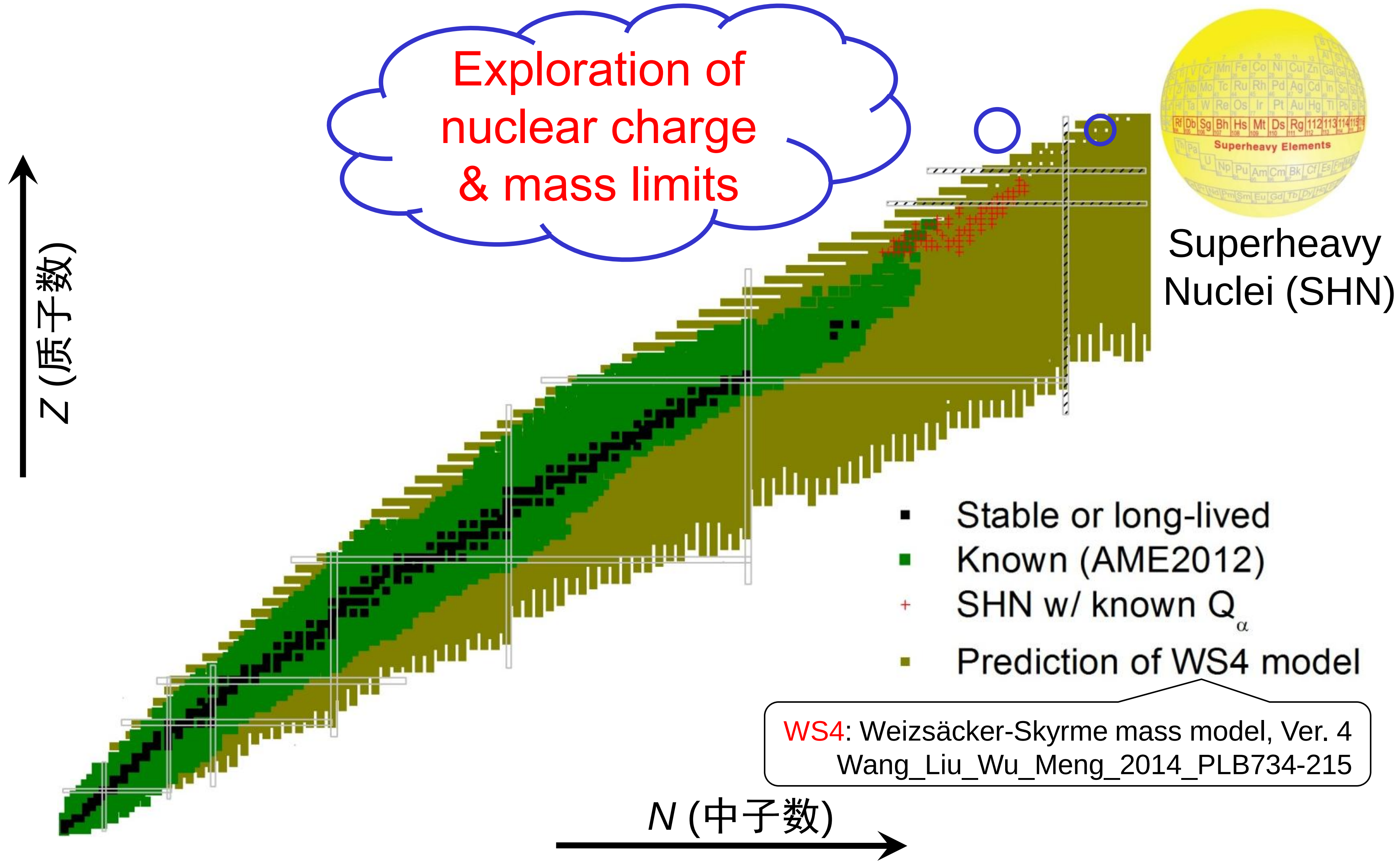
10^{-14} m

Chart of nuclides



Nuclear chart: courtesy of Ning Wang (王宁)

Extension of chart of nuclides: Superheavy nuclei



WS4: Weizsäcker-Skyrme mass model, Ver. 4
Wang_Liu_Wu_Meng_2014_PLB734-215

Nuclear chart: courtesy of Ning Wang (王宁)

Main content of lectures

- Predictions, experimental progress & challenges
- Structure, decay & fission properties
- Synthesis mechanism: Heavy-ion fusion & multi-nucleon transfer reactions

Further readings:

- *Special Issue on Superheavy Elements*, Nucl. Phys. A 944 (2015)
- Lu, Zhao & SGZ, Chapter 5 in *Relativistic Density Functional for Nuclear Structure* (World Scientific, 2016, Editor: Jie Meng)
- Ackermann & Theisen, Phys. Scr. 92 (2017) 083002
- Giuliani et al., Rev. Mod. Phys. 91 (2019) 011001

Lecture 1

- Predictions of the island of stability of SHN

- Experimental progress on synthesis of SHN

- Challenges in synthesizing SHN

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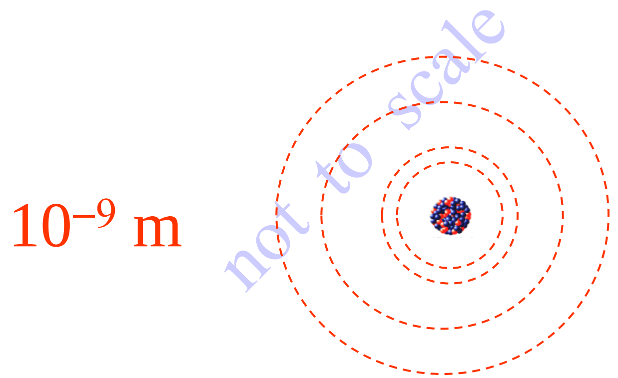
- Experimental progress on synthesis of SHN
- Challenges in synthesizing SHN

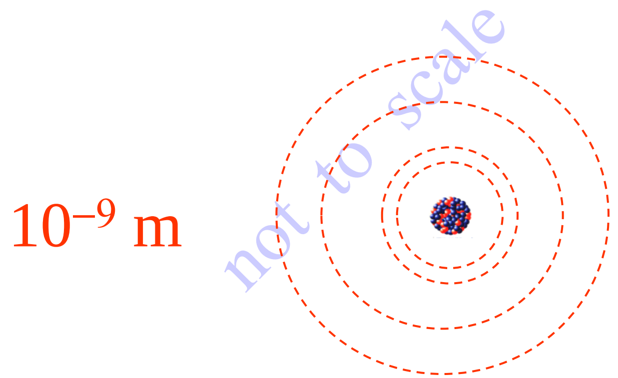
Nuclear charge limit on atomic level



- Bohr's model: Velocity of innermost electron
  - Hydrogen: $v_1 = \alpha c$
  - Heavy atoms: $v_1 \sim Z\alpha c$, $Z < 137$

Greiner & Reinhardt 1994, QED
Indelicato 2013, Nature 498, 40-41

Nuclear charge limit on atomic level



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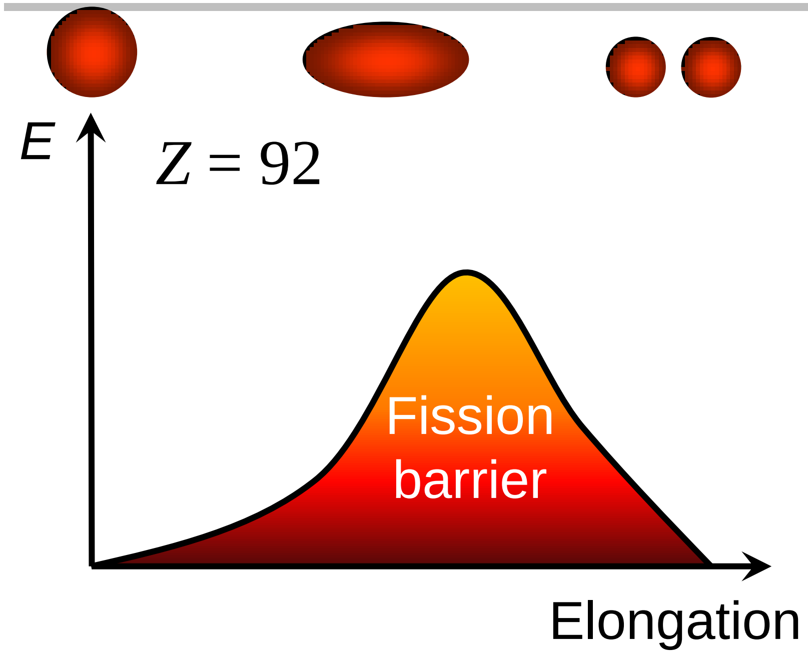
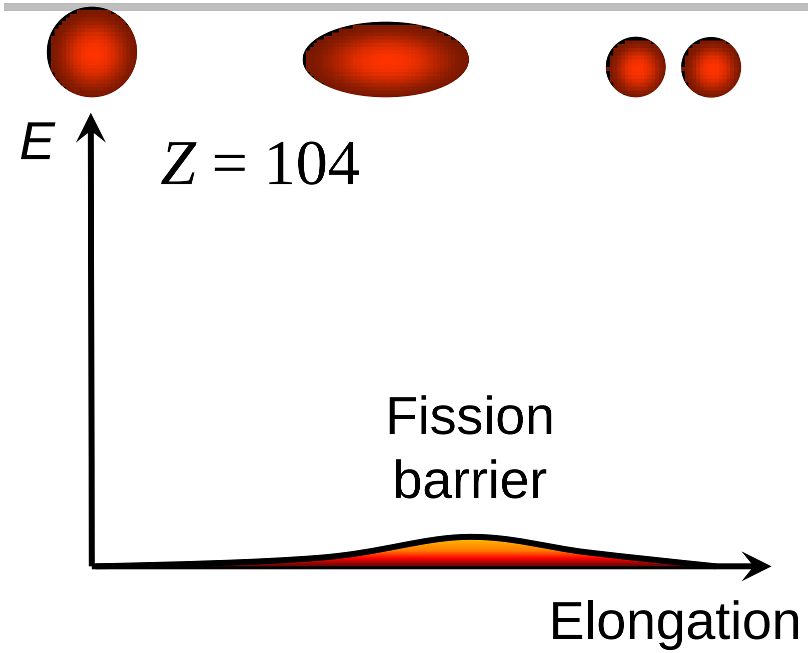
- Bohr's model: Velocity of innermost electron
  - Hydrogen: $v_1 = \alpha c$
  - Heavy atoms: $v_1 \sim Z\alpha c$, $Z < 137$
- QED: Energy of innermost electron
  - Point-like nucleus:
    $E_1 \sim m_e c^2[(1-(Z\alpha)^2)^{1/2}-1]$, $Z < 137$
  - Finite-size nucleus: $Z < 173$

Nuclear charge & mass limits on nuclear level



- Nuclear force: Short-ranged, attractive & saturated
- Coulomb force: Long-ranged & repulsive
- As charged liquid drops, nuclear charge & mass limited by competition of nuclear & Coul. forces

Nuclear charge & mass limits on nuclear level



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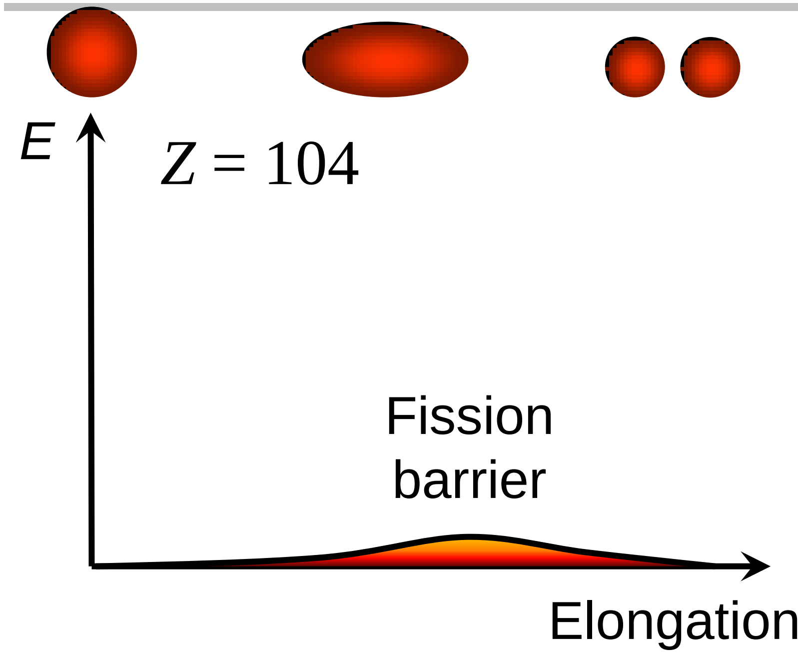
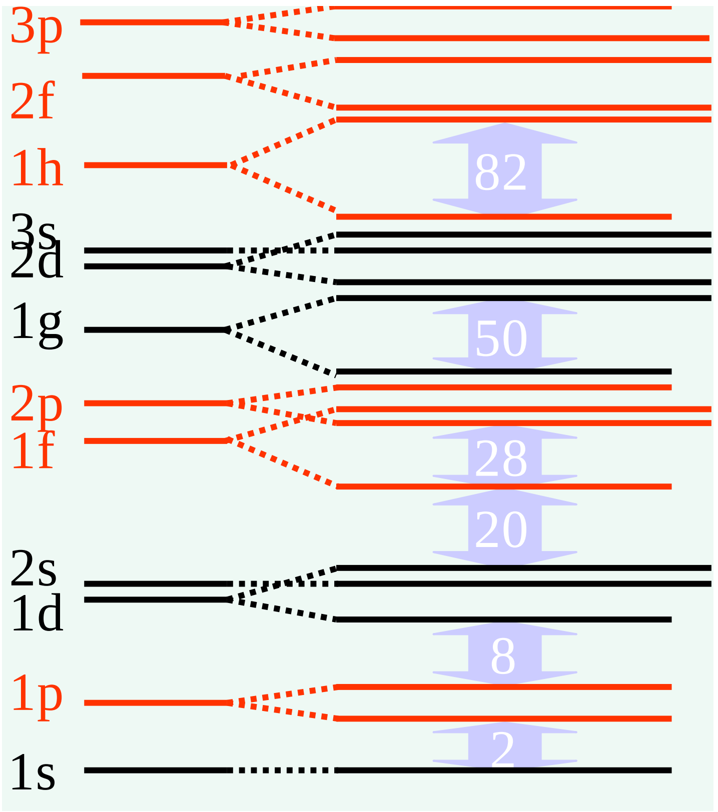
Quantum shell effects





Single nucleon potential, spectra & magicities

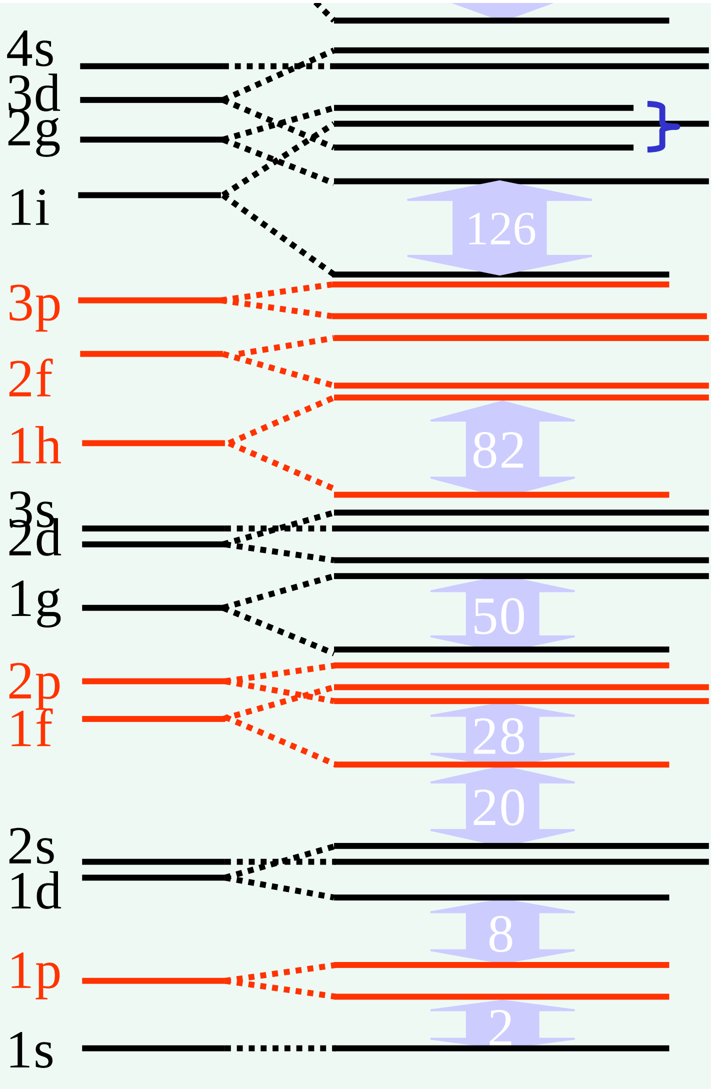
- Harmonic oscillator & square well
- Woods-Saxon
- Self-consistent (self-bound)

Eugene Paul Wigner

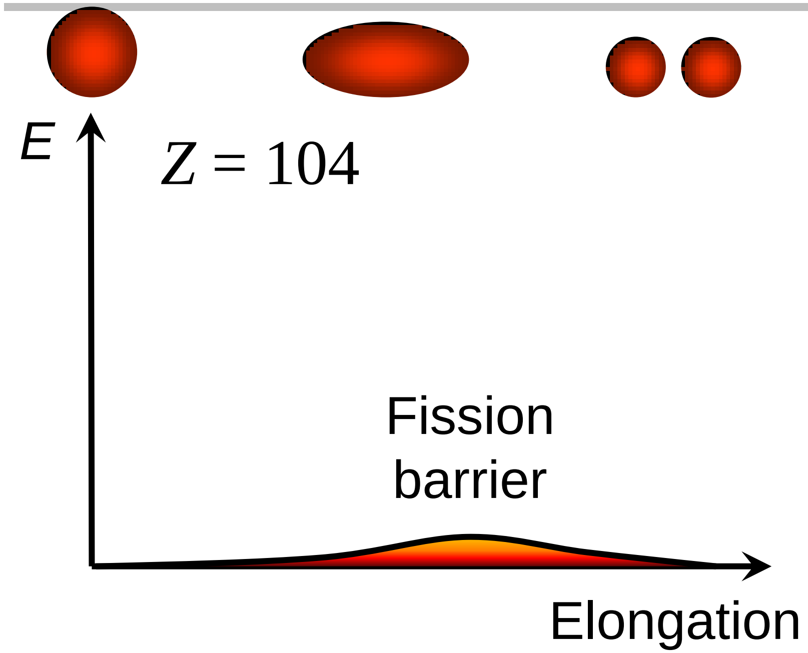
Maria Goeppert Mayer

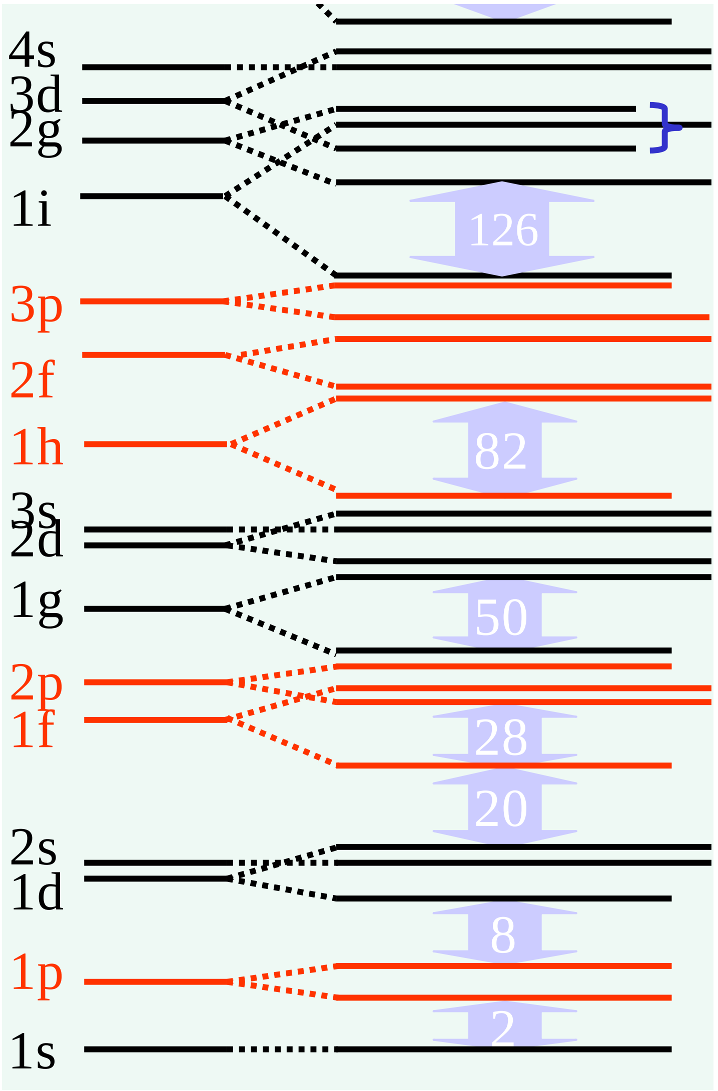
J. Hans D. Jensen

Nobel Prize of Physics (1963)

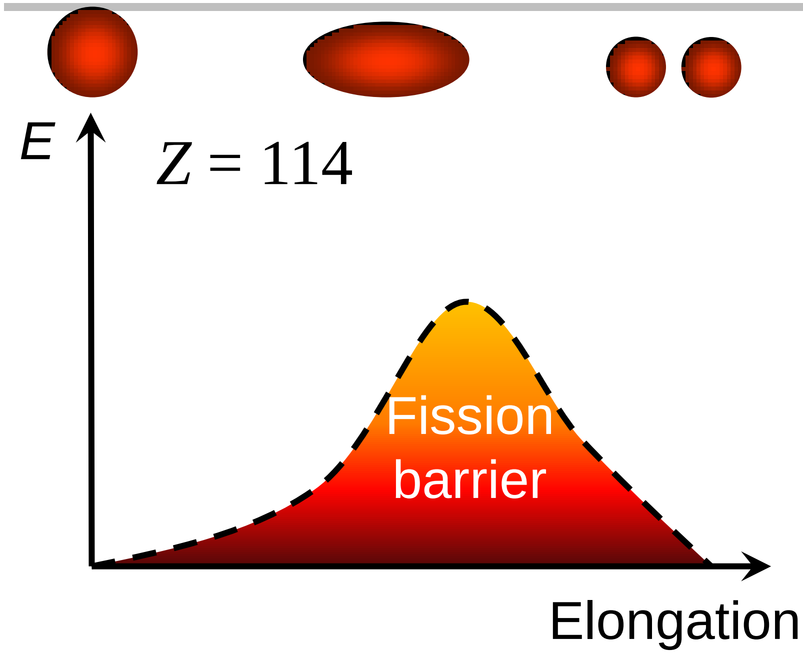


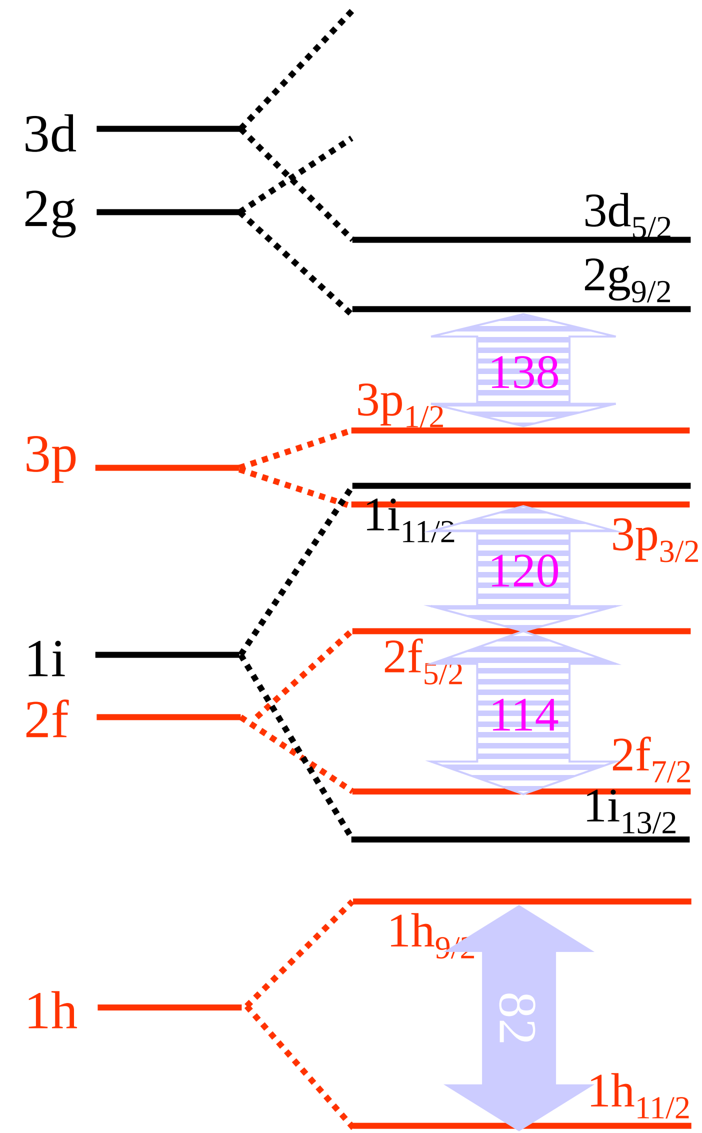
Quantum shell effects





Quantum shell effects ⇒ Superheavy nuclei





Before 1966: Extrapolation of shell structrure

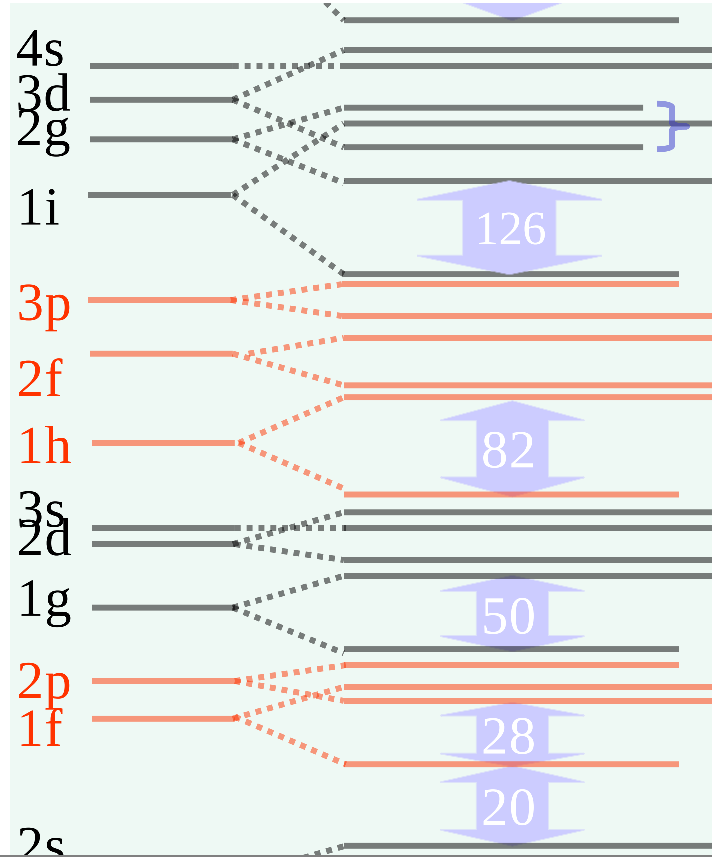
Wheeler 1955, in N. Bohr & Development of Phys.

bility analysis of very heavy nuclei. In so far as one can extrapolate the stability criteria for very heavy nuclei, one is led to expect the existence of nuclei twice as heavy as known nuclear species, that can be created by massive neutron irradiation, and that will live long enough to be studied in the laboratory.

Scharff-Goldhaber1957_Nucleonics15-122

Relatively long-lived isotopes may well be found among the far-transuranic nuclides because of magic-number stability

There may be, for instance, another region of relative stability at the doubly magic nucleus $_{126}X^{310}$ (the closing of the *j* neutron shell).



Werner_Wheeler1958_PR109-126

PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

Superheavy Nuclei

FREDERICK G. WERNER AND JOHN A. WHEELER
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received August 19, 1957)

1966: Semi-quantitative shell effects

1.E.2:
1.D.4

Nuclear Physics **81** (1966) 1—60; © *North-Holland Publishing Co., Amsterdam*

NUCLEAR MASSES AND DEFORMATIONS

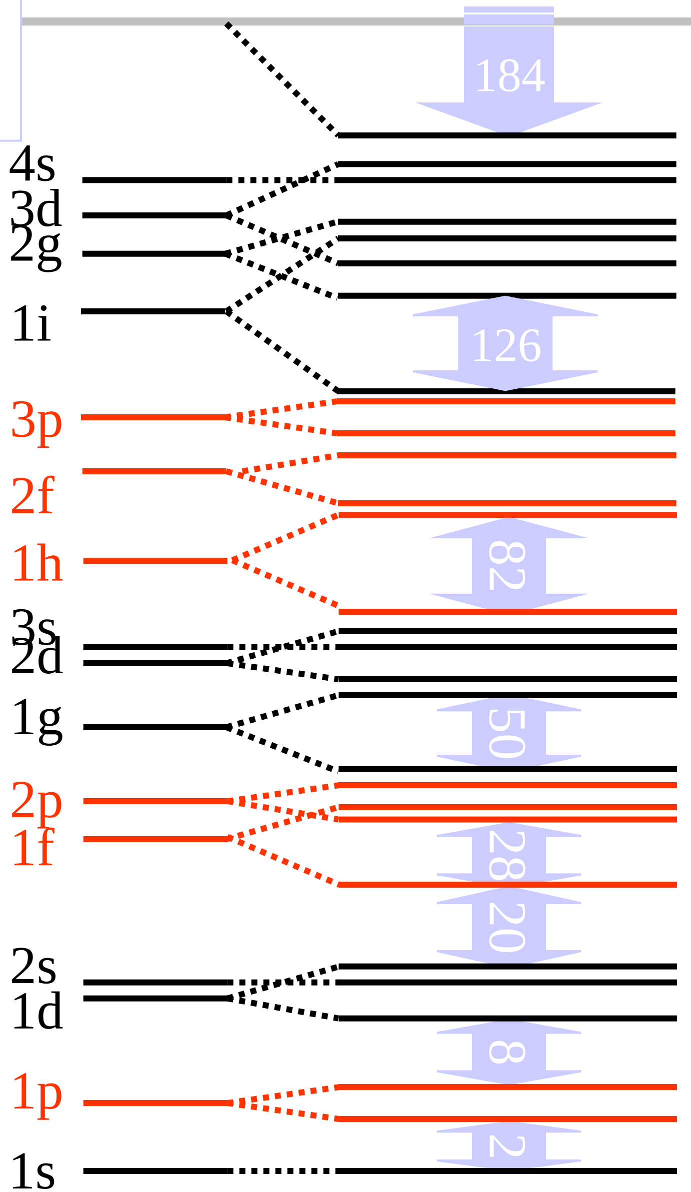
WILLIAM D. MYERS and WLADYSLAW J. SWIATECKI
Lawrence Radiation Laboratory, University of California, Berkeley, California †

Received 7 September 1965

half-life. This is illustrated in fig. 2 where we have plotted the deformation energy predicted by our mass formula for the case $Z = 126$, $N = 184$. This nucleus has a fissility parameter $x = 1.05$; as a result, in the absence of shell effects, it would have a vanishing barrier against fission and a spontaneous fission half-life of the order of nuclear collective oscillations or 10^{-22} sec. Because of the assumed doubly magic number, however, the ground-state mass of this nucleus would be depressed (by about 10.2 MeV according to our formula). Since this depression is, according to our treatment, a rapidly decreasing function of deformation, there results a considerable barrier against fission, with a height of 9.0 MeV: the extra binding associated with the doubly magic number has stabilized the otherwise highly fissile nucleus. An

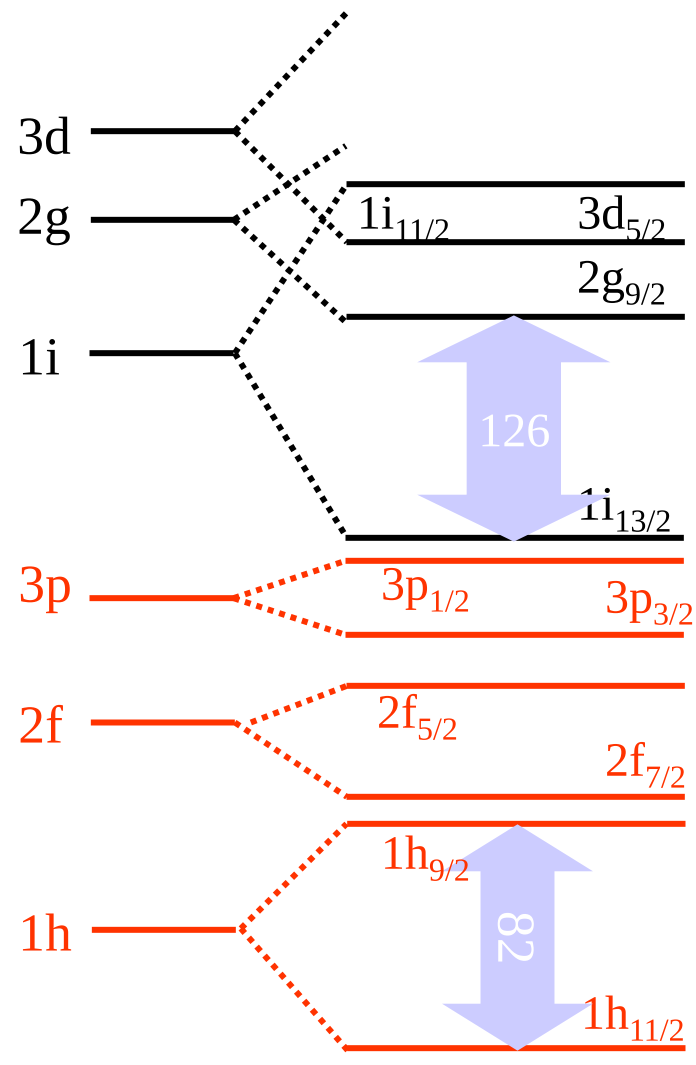
Strong Coulomb effects on proton shell structure

Large *A*
Large *Z*



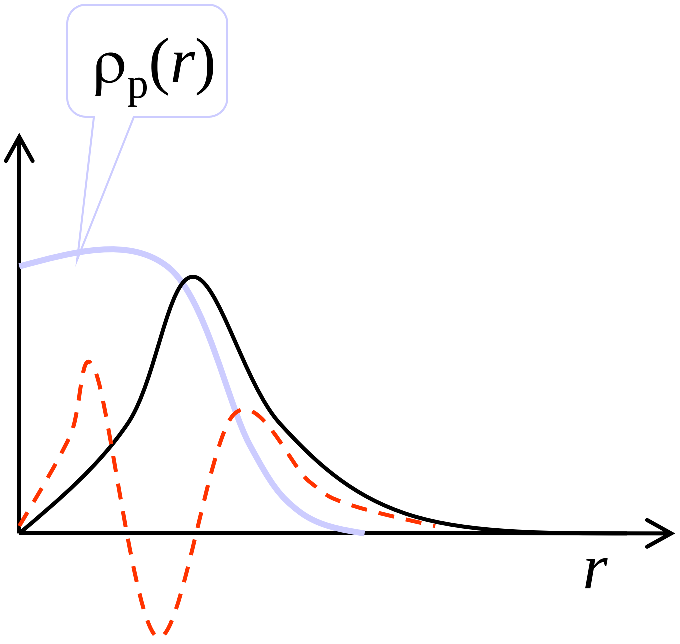
Strong Coulomb effects on proton shell structure

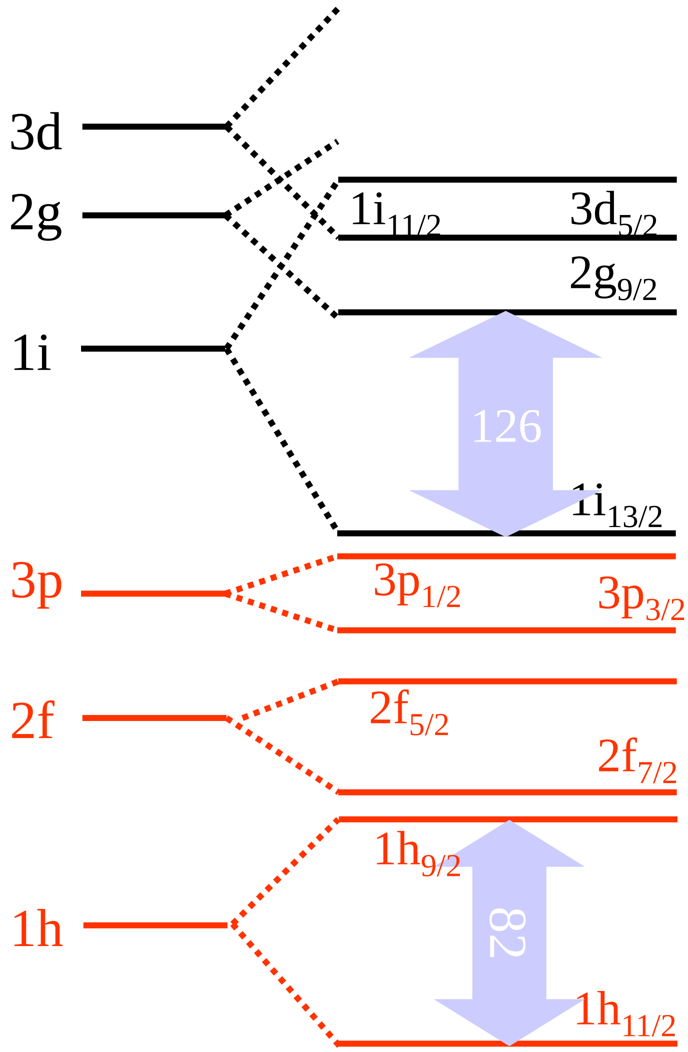
Coulomb Repulsion



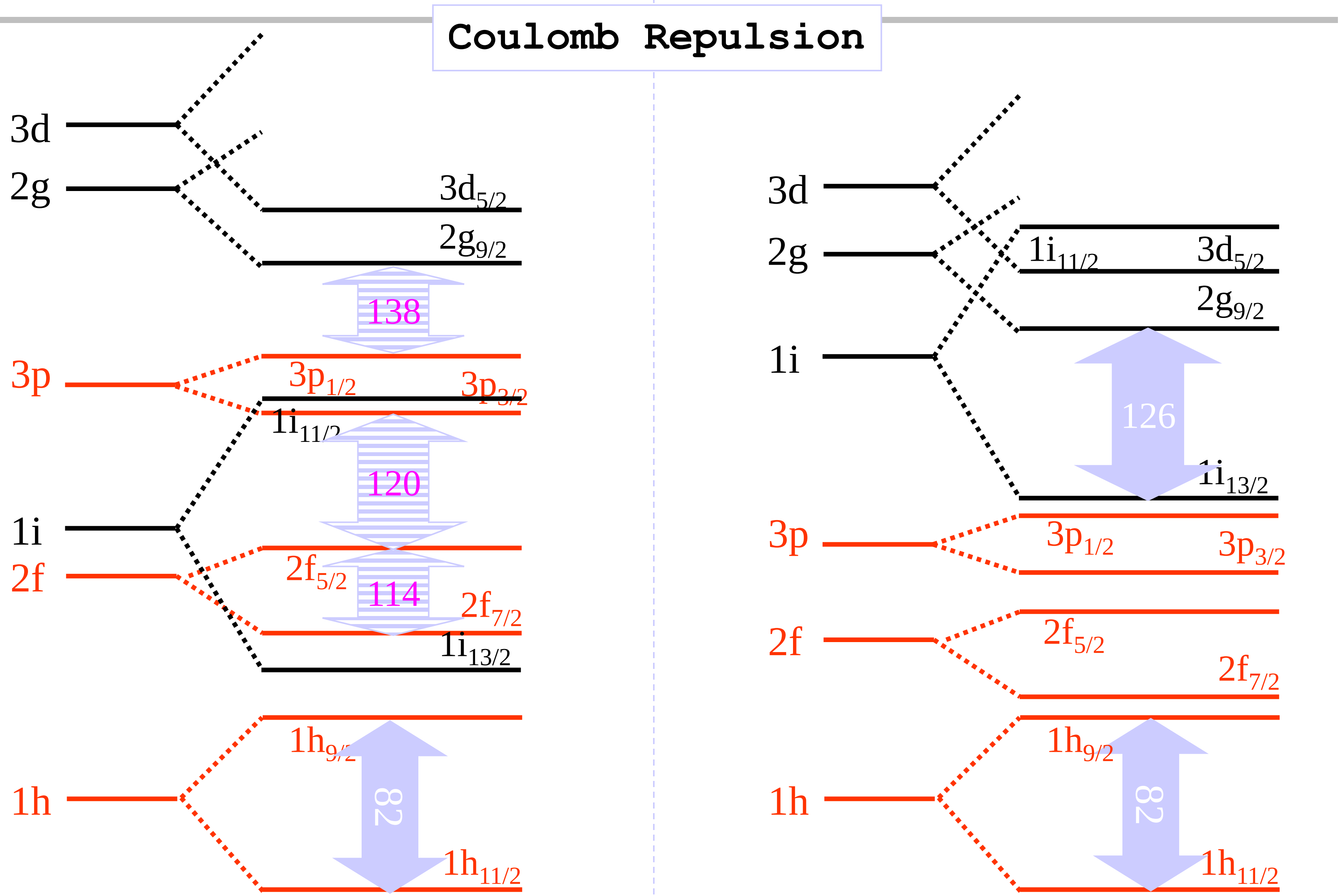
Strong Coulomb effects on proton shell structure

Coulomb Repulsion





Strong Coulomb effects on proton shell structure



1966 & after: Quantitative shell effects

- Closed shells for Z > 82 and N > 126 in a diffuse potential well
  - A Woods-Saxon potential Sobiczewski...1966_PhysLett22-500
  - Z = 114 & N = 184; B_f = 10 MeV
- Predictions of new magic regions and masses for super-heavy nuclei from calculations with realistic shell model single particle Hamiltonian
  - A non-local potential Meldner1967_ArkivFysik36-593
  - Z = 114 & N = 184

1967: A different opinion

VOLUME 18, NUMBER 17 PHYSICAL REVIEW LETTERS 24 APRIL 1967

SHAPE OF HEAVY NUCLEI*

Philip J. Siemens† and H. A. Bethe
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York
(Received 10 March 1967)

The energy reduction for this semimagic nucleus is likely to be considerably less than for Pb^{208} for which it is about 15 MeV. On the other hand, without shell structure, the elongated shape has an energy about 18 MeV less than the sphere for $Z = 114$. We therefore believe that shell effects are unlikely to make the nucleus $Z = 114$ stable.

1967: A different opinion

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- More quantitative investigations needed !!!
  - Single particle shell structure
  - How much stability the closed shell brings

1966 & after: Quantitative shell effects

- Closed shells for Z > 82 and N > 126 in a diffuse potential well
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  - Z = 114 & N = 184; B_f = 10 MeV
- Predictions of new magic regions and masses for super-heavy nuclei from calculations with realistic shell model single particle Hamiltonian
  - A non-local potential — Meldner1967_ArkivFysik36-593
  - Z = 114 & N = 184
- "On the spontaneous fission of nuclei with Z near 114 and N near 184"
  - Nilsson potential; potential energy surface with shell corrections calculated by the Strutinsky method — Nilsson…1968_NPA115-545
  - B_f = 10 MeV & $T_{1/2}$(s.f.) ~ 10^{19} years
- "On the stability of superheavy nuclei against fission"
  - Nilsson potential; potential energy surface with rotational invariance
  - $T_{1/2}$(s.f.) ~ 10^{0-17} years — Mosel_Greiner1969_ZPA226-261

More investigations

Not the end yet ! For the location of the island of stability, more different predictions:

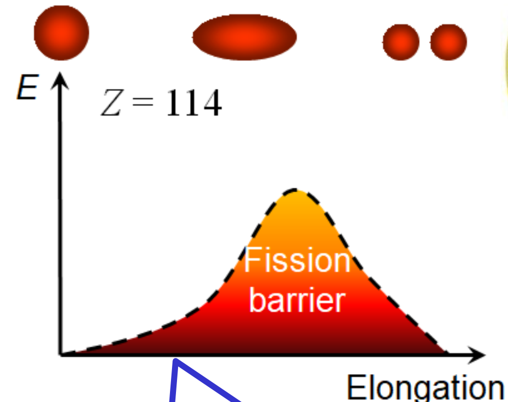
- Macroscopic-microscopic models
- Self-consistent approaches
  - Non-relativistic
  - Relativistic
- ...

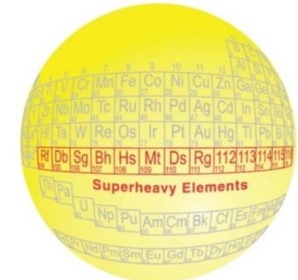
What are “Superheavy Nuclei” ?

- Can not exist if described as a charged liquid drop
- Stabilized by quantum shell effects

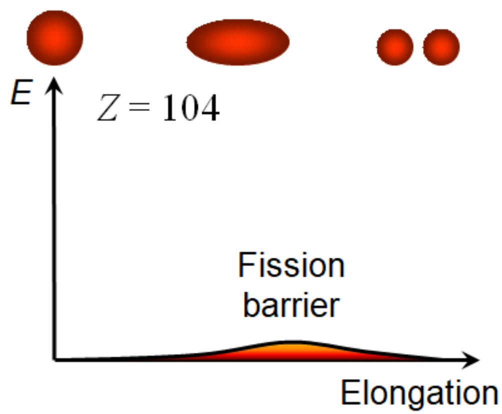
What are superheavy nuclei?

As charged liquid drops, no existence of nuclei w/ $Z > 104$

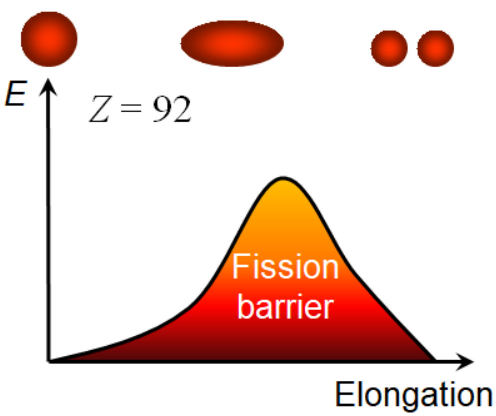




SHE/SHN



Based on quantum shell effects, predictions made of an island of stability of SHN around $(Z, N) = (114, 184)$

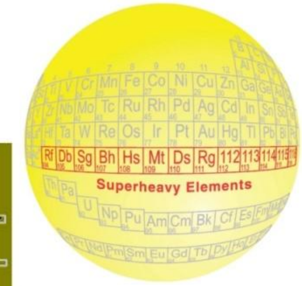


SHN: Charge & mass limits of nuclear existence

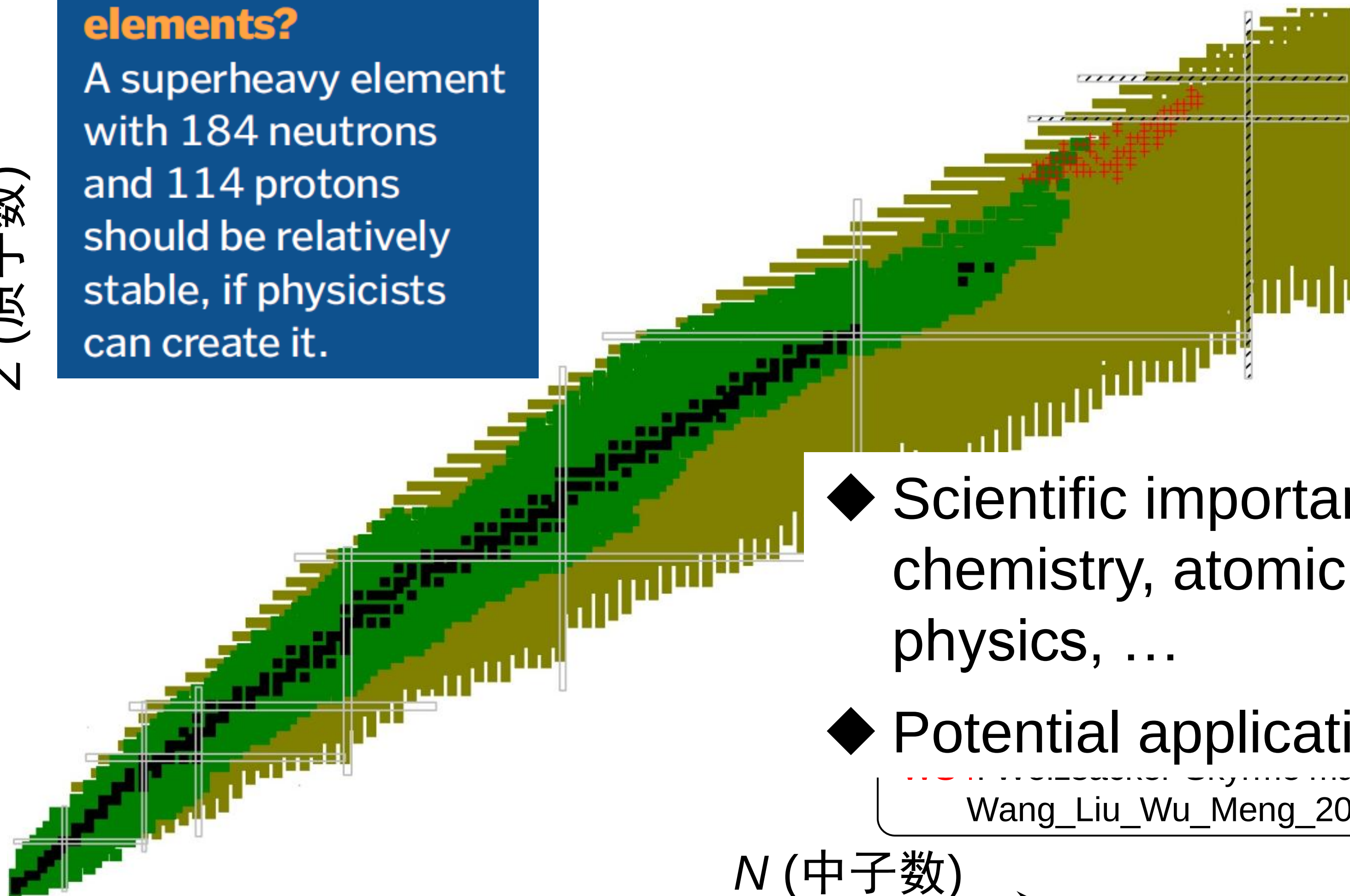
Are there stable high-atomic-number elements?

A superheavy element with 184 neutrons and 114 protons should be relatively stable, if physicists can create it.

Top 125 science questions
Science July 2005



Z (质子数)



- Scientific importance in chemistry, atomic & nuclear physics, …
- Potential applications

Wang_Liu_Wu_Meng_2014_PLB734-215

N (中子数)

Nuclear chart: courtesy of Ning Wang (王宁)

Periodic table of elements: End?

带*为放射性元素

其中黑色为天然放射性元素

红色为人造元素

蓝色为新命名元素

主族金属	锕系元素	非金属元素
副族金属	镧系元素	稀有气体

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 氢 H																	2 氦 He
2	3 锂 Li	4 铍 Be											5 硼 B	6 碳 C	7 氮 N	8 氧 O	9 氟 F	10 氖 Ne
3	11 钠 Na	12 镁 Mg											13 铝 Al	14 硅 Si	15 磷 P	16 硫 S	17 氯 Cl	18 氩 Ar
4	19 钾 K	20 钙 Ca	21 钪 Sc	22 钛 Ti	23 钒 V	24 铬 Cr	25 锰 Mn	26 铁 Fe	27 钴 Co	28 镍 Ni	29 铜 Cu	30 锌 Zn	31 镓 Ga	32 锗 Ge	33 砷 As	34 硒 Se	35 溴 Br	36 氪 Kr
5	37 铷 Rb	38 锶 Sr	39 钇 Y	40 锆 Zr	41 铌 Nb	42 钼 Mo	43 锝* Tc	44 钌 Ru	45 铑 Rh	46 钯 Pd	47 银 Ag	48 镉 Cd	49 铟 In	50 锡 Sn	51 锑 Sb	52 碲 Te	53 碘 I	54 氙 Xe
6	55 铯 Cs	56 钡 Ba	57-71 镧系 La-Lu	72 铪 Hf	73 钽 Ta	74 钨 W	75 铼 Re	76 锇 Os	77 铱 Ir	78 铂 Pt	79 金 Au	80 汞 Hg	81 铊 Tl	82 铅 Pb	83 铋 Bi	84 钋 Po	85 砹* At	86 氡* Rn
7	87 钫* Fr	88 镭* Ra	89-103 锕系 Ac-Lr	104 𬬻* Rf	105 𬭊* Db	106 𬭳* Sg	107 𬭛* Bh	108 𬭶* Hs	109 鿏* Mt	110 𫟼* Ds	111 𬬭* Rg	112 鎶* Cn	113 Uut* Uut	114 𫓧* Fl	115 Uup* Uup	116 𫟷* Lv	117 Uus* Uus	118 Uuo* Uuo

SGZ, SHN & SHE, Physics 43 (2014) 817−825 (in Chinese)

镧系	57 镧 La	58 铈 Ce	59 镨 Pr	60 钕 Nd	61 钷* Pm	62 钐 Sm	63 铕 Eu	64 钆 Gd	65 铽 Tb	66 镝 Dy	67 钬 Ho	68 铒 Er	69 铥 Tm	70 镱 Yb	71 镥 Lu
锕系	89 锕* Ac	90 钍* Th	91 镤* Pa	92 铀* U	93 镎* Np	94 钚* Pu	95 镅* Am	96 锔* Cm	97 锫* Bk	98 锎* Cf	99 锿* Es	100 镄* Fm	101 钔* Md	102 锘* No	103 铹* Lr

Courtesy of Xu Meng (孟旭)

Lecture 1

- Predictions of the island of stability of SHN
- Experimental progress on synthesis of SHN
- Challenges in synthesizing SHN

Expt. exploration of SHN & island of stability

- If half-life of SHN long enough (e.g, $T_{1/2}$~10^8) & produced in nucleosynthesis

Herrmann1979_Nature280-543

  - SHE/SHN may exist in Nature
  - No confirmed evidence, but efforts still being made

- ✓ 1860 (1861), Bunsen & Kirchhoff found cesium (rubidium) in mineral water (lepidolite) by using the flame spectroscopy
- ✓ 1868, Janssen & Lockyer recorded helium spectral line during solar eclipse
- ✓ …
- ✓ 1898, Curies discovered polonium (radium) in uranium ore pitchblende (uraninite) by identifying strong radioactivity

Expt. exploration of SHN & island of stability

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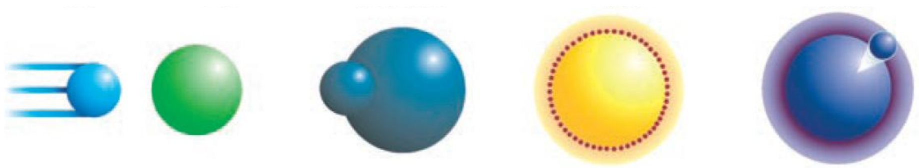
- In Lab, via heavy ion fusion reactions
  - GSI in Darmstadt, Germany
  - Flerov Laboratory of Nuclear Reactions in Dubna, Russia
  - Lawrence Berkeley National Laboratory, USA
  - Lawrence Livermore National Laboratory, USA
  - RIKEN in Wako, Japan
  - GANIL in Caen, France



Hofmann_Münzenberg2000_RMP72-733

Morita...2004_JPSJ73-2593

Oganessian...2007_JPG34-R165

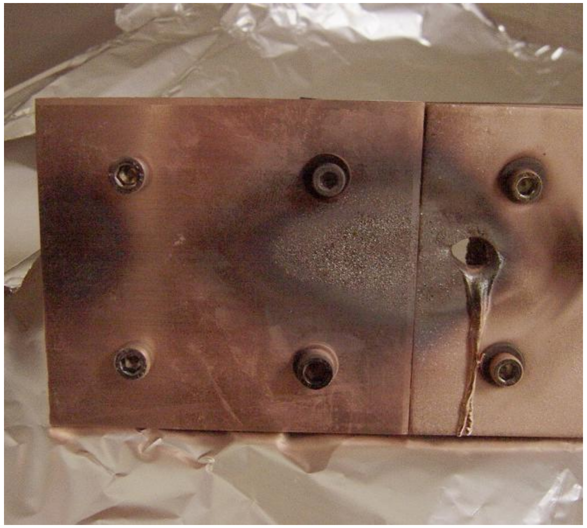
Oganessian...2010_PRL104-142502

Zhang…2012_CPL29-012502

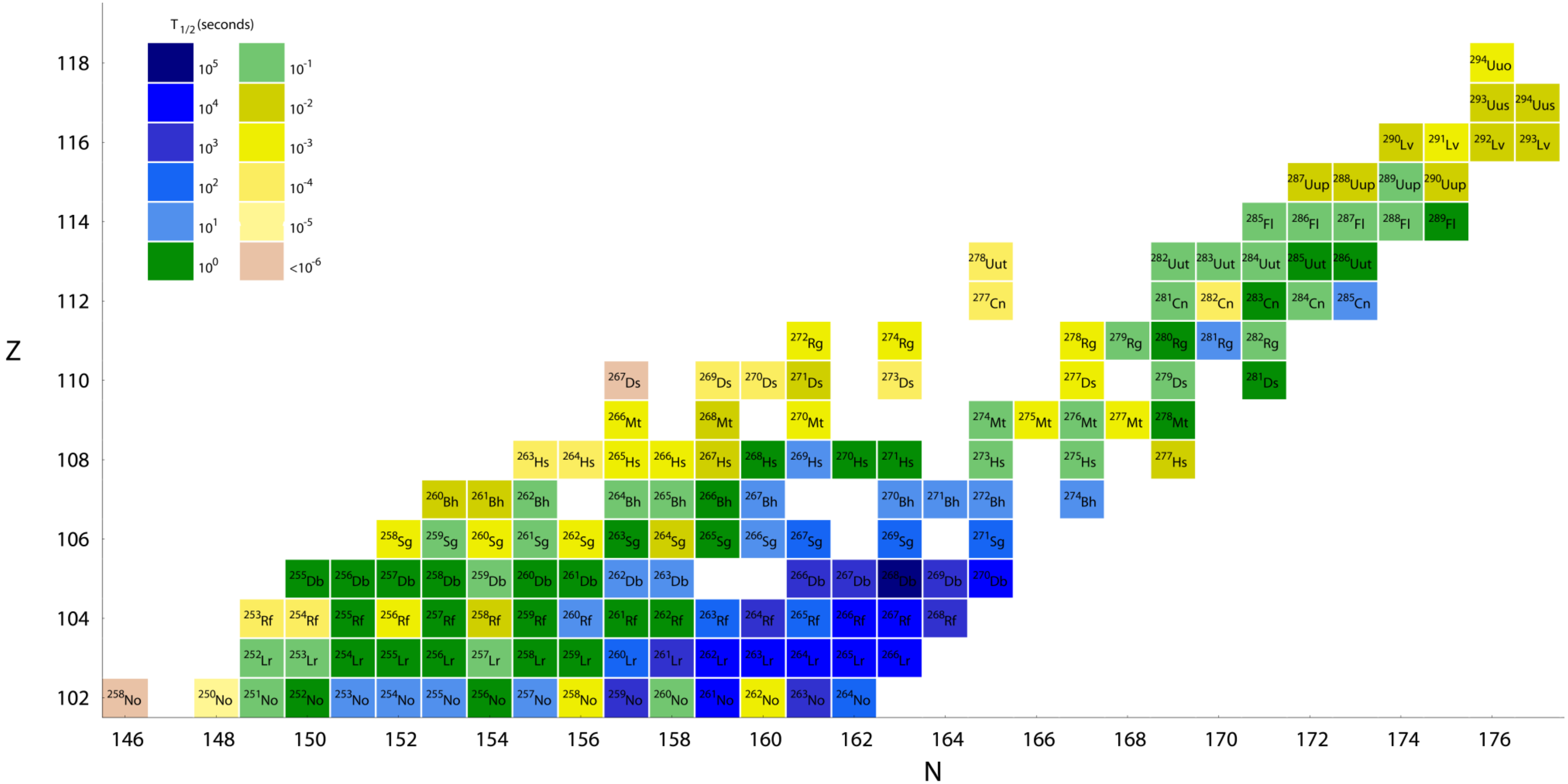
Synthesis of SHN in Labs

- Neutron capture followed by β decay
  - Up to fermium

- Light ions (H, D, T & α) as projectiles
  - Up to mendelevium
- Heavy ions as projectiles
  - Cold fusion: ^{208}Pb or ^{209}Bi as targets, up to nihonium
  - Hot fusion: ^{48}Ca as projectiles, up to oganesson



Expt. progress on synthesis of SHN



SHE with $Z \leq 118$ have been synthesized & named
Recent naming for elements with Z = 113, 115, 117 & 118

Courtesy of Kai Wen (温凯)

Periodic table of elements: End?

带*为放射性元素

其中黑色为天然放射性元素

红色为人造元素

蓝色为新命名元素

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4	19 钾 K	20 钙 Ca	21 钪 Sc	22 钛 Ti	23 钒 V	24 铬 Cr	25 锰 Mn	26 铁 Fe	27 钴 Co	28 镍 Ni	29 铜 Cu	30 锌 Zn	31 镓 Ga	32 锗 Ge	33 砷 As	34 硒 Se	35 溴 Br	36 氪 Kr
5	37 铷 Rb	38 锶 Sr	39 钇 Y	40 锆 Zr	41 铌 Nb	42 钼 Mo	43 锝* Tc	44 钌 Ru	45 铑 Rh	46 钯 Pd	47 银 Ag	48 镉 Cd	49 铟 In	50 锡 Sn	51 锑 Sb	52 碲 Te	53 碘 I	54 氙 Xe
6	55 铯 Cs	56 钡 Ba	57-71 镧系 La-Lu	72 铪 Hf	73 钽 Ta	74 钨 W	75 铼 Re	76 锇 Os	77 铱 Ir	78 铂 Pt	79 金 Au	80 汞 Hg	81 铊 Tl	82 铅 Pb	83 铋 Bi	84 钋 Po	85 砹* At	86 氡* Rn
7	87 钫* Fr	88 镭* Ra	89-103 锕系 Ac-Lr	104 𬬻* Rf	105 𬭊* Db	106 𬭳* Sg	107 𬭛* Bh	108 𬭶* Hs	109 鿏* Mt	110 𫟼* Ds	111 𬬭* Rg	112 鿔* Cn	113 Uut* Uut	114 𫓧* Fl	115 Uup* Uup	116 𫟷* Lv	117 Uus* Uus	118 Uuo* Uuo

SGZ, SHN & SHE, Physics 43 (2014) 817−825 (in Chinese)

镧系	57 镧 La	58 铈 Ce	59 镨 Pr	60 钕 Nd	61 钷* Pm	62 钐 Sm	63 铕 Eu	64 钆 Gd	65 铽 Tb	66 镝 Dy	67 钬 Ho	68 铒 Er	69 铥 Tm	70 镱 Yb	71 镥 Lu
锕系	89 锕* Ac	90 钍* Th	91 镤* Pa	92 铀* U	93 镎* Np	94 钚* Pu	95 镅* Am	96 锔* Cm	97 锫* Bk	98 锎* Cf	99 锿* Es	100 镄* Fm	101 钔* Md	102 锘* No	103 铹* Lr

Courtesy of Xu Meng (孟旭)

Element 113

JWP ASSESSMENT: Three chains of ^{278}113 observed by the RIKEN collaborations, the first in 2004 [9], the second in 2007 [10], and the third in 2012 [16], are now construed as being consistent. Firm connection to established nuclides is provided. The remaining criterion achieved for acknowledgement of discovery is an identification of *Z* which is now embodied in the cross reaction production and characterization of the chain beginning with ^{266}Bh as found by the RIKEN collaboration in 2009 [14] and by Qin *et al*. in 2006 [12]. The Criteria for discovery have been met.

Karol+2016_PureApplChem88-139

Morita+2004

Morita+2007

Qin+2006

Morita+2009

Morita+2012

[9] K. Morita, K. Morimoto, D. Kaji, T. Akiyama, S. Goto, H. Haba, E. Ideguchi, R. Kanungo, K. Katori, H. Koura, H. Kudo, T. Ohnishi, A. Ozawa, T. Suda, K. Sueki, H. Xu, T. Yamaguchi, A. Yoneda, A. Yoshida, Y.-L. Zhao. *J. Phys. Soc. Jpn*. **73**, 2593 (2004).

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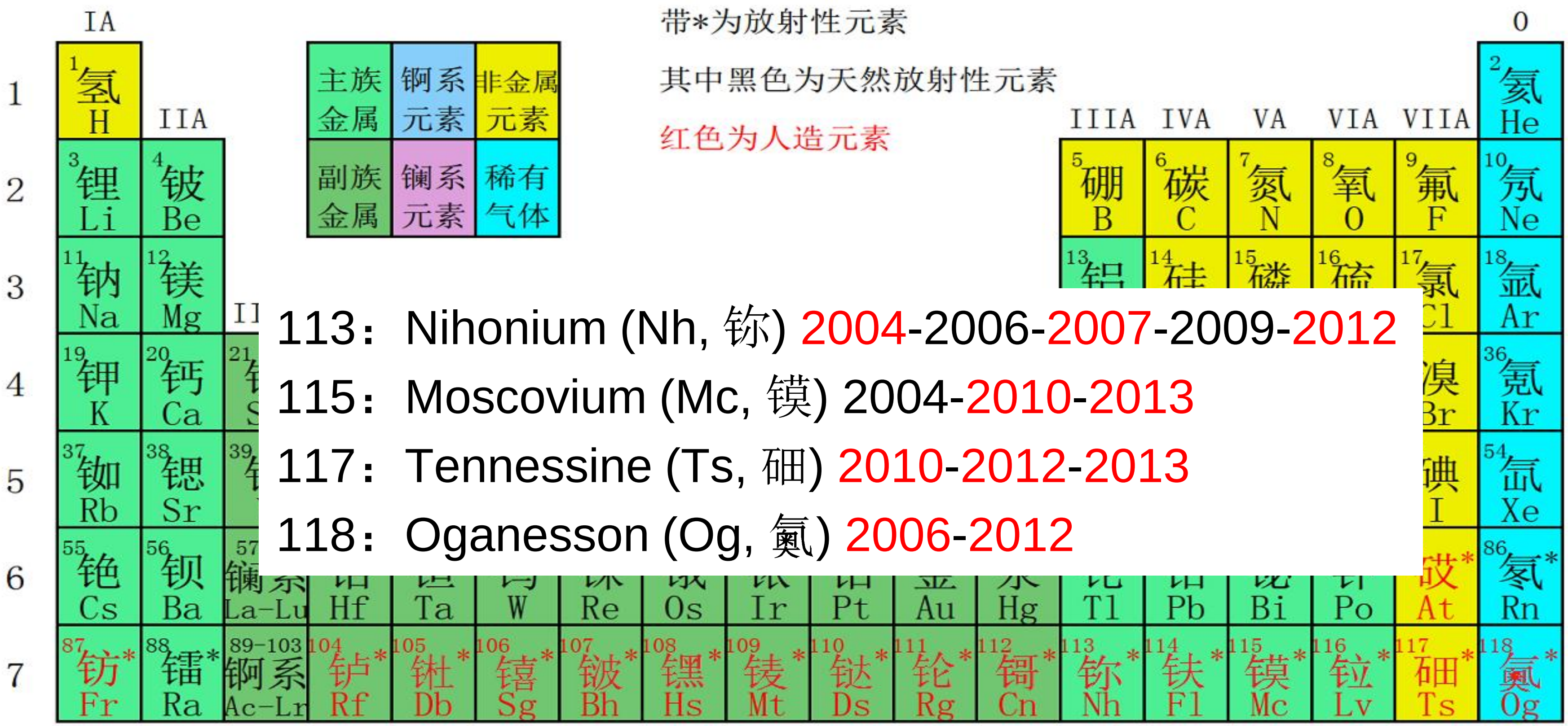
Periodic table of elements: End?



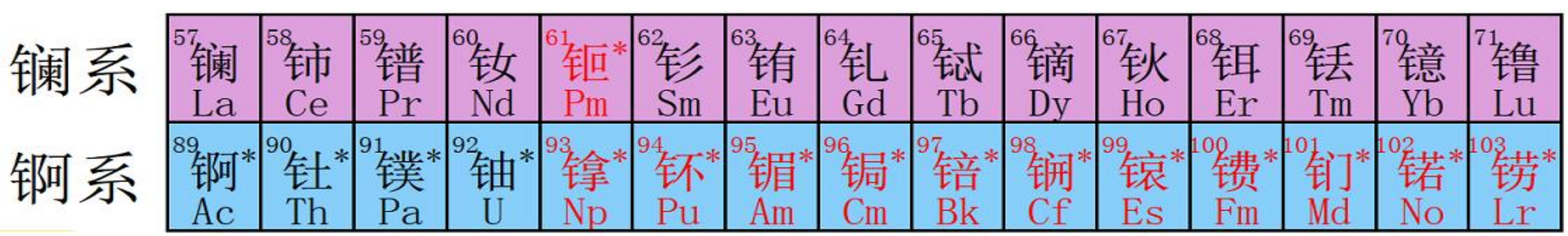
113：Nihonium (Nh, 鿭) 2004-2006-2007-2009-2012

115：Moscovium (Mc, 镆) 2004-2010-2013

117：Tennessine (Ts, 鿬) 2010-2012-2013

118：Oganesson (Og, 鿫) 2006-2012

SGZ, SHN & New Elements, Nucl. Phys. Rev. 34 (2017) 318-331 (in, Chinese)



Courtesy of Xu Meng (孟旭)

Periodic table of elements: End?

带*为放射性元素

其中黑色为天然放射性元素

红色为人造元素

主族金属	锕系元素	非金属元素
副族金属	镧系元素	稀有气体

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII	VIII	VIII	IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 氢 H																	2 氦 He
2	3 锂 Li	4 铍 Be											5 硼 B	6 碳 C	7 氮 N	8 氧 O	9 氟 F	10 氖 Ne
3	11 钠 Na	12 镁 Mg											13 铝 Al	14 硅 Si	15 磷 P	16 硫 S	17 氯 Cl	18 氩 Ar
4	19 钾 K	20 钙 Ca	21 钪 Sc	22 钛 Ti	23 钒 V	24 铬 Cr	25 锰 Mn	26 铁 Fe	27 钴 Co	28 镍 Ni	29 铜 Cu	30 锌 Zn	31 镓 Ga	32 锗 Ge	33 砷 As	34 硒 Se	35 溴 Br	36 氪 Kr
5	37 铷 Rb	38 锶 Sr	39 钇 Y	40 锆 Zr	41 铌 Nb	42 钼 Mo	43 锝* Tc	44 钌 Ru	45 铑 Rh	46 钯 Pd	47 银 Ag	48 镉 Cd	49 铟 In	50 锡 Sn	51 锑 Sb	52 碲 Te	53 碘 I	54 氙 Xe
6	55 铯 Cs	56 钡 Ba	57-71 镧系 La-Lu	72 铪 Hf	73 钽 Ta	74 钨 W	75 铼 Re	76 锇 Os	77 铱 Ir	78 铂 Pt	79 金 Au	80 汞 Hg	81 铊 Tl	82 铅 Pb	83 铋 Bi	84 钋 Po	85 砹* At	86 氡* Rn
7	87 钫* Fr	88 镭* Ra	89-103 锕系 Ac-Lr	104 𬬻* Rf	105 𬭊* Db	106 𬭳* Sg	107 𬭛* Bh	108 𬭶* Hs	109 鿏* Mt	110 𫟼* Ds	111 𬬭* Rg	112 鿔* Cn	113 鉨* Nh	114 𫓧* Fl	115 镆* Mc	116 𫟷* Lv	117 鿬* Ts	118 鿫* Og

SGZ, SHN & New Elements, Nucl. Phys. Rev. 34 (2017) 318-331 (in, Chinese)

镧系	57 镧 La	58 铈 Ce	59 镨 Pr	60 钕 Nd	61 钷* Pm	62 钐 Sm	63 铕 Eu	64 钆 Gd	65 铽 Tb	66 镝 Dy	67 钬 Ho	68 铒 Er	69 铥 Tm	70 镱 Yb	71 镥 Lu
锕系	89 锕* Ac	90 钍* Th	91 镤* Pa	92 铀* U	93 镎* Np	94 钚* Pu	95 镅* Am	96 锔* Cm	97 锫* Bk	98 锎* Cf	99 锿* Es	100 镄* Fm	101 钔* Md	102 锘* No	103 铹* Lr

Courtesy of Xu Meng (孟旭)

Chinese names of new elements

- 113: Nihonium (Nh)
  - Proposals of Chinese name: 鿭 , ⿰钅兒, ⿰钅匿 & ⿰钅宏
- 115: Moscovium (Mc)
  - Proposal of Chinese name: 镆
- 117: Tennessine (Ts)
  - Proposals of Chinese name: 鿬 & 磌
- 118: Oganesson (Og)
  - Proposals of Chinese name: 鿫 & ⿹气区

Chinese names of new elements

核データニュース，No.118 (2017)

話題・解説 (I)

Chinese Names of New Elements with Z = 113, 115, 117 & 118

Shan-Gui Zhou (周善贵/周善貴)[1]

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(中国科学院理论物理研究所/中國科學院理論物理研究所)

sgzhou@itp.ac.cn

SGZ, Nuclear Data News 118 (2017) 12

HIRFL China: ^{271}Ds (Z = 110)

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

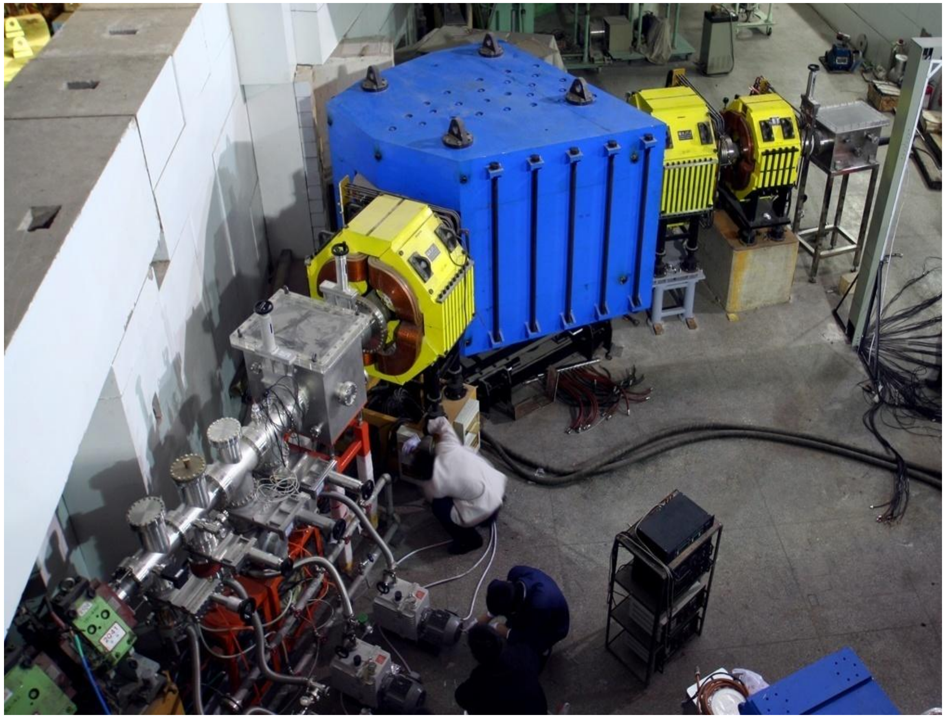
2011.03.15 $^{64}Ni + ^{208}Pb \rightarrow ^{272}Ds^*$ 13 days

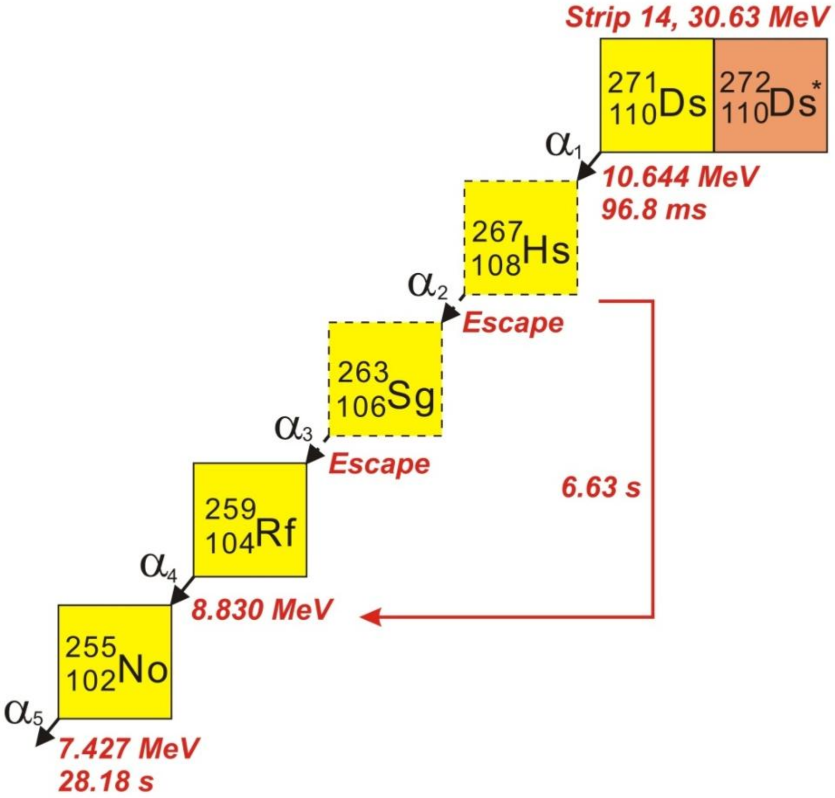
2001: ^{259}Db (Z=105)
2004: ^{265}Bh (Z=107)

IMP/CAS, ITP/CAS

Nanjing Univ, CIAE

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





Courtesy of Zai-Guo Gan (甘再国)

Lecture 1

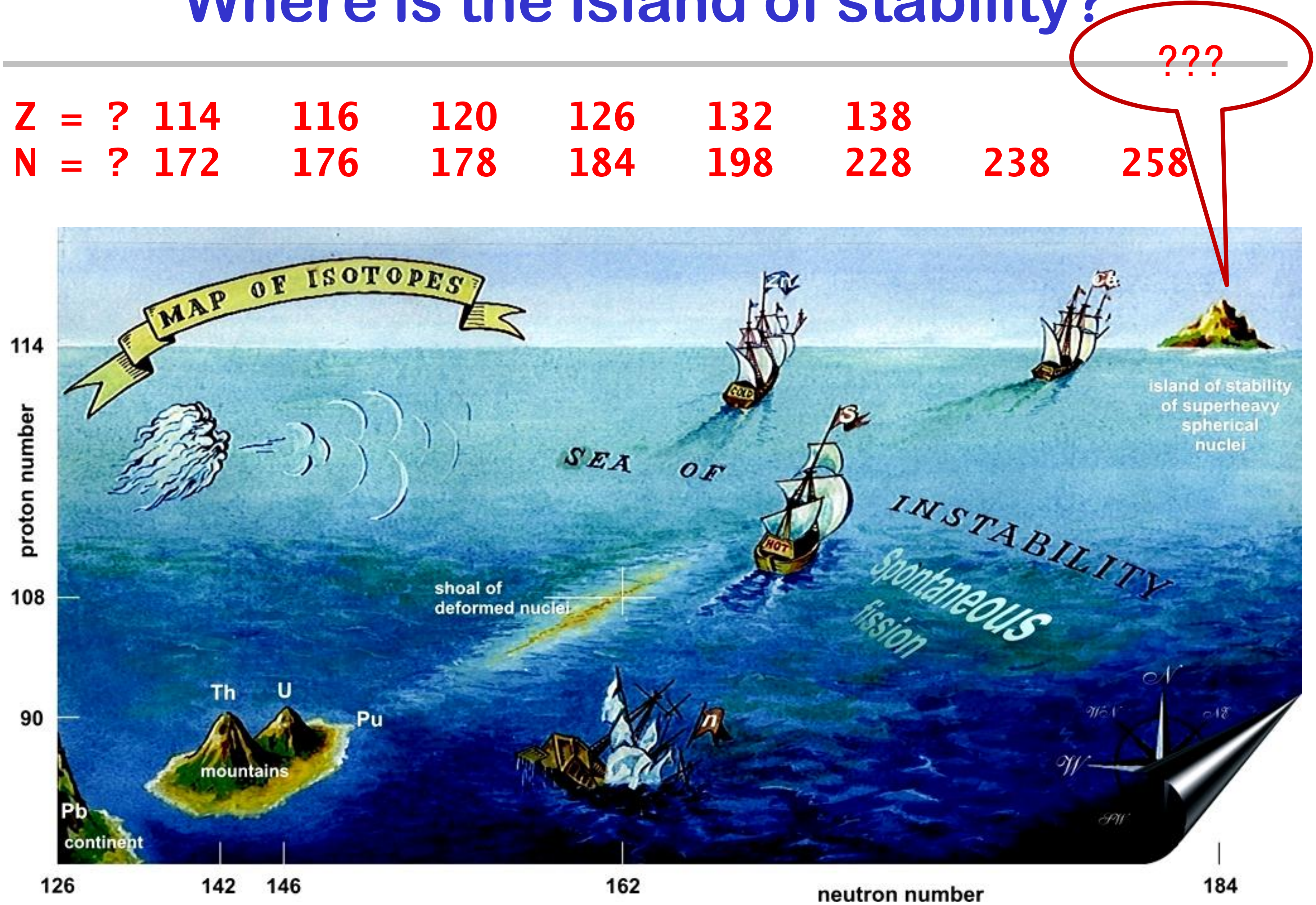
- Predictions of the island of stability of SHN
- Experimental progress on synthesis of SHN
- Challenges in synthesizing SHN

Challenges to synthesize SHN & new SHEs

- Elusive island of stability

Where is the island of stability?

Z = ?	114	116	120	126	132	138		
N = ?	172	176	178	184	198	228	238	258

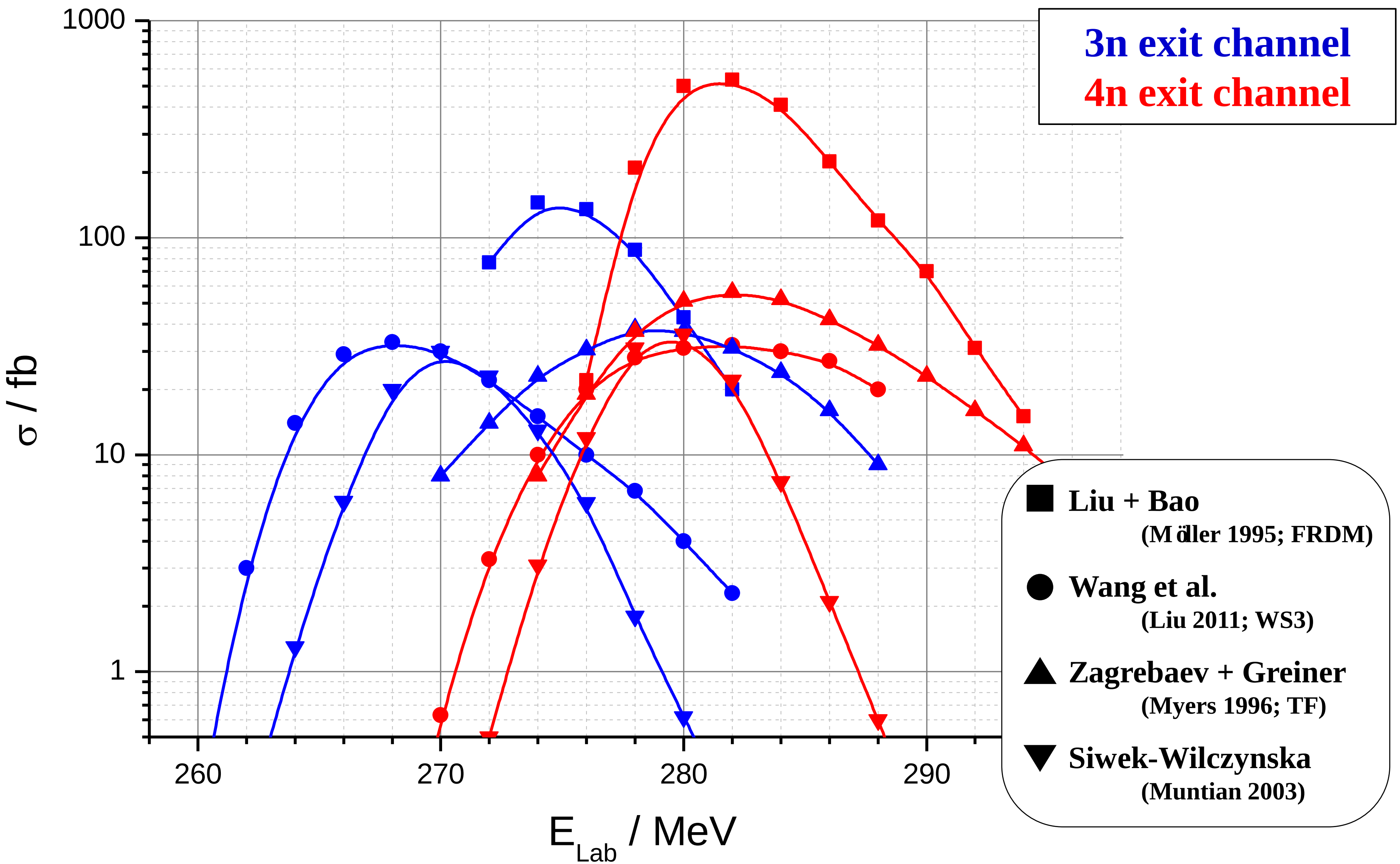


Challenges to synthesize SHN & new SHEs

- Elusive island of stability

- Tiny cross sections w/ huge uncertainties
  - ^{271}Ds: $\sigma \sim 10$ pb; HIRFL: 1 event in 20 days
  - ^{278}Nh: $\sigma \sim 0.02$ pb; RIKEN: 3 events in 553 days

Uncertainties in predicted xsections for Z = 119



From Ch. E. Duellman (FUSHE2012)

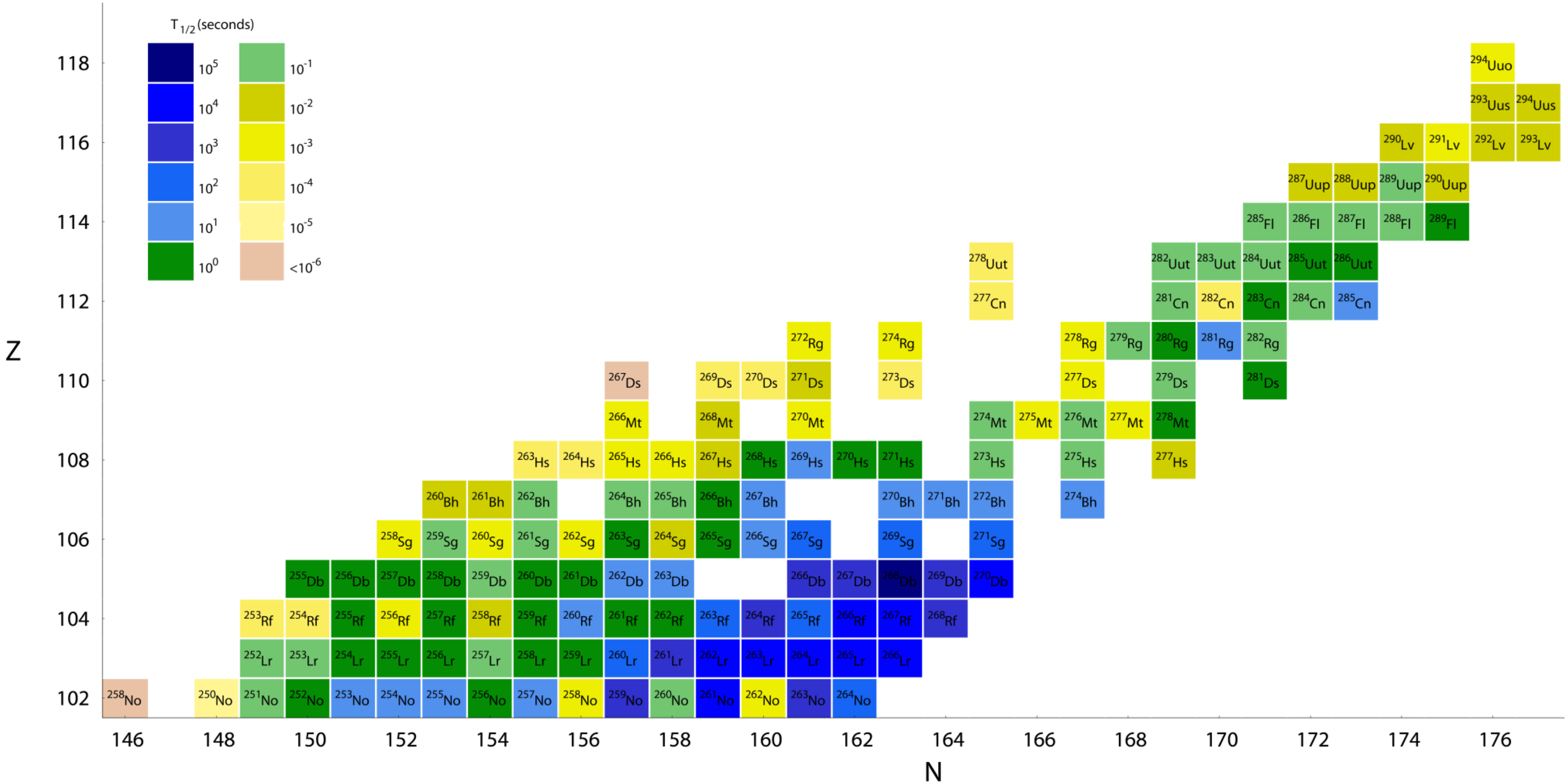
Challenges to synthesize SHN & new SHEs

- Elusive island of stability

- Tiny cross sections w/ huge uncertainties
  - ^{271}Ds: $\sigma \sim 10$ pb; HIRFL: 1 event in 20 days
  - ^{278}Nh: $\sigma \sim 0.02$ pb; RIKEN: 3 events in 553 days

- Only neutron-deficient SHN, far away from $N = 184$

Only neutron deficient SHN produced via HI fusion



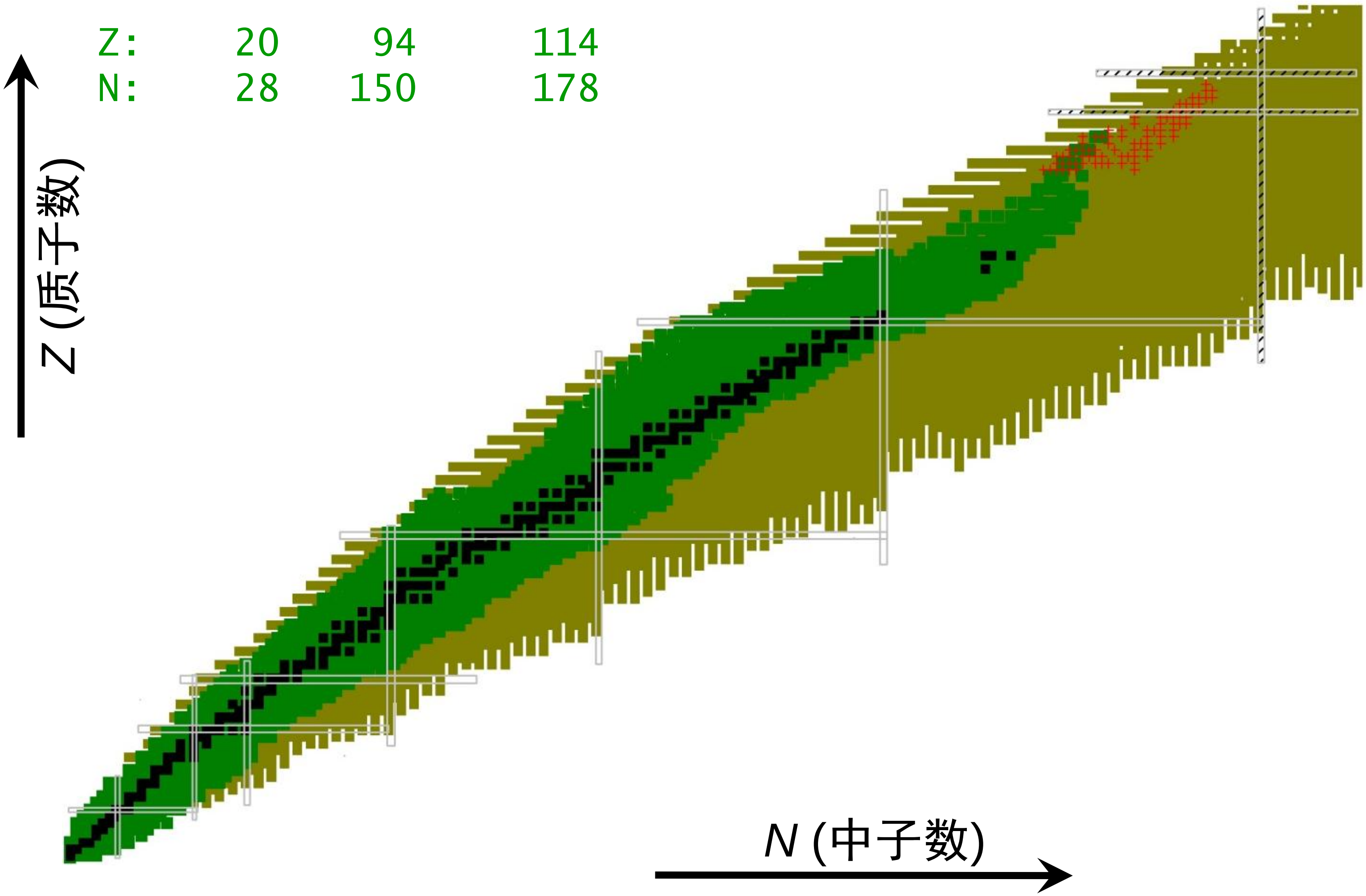
Life-time longer w/ increasing *N* !

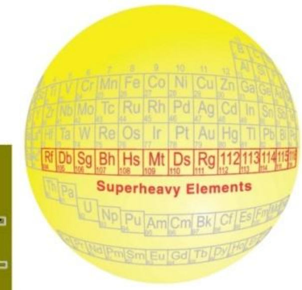
Courtesy of Kai Wen (温凯)

Only neutron deficient SHN produced via HI fusion

$$^{48}\mathrm{Ca} + {}^{244}\mathrm{Pu} \longrightarrow {}^{292}\mathrm{Fl}^{*} \longrightarrow {}^{292\text{-}x}\mathrm{Fl} + xn$$

Z:	20	94	114
N:	28	150	178





Nuclear chart: courtesy of Ning Wang (王宁)

Lecture 2

- Challenges in synthesizing SHN

- Theoretical study of structure of SHN
  - Nuclear models
  - Next shell closures beyond ^{208}Pb as seen from single particle spectra, shell correction energy & nuclear shapes
  - Exotic shapes in SHN
  - Low-lying spectra of SHN & magicities

- Theoretical study of decay of SHN

Study of SHN: Theory & experiment

- Theory and experiment has progressed hand in hand
  - 1960s, heavy ion accelerators & detectors built for SHN following theoretical predictions; 1980s, important progress made in experiments
  - …
  - 2010, element with Z = 117

Selected for a Viewpoint in *Physics*

PRL **104,** 142502 (2010) PHYSICAL REVIEW LETTERS week ending 9 APRIL 2010

Synthesis of a New Element with Atomic Number $Z = 117$

Yu. Ts. Oganessian,[1,*] F. Sh. Abdullin,[1] P. D. Bailey,[2] D. E. Benker,[2] M. E. Bennett,[3] S. N. Dmitriev,[1] J. G. Ezold,[2]
J. H. Hamilton,[4] R. A. Henderson,[5] M. G. Itkis,[1] Yu. V. Lobanov,[1] A. N. Mezentsev,[1] K. J. Moody,[5] S. L. Nelson,[5]
A. N. Polyakov,[1] C. E. Po
R. N. Sagaidak,[1] D. A. Shau
Yu. S. Tsy
[1]*Joi*

[12] C. Shen *et al.*, Int. J. Mod. Phys. E **17**, 66 (2008).
[13] V. Zagrebaev *et al.*, Phys. Rev. C **78**, 034610 (2008).
[14] Z. H. Liu *et al.*, Phys. Rev. C **80**, 034601 (2009).

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[5]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
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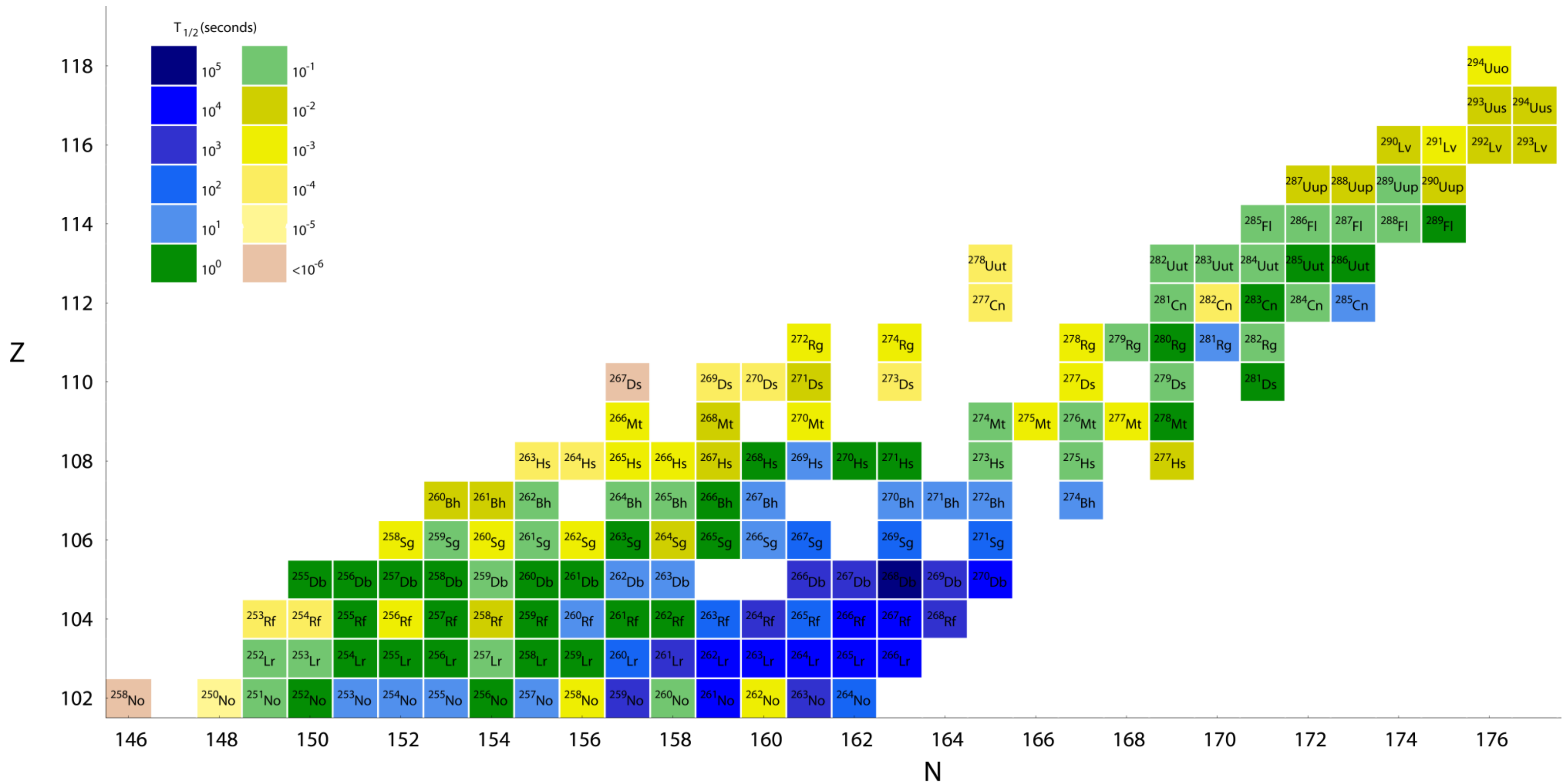
(Received 15 March 2010; published 9 April 2010)

Is there new physics on the island of stability?

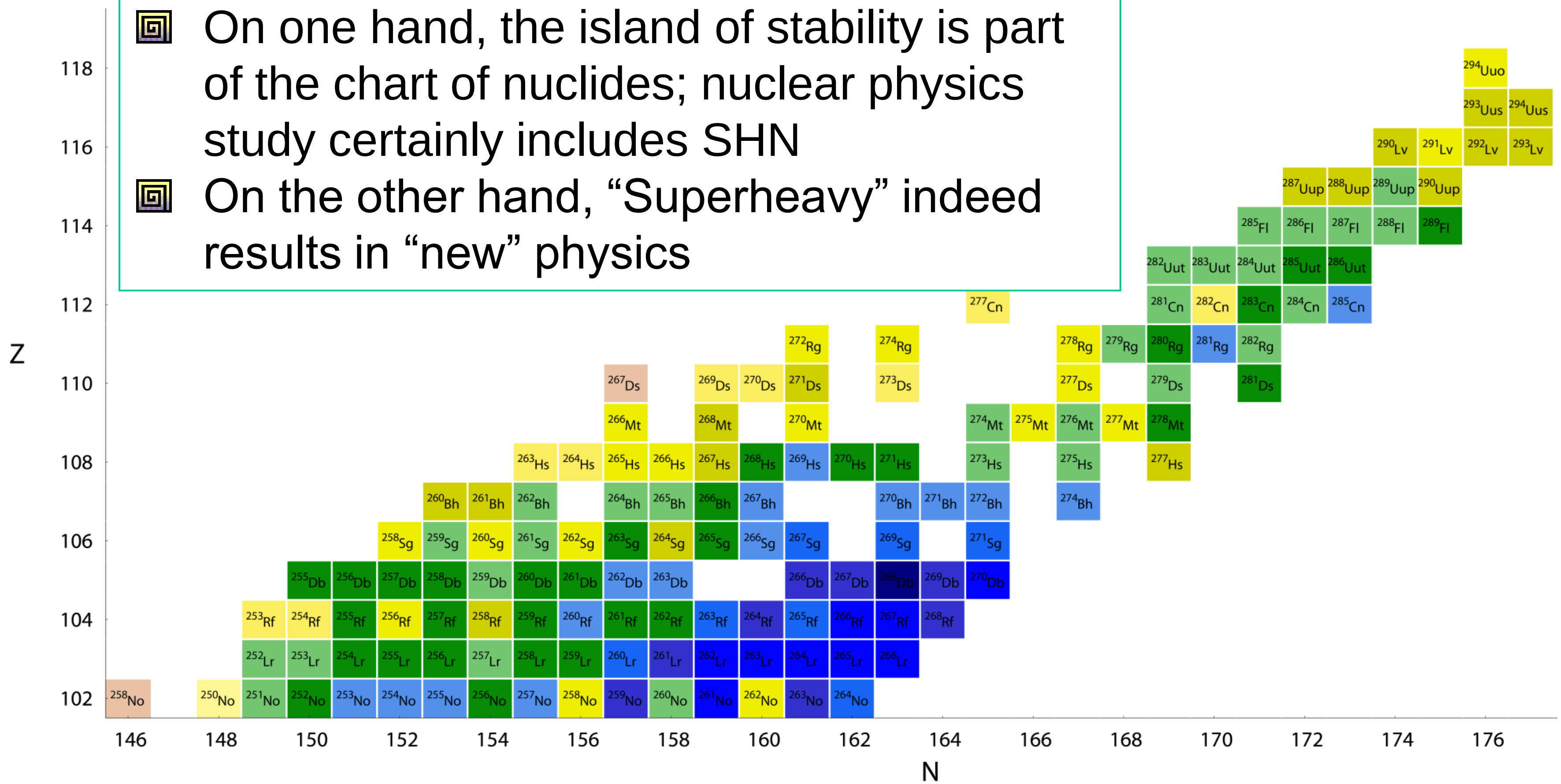


SHE with $Z \leq 118$ have been synthesized & named
Recent naming for elements with Z = 113, 115, 117 & 118

Courtesy of Kai Wen (温凯)

Is there new physics on the island of stability?

- On one hand, the island of stability is part of the chart of nuclides; nuclear physics study certainly includes SHN
- On the other hand, "Superheavy" indeed results in "new" physics

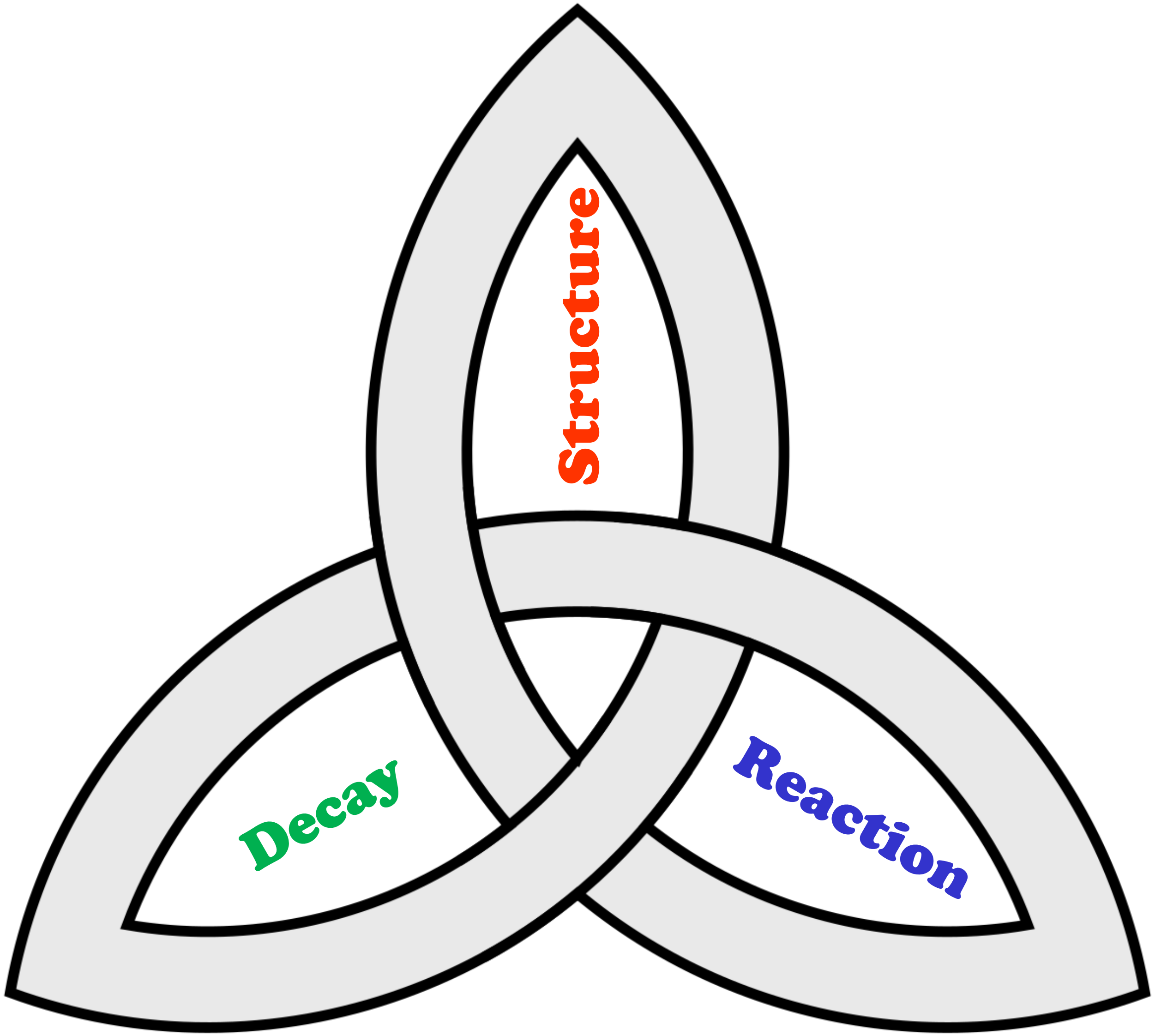


SHE with $Z \leq 118$ have been synthesized & named

Recent naming for elements with $Z = 113, 115, 117$ & 118

Courtesy of Kai Wen (温凯)

Trinity in nucl. phys.: Structure, decay & reaction



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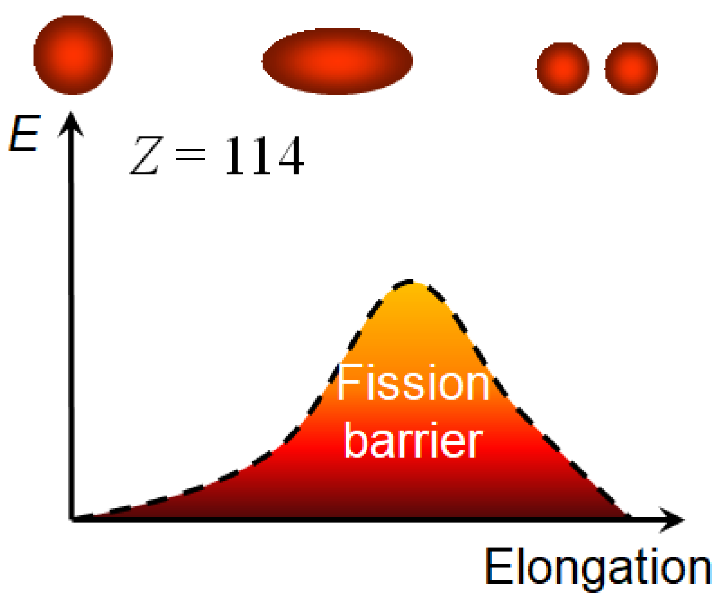
  - Exotic shapes in SHN
  - Low-lying spectra of SHN & magicities

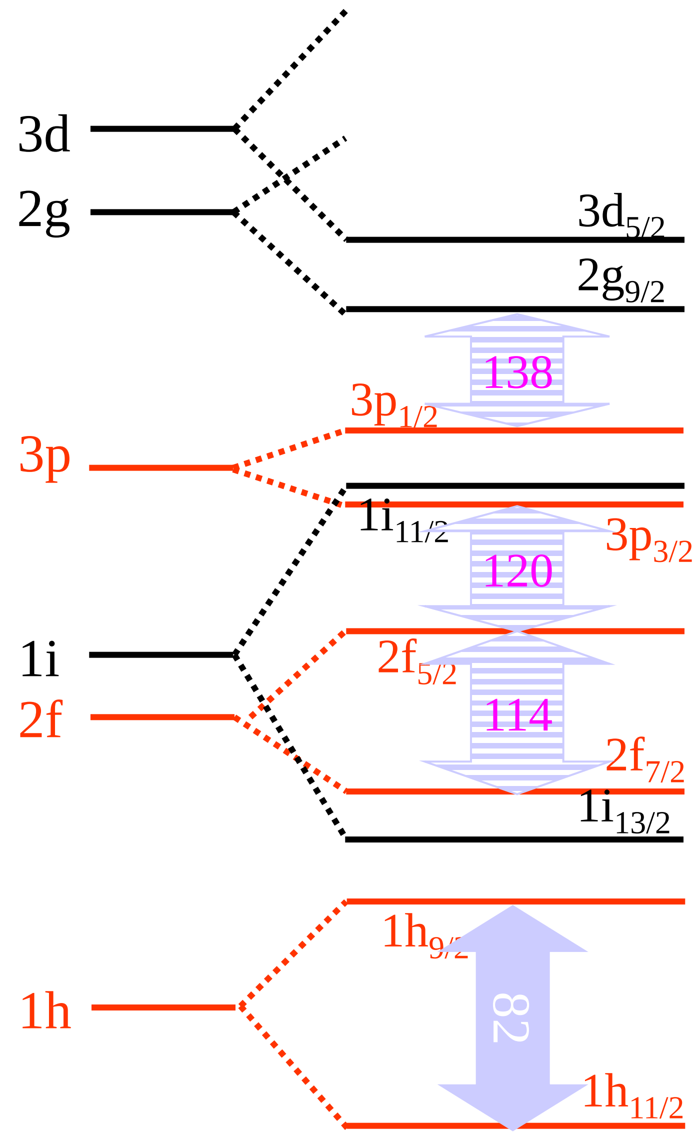
- Theoretical study of decay of SHN

Structure of SHN

Structure

- Ground state properties
- Low-E spectroscopy
- Fission barrier
- Isomeric states
- …





Lecture 2

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- Theoretical study of decay of SHN

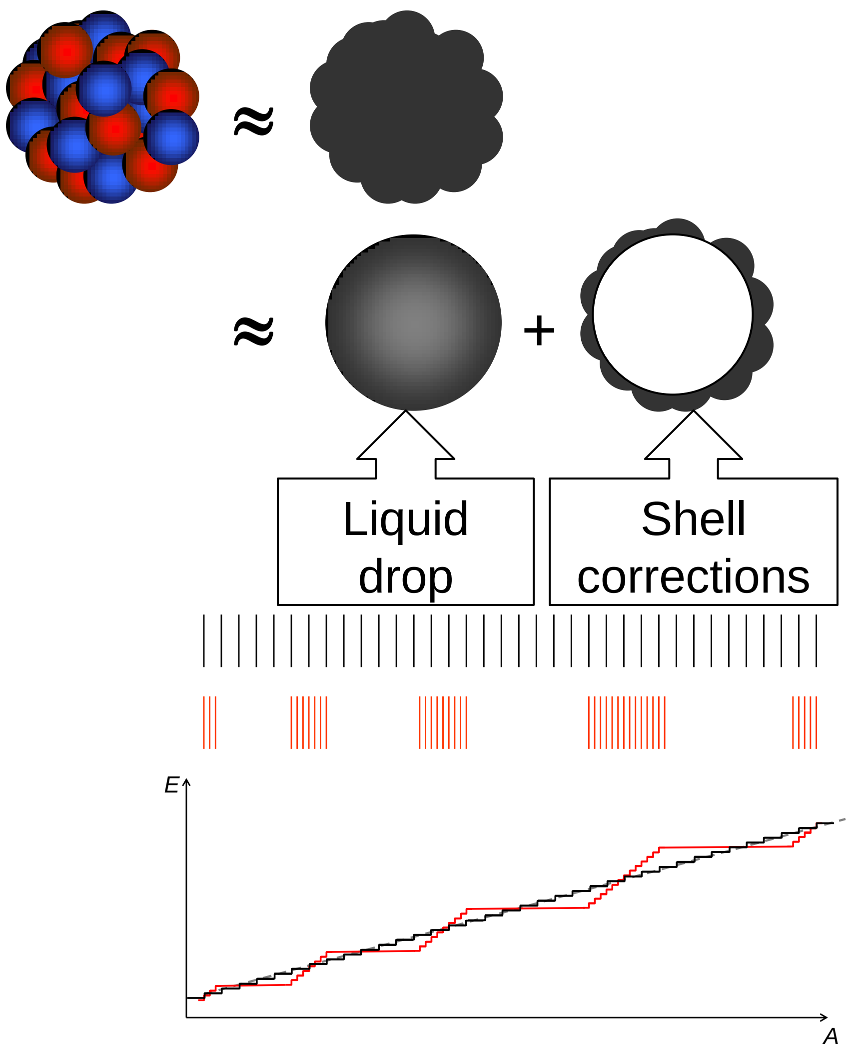
Nuclear models

- Macroscopic models
  - Global behavior & average effects
- Macroscopic-microscopic models
  - Global behavior & average effects
  - Correction from single particle motion on whole nucleus
- Microscopic models
  - Starting from nucleons; correlations among nucleons
  - NN interaction, mean-field approximation, residual interaction

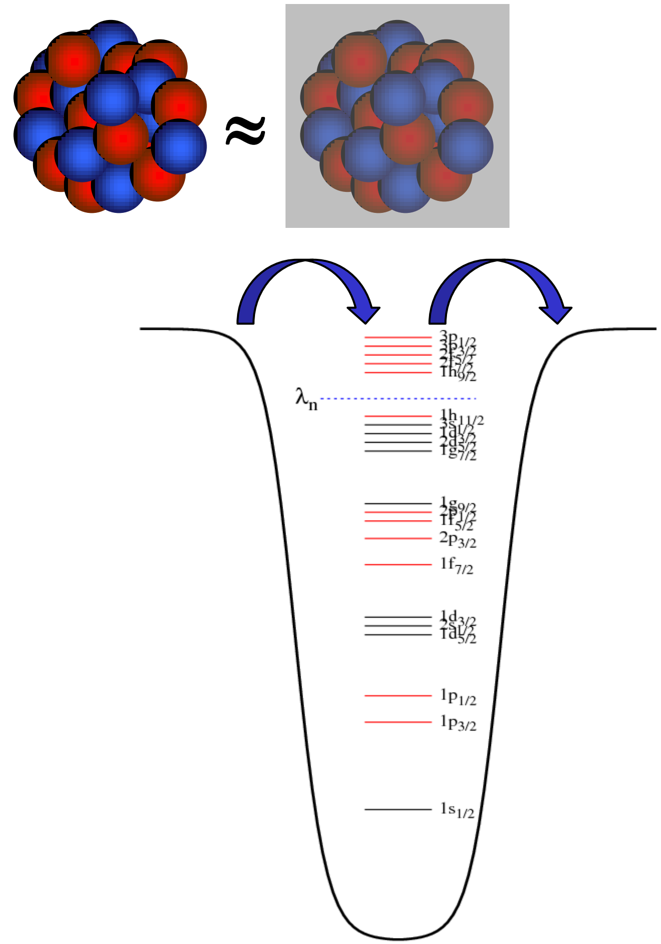
Hu & Zhong, Macroscopic models for nuclei, 1998 (in Chinese)
Greiner & Maruhn, Nuclear models, Springer, 1995
Ring & Schuck, The Nuclear Many−Body Problem, Springer, 1980

Nuclear models

Mac-mic models

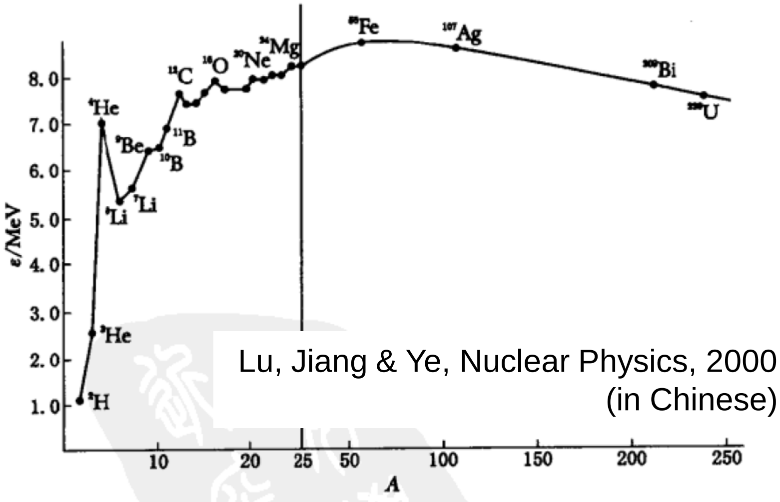


Self-consistent models



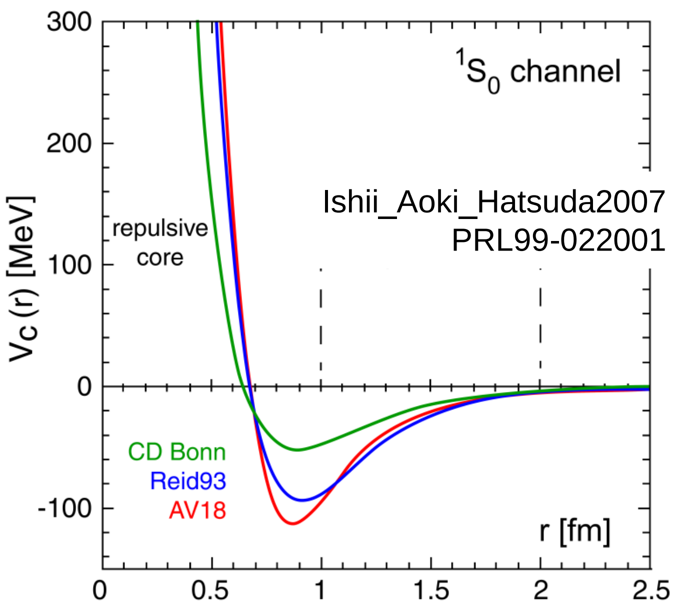
Liquid drop model: Nucleus ~ charged LD

- **Similarities**
  - ➢ $B/A \sim 8\ \mathrm{MeV} \Rightarrow$ Saturation of nuclear force
  - ➢ $R \sim A^{1/3} \Rightarrow$ Incompressibility of nuclear matter



Lu, Jiang & Ye, Nuclear Physics, 2000 (in Chinese)

- **Differences**
  - ➢ Mean distance between nucleons larger than that corresponding to the minimum in NN potential
  - ➢ Mean free path of nucleon comparable to nuclear size (Fermi gas model)



Ishii_Aoki_Hatsuda2007 PRL99-022001

Liquid drop model: Nucleus ~ charged LD

$$B(Z,A) = a_{\rm v}A - a_{\rm s}A^{2/3} - a_{\rm c}Z^2A^{-1/3} - a_{\rm a}\left(\frac{A}{2}-Z\right)^2A^{-1} + \delta a_{\rm p}A^{-1/2}$$

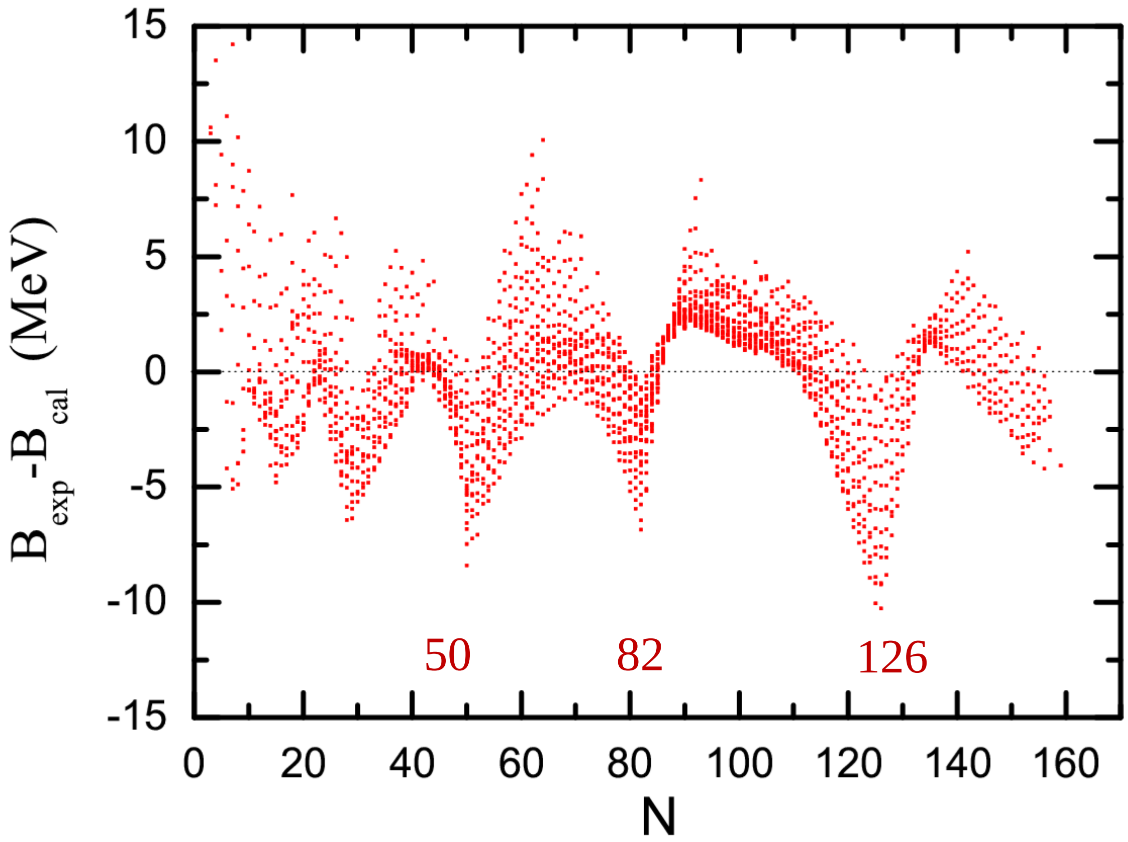
- □ Volumn
- □ Surface
- □ Coulomb
- □ Symmetry
- □ Pairing

Symmetry, Pairing: Quantum effects

$$\delta = \begin{cases} 1 & \text{Even-even} \\ 0 & \text{Odd-}A \\ -1 & \text{Odd-odd} \end{cases}$$

Lu, Jiang & Ye, Nuclear Physics, 2000 (in Chinese)

Comparison w/ experiment

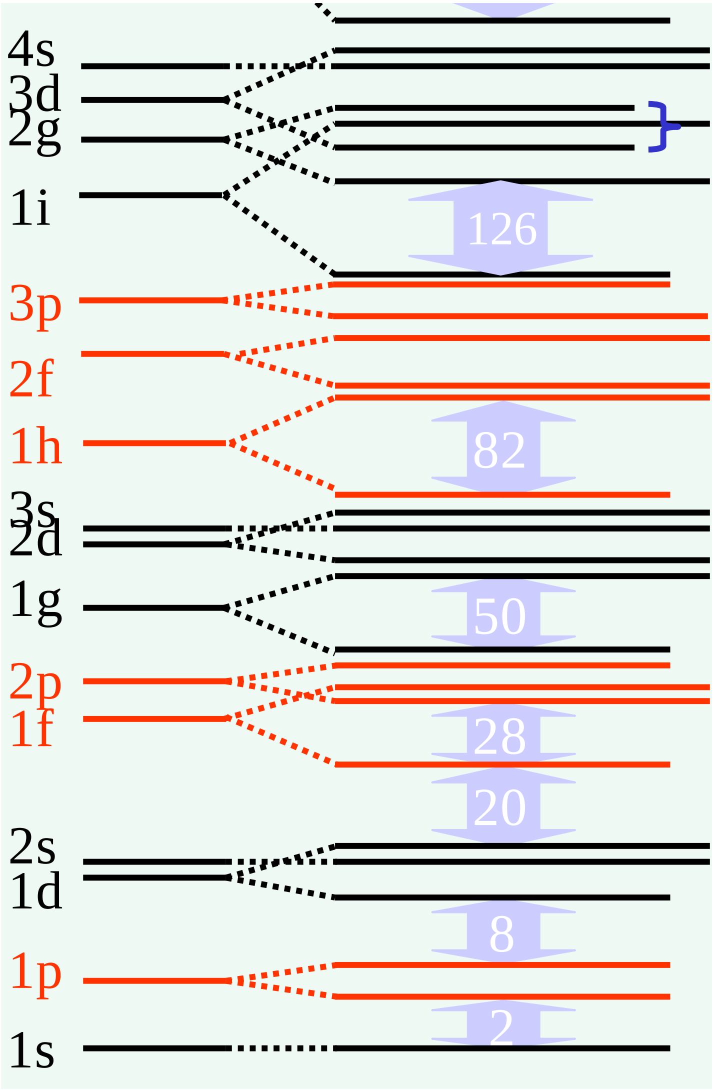


$$B(Z,N) = a_V A - a_S A^{2/3} - \frac{a_C Z^{5/3}}{1 + 0.452(T_z - T_z^*)/A} - a_a T_z(T_z + 1)A^{-0.86} + a_P A^{-1/2}$$

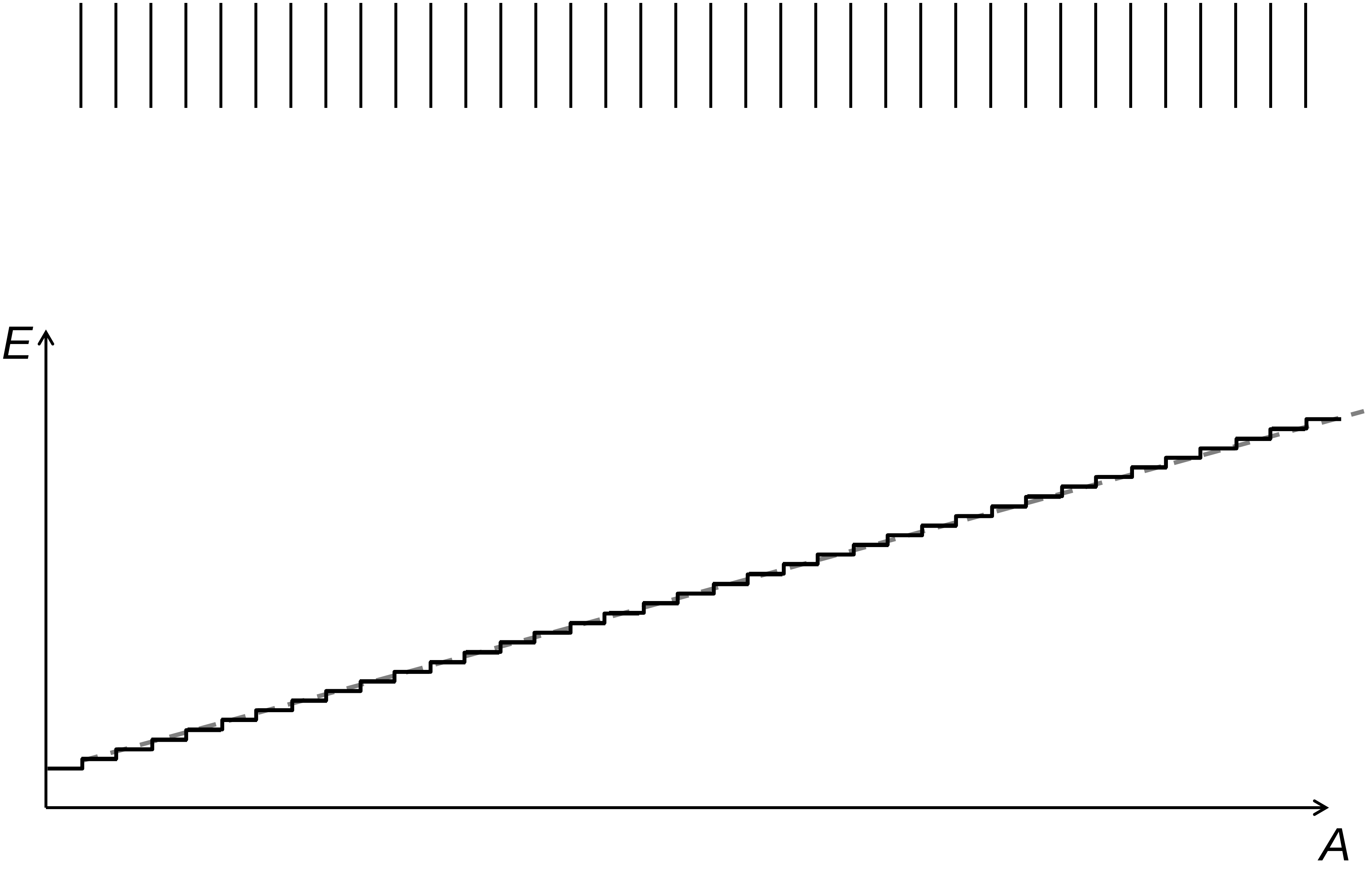
Courtesy of Yu-Chen Cao (曹宇晨)

Single nucleon potential, spectra & magicities

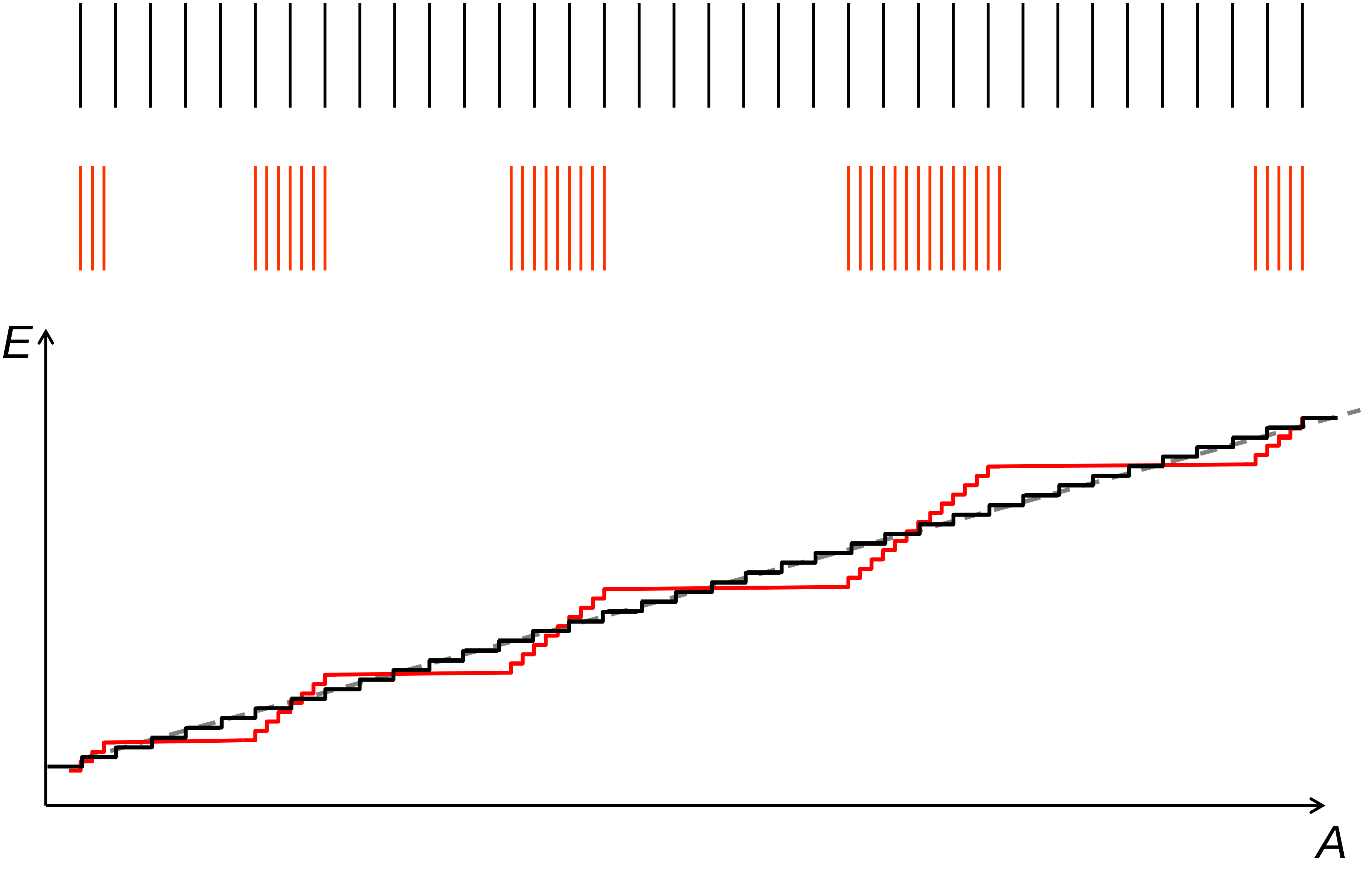
- Harmonic oscillator & square well
- Woods-Saxon
- Self-consistent (self-bound)



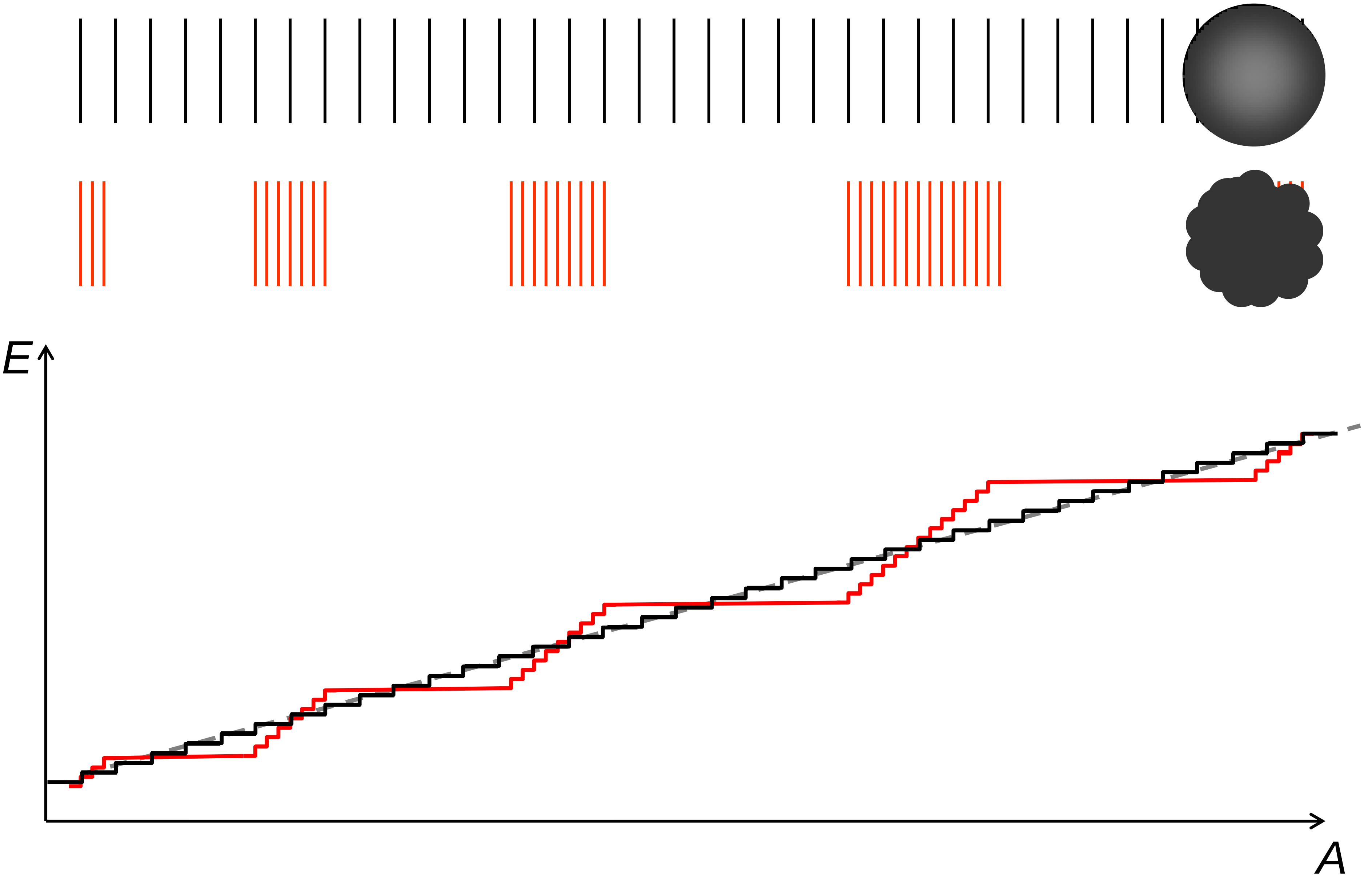
Quantum shell effects



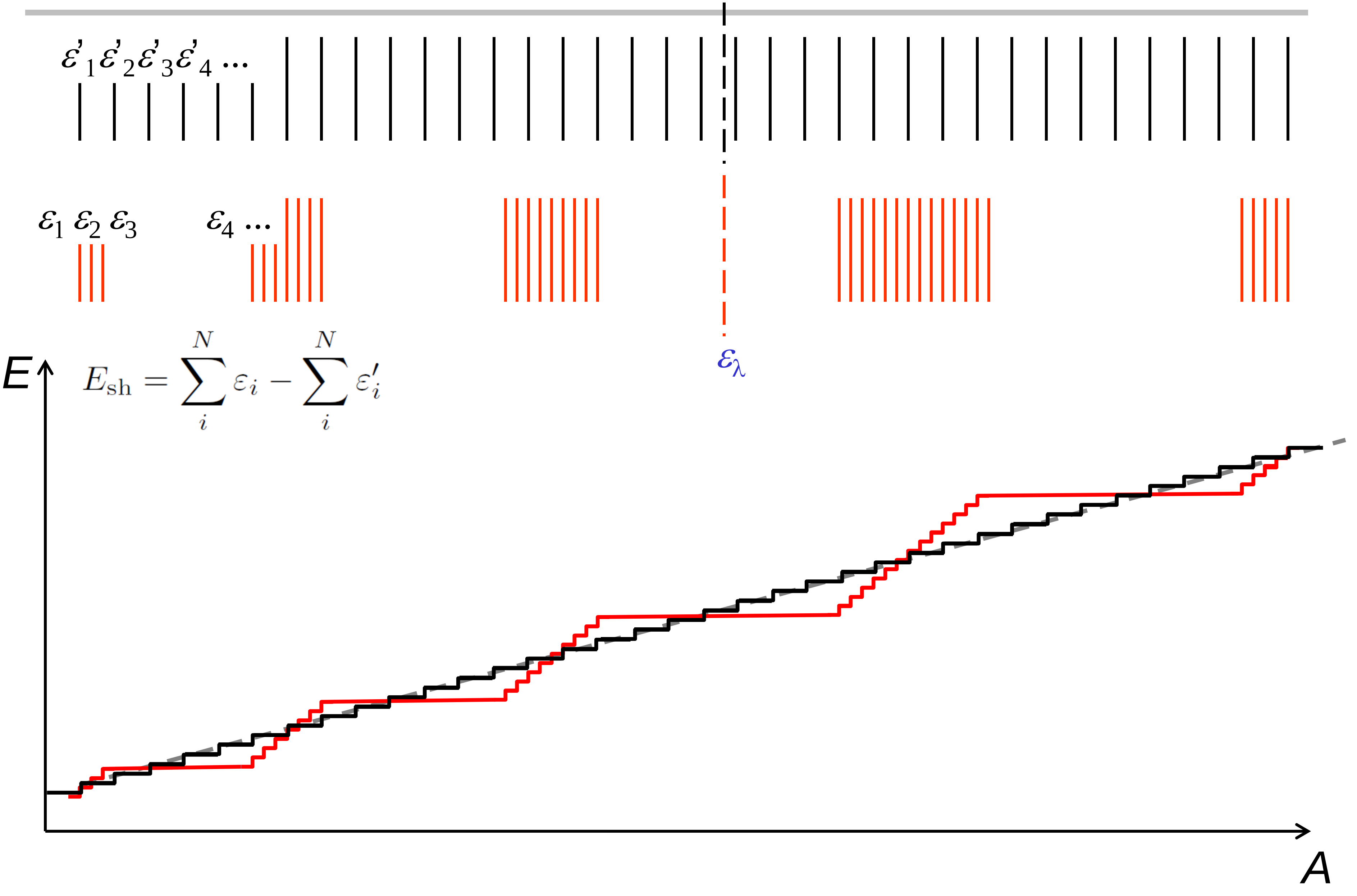
Quantum shell effects



Quantum shell effects

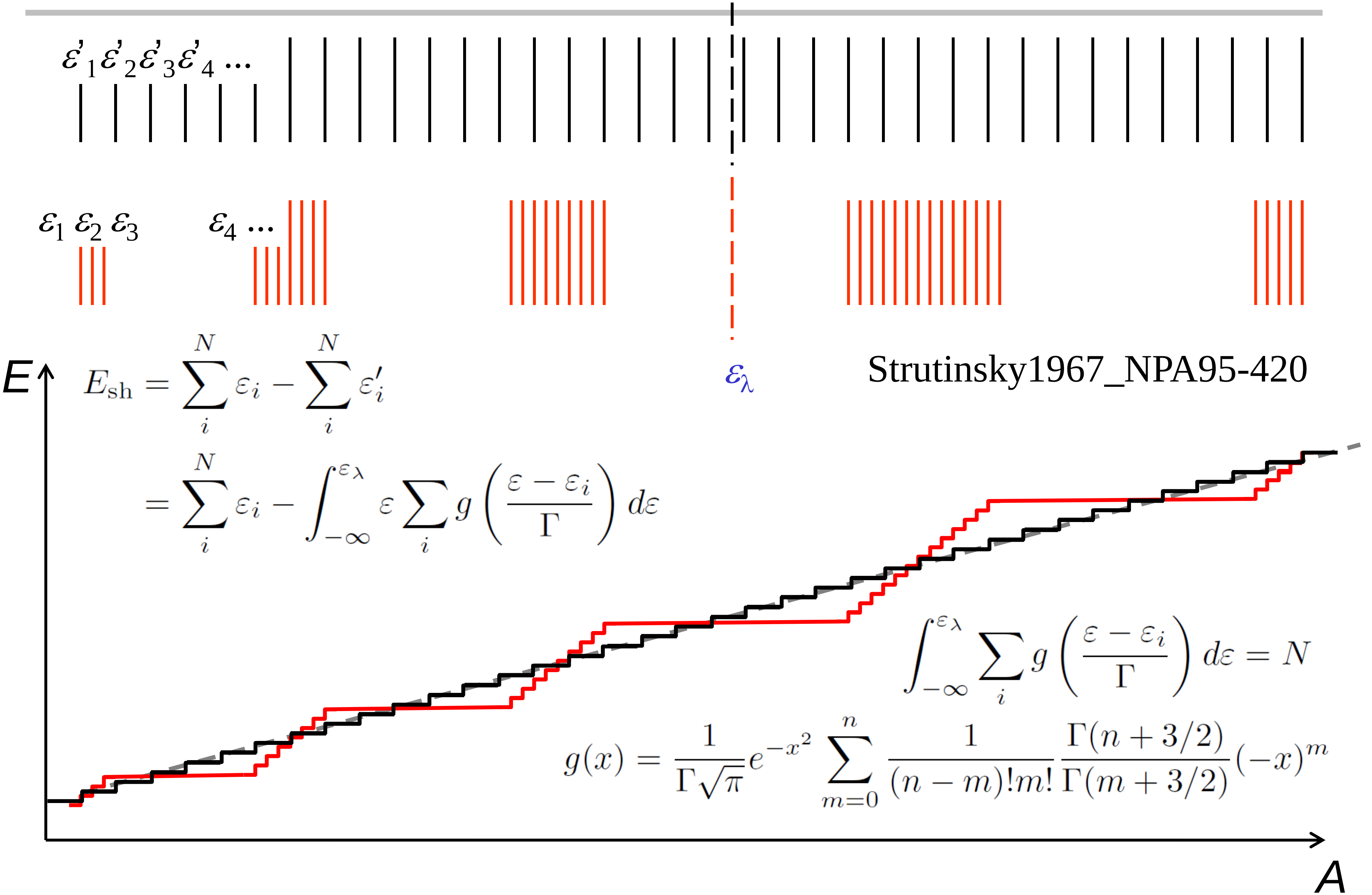


Microscopic shell corrections



$$E_{\rm sh} = \sum_i^N \varepsilon_i - \sum_i^N \varepsilon'_i$$

Shell corrections: Strutinsky mothod



Strutinsky1967_NPA95-420

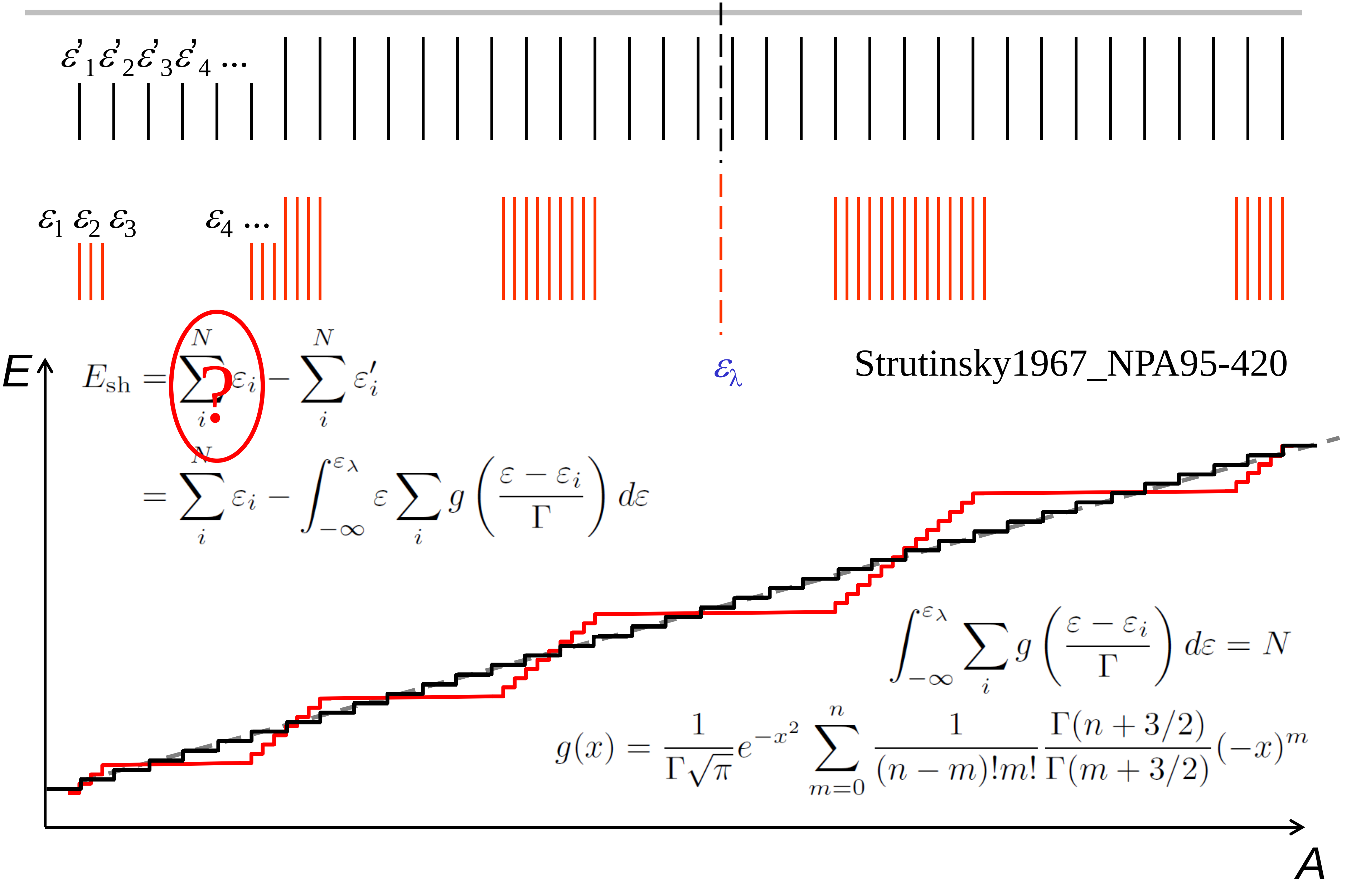
$$E_{\rm sh} = \sum_i^N \varepsilon_i - \sum_i^N \varepsilon'_i$$

$$= \sum_i^N \varepsilon_i - \int_{-\infty}^{\varepsilon_\lambda} \varepsilon \sum_i g\left(\frac{\varepsilon - \varepsilon_i}{\Gamma}\right) d\varepsilon$$

$$\int_{-\infty}^{\varepsilon_\lambda} \sum_i g\left(\frac{\varepsilon - \varepsilon_i}{\Gamma}\right) d\varepsilon = N$$

$$g(x) = \frac{1}{\Gamma\sqrt{\pi}} e^{-x^2} \sum_{m=0}^{n} \frac{1}{(n-m)!m!} \frac{\Gamma(n+3/2)}{\Gamma(m+3/2)} (-x)^m$$

Shell corrections: Strutinsky mothod



Strutinsky1967_NPA95-420

$$E_{\rm sh} = \sum_i^N \varepsilon_i - \sum_i^N \varepsilon'_i$$

$$= \sum_i^N \varepsilon_i - \int_{-\infty}^{\varepsilon_\lambda} \varepsilon \sum_i g\left(\frac{\varepsilon - \varepsilon_i}{\Gamma}\right) d\varepsilon$$

$$\int_{-\infty}^{\varepsilon_\lambda} \sum_i g\left(\frac{\varepsilon - \varepsilon_i}{\Gamma}\right) d\varepsilon = N$$

$$g(x) = \frac{1}{\Gamma\sqrt{\pi}} e^{-x^2} \sum_{m=0}^{n} \frac{1}{(n-m)!m!} \frac{\Gamma(n+3/2)}{\Gamma(m+3/2)} (-x)^m$$

Finite range droplet model (FRDM)

Moeller+2016_ADNDT109-110-1

$E_{\mathrm{mac}}(Z, N, \text{shape}) =$

$M_{\mathrm{H}}Z + M_{\mathrm{n}}N$

mass excesses of Z hydrogen atoms and N neutrons

$+ \left(-a_1 + J\bar{\delta}^2 - \frac{1}{2}K\bar{\varepsilon}^2\right)A$ volume energy

$+ \left(a_2 B_1 + \frac{9}{4}\frac{J^2}{Q}\bar{\delta}^2\frac{B_{\mathrm{s}}{}^2}{B_1}\right)A^{2/3}$ surface energy

$+ a_3 A^{1/3} B_{\mathrm{k}}$ curvature energy

$+ a_0 A^0$ A^0 energy

$+ c_1 \frac{Z^2}{A^{1/3}} B_3$ Coulomb energy

$- c_2 Z^2 A^{1/3} B_{\mathrm{r}}$ volume redistribution energy

$- c_4 \frac{Z^{4/3}}{A^{1/3}}$ Coulomb exchange correction

$- c_5 Z^2 \frac{B_{\mathrm{w}} B_{\mathrm{s}}}{B_1}$ surface redistribution energy

$+ f_0 \frac{Z^2}{A}$ proton form-factor correction to the Coulomb energy

$- c_{\mathrm{a}}(N - Z)$ charge-asymmetry energy

$+ W\left(|I| + \begin{cases} 1/A, & Z \text{ and } N \text{ odd and equal} \\ 0, & \text{otherwise} \end{cases}\right)$

Wigner energy

$+ \begin{cases} +\overline{\Delta}_{\mathrm{p}} + \overline{\Delta}_{\mathrm{n}} - \delta_{\mathrm{np}}, & Z \text{ and } N \text{ odd} \\ +\overline{\Delta}_{\mathrm{p}}, & Z \text{ odd and } N \text{ even} \\ +\overline{\Delta}_{\mathrm{n}}, & Z \text{ even and } N \text{ odd} \\ +0, & Z \text{ and } N \text{ even} \end{cases}$

average pairing energy

$- a_{\mathrm{el}} Z^{2.39}$ energy of bound electrons

Weizsäcker-Skyrme (WS) mass model

$$E(A,Z,\beta) = E_{\mathrm{LD}}(A,Z)\prod_{k\geqslant 2}\left(1+b_k\beta_k^2\right) + \Delta E(A,Z,\beta) + \Delta_{\mathrm{res}}$$

Liquid drop | Deformation | Shell | Residual

$$E_{\mathrm{LD}}(A,Z) = a_v A + a_s A^{2/3} + E_C + a_{\mathrm{sym}} I^2 A + a_{\mathrm{pair}} A^{-1/3}\delta_{np}$$

$\Delta E(A, Z, \beta)$: Shell corrections

Δ_{res} (residual): Mirror, pairing, Wigner corrections, ...

Macro-micro concept & Skyrme energy density functional

N. Wang, M. Liu, et al., PRC81-044322; PRC82-044304; PRC84-014333

Covariant Density Functional Theory (CDFT)

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

Serot_Walecka1986_ANP16-1

Reinhard1989 RPP52-439

Ring1996_PPNP37-193

Vretenar_Afanasjev_Lalazissis_Ring2005_PR409-101

Meng_Toki_SGZ_Zhang_Long_Geng2006_PPNP57-470

$$(\boldsymbol{\alpha}\cdot\mathbf{p} + \beta(M + S(\mathbf{r})) + V(\mathbf{r}))\psi_i = \epsilon_i\psi_i$$

Liang_Meng_SGZ2015_PR570-1

Meng_SGZ2015_JPG42-093101

$$\left(-\nabla^2 + m_\sigma^2\right)\sigma = -g_\sigma\rho_S - g_2\sigma^2 - g_3\sigma^3$$

$$\left(-\nabla^2 + m_\omega^2\right)\omega = g_\omega\rho_V - c_3\omega^3$$

$$\left(-\nabla^2 + m_\rho^2\right)\rho = g_\rho\rho_3$$

$$-\nabla^2 A = e\rho_C$$

Various nuclear mass models: Comparison

c Sobiczewski_Litvinov&Palczewski2018_ADNDT119-1

ELSEVIER

Atomic Data and Nuclear Data Tables

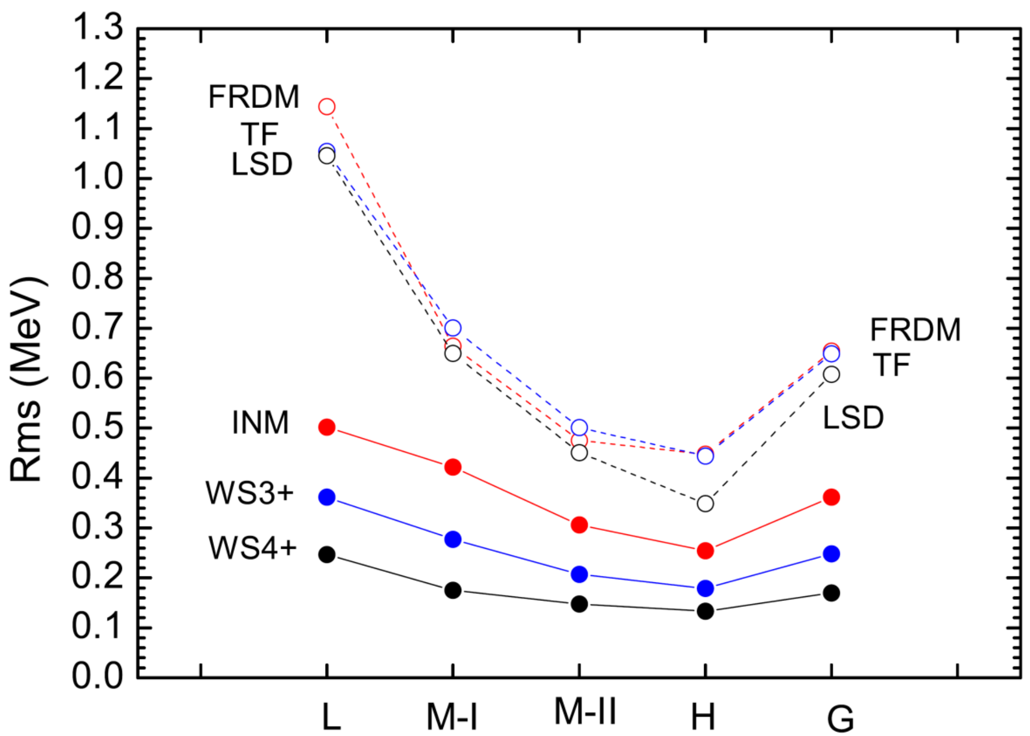
journal homepage: www.elsevier.com/locate/adt

Detailed illustration of the accuracy of currently used nuclear-mass models

CrossMark

A. Sobiczewski [a,b,c,*], Yu.A. Litvinov [c], M. Palczewsk

[a] *National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*
[b] *Joint Institute for Nuclear Research, 141980 Dubna, Russian Federation*
[c] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*



Relativistic continuum Hartree-Bogoliubov (RCHB) theory

Contents lists available at ScienceDirect

Atomic Data and Nuclear Data Tables

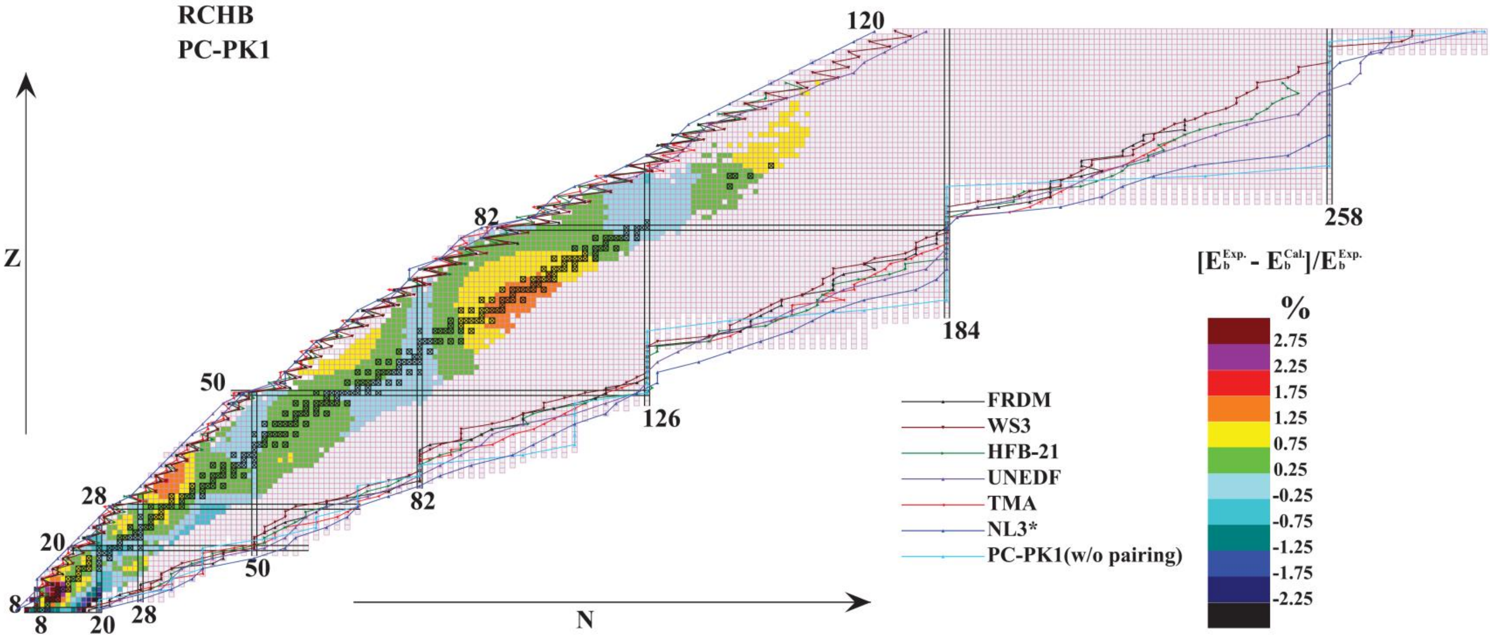
journal homepage: www.elsevier.com/locate/adt

Xia+2018_ADNDT121-122-1

The limits of the nuclear landscape explored by the relativistic continuum Hartree–Bogoliubov theory

X.W. Xia [a], Y. Lim [b,c], P.W. Zhao [d,e], H.Z. Liang [f], X.Y. Qu [a,g], Y. Chen [d,h], H. Liu [d], L.F. Zhang [d], S.Q. Zhang [d], Y. Kim [c], J. Meng [d,a,i,*]

[a] School of Physics and Nuclear E
[b] Cyclotron Institute, Texas A&M
[c] Rare Isotope Science Project, Ins
[d] State Key Laboratory of Nuclear
[e] Physics Division, Argonne Natio
[f] RIKEN Nishina Center, Wako 35
[g] School of Mechatronics Enginee
[h] Institute of materials, China Acc
[i] Department of Physics, Universi



RCHB + radial basis function approach

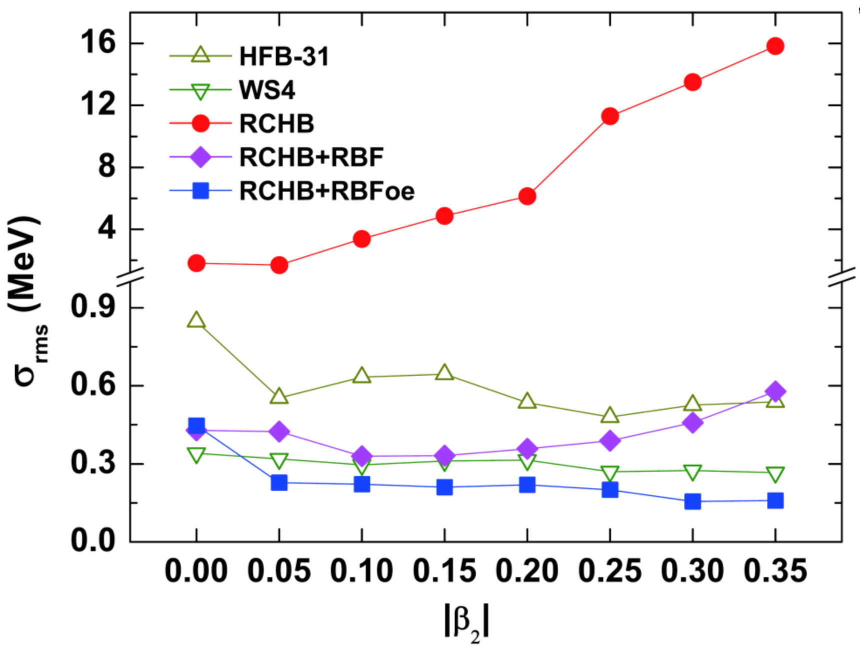
Chinese Physics C Vol. 43, No. 7 (2019) 074104

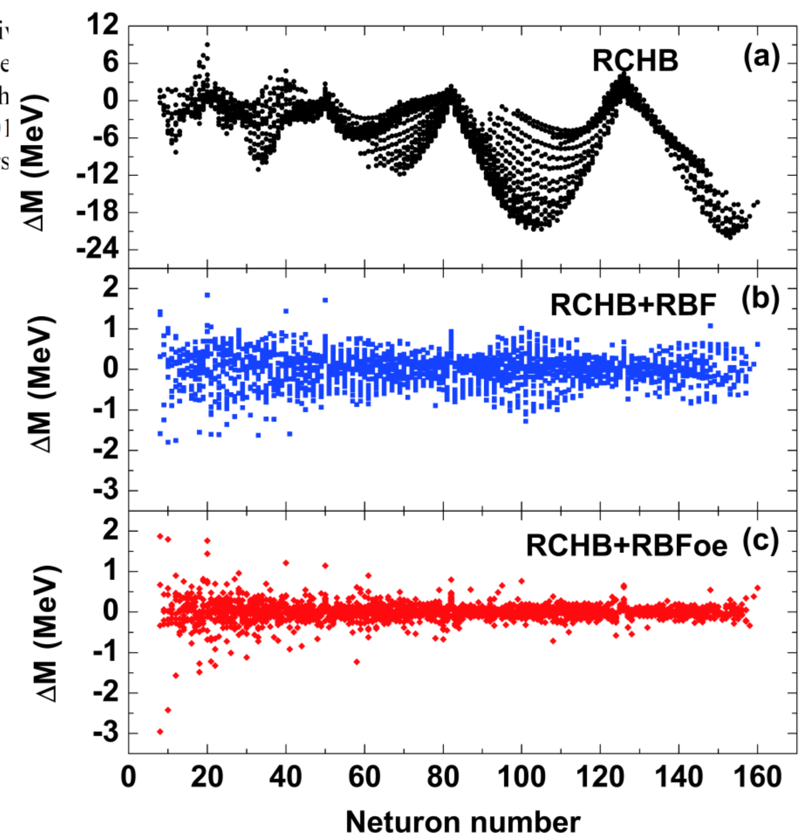
Shi_Niu_Liang2019_ChinPhysC43-074104

Mass predictions of the relativistic continuum Hartree-Bogoliubov model with radial basis function approach*

Min Shi(仕敏)[1] Zhong-Ming Niu(牛中明)[2,3;1)] Hao-Zhao Liang(梁豪兆)[4,5]

[1]School of Mathematics and Physics, Anhui Jianzhu Uni
[2]School of Physics and Materials Science, Anhui Unive
[3]Institute of Physical Science and Information Technology, Anh
[4]RIKEN Nishina Center, Wako 351-01
, The Univers





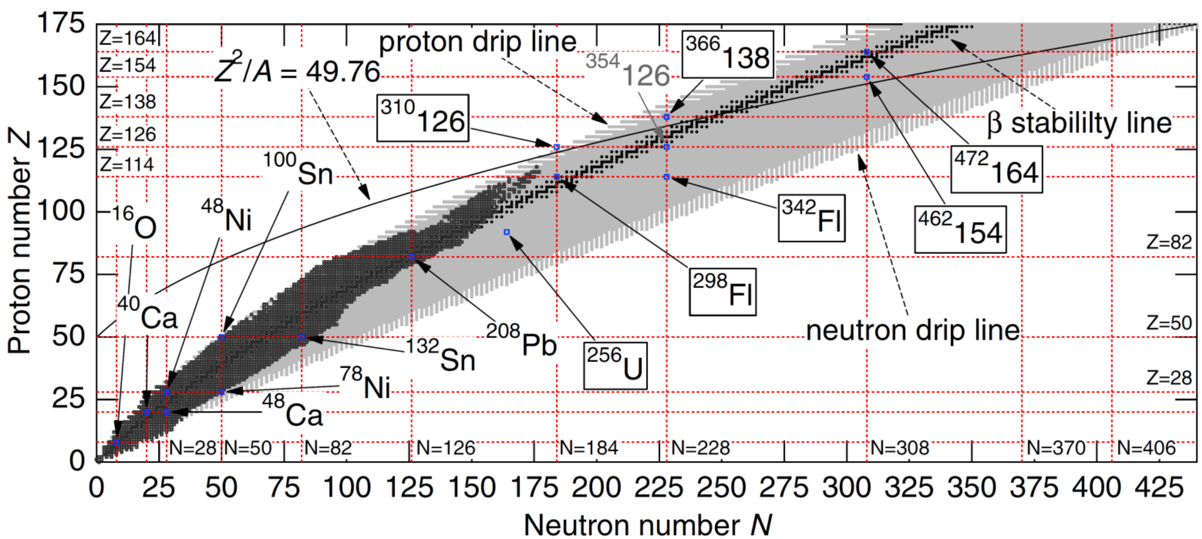
Lecture 2

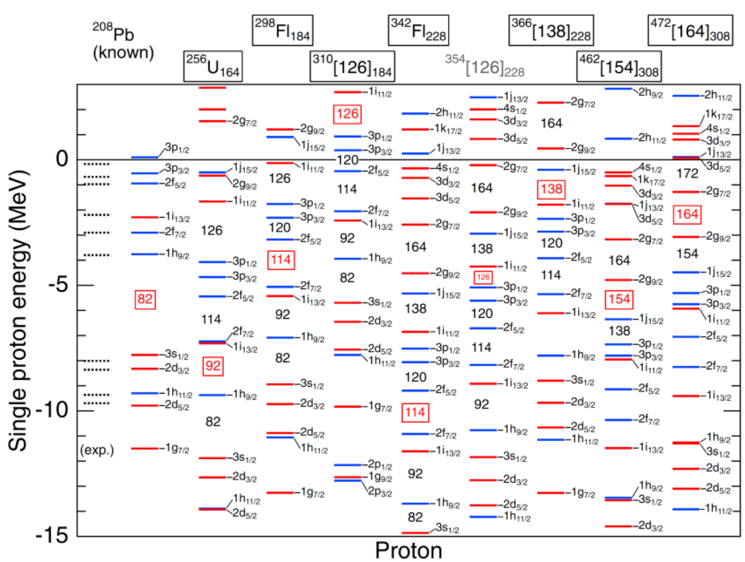
- Challenges in synthesizing SHN

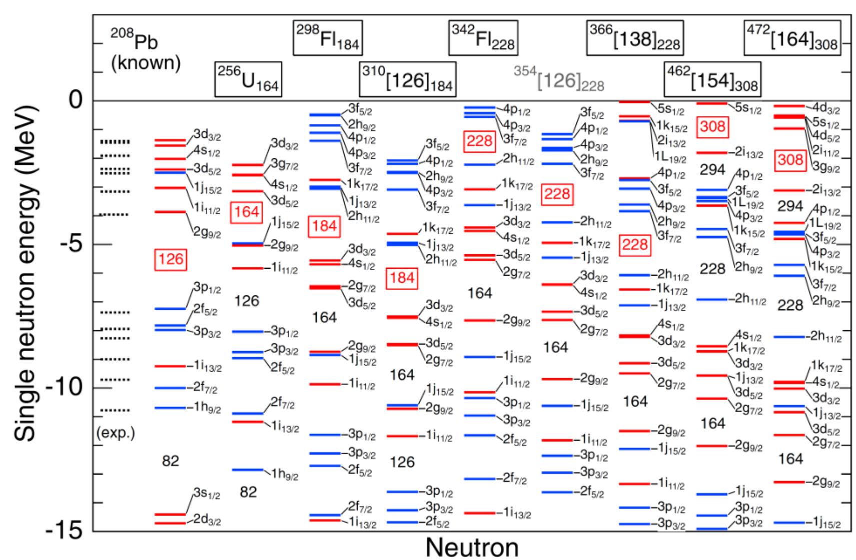
- Theoretical study of structure of SHN
  - Nuclear models
  - Next shell closures beyond ^{208}Pb as seen from single particle spectra, shell correction energy & nuclear shapes
  - Exotic shapes in SHN
  - Low-lying spectra of SHN & magicities

- Theoretical study of decay of SHN

Modified Woods-Saxon potential







Koura&Chiba2013_JPSJ82-014201

Hyperheavy nuclei

Afanasjev_Agbemava_Ring2018_PLB782-533

Contents li

Physics Letters B

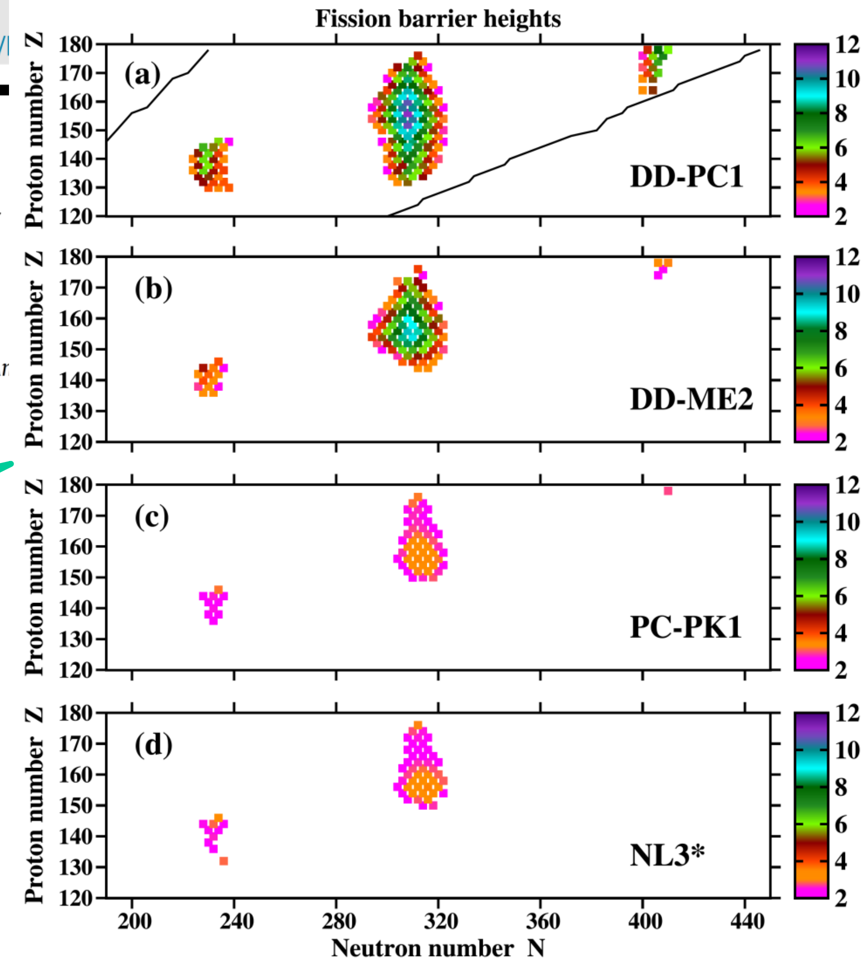
www.elsevier.com/l

Hyperheavy nuclei: Existence and stability

A.V. Afanasjev *, S.E. Agbemava, A. Gyawali

Department of Physics and Astronomy, Mississippi State University, MS 39762, United States of Ar

Z	*N*
138	230
156	310
174	410

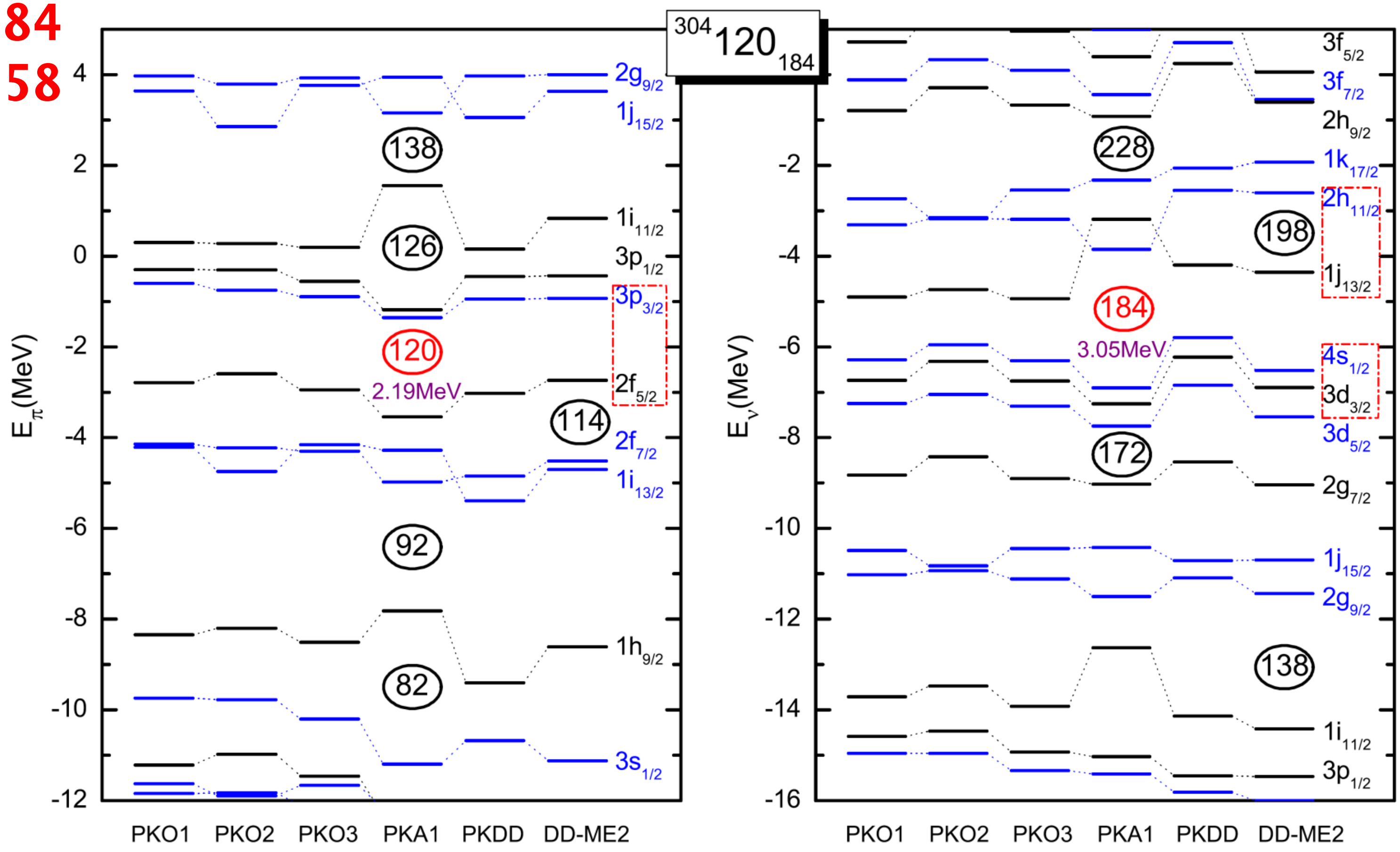


Relativistic Hartree-Fock-Bogoliubov model

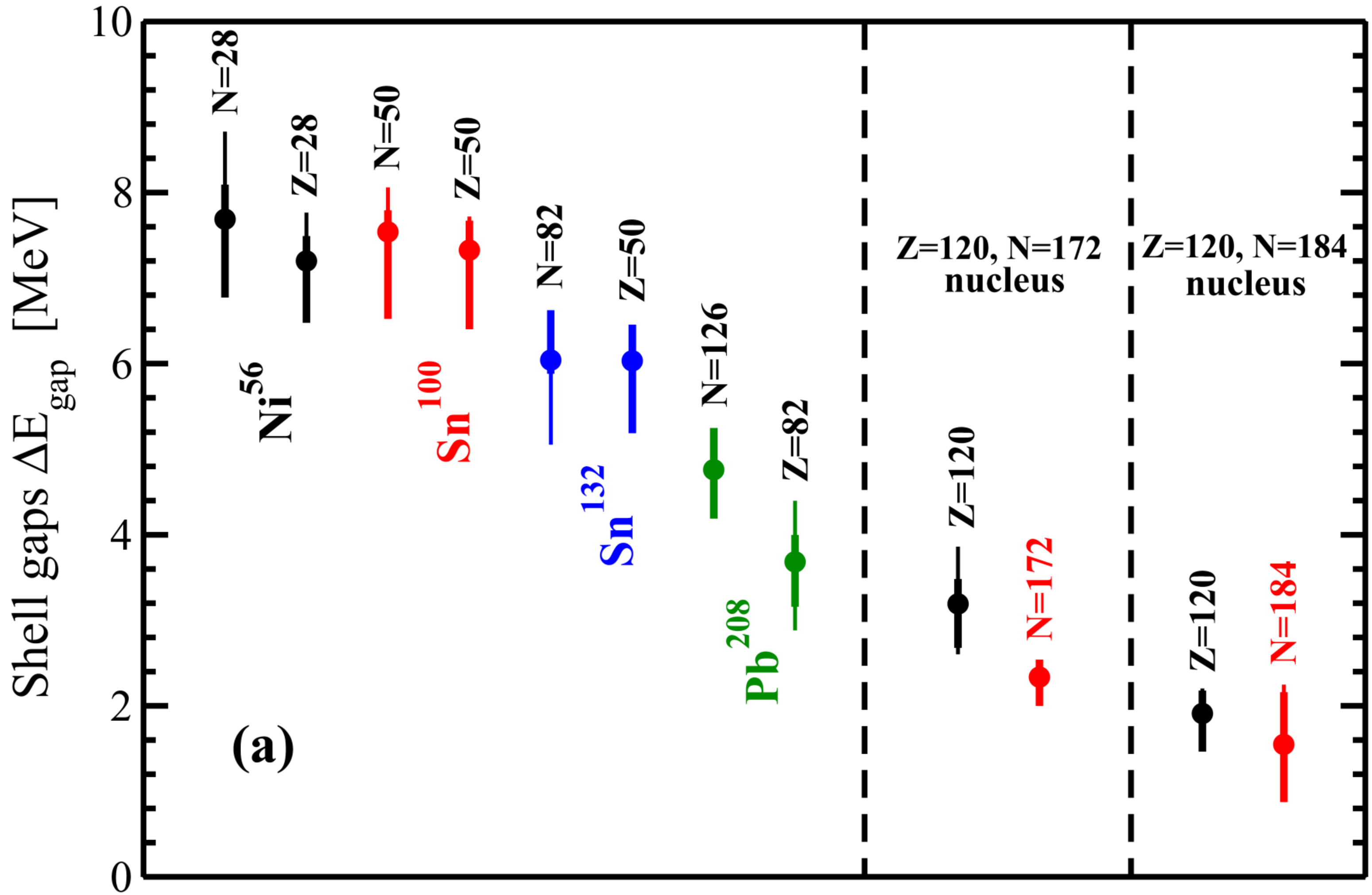
Z = 120 138

N = 172 184
228 258

Li_Long_Margueron_Giai2014_PLB732-169



Single-particle level densities & gaps

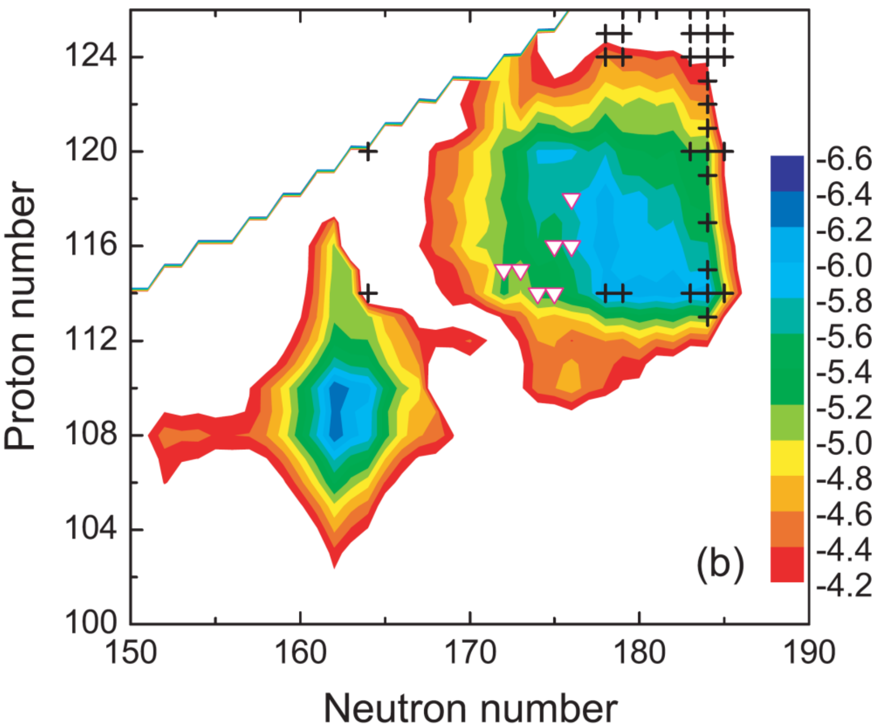


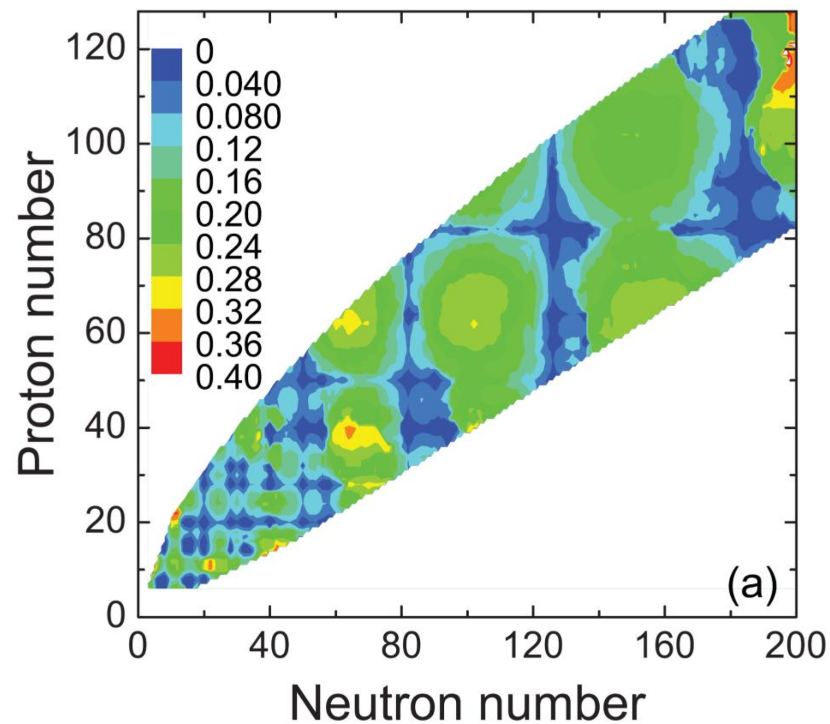
Agbemava_Afanasjev_Nakatsukasa&Ring2015_PRC92-054310

Microscopic correction energies & deformations

Z = 114
N = 178

Z = 116~120
N = 176~178





Shell correction energy

Quadrupole def. $|\beta_2|$

Wang_Liu_Wu2010_PRC81-044322

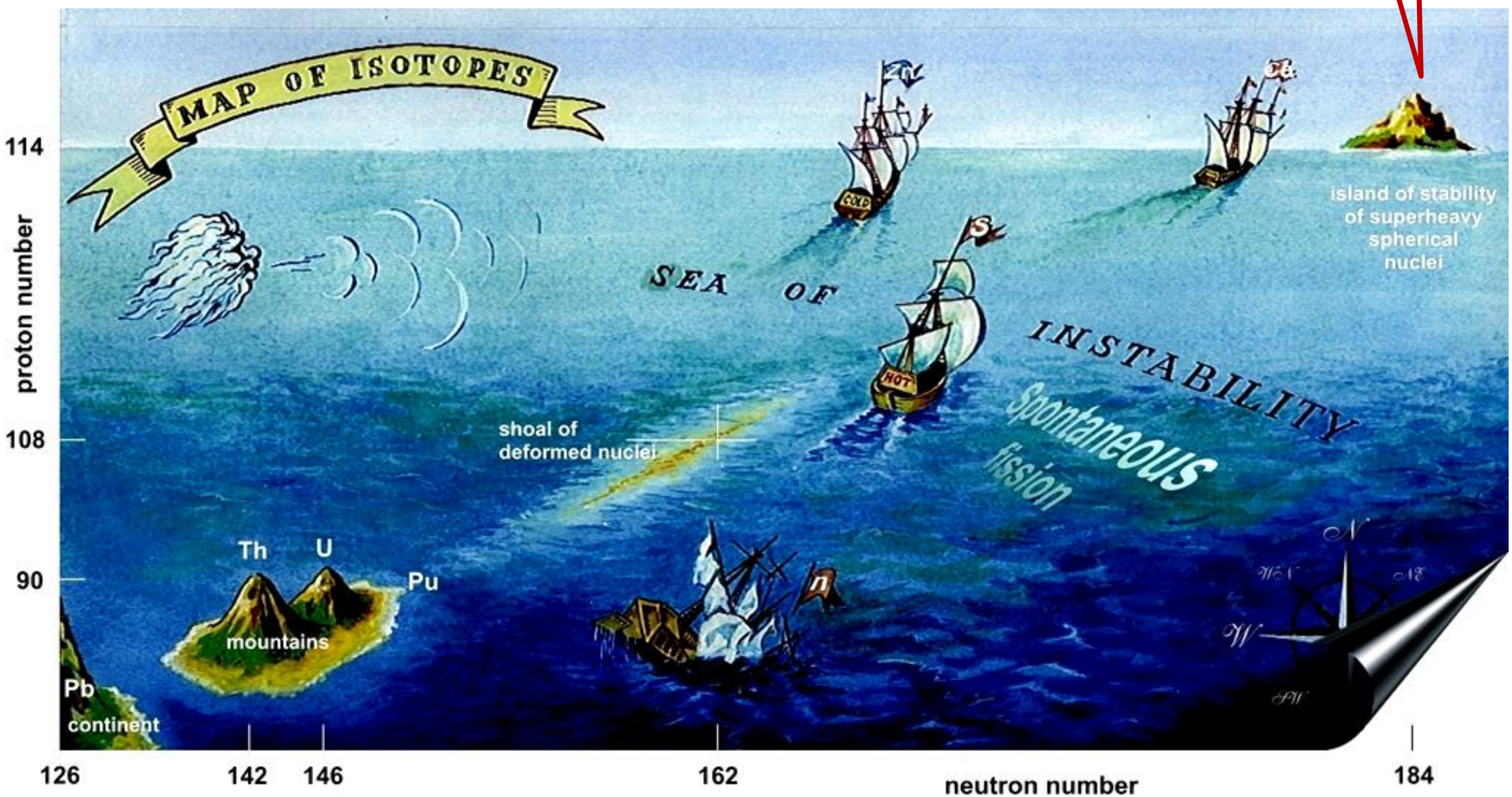
Wang_Liang_Liu_Wu2010PRC82-044304

Where is the island of stability?

???

Z = ? 114 116 120 126 132 138

N = ? 172 176 178 184 198 228 238 258



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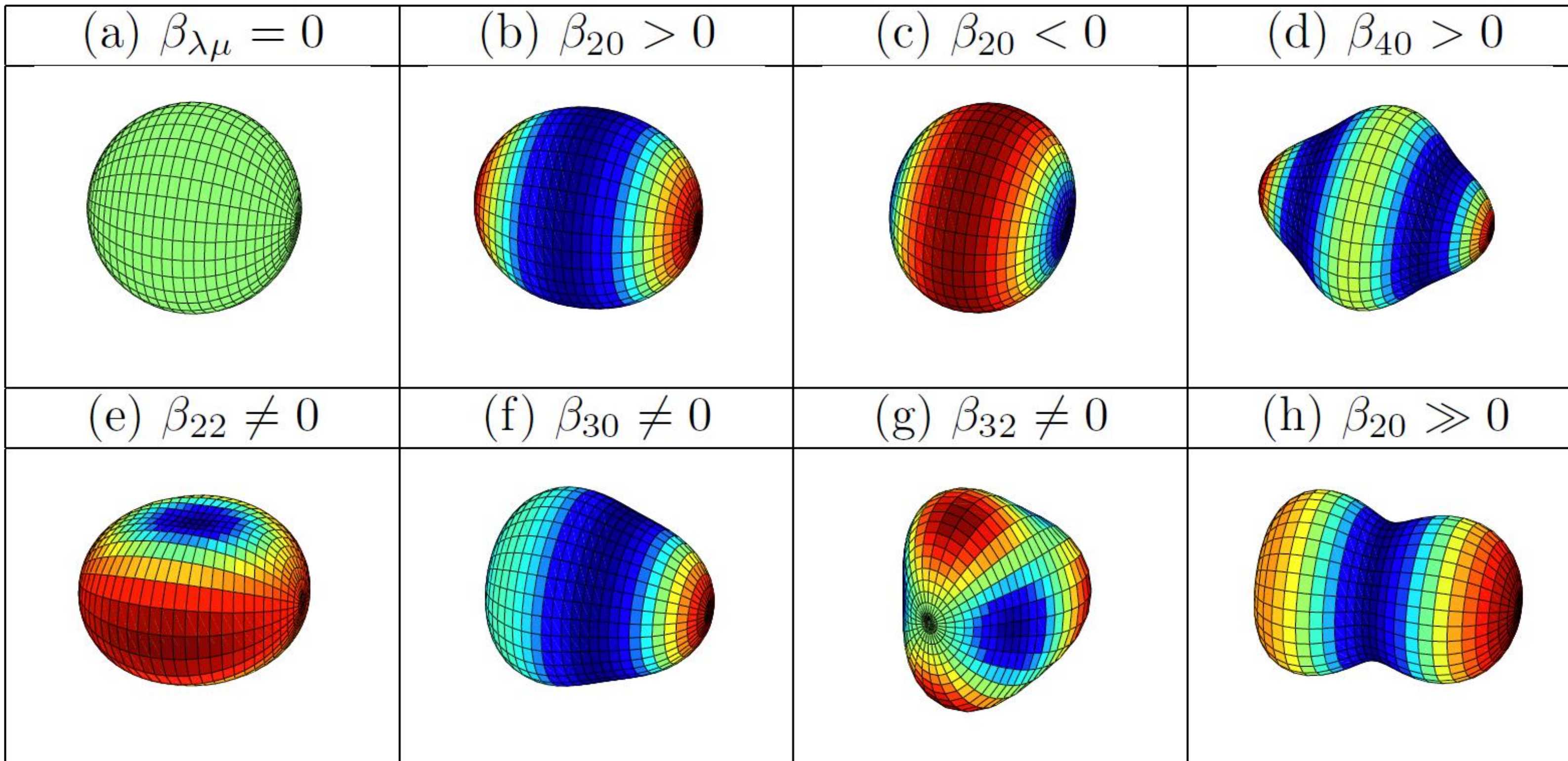
Nuclear shapes

$$R(\theta,\varphi) = R_0\left[1 + \beta_{00} + \sum_{\lambda=1}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\beta^*_{\lambda\mu}Y_{\lambda\mu}(\theta,\varphi)\right]$$



Courtesy of Bing-Nan Lu (吕炳楠)

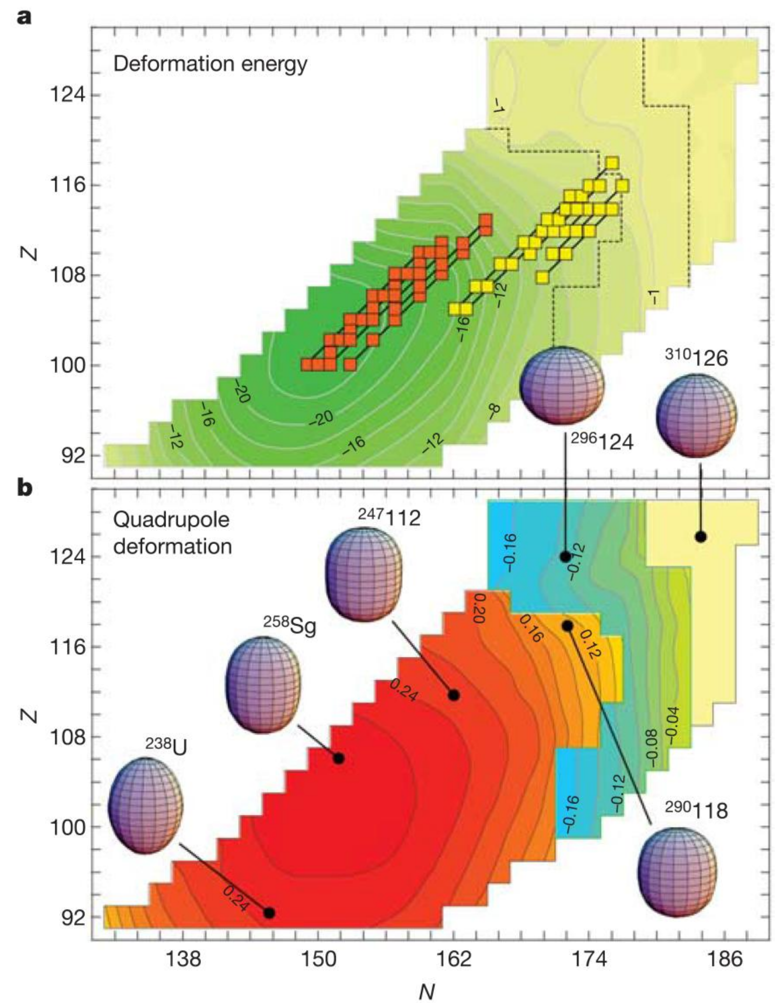
Shapes of SHN: Triaxial & octupole

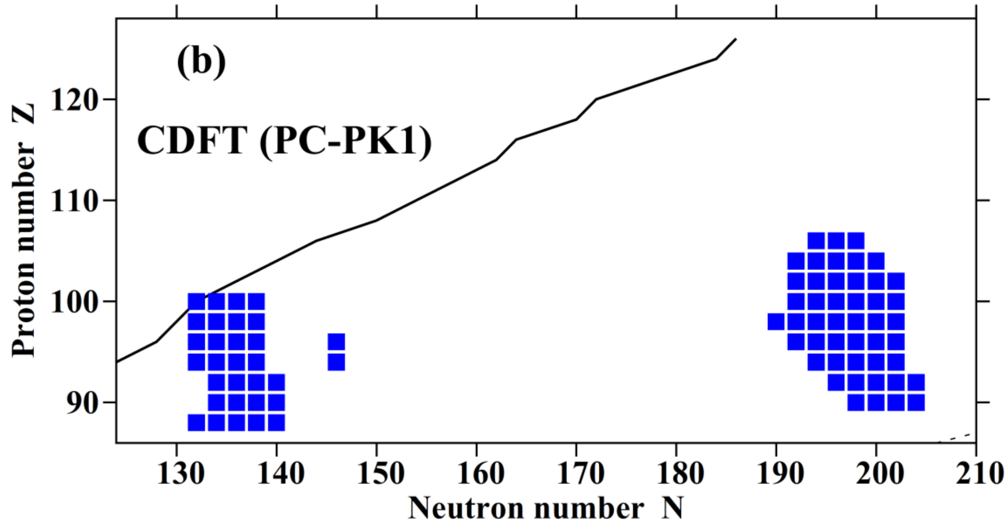
Cwiok_Heenen&Nazarewicz2005_Nature433-705

Shape coexistence and triaxiality in the superheavy nuclei

S. Ćwiok[1]*, P.-H. Heenen[2] & W. Nazarewicz[3,4,5]

[1]*Institute of Physics, Warsaw University of Technology, ul. Koszykowa 75, PL-00662, Warsaw, Poland*
[2]*Service de Physique Nucléaire Théorique, Université Libre de Bruxelles, CP 229, B-1050 Brussels, Belgium*
[3]*Department of Physics and Astronomy, The University of Tennessee, Knoxville, Tennessee 37996, USA*
[4]*Physics Division, Oak Ridge National Laboratory, PO Box 2008, Oak Ridge, Tennessee 37831, USA*
[5]*Institute of Theoretical Physics, Warsaw University, ul. Hoza 69, PL-00681, Warsaw, Poland*

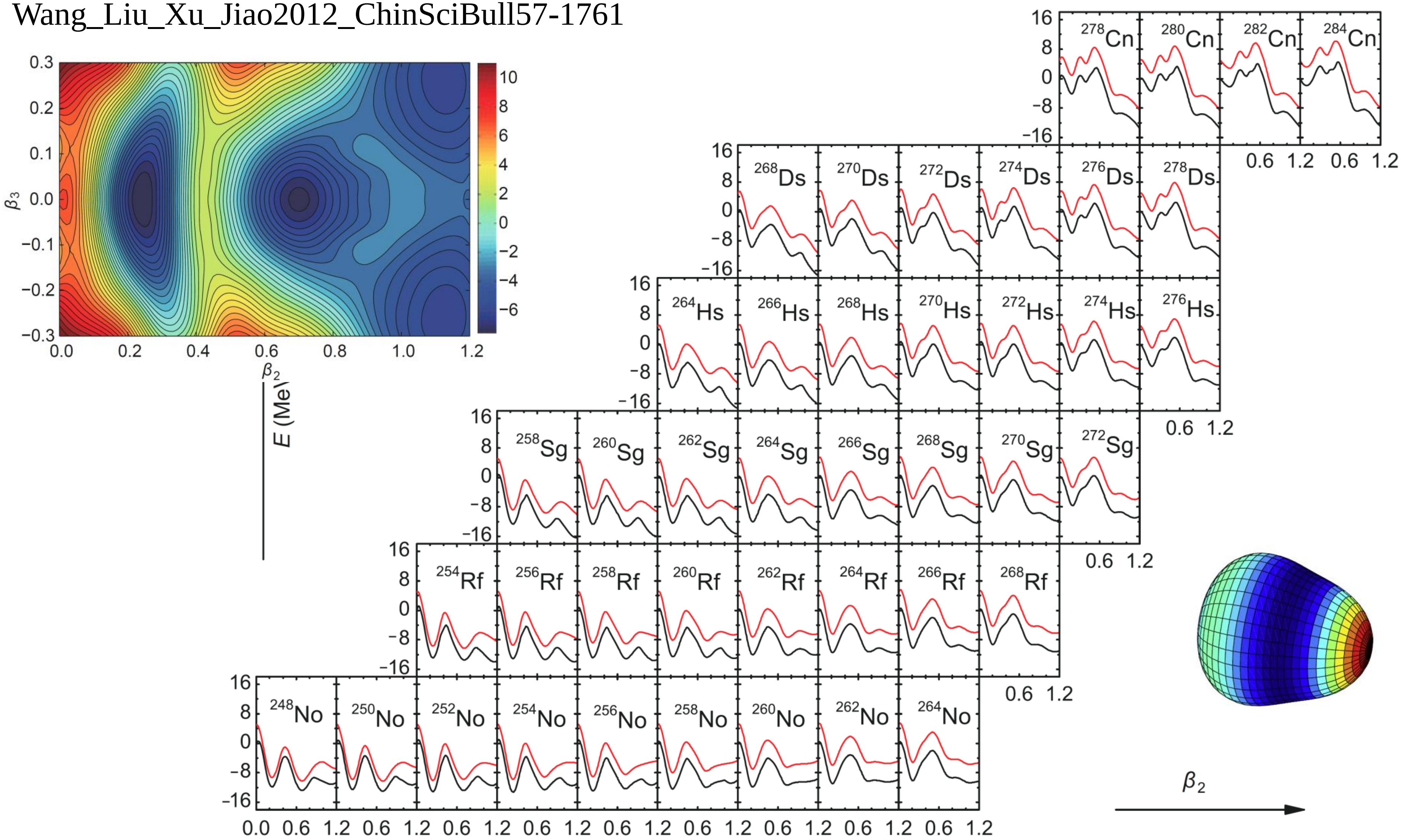




Agbemava&Afanasjev2017_PRC96-024301

Octupole correlations in SHN

Wang_Liu_Xu_Jiao2012_ChinSciBull57-1761

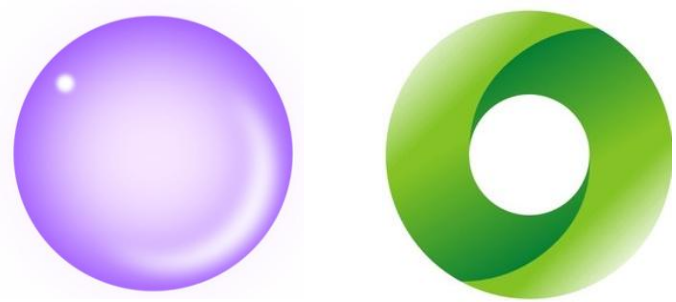


Possible exotic shapes in SHN

- Bubble or toroidal

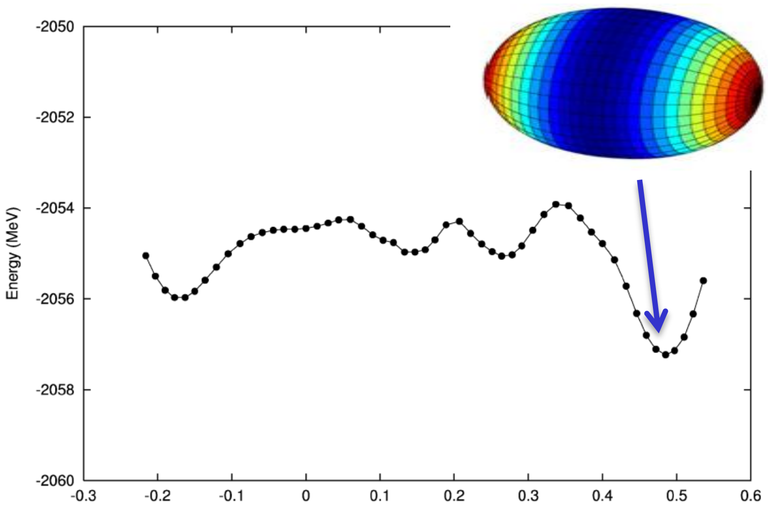
  1960s, H. A. Bethe, J. A. Wheeler, …

  Wong1973_APNY77-279
  Dietrich_Pomorski1998_PRL80-37
  Pei_Xu_Stevenson 2005_PRC71-034302
  …



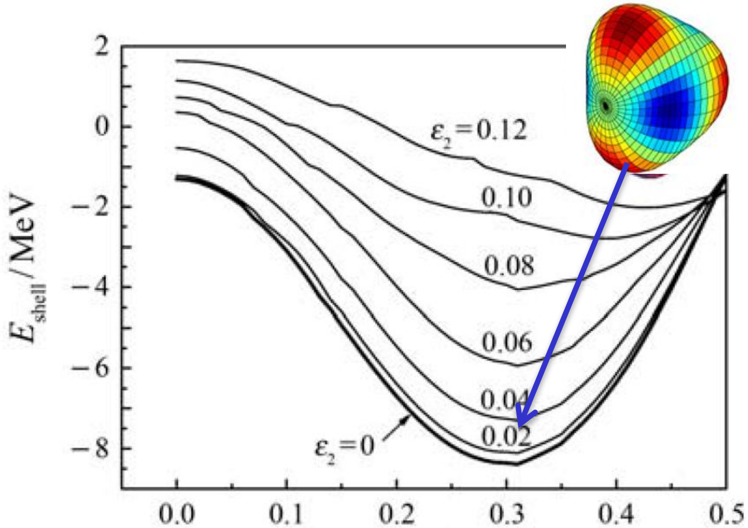
- Superdeformed or tetrahedral

  Ren_Toki2001_NPA689-691
  Ren2002_PRC65-051304R



Elongation def.

Chen_Gao2010_NPA834-380c
2013_NPR30-278



Tetrahedral def.

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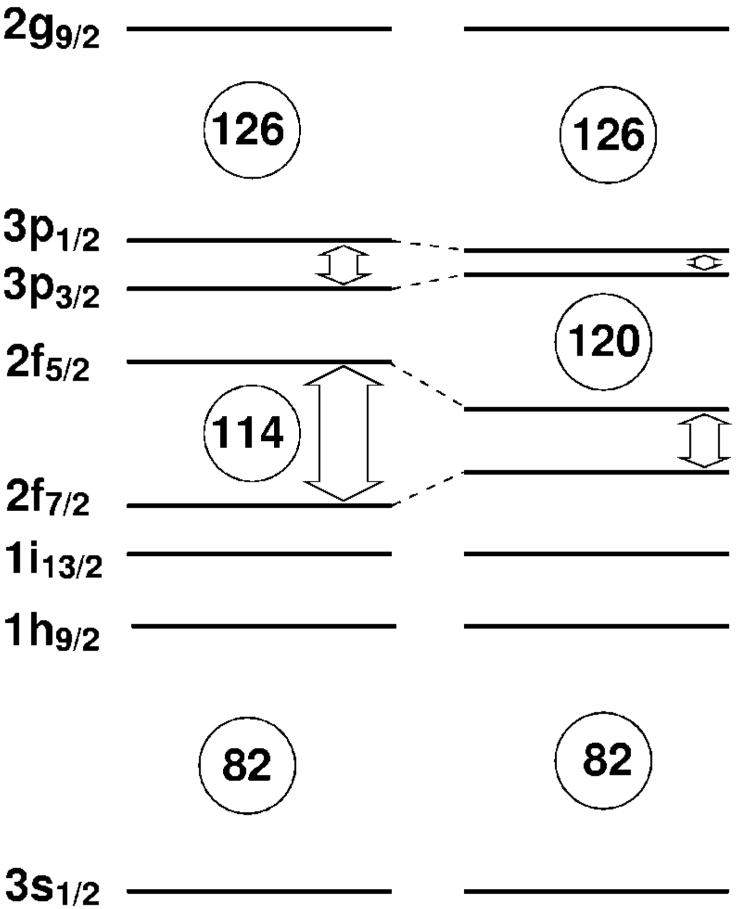
Spectroscopy of nuclei with Z~100

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])

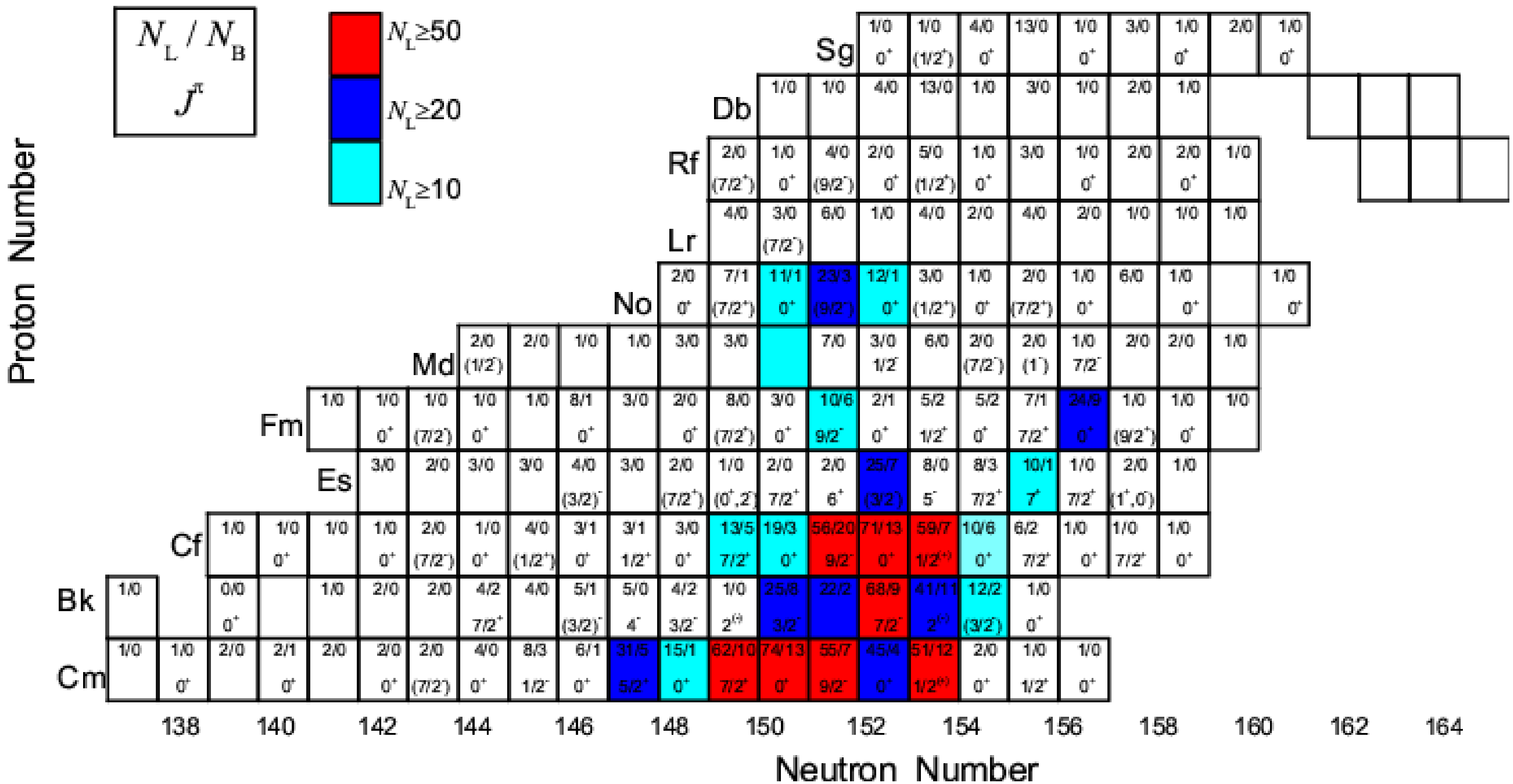


Herzberg_Greenlees_Butler...
2006_Nature442-896

Experimental facilities & status

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

Data from ENSDF (Apr., 2012) by Zhen-Hua Zhang (张振华)



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_PRC84-024324

- 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 84-024324

- 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
Liu...2012_PRC86-011301R
Zhang...2012_PRC85_014324
Zhang...2013_PRC87-054308

Cranked Nilsson model w/ pairing treated by a particle number conserving method

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

$$\begin{aligned} H_{\rm Nil} &= \frac{1}{2}\hbar\omega_0(\varepsilon_2,\varepsilon_4)\left[-\nabla_\rho^2 + \frac{1}{3}\left(2\frac{\partial^2}{\partial\zeta^2} - \frac{\partial^2}{\partial\xi^2} - \frac{\partial^2}{\partial\eta^2}\right) + \rho^2 \right. \\ &- \left. \frac{2}{3}\varepsilon_2\rho^2 P_2(\cos\theta_t) + 2\varepsilon_4\rho^2 P_4(\cos\theta_t)\right] \\ &- 2\kappa\hbar\mathring{\omega}_0\left(\vec{s}\cdot\vec{l}_t - \mu\left(\rho^4 - \langle\rho^4\rangle_N\right)\right) \quad , \end{aligned}$$

Zhang...2011_PRC83-011304R

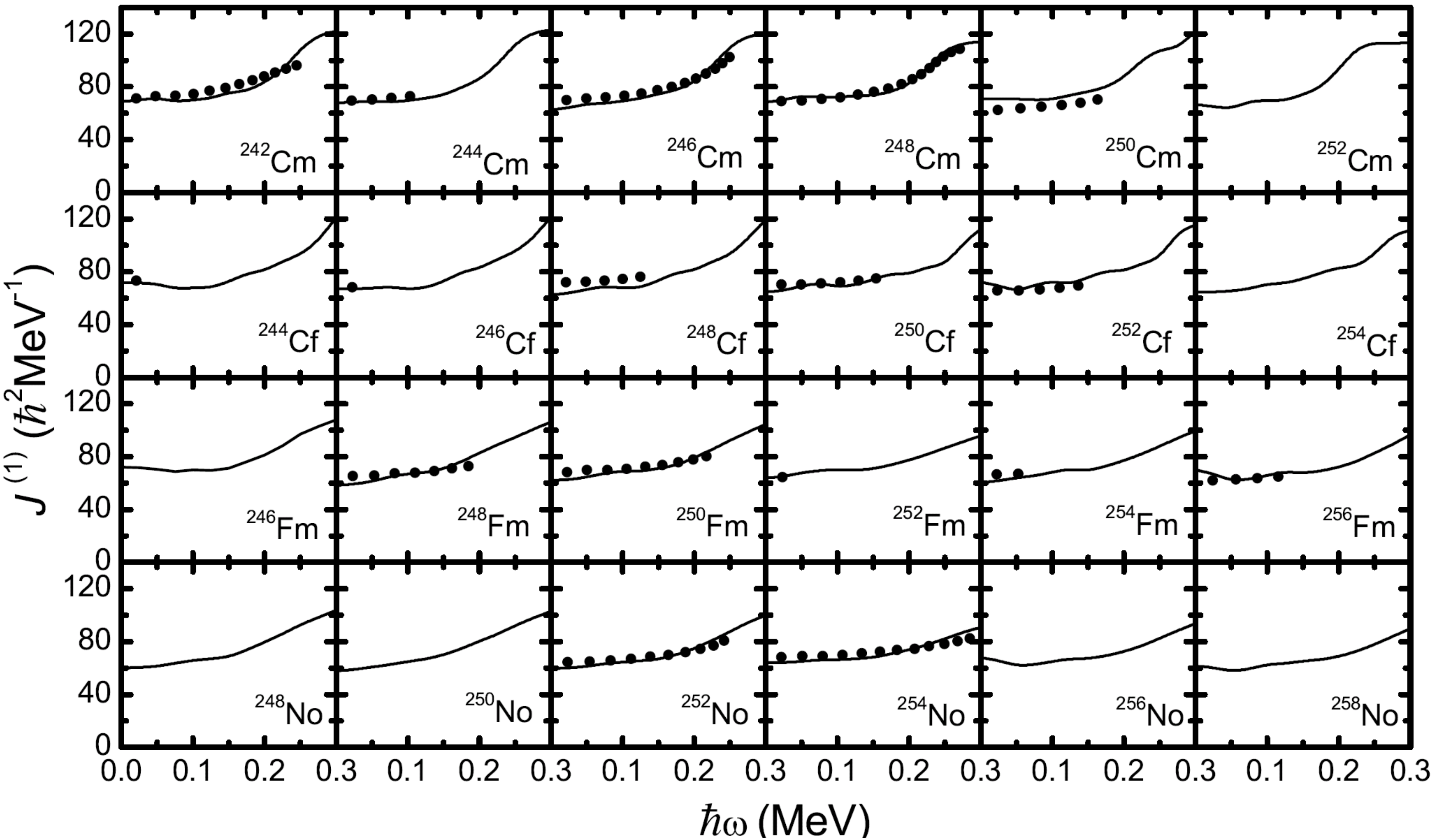
Zhang...2012_PRC85_014324

Z. H. Zhang (张振华)
PhD Thesis, ITP (2012)

$$H_{\rm P}(0) = -G_0 \sum_{\xi\eta} a^\dagger_\xi a^\dagger_{\bar\xi} a_{\bar\eta} a_\eta \qquad H_{\rm P}(2) = -G_2 \sum_{\xi\eta} q_2(\xi) q_2(\eta) a^\dagger_\xi a^\dagger_{\bar\xi} a_{\bar\eta} a_\eta$$

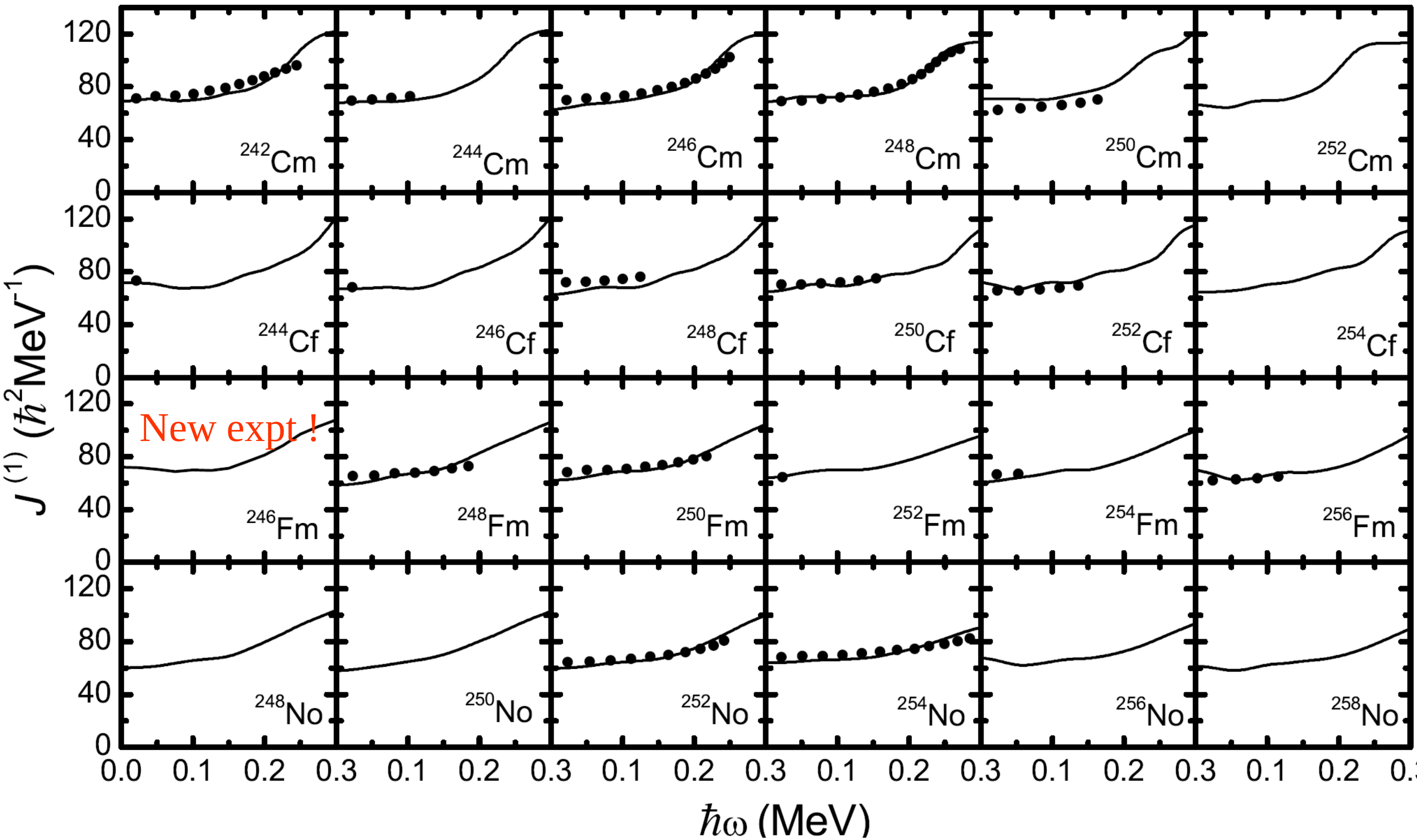
N	l	κ_p	μ_p	N	l	κ_n	μ_n
4	0,2,4	0.0670	0.654				
5	1	0.0250	0.710	6	0	0.1600	0.320
	3	0.0570	0.800		2	0.0640	0.200
	5	0.0570	0.710		4,6	0.0680	0.260
6	0,2,4,6	0.0570	0.654	7	1,3,5,7	0.0634	0.318

Moments of inertia of even-even nuclei



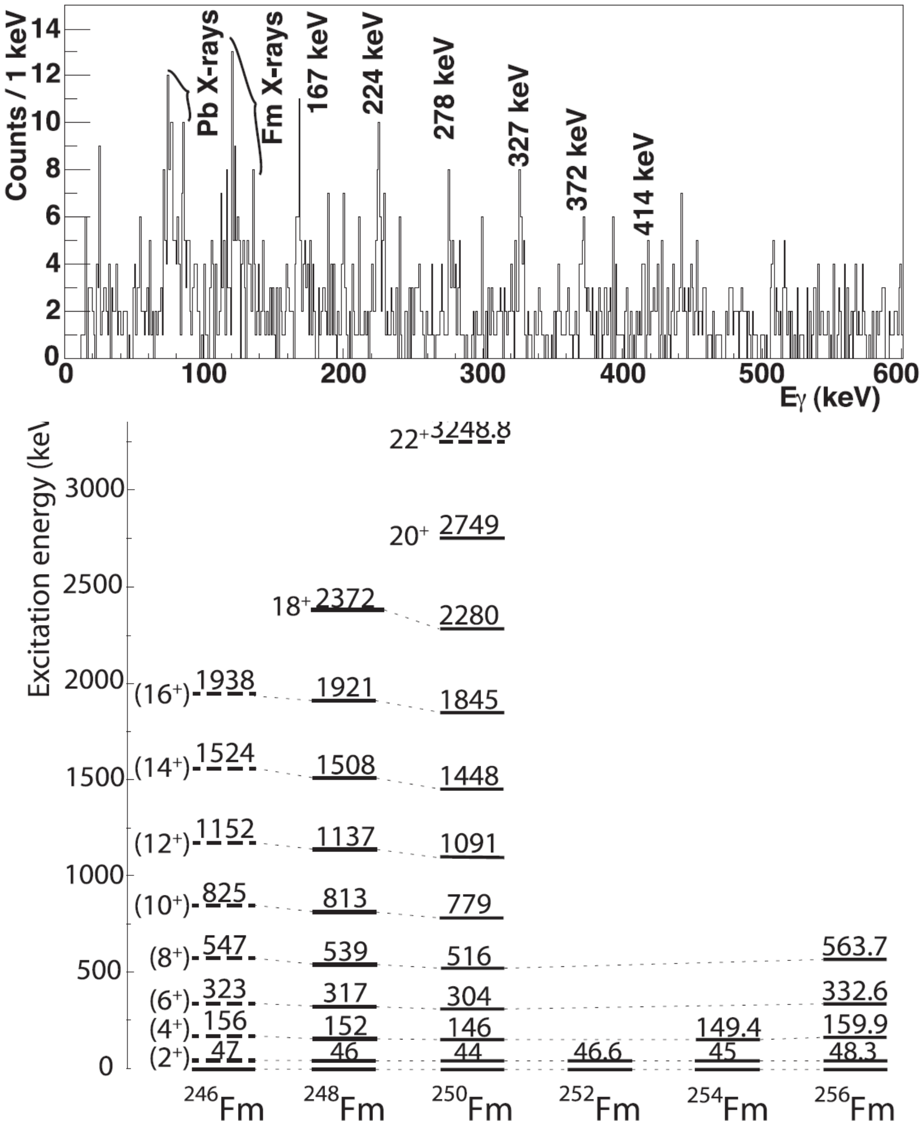
Zhang_He_Zeng_Zhao_SGZ2012_PRC85_014324

Moments of inertia of even-even nuclei



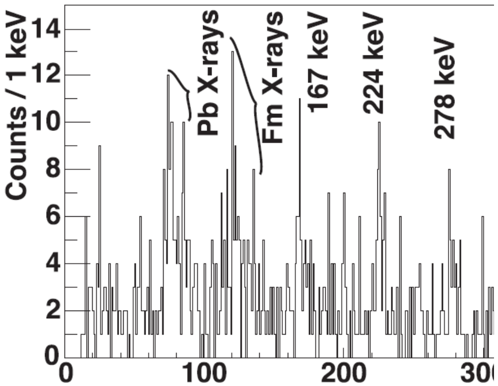
Zhang_He_Zeng_Zhao_SGZ2012_PRC85_014324

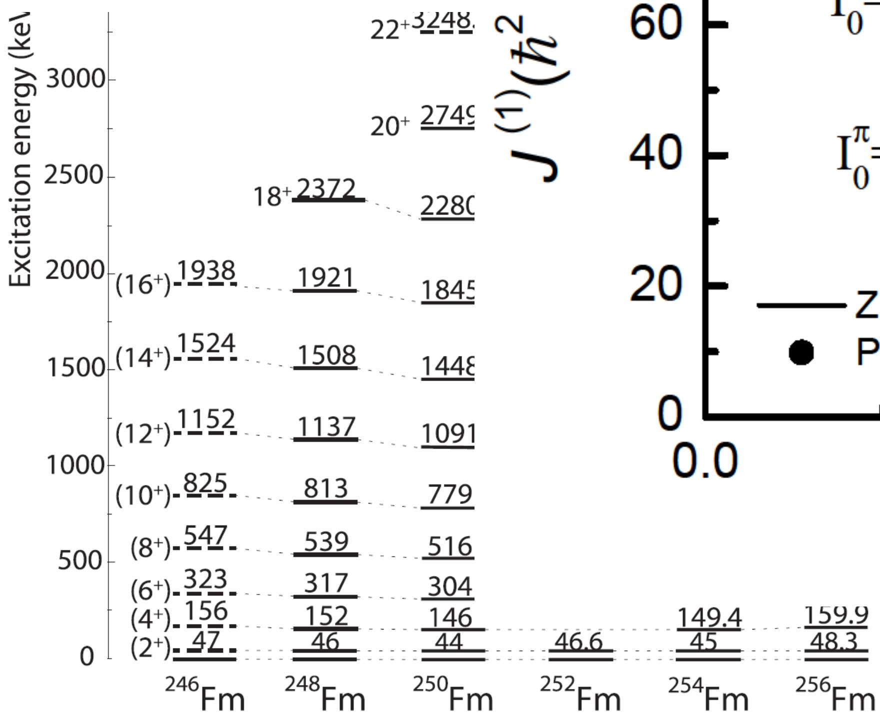
^{246}Fm: ground state band observed @ Jyvaskyla

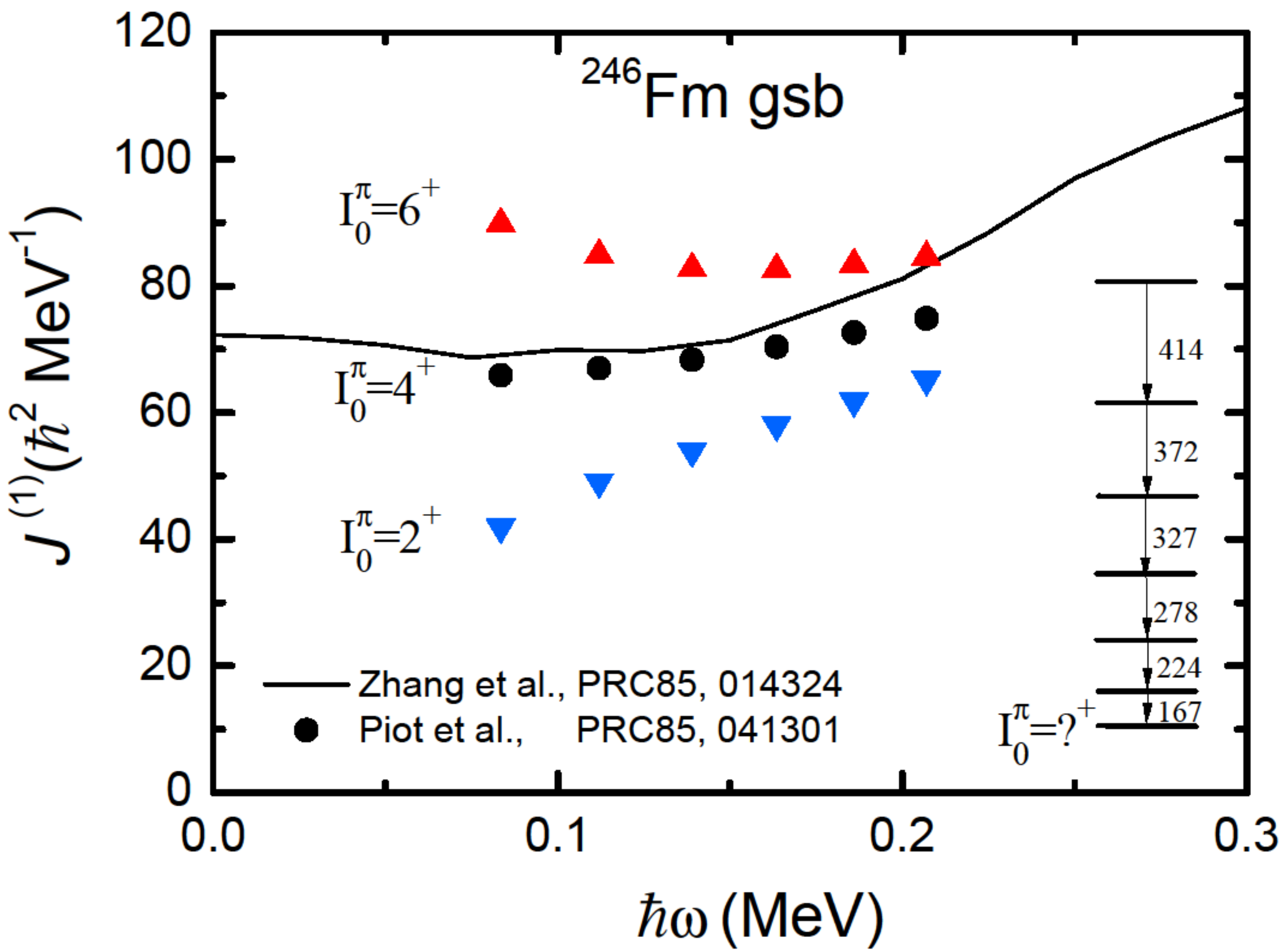


Piot...2012 PRC85_041301R

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







Piot...2012 PRC85_041301R

^{256}Rf: ground state band observed @ Jyvaskyla

Selected for a Viewpoint in *Physics*
PRL **109,** 012501 (2012) PHYSICAL REVIEW LETTERS week ending 6 JULY 2012

Shell-Structure and Pairing Interaction in Superheavy Nuclei: Rotational Properties of the $Z=104$ Nucleus ^{256}Rf

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^{256}Rf: ground state band observed @ Jyvaskyla

Selected for a Viewpoint in *Physics*
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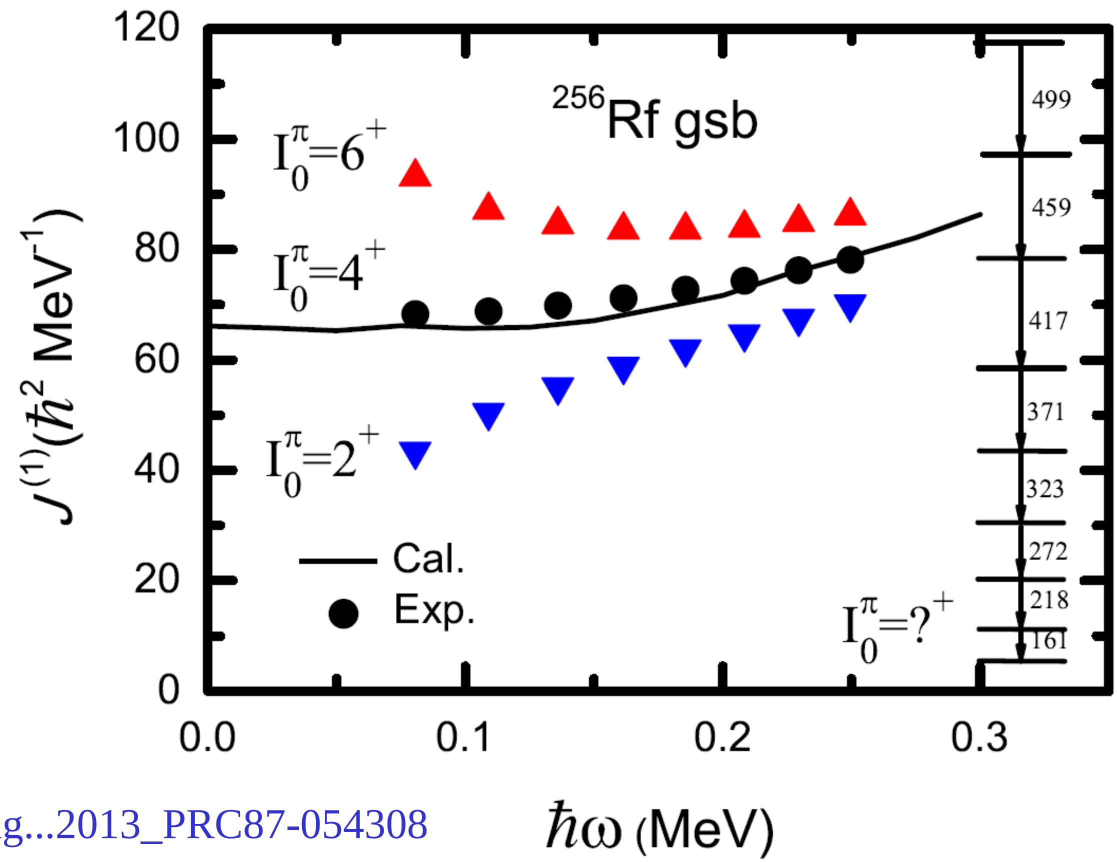
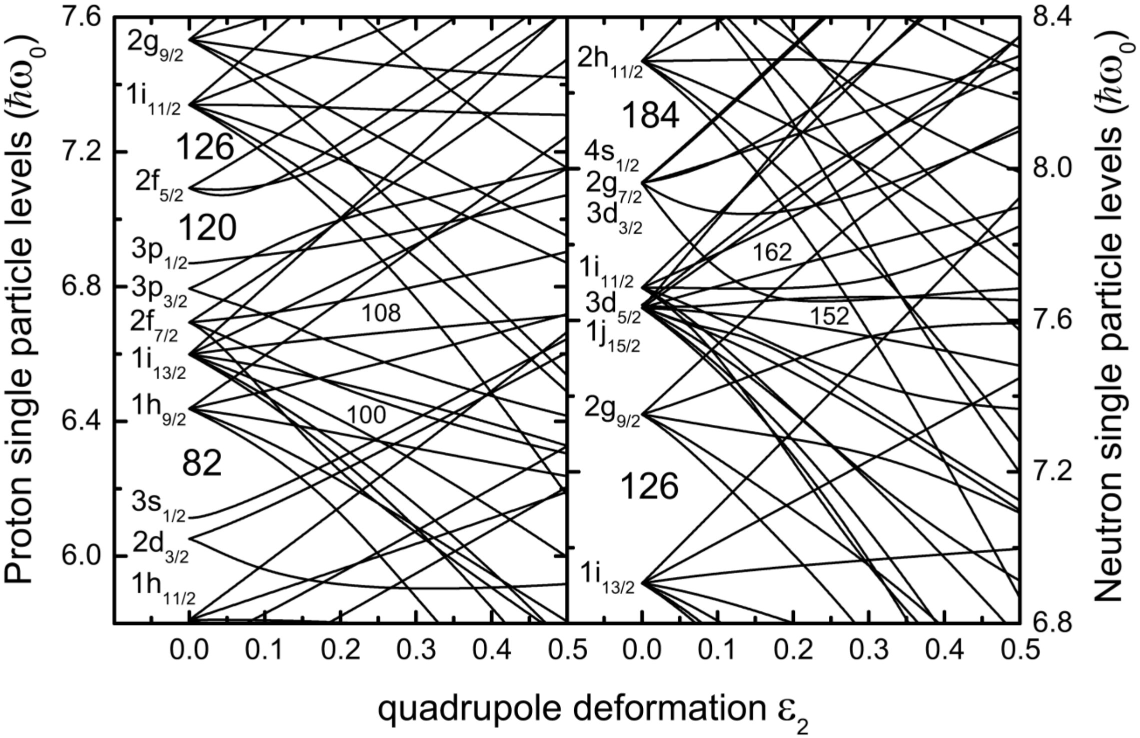
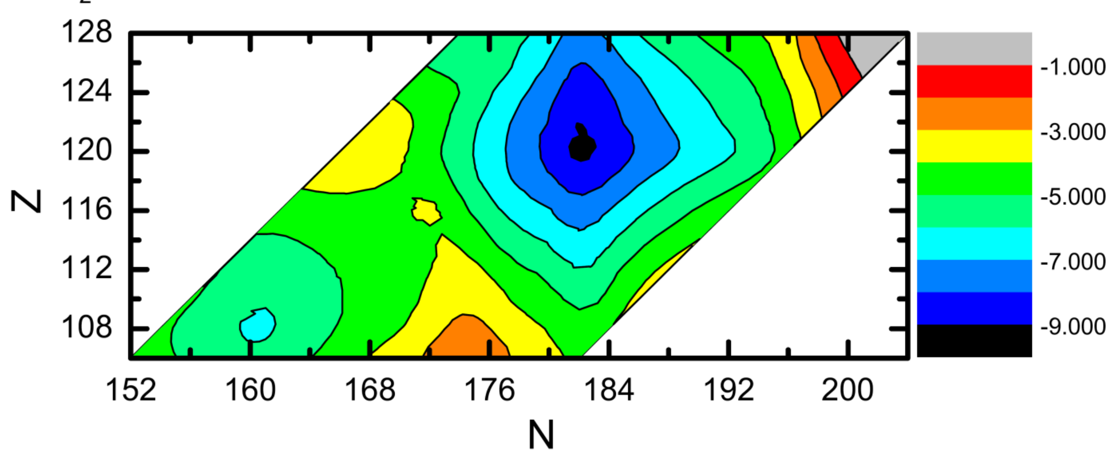


Zhang...2013_PRC87-054308

Nilsson diagrams & E_{mic}



Z. H. Zhang (张振华)
PhD Thesis, ITP (2012)



Lecture 2

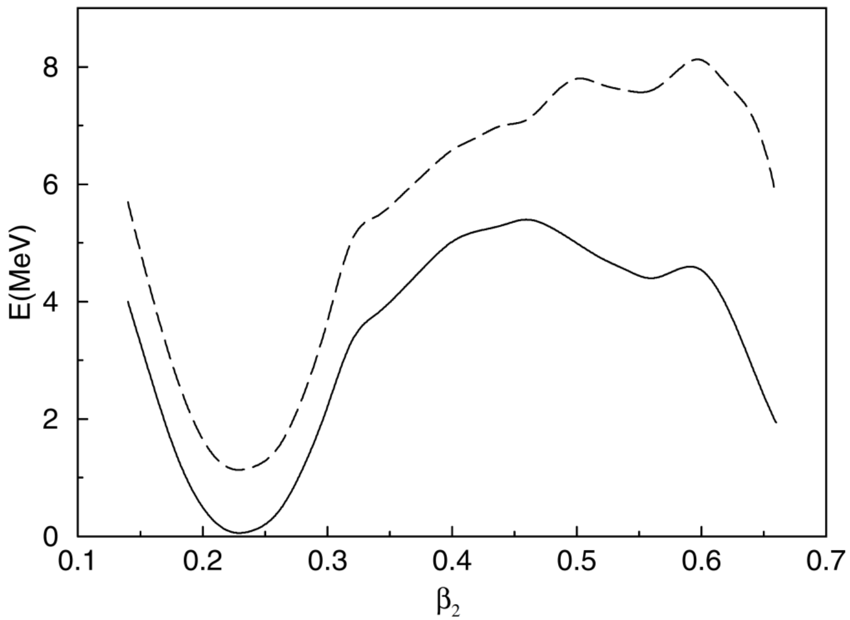
- Challenges in synthesizing SHN

- Theoretical study of structure of SHN
  - Nuclear models
  - Next shell closures beyond ^{208}Pb as seen from single particle spectra, shell correction energy & nuclear shapes
  - Exotic shapes in SHN
  - Low-lying spectra of SHN & magicities

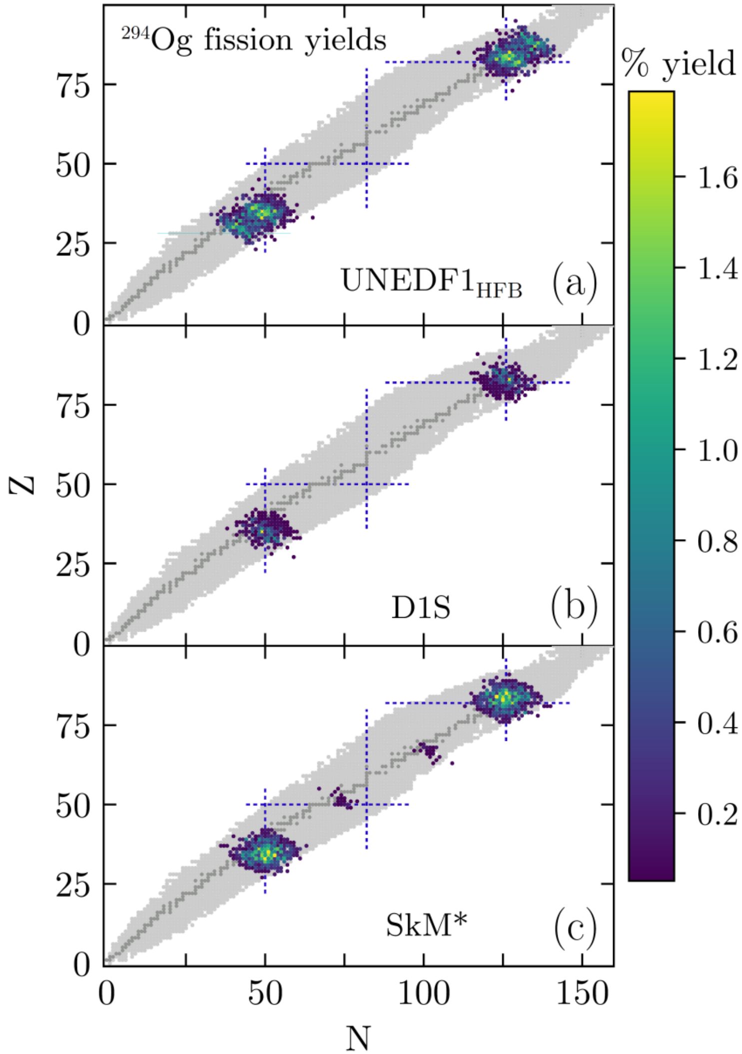
- Theoretical study of decay of SHN

Decay & spontaneous fission of SHN

- α, β & γ decays
- Spontaneous fission
- Long-lived isomers
- Cluster radioactivity



Xu_Zhao_Wyss&Walker2004_PRL92-252501



Matheson…2018_arXiv1812.06490

Zhang&Wang2018_PRC97-014318

Lectures 3 & 4

- Challenges in synthesizing SHN

- Synthesis mechanism of SHN
  - Large uncertainties in predicted Xsections
  - Heavy ion fusion reactions
    - Capture
    - Fusion
    - Survival against fission
  - Multi-nucleon transfer reactions
  - Reactions w/ radioactive ion beams

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How to synthesize SHE w/ Z>118 ?

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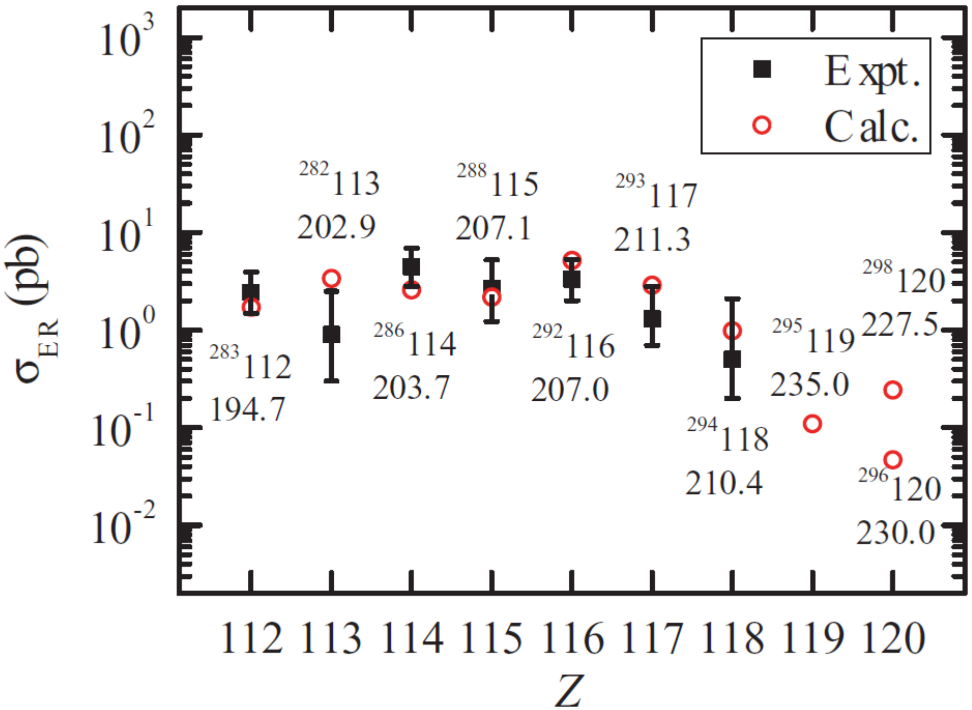
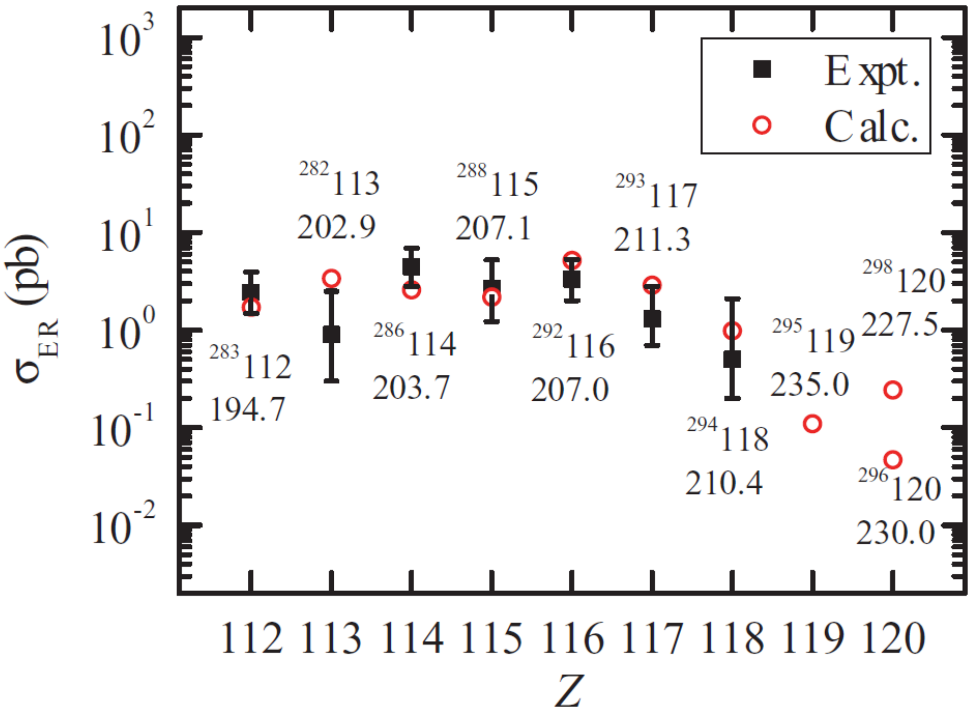


Wang_Zhao_Scheid_SGZ 2012 PRC85-041601R

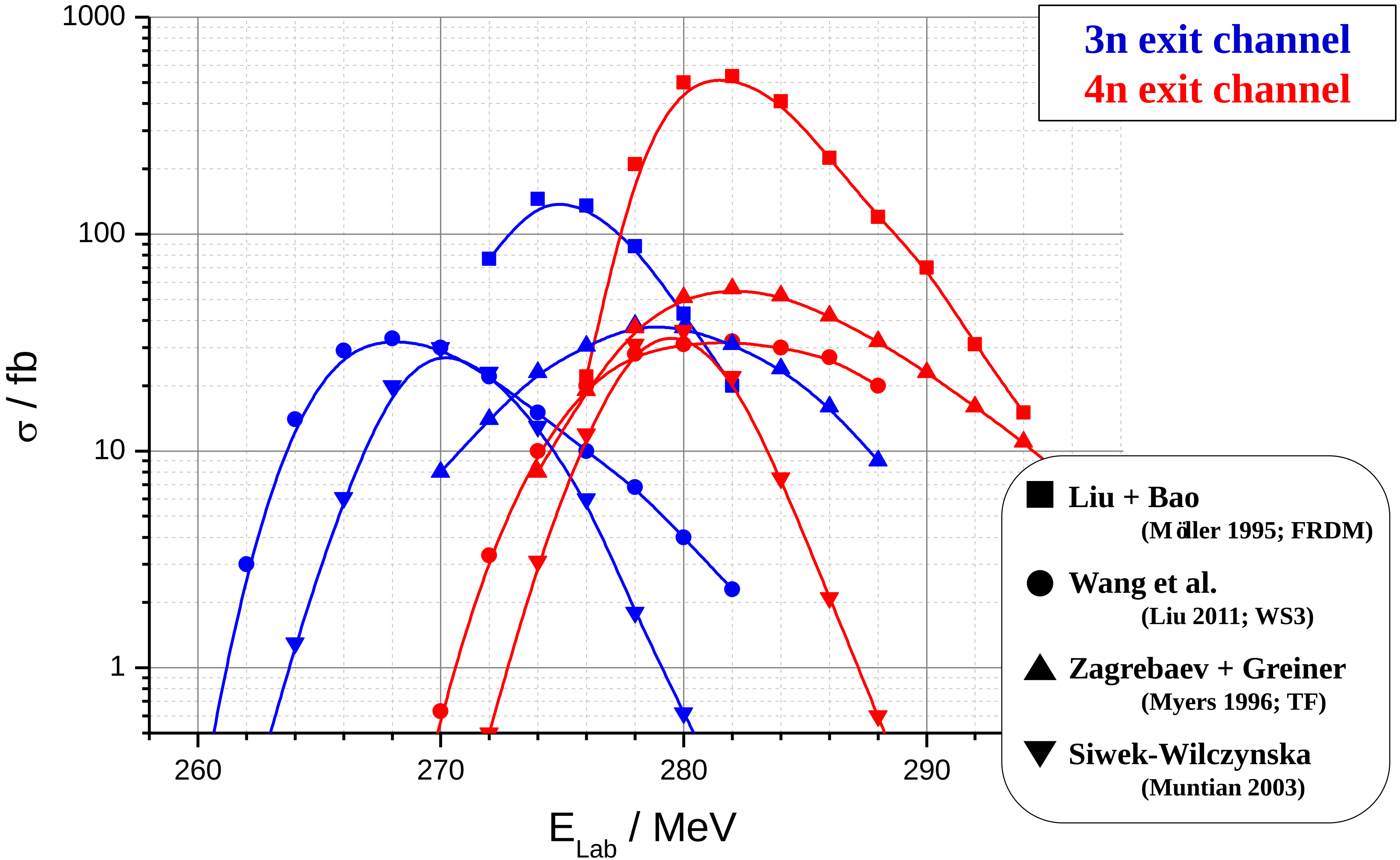
How to synthesize SHE w/ Z>118 ?

Feng_Jin_Li_Scheid2007_PRC76-044606
Nasirov_Giardina_Mandaglio_Manganaro_Hanappe_
    Heinz_Hofmann_Muminov_Scheid2009_PRC79-024606
Adamian_Antonenko_Scheid2009_EPJA41-235
Gan_Zhou_Huang_Feng_Li2011_SciChinaPMA54S1-61
Nasirov_Mandaglio_Giardina_Sobiczewski_Muminov2011_PRC84-044612
Liu_Bao2009_PRC80-054608
Siwek-Wilczynska_Cap_Wilczynski2010_IJMPE19-500
Liu_Bao2011_PRC83-044613
Liu_Bao2011_PRC84-031602R
Zagrebaev_Greiner2008_PRC78-034610
Wang_Tian_Scheid2011_PRC84-061601R
Siwek-Wilczynska_Cap_Kowal_Sobiczewski_
    Wilczynski 2012_PRC86-014611
Liang_ Zhu_Liu_Wang 2012_PRC86-037602
Liu_Bao2013_PRC87-034616
Zhang_Wang_Ren2013_NPA909-36
Zhu_Xie_Zhang2014_PRC89-024615
Bao_Gao_Li_Zhang2015_PRC91-011603R
Bao_Gao_Li_Zhang2015_PRC92-034612
Liu_Shen_Li_Tu_Wang_Wang2016_EPJA52-35
Santhosh_Safoora2016_PRC94-024623
Ghahramany_Ansari2016_EPJA52-287
Hong_Adamian_Antonenko2016_EPJA52-305
Santhosh_Safoora2017_PRC96-034610
Adamian_Antonenko_Lenske2018_NPA970-22
……



Wang_Zhao_Scheid_SGZ 2012 PRC85-041601R

A big issue in synthesizing SHE w/ Z>118



From Ch. E. Düllman (FUSHE2012)

Lectures 3 & 4

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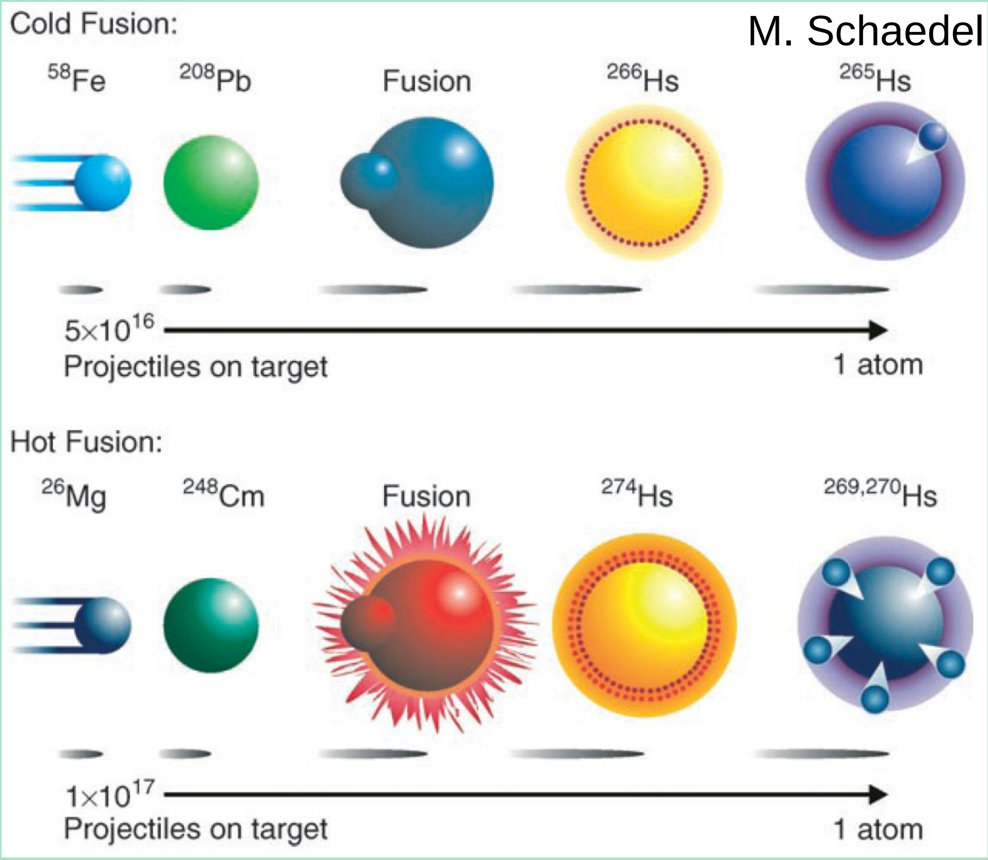
Three steps to a SHN via heavy-ion EvR reaction

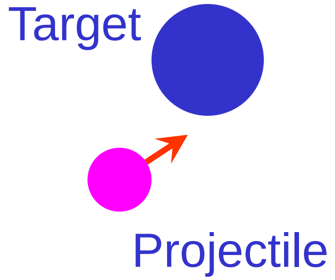
- Capture
- Formation of CN
- Deexcitation of CN



Capture | CN formation | neutron(s) emission

$$\sigma_{\mathrm{ER}}(E_{\mathrm{cm}}) = \sum_J \sigma_{\mathrm{cap}}(E_{\mathrm{cm}}, J)\, P_{\mathrm{CN}}(E_{\mathrm{cm}}, J)\, W_{\mathrm{sur}}(E_{\mathrm{cm}}, J)$$

Three steps to a SHN via heavy-ion EvR reaction



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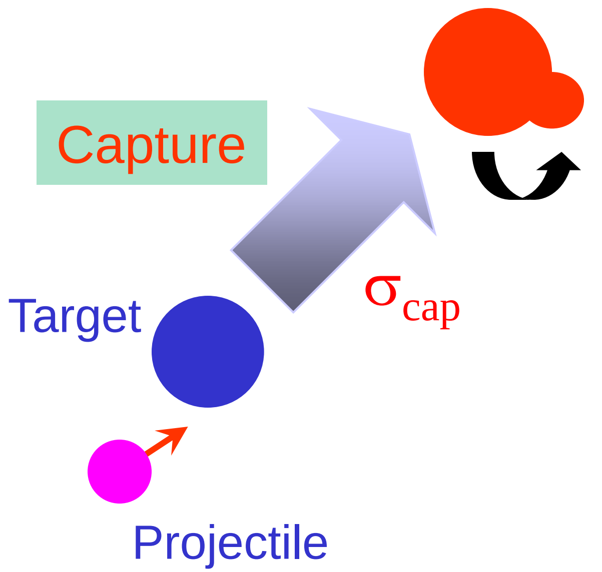

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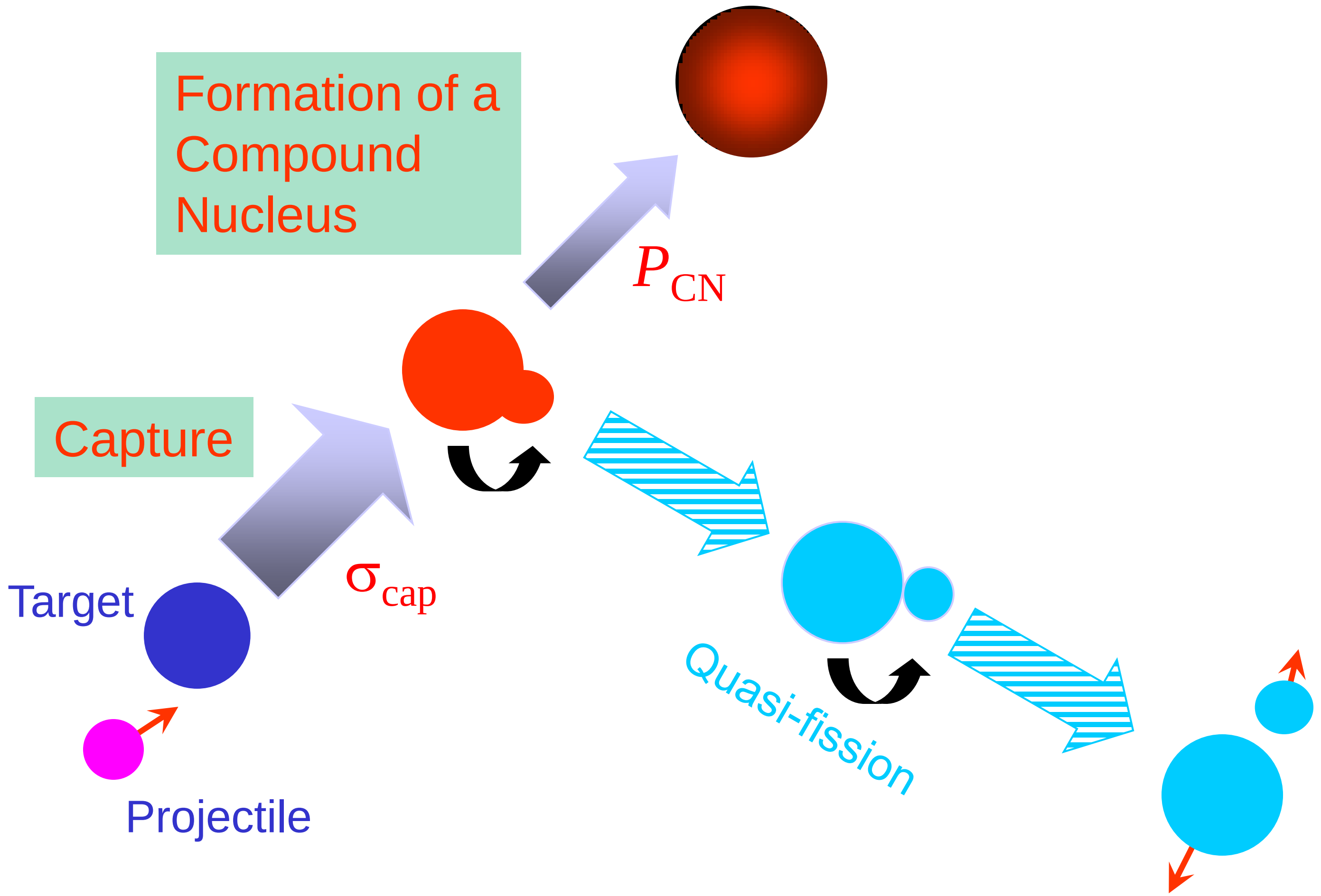
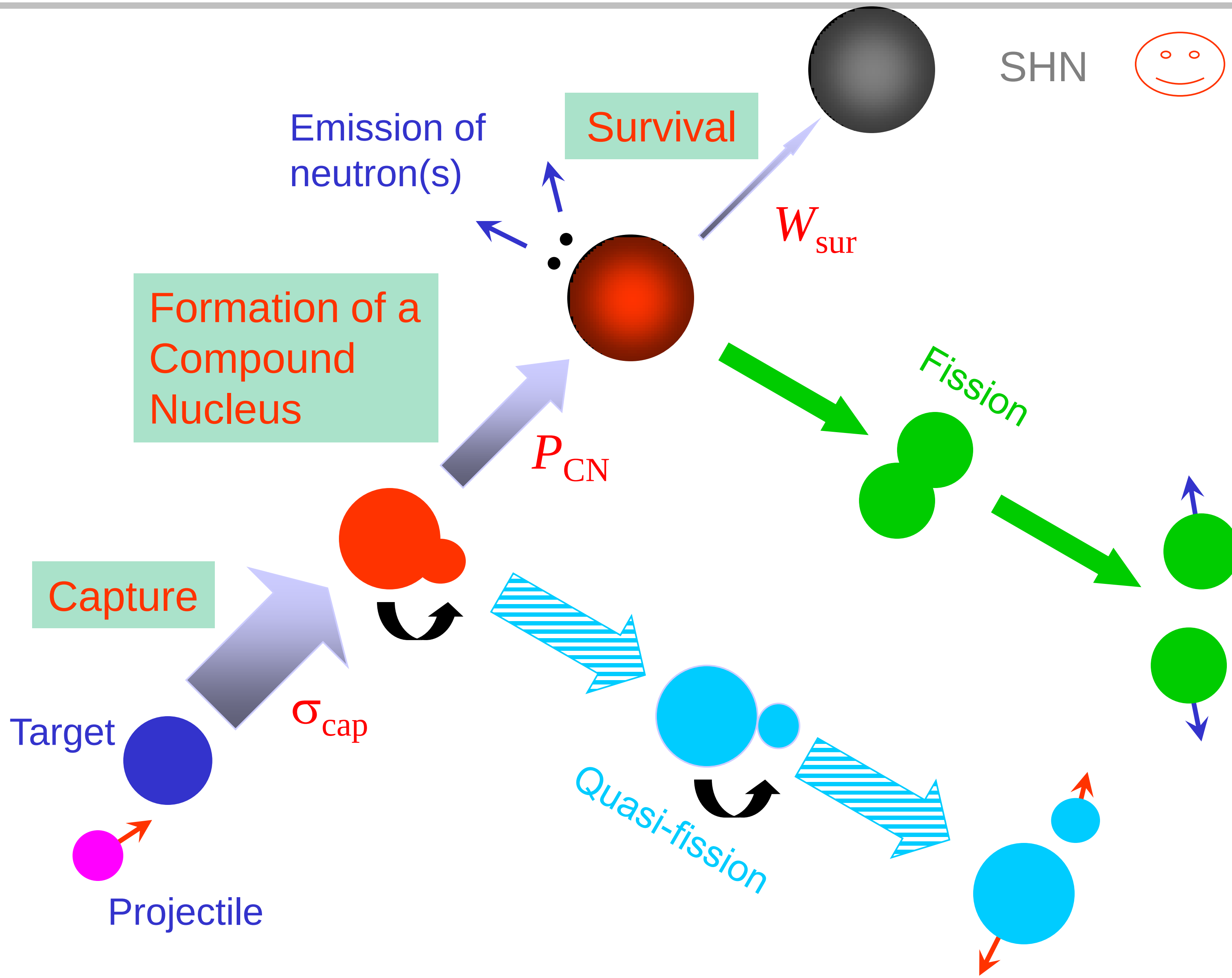


Three steps to a SHN via heavy-ion EvR reaction



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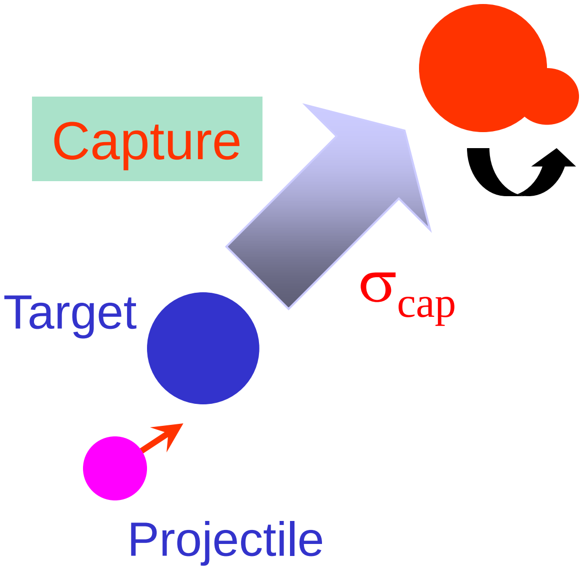
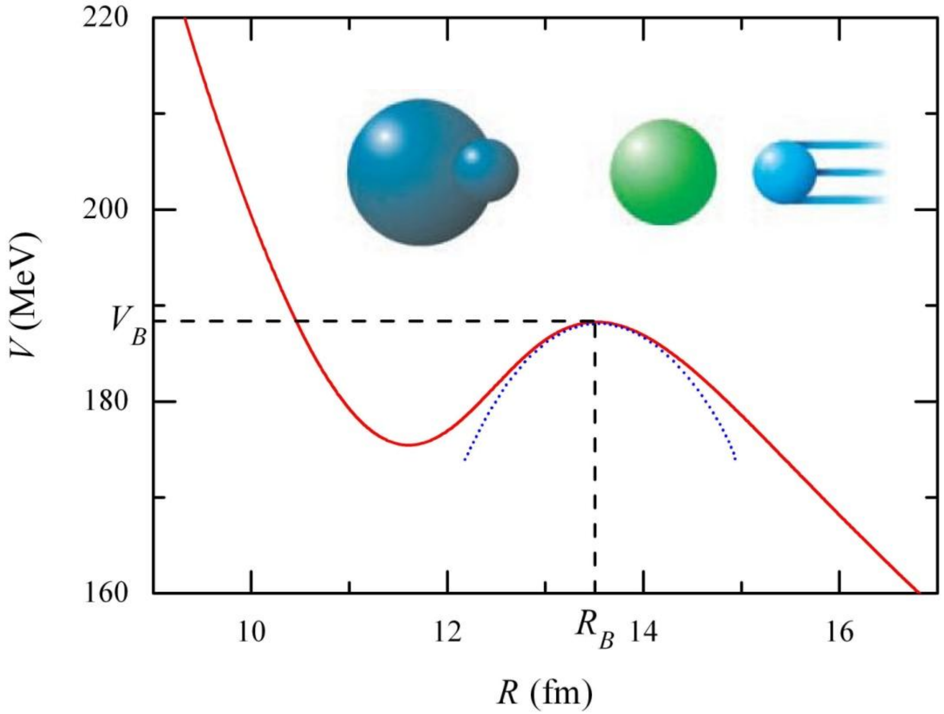
Three steps to a SHN via heavy-ion EvR reaction

$$\sigma_{cap}$$



The capture process



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

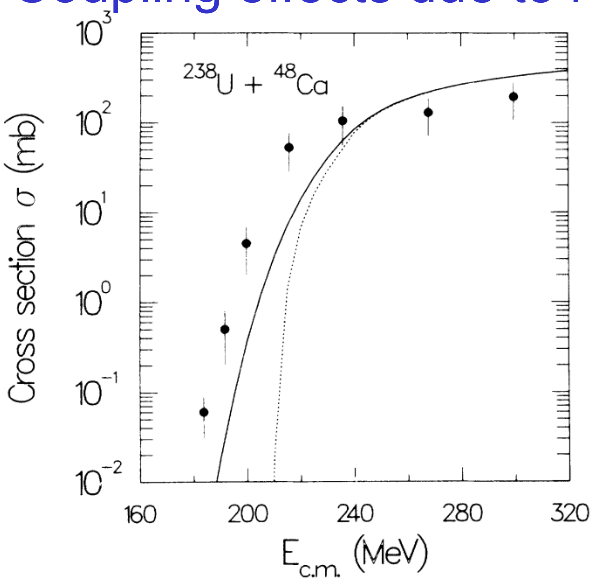
$$\sigma_{\text{cap}}(E_{\text{cm}}, J) = \frac{\pi\hbar^2}{2\mu E_{\text{cm}}}(2J+1)\,T(E_{\text{cm}}, J)$$

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

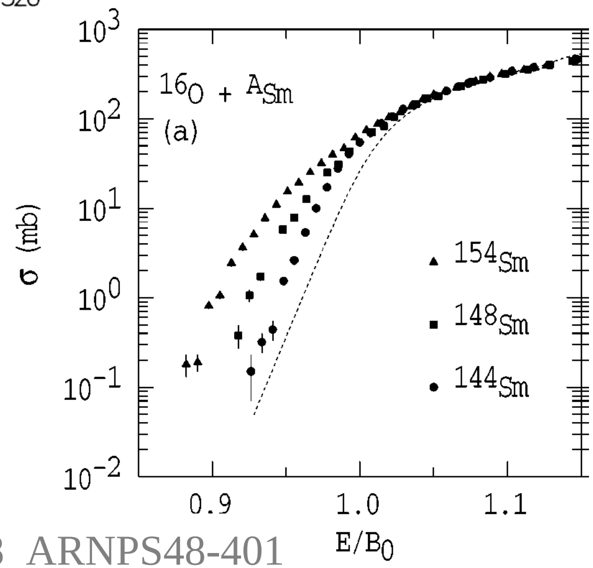
Hill_Wheeler1953_PR089-1102

Channel coupling effects

Coupling effects due to rotation, vibration, nucleon transfer, …



Shen+1987_PRC36-115



Dasgupta+1998_ARNPS48-401

Channel coupling effects

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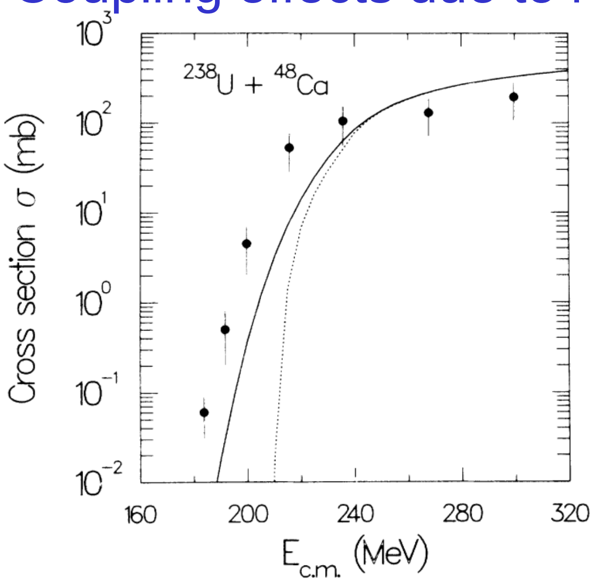
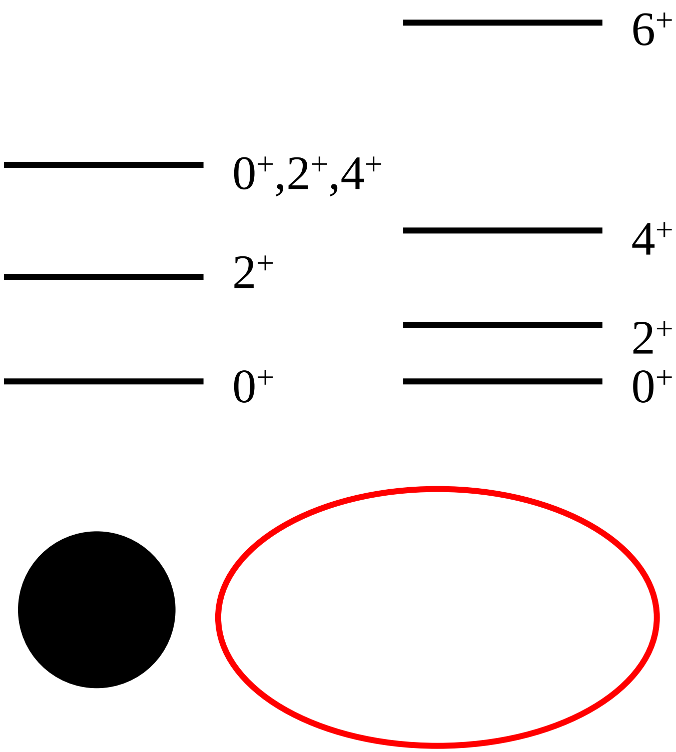
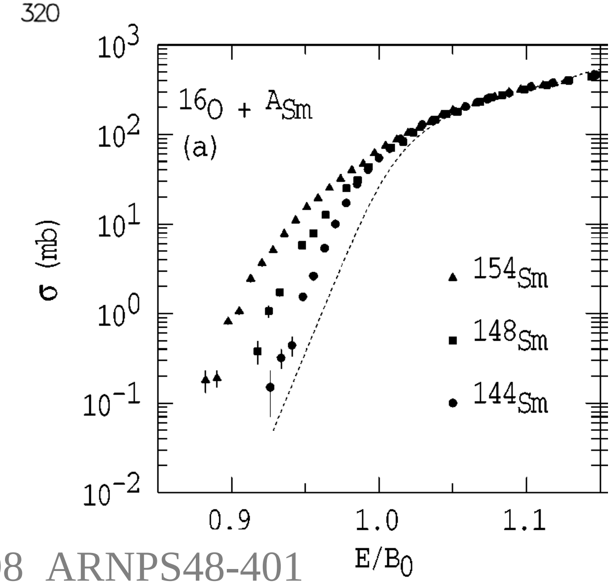


Shen+1987_PRC36-115



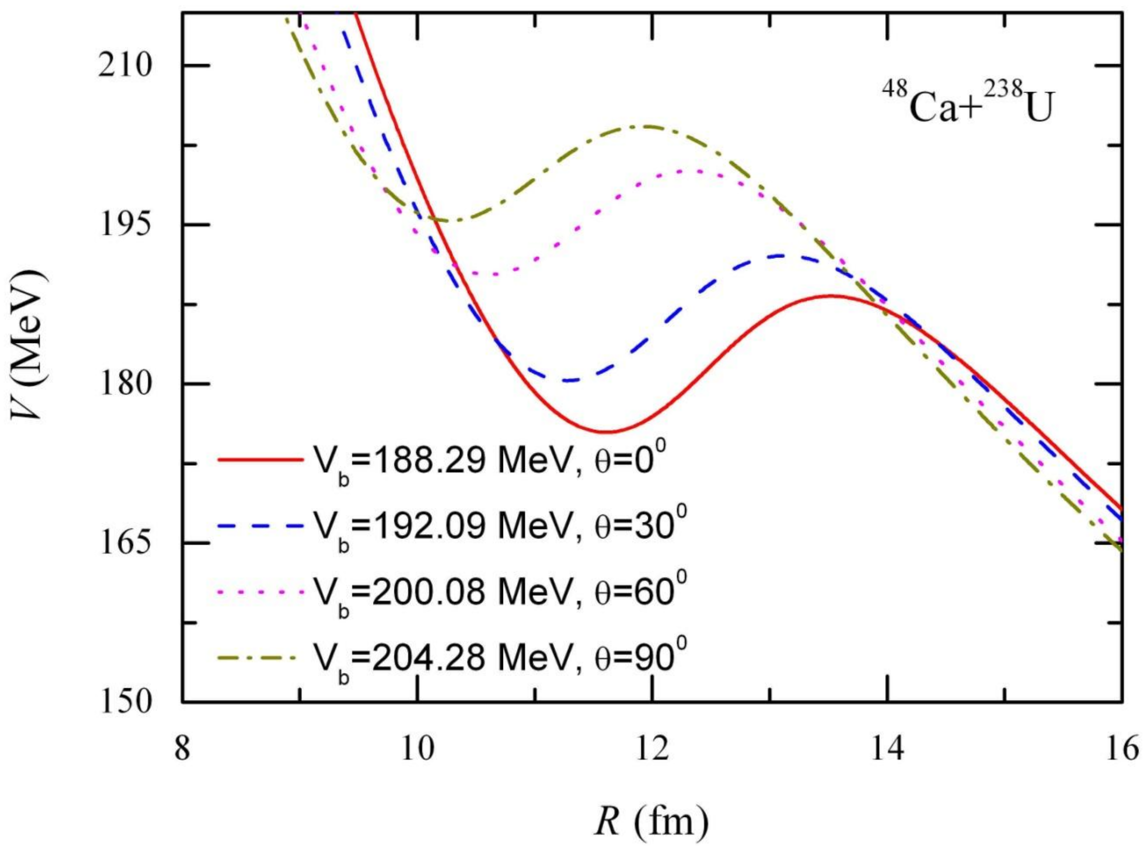


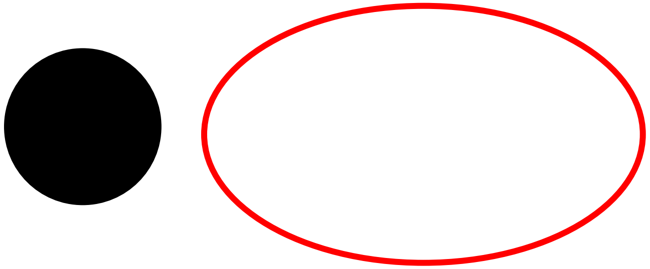
Dasgupta+1998_ARNPS48-401

Barrier distribution

Coupling effects due to rotation, vibration, nucleon transfer, …

are taken into account empirically by introducing a barrier distribution





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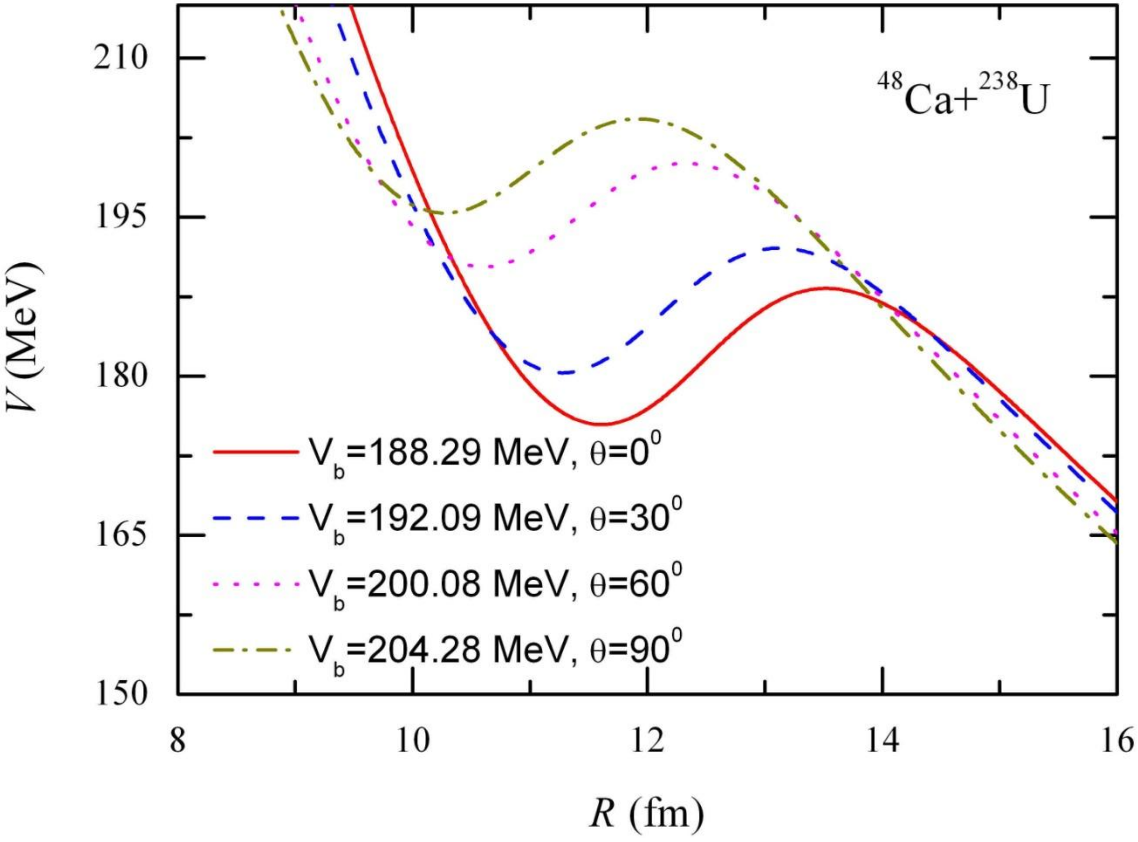

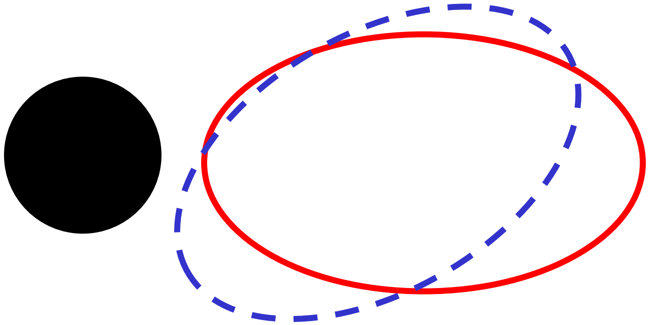

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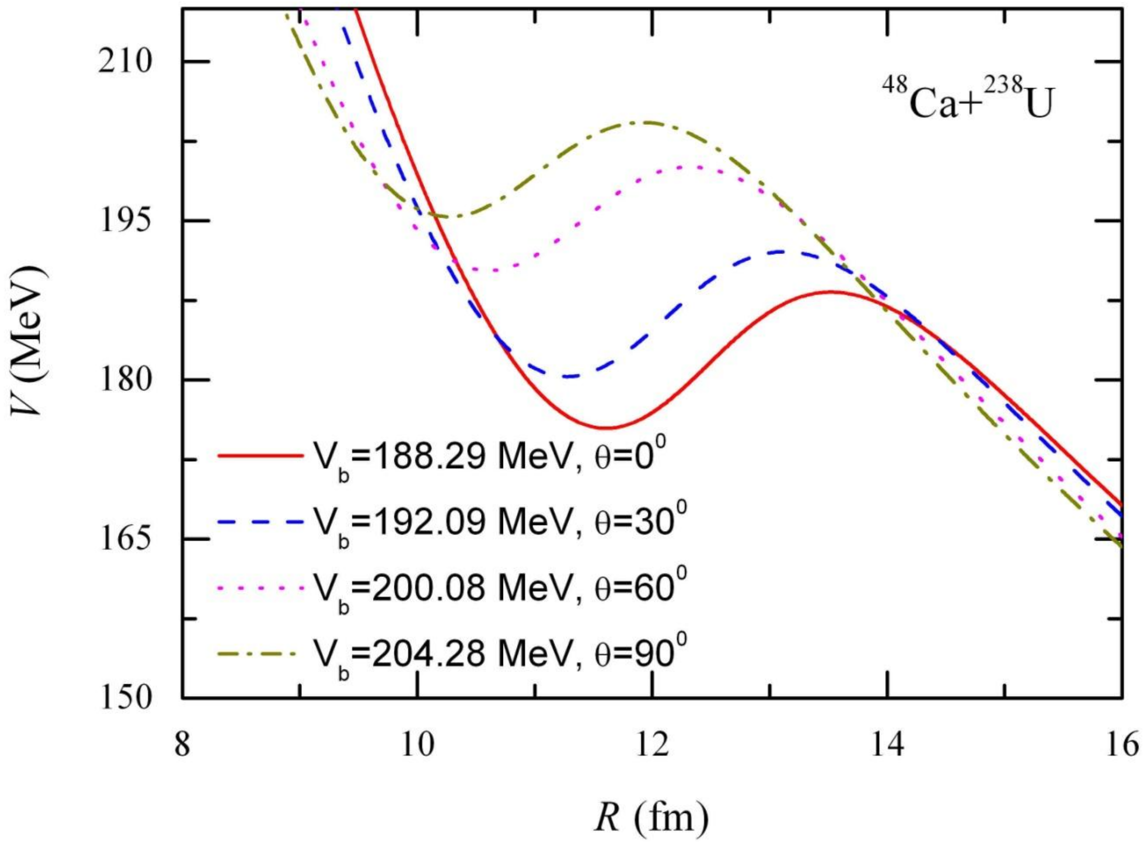

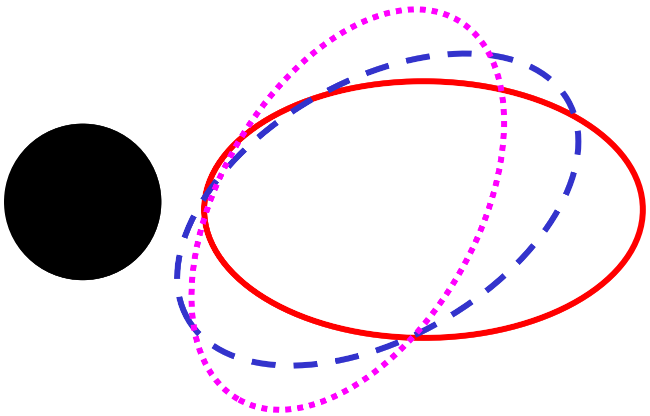

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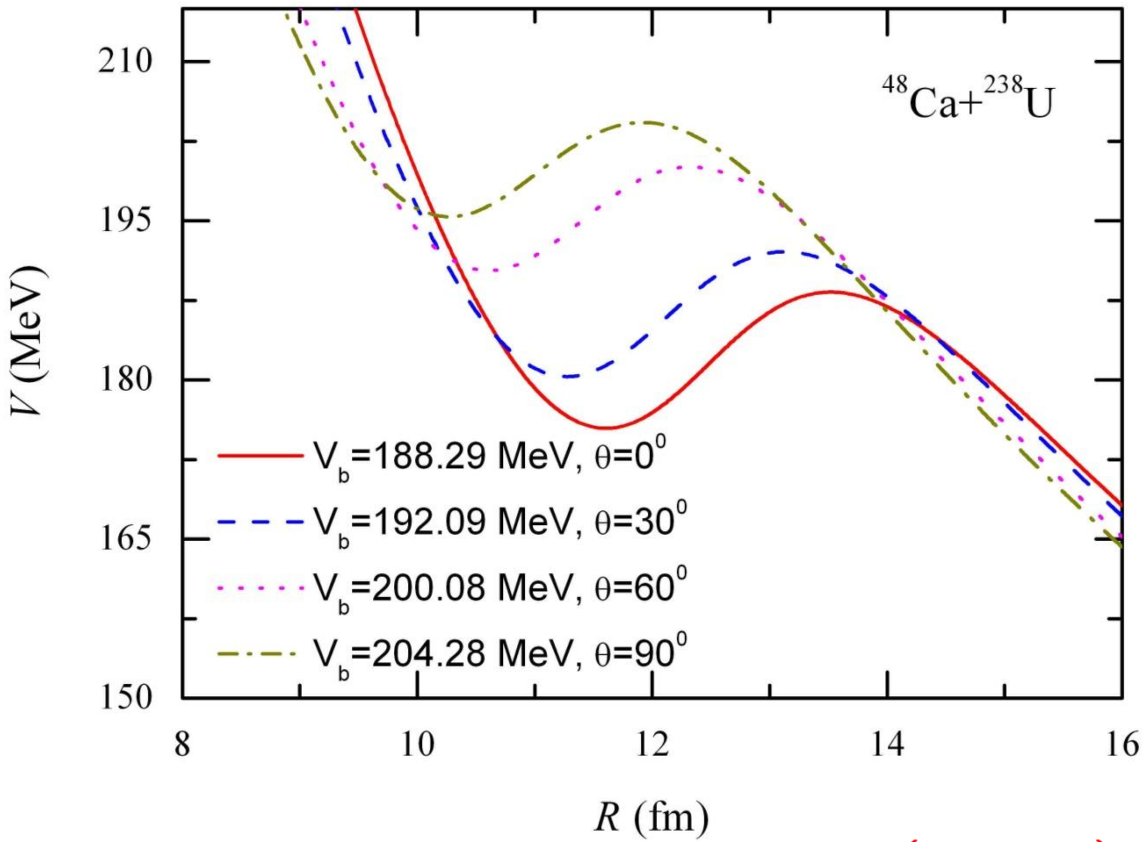

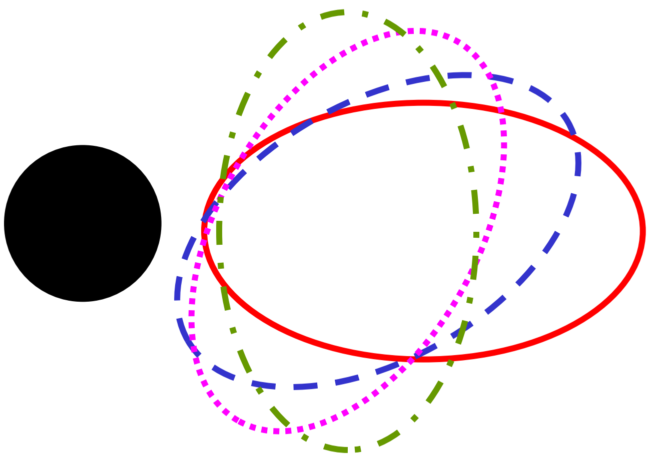

$$T\left(E_{\mathrm{cm}}, J\right) = \int dB\ f(B)\ T\left(E_{\mathrm{cm}}, B, J\right)$$

The empirical CC (ECC) model

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At. Data & Nucl. Data Tables 114 (2017) 281

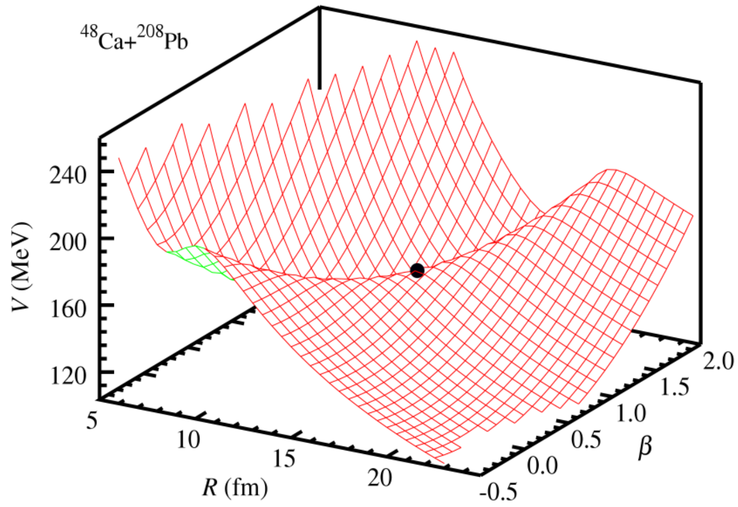
- Capture cross section

$$\sigma_{\mathrm{capture}}(E) = \frac{\pi\hbar^2}{2\mu E}\sum_{J}^{J_{\max}}(2J+1)T(E,J)$$

$$T(E,J) = \int f(B) T_{\mathrm{HW}}(E,J,B)\mathrm{d}B$$

- Barrier distribution

$$f(B) = \begin{cases} \frac{1}{N}\exp\left[-\left(\frac{B-B_{\mathrm{m}}}{\Delta_1}\right)^2\right], & B < B_{\mathrm{m}} \\ \frac{1}{N}\exp\left[-\left(\frac{B-B_{\mathrm{m}}}{\Delta_2}\right)^2\right], & B > B_{\mathrm{m}} \end{cases}$$



$$\begin{aligned} B_{\mathrm{m}} &= aV_{\mathrm{B}}^{\mathrm{Sp}} + (1-a)V_{\mathrm{B}}^{\mathrm{S}}, \\ \Delta_1 &= bE_{\mathrm{D}}, \\ \Delta_2 &= cE_{\mathrm{D}}, \end{aligned}$$

$$E_{\mathrm{D}} = \frac{1}{2}\sum_{i=\mathrm{P,T}} C_i \left(\beta_i^{\mathrm{S}}\right)^2$$

For reactions w/ positive *Q*-values for 2n transfer

$$\Delta_1 \to gQ(2n) + \Delta_1$$
$$\Delta_2 \to gQ(2n) + \Delta_2$$

Model parameters

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- Nucleus-nucleus potential

$$V_N(R, \beta_P^0, \beta_T^0, \theta_P, \theta_T) = \frac{-V_0}{1 + \exp\left[(R - R_P - R_T)/a\right]},$$

with

$$R_P = R_{0P}[1 + (5/4\pi)^{1/2}\beta_P^0 P_2(\cos\theta_P)],$$
$$R_T = R_{0T}[1 + (5/4\pi)^{1/2}\beta_T^0 P_2(\cos\theta_T)],$$
$$R_{0i} = r_0 A_i^{1/3}, \quad i = \mathrm{P}, \mathrm{T},$$

$$V_0 = 80 \text{ MeV},$$
$$r_0 = 1.16 \text{ fm},$$
$$a = \left\{1.17\left[1 + 0.53\left(A_P^{-1/3} + A_T^{-1/3}\right)\right]\right\}^{-1} \text{ fm}.$$

Deformation parameters: Möller_Nix_Myers_Swiatecki_ ADNDT59-185

- Barrier distribution

Reactions w/ spherical T & P

$$a = \begin{cases} 0.26, & Z_P Z_T < 1150, \\ 0.5, & Z_P Z_T \geq 1150, \end{cases}$$
$$b = 0.32,$$
$$c = 0.93.$$

Reactions w/ deformed T or P

$$a = \begin{cases} 0.23, & Z_P Z_T < 1150, \\ 0.37, & Z_P Z_T \geq 1150, \end{cases}$$
$$b = 0.12,$$
$$c = 1.12.$$

$g = 0.32$

Fusion reactions w/ well bound projectiles

- 220 reactions with $182 \leq Z_P Z_T \leq 1640$

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At. Data & Nucl. Data Tables
114 (2017) 281

Table 2
The experimental and calculated excitation functions for a total of 217 reaction systems. See page 56 for Explanation of Tables.

Reaction	Detected particles	Data obtained	E_{lab} (MeV)	$E_{\mathrm{c.m.}}$ (MeV)	σ (mb)	$\delta\sigma$ (mb)	σ^{cal} (mb)
^{12}C+^{89}Y	EvR	authors' graph	30.682	27.037	0.033	—	0.195
		[103]	32.403	28.554	0.668	—	1.697
		E_{lab}	33.789	29.774	4.757	—	9.135
			35.387	31.183	29.865	—	47.223
			36.912	32.526	96.919	—	132.929
			39.174	34.520	287.692	—	302.095
			41.019	36.145	369.296	—	434.894
			43.207	38.074	597.752	—	575.375
			46.281	40.783	665.270	—	744.850
^{12}C+^{92}Zr	EvR	authors' table	31.88	28.20	0.19	0.1	0.456
		[104]	32.88	29.09	1.45	0.2	1.613
		$E_{\mathrm{c.m.}}$	33.89	29.98	2.91	0.2	5.554
			34.89	30.86	13.2	0.5	17.351
			35.89	31.75	38.6	1.1	45.991
			36.89	32.63	83.6	1.2	95.738
			37.89	33.52	136	3	163.147
			38.89	34.40	197	2	237.855
			39.90	35.30	253	3	315.353
			40.90	36.18	308	3	388.645
			41.91	37.07	366	3	459.032
			42.90	37.95	421	3	524.753
			43.89	38.83	476	4	586.786
			45.90	40.60	570	5	701.389
			47.91	42.38	664	5	804.554
			49.91	44.15	731	9	896.774
^{12}C+^{144}Sm	EvR	authors' graph	46.464	42.890	0.377	—	0.815
		[105]	46.968	43.355	0.975	—	1.489
		E_{lab}	47.407	43.760	1.458	—	2.508
			[illegible]	[illegible]	[illegible]		[illegible]

"Good" examples

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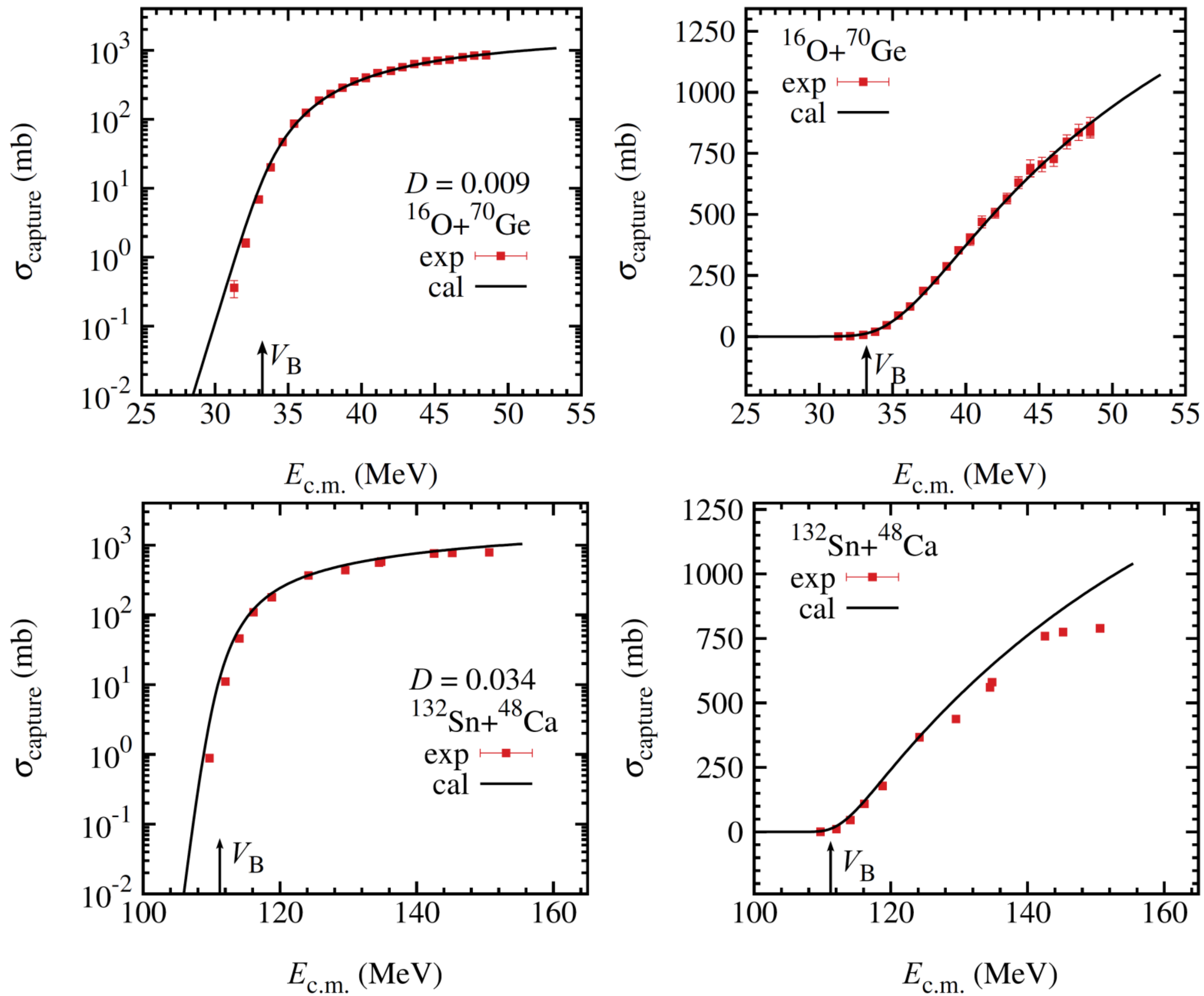

$^{32}S(^{40}Ca)+$ ^{96}Zr

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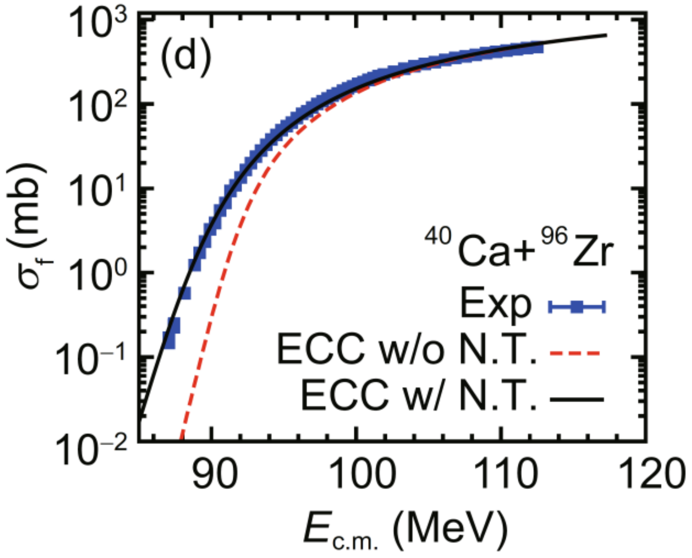
Sci. China-Phys. Mech. & Astron. 59 (2016) 642002



“Bad” examples

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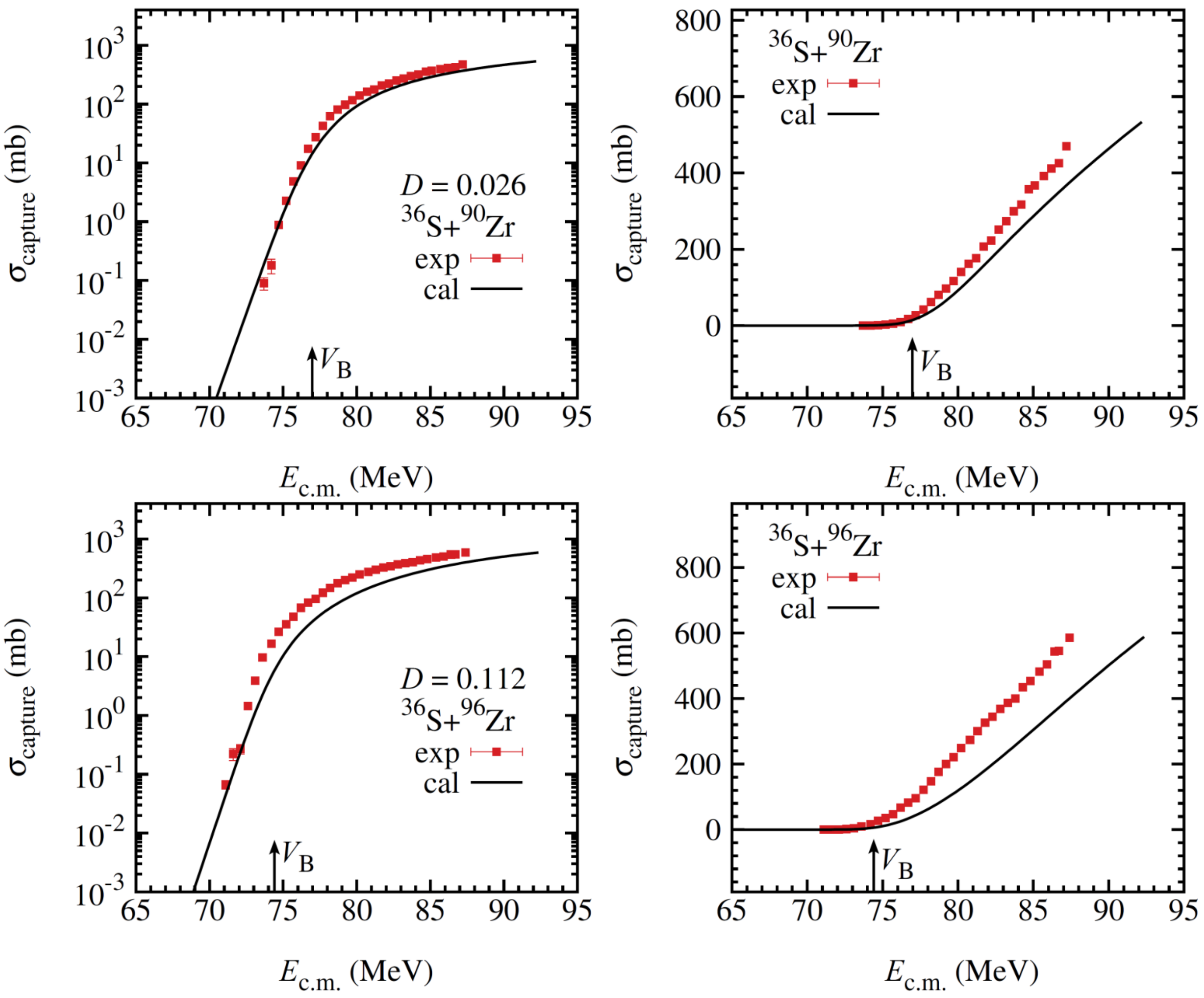

$^{40}Ca+^{94,96}Zr$

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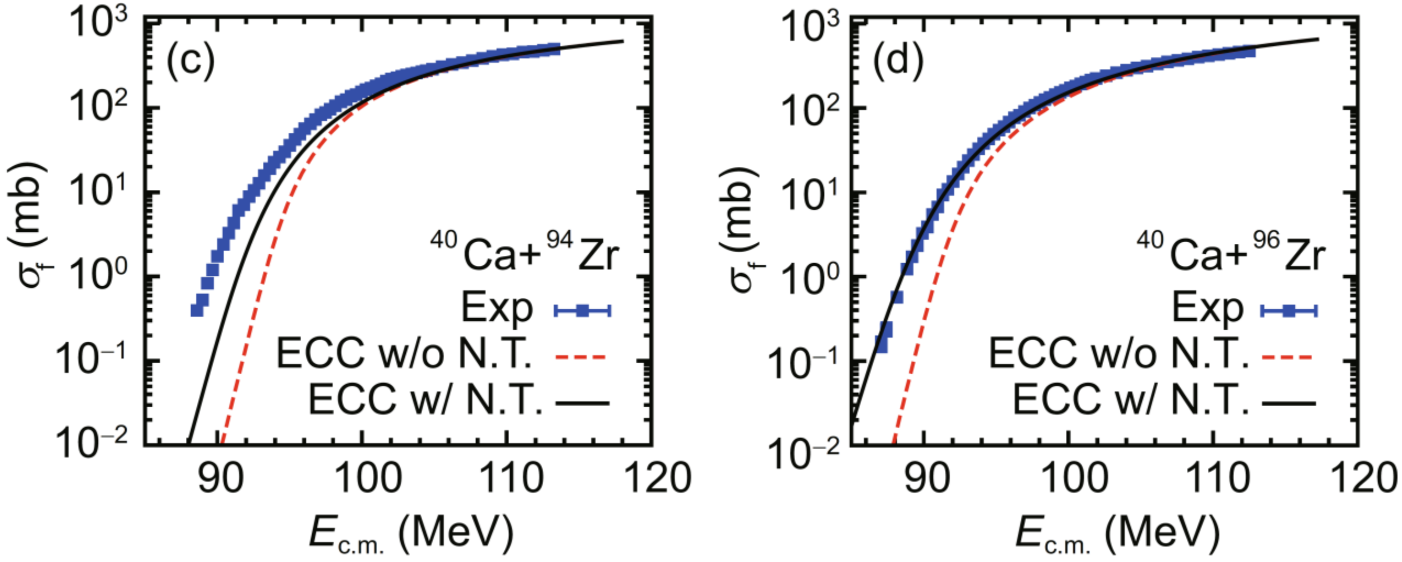

$^{40}Ca+^{94,96}Zr$

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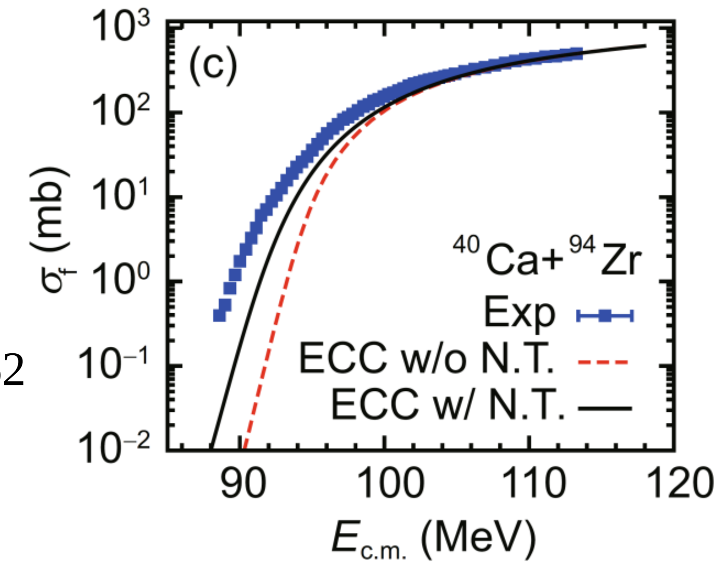
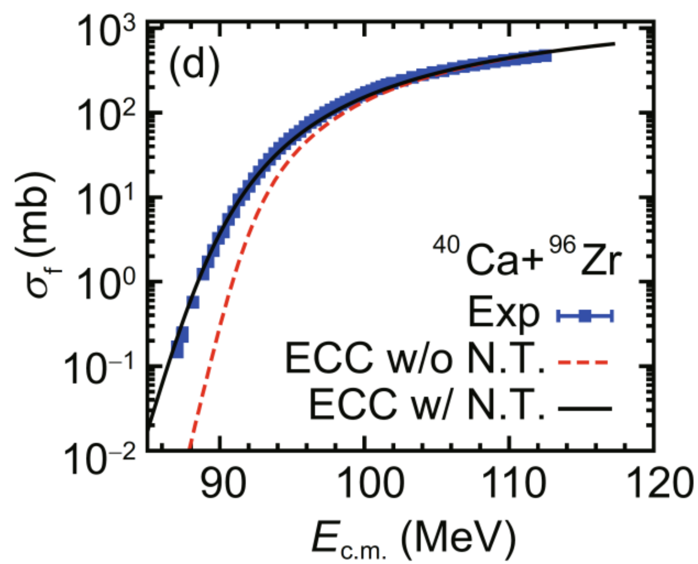
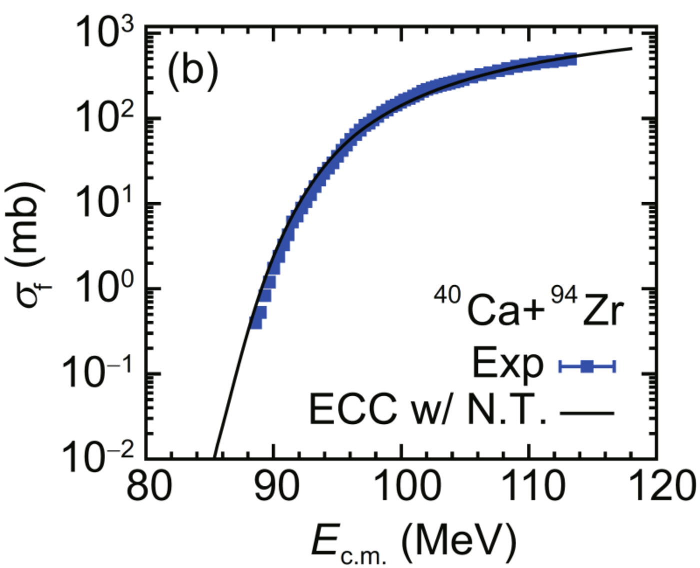
$\beta = 0.062$





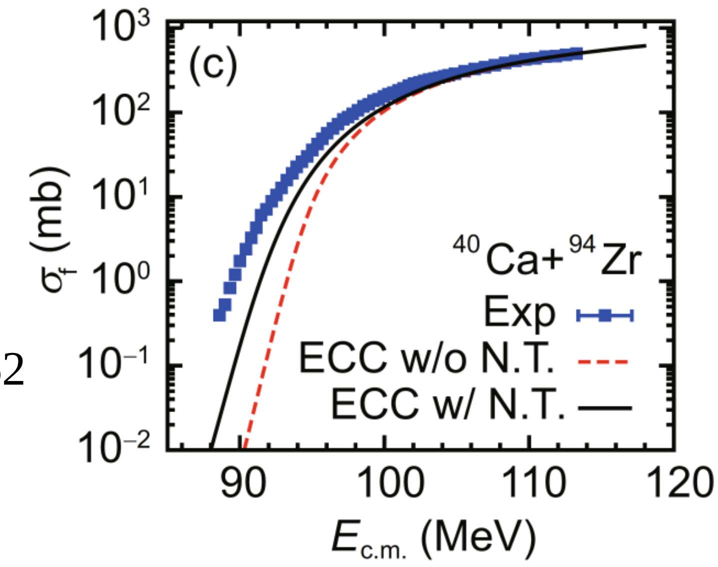
$\beta = 0.217$

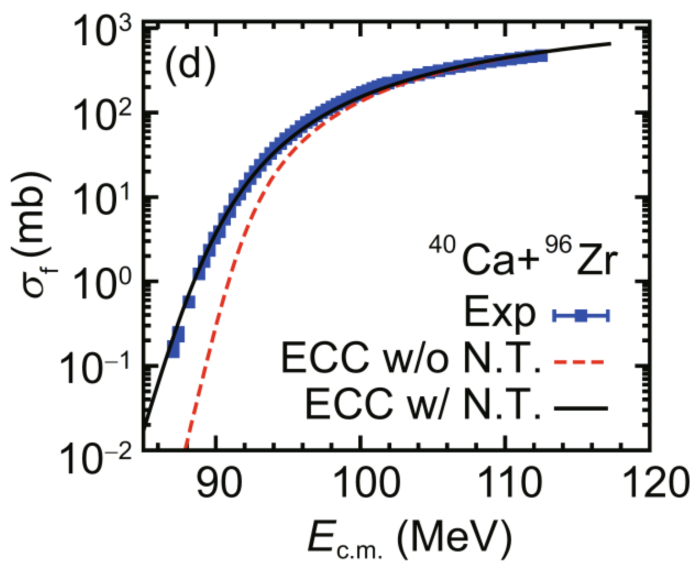


$^{40}Ca+^{94,96}Zr$

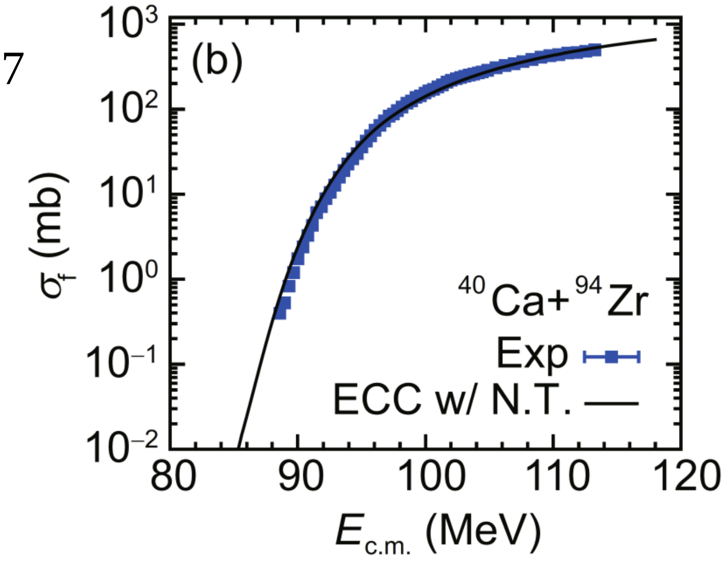
Wang, Zhao, Zhao & SGZ
Sci. China-Phys. Mech. & Astron. 59 (2016) 642002

$\beta = 0.062$





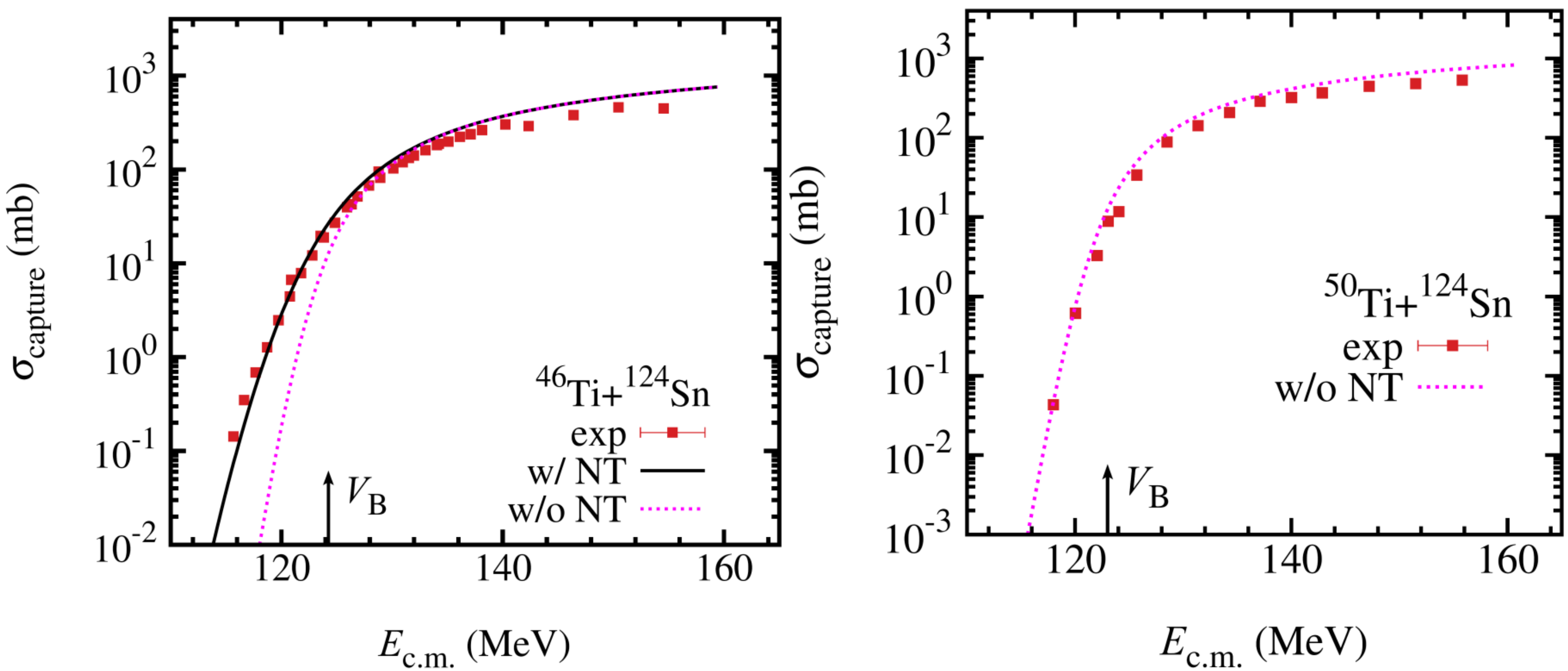
$\beta = 0.217$



Problems of this model

- (Too) simple
- Depth of nucleus-nucleus potl. fixed
- Higher-order def.: β_3, β_4, …
- Mainly around Coulomb barrier
- …

Predictions: ^{46,50}Ti+^{124}Sn



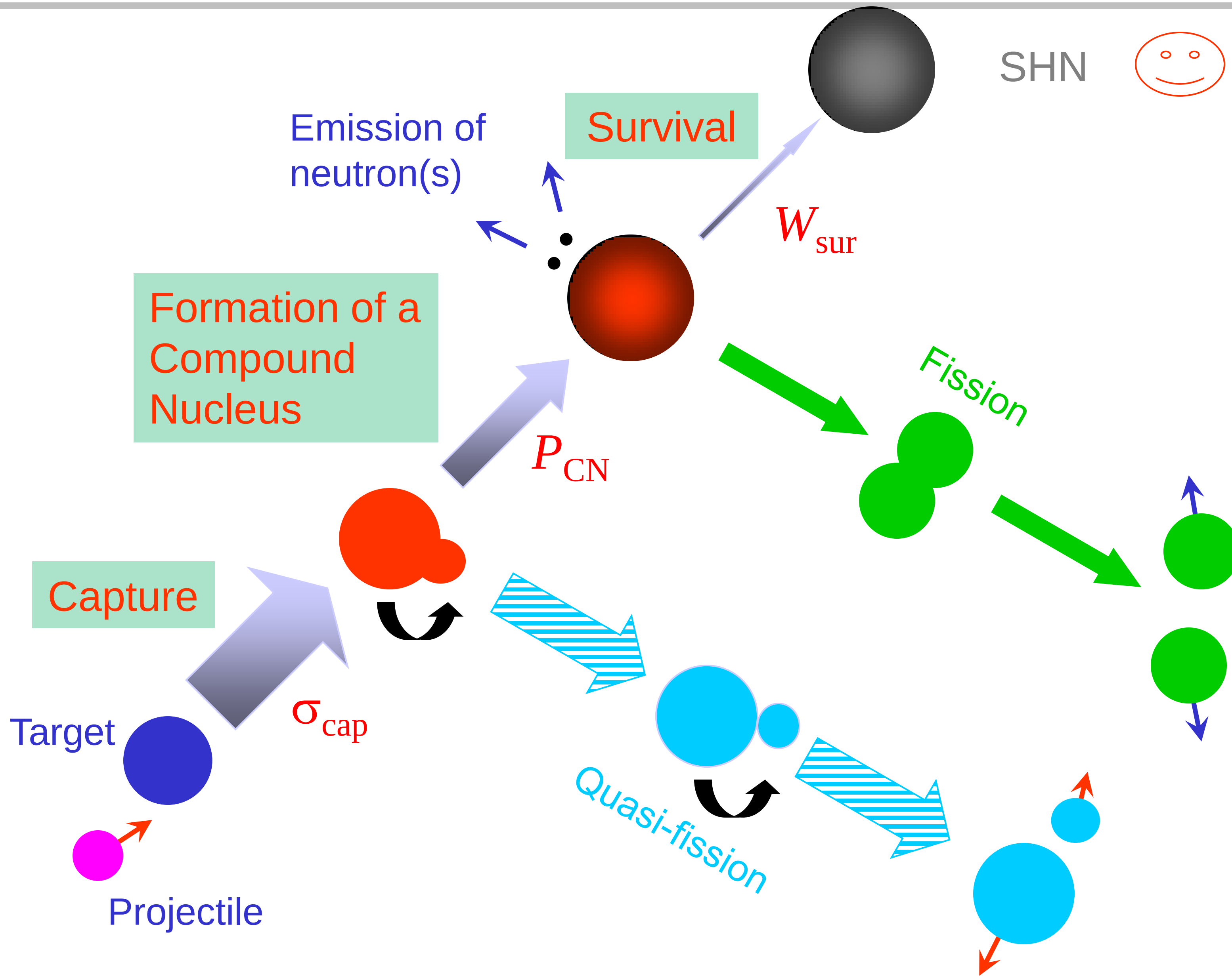
Expt: Liang+2016_PRC94-024616

Lectures 3 & 4

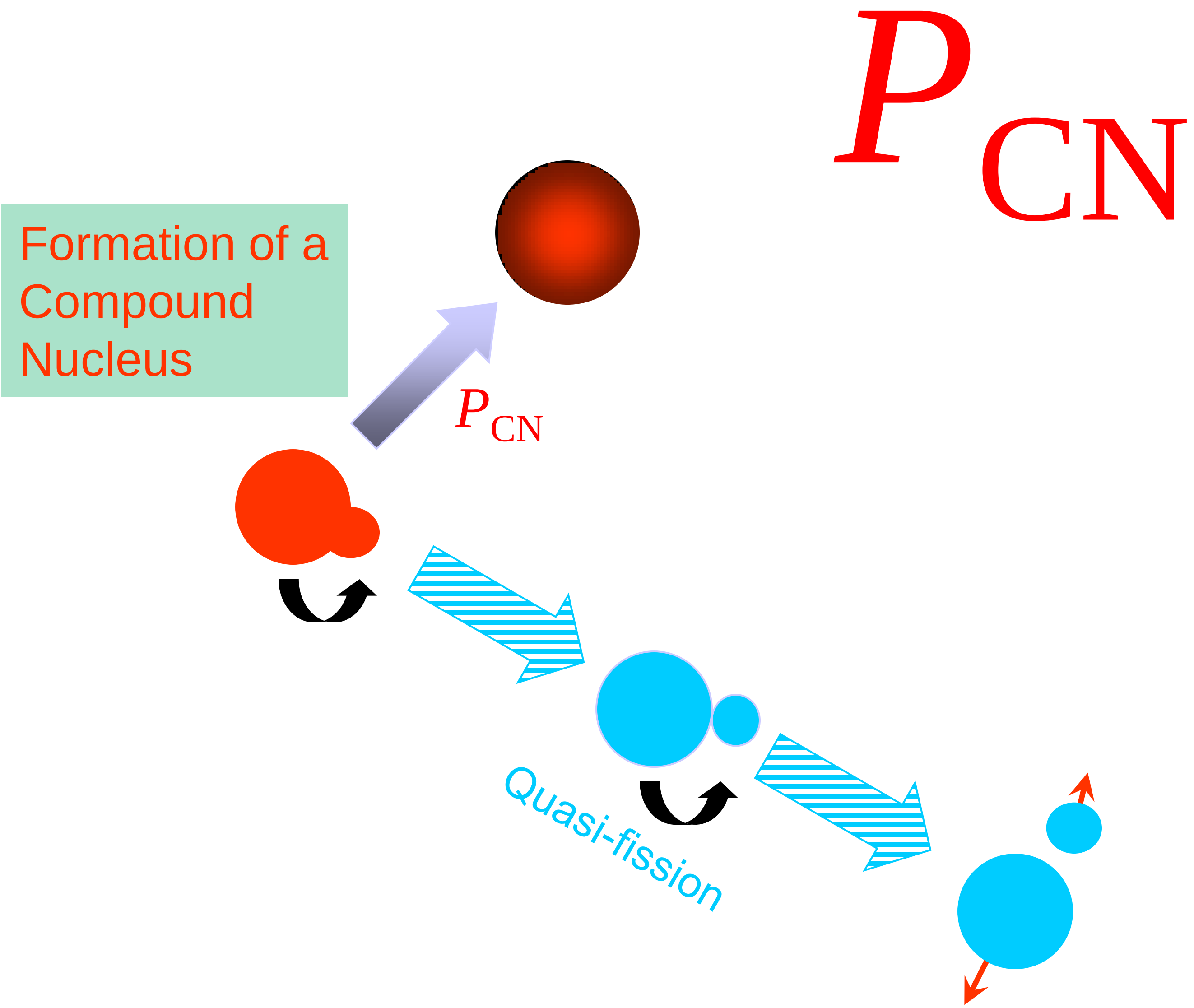
- Challenges in synthesizing SHN

- Synthesis mechanism of SHN
  - Large uncertainties in predicted Xsections
  - Heavy ion fusion reactions
    - Capture
    - Fusion
    - Survival against fission
  - Multi-nucleon transfer reactions
  - Reactions w/ radioactive ion beams

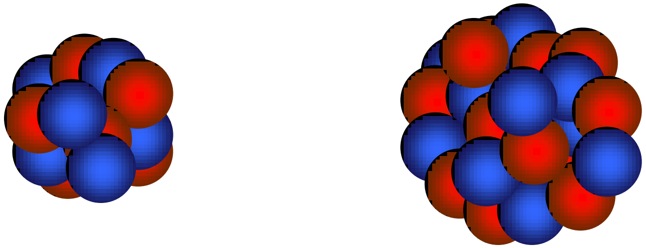
Three steps to a SHN via heavy-ion EvR reaction



Three steps to a SHN via heavy-ion EvR reaction

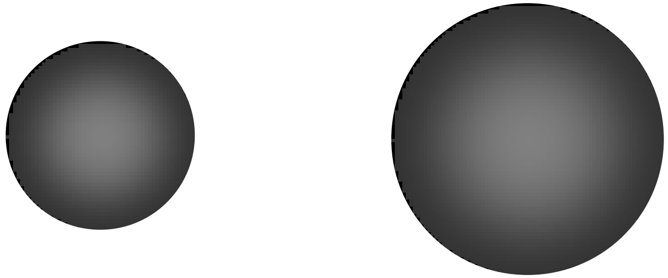


Fusion of two many-body systems

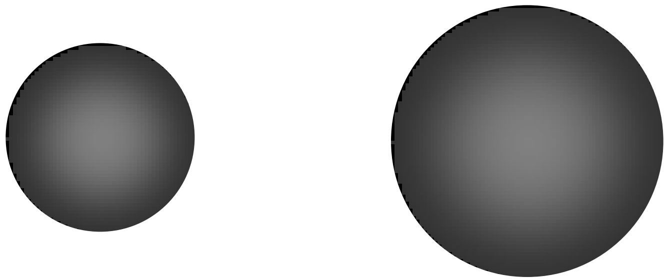


Fusion of two charged liquid drops

Fusion of two charged liquid drops



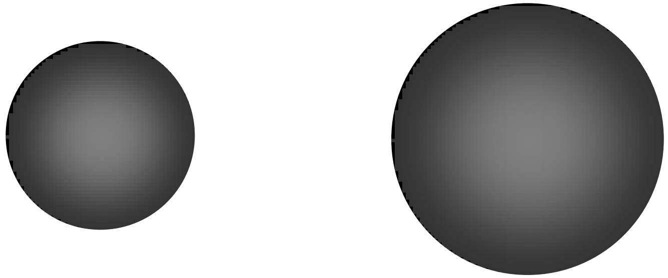
Fusion of two charged liquid drops



Mac. DoFs

- Relative distance
- Mass & charge
- Shape & orientation
- Neck formation
- Transfer of nucleons

Fusion of two charged liquid drops



Mac. DoFs

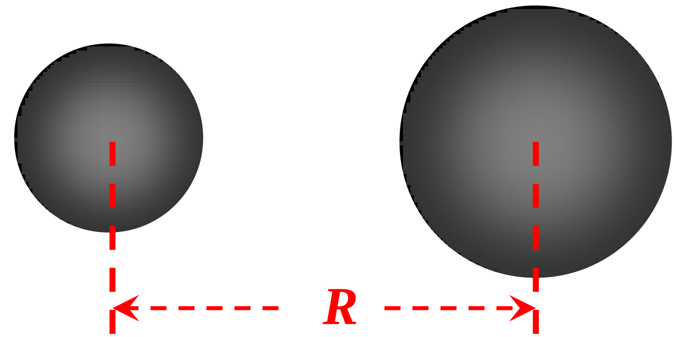
- Relative distance
- Mass & charge
- Shape & orientation
- Neck formation
- Transfer of nucleons
- ……

Fusion of two charged liquid drops

☐ Langevin dynamics

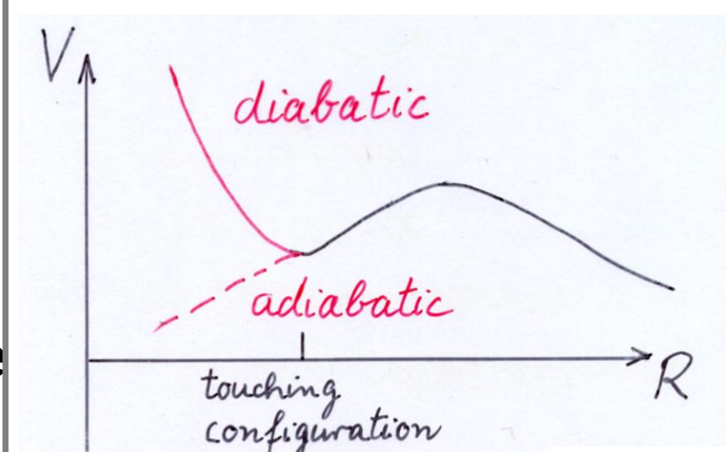
$$\begin{cases} \dfrac{du(t)}{dt} = -\displaystyle\int_{-\infty}^{t} \gamma(t-t')u(t')dt' + \frac{1}{\mu}\delta F(t) - \frac{1}{\mu}\frac{dV(R)}{dR} \\ u(t) = \dfrac{dR(t)}{dt} \end{cases}$$

- $R(t)$: Rel. distance
- $u(t)$: Rel. velocity
- $V(R)$: Interaction potl.
- d$F(t)$: Random force
- g(t-t’): Friction force



☐ Dinuclear system (DNS) model

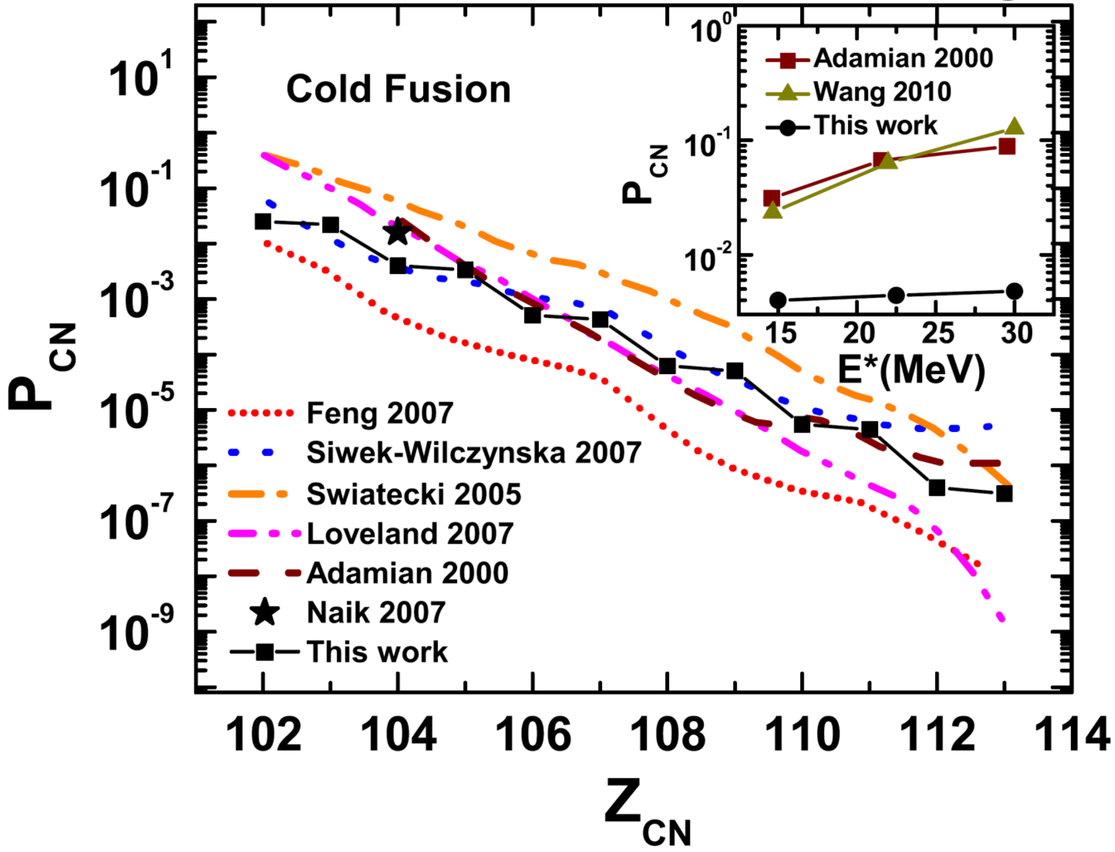
- ➢Projectile & target keep staying in the potl. Pocket and individuality
- ➢Transfer of nucleons betw. Projectile & target may lead to fusion



W. Scheid

Large uncertainties in P_{CN} from various models

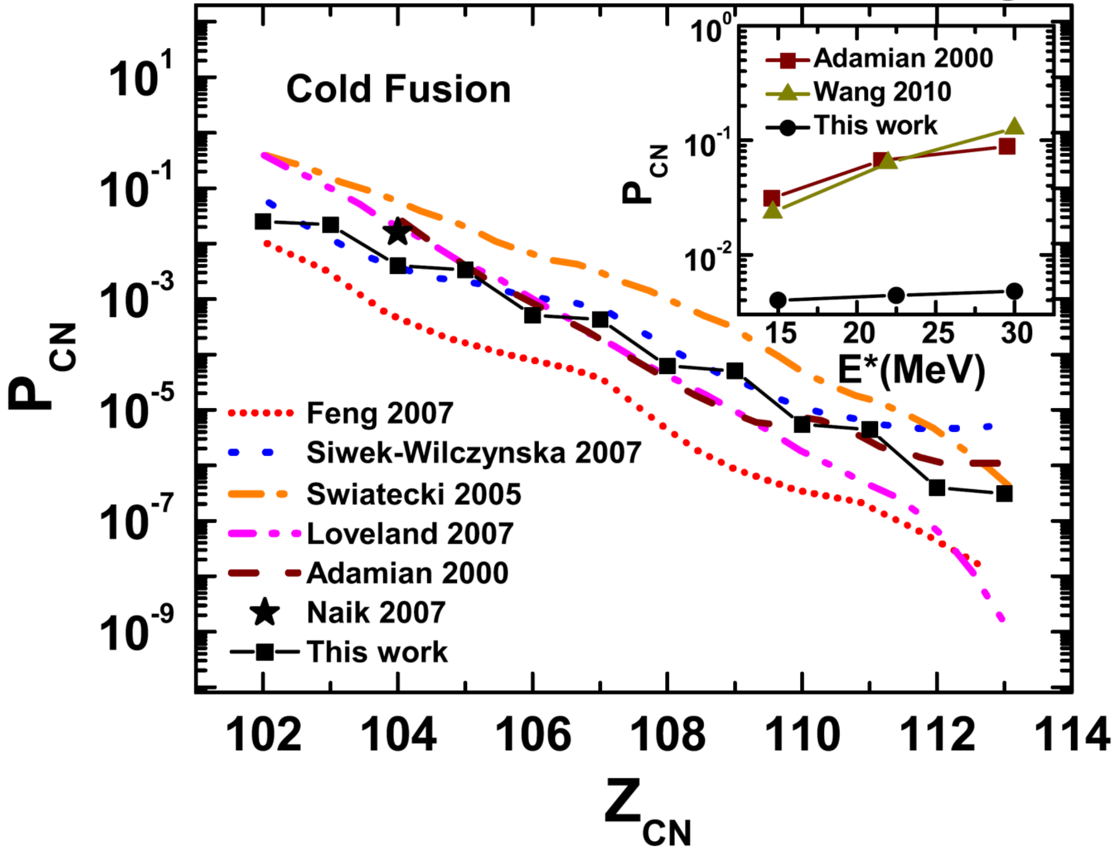
Zhu_Xie_Zhang2014_PRC89-024615



Large uncertainties in P_{CN} from various models

- Experimental study? Systematics?
- Microscopic study of fusion mechanism

Zhu_Xie_Zhang2014_PRC89-024615



Large uncertainties in P_{CN} from various models

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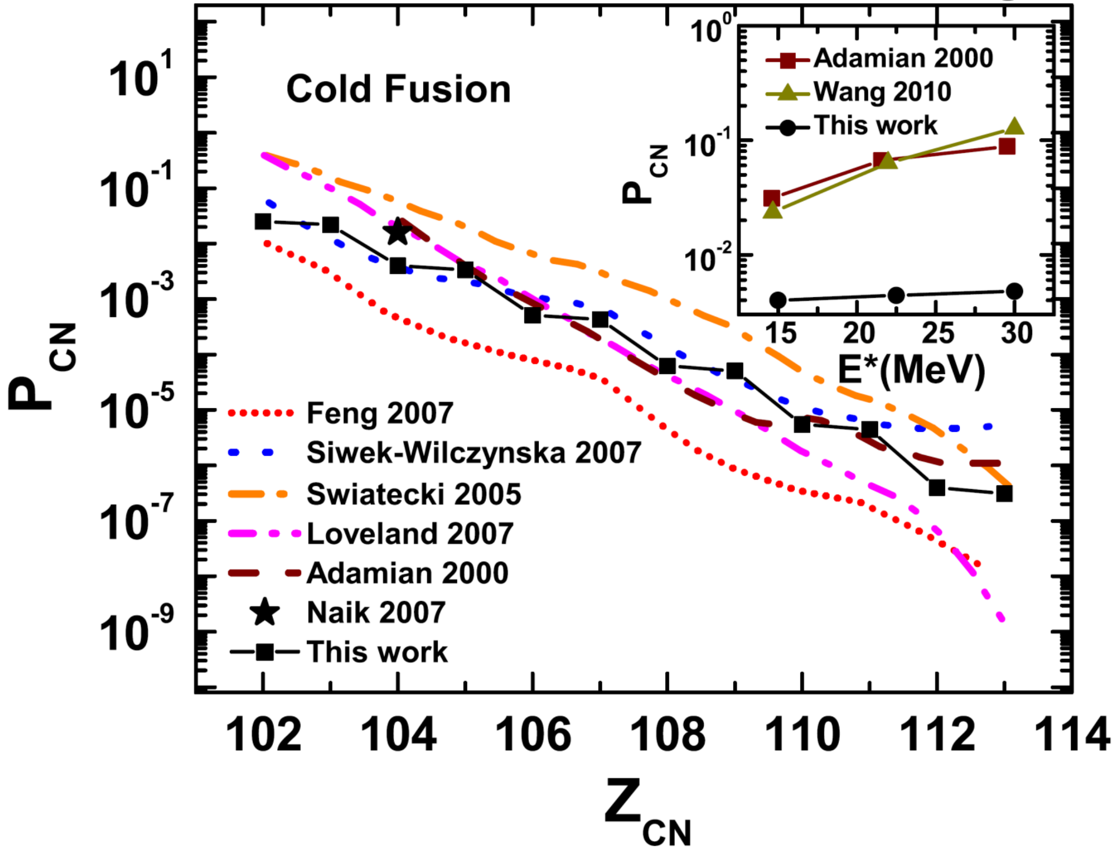
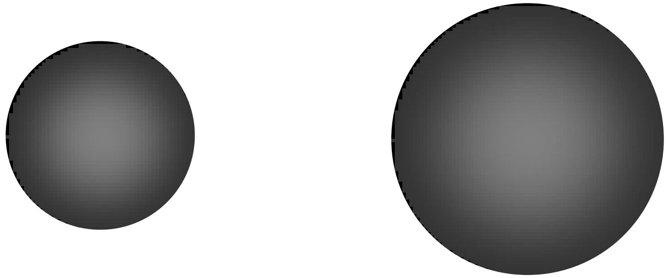
Zhu_Xie_Zhang2014_PRC89-024615



Fusion of two charged liquid drops



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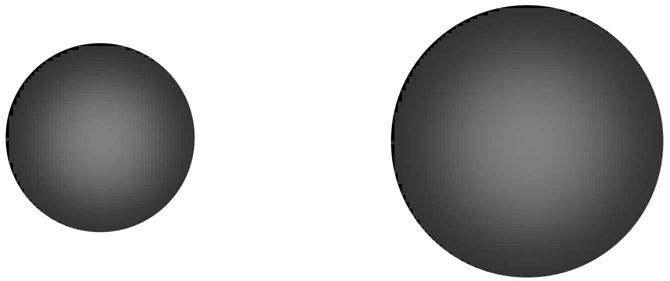
Fusion of two charged liquid drops



Mac. DoFs

- Relative distance
- Mass & charge
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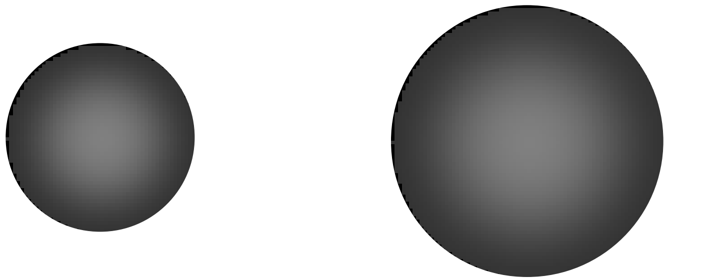
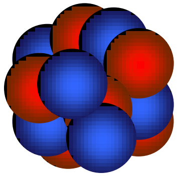
- ……

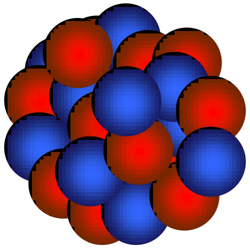
Fusion of two charged liquid drops



Fusion of two charged liquid drops

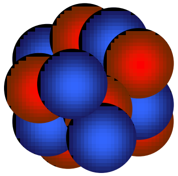
Fusion of two many-body systems

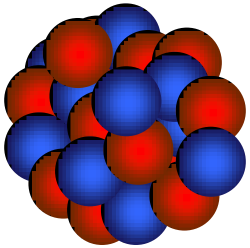




Fusion of two many-body systems

Time dependent Hartree-Fock theory





$$\mathcal{S} = \int_{t_1}^{t_2} dt \langle \Phi(t) | H - i\hbar\partial_t | \Phi(t) \rangle$$

$$H = \sum_{i}^{A} t_i + \sum_{i<j}^{A} v_{ij}$$

$$\Phi(r_1, r_2, \cdots, r_A, t) = \frac{1}{\sqrt{A!}} \det |\phi_\lambda(r_i, t)|$$

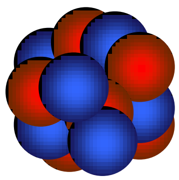
$$i\hbar \frac{\partial \phi_\lambda}{\partial t} = h\phi_\lambda$$

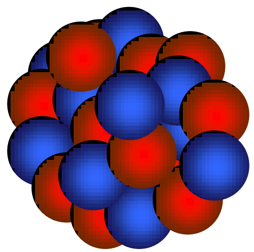
- Advantages
  - Microscopic
  - Successful in structure & reaction
- Disadvantages
  - Only one-body dissipation (collisions with “wall” of mean field)

Negele 1982 Rev. Mod. Phys. 54-913
Guo…2007 Phys. Rev. C76-014601
Guo…2008 Phys. Rev. C77-041301(R)
…
Simenel 2012 Euro. Phys. J. A 48-152

Fusion of two many-body systems

Quantum Molecular Dynamics (QMD)





$$\phi_i(\boldsymbol{r}) = \frac{1}{(2\pi\sigma_r^2)^{3/4}} \exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{r}_i)^2}{4\sigma_r^2} + \frac{i}{\hbar}\boldsymbol{r}\cdot\boldsymbol{p}_i\right]$$

$$\dot{\boldsymbol{r}}_i = \frac{\partial H}{\partial \boldsymbol{p}_i}, \quad \dot{\boldsymbol{p}}_i = -\frac{\partial H}{\partial \boldsymbol{r}_i}$$

Aichelin 1991 Phys. Rep. 202-233
…
Wang_Li_Wu 2002 PRC65-064608
Wang...2004 PRC69-034608

- Advantages
  - Microscopic
  - Both mean field & collision terms included
- More attentions should be paid on
  - Pauli exclusive principle
  - Shell effects

ImQMD & TDHF: DIC & multi-nucleon transfer leading to n-rich isotopes

Wang&Guo2016_PLB760-236

Physics Letters B 760 (2016) 236–241

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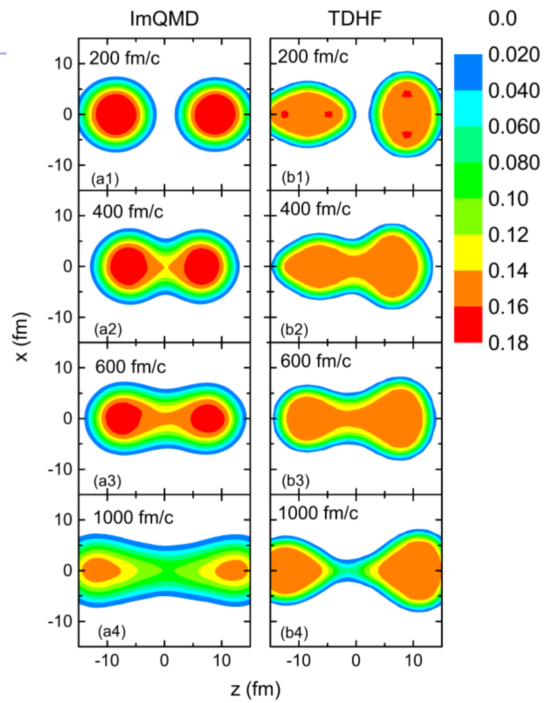
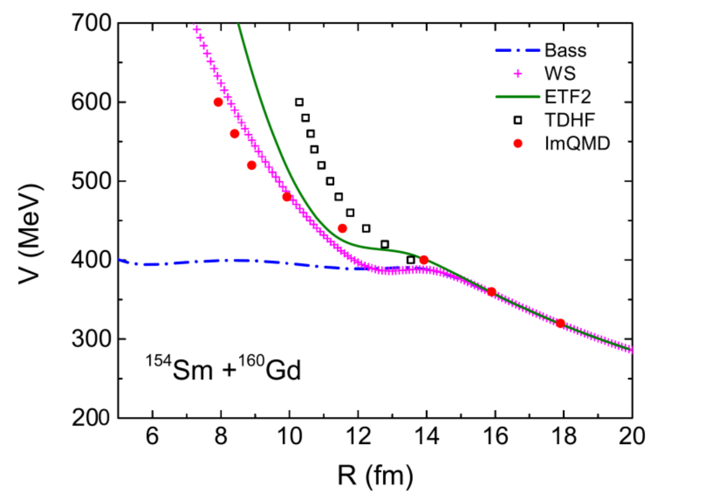
New neutron-rich isotope production in $^{154}Sm+^{160}Gd$

CrossMark

Ning Wang[a,*], Lu Guo[b,c]





TDHF: quasifission dynamics

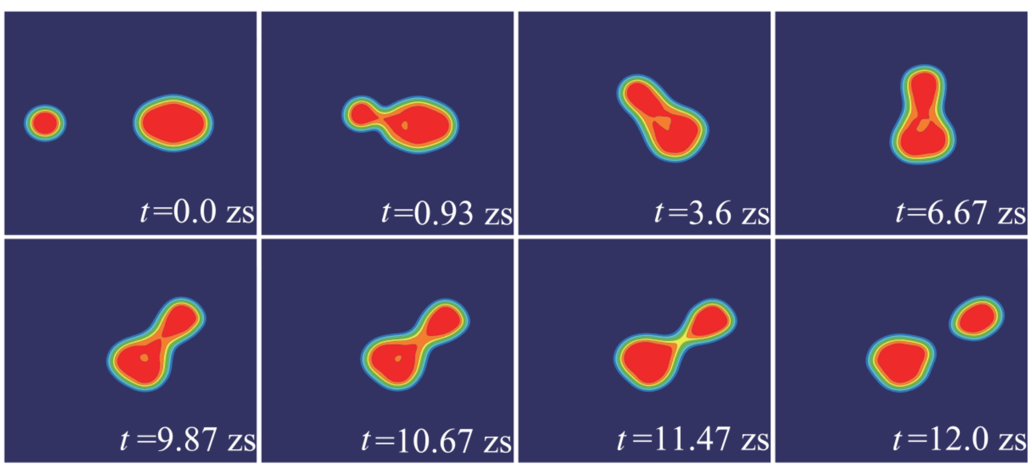
SCIENCE CHINA
Physics, Mechanics & Astronomy

• Article •

September 2017 Vol. 60 No. 9: 092011
doi: 10.1007/s11433-017-9063-3

Angular momentum dependence of quasifission dynamics in the reaction $^{48}Ca+^{244}Pu$

Chong Yu, and Lu Guo*



- Q.f. dynamics is sensitive to the angular momentum
- Contact time of q.f. decreases w/ the angular momentum
- Q.f. is accompanied by MNT

TDHF: fusion dynamics

Physics Letters B 782 (2018) 401–405

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

The role of tensor force in heavy-ion fusion dynamics

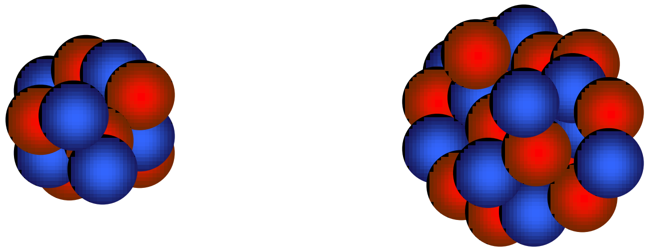
Lu Guo [a,*], Cédric Simenel [b], Long Shi [a], Chong Yu [a]

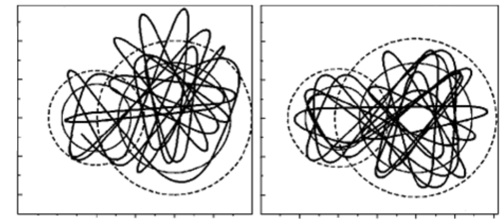
[a] School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China
[b] Department of Nuclear Physics, RSPE, Australian National University, Canberra, Australia

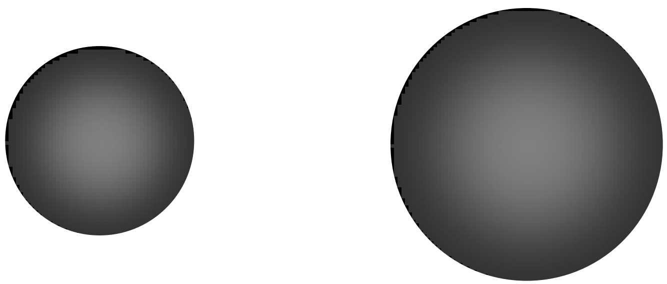
- Notable effects on fusion barriers & Xsections are observed by the inclusion of tensor force
- The effects are essentially attributed to the shift of low-lying vibration states of colliding partners & nucleon transfer in the asymmetric reactions

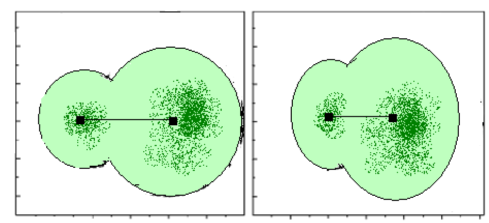
Fusion: Bridging microscopic & macroscopic description

Improved QMD simulations









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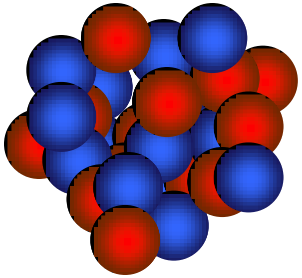
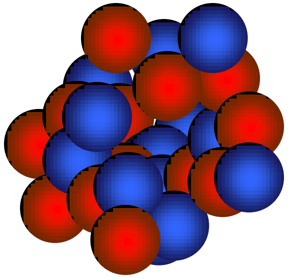
ImQMD simulations

- $^{90}Zr+^{90}Zr$: Monte Carlo sampling; 10,000 events





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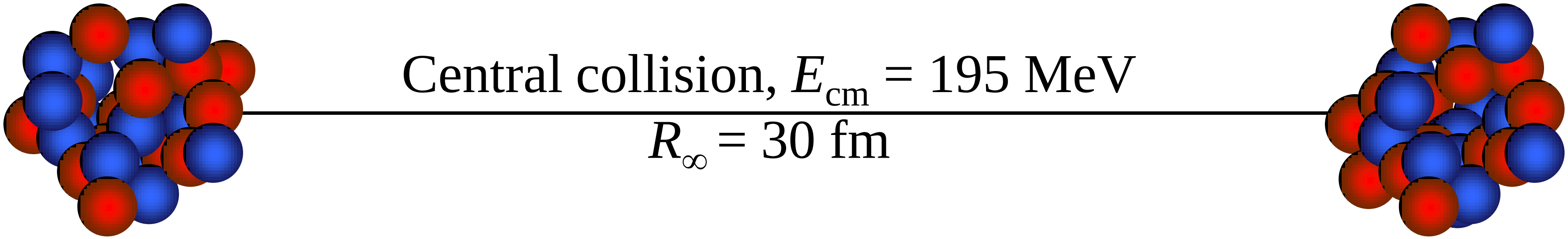
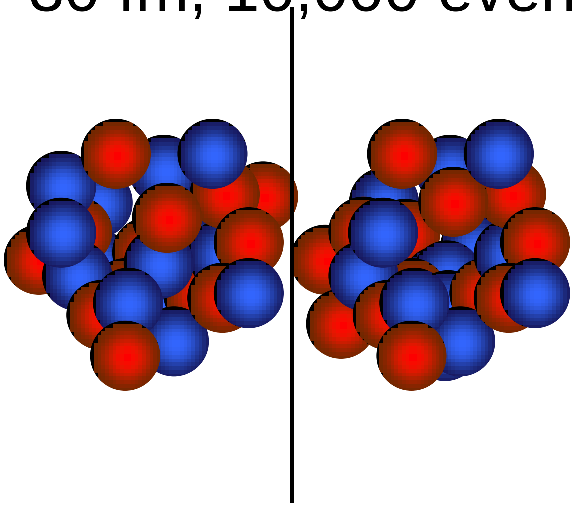


ImQMD simulations

- $^{90}Zr+^{90}Zr$: b=0, $E_{c.m.}$=195 MeV, R_{∞}=30 fm, 10,000 events



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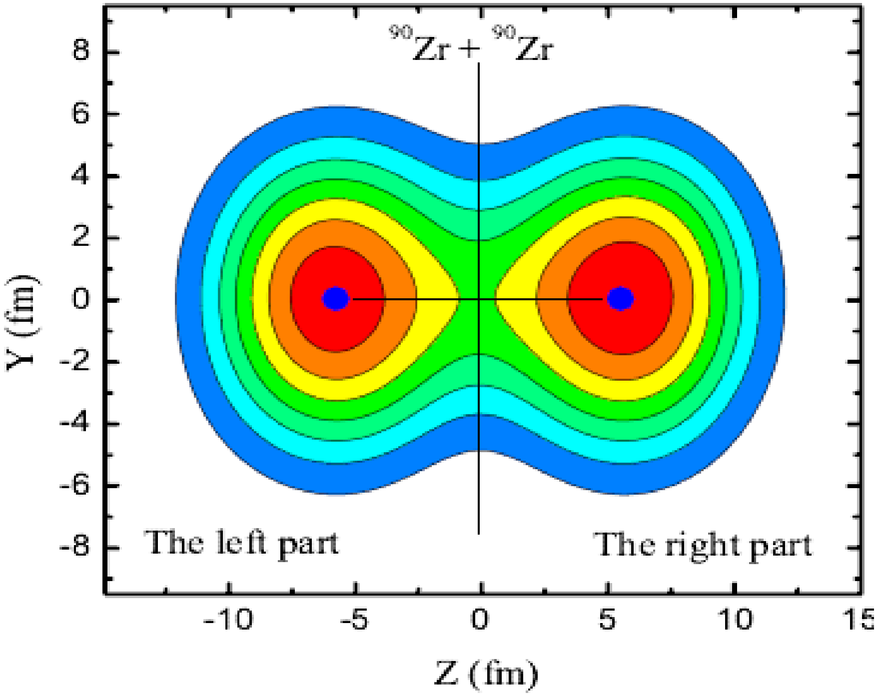

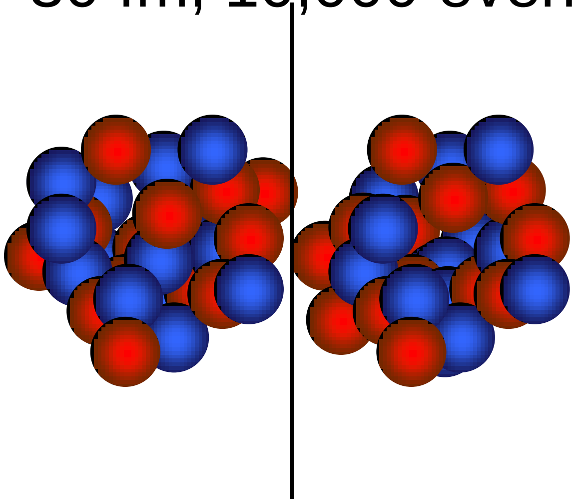

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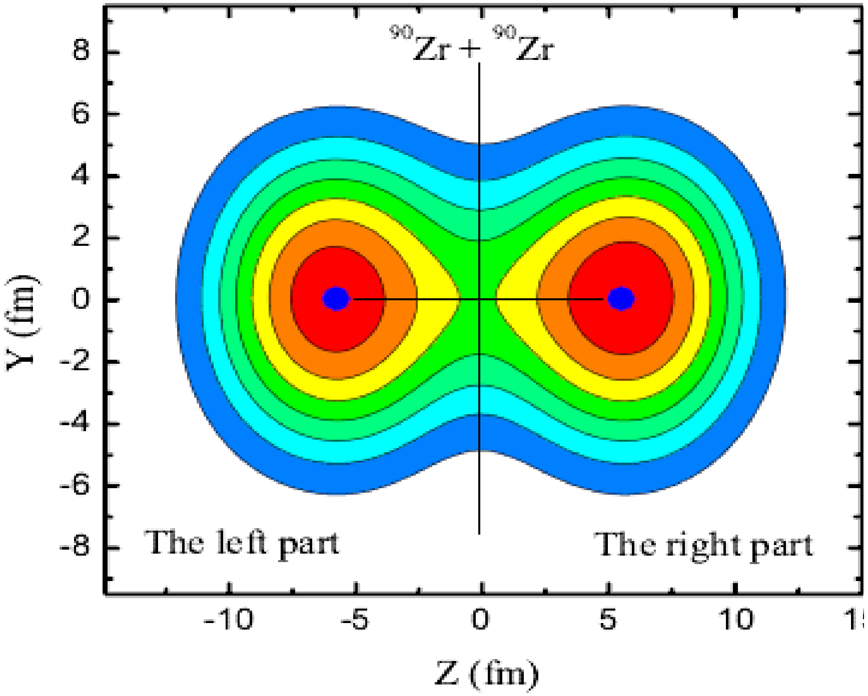
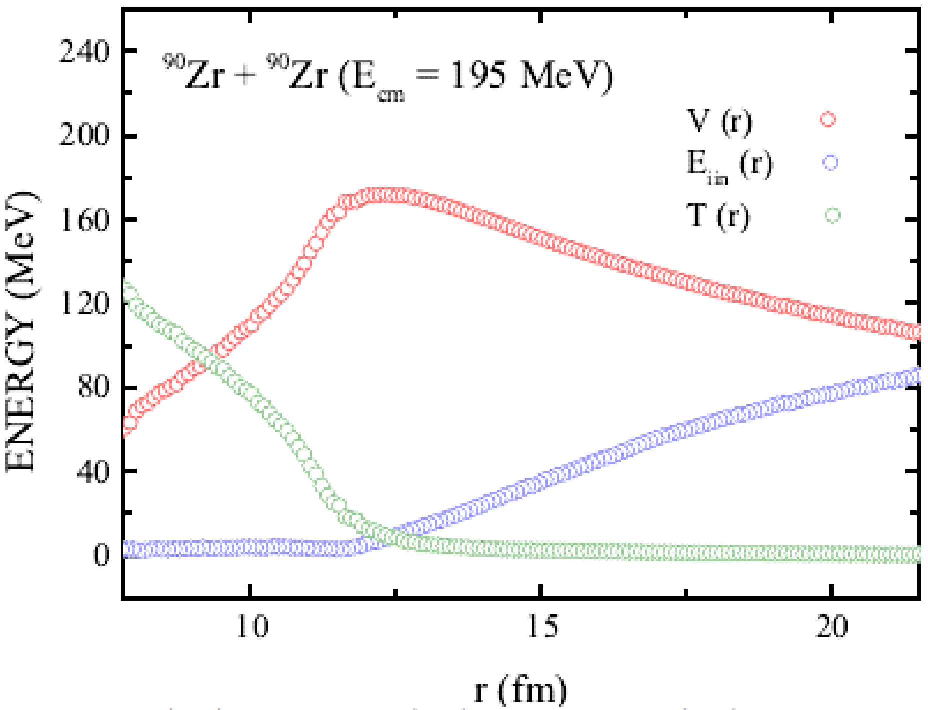




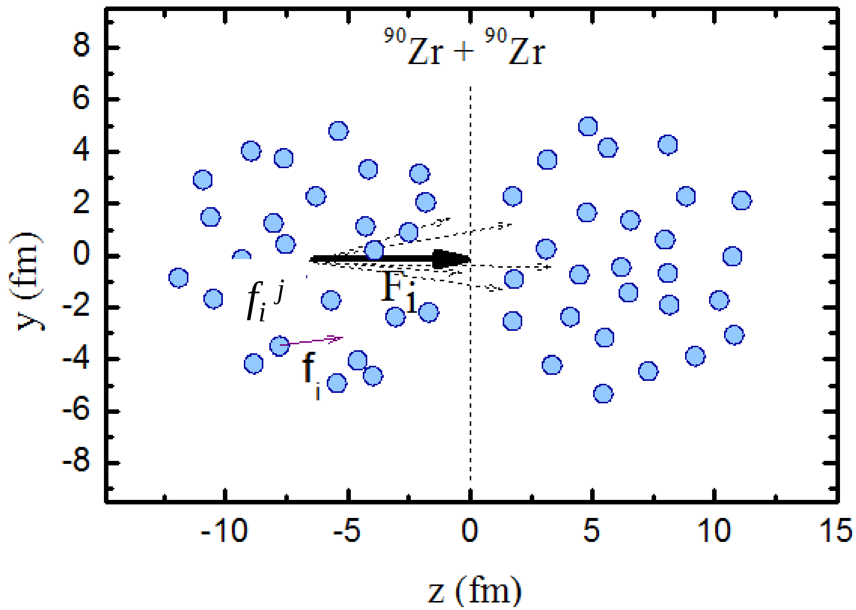
Potential: $$V(R) = E_{\mathrm{tot}}(R) - E_{\mathrm{left}}(R) - E_{\mathrm{right}}(R),$$

Collective Energy: $$E_{\mathrm{coll}}(R) = P^2/2\mu + V(R).$$

Intrinsic Energy: $$E_{\mathrm{intr}}(R) \equiv E_{\mathrm{tot}}(R) - E_{\mathrm{coll}}(R)$$

Macroscopic reduction of random force

- Fluctuations from initialization & collisions



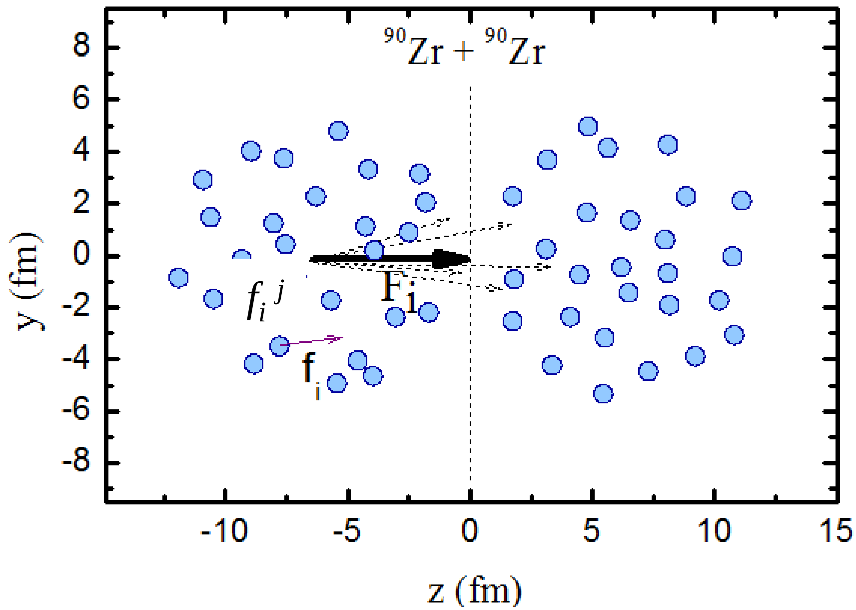
For the *i*-th event: $F_i(x) \equiv \sum_{j=1}^{A} f_i^j(x)$

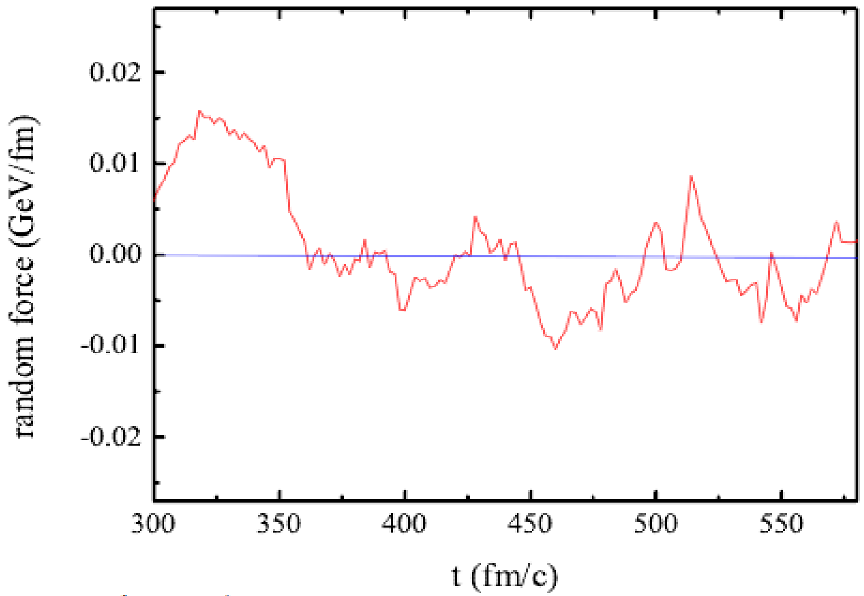
On average: $\langle F(x)\rangle \equiv \frac{1}{n}\sum_{i=1}^{n} F_i(x)$

Random force: $\delta F(x)_i \equiv F_i(x) - \langle F(x)\rangle, \quad x = t \text{ or } R,$

Macroscopic reduction of random force

- Fluctuations from initialization & collisions





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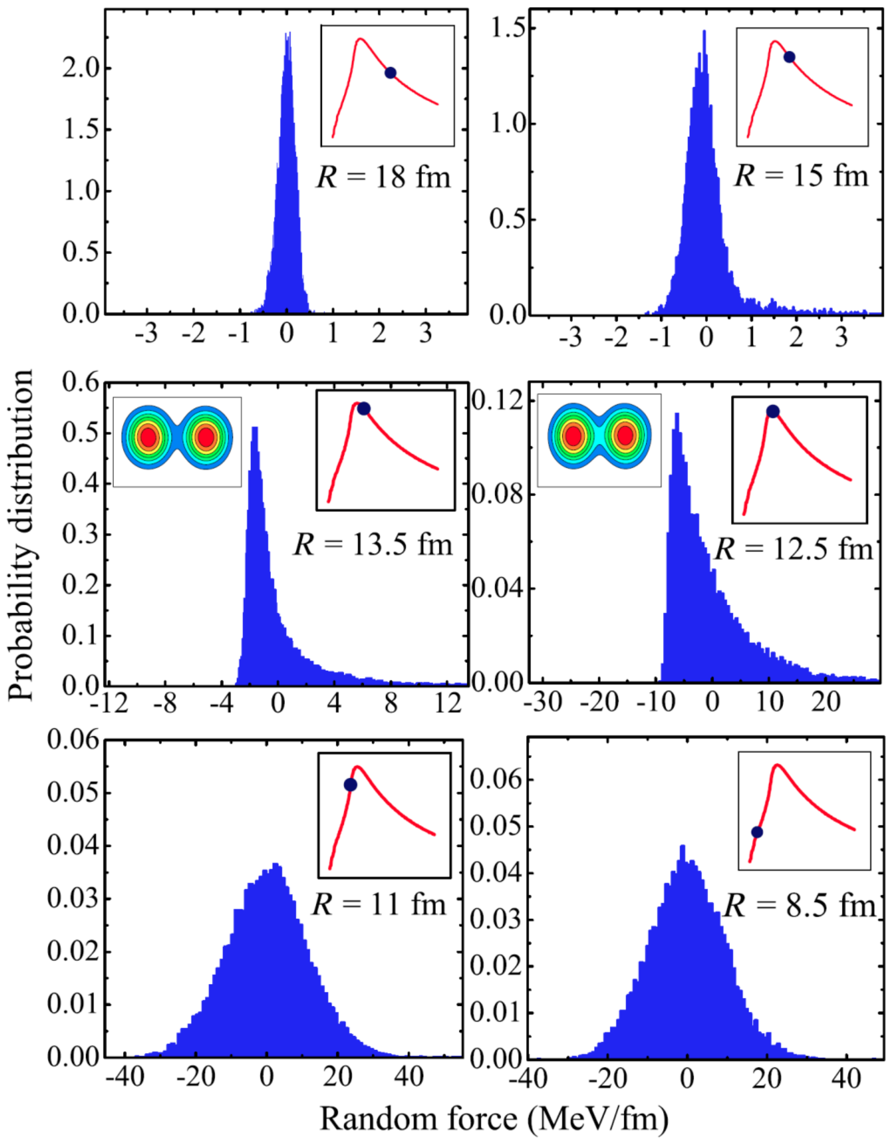
Random force: $\delta F(x)_i \equiv F_i(x) - \langle F(x) \rangle, \quad x = t \text{ or } R,$

Distribution of random force



Approaching stage

Touching & fusion stage

Post-fusion stage

Wen_Sakata_Li_Wu_Zhang_SGZ 2013
Phys. Rev. Lett. 111, 012501

Fusion: Bridging microscopic & macroscopic description

- Macroscopic parameters, including the random force and the fricition coefficient, characterizing the Langevin type description of the nuclear fusion are extracted from the microscopic QMD dynamics around the Coulomb barrier

- The dissipation dynamics of the relative motion between two fusing nuclei is associated with non-Gaussian distributions of the random force

- A proper treatment of the non-Markovian (memory) effects in the Langevin dynamics is crutial for the dynamics of emergence in the nuclear dissipative fusion motion

Wen_Sakata_Li_Wu_Zhang_SGZ 2013 Phys. Rev. Lett. 111, 012501

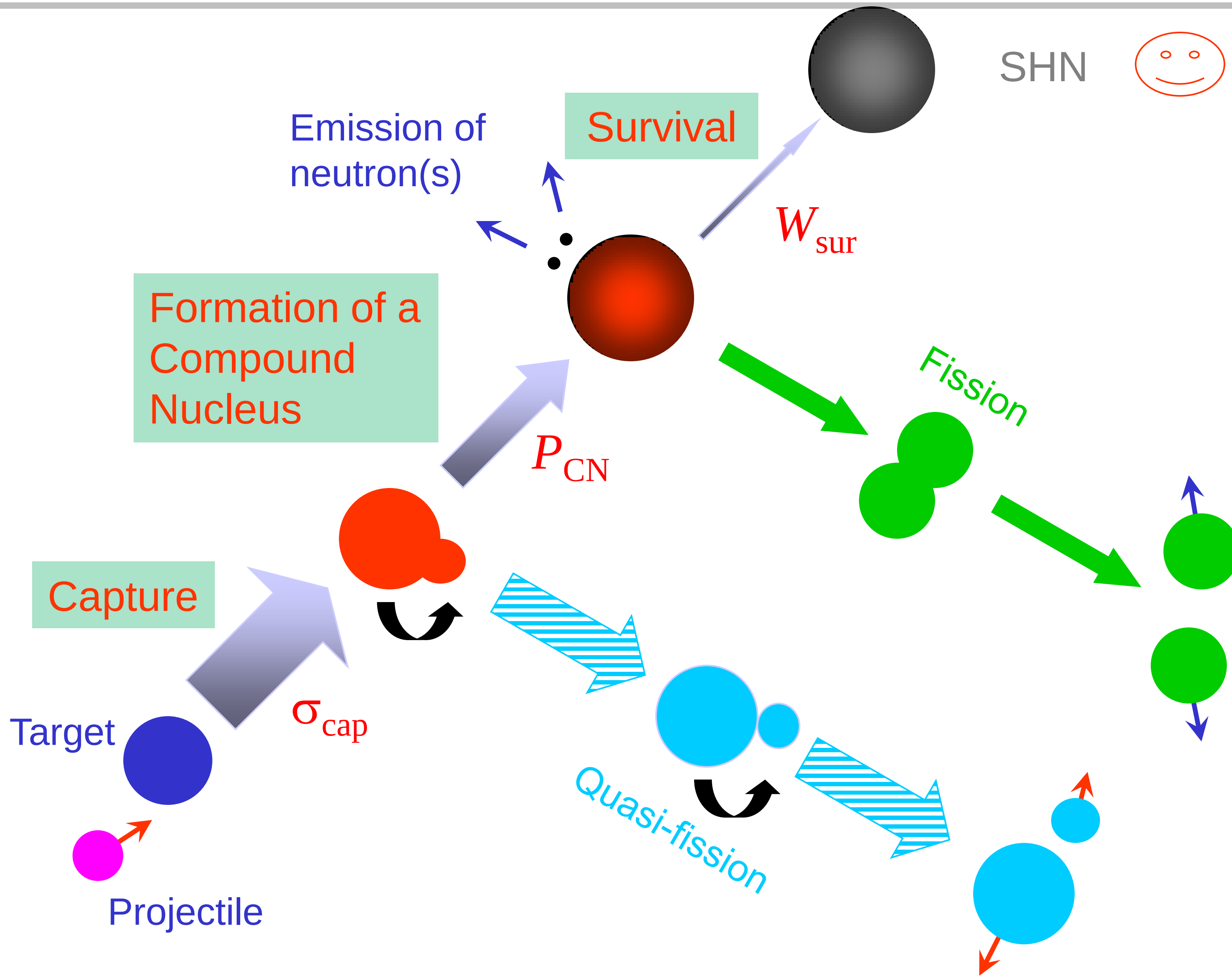
Wen_Sakata_Li_Wu_Zhang_SGZ 2014 Phys. Rev. C90, 054613

Lectures 3 & 4

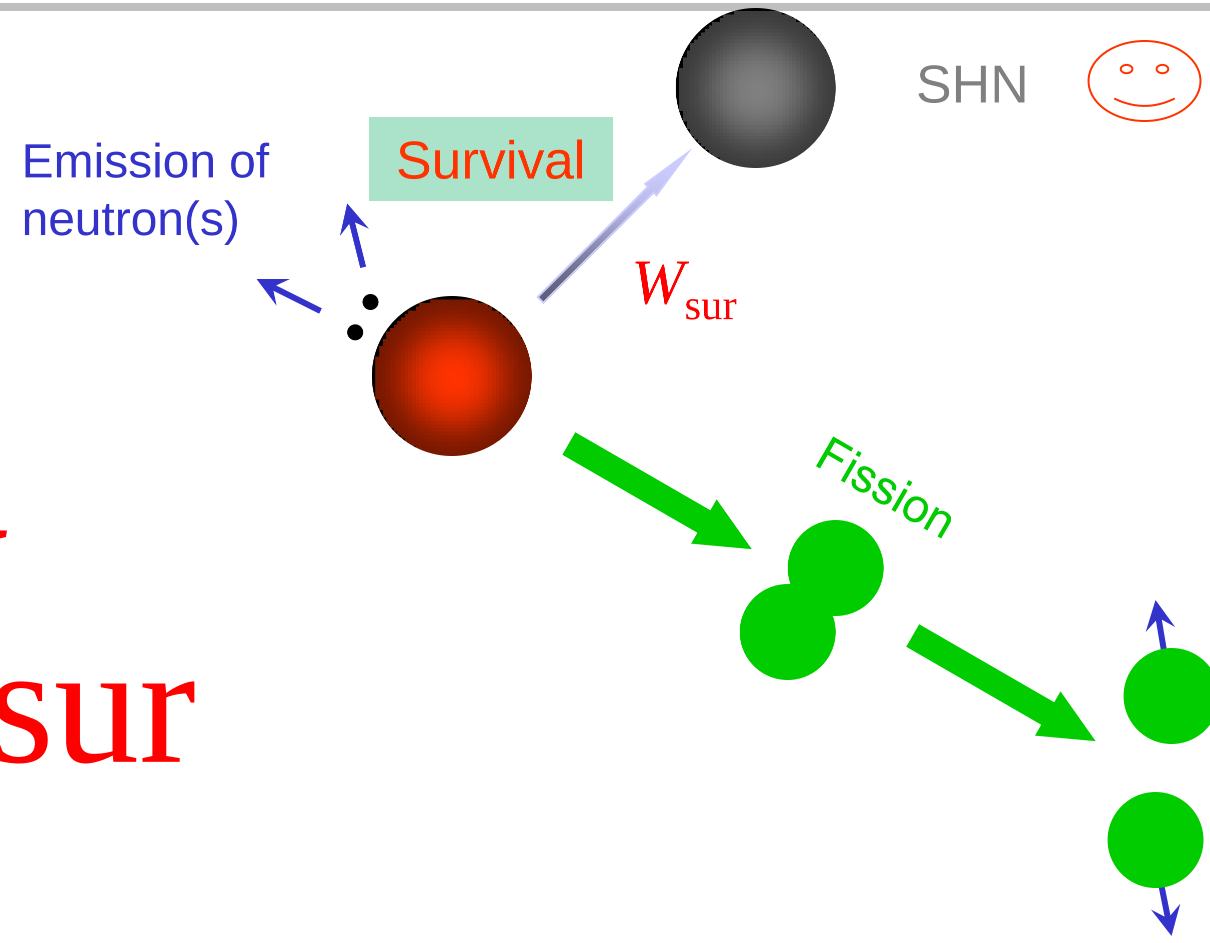
- Challenges in synthesizing SHN

- Synthesis mechanism of SHN
  - Large uncertainties in predicted Xsections
  - Heavy ion fusion reactions
    - Capture
    - Fusion
    - Survival against fission
  - Multi-nucleon transfer reactions
  - Reactions w/ radioactive ion beams

Three steps to a SHN via heavy-ion EvR reaction



Three steps to a SHN via heavy-ion EvR reaction



W_{sur}

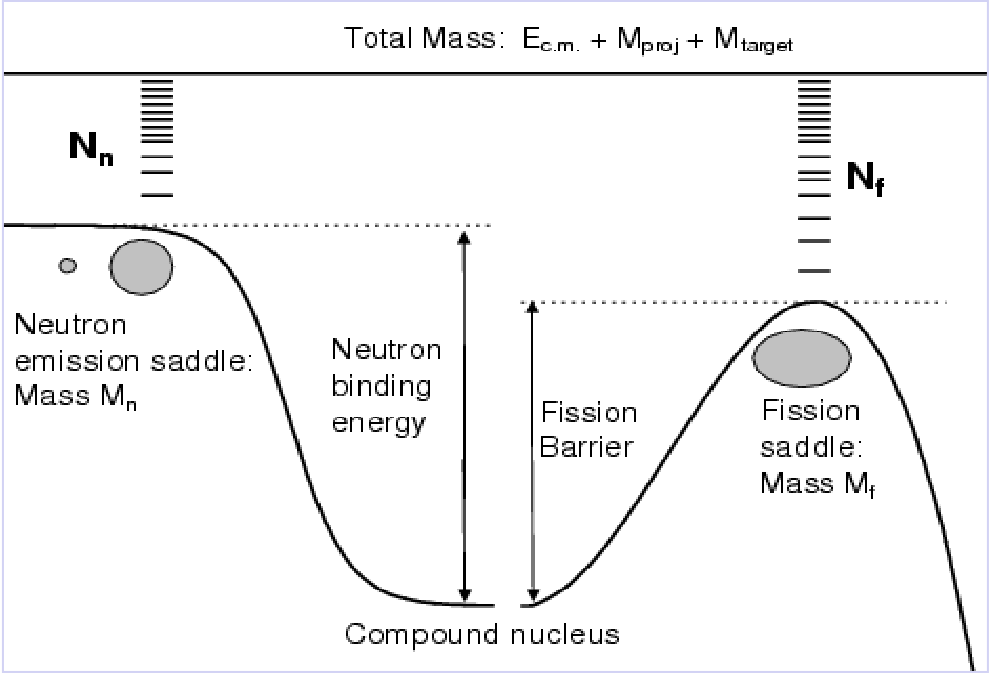
Fission of heavy & superheavy nuclei

De-excitation of excited CN

- Fission
- Neutron emission
- ...

Parameters needed

- Fission barrier
- Neutron separation energy
- ...



Swiatecki_Siwek-Wilczynska_Wilczynski2005_PRC71-014602

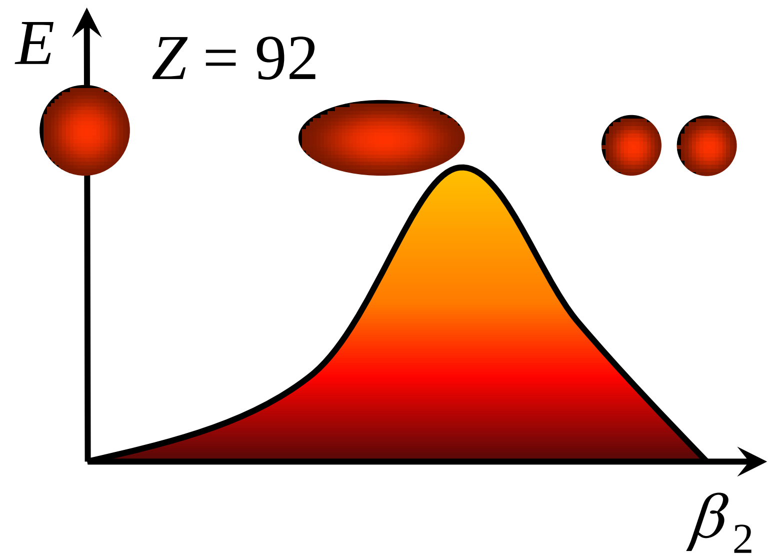
Theoretical approaches for calculating fission barriers:

- Macroscopic-microscopic approaches
- Self-consistent approaches

Multi-dim. constrained relativistic mean field models
(β_{20}, β_{22}, β_{30}, ...)

Nuclear fission

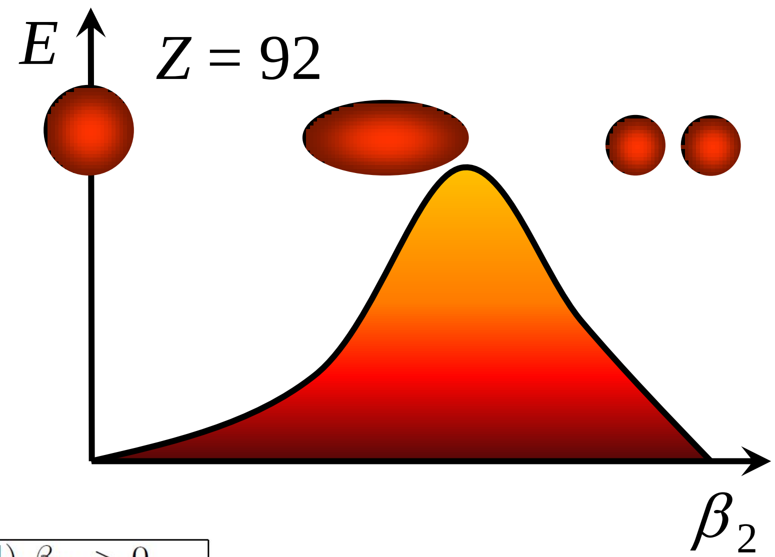
- Fission barrier is crucial for the description of fission



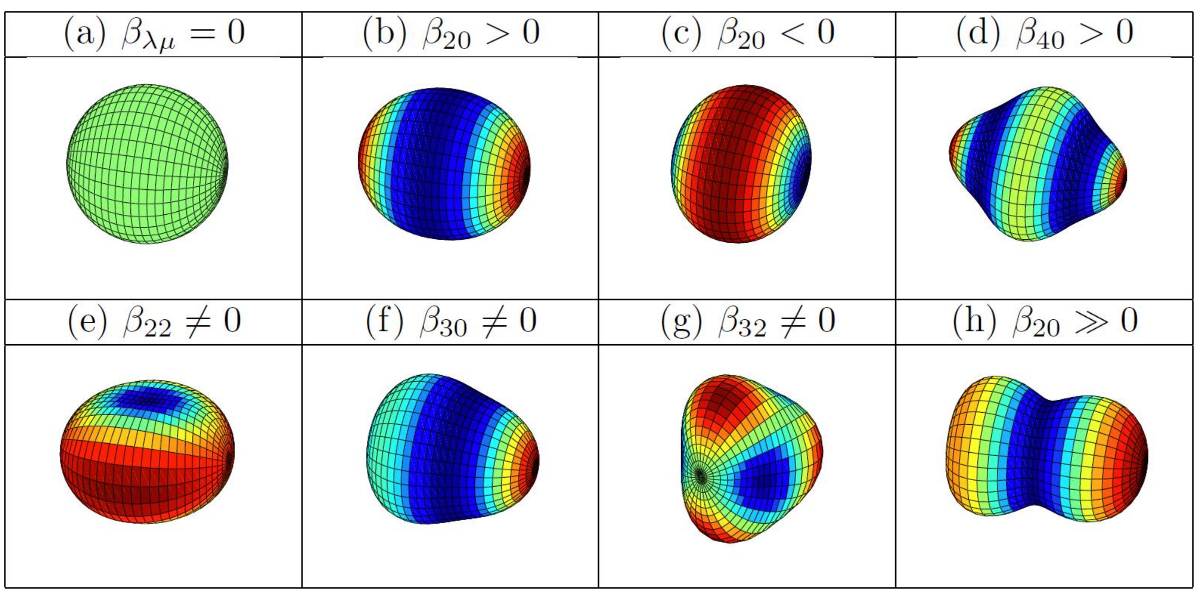
Courtesy of Bing-Nan Lu (吕炳楠)

Nuclear fission

- Fission barrier is crucial for the description of fission
- Various shapes may appear during fission



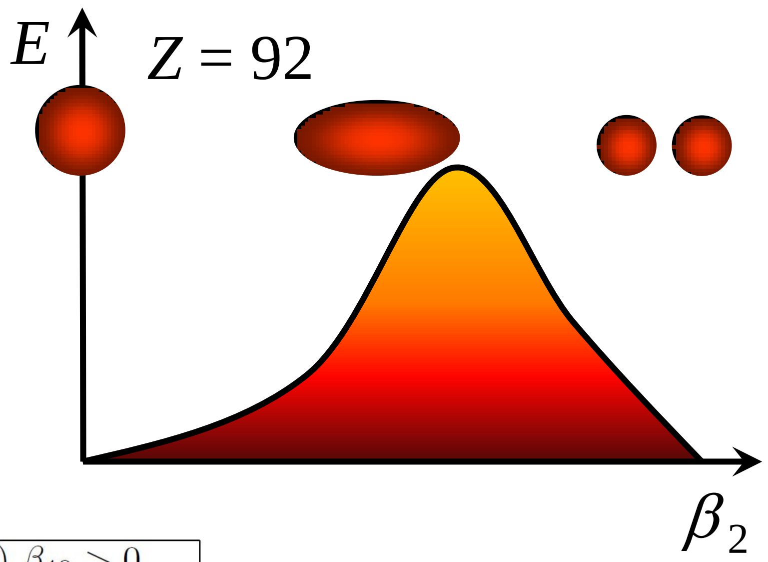
$$R(\theta,\varphi) = R_0\left[1 + \beta_{00} + \sum_{\lambda=1}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\beta^*_{\lambda\mu}Y_{\lambda\mu}(\theta,\varphi)\right]$$



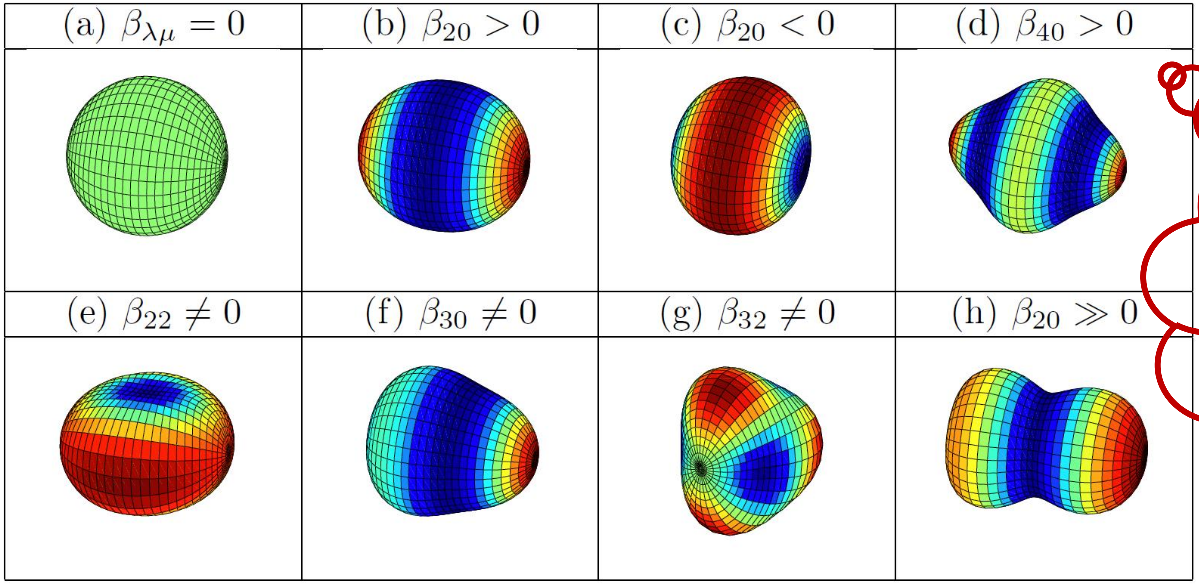
Courtesy of Bing-Nan Lu (吕炳楠)

Nuclear fission

- Fission barrier is crucial for the description of fission
- Various shapes may appear during fission



$$R(\theta,\varphi) = R_0\left[1 + \beta_{00} + \sum_{\lambda=1}^{\infty}\sum_{\mu=-\lambda}^{\lambda}\beta^*_{\lambda\mu}Y_{\lambda\mu}(\theta,\varphi)\right]$$



To include as many shape degrees of freedom as possible

Courtesy of Bing-Nan Lu (吕炳楠)

Covariant Density Functional Theory (CDFT)

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

Serot_Walecka1986_ANP16-1

Reinhard1989 RPP52-439

Ring1996_PPNP37-193

Vretenar_Afanasjev_Lalazissis_Ring2005_PR409-101

Meng_Toki_SGZ_Zhang_Long_Geng2006_PPNP57-470

$$(\boldsymbol{\alpha}\cdot\mathbf{p} + \beta(M + S(\mathbf{r})) + V(\mathbf{r}))\psi_i = \epsilon_i\psi_i$$

Liang_Meng_SGZ2015_PR570-1

Meng_SGZ2015_JPG42-093101

$$\left(-\nabla^2 + m_\sigma^2\right)\sigma = -g_\sigma\rho_S - g_2\sigma^2 - g_3\sigma^3$$

$$\left(-\nabla^2 + m_\omega^2\right)\omega = g_\omega\rho_V - c_3\omega^3$$

$$\left(-\nabla^2 + m_\rho^2\right)\rho = g_\rho\rho_3$$

$$-\nabla^2 A = e\rho_C$$

MDC-CDFT (β_{20}, β_{22}, β_{30}, β_{32}, β_{40}, …)

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

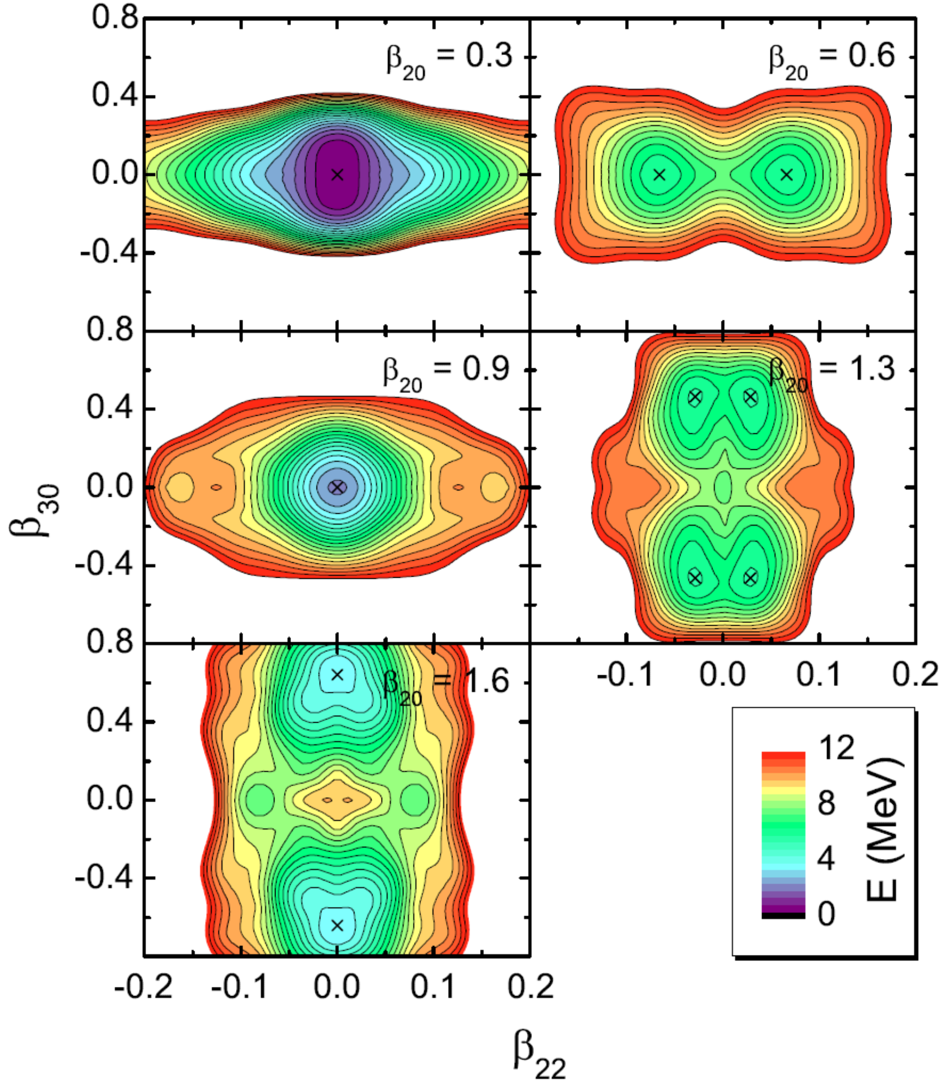
MDC-RMF   MDC-RHB

pp channel	BCS	Bogoliubov
Constant gap	√	
Constant strength	√	
Delta force	√	√
Separable force	√	√

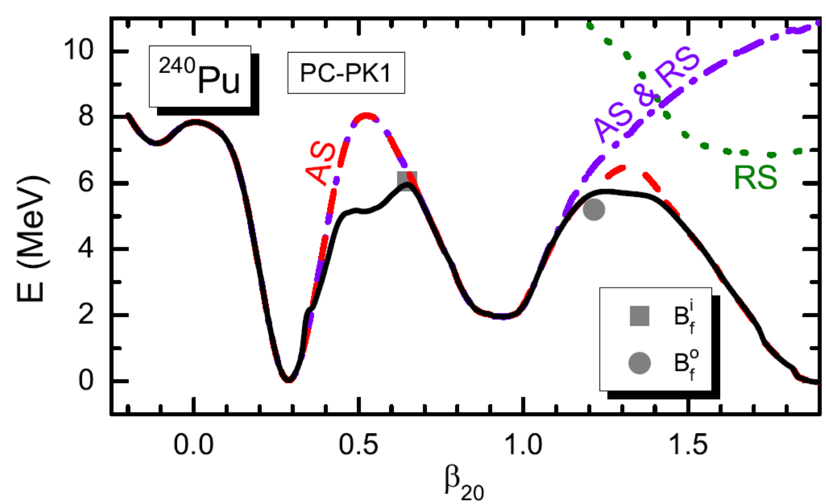
Lu_Zhao_SGZ 2011_PRC84-014328   Lu_Zhao_SGZ 2012_PRC85-011301R

Zhao_Lu_Zhao_SGZ 2012_PRC86-057304   Lu_Zhao_Zhao_SGZ 2014_PRC89-014323

^{240}Pu: 3-dim. PES (β_{20}, β_{22}, β_{30})

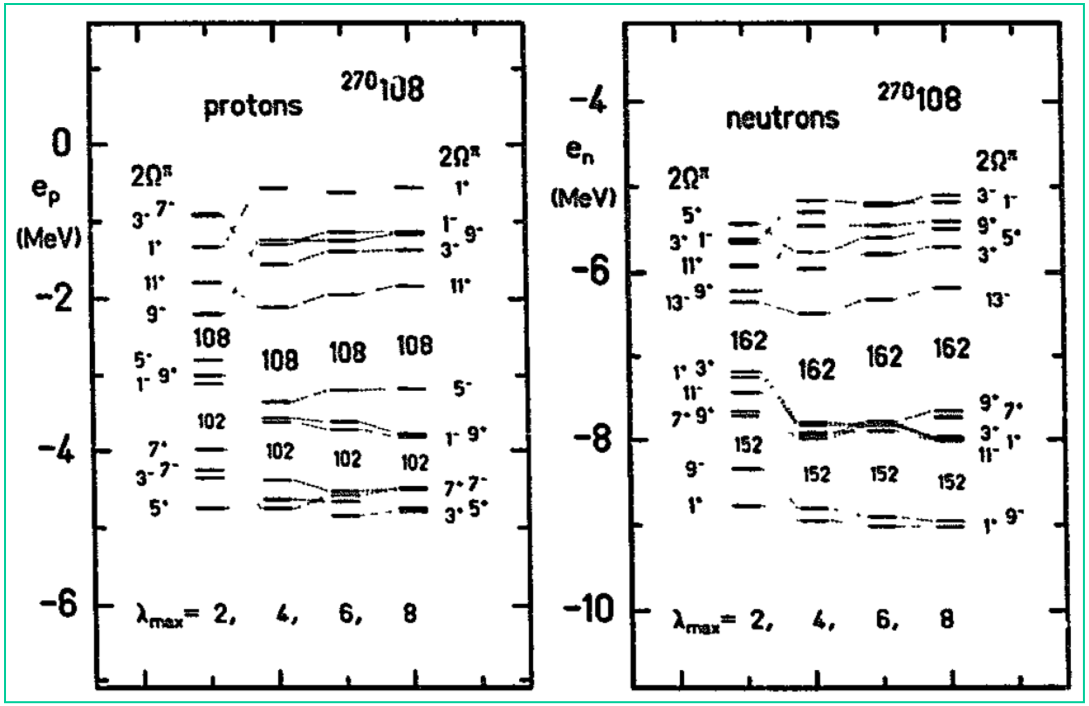


- AS & RS for g.s. & isomer, the latter is stiffer
- Triaxial & octupole shape around the outer barrier
- Triaxial deformation crucial around barriers



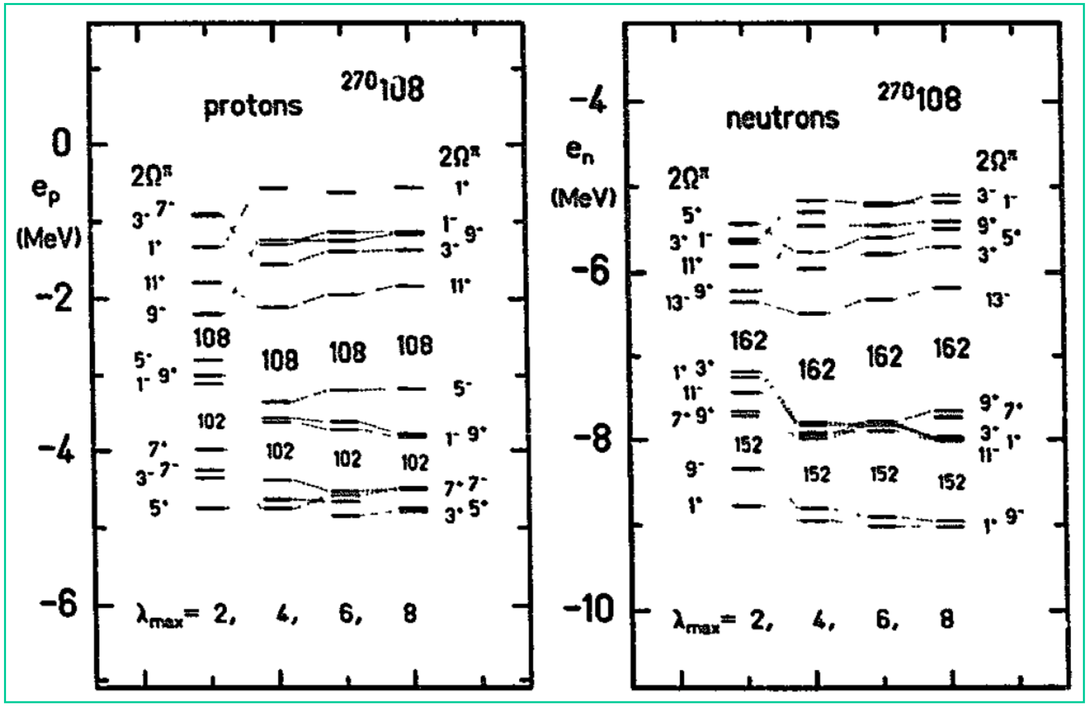
Lu_Zhao_SGZ 2012_PRC85-011301R

^{270}Hs: A doubly magic deformed SHN

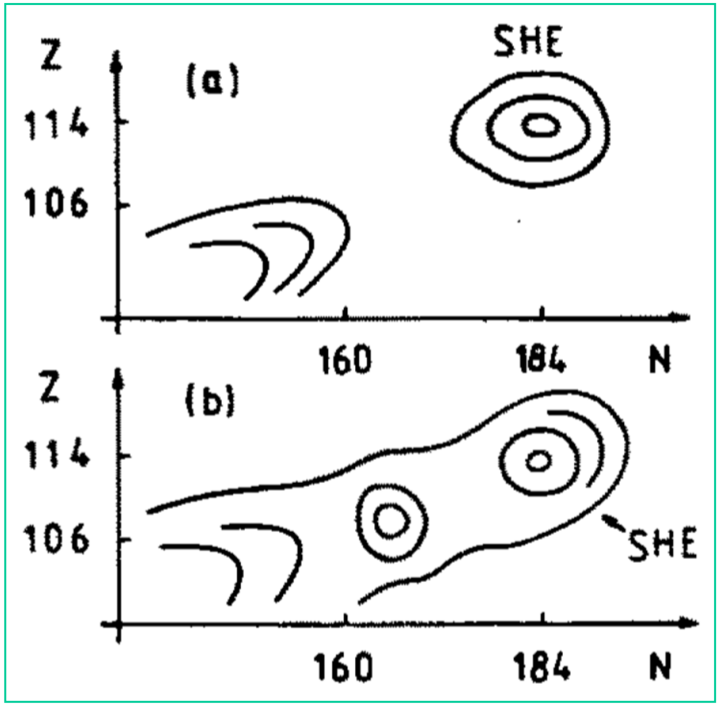


Patyk_Sobiczewski1991_NPA533-132

^{270}Hs: A doubly magic deformed SHN

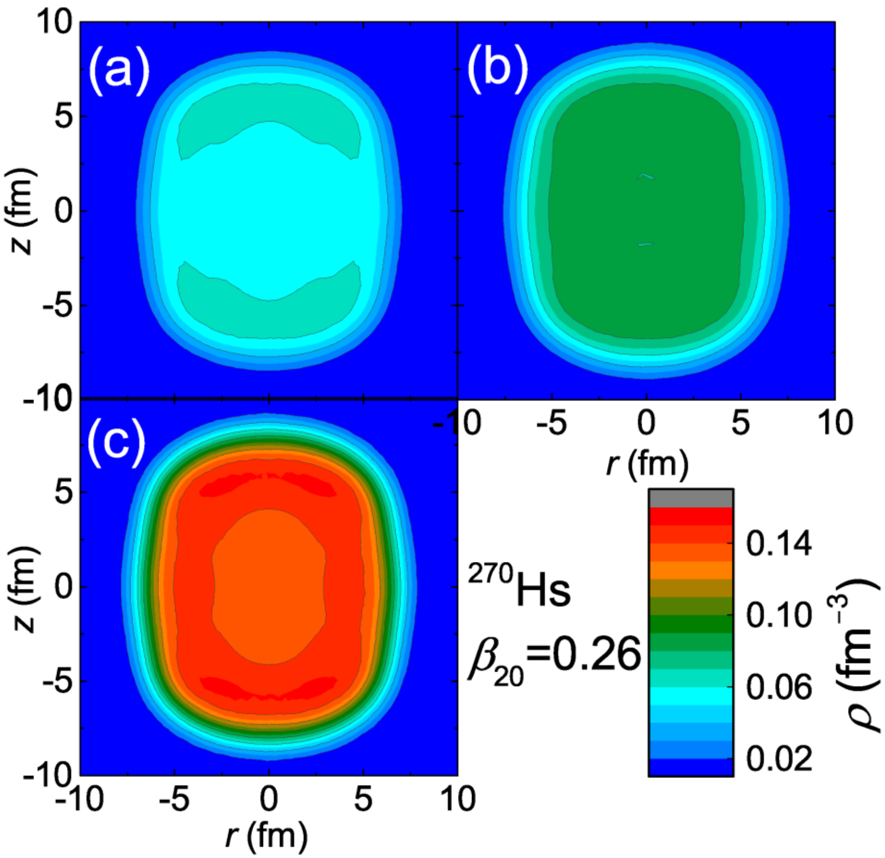


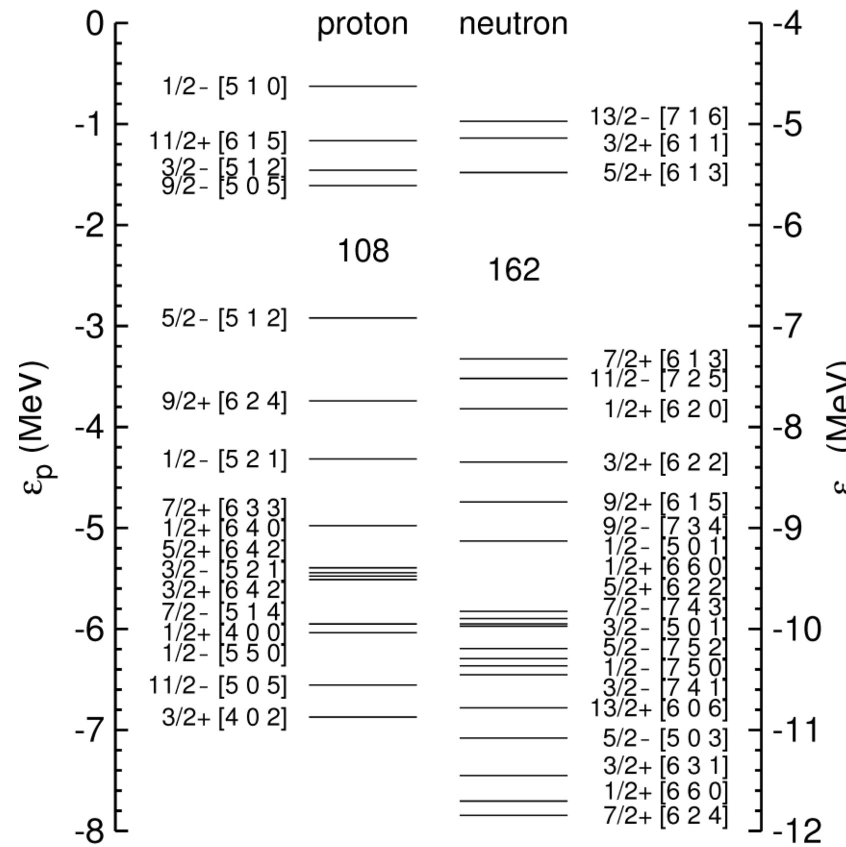
Patyk_Sobiczewski1991_NPA533-132



Patyk_Skalski_Sobiczewski_Cwiok 1989_NPA502-591c

^{270}Hs: ground state from MDC-RMF calc.

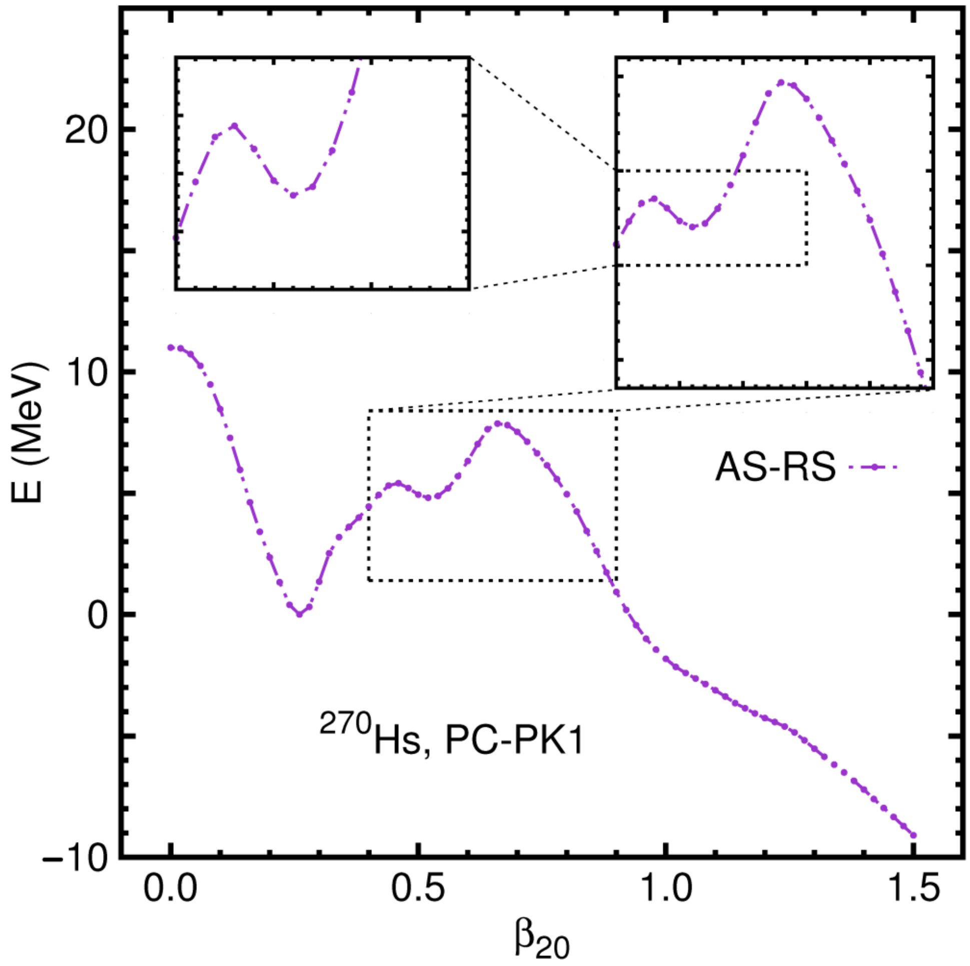




Xu Meng (孟旭), PhD thesis

Meng_Lu_Zhou2020
Sci. China-Phys. Mech. Astron. 63, 212011

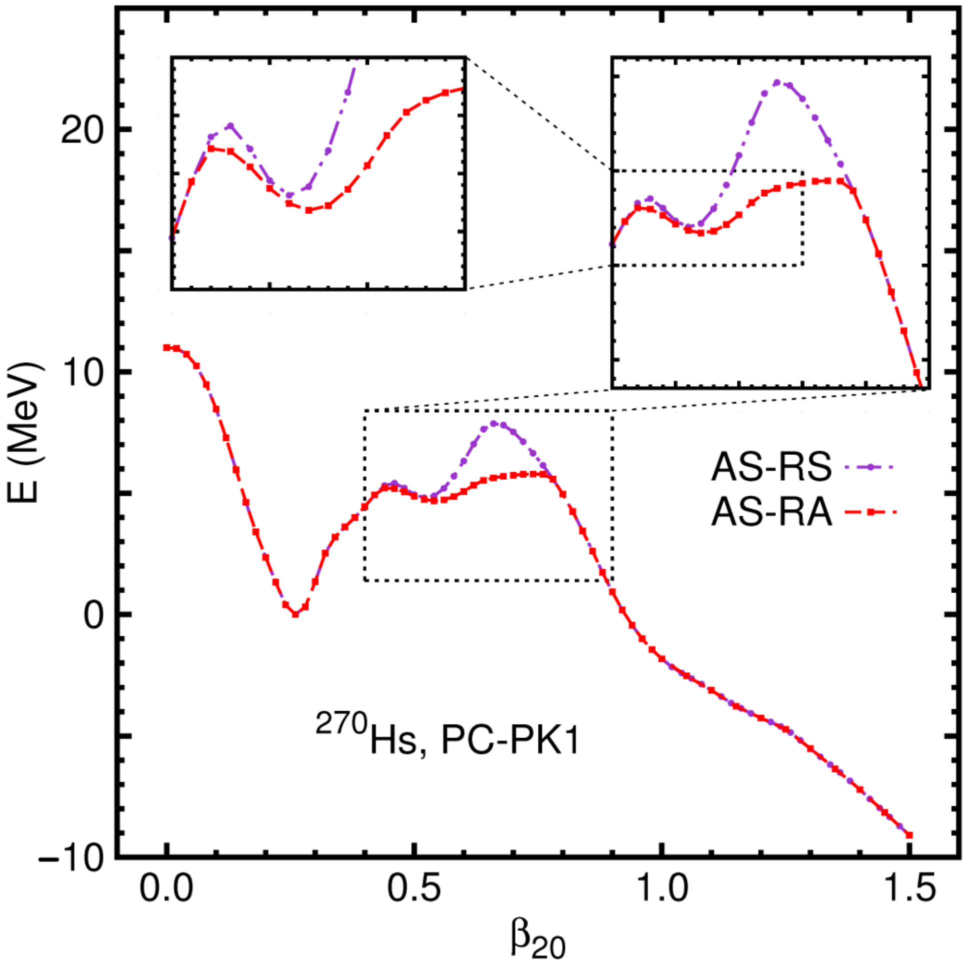
^{270}Hs: 1D PEC from MDC-RMF calc.



AS-RS: Axially-Symmetric & Reflection Symmetric

Courtesy of Xu Meng (孟旭)

^{270}Hs: 1D PEC from MDC-RMF calc.

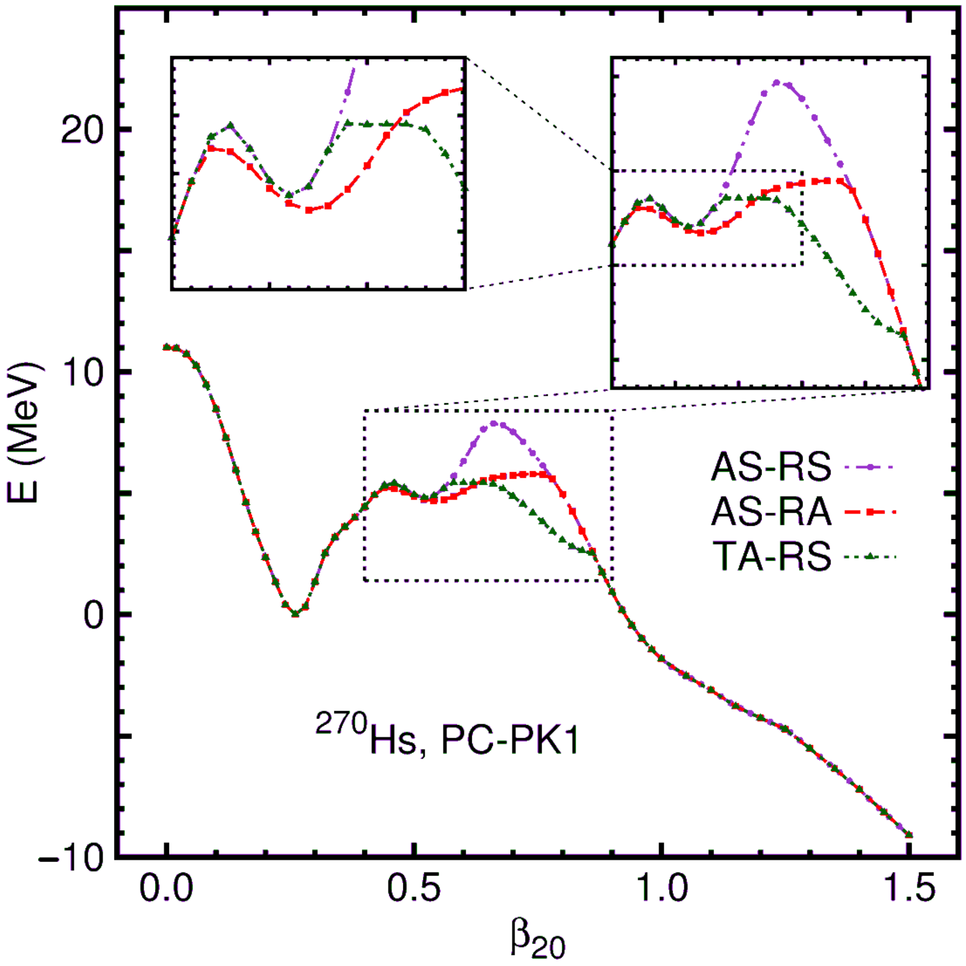


AS-RS: Axially-Symmetric & Reflection Symmetric

AS-RA: Axially-Symmetric & Reflection Asymmetric

Courtesy of Xu Meng (孟旭)

^{270}Hs: 1D PEC from MDC-RMF calc.



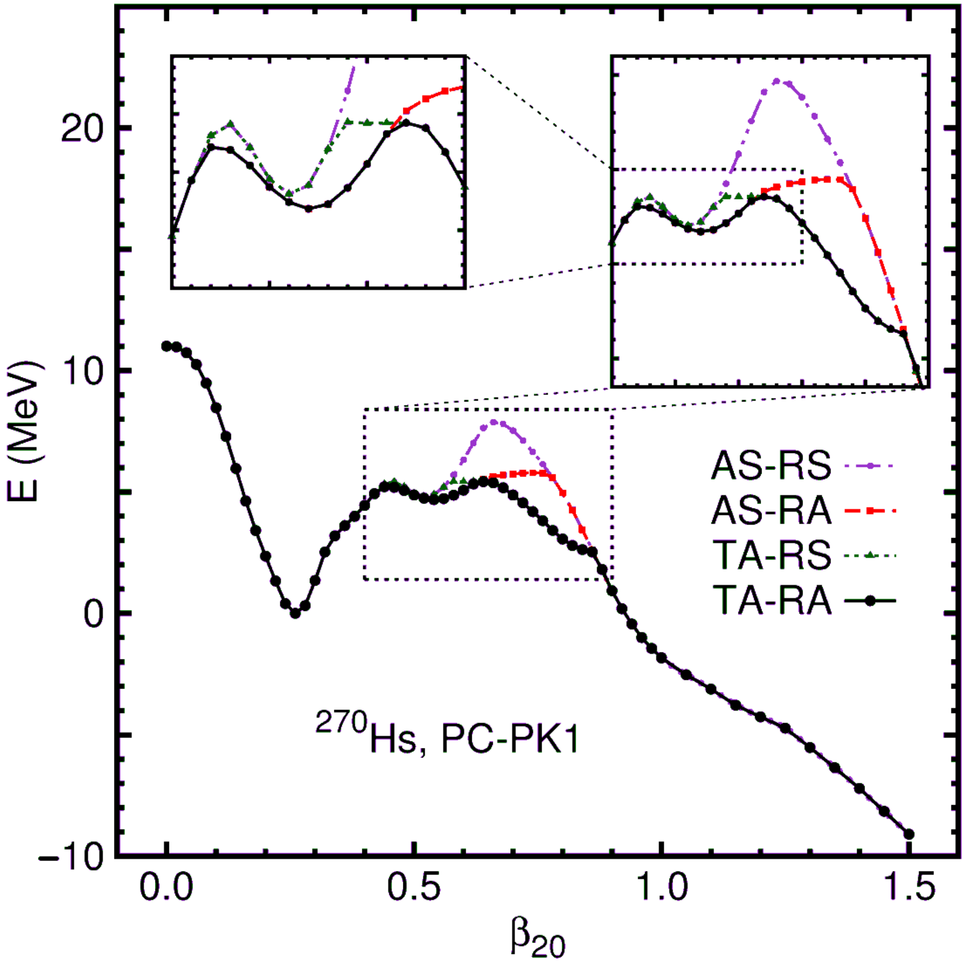
AS-RS: Axially-Symmetric & Reflection Symmetric

AS-RA: Axially-Symmetric & Reflection Asymmetric

TA-RS: TriAxial & Reflection Symmetric

Courtesy of Xu Meng (孟旭)

^{270}Hs: 1D PEC from MDC-RMF calc.



AS-RS: Axially-Symmetric & Reflection Symmetric

AS-RA: Axially-Symmetric & Reflection Asymmetric

TA-RS: TriAxial & Reflection Symmetric

TA-RA: TriAxial & Reflection Asymmetric

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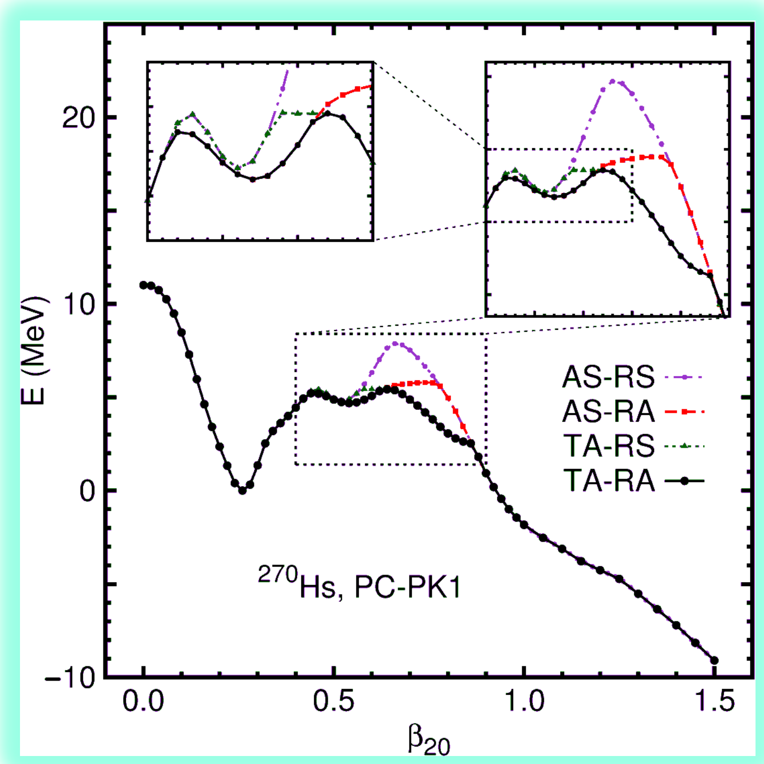
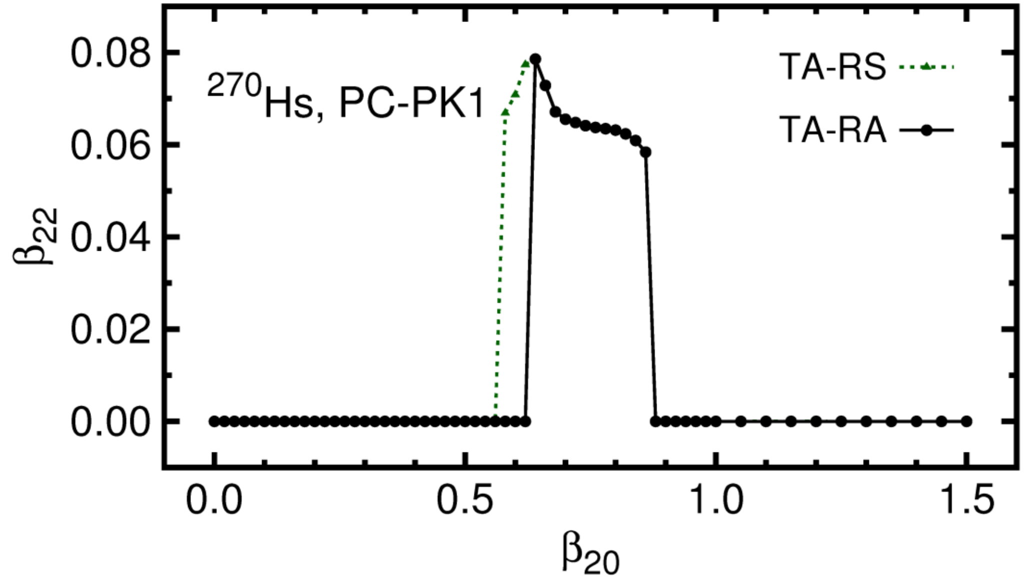
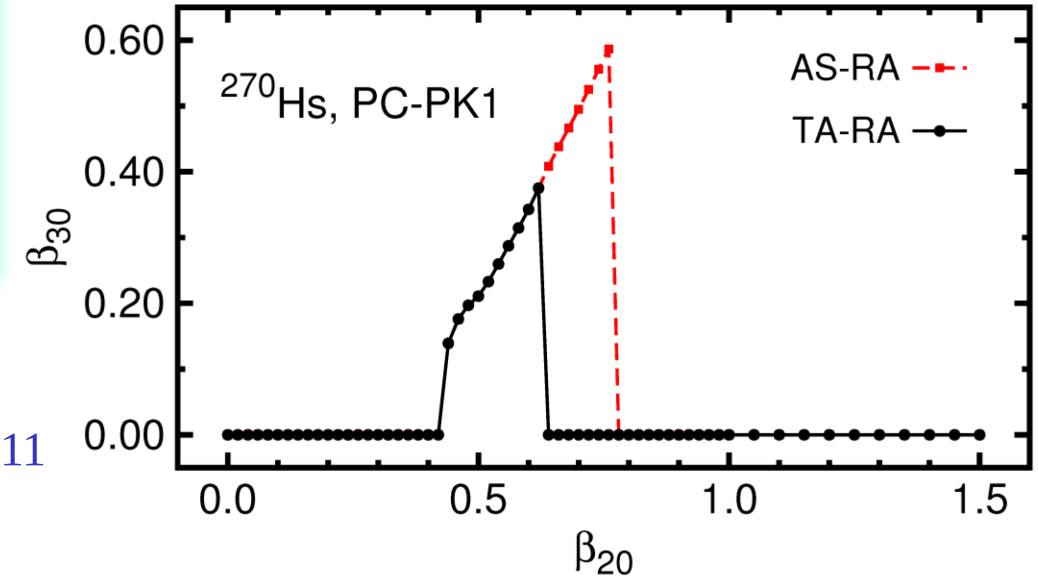
Discontinuities in 1D PECs







Meng_Lu_Zhou2020
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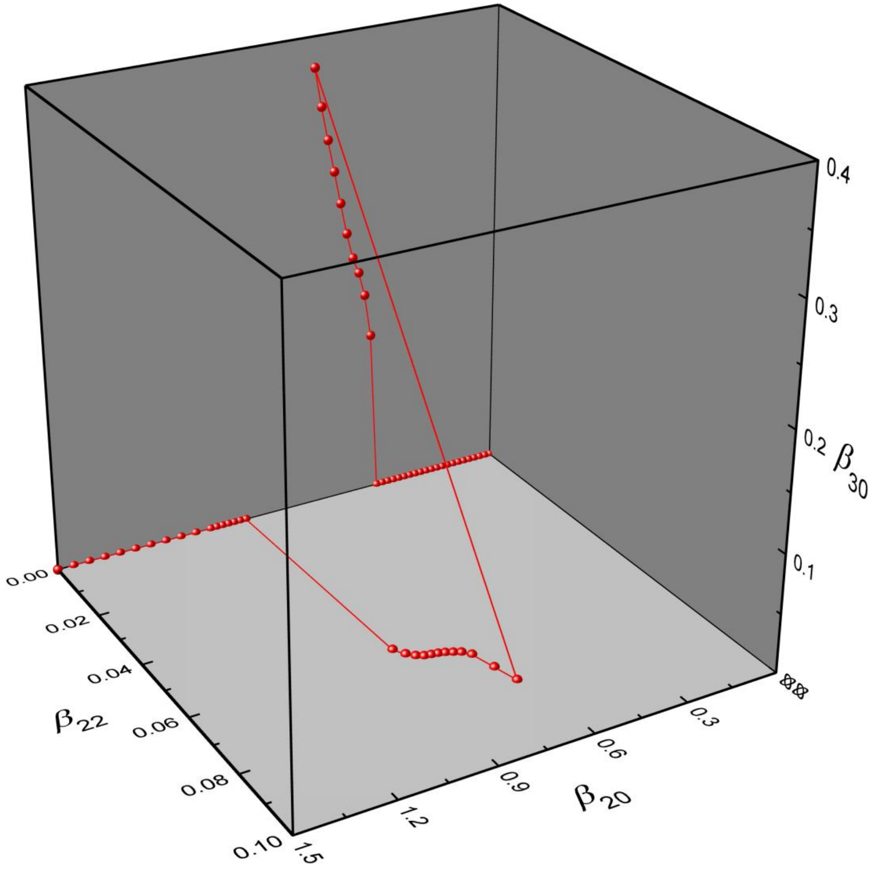
^{270}Hs: 1D TA-RA "PEC" viewed in 3D def. space

(β_{20}, β_{22}, β_{30}) deformation space



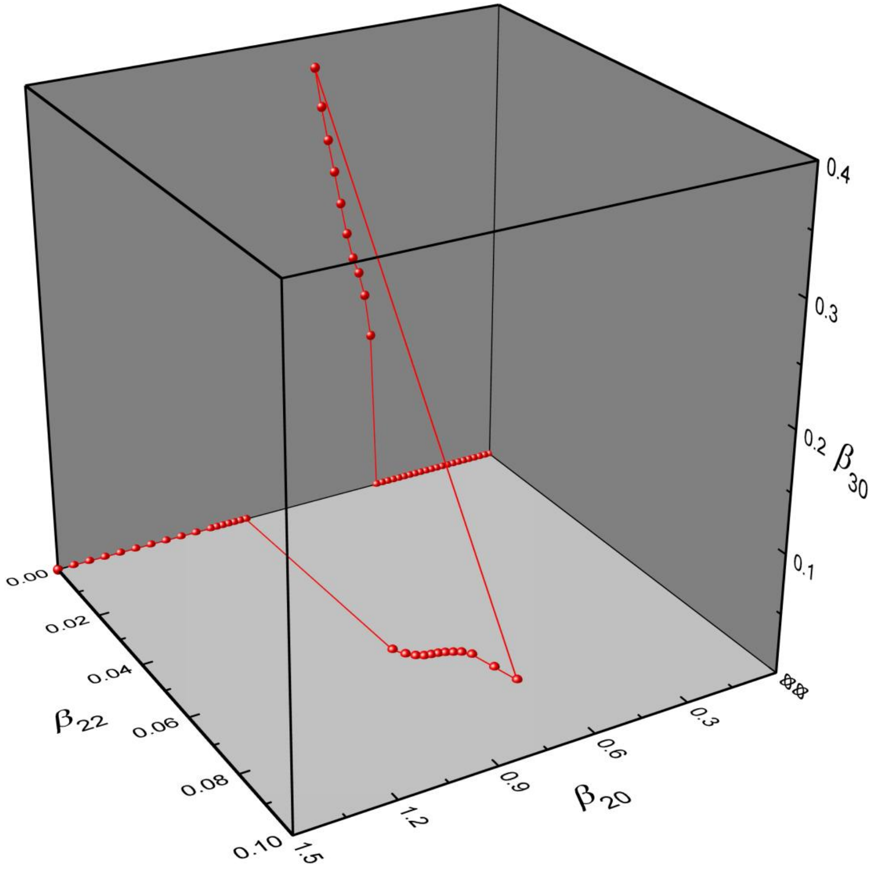
Courtesy of Xu Meng (孟旭)

TA-RA "PEC" consists of 4 segments:

- $\beta_{20} = (0\quad, 0.42)$, $\beta_{22} = 0$, $\beta_{30} = 0$
- $\beta_{20} = (0.44, 0.62)$, $\beta_{22} = 0$, $\beta_{30} \neq 0$
- $\beta_{20} = (0.64, 0.86)$, $\beta_{22} \neq 0$, $\beta_{30} = 0$
- $\beta_{20} = (0.88, 1.50)$, $\beta_{22} = 0$, $\beta_{30} = 0$

^{270}Hs: 1D TA-RA "PEC" viewed in 3D def. space

(β_{20}, β_{22}, β_{30}) deformation space



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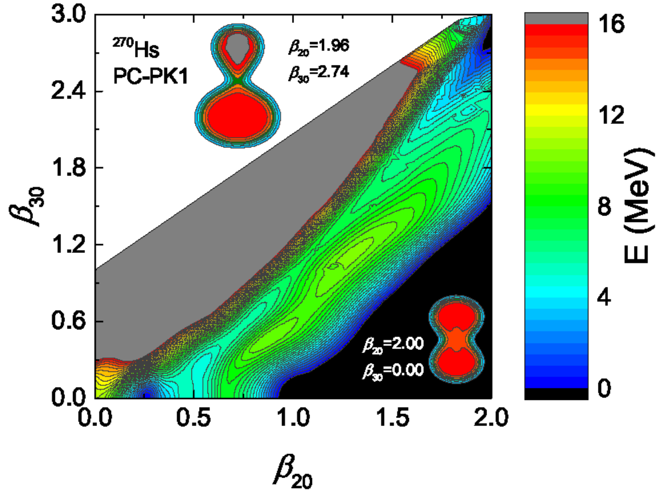
How can a nucleus change its shape so suddenly ?

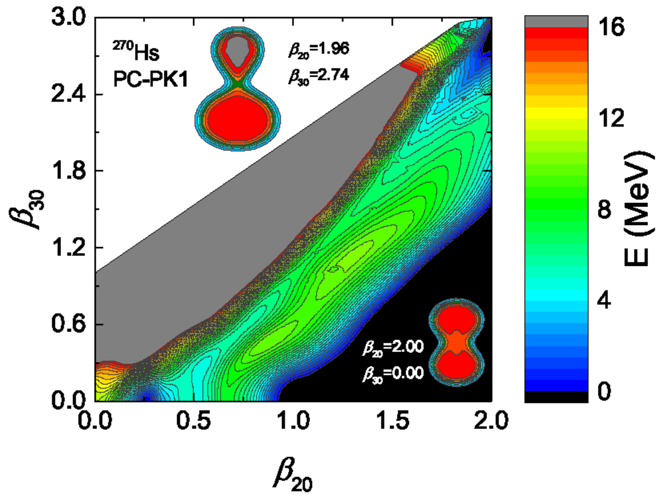
Courtesy of Xu Meng (孟旭)

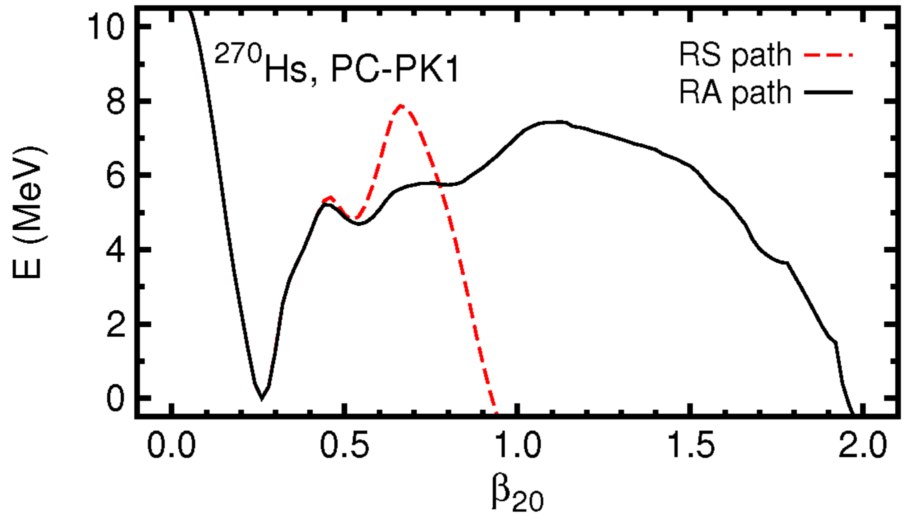
^{270}Hs: 2D PES & optimal static fission path



Meng_Lu_Zhou2020 Sci. China-Phys. Mech. Astron. 63, 212011

^{270}Hs: 2D PES & optimal static fission path





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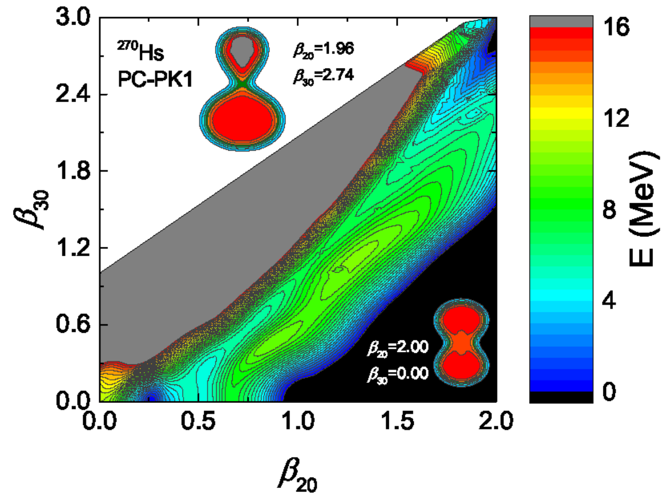
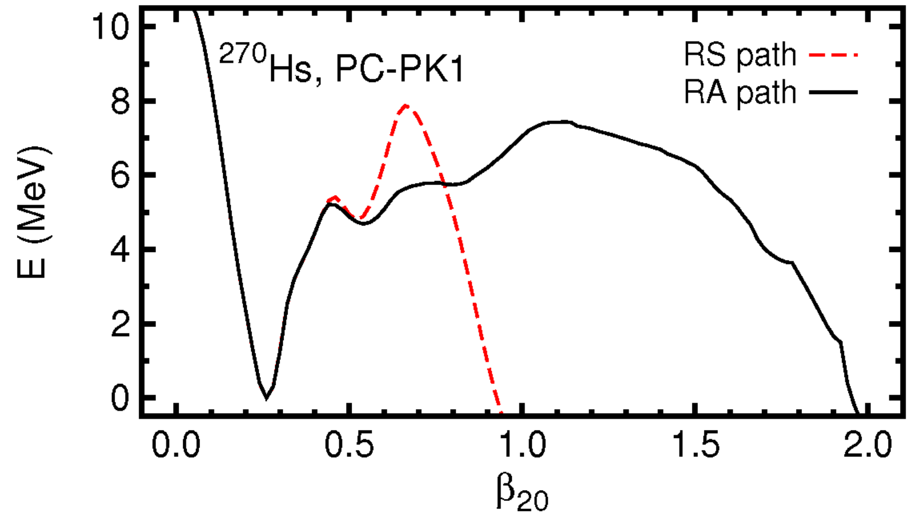
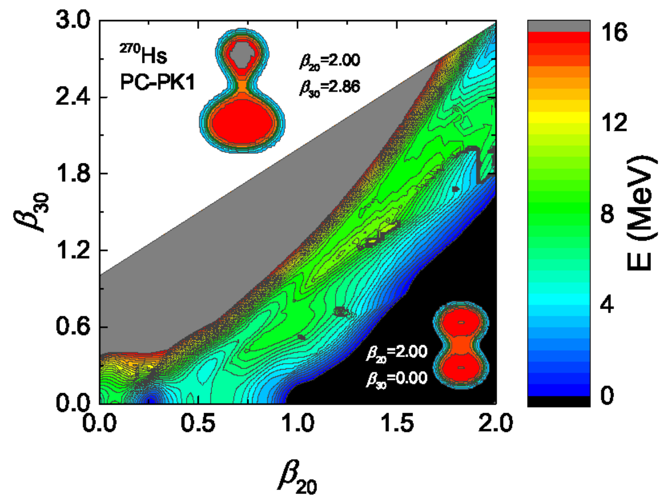
^{270}Hs: 2D PES & optimal static fission path







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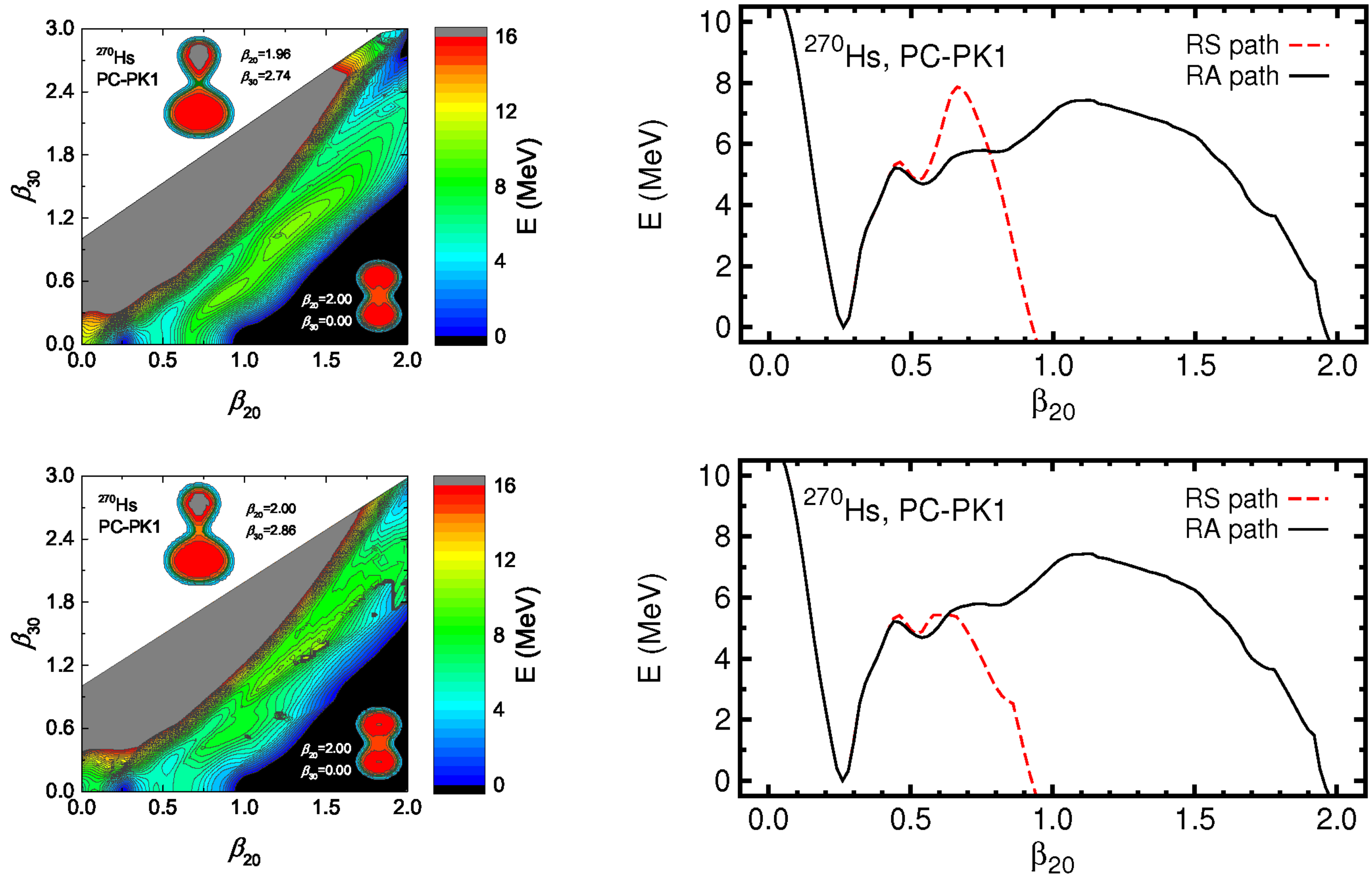
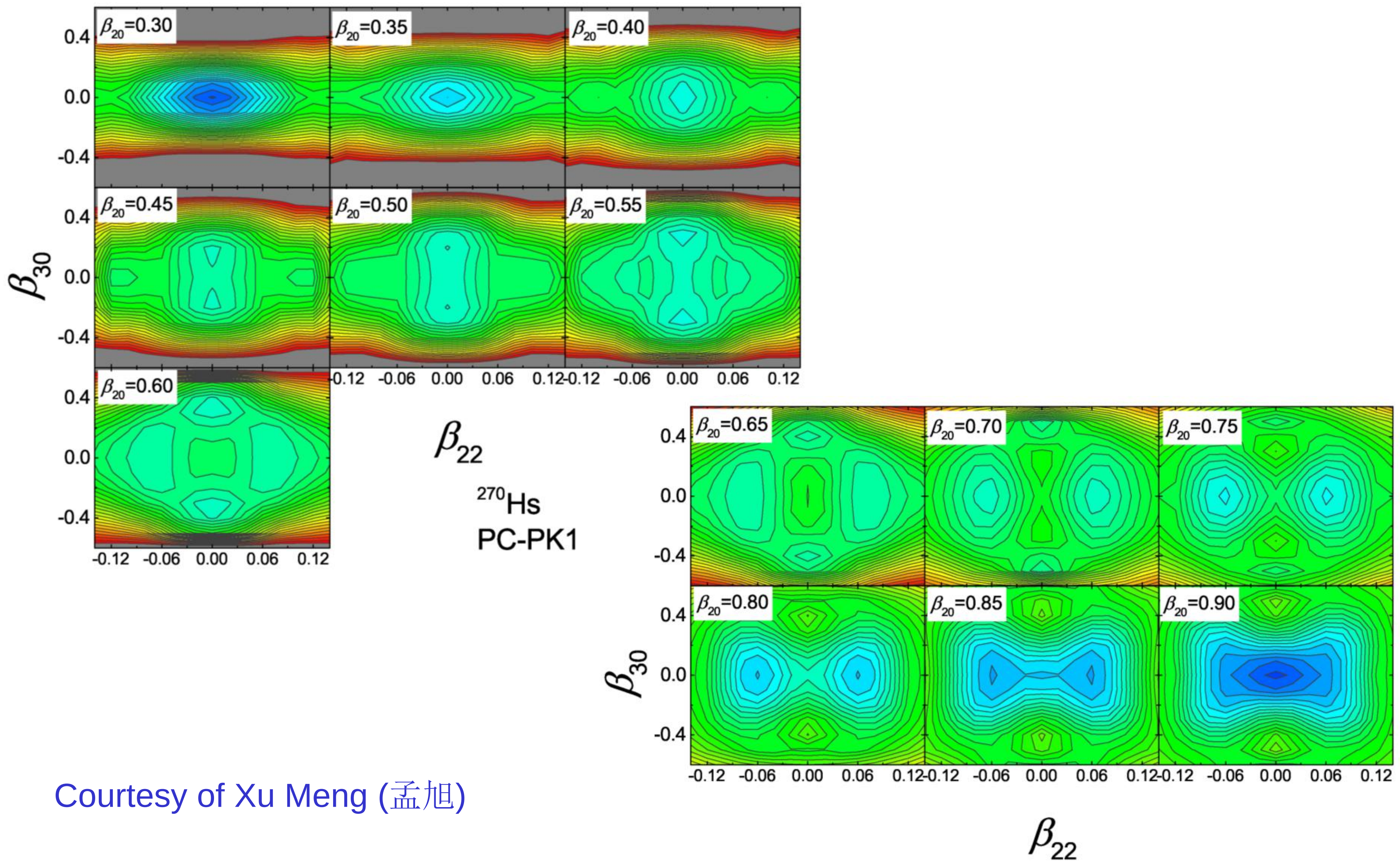
^{270}Hs: 2D PES & optimal static fission path



Meng_Lu_Zhou2020 Sci. China-Phys. Mech. Astron. 63, 212011

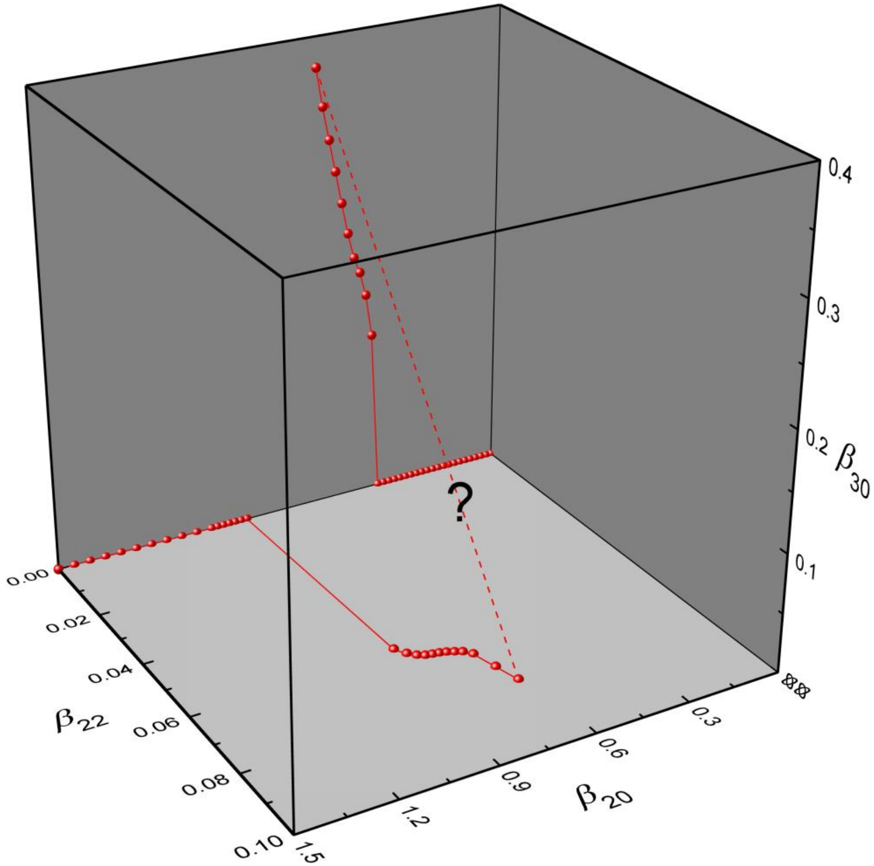
^{270}Hs: 3D PES



Courtesy of Xu Meng (孟旭)

^{270}Hs: 1D TA-RA "PEC" viewed in 3D def. space

(β_{20}, β_{22}, β_{30}) deformation space



Courtesy of Xu Meng (孟旭)

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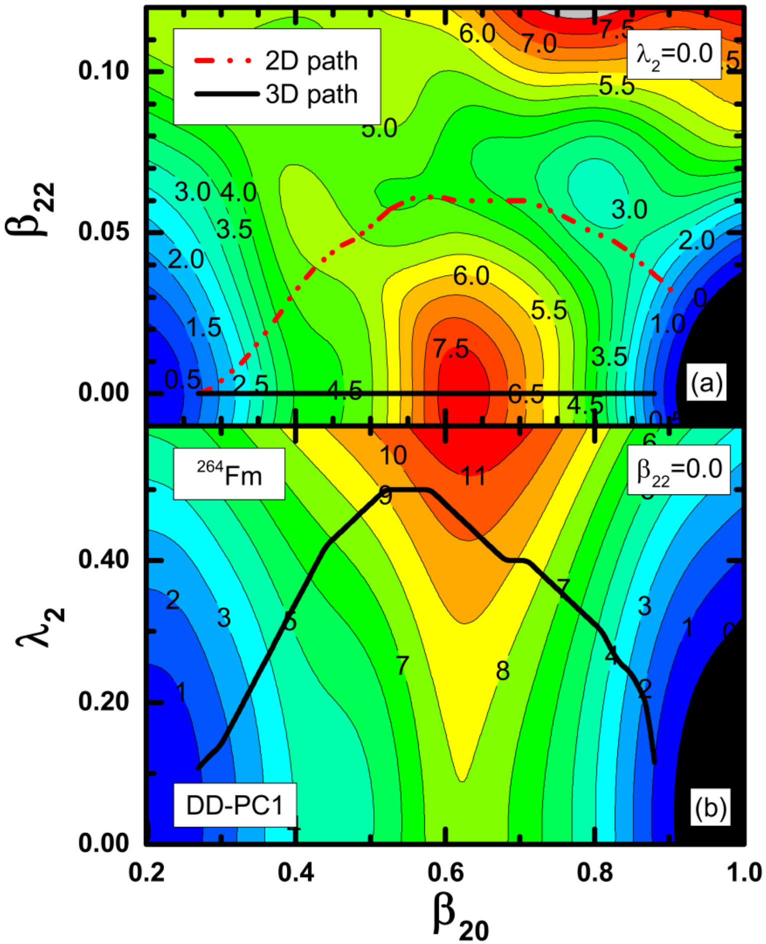
- $\beta_{20} = (0.88, 1.50)$, $\beta_{22} = 0$, $\beta_{30} = 0$

How can a nucleus change its shape so suddenly ?

It may do it through when shape DoFs are considered explicitly !

MDC-RMF study of spontaneous fission: Coupling between shape and pairing

WKB w/ action in coll. spaces based on PES from MDC-RMF



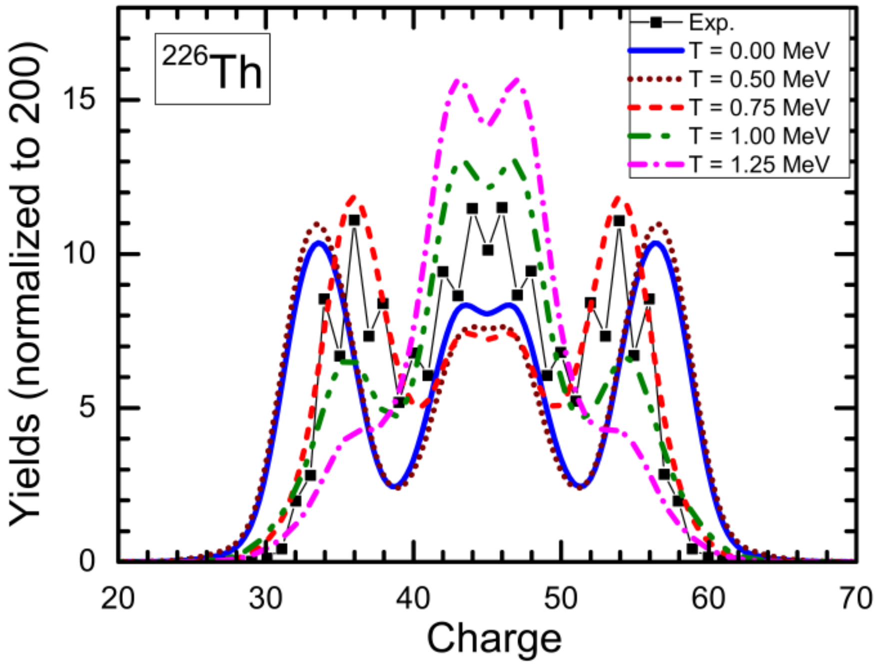
- ☐ Pairing favors axially symmetric shapes along the dynamic path of the fissioning system, amplifies pairing as the path traverses the fission barriers, significantly reduces the action integral, and shortens the corresponding SF half-life.

Zhao_Lu_Niksic_Vretenar_SGZ
2016_PRC93-044315

Micro. self-consistent description of induced fission dyn.: finite temperature (FT) effects

TDGCM + GOA based on PES from FT MDC-RMF

- The model can qualitatively reproduce the empirical triple-humped structure of the fission charge and mass distributions at T = 0
- But the precise expt. position of the asymmetric peaks & the symmetric-fission yield can only be accurately reproduced when FT effects included



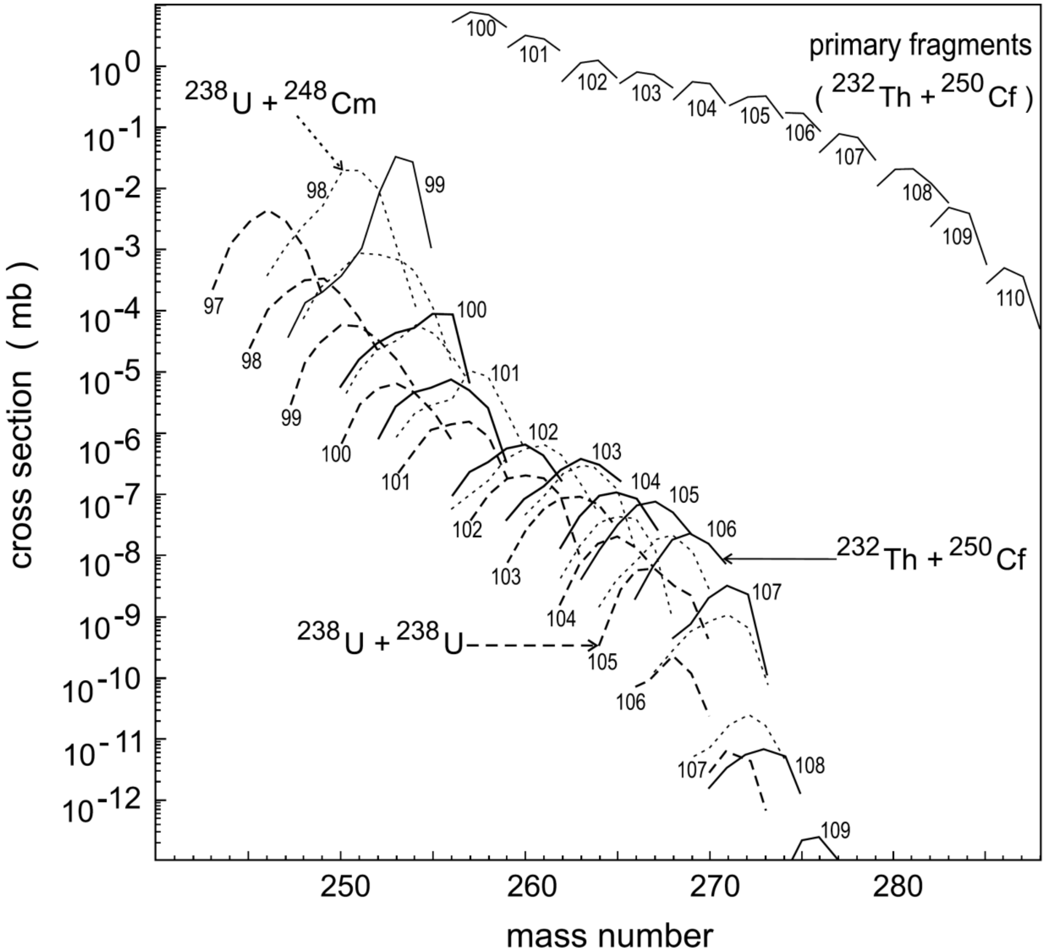
Zhao_Niksic_Vretenar_SGZ
2018_arXiv1809.06114

Lectures 3 & 4

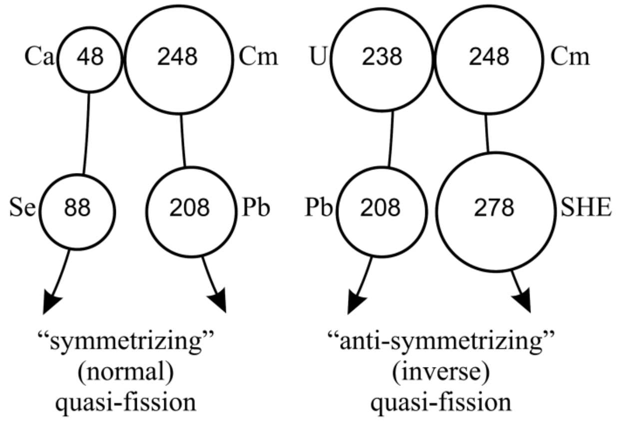
- Challenges in synthesizing SHN

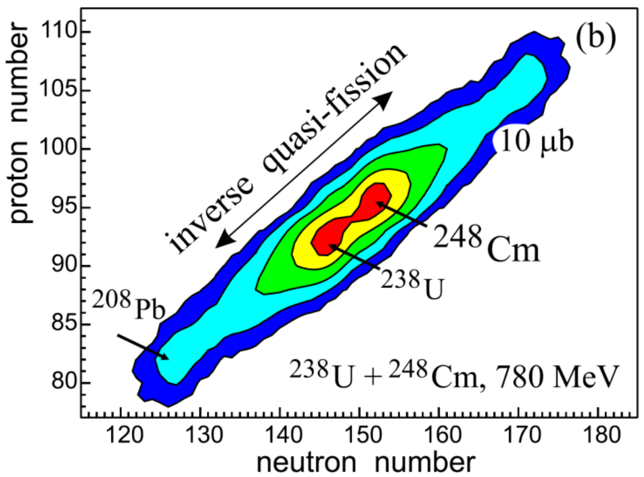
- Synthesis mechanism of SHN
  - Large uncertainties in predicted Xsections
  - Heavy ion fusion reactions
    - Capture
    - Fusion
    - Survival against fission
  - Multi-nucleon transfer reactions
  - Reactions w/ radioactive ion beams

Multi-nucleon transfer reactions: Langevin dynamics



Inverse quasi-fission

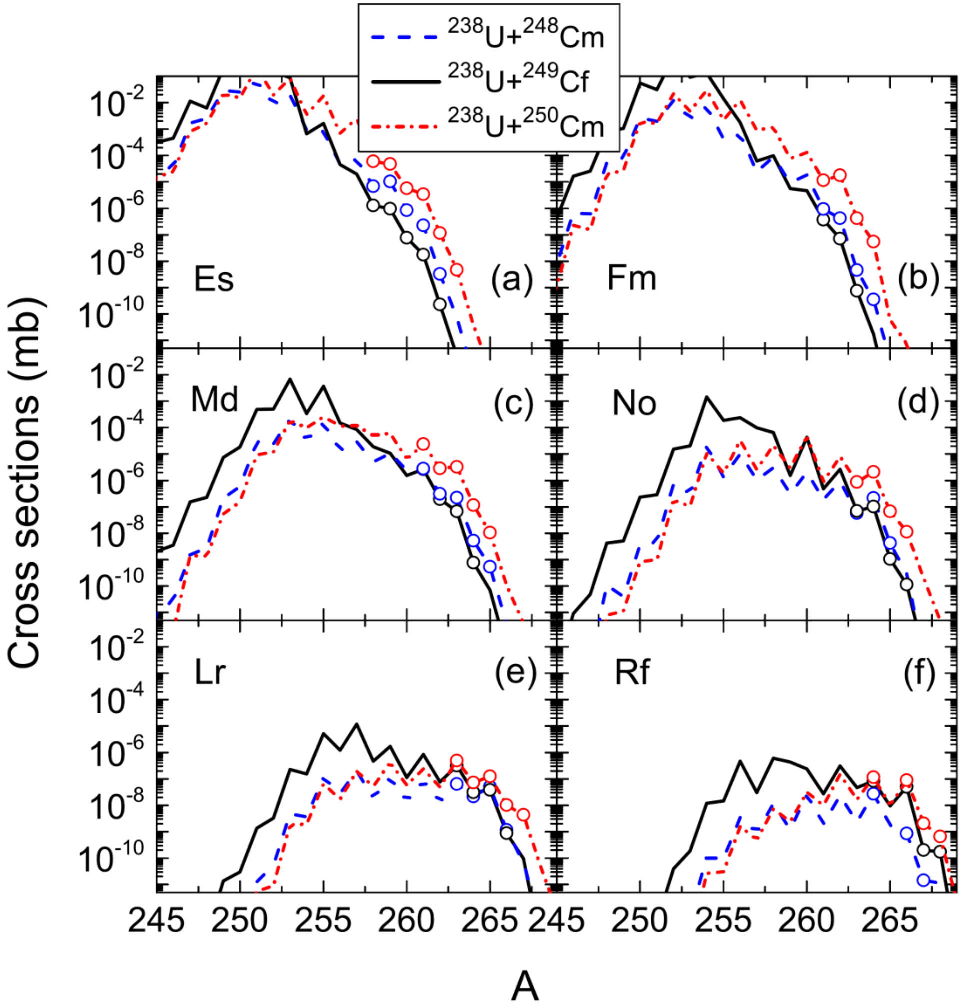




Zagrebaev+2006_PRC73-031602R

Zagrebaev&Greiner2015_NPA944-257

Multi-nucleon transfer reactions: DNS model

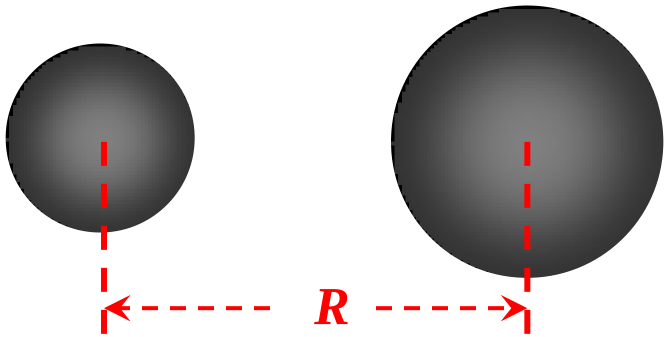


Zhu+2016_PRC94-054606

Fusion of two charged liquid drops

Langevin dynamics

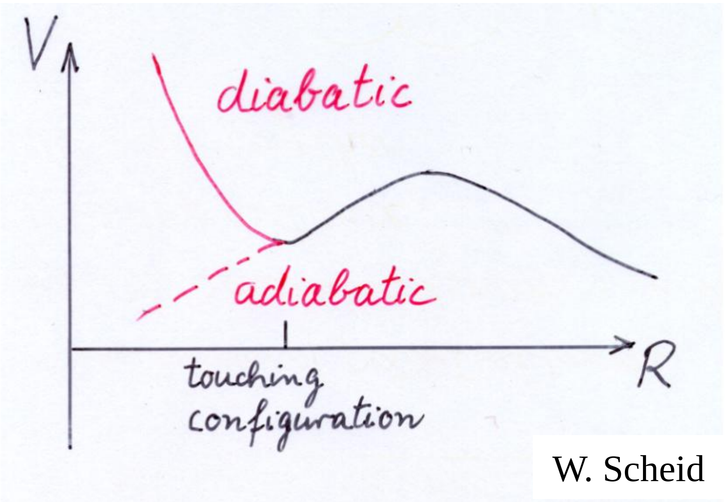
$$\begin{cases} \dfrac{du(t)}{dt} = -\displaystyle\int_{-\infty}^{t} \gamma(t-t')u(t')dt' + \frac{1}{\mu}\delta F(t) - \frac{1}{\mu}\frac{dV(R)}{dR} \\ u(t) = \dfrac{dR(t)}{dt} \end{cases}$$



- *R*(*t*): Rel. distance
- *u*(*t*): Rel. velocity
- *V*(*R*): Interaction potl.
- d*F*(*t*): Random force
- g(*t*-*t'*): Friction force

Dinuclear system (DNS) model

- Projectile & target keep staying in the potl. Pocket and individuality
- Transfer of nucleons betw. Projectile & target may lead to fusion



Nucleon(s) transfer betw. two charged liquid drops

☐ Langevin dynamics

$$\begin{cases} \dfrac{du(t)}{dt} = -\displaystyle\int_{-\infty}^{t} \gamma(t-t')u(t')dt' + \frac{1}{\mu}\delta F(t) - \frac{1}{\mu}\frac{dV(R)}{dR} \\ u(t) = \dfrac{dR(t)}{dt} \end{cases}$$

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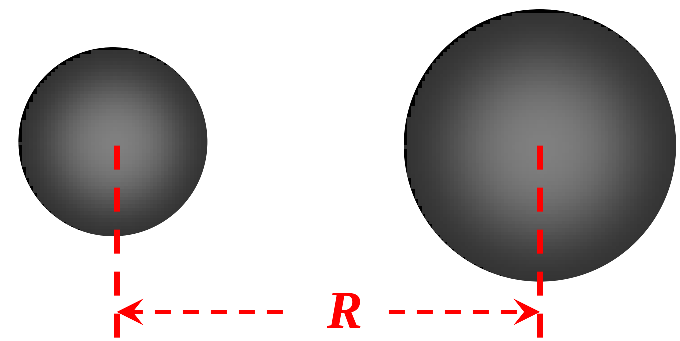

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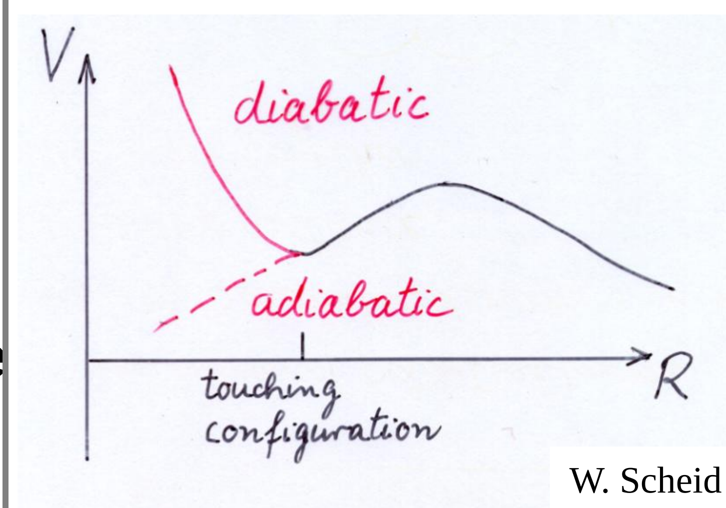
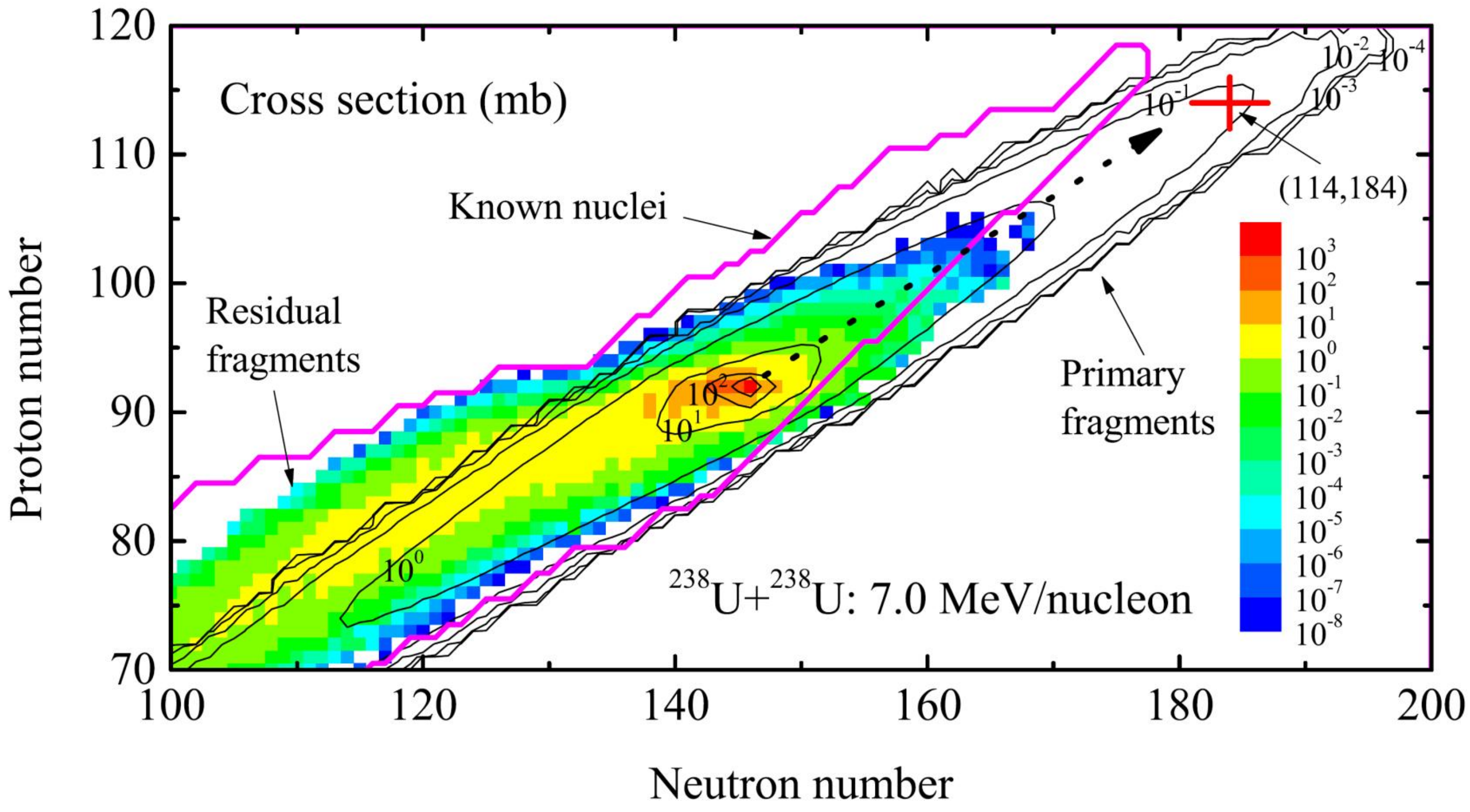
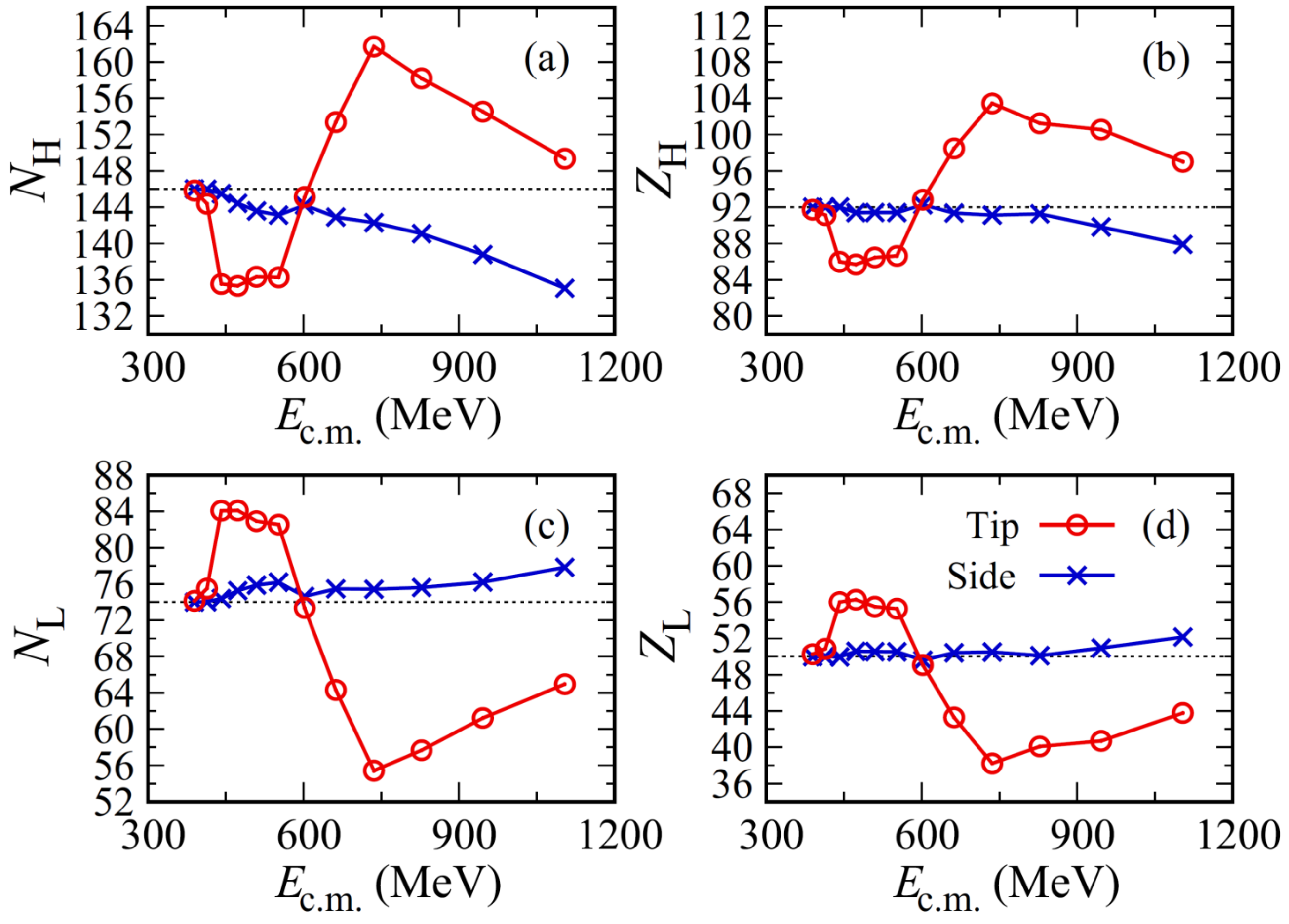


Multi-nucleon transfer reactions: ImQMD model



Zhao+2016_PRC94-024601

Multi-nucleon transfer reactions: TDHF theory



Sekizawa2017_PRC96-041601R

Lectures 3 & 4

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    - Fusion
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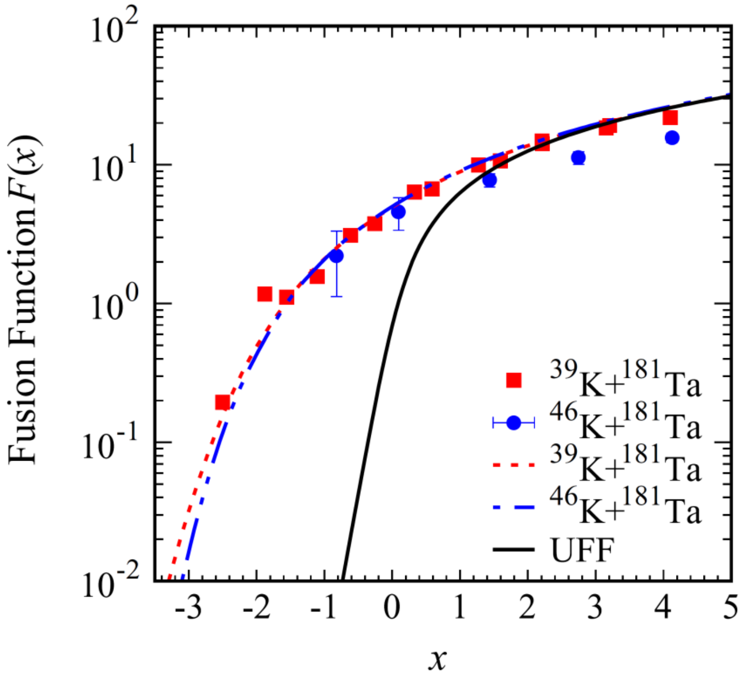
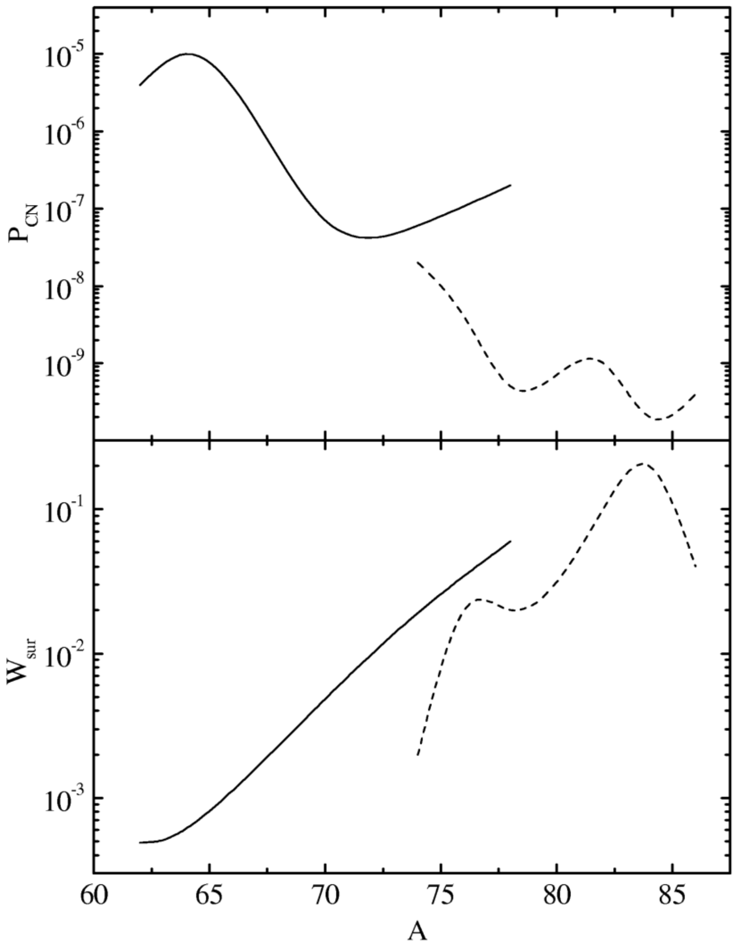
Synthesis of SHN w/ radioactive ion beams

$$\sigma_{\mathrm{ER}}(E_{\mathrm{cm}}) = \sum_J \sigma_{\mathrm{cap}}(E_{\mathrm{cm}}, J)\; P_{\mathrm{CN}}(E_{\mathrm{cm}}, J)\; W_{\mathrm{sur}}(E_{\mathrm{cm}}, J)$$



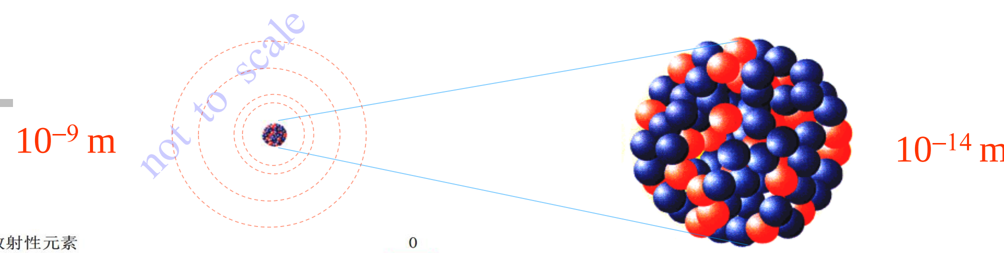
Wang+2018_PRC98-014615

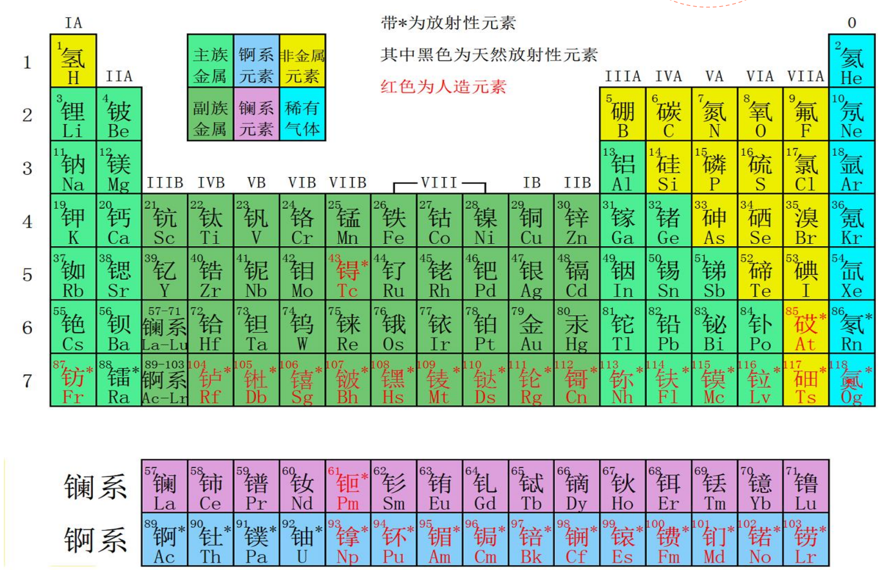


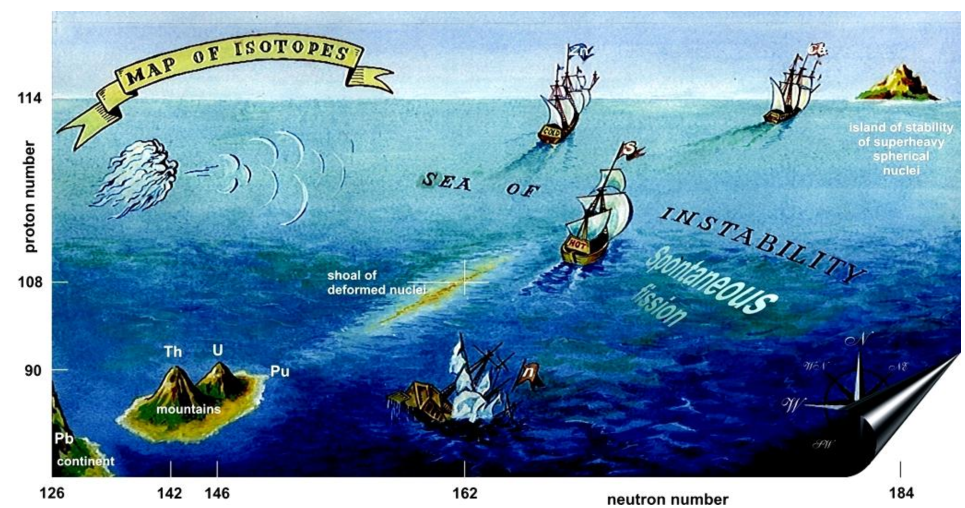
A thorough investigation:
Wu+2018_PRC97-064609

Adamian_Antonenko&Scheid2000_NPA678-24

Summary







- Where is the end of PT of elements?
- Are there stable high-atomic-number elements?
- What are similarities & differences in chemistry of SHEs & their lighter homologs
- …

- Where is the island of stability of SHN?
- Are there stable or long-lived SHN?
- How to reach the island of stability?
- Are there exotic shapes in SHN?
- Are there isomers in SHN longer-lived than their ground states?
- …