中国科学技术大学交叉学科理论研究中心&彭桓武高能基础理论研究中心
2024年11月29日

超重原子核与新元素研究

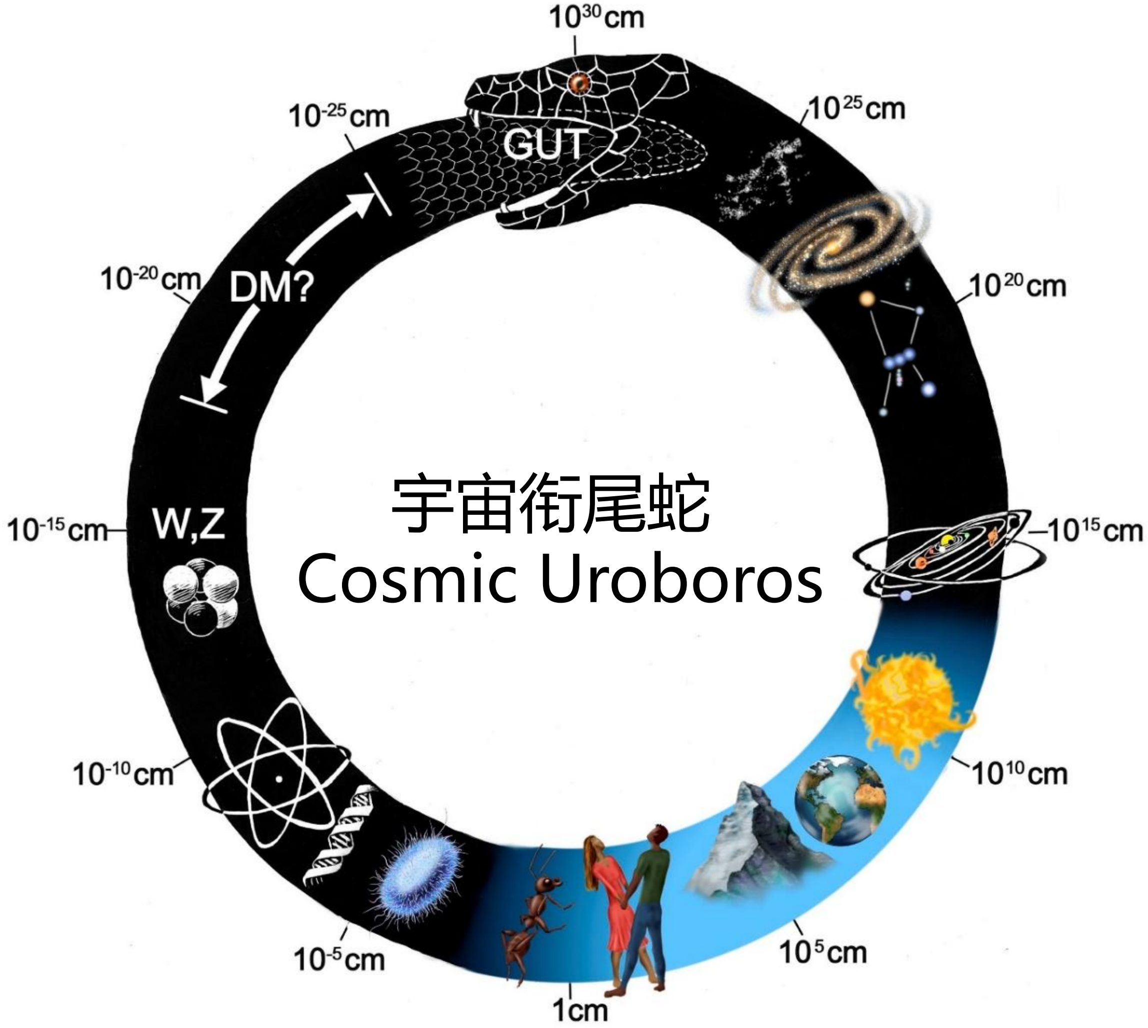
周善贵

中国科学院理论物理研究所 / 理论物理前沿重点实验室
中国科学院大学 物理科学学院 / 核科学与技术学院

Supported by: NSFC & MOST;
HPC Cluster of KLFTP/ITP-CAS
ScGrid of CNIC-CAS

原天地之美而达万物之理

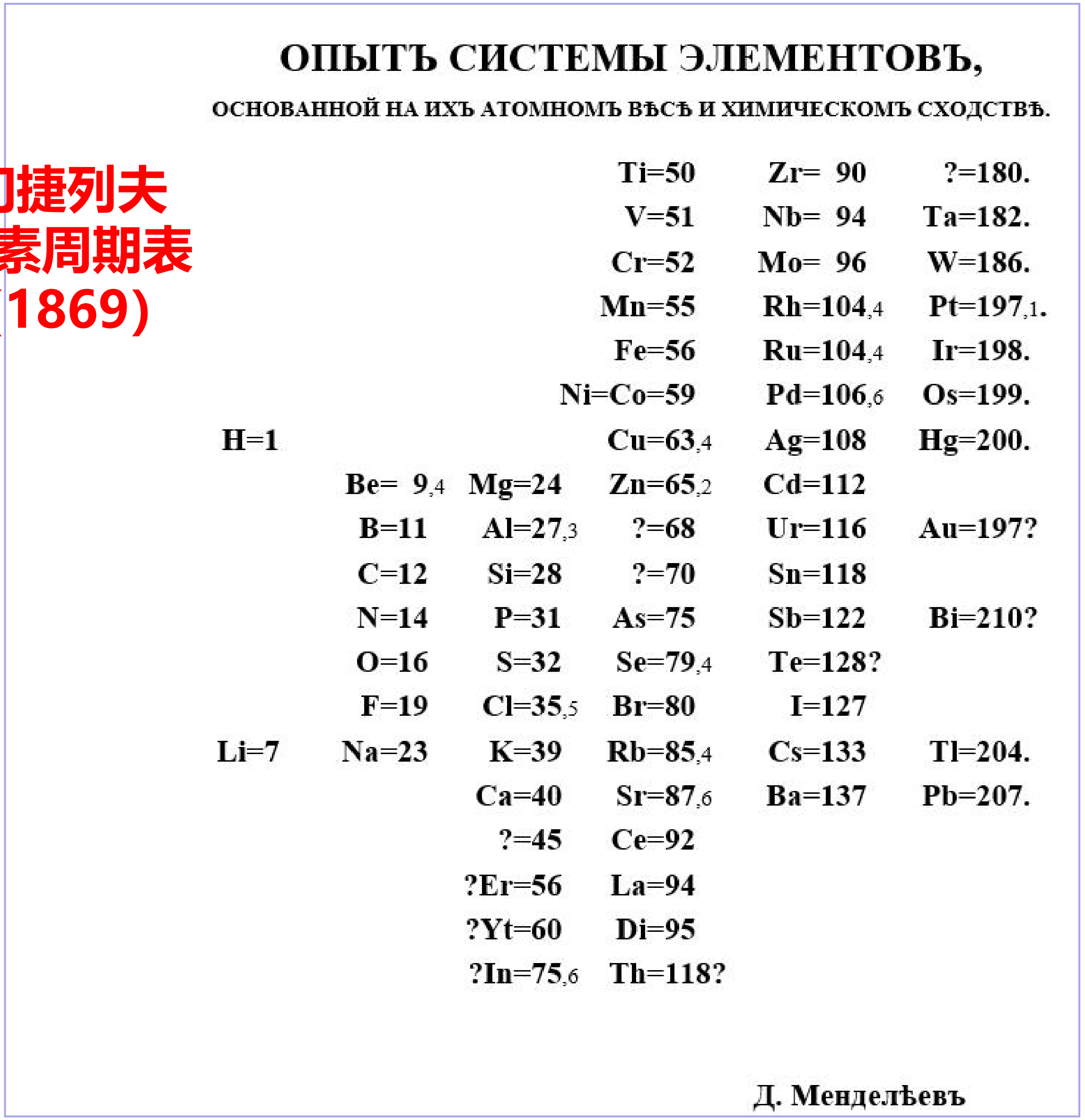
- 物理学探究蕴藏在大自然和人工系统中各种现象和效应背后的基本规律
- 物理学研究涵盖从微观、宏观到宇观的极小、极大和极复杂的体系
- 物理学研究推动基础科学的发展，催生技术革命，培养创新性人才，进而为促进国家经济和社会发展作出贡献



宇宙衔尾蛇
Cosmic Uroboros

元素周期律

门捷列夫
元素周期表
(1869)

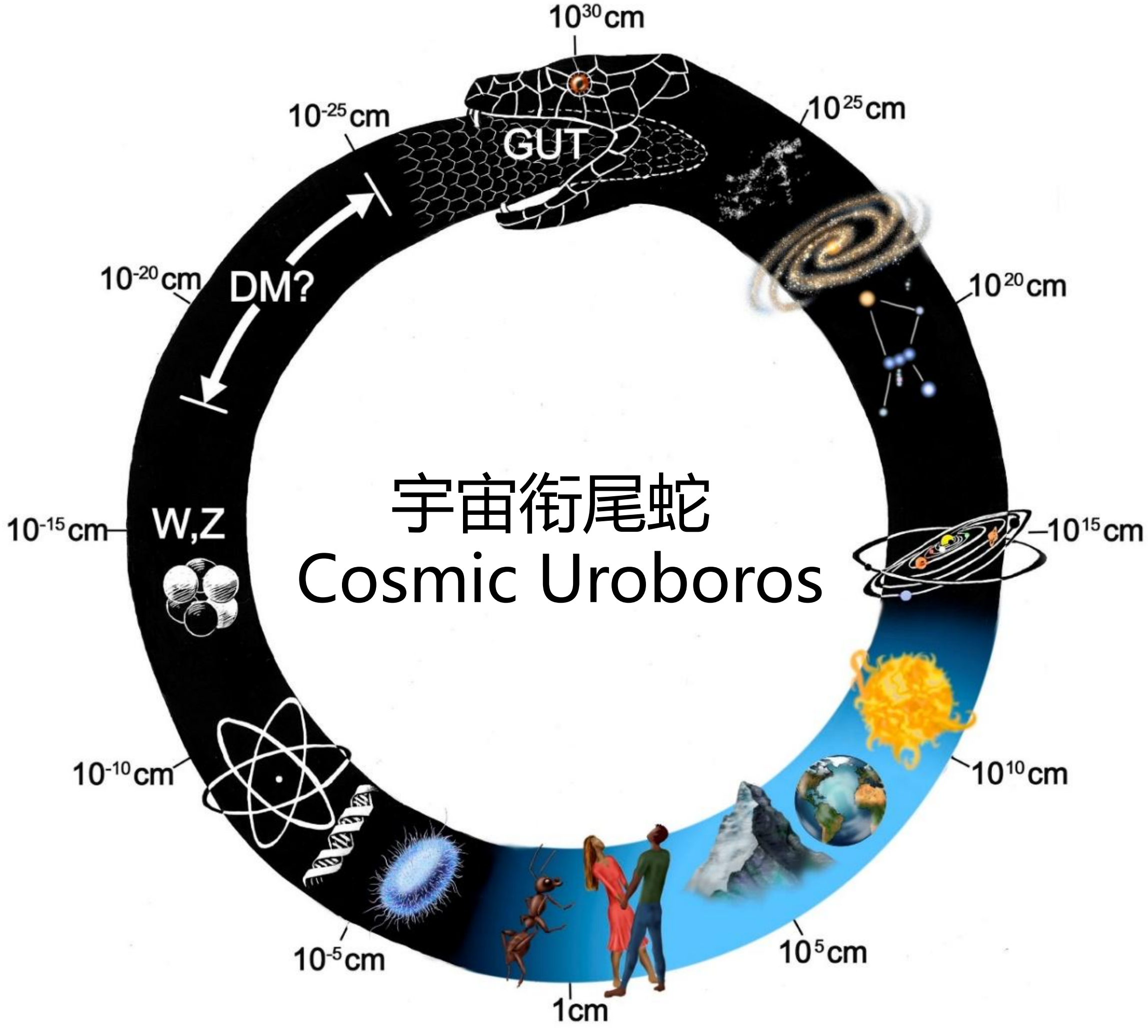


ОПЫТЪ СИСТЕМЫ ЭЛЕМЕНТОВЪ,

ОСНОВАННОЙ НА ИХЪ АТОМНОМЪ ВѢСѢ И ХИМИЧЕСКОМЪ СХОДСТВѢ.

			Ti=50	Zr= 90	?=180.
			V=51	Nb= 94	Ta=182.
			Cr=52	Mo= 96	W=186.
			Mn=55	Rh=104,4	Pt=197,1.
			Fe=56	Ru=104,4	Ir=198.
			Ni=Co=59	Pd=106,6	Os=199.
H=1			Cu=63,4	Ag=108	Hg=200.
	Be= 9,4	Mg=24	Zn=65,2	Cd=112	
	B=11	Al=27,3	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79,4	Te=128?	
	F=19	Cl=35,5	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85,4	Cs=133	Tl=204.
		Ca=40	Sr=87,6	Ba=137	Pb=207.
		?=45	Ce=92		
		?Er=56	La=94		
		?Yt=60	Di=95		
		?In=75,6	Th=118?		

Д. Менделѣевъ



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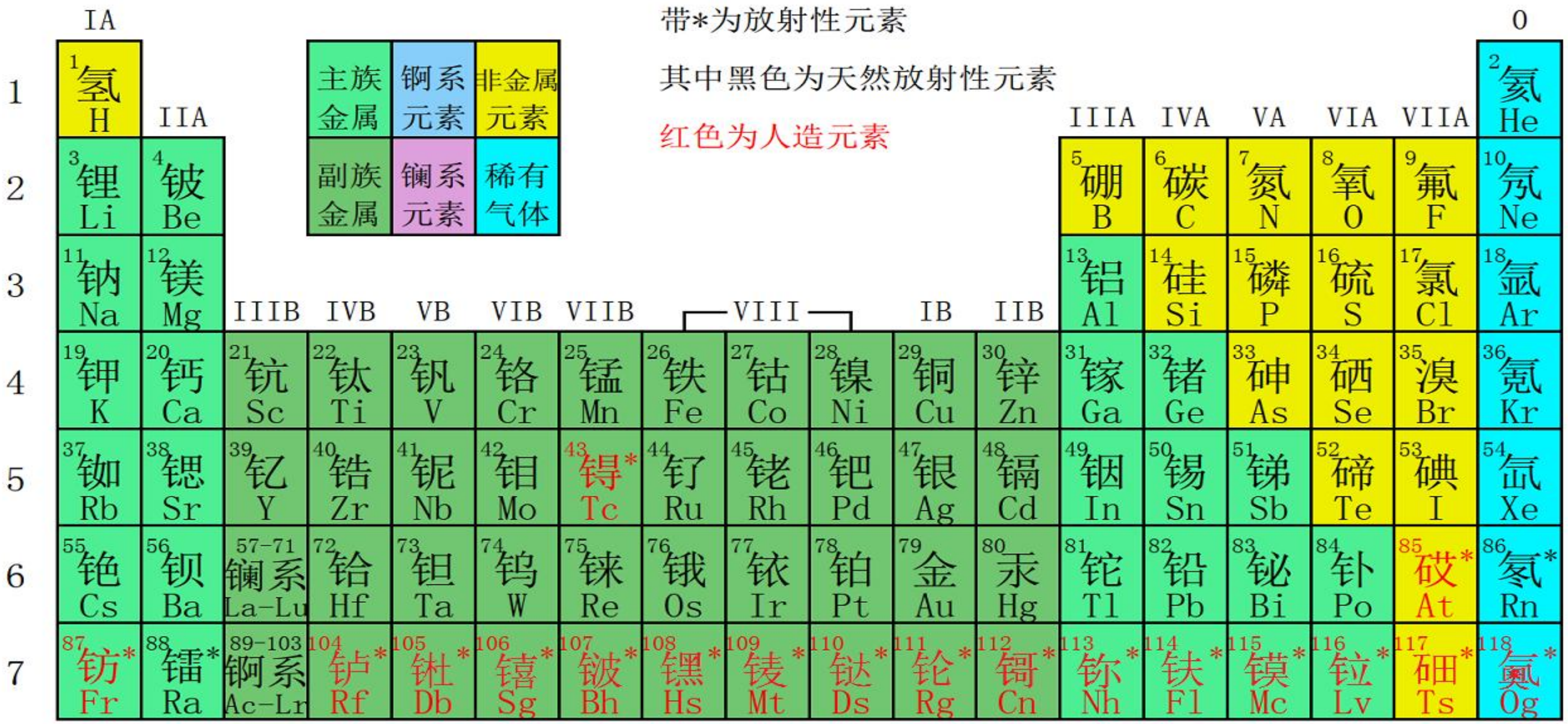

带*为放射性元素

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
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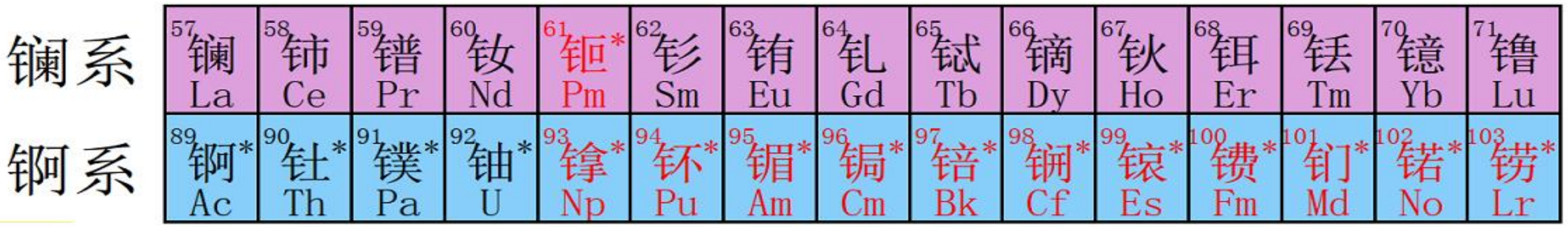
周善贵，超重原子核与新元素研究，原子核物理评论 34 (2017) 318-331



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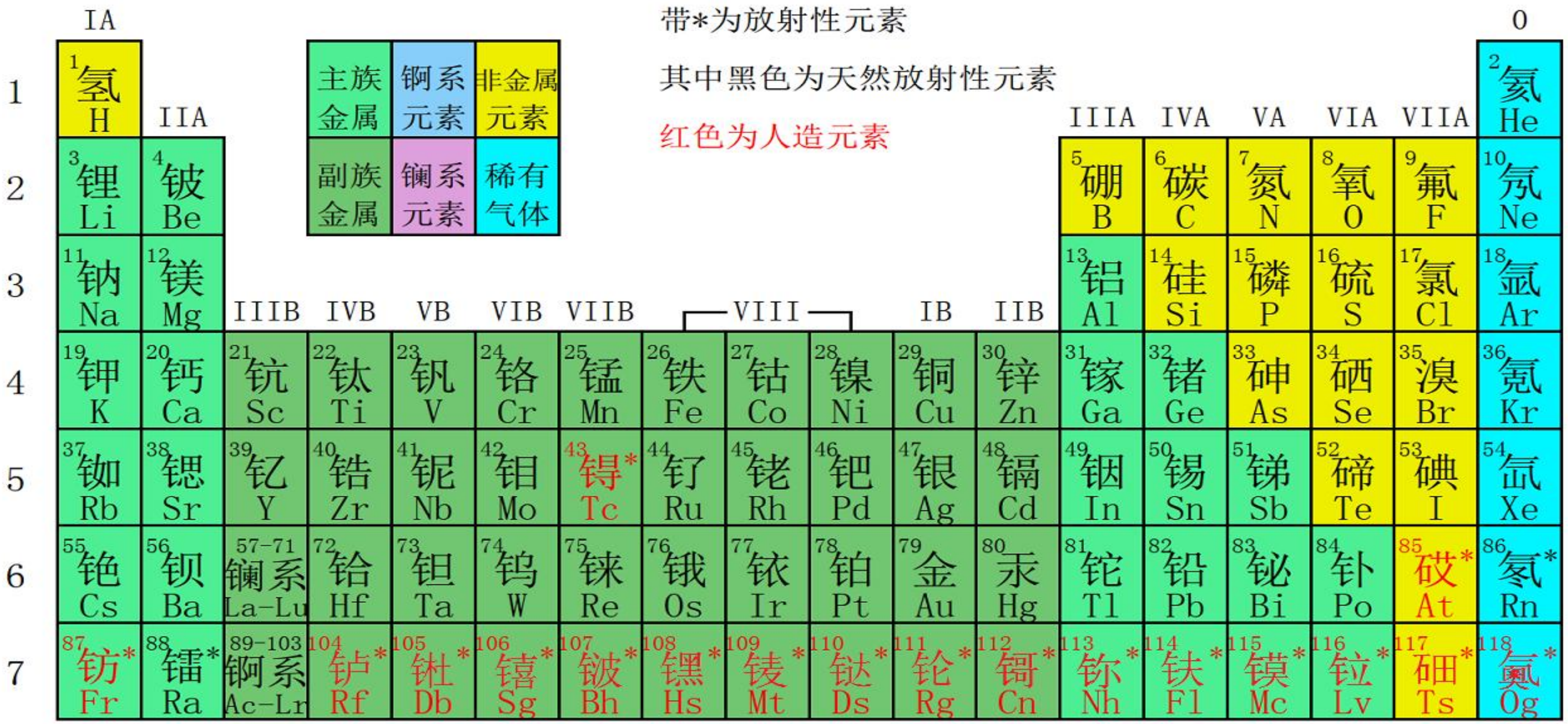
元素周期律与原子中电子的壳层排布



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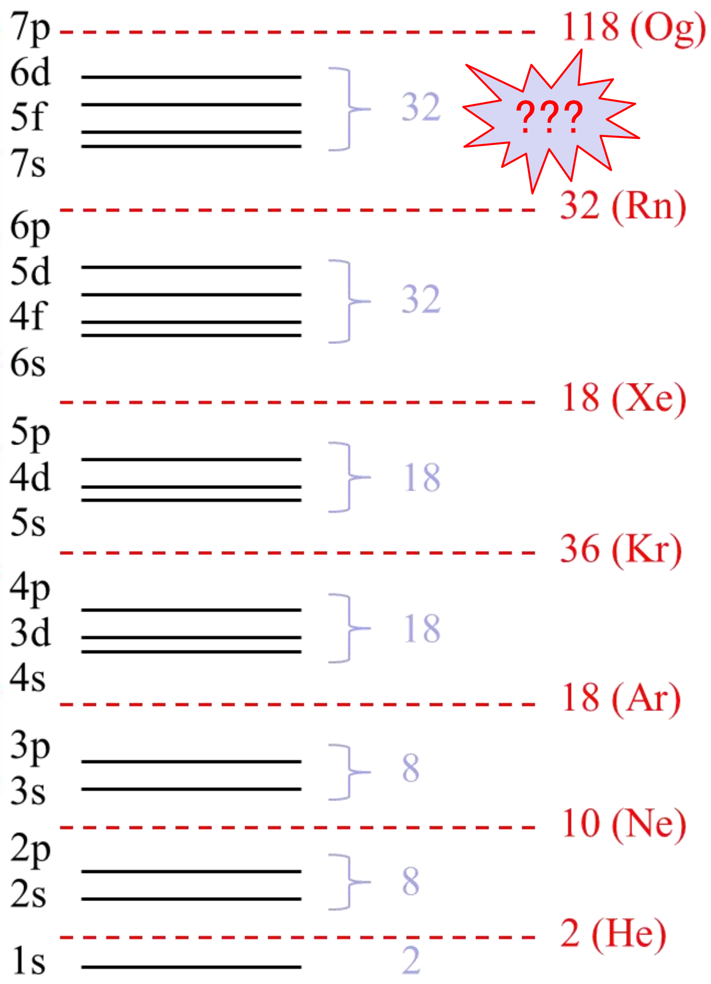

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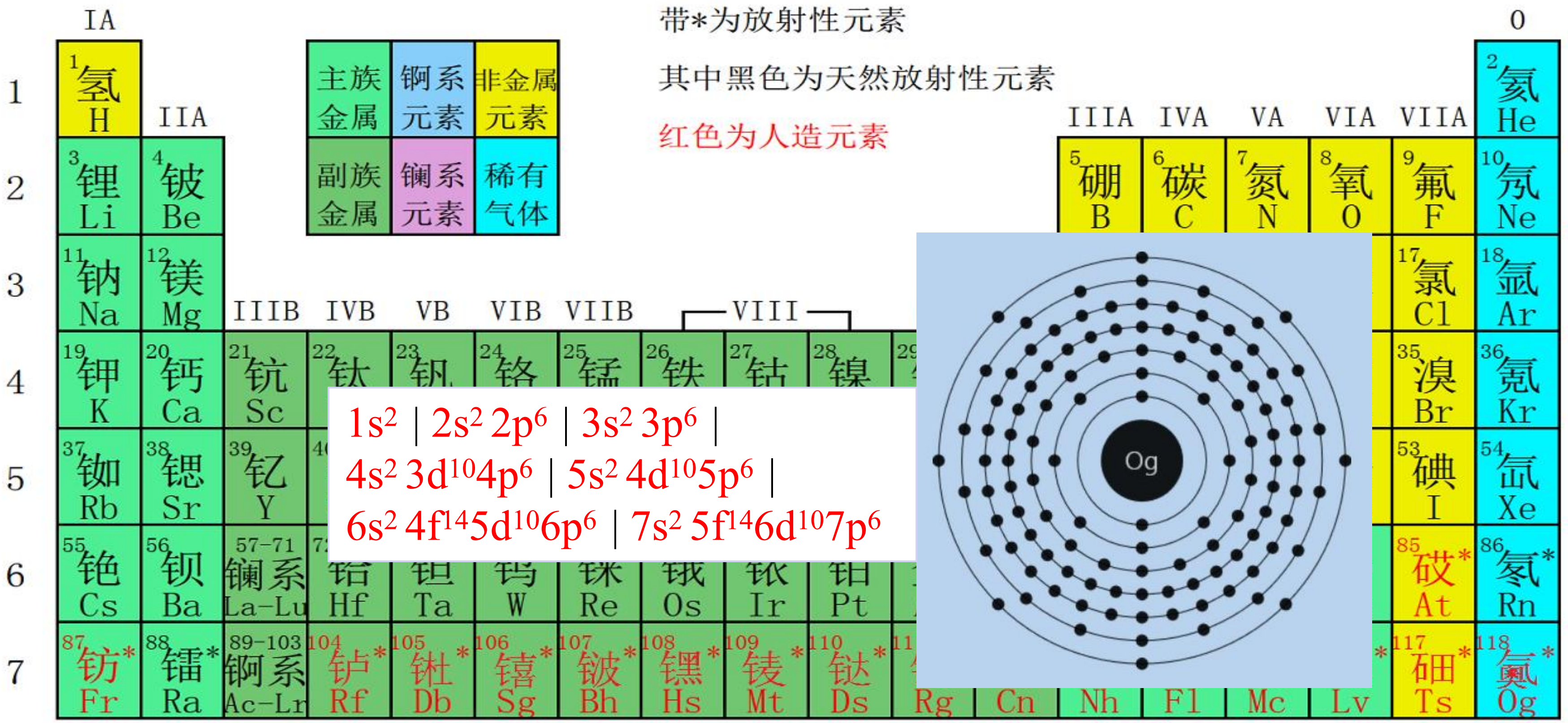

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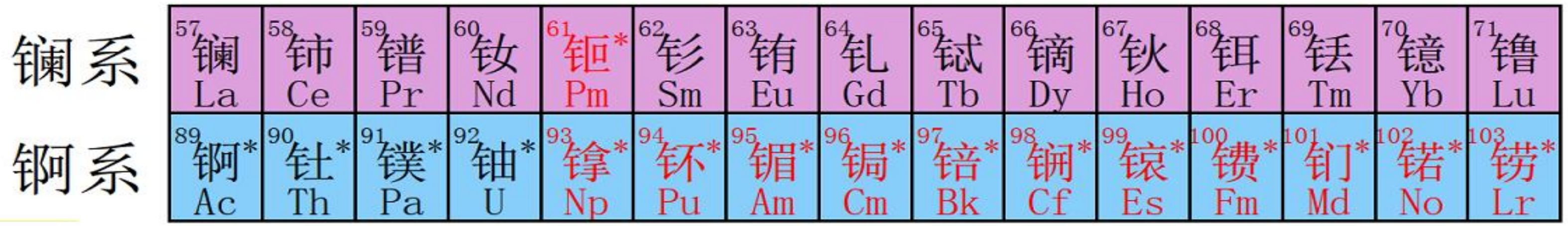
$1s^2$ | $2s^2\,2p^6$ | $3s^2\,3p^6$ |
$4s^2\,3d^{10}4p^6$ | $5s^2\,4d^{10}5p^6$ |
$6s^2\,4f^{14}5d^{10}6p^6$ | $7s^2\,5f^{14}6d^{10}7p^6$

周善贵，超重原子核与新元素研究，原子核物理评论 34 (2017) 318-331



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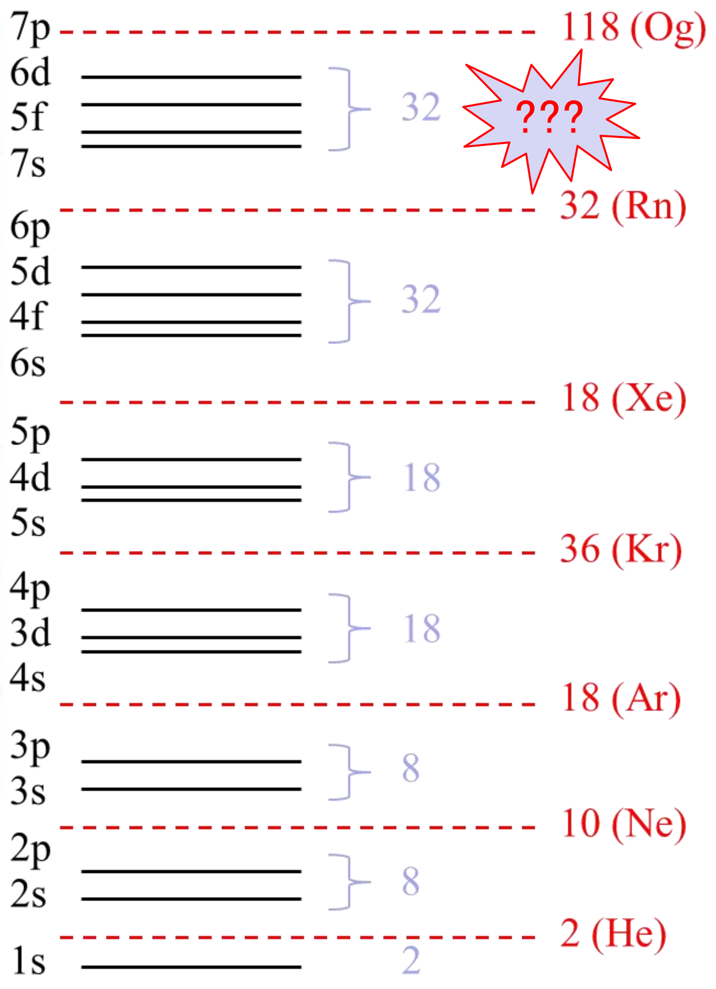
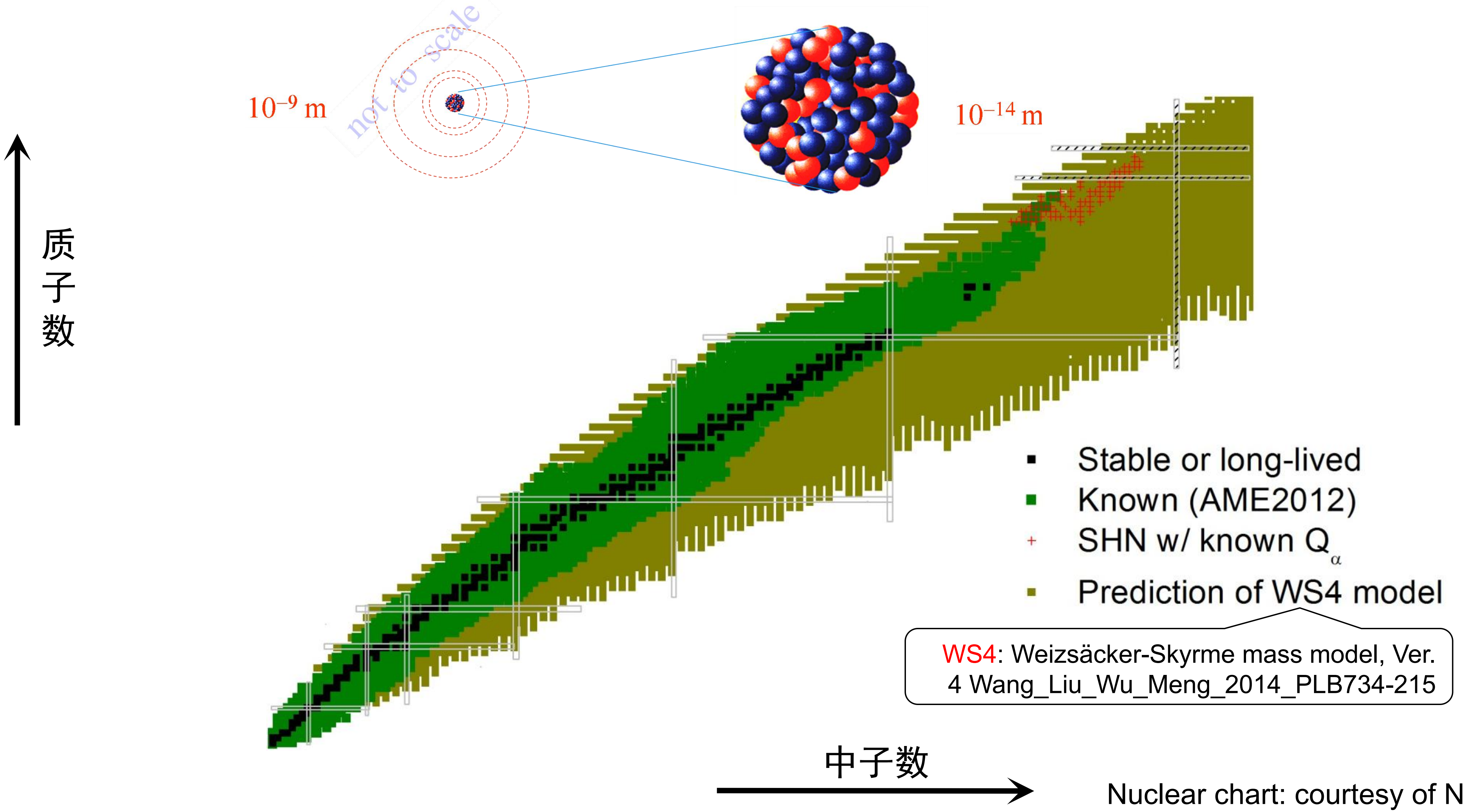


核素图

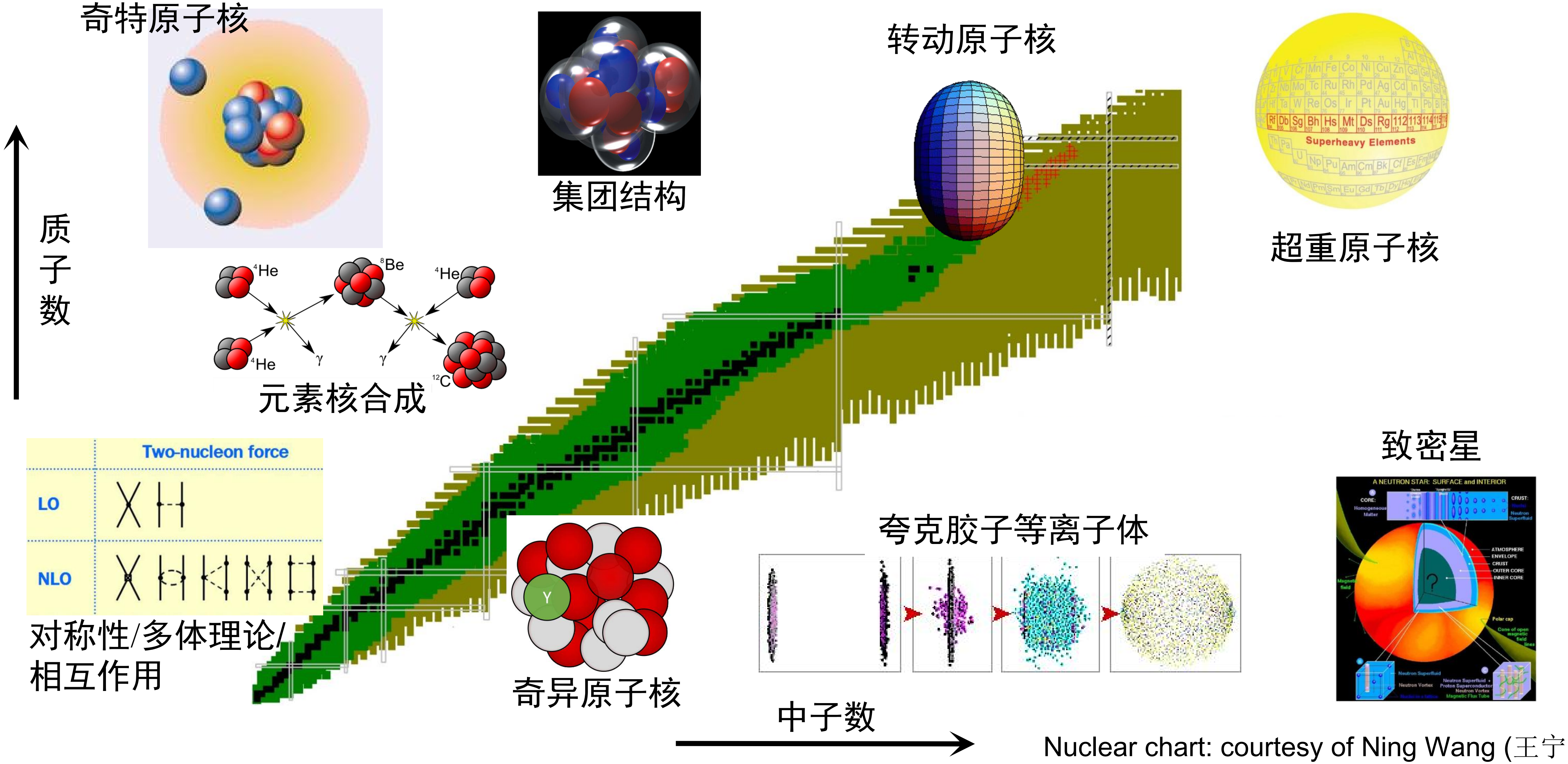


- ■ Stable or long-lived
- 🟩 Known (AME2012)
- \+ SHN w/ known Q_α
- ■ Prediction of WS4 model

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

Nuclear chart: courtesy of Ning Wang (王宁)

核物理研究前沿领域



奇特原子核

集团结构

转动原子核

超重原子核

质子数

元素核合成

对称性/多体理论/相互作用

奇异原子核

夸克胶子等离子体

致密星

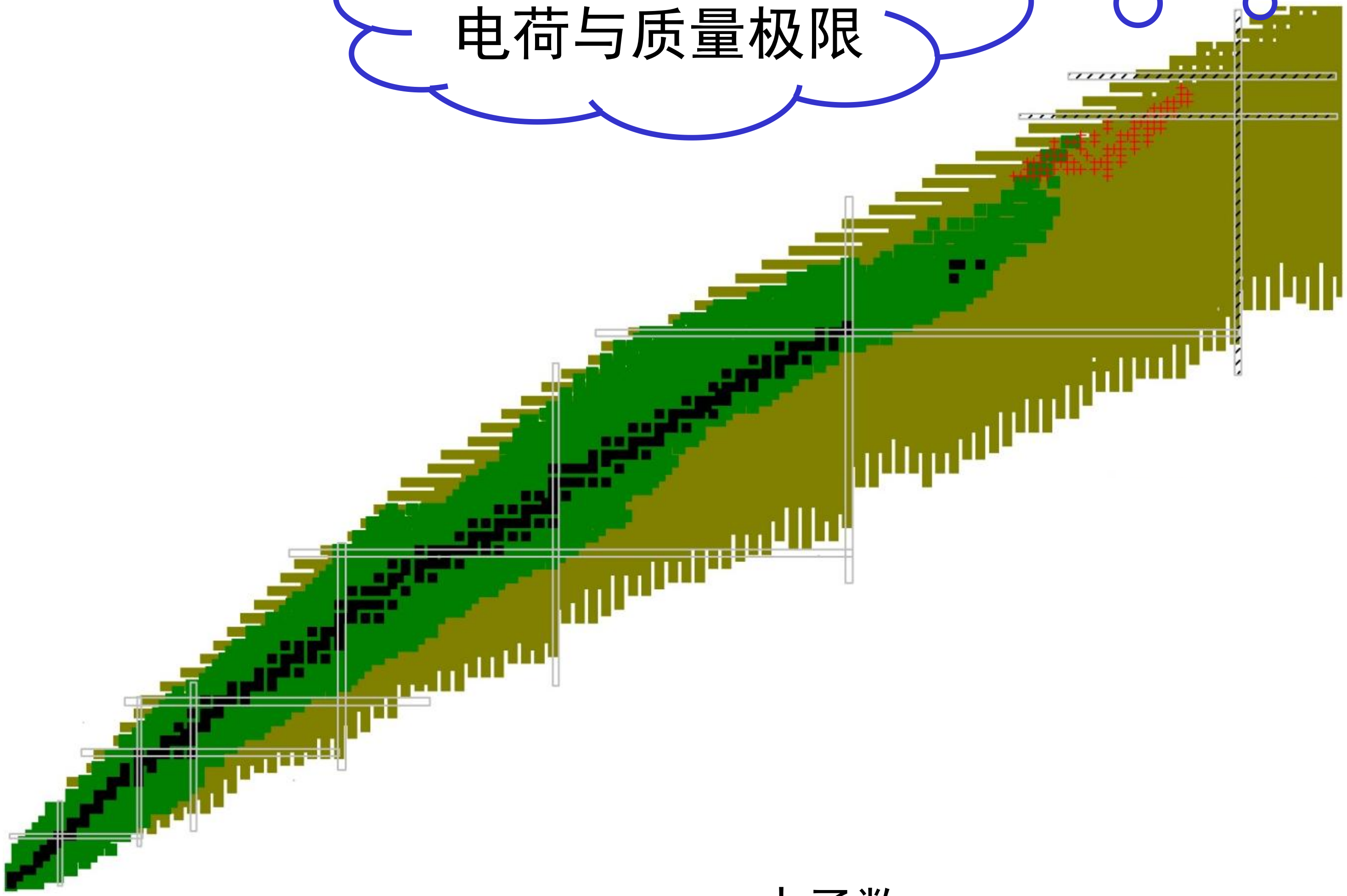
中子数

Nuclear chart: courtesy of Ning Wang (王宁)

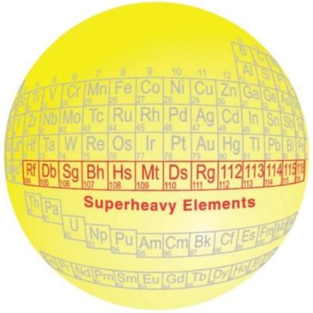
超重原子核

探索原子核的
电荷与质量极限

质
子
数



中子数



超重原子核

Nuclear chart: courtesy of Ning Wang (王宁)

内容提要

- □ 引言
- □ 超重原子核
  - ➢ 超重岛的理论预言与实验进展
  - ➢ 超重新元素合成面临的问题与挑战
  - ➢ 超重原子核性质及合成机制研究
- □ 小结

周善贵，超重原子核与超重元素，物理 43 (2014) 817-825

李璐璐、吕炳楠、王楠、温凯、夏铖君、张振华、赵杰、赵恩广、周善贵，超重核性质与合成机制的理论研究，原子核物理评论 31 (2014) 253-272

吕炳楠、赵杰、赵恩广、周善贵，Superheavy nuclei and fission barriers, Chapter 5 in *Relativistic Density Functional for Nuclear Structure* (World Scientific, 2016, Editor: Jie Meng)

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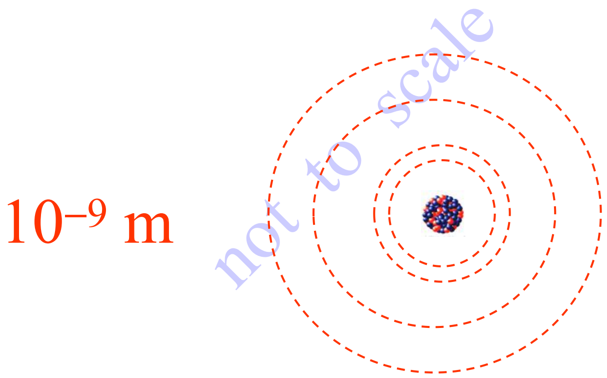
核电荷和质量极限——从原子层次看



杨福家，1985，原子物理学
Greiner & Reinhardt 1994, QED
Indelicato 2013, Nature 498, 40-41

□ 玻尔原子理论：原子最内层轨道上的电子运动速度为

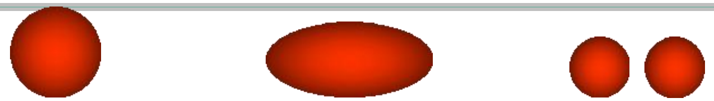
- 氢原子：$v_1 = \alpha c$
- 重原子：$v_1 \sim Z\alpha c$, $Z < 137$

□ 量子电动力学：原子最内层轨道上的电子能量为

- 假设原子核为点电荷：

  $E_1 \sim m_e c^2[(1-(Z\alpha)^2)^{1/2}-1]$, $Z < 137$
- 考虑原子核的大小：…, $Z < 173$

核电荷和质量极限——从原子核层次看



- 核　力：力程短、吸引，而且具有饱和性
- 库仑力：力程长、排斥
- 把原子核看成带电液滴：稳定性由长程库仑排斥与短程核力的吸引之间的竞争

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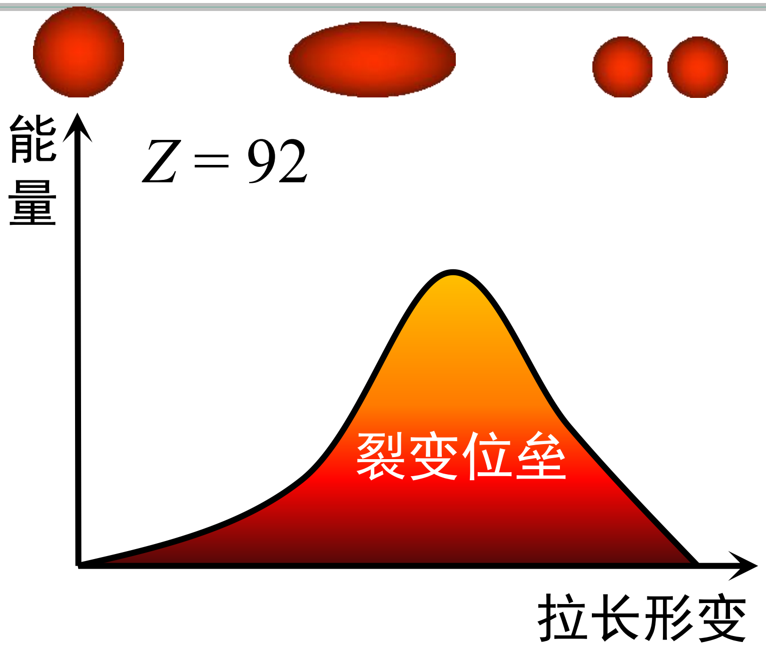

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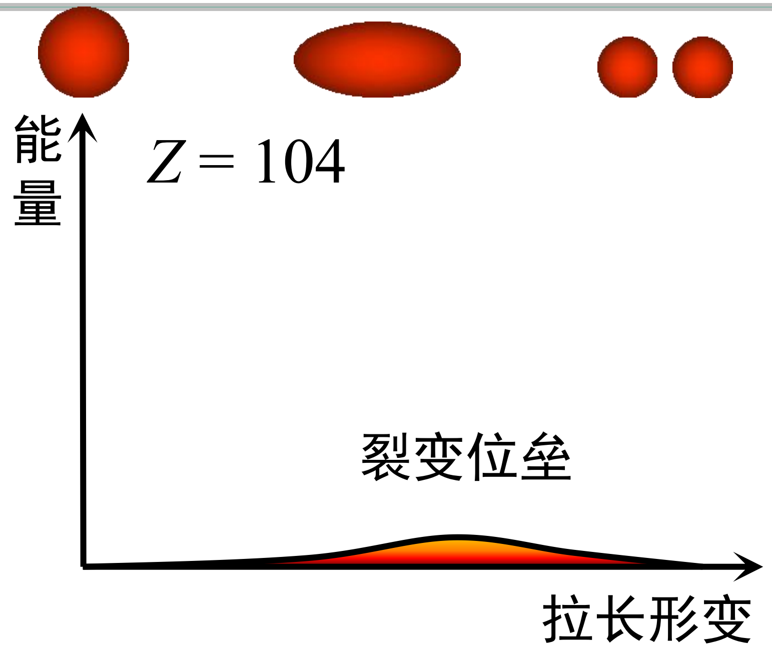

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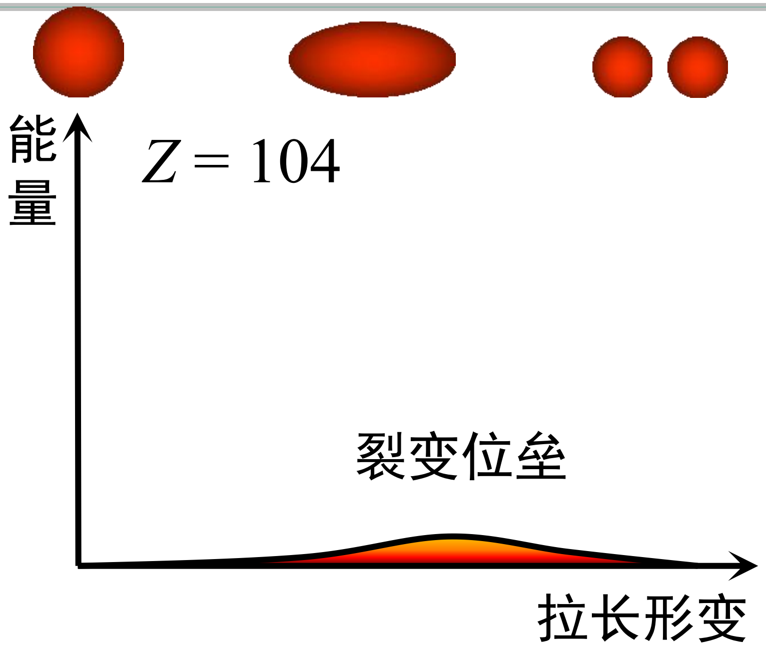
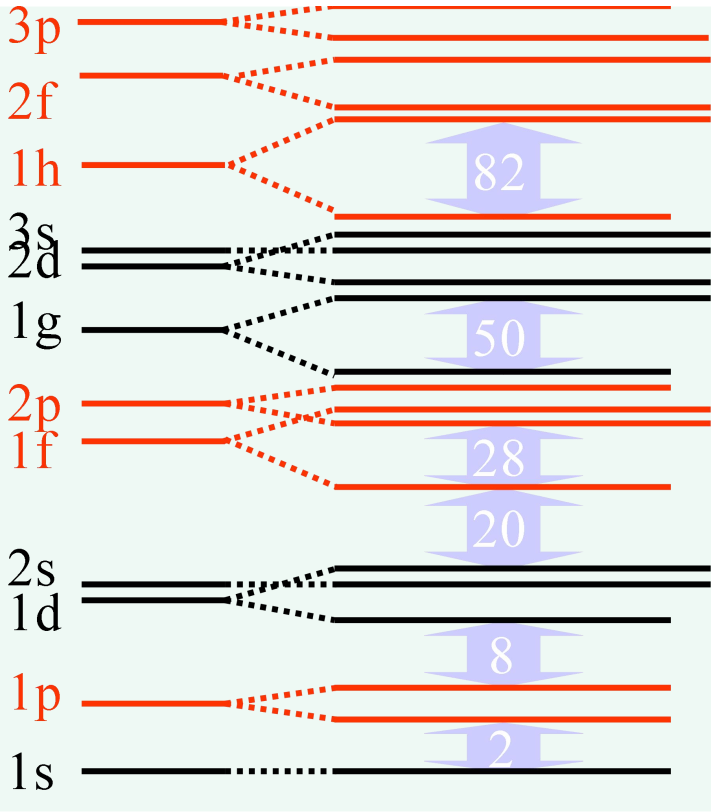
超重核的存在源于量子效应



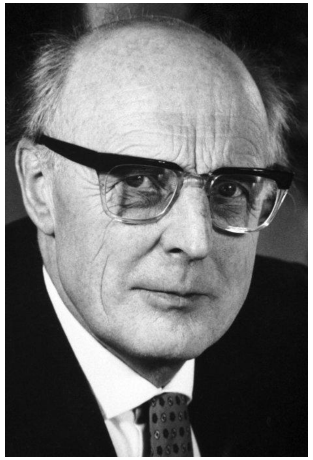


单粒子势及能级、量子壳效应、幻数

- □ 谐振子势、球方势阱
- □ Woods-Saxon势
- □ 自洽势（自束缚）

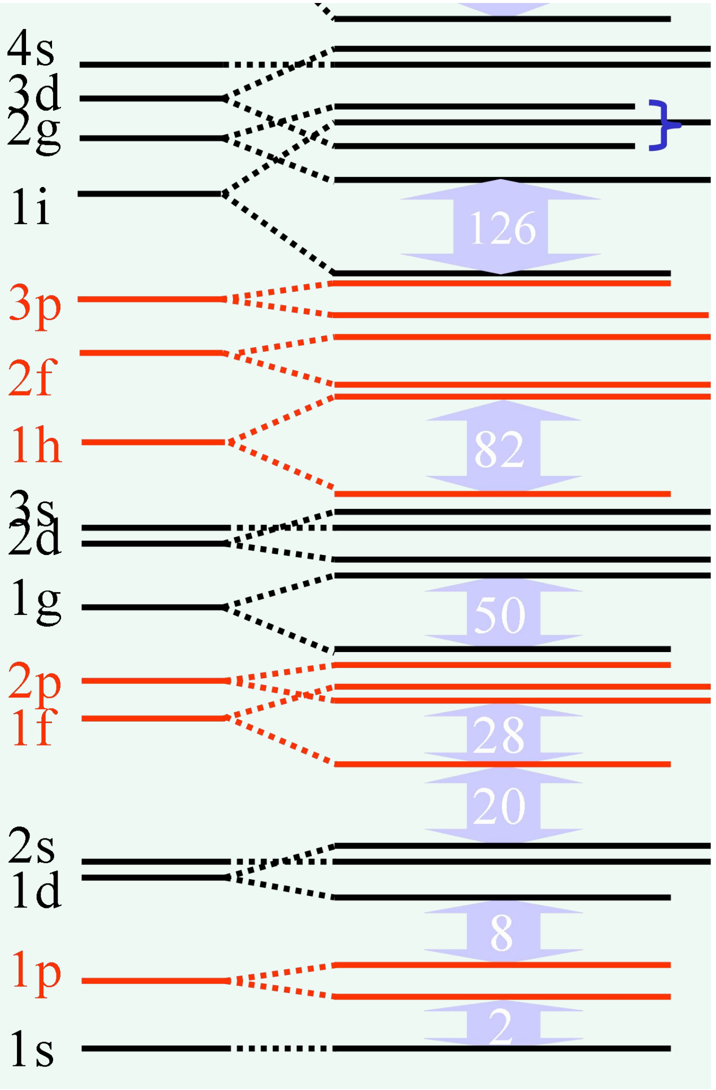
Eugene Paul Wigner

Maria Goeppert Mayer



J. Hans D. Jensen

1963年诺贝尔物理奖



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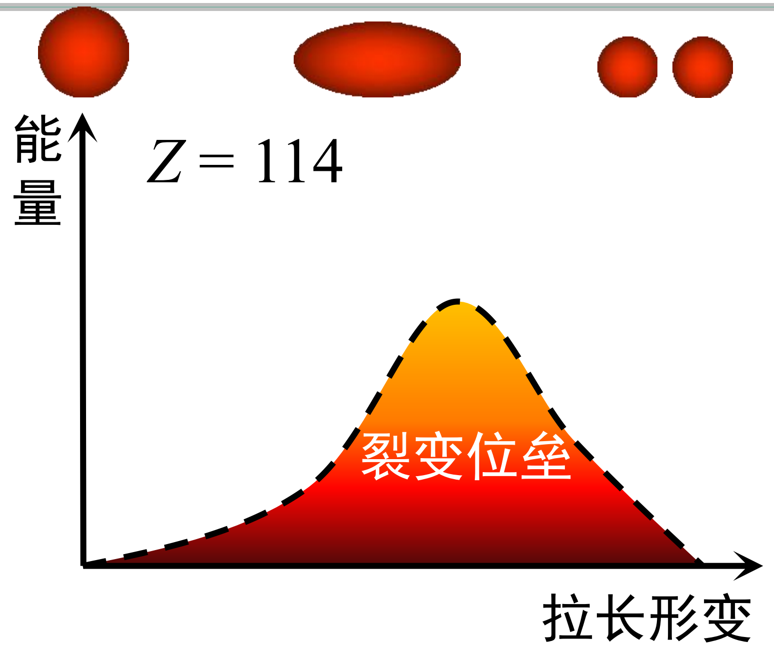
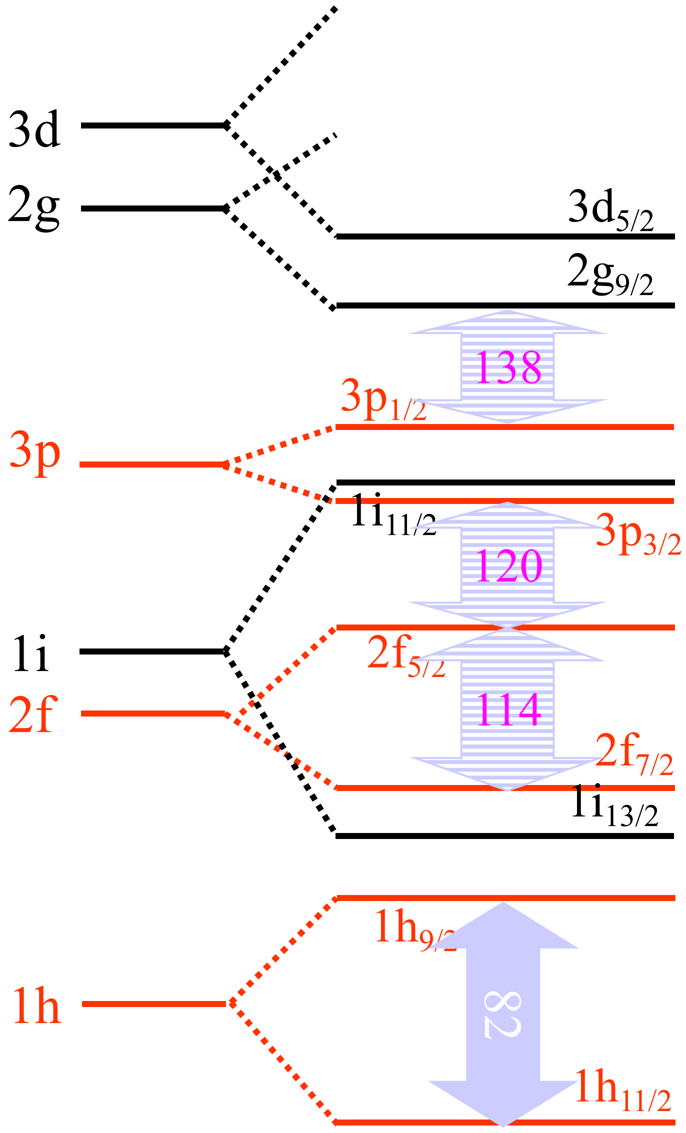
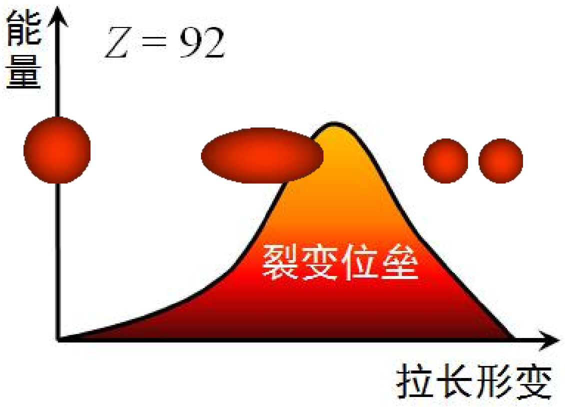
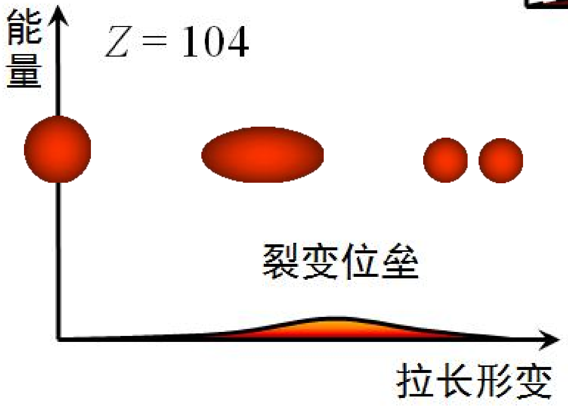


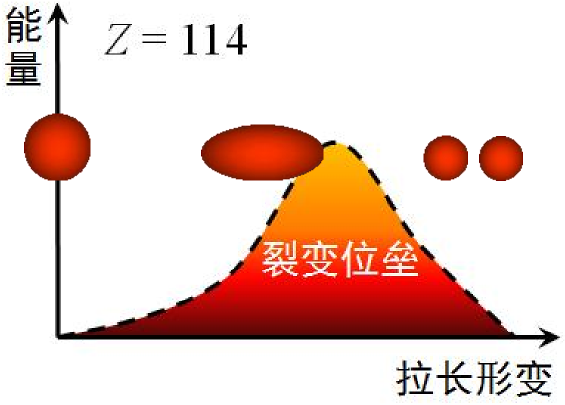


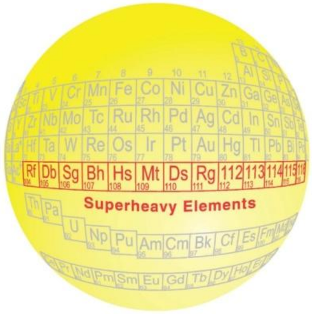
何为超重原子核?

把原子核看成是经典带电液滴，则不存在104 号以上的元素









超重原子核

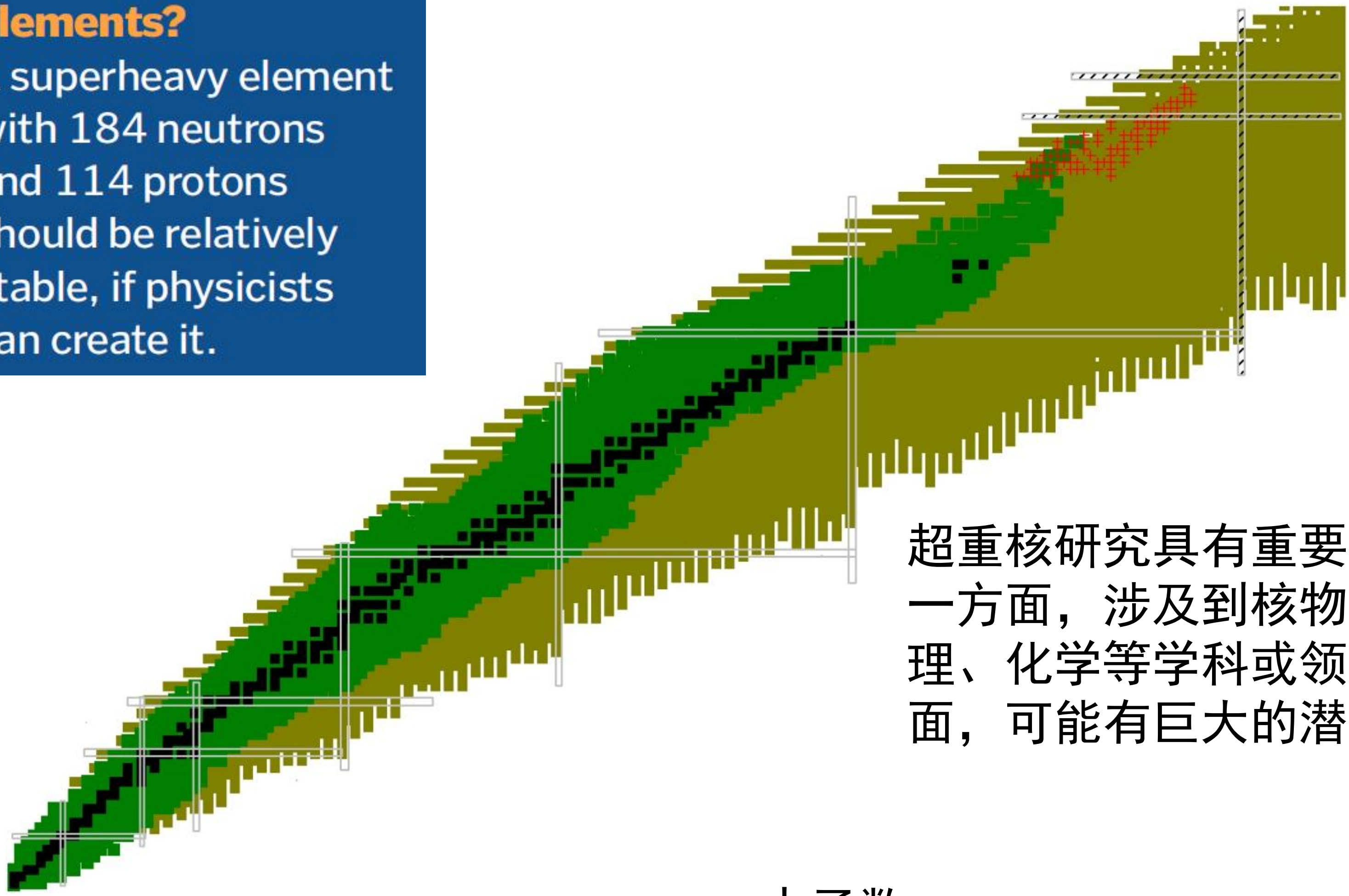
理论预言，由于量子壳效应，存在一个超重岛

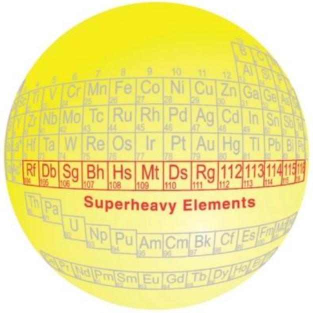
超重原子核（SHN）——电荷与质量极限

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



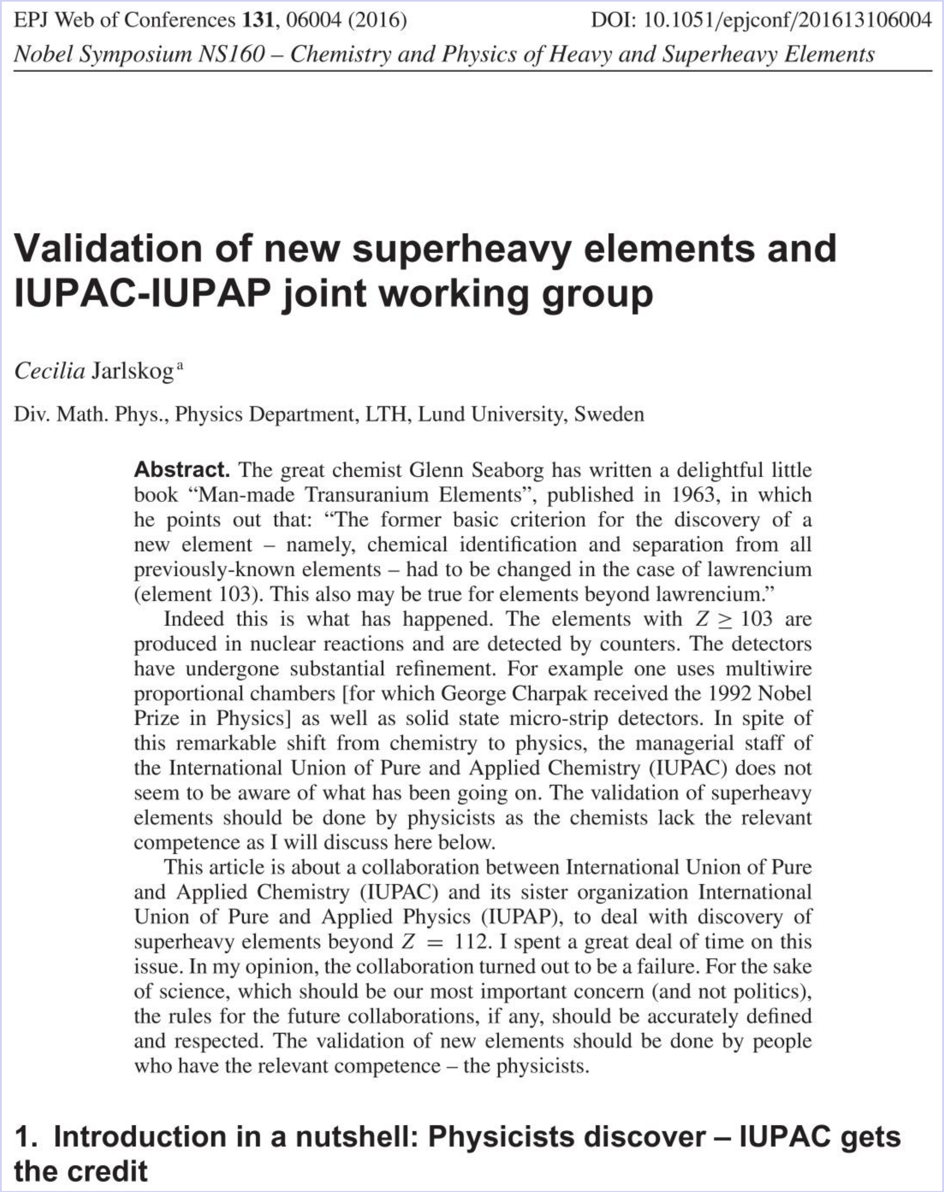


超重原子核

超重核研究具有重要的科学意义，一方面，涉及到核物理、原子物理、化学等学科或领域，另一方面，可能有巨大的潜在应用价值。

Nuclear chart: courtesy of Ning Wang (王宁)

Physics & Chemistry: Collaborating?



EPJ Web of Conferences **131**, 06004 (2016) DOI: 10.1051/epjconf/201613106004
Nobel Symposium NS160 – Chemistry and Physics of Heavy and Superheavy Elements

Validation of new superheavy elements and IUPAC-IUPAP joint working group

Cecilia Jarlskog[a]

Div. Math. Phys., Physics Department, LTH, Lund University, Sweden

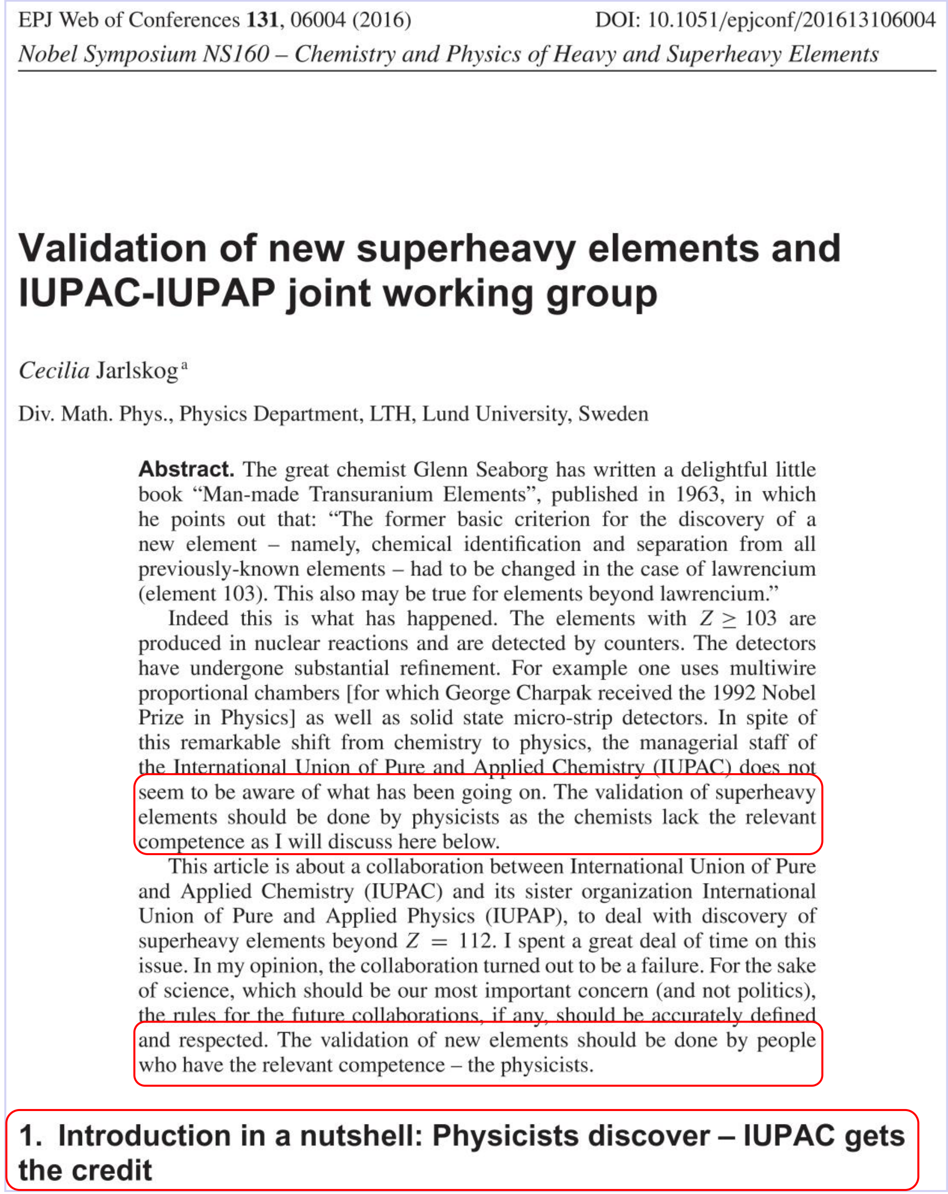
Abstract. The great chemist Glenn Seaborg has written a delightful little book "Man-made Transuranium Elements", published in 1963, in which he points out that: "The former basic criterion for the discovery of a new element – namely, chemical identification and separation from all previously-known elements – had to be changed in the case of lawrencium (element 103). This also may be true for elements beyond lawrencium."

Indeed this is what has happened. The elements with $Z \geq 103$ are produced in nuclear reactions and are detected by counters. The detectors have undergone substantial refinement. For example one uses multiwire proportional chambers [for which George Charpak received the 1992 Nobel Prize in Physics] as well as solid state micro-strip detectors. In spite of this remarkable shift from chemistry to physics, the managerial staff of the International Union of Pure and Applied Chemistry (IUPAC) does not seem to be aware of what has been going on. The validation of superheavy elements should be done by physicists as the chemists lack the relevant competence as I will discuss here below.

This article is about a collaboration between International Union of Pure and Applied Chemistry (IUPAC) and its sister organization International Union of Pure and Applied Physics (IUPAP), to deal with discovery of superheavy elements beyond $Z = 112$. I spent a great deal of time on this issue. In my opinion, the collaboration turned out to be a failure. For the sake of science, which should be our most important concern (and not politics), the rules for the future collaborations, if any, should be accurately defined and respected. The validation of new elements should be done by people who have the relevant competence – the physicists.

1. Introduction in a nutshell: Physicists discover – IUPAC gets the credit

Physics & Chemistry: Collaborating?



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Physicists discover – IUPAC gets the credit

内容提要

□ 引言

□ 超重原子核

- 超重岛的理论预言与实验进展
- 超重新元素合成面临的问题与挑战
- 超重原子核性质及合成机制研究

□ 小结

周善贵，超重原子核与超重元素，物理 43 (2014) 817-825

李璐璐、吕炳楠、王楠、温凯、夏铖君、张振华、赵杰、赵恩广、周善贵，超重核性质与合成机制的理论研究，原子核物理评论 31 (2014) 253-272

吕炳楠、赵杰、赵恩广、周善贵，Superheavy nuclei and fission barriers, Chapter 5 in *Relativistic Density Functional for Nuclear Structure* (World Scientific, 2016, Editor: Jie Meng)

周善贵，超重原子核与新元素研究，原子核物理评论 34 (2017) 318-331

超重核和超重稳定岛的实验探索

- 如果超重核半衰期$T_{1/2}$~10^8 年且已在元素核合成过程中生成
  - 超重核应在自然界中存在

Herrmann1979_Nature280-543

超重核和超重稳定岛的实验探索

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  - ➢ 超重核应在自然界中存在

Herrmann1979_Nature280-543

- ✓ 1860、1861年，德国化学家本生在一种矿泉水中提取出铯和铷
- ✓ 1861年，英国化学家克鲁克斯在一种淤泥中发现重金属铊
- ✓ 1868年，英、法天文学家在太阳光谱中发现新谱线，对应着氦
- ✓ …
- ✓ 1898年，居里夫妇在沥青铀矿提纯物中观测到新的放射线，发现钋和镭

超重核和超重稳定岛的实验探索

□ 如果超重核半衰期$T_{1/2}$~10^8 年且已在元素核合成过程中生成

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Herrmann1979_Nature280-543

- 目前仍无确切证据表明自然界中存在超重元素，但相关研究意义重大

Ter-Akopian_Dmitriev2015_NPA944-177

□ 实验室里，利用重离子熔合蒸发反应合成超重核

- 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
- HIRFL in Lanzhou, China

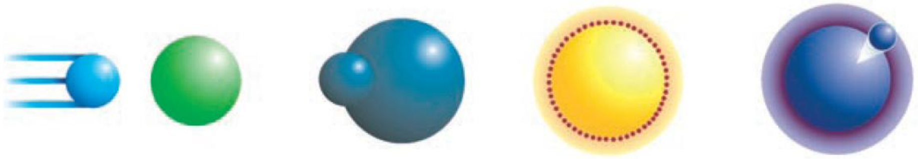
Hofmann_Münzenberg2000_RMP72-733

Morita...2004_JPSJ73-2593

Oganessian...2007_JPG34-R165

Oganessian...2010_PRL104-142502

Zhang…2012_CPL29-012502

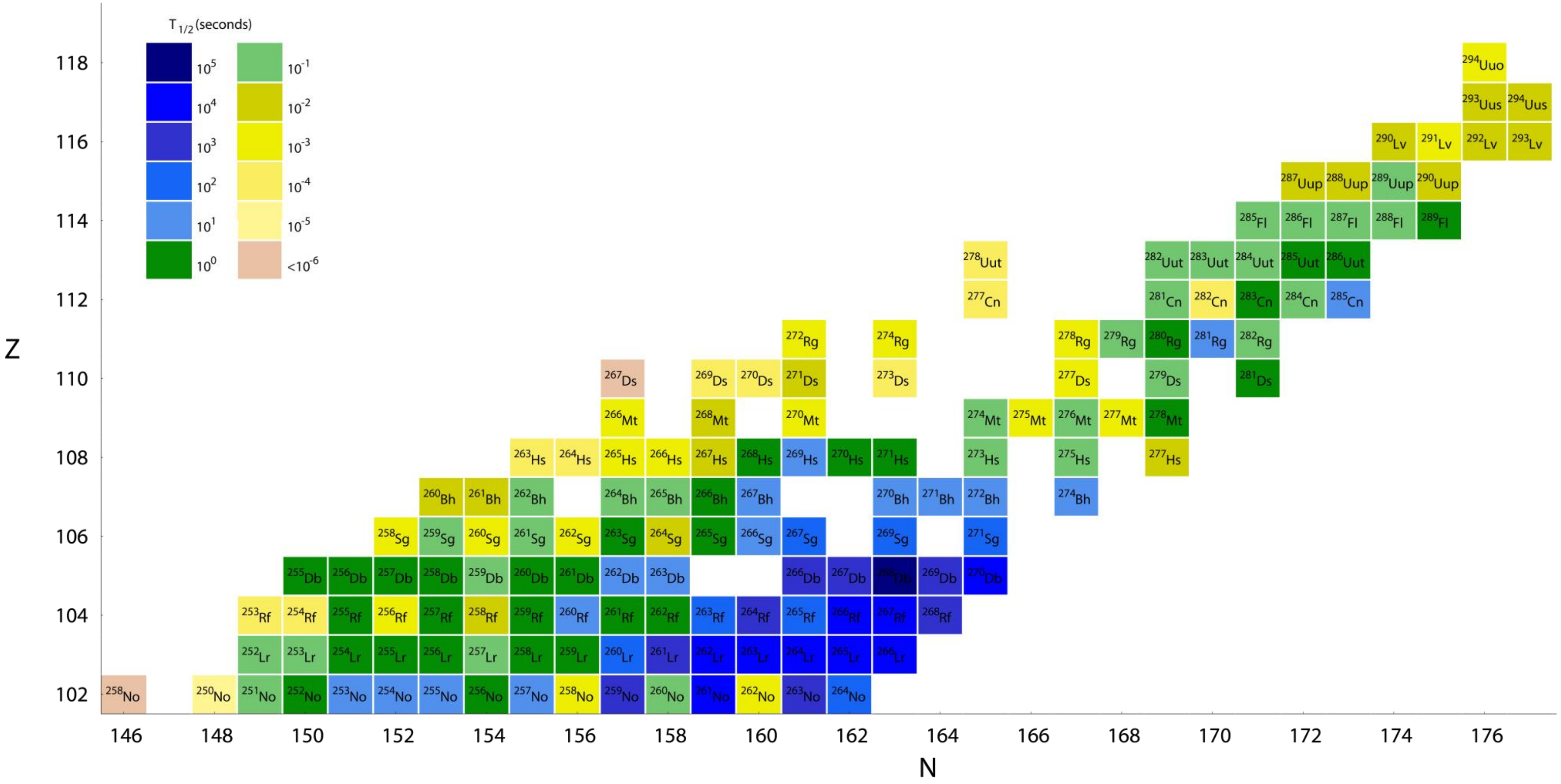


实验室合成超重核

- 俘获中子，之后进行β衰变
  - 反应堆：94号元素钚至100号元素镄
  - 核爆炸：98号元素锎至100号元素镄

- 轻离子（氢、氘、氚、氦）轰击靶核：最重到101号元素钔
- 重离子轰击靶核
  - 冷熔合：用^{208}Pb（铅-208）和^{209}Bi（铋-209）做靶，目前最重合成至113号元素
  - 热熔合：用^{48}Ca（钙-48）做炮弹，目前最重合成到118号元素

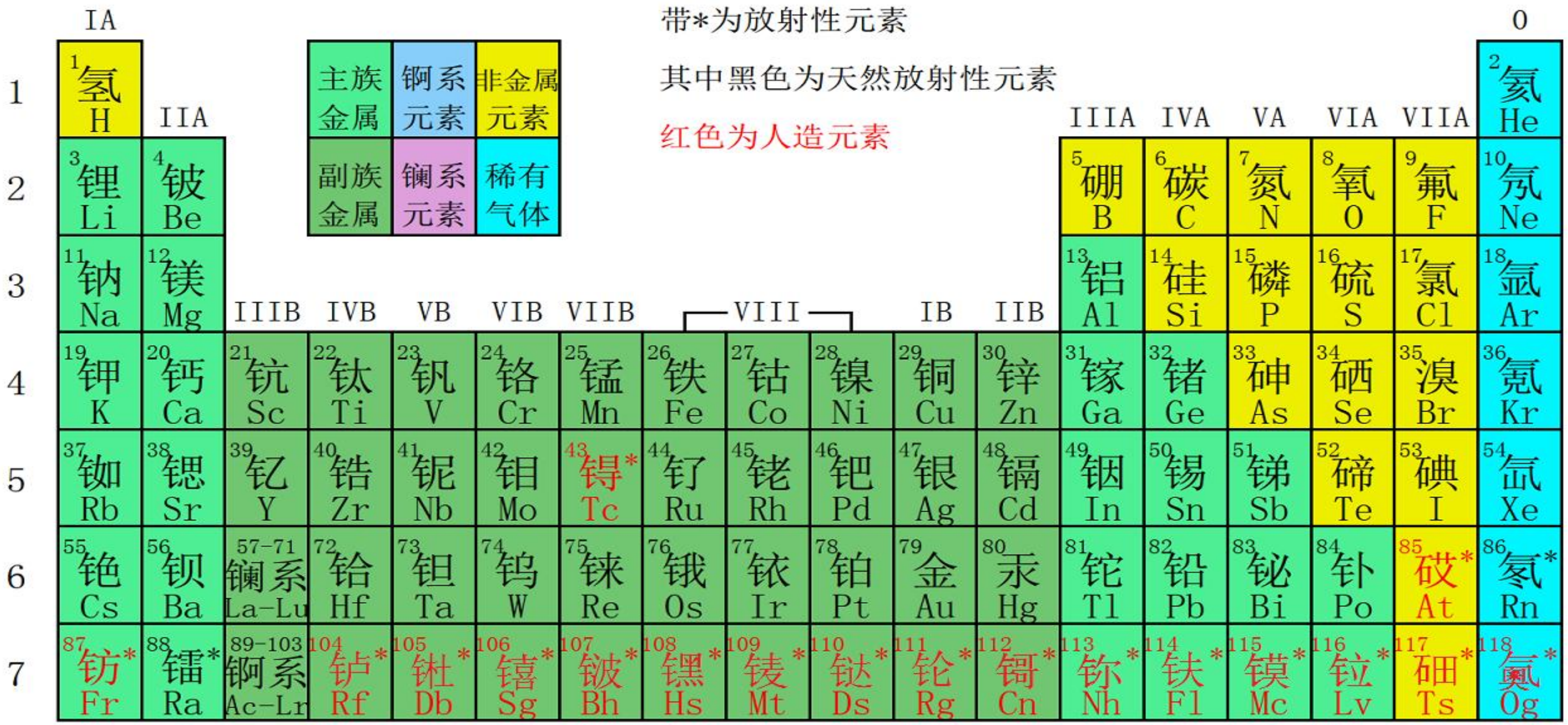
超重原子核（SHN）——实验进展



实验室合成了118号及118号以下的超重元素
这些元素都已经被命名，其中，最近的四个：
Z = 113、115、117和118号

Courtesy of Kai Wen (温凯)

元素周期表——何处是尽头？



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

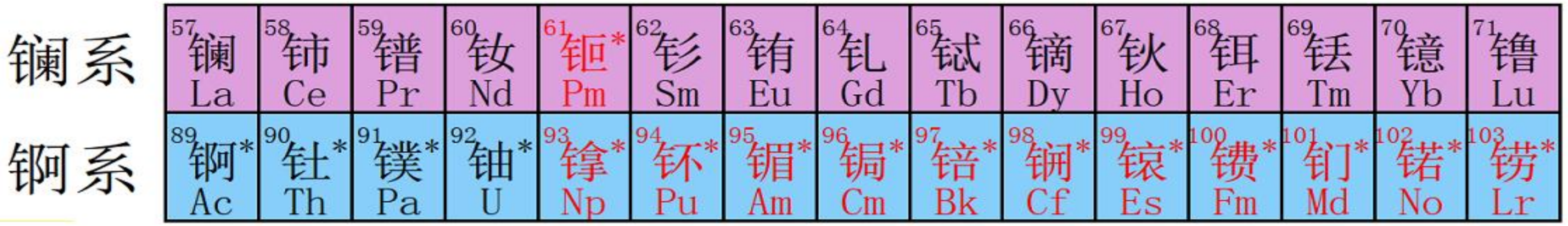
带*为放射性元素

其中黑色为天然放射性元素

红色为人造元素

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	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 鿭* Nh	114 𫓧* Fl	115 镆* Mc	116 𫟷* Lv	117 鿬* Ts	118 鿫* Og

周善贵，超重原子核与新元素研究，原子核物理评论 34 (2017) 318-331



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

兰州重离子加速器国家实验室：^{271}Ds (Z=110)

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

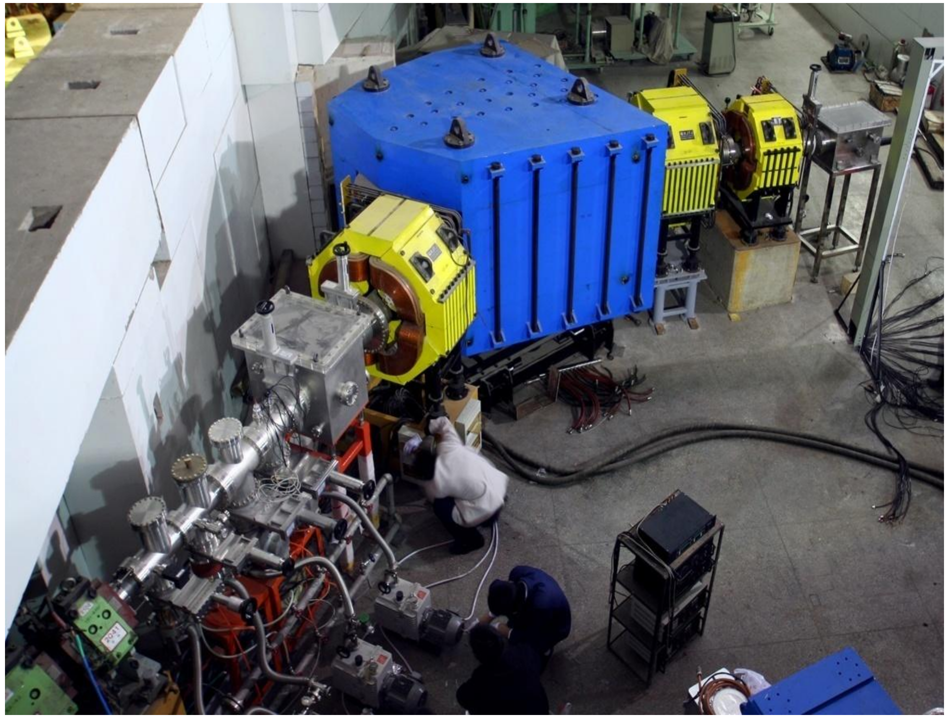
2011.03.15 $^{64}\text{Ni} + {}^{208}\text{Pb} \rightarrow {}^{272}\text{Ds}^*$ 13 days

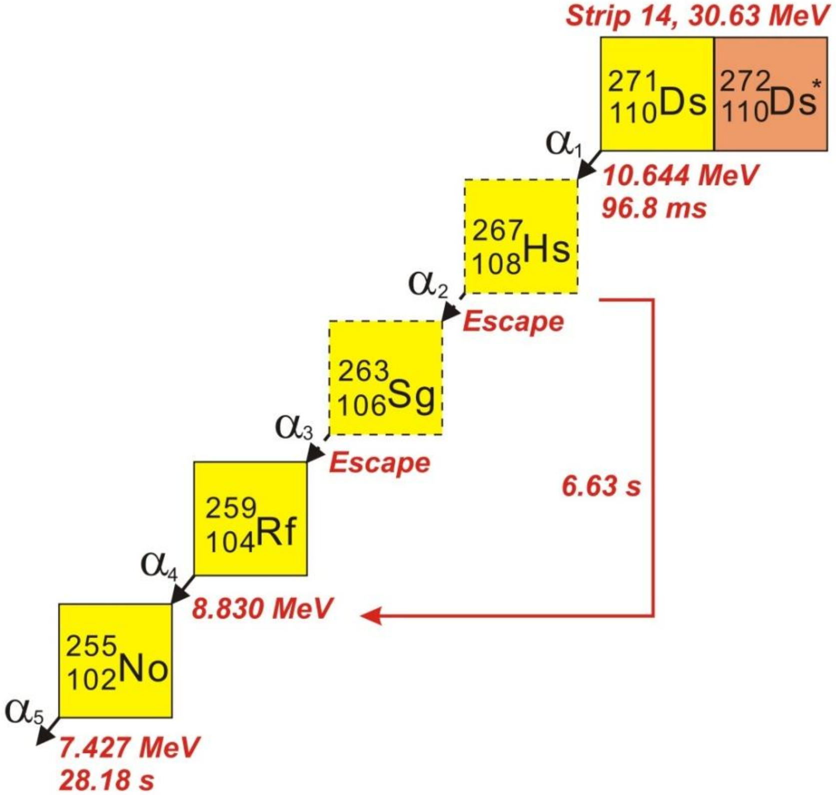
2001: ^{259}Db (Z=105)
2004: ^{265}Bh (Z=107)

IMP/CAS, ITP/CAS

Nanjing Univ, CIAE

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





Courtesy of Zai-Guo Gan (甘再国)

HIRFL +SHANS

SHANS

Spectrometer for Heavy Atoms and Nuclear Structure (SHANS)

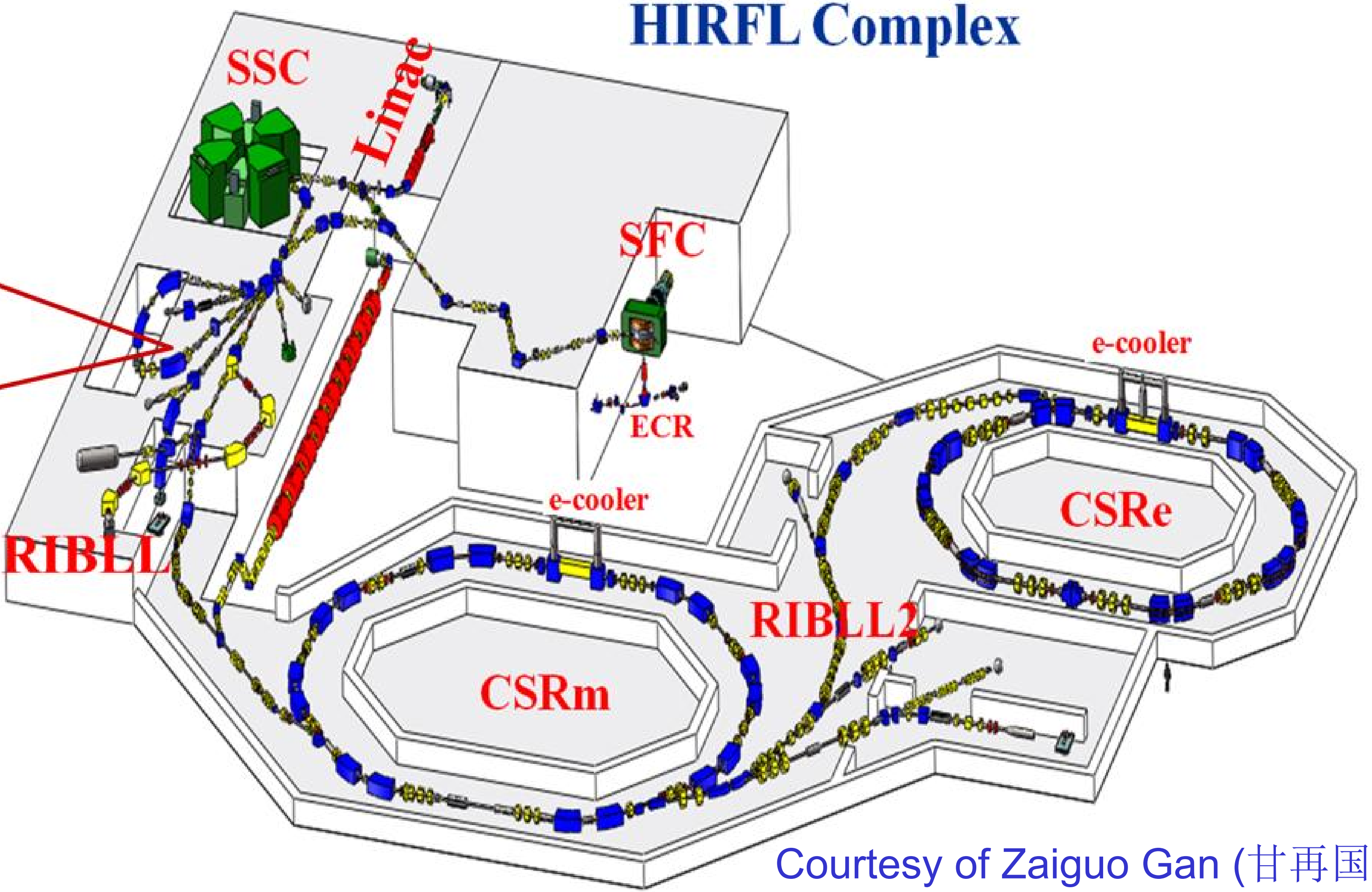
Mode: ECR/SECR + SFC

Ions: Ar, Ca, Ne, Mg, Ni, Kr, …

Energy: ~ 5 MeV/u

Typical Intensity: ~500 pnA (^{36,40}Ar)

200~500 pnA (^{40}Ca)



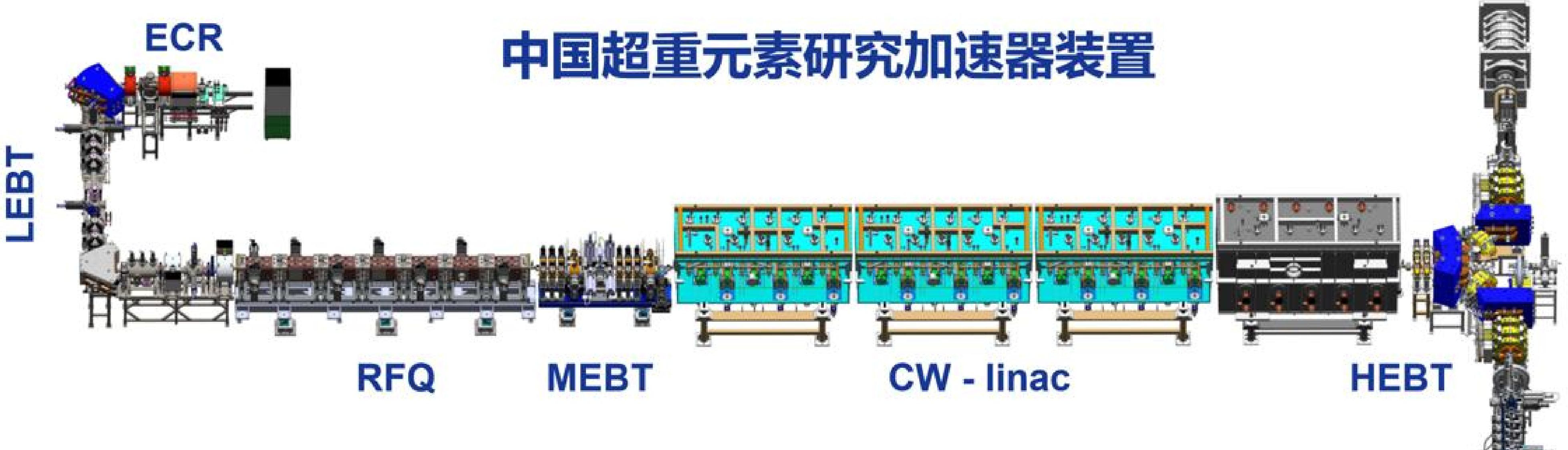
Courtesy of Zaiguo Gan (甘再国)

Heavy Ion Research Facility in Lanzhou (HIRFL), China

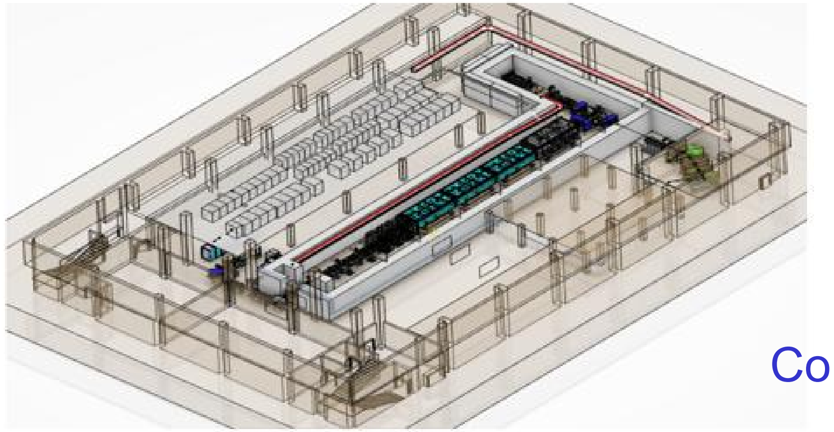
CAFE2+SHANS2

China Accelerator Facility for Superheavy Elements (CAFE2)

中国超重元素研究加速器装置

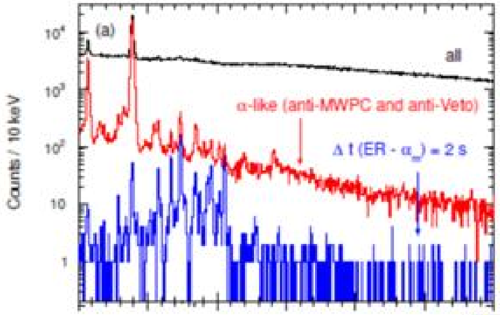


Designed parameters	Goal
Ions	Ca～Fe
A/Q	3
Beam energy	4.5-7 MeV/u
Beam current	3～5 puA
Running mode	CW



Courtesy of Zaiguo Gan (甘再国)

Re-investigation on ^{288}Mc



Chain 1
E_{imp}: 11.45 MeV
StripX: 66, StripY: 41
2023-11-18

- ^{288}Mc → α1: E_α: 10.24 MeV, Δt: 401 ms
- ^{284}Nh → α2: E_α: 9.98 MeV, Δt: 0.40 s
- ^{280}Rg → α3: E_α: 9.75 (=3.11+6.64) MeV, Δt: 14 s
- ^{276}Mt → α4: E_α: 9.78 MeV, Δt: 0.72 s
- ^{272}Bh → α5: E_α: 9.04 (=0.62+8.42) MeV, Δt: 8.9 s
- ^{268}Db → α6: E_α: ?, Δt: ?
- ^{264}Lr
- E_{SF}: 170 MeV, Δt: 64 h (since α5)

Chain 2
E_{imp}: 8.42 MeV
StripX: 51, StripY: 27
2023-11-19

- ^{288}Mc → α1: E_α: 10.34 (=0.18+10.26) MeV, Δt: 122 ms
- ^{284}Nh → α2: E_α: 9.96 MeV, Δt: 0.83 s
- ^{280}Rg → α3: E_α: 9.76 MeV, Δt: 4.5 s
- ^{276}Mt → α4: E_α: 9.59 MeV, Δt: 0.25 s
- ^{272}Bh → α5: E_α: 9.05 MeV, Δt: 26 s
- ^{268}Db → α6: E_α: ?, Δt: ?
- ^{264}Lr
- E_{SF}: 182 (=136+46) MeV, Δt: 8.8 h (since α5)

Chain 3
E_{imp}: 12.28 MeV
StripX: 41, StripY: 21
2023-11-19

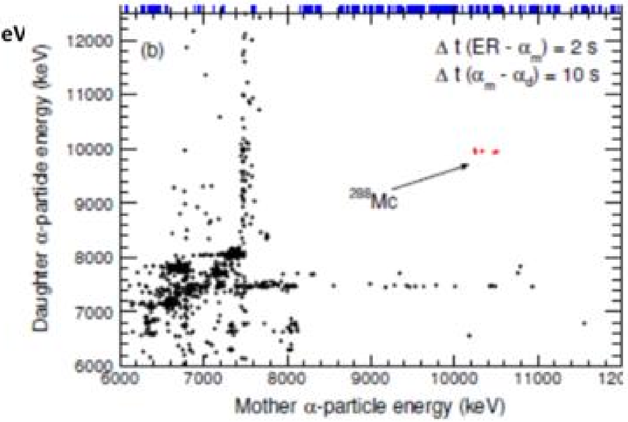
- ^{288}Mc → α1: E_α: 10.25 (=0.37+9.88) MeV, Δt: 142 ms
- ^{284}Nh → α2: E_α: 9.92 (=0.64+9.28) MeV, Δt: 0.65 s
- ^{280}Rg → α3: E_α: 9.72 (=0.66+9.06) MeV, Δt: 11 s
- ^{276}Mt → α4: missing
- ^{272}Bh → α5: E_α: 9.07 (=1.05+8.02) MeV, Δt: 12 s (α4+α5)
- ^{268}Db → α6: E_α: ?, Δt: ?
- ^{264}Lr
- E_{SF}: 166 MeV, Δt: 32.4 h (since α5)

Chain 4
E_{imp}: 12.46 MeV
StripX: 47, StripY: 25
2023-11-22

- ^{288}Mc → α1: E_α: 10.47 MeV, Δt: 375 ms
- ^{284}Nh → α2: E_α: 9.94 (=0.43+9.51) MeV, Δt: 1.2 s
- ^{280}Rg → α3: E_α: 9.74 MeV, Δt: 7.3 s
- ^{276}Mt → α4: E_α: 9.53 MeV, Δt: 0.23 s
- ^{272}Bh → α5: missing

Chain 5
E_{imp}: 11.36 MeV
StripX: 110/111, StripY: 15
2023-11-23

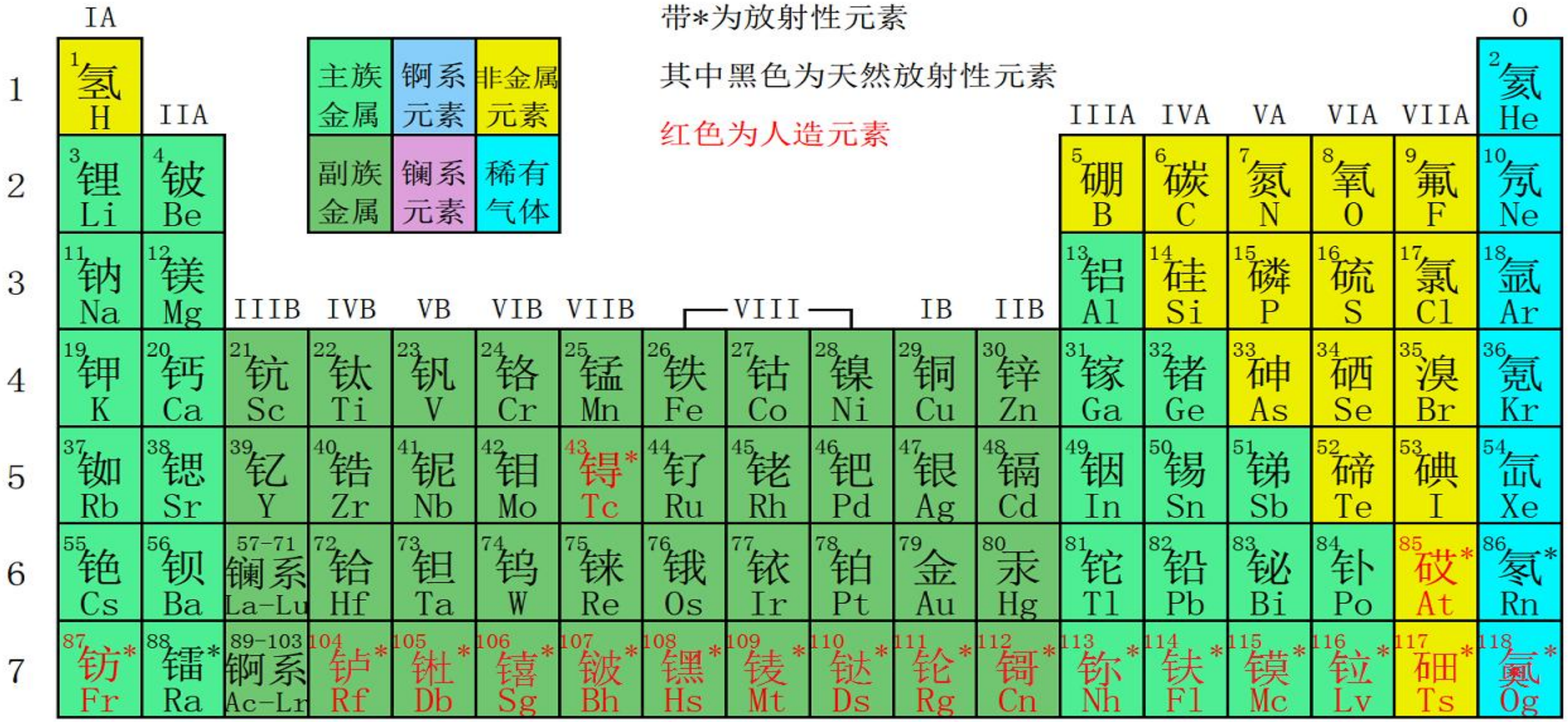
- ^{288}Mc → α1: E_α: 10.52 MeV, Δt: 152 ms
- ^{284}Nh → α2: E_α: 9.95 (=0.58+9.37) MeV, Δt: 0.20 s
- ^{280}Rg → α3: E_α: 9.72 MeV, Δt: 2.8 s
- ^{276}Mt → α4: E_α: 9.72 MeV, Δt: 1.1 s
- ^{272}Bh → α5: E_α: 9.04 MeV, Δt: 2.5 s
- ^{268}Db → α6: E_α: 7.81 MeV, Δt: 41.2 h
- ^{264}Lr
- E_{SF}: 228 (=168+60) MeV, Δt: 6.6 h



- ✓ Five α-decay chains, assigned to the decay of ^{288}Mc, were detected.
- ✓ The measured α-decay properties of ^{288}Mc as well as its descendent nuclei are consistent with known data.

Courtesy of Zaiguo Gan (甘再国)

元素周期表



带*为放射性元素

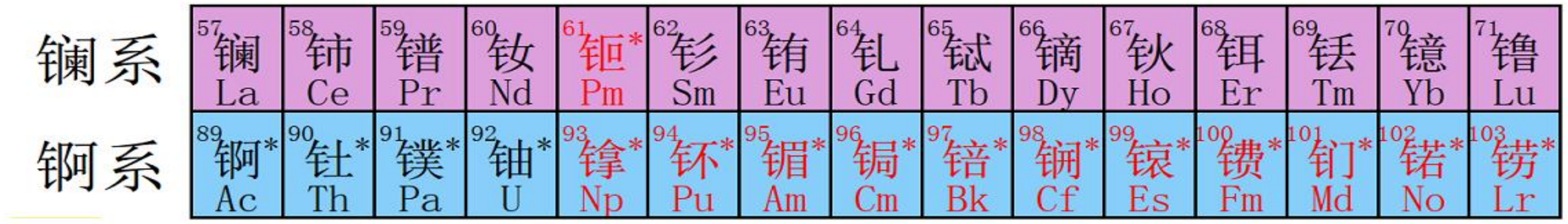
其中黑色为天然放射性元素

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 鎶* Cn	113 鿭* Nh	114 𫓧* Fl	115 镆* Mc	116 𫟷* Lv	117 鿬* Ts	118 鿫* Og

冷熔合反应：107-113；热熔合反应：114-118



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

Yuri Oganessian: Grandfather of SHE

卢* f	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 鿭* Nh	114 𫓧* Fl	115 镆* Mc	116 𫟷* Lv	117 鿬* Ts	118 鿫* Og

冷熔合反应：107-113　**热熔合反应：114-118**

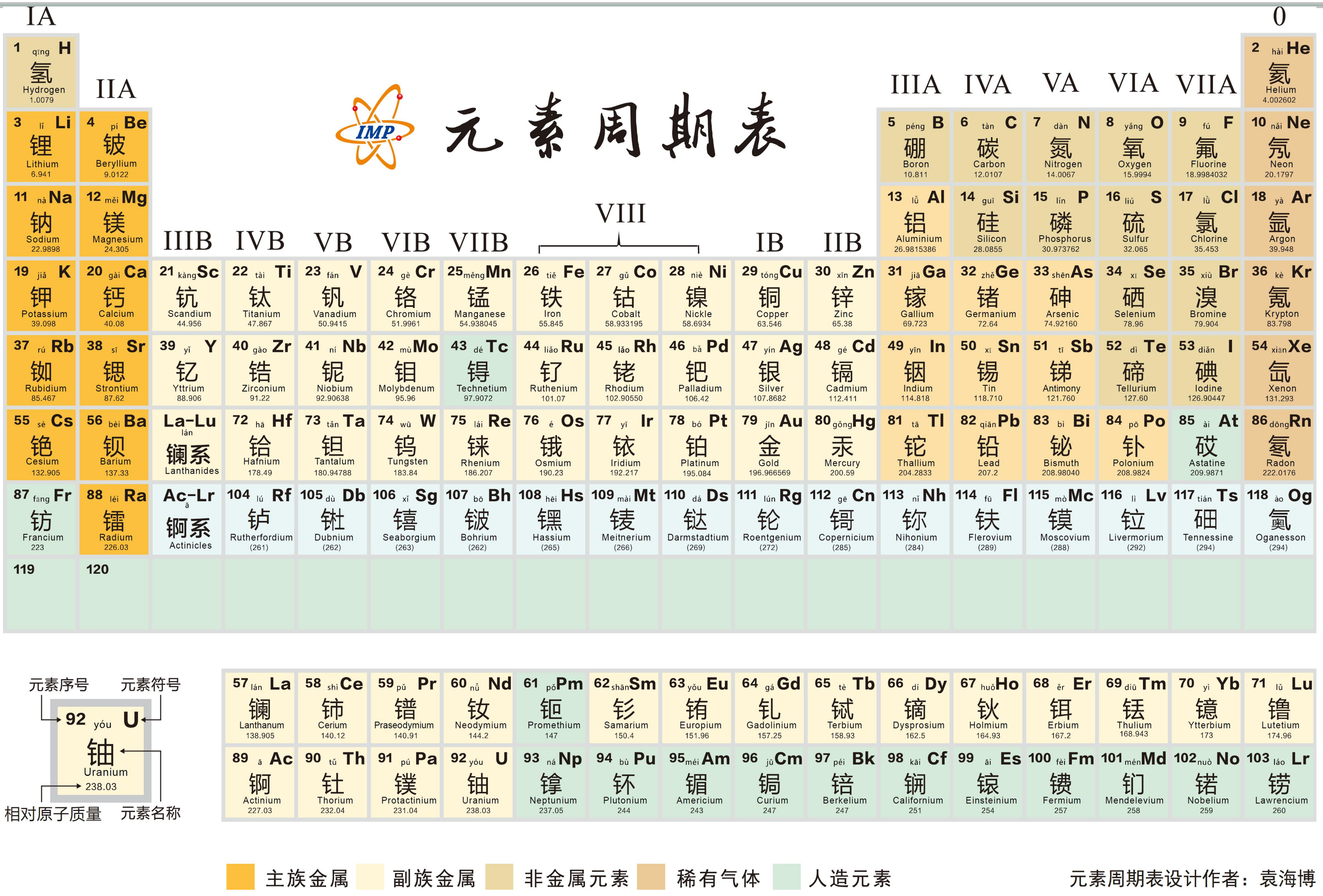
SCIENCE BRINGS NATIONS TOGETHER

International Conference «50 Years of Cold Fusion»

2024年11月19日 00:00 → 2024年11月24日 23:59 Europe/Moscow

Ramada Hotel & Suites by Wyndham Yerevan, Republic of Armenia

元素周期表——何处是尽头？



元素周期表

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1 qīng H 氢 Hydrogen 1.0079																	2 hài He 氦 Helium 4.002602
3 lǐ Li 锂 Lithium 6.941	4 pí Be 铍 Beryllium 9.0122											5 péng B 硼 Boron 10.811	6 tàn C 碳 Carbon 12.0107	7 dàn N 氮 Nitrogen 14.0067	8 yǎng O 氧 Oxygen 15.9994	9 fú F 氟 Fluorine 18.9984032	10 nǎi Ne 氖 Neon 20.1797
11 nà Na 钠 Sodium 22.9898	12 měi Mg 镁 Magnesium 24.305											13 lǚ Al 铝 Aluminium 26.9815386	14 guī Si 硅 Silicon 28.0855	15 lín P 磷 Phosphorus 30.973762	16 liú S 硫 Sulfur 32.065	17 lǜ Cl 氯 Chlorine 35.453	18 yà Ar 氩 Argon 39.948
19 jiǎ K 钾 Potassium 39.098	20 gài Ca 钙 Calcium 40.08	21 kàng Sc 钪 Scandium 44.956	22 tài Ti 钛 Titanium 47.867	23 fán V 钒 Vanadium 50.9415	24 gè Cr 铬 Chromium 51.9961	25 měng Mn 锰 Manganese 54.938045	26 tiě Fe 铁 Iron 55.845	27 gǔ Co 钴 Cobalt 58.933195	28 niè Ni 镍 Nickle 58.6934	29 tóng Cu 铜 Copper 63.546	30 xīn Zn 锌 Zinc 65.38	31 jiā Ga 镓 Gallium 69.723	32 zhě Ge 锗 Germanium 72.64	33 shēn As 砷 Arsenic 74.92160	34 xī Se 硒 Selenium 78.96	35 xiù Br 溴 Bromine 79.904	36 kè Kr 氪 Krypton 83.798
37 rú Rb 铷 Rubidium 85.467	38 sī Sr 锶 Strontium 87.62	39 yǐ Y 钇 Yttrium 88.906	40 gào Zr 锆 Zirconium 91.22	41 ní Nb 铌 Niobium 92.90638	42 mù Mo 钼 Molybdenum 95.96	43 dé Tc 锝 Technetium 97.9072	44 liǎo Ru 钌 Ruthenium 101.07	45 lǎo Rh 铑 Rhodium 102.90550	46 bǎ Pd 钯 Palladium 106.42	47 yín Ag 银 Silver 107.8682	48 gé Cd 镉 Cadmium 112.411	49 yīn In 铟 Indium 114.818	50 xī Sn 锡 Tin 118.710	51 tī Sb 锑 Antimony 121.760	52 dì Te 碲 Tellurium 127.60	53 diǎn I 碘 Iodine 126.90447	54 xiān Xe 氙 Xenon 131.293
55 sè Cs 铯 Cesium 132.905	56 bèi Ba 钡 Barium 137.33	La-Lu lán 镧系 Lanthanides	72 hā Hf 铪 Hafnium 178.49	73 tǎn Ta 钽 Tantalum 180.94788	74 wū W 钨 Tungsten 183.84	75 lái Re 铼 Rhenium 186.207	76 é Os 锇 Osmium 190.23	77 yī Ir 铱 Iridium 192.217	78 bó Pt 铂 Platinum 195.084	79 jīn Au 金 Gold 196.966569	80 gǒng Hg 汞 Mercury 200.59	81 tā Tl 铊 Thallium 204.2833	82 qiān Pb 铅 Lead 207.2	83 bì Bi 铋 Bismuth 208.98040	84 pō Po 钋 Polonium 208.9824	85 ài At 砹 Astatine 209.9871	86 dōng Rn 氡 Radon 222.0176
87 fāng Fr 钫 Francium 223	88 léi Ra 镭 Radium 226.03	Ac-Lr ā 锕系 Actinicles	104 lú Rf 𬬻 Rutherfordium (261)	105 dù Db 𬭊 Dubnium (262)	106 xǐ Sg 𬭳 Seaborgium (263)	107 bō Bh 𬭛 Bohrium (262)	108 hēi Hs 𬭶 Hassium (265)	109 mài Mt 鿏 Meitnerium (266)	110 dá Ds 𫟼 Darmstadtium (269)	111 lún Rg 𬬭 Roentgenium (272)	112 gē Cn 鎶 Copernicium (285)	113 nǐ Nh 鉨 Nihonium (284)	114 fū Fl 𫓧 Flerovium (289)	115 mò Mc 镆 Moscovium (288)	116 lì Lv 𫟷 Livermorium (292)	117 tián Ts 鿬 Tennessine (294)	118 ào Og 鿫 Oganesson (294)
119	120																

57 lán La 镧 Lanthanum 138.905	58 shì Ce 铈 Cerium 140.12	59 pǔ Pr 镨 Praseodymium 140.91	60 nǚ Nd 钕 Neodymium 144.2	61 pǒ Pm 钷 Promethium 147	62 shān Sm 钐 Samarium 150.4	63 yǒu Eu 铕 Europium 151.96	64 gá Gd 钆 Gadolinium 157.25	65 tè Tb 铽 Terbium 158.93	66 dí Dy 镝 Dysprosium 162.5	67 huǒ Ho 钬 Holmium 164.93	68 ěr Er 铒 Erbium 167.2	69 diū Tm 铥 Thulium 168.943	70 yì Yb 镱 Ytterbium 173	71 lǔ Lu 镥 Lutetium 174.96
89 ā Ac 锕 Actinium 227.03	90 tǔ Th 钍 Thorium 232.04	91 pú Pa 镤 Protactinium 231.04	92 yóu U 铀 Uranium 238.03	93 ná Np 镎 Neptunium 237.05	94 bù Pu 钚 Plutonium 244	95 méi Am 镅 Americium 243	96 jū Cm 锔 Curium 247	97 péi Bk 锫 Berkelium 247	98 kāi Cf 锎 Californium 251	99 āi Es 锿 Einsteinium 254	100 fèi Fm 镄 Fermium 257	101 mén Md 钔 Mendelevium 258	102 nuò No 锘 Nobelium 259	103 láo Lr 铹 Lawrencium 260

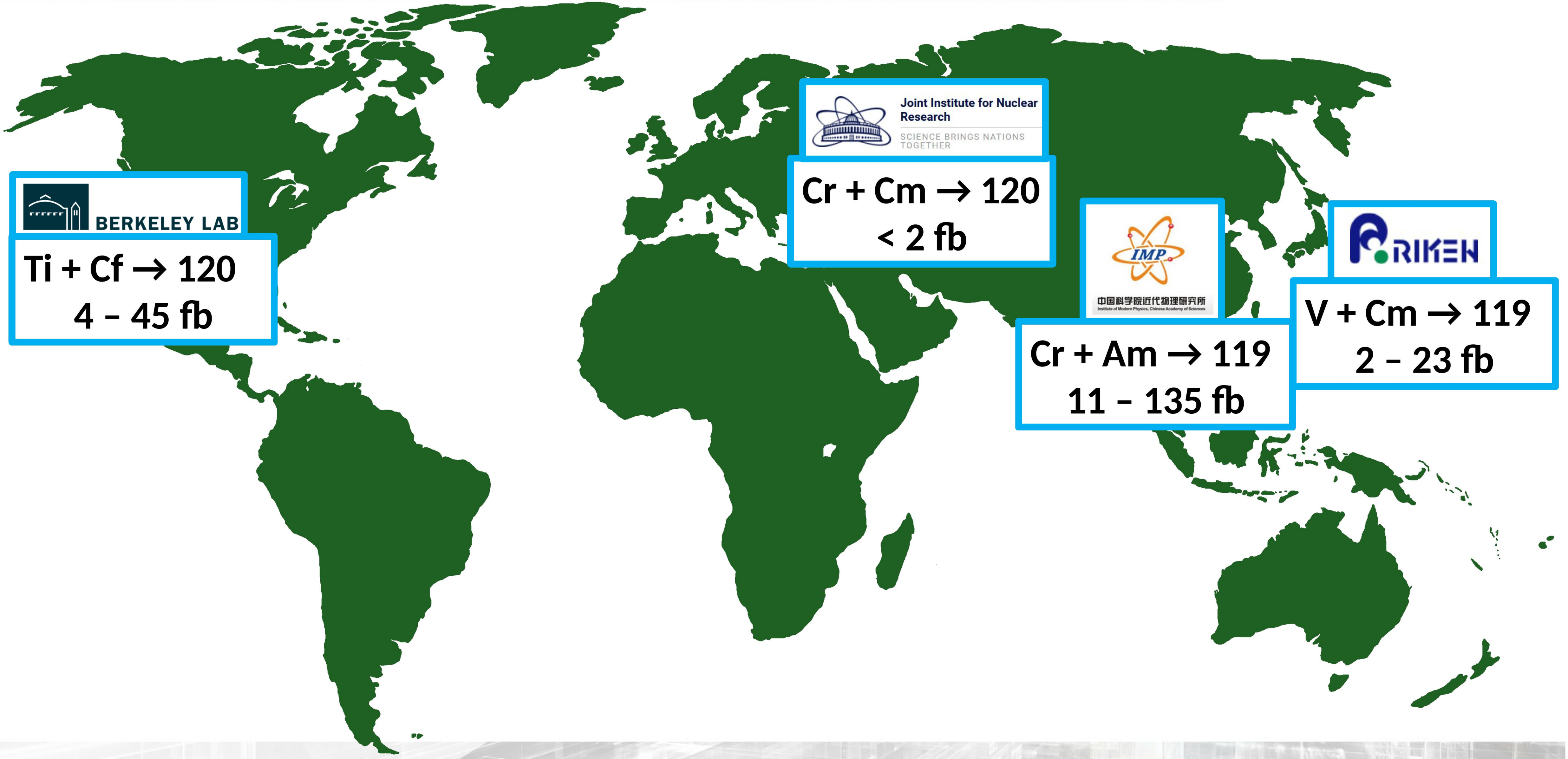
元素序号 元素符号

92 yóu U
铀
Uranium
238.03

相对原子质量 元素名称

🟧 主族金属 🟨 副族金属 🟫 非金属元素 🟫 稀有气体 🟩 人造元素

元素周期表设计作者：袁海博



BERKELEY LAB

Ti + Cf → 120
4 – 45 fb

Joint Institute for Nuclear Research
SCIENCE BRINGS NATIONS TOGETHER

Cr + Cm → 120
< 2 fb

IMP
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Cr + Am → 119
11 – 135 fb

RIKEN

V + Cm → 119
2 – 23 fb

NARODOWE
CENTRUM
BADAŃ
JĄDROWYCH
ŚWIERK

Courtesy of Tomasz Cap

内容提要

□ 引言

□ 超重原子核

- 超重岛的理论预言与实验进展
- 超重新元素合成面临的问题与挑战
- 超重原子核性质及合成机制研究

□ 小结

周善贵，超重原子核与超重元素，物理 43 (2014) 817-825

李璐璐、吕炳楠、王楠、温凯、夏铖君、张振华、赵杰、赵恩广、周善贵，超重核性质与合成机制的理论研究，原子核物理评论 31 (2014) 253-272

吕炳楠、赵杰、赵恩广、周善贵，Superheavy nuclei and fission barriers, Chapter 5 in *Relativistic Density Functional for Nuclear Structure* (World Scientific, 2016, Editor: Jie Meng)

周善贵，超重原子核与新元素研究，原子核物理评论 34 (2017) 318-331

超重元素合成面临的问题与挑战

- □ 现有方法合成截面极低，实验周期长
  - ➢ ^{271}Ds: σ ~ 10 pb；兰州： 20天，1个事件
  - ➢ ^{278}Nh: σ ~ 0.02 pb；RIKEN：553天，3个事件

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- □ 靶材料不易制备
- □ 长寿命超重核如何探测
- □ …

超重元素合成面临的问题与挑战

□ 现有方法合成截面极低，实验周期长

- ➢ ^{271}Ds: $\sigma \sim 10$ pb；兰州：
- ➢ ^{278}Nh: $\sigma \sim 0.02$ pb；RIKEN：

更强（束流）、更厚（靶）、更高（探测效率）

✓ SHE Factory @ Dubna

✓ CAFE2+SHAN2@Lanzhou; HIAF @ Huizhou

□ 现有方法只能合成缺中子超重核，离预言的超重岛中心很远

多核子转移反应；丰中子束流？

Bao_Gao_Li_Zhang2015_PRC91-064612

□ 靶材料不易制备

□ 长寿命超重核如何探测

SHANS @ Lanzhou or Huizhou

□ …

布居超重核的同核异能态　　Xu_Zhao_Wyss_Walker2004_PRL92-252501

内容提要

- □ 引言
- □ 超重原子核
  - ➢ 超重岛的理论预言与实验进展
  - ➢ 超重新元素合成面临的问题与挑战
  - ➢ 超重原子核性质及合成机制研究
- □ 小结

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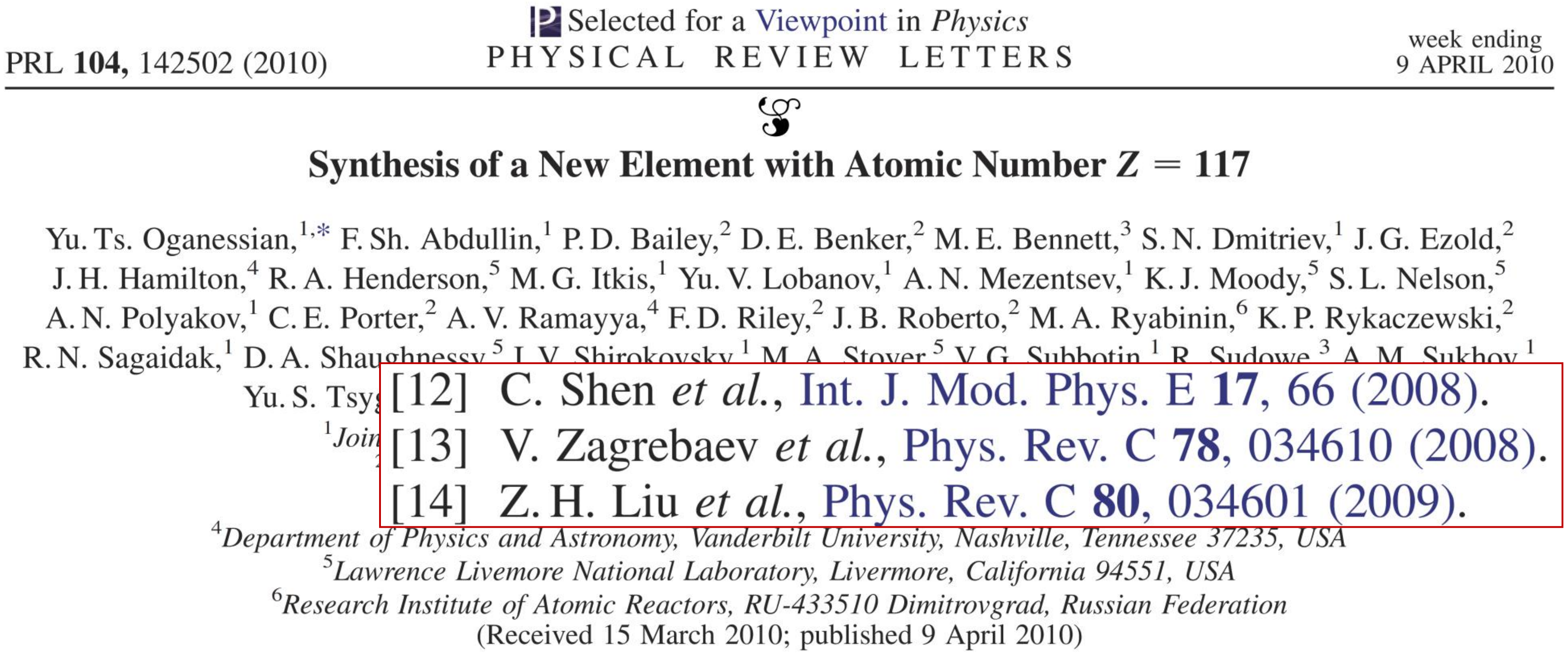
周善贵，超重原子核与新元素研究，原子核物理评论 34 (2017) 318-331

超重核研究——理论与实验结合

□ 超重核研究是理论与实验相互结合、相互促进的典型例子

- 1960年代，超重岛的理论预言促进了重离子加速器的建造；1980年代，超重核合成实验开始取得重要进展
- …
- 2010年，117号元素的合成



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 $Z = 117$

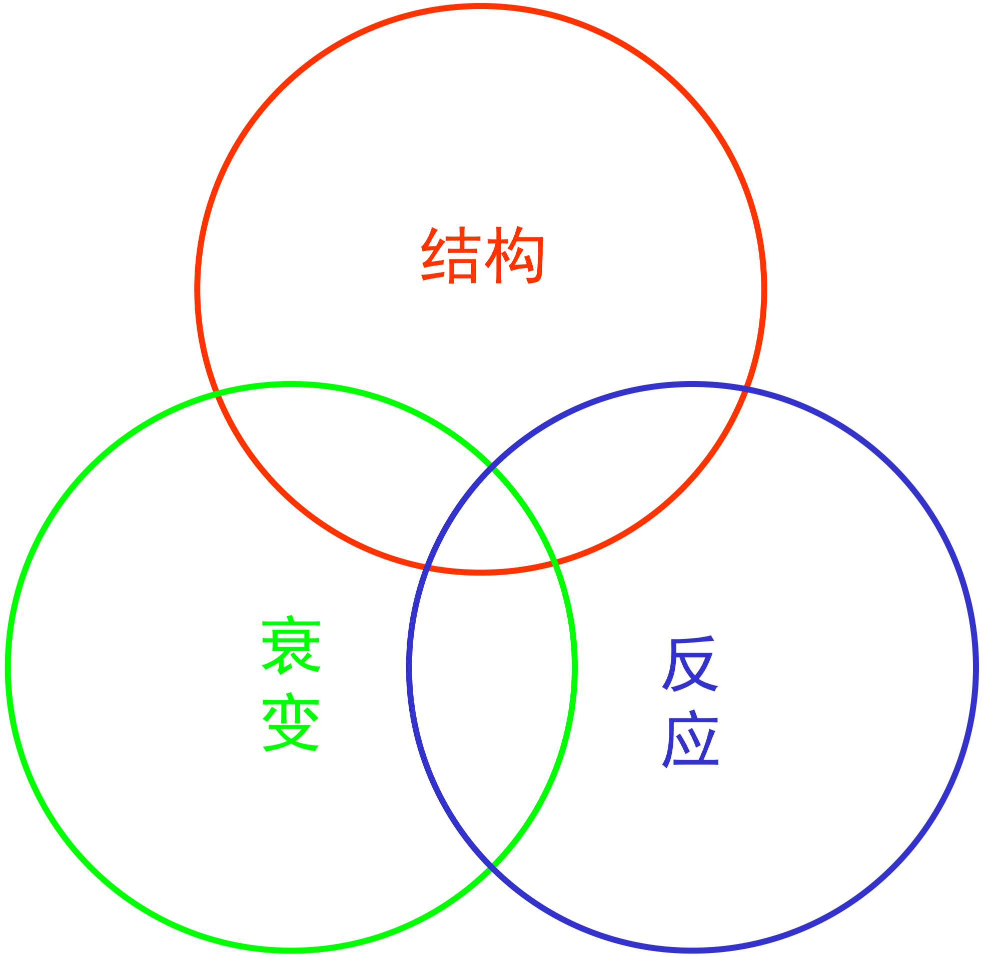
Yu. Ts. Oganessian,[1,*] F. Sh. Abdullin,[1] P. D. Bailey,[2] D. E. Benker,[2] M. E. Bennett,[3] S. N. Dmitriev,[1] J. G. Ezold,[2]
J. H. Hamilton,[4] R. A. Henderson,[5] M. G. Itkis,[1] Yu. V. Lobanov,[1] A. N. Mezentsev,[1] K. J. Moody,[5] S. L. Nelson,[5]
A. N. Polyakov,[1] C. E. Porter,[2] A. V. Ramayya,[4] F. D. Riley,[2] J. B. Roberto,[2] M. A. Ryabinin,[6] K. P. Rykaczewski,[2]
R. N. Sagaidak,[1] D. A. Shaughnessy,[5] I. V. Shirokovsky,[1] M. A. Stoyer,[5] V. G. Subbotin,[1] R. Sudowe,[3] A. M. Sukhov,[1]
Yu. S. Tsy

[1]*Join*

[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).

[4]*Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235, USA*
[5]*Lawrence Livermore National Laboratory, Livermore, California 94551, USA*
[6]*Research Institute of Atomic Reactors, RU-433510 Dimitrovgrad, Russian Federation*
(Received 15 March 2010; published 9 April 2010)

超重原子核结构、衰变及合成机制

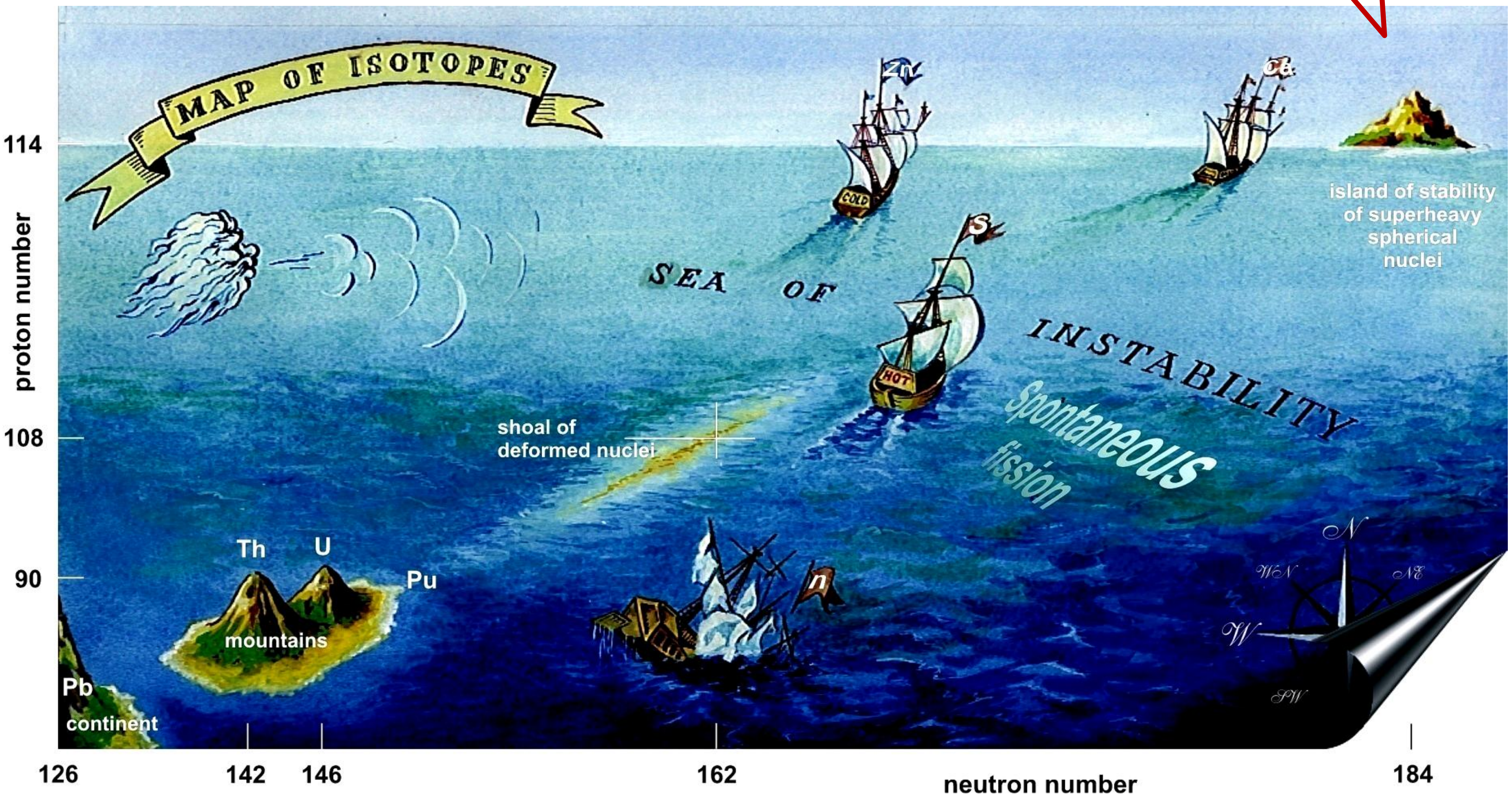


超重岛在哪儿?

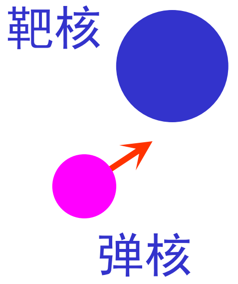
Z = ? 114 120 126 132 138

N = ? 172 184 198 228 238 258

超重岛?



利用重离子熔合反应合成超重核的三步过程



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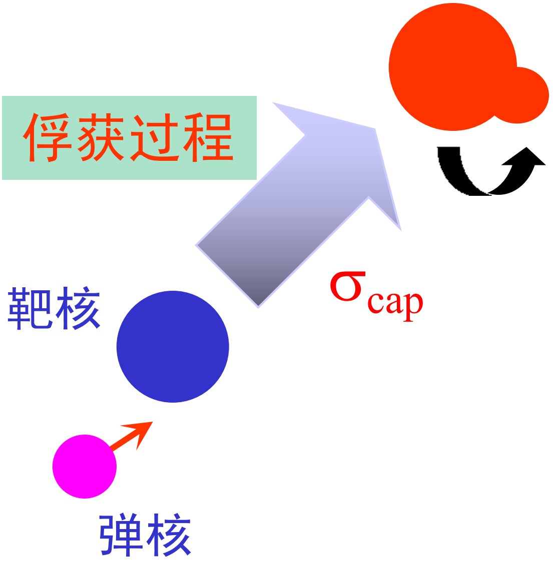

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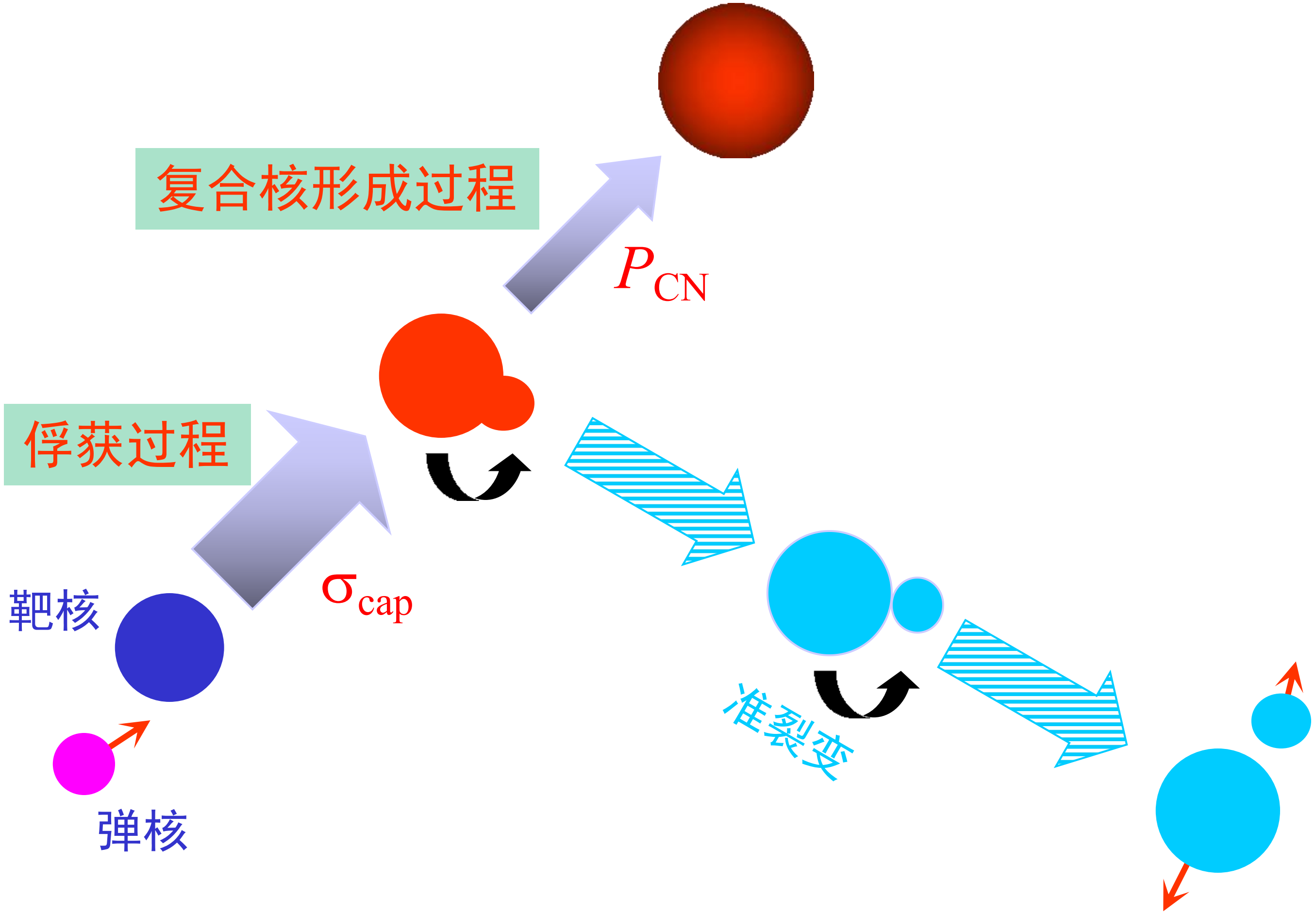


复合核形成过程

P_{CN}

俘获过程

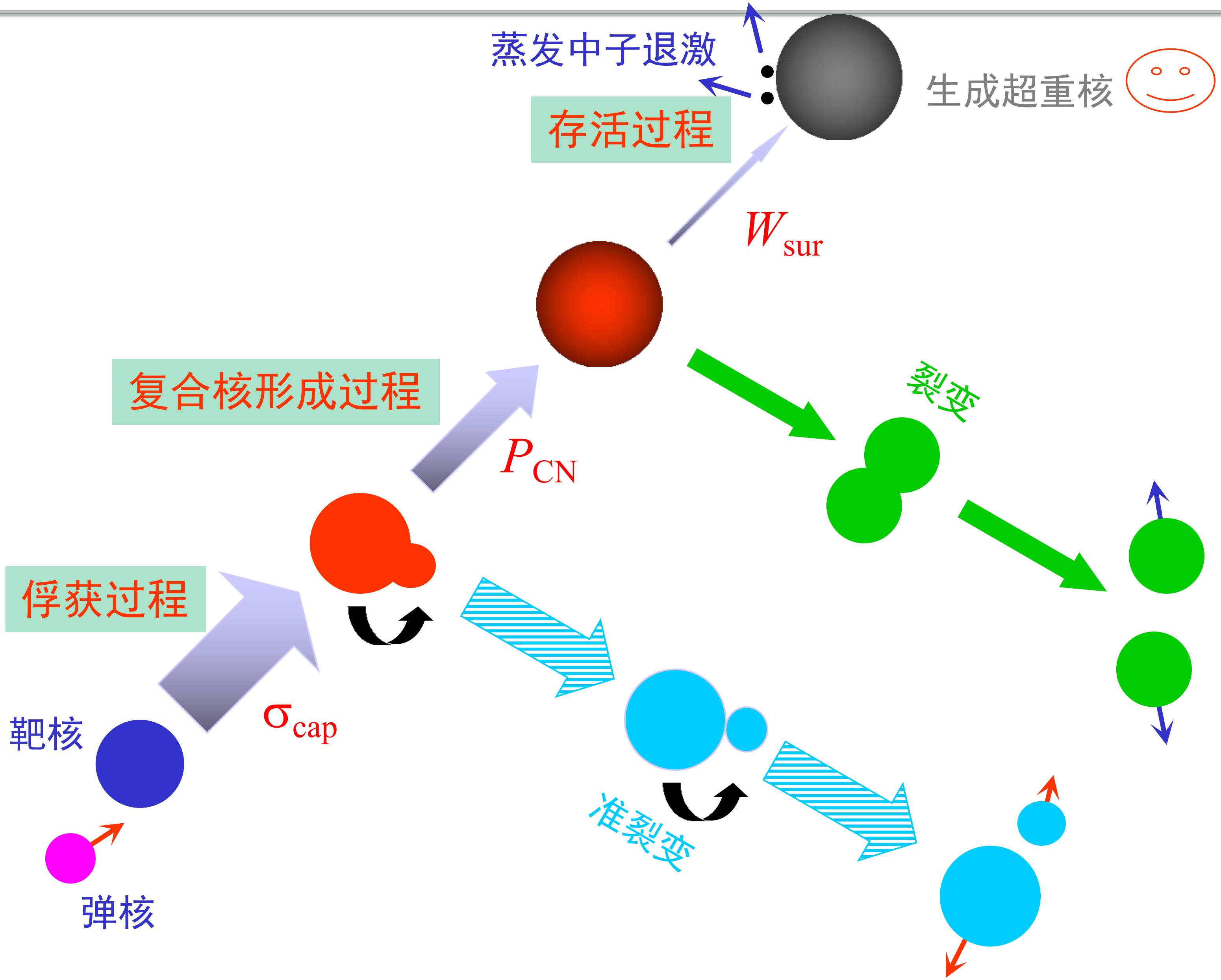
σ_{cap}

靶核

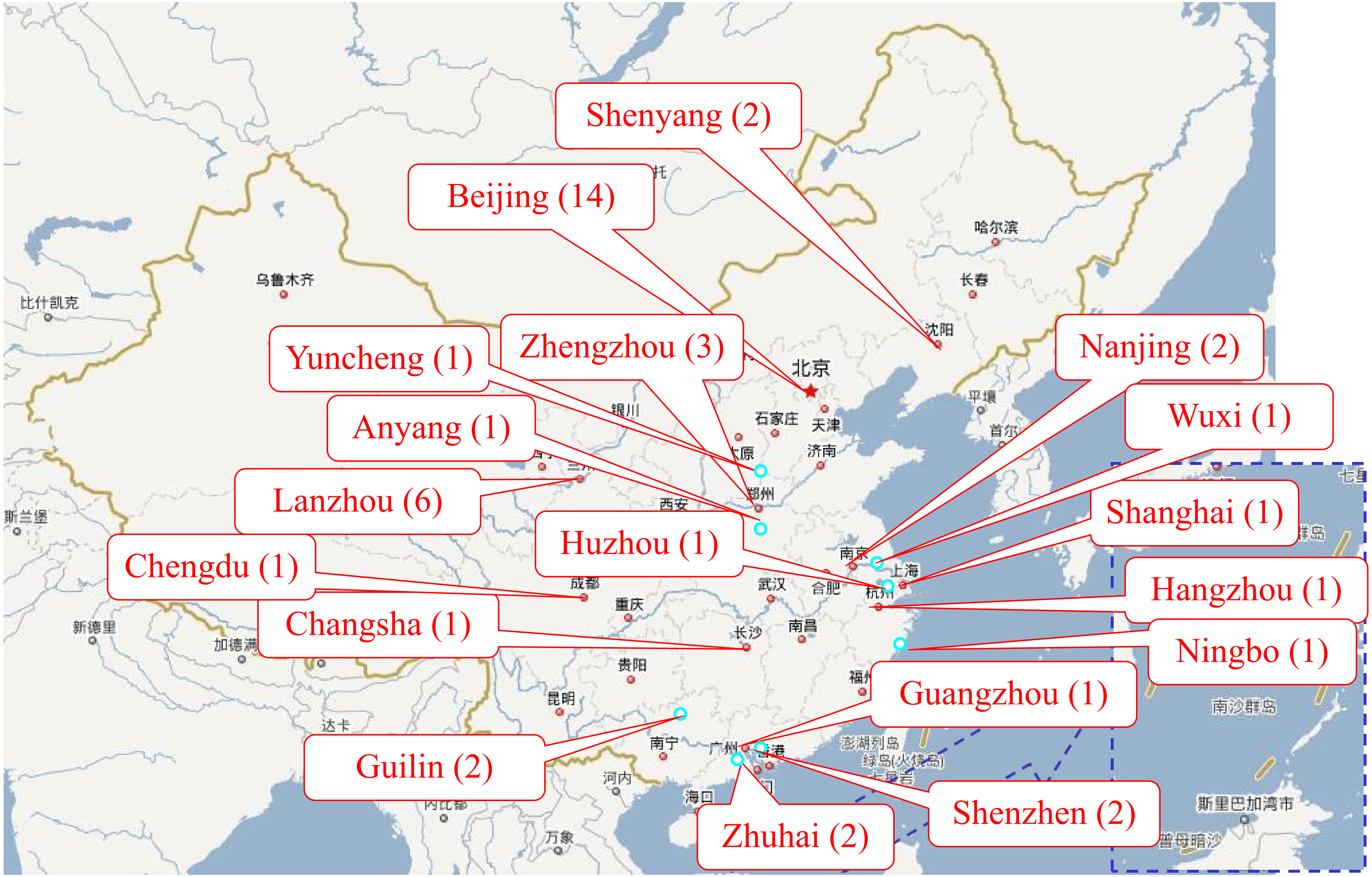
弹核

准裂变

利用重离子熔合反应合成超重核的三步过程



超重核合成的理论研究——模型、物理和队伍



超重核合成的理论研究——模型、物理和队伍

模型

A. 双核模型
B. 涨落-耗散模型
C. QMD模型
D. TDHF理论
E. BUU模型
F. 其他

物理

1. 合成截面
2. 俘获动力学
3. 裂变、准裂变
4. 熔合机制
5. 存活概率
6. 多核子转移
7. 其他

研究人员

- □ 包景东 (北师大: B1B4)；包小军 (湖南师大: A1)；卞宝安 (江南大学: C4)；樊铁栓（北大: F3）冯兆庆 (华南理工: A1C2)
- □ 郭璐 (国科大: D2D3D4)；高远 (杭州电子大学: A1)；黄明辉 (近物所: A1A4)；黄天衡 (近物所: A1A4)；蒋翔 (深圳: C4D4)；靳根明 (近物所: A1)
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- □ ……

超重核合成的理论研究——模型、物理和队伍

模　　型

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D. TDHF理论
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F. 其他

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- □ 包景东 (北师大: B1B
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- □ 郭璐 (国科大: D2D3
  衡 (近物所: A1A4)；
- □ 李君清 (近物所: A1A
  师大: A1)；刘玉鑫 (
  (北大: F1F3)；任中
- □ 沈彩万 (湖州: B1)；
  大: B1)；王兵 (郑大:
  能院: C4)；夏铖君 (
  C4D4)；许昌 (南大:
- □ 张丰收 (北师大: A1C
  C4)；周善贵 (理论物
  城实验室: F3)；赵凯
  A1)；左维 (近物所: A1)
- □ ……

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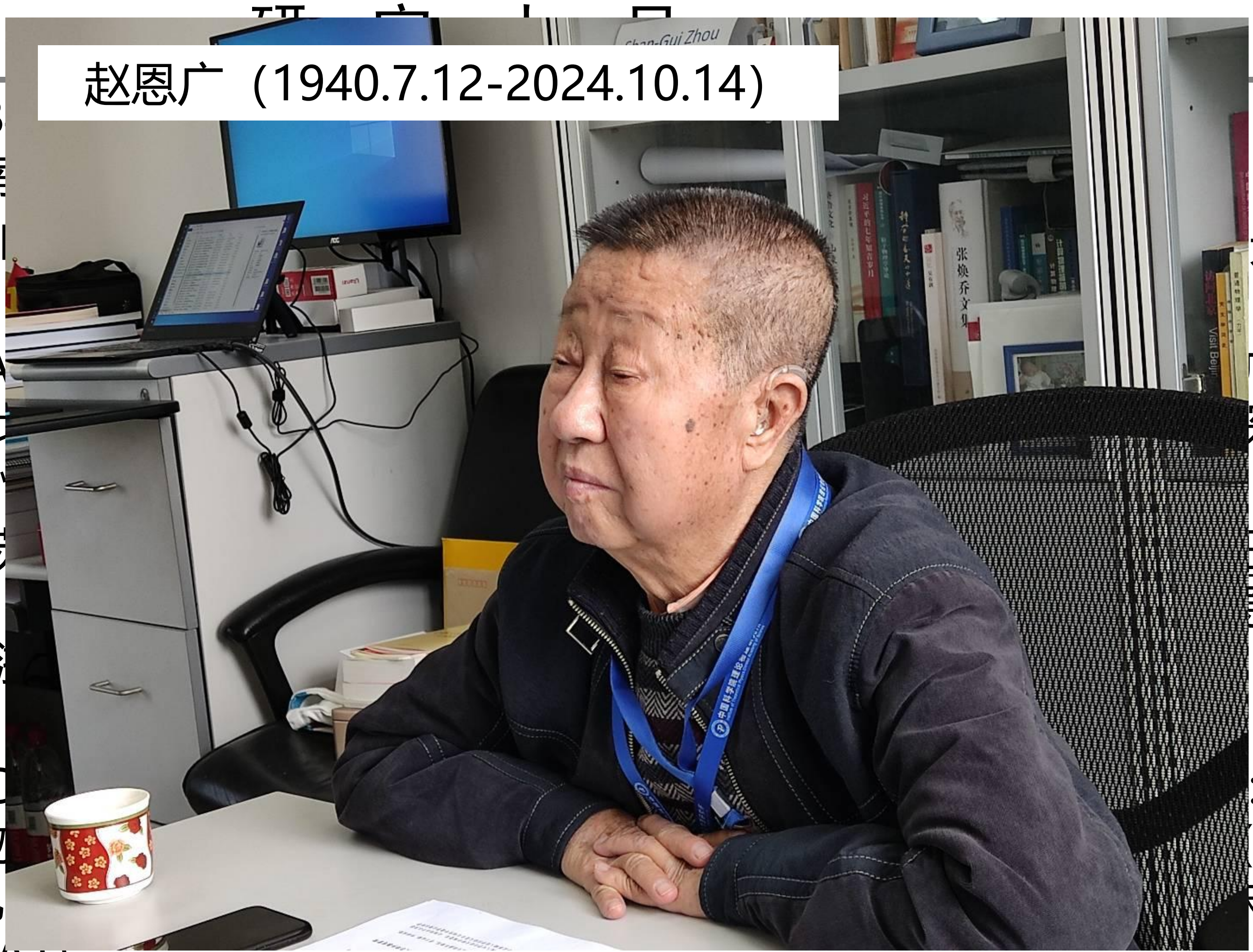
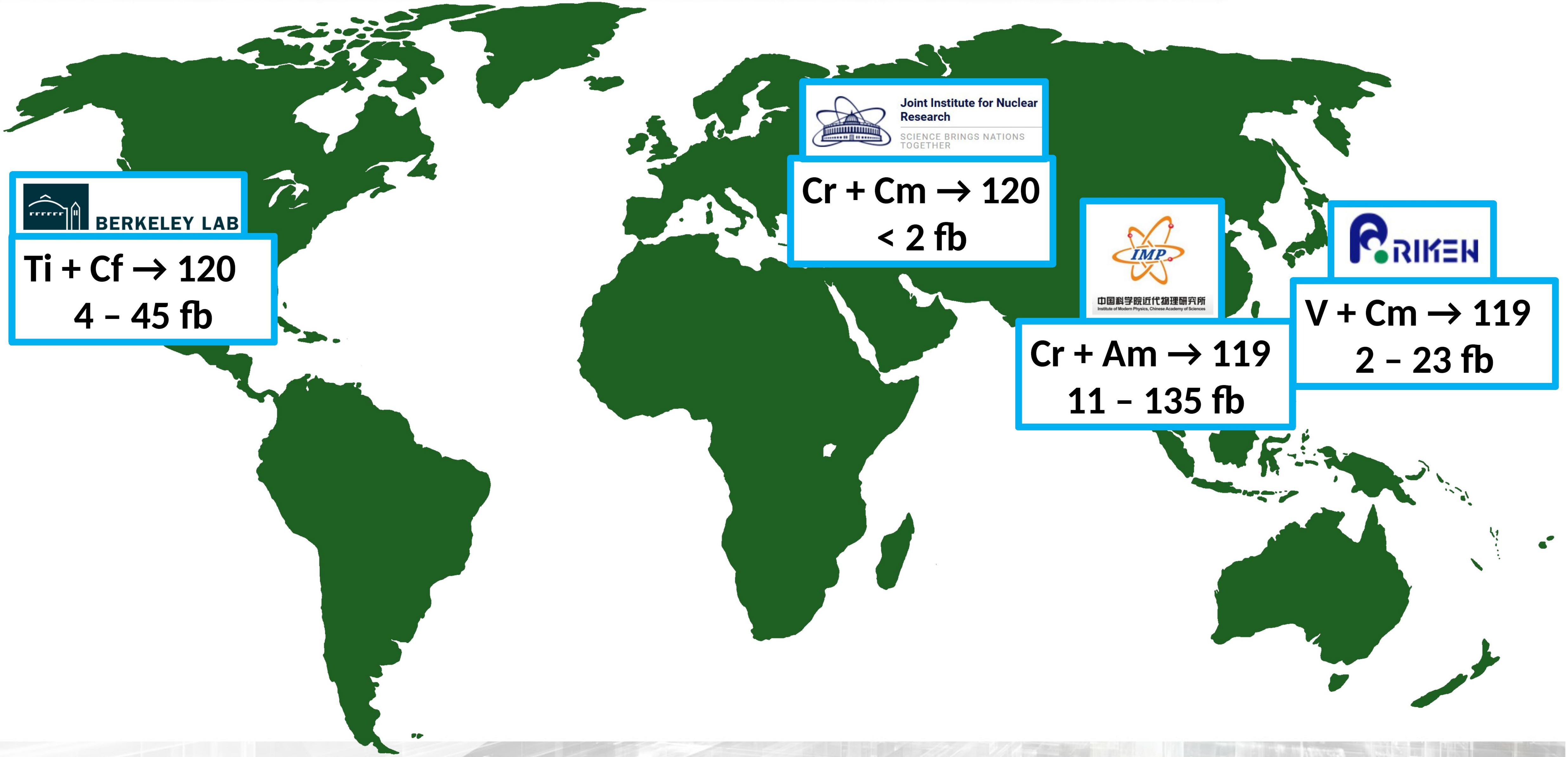


赵恩广（1940.7.12-2024.10.14）



BERKELEY LAB

Ti + Cf → 120
4 – 45 fb

Joint Institute for Nuclear Research
SCIENCE BRINGS NATIONS TOGETHER

Cr + Cm → 120
< 2 fb

IMP
中国科学院近代物理研究所
Institute of Modern Physics, Chinese Academy of Sciences

Cr + Am → 119
11 – 135 fb

RIKEN

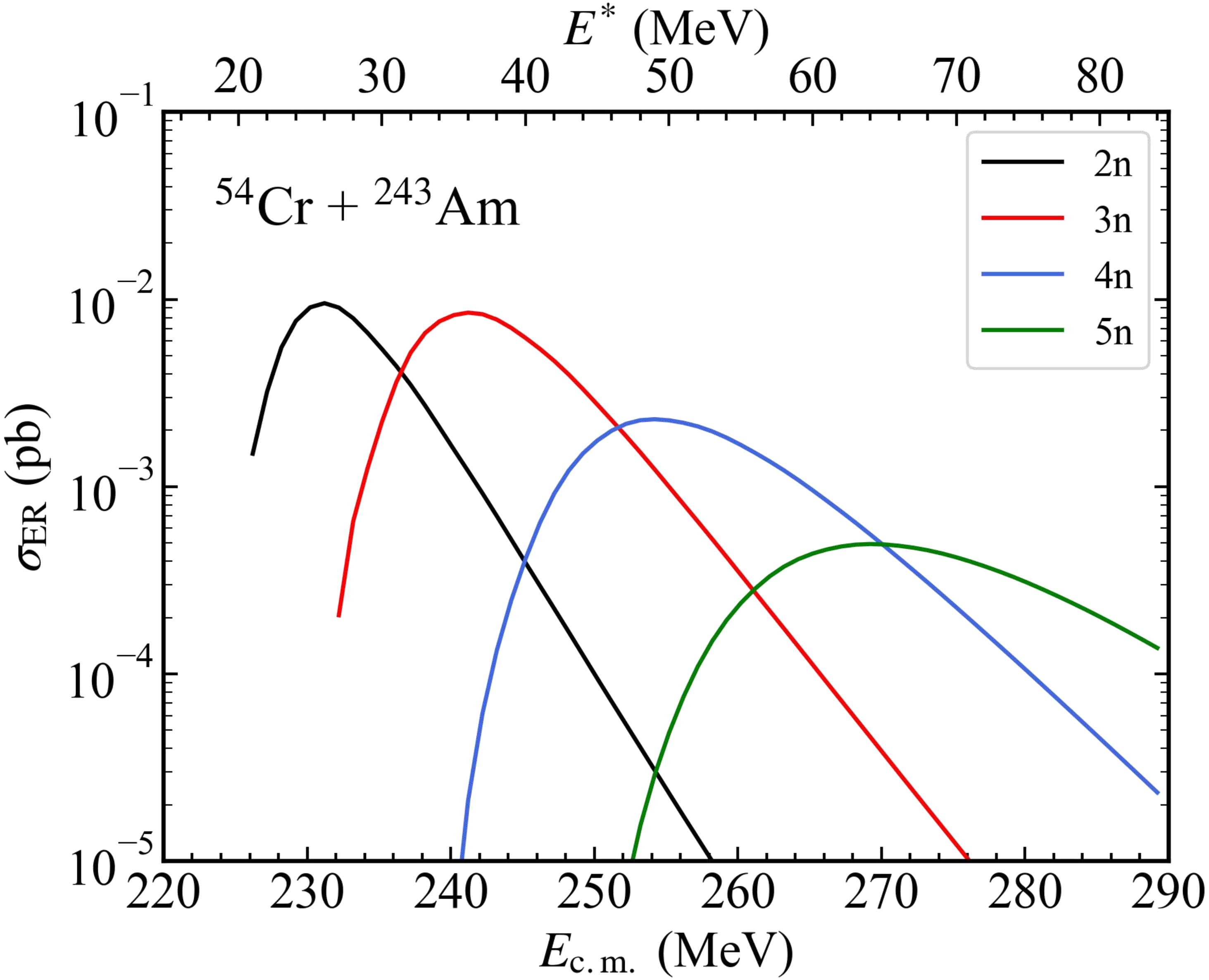
V + Cm → 119
2 – 23 fb

NARODOWE
CENTRUM
BADAŃ
JĄDROWYCH
ŚWIERK

Courtesy of Tomasz Cap

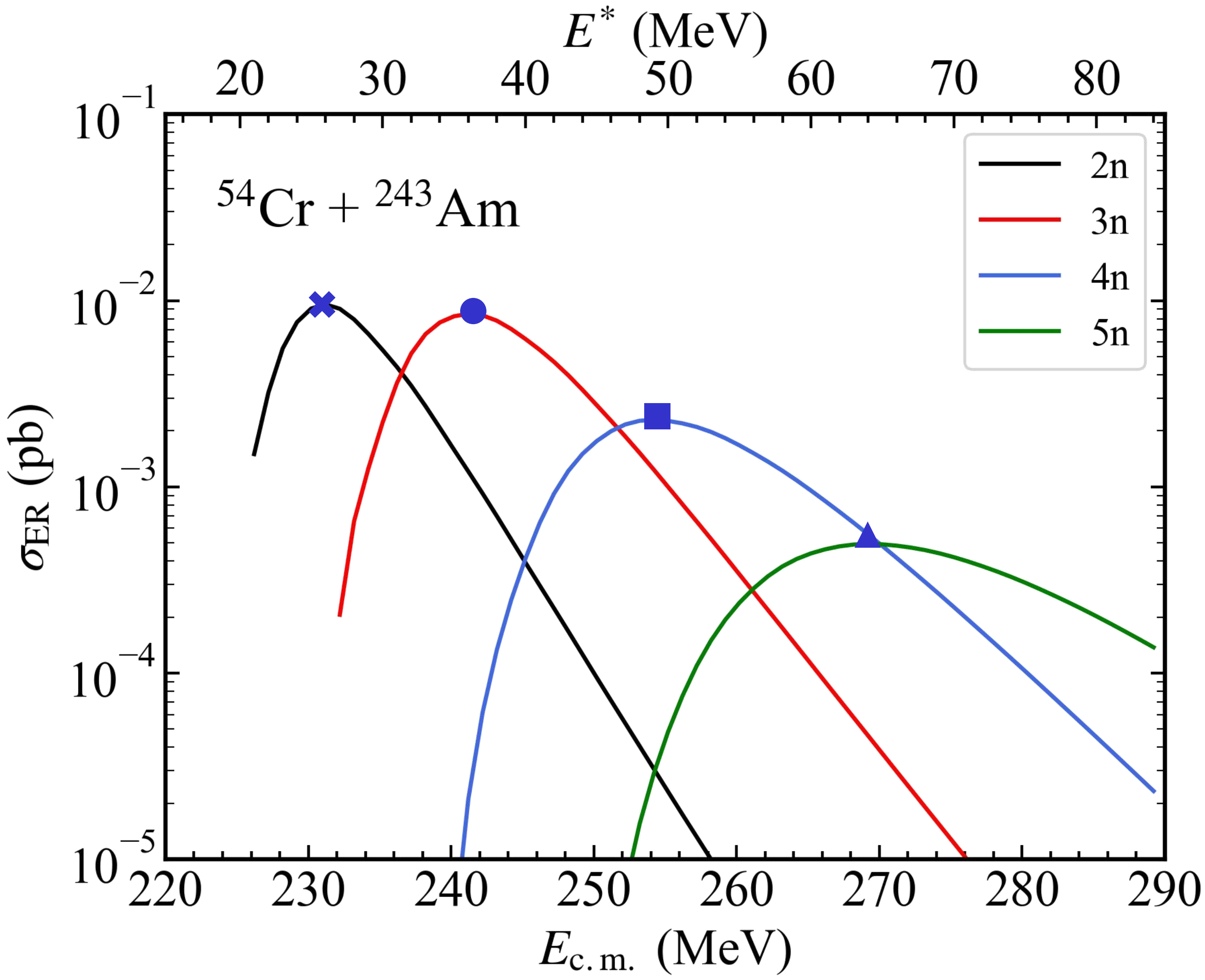
$^{54}\mathrm{Cr} + {}^{243}\mathrm{Am} \rightarrow {}^{297-x}119 + xn$

邓祥泉：双核模型

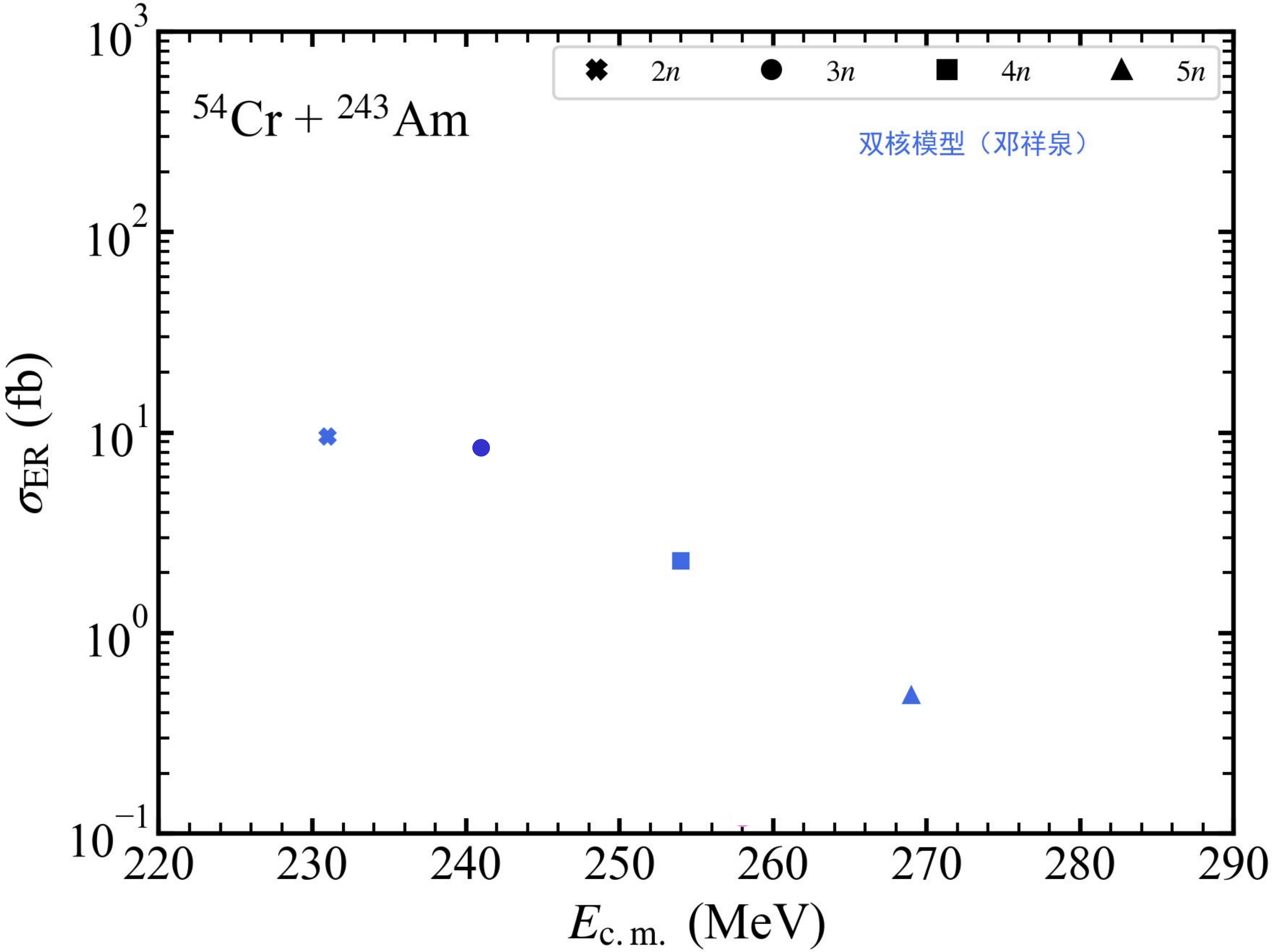


$^{54}Cr + ^{243}Am \rightarrow ^{297-x}119 + xn$

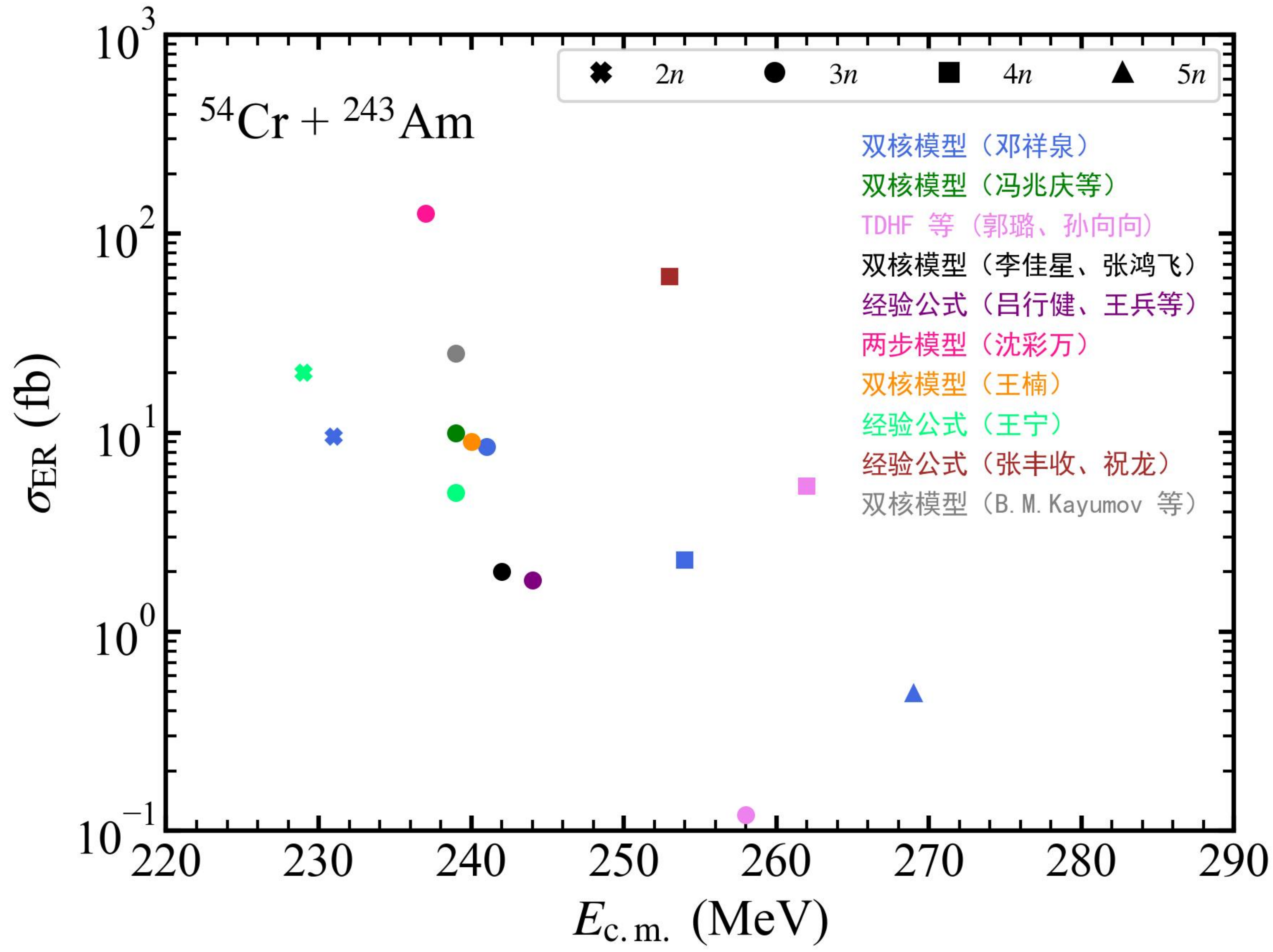
邓祥泉：双核模型



$^{54}\mathrm{Cr} + ^{243}\mathrm{Am} \rightarrow ^{297-x}119 + xn$



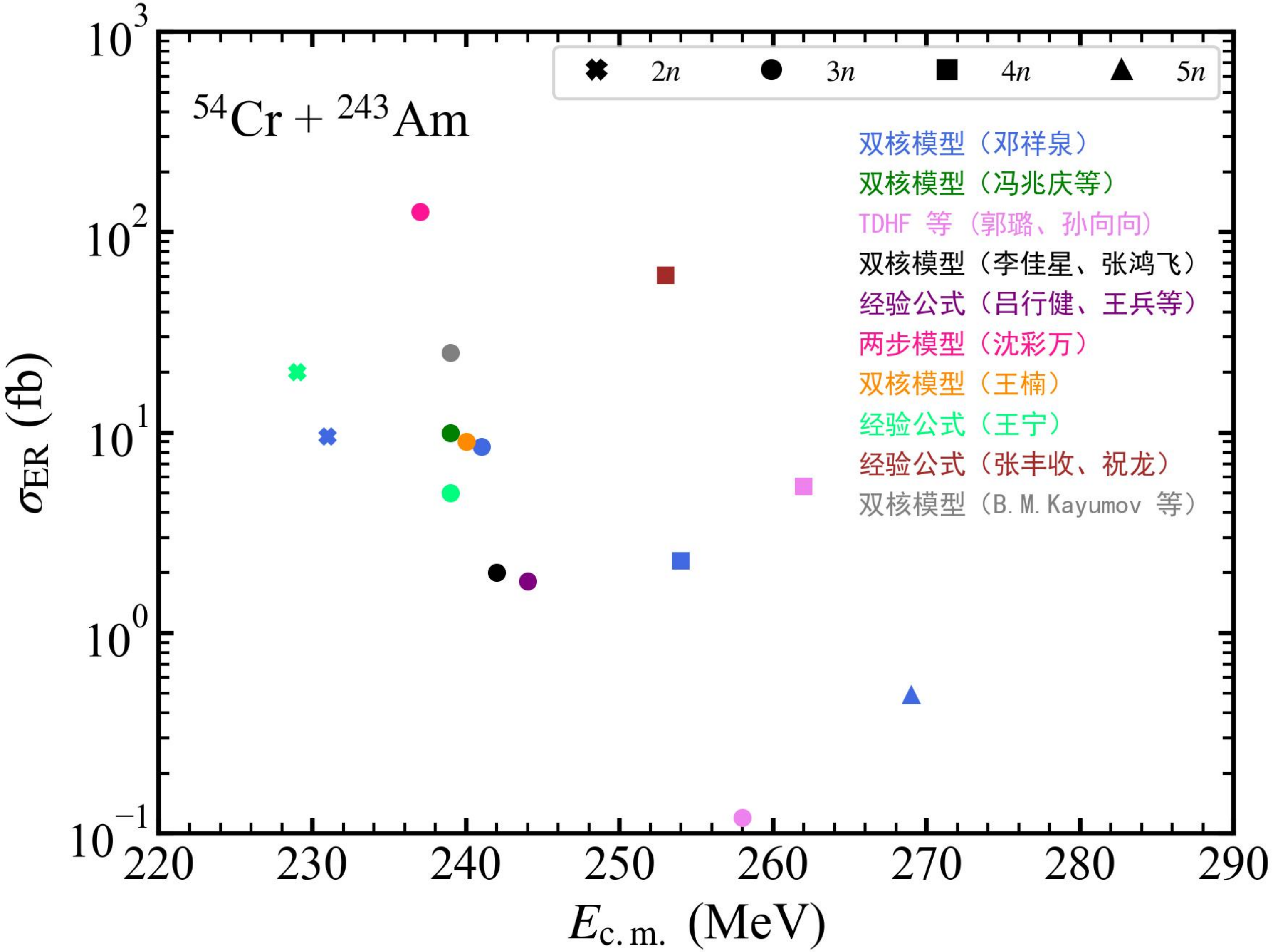
$^{54}\mathrm{Cr} + {}^{243}\mathrm{Am} \rightarrow {}^{297-x}119 + xn$



$^{54}\mathrm{Cr} + {}^{243}\mathrm{Am} \rightarrow {}^{297-x}119 + xn$

$3n$ 道	$E_{\mathrm{c.m.}}$ (MeV)	σ_{ER} (fb)
平均值（不含 TDHF+）	240	24/9
标准差（不含 TDHF+）	2	40/4
平均值（包含 TDHF+）	242	21/6
标准差（不含 TDHF+）	6	38/6

斜线后的数值为先对截面取对数，再求平均值和标准差（感谢袁岑溪！）



$^{54}\mathrm{Cr} + {}^{243}\mathrm{Am} \rightarrow {}^{297-x}119 + xn$

$3n$ 道	$E_{\mathrm{c.m.}}$ (MeV)	σ_{ER} (fb)
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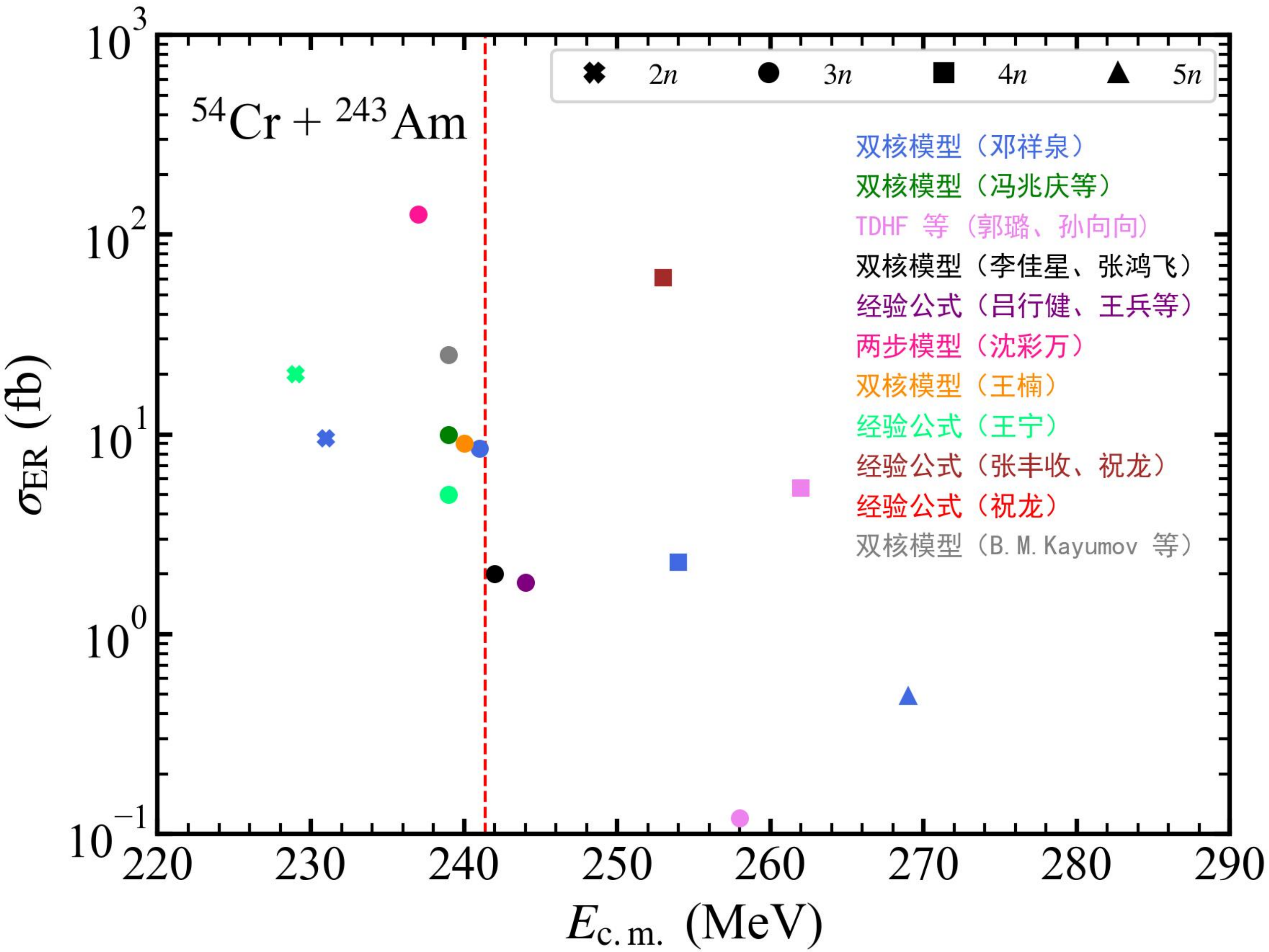
经验公式（祝龙）：241.4 MeV



内容提要

- □ 引言
- □ 超重原子核
  - ➢ 超重岛的理论预言与实验进展
  - ➢ 超重新元素合成面临的问题与挑战
  - ➢ 超重原子核性质及合成机制研究
- □ 小结

周善贵，超重原子核与超重元素，物理 43 (2014) 817-825

李璐璐、吕炳楠、王楠、温凯、夏铖君、张振华、赵杰、赵恩广、周善贵，超重核性质与合成机制的理论研究，原子核物理评论 31 (2014) 253-272

吕炳楠、赵杰、赵恩广、周善贵，Superheavy nuclei and fission barriers, Chapter 5 in *Relativistic Density Functional for Nuclear Structure* (World Scientific, 2016, Editor: Jie Meng)

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内容提要

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□ 小结

Thanks

谢谢

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