Elements and Nuclear Physics
元素和核物理

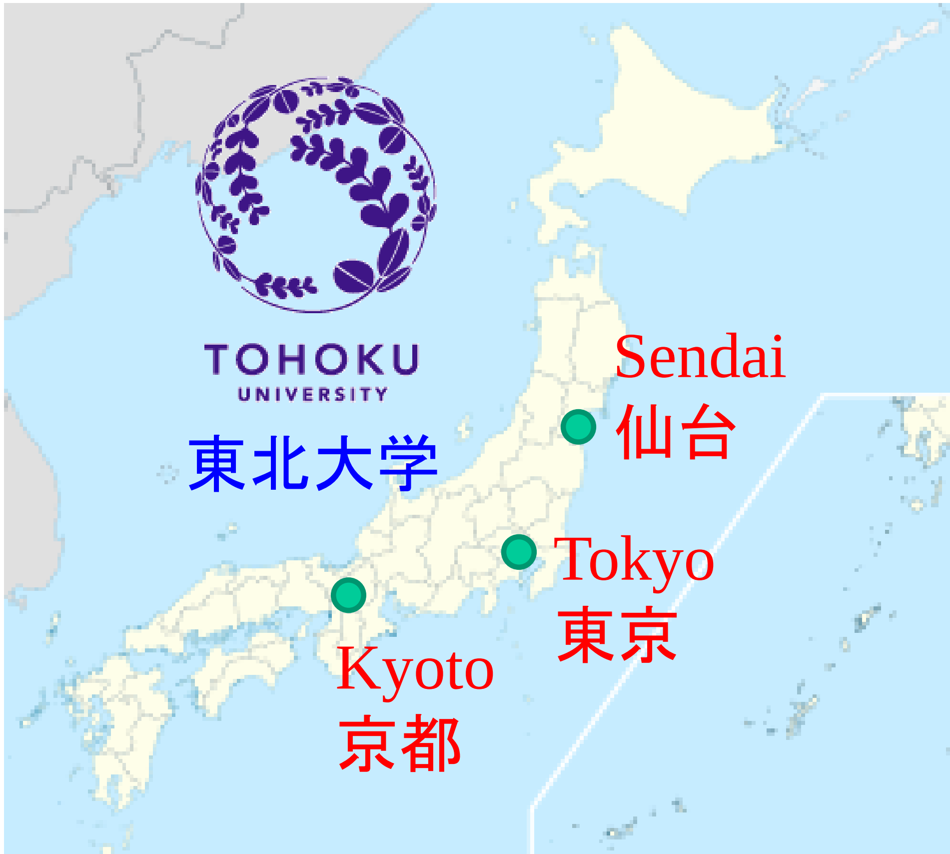
Kouichi Hagino
Tohoku University, Sendai, Japan

TOHOKU UNIVERSITY

您好!

萩野浩一
東北大学（仙台、日本）

Introduction of Tohoku University and Sendai



Sendai（仙台）:

- ✓ the largest town in the Tohoku region
- ✓ population: about 1 million

city of trees

Introduction of Tohoku University and Sendai

Matsushima 松島 (one of the
“3 most beautiful places” in Japan)

Sendai castle 仙台城

nice sea-foods 寿司

Introduction of Tohoku University and Sendai

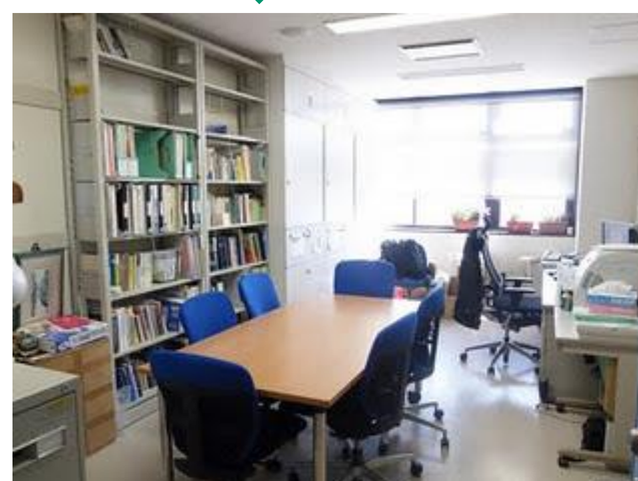
March 11, 2011 a huge earthquake 地震

津波

Sendai airport

after 1 month

after 1 month



Introduction of Tohoku University and Sendai

Tohoku University

TOHOKU
UNIVERSITY

東北大学

- Established in 1907 (110 years ago)
- the third oldest university in Japan
- the first university in Japan which accepted female students (in 1913)

· 鲁迅和东北大学

東北大学

MIYAGI HISTORY

摄于1906年3月,左第一人为鲁迅,即将离开仙台时与同班同学的合影。

历史和鲁迅

史迹,鲁迅生活过的地方

约400年前,作为伊达六十万石的城邑而发展起来,
与中国著名文学家鲁迅有深缘的仙台,
还有受伊达政宗藩主之命支仓常长一行
罗马旅行的出发地石卷。
向您介绍宫城县各地的历史风情。

回忆仙台时代生活的段落,写于1926年,引自《朝花夕拾》。

鲁迅最初寄宿的"佐藤屋"旧址,现在的米袋一丁目。

藤野厳九郎教授
藤野严九郎教授

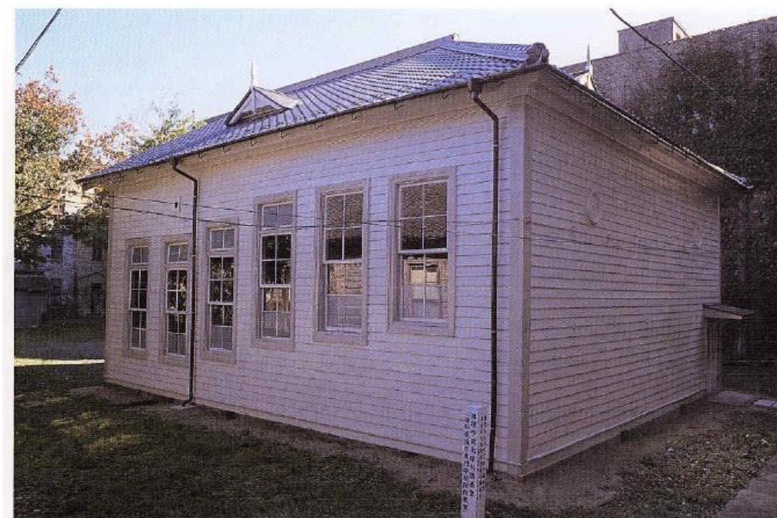
藤野教授

鲁迅(原名:周树人)1881年9月25日出生于清朝(现在的中华人民共和国)的长江下游浙江省绍兴县。1902年1月毕业南京的江南陆师学堂附属矿务铁路学堂之后,同年4月作为清朝留学生来我国留学,先就读于东京的弘文学院普通速成科。在此学院鲁迅学习了日语和基础科目。

应鲁迅的要求,1904年5月20日当时的清朝·杨公使向仙台医学专门学校(现在的东北大学医学部)提出了就鲁迅的入学要求进行妥善处理的照会信。

仙台医学专门学校对此以文部省有关入学规则为依据进行探讨之后,决定允许免试入学。并于5月23日给杨公使寄送了入学许可通知书。

同年9月,鲁迅进入了仙台医学专门学校。



鲁迅が学んだ仙台医学専門学校階段教室外景
(鲁迅曾就读的仙台医学专门学校教学楼外景)

鲁迅阶梯教室

Elements and Nuclear Physics
元素和核物理

Kouichi Hagino

Tohoku University, Sendai, Japan

TOHOKU UNIVERSITY

1. Elements
2. Introduction of Nuclear Physics
3. Superheavy elements
4. Quantum mechanics of many-fermion systems

Contents (a plan):

Monday, Aug. 13 (today) 10:30 am
Elements and Nuclear Physics 1

Tuesday, Aug. 14 (tomorrow) 9:00 am
Elements and Nuclear Physics 2

Thursday, Aug. 16 9:00 am
Magic numbers in electrons and nuclei:
quantum mechanics of many-Fermion systems

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quantum mechanics of many-Fermion systems

一清、二白、三紅、四緑、五黄

clear lectures（清）?

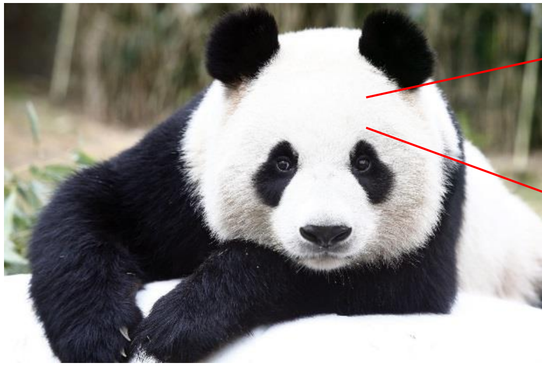
Elements and Nuclear Phyics - 1

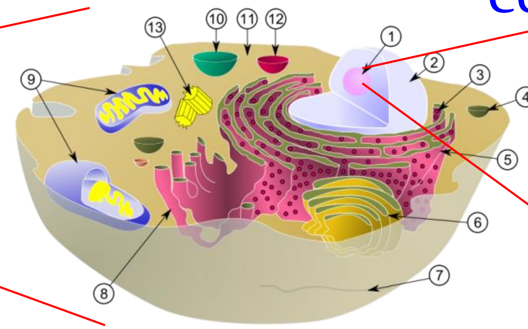
Kouichi Hagino

Tohoku University, Sendai, Japan

- What are elements? What are nuclei?
- Brief introduction to Nuclear Physics

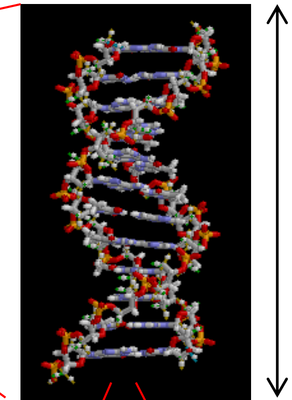
Introduction: atoms and atomic nuclei





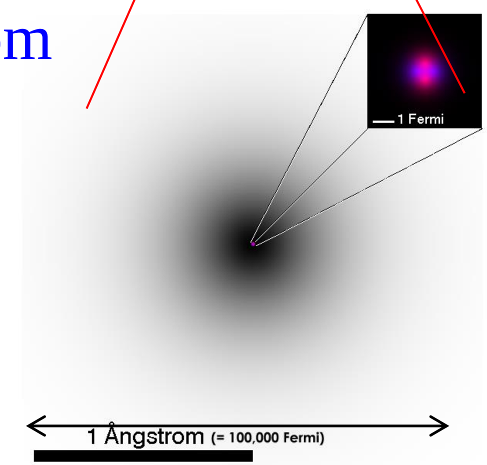
cells

DNA



$\sim 10^{-8}$ m

atom

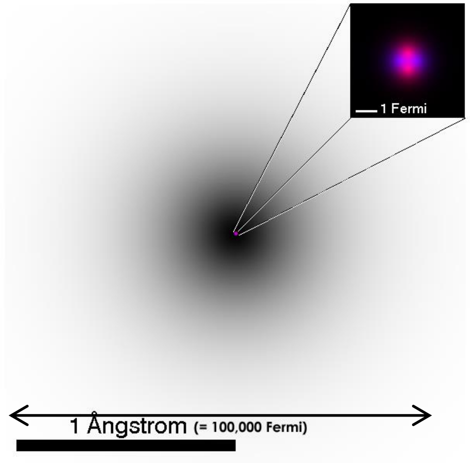


$\sim 10^{-10}$ m

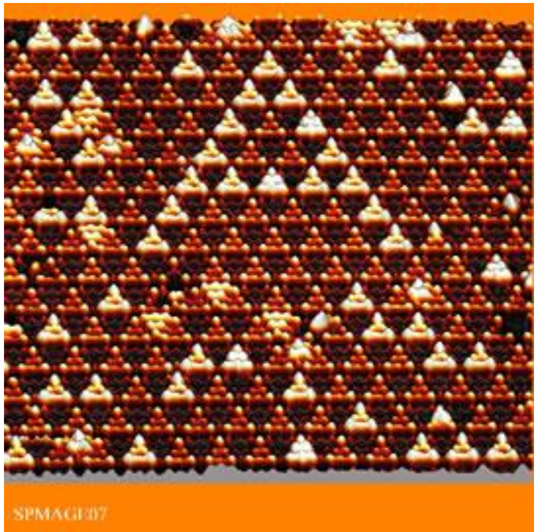
Everything is made of atoms.




- Thales, Democritus (ancient Greek)
- Dalton (chemist, 19th century)
- Boltzmann (19th century)
- Einstein (1905)

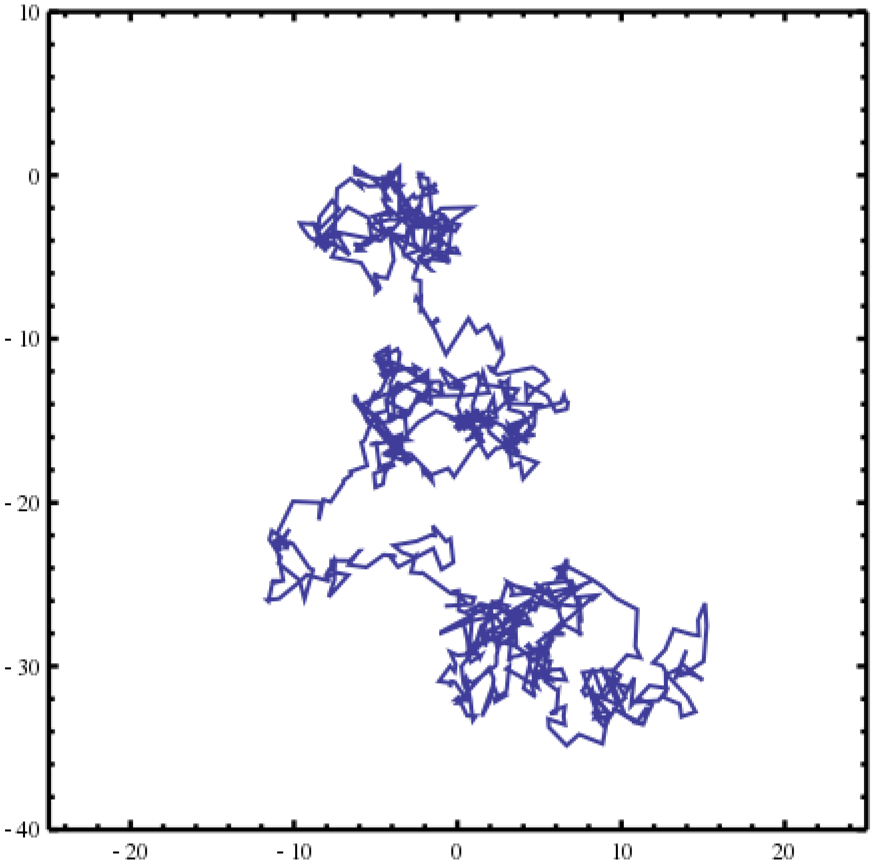


~ 10^{-10} m



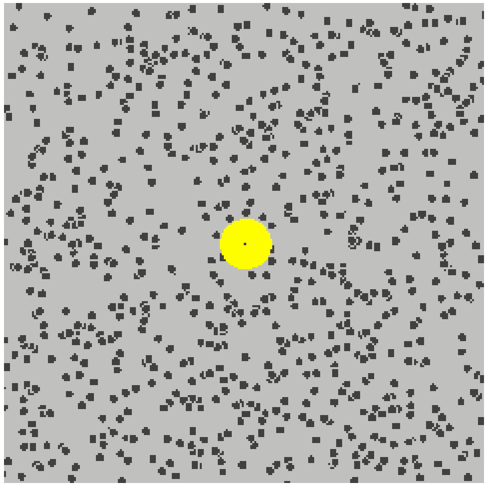
STM image
(surface physics group,
Tohoku university)

Brownian motion



Wikipedia

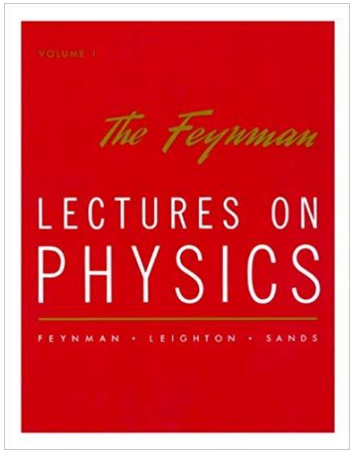
Einstein (1905):
collisions between a particle and water molecules

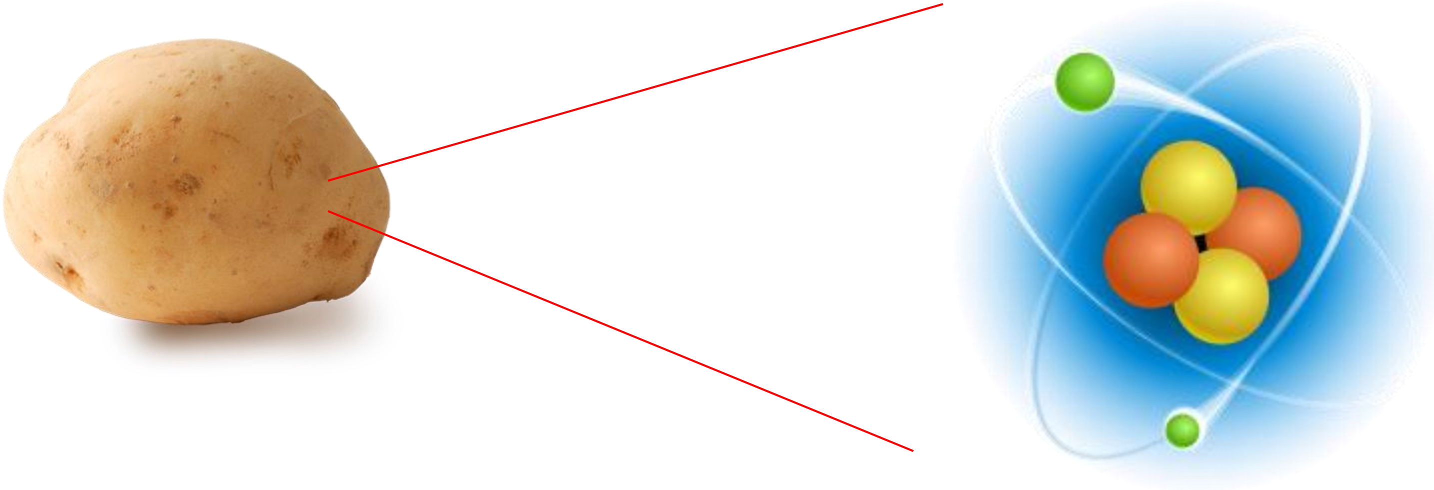


Everything is made of atoms.

If, in some cataclysm, all of scientific knowledge were to be destroyed, and only one sentence passed on to the next generation of creatures, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis that *all things are made of atoms.* (Richard Feynman)

Richard Feynmann (1918-1988)
Nobel prize in physics (1965)
(photo:The Nobel Foundation)





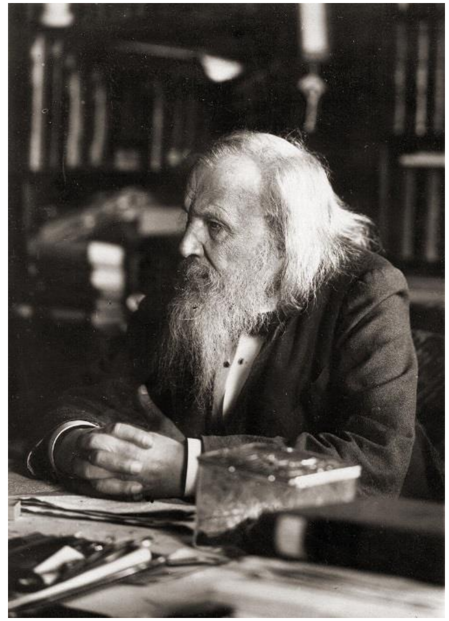
atom

Several kinds of atoms = elements

- Hydrogen
- Oxygen
- Carbon
- Calcium
- Magnesium
- Sulfer

etc.

Periodic Table of elements



Mendeleev
(1834-1907)

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

Periodic Table of elements

Group → / ↓ Period	1	2	3	4	5	6	7		9	10	11	12	13	14	15	16	17	18
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5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn

2019 IYPT

International Year
of the Periodic Table
of Chemical Elements

Each column: elements with the same chemical properties (Mendeleev, 1869)

⟶ Prediction of the properties of unknown atoms

Discovery of Ga (1874)

Dicsovery of Ge (1879)

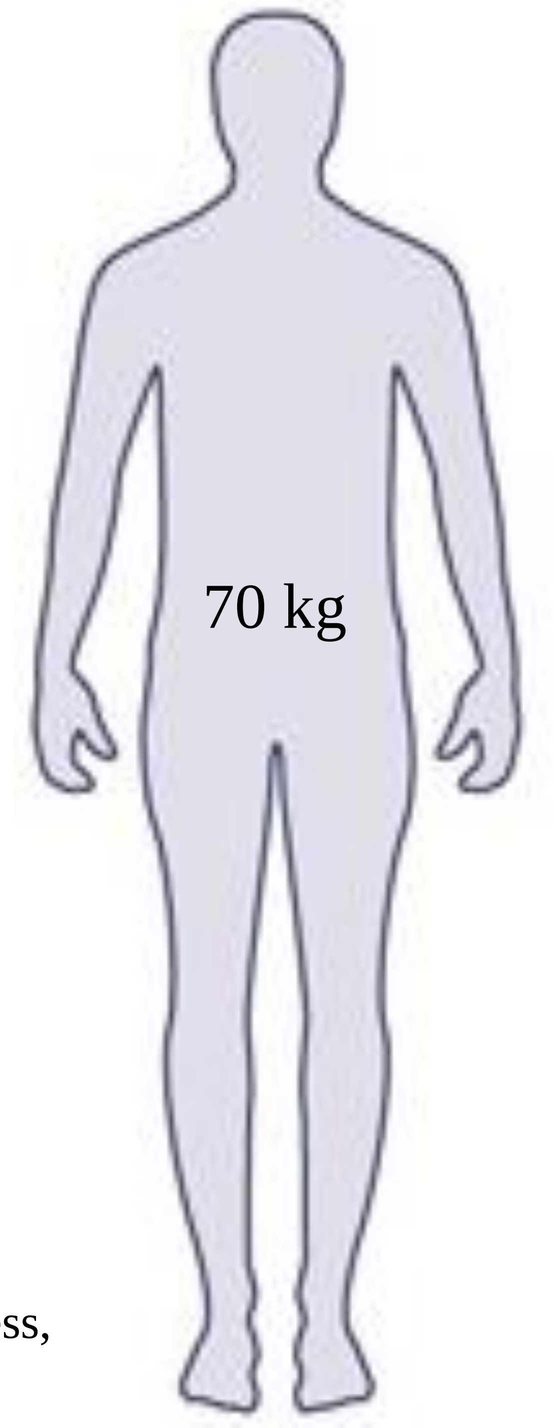
What are we made of ?

oxygen 43 kg
carbon 16 kg
hydrogen 7 kg
nitrogen 1.8 kg
calcium 1.0 kg
phosphorus 780 g
potassium 140 g
sulphur 140 g
sodium 100 g
chlorine 95 g
magnesium 19 g
iron 4.2 g
fluorine 2.6 g
zinc 2.3 g
silicon 1.0 g
rubidium 0.68 g
strontium 0.32 g
bromine 0.26 g
lead 0.12 g
copper 72 mg
aluminium 60 mg
cadmium 50 mg

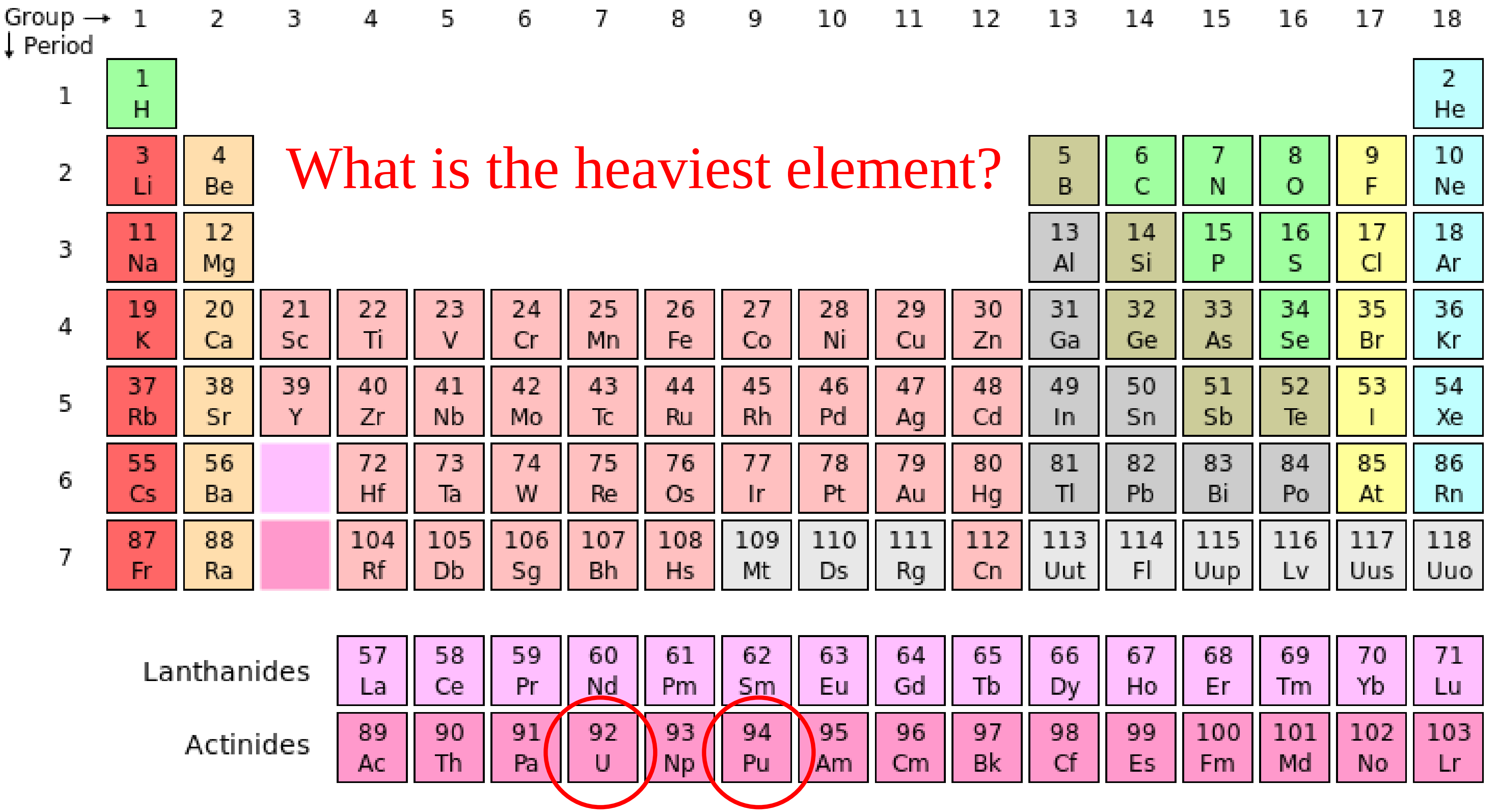
cerium 40 mg
barium 22 mg
iodine 20 mg
tin 20 mg
titanium 20 mg
boron 18 mg
nickel 15 mg
selenium 15 mg
chromium 14 mg
manganese 12 mg
arsenic 7 mg
lithium 7 mg
caesium 6 mg
mercury 6 mg
germanium 5 mg
molybdenum 5 mg
cobalt 3 mg
antimony 2 mg
silver 2 mg
niobium 1.5 mg
zirconium 1 mg
lanthanum 0.8 mg

gallium 0.7 mg
tellurium 0.7 mg
yttrium 0.6 mg
bismuth 0.5 mg
thallium 0.5 mg
indium 0.4 mg
gold 0.2 mg
scandium 0.2 mg
tantalum 0.2 mg
vanadium 0.11 mg
thorium 0.1 mg
uranium 0.1 mg
samarium 50 µg
beryllium 36 µg
tungsten 20 µg

John Emsley,
"The Elements",
3rd ed. Clarendon Press,
Oxford, 1998



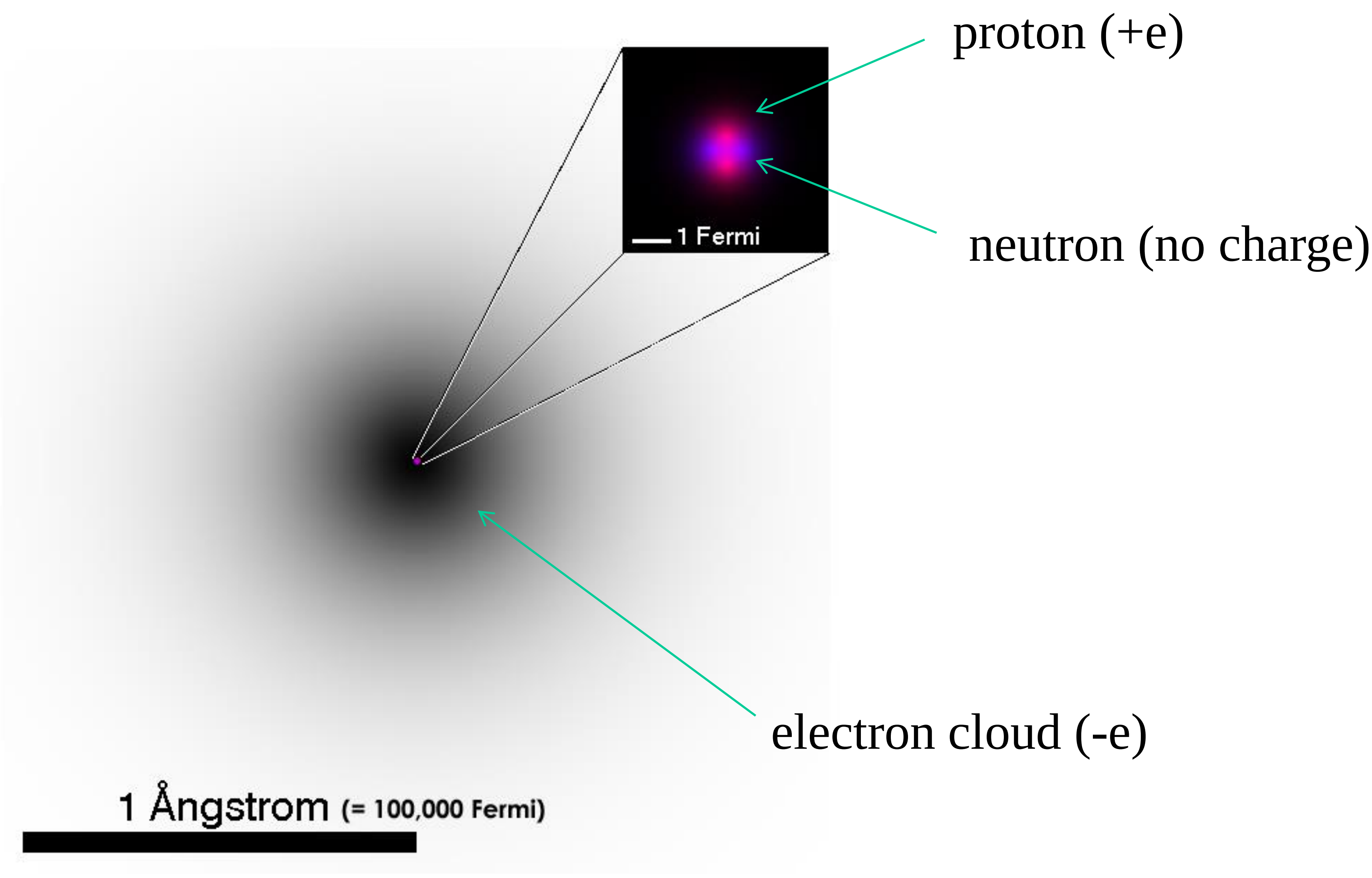
Periodic table of chemical elements

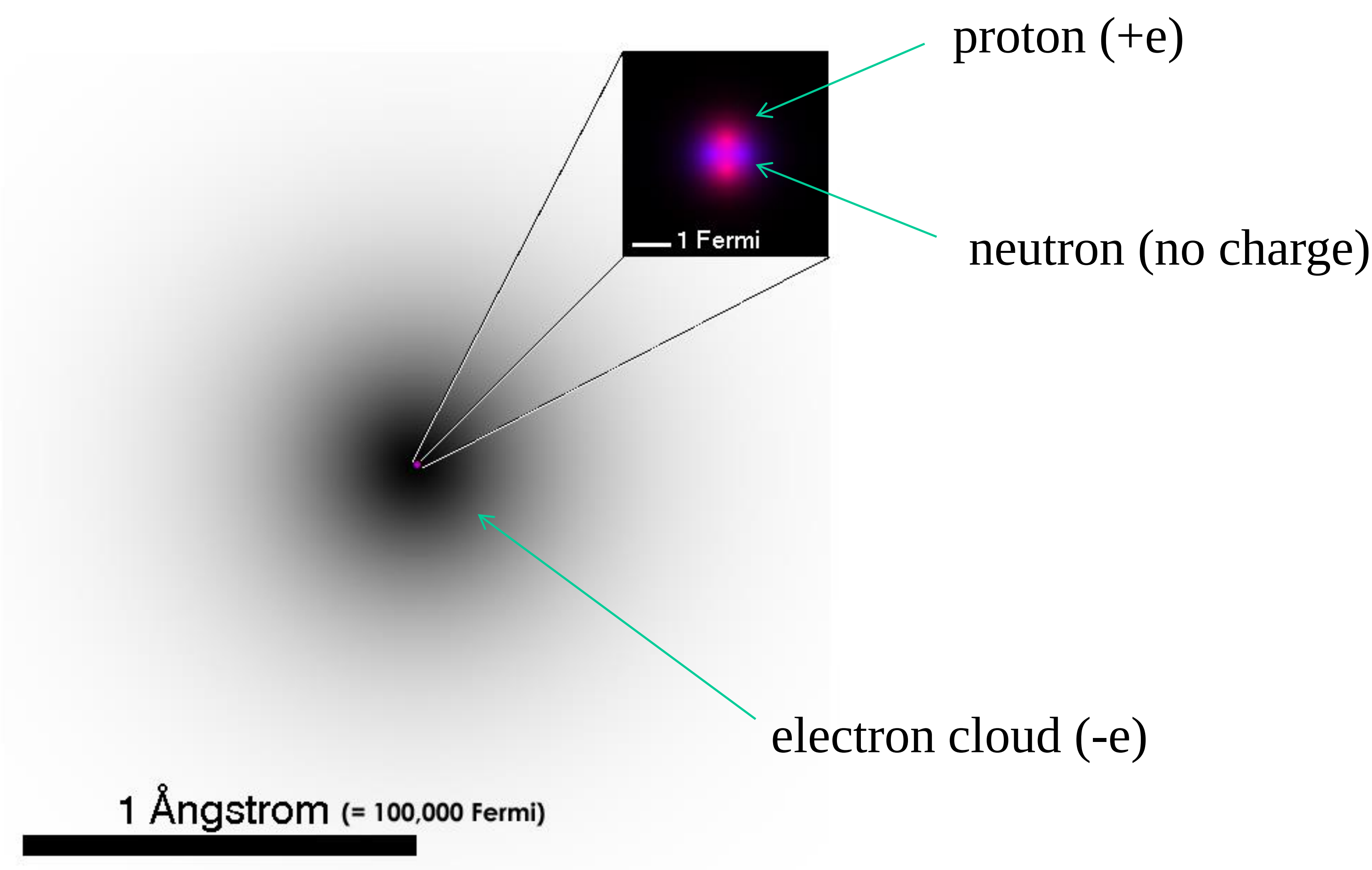


natural elements: **Pu** (Z=94) ⟶ a tiny amount in nature
U (Z=92)

What determines these numbers??

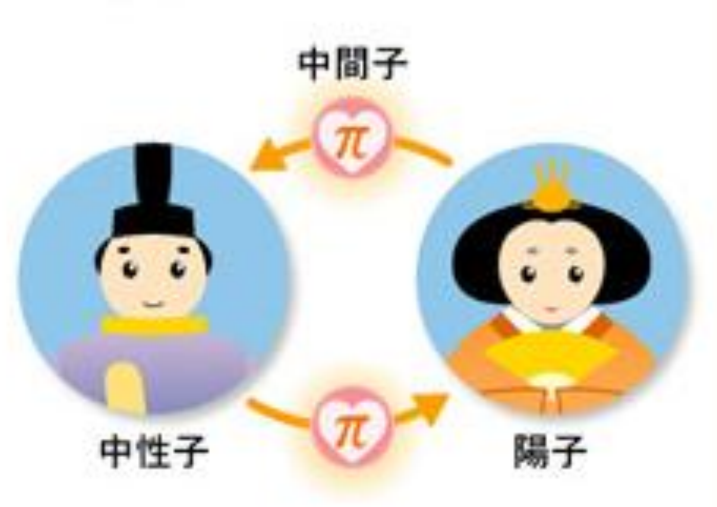
Atomic Nucleus





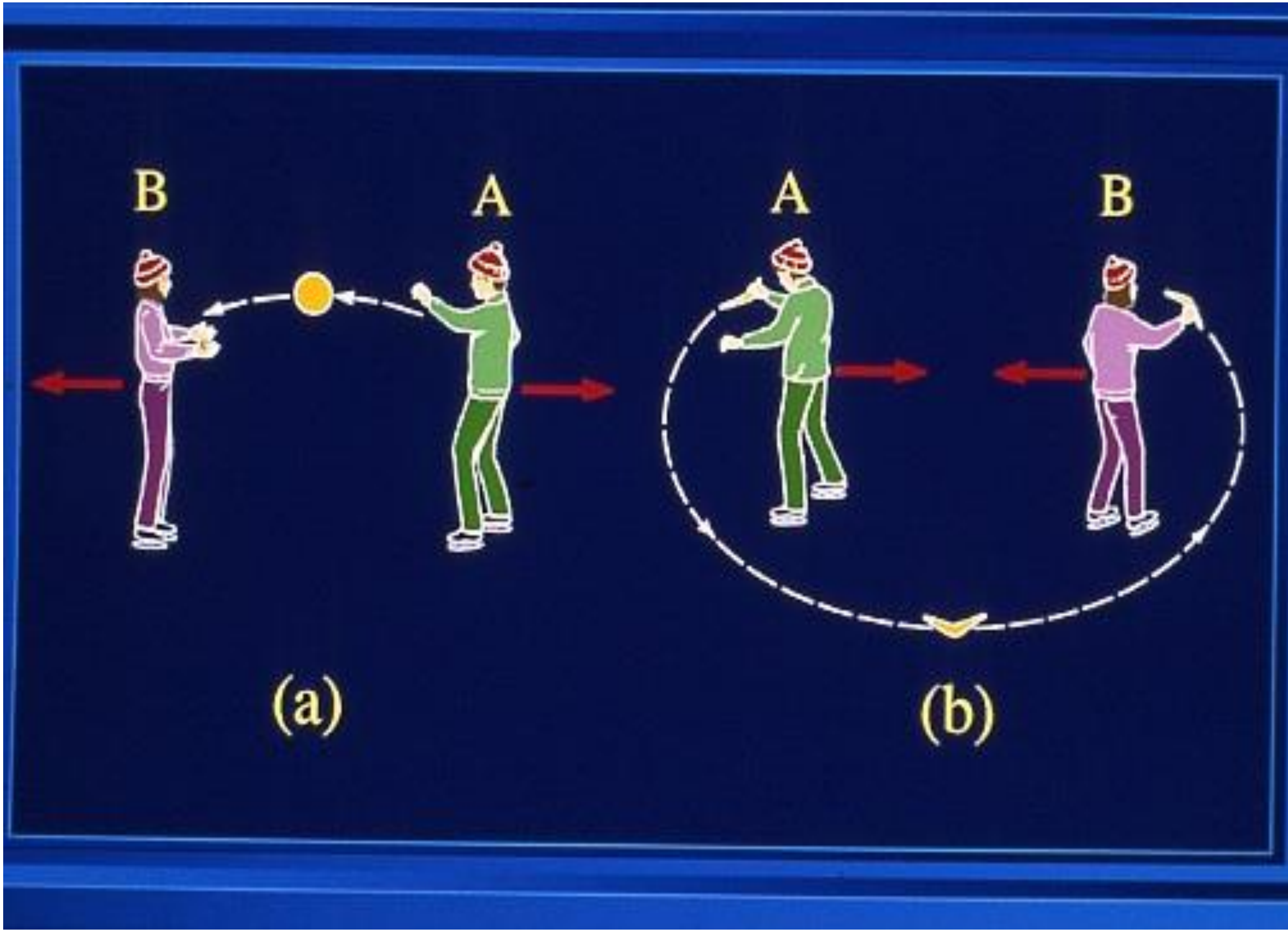
- Neutral atoms: # of protons = # of electrons
- Chemical properties of atoms ⟶ # of electrons
- $M_p \sim M_n \sim 2000\ M_e$ ⟶ the mass of atom ~ the mass of nucleus

How can protons be confined in a small place like atomic nucleus?



Meson exchange theory (Hideki Yukawa 湯川秀樹)
nucleons (protons and neutrons) exchange mesons and feel attraction (strong interaction)

http://www.riken.jp/r-navi/face/009/index.html


B
A
A
B
(a)
(b)

Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

What is the heaviest element?

natural elements: Pu (Z=94) $\longrightarrow$ a tiny amount in nature

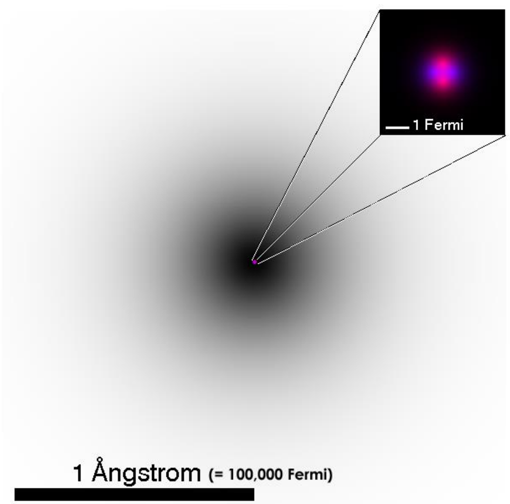
U (Z=92)

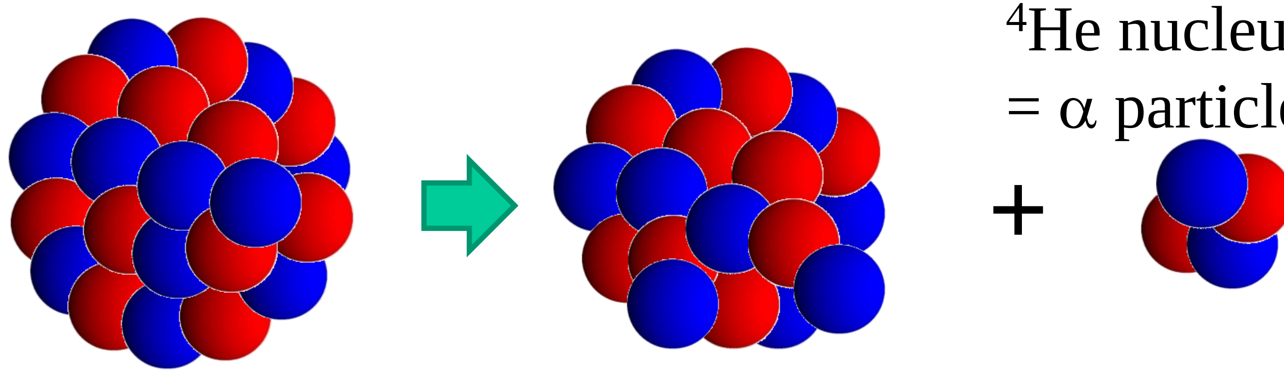
What determines these numbers?

heavy nuclei $\longrightarrow$ large Coulomb repulsion

$\downarrow$

unstable against α decay

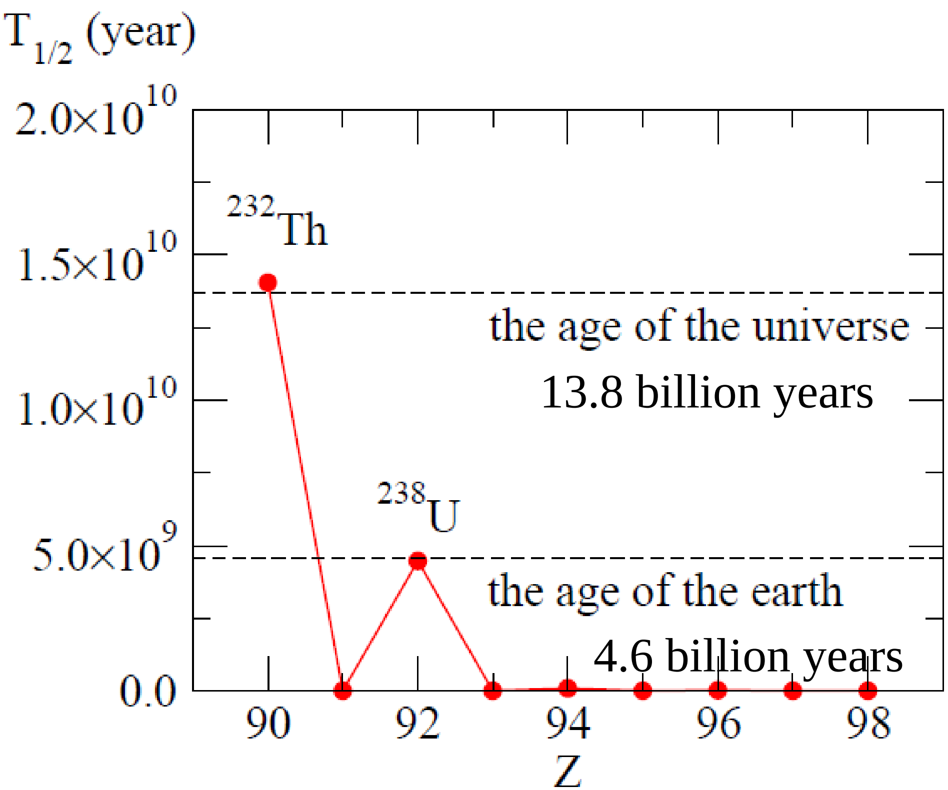


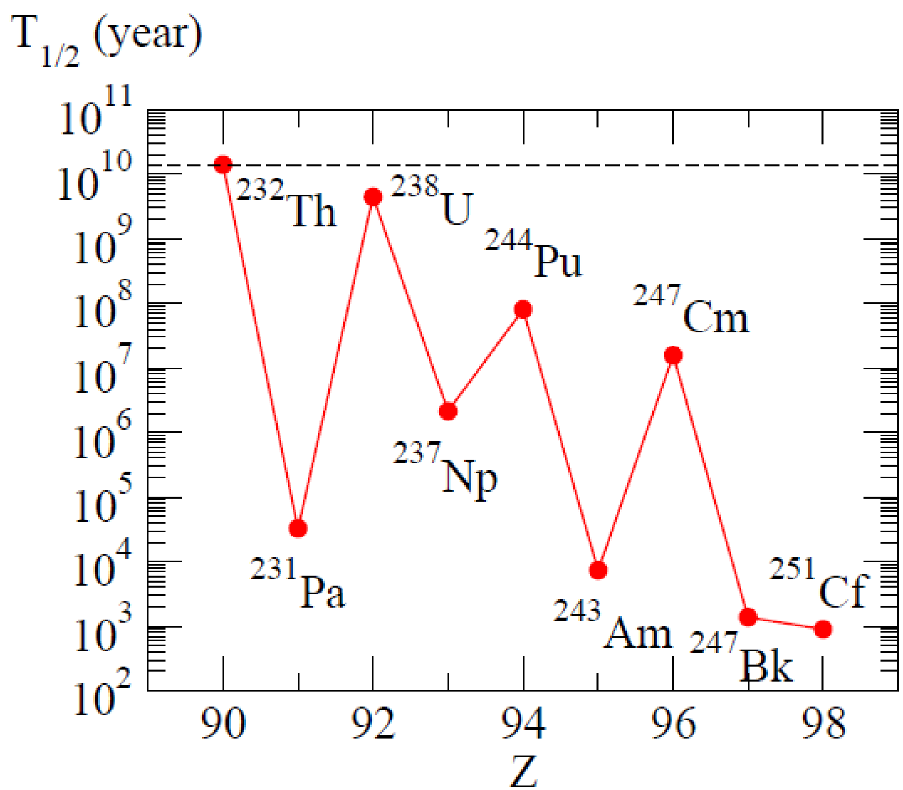


^{4}He nucleus = α particle

(Z,N) (Z-2,N-2) (Z=2,N=2)

Decay half-lives of heavy nuclei



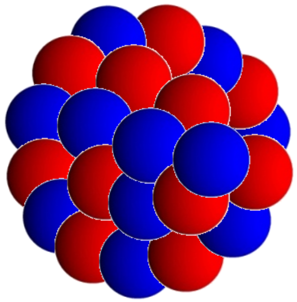


^{232}Th 1.405 x 10^{10} years

^{238}U 4.468 x 10^{9} years

^{244}Pu 8.08 x 10^{7} years

^{247}Cm 1.56 x 10^{7} years



Nuclei : protons + neutrons

Where are neutrons?

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Lanthanides	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
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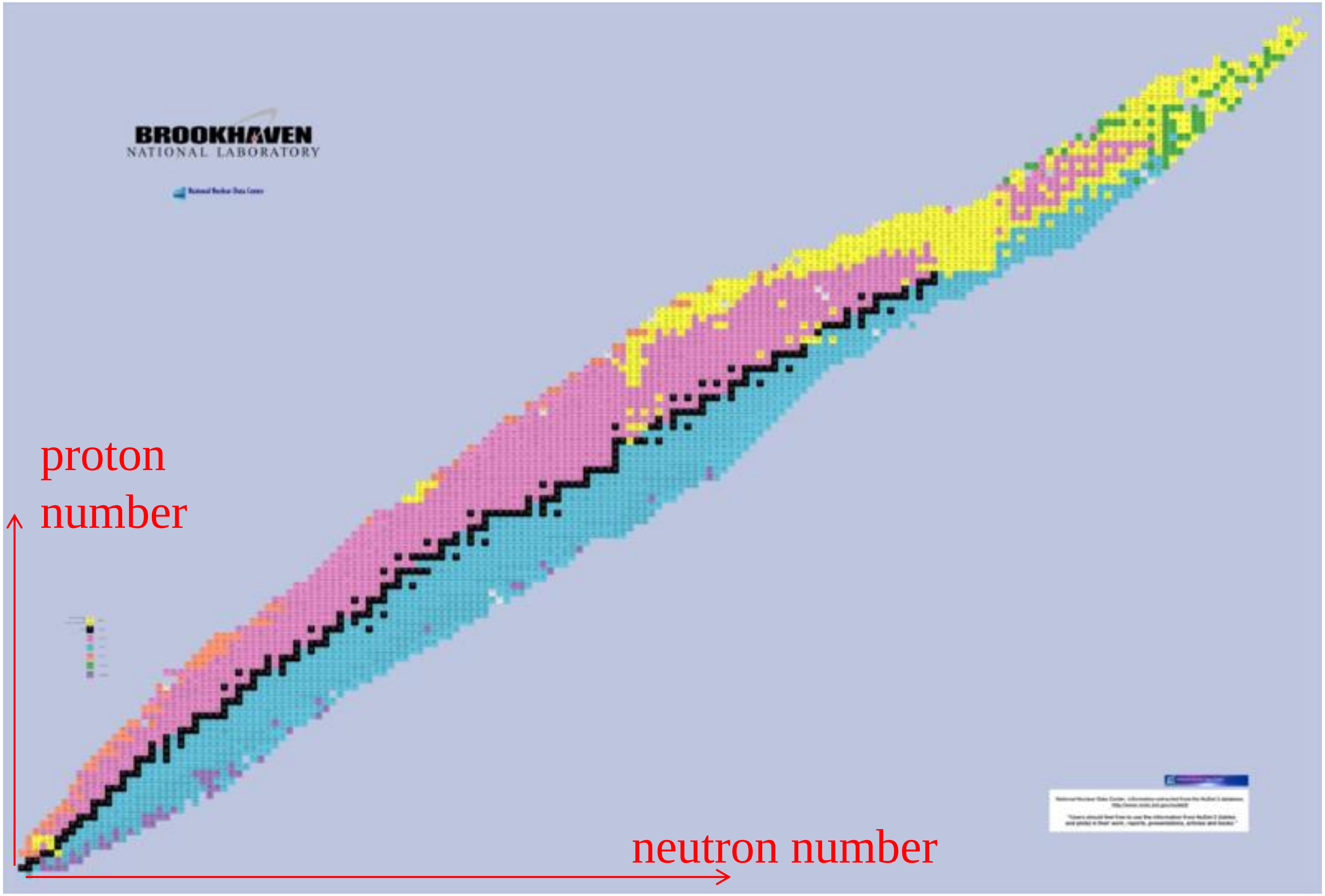
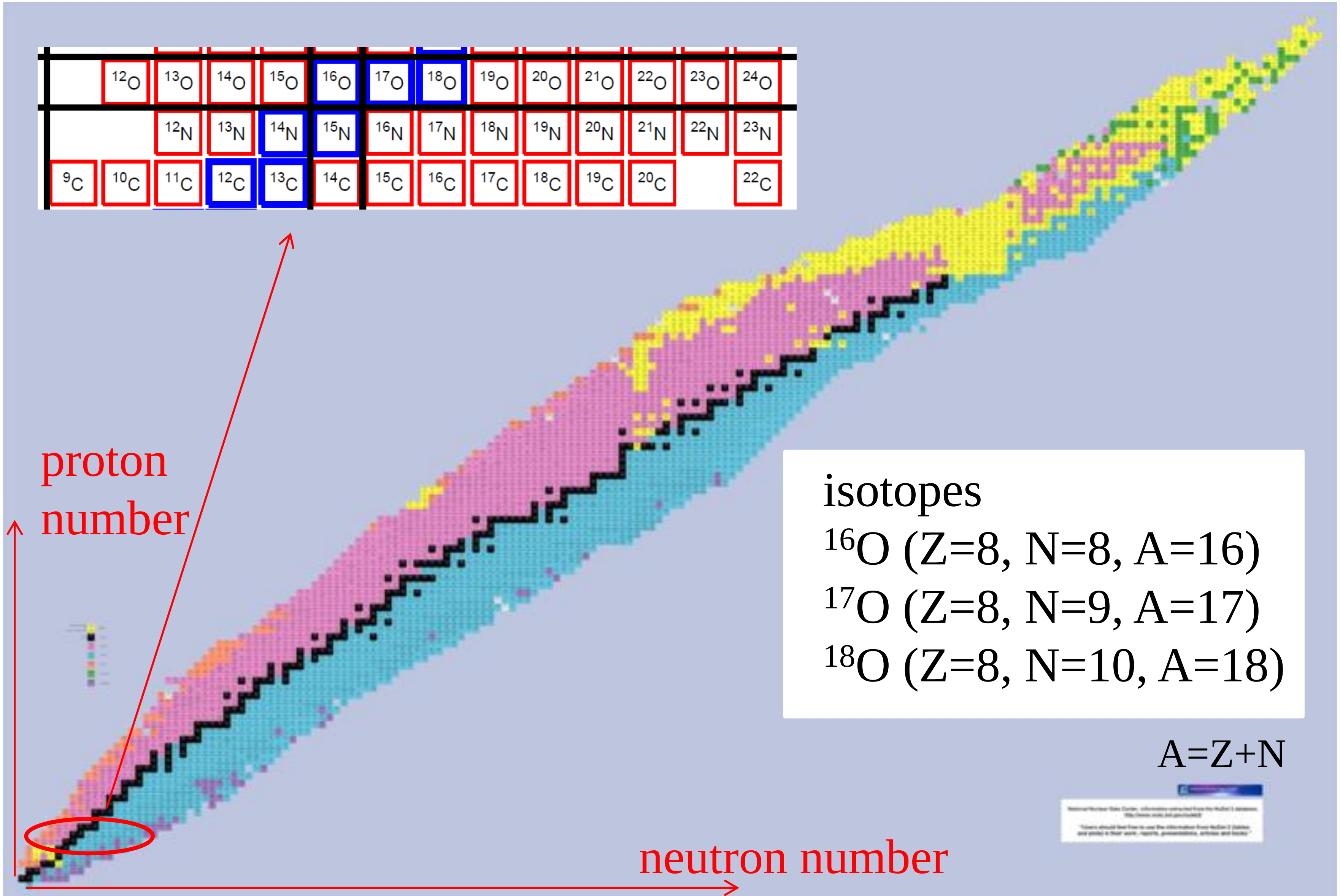
Extension of Periodic table: Nuclear Chart ~2D map of atomic nuclei~



Extension of Periodic table: Nuclear Chart ~2D map of atomic nuclei~



isotopes

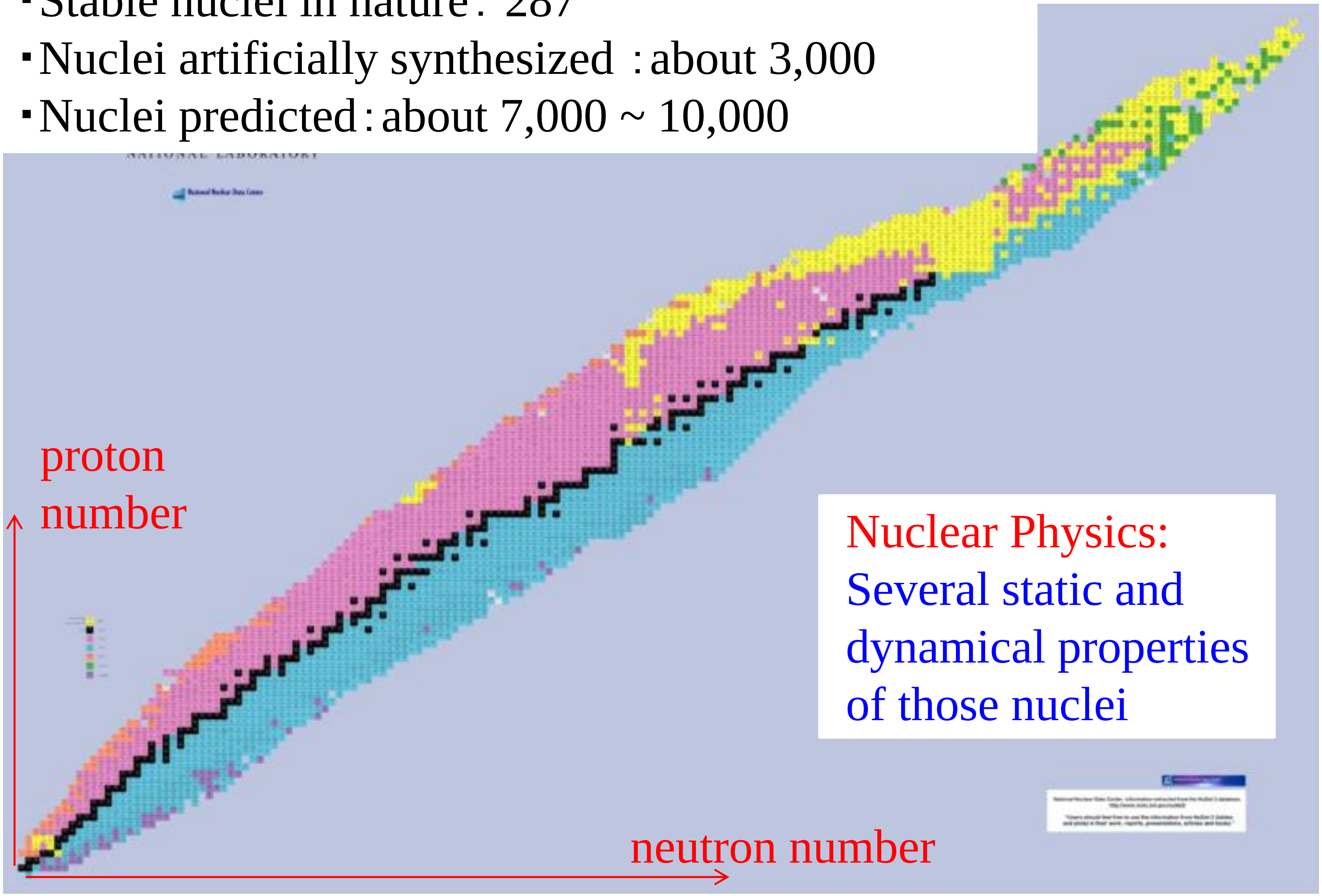
^{16}O (Z=8, N=8, A=16)

^{17}O (Z=8, N=9, A=17)

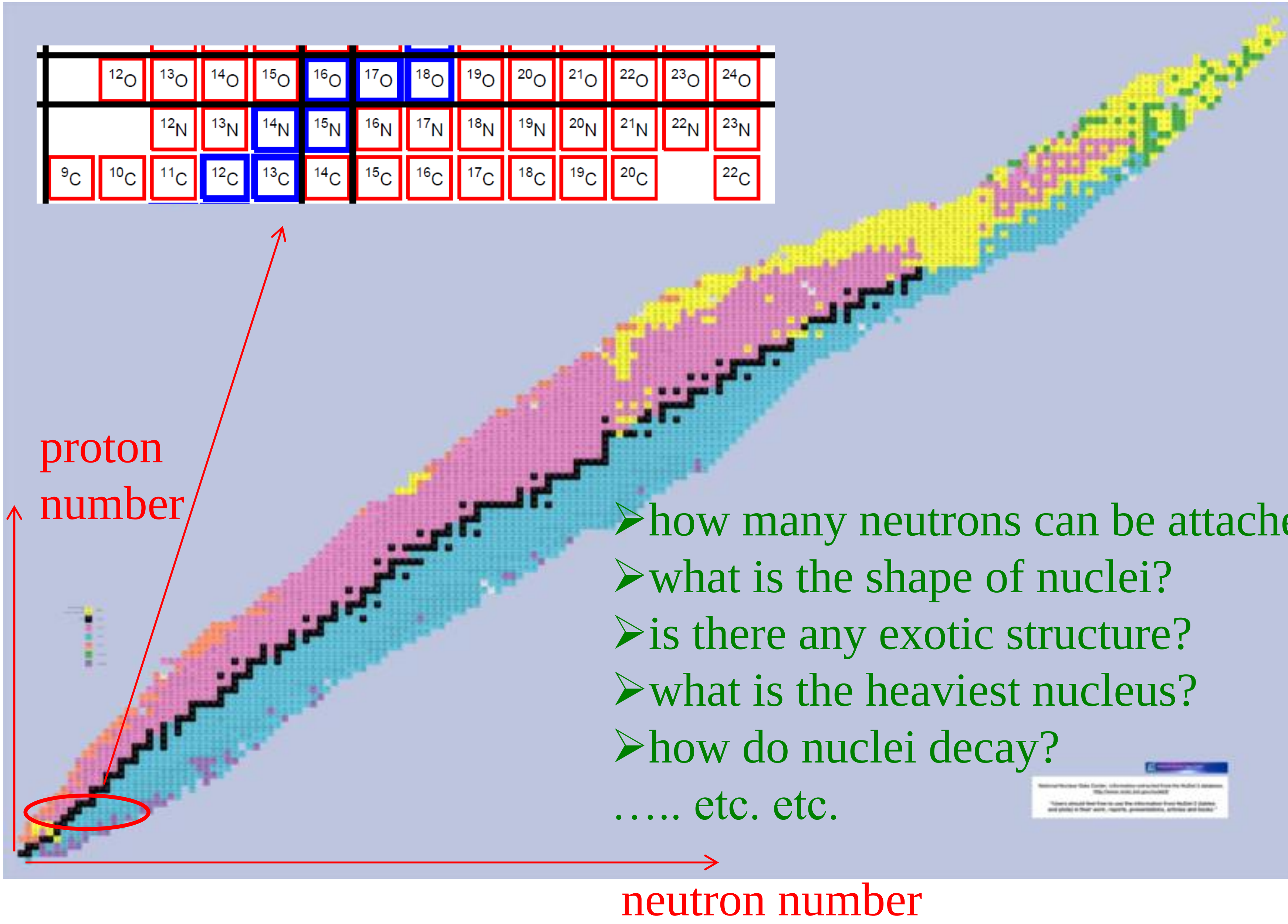
^{18}O (Z=8, N=10, A=18)

A=Z+N

- Stable nuclei in nature： 287
- Nuclei artificially synthesized ：about 3,000
- Nuclei predicted：about 7,000 ~ 10,000



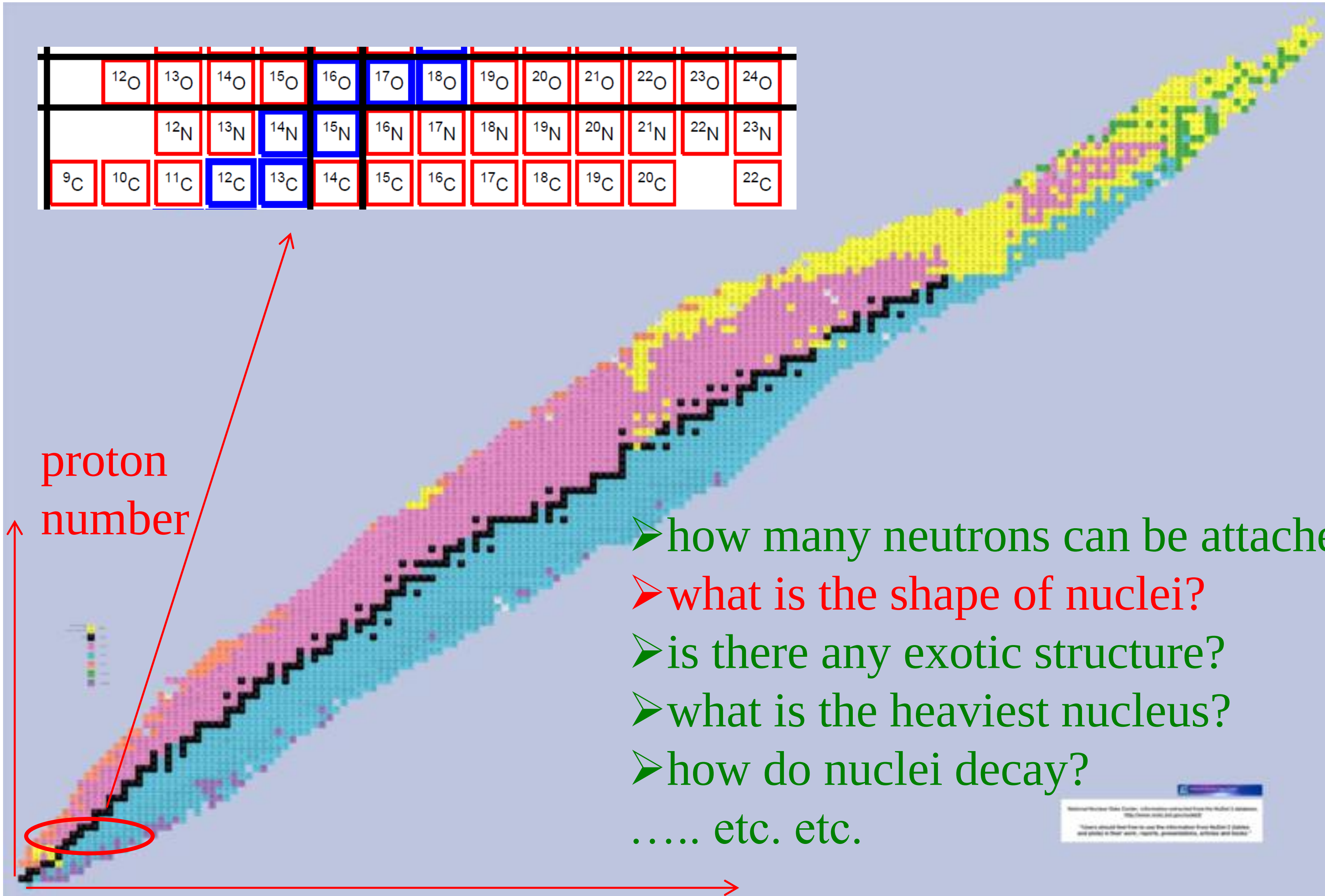
Nuclear Chart: 2D map of atomic nuclei



- how many neutrons can be attached?
- what is the shape of nuclei?
- is there any exotic structure?
- what is the heaviest nucleus?
- how do nuclei decay?

….. etc. etc.

Nuclear Chart: 2D map of atomic nuclei



- ➢how many neutrons can be attached?
- ➢what is the shape of nuclei?
- ➢is there any exotic structure?
- ➢what is the heaviest nucleus?
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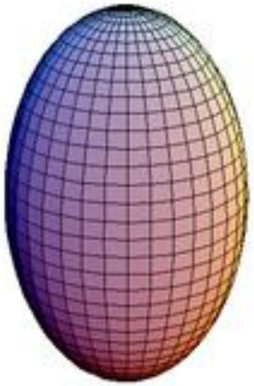
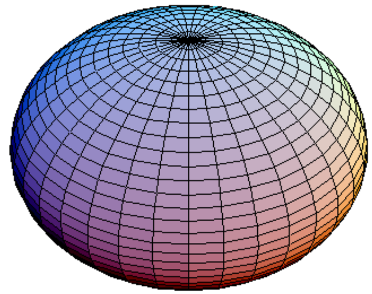
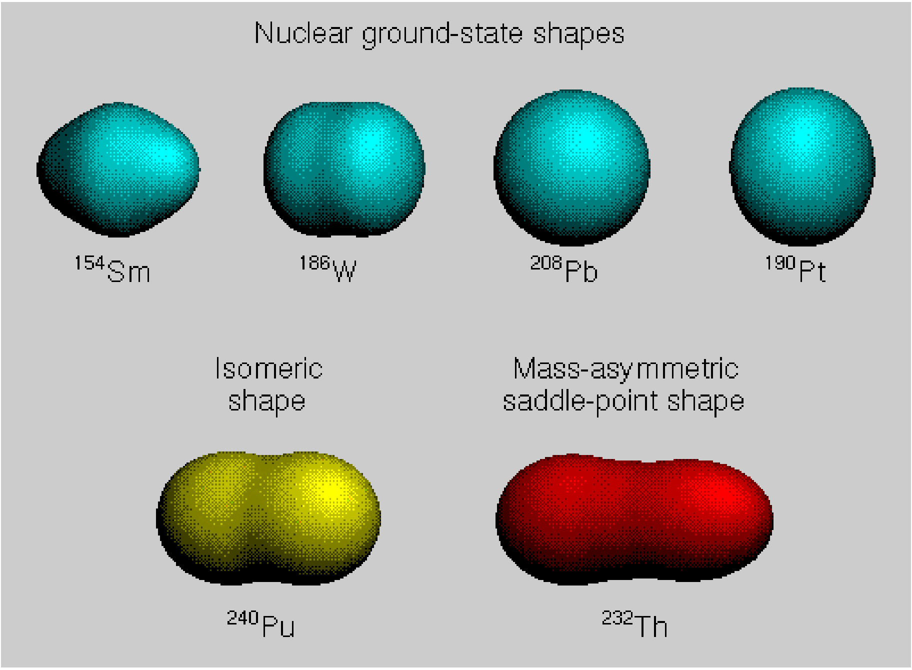
….. etc. etc.

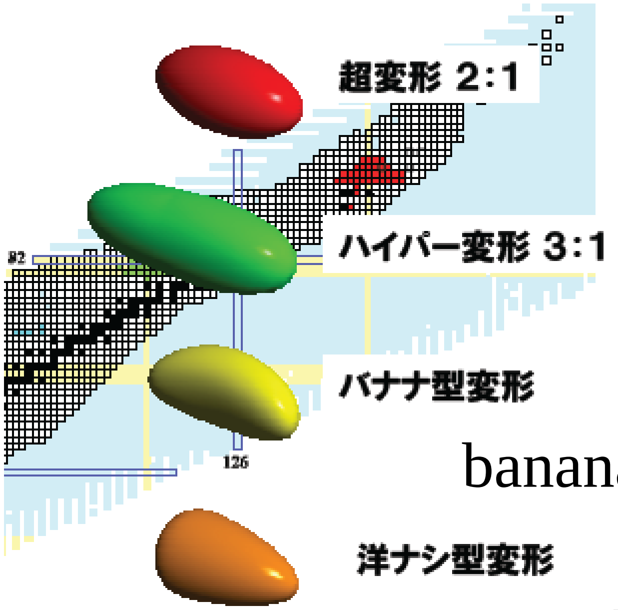
a nucleus is not always spherical

Quantum shape dynamics









banana shape

pear shape

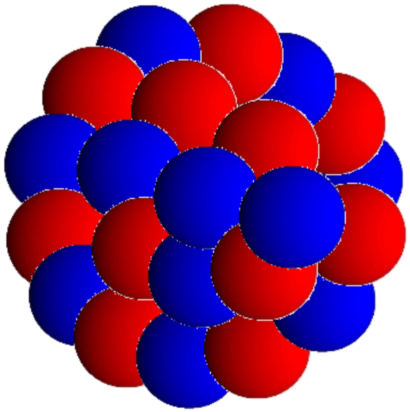
Some nuclei are deformed in the ground state!

what are combinations of (Z,N) which yield a deformation?

(Low-energy) Nuclear Physics:

to understand rich nature of atomic nuclei starting from nucleon-nucleon interactions

- size, mass, density, shape
- excitations
- decays
- nuclear reactions



two kinds of particle: protons and neutrons

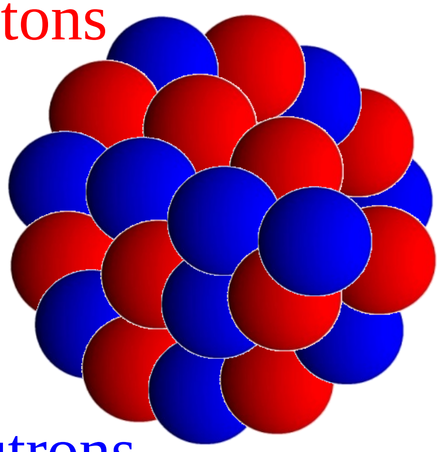
Basic ingredients:

	charge	mass (MeV)	spin,parity
Proton	+e	938.256	$1/2^+$
Neutron	0	939.550	$1/2^+$

(note) $n \rightarrow p + e^- + \bar{\nu}$ (10.4 min)

protons and neutrons: Fermions → Pauli principle

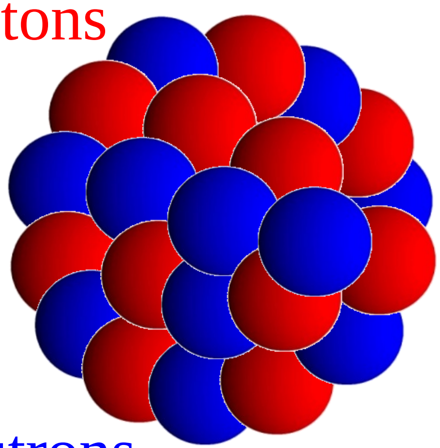
(in the last lecture)



- Nucleons are not stopping inside a nucleus.
  (they move relatively freely)

- Yet, they are not completely independent.
  a nucleus keeps its shape
  due to the interactions among nucleons

  a self-bound system



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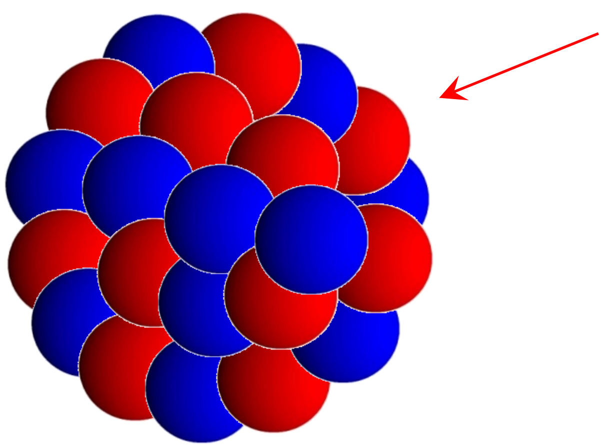
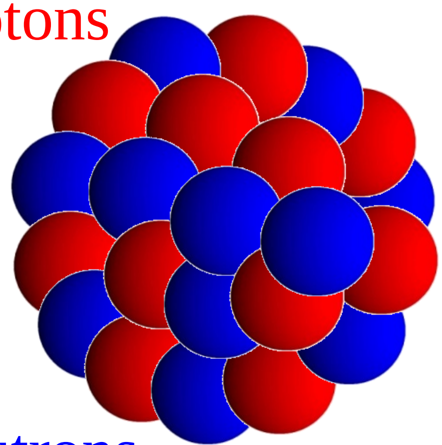
What happens if a photon is absorbed into a nucleus?
- one nucleon simply starts moving faster?



protons



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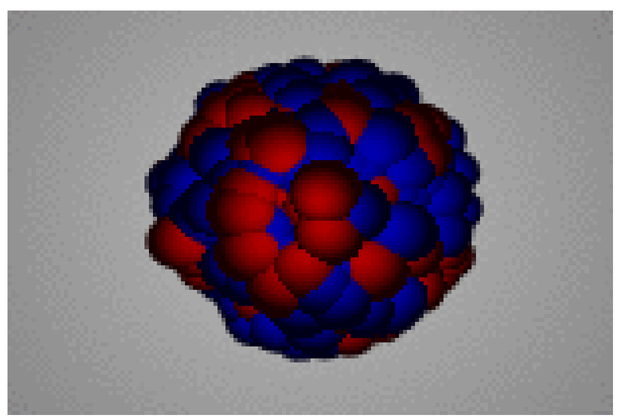
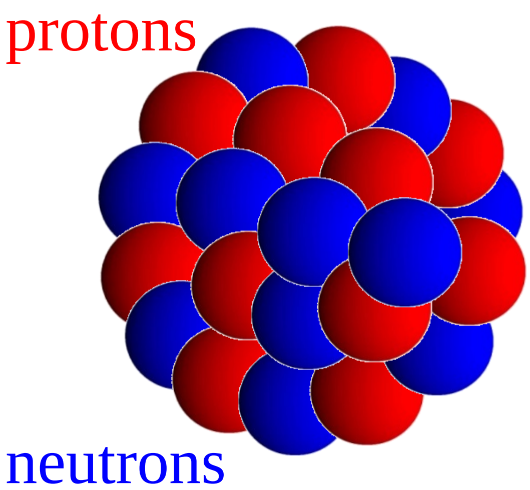


Very coherent motion can happen due to the correlation

Collective motions



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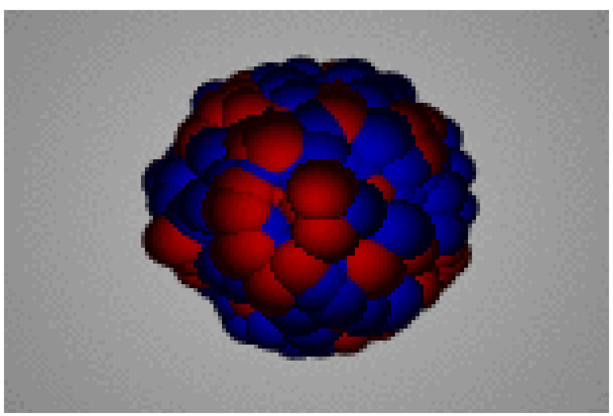
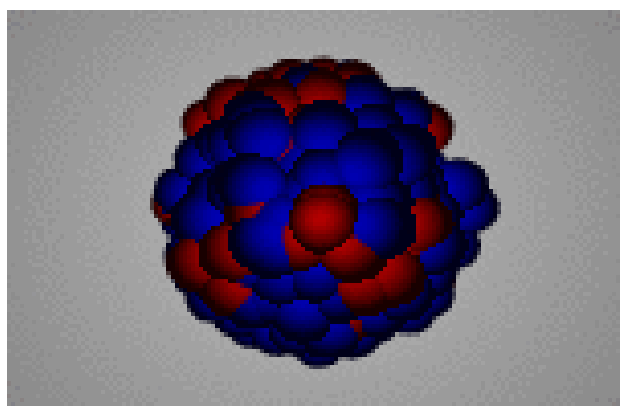
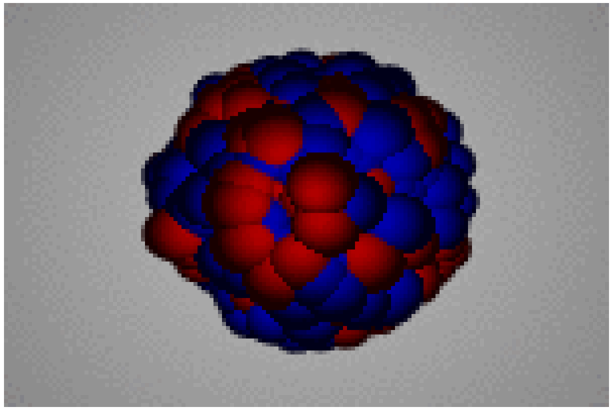
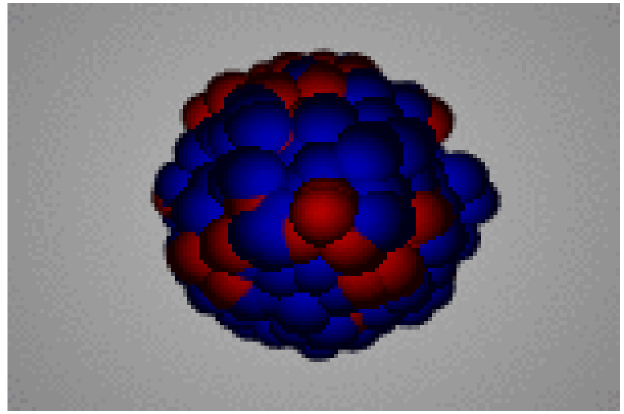




Very coherent motion can happen due to the correlations

Collective motions





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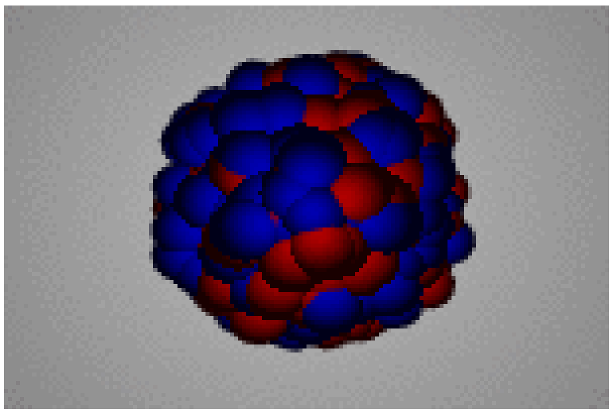
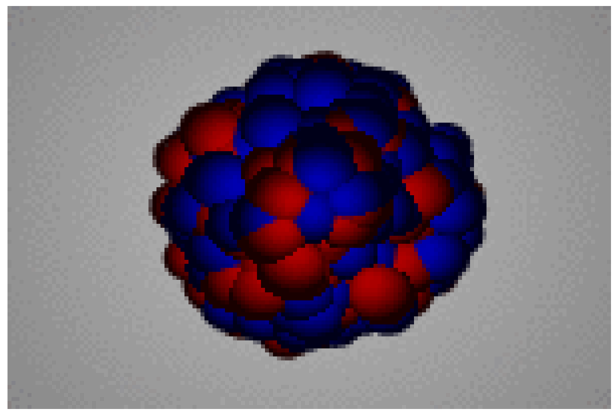
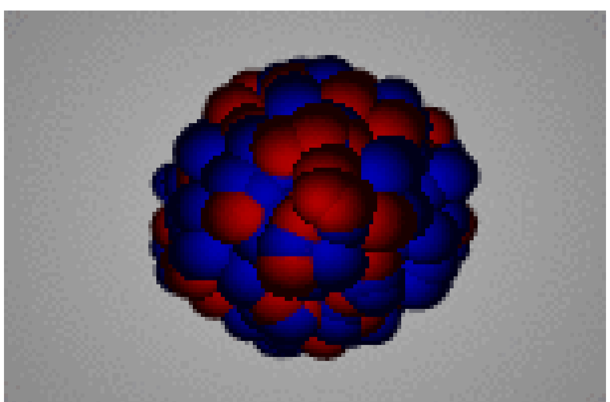
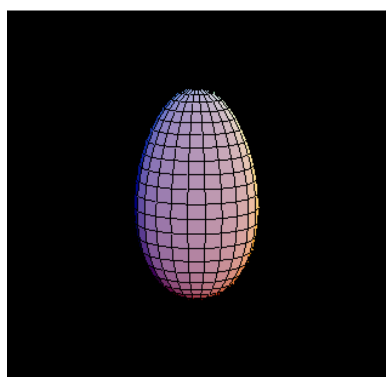
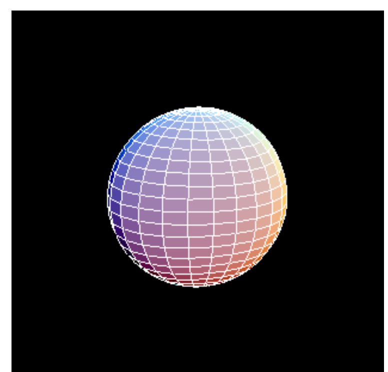


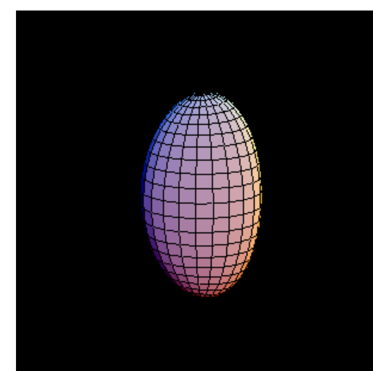


a variety of motions
→ very rich!



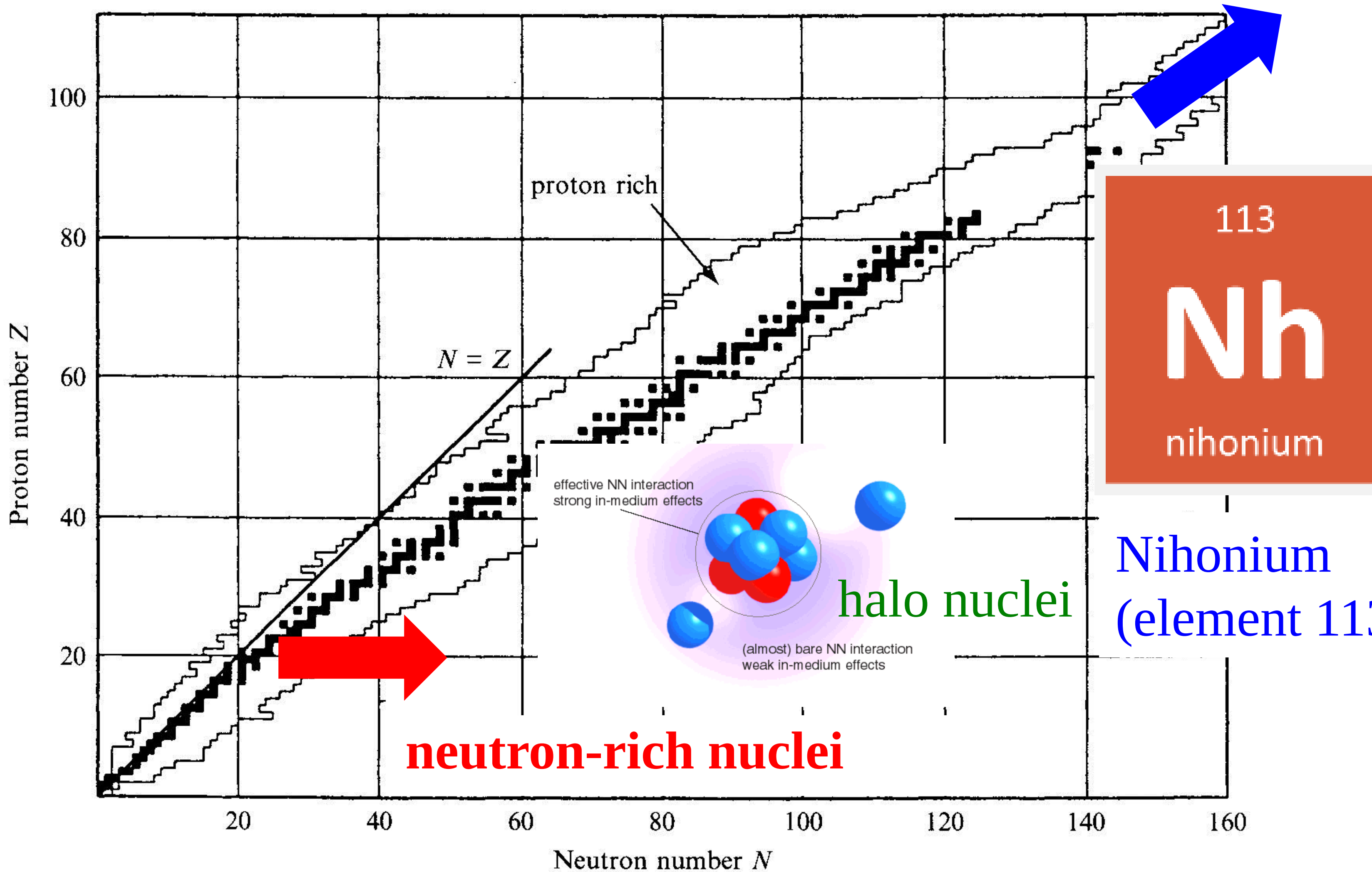






Extension of nuclear chart: frontier of nuclear physics

superheavy elements

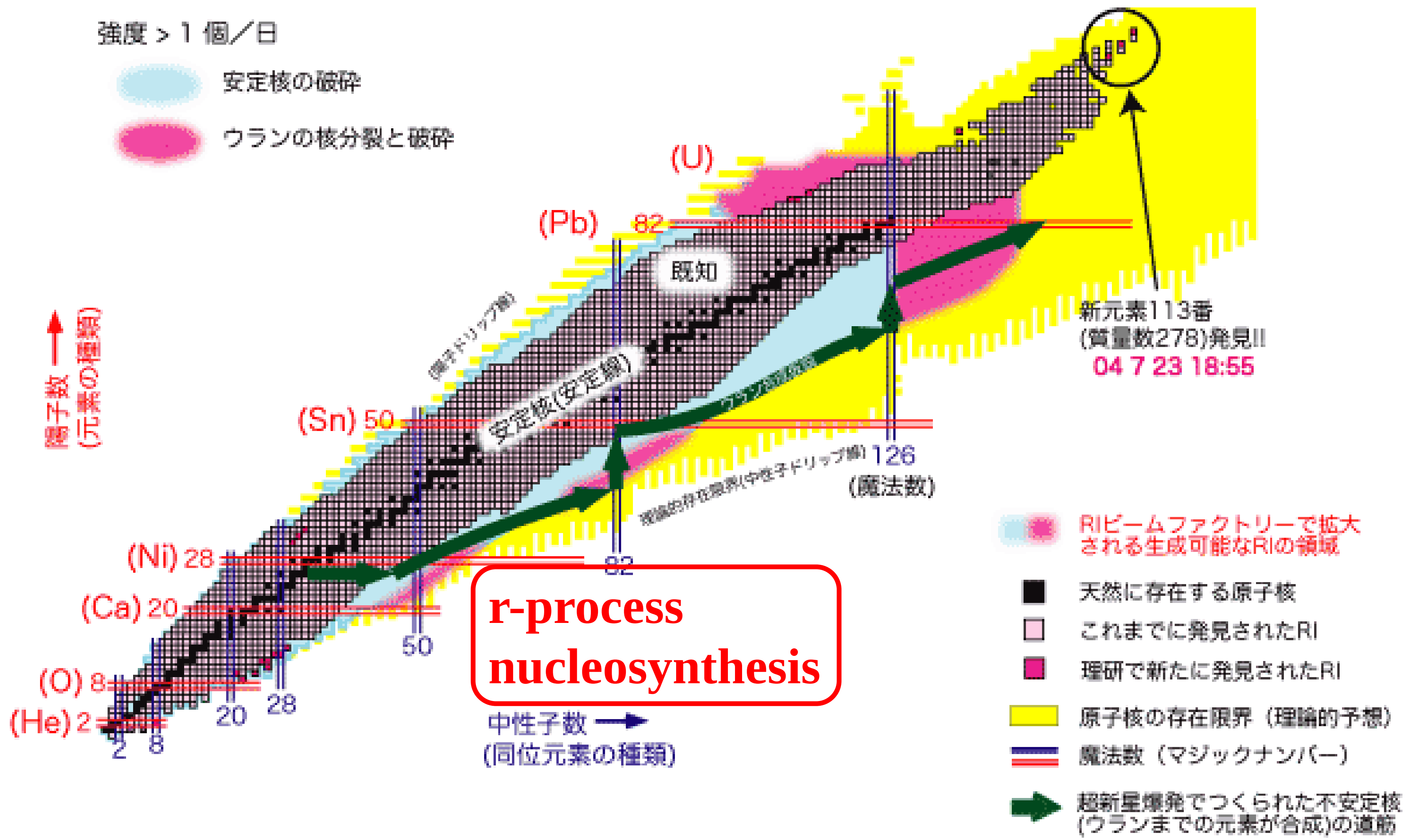


halo nuclei

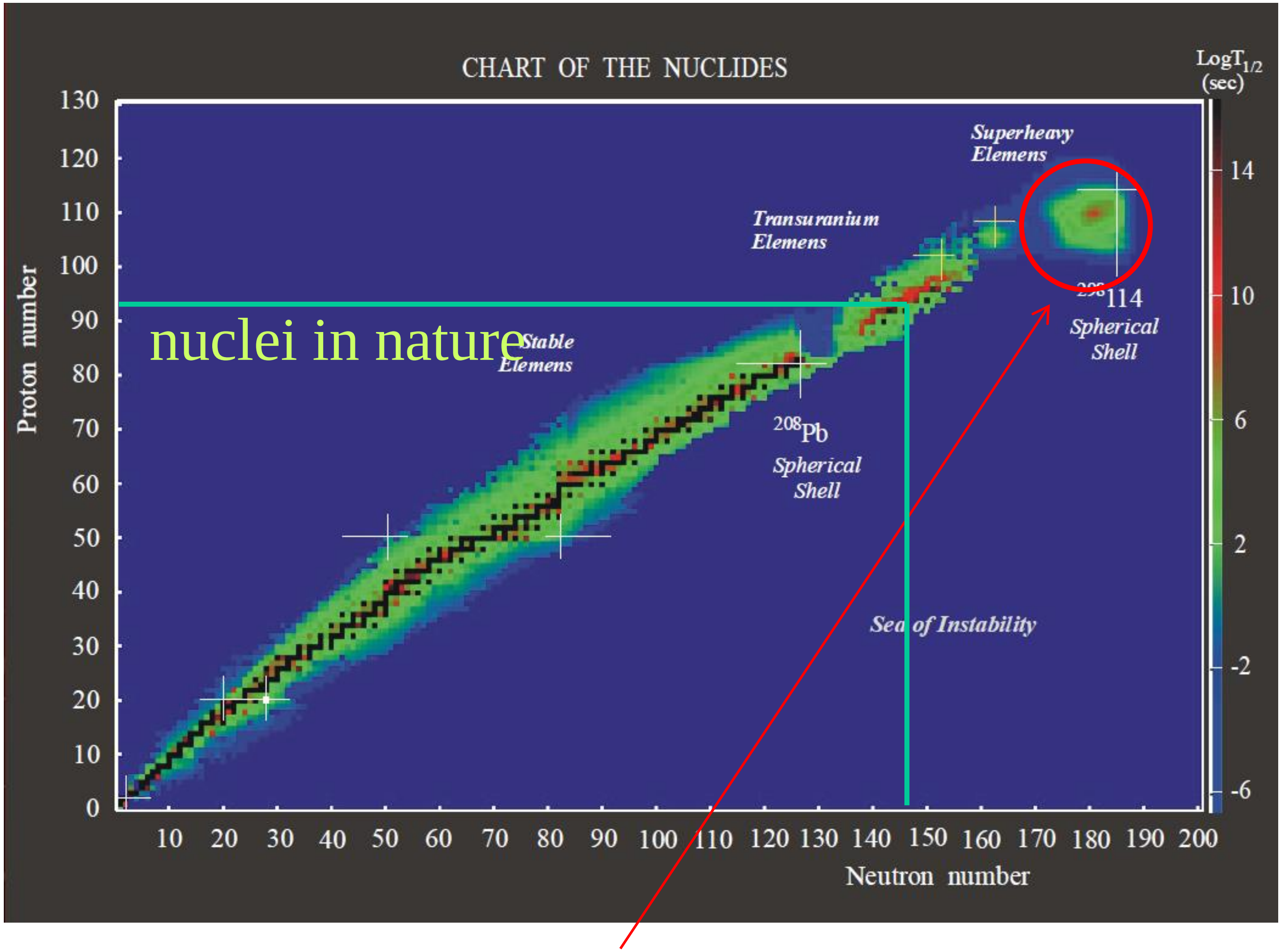
neutron-rich nuclei

Nihonium (element 113)

Neutron-rich nuclei



Prediction of island of stability: an important motivation of SHE study



island of stability around Z=114, N=184

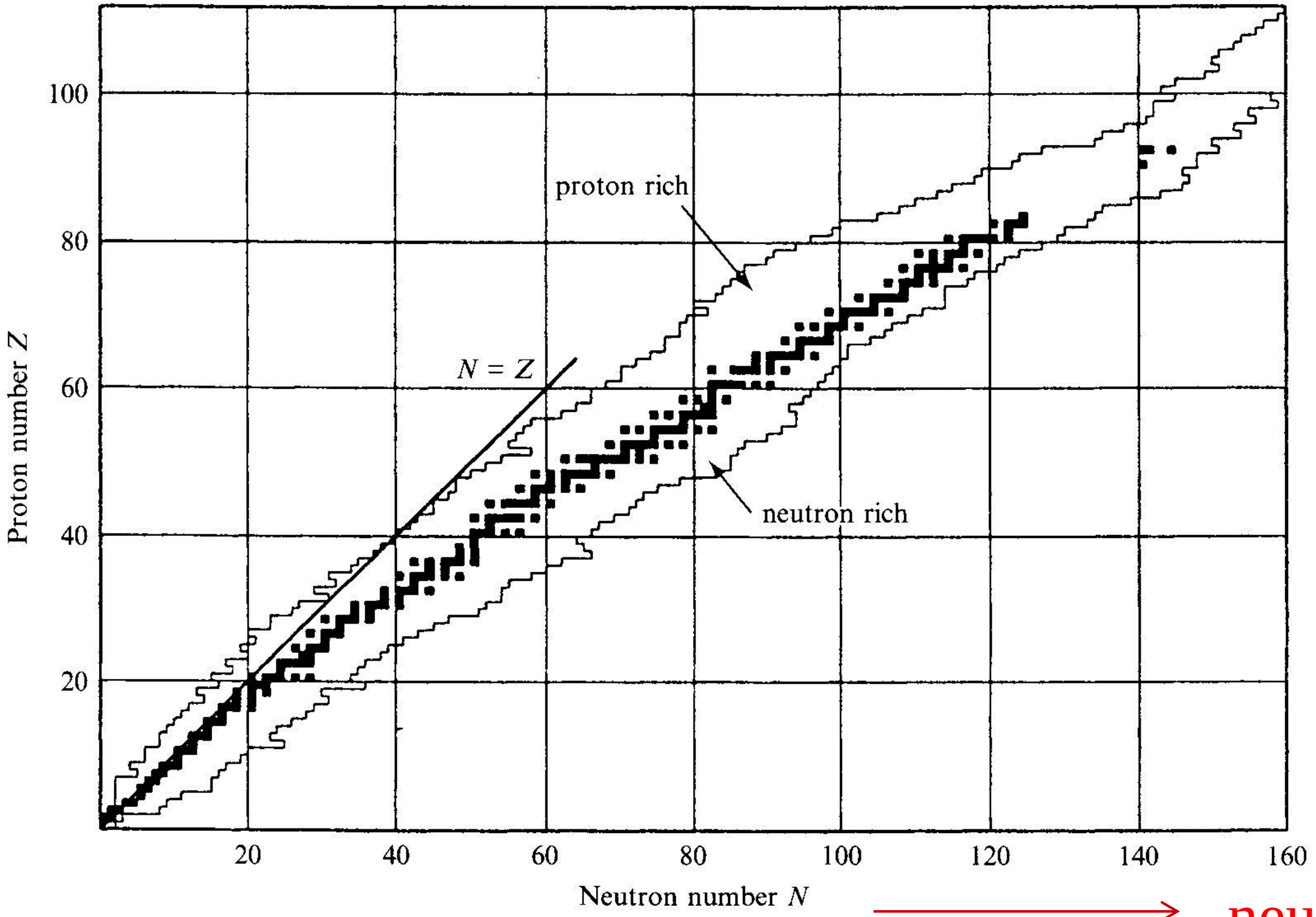
Yuri Oganessian

W.D. Myers and W.J. Swiatecki (1966), A. Sobiczewski et al. (1966)

… more tomorrow

Nuclear chart

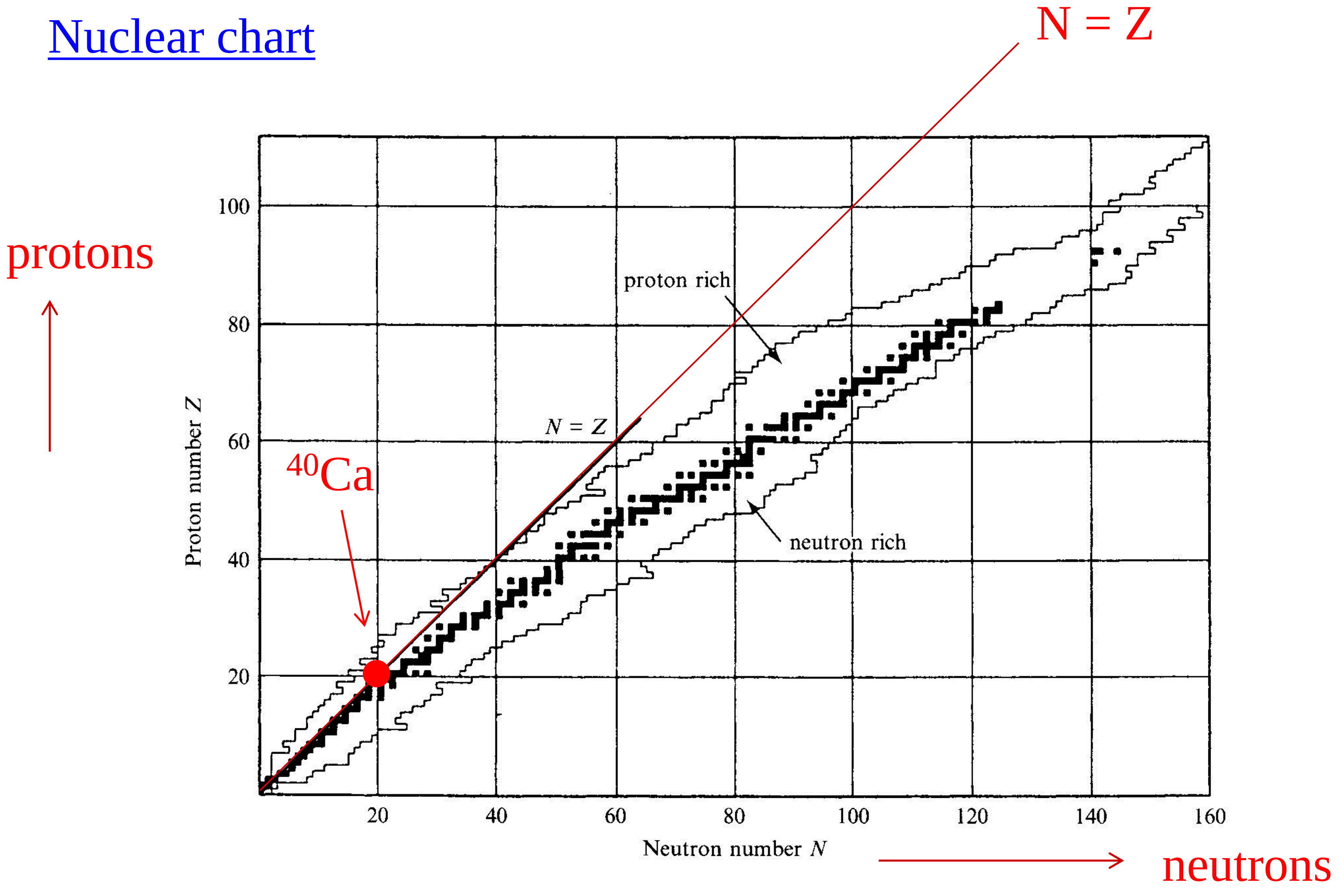
protons



neutrons

2-dimensional map of atomic nuclei
(■: stable nuclei found in nature)

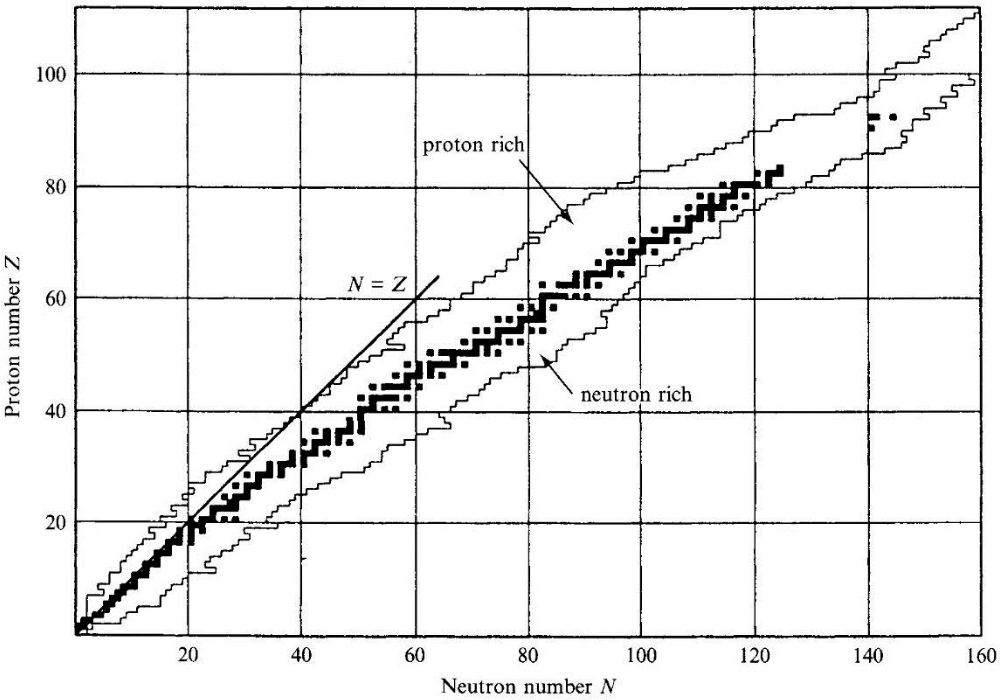
Nuclear chart



2-dimensional map of atomic nuclei

(■: stable nuclei found in nature)

Nuclear chart



2-dimensional map of atomic nuclei
(■: stable nuclei found in nature)

- Z ~20 → N~Z
- Z > 20 → N > Z

Can you imagine why?

p-p interaction

p-n interaction

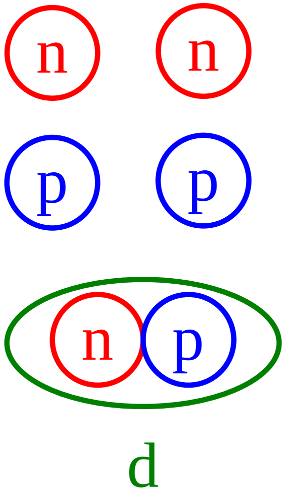
n-n interaction

the same strength?

n-n → no bound state

p-p → no bound state

n-p → bound (deuteron)



→ pn interaction: stronger

- the reason for “Z ~20 → N~Z” (symmetry energy)

  to maximize the number of pn pair

  cf. another reason: Pauli principle

- the reason for “Z > 20 → N > Z”

  the effect of Coulomb repulsion

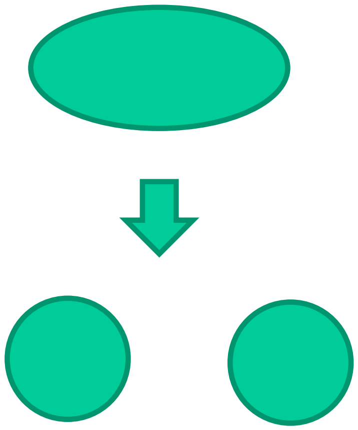
  pp, pn, nn : nuclear force (strong attraction)
  pp : +Coulomb force (repulsive)

  ➡ gain attraction by increasing the number of neutrons
  (in order to compensate the Coulomb repulsion)

  *unfavorable for symmetry energy,
  but favorable in total

nuclear power plants and radioactivities

$^{235}U + n \rightarrow {}^{236}U^* \rightarrow$ fission ($^{93}Rb + {}^{141}Cs + 2n$ etc.)



- Z ~20 → N~Z
- Z > 20 → N > Z

^{236}U (Z = 92, N = 144) : N/Z = 1.565

fission fragments: similar N/Z ratio → neutron-rich nuclei

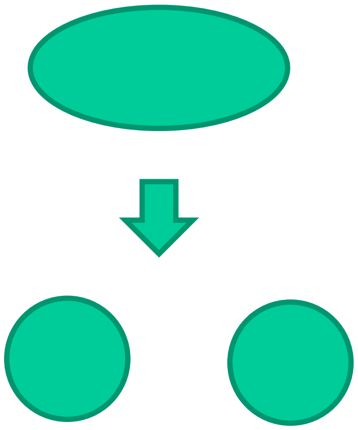
^{93}Rb (Z = 37, N = 56) : N/Z = 1.514

^{141}Cs (Z = 55, N = 86) : N/Z = 1.564

nuclear power plants and radioactivities

$^{235}U + n \rightarrow {}^{236}U^* \rightarrow$ fission $({}^{93}Rb + {}^{141}Cs + 2n$ etc.)

- $Z \sim 20 \rightarrow N \sim Z$
- $Z > 20 \rightarrow N > Z$



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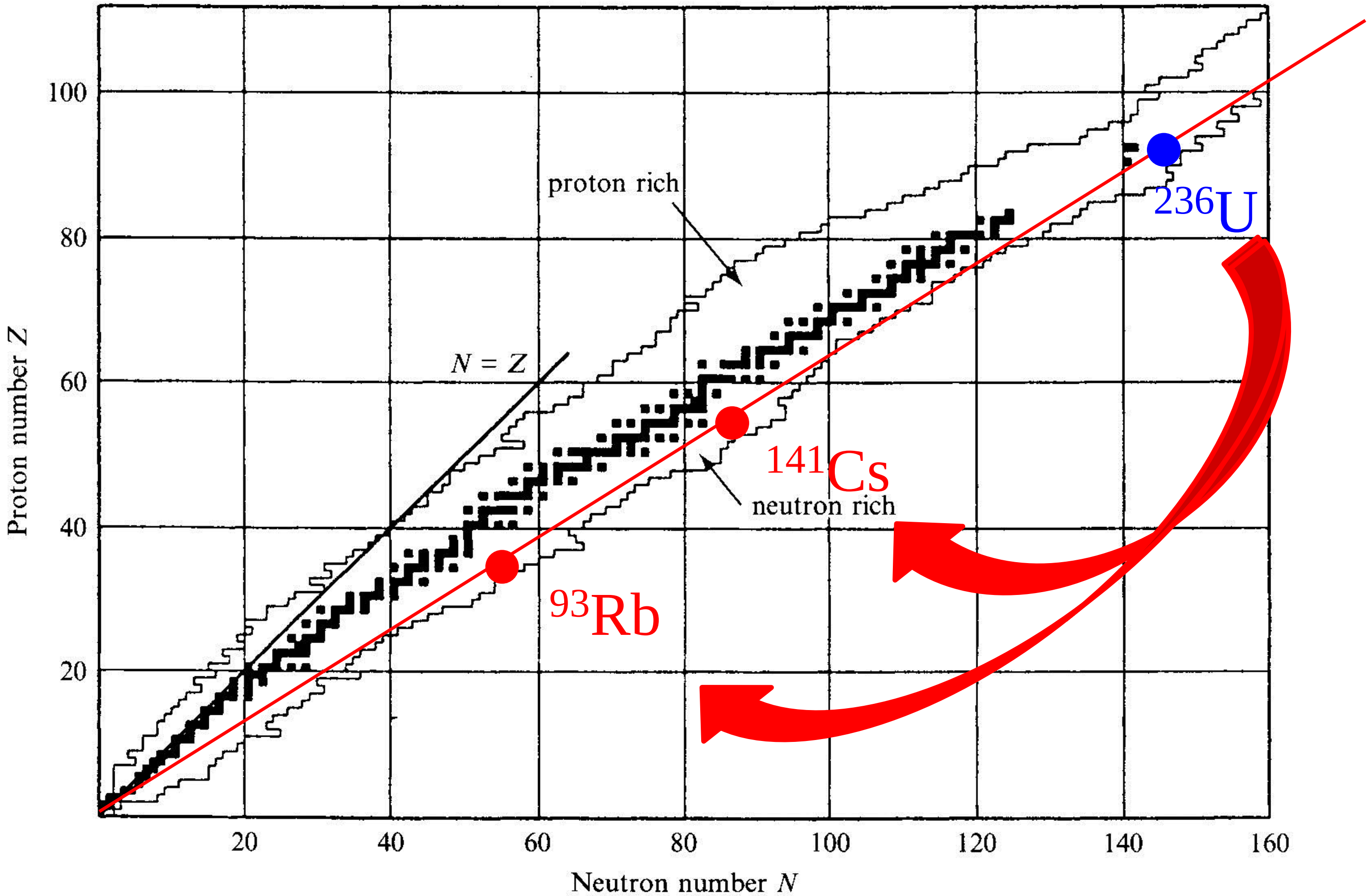
stable Cs and Rb: ^{133}Cs ($N/Z = 1.418$) and ^{85}Rb ($N/Z = 1.297$) etc.

⇒ radioactivities when fission fragments change to stable nuclei

Nuclear chart

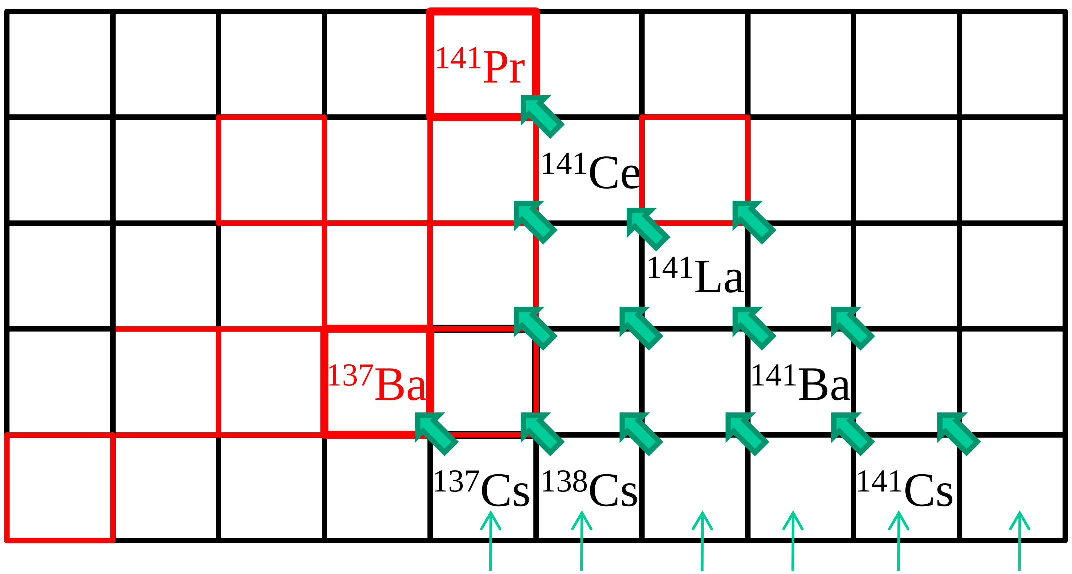


2-dimensional map of atomic nuclei
(■: stable nuclei found in nature)

beta decays: $n \longrightarrow p + e^{-} + \bar{\nu}$

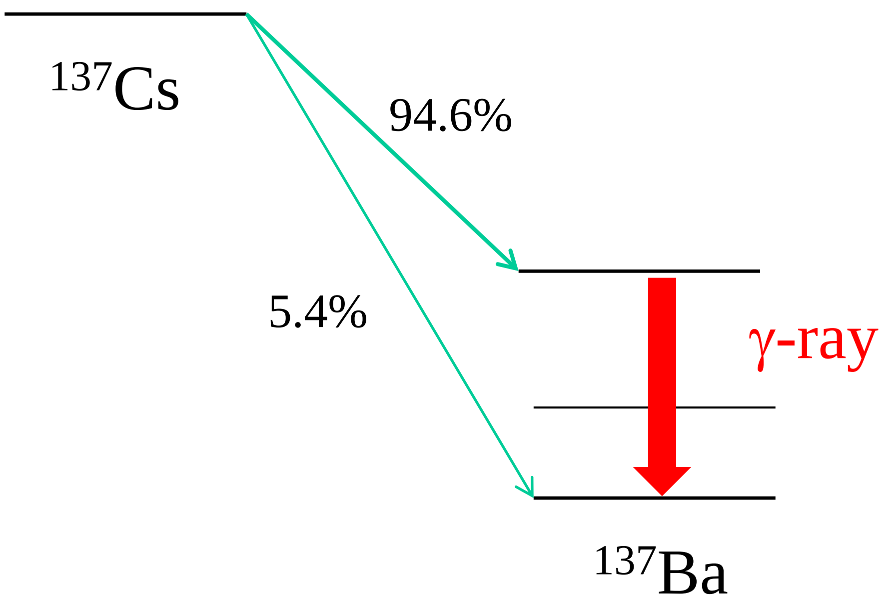
beta particle

if inside a nucleus: $(N,Z) \longrightarrow (N\text{-}1,Z+1) + e^{-} + \bar{\nu}$



$^{235}U + n \rightarrow$ fission

if beta decay to an excited state



Elements and Nuclear Phyics - 2

Kouichi Hagino

Tohoku University, Sendai, Japan

- How were elements created?
- Physics and chemistry of superheavy elements