Physics of weakly-bound many-body systems
弱束縛量子多体系の物理

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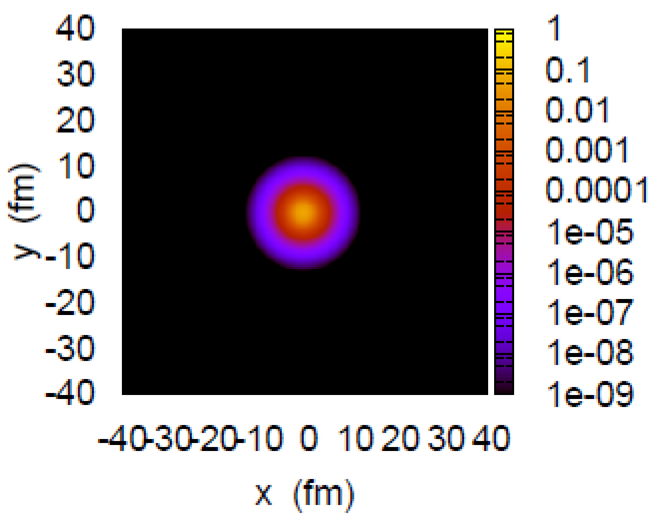
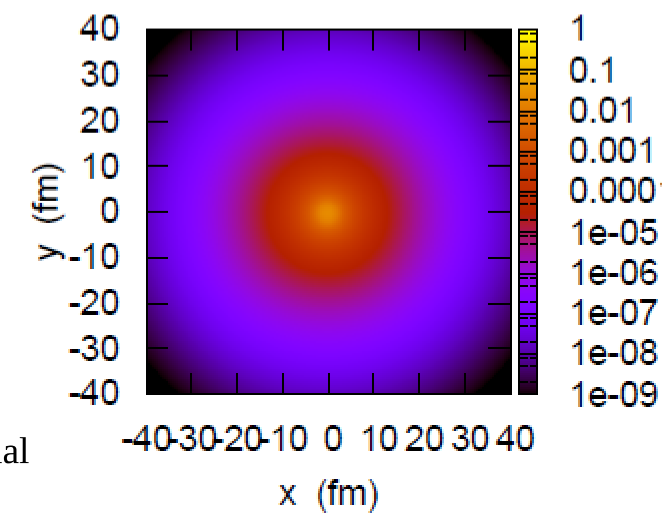


weakly bound

s-wave bound state
in a square well potential



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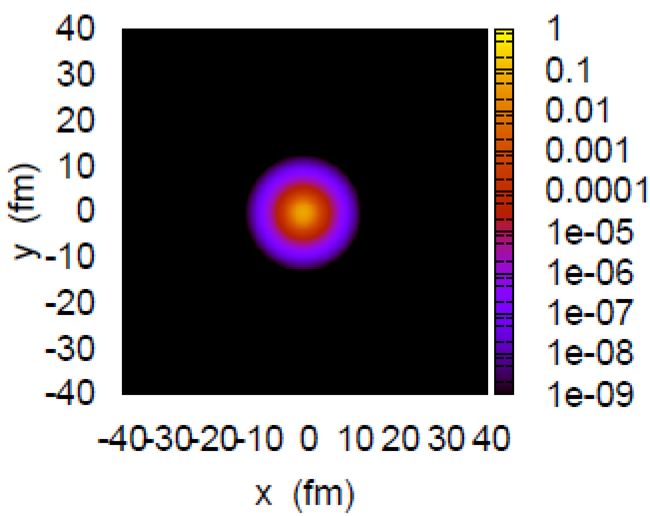

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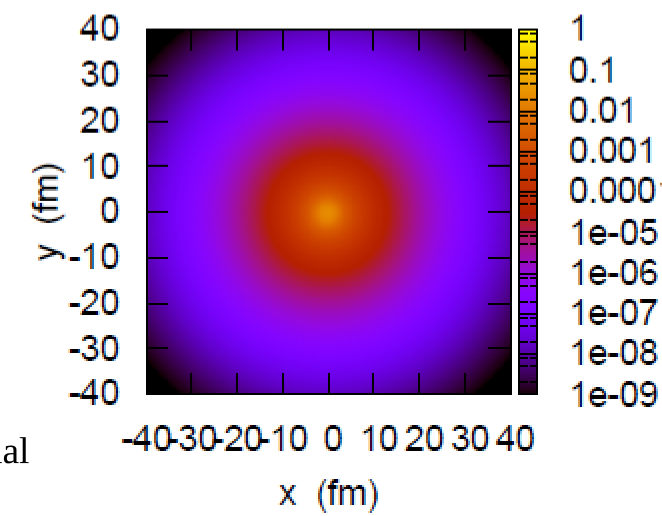
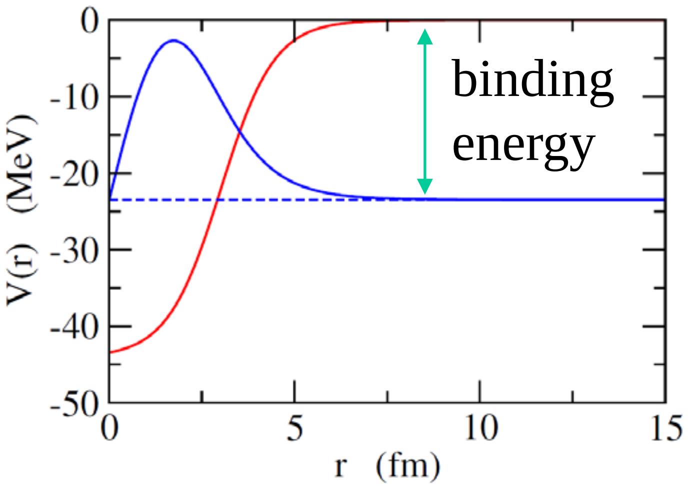


s-wave bound state
in a square well potential

weakly bound state

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2mr^2}+V(r)-\epsilon_l\right]u_l(r)=0$$

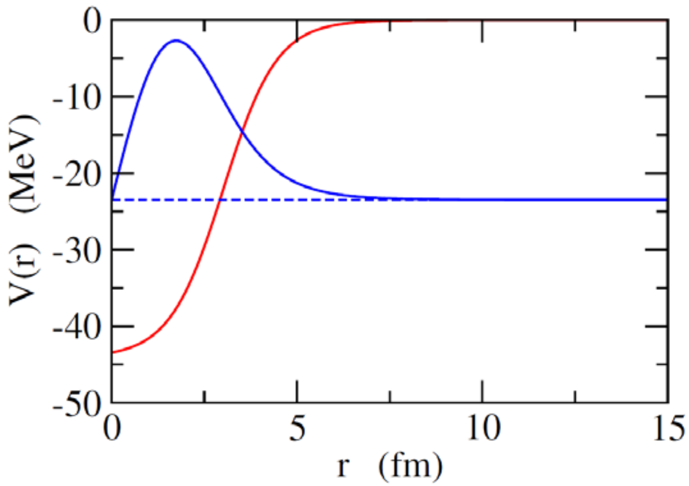


Consider a bound state in a potential *V*

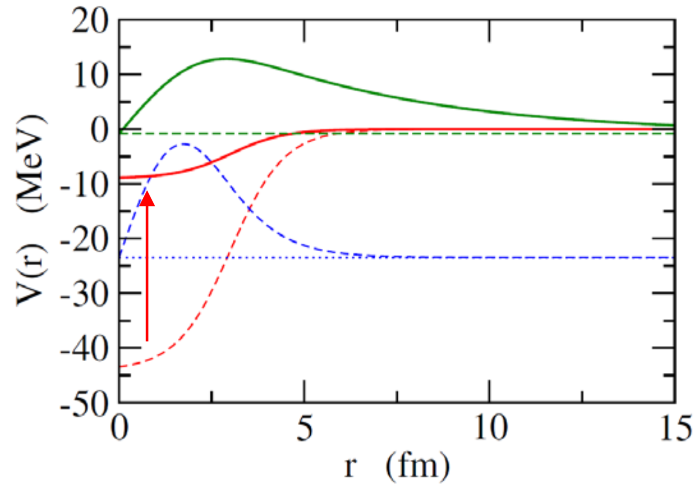
What would you do if you want to investigate properties of a weakly bound system within this model?

weakly bound state

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2mr^2}+V(r)-\epsilon_l\right]u_l(r)=0$$



make the pot. shallower (or narrower)

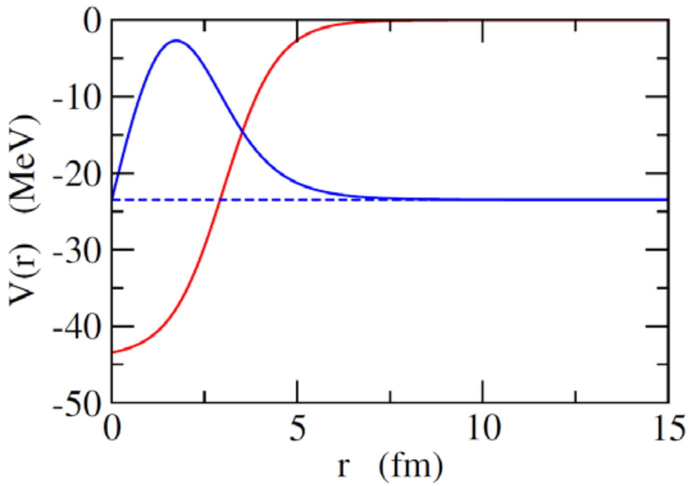


$$\psi(r)\sim\exp(-\kappa r)$$

$$\kappa=\sqrt{2m|\epsilon|/\hbar^2}$$

weakly bound state

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2mr^2}+V(r)-\epsilon_l\right]u_l(r)=0$$



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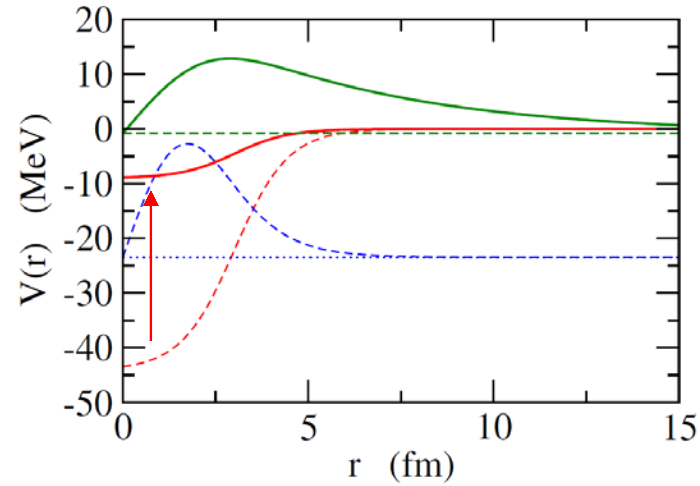
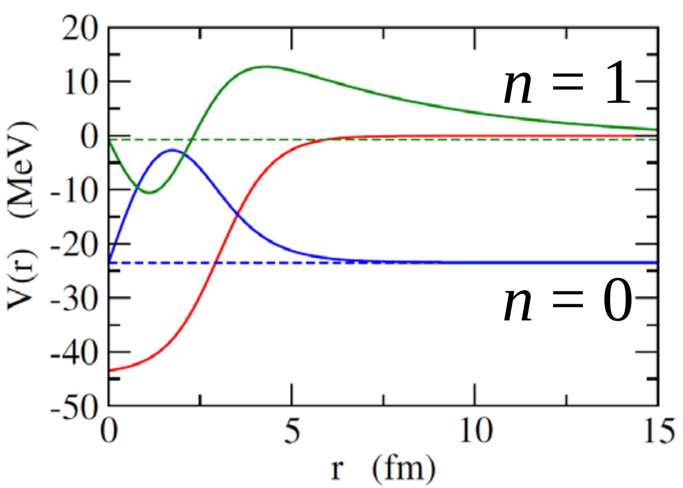


$$\psi(r)\sim\exp(-\kappa r)$$

$$\kappa=\sqrt{2m|\epsilon|/\hbar^2}$$

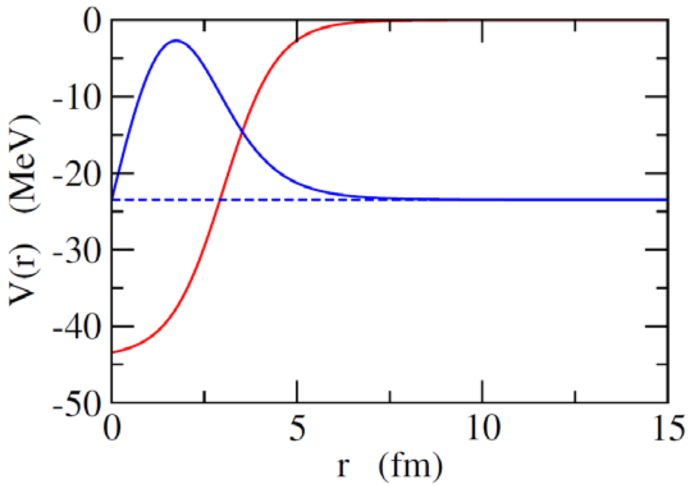
investigate excited states



- ✓ excite the system
- ✓ increase the number of particles (Fermion)

weakly bound state

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2mr^2}+V(r)-\epsilon_l\right]u_l(r)=0$$



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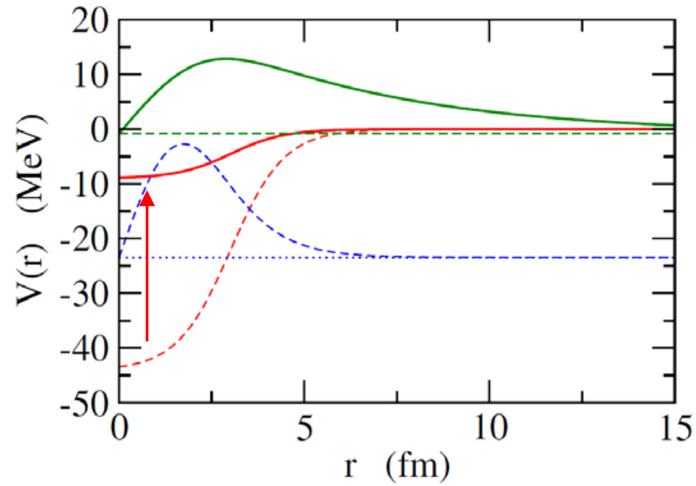
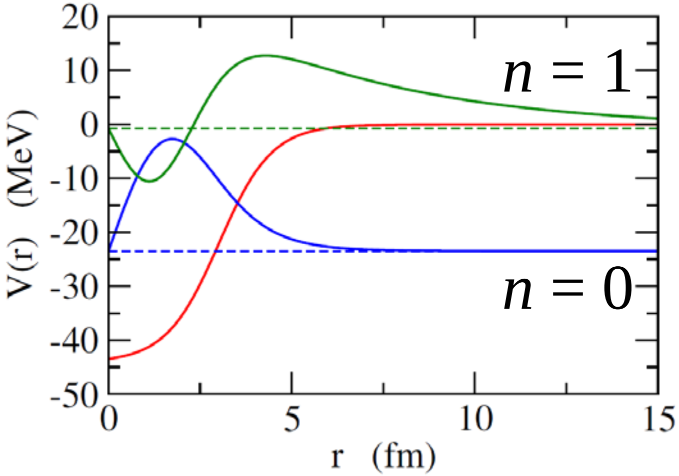
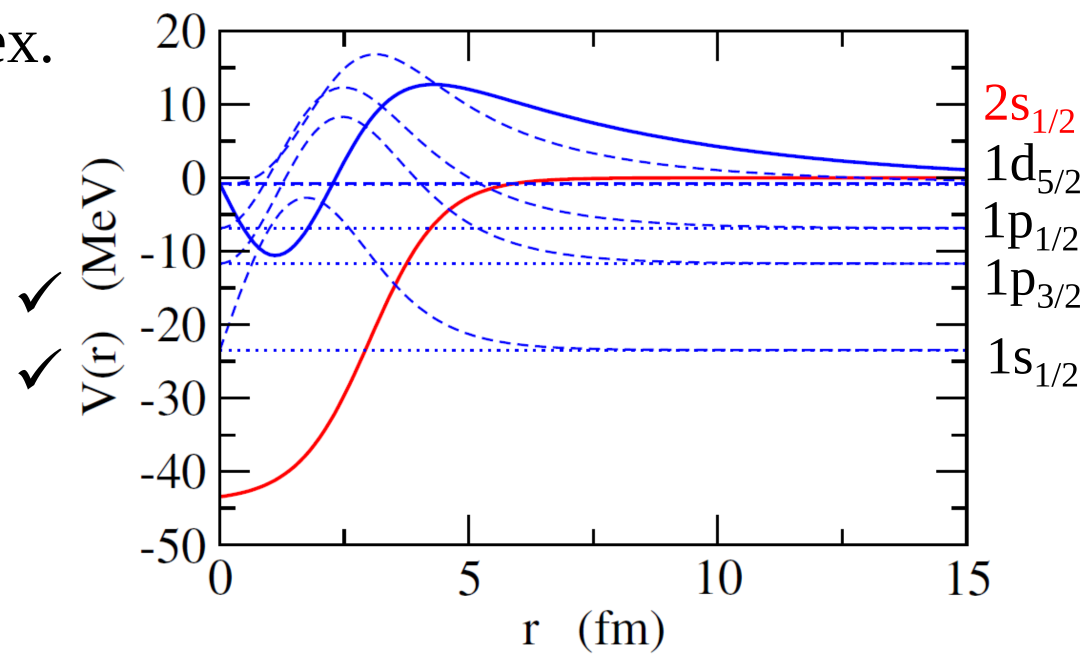


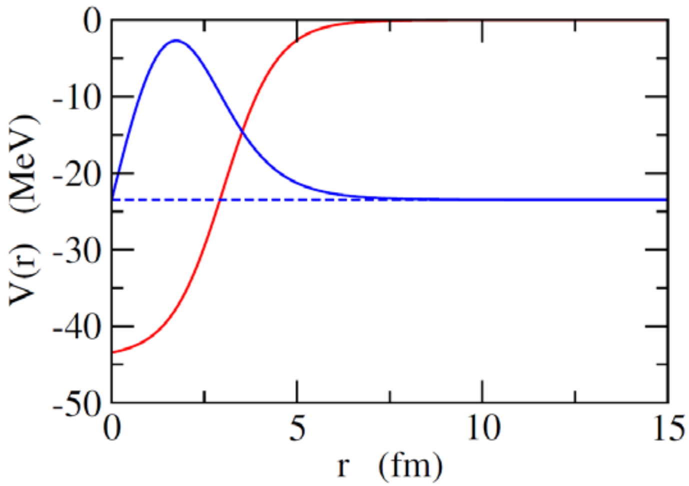
investigate ex. states



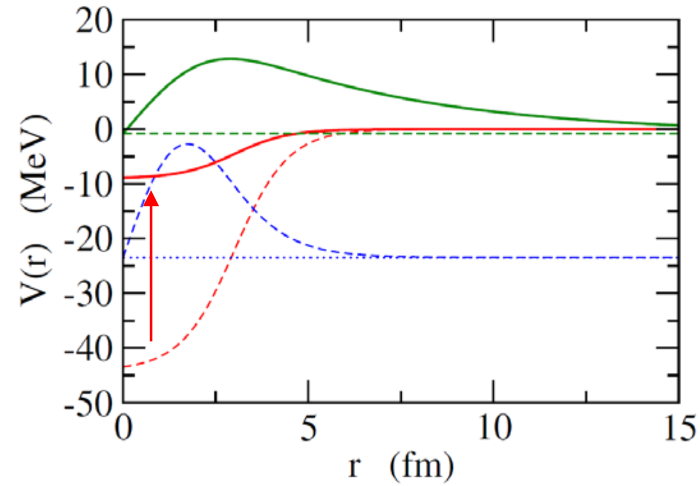


weakly bound state

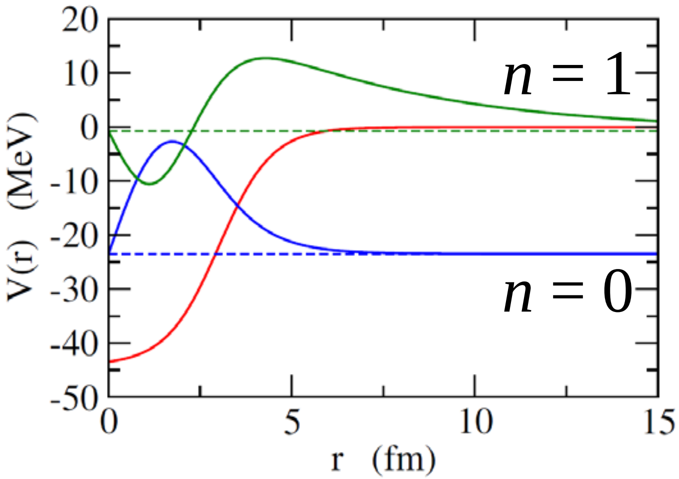
$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dr^2}+\frac{l(l+1)\hbar^2}{2mr^2}+V(r)-\epsilon_l\right]u_l(r)=0$$



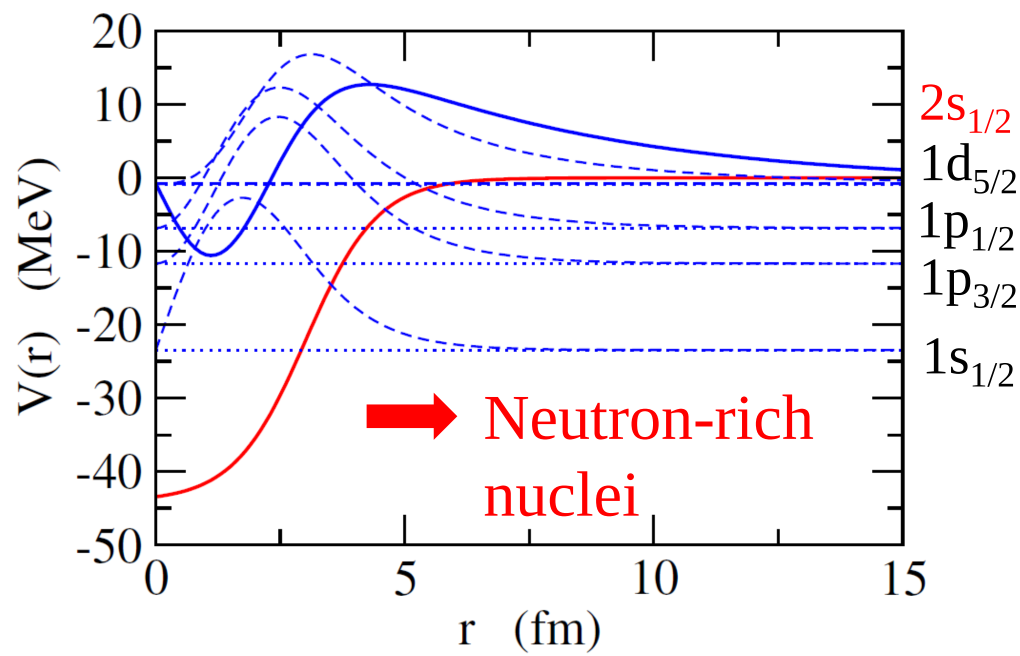
make the pot. shallower (or narrower)



investigate ex. states



✓
✓



Plan of this lecture

1. Introduction: physics of neutron-rich nuclei — today
   overview, r-process nucleosynthesis

2. Properties of one-neutron halo nuclei — 11/2 morning
   angular momentum and halo phenomena

3. Unbound nuclei and resonance states — 11/2 afternoon
   general theory of potential resonances
   proton radioactivities

4. Deformed neutron-rich nuclei — 11/5 afternoon-1
   resonance state of a deformed potential

5. Pairing correlations and two-neutron halo nuclei — 11/5 afternoon-2
   Borromean nuclei, di-neutron correlation

6. Coulomb excitations and two-neutron emissions — 11/9 morning

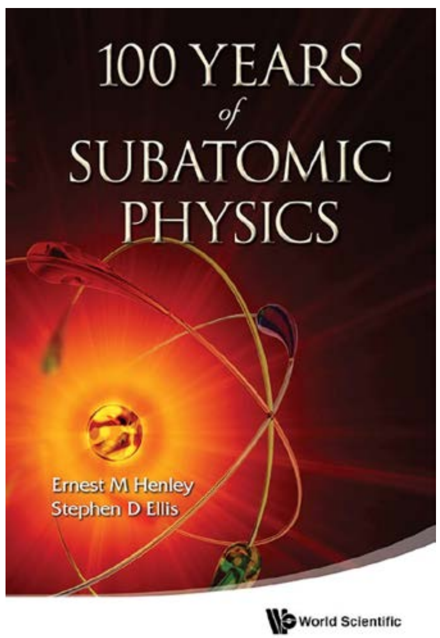
7. Superheavy elements and neutron-rich nuclei — 11/9 afternoon

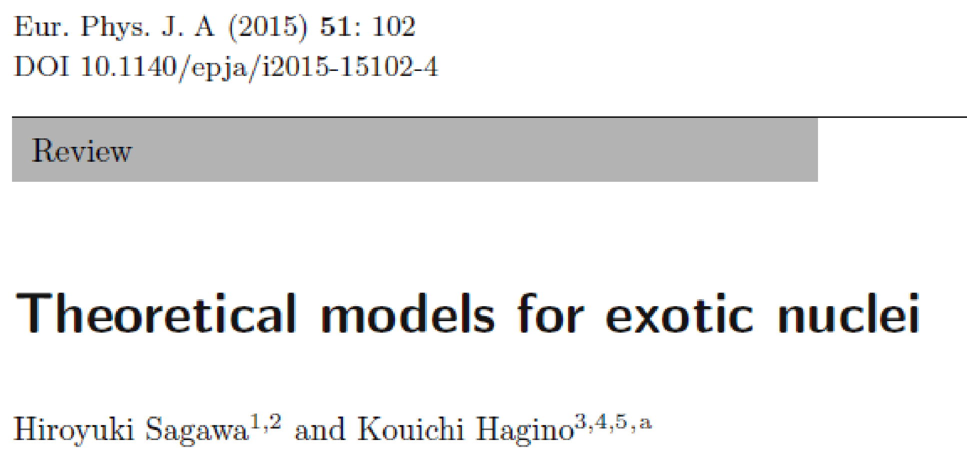
➢Lecture notes

http://www2.yukawa.kyoto-u.ac.jp/~kouichi.hagino/lecture2.html

「Nuclear theory group, Kyoto University」→「Kouichi Hagino」→「Lecture notes」

➢References




Eur. Phys. J. A (2015) **51**: 102
DOI 10.1140/epja/i2015-15102-4

Review

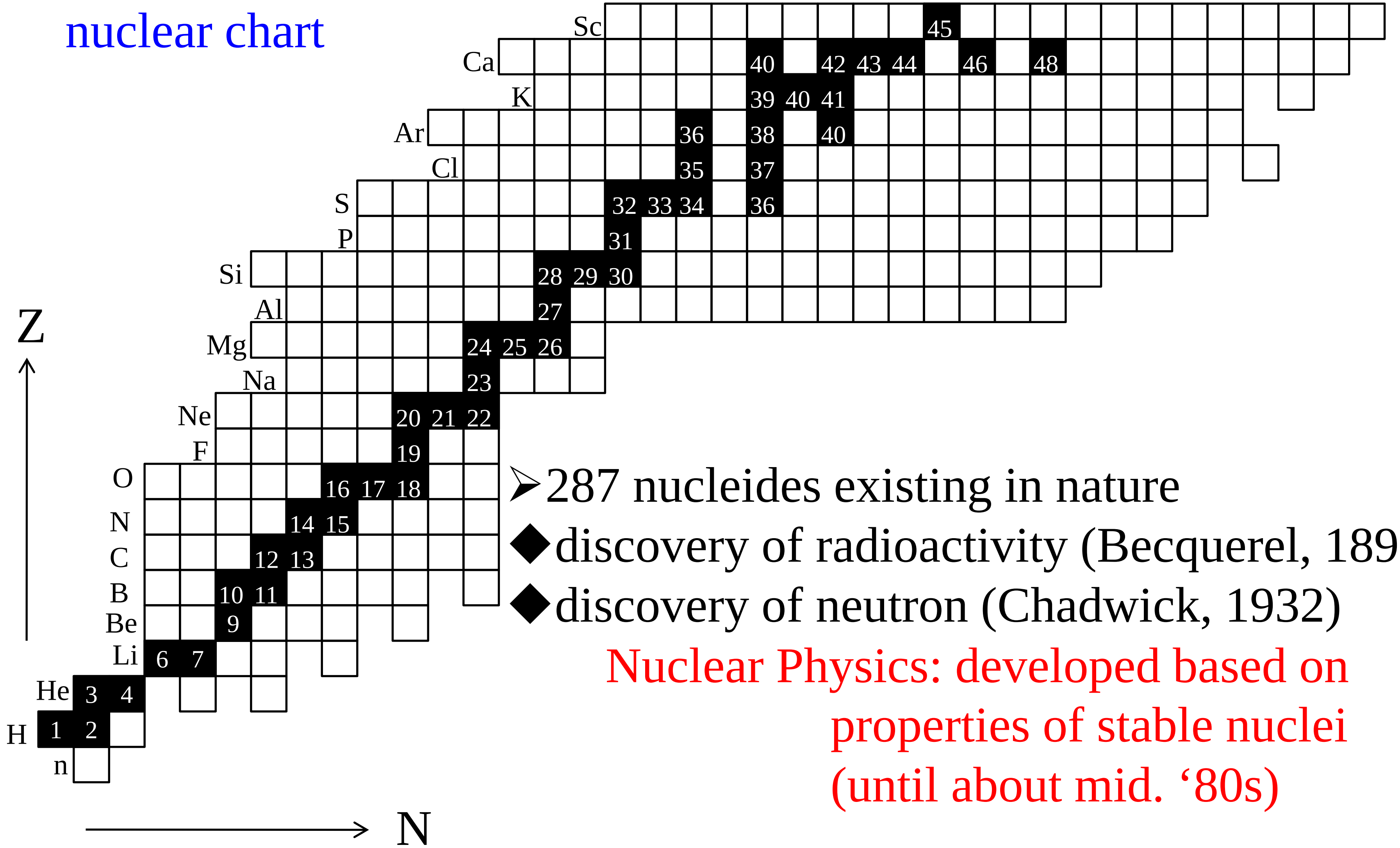
Theoretical models for exotic nuclei

Hiroyuki Sagawa[1,2] and Kouichi Hagino[3,4,5,a]

"Physics of Unstable Nuclei" Prof. T. Nakamura

Introduction

nuclear chart



- 287 nucleides existing in nature
- discovery of radioactivity (Becquerel, 1896)
- discovery of neutron (Chadwick, 1932)

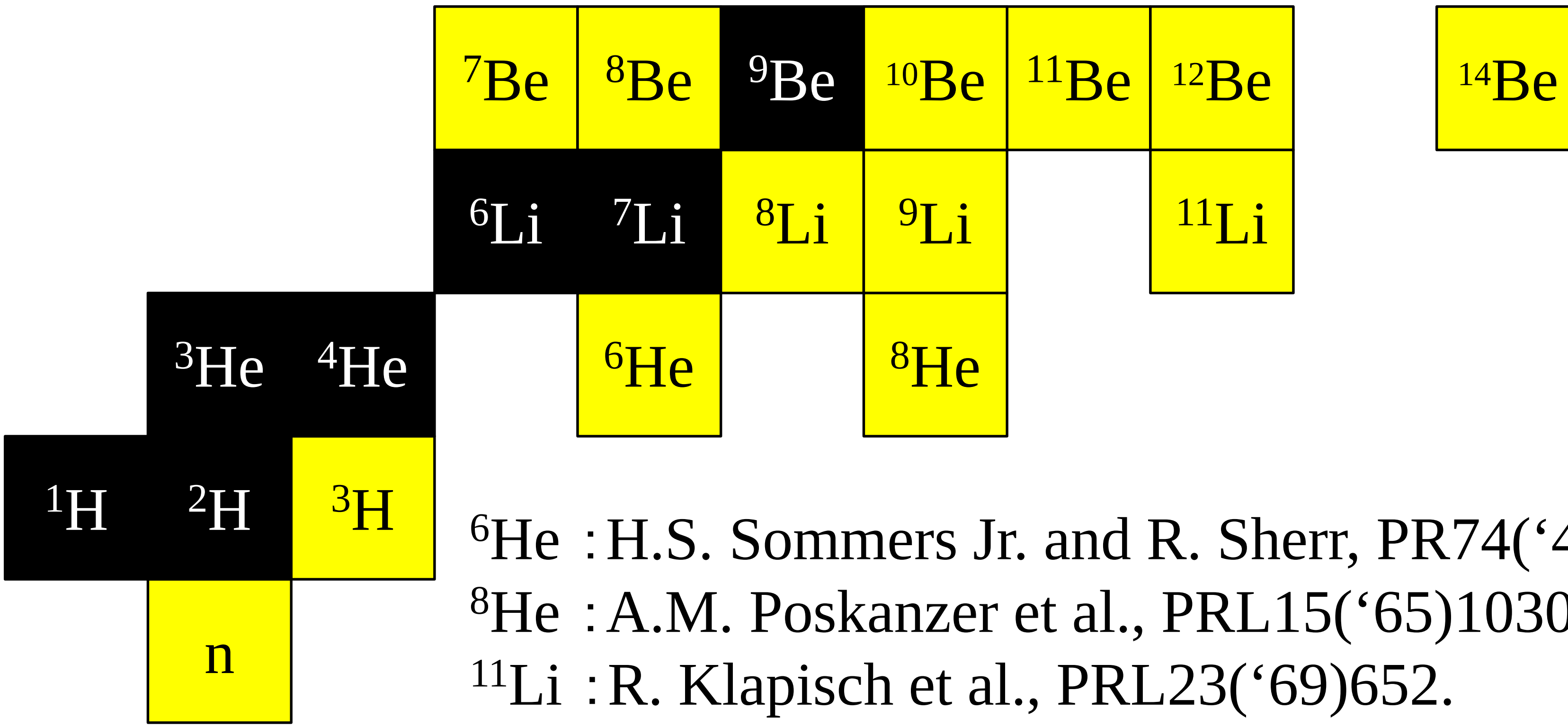
Nuclear Physics: developed based on properties of stable nuclei (until about mid. '80s)

saturation, radii, binding energy, magic numbers…..

Nuclear Physics: based on properties of stable nuclei

→ Nevertheless, there has existed a natural question since old time

"how many neutrons can be put into a nucleus for a given number of protons?"



^{6}He : H.S. Sommers Jr. and R. Sherr, PR74('48)1192.

^{8}He : A.M. Poskanzer et al., PRL15('65)1030.

^{11}Li : R. Klapisch et al., PRL23('69)652.

"Int. Symp. on why and how should we investigate nucleides far off the stability line", Lysekil, Sweden (1966). etc.

Nuclear Physics: based on properties of stable nuclei

→ Nevertheless, there has existed a natural question since old time

"how many neutrons can be put into a nucleus for a given number of protons?"

"Int. Symp. on why and how should we investigate nucleides far off the stability line", Lysekil, Sweden (1966). etc.

Questions discussed at that time:

- how many neutrons?
- how good are models developed for stable nuclei?
- r-process nucleosynthesis

Nuclear Physics: based on properties of stable nuclei

⟶ Nevertheless, there has existed a natural question since old time "how many neutrons can be put into a nucleus for a given number of protons?"

"Int. Symp. on why and how should we investigate nucleides far off the stability line", Lysekil, Sweden (1966). etc.

Questions discussed at that time:

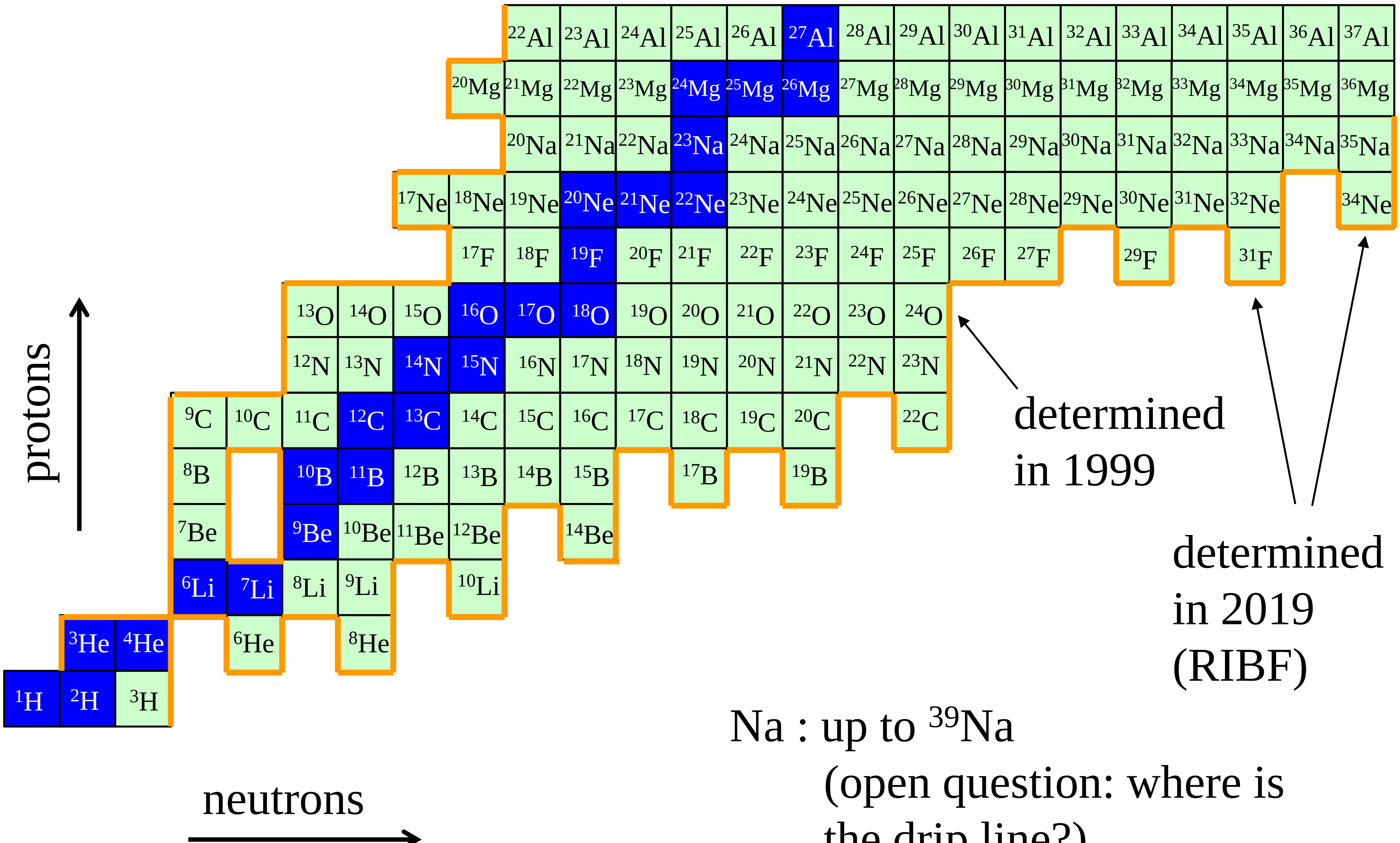
- how many neutrons?
- how good are models developed for stable nuclei?
- r-process nucleosynthesis

⇧

many questions still remain as current questions

+ are there interesting phenomena which exist only in weakly bound systems?

“how many neutrons can be put into a nucleus for a given number of protons?” → where is the neutron drip-line?



Na : up to ^{39}Na

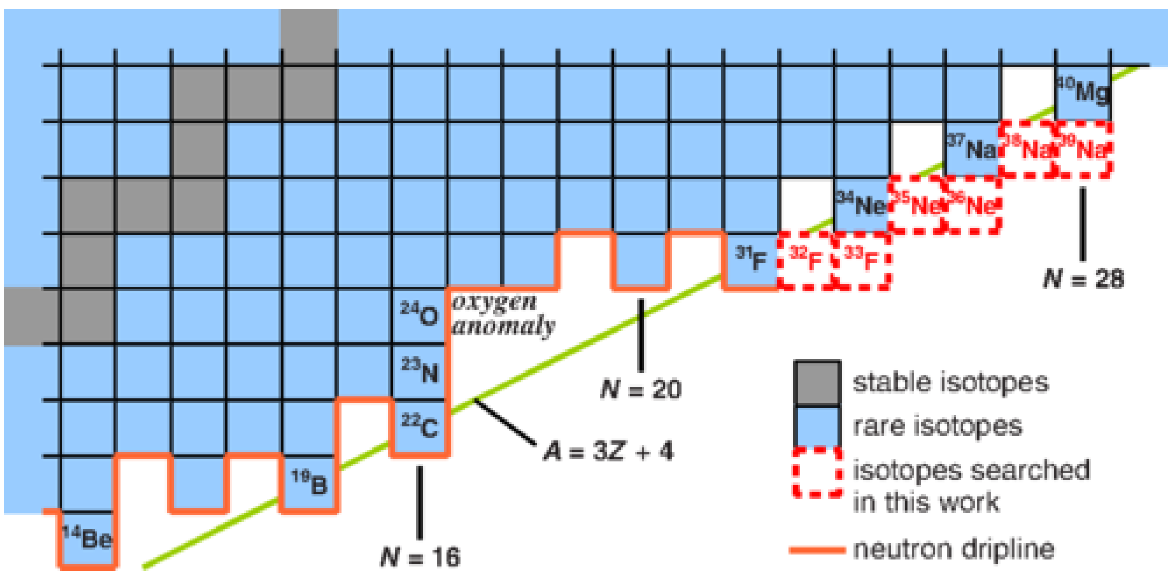
(open question: where is the drip line?)

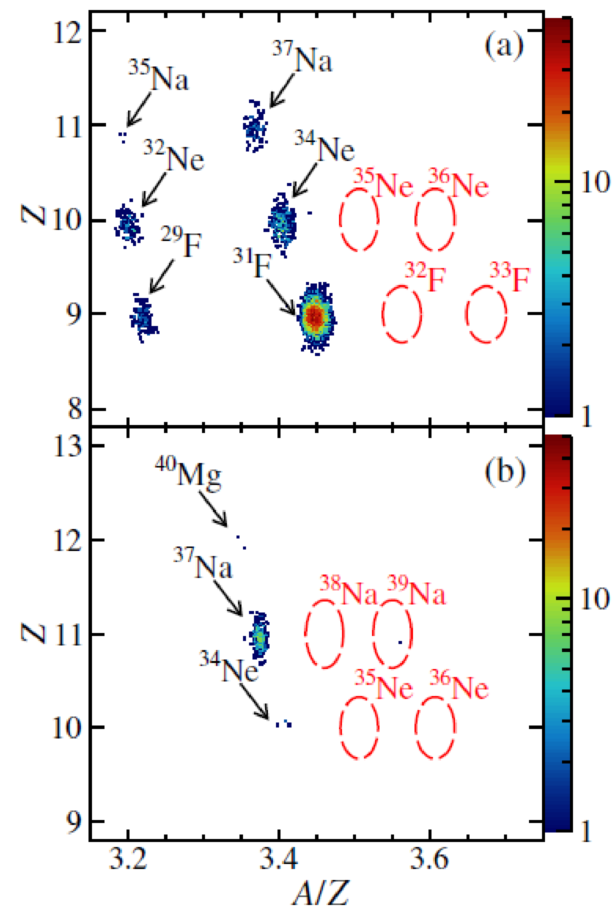
PHYSICAL REVIEW LETTERS **123,** 212501 (2019)

Editors' Suggestion | Featured in Physics

Location of the Neutron Dripline at Fluorine and Neon

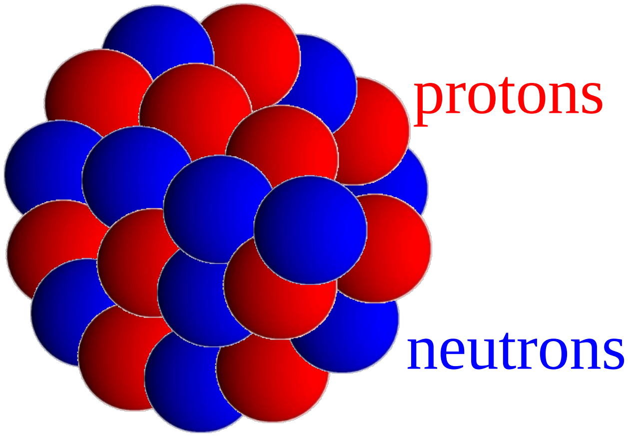
D. S. Ahn,[1] N. Fukuda,[1] H. Geissel,[5] N. Inabe,[1] N. Iwasa,[4] T. Kubo,[1,*,†] K. Kusaka,[1] D. J. Morrissey,[6] D. Murai,[3] T. Nakamura,[2] M. Ohtake,[1] H. Otsu,[1] H. Sato,[1] B. M. Sherrill,[6] Y. Shimizu,[1] H. Suzuki,[1] H. Takeda,[1] O. B. Tarasov,[6] H. Ueno,[1] Y. Yanagisawa,[1] and K. Yoshida[1]





fragmentation of ^{48}Ca with Be at RIBF

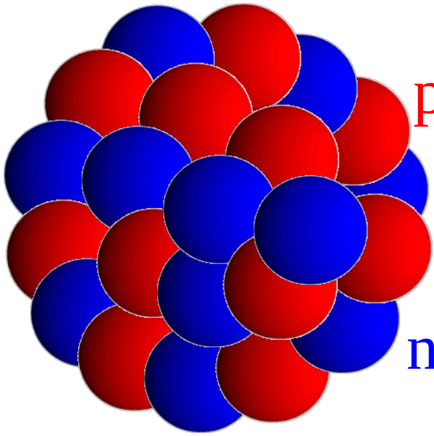
Properties of nuclei as nuclear many-body systems



nucleus = an aggregate of particles with strong interaction

- finite quantum many-body system
- self-bound system

Properties of nuclei as nuclear many-body systems



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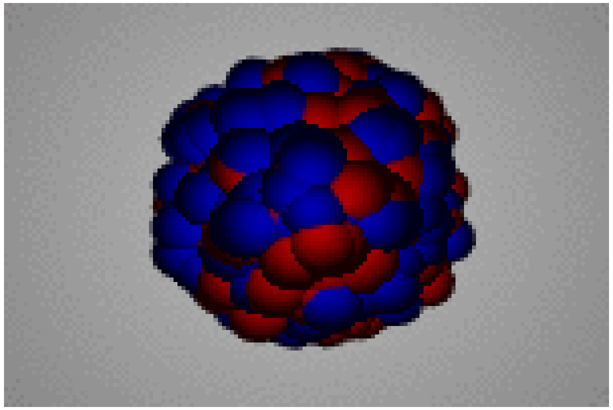
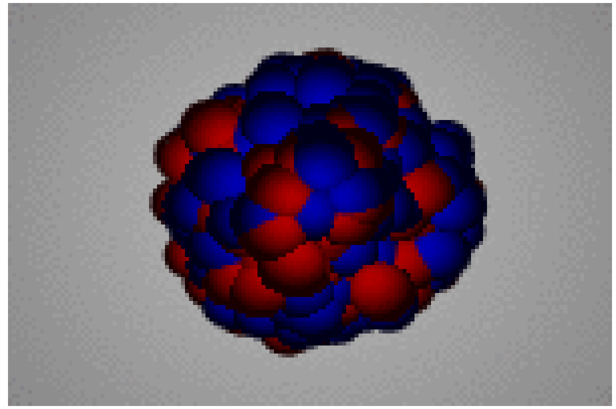
correlations of two-kinds particles: protons and neutrons
→rich and variety of phenomena

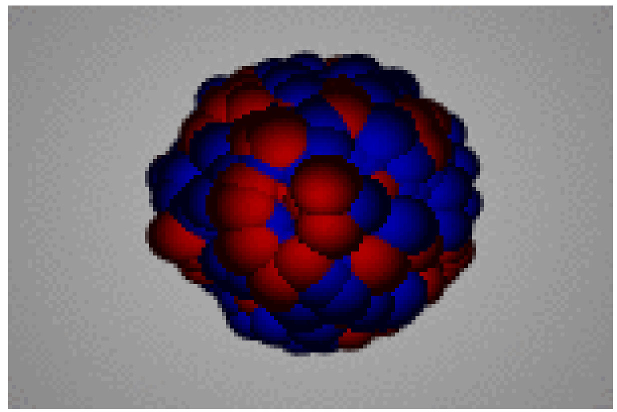


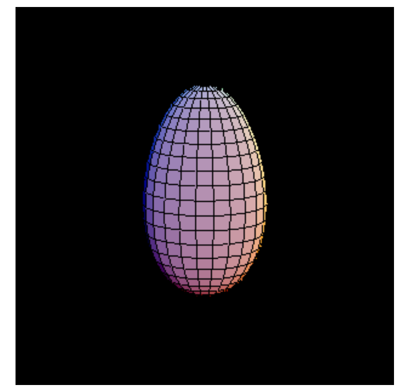


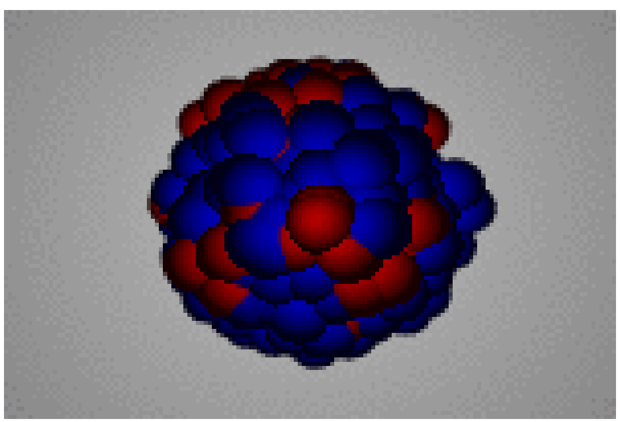
very regular motion

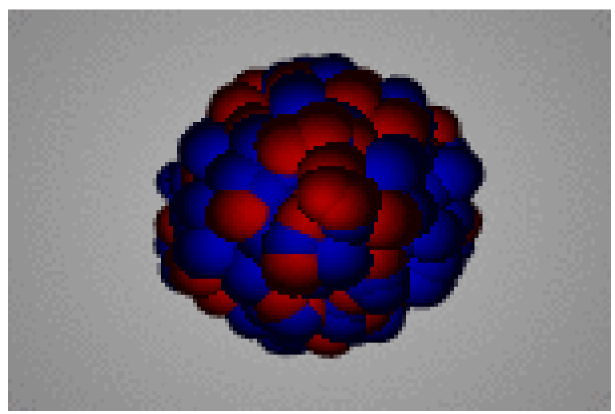
“collective motions”

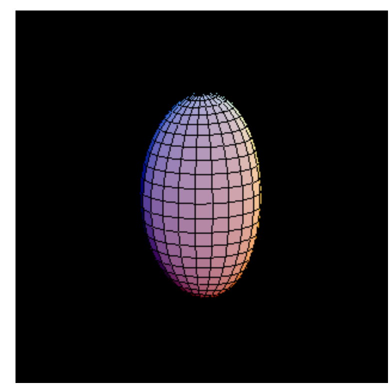
varieties
due to two kinds of
particles



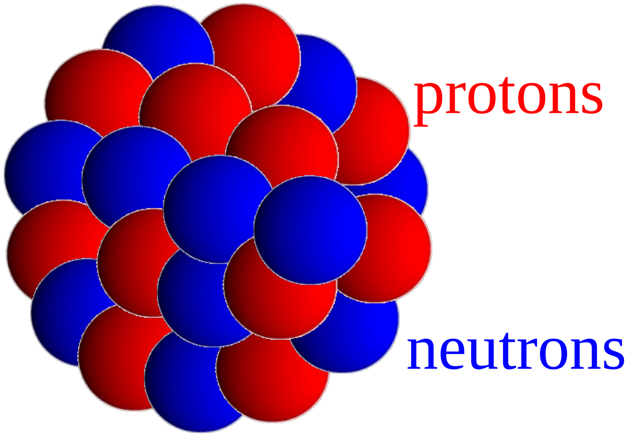








Properties of nuclei as nuclear many-body systems



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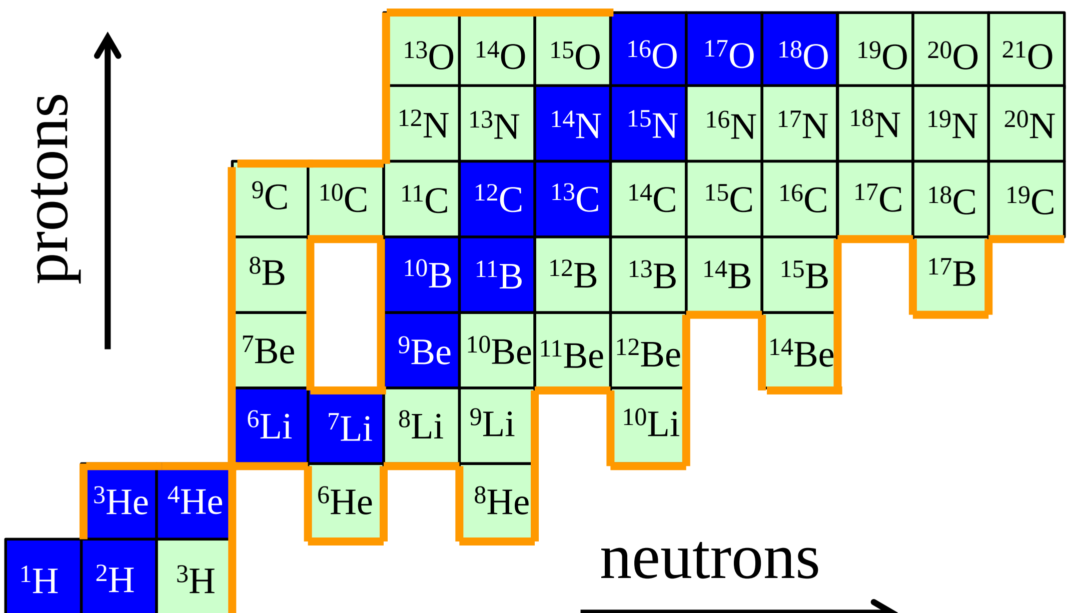
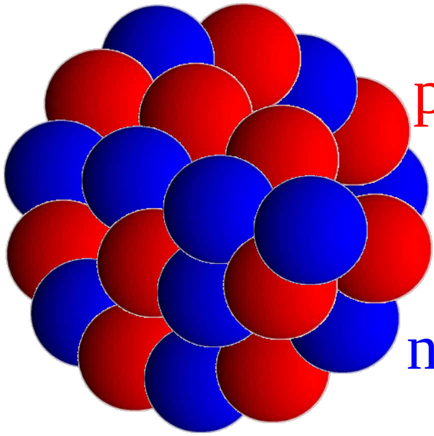
correlations of two-kinds particles: protons and neutrons
→rich and variety of phenomena



previously: a large restriction of N/Z ratio as only stable nuclei could be studied

Properties of nuclei as nuclear many-body systems



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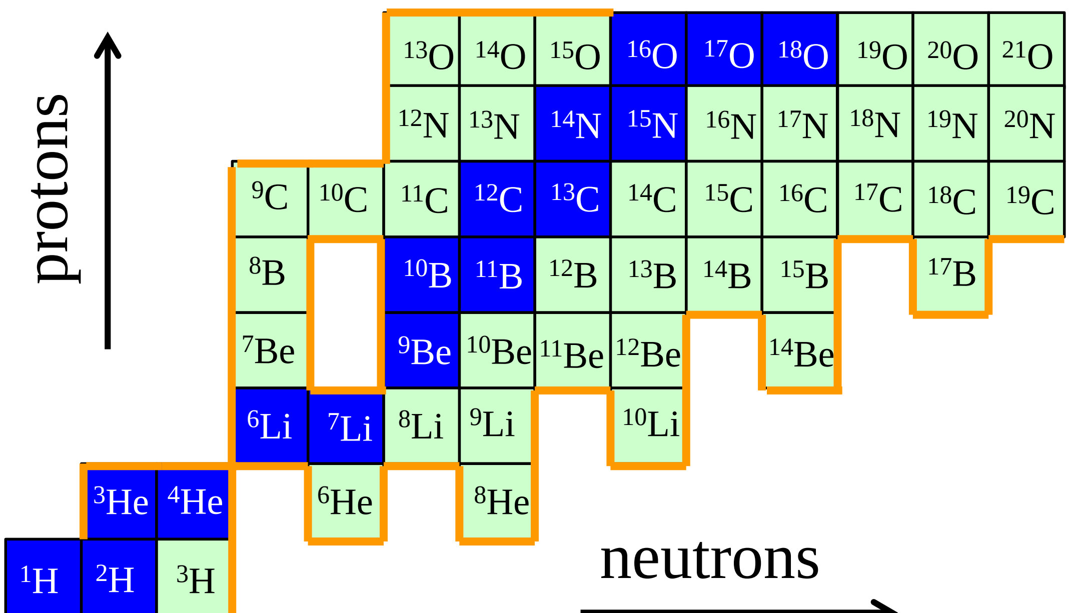
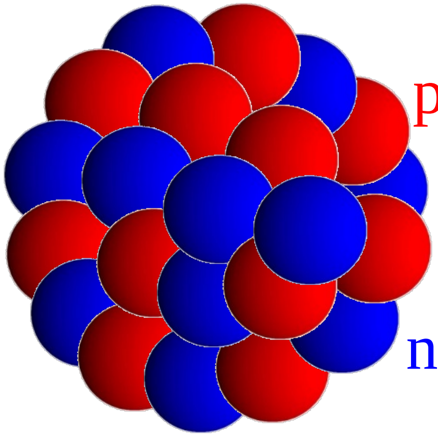


previously: a large restriction of N/Z ratio as only stable nuclei could be studied

the situation has been largely changed after neutron-rich nuclei could be accessed

Properties of nuclei as nuclear many-body systems



nucleus = an aggregate of particles
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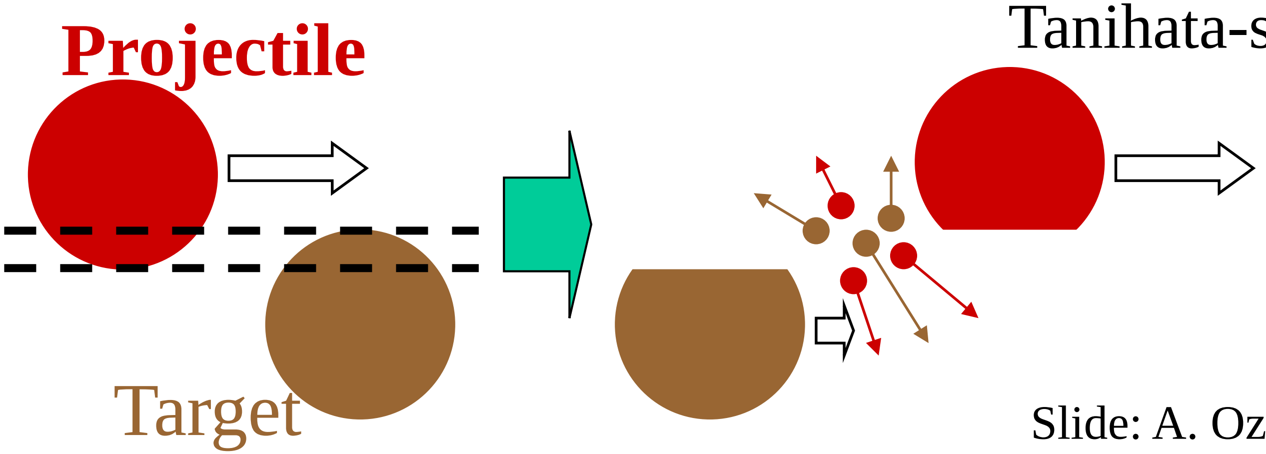
correlations of two-kinds particles: protons and neutrons
→rich and variety of phenomena

Physics of unstable nuclei:
unveil new properties of atomic nuclei by controlling the proton and neutron numbers

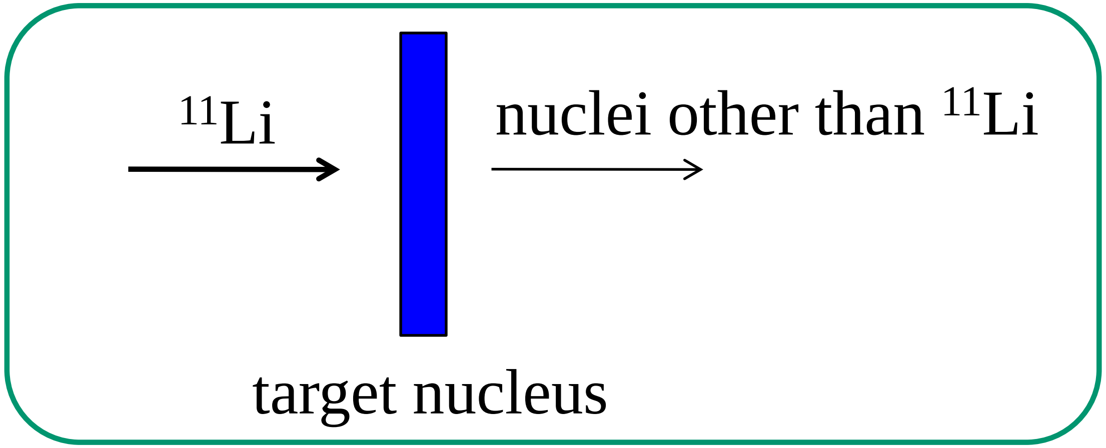
✓ what are properties of neutron-rich and proton-rich nuclei?
✓ how are they different from stable nuclei?

Real start of physics of unstable nuclei: interaction cross sections (1985)

Tanihata-san@Berkeley



Slide: A. Ozawa



Real start of physics of unstable nuclei: interaction cross sections (1985)

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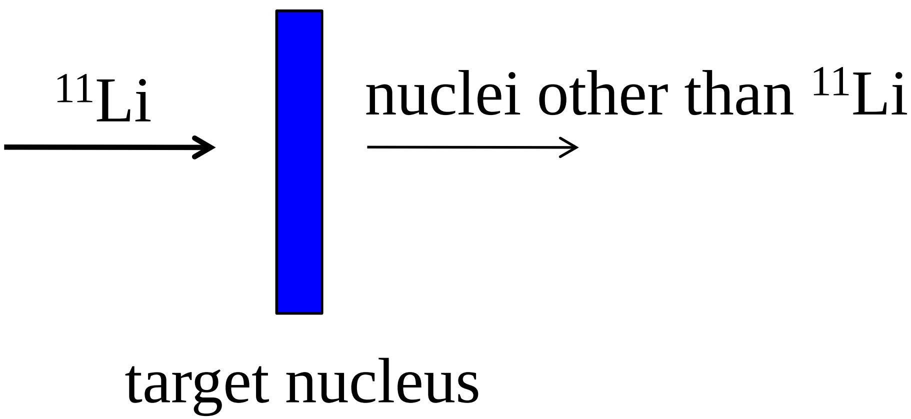

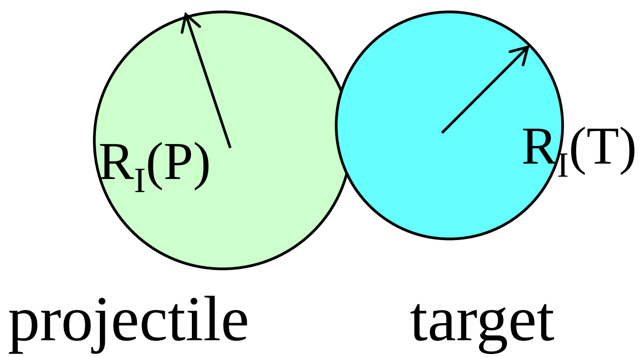

if a reaction takes place when two nuclei overlap:

$$\sigma_I \sim \pi[R_I(P) + R_I(T)]^2$$

$\longrightarrow$ $R_I(P)$

Real start of physics of unstable nuclei: interaction cross sections (1985)

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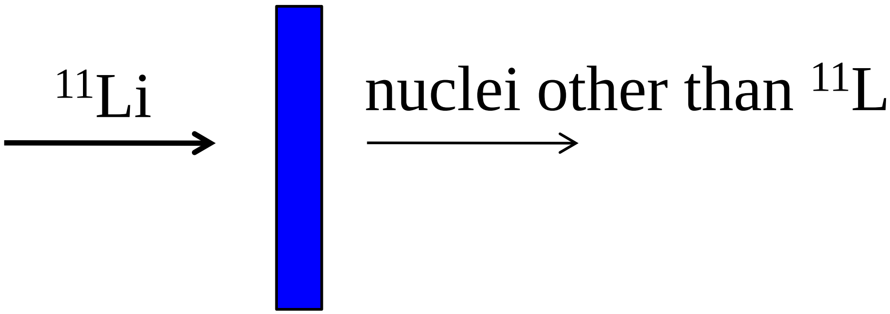
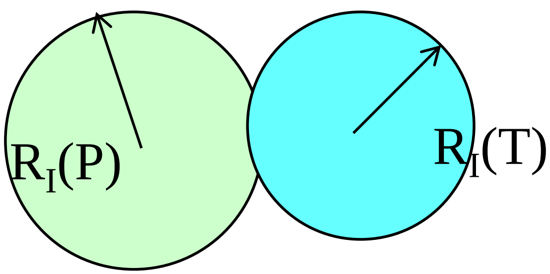


target nucleus

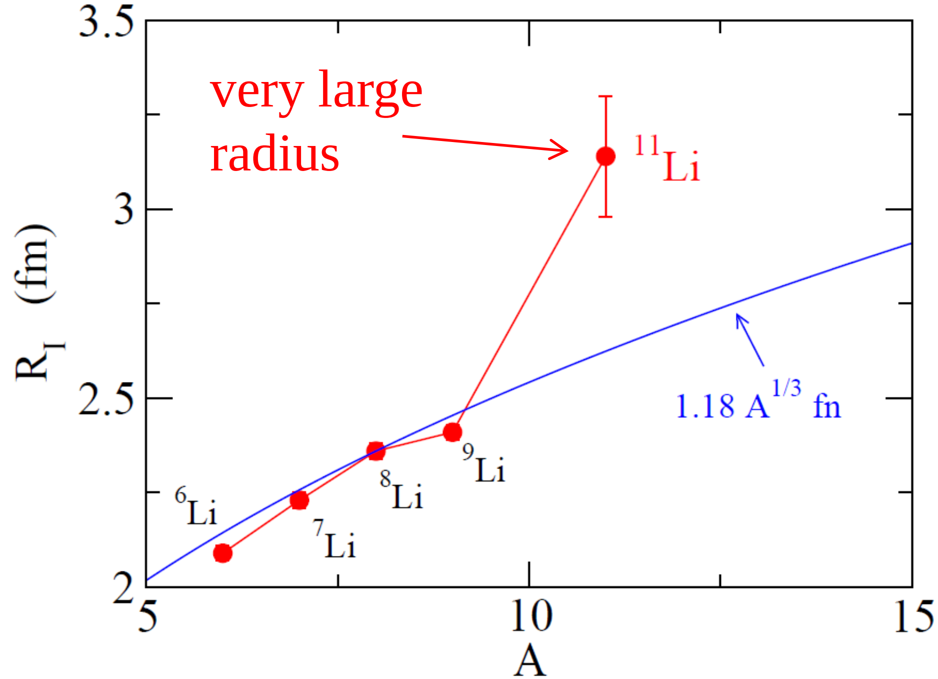


projectile target

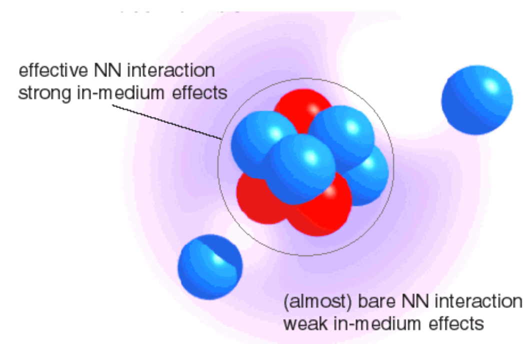
if a reaction takes place when two nuclei overlap:

$$\sigma_I \sim \pi[R_I(P) + R_I(T)]^2$$

$\longrightarrow$ $R_I(P)$



I. Tanihata et al., PRL55 ('85) 2676



discovery of halo

New generation RI beam facility: RIKEN RIBF (2007-)

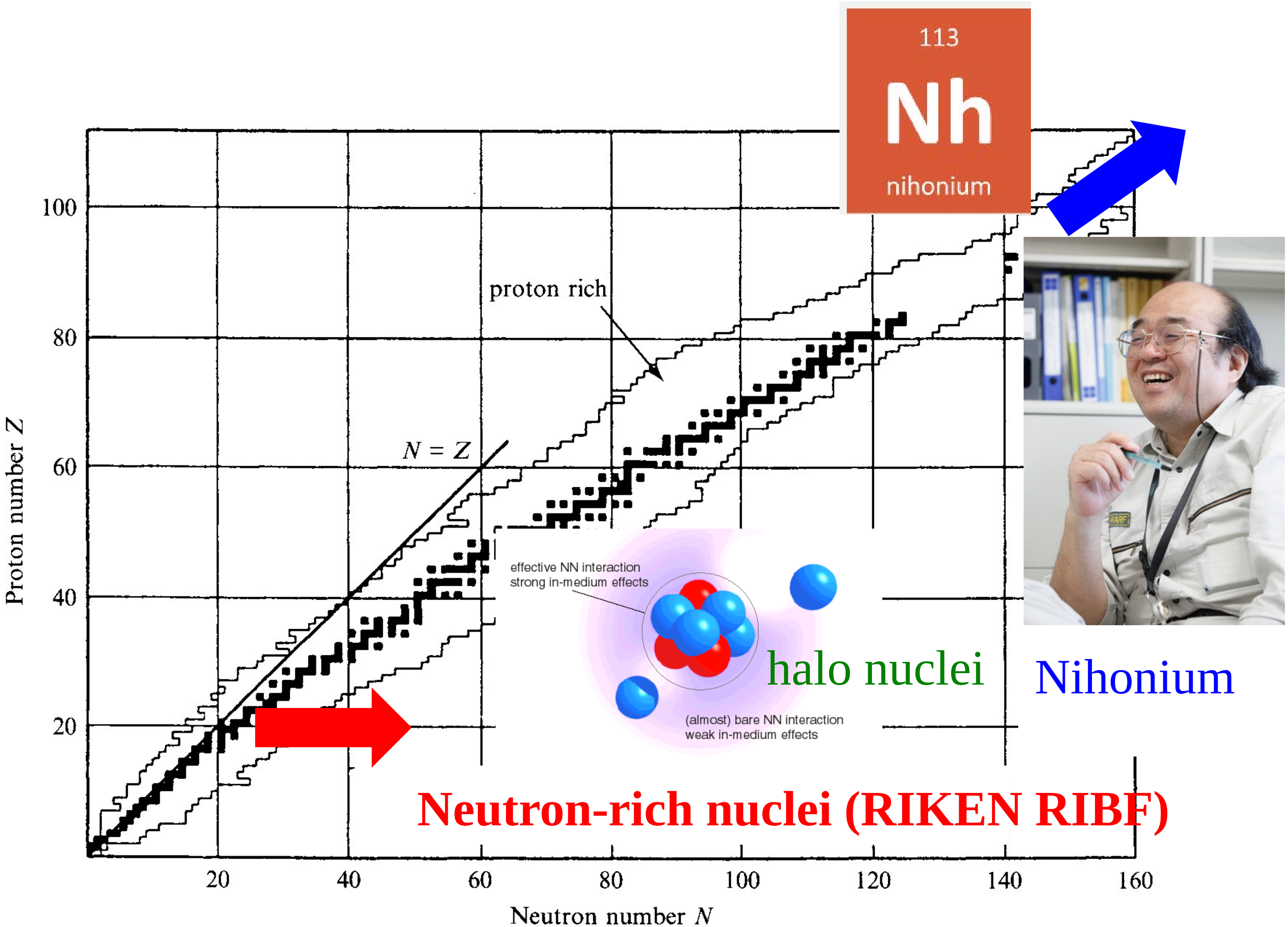
a facility for unstable nuclei with the world largest intensity

RI	「放射性同位元素(RI)」を
B	「ビーム」としてとりだし
F	「ファクトリー」のように大量生産する。

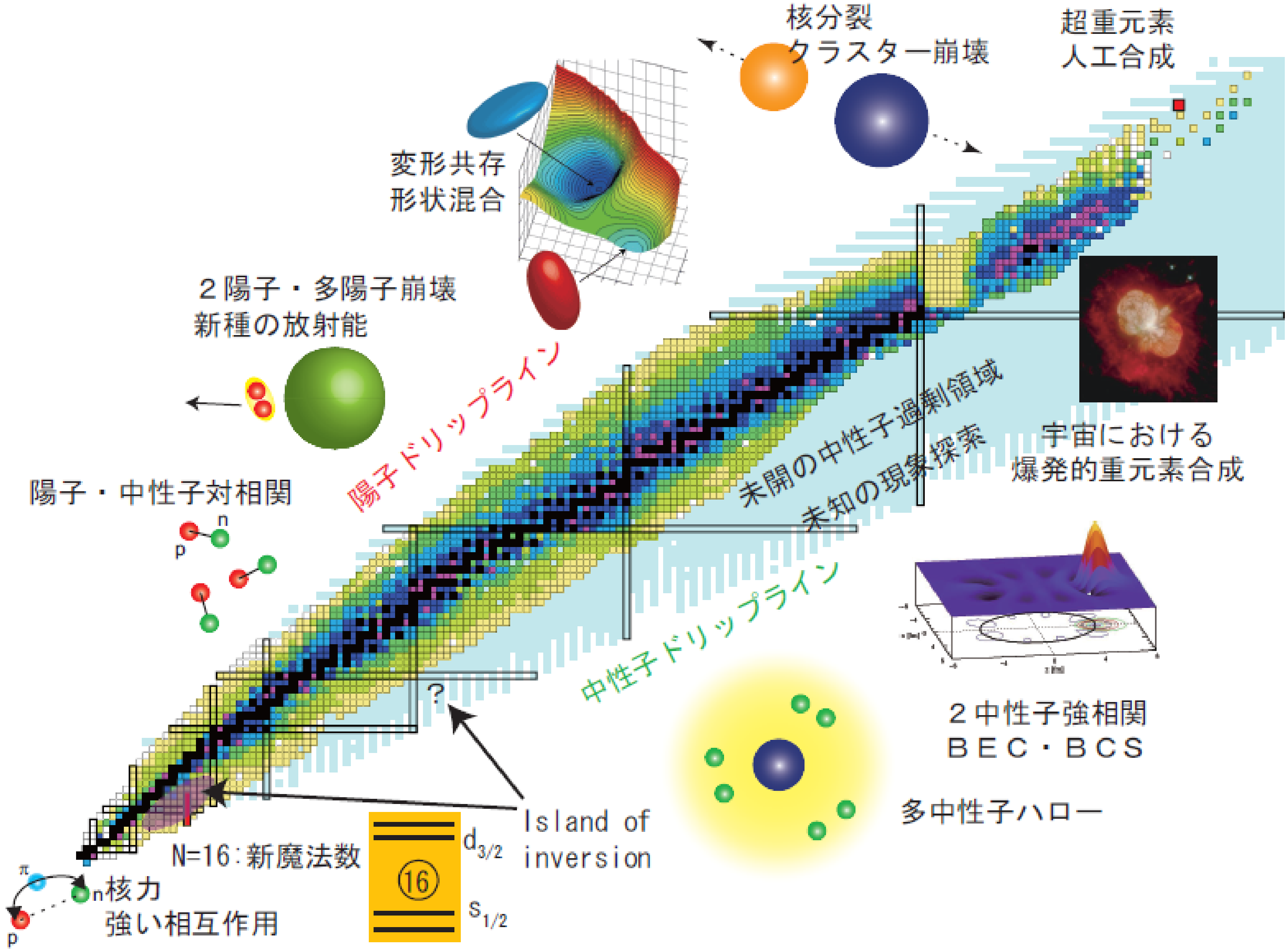
- physics of unstable nuclei
- the origin of elements
- superheavy nuclei (Nihonium and beyond)

slide: Sakurai-san

Extension of nuclear chart: the frontier of nuclear physics

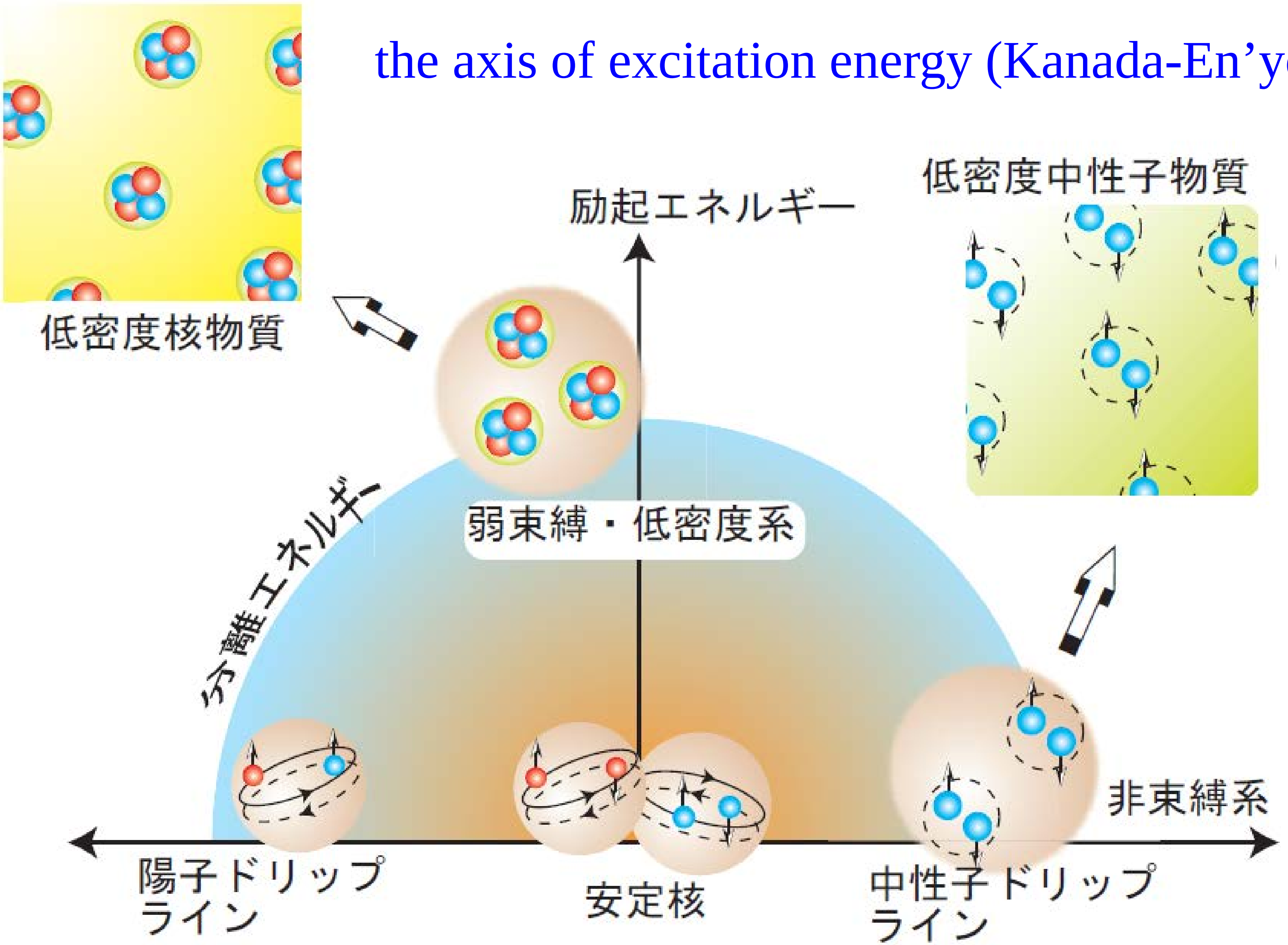


Physics of proton-rich and neutron-rich nuclei



「RIBFの物理」RIBF理論研究推進会議　より

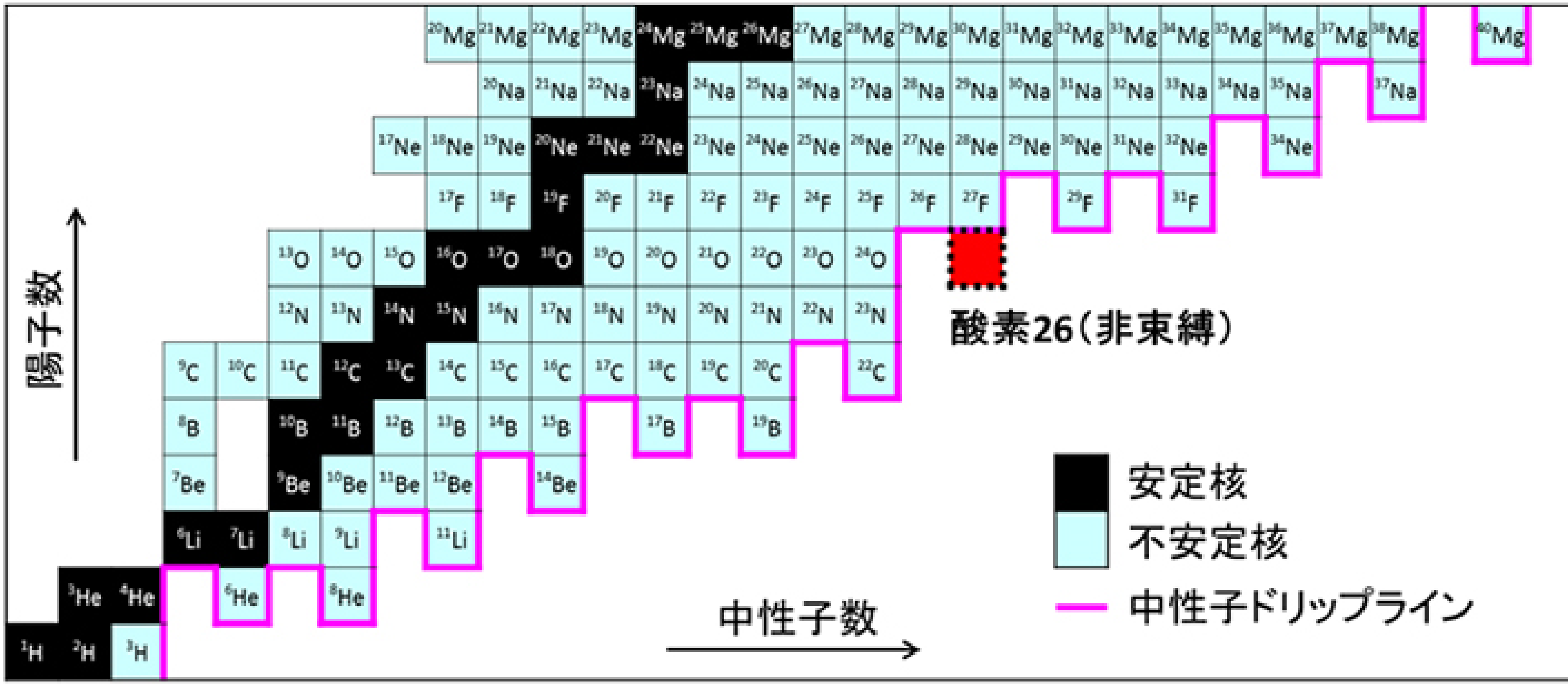
the axis of excitation energy (Kanada-En’yo)



Stable nuclei become weakly bound if they are excited.

「RIBFの物理」RIBF理論研究推進会議　より

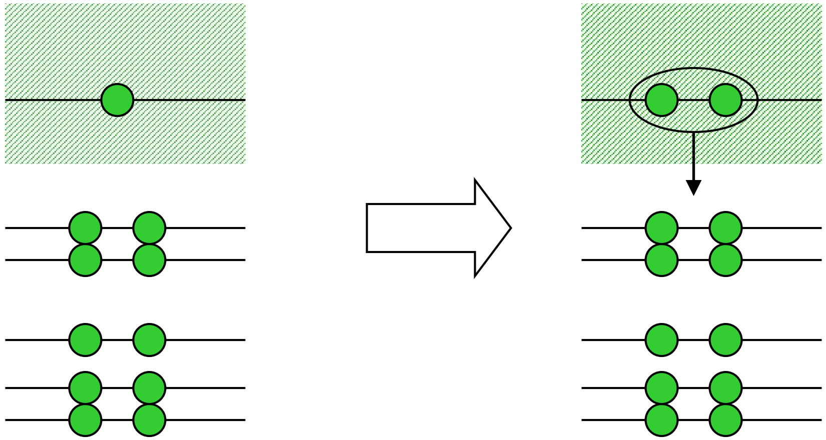
nucleon correlations



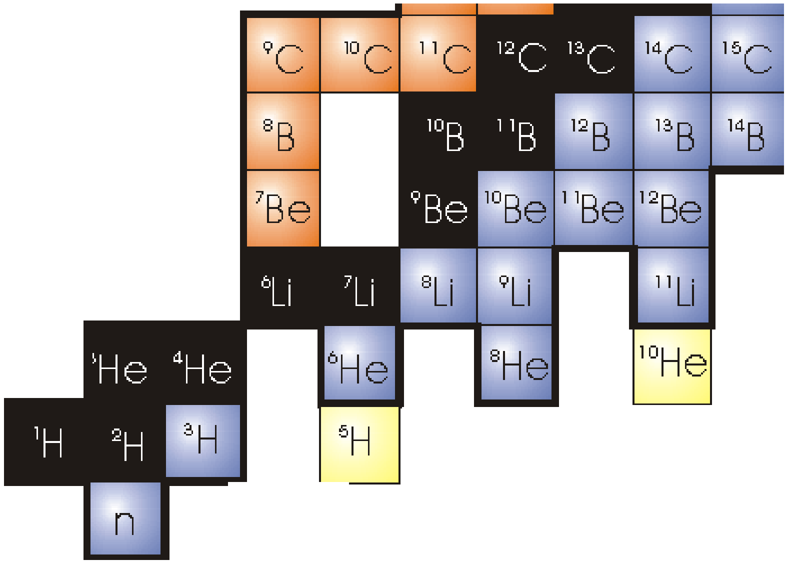
Press release of Tokyo Tech.

why is the drip-line jagged（ぎざぎざ）?

due to pairing correlation



unstable stable



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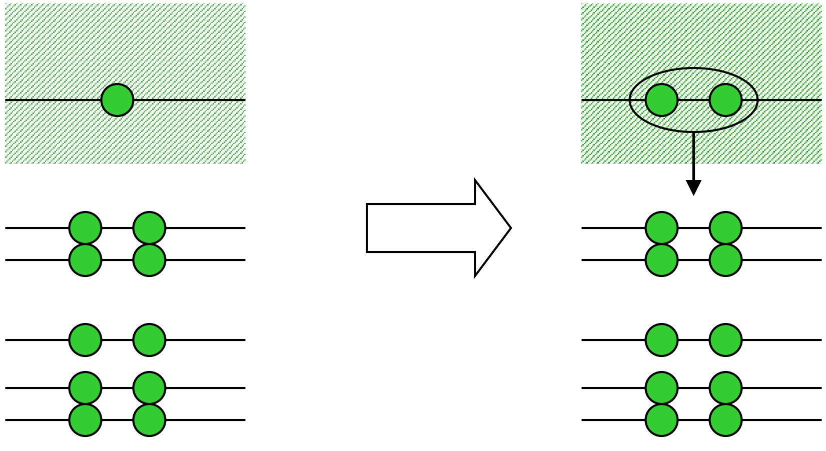
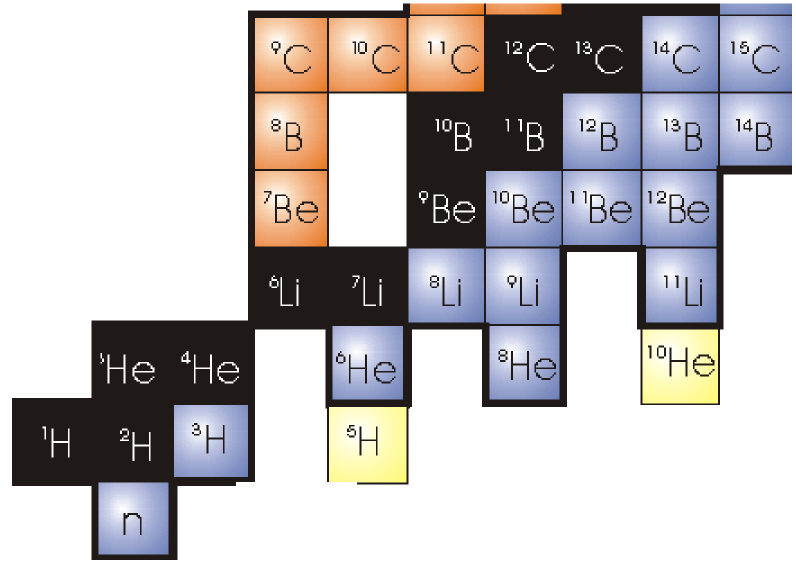
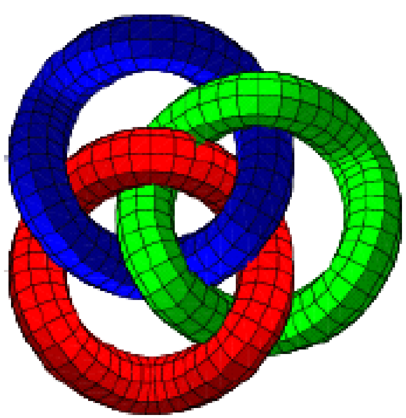


unstable stable



<u>Borromean nuclei</u>



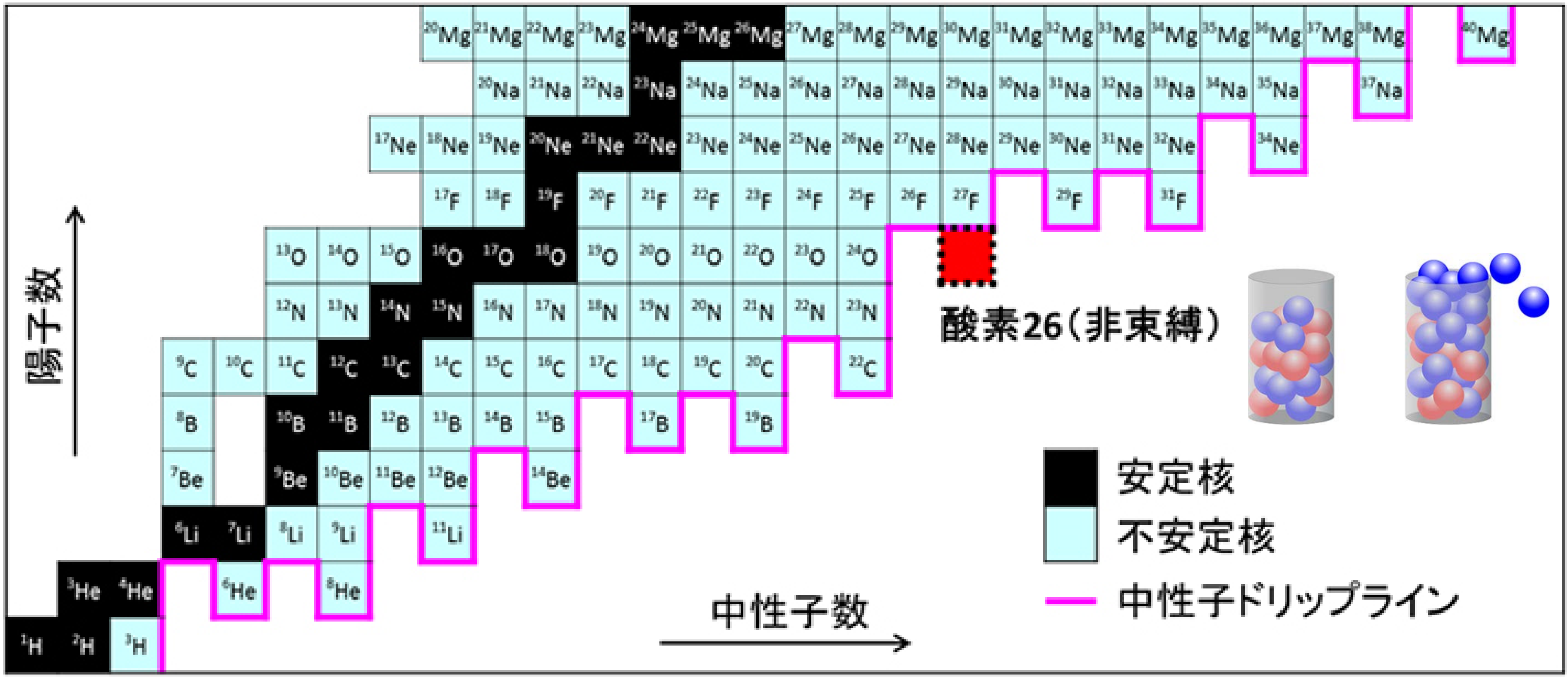
bound as a three-body system

^{6}He = ^{4}He + n + n

^{11}Li = ^{9}Li + n + n etc.

dynamics of Borromean nuclei

: on Thursday, 11/5

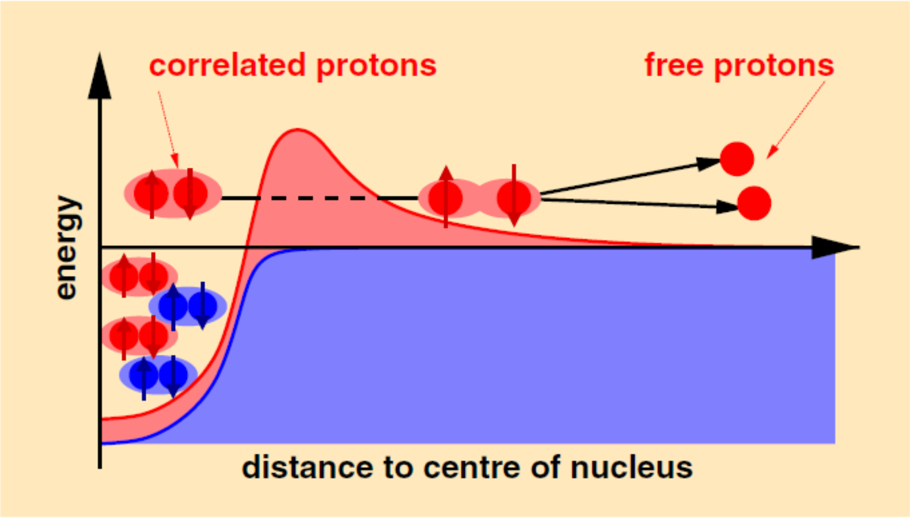


Press release of Tokyo Tech.

✓ why is the drip-line jagged? → due to pairing correlation

✓ a nucleus may exist for a short time <u>as a resonance state</u> when there is a potential barrier

how does the pairing correlation affect the decay dynamics of a resonance state : on Monday, 11/9

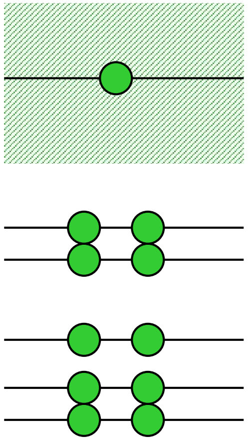
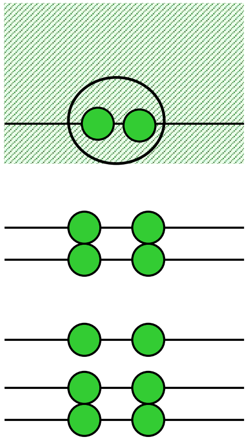


barrier:

✓ Coulomb+centrifugal (for p)

✓ centrifugal (for n)

B. Blank and M. Ploszajczak, Rep. Prog. Phys. 71('08)046301

resonance  → decay  → decay

1 particle emission   2 particle emission

physics of drip-lines = physics of weakly bound nuclei
+physics of many-body resonances

particle emission decays of unstable nuclei

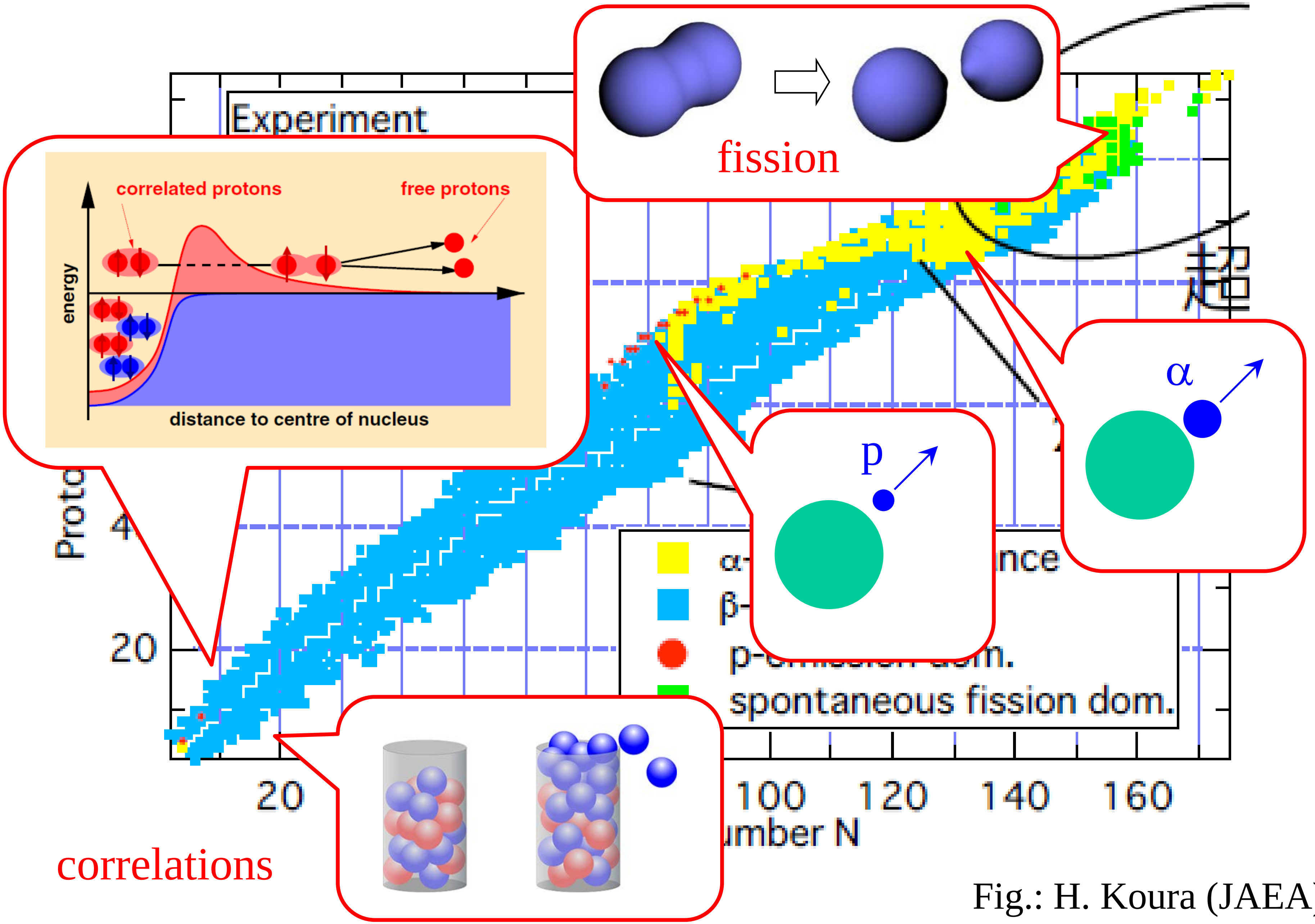


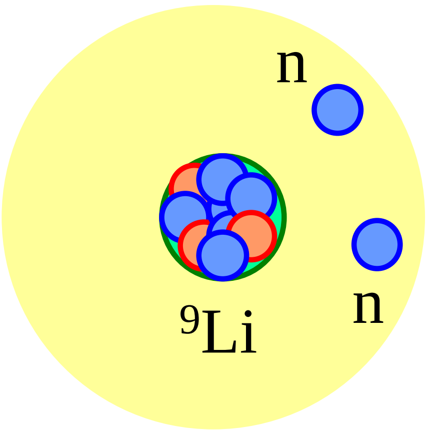
Fig.: H. Koura (JAEA)

Connection to hadron physics?

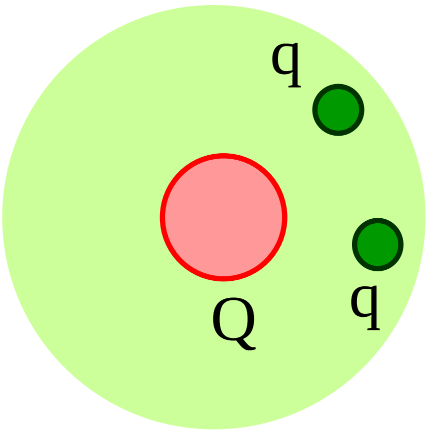
- three-body systems

$^{6}He = {}^{4}He + n + n$

$^{11}Li = {}^{9}Li + n + n$



baryons with a charm quark



Connection to hadron physics?

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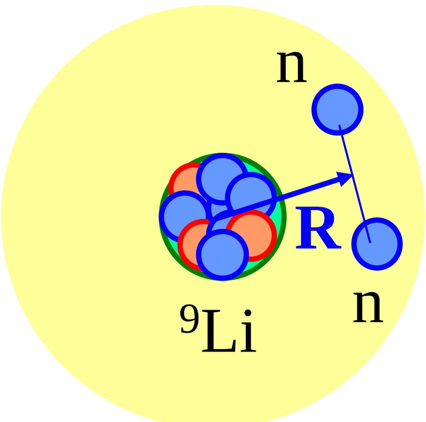
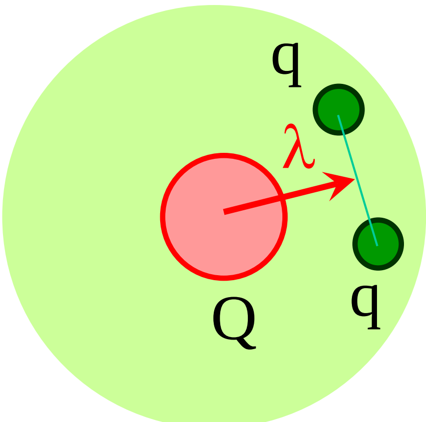


$$\hat{T}_{E1} \propto \boldsymbol{R}$$

E1excitation

baryons with a charm quark



λ mode

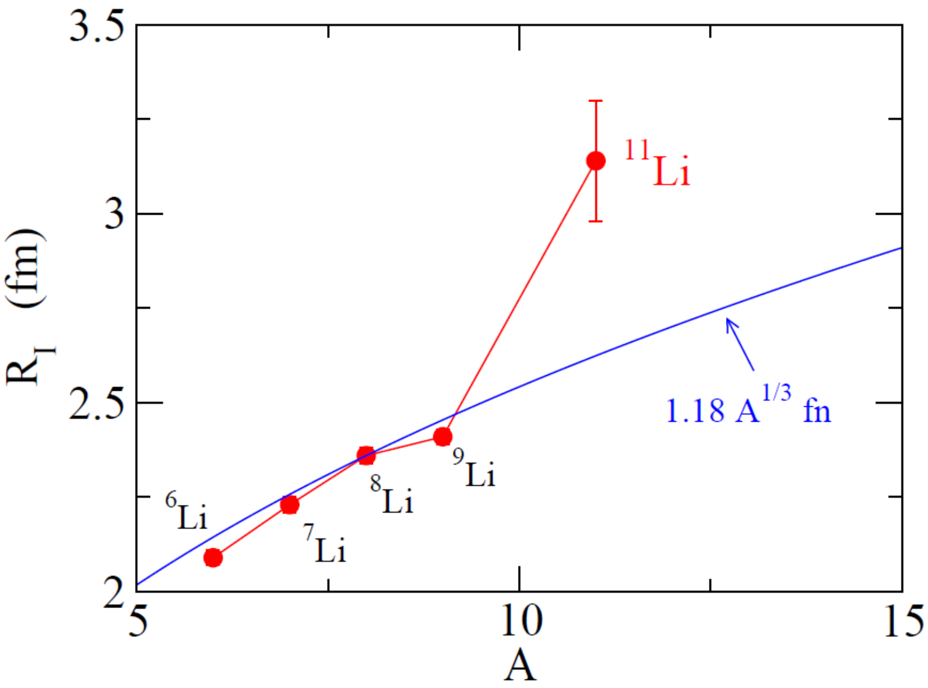
on Thursday, 11/5

Any question?

Any question?

➢ Why do you think I am talking about neutron-rich nuclei, rather than proton-rich nuclei?

➢ Do you know why ^{10}Li is absent in this figure?



r-process nucleosynthesis and neutron-rich nuclei

r-process nucleosynthesis and neutron-rich nuclei

Big bang
(13.8 billion years ago)

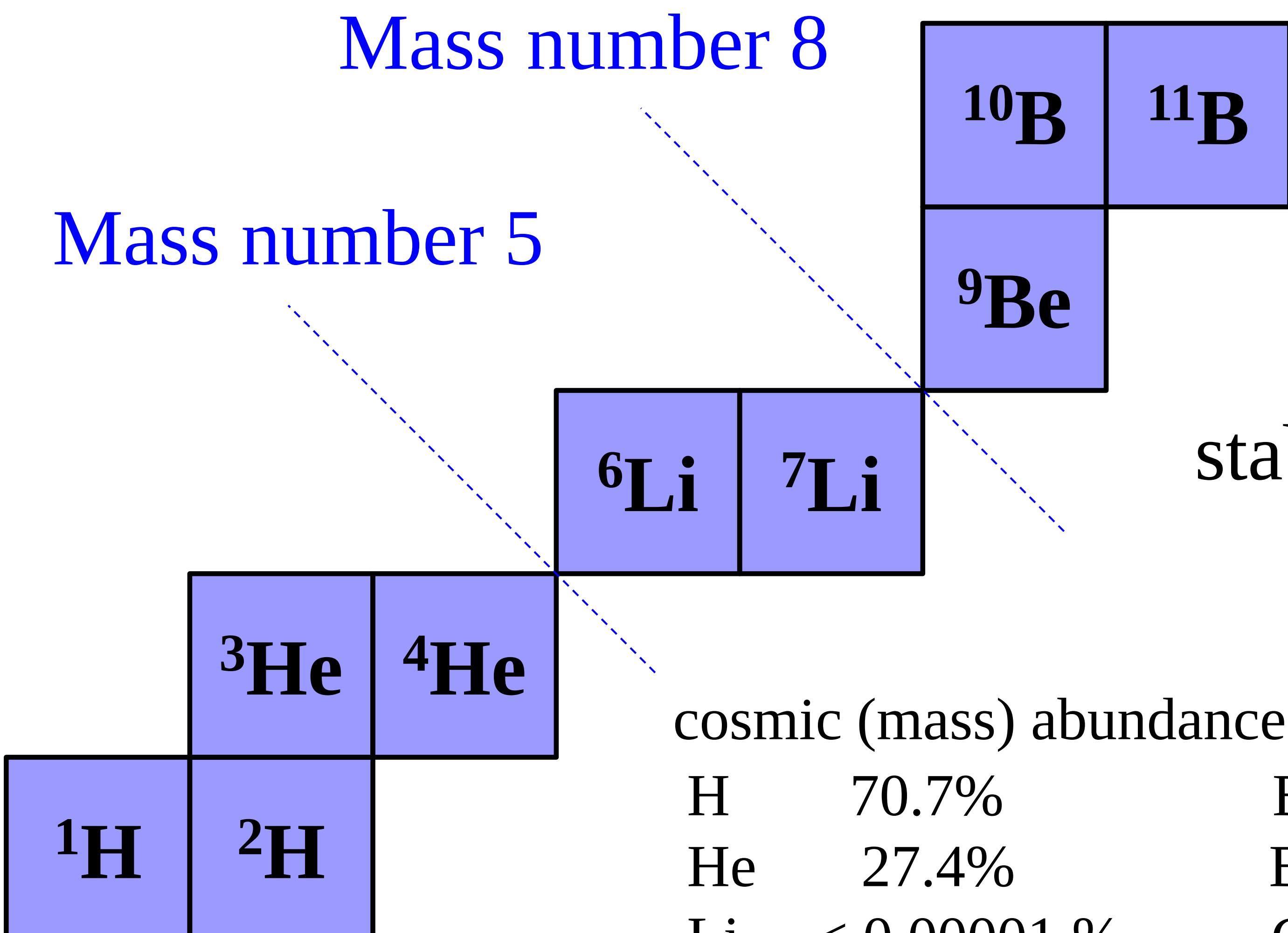
r-process nucleosynthesis and neutron-rich nuclei

Big bang
(13.8 billion years ago)

Li

the reason why only little amount of Li was created

the reason why only little amount of Li was created



a big wall at A=5 and 8

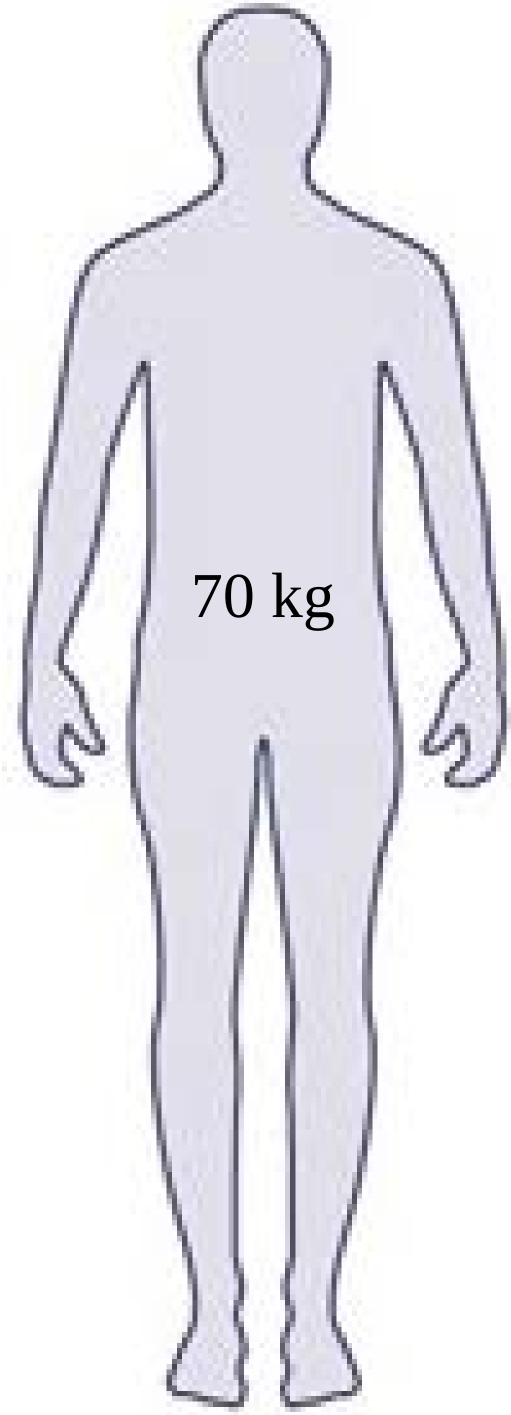
stable isotopes

cosmic (mass) abundance of elements

H	70.7%	Be	< 0.00001%
He	27.4%	B	< 0.00001%
Li	< 0.00001 %	C	0.3 %

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



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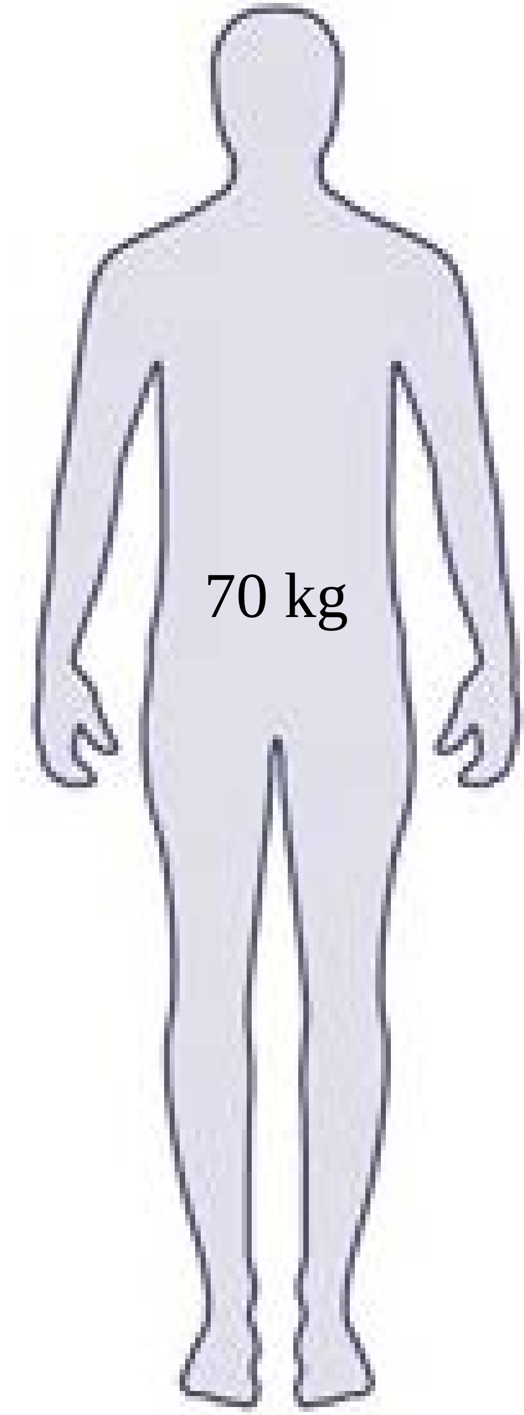
copper 72 mg
aluminium 60 mg
cadmium 50 mg

these hydrongens were created 13.8 billion years ago!!

Big bang (13.8 billion years ago)

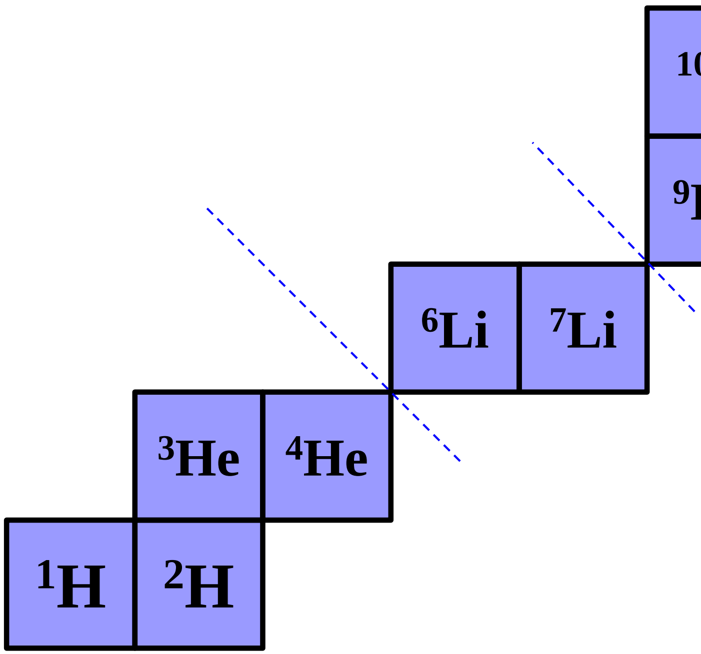


How were elements up to Fe created?

The origin of elements up to Fe

Nuclear fusion inside (massive) stars

$\longrightarrow$ the reason why stars are shining



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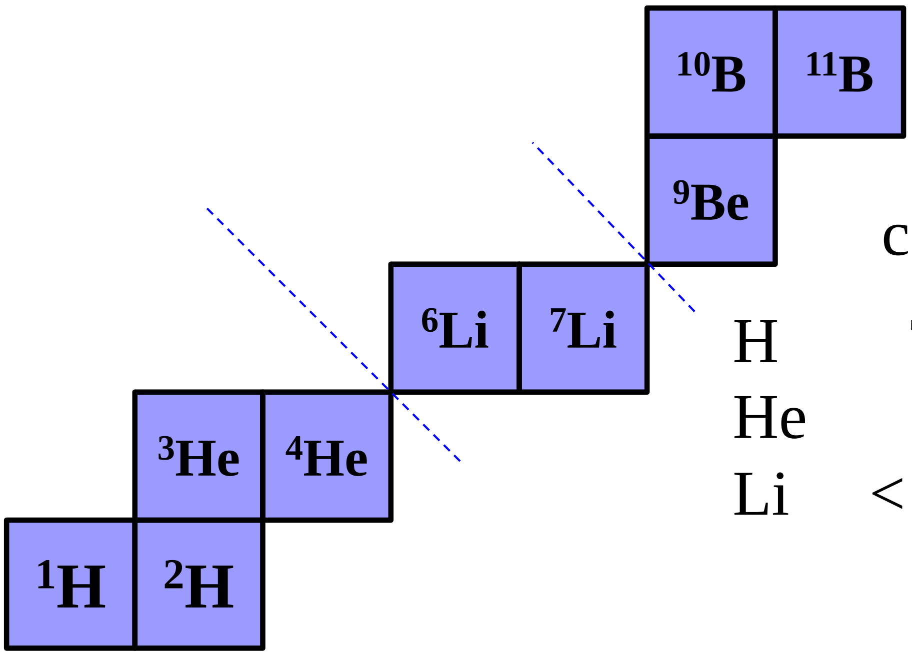

cosmic (mass) abundance of elements

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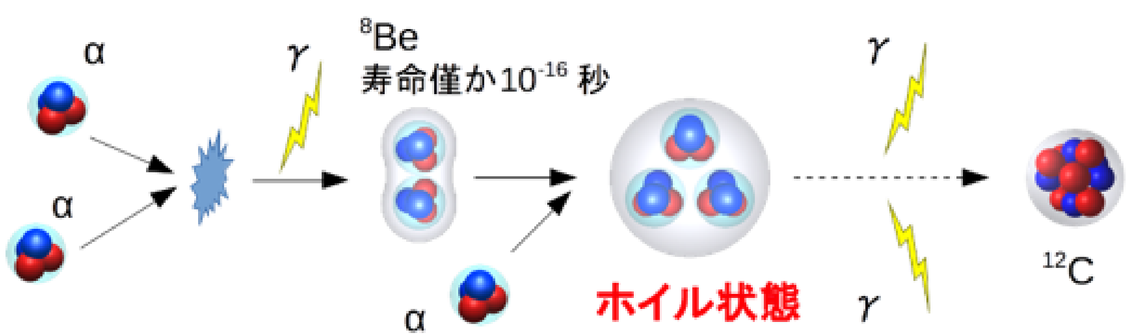
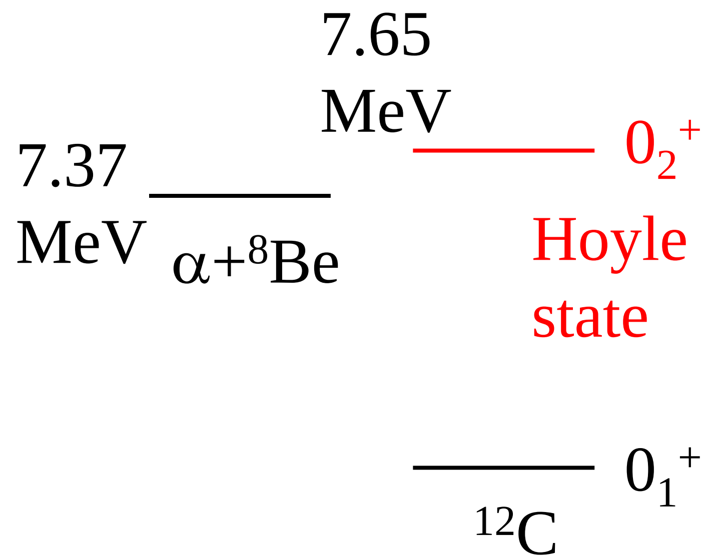
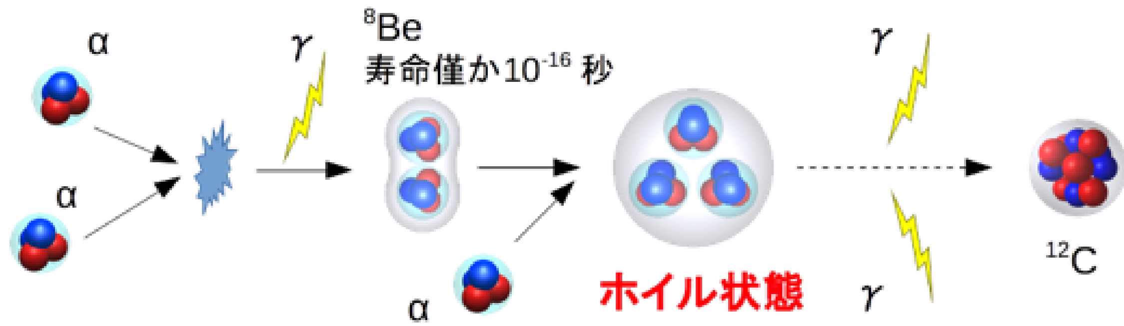
Triple alpha reactions

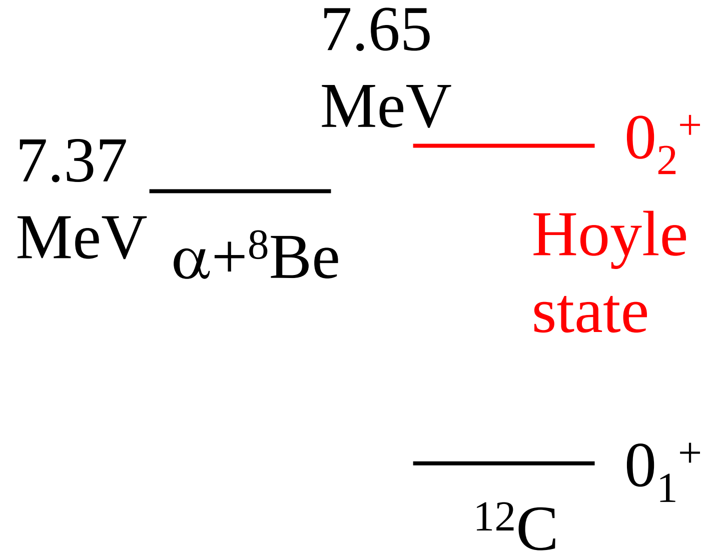


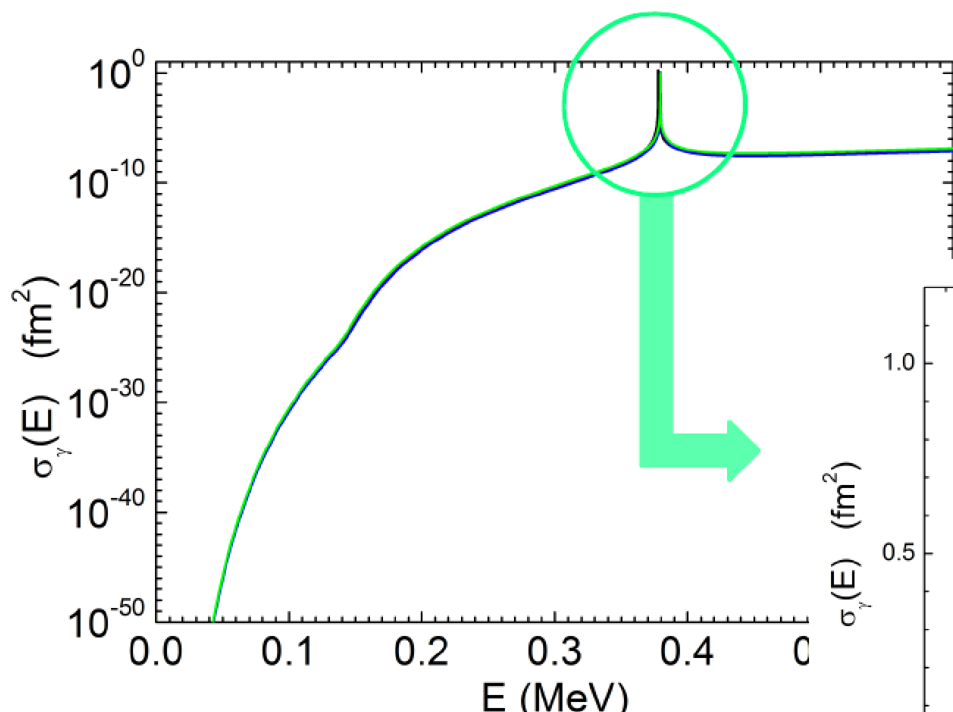


http://www.phys.tohoku.ac.jp/topics/topics-2052/

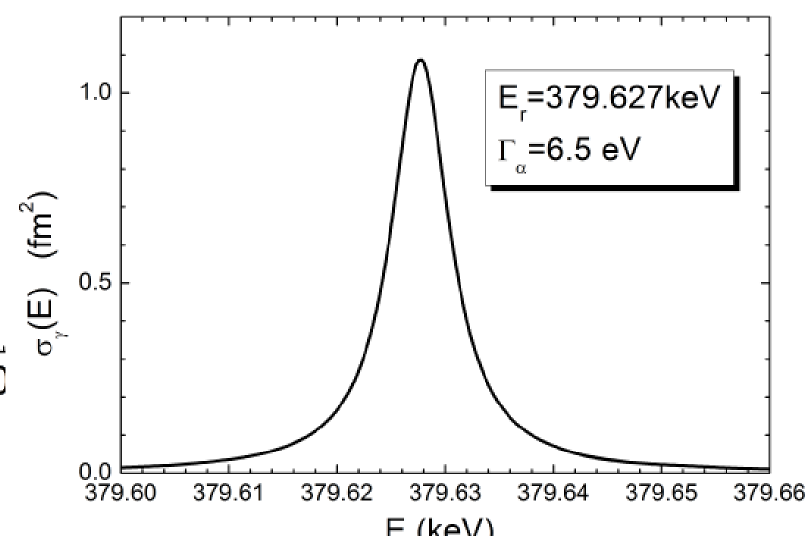
Triple alpha reaction







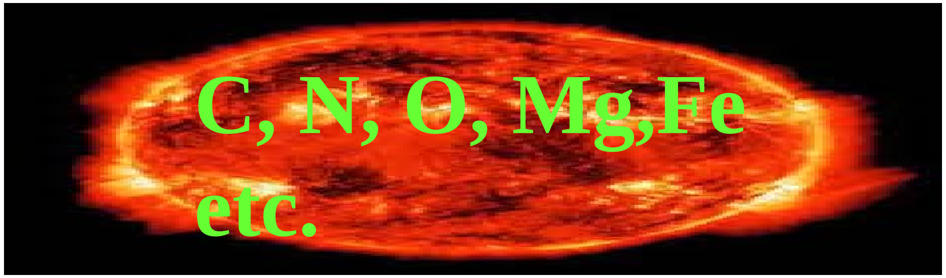
F. Hoyle: a prediction for a resonance state in ^{12}C (1952)



S. Ishikawa, PRC87 ('13) 055804

Why up to Fe?

The origin of elements up to Fe

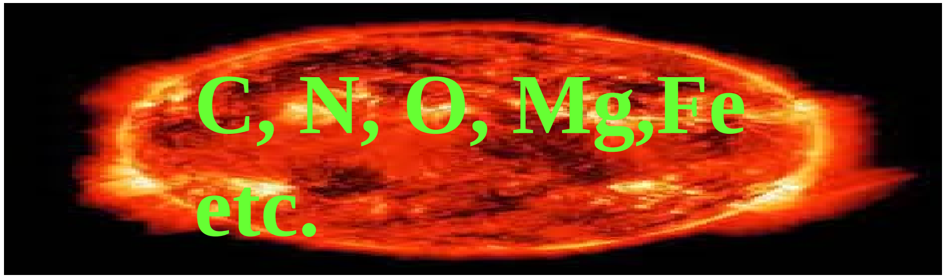


Nuclear fusion inside (massive) stars

⟶ the reason why stars are shining

Why up to Fe?

The origin of elements up to Fe



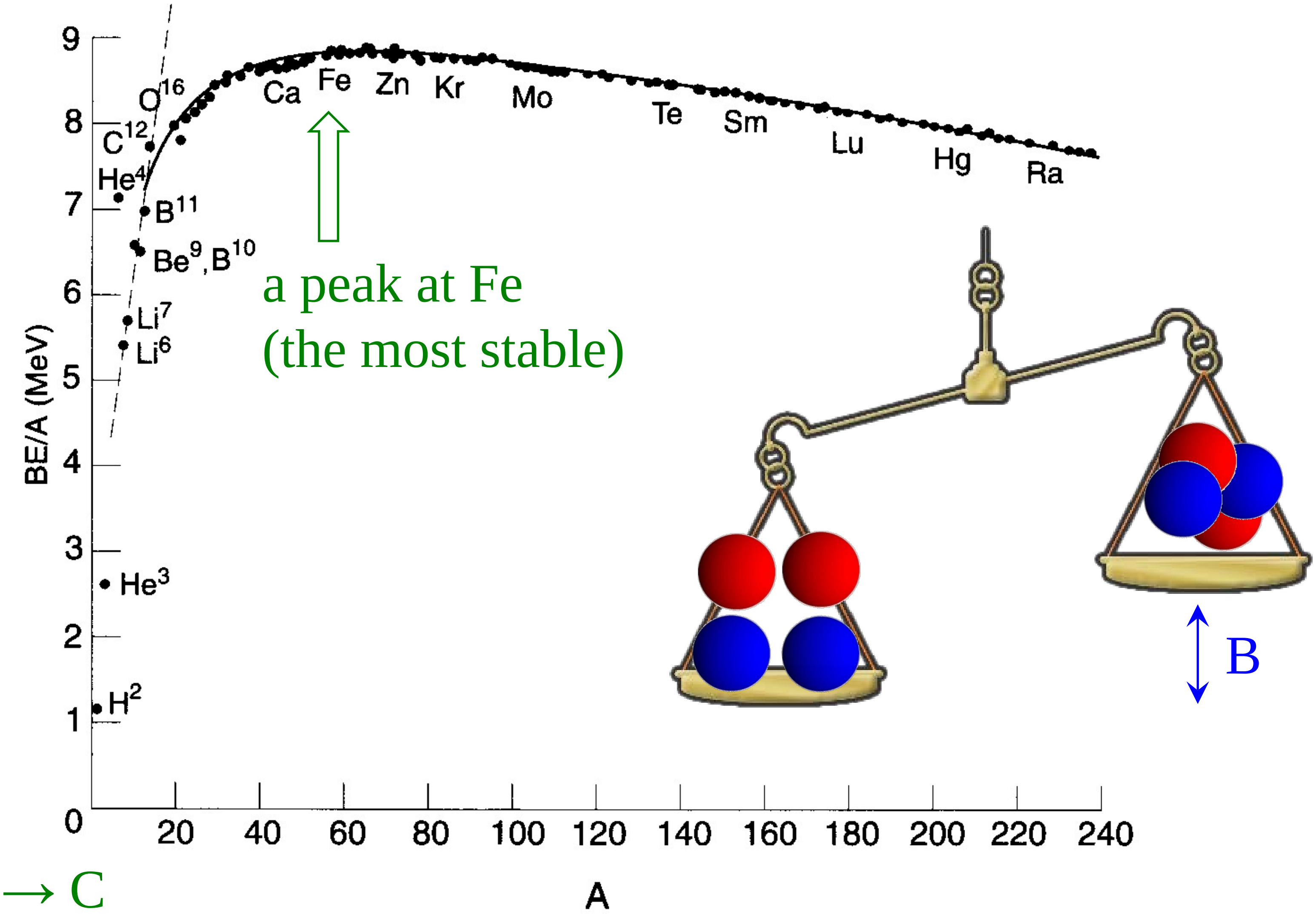
Nuclear fusion inside (massive) stars

⟶ the reason why stars are shining

- up to Fe: exothermal reactions 発熱反応
- from Fe: endothermal reactions 吸熱反応

⟶ fusion stops at Fe

Binding energy of atomic nuclei

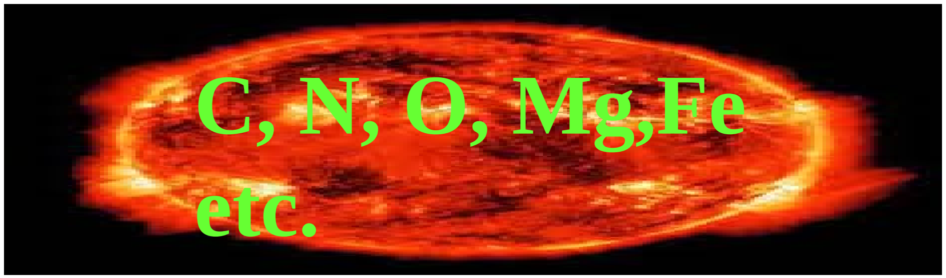


$A + B \rightarrow C$

- up to Fe: $m_A + m_B > m_C$ (exothermal) creation of energy
- from Fe: $m_A + m_B < m_C$ (endothermal) extra energy required

Why up to Fe?

The origin of elements up to Fe



Nuclear fusion inside (massive) stars

⟶ the reason why stars are shining

- up to Fe: exothermal reactions
- from Fe: endothermal reactions

⟶ fusion stops at Fe

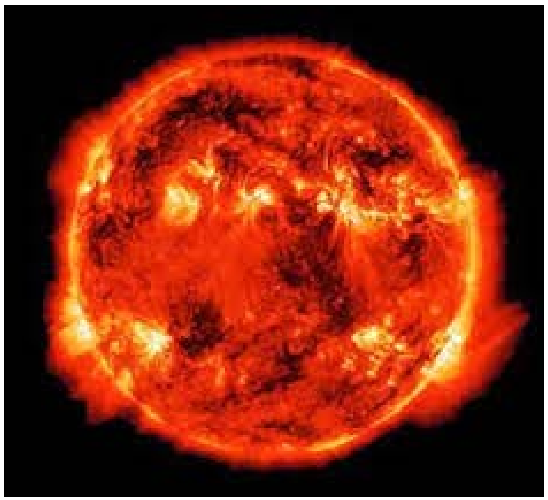
How to create heavier elements (e.g., Pb and U)?

How to create heavier elements than Fe?

Neutron captures (neutrons: no charge)

How to create heavier elements than Fe?

Neutron captures (neutrons: no charge)

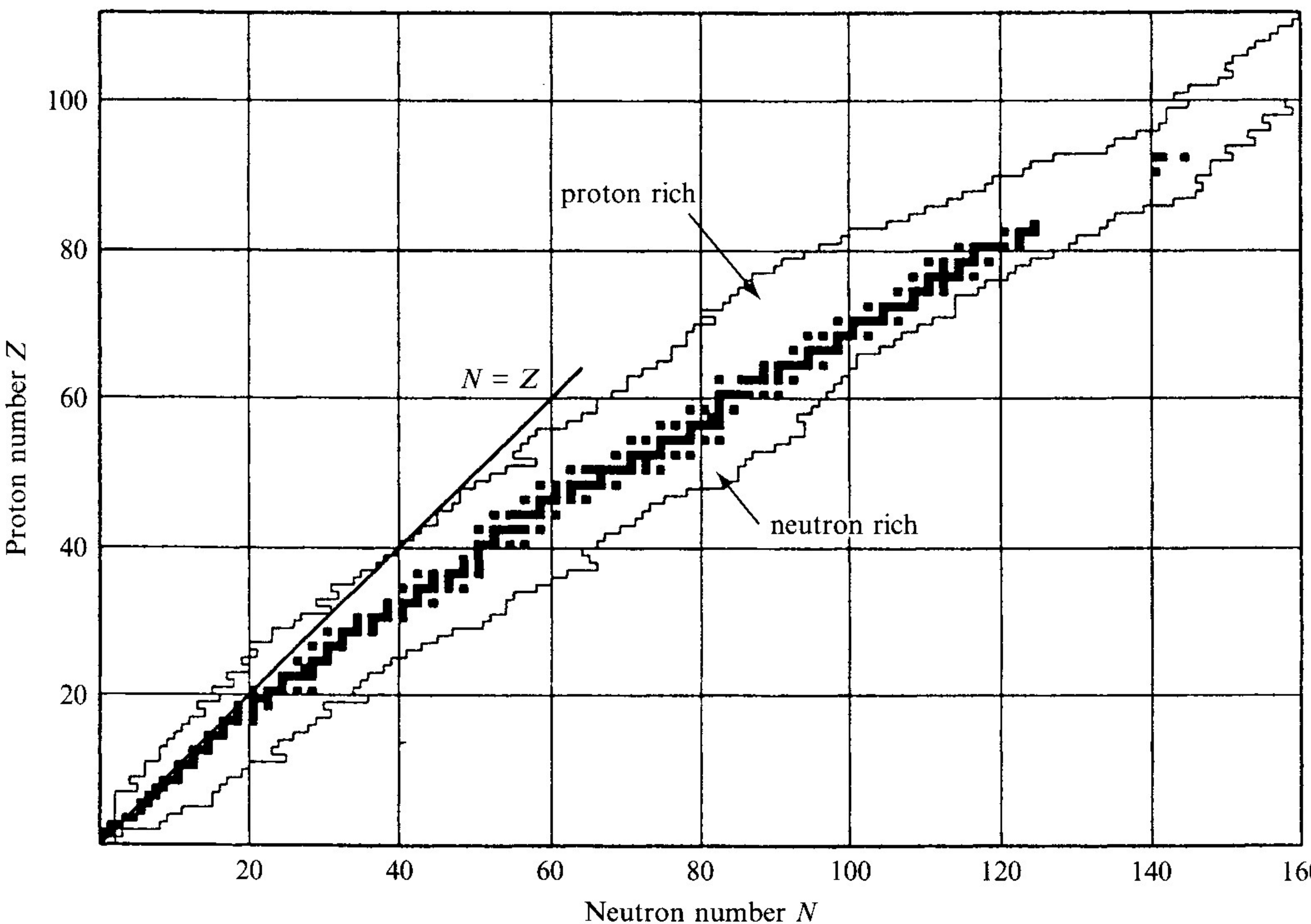


red giant

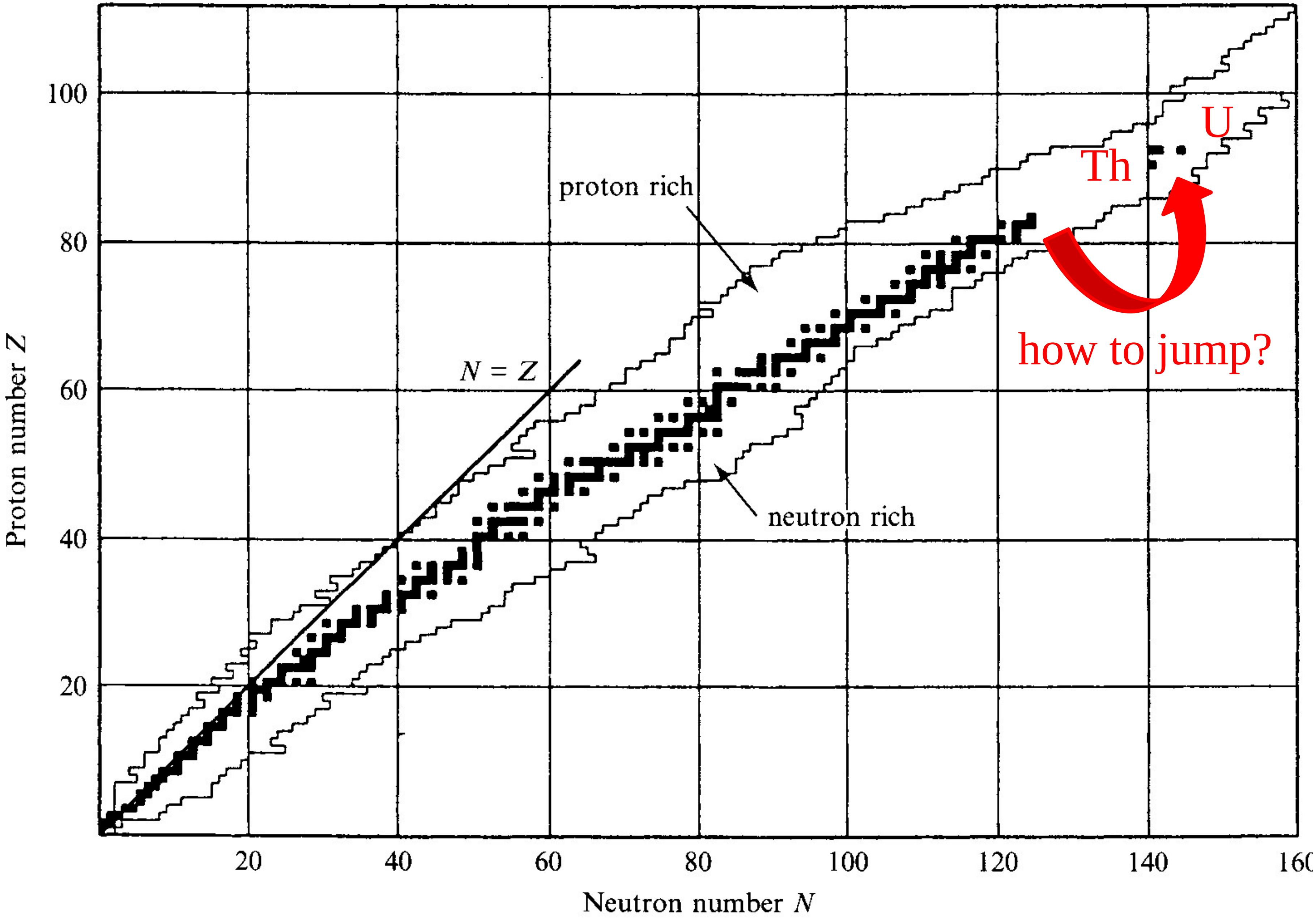
↓

s-process

Ba, La, Pb, Bi etc.



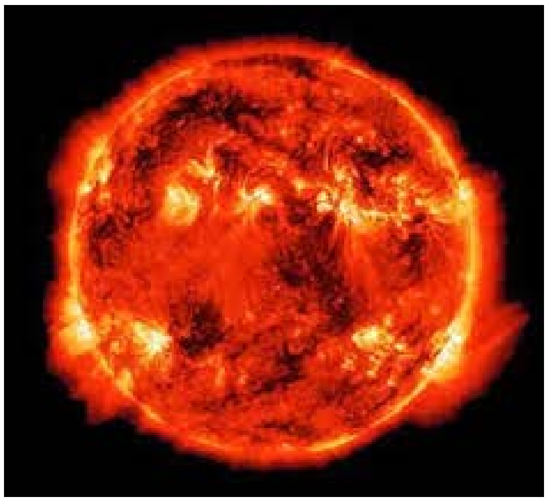
proton rich
neutron rich
N = Z
Proton number Z
Neutron number N
20
40
60
80
100
20
40
60
80
100
120
140
160

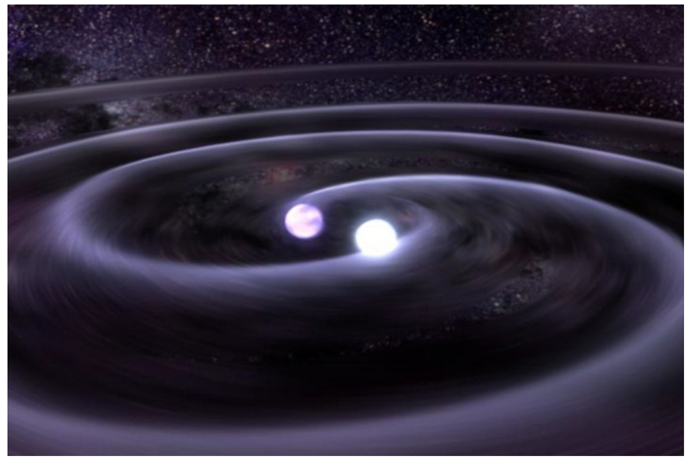


100
80
60
40
20
Proton number Z
20
40
60
80
100
120
140
160
Neutron number N
N = Z
proton rich
neutron rich
Th
U
how to jump?

How to create heavier elements than Fe?

Neutron captures (neutrons: no charge)





red giant

↓

s-process

Ba, La, Pb, Bi etc.

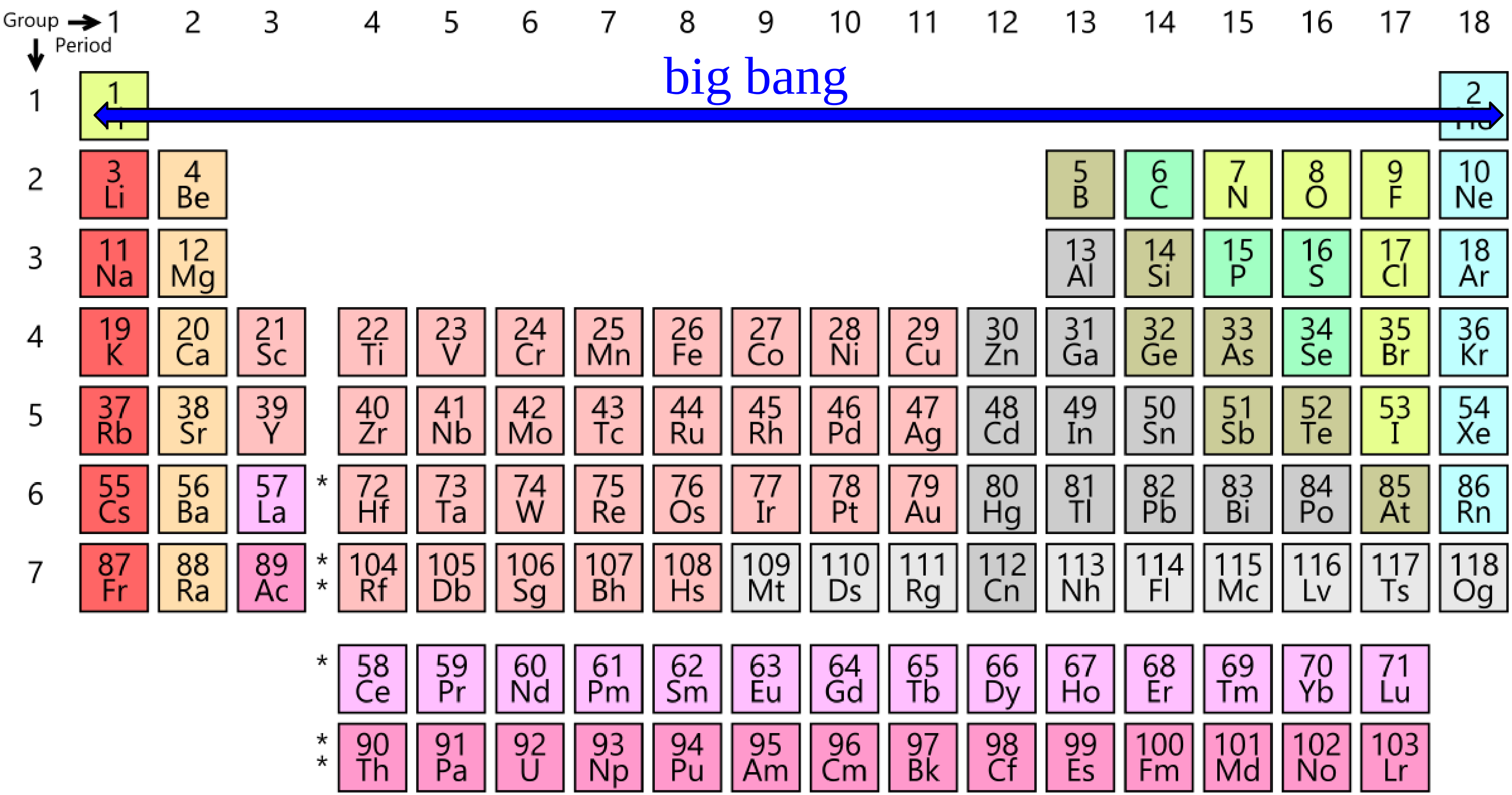
neutron star merger

↓

r-process

Th, Eu, U etc.

3 steps of nucleosynthesis



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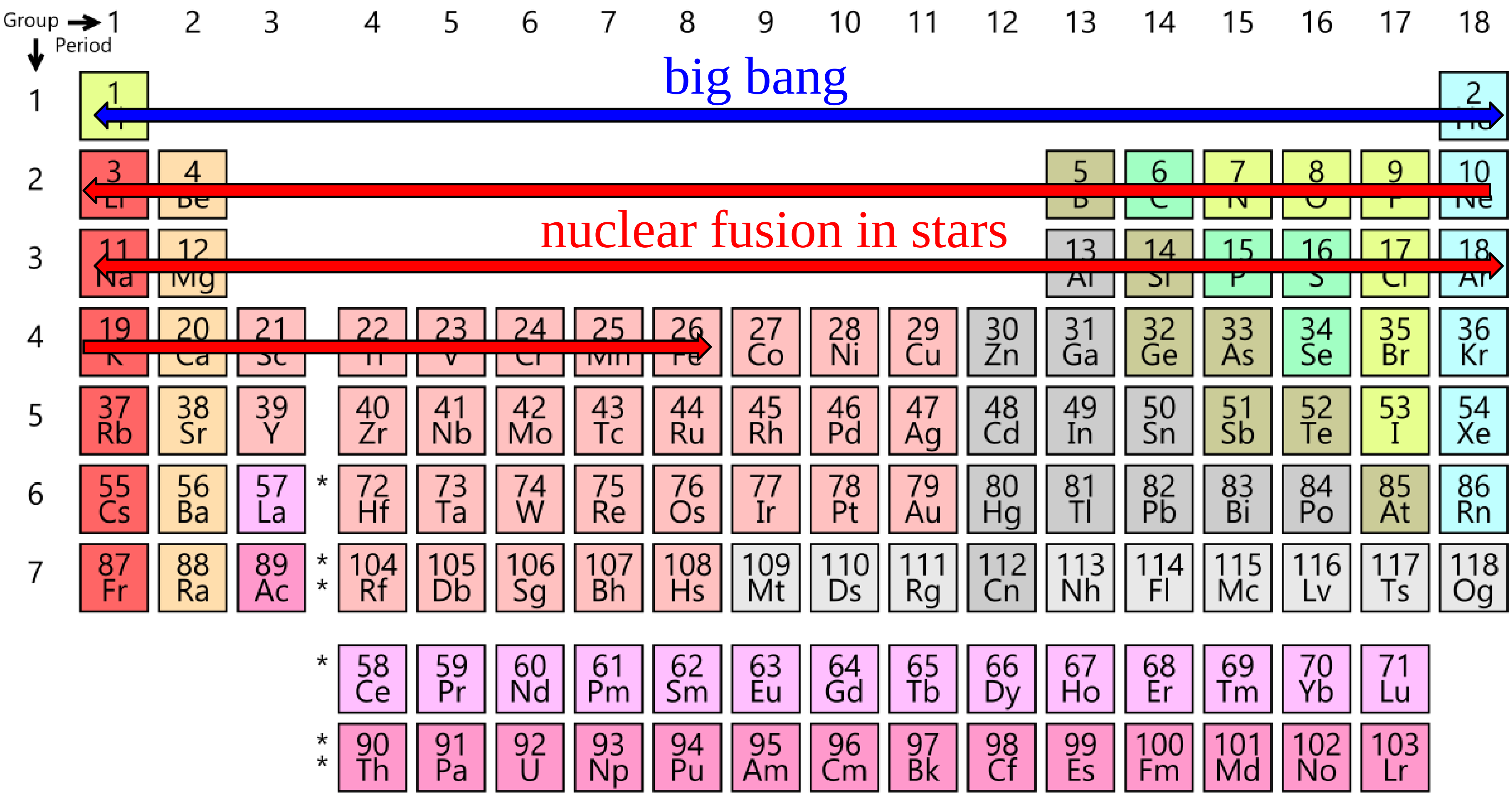
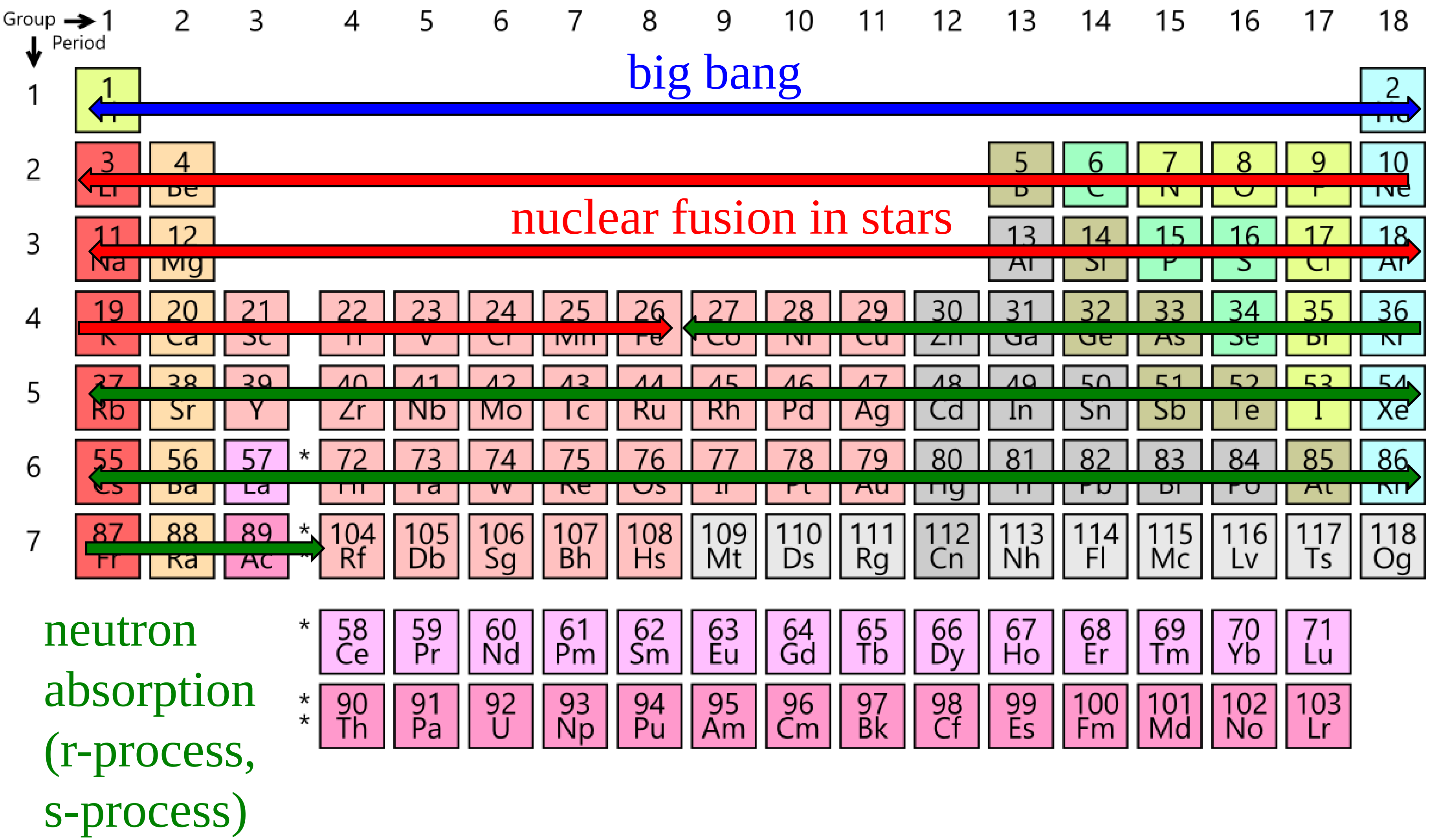


3 steps of nucleosynthesis



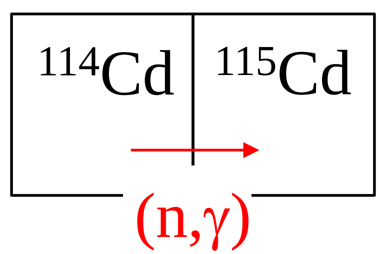
s-process nucleosynthesis and r-process nucleosynthesis

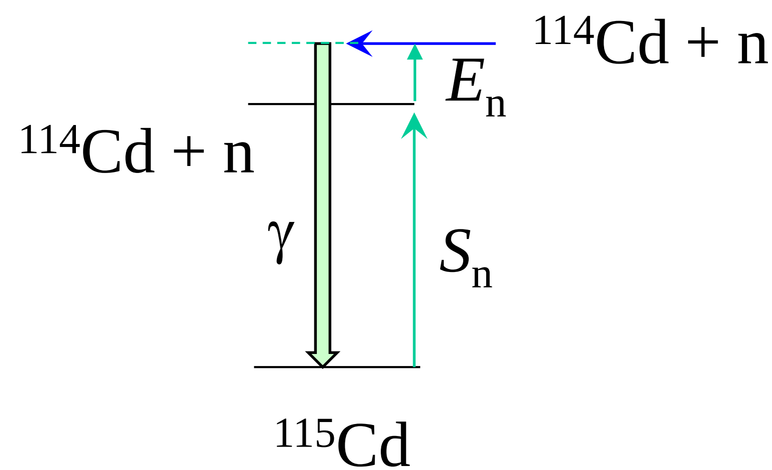
neutron capture reactions

example) ${}^{114}_{48}Cd_{66} + n \rightarrow {}^{115}_{48}Cd_{67}^{*} \rightarrow {}^{115}_{48}Cd_{67}$ (ground state) + γ

(n,γ) reaction

on the nuclear chart :



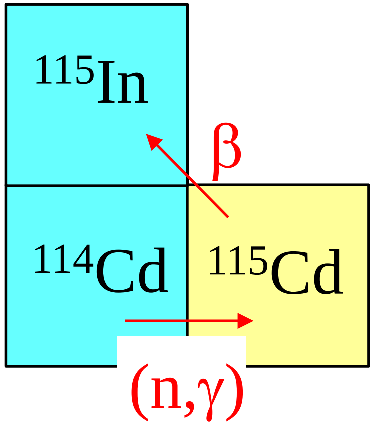


two possibilities after $^{114}Cd \rightarrow {}^{115}Cd$

- ✓ when neutron capture is slow:

  $^{114}Cd \rightarrow {}^{115}Cd \rightarrow {}^{115}In$

β decay before n-capture



s-process (slow process)

two possibilities after $^{114}Cd \rightarrow {}^{115}Cd$

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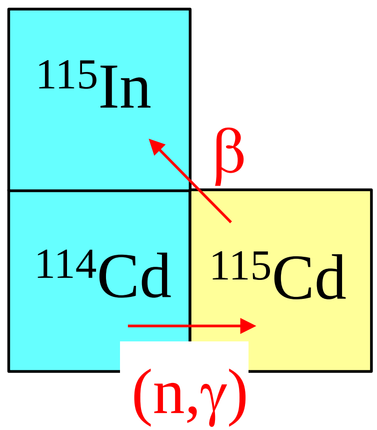
β decay before n-capture

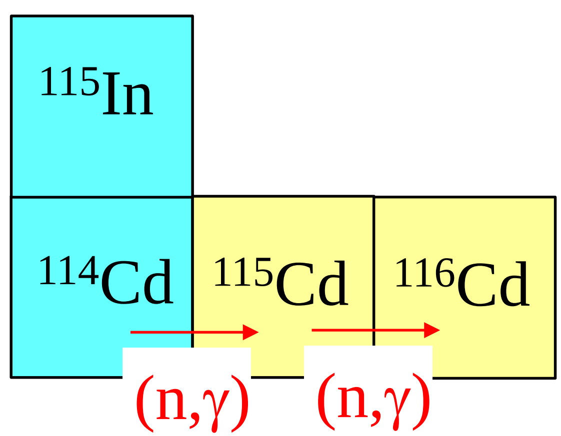


s-process
(slow process)

- ✓ when neutron capture is fast:

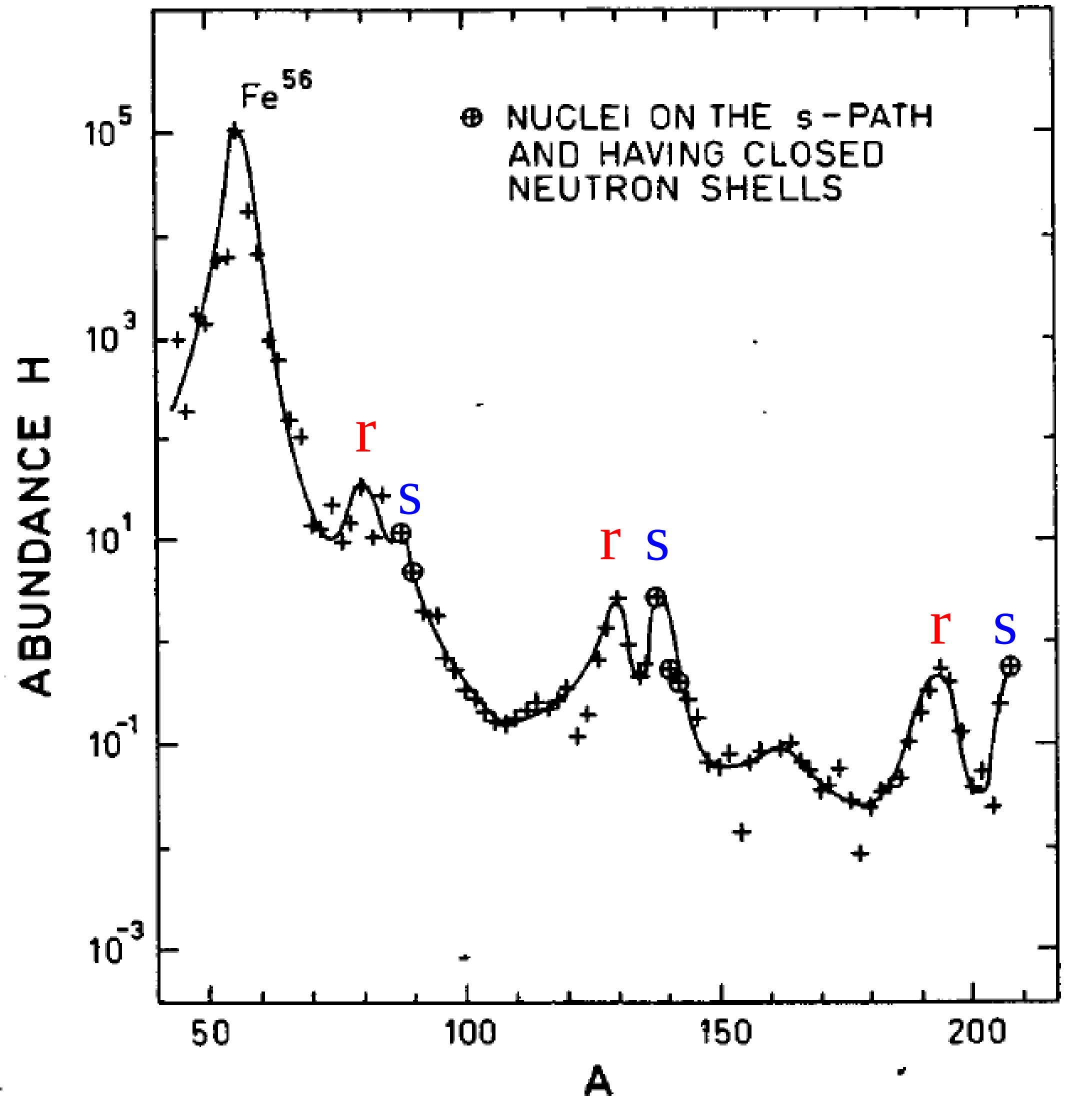
$$^{114}Cd \rightarrow {}^{115}Cd \rightarrow {}^{116}Cd$$

n-capture before β decay



r-process
(rapid process)

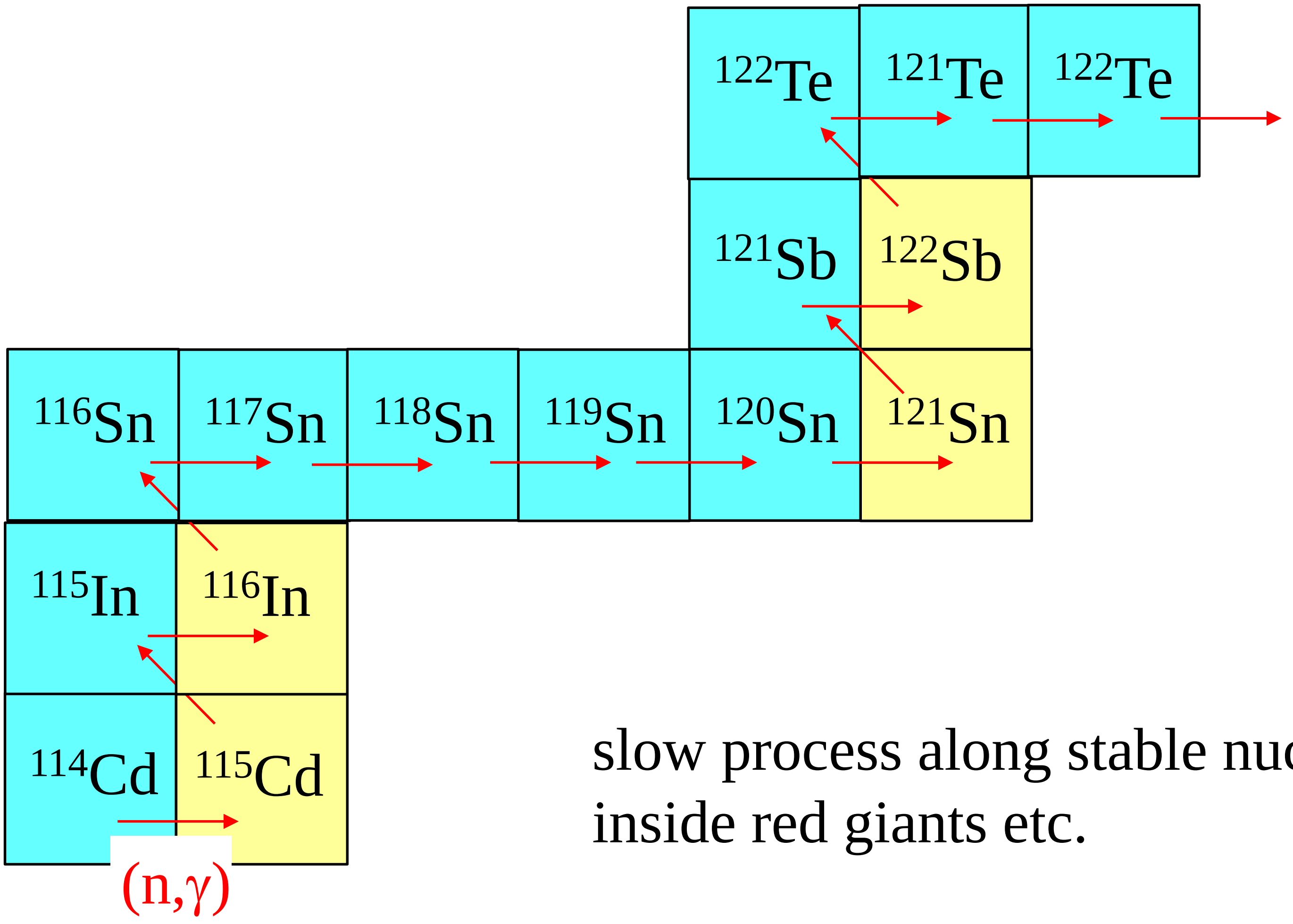
cosmic abundance of elements



Bohr-Mottelson, “Nuclear Structure”

two peaks due to s- and r- processes

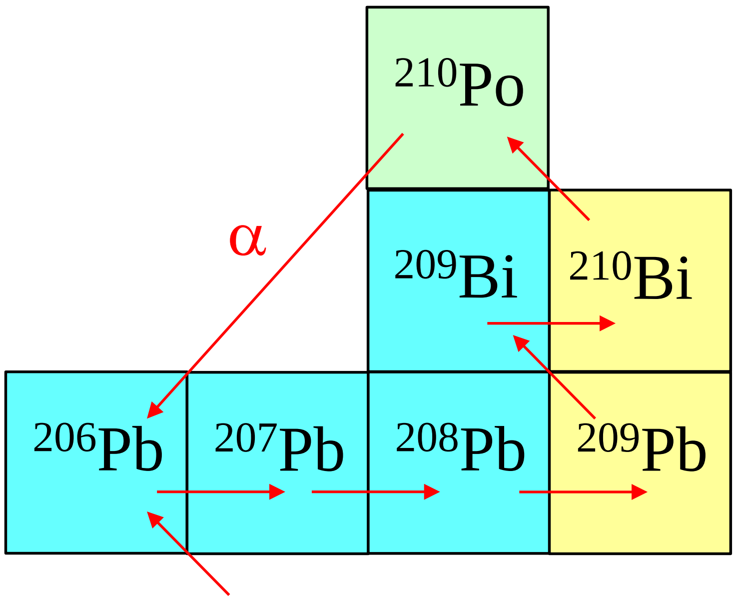
s-process nucleosynthesis



slow process along stable nuclei
inside red giants etc.

s-process nucleosynthesis

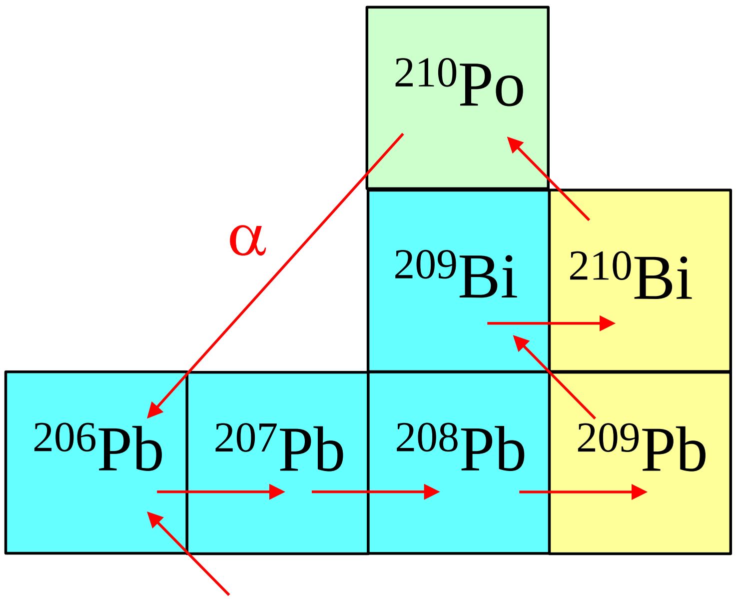
the end point of s-process

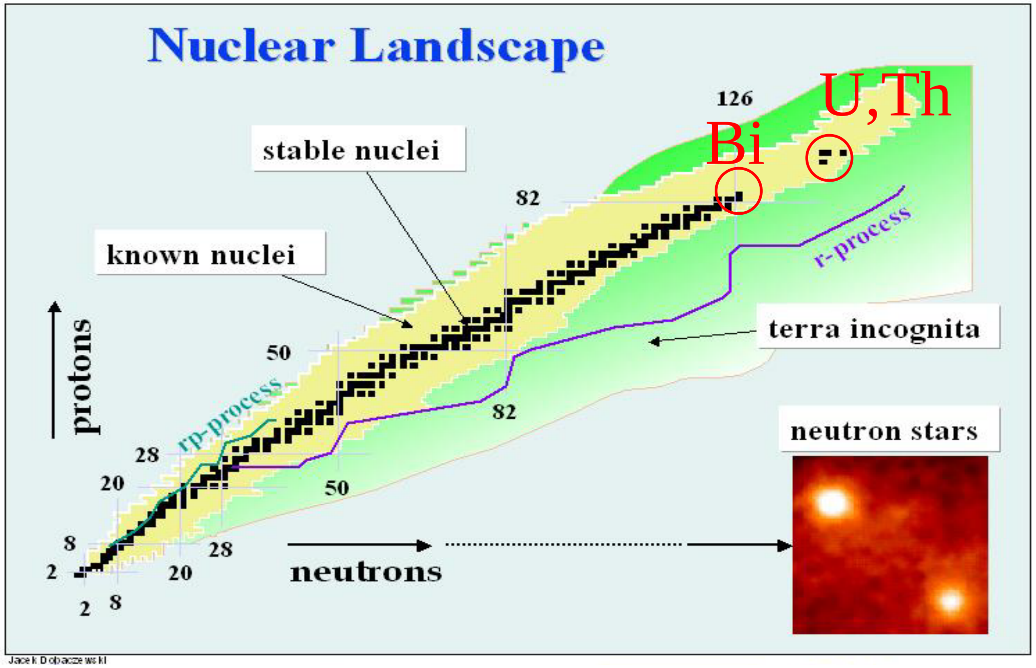


s-process: up to ^{209}Bi

s-process nucleosynthesis

the end point of s-process



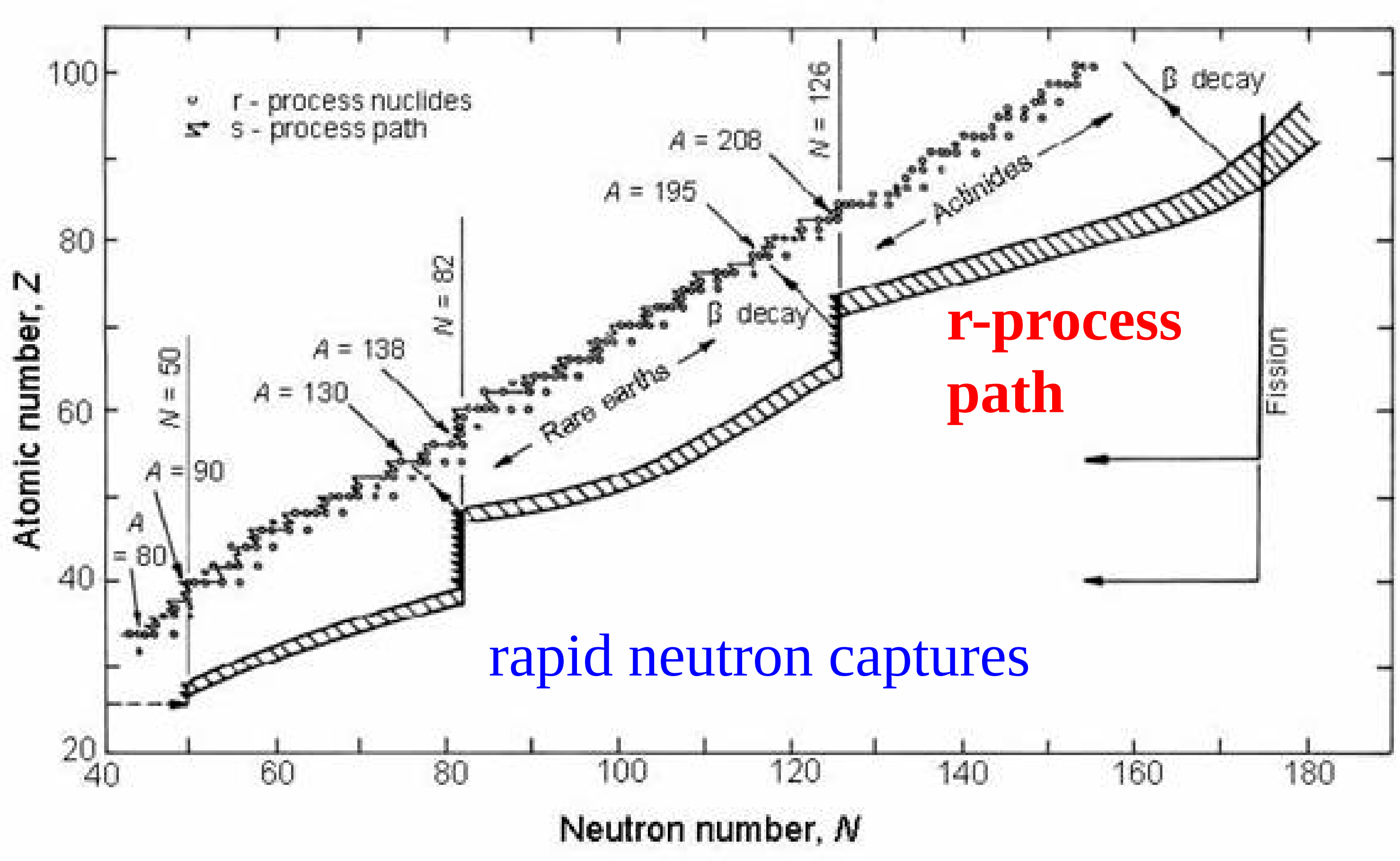


s-process: up to ^{209}Bi

U, Th cannot be synthesized in s-process

→ r-process

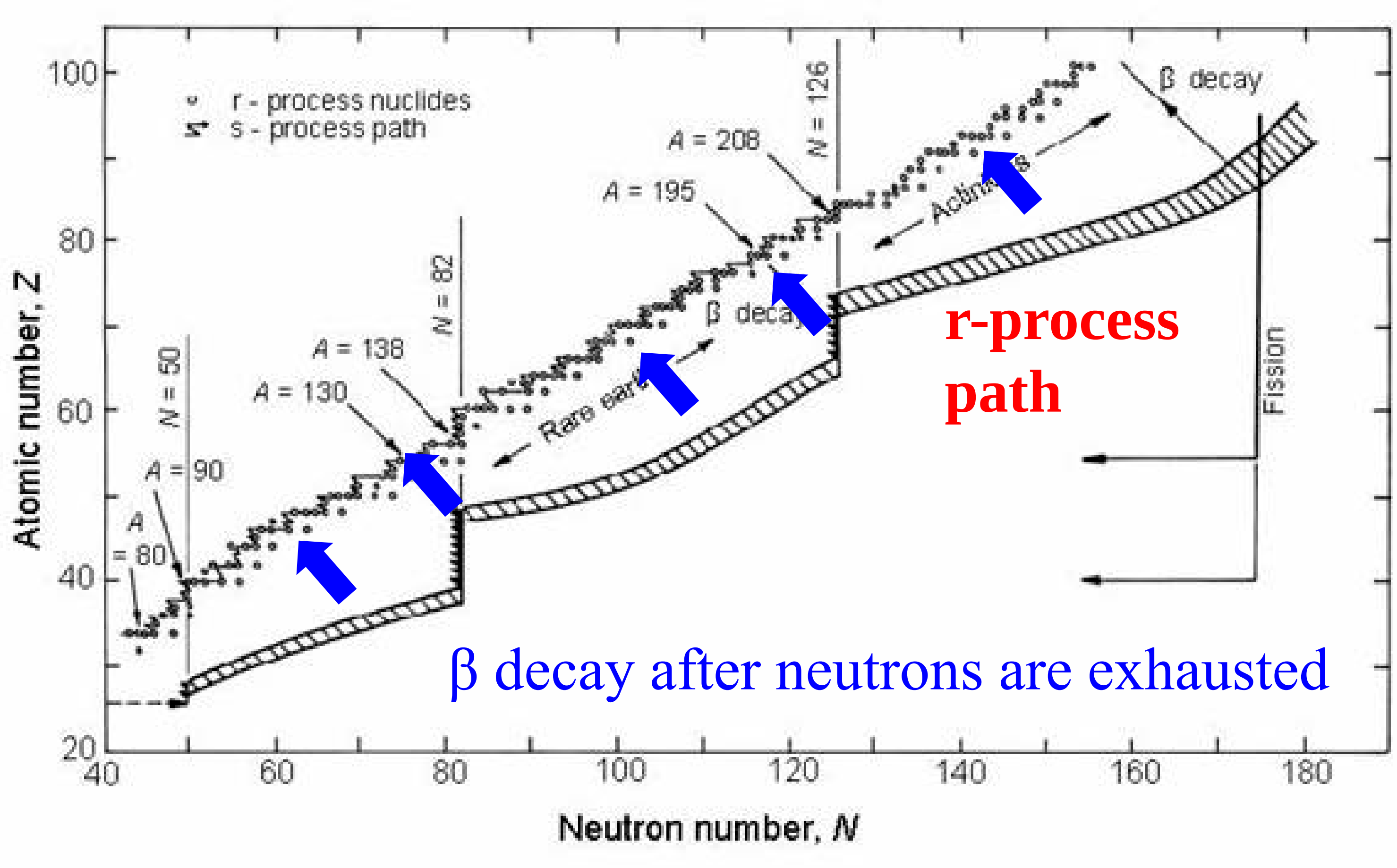
r-process nucleosynthesis



r-process path

rapid neutron captures

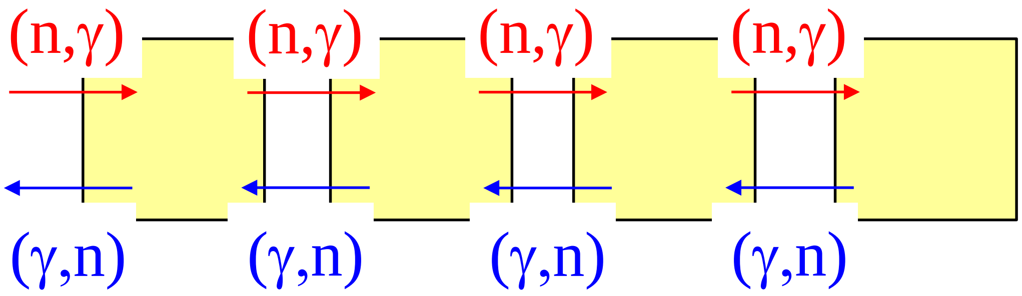
r-process nucleosynthesis



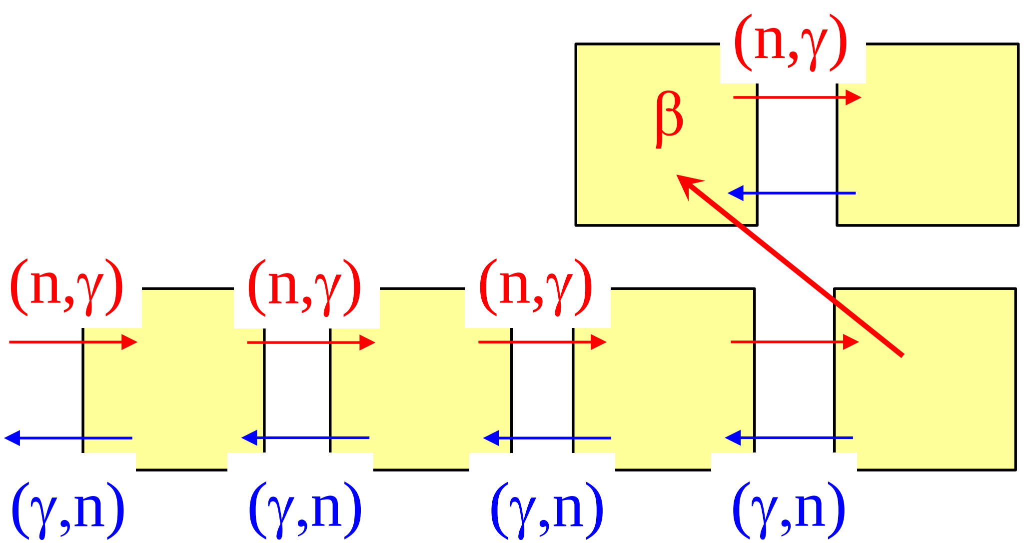
movies of r-process nucleosynthesis

by Dr. N. Nishimura (RIKEN)

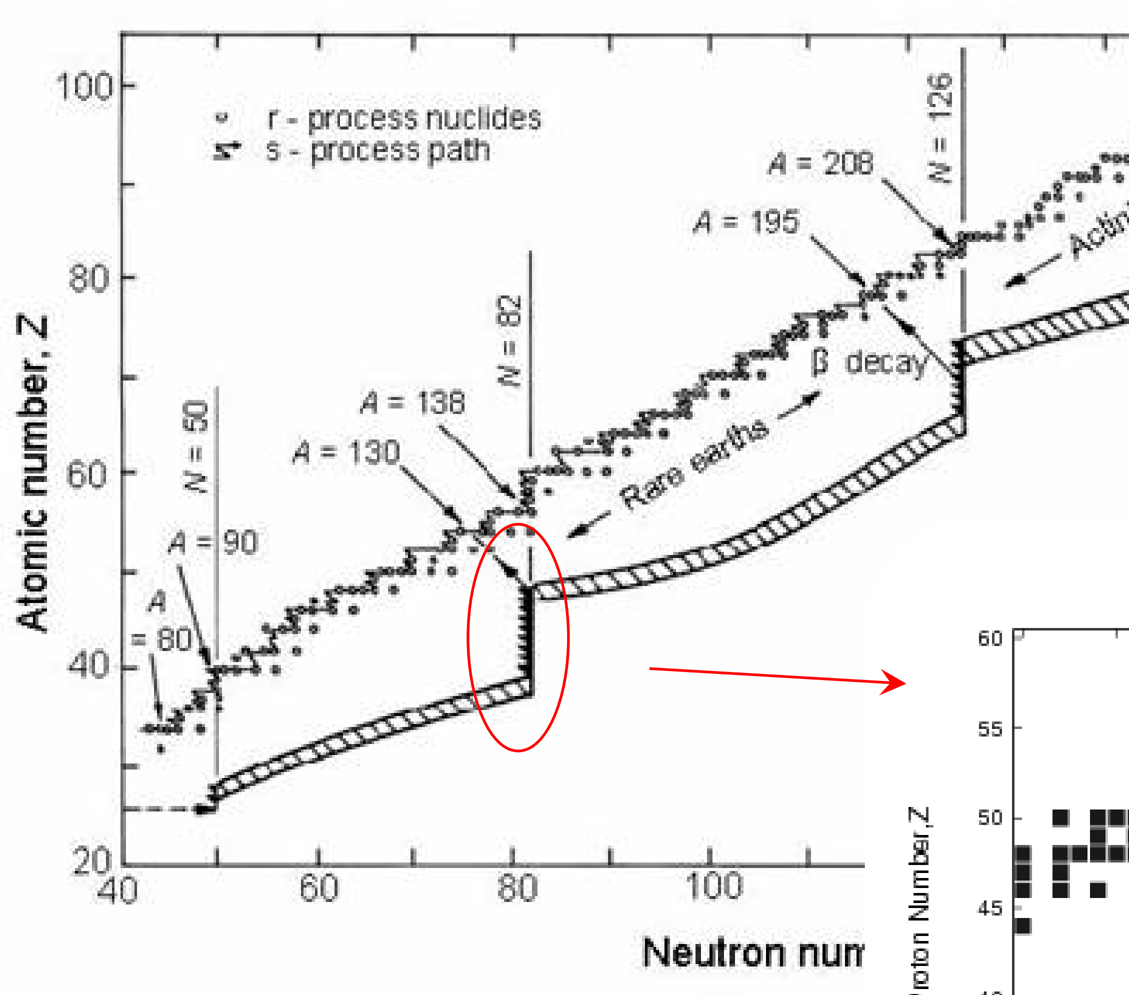
waiting point nuclei

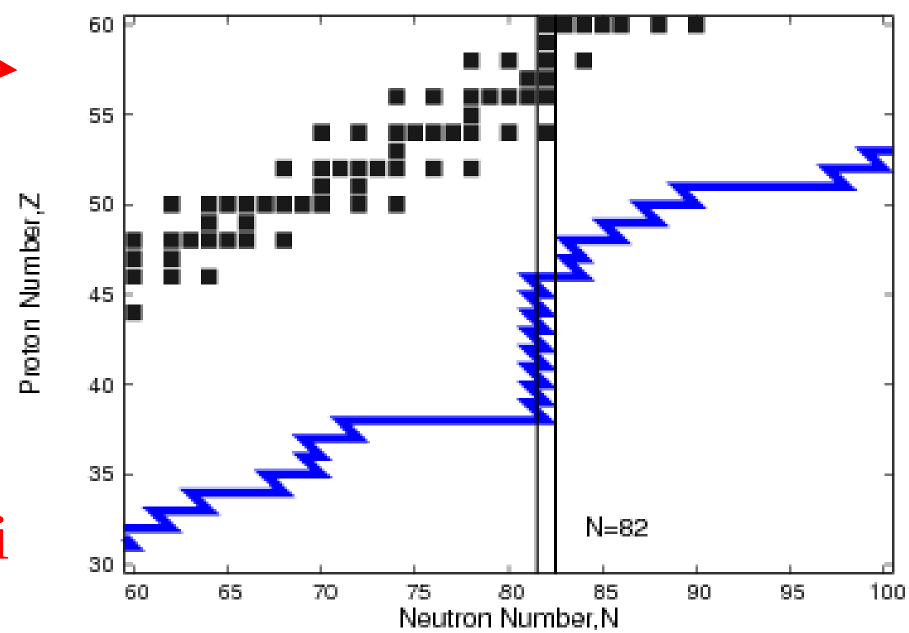


the n-capture stops when the reaction rate is small



β-decay
→ different element



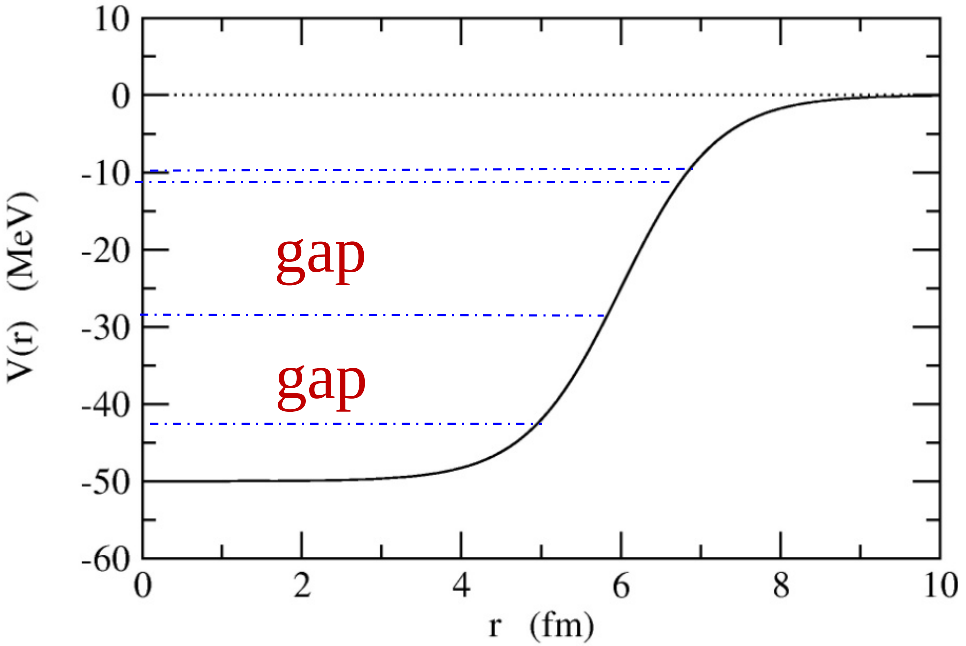


waiting point nuclei

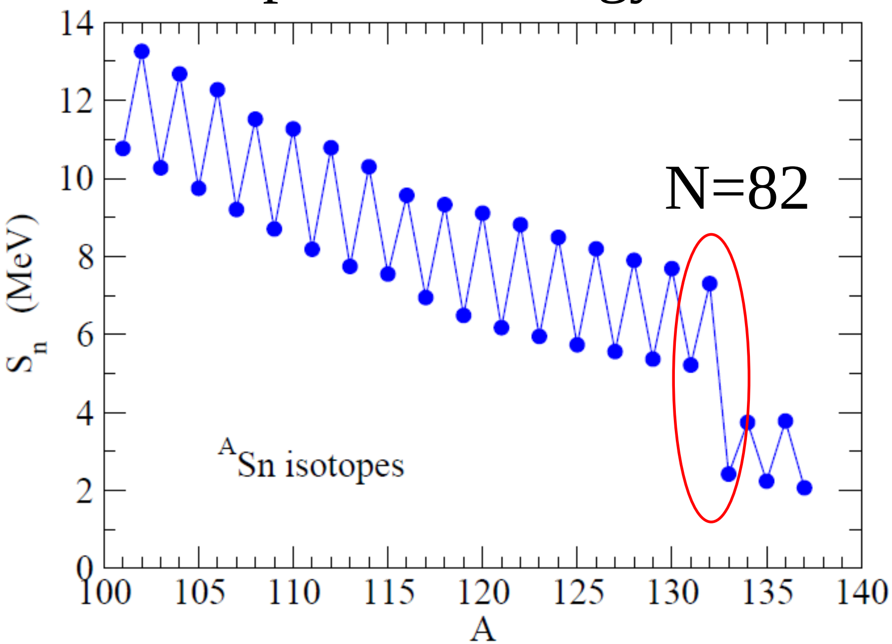
where does the r-process wait?

→ nuclei with a magic number: a small n-capture rate

potential for neutrons



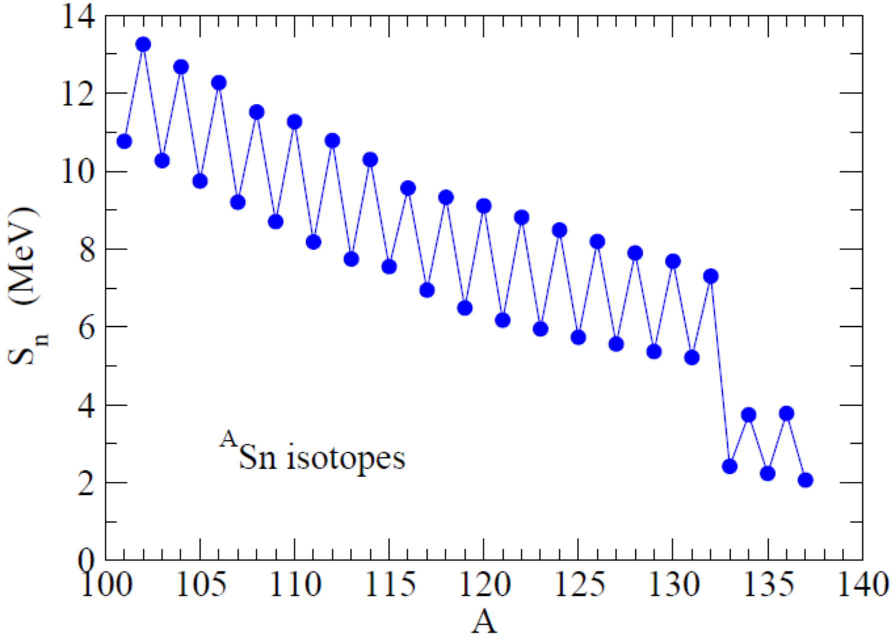
1n separation energy of Sn

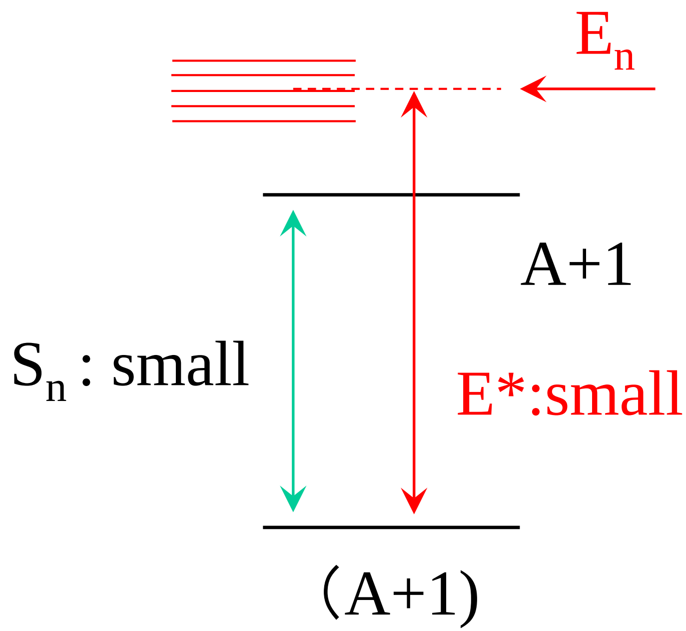


energy gap → stable
= shell structure

for N > 83
→ smaller 1n-separation energy

shell closure + 1 neutron:





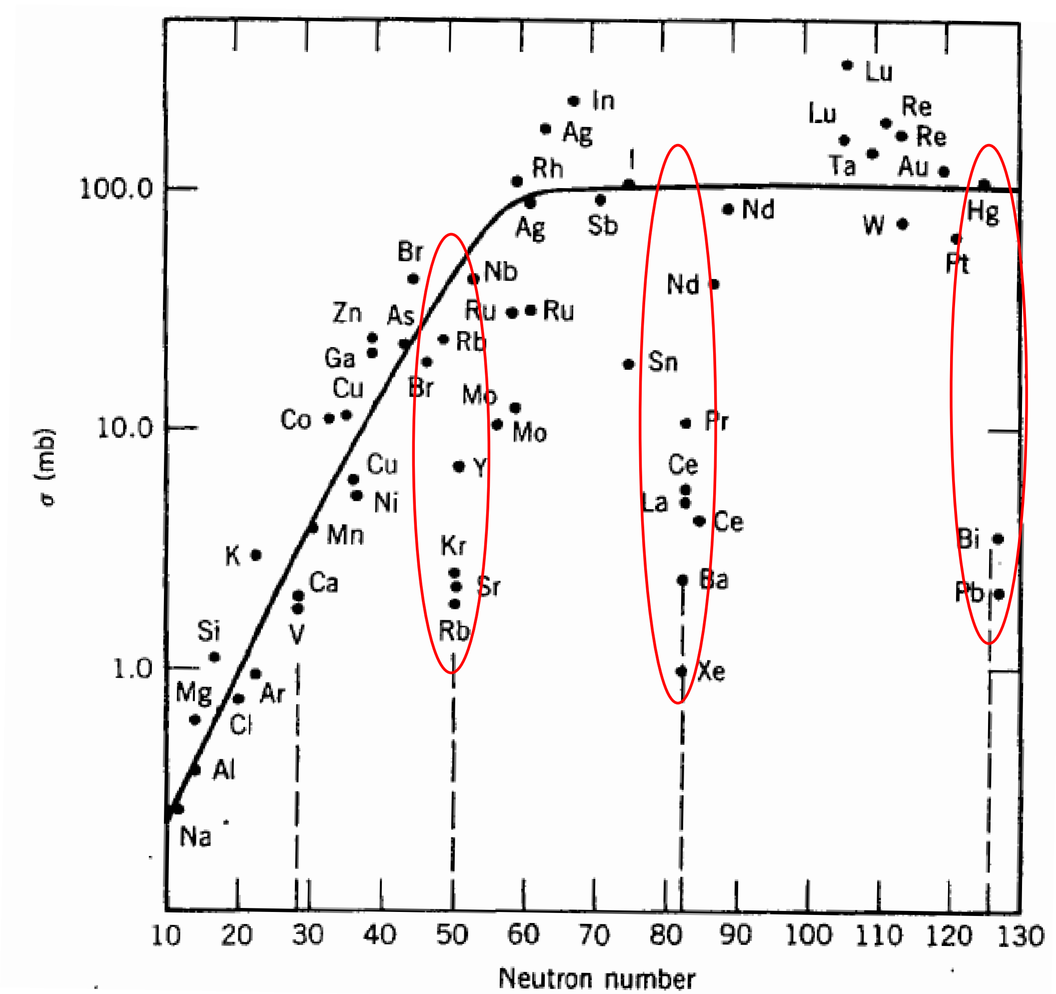
low level density

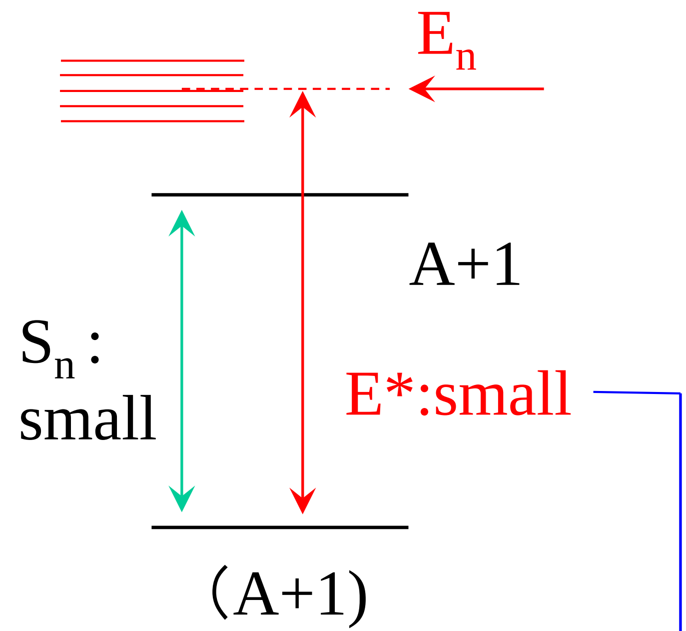
n-capture rate
:small

$$\Gamma_{i\to f} = \frac{2\pi}{\hbar} |\langle f|V|i\rangle|^2 \rho(E_f)$$

shell closure + 1 neutron:

neutron capture cross sections

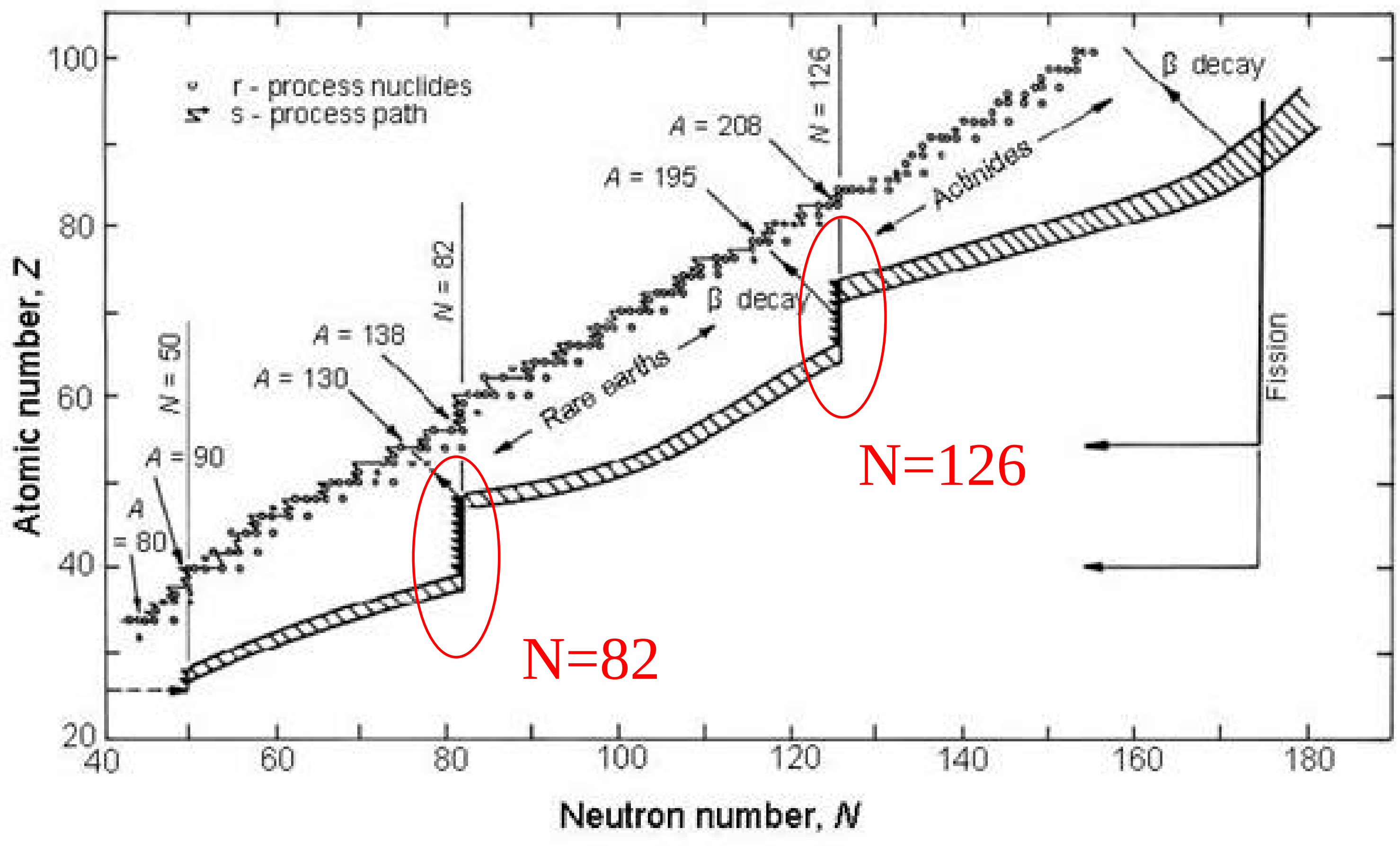




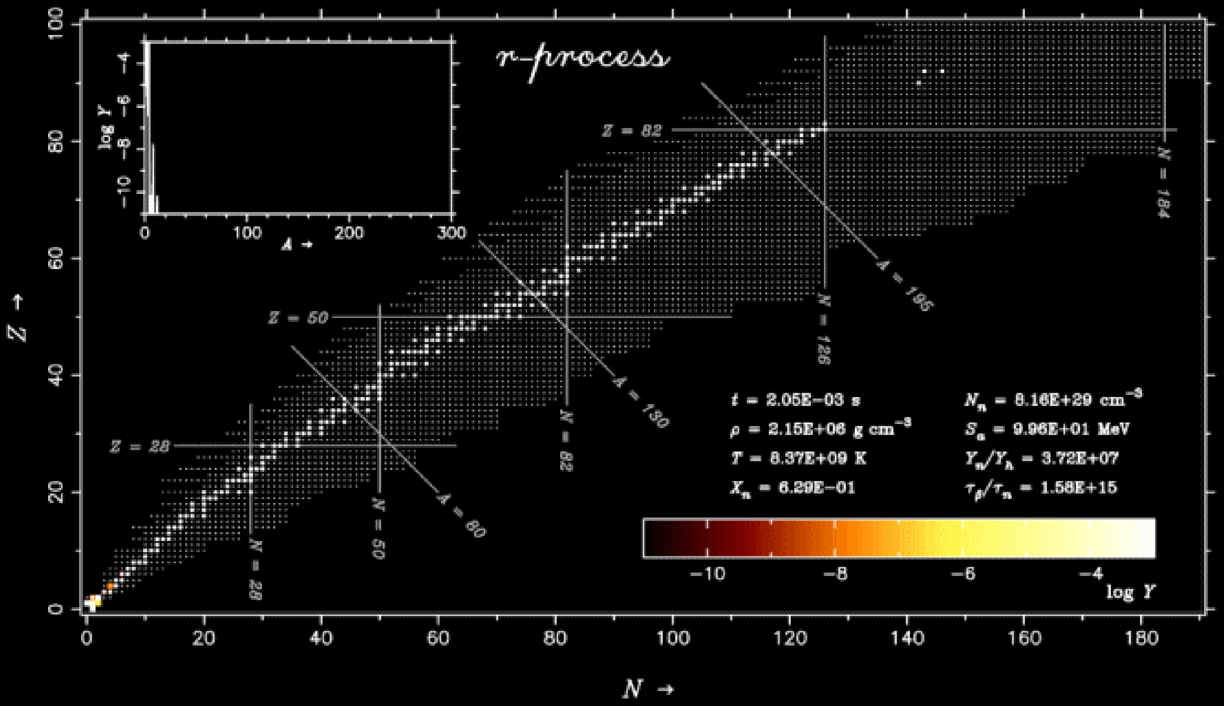
low level density

n-capture rate
:small

K.S. Krane, "Introductory Nuclear Physics"



r - process nuclides
s - process path
Atomic number, Z
Neutron number, N
N = 50
N = 82
N = 126
A = 80
A = 90
A = 130
A = 138
A = 195
A = 208
Rare earths
β decay
Actinides
β decay
Fission
N=82
N=126

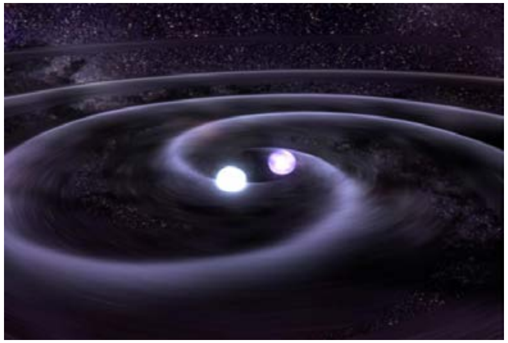


As a matter of fact, it is not known well how Au and U were created….

Open issues in r-process nucleosyntehsis

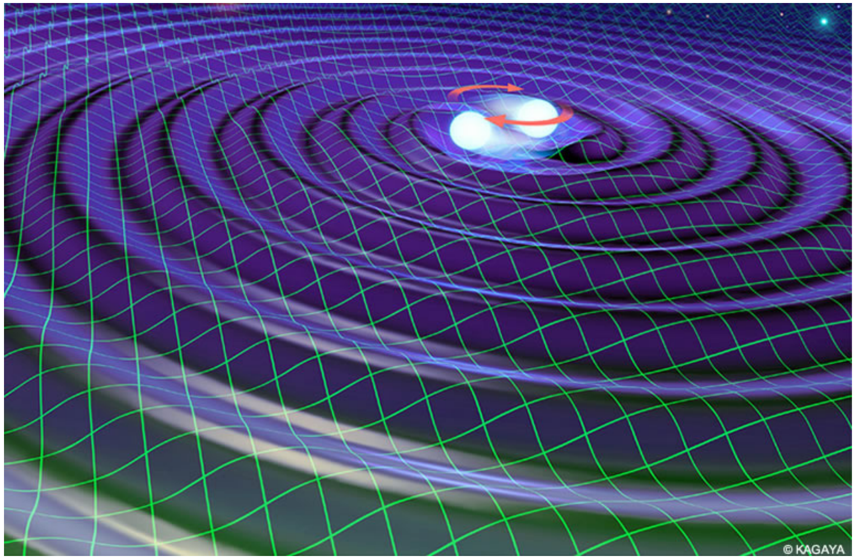
- where is the main site?

SN explosion



Neutron star merger

gravitational wave due to
a neutron star merger

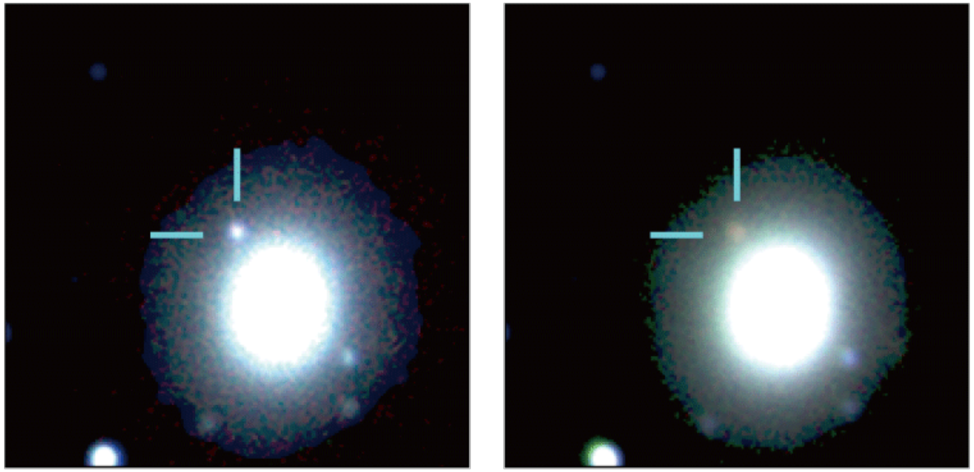


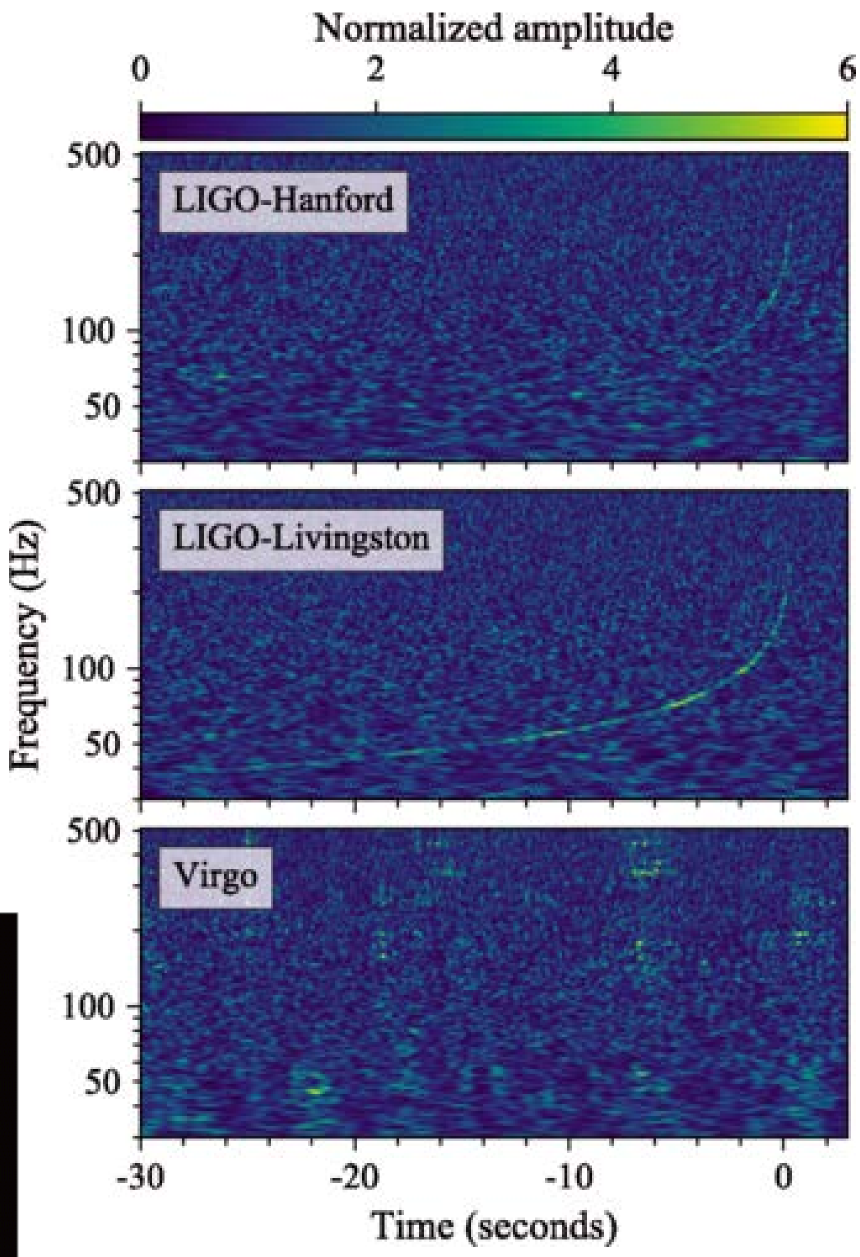
NAOJ

photons from r-process

2017.08.18-19

2017.08.24-25





B.P. Abbott et al., PRL119 ('17) 161101

Open issues in r-process nucleosyntehsis

- where is the main site?

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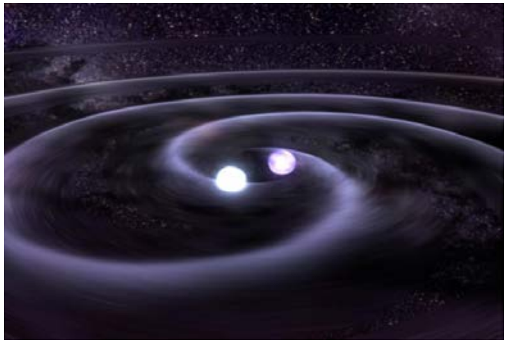
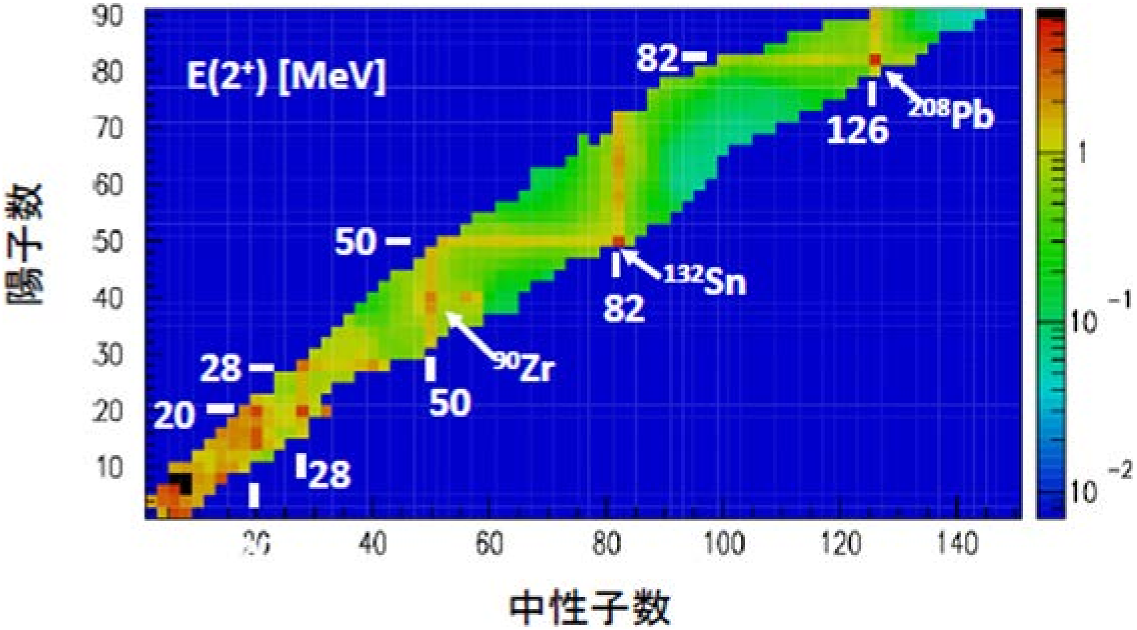


Neutron star merger

- how well do we know the properties of neutron-rich nuclei?
  - mass
  - β-decay (life-time)
  - magic numbers

physics of neutron-rich nuclei



Important findings at RIBF:

Disappearance of N=20, 28
Appearance of New magic # N=34

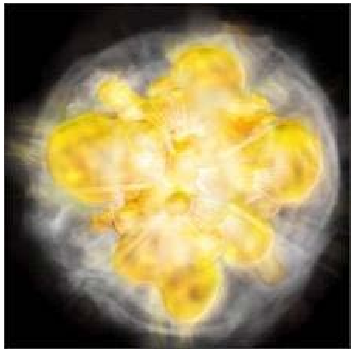
Magic number in heavy neutron-rich nuclei?

One of the main issues in RIBF

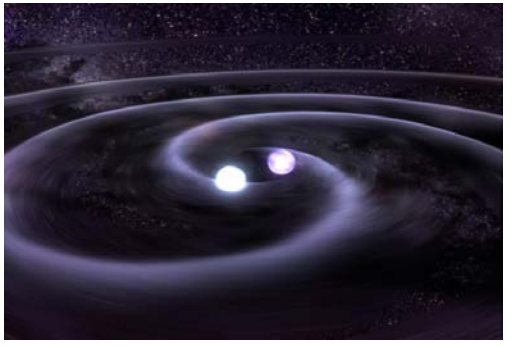
Nature, vol. 502 (2013)
Discovery of the new magic number N=34

Open issues in r-process nucleosyntehsis

- where is the main site?



SN explosion



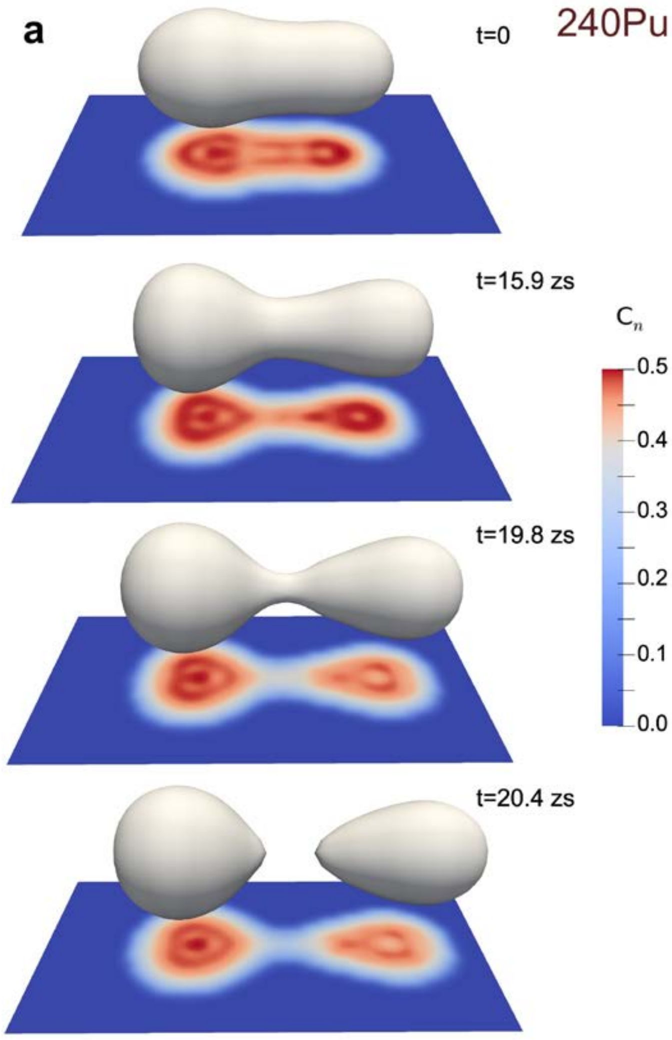
Neutron star merger

- how well do we know the properties of neutron-rich nuclei?
  - mass
  - β-decay (life-time)
  - magic numbers

physics of neutron-rich nuclei

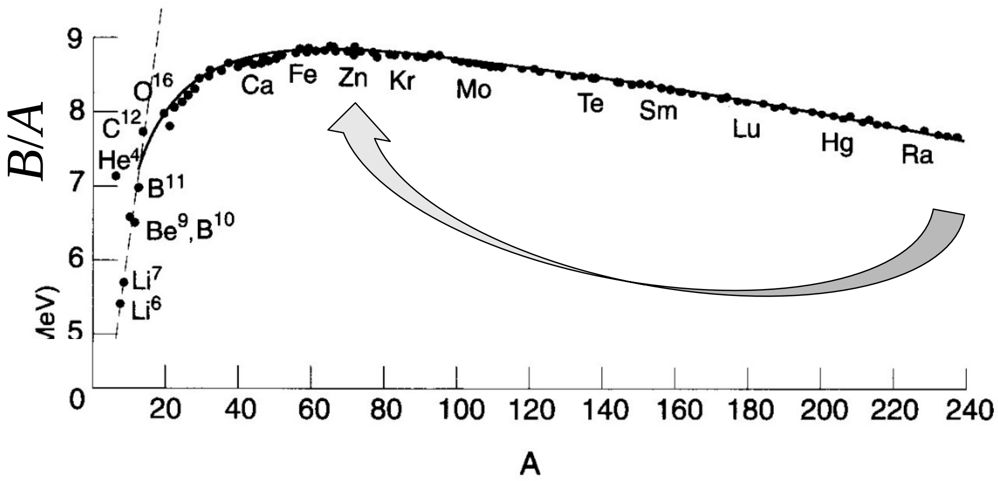
- role of fission?
  - spontaneous and neutron-induced fissions
  - β-delayed fission

nuclear fission



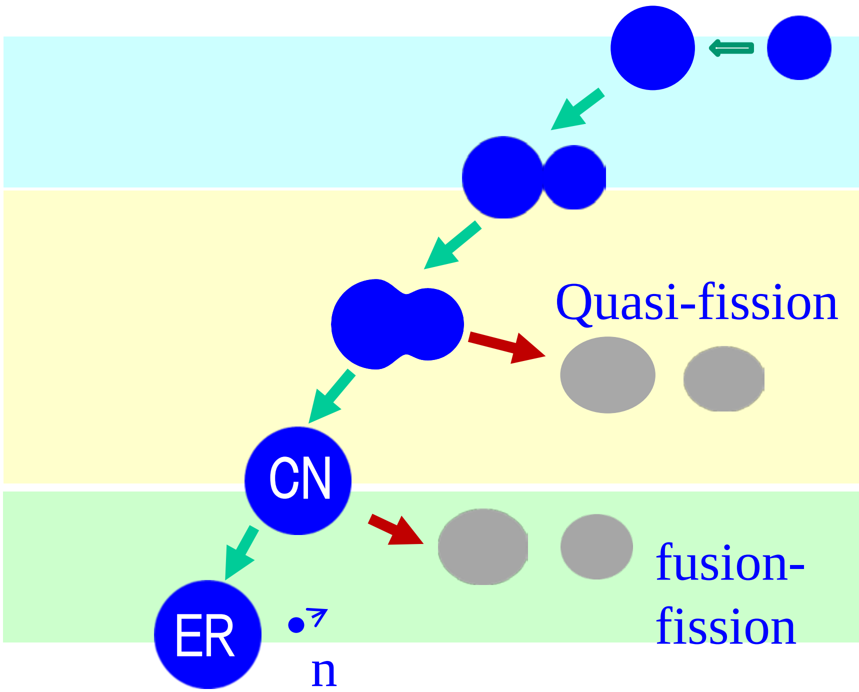
G. Scamps and C. Simenel, Nature 564 (2018) 382

- discovered about 80 years ago (in 1938) by Hahn and Strassmann
- a primary decay mode of heavy nuclei

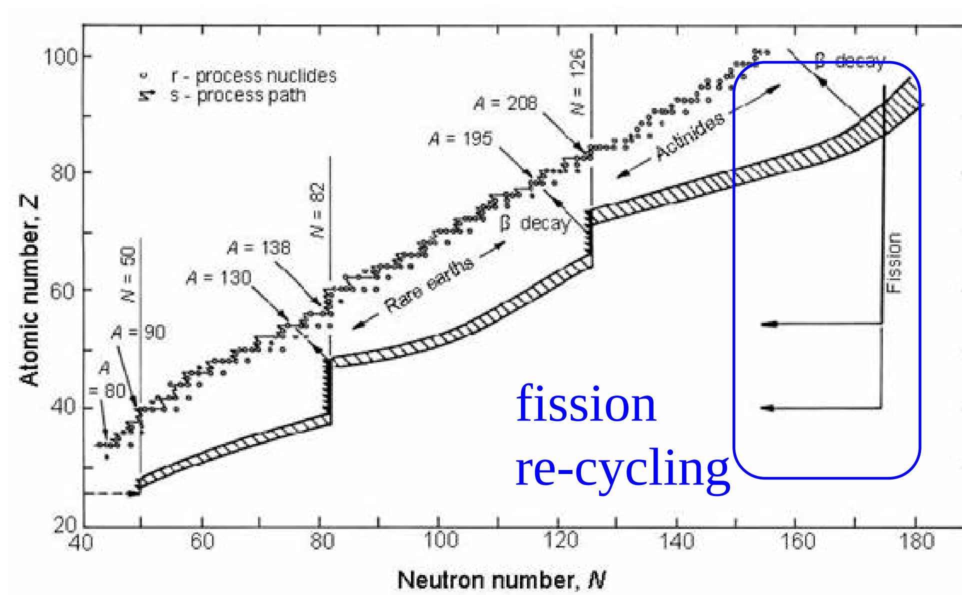


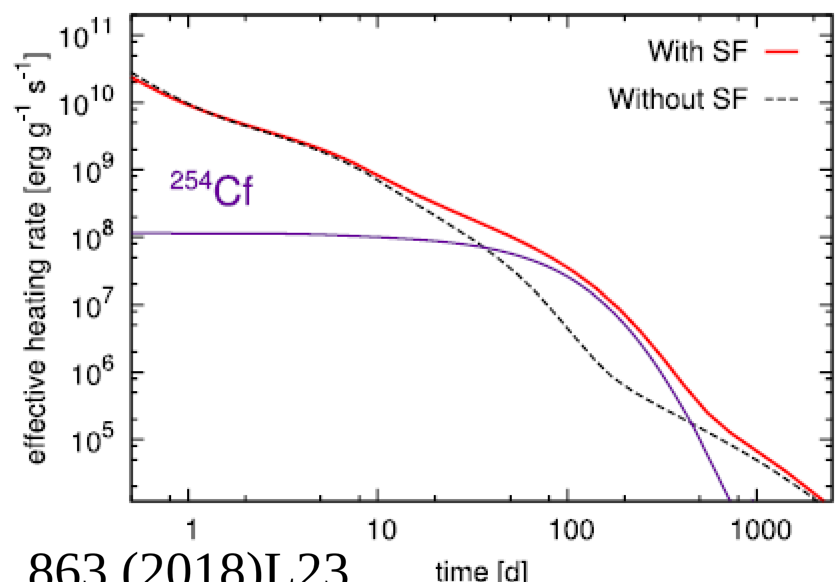
- important role in:
  - energy production
  - superheavy elements
  - r-process nucleosynthesis
  - production of neutron-rich nuclei

fission in SHE



fission in r-process nucleosynthesis





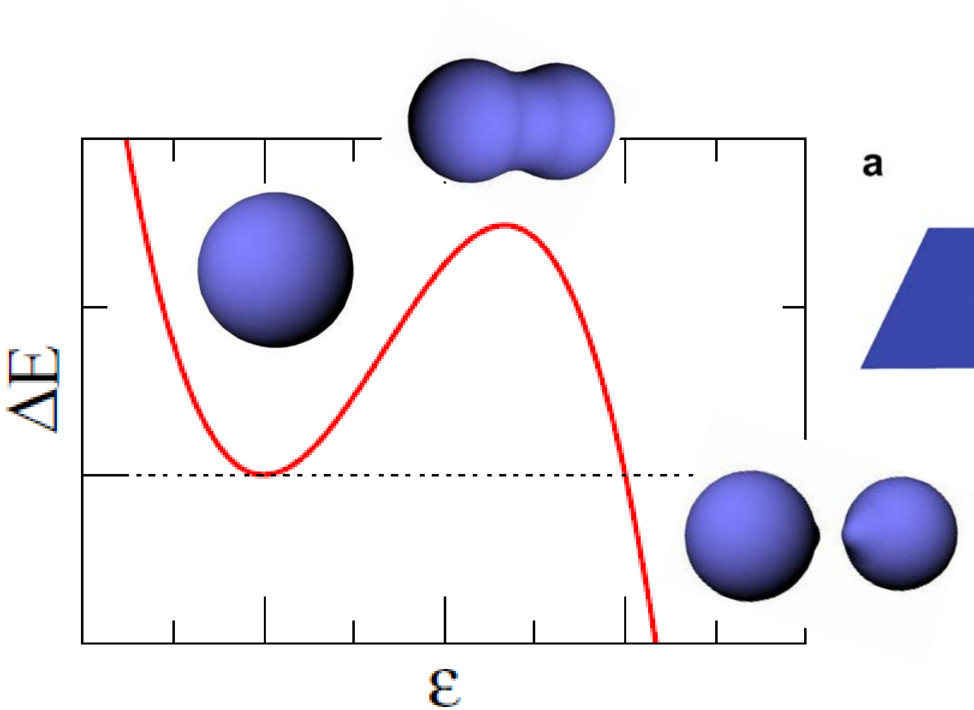
Y. Zhu et al.,
Astrophys. J. Lett. 863 (2018)L23

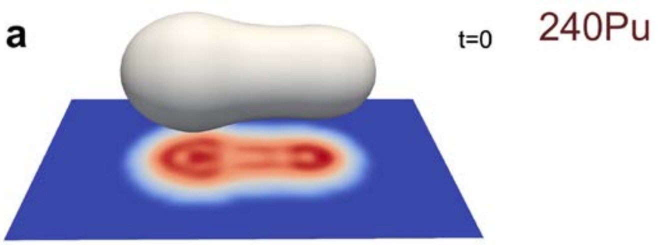
nuclear fission

- macroscopic understanding:

  competition between the surface and the Coulomb energies

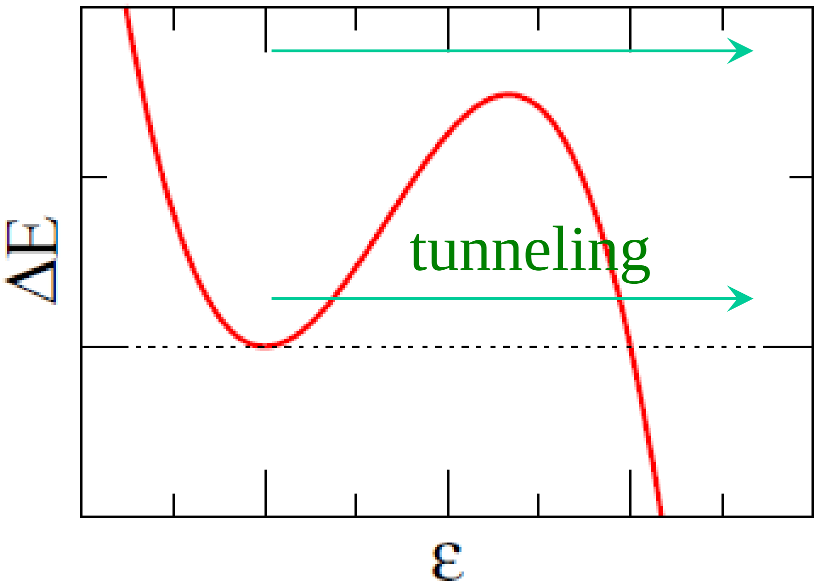
  → fission barrier





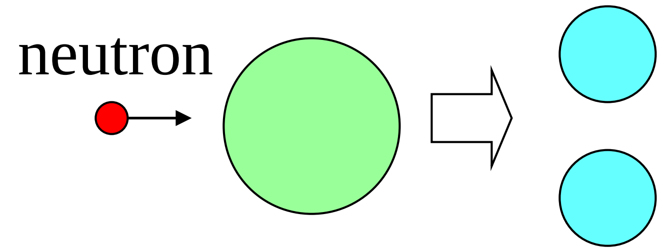
nuclear fission

- various fission processes

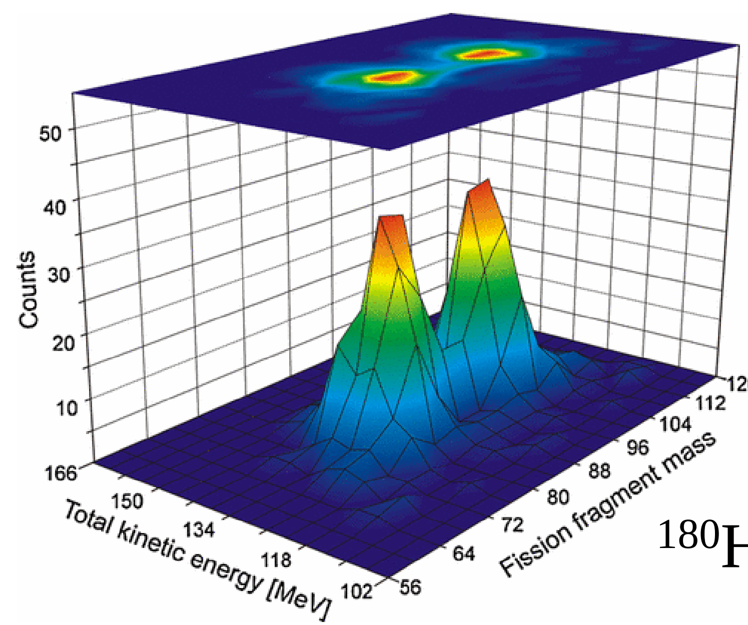


induced fission

spontaneous fission



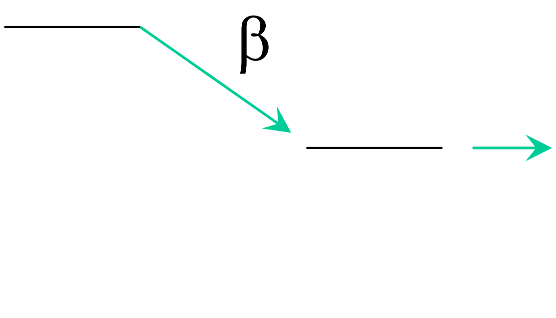
asymmetric fission



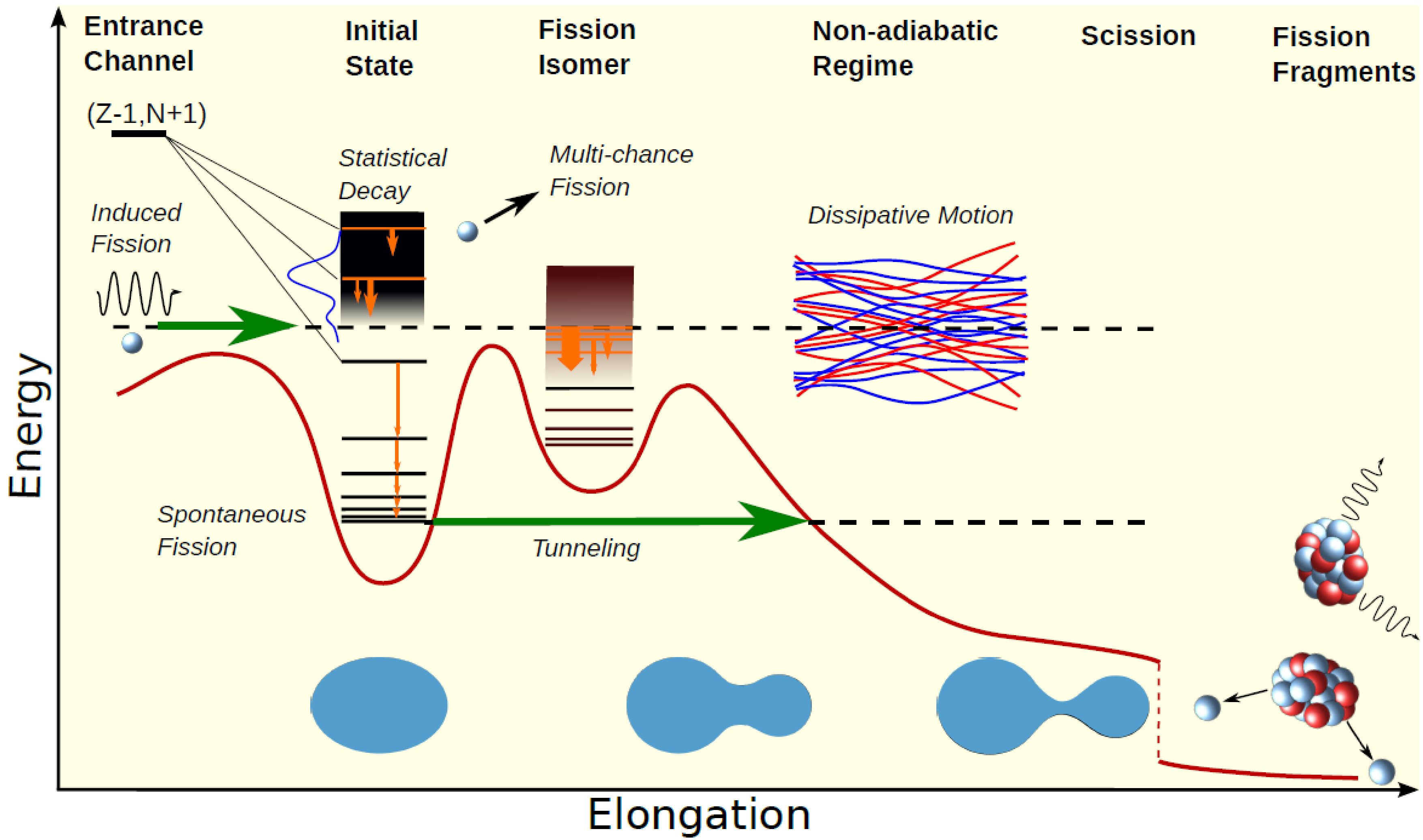
^{180}Hg

A.N. Andreyev et al., PRL105('10)252502

beta-delayed fission



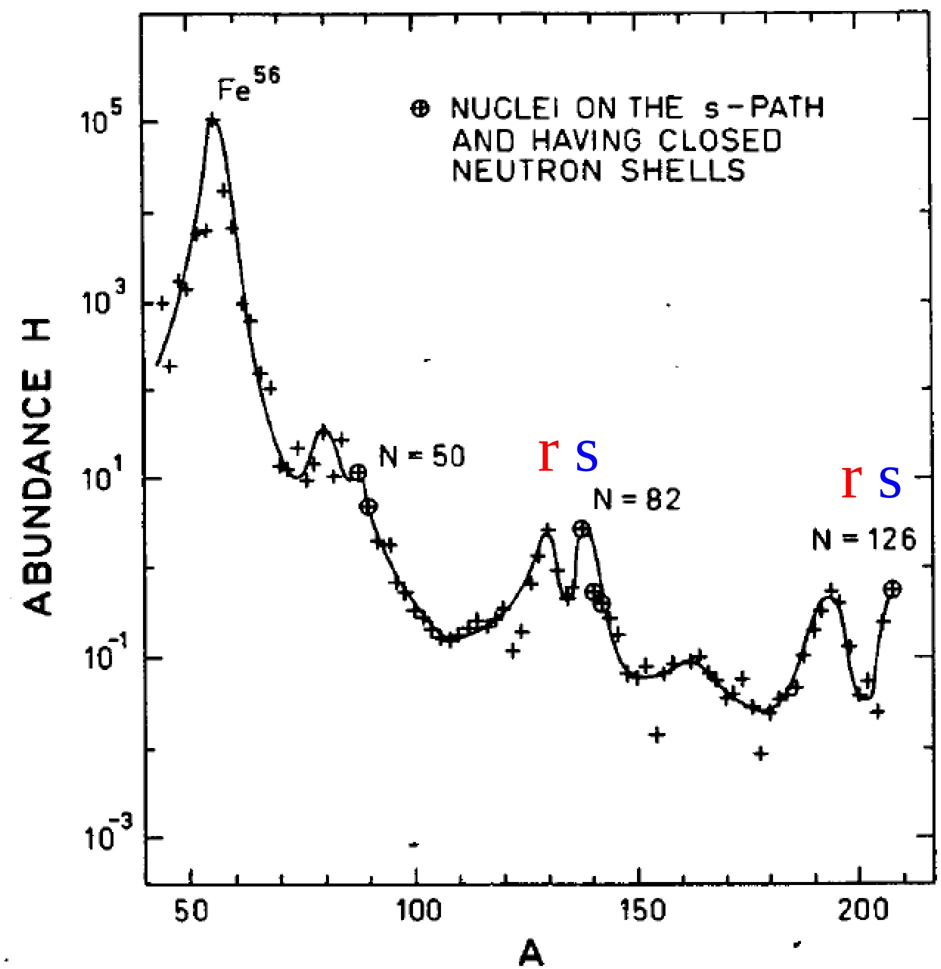
fission



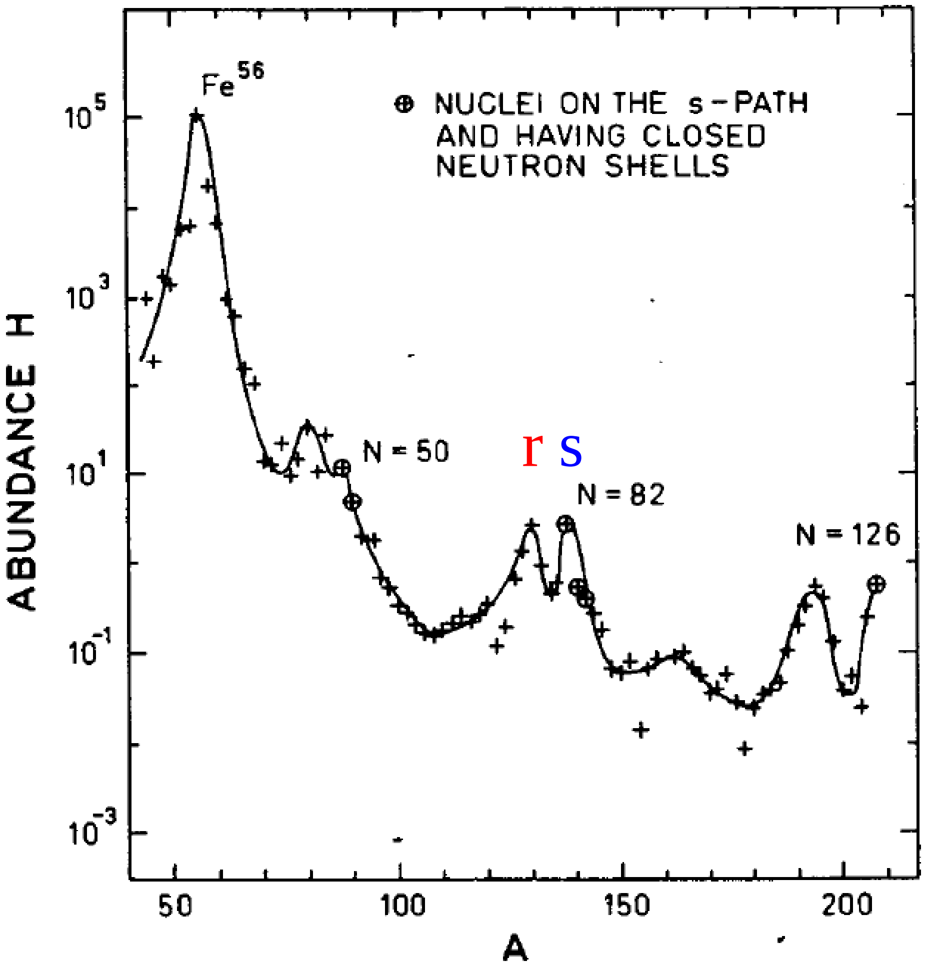
"Future of fission theory" White paper

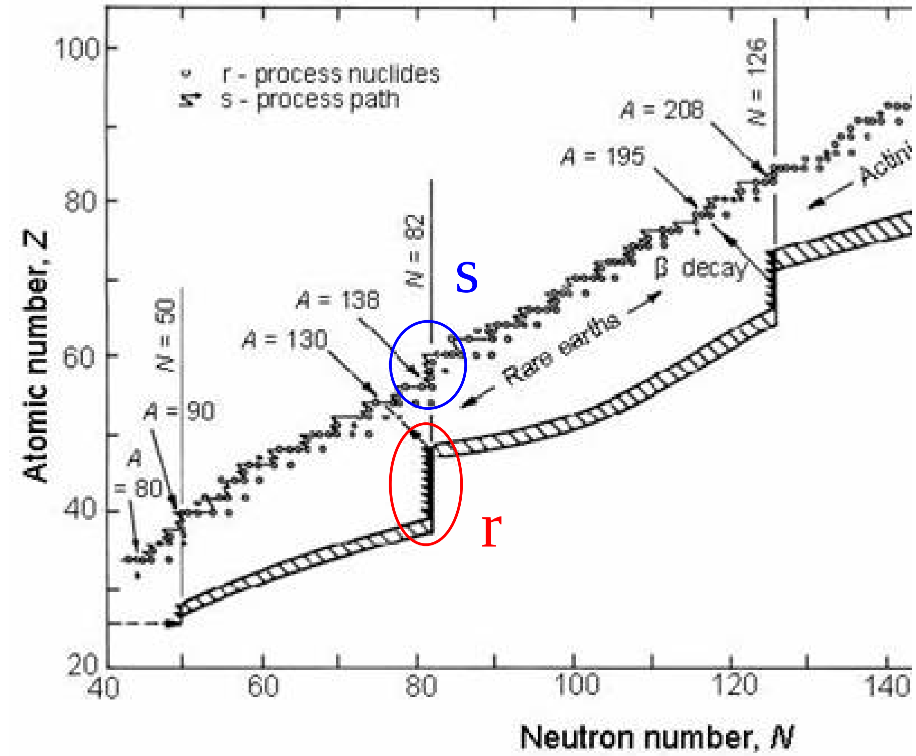
Any question?

Any question?



why are the r-process peaks on the left hand-side?





the r-process peaks: the left hand-side

← a path goes through the neutron-rich region