Nuclear Structure Theory for Cluster Physics

Masaaki Kimura (Hokkaido U.)

1. Self Introduction
2. Introduction to nuclear cluster physics
3. Appendix (Nuclear Data)

Self introduction

Masaaki Kimura（木村 真明）

A physicist for theoretical nuclear physics

- 2002 Ph. D at Kyoto U.
- 2003-2007 Post Doc. at RIKEN, Kyoto and Tsukuba
- 2008- Hokkaido U.
- 2017- Head of **nuclear data center** at Hokkaido U.

Research interests

- Structure of neutron-rich nuclei (magic #, n-halos)
- Nuclear clustering in stable and unstable nuclei, and related astrophysics
- Structure of hypernuclei

Plan of this lecture

PART 1: Introduction to nuclear cluster physics

- What is nuclear cluster?
- Ikeda diagram
- Clusters and astrophysics

PART 2: A story of the Hoyle state

Tomorrow:

PART 3: Introduction to novel nuclear model for clustering

Part I
An introduction to nuclear cluster physics

– What is nuclear cluster?
– Ikeda diagram
– Clusters and astrophysics

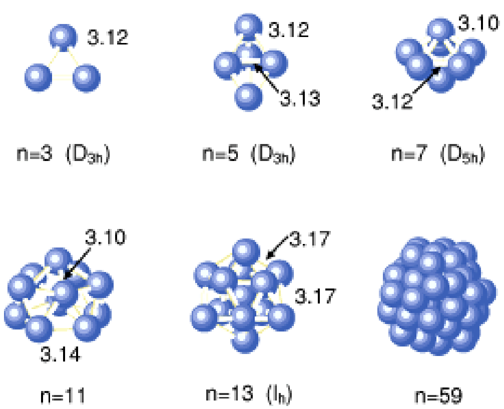
What is cluster ?

クラスター　Wikipediaより

クラスター、クラスタ(cluster)は、英語で「房」「集団」「群れ」のこと。

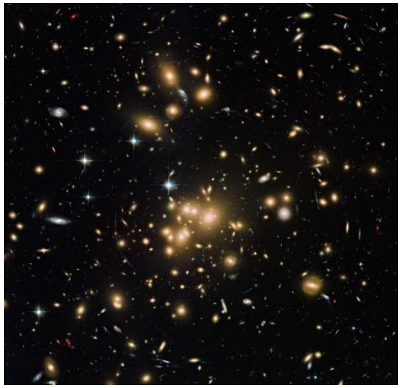
- クラスター (物質科学) – 原子および分子の、数個から数十個ないしそれ以上の集合。
- 星団(star cluster) – 恒星の集団。
- 銀河団(cluster of galaxies) – 銀河の集団。

Metal clusters



星団(昴)

銀河団



An universal phenomena in the interacting many-body systems

What is cluster in nuclear physics ？

クラスター

Wikipediaより

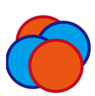
クラスター、クラスタ(cluster)は、英語で「房」「集団」「群れ」のこと。

- Clusters in atomic nuclei

  A group of tightly bound nucleons

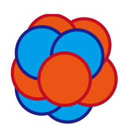
- Typical example of clusters

α cluster
(^{4}He 原子核)



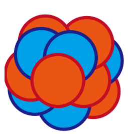
Z=N=2

^{12}C cluster



Z=N=6

^{16}O cluster



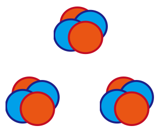
Z=N=8

What is cluster in nuclear physics ?

- There are the excited states of atomic nuclei which is composed of clusters (cluster states)

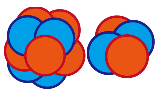
- Typical cluster states

Excited state
3α clusters



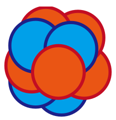
7.7 MeV

Excited state
$^{12}C + \alpha$ clusters

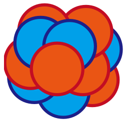


6.0 MeV

^{12}C ground state



^{16}O ground state



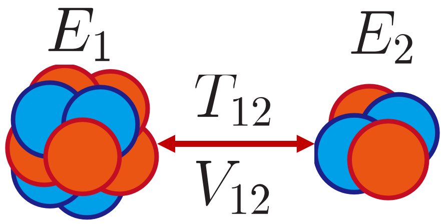
◎ In the cluster states, the nucleons are confined within clusters. Clusters are weakly bound and constitute meta-stable states

Clusters and threshold rule

- When clusters are formed?

◎ Consider the energy of the cluster state composed of two clusters

$$E_{cluster} = E_1 + E_2 + T_{12} + V_{12}$$



◎ Interaction between clusters should be weak, $V_{12} \simeq 0$

Otherwise, the clusters should be dissolved

◎ Kinetic energy between clusters should be small, $T_{12} \simeq 0$

Otherwise, they cannot form a meta-stable state

◎ Therefore, the energy of the cluster state is approximately equal to "The sum of the internal energies of clusters"

$$E_{cluster} \simeq E_1 + E_2$$

= "The energy required to decompose the system into clusters" (Threshold energy)

Clusters and threshold rule

An example: ^{16}O nucleus

◎ The energy of the ^{12}C+α cluster states

≃ 「Sum of the energy of the ^{12}C, α clusters"

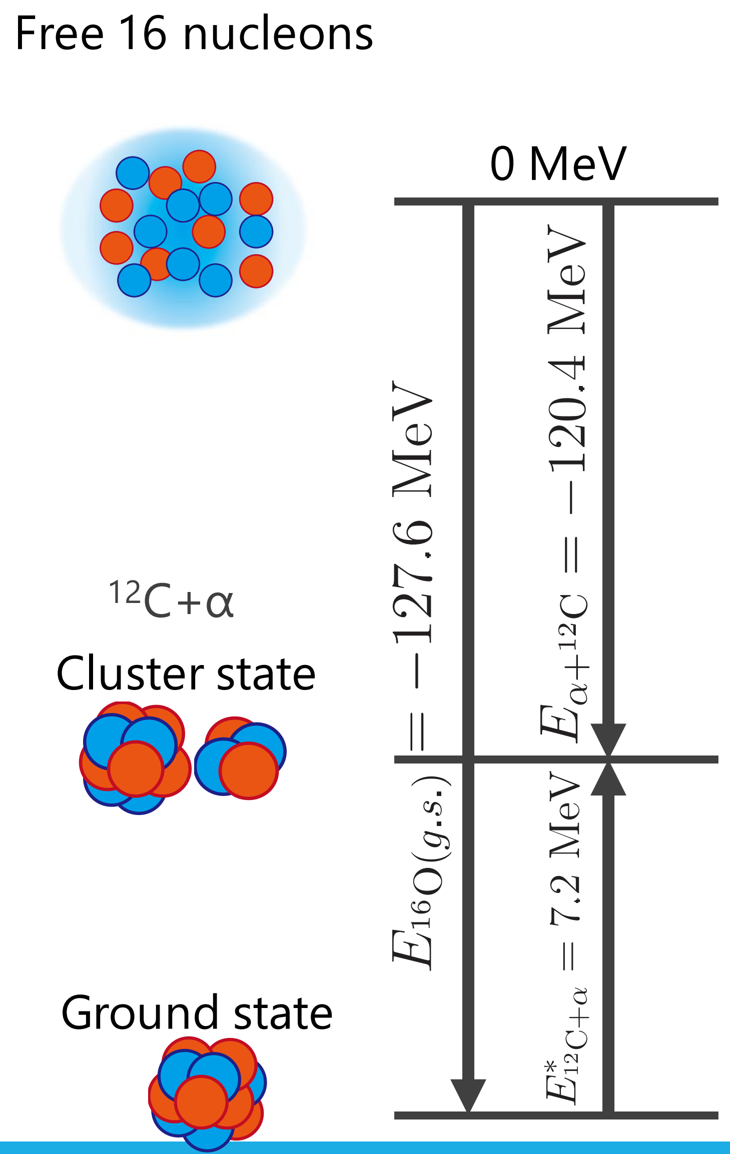
$$E_{\alpha+{}^{12}\mathrm{C}} = E_{{}^{12}\mathrm{C}} + E_{\alpha}$$
$$= -92.1\ \mathrm{MeV} - 28.3\ \mathrm{MeV}$$
$$= -120.4\ \mathrm{MeV}$$

◎ The energy of ^{16}O ground state

$$E_{{}^{16}\mathrm{O}(g.s.)} = -127.6\ \mathrm{MeV}$$

◎ Excitation energy of the ^{12}C+α cluster state

$$E^{*}_{{}^{12}\mathrm{C}+\alpha} \simeq E_{\alpha+{}^{12}\mathrm{C}} - E_{{}^{16}\mathrm{O}(g.s.)}$$
$$= 7.2\ \mathrm{MeV}$$



Clusters and threshold rule

An example: ^{16}O nucleus

◎ ^{12}C+α cluster state should exist at approximately 7.2MeV in the excited state of ^{16}O

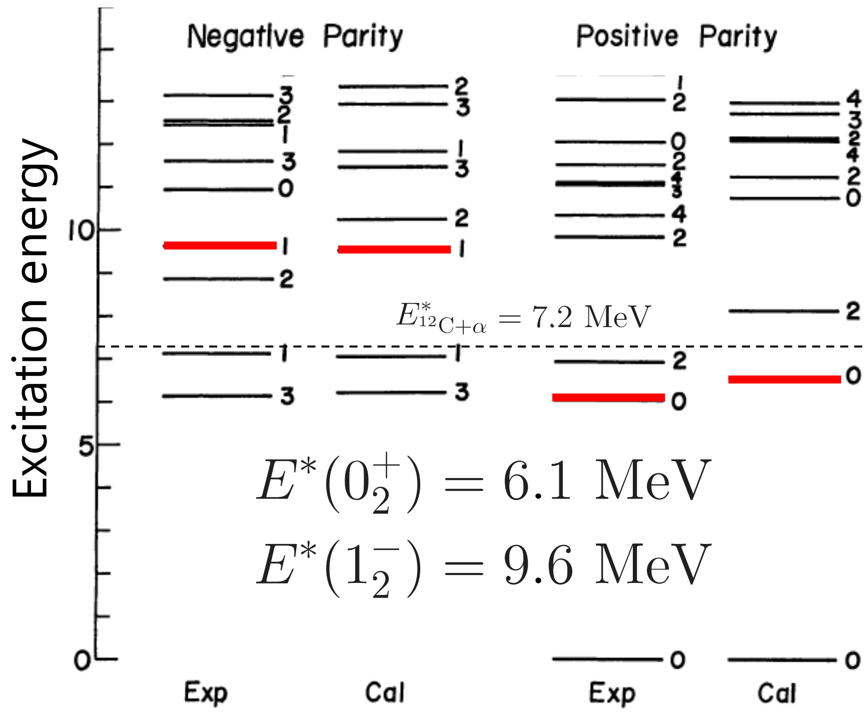
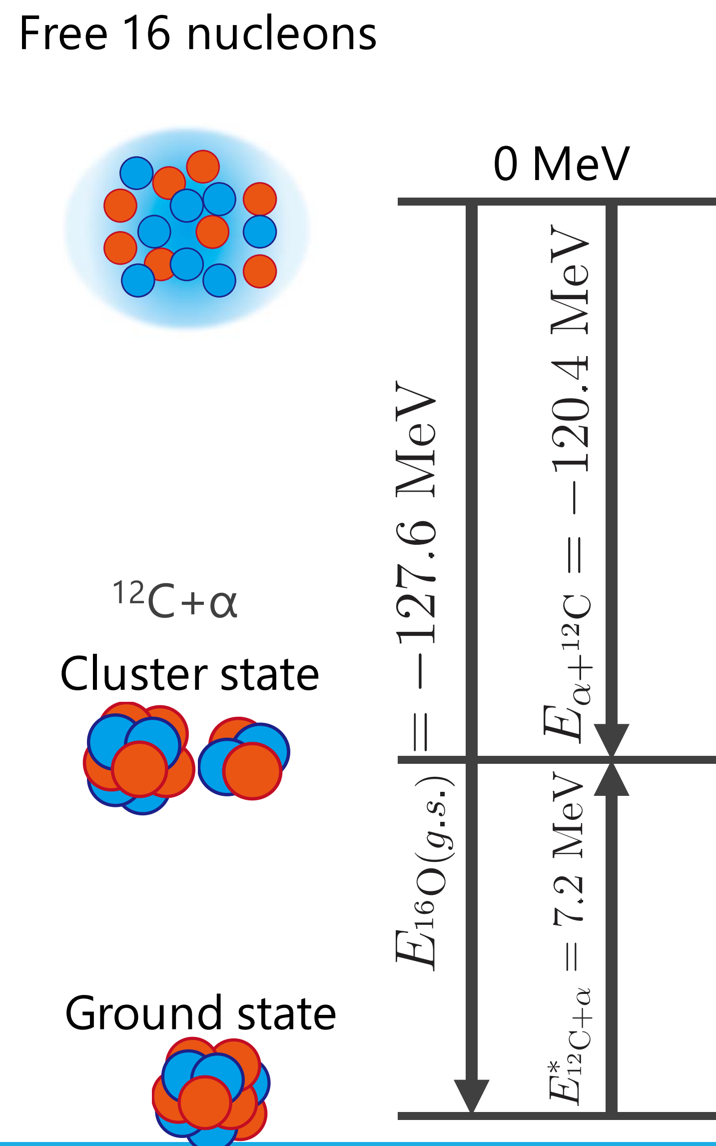


Fig. 3-3. $T=0$ energy spectrum in ^{16}O calculated by the ^{12}C+α orthogonality condition model.

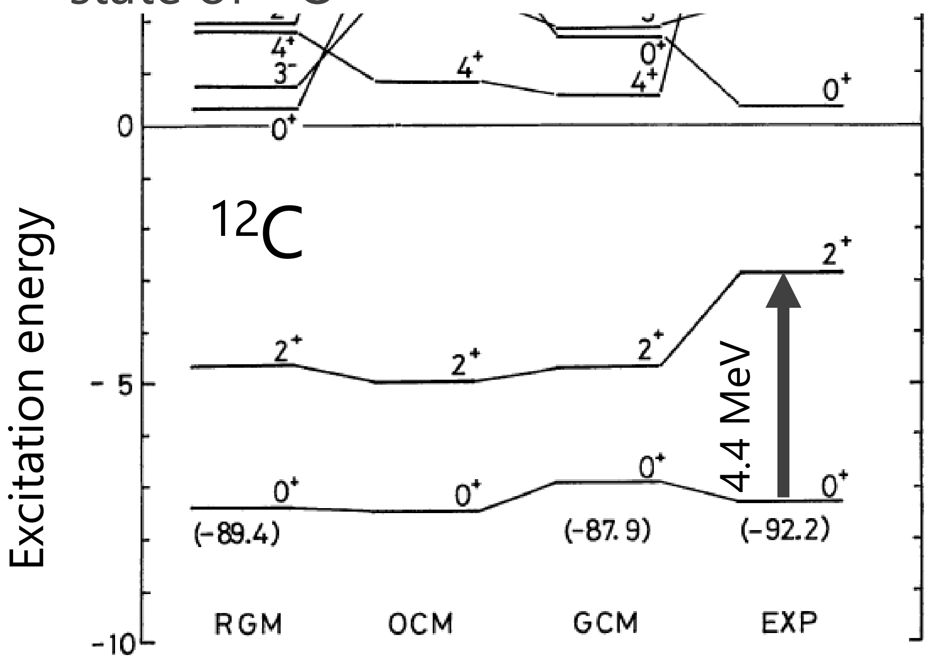


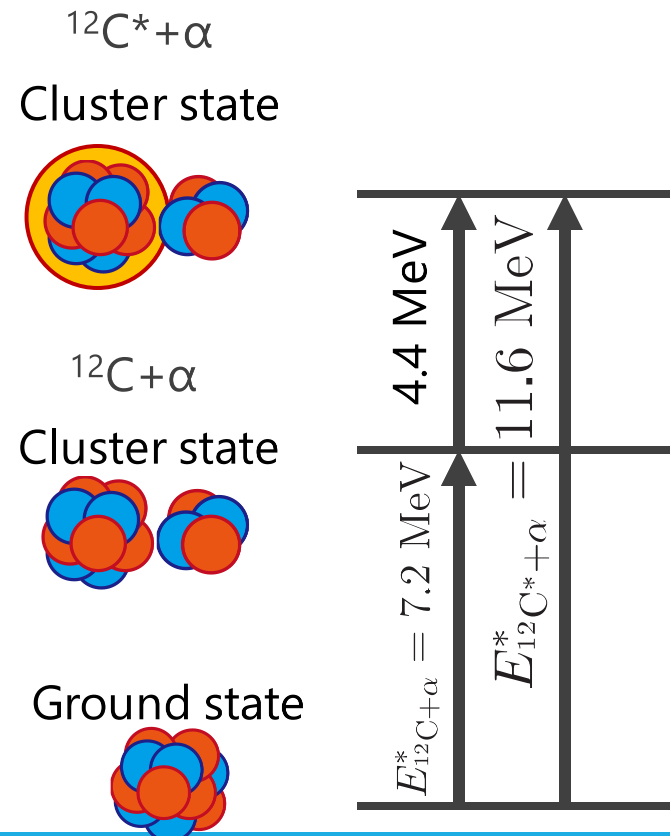
Clusters and threshold rule

An example: ^{16}O nucleus

◎ Consider ^{12}C*+α cluster state, in which ^{12}C cluster is excited to 2^+ state (4.4 MeV)

◎ ^{12}C*+α cluster state should exist at approximately 11.6MeV in the excited state of ^{16}O





Clusters and threshold rule

- An example: ^{16}O nucleus

◎ ^{12}C*+α cluster state should exist at approximately 11. 6MeV in the excited state of ^{16}O

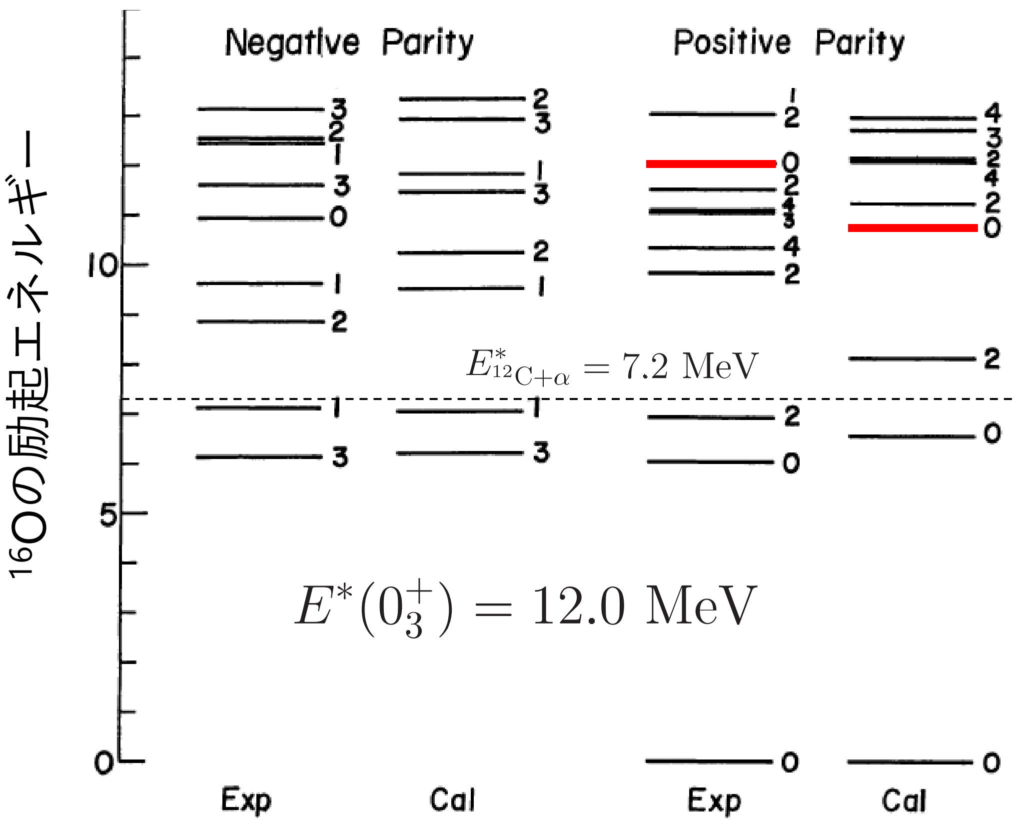
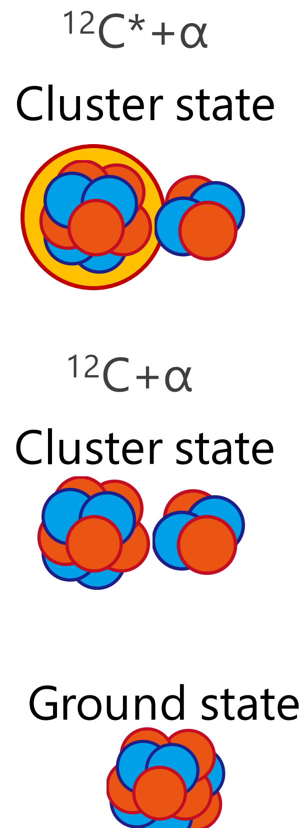
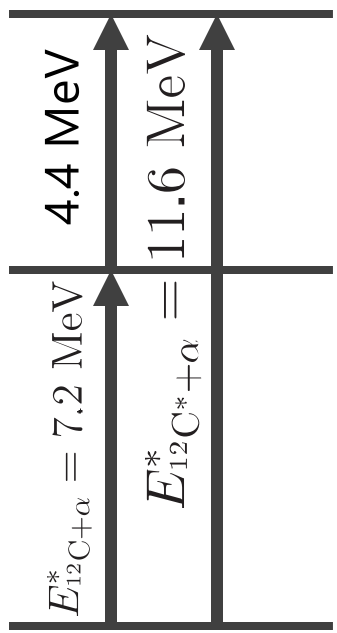


Fig. 3-3. $T=0$ energy spectrum in ^{16}O calculated by the ^{12}C+α orthogonality condition model.





Clusters and threshold rule

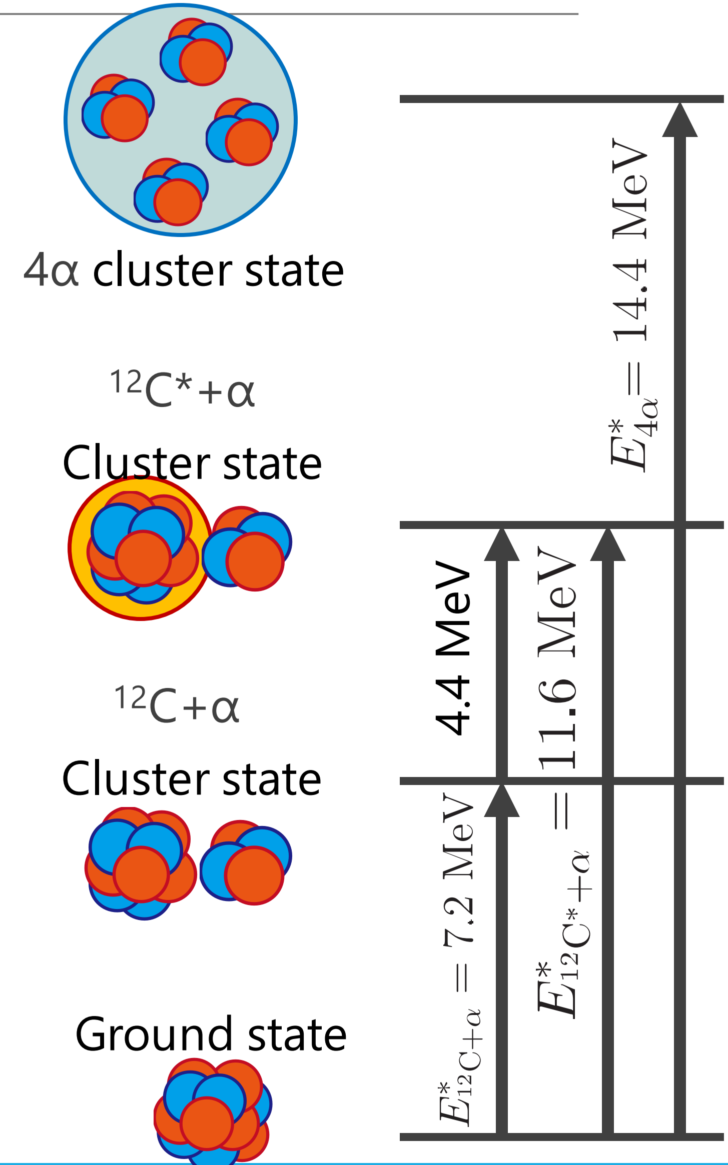
An example: ^{16}O nucleus

◎ Decompose ^{16}O into 4α clusters

$$
\begin{aligned}
E^*_{4\alpha} &\simeq 4E_\alpha - E_{^{16}\mathrm{O}(g.s.)} \\
&= -4 \times 28.3\ \mathrm{MeV} + 127.6\ \mathrm{MeV} \\
&= 14.4\ \mathrm{MeV}
\end{aligned}
$$

◎ 4α cluster state should exist at approximately 14. 4MeV in the excited state of ^{16}O

This state will be discussed later



Clusters and threshold rule

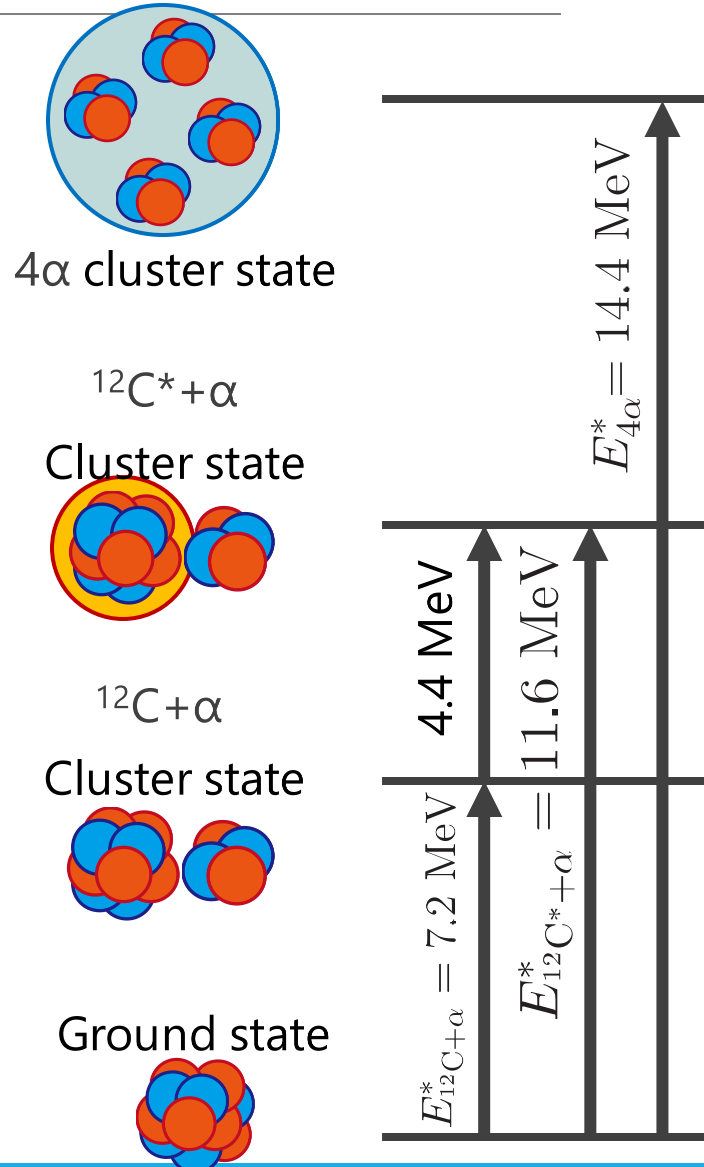
- We can extend this idea

◎ Cluster states will appear at the threshold which is equal to the energy required to decompose the system to clusters

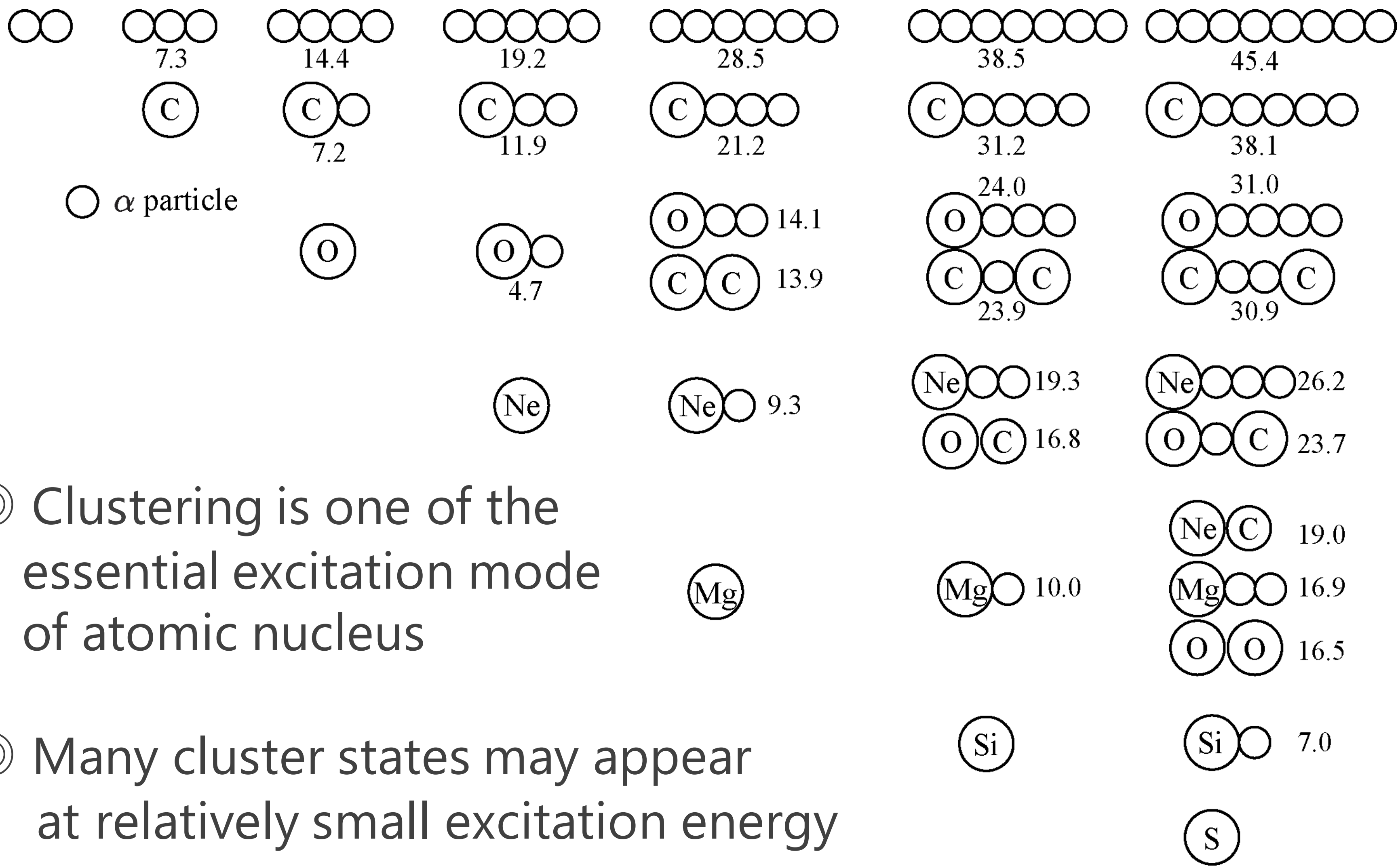
◎ As the excitation energy increases, various cluster states will appear

◎ Clustering should occur as function of the excitation energy

The so-called "Ikeda diagram" illustrates this idea



Ikeda Diagram



◎ Clustering is one of the essential excitation mode of atomic nucleus

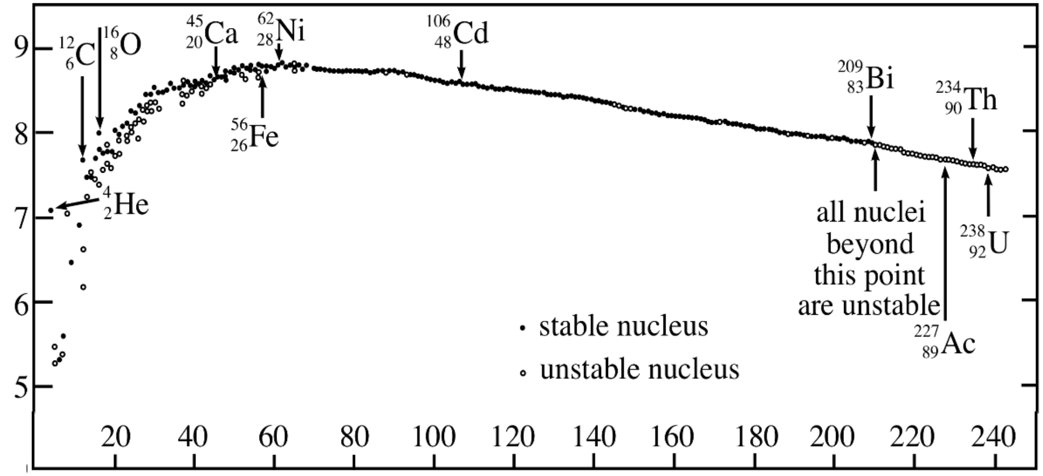
◎ Many cluster states may appear at relatively small excitation energy

Clustering and basic properties of nuclei

◎ Why many cluster states can appear at small excitation energy?
⇒ It is closely related to the basis properties of nuclei

Reason 1 Saturation of energy

「Binding energy is almost equal to 8MeV/A」



○ If the binding energy is exactly equal to 8MeV/A, all threshold energy is equal to 0 MeV

$$E^*_{cluster} = E_1 + E_2 - E_{g.s.} = 8A - 8C_1 - 8C_2 = 0 \quad (C_1 + C_2 = A$$

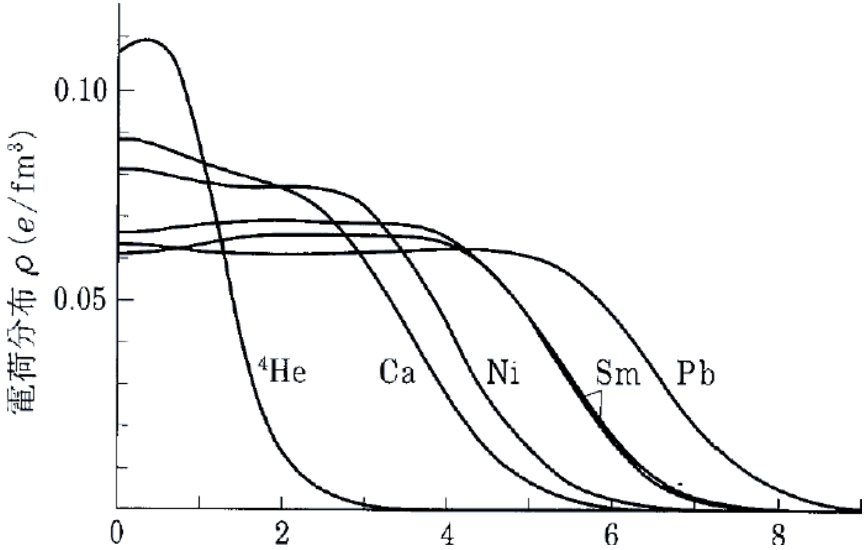
○ This also explains why are ^{4}He, ^{12}C, ^{16}O typical clusters

Clustering and basic properties of nuclei

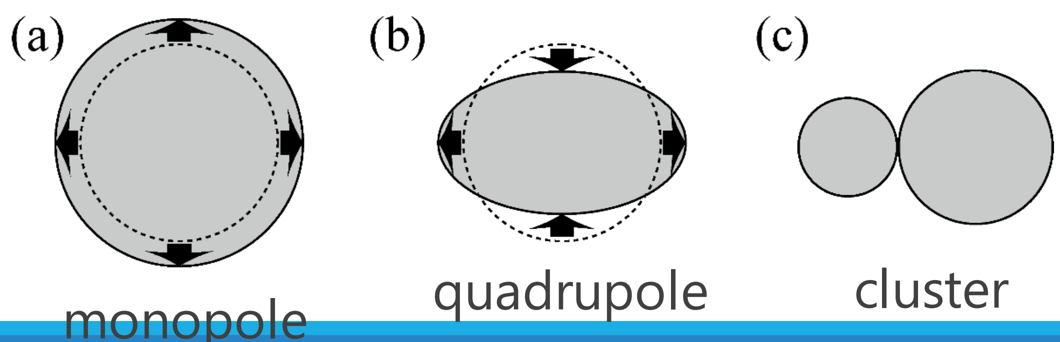
◎ Why many cluster states can appear at small excitation energy?
⇒ It is closely related to the basis properties of nuclei

Reason 2 Saturation of density

「Density is almost constant」
＝ 「Nucleus is incompressible」
＝ 「We need large energy
to change the density」



○ Excitation mode which changes the density requires large energy



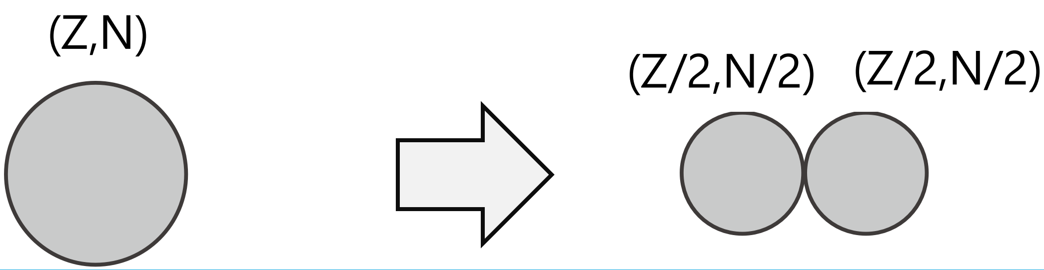
Clustering and basic properties of nuclei

Exercise 1

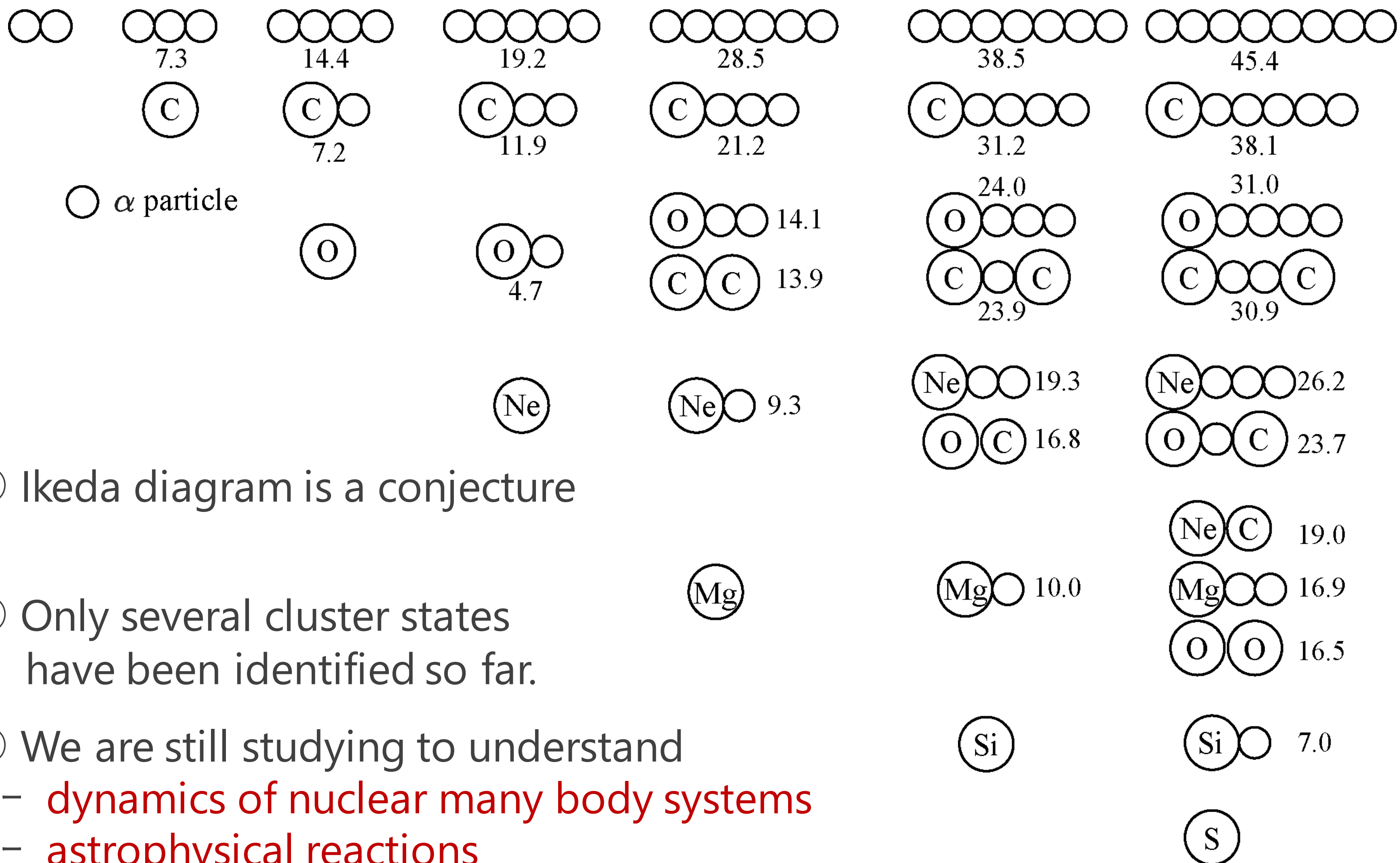
Using Bethe Weizsacker mass formula, estimate the energy difference between the spherical ground state and clustered state

- Assume that proton number equals to neutron number (N=Z)
- Assume a symmetric clustering
- Neglect the kinetic energy and potential between clusters

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(A-2Z)^2}{A}$$



Ikeda diagram

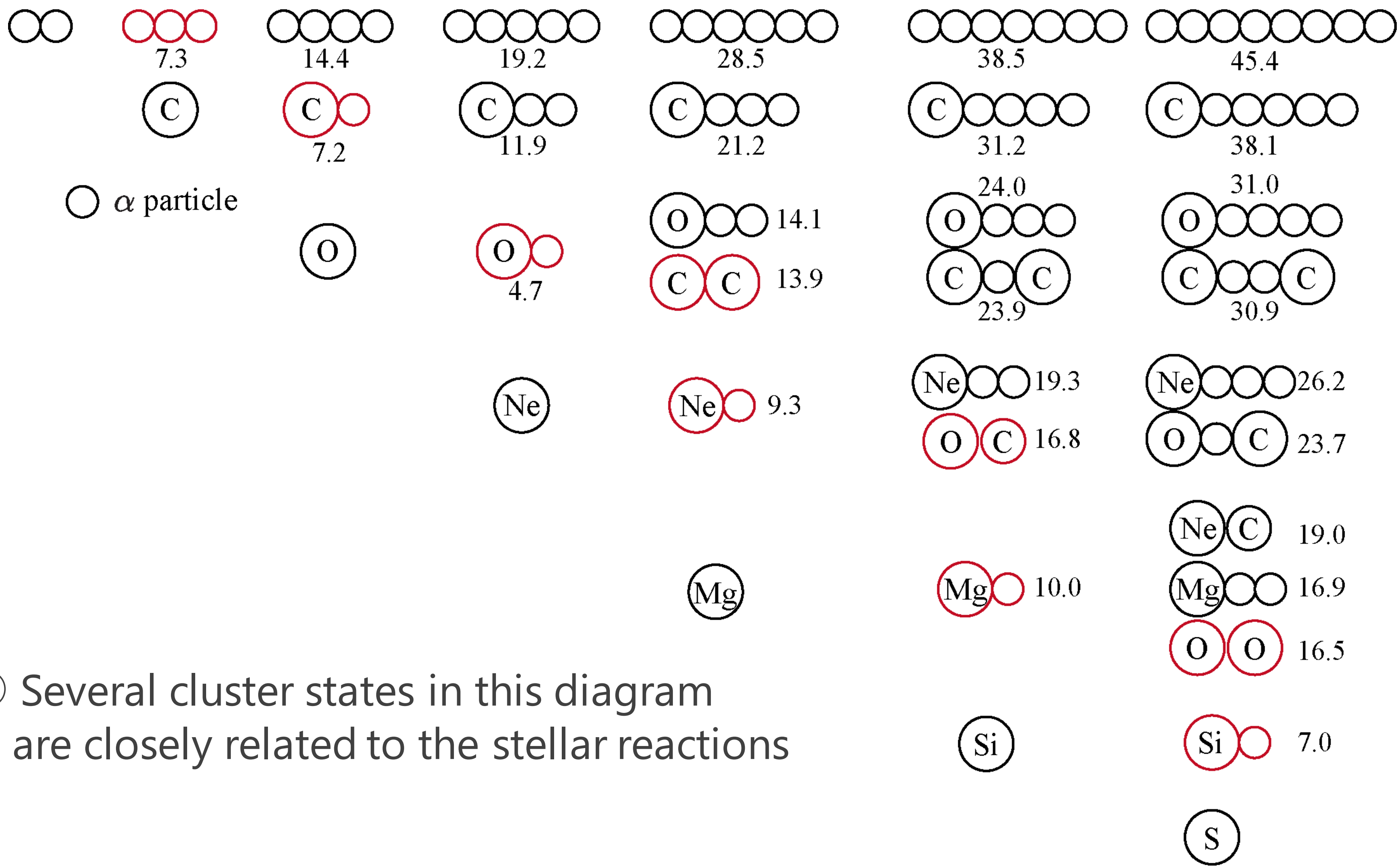


◎ Ikeda diagram is a conjecture

◎ Only several cluster states have been identified so far.

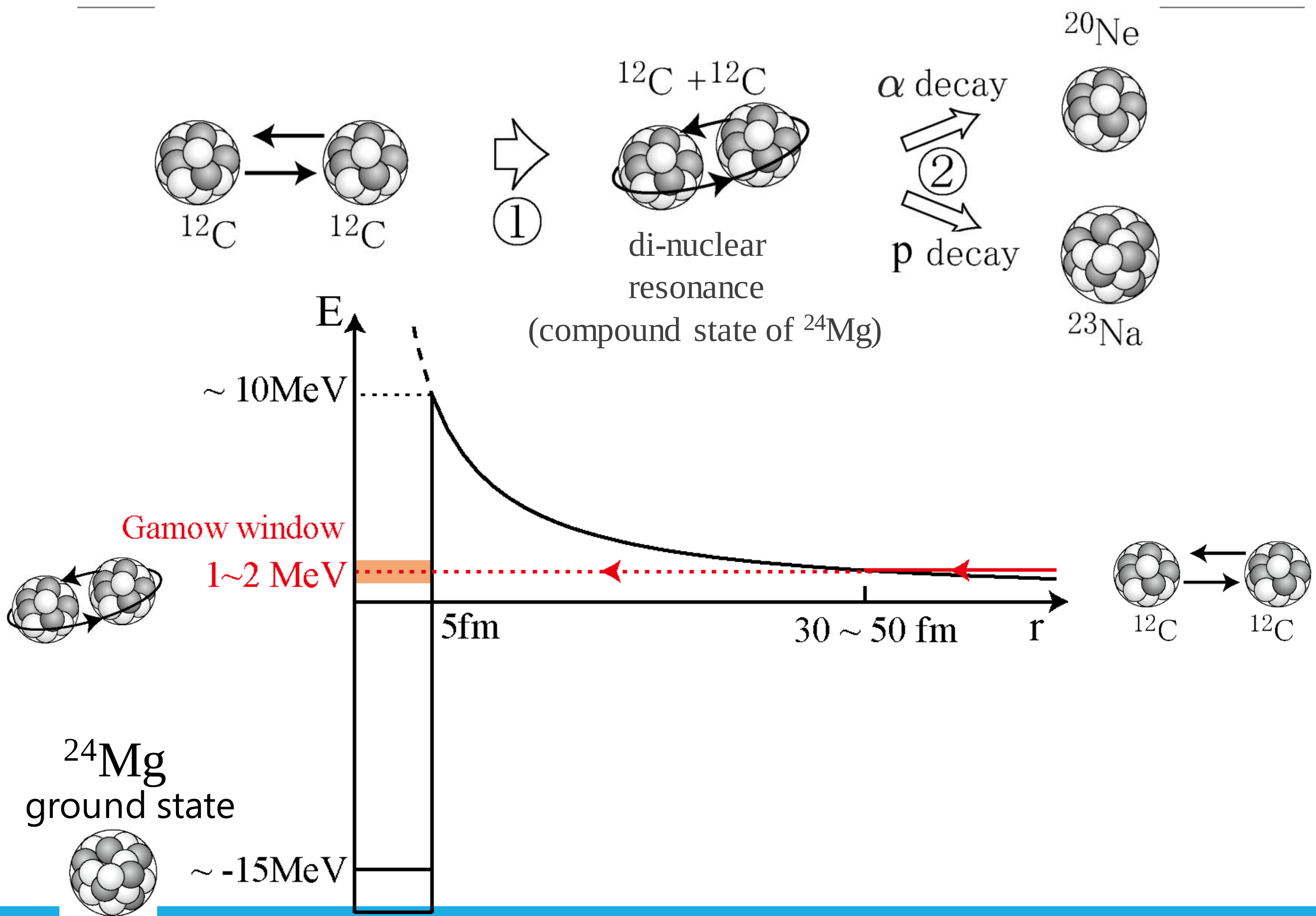
◎ We are still studying to understand
- dynamics of nuclear many body systems
- astrophysical reactions

Ikeda diagram and astrophysical reactions



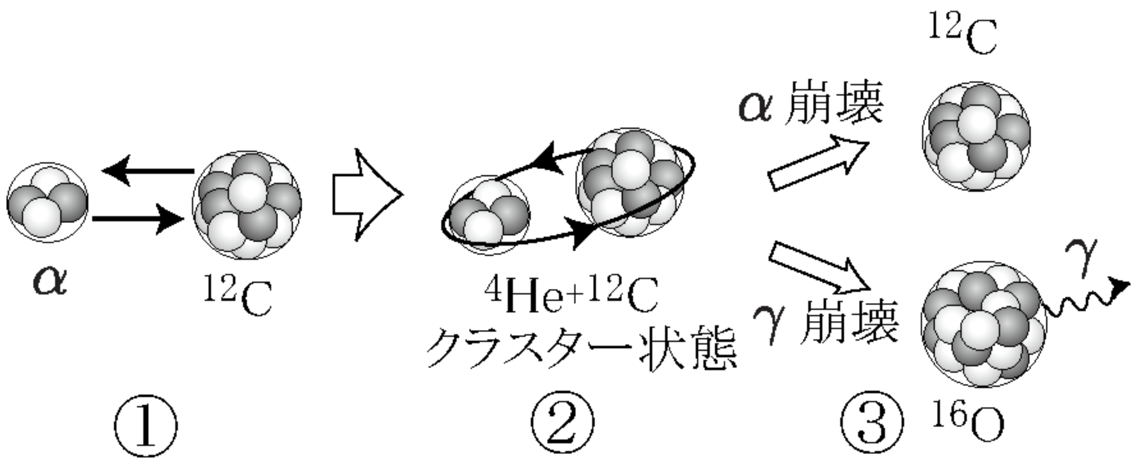
◎ Several cluster states in this diagram are closely related to the stellar reactions

Ikeda diagram and astrophysical reactions



Ikeda diagram and astrophysical reactions

- Fusion reactions occurs in the stars



① He collides other nucleus

② If the incident energy is equal to the energy of the cluster state (resonance), the reaction cross section increases in order of magnitude

③ In this case, the reaction products are determined by the decay mode of the cluster state (resonances)

◎ To understand the stellar reactions, we need to know the energy and decay mode of the cluster states (resonances)

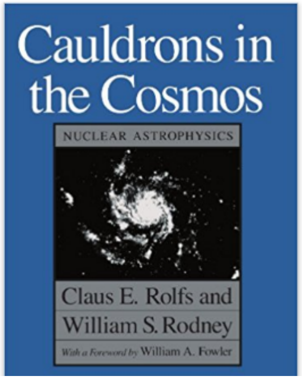
References（天体核反応）

Cauldrons in the Cosmos: Nuclear Astrophysics (Theoretical Astrophysics) 1st Edition

by Claus E. Rolfs (Author), William S. Rodney (Author)

2 customer reviews

Look inside



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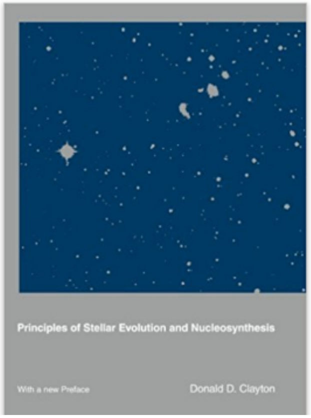

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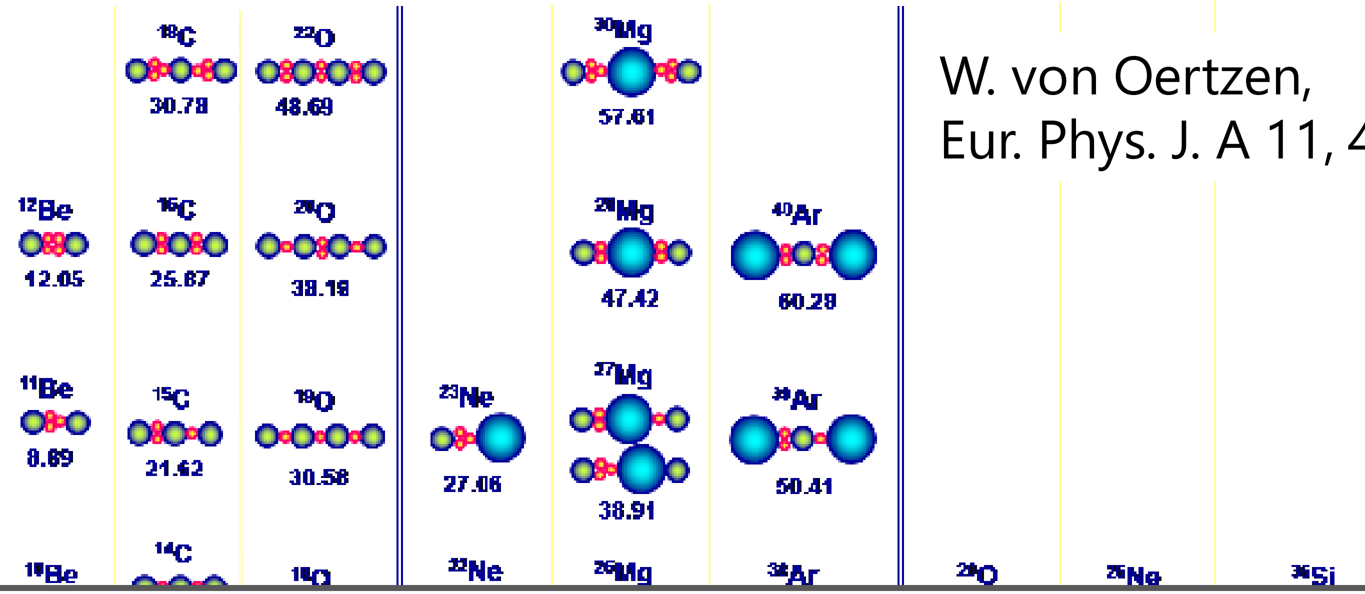
Extension of the Ikeda diagram

Extended Ikeda Diagram （+valence neutrons, N≠Z nuclei）



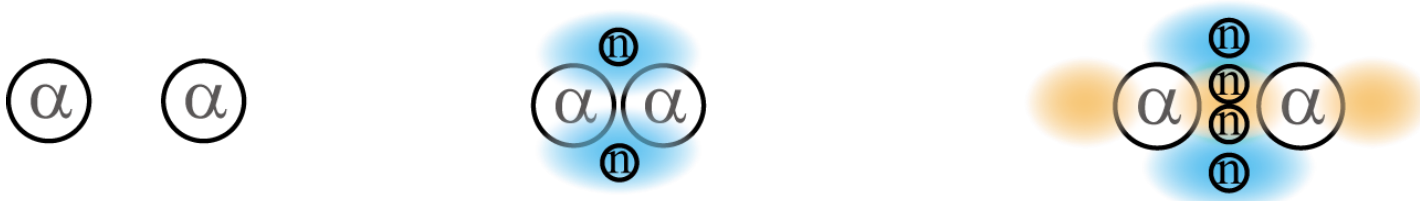
W. von Oertzen,
Eur. Phys. J. A 11, 403 (2001).

◎ Unstable nucleus have the cluster states different from the ordinary nuclei

◎ These novel type of clustering cannot be understood by the Ikeda diagram

Molecular states in Be isotopes

If we add neutrons to N=Z nucleus



^{8}Be unbound | ^{10}Be(^{8}Be+2n) bound | ^{12}Be(^{8}Be+4n) bound

◎ unbound 2 α clusters are bound by neutrons
⇒ valence neutrons plays a glue-like role to bound custers

◎ It is analogous to the covalent molecules (共有結合)

◎ This kind of novel types of clusters in neutron rich nuclei are intensively studied in these years.

Summary of Part 1

◎ What is cluster? What is cluster state

Cluster: A group of tightly bound nucleons

Cluster state: Nuclear state composed of clusters

◎ Ikeda diagram

Cluster state should appear at the threshold energy

◎ Ikeda diagram and stellar reactions

Cluster states increase the stellar reaction rate in order of magnitude

◎ Extension of Ikeda diagram

Novel type of cluster state appears in neutron rich nuclei. They are intensively studied in these years.

Appendix

A brief introduction to nuclear database

Self introduction

Masaaki Kimura（木村 真明）

A physicist for theoretical nuclear physics

- ◯ 2002 Ph. D at Kyoto U.
- ◯ 2003-2007 Post Doc. at RIKEN, Kyoto and Tsukuba
- ◯ 2008- Hokkaido U.
- ◯ 2017- Head of **nuclear data center** at Hokkaido U.

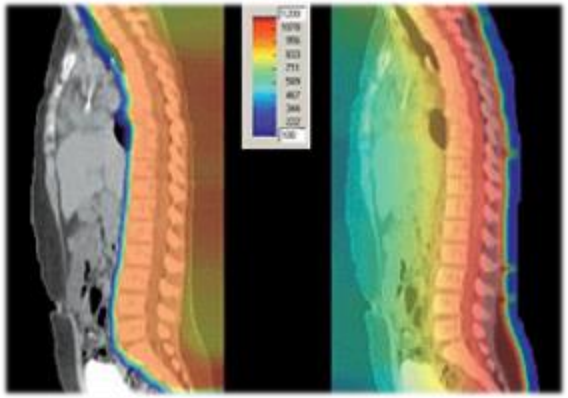
Research interests

- ◯ Structure of neutron-rich nuclei (magic #, n-halos)
- ◯ Nuclear clustering in stable and unstable nuclei, and related astrophysics
- ◯ Structure of hypernuclei

What is the **nuclear reaction database** ?

Multiuse of Nuclear Reactions (radio activities)

Energy



Medical treatment

Food

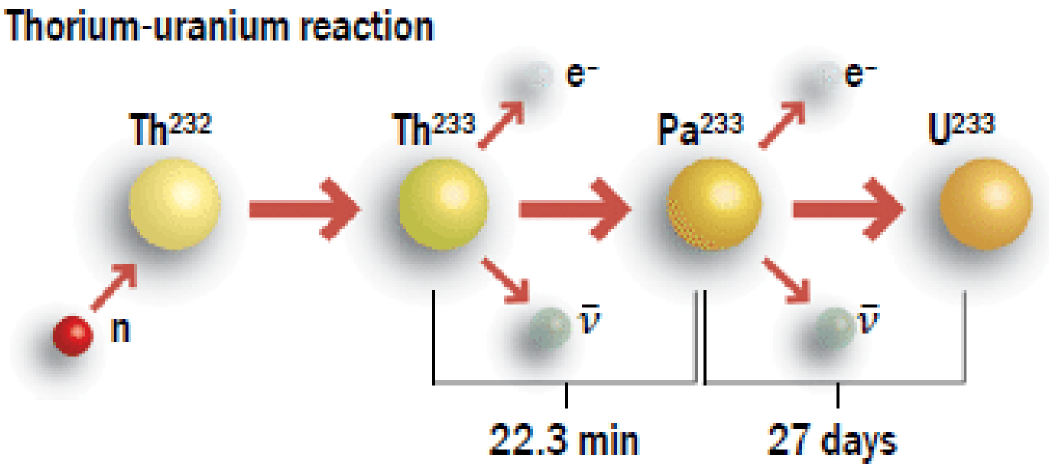
Industry

Academic research

What is the **nuclear reaction database** ?

Knowledge on the Nuclear Reactions is essential for multiuse of Nuclear Reactions

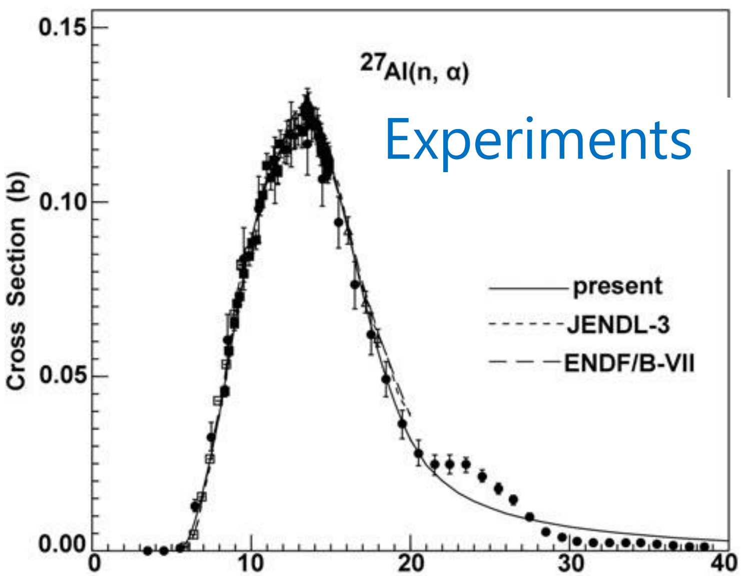
- ◯ How often Nuclear Reactions occur?
- ◯ What will be produced by the Nuclear Reactions?



Nuclear Reaction Data is the most fundamental part for the safety and effective use of Nuclear Reactions

What is the **nuclear reaction database** ?

Knowledge on the Nuclear Reactions is essential
for multiuse of Nuclear Reactions

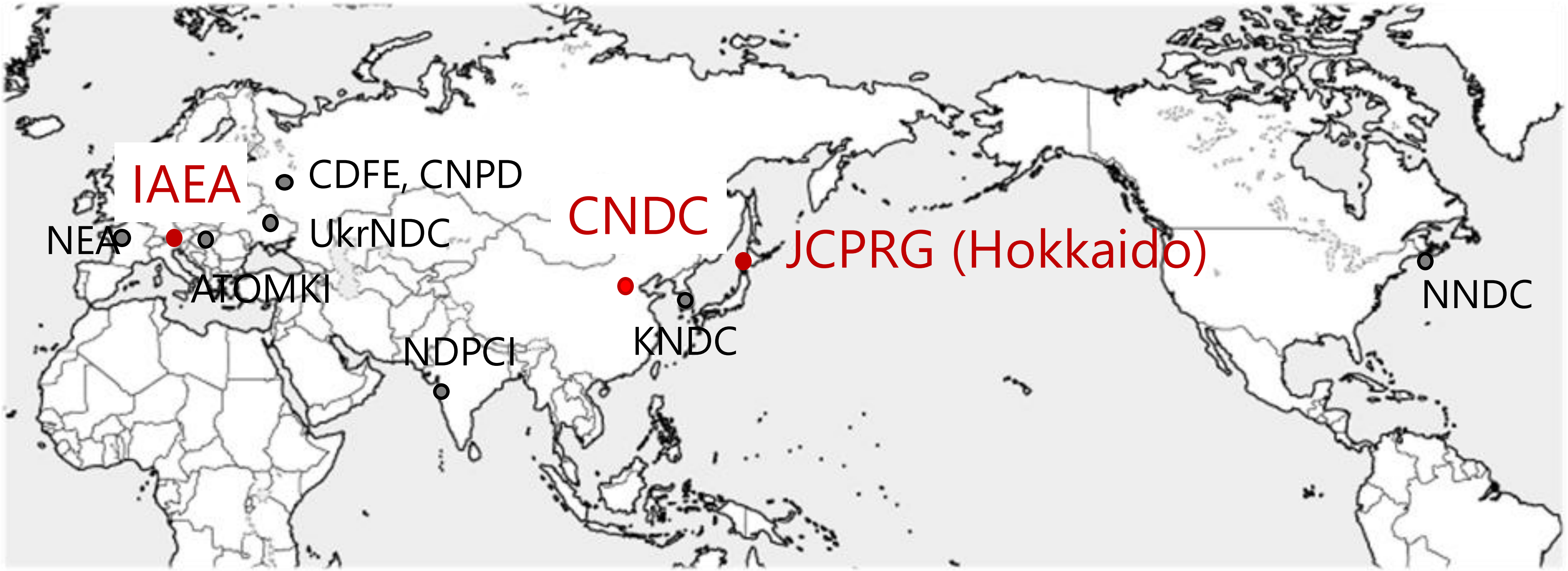


EXFOR; the database for
Nuclear Reactions

All experimental data are transformed into universal common database format called EXFOR, and stored

EXFOR: the database for Nuclear Reactions

EXFOR is developed and maintained
by the International Atomic Energy Agency (IAEA) and
Int. Network of Nuclear Reaction Data Centre (NRDC)



JCPRG is one of the centers of NRDC

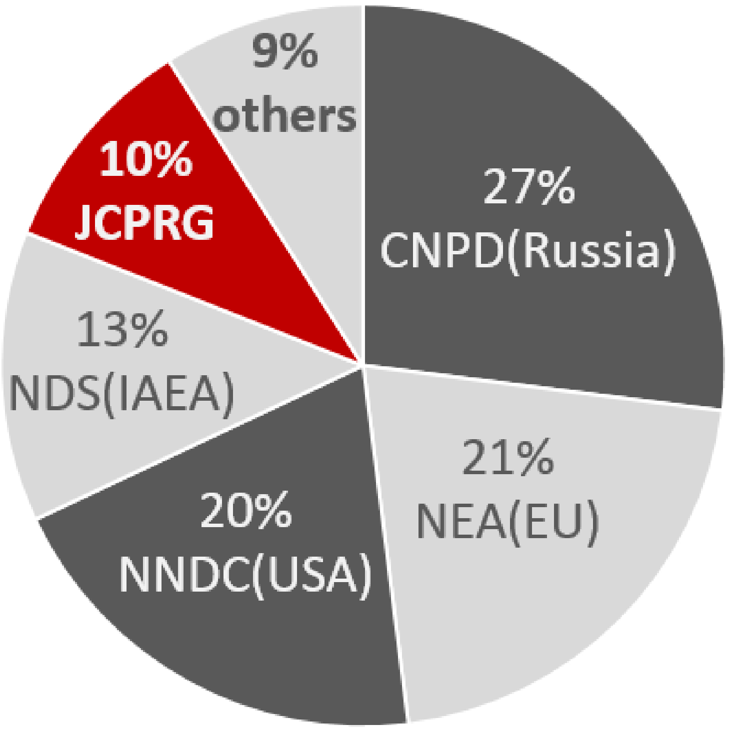
EXFOR: the database for Nuclear Reactions

Today, EXFOR includes approximately 22,000 experiments, 170,000 data sets, and 15,000,000 data points for 2,600 nuclear reactions.

We are compiling database for all experiments in Japan

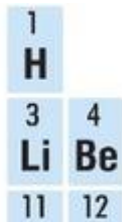
Our contribution to EXFOR reaches 10% of total entries.

(Chinese contribution is rapidly increasing (2%～))



EXFOR: the database for Nuclear Reactions

Finding of the new element “Ninohium”
by Prof. Morita



New Element #113, Nihonium

鉨

Journal of the Physical Society of Japan
Vol. 73, No. 10, October, 2004, pp. 2593–2596

Experiment on the Synthesis of Element 113 in the Reaction ^{209}Bi(^{70}Zn,n)^{278}113

Kosuke MORITA[1*], Kouji MORIMOTO[1], Daiya KAJI[1], Takahiro AKIYAMA[1,2], Sin-ichi GOTO[3], Hiromitsu HABA[1], Eiji IDEGUCHI[4], Rituparna KANUNGO[1], Kenji KATORI[1], Hiroyuki KOURA[5], Hisaaki KUDO[6], Tetsuya OHNISHI[1], Akira OZAWA[7], Toshimi SUDA[1], Keisuke SUEKI[7], HuShan XU[8], Takayuki YAMAGUCHI[2], Akira YONEDA[1], Atsushi YOSHIDA[1] and YuLiang ZHAO[9]

EXFOR: the database for Nuclear Reactions

The first paper for the Element 113th was also compiled by us.

(EXFOR entry E1920)

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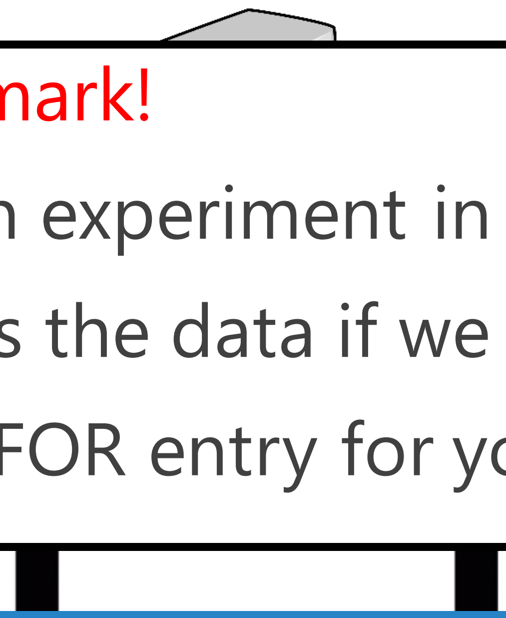
ENTRY            E1920   20180123                                 E192000000001
SUBENT        E1920001   20180123                                 E192000100001
BIB                 14         53                                 E192000100002
TITLE      Experiment on the synthesis of element 113 in the      E192000100003
           reaction 209Bi(70Zn,n)278-113                          E192000100004
AUTHOR     (K.Morita, K.Morimoto, D.Kaji, T.Akiyama, S.Goto,      E192000100005
            H.Haba, E.Ideguchi, R.Kanungo, K.Katori, H.Koura,     E192000100006
            H.Kudo, T.Ohnishi, A.Ozawa, T.Suda, K.Sueki, H.S.Xu,  E192000100007
            T.Yamaguchi, A.Yoneda, A.Yoshida, Y.L.Zhao)           E192000100008
INSTITUTE  (2JPNIPC)                                              E192000100009
           (2JPNSUU) Department of Physics                        E192000100010
           (2JPNNII) Center for Instrumental Analysis             E192000100011
           (2JPNTOK) Center for Nuclear Study                     E192000100012
           (2JPNJAE) Advanced Science Research Center             E192000100013
           (2JPNNII) Department of Chemistry                      E192000100014
           (2JPNTSU)                                              E192000100015
           (3CPRIMP)                                              E192000100016
           (3CPRIHP)                                              E192000100017
REFERENCE  (J,JPJ,73,(10),2593,200410)                            E192000100018
DECAY-DATA (113-NH-278,,A,11680.)                                 E192000100019
           Alpha decay (11.68+-0.04 MeV, 344 micro-sec) measured  E192000100020
           (111-RG-274,,A,11150.)                                 E192000100021
           Alpha decay (11.15+-0.07 MeV, 9.26 msec) measured      E192000100022
           (109-MT-270,,A,10030.)                                 E192000100023
           Alpha decay (10.03+-0.07 MeV, 7.16 msec) measured      E192000100024
           (107-BH-266,,A,9080.)                                  E192000100025
           Alpha decay (9.08+-0.04 MeV, 2.47 sec) measured        E192000100026

SUBENT        E1920002   20180123                                 E192000200001
BIB                  3          3                                 E192000200002
REACTION   (83-BI-209(30-ZN-70,N)113-NH-278,,SIG)                 E192000200003
STATUS     (TABLE) Taken from text, p2595 in reference            E192000200004
HISTORY    (20170925A) SE: SF4:113-*-278 -> 113-NH-278            E192000200005
ENDBIB               3          0                                 E192000200006
NOCOMMON             0          0                                 E192000200007
DATA                 4          1                                 E192000200008
EN         DATA       +ERR-S     -ERR-S                           E192000200009
MEV        FB         FB         FB                               E192000200010
      349.0       55. 150.        45.                             E192000200011
ENDDATA              3          0                                 E192000200012
ENDSUBENT           11          0                                 E192000299999
ENDENTRY             2          0                                 E192099999999
```

EXFOR: the database for Nuclear Reactions

EXFOR is an important bridge which links our academic research in the University and the social activities outside of University

EXFOR; the database for Nuclear Reactions



An important remark!

If you perform an experiment in Japanese facility, you must send us the data if we request.

We'll compile EXFOR entry for your experiment