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# Role of clusters in nuclear astrophysics with Cluster Nucleosynthesis Diagram (CND)

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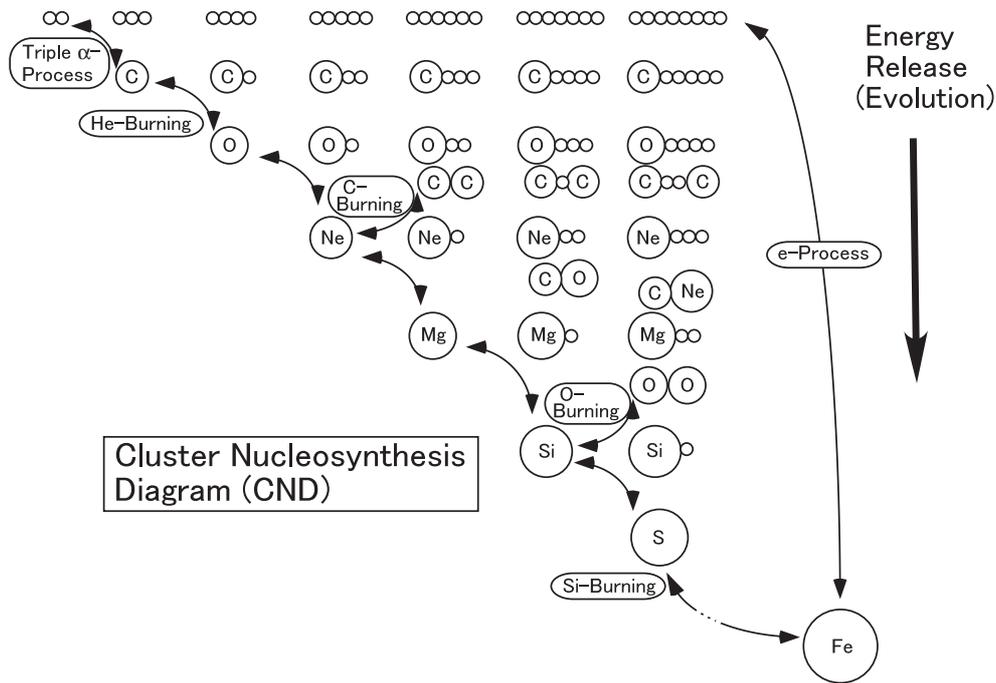
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**Abstract.** The role of nuclear clustering in stellar reactions is discussed, with Cluster Nucleosynthesis Diagram (CND) proposed before, for nucleosynthesis in stellar evolution and explosive stellar phenomena. Special emphasis is placed on  $\alpha$ -induced stellar reactions. We report here the first experimental evidence that  $\alpha$  cluster resonances dominate the ( $\alpha$ ,p) stellar reaction cross sections that is crucial for the  $\nu$ p-process in core-collapse supernovae.

## 1. Introduction

Nuclear processes play a crucial role in evolution of the universe as well as in various stellar phenomena. Especially, nuclear reactions lead to synthesis of almost all elements in our universe, and large energy generation which drives stars to evolve. Hydrogen burning is the main energy source and the burning takes place hydrostatically or explosively. After the hydrogen burning, the ashes of the hydrogen burning, helium, become the fuel for the next nuclear burning. Subsequently, carbon and oxygen burn to produce heavier elements, mostly Si. Along the stellar evolution, these lead to Si burning to produce the iron core in the middle of massive





**Figure 1.** Cluster Nucleosynthesis Diagram (CND) [2] for nucleosynthesis along the stellar evolution. Small circles indicate  $\alpha$ -clusters. The processes to go to lower levels imply energy releases.

stars. Thus, nucleosynthesis after hydrogen burning involves  $\alpha$ ,  $^{12}\text{C}$ , etc., which can be via the well-known, very interesting clusters in nuclei.

## 2. Cluster Nucleosynthesis Diagram (CND)

The successive nucleosynthetic processes after hydrogen burning can be summarized in Fig. 1 [1], where the smallest circles indicate alpha particles. As mentioned above, after hydrostatic hydrogen burning, the helium ashes become the fuel in the next stage, called helium burning. Subsequent burning processes involve C, O and Si as fuels.

Figure 1. depicts the idea of these nuclear burning processes in stars till the epoch of the iron-core formation. This idea also applies to other burning phenomena as well. This diagram was proposed in 1992 [2], to give a natural way of understanding the stellar nucleosynthesis. This is very much like the Ikeda diagram for cluster physics, but it includes the way of stellar evolution in terms of production of energies and elements. The most important point here is that this diagram is derived by physics point of view. Since the relevant scattering energy is small in stellar environments, resonances near the cluster threshold are crucial in nucleosynthesis. This is actually where one should expect states that have a large parentage of the cluster configuration from the cluster threshold rule.

The first step of the helium burning is the synthesis of  $^{12}\text{C}$  by capture of an  $\alpha$  particle on  $^8\text{Be}$  mainly through the Hoyle state in  $^{12}\text{C}$ . The second step is the  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$  reaction. Hydrostatic helium burning process is considered to terminate at this point. After the helium burning, the ashes of helium burning,  $^{12}\text{C}$  and  $^{16}\text{O}$ , become the fuel and lead to C and O burning, which go through the fusion reactions of  $^{12}\text{C} + ^{12}\text{C}$  and  $^{16}\text{O} + ^{16}\text{O}$ , respectively, at very low energies mainly emitting  $\alpha$  particles, together with subsequent  $\alpha$ -induced reactions on even-even sd-shell nuclei. Eventually, the silicon burning begins from  $^{28}\text{Si}$  with successive  $(\alpha,\gamma)$  and  $(\alpha,p)$  reactions

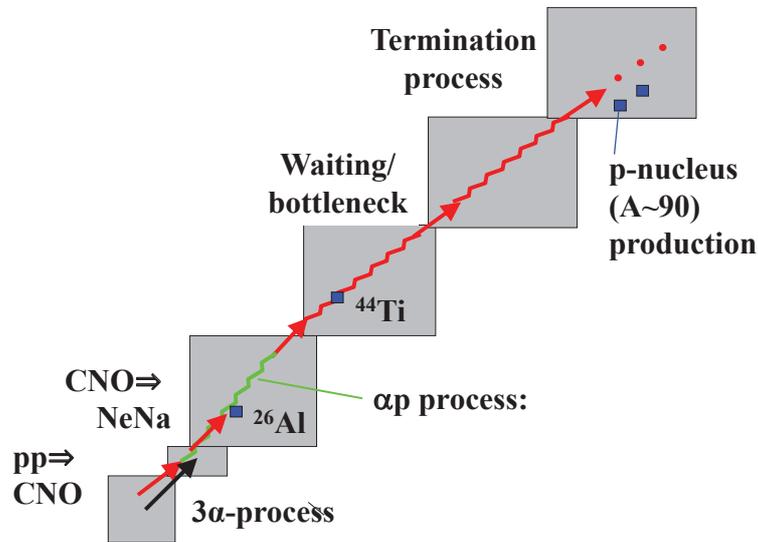


Figure 2. Sketch of the  $\nu p$ -process and the problems.

together with photo-disintegration of  $^{28}\text{Si}$ , etc. Here, an interesting observation is that in nuclear physics, one may add excitation energy to the nuclear system to see the evolution of clusters. For instance, in  $^{24}\text{Mg}$  there appears an  $\alpha$ -cluster state, then a  $2\alpha$ -cluster state or  $^{12}\text{C}+^{12}\text{C}$  molecular state, etc., whereas nucleosynthesis in nature goes in other way around. Nucleosynthesis here is a series of successive processes of crushing clusters to form a one-body system, gaining the difference in binding energies as thermal energy. Thus, the vertical axis in the figure should be regarded as the energy release during the progression of stellar evolution.

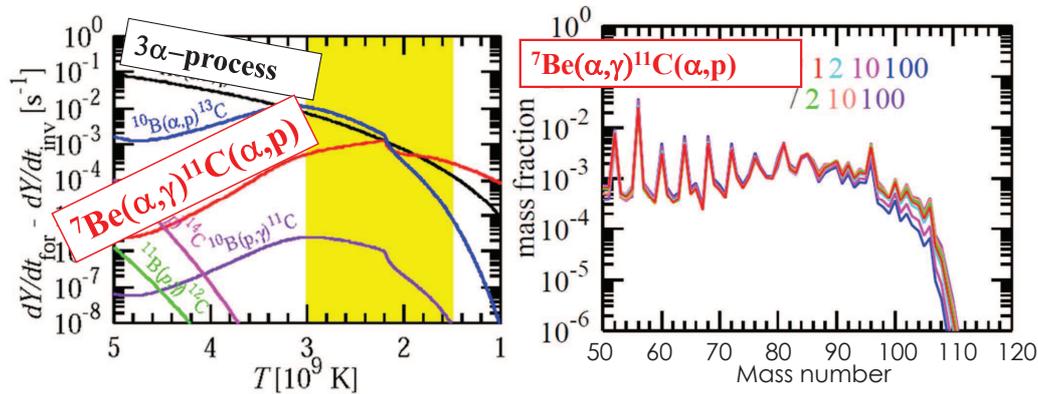
Here, the most important fact is that the CND diagram arises naturally from "the cluster threshold rule", as mentioned above. Namely, the rule says that there is a good chance that cluster states play an important role for nucleosynthesis. There have been many efforts for studying nuclear reactions of hydrogen burning, but not much for burning of helium, C and heavier clusters. Especially, the reactions that involve unstable nuclei for these reactions are very scarce. Since  $^4\text{He}$  is the second most abundant isotope, there are many environments where  $\alpha$  induced reactions play a role in the universe. They include  $(\alpha, \gamma)$ ,  $(\alpha, p)$  and  $(\alpha, n)$  reactions. Because of the charge of  $\alpha$  particle,  $\alpha$ -induced stellar reactions play usually a role at higher energies than proton induced reactions, but in the light mass regions.

In this talk, I will concentrate my discussion on  $\alpha$ -induced stellar reactions in the  $\nu p$ -process [3, 4, 5], which supposed to take place in the very early epoch in type II supernovae.

### 3. The $\nu p$ -Process in Type II Supernovae

We discuss here the role of  $\alpha$  clusterization in the  $\nu p$ -process [3, 4, 5] which is considered to be one of the challenging subjects for investigating the mechanism of type II supernovae, because it involves a variety of wide-range problems for nucleosynthesis.

The  $\nu p$ -process [3, 4, 5] was proposed in 2006 which would take place at the very early epoch of type II supernovae in the ejecta near the inner core due to the neutrino processes there. Here, it can be proton-rich, because of the high-intensity neutrino flux through the neutrino processes. This process also has been discussed as a source of p-nuclei near  $A=90$ , which have anomalously large isotopic abundances among the p-nuclei [6]. If the  $\nu p$ -process runs up to the mass 100 region, it will contribute to the p-nuclei productions. See Fig. 2.



**Figure 3.** Nuclear reaction rate sensitivities for heavy element synthesis in the  $\nu p$ -process [7].

Recently, we made analysis on the uncertainties among the  $\nu p$ -process extensively in ref. [7]. There are many unknown nuclear physics problems in the  $\nu p$ -process, which involves many proton capture reactions at extremely high temperatures, but very few of them are known yet. In addition, because the site has certain fractions of neutrons and alpha particles, the  $\nu p$ -process involves also neutron-induced reactions as well as alpha induced reactions, which will involve high-lying states of proton-rich unstable nuclei. The latter reactions would be relevant to  $\alpha$  cluster resonances and the former reactions giant resonances. An interesting consequence of neutron induced reactions will be discussed later in the last section.

Along the stellar evolution, nuclear burning around the  $N=Z$  line or proton rich side is important. At higher temperature and higher density condition of hydrogen and helium rich material,  $(\alpha, p)$  reactions dominate the burning process in the light mass regions, which is called the  $\alpha p$ -process. This process would play a crucial role in various stage of the evolution and phenomena. For instance, the  $^{14}\text{O}(\alpha, p)^{17}\text{F}$  [8] and  $^{18}\text{Ne}(\alpha, p)^{21}\text{Na}$  [9] reactions are important for ignition of X-ray bursts, which still await experimental investigation. Similarly,  $(\alpha, n)$  reactions play a crucial role in the early stage of the r-process in neutron-rich nuclear regions.

A detailed discussion on the nuclear reactions in the  $\nu p$ -process will be made in the following sections including recent experimental investigations on the alpha-induced stellar reaction relevant.

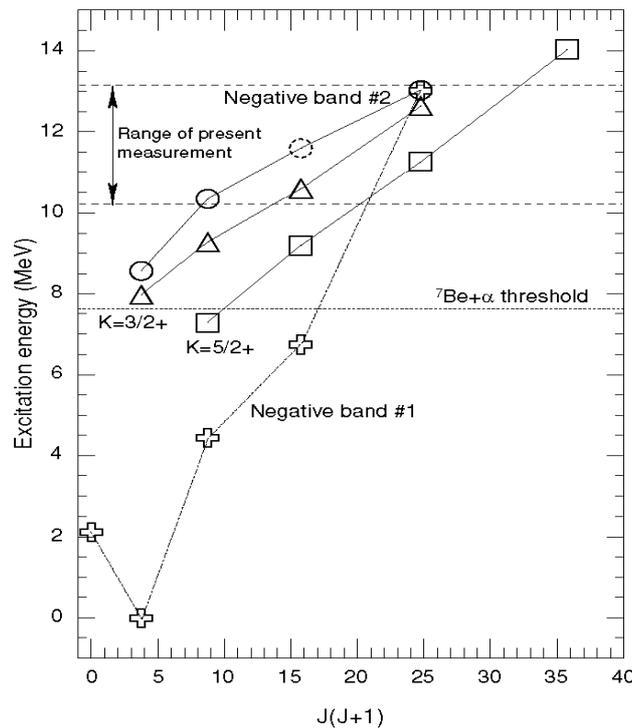
#### 4. $(\alpha, p)$ reactions in the $\nu p$ process

The  $\alpha$  induced reactions, especially the  $(\alpha, p)$  reactions play a crucial role in the  $\nu p$ -process like in the rp-process. At high-temperature and high-density sites, this type reaction will dominate and possibly bypass the waiting point of the nucleosynthesis flow and the breakout from one region to the next in the proton-rich mass region. However, the role of  $\alpha$  cluster states just above the  $\alpha$ -threshold are not studied yet, although we expect an important role of  $\alpha$  clusters there from the CND.

The  $(\alpha, p)$  reactions are of course favored in the proton-rich nuclear region because of the positive  $Q$  values. A resonant contribution to the reaction rate in the  $(\alpha, p)$  reaction can be written as follows;

$$\langle \sigma v \rangle \propto \frac{\Gamma_{\alpha} \Gamma_p}{\Gamma_{tot}},$$

where  $\Gamma_{\alpha}$ ,  $\Gamma_p$  are the  $\alpha$  and  $p$  decay widths of the resonance, respectively. Thus,  $\alpha$  resonant elastic scattering study is important together with the  $(\alpha, p)$  cross section measurement for the



**Figure 4.** A new rotational band of  $\alpha$  clusters observed by a thick target method of  ${}^4\text{He} + {}^7\text{Li}$  [15].

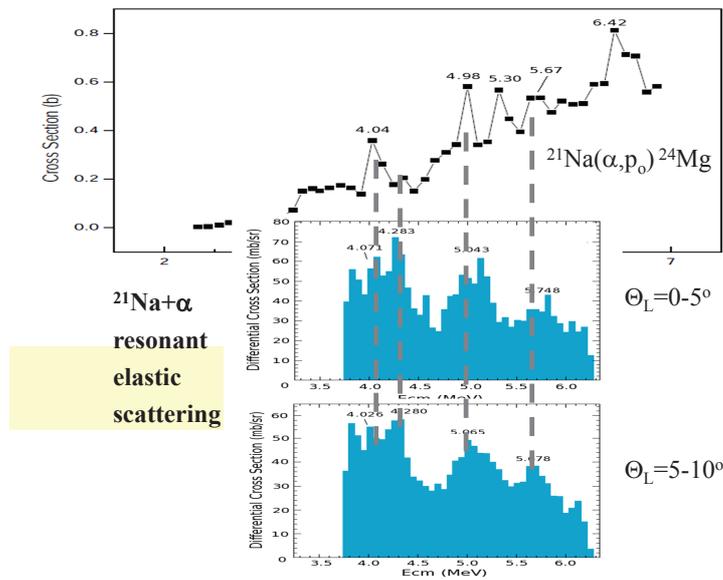
present study.

A series of experiments on  $(\alpha, p)$  reactions as well as resonant elastic scattering of  $(\alpha, \alpha)$  have been made at the low-energy RI beam facility, CRIB [10, 11], of Center for Nuclear Study, the University of Tokyo. This is a part of RIBF in RIKEN.

I will first discuss here the pathway from the pp-chain region to the CNO region. The main process for synthesis of CNO elements is considered to be the triple alpha process. However, in addition,  $\alpha$ -induced reactions on proton-rich nuclei would have led to synthesis of CNO elements. These reactions are not known well and thus need to be investigated experimentally. There are possible three major side flows that reach CNO elements,  ${}^7\text{Be}(p, \gamma){}^8\text{B}(p, \gamma){}^9\text{C}(\alpha, p){}^{12}\text{N}$ ,  ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}(\alpha, p){}^{14}\text{N}$ , and  ${}^7\text{Be}(\alpha, p){}^{10}\text{B}(\alpha, p){}^{13}\text{C}$ .

The  ${}^7\text{Be} + \alpha$  and  ${}^7\text{Li} + \alpha$  resonant elastic scattering was studied recently by a thick target method [12, 13] in order to learn the entrance channel of  ${}^7\text{Be} + \alpha$  for these reaction chains. Here, an intense  ${}^7\text{Be}$  beam [14] was obtained at CRIB. Some new resonances were identified in the  ${}^7\text{Li} + \alpha$  scattering [15], suggesting a rotational band which could have a cluster structure of  $2\alpha + t$ . See Fig. 4. Similar results are expected to be seen in the study of  ${}^7\text{Be} + \alpha$ , which will be published soon.

One of the crucial branching points for the breakout from the pp-chain region should be the nucleus  ${}^{11}\text{C}$ , where the three processes are competing;  ${}^{11}\text{C}(\alpha, p){}^{14}\text{N}$ ,  ${}^{11}\text{C}(p, \gamma){}^{12}\text{N}$  and the beta decay to  ${}^{11}\text{B}$ . The least known process among them was the  ${}^{11}\text{C}(\alpha, p){}^{14}\text{N}$  reaction, which was investigated previously only by the time reverse reaction with an activation method [16]. Recently, a successful experiment was performed for the first time using a low-energy, high intensity  ${}^{11}\text{C}$  beam at CRIB [17]. The cross sections were measured at  $E_{cm} = 1.0 \sim 4.5$  MeV, which covers an effective temperature range of  $T = 1 - 5 \times 10^9$  K. The  ${}^{11}\text{C}(\alpha, p){}^{14}\text{N}$



**Figure 5.**  $\alpha$  resonances observed in the thick target experiment of  $^4\text{He} + ^{21}\text{Na}$  [19], compared with the  $^{21}\text{Na}(\alpha, p_0)^{24}\text{Mg}$  reaction cross sections measured by the time reverse process [20].

reaction for the low-lying excited states in  $^{14}\text{N}$  were also successfully observed [17], but with a large uncertainty at the lowest energy. This experiment now provides reliable reaction rate at the temperature range for the  $\nu p$ -process. The experiment also has confirmed the previous data of  $^{11}\text{C}(\alpha, p_0)^{14}\text{N}(\text{g.s.})$  by the activation method. The observed excitation functions of the  $^{11}\text{C}(\alpha, p)^{14}\text{N}$  cross sections were characterized by individual resonances, especially those with large  $\alpha$  widths, and considerably deviate from the statistical model calculations. The experimental cross sections of the  $^{11}\text{C}(\alpha, p_1)^{14}\text{N}$  reaction are also smaller than the statistical model prediction roughly by a factor of two. The present results demonstrate that one should study directly the  $(\alpha, p)$  reaction cross sections identifying each level in these low mass regions.

After production of CNO elements in the  $\alpha p$ -process, the next step of the nucleosynthesis is a flow out from the CNO region to the heavier element region. The first half of the sd shell nuclear region is of great interest because of the observation of nuclear gamma rays from long-lived nuclei  $^{26}\text{Al}$  and  $^{22}\text{Na}$  [18].

A successful experimental result was obtained recently in a study of the  $^{21}\text{Na}(\alpha, p)$  stellar reaction [19], which was suggested to play an important role in the  $\alpha p$ -process [7]. A  $^{21}\text{Na}$  beam was obtained from the CRIB separator. As can be seen in Fig. 5, the four prominent peaks appear to correspond to the peaks in the excitation function of the  $^{21}\text{Na}(\alpha, p)^{24}\text{Mg}$  reaction, which was measured by the time reverse reaction using an activation method [20], although the correspondences are not perfect in detail. The R-matrix analysis revealed that all these resonances have quite large  $\alpha$  widths which exhausted large fractions of the Wigner limits. This result implies that  $\alpha$ -resonances have a major role for the  $^{21}\text{Na}(\alpha, p)$  reaction rate, as expected by the CND [2]. We also have succeeded to measure directly the cross sections of  $^{21}\text{Na}(\alpha, p)^{24}\text{Mg}$ , which show much larger cross sections than those obtained by the activation method [20].

## 5. Scope

The Cluster Nucleosynthesis Diagram (CND), introduced before [1], was re-discussed here in order to emphasize importance of nuclear clusterization for nucleosynthesis in the universe. It gives a natural way of understanding of the evolution of nucleosynthesis and also suggests

interesting stellar reactions which need to be investigated in nuclear astrophysics.

Specifically, we discussed here the role of alpha clusters for the  $\alpha p$ -process, which use low-energy RI beams from the CRIB facility. Especially, our main efforts have been placed for the moment on  $(\alpha, p)$  stellar reactions which set in under high-temperature and high-density hydrogen burning conditions. A crucial role of  $\alpha$  resonances to the  $(\alpha, p)$  stellar reactions has been demonstrated experimentally for the first time, as suggested by the CND.

In this talk, the  $(\alpha, p)$  stellar reactions on proton-rich unstable nuclei were mainly discussed. However, there are other interesting nuclear physics problems in order to understand fully the mechanism of type II supernovae. Since there are significant amount of neutrons in the environment of the  $\nu p$ -process, neutron induced reactions on proton-rich unstable nuclei are of great interest and challenging. The  $(n, p)$  and  $(n, \gamma)$  reactions would accelerate the nucleosynthesis flow at the waiting point nuclei of ordinary hydrogen burning, which will eventually affect greatly the production rate of heavy nuclei at around mass 100 [5]. A sensitivity test of the  $^{56}\text{Ni}(n, p)$  rate indicates quite large effect to the yields of the nuclei there. Here, the  $n$ -induced reactions involve high-lying states of unstable neutron-deficient nuclei, which are totally unknown yet. They are treated by the Hauser-Feshbach model together with E1 giant resonances. Recent theoretical works on giant resonances for wide-range unstable nuclei would improve the estimate for the rate. This subject is very important but it is one of the toughest challenges for nuclear astrophysics experiments. One possibility would be the Trojan Horse Method with proton-rich beams.

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