

Alpha-Cluster Dominance in the α p Process in Explosive Hydrogen Burning

Shigeru KUBONO,¹ N. Binh DAM,² S. HAYAKAWA,¹ H. HASHIMOTO,¹ D. KAHL,¹
H. YAMAGUCHI,¹ Y. WAKABAYASHI,³ T. TERANISHI,⁴ N. IWASA,⁵
T. KOMATSUBARA,⁶ S. KATO,⁷ A. CHEN,⁸ S. CHERUBINI,⁹ S. H. CHOI,¹⁰
I. S. HAHN,¹¹ J. J. HE,¹² Hong Khiem LE,² C. S. LEE,¹³ Y. K. KWON,¹³
S. WANAJO¹⁴ and H.-T. JANKA¹⁴

¹*Center for Nuclear Study, University of Tokyo, Wako 351-0198, Japan*

²*Institute of Physics, VAST, Hanoi, Vietnam*

³*Japan Atomic Energy Agency, Tokai, Ibaraki 351-1195, Japan*

⁴*Department of Physics, Kyushu University, Fukuoka 812-8581, Japan*

⁵*Department of Physics, Tohoku University, Sendai 980-8578, Japan*

⁶*Department of Physics, Tsukuba University, Tsukuba 305-8571, Japan*

⁷*Faculty of Science, Yamagata University, Yamagata 990-8560, Japan*

⁸*Department of Physics, University of McMaster, Canada*

⁹*Universita di Catania and INFN-LNS, Catania, Italy*

¹⁰*Department of Physics, Seoul National University, Seoul, Korea*

¹¹*Ewha Womans' University, Seoul, Korea*

¹²*Institute of Modern Physics, Lanzhou, China*

¹³*Department of Physics, Chung Ang University, Seoul, Korea*

¹⁴*Max-Planck-Institut für Astrophysik, D-85748 Garching, Germany*

Nucleosynthesis by alpha particles and heavier 4n nuclei are of great interest as they would involve nuclear cluster resonances. The role of nuclear clustering is discussed for nucleosynthesis with the Cluster Nucleosynthesis Diagram (CND) proposed before, especially those involving alpha induced reactions, based on our recent works of (α ,p) reactions with low energy RI beams. We present experimental results that alpha resonances play a crucial role for the (α ,p) reaction cross sections. Molecular resonances are also briefly discussed along this line for O- and C-burning.

§1. Cluster nucleosynthesis diagram (CND)

Nuclear reactions play a key role for the evolution of stars in terms of production of large energies as well as new elements. 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 until the iron core formation.¹⁾ Figure 1 depicts the idea of these nuclear burning processes in stars from the He burning stage till the epoch of the iron-core formation.

This diagram was proposed, to give a natural way of understanding the stellar nucleosynthesis.^{2),3)} 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 from physics point of view. Since the relevant energy of nucleosynthesis is small, resonances near

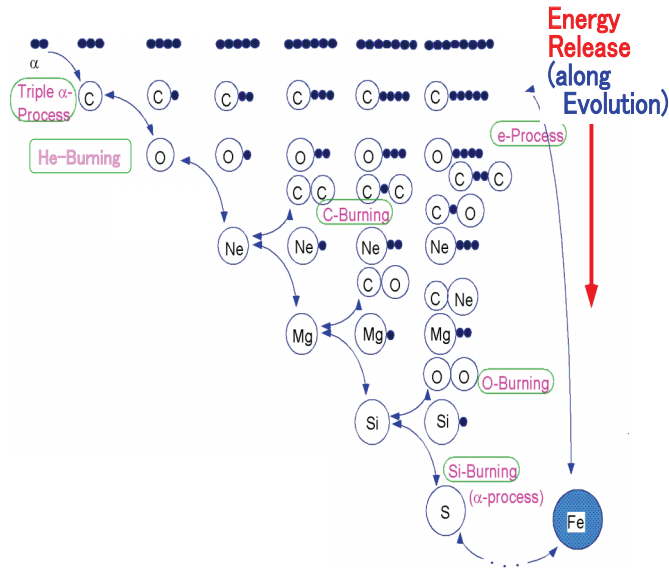


Fig. 1. Cluster Nucleosynthesis Diagram (CND)^{2),3)} for nucleosynthesis along stellar evolution. The small closed circles indicate α particles. The processes going to lower levels imply energy generation.

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 helium burning is the synthesis of ^{12}C by capture of an α particle on ^8Be through α -cluster states in ^{12}C . The second step is the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction. After the helium burning, the ashes of helium burning, ^{12}C and ^{16}O , become the fuel and lead to C- and O-burning, which largely go through the fusion reactions emitting α particles, together with subsequent α -induced reactions on even-even sd-shell nuclei. Eventually, silicon burning begins from ^{28}Si with successive (α, γ) and (α, p) reactions together with photo-disintegration of ^{28}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}Mg there appears an α -cluster state first, then a 2α -cluster state or $^{12}\text{C}+^{12}\text{C}$ molecular state, etc. as one goes upward in Fig. 1, 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^{2),3)} arises naturally from the cluster threshold rule that has been long recognized and has been an important guide-line for finding cluster states in nuclei. Namely, the rule says that one may find cluster states near the cluster threshold. In nucleosynthesis, the scattering energies are small, and thus states near the threshold influence the rate of the nucleosynthesis. This means that

there is a good chance that cluster states play an important role for synthesis. For instance, α -cluster states would appear close to the α -threshold and have a possibility to play a significant role for nucleosynthesis.

§2. The α p-process in explosive hydrogen burning

Since ${}^4\text{He}$ is the second most abundant isotope, there are many environments where α induced reactions play an important role in the universe. They include (α, γ) , (α, p) and (α, n) reactions. Because of the charge of α particle, α -induced stellar reactions play a role at higher energies than ordinary proton induced reactions.

In general, the (α, p) reactions play an important role in high-temperature hydrogen burning process in X-ray bursts, for instance. The (α, p) reactions on ${}^{14}\text{O}^{(4,5)}$ and ${}^{18}\text{Ne}$ are the crucial breakout reactions from the CNO region yet to be investigated well. Many other (α, p) reactions also will set in this mass region. Other (α, p) reactions on the waiting point nuclei like ${}^{22}\text{Mg}$ and ${}^{30}\text{S}$ are of great interest. The ${}^{21}\text{Na}(\alpha, p)$ reaction is also crucial for the problem of nuclear gamma ray observations of ${}^{22}\text{Na}$ and ${}^{44}\text{Ti}^{(14), (15)}$ which will be discussed in the next section.

These (α, p) reactions are of course favored in the proton-rich nuclear region because of the positive Q values, as shown in Fig. 2. A resonant contribution to the reaction rate of an (α, p) reaction can be written as follows:

$$\langle \sigma v \rangle \propto \frac{\Gamma_\alpha \Gamma_p}{\Gamma_{\text{total}}}, \quad (2.1)$$

where Γ_p and Γ_α are the proton and alpha decay widths of the resonance, respectively. This implies that one may estimate the (α, p) reaction rate by knowing the widths of α and p decays of the resonance. Thus, α resonant elastic scattering study is important for the (α, p) reaction rate. Of course, α -cluster structure is also interesting for nuclear physics in proton-rich unstable nuclear region, especially near and above the α -threshold because of the cluster threshold rule,^{(2), (3)} which is also a frontier subject in nuclear physics. Since resonance energies are not large even in the νp -process environment, Γ_α cannot be so large, whereas the proton width can be larger,

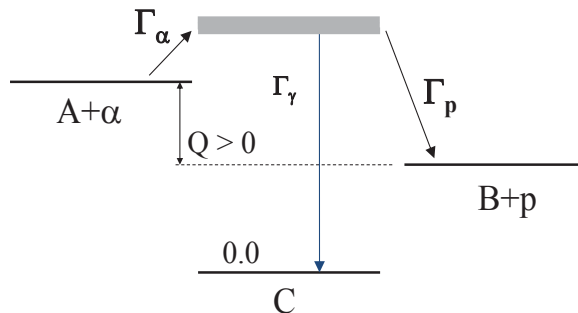


Fig. 2. $A(\alpha, p)B$ stellar reaction in the proton-rich nuclear regions.

because the proton threshold is much lower in energy. Therefore, large (α, p) cross sections can be obtained when Γ_α is not small.

Another interesting mass region that (α, p) reactions will play a crucial role is breakout path from the pp-chain region to the CNO region. Specifically, this bridge will be crucial in the νp -process environment,^{7)–10)} where the main process for synthesis of CNO elements is considered to be the triple alpha process. However, α -induced reactions on proton-rich nuclei would also contribute to synthesize CNO elements significantly. These reactions are not known well and need to be investigated experimentally. This subject should be important in relevance to the νp -process,¹⁰⁾ because it takes place at extremely high temperature and high density condition at the very early epoch of type II supernovae due to the neutrino process. This process is very much like the rp-process. Here, nuclear burning around the $N = Z$ line are important.

§3. Experimental approach to the αp -process

There are very few stellar (α, p) reactions investigated well yet in the proton-rich nuclear region. A series of experiments on (α, p) reactions has been made at the low-energy RI beam facility, CRIB,^{11), 12)} of Center for Nuclear Study, the University of Tokyo. We will discuss two experimental results of the (α, p) reactions. The first one is the $^{11}\text{C}(\alpha, p)^{14}\text{N}$ reaction, which is one of the possible crucial breakout reactions from the pp-chain region to the CNO region in the νp -process, but it was not known well before. This path is considered to be an important side flow in addition to the triple-alpha process.

The nucleosynthesis flow of the pp-chain at extremely high temperature comes to nucleus ^{11}C , where three destruction 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}B . The least known process was $^{11}\text{C}(\alpha, p)^{14}\text{N}$ reaction, which was investigated previously only by the time reverse reaction with an activation method.

Recently, a successful experiment was performed for the first time using a low-energy, high intensity beam of ^{11}C at CRIB. 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 $^{11}\text{C}(\alpha, p)^{14}\text{N}$ reaction for the low-lying excited states in ^{14}N were also successfully observed for the first time,¹³⁾ but with a large uncertainty at the lowest energy. This experiment now provides much reliable reaction rate at the temperature range for the αp -process. The experiment also has confirmed the previous data of $^{11}\text{C}(\alpha, p_0)^{14}\text{N}$ 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, which cannot be explained by a statistical model calculation. The experimental cross sections of the $^{11}\text{C}(\alpha, p_1)$ reaction are smaller than the statistical model prediction roughly by a factor of two, whereas those of $^{11}\text{C}(\alpha, p_2)$ larger than the statistical model by a factor of two. The present results demonstrate that one needs to study directly the (α, p) reaction cross sections identifying each level in these low mass regions. Most peaks in the excitation functions observed are characterized by resonances that have large alpha widths, indicating

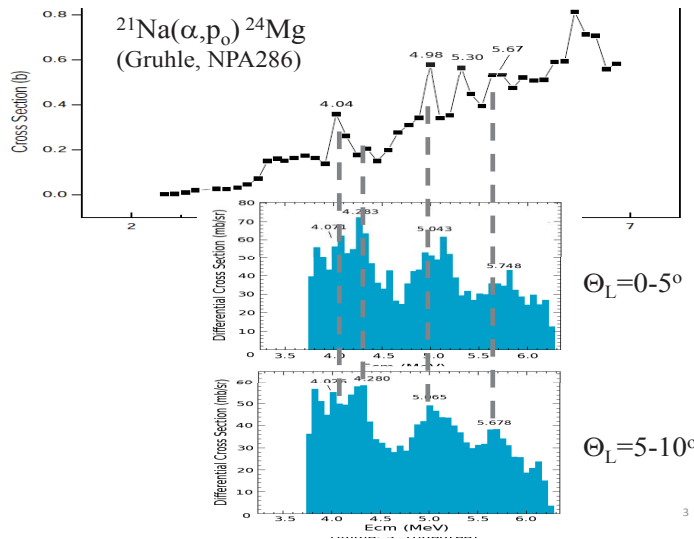


Fig. 3. α resonant elastic scattering and the $^{21}\text{Na}(\alpha, p_0)^{24}\text{Mg}$ reaction cross sections.¹⁷⁾

that alpha cluster states dominate the (α, p) reaction cross sections. Some other experimental studies along the breakout process are also under way.

The second study is the $^{21}\text{Na}(\alpha, p)^{24}\text{Mg}$ reaction study. After production of CNO elements in the αp -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}Al and ^{22}Na .¹⁴⁾

A beautiful experimental result was obtained recently in a study of the $^{21}\text{Na}(\alpha, p)$ stellar reaction,¹⁶⁾ which was suggested to play an important role in the νp -process.¹⁰⁾ A ^{21}Na beam was obtained from the CRIB separator. As can be seen in Fig. 4, the four prominent peaks appear to correspond to the peak energies in the excitation function of the $^{21}\text{Na}(\alpha, p_0)^{24}\text{Mg}$ reaction, which was measured by the time reverse reaction using an activation method,¹⁷⁾ although the correspondences are not perfect in detail. The R-matrix analysis revealed that all these resonances have quite large α widths which exhausted large fractions of the Wigner limits. This result implies that α -resonances have a major role for the $^{21}\text{Na}(\alpha, p)$ reaction rate, as expected by the CND.^{2), 3)} 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 accepted before.

§4. Outlook; study of nucleosynthesis of carbon and oxygen burning

Recently, the C burning and O burning processes have re-attracted nuclear astrophysicists very much. New measurements of the fusion cross sections of $^{12}\text{C}+^{12}\text{C}$ at lower energies than that known before indicates cross sections which is quite different from the high-energy extrapolation toward the Gamow window at low energy. For studies of these burning process, it is important to investigate molecular states as suggested by the CND diagram. Due to the cluster threshold rule, we have a

large chance that the molecular resonances are located near the $^{16}\text{O} + ^{16}\text{O}$ threshold and influence the fusion cross sections seriously. We just note that, interestingly, such a study was performed for finding possible molecular state of $^{16}\text{O} + ^{16}\text{O}$ some time ago.¹⁸⁾ The $^{16}\text{O}(^{20}\text{Ne}, \alpha_1)^{32}\text{S}^*(\alpha_2)^{28}\text{Si}$ reaction was chosen to study possible molecular state of $^{16}\text{O} + ^{16}\text{O}$ in ^{32}S near the $^{16}\text{O} + ^{16}\text{O}$ threshold, because the ground state of ^{20}Ne has a large parentage of $\alpha + ^{16}\text{O}$ configuration. The angular correlation functions of α_1 and α_2 provided successfully a unique spin assignment for the resonances observed in the α_1 spectrum. The result suggests strongly presence of possible molecular resonances around the $^{16}\text{O} + ^{16}\text{O}$ threshold. Clearly, such resonances would affect the reaction rate of the O burning. It is suggested that indirect methods such as the Trojan Horse Method¹⁹⁾ would be applicable for further investigation.

In summary, we discussed the role of nuclear clusters for astrophysics, especially of alpha clusters for nucleosynthesis at high temperatures with our new (α, p) experiments using low-energy RI beams from the CRIB facility. We have measured successfully the (α, p) cross sections directly at the temperatures of interest, and the (α, p) cross sections have been shown to be characterized strongly by alpha cluster resonances, as expected by the Cluster Nucleosynthesis Diagram. A possibility of studying molecular resonances was also discussed for C and O burning.

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