Experimental Challenge to the $\nu p$-Process in Type II Supernovae

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Abstract. The $\nu p$-process is a new nucleosynthetic scenario, proposed 2006, which is supposed to take place at the very early epoch of type II supernova, involving nuclear reactions of proton-rich nuclei not only with protons and alphas, but also with neutrons due to the neutrino processes. The $\nu p$-process is one of the key processes for investigating the mechanism of type II supernovae, and the process could be possibly responsible for the anomalously abundant $p$-nuclei around mass 90-100. Specifically, the nuclear physics problems in the $\nu p$-process were discussed in this talk including our recent experimental results with low-energy RI beams and a simulation study. Alpha cluster resonances have been identified experimentally which play a crucial role for the stellar ($\alpha$,p) and ($\alpha$,\gamma) reactions just above the alpha threshold. Neutron induced reactions in the proton-rich nuclear regions in the $\nu p$-process are also suggested to play an important role, which will discard the waiting points, and accelerate the flow to heavier nuclei. This process involves nuclear structures of very high level density at high excitation energies in neutron deficient nuclei, and both of the projectile and the target are unstable, which is a quite difficult experimental challenge in nuclear astrophysics in the coming years. Some experimental challenges are discussed.

1. The $\nu p$-process and the key stellar reactions for heavy element synthesis

Nuclear physics plays a crucial role in understanding evolution of the universe as well as various stellar phenomena. Specifically, explosive phenomena such as supernovae are considered to involve a variety of nuclear physics aspects which are not well known yet. They include neutrino interactions with nuclei, EOS of nuclear matter, as well as the nuclear properties in unstable nuclear regions and the reactions [1]. We discuss here the $\nu p$-process [2-4] which is considered to be one of the most challenging subjects for investigating the mechanism of type II supernovae, because it involves typical, wide-range problems for nucleosynthesis. Recently, we made a sensitivity test on the reaction rate uncertainties for the $\nu p$-process in ref. [5], identifying important nuclear reactions of (p,\gamma) and ($\alpha$,p) as well as (n,p) and (n,\alpha) reactions on neutron-deficient nuclei.
The $\nu p$-process was proposed by three groups in 2006, which would take place at the very early epoch of type II supernovae in the ejecta near the inner core region \cite{2-4}. Here, it can be proton-rich, because of the extremely high-intensity neutrino flux through the neutrino processes:

$$\nu_e + n \leftrightarrow p + e^-, \quad \nu_e + p \leftrightarrow n + e^+. \quad (1)$$

Since then, there have been some discussions about the electron fraction $Y_e$ in the very early epoch of type II supernovae mainly due to the medium effect of neutrinos, which makes $Y_e$ slightly smaller than 0.5, but soon it becomes larger than 0.5 in time \cite{6,7}. However, the site of the $\nu p$-process may be not so much influenced by this effect because the matter density of the site for this process is not so high.

The $\nu p$-process has been discussed as a possible source of p-nuclei near $A=90-100$, which have anomalously large isotopic abundances among the p-nuclei \cite{8}. If the $\nu p$-process runs up to this mass region, it will contribute to the p-nuclei productions. See Fig. 1. However, there are many unknown problems in nuclear physics involved in the $\nu p$-process. It includes many proton capture reactions on the neutron deficient nuclei 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 excited states in proton-rich unstable nuclei. The situation can be seen in Fig. 2. The latter reactions would be relevant to $\alpha$ cluster resonances and the former reactions to the nuclear properties in the very high level-density region.

Apparently, there are very few reaction studies made for the ($\alpha$,p) reactions, and almost none for the neutron induced reactions. Theoretical studies of the $\nu p$-process are mostly using statistical model calculations for almost all stellar reactions induced by alphas and neutrons. The statistical models in general are known that the models are not good in the light mass regions and it is also not known well in the neutron-deficient nuclear regions, because the models were studied only along the line of stability. This study should be very important.

Since the site has a significant fraction of alpha particles, alpha induced reactions would play a crucial role for the nucleosynthesis. Especially in the light mass region, ($\alpha$,p) reactions will dominate in the $\nu p$-process. Here, the nuclear excitation energy region relevant for $\alpha$s’ is much higher than that for protons, but we expect alpha resonances there due to the cluster threshold rule, which is
naturally suggested by the Cluster Nucleosynthesis Diagram (CND) [9,10].

The nucleosynthesis in the vp-process is expected to run through neutron-deficient nuclear regions like the rp-process at high temperatures. However, an interesting consequence of neutron induced reactions in the vp-process is that the nucleosynthesis flow will skip the slow beta-decays around the waiting point nuclei along the path way of the nucleosynthesis. This would accelerate the nucleosynthesis flow to heavier mass regions, affecting the p-nucleus production more or less. Along the possible pathways, there are some critical paths to be clarified in nuclear physics in order to really establish the condition of the vp-process.

A detailed discussion on the alpha-induced stellar reactions in the vp-process will be made in sec. 2 especially for the breakout process from the pp-chain region, the discussion on the neutron induced reactions in sec. 3, and the scope of the vp-process study in summary.

2. The alpha-induced stellar reactions on the breakout process from the pp-chain region

In general, the ($\alpha$,p) reactions play an important role in high-temperature hydrogen burning process in the light mass region (at $A \leq 40$). The ($\alpha$,p) reactions on $^{14}\text{O}$ [11,12] and $^{18}\text{Ne}$ [13] are the crucial breakout reactions from the CNO region yet to be investigated. Many other ($\alpha$,p) reactions on such as $^{22}\text{Mg}$ and $^{30}\text{S}$ also will set in. The $^{21}\text{Na}(\alpha,p)$ reaction is also possibly crucial for the problem of $^{22}\text{Na}$ nuclear gamma ray observation [14].

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

\[ <\sigma v> \propto \frac{\Gamma_{\alpha} \Gamma_{p}}{\Gamma_{tot}}, \]

where $\Gamma_{\alpha}$ and $\Gamma_{p}$ are the proton and alpha decay widths of the resonance, respectively. This implies that one may estimate the ($\alpha$,p) reaction rate by simply knowing the widths of $\alpha$ and p decays of the resonance. Thus, $\alpha$ resonant elastic scattering study is an important piece of information for the ($\alpha$,p) reaction rate. Of course, $\alpha$-cluster structure is also interesting for nuclear physics in proton-rich unstable nuclear region, especially near and above the $\alpha$-threshold because of the cluster threshold rule [9,10], as discussed in sec. 1. Since resonance energies relevant are not large even in the vp-process environment, $\Gamma_{\alpha}$ cannot be so large, whereas the proton width can be often much larger, because the proton threshold is much lower in energies. Therefore, large ($\alpha$,p) reaction rates can be obtained usually when $\Gamma_{\alpha}$ is large.
The breakout process from the pp-chain region may have possibly a common problem of nuclear physics for evolution of the first generation stars. Recent astronomical observations [15] are reporting interesting stellar objects which could be the first or the second generation stars which show a strongly enhancement of CNO elements, and very few irons together with high Sr abundance. Here, the alpha-induced reactions are expected to play a key role, which will be discussed next.

A series of experiments were made on the alpha-induced stellar reactions along the breakout process from the pp-chain region. The experiments have been made at the low-energy RI beam facility, CRIB [16,17], of Center for Nuclear Study, the University of Tokyo. There are possible three major side flows that reach CNO elements, \( ^7\text{Be}(\alpha,\gamma)^{11}\text{C}(\alpha,p)^{14}\text{N} \), \( ^7\text{Be}(\alpha,\gamma)^{11}\text{C}(\alpha,p)^{14}\text{N} \), and \( ^7\text{Be}(\alpha,p)^{10}\text{B}(\alpha,p)^{13}\text{C} \) [5]. Specifically, we discuss here our efforts on the crucial pathway, \( ^7\text{Be}(\alpha,\gamma)^{11}\text{C}(\alpha,p)^{14}\text{N} \).

The \( ^7\text{Be}(\alpha,\gamma)^{11}\text{C} \) stellar reaction was studied by measuring elastic and inelastic scattering of \( \alpha + ^7\text{Be} \) [18]. A new resonance at 8.90 MeV, which is the third resonance above the alpha threshold, was identified for the first time, with possible spin-parity assignment of \( (9/2^+) \) or \( 3/2^+ \), where the R-matrix analysis did not give a unique assignment [18]. New rotational bands were identified that have large alpha reduced widths. The reaction rates estimated through this resonance suggests about 10% increase of the total reaction rate of \( ^7\text{Be}(\alpha,\gamma)^{11}\text{C} \), making an assumption for the gamma width for the new resonance. Since this reaction rate is considered to have the decisive role for breakout from the pp-chain region, this gamma width needs to be investigated experimentally.

One of the crucial branching points for the breakout from the pp-chain region could 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 was \(^{11}\text{C}(\alpha,p)^{14}\text{N}\) reaction, which was investigated previously only by the time reverse reaction with an activation method. The \(^{11}\text{C}(\alpha,p)^{14}\text{N}\) reaction study was made for the first time directly at the temperature region of interest using a low-energy, high intensity beam of \(^{11}\text{C}\) at CRIB [19].

The cross sections were measured at \( E_{\text{cm}} = 1.0 - 4.5 \) 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 \(^{14}\text{N}\) were also successfully observed [19], 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 [19], which is sensitive only to the ground state transition. 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 calculations. 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. The present results demonstrate that it is important to study directly the \((\alpha,p)\) reaction cross sections by identifying each resonance. Some other experimental studies along the breakout process are also under way.
3. The neutron-induced stellar reaction around possible bottle neck regions

Another interesting aspect of the $\nu p$-process is that a significant amount of neutrons also exist in the site, and thus the neutron induced reactions such as $(n,p)$ and $(n,\gamma)$ reactions would play an important role for the flow. These neutron induced reactions on proton-rich unstable nuclei are one of the most challenging subjects for experimental nuclear astrophysics. As was discussed in sec. 1, the $(n,p)$ reactions would accelerate the process at the waiting point nuclei, which will affect eventually the production of heavy nuclei at around mass 90-100. Figure 5 shows a sensitivity test of the $^{56}\text{Ni}(n,p)$ rate to the heavy mass nucleus production in the $\nu p$-process [5]. The yields of $A \sim 100$ changes drastically. Here, the neutron-induced reactions involve high-lying states of unstable neutron-deficient nuclei, which are totally unknown yet, as discussed earlier. They are treated by the Hauser-Feshbach model. Recent theoretical works on giant resonances for wide-range unstable nuclei would improve the estimate for the rate. This subject is very interesting but it is one of the toughest challenges for nuclear astrophysics experiments. One possibility is to use an indirect method, the Trojan Horse Method (THM) with proton-rich unstable nuclear beams [21].

A successful application of the THM was made for the study of the $^{18}\text{F}(n,\alpha)^{15}\text{O}$ stellar reaction using an RI beam of $^{18}\text{F}$ on an $^2\text{H}$ target. The stellar cross sections of $^{18}\text{F}(p,\alpha)^{15}\text{O}$ studied simultaneously was already analyzed successfully [21]. Similar quality data were obtained for the $^{18}\text{F}(n,\alpha)$ reaction, and the analysis is underway.

4. Summary

We discussed nuclear physics problems for the $\nu p$-process including our experimental efforts, which used low-energy RI beams from the CRIB facility. Especially, our main efforts have been placed on the $(\alpha,p)$ and $(\alpha,\gamma)$ stellar reactions which set in under high-temperature and high-density hydrogen burning conditions in the light mass regions. A crucial role of $\alpha$ resonances to the $(\alpha,p)$ and $(\alpha,\gamma)$ stellar reactions has been demonstrated for the first time, as suggested by the CND. Neutron induced stellar reactions on neutron deficient nuclei should be a very important but very tough experimental challenge as both the projectile and the target are unstable. An indirect method THM has been applied successfully for a test case of $^{18}\text{F}(n,\alpha)$ stellar reaction study. It should be of great interest to make an innovative experimental facility like a storage ring of RI beam merging with a high-intensity neutron beam in the future for nuclear astrophysics.
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