第 33 卷 第 2 期　　原 子 核 物 理 评 论　　Vol. 33, No. 2
2016 年 6 月　　Nuclear Physics Review　　June , 2016

Article ID: 1007-4627(2016) 02-0212-05

Neutron and Alpha Structure in Neutron Deficient Nuclei in Astrophysics

S. Kubono[1,2,3], HE Jianjun(何建军)[1], H. Yamaguchi[3], D. M. Kahl[3], S. Hayakawa[3], T. Teranishi[4], S. Cheribini[5], M. Gulino[5], Y. K. Kwon[6], T. Hashimoto[6], Y. Wakabayashi[2], N. Iwasa[7], S. Kato[8], T. Komatsubara[2], D. N. Binh[9], L. H. Khiem[9], N. N. Duy[9], T. Kawabata[10], C. Spitaleri[5], G. G. Rapisarda[5], M. La Cognata[5], L. Lamia[5], R. G. Pizzone[5], S. Romano[5], A. Coc[11], N. de Sereville[11], F. Hammache[11], G. Kiss[12], S. Bishop[13]

(*1. Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 73000, China;*
2. RIKEN Nishina Center,2-1 Hirosawa, Wako, Saitama 351-0198, Japan;
3. Center for Nuclear Study, University of Tokyo, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan;
4. Department of Physics, Kyushu University, 6-10-1 Hakozaki, Fukuoka 812-858, Japan;
5. Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, Via S. Sofia 62, 95125 Catania, Italy;
6. Institute for Basic Science, 70, Yuseong-daero 1689-gil, Yuseong-gu, Daejeon 305-81, Korea;
7. Department of Physics, Tohoku University, Aoba, Sendai, Miyagi 980-8578, Japan;
8. Department of Physics, Yamagata University, Yamagata 990-8560, Japan;
9. Institute of Physics, Vietnam Academy for Science and Technology, Hanoi, Vietnam;
10. Department of Physics, Kyoto University, Kyoto 660-8502, Japan;
11. IN2P3, F-91405 Orsay, France;
12. Institute for Nuclear Research (MTA-ATOMKI), Debrecen, Hungary;
13. TUM, Garching, Germany)

Abstract: The paper includes discussions on the important role of neutron and alpha configurations in proton-rich nuclei in nuclear astrophysics in terms of nucleosynthesis under extremely high-temperature hydrogenburning conditions. The νp-process, which is supposed to take place at the very early epoch of type II supernovae, has considerable neutrons and alphas together with protons. The alpha-induced reactions on proton-rich unstable nuclei in the light mass regions is expected to play a crucial role, but very few of them were investigated well yet because of the experimental difficulties. Specifically, I report our recent experimental effort for the breakout process from the pp-chain region, ^{7}Be(α,γ)^{11}C(α,p)^{14}N under the νp-process. The neutron-induced reactions on proton-rich nuclei, which is even more a challenging subject, were investigated previously for very few nuclei. One possible experimental method is the Trojan Horse Method (THM). We successfully have applied THM to the ^{18}F(n,α)^{14}N reaction study with an unstable beam of ^{18}F.

Key words: alpha- and neutron-induced stellar reactions in proton-rich nuclear region; νp-process; pp-chain breakout; nuclear cluster structures in astrophysics; low-energy RI beam

CLC number: O571.1　**Document code:** A　**DOI:** 10.11804/NuclPhysRev.33.02.212

1 Experimental challenge to explosive hydrogen burning at extremely high temperatures

Observation of elements is one of the keys for studying the evolution of the universe as well as various stellar phenomena. Almost all the elements were produced by nuclear reactions along the evolution of the universe, but the reactions responsible are known precisely for a quite limited number of cases. Specifically, the nuclear reactions under explosive burnings are the problems. There are many occasions that hydrogen

---

Received date: 2 Sep. 2015;
Foundation item: Japan Society for the Promotion of Science (JSPS) Research (KAKENHI)(26287058)
Biography: S. Kubono (1947–), male, Tochigi, Japan, Ph.D., working on experimental nuclear physics; kubono@riken.jp.

burns explosively along the history of the universe, as hydrogen is the most abundant and inflammable element among the charged particles. They may include novae, X-ray bursts, supernovae, *etc.* Experimental efforts have been made more than two decades for the nuclear reactions for the explosive hydrogen burning using proton-rich unstable nuclear beams, where major efforts were made for proton capture reactions[1−2].

However, most of the reactions are not well determined by the experiments, because of the two difficulties, small cross sections due to the Coulomb penetrability at low energies, and the small production efficiency of proton-rich unstable nuclear beams, although there are many RI beam facilities established in the world[2].

Specifically, the hydrogen burning at extremely high temperatures is of great importance, but it is difficult to study because nuclear reactions involve not only protons but also alphas, and even neutrons in some occasions like the νp-process in type II supernovae. The alpha-induced reactions become more effective, and play a dominant role in hydrogen burning at such high temperatures in the light mass regions at $A < 60$. They may bypath the beta decay-limited waiting points, and accelerate the nucleosynthetic flow to heavier mass regions. Very few of them were studied experimentally, and almost none of them are known well yet by experiments[3].

The νp-process, proposed in 2006[4−6], may take place at the very early epoch of type II supernovae in the ejecta near the inner core. Here, it can be proton-rich with some fraction of neutrons at very high temperatures because they are in equilibrium through weak interaction; $\nu_e + n \leftrightarrow p + e^-$, $\bar{\nu}_e + p \leftrightarrow n + e^+$. This process also has been discussed as a possible source of p-nuclei near $A = 90 \sim 100$, which have anomalously large isotopic abundances[7]. To investigate this process, we need to study not only protons and alphas, but also neutron induced reactions on proton-rich nuclei. Apparently, the νp-process scenario is different from that of the rp-process, because neutron-induced reactions will discard the waiting points by the (n,p) and (n,α) reactions, and thus accelerate the nucleosynthetic flow to heavier mass regions[8].

Fig. 1 shows a situation for various thermonuclear reactions expected in the proton-rich nuclear regions under the νp-process. The proton capture reactions may be sensitive to low-lying proton resonances of a single particle configuration. Pigmy resonances might also contribute to the (p,γ) reaction if they exist in this energy region, and alpha cluster resonances to the alpha-induced reactions. This possibility is backed up by the cluster threshold rule[9]. Of course, there are very few experimental studies on alpha cluster resonances in proton-rich unstable nuclear region yet. The neutron thresholds in proton-rich nuclei locate at much higher energy region, where almost no nuclear structure information are available in nuclear physics yet.

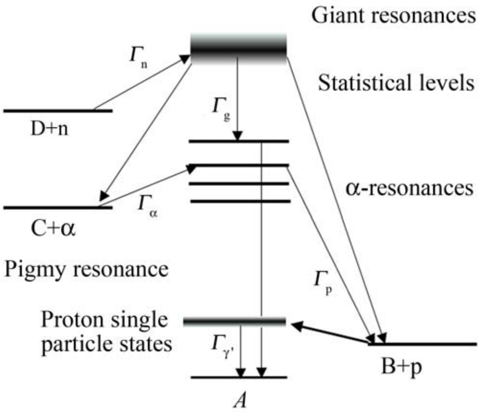

Fig. 1　Possible nuclear reactions and the structures to be involved in the νp-process.

The neutron-induced reactions on proton-rich unstable nuclei are very difficult to study, because both the projectile and the target are unstable. If the reactions involve proton-rich nuclei located close to the line of stability, there is a possibility to study it by a time-reverse reactions. If the proton-rich nuclei have a long half-lives, one may make a target for the study. These are, however, very limited, and mostly the proton-rich nuclei relevant are short-lived nuclei away from the line of stability, which cannot be reached by the time reverse reactions. Currently, people are usually using statistical models to estimate the alpha-induced reaction cross sections for most of them, although statistical models are known to be not precise enough in the light mass regions, and further the statistical models are not investigated so much in unstable nuclear regions. Thus, the experimental studies of the stellar reactions by alpha and neutrons should be very important and the challenges for the coming years in nuclear astrophysics[8]. The paper will discuss these subjects along with our recent experimental efforts. Specifically, The paper will discuss key reaction studies of proton-rich nuclei for the νp-process.

As has been discussed in the past decades, there are some possibilities of innovative approaches, like an RIB storage ring merging with high-intensity neutron beams, an RIB storage ring that goes through the peripheral of a fission reactor, etc. These should be a real challenge in the next-generation facilities. For the moment, one may approach by the indirect methods: One may study the decay properties of the relevant resonances. But, one of the most powerful indirect methods could be the Trojan Horse Method (THM), with which one may study the (n,p) and (n,α) reactions on proton-rich nuclei without using any neutron beam.

In the following sections our experimental effort to study the alpha and neutron induced reactions on proton-rich nuclei will be discussed.

2 The α-induced reactions for breakout from the pp-chain region

The nucleosynthetic flows through the proton-rich nuclear side in the pp-chain region are considered to affect significantly the production of heavy nuclei in the νp-process. However, the critical reaction rates relevant are not known well, especially those involving unstable nuclei. At extremely high temperatures, alpha induced reactions are expected to play a key role. Fig. 2 depicts possible breakout pathways from the pp-chain region in the νp-process. There are a few pathways for breakout from the pp-chain region.

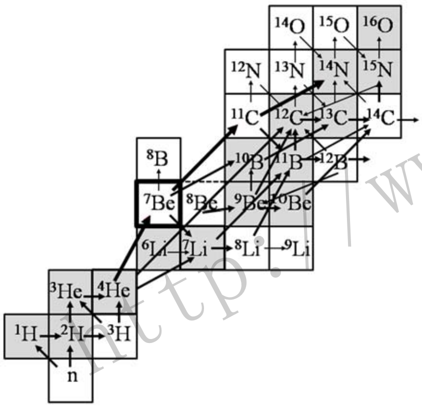

Fig. 2 The nucleosynthesis flow expected in the νp-process, including the breakout pathways from the pp-chain region.

Among them, the least investigated but very crucial pathway is ^{7}Be(α,γ)^{11}C(α,p)^{14}N. The first step reaction ^{7}Be(α,γ)^{11}C, which is considered to have the decisive role in the pathway, was studied previously by the direct method using a ^{7}Be target, but it was limited up to the second resonance above the α-threshold. We need to know the contributions from the high-lying resonances in ^{11}C, which might have significant contributions at extremely high temperatures.

In order to study the high-lying resonances, an experiment was performed[10] for ^{7}Be+α resonant scattering with a thick-target method using a high-intensity, nearly pure ^{7}Be beam from the CRIB facility[11–12] of the University of Tokyo set in the RIKEN RIBF facility. The ^{7}Be beam was about 2×10^{5} atoms/s and 17.9 MeV. Both elastic and inelastic events were measured separately by using a $\Delta E-E$ Si detector telescope together with 10 NaI(Tl) detectors for identifications.

The elastic and inelastic scattering of α+^{7}Be were measured together with the ^{7}Be(α,p) reaction. 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 5/2+, where the R-matrix analysis did not give a unique assignment[10]. The reaction rates estimated through this resonance are shown by (a) and (b) in Fig. 3. Here, the gamma decay width of this state was simply assumed to be a typical value, 0.1 of the Weisskopf unit. This work suggests about 10% contribution for the total reaction rate of ^{7}Be(α,γ)^{11}C from the third resonance above the alpha threshold in ^{11}C. 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.

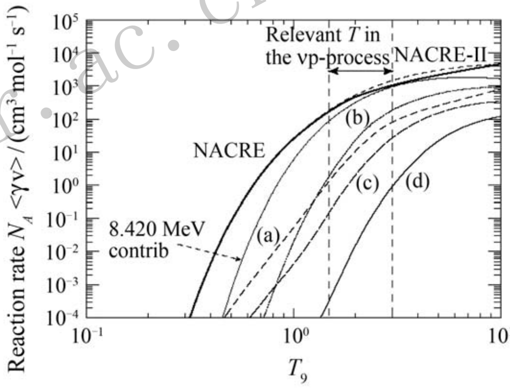

Fig. 3 The ^{7}Be(α)^{11}C reaction rate estimated based on the present experiments. (a) and (b) are the rates due to the third resonance ($E_x = 8.9$ MeV) above the alpha threshold, where the spin-parity was assumed to be 9/2+ and 3/2+ for (a) and (b), respectively[10].

The second reaction ^{11}C(α,p)^{14}N along the breakout sequence was studied recently[13] by the direct method for the first time using a high-intensity ^{11}C beam at very low energies at CRIB. This reaction was previously studied only by the time-reverse reaction ^{14}N(p,α)^{11}C with an activation method(Fig. 4).

Apparently, the time reverse reaction study is not sensitive to the reactions leading to the excited states in ^{14}N. It should be also worthwhile to confirm by the direct method the cross sections to the ground state derived previously by the activation method.

The ^{11}C(α,p)^{14}N experiments were measured directly at the CRIB facility. The ^{11}C beam at low energies were produced at the CRIB facility; 3×10^{5} pps at 10.1 MeV, and 1×10^{5} pps at 16.9 MeV with a purity better than 97%. A new method was developed for efficient measurement of the excitation functions of the ^{11}C(α,p)^{11}N reaction cross sections for the low-lying excited states as well as for the ground state. We adopted a thick-target method with an extended gas target together with two position sensitive beam monitors, and position sensitive Si telescopes for the measurement of protons. Using the TOF information together, one can identify the reaction points in the target, and thus the reaction energies of the (α,p) reaction. Very precise excitation functions were obtained for the ^{11}C(α,p)^{11}N reactions for the ground states and the first and second excited states. The cross sections for the ground state transitions obtained agree well with the cross sections previously measured by the time-reverse reaction with the activation method. The cross sections for the first and second excited states were also obtained for the first time, and our data consistently disagree with the statistical model predictions roughly by a factor of 2 ~ 5.

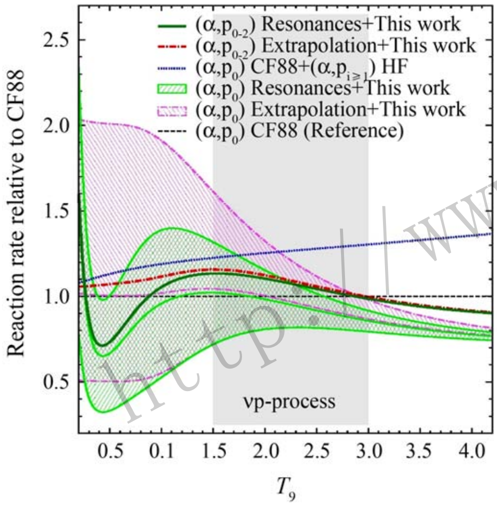

Fig. 4 (color online) The new reaction rate of ^{11}C(α,p)^{11}N, deduced based on the present experiment[13].

The R-matrix analysis identified several new resonances, and new resonance parameters for the known states in ^{14}N. This is the first extensive, direct measurement of the stellar (α,p) reaction cross sections with the proton-rich unstable nuclei, identifying each resonance and the resonance parameters. It is interesting to note that alpha cluster states enhance the reaction rates; some large peaks of the reaction rates are due to large alpha widths, as expected.

This experiment has successfully determined for the first time the ^{11}C(α,p)^{11}N reaction rates at the temperature region important for the νp-process, including the transition to the excited states in ^{14}N. The present result supports the νp-process simulation that nucleosynthesis-flow runs up to the mass region of $A = 90 \sim 100$. This study also has confirmed the cross sections for the ^{11}C(α,p$_0$)^{11}N(g.s.) reaction by the time-reverse reaction with the activation method.

3 Neutron-induced reactions discarding the waiting points

The environment where the νp-process[4−6] takes place in the early epoch of type II supernovae also has a considerable neutron flux together with protons, as was discussed in Sec. 1. Fig. 5 shows a nucleosynthesisflow near ^{56}Ni, predicted in the νp-process simulation[8]. The red arrows indicate the (n,p) reactions, which accelerate the flow very much by discarding the waiting points. The sensitivity test was shown in Fig. 5(b), which presents considerable impact to the production of nuclei at around $A = 90 \sim 100$, where we

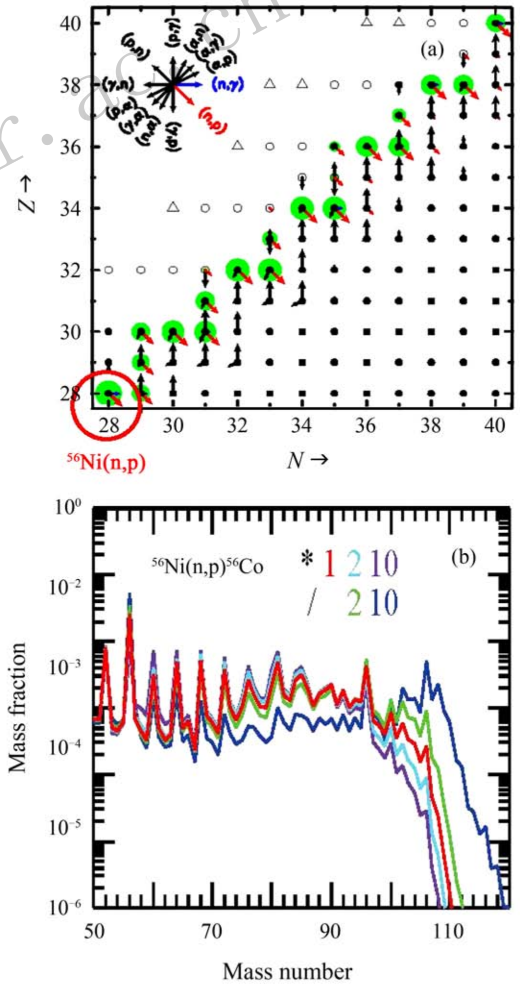

Fig. 5 (color online) (a) The nucleosynthetic flow near the possible bottle neck ^{56}Ni in the νp-process. The red arrow indicates the (n,p) reactions. (b) Sensitivity test of the ^{56}Ni(n,p) reaction rate on heavy nuclei production[8].

have the anomalously abundant p-nuclei like ^{92}Mo. The (n,p) reactions on neutron deficient nuclei go into highly excited states at about 10 MeV, as pointed out in Sec. 1. Apparently, nuclear physics is playing a crucial role there, although we do not know well the nuclear properties and the reactions[1].

It is a challenging subject to study neutron-induced reactions on neutron deficient nuclei. One possibility is to apply the THM. This method has been proven to be applicable also for the neutron induced reactions, ^{17}O(n,α)^{14}C[14]. Recently, we have applied THM for studying the ^{18}F(n,α)^{15}N reaction using a ^{18}F beam on ^{2}H target. The ^{18}F(p,α)^{15}O reaction, studied simultaneously, was investigated, and the S-factor was successfully derived down to zero energy[15]. The same quality data was obtained for the ^{18}F(n,α)^{15}O reaction, whose analysis is now in progress.

4 Summary

Nucleosynthesis of explosive hydrogen burning at extremely high temperatures is one of the most important processes to be investigated for understanding the stellar evolution and various phenomena. This paper discussed our experimental challenges to study the neutron and alpha configuration in the neutron deficient nuclei and the reactions important for the νp-process, which is a new subject to be investigated in nuclear astrophysics. Especially, the neutron induced reactions require new innovative approach in the future.

References:

[1] KUBONO S, HAYAKAWA T, KAJINO T, *et al.* AIP Conf Proc 2012: **1484**; JEONG S, IMAI N, MIYATAKE H, *et al.* AIP Conf Proc 2013: **1594**; LATTANZIO J, KARAKAS A, LUGARO M, *et al.* Proceedings of Science (NIC XII).

[2] KUBONO S. Nucl Phys A, 2001, **693**: 221.

[3] WALLACE R K, WOOSLEY S E. Astrophys J, 1981, **45**: 389.

[4] FRÖHLICH C, MARTÍNEZ-PINEDO G, LIEBENDÖRFER M, *et al.* Phys Rev Lett, 2016, **96**: 142502.

[5] PRUET J, HOFFMAN R D, WOOSLEY S E, *et al.* Astrophys J, 2006, **644**: 1028.

[6] WANAJO S. Astrophys J, 2006, **647**: 1323.

[7] ARNOULD M. GORIELY S. Phys Rep, 2003, **384**: 1.

[8] WANAJO S, JANKA H T, KUBONO S. Astrophys J, 2011, **729**: 46.

[9] KUBONO S. 10th International Conference on Clustering Aspects of Nuclear Structure and Dynamics IOP Conf, 2013, **436**: 012071.

[10] YAMAGUCHI H, KAHL D, WAKABAYASHI Y, *et al.* Phys Rev C, 2013, **87**: 034303.

[11] KUBONO S, YANAGISAWA Y, TERANISHI T, *et al.* Eur Phys J A, 2002, **13**: 217.

[12] YANAGISAWA Y, KUBONO S, TERANISHI T, *et al.* Nucl Instr Meth A, 2005, **539:** 74.

[13] HAYAKAWA S. Ph. D. thesis of the University of Tokyo, 2012.

[14] GULINO M, SPITALERI C, TANG X D, *et al.* Phys Rev C, 2013, **87**: 01280(R).

[15] CHERUBINI S, GULINO M, SPITALERI C, *et al.* Phys Rev C, 2015, **92**: 015805.