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New Experiments for the Breakout off the Hot-CNO Cycle

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Abstract. Experimental investigation of critical nuclear reactions for the breakout off the Hot-CNO cycle are in progress. One is the $^{15}O(\alpha, \gamma)^{19}Ne$ reaction, which could be the limiting reaction of the breakout at relatively low temperature ($T < 5 \times 10^8$ K), and the others are $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne$ at higher temperatures. Some new results on these experiments and the astrophysical implication are discussed.

I. EXPLOSIVE HYDROGEN BURNING

Nuclear reactions on possible breakout processes off the Hot-CNO (HCNO) cycle are of great interest in nuclear astrophysics. This subject is probably directly related to the problem of nucleosynthesis in novae and X-ray bursts, for instance. An interesting question here is if CNO material is really transmuted into heavier elements in explosive phenomena such as novae. This is
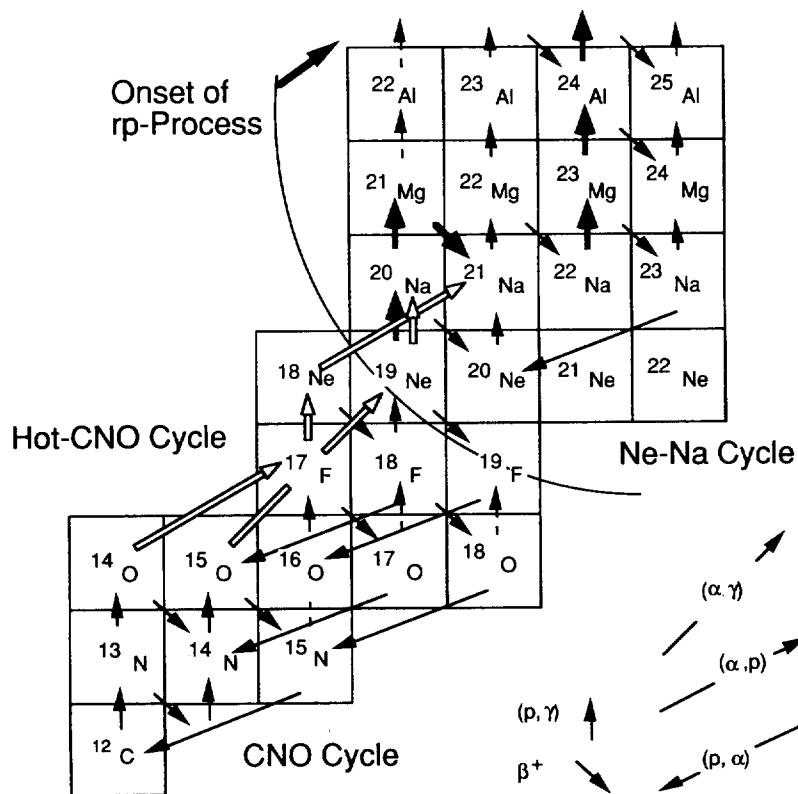
FIGURE 1. The nucleosynthesis flow diagram of the HCNO cycle and the rp-process. The white arrows indicate possible breakout processes off the HCNO cycle and the thick arrows the nuclear processes studied in our project before.

also an important question for energy generation. However, crucial reactions for this problem are not well known yet.

The breakout process off the HCNO cycle, which leads to explosive hydrogen burning (rp-process), was first pointed out by Wallace and Woosely [1]. The reaction sequence of $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$ is considered to be one of them [2]. Because of lack of experiment, the $^{19}Ne(p,\gamma)^{20}Na$ reaction was considered to be the limiting reaction for ignition of the rp-process at the time.

We performed before a series of experiments [7] to clarify the onset mechanism at the SF cyclotron of the Center for Nuclear Study (CNS), University of Tokyo. Many new resonances were discovered above the proton thresholds, including the one at 2.64 MeV in ^{20}Na [8], which is much lower in energy than the level known before at 2.9 MeV, where the proton threshold energy is 2.20 MeV. This new resonance reduces the ignition temperature nearly by a factor of two. The new estimates, obtained based on the experimental results, for the ignition of the onset and early stage of the rp-process is summarized in
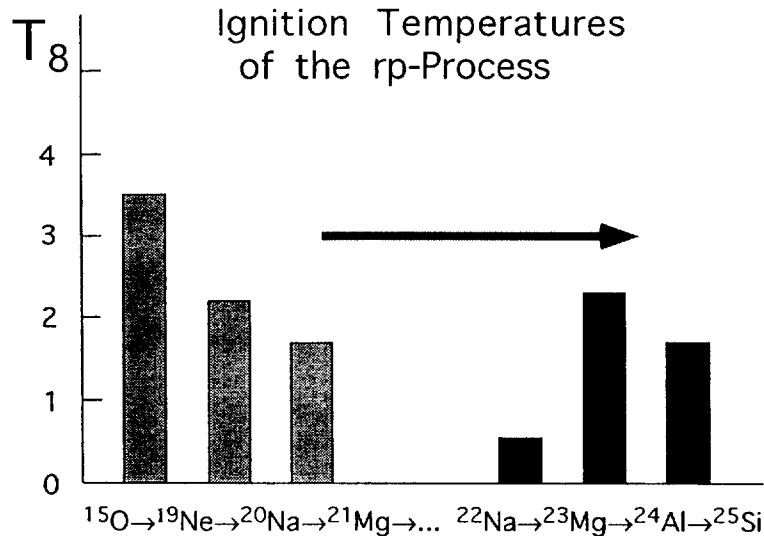
T_8

Ignition Temperatures
of the rp-Process

4

3

2

1

0

$^{15}O\rightarrow^{19}Ne\rightarrow^{20}Na\rightarrow^{21}Mg\rightarrow...$ $^{22}Na\rightarrow^{23}Mg\rightarrow^{24}Al\rightarrow^{25}Si$

FIGURE 2. Estimates of ignition temperatures of the onset and the early stage of the rp-process. See text for details.

Fig. 2. Here, the estimate for the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction was taken from ref. [9]. Thus, the $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is likely the limiting reaction of the onset of the rp-process. However, note that none of the rates of the reactions in Fig. 2 is determined experimentally at the temperature region of interest.

The second possible reaction sequence for the breakout off the HCNO cycle [1], more likely at higher temperature, is $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$. Here, a new type reaction (α,p) sets in for the explosive burning phase in the low mass region of the nuclear chart. The reaction rate of $^{14}O(\alpha,p)^{17}F$ was investigated with updated data [3] and with a theoretical model [4]. However, there still is a large uncertainty in the rate, although many experimental efforts were made [5,6]. The other reactions of this sequence also are not known well yet.

Therefore, we have started to investigate these breakout reactions experimentally. Since the experiments and the analysis are in progress, I will just discuss the problems and some preliminary results.

II. THE RP-PROCESS IN NOVAE

As was discussed in sec. I, the limiting reaction for the onset of the rp-process in novae is considered to be $^{15}O(\alpha,\gamma)^{19}Ne$ from the estimates shown in Fig. 2 [7]. The relevant levels in ^{19}Ne were studied before by the $^{20}Ne(^3He,\alpha)^{19}Ne$ reactions, the $^{21}Ne(p,t)^{19}Ne$ reaction, etc. [11]. The total widths are not known for the states in this energy region in ^{19}Ne. Since the mirror nucleus ^{19}F is well studied, the analog relation is established up to
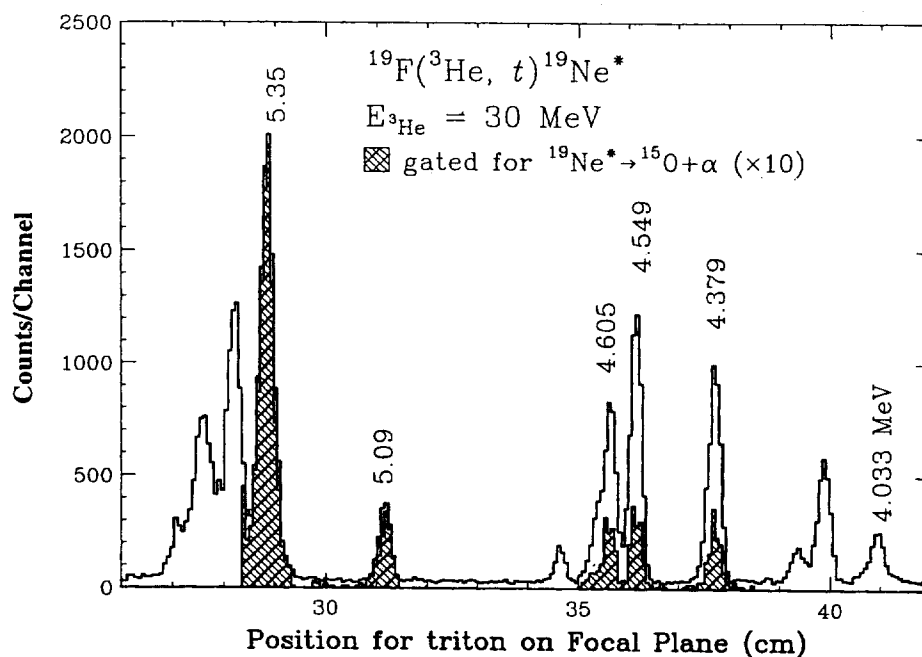
FIGURE 3. Triton spectra of $^{19}F(^3He,t)^{19}Ne$ of singles (white part) and of coincidence with decay particles (shaded part), measured at 0°. The coincidence spectrum was multiplied by a factor of ten.

around the alpha threshold energy, 3.528 MeV. However, it is not so clear above the threshold. Nevertheless, the resonance strengths for the important resonances seem to be predominantly determined by the alpha decay widths.

The most crucial level predicted for burning under nova conditions (T= 2 ~ 5 x 10^8 K, $\rho = 10^{3 \sim 4}$ g/cm^3) is the 4.033 MeV $3/2^+$ state, which is about 505 keV above the α threshold in ^{19}Ne. This state was very strongly excited by the (p,t) reaction, but not so by the $(^3He,\alpha)$ reaction [11]. Thus, it is considered to have a main shell-model component of 5p-2h configuration, but the resonance strength of this state is not known. The decay widths calculated by Langanke et al. [2] are $\Gamma_\alpha = 7.2$ μeV and $\Gamma_\gamma = 73$ meV. Recently, the alpha width was estimated from α-transfer data of $^{15}N(^6Li,d)^{19}F$ and $^{16}O(^6Li,d)^{20}Ne$, giving $\Gamma_\alpha = 9.9 \pm 1.5$ μeV [10].

An experimental investigation of the astrophysical $^{15}O(\alpha,\gamma)^{19}Ne$ reaction is underway at CNS using the $^{19}F(^3He,t)^{19}Ne^*(\alpha)$ reaction at 30 MeV. Since the α-decay width is the crucial parameter, we are trying to measure the branching ratios of the α-decays first. The tritons from the reaction were measured at 0° with a magnetic spectrograph, and the decay α particles were measured in coincidence using strip silicon detectors placed in the scattering chamber. Alpha decays were observed from some states above the α threshold in ^{19}Ne.

Figure 3 shows two triton spectra measured on the focal plane of the spectrograph. The shaded bars indicate the triton spectrum measured in coincidence with the particle detection in the scattering chamber, whereas the other part (open bars) is the singles spectrum of tritons. The yields of the coincidence spectrum are multiplied by a factor of ten, since the solid angle of the decay particle detector is roughly 10 %.

The 5.35 MeV state shows a large α-decay branching ratio, whereas the levels at lower energies near the α-threshold have less yields. Random coincident events are also included in the coincident events shown in the figure; for instance, roughly a half of the yields is the background for the 4.379 MeV state. This poor signal to noise ratio comes from the setup condition and partly from the electronic noises. These will be improved for the final run.

III. HIGH TEMPERATURE RP-PROCESS

The second possible breakout process, $^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne \ldots$, was also investigated here by the $^{20}Ne(p,t)^{18}Ne$ reaction. The nuclear structure of ^{18}Ne is directly related to the first two reactions in the sequence. Specifically, the properties of the levels just above the proton and α thresholds are the problems in ^{18}Ne. However, even spin parities are not determined for them.

Figure 4 shows the level schemes of ^{18}Ne and the mirror nucleus ^{18}O. The levels at 5.11 and 5.15 MeV states were assigned to have 3^- and 2^+, respectively, in the previous predictions [3,4]. Hahn et al. [6], however, discussed inverted assignments for them from Thomas-Ehrman shift calculations.

Similar discussions were made for the states at 6.29 and 6.35 MeV states. The state at 6.15 MeV, which was observed only by the reactions of $^{16}O(^{3}He,n)$ and $^{12}C(^{12}C,^{6}He)$ [6], was not seen at any angles measured in the present (p,t) spectra. A possibility is that this state has many-particle many-hole configuration. There should be analog states of the 6.20 MeV 1^- state and the 6.40 MeV 3^- state of ^{18}O in this energy region. These correspondences will be clarified by identifying the spin parity from measurements of the (p,t) angular distributions. These states could have major contributions to the reaction rate of $^{14}O(\alpha,p)^{17}F$ [3].

A special effort was placed on identifying a possible 3^+ state around 4.5 MeV. A 3^+ state is known at 5.38 MeV in ^{18}O. A Thomas-Ehrman shift calculation [12] predicted the 3^+ state to be around 4.33 MeV in ^{18}Ne, suggesting that this state will enhance considerably the reaction rate of $^{17}F(p,\gamma)^{18}Ne$, although there was no clear experimental evidence seen so far for the presence of the 3^+ state. Only a possibility was suggested at 4.56 MeV experimentally by the $^{16}O(^{3}He,n)^{18}Ne$ reaction [5]. Since 4.56 MeV is just in the middle of the known doublet of 4.52 and 4.59 MeV, we made a careful search with high resolution measurement using a Ne-implanted carbon target of about 50 $\mu g/cm^3$ (about 7 $\mu g/cm^3$ of Ne). Several spectra were taken for the $^{20}Ne(p,t)^{18}Ne$
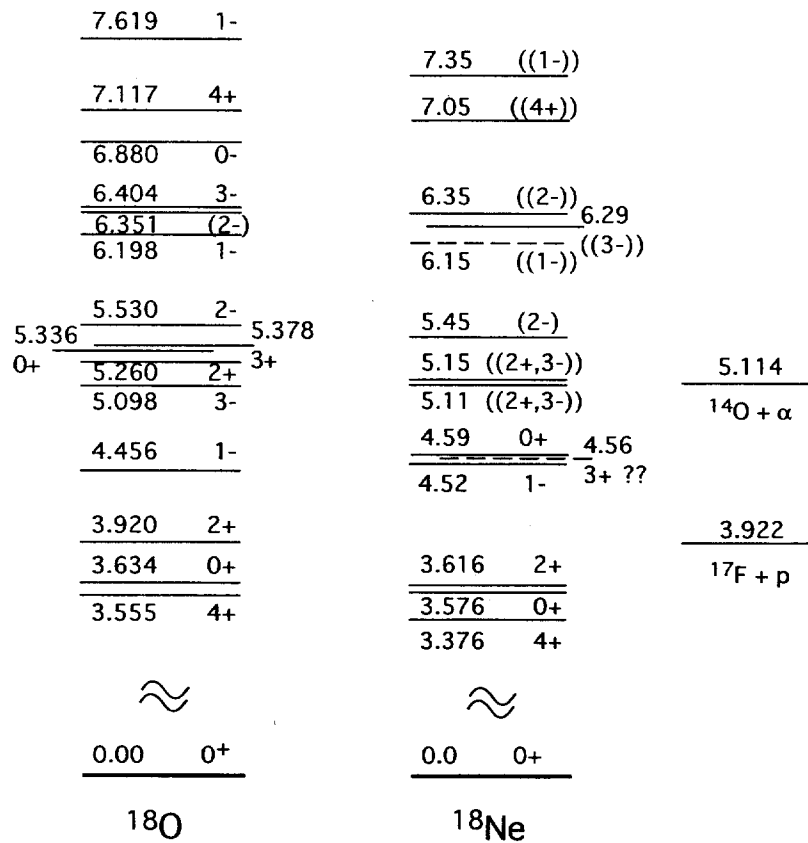
FIGURE 4. Level schemes of A = 18.

reaction using a magnetic spectrograph. The overall energy resolution was about 12 keV, which is sufficient enough to see the peak suggested if the energy suggested is correct and the intensity is of the same order as in the (^{3}He,n) reaction. However, there was no evidence seen in the spectra for a state between the doublet states. The background level is also better than a previous spectrum [6]. We observed small contamination peaks which were not seen before. It should be noted that the (p,t) reaction is not the best reaction for this search because the residual state has an unnatural parity.

Since the energy resolution is good, the excitation energies and the natural widths of some states crucial for the (p,γ) and (α,p) reactions will be determined precisely. Eventually, the resonance strengths of the (α,p) reaction are needed to be determined. However, the direct simulation study of the ^{14}O(α,p)^{17}F reaction using an ^{14}O beam is really awaited for since the direct reaction contribution would not be negligible, but it will be determined only by this method.

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