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HIGH-TEMPERATURE RAPID-PROTON CAPTURE PROCESS

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1 Explosive hydrogen burning under a high-temperature and high-density condition

Nuclear reactions on possible breakout processes off the Hot-CNO (HCNO) cycle are of great interest in nuclear astrophysics. This subject could be directly related to the problem of nucleosynthesis in novae and X-ray bursts. An interesting question here is if the CNO material is really transmuted into heavier elements in the explosive phenomena. This is also an important question for energy generation. However, crucial reactions for this problem are not well known yet.

Two breakout processes off the HCNO cycle, which lead to explosive hydrogen burning (rp-process), were first pointed out by Wallace and Woosely[1]. The reaction sequence of ^{15}O$(\alpha,\gamma)^{19}$Ne(p,γ)^{20}Na is considered to be one of them[2]. This breakout process was extensively investigated experimentally, although none of the reaction rates has been determined yet. Further, the early stage of the rp-process just after ^{20}Na was investigated systematically up to ^{25}Si at the CNS Cyclotron[3]. Many new resonances were discovered at the crucial temperature regions above the proton thresholds. These new resonances mostly are found to reduce the ignition temperatures considerably. Conse-

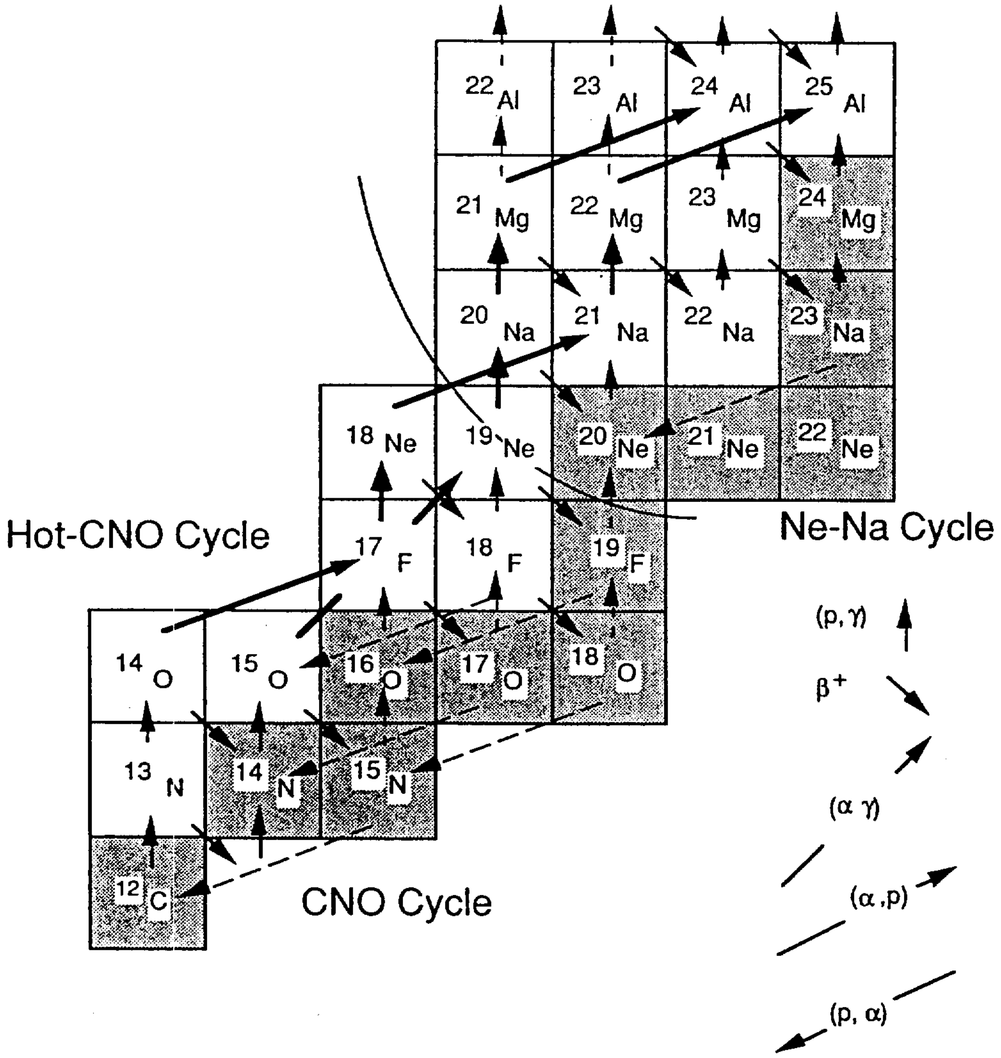

Figure 1: The nucleosynthesis flow diagram of the HCNO cycle and the rp-process. The thick arrows indicate possible breakout processes off the HCNO cycle.

quently, it is suggested that the ^{15}O$(\alpha,\gamma)^{19}$Ne reaction is the limiting reaction for the onset of the rp-process[3].

The second possible reaction sequence for the breakout off the HCNO cycle[1], would take place more likely in a stellar site under higher-temperature and higher-density conditions. We call it here HT rp-process in short. It is a reaction chain of ^{14}O$(\alpha$,p$)^{17}$F(p,$\gamma)^{18}$Ne $(\alpha$,p$)^{21}$Na, and is very little investigated. Here, a new type reaction $(\alpha$,p) sets in for the explosive burning phase in the low mass region on the nuclear chart. Nuclear levels in ^{18}Ne are not known well above the α threshold. The cross section of the second reaction in the sequence also is not determined yet. Therefore, we have started to investigate these breakout reactions experimentally. I will just discuss the problems

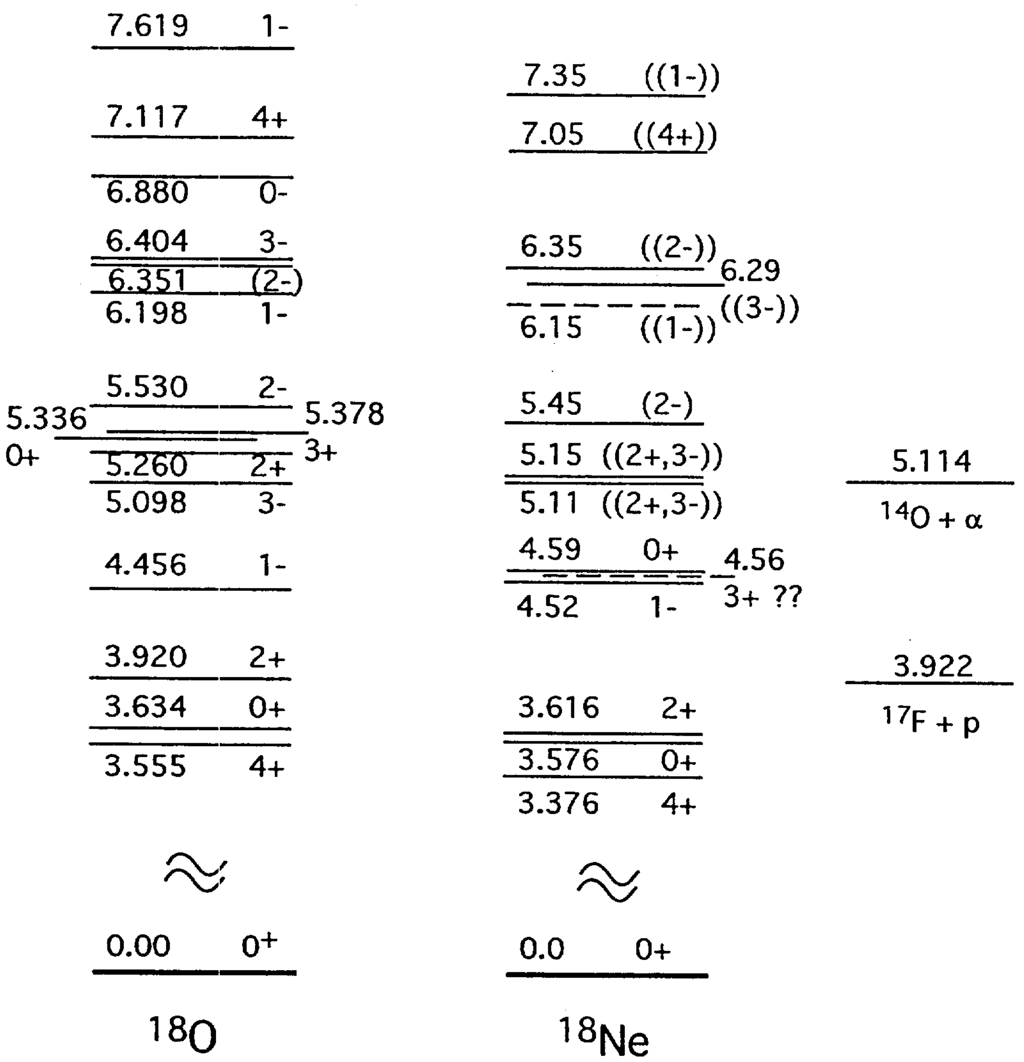

Figure 2: Level schemes of A = 18 nuclei.

and some results of the experiments.

2 Onset of the high temperature (HT) rp-process

Among the reaction chain for the onset of the HT rp-process mentioned above, the reaction of ^{14}O(α,p)^{17}F was investigated some time ago[4,5,6], and recently by indirect methods[7]. The nuclear structure of ^{18}Ne is crucial for the first two reactions along the reaction chain.

Figure 2 shows the level schemes of ^{18}Ne and the mirror nucleus ^{18}O[8,7]. The levels at 5.11 and 5.15 MeV states in ^{18}Ne were suggested to have 3^- and 2^+, respectively, in the previous predictions [4,5]. Hahn et al.[7], however, discussed inverted assignments for them from Thomas-Ehrman shift calculations. The levels near and above the α threshold is crucial for the first reaction,

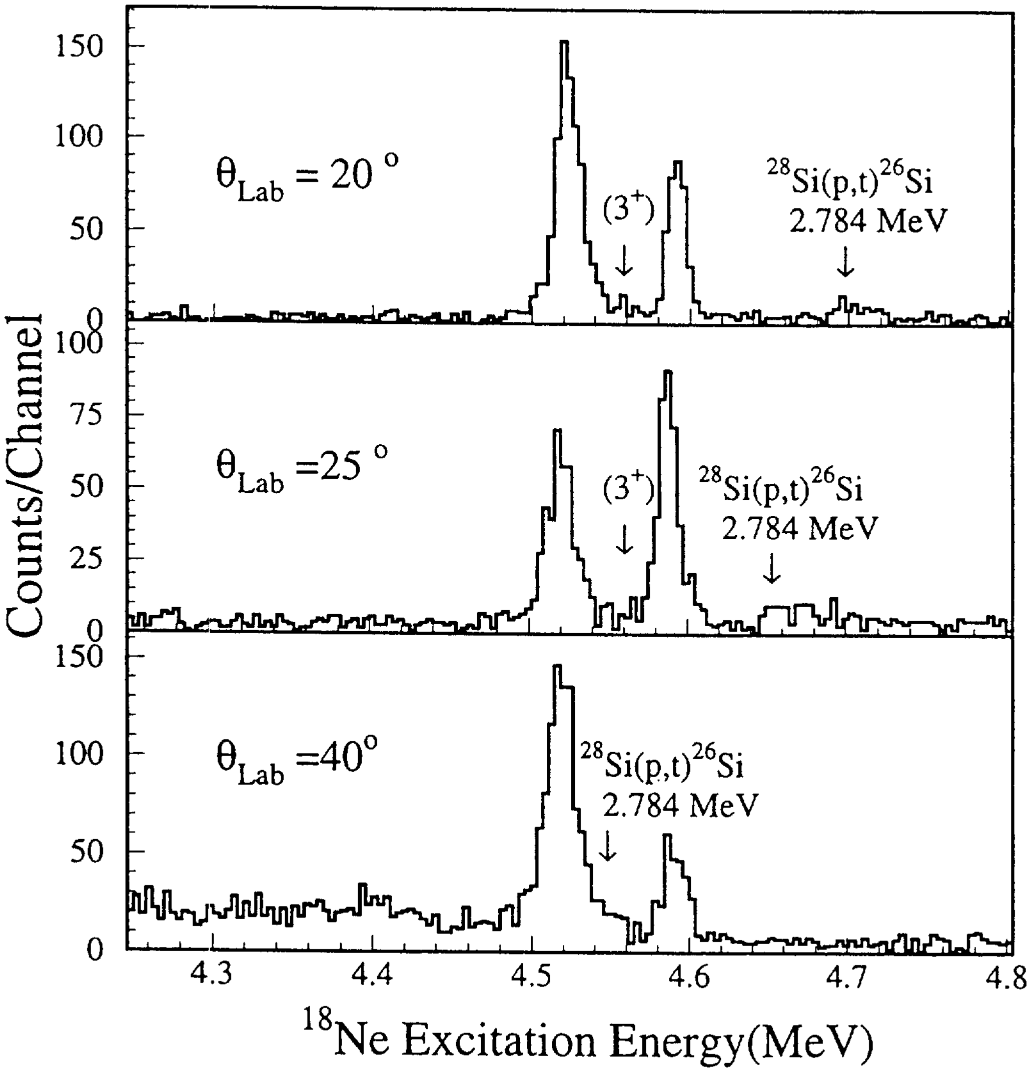

Figure 3: The triton spectra from the ^{20}Ne(p,t)^{18}Ne reaction at 35 MeV, measured at three angles denoted. The small peaks indicated by arrows are the tritons from the ^{28}Si(p,t) reaction.

^{14}O(α,p)^{17}F. However, some levels are not experimentally identified yet.

Experiment was made here with high resolution measurements using a Ne-implanted carbon target of about 50 μg/cm^2 (about 7 μg/cm^2 of Ne). Several spectra were taken for the ^{20}Ne(p,t)^{18}Ne reaction using a QDD-type magnetic spectrograph. The overall energy resolution was about 12 keV. The levels observed in the present experiment are summarized in Table 1. 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)[7], was not seen at any angles measured in the present experiment. A possibility is that this state has a quite different structure from a 2p-2h structure, such as many-particle many-hole configuration, and thus was not excited by the two-nucleon transfer reaction. Another possibility is that this

Table 1: Level widths and the spin parity of ^{18}Ne states observed in the present ^{20}Ne(p,t)^{18}Ne reaction. Here, a) is from ref. [7] and b) from ref. [8].

Excitation energy (MeV) $^{a)}$	Spin-parity adopted	Width (keV)
4.520	$1^{-\ b)}$	9±6
4.589	$0^{+\ b)}$	2±6
5.106	(2^+)	45±7
5.153	(3^-)	8±5
5.454		6±5
6.286		8±7
6.345		18±9

state is buried in the background which was relatively high due to the target. There are two states seen around 6 MeV. They could be analog states of the 6.20 MeV 1^- state and the 6.40 MeV 3^- state in ^{18}O[4]. 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(α,p)^{17}F.

The levels near and above the proton threshold are the main concern for the second reaction, ^{17}F(p,γ)^{18}Ne. A 3^+ state is known at 5.378 MeV in the mirror nucleus ^{18}O. However, the analog 3^+ state is not known in this energy region in ^{18}Ne. A special effort was placed on identifying the possible 3^+ state around 4.5 MeV. A Thomas-Ehrman shift calculation[14] 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,γ)^{18}Ne[4], 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[6]. A careful search was made here with high resolution measurements using the Ne target since 4.56 MeV is just in the middle of the known doublet of 4.52 and 4.59 MeV. However, there was no evidence observed in the spectra for a state between the doublet states. See Fig. 3. The background level is better than the previous spectrum[7] roughly by a factor of two. We observed small contamination peaks of ^{26}Si 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.

Eventually, the resonance strengths of the ^{14}O(α,p)^{17}F reaction are needed to be determined. Thus, the direct simulation study of the (α,p) reaction using an ^{14}O beam is really awaited for since the direct reaction contribution would not be negligible, and it will be determined only by the direct simulation method.

3 Some other problems in the HT rp-process

The flow of nucleosynthesis after the onset of the HT rp-process is very little known, mainly due to lack of nuclear physics information. Therefore, there are many other interesting problems in the scenario of the HT rp-process, such as the waiting points, the flow path at A > 60 region and the termination process.

The nucleus ^{22}Mg is considered to be the waiting point under nova conditions. This point would be skipped by the (α,p) reaction in the HT rp-process. This reaction will carry the flux from ^{22}Mg to ^{25}Al, resulting in skipping the beta decay of ^{22}Mg ($T_{1/2}$ = 3.86 sec) and other nuclear processes up to ^{25}Al. Thus, the explosion would not need to wait for the slow beta-decay processes there. The role of the (α,p) reactions, however, will be limited within a light mass region due to the Coulomb barrier. The flows around A=40 and 60 would be the critical bottle necks of the process. The reaction rates have to be investigated quantitatively. In addition under extremely high temperature conditions, two-proton capture process might take place and play an important role, as suggested in ref. [15].

The origin of the p-nuclei around A=100 is another interesting subject[16]. The HT rp-process was suggested to be one of the origins. The p-nuclei problem may be related to the termination process of the HT rp-process. All these problems of the nuclei and the reactions near the proton-drip line in the mass region of A = 60 - 100 should be of great interest for the HT rp-process.

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