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One of the critical stellar reactions for the onset of explosive hydrogen burning, $^{15}O(\alpha,\gamma)^{19}Ne$, is discussed with our recent experimental effort and a new possibility in our new RIB project. This reaction was investigated experimentally by indirect methods. Single particle nature of the threshold states was studied by the analog reactions, (d,t) and (d,^{3}He) on ^{20}Ne. The α-branching ratios for some states were also measured by a coincidence measurement of a triton and α from $^{19}F(^3He,t)^{19}Ne^*(\alpha)^{15}O(g.s.)$. Experimental plan for the problem was also discussed that uses a new low-energy RIB facility at CNS, called CRIB, which will come into operation soon.

1 Introduction

Proton-rich unstable nuclei play a crucial role in explosive hydrogen burning, which is called the rapid-proton capture process (rp-process) [1]. Nova is a typical site that involves the rp-process, where a chain of successive nuclear reactions together with beta decays lead to abundant production of variety of heavy elements such as Si, which is a stringent clue for understanding the rp-process [1,2]. Similarly, a recent x-ray observation gives us elemental distributions in the expanding outburst of the supernovae, partly of which might come from the rp-process. Line gamma-ray observations give us an interesting mapping of nuclides such as ^{26}Al in the galaxy [3], which also provides a very critical test of the models. The rp-process is discussed as a candidate for the production.

In the rp-process under a condition of novae, the CNO material would be transmuted to heavier elements. The first step of the process is considered to be ^{15}O(α,γ)^{19}Ne in the scenario [1], and could be followed by a chain of the reactions; ^{19}Ne(p,γ)^{20}Na(p,γ)^{21}Mg($\nu\beta^+$)^{21}Na(p,γ)^{22}Mg($\nu\beta^+$)^{22}Na(p,γ)^{23}Mg(p,γ)^{24}Al (p,γ)^{25}Si ... [1,2,4]. Here, most of the nuclear reactions in the chain were studied previously by indirect methods, and many resonances near and above the proton thresholds were discovered [2]. Consequently, most of the reaction rates from ^{19}Ne to ^{25}Si are enhanced, resulting in reduction of the ignition temperature of the processes. From our estimates of the reaction rates, the limiting reaction of the chain is considered to be the first step, ^{15}O(α,γ)^{19}Ne. However, the reaction rate of this process is not known well.

We have studied the properties of the ^{19}Ne excited states relevant to the ^{15}O(α,γ)^{19}Ne reaction by the mirror reactions, (d,t) and (d,^{3}He) on ^{20}Ne, exciting the mirror states. The branching ratio measurement of the threshold states was also tried using the reaction ^{19}F(^{3}He,t)^{19}Ne*(α)^{15}O(g.s.). We discuss in sec. 2 on the spectroscopic nature of ^{19}Ne threshold states, and in sec. 3 the measurement of α-branching ratios of the states in ^{19}Ne. A possibility of measurement of the α-widths, that provide the resonance strengths, using a new low-energy RIB separator which is under installation at Center for Nuclear Study, University of Tokyo (CNS), is also discussed in sec. 4.

2 Spectroscopic nature of the α-threshold states in ^{19}Ne

The possible limiting reaction for ignition of the rp-process, ^{15}O(α,γ)^{19}Ne, was investigated first by studying the property of the threshold states in ^{19}Ne with the charge symmetric reactions, ^{20}Ne(d,t)^{19}Ne and ^{20}Ne(d,^{3}He)^{19}F [5]. If the reaction particles and the residual states associated are all mirror states, the two reactions leading to the analog states would show similar angular distributions. This will be true because intermediate states which couple in the reactions would be also the mirror states and thus multi-step contributions could be roughly the same, resulting in angular distributions of similar shape. We may identify the mirror relation, and also get spectroscopic information on the states of interest.

Figure 1 displays the level schemes of A = 19 nuclei, taken from ref. [6]. Since the peak temperature of novae is somewhere around T_9 = 0.2 – 0.4, the nuclear levels relevant are those below 5 MeV in ^{19}Ne. Especially, the main contribution of the ^{15}O(α,γ)^{19}Ne stellar reaction is considered to come from the 4.033 MeV 3/2$^+$

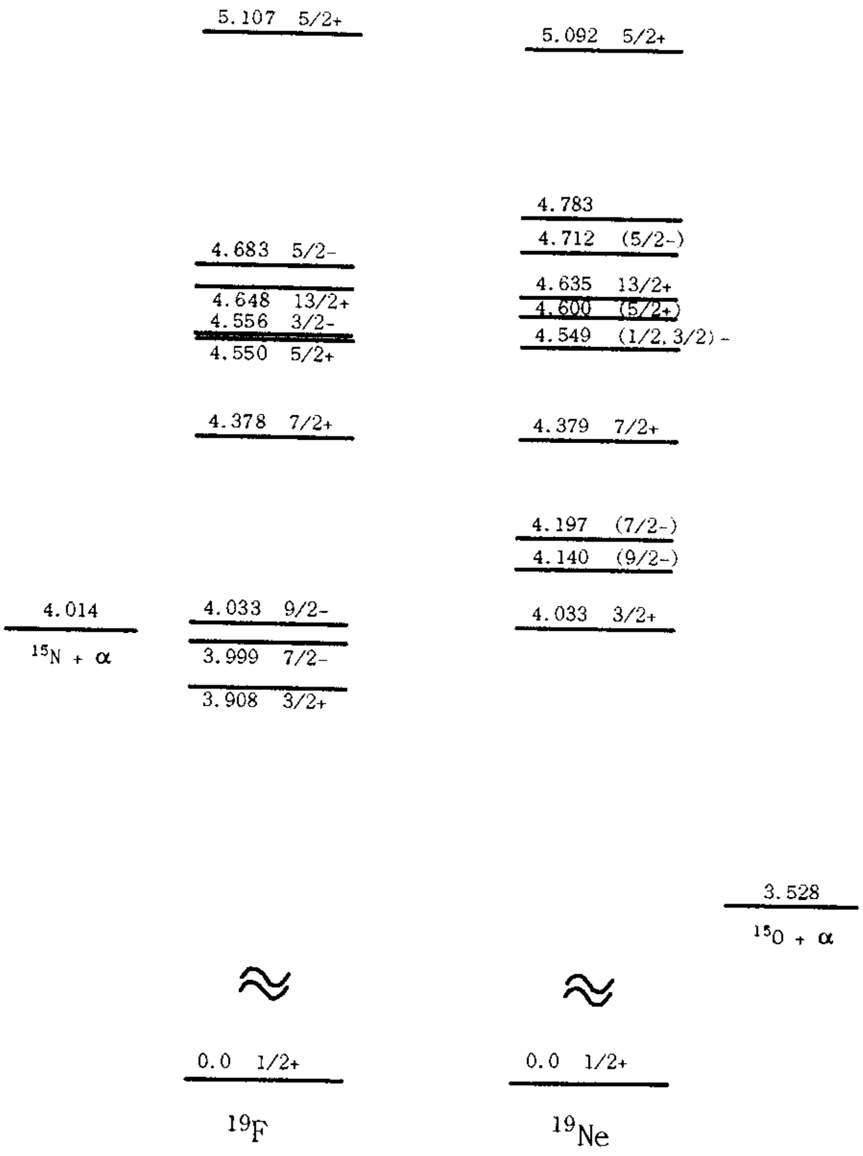

Fig. 1 Nuclear level schemes of ^{19}F and ^{19}Ne [6].

state. However, the property of the level as well as of the nearby-levels are not known well yet. For instance, the spin assignment for the levels at 4.140 and 4.197 MeV is not determined yet. They would contribute to the synthesis to some extent if they are the analog states of the 3.999 MeV $7/2^-$ state and the 4.033 MeV $9/2^-$ state in ^{19}F.

The experiment was made using a 30-MeV deuteron beam from the SF cyclotron at CNS. The reaction products tritons and ^{3}Hes' were momentum analyzed by a QDD spectrograph, and detected by a hybrid-type gas proportional counter and a plastic scintillator set behind on the focal plane. Figure 2 shows some spectra of the (d,t) and (d,^{3}He) reactions on ^{20}Ne at 30 MeV. The 4.033-MeV state

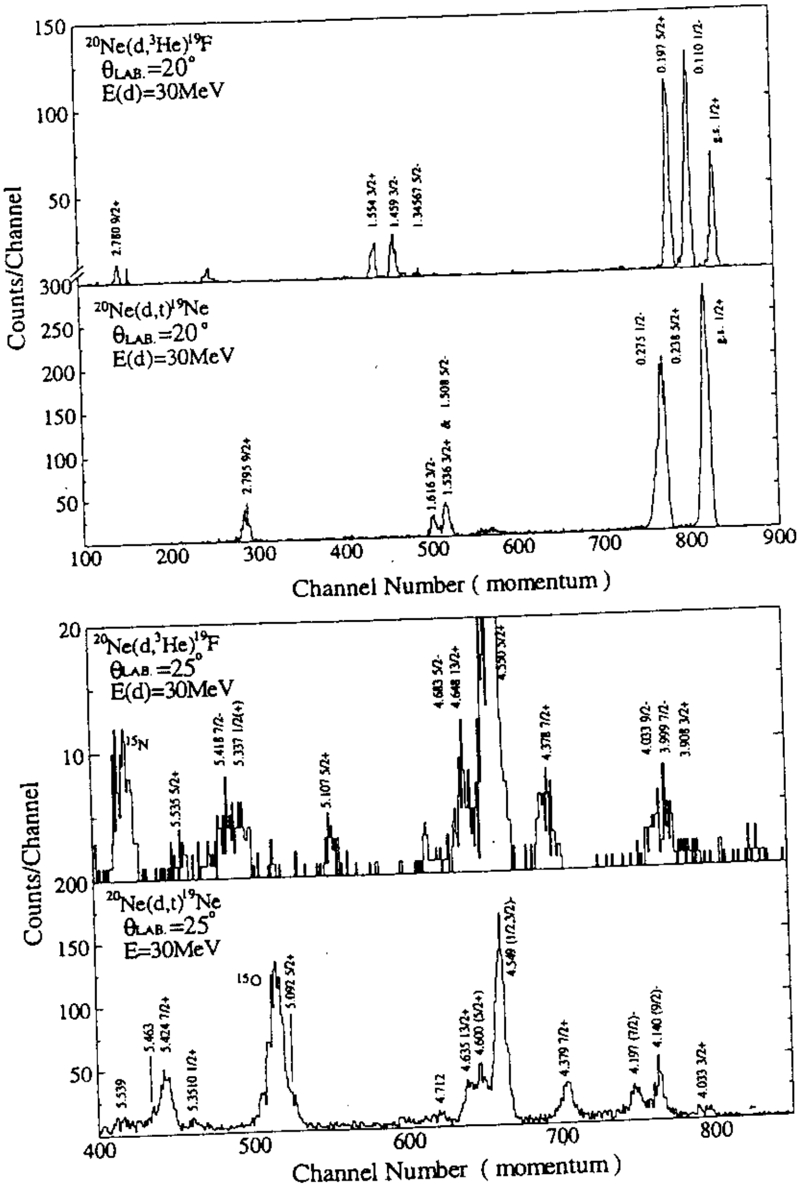

Fig. 2 Triton and ^{3}He spectra from the (d,t) and (d,^{3}He) reactions on ^{20}Ne, measured at 20 degrees with a 30-MeV deuteron beam.

in ^{19}Ne was very weakly excited by the (d,t) reaction. This suggests that there is very little $d_{3/2}$ single particle component in this state. The doublet at 4.140 and 4.197 MeV, which could be weak-coupled α-cluster states, is excited with larger cross sections. The angular distributions were measured for these levels in ^{19}Ne and the analog states in ^{19}F.

A DWBA analysis explains well the angular distribution for the 4.033 MeV state in ^{19}Ne with the angular momentum transfer l = 2, confirming the spin assignment of $3/2^+$ for the state. The spectroscopic factor derived for the state is as small as S = 0.04. This state, however, was excited strongly by the ^{21}Ne(p,t) ^{19}Ne reaction [6]. These suggest that this state has a 5-particle 2-hole nature. The stellar reaction, ^{15}O(α,γ)^{19}Ne, would proceed only through a small component of 2p-3h in ^{15}O. This is very much consistent with the very small α width, 9.9 ± 1.5 μeV, estimated by an α-transfer reaction leading to the analog state in ^{19}F [7].

3 Measurement of α–branching ratios of the threshold states in ^{19}Ne

If a radiative capture reaction of interest is dominated by a resonance, the reaction rate is roughly proportional to the resonance strength $\omega\gamma$. Here, ω is the spin factor and γ is the particle-width of the resonance when the resonance sits close to the particle threshold and thus the total width of the resonance is dominated by the gamma width. The present ^{15}O(α,γ)^{19}Ne stellar reaction is just a typical case that the resonance is located close to the particle decay threshold. The critical state estimated is the 4.033 MeV $3/2^+$ state for the problem of novae, as mentioned earlier. This state is excited with a reasonable cross section by the (^{3}He,t) reaction at 30 MeV.

The experiment was performed at the SF cyclotron of CNS. The target was CaF_2 of about 70 μg/cm^2, evaporated on C. The tritons from ^{19}F(^{3}He,t)^{19}Ne*(α)^{15}O were momentum analyzed by the QDD magnetic spectrograph, and detected by the focal plane detector mentioned in sec. 2. The tritons were uniquely identified by ΔE, E, and Time-of-Flight. The decay α particles were measured at backward angles in coincidence with the tritons by four Si detectors of 60x60 mm^2 area that have 12 strips, which covers about 11 % of 4π.

Figure 3 shows the energy spectra of the decay α particles from the excited states in ^{19}Ne. The spectra for the states above 4.5 MeV show clearly the α decay peaks, but it is not clear among the background in the spectra for the states below 4.5 MeV. The angular correlation function of the α decays from the 5.35 MeV state shows an isotropic distribution because it has $J^\pi = 1/2^+$, where the energy spectra were deduced for 8 angles by summing some strips to get better counting statistics. This correlation function assures that the system is working properly. The branching ratios were deduced from the coincidence probabilities of the tritons relevant. Here, the total yields of α particles were derived by extrapolating the angular correlation functions to the unmeasured angles.

The α–branching ratios were determined with a little better statistics in the present experiment than in the previous experiment [8], but are consistent with them for the high-lying states. However, the branching ratios of the critical levels at 4.033

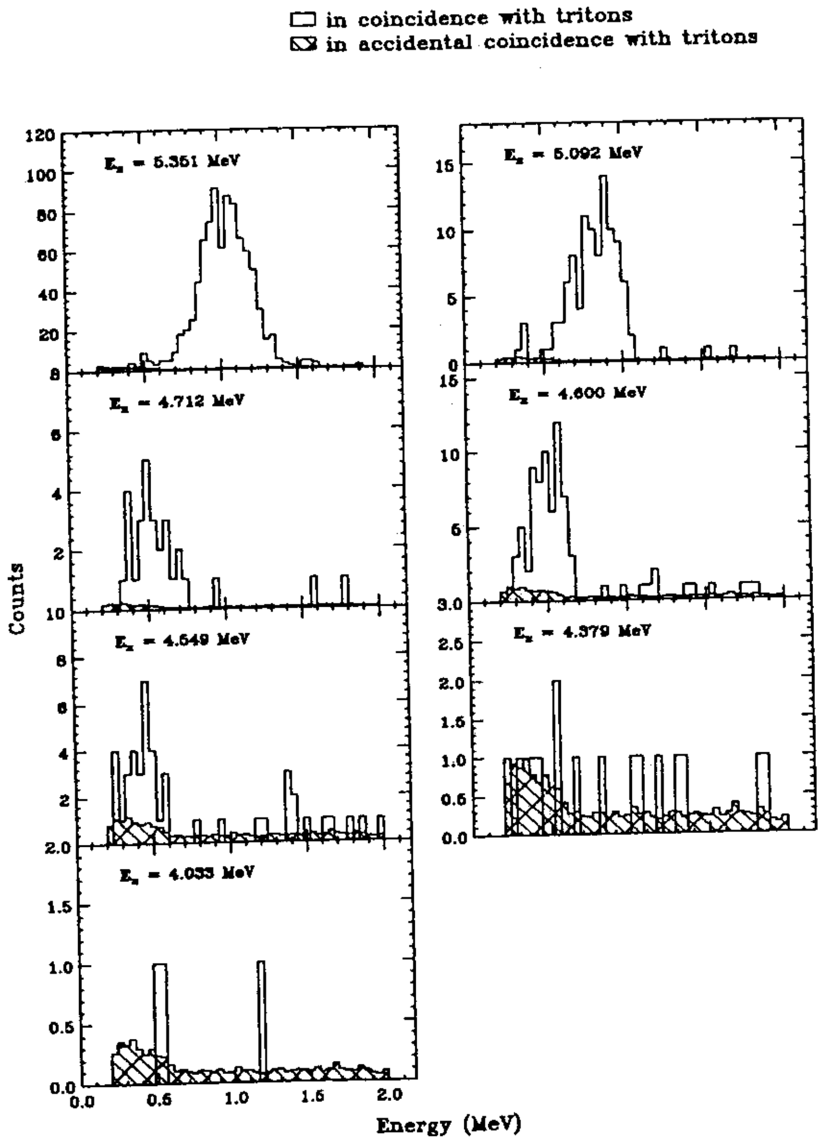

Fig. 3 Energy spectra of decaying alpha particles from the states denoted in ^{19}Ne, following the ^{19}F(^{3}He,t)^{19}Ne reaction.

and 4.379 MeV were not determined in the present experiment. Because of the very small α width, it is quite difficult to measure the branching ratio. It seems also quite difficult by the same reason to measure directly the cross section of the ^{4}He(^{15}O,γ)^{19}Ne reaction using an ^{15}O beam at the stellar energies.

4 Study of $^{15}O(\alpha,\gamma)^{19}Ne$ with a new RIB separator CRIB

The direct measurement of $^{15}O(\alpha,\gamma)^{19}Ne$ seems quite difficult because the yield rate expected would be very low, as discussed in the last section. An alternative way is to use a semi-direct method for the reaction, i.e., a direct α-transfer reaction to deduce the α width.

It could be investigated using the secondary beam of ^{15}O from the new low-energy RIB beam separator, CRIB, which is under construction at CNS in the RIKEN accelerator facility. As can be seen in Fig. 4, the system is composed of a gas target for the secondary beam production, a double achromatic separator with a degrader in between the two dipole magnets, and a Wien filter at end to get high purity secondary beams. Since the ion source technology has developed considerably in the recent years, one should be able to deduce the ^{15}O beam of $10^{8\text{-}9}$ aps on target. Since one may use (p,n) reaction at the energy just above the threshold energy in the inverse kinematics, the energy spread of the ^{15}O beam should

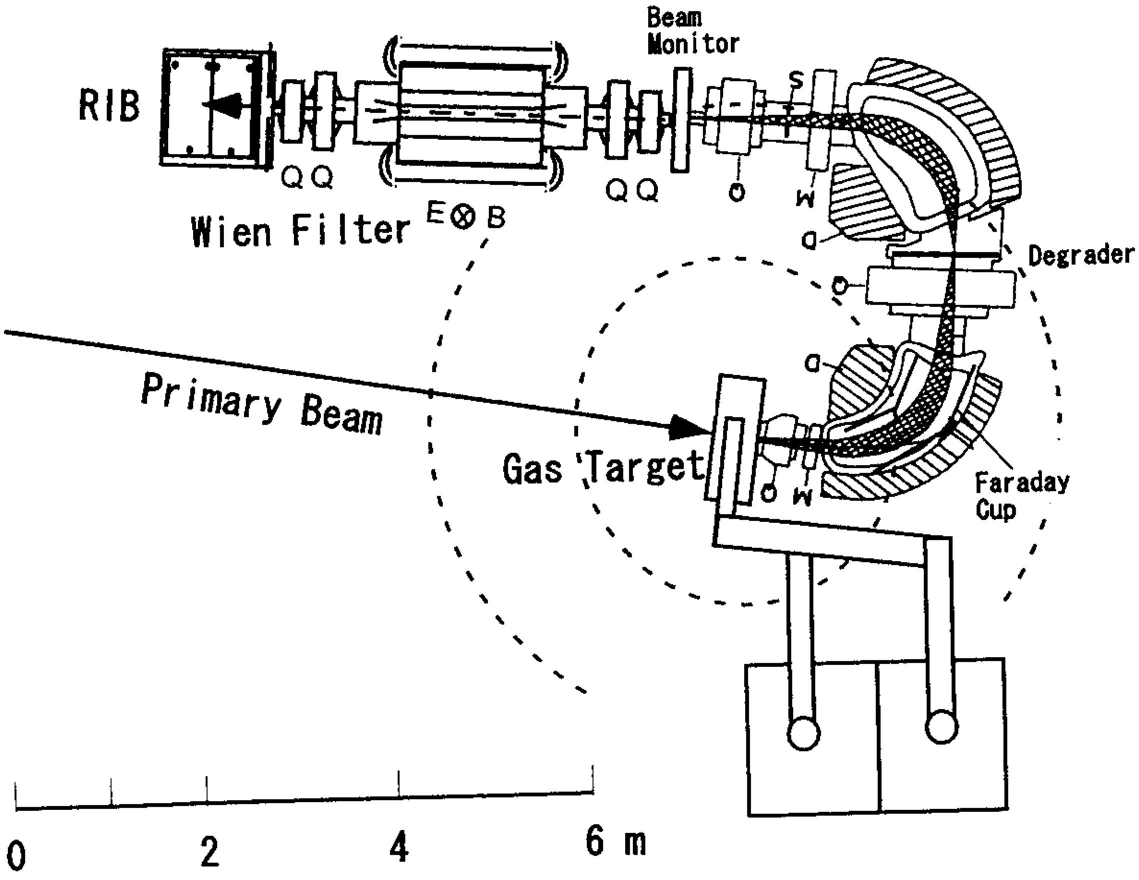

Fig. 4 A new low-energy RIB separator, CRIB, being installed at CNS, in the RIKEN accelerator facility.

be reasonably small, about 1 %, and the beam spot size of a few mm diameter at the focal plane.

If one can use an ^{15}O beam of 10^9 aps on target, one could measure the angular distribution for the ^{6}Li(^{15}O,^{19}Ne*(4.033))d reaction either measuring deuterons at backward angles or ^{19}Ne particles at forward angles from the reaction with a reasonable count rate, something like a few events per hour or more. Since the secondary beam has a certain energy spread, the energy resolution is the matter for the measurement of the direct α–transfer reaction, which should be taken care of in the experimental setups with the velocity filter at end.

Since the CRIB is simply an in-flight beam separator, one does not need to develop ion source technology for RIB production. The production of nuclear spices is very much limited to the nuclei close to the line of stability, as we use an AVF cyclotron of K = 70 as the driver machine. However, the production rate is very high because of the inverse kinematics we adopt here and also the large cross sections for production, although the available target thickness is small. This weak point will be compensated with very high beam intensities from ECR ion sources. This method for low energy RIB production should be, thus, very useful in practice. The CRIB is the first extensive RIB facility constructed with this method at low energies. The beam energies of 5 -15 MeV/u is just a good energy region for nuclear spectroscopy for both in-beam gamma spectroscopy as well as charged particle spectroscopy.

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