High-resolution study of the ^{18}Ne excited states relevant to the hot CNO cycle

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The ^{20}Ne(p,t) ^{18}Ne reaction has been studied in order to investigate the properties of ^{18}Ne excited states. A missing 3^+ state of ^{18}Ne, which could have a great influence on the ^{17}F(p,γ) ^{18}Ne reaction rate, was searched for, but the existence of this state was not clearly verified. The spins and parities of the 5.11- and 5.15-MeV states were assigned tentatively by angular distribution measurements, as 2^+ and 3^-, respectively. We were able to resolve the doublets at 4.5, 5.1, and 6.3 MeV clearly for the first time due to our high precision system, which allowed us to determine the widths of some critical states above the proton threshold of ^{18}Ne more precisely. [S0556-2813(99)06502-4]

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Hydrogen burning at high temperatures is known to proceed through the hot CNO (HCNO) cycle. In explosive environments such as novas and x-ray bursts, the rapid proton (rp) capture process plays an important role and can produce heavier elements. The rate of energy release in the HCNO cycle, however, is limited by the β^+ decays of ^{14}O and ^{15}O, and the reaction sequence ^{14}O(α,p) ^{17}F(p,γ) ^{18}Ne$(\beta^+\nu)$ ^{18}F(p,α) ^{15}O can bypass the β^+ decay of ^{14}O, resulting in a speeding up of the HCNO cycle [1]. Moreover, these reaction rates can also be related to the break out from the HCNO cycle and the onset of the rp capture process at higher temperatures. Therefore, the ^{14}O(α,p) ^{17}F and ^{17}F(p,γ) ^{18}Ne reaction rates become very important astrophysically. At present, the ^{14}O(α,p) ^{17}F and ^{17}F(p,γ) ^{18}Ne reaction rates have not been determined by direct measurement because of the instability of ^{14}O and ^{17}F and very small cross sections of the reactions. It is, however, often possible to calculate such rates by using resonance parameters obtained from other reactions with stable nuclei, such as ^{20}Ne(p,t) ^{18}Ne in this case. The excitation energies, decay branching ratios, widths, spins, and parities of the ^{18}Ne states play a decisive role in these respects.

Wiescher *et al.* [2] estimated the excitation energy of a missing 3^+ state in ^{18}Ne to be about 4.33 MeV from Thomas-Ehrman shift calculations. This missing state could have a decisive influence on the ^{17}F(p,γ) ^{18}Ne reaction rate. García *et al.* [3] searched for the missing state using the ^{16}O(^{3}He,n) reaction, and they reported a peak possibly caused by the 3^+ state located between the states of the 4.5-MeV doublet in ^{18}Ne. It was seen, however, at only one angle and one beam energy, and no other observation concerning this state has been reported.

Wiescher *et al.* [4] calculated the rate of alpha burning of ^{14}O based on the resonance structure of ^{18}Ne, obtained by comparison with analog states in ^{18}O and Thomas-Ehrman shift calculations. Funck *et al.* [5] pointed out the important contributions to the ^{14}O(α,p) reaction rate by the direct reaction process for temperatures $T_9 \leqslant 0.3$. Recently, Hahn *et al.* [6] studied the excited states of ^{18}Ne extensively using the ^{16}O(^{3}He,n) ^{18}Ne, ^{12}C(^{12}C,^{6}He) ^{18}Ne, and ^{20}Ne(p,t) ^{18}Ne reactions. Excitation energies, widths, absolute cross sections, and angular distributions were measured for ^{18}Ne states up to an excitation energy of 10 MeV, although their experiments had moderate experimental resolution.

In the present work, we studied the excited states of ^{18}Ne with high resolution by using the ^{20}Ne(p,t) ^{18}Ne reaction at a beam energy of 35 MeV. The proton beam was delivered by the sector-focusing cyclotron at the Center for Nuclear Study (CNS), University of Tokyo. The ^{20}Ne target was made by implanting ^{20}Ne into a 52.7-μg/cm^2 carbon foil. The target areal density of ^{20}Ne, determined from the yields of elastic scattering, turned out to be 5.8 μg/cm^2. Tritons were detected with a high-resolution QDD (quadrupole dipole dipole)-type magnetic spectrograph, where a position-sensitive gas proportional counter was placed on the focal plane. The focal plane detector has an effective length of 80 cm and a hybrid structure of a drift-space and proportional chamber. It has three thin position-sensitive counters, two ΔE counters, and a plastic E counter. The triton events were extracted cleanly by using gates on ΔE, E, and the time of

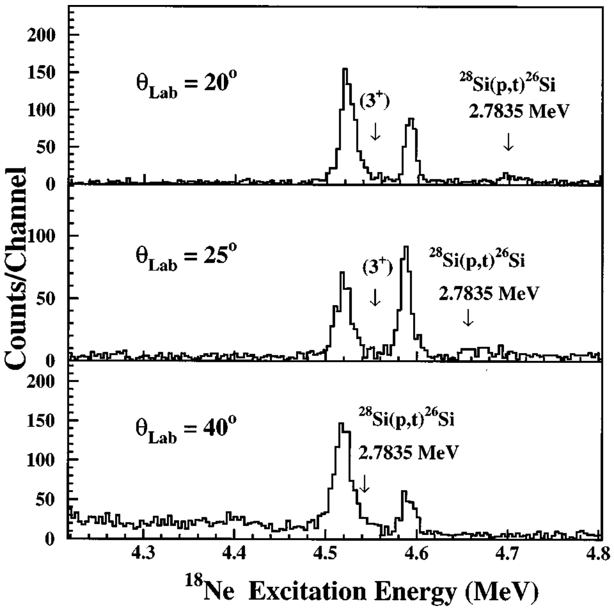

FIG. 1. Excitation energy spectra in the region $4.25\,\mathrm{MeV} \leqslant E_x \leqslant 4.8\,\mathrm{MeV}$ in ^{18}Ne.

flight from the target to the detector. The overall instrumental energy resolution achieved was about 12 keV. This excellent resolution was attributed to the thin solid target as well as to the high resolving power of the spectrograph. To date, no other data with such high resolution have been reported for the $^{20}\mathrm{Ne}(p,t)\,^{18}\mathrm{Ne}$ reaction. The three doublets near 4.5 MeV (4.520 and 4.589), 5.1 MeV (5.106 and 5.153), and 6.3 MeV (6.305 and 6.358) in ^{18}Ne were fully resolved in the present work, which enabled us to measure their widths and angular distributions better than previously.

We searched for a peak caused by the missing 3^+ state in ^{18}Ne. High-resolution excitation energy spectra were reconstructed from the triton energy, in the region $3.2\,\mathrm{MeV} \leqslant E_x \leqslant 5.6\,\mathrm{MeV}$, at $\theta_{\mathrm{lab}} = 20°$. Spectra were also taken at $\theta_{\mathrm{lab}} = 25°$ and 40°, to decide kinematically whether peaks corresponded to states in ^{18}Ne. Most of the peaks observed in the spectra were identified as states in ^{18}Ne resulting from ^{20}Ne in the target, states in ^{10}C and ^{11}C from the carbon backing, and states in ^{26}Si from ^{28}Si impurities. We investigated the region of the 4.5-MeV doublet, where García *et al.* [3] reported the possible peak for the missing 3^+ state. At $\theta_{\mathrm{lab}} = 20°$ a small bump structure appeared at the excitation energy consistent with the previous suggestion [3]. It is, however, hard to verify the existence of similar structure at $\theta_{\mathrm{lab}} = 25°$, as shown in Fig. 1. A broad structure, which was observed at $\theta_{\mathrm{lab}} = 20°$ and 25°, above the 4.5-MeV doublet, was identified as the 2.784-MeV state in ^{26}Si. This impurity peak moved relative to the ^{18}Ne peaks as the angle changed and is located near the 4.5-MeV doublet at $\theta_{\mathrm{lab}} = 40°$. No possible peak appeared within experimental limits below the 4.5-MeV doublet, where Wiescher *et al.* [2] had suggested the missing 3^+ state should lie. Even with the enhanced resolution, but with our limited statistics, the present experiment does not give a decisive indication of the missing state. It should be noted that this unnatural parity state is not expected to be strongly excited in the $^{20}\mathrm{Ne}(p,t)$ reaction via direct pickup of two neutrons paired to $S=0$, as in the triton. Similar considerations also apply to the direct stripping of a pair of $S=0$ protons via the $^{16}\mathrm{O}(^{3}\mathrm{He},n)\,^{18}\mathrm{Ne}$ reaction in which this 3^+ state was populated only very weakly compared to the neighboring 1^- and 0^+ states.

The spins and parities of the highly excited states of ^{18}Ne have not been assigned definitively previously. The spin and parity of the 5.15-MeV state above the α threshold (5.114 MeV) would greatly influence the $^{14}\mathrm{O}(\alpha,p)\,^{17}\mathrm{F}$ reaction rate [6]. In previous work [8], Falk *et al.* reported that the 5.1-MeV doublet is comprised of 2^+ and 3^- states, from angular distributions of tritons from the $^{20}\mathrm{Ne}(p,t)\,^{18}\mathrm{Ne}$ reaction, in which the 5.1-MeV doublet of ^{18}Ne had not been resolved. On the basis of the $T=1$ analog levels of ^{18}O and ^{18}Ne, the spin and parity of the 5.15-MeV state was possibly assigned 2^+ [4]. Recently, Hahn *et al.* [6] suggested J^π's of the 5.11- and 5.15-MeV states in ^{18}Ne as 2^+ and 3^-, respectively. Their assignments were based on penetrability considerations; i.e., a level emitting protons with lower l values generally has a larger width than a state with a higher l. On that basis it appeared that the spins and parities of the 5.11- and 5.15-MeV states in ^{18}Ne should be 2^+ and 3^-, respectively, but they had not been definitively determined by their experiment.

We measured triton angular distributions for the 5.11- and 5.15-MeV states for the first time. Distorted-wave Born approximation (DWBA) calculations were performed using the code DWUCK4 for comparison with the measured angular distributions. The optical potential parameters for the entrance channel were obtained from Falk *et al.* [8] at a proton energy of 42.5 MeV. Some parameters of this set were varied slightly to fit elastic scattering of 35-MeV protons on ^{20}Ne [7]. The parameters of the $t+{}^{18}\mathrm{Ne}$ exit channel were adjusted to give a better fit to the angular distributions for the states at 5.11 and 5.15 MeV. The parameters used are listed in Table I. The comparison with data, shown in Fig. 2, enables one to assign the spin and parity for the two states. The match between these calculations and our measured angular distributions strongly supports the assignments of $J^\pi = 2^+$ to the 5.11-MeV state and $J^\pi = 3^-$ to the 5.15-MeV state. The results of the penetration arguments of Hahn *et al.* [6] are consistent with our assignments.

The widths of the states above the proton threshold are also of interest in determining the $^{14}\mathrm{O}(\alpha,p)\,^{17}\mathrm{F}$ and $^{17}\mathrm{F}(p,\gamma)\,^{18}\mathrm{Ne}$ reaction rates. The energy resolution of about

TABLE I. Optical-model potential parameters used for the DWBA calculations.

	V_0 (MeV)	r_0 (fm)	a_0 (fm)	W_v (MeV)	r_v (fm)	a_v (fm)	W_D (MeV)	r_D (fm)	a_D (fm)
$p+{}^{20}\mathrm{Ne}$	−42.33	1.197	0.746	−11.31	1.196	0.786	00.72	1.196	0.786
$t+{}^{18}\mathrm{Ne}$	−100.0	1.38	0.75	−85.00	1.55	0.85	45.00	1.90	0.50

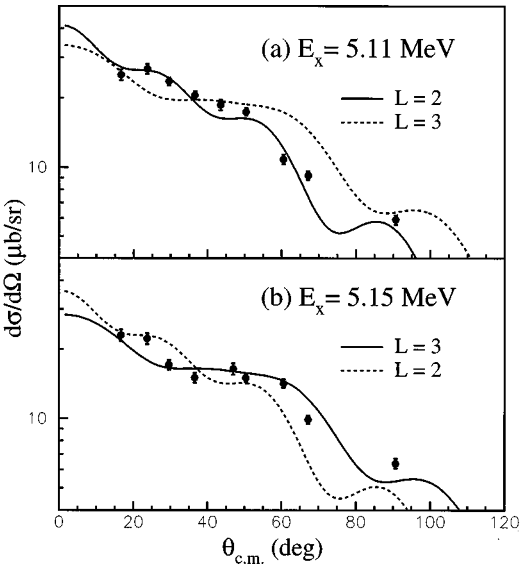

FIG. 2. Angular distributions of the ^{20}Ne(p,t) ^{18}Ne reaction leading to the 5.11- and the 5.15-MeV states. The curves are the results of DWBA calculations. The solid curves are for $l=2$ in the 5.11-MeV state case and for $l=3$ in the 5.15-MeV state case. The dashed ones are for $l=3$ in the 5.11-MeV case and for $l=2$ in the 5.15-MeV case.

12 keV in the present work resulted in more precise values in determining the widths of the levels in ^{18}Ne than previous results [6], where the resolution was about 20–25 keV. The instrumental width is mainly contributed from the incident proton beam energy spread, the spread in energy loss of the tritons through the target, the resolution of the spectrograph, and that of the focal plane detector. The instrumental width was extracted from a particle bound state at 3.616 MeV excitation. It was assumed that the instrumental spreads are Gaussian distributions, but the resonance structures are Lorentzian distributions. Hence two different functions were convoluted for each peak, in order to deduce the intrinsic widths of the states. The extracted widths of observed states are shown in Table II and are compared with the previous results [6].

TABLE II. Summary of ^{18}Ne levels above the proton decay threshold.

Previous result [6]		Our work	
E_x (MeV±keV)	Γ (keV)	E_x (MeV±keV)	Γ (keV)
4.520± 7	9±6		9±6
4.589± 7	4±4		2±6
5.106± 8	49±6, 45±5		45±7
5.153± 8	≤20, ≤15		8±5
5.454± 8	≤20	5.467±5[a]	6±6
6.286±10	≤20	6.305±4[a]	8±7
6.345±10	45±10	6.358±5[a]	18±9

[a]The levels in ^{10}B, ^{13}N, and ^{17}F from ^{13}C(p,α), ^{16}O(p,α), and ^{20}Ne(p,α) were used for the energy calibration.

To summarize, we have studied the states of ^{18}Ne above the proton threshold with improved resolution. No peak for the missing 3^+ state was clearly identified with our ^{20}Ne(p,t) ^{18}Ne reaction study. Spin and parity assignments for the 5.11- and 5.15-MeV states have been made based on measured angular distributions for the first time, and more accurate widths have been deduced for the ^{18}Ne states above the ^{17}F$+p$ threshold. The current work, which displays smaller uncertainties due to the use of a high-resolution detection system, makes it possible to calculate the ^{14}O(α,p) ^{17}F reaction rate more accurately. Further spectroscopic study of ^{18}Ne will be of great interest; however, finding the non-normal-parity 3^+ state by (p,t) or (t,p) reactions may prove difficult, as pointed out above, because of the pairing of the two neutrons in the triton to $S=0$.

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