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The high-resolution study of the ^{18}Ne structure relevant to the hot CNO cycle

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Abstract

The ^{20}Ne(p,t)^{18}Ne reaction has been studied in order to investigate the property of ^{18}Ne excited states. The missing 3^+ state of ^{18}Ne, which should 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 MeV and the 5.15 MeV states were assigned tentatively by the angular distribution measurements, as 2^+ and 3^-, respectively. The high resolution of our system could resolve the doublets which has been impossible before, and the width of some critical states above the proton threshold of ^{18}Ne were determined more precisely.

PACS number(s): 26.20.+f, 25.55.Hp, 27.20+n, 97.39.Qt

The hydrogen burning at high temperature is known to be carried out through the hot CNO (HCNO) cycle. At the explosive environment such as novae, and x-ray burst, the rp (rapid proton capture)-process plays an important role. Heavy elements could be produced through the rp-process. The energy release in the HCNO cycle, however, is limited by the β^+ decay of ^{14}O and ^{15}O, and the reaction sequence of ^{14}O(α,p)^{17}F(p,γ)^{18}Ne($\beta^+\nu$)^{18}F(p,α)^{15}O can be an alternative path to the β^+ decay of ^{14}O, which results in speeding up the HCNO cycle [1]. Therefore, the reaction rates of ^{14}O(α,p)^{17}F and ^{17}F(p,γ)^{18}Ne become very important astrophysically. Moreover, these reaction rates can be related to the break out off the HCNO cycle and the onset of the rp process at high temperature. At present the reaction rates of ^{14}O(α,p)^{17}F and ^{17}F(p,γ)^{18}Ne are not determined by the direct measurement because of the instability of ^{14}O and ^{17}F nuclei. It is, however, possible to calculate the rates using the resonance parameters obtained from other reactions with stable nuclei, such as ^{20}Ne(p,t)^{18}Ne. The excitation energies, the decay branching ratios, the widths, the spins, and parities of the ^{18}Ne states have a decisive role in these respects.

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

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

In the current work, we studied the structure 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 from 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 carbon foil of 52.7 μg/cm^2 thick. The target thickness 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-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 chambers. It has three thin position counters, two ΔE counters, and a plastic E counter. The triton events were extracted uniquely by using the gates on ΔE, E, and the time-of-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 fabricated by implantation as well as to the high resolving power of the spectrograph. To date, no other data with such high resolution have been reported in the ^{20}Ne(p,t)^{18}Ne reaction study. The three doublets near 4.5 (4.520 and 4.589), 5.1 (5.106 and 5.153), and 6.3 (6.305 and 6.358) MeV in ^{18}Ne were fully resolved in the present work, which enabled us to measure widths and angular distributions to a high level of accuracy.

We tried to observe the peak of the missing 3^+ state in ^{18}Ne. High resolution spectrum of the ^{18}Ne excitation was reconstructed from the triton energy, in the region of 3.2 MeV $\leq$ $E_x \leq$ 5.6 MeV, at $\theta_{Lab} = 20^o$. The spectra were also taken at $\theta_{Lab} = 25^o$, and 40^o, to decide kinematically whether small peaks belong to the states in ^{18}Ne. Most of the peaks observed in the spectra were identified as states in ^{18}Ne resulting from the ^{20}Ne target, states in ^{10}C and ^{11}C from the carbon backing, and states in ^{26}Si from ^{28}Si impurities, respectively. We investigated the region of the 4.5 MeV doublet, where García *et al.* [3] reported the possible peak of the missing 3^+ state. A small bump structure appeared at the excitation consistent with the previous suggestion at $\theta_{Lab} = 20^o$ [3]. It is, however, hard to verify the existence of the similar structure at $\theta_{Lab} = 25^o$, as shown in Fig. 1. A broad structure, which was observed at $\theta_{Lab} = 20^o$ and 25^o above the 4.5 MeV doublet, was identified as the 2.784 MeV state in ^{26}Si. This impurity peak is moved as the angle changes, and is located around the 4.5 MeV doublet at $\theta_{Lab} = 40^o$. No possible peak appeared within an experimental level below the 4.5 MeV doublet, where Wiescher *et al.* [2] had suggested the missing 3^+ state lie. Given enhanced resolution and limited statistics, the results of the present experiment do not give decisive indication of the missing state.

The spins and parities of the highly excited states of ^{18}Ne have not been assigned exactly yet. The spin and parity of the 5.15 MeV state above the α-threshold (5.114 MeV) greatly influences the ^{14}O(α,p)^{17}F reaction rate [6]. In the previous work [8], Falk *et al.* reported that the 5.1 MeV doublet is comprised of a 2^+ and a 3^- states, from the angular distributions of tritons from the ^{20}Ne(p,t)^{18}Ne reaction, in which the 5.1 MeV doublet of ^{18}Ne had not been resolved. On the basis of the T=1 analog structure 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 MeV and 5.15 MeV states in ^{18}Ne as 2^+ and 3^-, respectively. These assignments are based on the penetrability consideration, i.e., a level emitting protons with lower l values generally has a larger width than a state with a higher l. The spins and parities of the 5.11 MeV state and 5.15 MeV state in ^{18}Ne could be 2^+, or 3^-, but they have not been exactly determined by experiment yet.

We measured the angular distributions for the 5.11 MeV and 5.15 MeV states for the first time. Distorted wave Born approximation (DWBA) calculations were performed using the code DWUCK4 to reproduce 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 fit to elastic scattering of 35-MeV protons on ^{20}Ne [7]. The parameters of the t + ^{18}Ne exit channel were adjusted slightly so that the calculated angular distributions give a better fit to the experimental angular distributions for the 5.11 MeV state and 5.15 MeV state, in considering that l could be 2 or 3 from the previous study. The parameters used are listed in Table I. The comparison between experimental and calculated angular distributions, shown in Fig. 2 enables us to assign the spin and parity for the 5.11 MeV to be 2^+, and that for the 5.15 MeV state to be 3^-. This spin assignment is consistent with the suggestion by Hahn *et al.* [6].

The widths of the states above the proton threshold are also of interest in determining the reaction rates of ^{14}O(α,p)^{17}F and ^{17}F(p,γ)^{18}Ne. The energy resolution of about 12 keV in the present work resulted in more precise value in determining the widths of the levels in ^{18}Ne than the previous result [6], in which the resolution had been 20 - 25 keV. The instrumental width is mainly contributed from the incident proton beam energy uncertainties, the energy loss of triton through the target, the resolution of the spectrograph, and that of the focal plane detector. The instrumental width was deduced from a particle bound state at 3.616 MeV excitation. It is also assumed that the instrumental uncertainties are of Gaussian shape but the resonance structure has a shape of Lorentzian distribution. Hence, two different functions are convoluted in 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].

To summarize, we studied the states of ^{18}Ne above the proton threshold with high resolution. The possible peak for the missing 3^+ state was not clearly identified in this experiment. The spins and parities of the 5.11 MeV and 5.15 MeV states could be 2^+ and 3^-, respectively, and the widths of the states above the proton threshold were deduced precisely. The current work, which displays less uncertainties due to the use of high resolution detecting system, makes it possible to calculate the reaction rate of the ^{14}O(α,p)^{17}F with high accuracy. Further spectroscopic study of ^{18}Ne should be of great interest for the current subject.

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FIGURES

FIG. 1. The excitation energy spectra at the region of 4.25 MeV $\leq$ E_x $\leq$ 4.8 MeV in ^{18}Ne.

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

TABLES

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

	V_o (MeV)	r_o (fm)	a_o (fm)	W_v (MeV)	r_v (fm)	a_v (fm)	W_D (MeV)	r_D (fm)	a_D (fm)
p+^{20}Ne	-42.33	1.197	0.746	-11.31	1.196	0.786	00.72	1.196	0.786
t+^{18}Ne	-100.0	1.38	0.75	-85.00	1.55	0.85	45.00	1.90	0.50

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

Previous Result [6]		Our Work	
E_x (MeV)	Γ (keV)	E_x (MeV)	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.

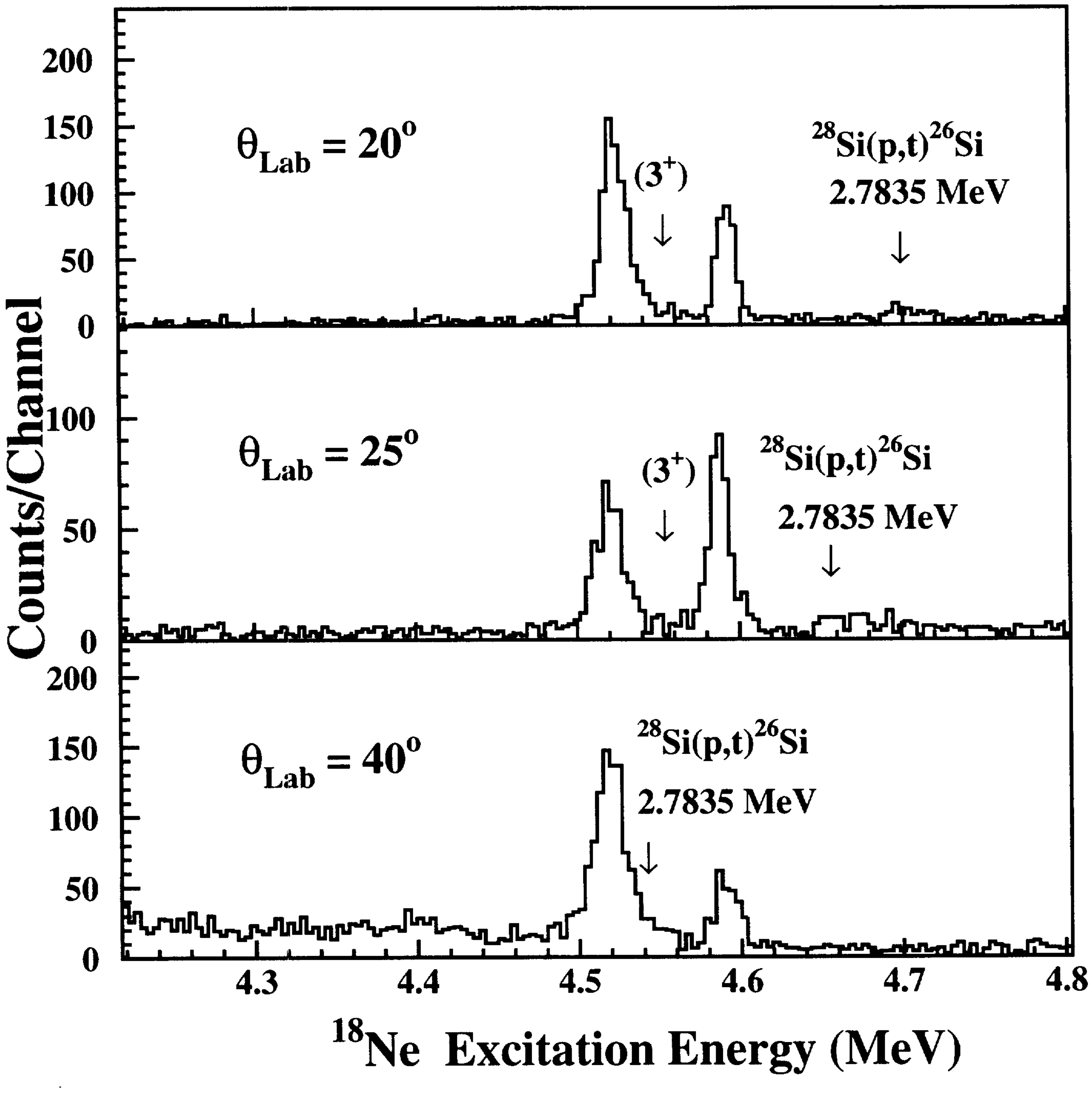
θLab = 20°
(3+)
28Si(p,t)26Si
2.7835 MeV
θLab = 25°
(3+)
28Si(p,t)26Si
2.7835 MeV
θLab = 40°
28Si(p,t)26Si
2.7835 MeV
Counts/Channel
0
50
100
150
200
0
50
100
0
50
100
150
200
4.3
4.4
4.5
4.6
4.7
4.8
18Ne Excitation Energy (MeV)

Fig. 1

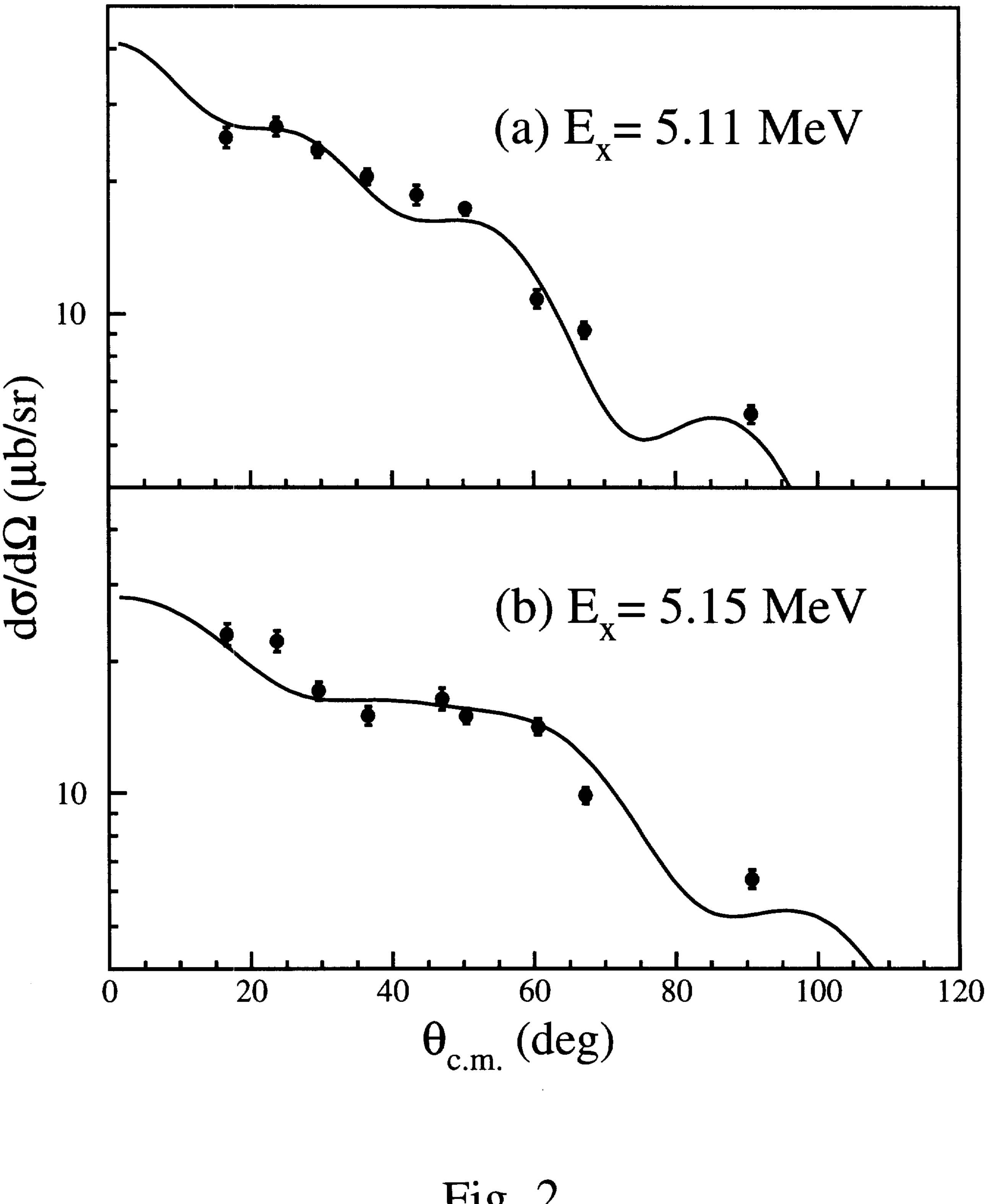
(a) E_x= 5.11 MeV
(b) E_x= 5.15 MeV
10
10
dσ/dΩ (μb/sr)
0
20
40
60
80
100
120
$\theta_{c.m.}$ (deg)

Fig. 2