Current progress of nuclear astrophysical reaction
and decay study at CIAE

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Abstract. Presented here was current progress of the study of nuclear astrophysical reaction
and decay at CIAE. We studied astrophysical $^{12}$N(p,$\gamma$)$^{13}$O reaction through the measurement
of the $^{12}$N(d,n)$^{13}$O angular distribution in inverse kinematics. Our result is in agreement with
that from the $^{14}$N($^{12}$N,$^{13}$O)$^{13}$C reaction and two shell model calculations. We also measured
the angular distributions of single neutron transfer reaction of $^{7}$Li($^{6}$Li,$^{7}$Li)$^{6}$Li, and derived the
reaction cross section for $^{6}$Li(n,$\gamma$)$^{7}$Li by using the present spectroscopic factor. The astrophysical
reaction rate is found to be higher by a factor of 1.7 than the value adopted in previous
reaction network calculations. In addition, half-life of $^{147}$Sm in metal samarium and Sm$_2$O$_3$
was measured. No significant change has been observed within the experimental uncertainty.

1. Introduction
Direct reactions like (d,n) can be used to determine the (p,$\gamma$) reaction cross sections indirectly,
using the asymptotic normalization coefficient (ANC) or spectroscopic factor (SF) extracted
from the measured (d,n) angular distribution [1]. As an example, we measured the $^{7}$Be(d,n)$^{8}$B
angular distribution in inverse kinematics at $E_{c.m.} = 5.8$ MeV and extracted the ANC for the
virtual decay $^{8}$B $\rightarrow$ $^{7}$Be + p based on distorted wave Born approximation (DWBA) analysis.
The astrophysical S-factor for the $^{7}$Be(p,$\gamma$)$^{8}$B reaction at zero energy was derived by ANC
method, for the first time [2]. This method was also used to indirectly determine astrophysical
S-factors for the $^{11}$C(p,$\gamma$)$^{12}$N [3] and $^{13}$N(p,$\gamma$)$^{14}$O [4] reactions. In this paper, we extended this
method to the reaction of $^{12}$N(p,$\gamma$)$^{13}$O.

The similar approach can be used to determine the (n,$\gamma$) reaction rates based on the (d,p) or
other one neutron transfer reaction. Since these are normally s-wave neutron capture reactions,
the contribution inside the nucleus is not negligible, and thus the ANC approach is no more
valid. Alternatively, the spectroscopic factor (SF) method by constraining the optical potential
parameters with their volume integrals per nucleon is developed to solve this problem. Its
feasibility is demonstrated by the fact that the volume integral per nucleon is nearly a constant
for 1p shell, and was successfully used to deduce the reaction rate of $^{8}$Li(n,$\gamma$)$^{9}$Li [5]. We showed
the application of this method to the case of $^{6}$Li(n,$\gamma$)$^{7}$Li reaction.

A possible influence of the quasi-free electron cloud in metallic environment on the $\alpha$-decay
process has attracted an intense interest in recent years. It was predicted [6, 7] that the $\alpha$-
decay rate could be enhanced by a factor greater than two in the metal hosts. Contrary to these
predictions, the theoretical calculation with quantum mechanical tunneling arguments indicated
that the change of α-decay rate in metals is negligibly small [8]. A change of decay rate will have significant astrophysical impact, since half-life is an important input to the astrophysical network calculation. In this paper, we presented the study of half-life of $^{147}$Sm in metal samarium and Sm$_2$O$_3$.

2. $^{12}$N(p,γ)$^{13}$O reaction

The $^{12}$N(p,γ)$^{13}$O reaction is one of the key reactions in rap-I and rap-II chains [9]. Due to the low Q-value (1.516 MeV), the $^{12}$N(p,γ)$^{13}$O cross sections at low energies of astrophysical interest are dominated by the direct capture into the ground state and the resonant capture via the first excited state of $^{13}$O. Currently, the extracted astrophysical S-factor S(0) at zero energy has large discrepancies.

The experiment was performed with the CNS Radioactive Ion Beam (CRIB) facility at CNS/RIKEN. A primary $^{10}$B beam with the energy of 82 MeV was yielded from the AVF cyclotron. The secondary $^{12}$N ions with the energy of 70 MeV were produced through the $^3$He($^{10}$B,$^{12}$N) reaction and then separated by the CRIB facility. Two parallel plate avalanche counters (PPACs) were used to trace incident each $^{12}$N particle and determine its incident angle and position on secondary target. After the two PPACs, the secondary $^{12}$N beam bombarded a (CD$_2$)$_n$ foil to study the $^2$H($^{12}$N,$^{13}$O)n reaction. The typical purity and intensity of $^{12}$N beam on target were approximately 30% and 200-600 pps, respectively. The reaction products $^{13}$O were detected and identified with a telescope consisting of a 23 μm silicon detector (ΔE) and a 57 μm double-sided silicon strip detector (DSSD).

The emitted angle of reaction products was determined by combining the information from the DSSD and the two PPACs. The selection of $^{13}$O events from $^2$H($^{12}$N,$^{13}$O)n were determined with a Monte Carlo (MC) simulation, which took into account the energy loss, kinematics, geometrical factor, angular and energy straggling effects in the two PPACs, secondary target and ΔE detector [4]. This simulation was calibrated with the $^{12}$N beam. The detection efficiency correction (due to the stopping of large angle events) from beam stopper was also computed via MC simulation. After beam normalization and background subtraction, the $^2$H($^{12}$N,$^{13}$O)n angular distribution in center of mass frame was obtained and shown in Fig. 1.

In the present calculation, two sets of optical potentials (Set1 and Set2) of nucleon-target were taken from Ref. [10, 11] respectively. The theoretical calculations on direct process with two sets of optical potential were displayed in Fig. 1, together with compound nucleus (CN) contribution obtained by UNF code [12]. After the subtracting the CN contribution, the first three data points were used to derive the SF of $^{13}$O by the normalization of experimental data to theoretical calculations. For one set of optical potential, three SFs can be obtained by using the first three data points, which is corresponding to the peripheral process. Their weighted value was then taken as SF for this set of optical potential. The ratio of 1$p_{3/2}$:1$p_{1/2}$ was derived to be 0.16 based on shell model calculation [13].

The SF was extracted to be 0.80 ± 0.30 (0.69 ± 0.26 for 1$p_{1/2}$ orbit, 0.11 ± 0.04 for 1$p_{3/2}$ orbit). The error results from the measurement (36%) and the uncertainty of optical potential (11%). Our result is in agreement with that from the $^{14}$N($^{12}$N,$^{13}$O)$^{13}$C reaction [14] and two shell model calculations [9, 13]. The calculation on astrophysical S-factors and reaction rates for $^{12}$N(p,γ)$^{13}$O is in progress now.

3. $^6$Li(n,γ)$^7$Li reaction

In the reaction network calculation of primordial nucleosynthesis and other astrophysical scenarios, the reactions involving lithium isotopes play an important role. $^6$Li(n,γ)$^7$Li is thought to be one of the important reactions for inhomogeneous Big Bang nucleosynthesis (IBBNs) [15]. In addition, the astrophysical significance of the $^6$Li(n,γ)$^7$Li reaction is that the $^6$Li/$^7$Li
Figure 1. Measured angular distribution of $^2$H($^{12}$N,$^{13}$O$_{g.s.}$)n at $E_{c.m.} = 8.4$ MeV, together with the theoretical calculations on direct process using two sets of optical potential (Set1 and Set2) and compound nucleus contribution (CN).

ratio stands for a measure of the time scale for star evolution [16]. The direct- and indirect measurements of the above reactions are highly desired. The astrophysical $^6$Li(n,$\gamma$)$^7$Li reaction rate can be studied via one-neutron transfer reaction $^7$Li($^6$Li,$^7$Li)$^6$Li. The SF of $^7$Li $\rightarrow$ $^6$Li + n can be deduced and then used to derive the cross sections of $^6$Li(n,$\gamma$)$^7$Li. The advantage of this system is that no other reaction is needed to get the SF of $^7$Li $\rightarrow$ $^6$Li + n because the same SFs appear at both vertices of elastic and neutron exchange amplitudes. In addition, the optical potential parameters of entrance- and exit channels can be extracted simultaneously through $^6$Li + $^7$Li elastic scattering.

The experiment was performed by using Q3D spectrometer, using a $^6$Li beam from the HI-13 tandem accelerator in Beijing and a $^7$LiF target. The focal plane detector was a 2-dimensional position sensitive silicon detector. The SFs of the ground and first excited states of $^7$Li were deduced to be 0.73 $\pm$ 0.05 and 0.90 $\pm$ 0.09 by DWBA fit to the angular distributions of $^6$Li + $^7$Li transfer data, respectively. Fig. 2 shows the result of deduced $^6$Li(n,$\gamma$)$^7$Li cross section. The current result is in excellent agreement with the experimental data of Ohsaki et al.[17]. The resultant astrophysical reaction rate is found to be higher by a factor of 1.7 than the value adopted in previous reaction network calculations [18].

4. Half-life of $^{147}$Sm in metal samarium and Sm$_2$O$_3$

The $^{147}$Sm-$^{143}$Nd method established by Lugmair [19] plays an important role in the dating of telluric, lunar and Martian rocks as well as meteorites. The half-life of $^{147}$Sm was reported to be $1.06 \times 10^{11}$ y [20, 21]. It is in fairly good agreement with a measured value of $(1.070 \pm 0.009) \times 10^{11}$ y in 2009 [22], yet clearly shorter than that of $(1.17 \pm 0.02) \times 10^{11}$ y reported in 2003 [23]. The new measurements are needful for clarifying the discrepancy of experimental results.

In order to investigate the possible influence of metallic environment on the alpha decay process, we have measured the $^{147}$Sm activities in the hosts of metal samarium and Sm$_2$O$_3$. The
The result of deduced $^6\text{Li}(n,\gamma)^7\text{Li}$ cross section in comparison with the experimental data[17].

$\alpha$-energy spectra obtained from the samples are shown in Fig. 3 together with the corresponding backgrounds.

The $^{147}\text{Sm}$ half-life was found to be $(1.06 \pm 0.01) \times 10^{11}$y in metal samarium and $(1.07 \pm 0.01) \times 10^{11}$y in $\text{Sm}_2\text{O}_3$, respectively [24]. No significant change has been observed within the experimental uncertainty. The result is not consistent with the prediction in Ref. [6, 7]. Due to the limited experimental precision in the present work (mainly due to the statistical uncertainties), a change of less than 3% is difficult to be observed, so it still is a controversial issue whether a slight influence of metallic environment on the $\alpha$-decay process exists or not [8, 25].

The absolute half-life derived in this work is in good agreement with the recent experimental result [22] and the reported value [20, 21]. Our experiment provides an independent examination to the existing data.

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Figure 3. Spectra taken for 100 hours: (A) Metal samarium sample, (B) Background for A, (C) Sm$_2$O$_3$ sample, (D) Background for C. The dashed lines denote the corresponding simulation results, taking into accounts of the energy loss and solid angle of $\alpha$ particles.

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