

Spectroscopic factors for low-lying ^{16}N levels and the astrophysical $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction rate

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Background: Fluorine is a key element for nucleosynthetic studies since it is extremely sensitive to the physical conditions within stars. The astrophysical site to produce fluorine is suggested to be asymptotic giant branch stars. In these stars the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction could affect the abundance of fluorine by competing with $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$.

Purpose: The $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction rate depends directly on the neutron spectroscopic factors of the low-lying states in ^{16}N . Shell model calculations and two previous measurements of the (d,p) reaction yielded the spectroscopic factors with a discrepancy by a factor of ~ 2 . The present work aims to explore these neutron spectroscopic factors through an independent transfer reaction and to determine the stellar rate of the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction.

Methods: The angular distributions of the $^{15}\text{N}(^7\text{Li},^6\text{Li})^{16}\text{N}$ reaction populating the ground state and the first three excited states in ^{16}N are measured using a Q3D magnetic spectrograph and are used to derive the spectroscopic factors of these states based on distorted wave Born approximation analysis.

Results: The spectroscopic factors of these four states are extracted to be 0.96 ± 0.09 , 0.69 ± 0.09 , 0.84 ± 0.08 , and 0.65 ± 0.08 , respectively. Based on the new spectroscopic factors we derive the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction rate.

Conclusions: The accuracy and precision of the spectroscopic factors are enhanced due to the first application of high-precision magnetic spectrograph for resolving the closely spaced ^{16}N levels which cannot be achieved in most recent measurements. The present result demonstrates that two levels corresponding to neutron transfers to the $2s_{1/2}$ orbit in ^{16}N are not good single-particle levels although ^{15}N is a closed neutron-shell nucleus. This finding is contrary to the shell model expectation. The present work also provides an independent examination to shed some light on the existing discrepancies in the spectroscopic factors and the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ rate.

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Fluorine (^{19}F , the only stable F isotope) is a crucial element for nucleosynthetic studies because it is extremely sensitive to the physical conditions within stars [1]. For a long time, the Solar System was the only location within the Galaxy with known fluorine abundance [2]. The astrophysical site of the production of fluorine has always been a puzzle. The possible scenario is suggested to be asymptotic giant branch (AGB) stars [3,4], core collapse of type II supernovae [5,6], and Wolf-Rayet stars [2]. Although the contribution of each source to the F evolution in the Galaxy is still uncertain, the inclusion of all three sources is necessary to explain the observed Galactic evolution of fluorine [7]. In 1992, spectroscopic observations of giant stars showed enhancements of ^{19}F by factors of up to 30 with respect to solar abundances, providing the first evidence for ^{19}F nucleosynthesis in this site [8]. This result has been later supported by the large F enhancements found in post-AGB stars [9] and planetary nebulae [10,11] which are the progeny of AGB stars. However, AGB model calculations have not yet been able to quantitatively reproduce the highest

values of observed ^{19}F enhancements [4,12]. Reduction of nuclear reaction rate uncertainties and a better understanding of the nucleosynthesis in the partial mixing zone could help to clarify the discrepancies [12]. A detailed understanding of the nuclear reactions occurring in AGB stars is desirable to simulate fluorine production.

^{19}F is produced in the He intershell and then dredged up to the surface of AGB stars. The production paths are $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^+)^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ and $^{14}\text{N}(n,p)^{14}\text{C}(\alpha,\gamma)^{18}\text{O}(p,\alpha)^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$. Neutrons and protons are liberated by the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ and $^{14}\text{N}(n,p)^{14}\text{C}$ reactions, respectively. Furthermore, the neutron- and proton-induced reactions must also be taken into account, although ^{19}F is produced in He-rich environments [12,13]. The $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction may play an important role in determining the ^{19}F abundance since it competes with the $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ reaction and removes both neutrons and ^{15}N from the chain of the ^{19}F production.

To date considerable work has been performed to study the $^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$ reaction [14–17]. As for the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction, only two experimental results [18,19] are available. In 1996, Meissner *et al.* [18] measured the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ cross

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section at neutron energies of 25, 152, and 370 keV. To interpret the results and calculate the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction rate, these authors [18] performed direct capture calculations based on the experimental spectroscopic factors of ^{16}N from measurement of the $^{15}\text{N}(d,p)^{16}\text{N}$ reaction [20] since the magnitude of the direct capture rate depends directly on the neutron spectroscopic factors of the four low-lying levels in ^{16}N . In that work [20] the $^{15}\text{N}(d,p)^{16}\text{N}$ angular distributions were measured by solid-state detector telescopes with an average energy resolution of 35 keV and yielded nearly equal spectroscopic factors of ~ 0.5 for the ground state and the first three excited states at $E_x = 0.120$, 0.298, and 0.397 MeV in ^{16}N . In 2008, Bardayan *et al.* [19] measured the angular distributions of the $^{15}\text{N}(d,p)^{16}\text{N}$ reaction in inverse kinematics by using silicon detector arrays and a recoil separator. Since closely spaced levels (ground state + 0.120 MeV level, 0.298 + 0.397 MeV levels) could not be resolved, they used two different methods to determine the spectroscopic factors of these four states. The resulting values are larger than the ones in Ref. [20] by a factor of ~ 2 , while they are in agreement with shell model expectations [18,20] where the four low-lying ^{16}N levels are thought to be good single-particle levels as ^{15}N is a closed neutron-shell nucleus. Furthermore, they derived the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ rate via direct capture calculations based on their experimental spectroscopic factors [19]. The updated reaction rate in Ref. [19] is nearly twice as fast as the ones in Ref. [18] since the spectroscopic factors used in these two works differ by a factor of ~ 2 .

In short, two previous measurements [19,20] of the (d,p) reaction led to the spectroscopic factors with a discrepancy by a factor of ~ 2 and further yielded different $^{15}\text{N}(n,\gamma)^{16}\text{N}$ rates. Therefore, it is worthwhile to perform a new measurement of the neutron spectroscopic factors for the four low-lying ^{16}N states via an independent transfer reaction. In this article we report accurate and precision measurement of the spectroscopic factors for these ^{16}N levels via the angular distribution of the $^{15}\text{N}(^7\text{Li},^6\text{Li})^{16}\text{N}$ reaction using a Q3D magnetic spectrograph. These spectroscopic factors are used to evaluate the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction rate.

The experiment was performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE) in Beijing. The experimental setup and procedures are similar to those previously reported [21–23]. Melamine $\text{C}_3\text{N}_3(^{15}\text{NH}_2)_3$ enriched to 99.35% in ^{15}N was employed as target material with a thickness of $46 \mu\text{g}/\text{cm}^2$, evaporated on a $30 \mu\text{g}/\text{cm}^2$ thick carbon foil. To improve thermal conductivity of the targets, metal gold was evaporated on melamine foil, accumulated to a thickness of $22 \mu\text{g}/\text{cm}^2$. The target thickness was determined by using an analytical balance with a precision of $1 \mu\text{g}$ and was verified with the well-known differential cross sections at $\theta_{\text{c.m.}} = 33.5^\circ$ and 49.2° of the $^7\text{Li} + ^{15}\text{N}$ elastic scattering [24,25]. An uncertainty of 5% was assigned for target thickness, which is reasonable by considering the balance precision and the error of the well-known differential cross sections.

A 44 MeV ^7Li beam was delivered to measure the angular distribution of the $^{15}\text{N}(^7\text{Li},^6\text{Li})^{16}\text{N}$ reaction leading to the ground state and the first three excited states in ^{16}N . The angular distribution of the $^7\text{Li} + ^{15}\text{N}$ elastic scattering was also measured to obtain the optical model potential (OMP) for

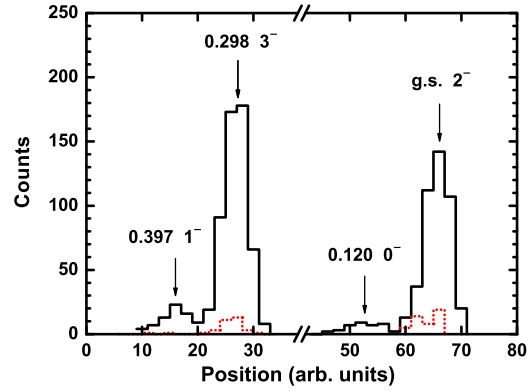


FIG. 1. (Color online) Focal-plane position spectrum of the ^6Li events at $\theta_{\text{lab}} = 10^\circ$ from the neutron-transfer reactions. The black solid and red dashed lines are the results from the enriched ^{15}N target and natural ^{14}N target, respectively. The break in the x axis denotes the narrow gap between two separated detectors.

the entrance channel of the transfer reaction. In addition, a 34.5 MeV ^6Li beam was delivered for measurement of the $^6\text{Li} + ^{15}\text{N}$ elastic scattering to evaluate the OMP for the exit channel.

The beam current was measured by a Faraday cup covering an angular range of $\pm 6^\circ$ in a laboratory frame and used for the absolute normalization of the cross sections at $\theta_{\text{lab}} > 6^\circ$. The Faraday cup was removed when measuring the cross sections at $\theta_{\text{lab}} \leq 6^\circ$. A Si ΔE -E telescope located at $\theta_{\text{lab}} = 25^\circ$ was employed for the relative normalization of the cross sections at $\theta_{\text{lab}} \leq 6^\circ$ by measuring the elastic scattering of the incident ions on the targets. The reaction products were analyzed with a Q3D magnetic spectrograph and recorded by a two-dimensional position-sensitive silicon detector (PSSD,

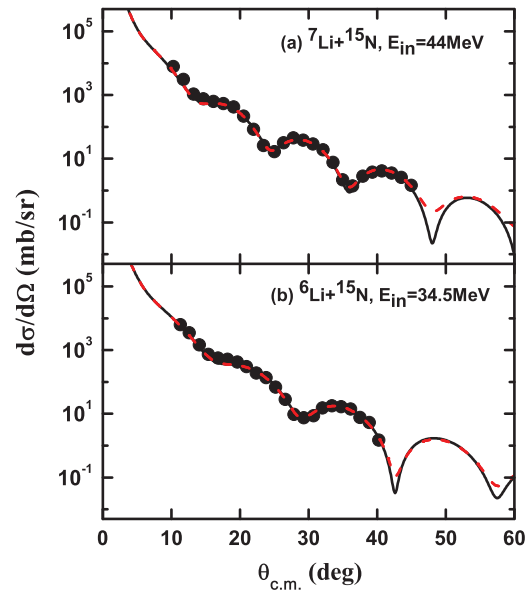


FIG. 2. (Color online) Angular distributions of the $^7\text{Li} + ^{15}\text{N}$ elastic scattering at incident energy of 44 MeV and $^6\text{Li} + ^{15}\text{N}$ elastic scattering at incident energy of 34.5 MeV. The black solid and red dashed curves represent the calculations using the fitted OMP parameters without and with a spin-orbit term, respectively.

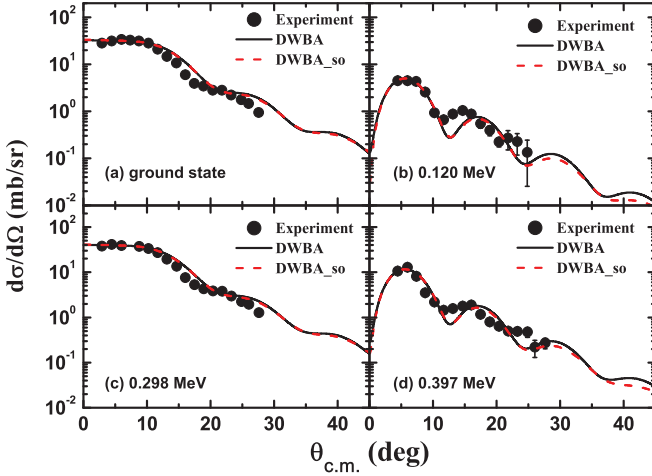


FIG. 3. (Color online) Angular distributions of the $^{15}\text{N}(^7\text{Li},^6\text{Li})^{16}\text{N}$ reaction leading to the ground and first three excited states in ^{16}N . The black solid and red dashed curves denote the DWBA calculations with the fitted OMP parameters without and with a spin-orbit term, respectively.

50 × 50 mm) placed at the focal plane of the spectrograph. The two-dimensional position information from the PSSD enabled the products emitted into the acceptable solid angle to be recorded completely.

As an example, Fig. 1 shows the focal-plane position spectrum of ^6Li at $\theta_{\text{lab}} = 10^\circ$ from the neutron-transfer reactions. The background from ^{14}N is negligibly small. After background subtraction and beam normalization, the angular distributions of the elastic scattering and the $^{15}\text{N}(^7\text{Li},^6\text{Li})^{16}\text{N}$ reaction leading to the ground and first three excited states in ^{16}N were obtained, as presented in Figs. 2 and 3.

The finite-range distorted wave Born approximation (DWBA) method with the FRESKO code [26] was used to analyze the experimental angular distributions. The OMP parameters for the entrance and exit channels were determined by fitting the present experimental angular distributions of the $^7\text{Li} + ^{15}\text{N}$ and $^6\text{Li} + ^{15}\text{N}$ elastic scattering (Fig. 2). The starting values of OMP parameters were obtained by fitting the single-folding nucleus-nucleus potential of Ref. [27]. The real potential was taken to be a squared Woods-Saxon shape, which fits the real part of the folding model potential better than the usual Woods-Saxon shape does [28]. For the imaginary potential, a Woods-Saxon shape was found

to be appropriate. In addition, we investigated the effect of spin-orbit potential parameters, although for heavy ions they are thought to have little or no influence on the cross sections [29]. Since the strength of the spin-orbit potential for heavy ions scales as $1/A$ as compared with the nucleon case [29], the depths of the entrance and exit channels were derived to be 0.843 and 0.983 MeV using the depth of 5.9 MeV for nucleon [30]. Both sets of OMP parameters (with and without spin-orbit potential) were used to study spectroscopic factors. Full complex remnant term interactions were included in the transfer reaction calculations. The parameters of the core-core ($^6\text{Li} + ^{15}\text{N}$) potential were obtained using the present ones of $^6\text{Li} + ^{15}\text{N}$ at 34.5 MeV and systematics in energy dependence of the potential parameters [27]. For the bound state $^{16}\text{N} = ^{15}\text{N} + n$, the standard geometrical parameters $r = 1.25$ fm and $a = 0.65$ fm were adopted, which have been extensively utilized to study the ground state neutron spectroscopic factors for 80 nuclei of $Z = 3-24$ [31] and 565 excited state neutron spectroscopic factors for $Z = 8-28$ nuclei [32]. All the parameters used in the calculation are listed in Table I.

The spectroscopic factors can be derived by the normalization of the DWBA calculation to the experimental angular distribution. The neutron spectroscopic factor of the ^7Li ground state needs to be chosen. So far considerable work has been performed to study it. Shell model calculations [33–36] predicted values of 0.80, 0.72, 0.79, and 0.77. Three measurements [37–39] of the $^7\text{Li}(p,d)$ reaction yielded consistent spectroscopic factors of 0.71, 0.72, and 0.87. However, two measurements [31,40] of the $^6\text{Li}(d,p)$ reaction derived very different values of 0.9 and 1.85. In addition, most recent measurement of the elastic-transfer $^7\text{Li}(^6\text{Li},^7\text{Li})$ reaction yielded a value of 0.73 [41]. In view of these different evaluations, we decided to use the value of 0.73 [34,37,38,41]. The $1p_{3/2}$ and $1p_{1/2}$ components in the spectroscopic factor of ^7Li were taken to be 1.5 based on the shell model calculation [34]. The spectroscopic factors of the ground state and the first three excited states in ^{16}N were then extracted to be 0.96 ± 0.09 , 0.69 ± 0.09 , 0.84 ± 0.08 , and 0.65 ± 0.08 , respectively. The errors result from the statistics (8%, 12%, 8%, 11%), the uncertainty of target thickness (5%), and the OMP parameters (1.6%, 2.2%, 1.2%, 3.1%), respectively. Additional model uncertainties were not included when evaluating the uncertainty of spectroscopic factors, as two previous work [19,20] did. In this work we also tested the

TABLE I. OMP parameters used in the present DWBA calculation. E_{in} denotes the incident energy in MeV for the relevant channels, V and W are the depths (in MeV) of the real and imaginary potentials with squared Woods-Saxon and usual Woods-Saxon shapes, and r and a are the radius and diffuseness (in fm).

Channel	E_{in}	V	r_v	a_v	W	r_w	a_w	V_{so}	r_{so}	a_{so}	r_C
$^7\text{Li} + ^{15}\text{N}$	44.0	138.7	0.911	1.26	45.0	0.966	0.820				1.30
		118.9	0.899	1.36	49.3	0.923	0.795	0.843	0.974	1.36	1.30
$^6\text{Li} + ^{16}\text{N}$	34.5	111.0	0.886	1.47	39.0	0.840	1.02				1.30
		91.0	0.930	1.43	29.3	0.841	1.12	0.983	0.786	1.37	1.30
$^6\text{Li} + ^{15}\text{N}$	37.7	132.0	0.901	1.37	31.3	0.945	0.918				1.30
$n + ^{15}\text{N}$		^a	1.25	0.65				6.0	1.25	0.65	1.25

^aThe depth was obtained by fitting to reproduce the binding energy of the neutron in ^{16}N .

TABLE II. Present spectroscopic factors of ^{16}N and other available results in the literature. nl_j is a single-particle shell quantum number.

E_x (MeV)	J^π	nl_j	Spectroscopic factor				
			OXBASH [18]	$^{15}\text{N}(d,p)$ [20] ^a	$^2\text{H}(^{15}\text{N}, p)$ [19]		Present
					Method1 ^b	Method2 ^c	
0	2^-	$1d_{5/2}$	0.93	0.55	0.96(15)	1.04(16)	0.96(9)
0.120	0^-	$2s_{1/2}$	0.95	0.46	0.80(12)	0.71(12)	0.69(9)
0.298	3^-	$1d_{5/2}$	0.87	0.54	0.91(14)	1.03(16)	0.84(8)
0.397	1^-	$2s_{1/2}$	0.96	0.52	0.88(13)	0.74(12)	0.65(8)

^a30% uncertainty for their spectroscopic factors.^bThe individual components were weighted by the relative spectroscopic factors reported in Ref. [20].^cThe magnitudes of the individual components were allowed to vary freely in fit.

effect of changing the geometrical parameters of the binding potential on spectroscopic factors. We changed the radius and diffuseness 20% around the standard values ($r = 1.25$ fm, $a = 0.65$ fm), and then found that the spectroscopic factors of the two states corresponding to $1d_{5/2}$ transfer vary by $\sim 20\%$ and those of the two states corresponding to $2s_{1/2}$ transfer vary by $\sim 8\%$. This difference in response to transfers to the $1d_{5/2}$ and $2s_{1/2}$ states may come from the different peripheralities of these two transitions.

The new spectroscopic factors are listed in Table II, together with the ones from two previous measurements of the $^{15}\text{N}(d,p)$ reaction [19,20] and the shell model calculation [18]. The present results are approximately twice larger than those from the $^{15}\text{N}(d,p)$ reaction [20], while they are in good agreement with those from the $^2\text{H}(^{15}\text{N},p)$ reaction using Method2 (namely, components allowed to vary freely) in Ref. [19] where two different methods were used to determine the spectroscopic factors since closely spaced levels (ground state + 0.120 MeV level, 0.298 + 0.397 MeV levels) in ^{16}N could not be resolved. The present results demonstrate that two levels corresponding to neutron transfers to the $1d_{5/2}$ orbit in ^{16}N are good single-particle levels but two levels corresponding to neutron transfers to the $2s_{1/2}$ orbit are not as good single-particle levels as the shell model expected [18].

We computed the direct capture cross section and the rate of $^{15}\text{N}(n,\gamma)^{16}\text{N}$ based on the measured spectroscopic factors using the RADCAP code [42]. At low energies of astrophysical interest, the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ direct capture cross section is dominated by the $E1$ transition from the incoming p wave to the bound state. Note that the same geometrical parameters need to be used when calculating the bound state wave function as those used for deriving the spectroscopic factors of ^{16}N . In addition, the parameters for computing the scattering wave function are identical to the ones for the bound state potential, as suggested by Huang *et al.* [43]. We also evaluated the contribution of the resonant capture via the state at $E_x = 3.523$ MeV using the resonance parameters given by Meissner *et al.* [18]. The resulting rates are shown in Fig. 4(a). The rate is dominated by the direct capture at temperatures of $T_9 < 2$. The total reaction rate at $T_9 = 0.1$ (typical temperature of AGB stars) was found to be 504 ± 66 $\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$. The error results from the uncertainty (12%) of the present spectroscopic factors and that (5.3%) of the geometrical parameters.

In Fig. 4(b) we compare the present rate with the previous ones available in the literature [18,19,44,45]. The present rate is about 20–50 times faster than the previous calculation [44] since it is a first order estimate of the p -wave capture contribution. The present rate is also nearly twice as fast as the experimental ones in Ref. [18]. This is because the present spectroscopic factors are larger than the ones from the $^{15}\text{N}(d,p)$ reaction [20] used in Ref. [18]. In addition, the new rate within 10% agrees with the ones in Refs. [19,45] since the new spectroscopic factors are consistent with those from the shell model calculation [45] and the $^2\text{H}(^{15}\text{N},p)$ reaction [19].

The new rate was fitted with the expression used in the astrophysical reaction rate library REACLIB [46],

$$N_A \langle \sigma v \rangle = \exp[6.38075 + 0.0159372T_9^{-1} - 1.80122T_9^{-1/3} + 4.02273T_9^{1/3} - 0.108521T_9 - 0.0221989T_9^{5/3} - 0.754253 \ln(T_9)]. \quad (1)$$

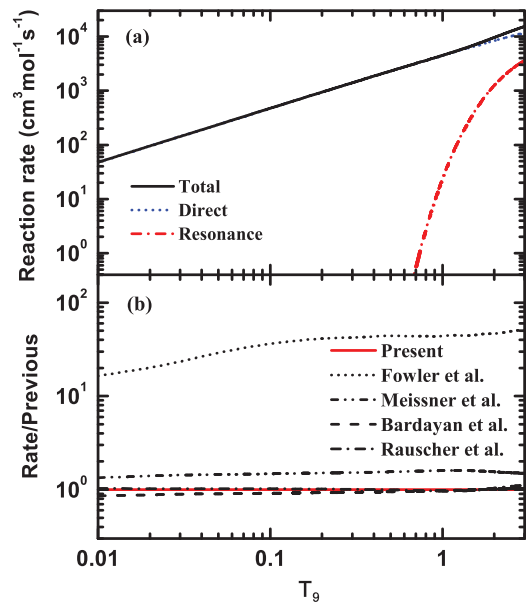


FIG. 4. (Color online) Present $^{15}\text{N}(n,\gamma)^{16}\text{N}$ rate for temperatures of 0.01–3 GK, and comparison of the present rate with the previous results by Fowler *et al.* [44], Rauscher *et al.* [45], Meissner *et al.* [18], and Bardayan *et al.* [19]. T_9 is the temperature in units of 1 GK. See text for details.

The overall fitting errors are less than 6% at temperatures from 0.01 to 10 GK.

In summary, the angular distributions of the $^{15}\text{N}(^7\text{Li},^6\text{Li})^{16}\text{N}$ reaction leading to the four low-lying ^{16}N levels were measured and used to derive their spectroscopic factors. The closely spaced levels in ^{16}N were resolved and the accuracy and precision of spectroscopic factors are enhanced due to the first application of high-precision magnetic spectrograph for study of the neutron transfer reaction on ^{15}N . The present work demonstrates that two levels corresponding to neutron transfers to the $1d_{5/2}$ orbit in ^{16}N are good single-particle levels but two levels corresponding to neutron transfers to the $2s_{1/2}$ orbit are not as good single-particle levels as the shell model expected [18].

We also derived the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction rate using the measured spectroscopic factors. The present rate is about 20–50 times faster than the previous calculation [44] and is

nearly two times faster than the experimental ones in Ref. [18]. In addition, the new rate is within 10% in agreement with the ones in Refs. [19,45]. The present work provides an independent examination to shed some light on the existing discrepancies in the spectroscopic factors of the four low-lying ^{16}N states and the stellar rate of the $^{15}\text{N}(n,\gamma)^{16}\text{N}$ reaction.

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