The astrophysical S-factor of the direct ^{18}O(p, γ)^{19}F capture by the ANC method

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Abstract. We attempted to determine the astrophysical S-factor of the direct part of the ^{18}O(p, γ)^{19}F capture by the indirect method of asymptotic normalization coefficients (ANC). We measured the differential cross section of the transfer reaction ^{18}O(^{3}He, d)^{19}F at a ^{3}He energy of 24.6 MeV. The measurement was realized on the cyclotron of the NPI in Řež, Czech Republic, with the gas target consisting of the high purity ^{18}O (99.9 %). The reaction products were measured by eight ΔE-E telescopes composed from thin and thick silicon surface-barrier detectors. The parameters of the optical model for the input channel were deduced by means of the code ECIS and the analysis of transfer reactions to 12 levels of the ^{19}F nucleus up to 8.014 MeV was made by the code FRESCO. The deduced ANCs were then used to specify the direct contribution to the ^{18}O(p, γ)^{19}F capture process and were compared with the mutually different results of two works.

1 Introduction

From the astrophysical point of view the radiative capture reaction ^{18}O(p, γ)^{19}F is important for the study of processes in AGB stars. The hydrogen burning of ^{18}O via the (p, γ) capture in AGB stars, i. e., in stars several times heavier than our Sun, is competing with the ^{18}O(p, α)^{15}N reaction [1]. The (p, α) reaction brings ^{15}N back into the CNO cycles while the (p, γ) capture, which rate is at solar energies about 3 orders lower, causes the escape to other cycles. The ratio ^{18}O/^{16}O represents an important parameter which can be used for the comparison of processes in the Sun and presolar nucleosynthesis with different stages of the evolution of AGB stars. The direct part of the (p, γ) process constitutes the substantial part of the whole cross section of the (p, γ) capture at astrophysical energies where only several channels for the decay of the compound nucleus are open.

A very thorough measurement of the ^{18}O(p, γ)^{19}F in the energy range E_p = 0.08-2.2 MeV was performed by Wiescher et al. [2] where the direct part of the (p, γ) capture was determined experimentally and also calculated theoretically. Later, Buckner et al. [3], when investigating reaction rates of ^{18}O(p, γ)^{19}F, measured the cross section and determined the direct part of this capture using different capture models. However, there is a substantial difference between the astrophysical S-factor of

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Wiescher et al. and of Buckner et al. at low energies. The tendency of values of Wiescher et al. is decreasing while that of Buckner et al. is increasing. Also their absolute values differ considerably. We therefore decided to determine the astrophysical S-factor of the direct capture $^{18}O(p,\gamma)^{19}F$ by the indirect method of astrophysical normalization coefficients (ANC). The method of ANC [4] was developed to determine the astrophysical S-factor of direct capture reactions at very low energies where the cross section is either too small to be measured directly or the nuclei participating in the reactions are radioactive. We compared our results of the direct capture obtained by the ANC method with the two above mentioned direct measurements and calculations. We measured the differential cross section of the $^{18}O(^3He,d)^{19}F$ transfer reaction and from it we deduced ANC values.

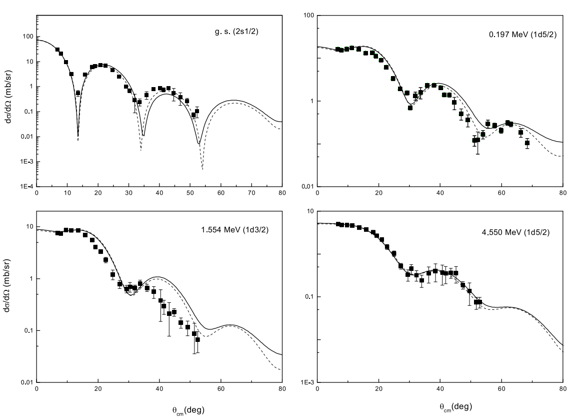

Figure 1. The angular distribution of the $^{18}O(^3He,d)^{19}F$ reaction for the transitions to the ground state and to the 0.197, 1.554 and 4.550 MeV states, respectively. Sets of optical model parameters are taken from our fits of elastic scattering with volume and surface absorbtion (solid and dashed line respectively) and for the output channel were taken from [5].

2 Analysis and results

The measurement of the cross section of the $^{18}O(^3He,d)^{19}F$ reaction on an oxygen gas target was carried out using a momentum analyzed 24.6 MeV ^3He beam from the isochronous cyclotron U-120M at the Nuclear Physics Institute of the Czech Academy of Sciences. The gas target chamber contained the high purity ^{18}O isotope (99.9%). The entrance window of the gas target was covered with a 2 μm thick Ti foil of 4 mm in diameter. The output window was covered with a 3 μm thick havar foil at the angular range from -40° to 65°. The gas pressure was kept at the level of 150 mbar and was monitored by a gas control system. Reaction products were registered by eight ΔE-E telescopes consisting of about 250-μm and 5-mm thick Si(Li) surface barrier detectors. All telescopes were equipped with a pair of collimating slits of dimensions 1 x 3 mm^2 and 1 x 4 mm^2. The front sides of the near 1 x 4 mm^2 and the far 1 x 3 mm^2 slits were located 105 mm and 185 mm, respectively, from the center of the gas target chamber. The effective target thickness, different at different reaction angles, was determined for the given geometry by calculation. Three telescopes were fixed on an upper plate at the angles of 17°, 27° and 37°, respectively, as monitors and the remaining five telescopes on the lower plate separated by 10° angular steps were movable in the angular range between 6.0° and 62°.

We have seen and analyzed 12 deuteron peaks corresponding to transitions to the bound states of the ^{19}F nucleus and to the first unbound state 8.014 MeV (proton emission threshold 7.9936 MeV). Other deuteron levels were populated weakly and were not considered in further analysis. For the analysis of the measured angular distributions the phenomenological optical potential was used with the sets of optical model parameters for the input channel obtained by the fit of the angular distribution of elastically scattered ^3He particles on the ^{18}O nucleus measured at the same energy as the transfer reaction itself. The optical model parameters for the outgoing deuterons were taken from the global formula of Perey and Perey [5]. The calculations of the theoretical angular distributions of the transfer reaction ^{18}O(^{3}He, d)^{19}F were performed using the computer code FRESCO by Thompson [6]. The example of the ^{18}O(^{3}He, d)^{19}F experimental angular distributions compared with calculated angular distributions are given in Fig. 1. From these comparisons we can deduce ANCs and also spectroscopic factors which are given in Table 1. The transitions with the largest ANCs in descending order are to the ground state and to the levels 0.197, 8.014 and 1.554 MeV of ^{19}F. ANC for the 8.014 MeV state was calculated assuming the proton binding energy 100 keV. The ANCs are less model dependent than spectroscopic factors and were therefore used in further calculations.

Table 1. ANCs and spectroscopic factors S_{lj} from the ^{18}O(^{3}He, d)^{19}F reaction. Experimental and model dependent uncertainties of ANCs are 20%.

^{19}F state $[MeV]$	j_{tr}	b_{lj} (see [4]) $[fm^{-1/2}]$	ANC(C^2_{Aplj}) $[fm^{-1}]$	S_{lj} this work	S_{lj} [7] Green	S_{lj} [8] Schmidt
0 $(1/2^+)$	2s1/2	16.364	78.3	0.292	0.45	0.32
0.197 $(5/2^+)$	1d5/2	5.1638	16.2	0.609	0.63	0.61
1.554 $(3/2^+)$	1d3/2	3.5842	4.14	0.322	0.44	0.38
4.550 $(5/2^+)$	1d5/2	1.9767	0.347	0.089	—	—
5.535 $(5/2^+)$	1d5/2	1.7195	7.55E-2	0.026	—	—
6.088 $(3/2^-)$	2p3/2	5.0714	8.96E-1	0.035	—	—
6.497 $(3/2^+)$	1d3/2	1.1438	2.42E-2	0.019	0.05	0.05
6.787 $(3/2^-)$	2p3/2	4.48	0.422	0.021	0.11	0.032
6.927 $(7/2^-)$	1f7/2	0.2625	6.82E-3	0.099	—	0.072
7.113 $(5/2^+)$	1d5/2	1.066	3.45E-2	0.030	0.13	0.022
7.540 $(5/2^+, T = 3/2)$	1d5/2	1.0907	0.464	0.39	0.41	0.332
8.014 $(5/2^+)$	1d5/2	7.3883	4.23	0.077	—	0.065

The direct capture cross section $\sigma(E)_{cap}$ was calculated by the computer code FRESCO [6] using derived ANCs from Table 1 under the assumption that the transfer reaction was of the surface character. The surface character was proved, e. g., by testing the dependence of the differential cross section on the cut-off radius. As the interaction we assumed the E1 multipole electromagnetic operator. By FRESCO we calculated the bound state wave function of the given level of the target nucleus on which a proton is captured and the wave function of the incoming proton in the field of the target nucleus. We calculated the bound state wave functions using the Woods-Saxon potential [2]. The scattered wave function of the proton can be also calculated by the Woods-Saxon potential or for instance by the optical model potential. We did calculations with three kinds of potentials for incoming protons: with the complex optical potential of Perey and Perey [5] and with the zero nuclear potential keeping only the Coulomb part to stress the fact that at low bombarding energies of protons the Coulomb potential could play a dominant role. For comparison we also simulated the hard sphere potential by putting V = -300 MeV as the repulsive potential into the code FRESCO. Resulting curves of the total S-factor from all three potentials are given in Fig. 2. Dominant contributions to the total S-factor come from the capture to the ground and 0.197 MeV states (60% together). We compared these curves with the low-energy calculations of ^{18}O(p, γ)^{19}F by Buckner et al. [3] and also with the direct measurement by Wiescher et al. [2]. While the S(E)-factor generated by the hard-sphere potential is almost constant at the value of 2 keV.b, our other two curves based on the optical and Coulomb potentials exhibit a rising tendency in the energy interval 0 to 2 MeV which is in correspondence with the calculation

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of Buckner et al. ($S(E) = 7.06 + 2.98 \times 10^{-3}E - 2.6 \times 10^{-7}E^2$ [keV.b]) but in contradiction with the direct measurement of Wiescher et al. ($S(E) = 15.7 - 0.34 \times 10^{-3}E - 1.21 \times 10^{-6}E^2$ [keV.b]). Our calculation of S-factor with the Coulomb potential when normalized to the measured direct capture cross section at $E_{c.m.} = 1751.9$ keV by Wiescher et al. [2] is even almost identical with the curve of Buckner et al.

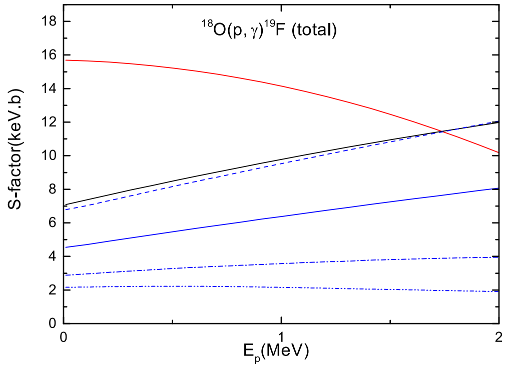

Figure 2. S-factor of the total direct proton capture ^{18}O(p, γ)^{19}F determined from the transfer reaction. Our blue solid, dash-dotted and dash-dot-dotted lines correspond respectively to the calculations with the zero nuclear potential, the global potential of Perey and Perey [5] and with the V = -300 MeV potential simulating the hard sphere potential. The red solid decreasing curve is based on the measurement of the direct contribution (p, γ) by Wiescher et al. [2] and the black solid increasing curve is the calculation by Buckner et al. [3]. The curve with the zero nuclear potential normalized to the measured point at $E_{c.m.} = 1751.9$ keV by Wiescher et al. is depicted by the blue dashed line.

3 Conclusion

The deduced values of ANCs were used for the determination of the direct part of the total astrophysical S-factor of the radiative capture ^{18}O(p, γ)^{19}F. Our values of the total astrophysical S-factor calculated with three different interaction potentials show in two cases similar tendency as was determined by Buckner et al. [3] and for the Coulomb interaction potential, after normalization, reproduce these data. The calculations with our interaction potentials without normalization are lower than the values of Buckner et al. at least about 35%.

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References

[1] Lorentz-Wirzba H., Schmalbrock P., Trautvetter H. P., Wiescher M. and Rolfs C., Nucl. Phys. **A313**, 346 (1979)
[2] Wiescher M., Becker H. W., Görres J., Kettner K.-U., Trautvetter H. P., Kieser W. E., Rolfs C., Azume R. E., Jackson K. P. and Hammer J. W., Nucl.Phys. **A349**, 165 (1980)
[3] Buckner M. Q., Iliadis C., Cesaratto J. M., Howard C., Clegg T. B., Champagne A. E. and Daigle S., Phys. Rev. **C86**, 065804 (2012)
[4] Xu H. M., Gagliardi C. A., Mukhamedzhanov A. M., Timofeyuk N. K., Tribble R. E., Phys. Rev. Lett. **73**, 2027 (1994)
[5] Perey C. M. and Perey F. G., At. Data Nucl. Data Tables **17**, 1-101 (1976)
[6] Thompson I. J., Comp. Phys. Rep. **7**, 167 (1988)
[7] Green L. L., Lennon C. O. and Naqib I. M., Nucl. Phys. **A142**, 137 (1970)
[8] Schmidt C. and Duhm H. H., Nucl. Phys. **A155**, 644 (1970)