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Nucleosynthesis in TP-AGB Stars and the Production of ^{19}F

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Low-energy resonances in the reaction ^{18}O(α,γ) have been measured using a highly efficient γ ray coincidence detector system. These resonances dominate the reaction rate for temperatures typical for TP-AGB stars (0.1 - 0.3 GK). Preliminary results reduce the reaction rate by up to a factor of three at these temperatures. While this leads to an enhancement of the fluorine production in TP-AGB stars, it is not sufficient to explain the observed fluorine abundances in the surface of red giants.

1. Introduction

The low elemental abundance of fluorine is caused by large cross sections of proton- and α- induced reactions which destroy ^{19}F, e.g. the ^{19}F(p,α)^{16}O and ^{19}F(α,p)^{22}Ne reactions. For this reason different astrophysical production sites of ^{19}F have been proposed. It has been suggested that ^{19}F can be produced during the core collapse of Type II supernova by the so called ν- process [1]. In this scenario ^{20}Ne, produced during the preceding C-burning, is destroyed by neutrino induced reactions leading to the production of ^{19}F. A different production scenario are thermally pulsing (TP-) AGB stars. Jorissen et al. [2] observed ^{19}F overabundances with respect to solar at the surface of red giants of type Ba, M, MS, S, SC, C(N), and C(J) correlated with the observed ^{12}C overabundances. This correlation suggests that fluorine is produced during the thermal pulses of AGB stars [2,3] by a chain of reactions. Starting with the neutron production by the ^{13}C(α,n) reaction and the subsequent ^{14}N(n,p) reaction, with ^{13}C and ^{14}N from H-burning ashes, secondary protons are produced leading to the formation of ^{19}F by the reaction sequence ^{14}N(α,γ)^{18}F($\beta^+\nu$)^{18}O(p,α)^{15}N(α,γ)^{19}F. At the present models can not explain the large observed fluorine abundances and "additional" ^{13}C has been invoked [2] to explain the highest abundances. However, the reaction rates of several of the involved reactions carry large uncertainties. Previously we have measured the reaction ^{14}N(α,γ)^{18}F [4] establishing a reaction rate which is based on experimental results for the temperature range of interest for helium burning. In the following we report on first results for the ^{18}O(α,γ)^{22}Ne reaction

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which is in competition with the $^{18}O(p,\alpha)^{15}N$ reaction and discuss the influence of the results on the fluorine production in TP-AGB stars. In addition, both (α,γ) reactions play also an important role for the s process during core He burning in massive stars [5].

2. The $^{18}O(\alpha,\gamma)^{22}Ne$ Experiment

The reaction rate of $^{18}O(\alpha,\gamma)^{22}Ne$ is dominated by the contributions of two low energy resonances at E_{Lab} = 470 keV and 566 keV. These resonances had not been observed directly but were populated in the α-transfer reaction $^{18}O(^6Li,d)^{22}Ne$ [6]. The resulting relative spectroscopic factors were used to calculate the resonance strengths of these resonances relative to the strength of the lowest known resonance at 660 keV [6]. However, no unique spin assignments were possible on the basis of the measured angular distributions. For this reason the resonance strengths of the 470 keV and 566 keV resonances carried large uncertainties. To reduce these uncertainties we have measured the reaction directly. The experiment was performed at the KN accelerator at the Institut für Kernphysik of the Forschungszentrum Karlsruhe with α beam currents of 50 - 100 μA. The beam energy was calibrated to ± 2 keV using well known resonances in $^{27}Al(p,\gamma)^{28}Si$ [7]. $Al_2^{18}O_3$ targets on Ta backings were prepared by reactive sputtering in an $Ar/^{18}O_2$ mixture at 0.4 Pa. The $^{18}O_2$ gas was isotopically enriched to 96.6 %. The same method has been used to prepare natural oxygen targets for background studies. These targets were very stable under bombardment with intense, low-energy α beams. The stability of the targets has been verified by measuring the strong $^{18}O(p,\gamma)^{19}F$ resonance at 1167 keV [8] before and after each low-energy α beam run. During a long run on top of the yield curve of the 660 keV resonance in $^{18}O(\alpha,\gamma)^{22}Ne$ the yield was reduced by less than 10 % for a total accumulated charge of 14 C. The stoichiometry of the target was tested by measuring the strong $^{27}Al(p,\gamma)^{28}Si$ resonance at 992 keV with a pure Al target and an Al_2O_3 target. The observed ratio of the γ yields is in excellent agreement with the expectation for an Al_2O_3 stoichiometry. The target thickness corresponds to an energy loss of 100 keV for an α energy of 600 keV.

The reaction γ rays were observed with a Ge clover detector in close geometry. First test measurements were performed with the clover detector at an angle of 45° with respect to the beam direction. Four BGO detectors were used for Compton suppression and the target as well as the detector system was shielded with 10 cm of lead. Cosmic ray induced events were suppressed using two large area plastic scintillator detectors. However, it was found that this setup was not sensitive enough to observe sub μeV resonance strengths. For this reason the setup was modified. The clover detector was placed at 0° which made it possible to place the BGO detectors upstream of the target covering a solid angle of nearly 2π. This allowed the observation of $\gamma - \gamma$ coincidences with very high efficiency. In the final analysis of the coincidence data, the clover detector was gated with events in the BGO detectors in the 3 to 11 MeV region. This approach reduced the background by more than two orders of magnitude while reducing the overall efficiency by a factor of 3.7. The γ efficiency was determined from the known γ decay of the $^{27}Al(p,\gamma)^{28}Si$ resonance at 992 keV [7,9] and the known resonance strength of $\omega\gamma = (1.91 \pm 0.11)$ eV [10] as well as calibrated sources and coincidence count rates of well known γ cascades. To search for the 566 keV resonance several long runs were made with beam energies between 600

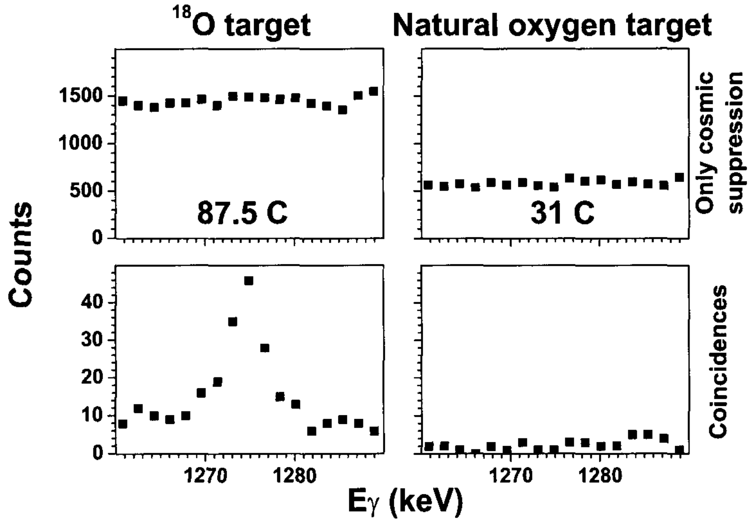

Figure 1. Relevant part of the Ge clover spectrum around the 1.27 MeV γ line measured with an ^{18}O (left) and a natural O target (right). The γ single spectra are shown on the top and the spectra in coincidence with events in the BGO detectors in the 3-11 MeV energy range on the bottom.

and 640 keV with a total charge of 87.5 C. The relevant part of the Ge spectrum around the 1.27 MeV line from the decay of the first excited state of ^{22}Ne to the ground state is shown in Fig. 1. The Ge spectrum in single mode (top) is dominated by background events and no γ line can be observed. However, by requiring coincidences with events in the BGO detectors in the energy range of 3-11 MeV (bottom of Fig. 1) the background is reduced by more than a factor of 100 and the 1.27 MeV line is clearly visible. As a comparison the corresponding spectra measured with a natural oxygen target and a comparable accumulated charge are shown on the right hand side of Fig. 1. As expected no 1.27 MeV line can be observed in these background spectra. To search for the 470 keV resonance a long run with a total accumulated charge of 33.3 C was measured at a beam energy of 530 keV. Unfortunately this run was hampered by the lower beam intensity (50 μA) available at such low beam energies. A long run with a natural oxygen target was also measured at this beam energy. In addition a room background spectrum was acquired over the same time period as the beam-on measurements.

A preliminary analysis indicates a resonance strength of about 1 μeV for the 566 keV resonance and an upper limit of 0.4 μeV for the 470 keV resonance. The observed strength of the 566 keV resonance is to our knowledge the smallest strength measured for an (α,γ)- resonance. The final analysis of the data is in progress and will be published in a forthcoming paper together with more information about experimental details [11].

3. Conclusions

Because of the coincidence requirement in the present experiment the observed resonance strengths are only partial strengths which do not include contributions which bypass the first excited state of ^{22}Ne. For this reason the γ decay of these states will be measured independently to correct for the bypass transitions. Nevertheless, the present preliminary results suggests that the 470 keV resonance has a spin $J^\pi = 1^-$ instead of 0^+ as Giesen et al. [6] adopted for the calculation of the reaction rate and the 566 keV has a spin of 2^+ instead of 4^+. This is also in good agreement with the results from the angular distribution of this state observed in a (t,p)- reaction [12]. To evaluate the influence of our new data we calculated a preliminary reaction rate for the ^{18}O(α,γ) reaction adopting the strengths calculated by Giesen for the revised spin assignments [6]. The resulting rate is up to a factor of three lower than the rate recommended by Nacre [13] at the temperatures of interest (0.1 - 0.3 GK) because at this temperatures the rate is dominated by the contribution of the 470 keV resonance.

Presently we are performing model calculations to test the influence of various rates on the production of fluorine in TP-AGB stars [14]. First calculations using updated reaction rates for several α- induced reactions (e.g. ^{14}C(α,γ), ^{14}N(α,γ), ^{18}O(α,γ), ^{19}F(α,p)) show that changes in individual rates influence the fluorine abundance by less than 10 %. But most changes lead to an increase in the fluorine abundance. This results in an overall increase of about 60 % when compared to calculation using the previous rates. This increase, however, is not large enough to explain the observed fluorine abundances.

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