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Implications of the Lowest l=0 Proton Resonance in ^{26}Si on the Nucleosynthesis of ^{26}Al

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Recently, a measurement with a beam of the radioactive isotope ^{25}Al established the lowest $l = 0$ proton resonance in ^{26}Si. We are investigating the implications of the resonance properties on the nucleosynthesis of ^{26}Al. We determine the limits of temperature and proton-density conditions under which nucleosynthesis of ^{26}Al$_g$ will occur.

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1. Introduction

The observation of the 1.8 MeV γ–rays from the radioactive decay of ^{26}Al ($T_{1/2} = 7.1 \cdot 10^5 a$) is one of the most important results of γ-ray astronomy[1, 2]. Its smooth distribution and correlation with regions of massive stars point to Core-Collapse Supernovae as the most likely sources of its continuing production [3]. Massive stars explode when the central region of the star collapses and forms a neutron star or black hole. At the surface of the neutron star, the still in-falling material forms a shock front which eventually moves outward [4, 5]. Until recently, it was believed that the shock front is revived by neutrinos on time scales of up to ten microseconds [6], resulting in the ejection of the envelope. However, during the last few years there has been growing evidence that magnetic fields, accretion disks and fall back of material may all contribute to the conditions of nucleosynthesis in Core-Collapse Supernovae [7, 8, 9]. Alternative sites for the production and emission of ^{26}Al were discussed [10], such as Wolf-Rayet stars [11] and supernova explosions in close binary systems [12]. As a result of all these investigations, the range of physical conditions and nuclear reactions to be considered in ^{26}Al nucleosynthesis has widened drastically, both with respect to the elements involved and the timescales, ranging from 10 ms to several minutes.

We have recently performed an experiment establishing the lowest $l = 0$ proton resonance in ^{26}Si, using a radioactive ^{25}Al beam delivered by the new RESOLUT facility at the Florida State University's Superconducting Accelerator Laboratory. The details and results of this experiment are submitted for publication [13]. In this article, we want to investigate the newly answered and still open questions regarding the nuclear reactions involved in the nucleosynthesis of ^{26}Al.

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2. Proton-induced steady-state nucleosynthesis of ^{26}Al

The identification of the lowest $l = 0$-proton resonance in ^{26}Al establishes the thermonuclear reaction rate of the $^{25}\mathrm{Al}(\mathrm{p},\gamma)^{26}\mathrm{Si}$ with greatly improved systematic uncertainties [13]. Here, we want to discuss the implications of this reaction rate in the context of steady-state nucleosynthesis, which is reached if nucleosynthesis continues for a period longer than the characteristic timescales involved and the final isotopic concentrations are independent of the initial concentrations.

The presence of a low-lying isomeric 0^+ state, $^{26}\mathrm{Al}_m$, whose population can only slowly reach thermal equilibrium with the 5^+ $^{26}\mathrm{Al}_g$ ground state, severely complicates the calibration of its nucleosynthesis. The reaction paths involved in the proton-induced nucleosynthesis of ^{26}Al are displayed in Fig.1. In the steady-state limit, the production of ^{26}Al proceeds from the isotope ^{25}Al in two distinct branches: The lower branch starts with a β^+–decay followed by a (p,γ) proton-capture and leads mainly to the $^{26}\mathrm{Al}_g$ ground state. The upper branch, a (p,γ) capture followed by a β^+–decay leads exclusively to the ^{26}Al isomeric 0^+ state. Therefore, the branching ratio between the lower branch and the upper branch has a large influence on the amount of $^{26}\mathrm{Al}_g$ synthesized in proton-induced nucleosynthesis.

2.1 Conditions of $^{26}\mathrm{Al}_g$ nucleosynthesis in the lower branch

Using the resonance parameters of our new measurement [13], we calculate the Maxwell-averaged reaction rates and analyze the critical proton density and temperature, for which both branches occur at the same rate. The upper and lower limits on the critical density are displayed

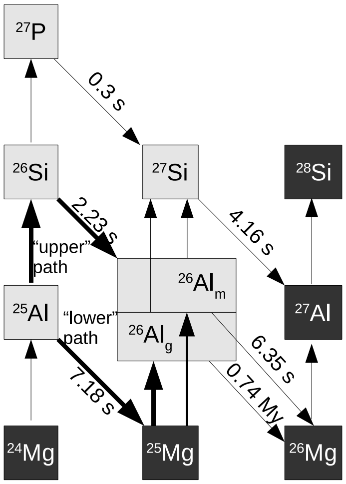

Figure 1: Reaction and decay paths involved in proton-induced nucleosynthesis of ^{26}Al

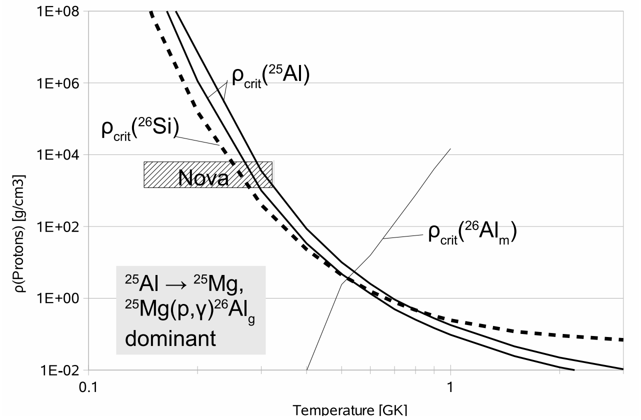

Figure 2: Proton-density and temperature regions characterizing the proton-induced nucleosynthesis of ^{26}Al$_g$ and ^{26}Al$_m$ (see text).

in Fig.2, labeled $\rho_{crit}(^{25}Al)$. Below this line, efficient nucleosynthesis of ^{26}Al$_g$ can proceed under steady-state conditions. The hatched region in Figure 2 represents temperatures and proton-densities typically assumed in calculations of Nova-explosions [16] and is consistent with efficient ^{26}Al$_g$ synthesis in the lower branch. Explosive Hydrogen-burning events at temperatures above 0.3 GK will bypass the direct population of the ground state and thereby not contribute to the galactic ^{26}Al$_g$ activity observed in γ–ray astronomy.

Nucleosynthesis of ^{26}Al$_g$ in the context of Core-Collapse Supernovae was studied in Refs. [14] and [3]. Common to these studies are conditions of very low proton density and a very short time-scale for the explosive nucleosynthesis. This leaves only time for the $^{25}\mathrm{Mg}(\mathrm{p},\gamma)^{26}\mathrm{Al}_\mathrm{g}$ to occur, thus converting the pre-existing ^{25}Mg and not reaching the steady state conditions studied above. However, the more complicated scenarios for Core-Collapse Supernovae include scenarios of accretion disks and material fallback, which may substantially change the physical conditions of material composition, temperatures and timescales under consideration.

2.2 Conditions for ^{26}Al$_g$ nucleosynthesis in the upper branch

In the following we want to investigate, whether the higher-temperature branch of nucleosynthesis can lead to additional, indirect production of ^{26}Al$_g$. Two conditions need to be fulfilled; First, that the decay of ^{26}Si to ^{26}Al$_m$ occurs at a rate higher than the destruction of ^{26}Si through (p,γ). The second condition is, that ^{26}Al$_m$ is converted to ^{26}Al$_g$ before ^{26}Al$_m$ itself is destroyed by (p,γ).

In order to study the first condition, we are relying on reaction rates of $^{26}\mathrm{Si}(\mathrm{p},\gamma)$ calculated in [15], which are based on experimental data from the mirror-nuclei. The resulting curve of critical density, at which the (p,γ) rate equals the $T_{1/2}$ = 2.23 s β decay of ^{26}Si, is displayed in Fig.2 as a dashed line labeled $\rho_{crit}(^{26}Si)$. The first condition corresponds to proton densities and temperatures lower than this curve, but higher than the critical density curve for ^{25}Al. Under these assumptions

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there is only a narrow region above T=0.6-0.7 GK and at proton-densities around $10^{-2}..10^{-1}$ g/cm^3, where the upper branch can effectively synthesize $^{26}\mathrm{Al}_g$.

The second condition, the conversion of $^{26}\mathrm{Al}_m$ to $^{26}\mathrm{Al}_g$ was studied in the context of thermal equilibration. It was argued [17] that at temperatures above 0.4 GK, the 0^+ $^{26}\mathrm{Al}_m$ and the 5^+ $^{26}\mathrm{Al}_g$ could reach thermal equilibrium through multi-step γ–ray absorption and emission. The equilibration process has more recently been studied by Gupta and Meyer in Ref. [18] based on a combination of experimental data and shell-model calculations.

Fig. 2 displays, as a line labeled $\rho_{crit}(^{26}Al_m)$, the critical proton-density for which the $\gamma\gamma'$–equilibration rate [18] is equal to the $^{26}\mathrm{Al}_m$ destruction through its $T_{1/2} = 6.345s$ β–decay or the $^{26}\mathrm{Al_m(p,\gamma)^{27}Si}$ reaction calculated in [15]. Equilibration, and thereby a production of the $^{26}\mathrm{Al}_g$ activity, can only effectively compete with the destruction of $^{26}\mathrm{Al}_m$ at higher temperatures and lower proton-densities than that line. Therefore, the temperature-proton-density region, which fulfills the first condition will also effectively thermalize the isomeric $^{26}\mathrm{Al}_m$ and ground state $^{26}\mathrm{Al}_g$ distributions.

The limits of this region depend very sensitively on the details of the $^{26}\mathrm{Si(p,\gamma)}$ and $^{26}\mathrm{Al_m(p,\gamma)}$ reaction rates, which have so far not been studied experimentally. We are preparing experiments to measure both reactions at the RESOLUT facility of Florida State University.

3. Conclusion

Using data from a recent radioactive beam experiment at RESOLUT[13], we have identified the regions of proton-density and temperature conditions, in which $^{26}\mathrm{Al}_g$ can be synthesized under steady-state conditions. The theoretical data currently available on the (p,γ) reactions destroying $^{26}\mathrm{Si}$ and $^{26}\mathrm{Al}_m$ allow us to identify an additional region in which an effective steady-state production of $^{26}\mathrm{Al}$ is possible through the "upper" branch nucleosynthesis initiated by the $^{25}\mathrm{Al(p,\gamma)^{26}Si}$ reaction. The limits of this temperature-density region depend sensitively on specific proton resonances, which should be studied with radioactive beam experiments in the near future.

More complicated scenarios for Core-Collapse Supernovae currently under investigation show the need to study nucleosynthesis rates under a large variety of physical conditions, with precise nuclear laboratory experiments using radioactive beams.

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