Search for Low-Energy Resonances in $^{25}$Mg($p, \gamma$)$^{26}$Al*

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The reaction $^{25}$Mg($p, \gamma$)$^{26}$Al has been investigated at $E_p(\text{lab})=80-350\text{keV}$. The existence of the resonance at $E_p=317\text{keV}$ has been verified and new resonances have been found at $E_p=198$, 255 and 304 keV. The $E_p=304\text{keV}$ resonance represents a new compound state in $^{26}$Al. Information on branching ratios, $\omega\gamma$ values, total widths and $J^\pi$ assignments for the observed resonances as well as upper limits on the $\omega\gamma$ strengths for the expected resonances at $E_p=97$ and 134 keV are given. The astrophysical aspects of the data are discussed in the light of the renewed interest in the precise location of $^{26}$Al nucleosynthesis.

**Nuclear Reactions.** $^{25}$Mg($p, \gamma$), $E=80-350\text{keV}$; measured $\sigma(E), Q, E_\gamma, E_p, I_x(\theta)$. $^{26}$Al deduced levels, resonance strengths, $\gamma$-ray branching ratios, $\Gamma, J, \pi$, astrophysical reaction rate. Enriched $^{25}$Mg targets. Ge(Li) detector.

1. Introduction

Certain inclusions in the Allende meteorite have been shown recently [1-3] to contain Mg with essentially normal $^{24}$Mg/$^{25}$Mg isotopic ratio, but characterized by an excess concentration of $^{26}$Mg, which correlates with the Al/Mg elemental ratio of the samples. This observation has been interpreted [1-3] as evidence for the live beta decay of the radioactive isotope $^{26}$Al ($t_{1/2}=7.2 \times 10^5\text{y}$) in inclusions, whose Mg and Al isotopic composition was initially homogeneous. This interpretation implies that some freshly produced material was added to the solar system material at a few percent level just before the beginning of its condensation phase. It has been suggested [4-8] that such an alien material originated from a single nearby supernova, which in addition triggered the formation of the solar system, or from many supernovae or from other astrophysical scenarios containing $^{26}$Al nucleosynthesis. In each case, the short half life of $^{26}$Al limits the time intervening between the nucleosynthesis of this isotope and its incorporation into the Allende inclusions.

In the various scenarios of nucleosynthesis, the isotope $^{26}$Al is primarily produced [7-9] by the capture reaction $^{25}$Mg($p, \gamma$)$^{26}$Al. A possible site for this reaction could be the so-called MgAl cycle [8, 9] during hydrogen burning (either explosive or hydrostatic) nucleosynthesis. Since this reaction is of major importance in determining the exact dynamics of $^{26}$Al nucleosynthesis, its reaction rate has to be known over a wide range of stellar temperatures. De Neijts et al. [10] have investigated this reaction in the energy range $E_p(\text{lab})=0.3-2.0\text{MeV}$, where the lowest-lying resonance at $E_p(\text{lab})=317\text{keV}$ corresponds to a stellar temperature of $T_9=0.3$. From the known level diagram [11] of $^{26}$Al above the proton separation energy, six additional resonances are expected to occur in the energy range $E_p(\text{lab})=42-259\text{keV}$ (Fig. 1) and these resonances can dominate the reaction rates at temperatures of $T_9<0.3$. A search for these resonances represents the subject of the present work.

The experimental equipment and set-up are described in Sect. 2 and followed by the experimental procedure, data analyses and results in Sect. 3. The astrophysical aspects of the data are discussed in Sect. 4.

2. Experimental Equipment and Set-Up

The 350kV accelerator at Münster supplied a proton beam of 150 to 460µA in the energy range of $E_p=80-350\text{keV}$. A description of the beam properties of this accelerator is given elsewhere [12].
The targets were fabricated [13] by reducing MgO powder* enriched to 93% in $^{25}$Mg (Sect. 3.4). The MgO powder was first mixed with Ta powder in a mass ratio of 1:80 and then placed in a cylindrical Ta boat. This boat was heated to 1,800°C by an electron gun in high vacuum (2 × 10⁻⁶ Torr), thereby oxidizing the Ta powder and releasing the reduced $^{25}$Mg component. The upper part of the Ta boat collimated the $^{25}$Mg vapour beam. A 0.25mm thick Ta sheet, placed 4cm from the evaporating source, was thus coated with $^{25}$Mg. With 1mg MgO in the Ta boat a target thickness of 30μg/cm² was achieved. These targets contained much less oxygen than the original MgO powder and were able to withstand proton bombardment of up to 460μA over running periods of several days without noticeable deterioration.

The γ-rays were detected in 80cm³ Ge(Li) detectors with an energy resolution of 2.1keV at $E_γ=1.3$ MeV. The efficiency curves of these detectors in close geometry were obtained [13, 14]) for $E_γ=0.1$-16.0 MeV using calibrated γ-rays from low-energy proton-capture resonances.

Fig. 1. Level diagram of $^{26}$Al above the proton threshold. The excitation energies and $J^T$ assignments are from [11]. The $E_x=317$keV resonance is the lowest resonance observed in previous work [10]. The energies of the expected resonances are indicated. Also shown are the energy regions of astrophysical interest for different stellar temperatures $T_9$ (in units of $10^9$ K).

Details of the experimental procedures and data analyses are described in the following subsections. The results on the properties of the $^{25}$Mg(p,γ)$^{26}$Al resonances are summarized in Tables 1 and 2.

3.1. Excitation Function

Due to the existence of 67 states in $^{26}$Al below the proton binding energy [11] ($Q=6.305$ MeV), only a small fraction of the γ-rays deexciting the resonances should be direct transitions to the ground state in $^{26}$Al. Most of the transition strength should be contained in the γ-gamma-cascades through the $J^T=3^+$, 417keV second excited state* (Fig. 1). This fact together with the improved sensitivity of the Ge(Li) detector for the 417keV γ-ray line (compared to the sensitivity for the high-energy and Doppler-broadened primary γ-ray transitions) was the basis for a preliminary establishment of the excitation function for $^{25}$Mg(p,γ)$^{26}$Al via the 417keV secondary γ-ray transition. At each proton energy, the full γ-ray spec-

* Purchased from Rohstoff-Einfuhr GmbH, Düsseldorf, W. Germany

* The isomeric first excited state at $E_x(J^T)=228(0^+)$keV decays exclusively by β-decay to the ground state of $^{25}$Mg