Populating $\alpha$-unbound states in $^{16}$O via $^{19}$F($p, \alpha\gamma$)$^{16}$O reaction

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Abstract. The $^{12}$C($\alpha, \gamma$)$^{16}$O reaction is important in the production of universal $^{16}$O, but its cross-section at the relevant energies of static helium burning is complex and uncertain. The total cross-section originates from a sum of resonance tails and direct captures, making the contributions of sub-threshold states difficult to estimate. One proposed method to estimate these contributions involves determining relevant reduced $\alpha$-widths of the sub-threshold states through indirect measurements. Therefore, $^{19}$F($p, \alpha\gamma$)$^{16}$O reaction was used to populate $\alpha$-unbound states in $^{16}$O using a 2.6 MeV proton beam on a $CaF_2$ target. A detection system consisting of single and telescope configurations of Si detectors was used to detect 2$\alpha$-particles and a $^{13}$C particle in coincidence. Scintillator detectors were included in the setup to study the de-excitation of the states populated in $^{16}$O to the ground state. Under good event conditions a preliminary identification of the particles detected has been conducted.

1 Introduction: $^{12}$C($\alpha, \gamma$)$^{16}$O key reaction

One of the reactions in Nuclear Astrophysics that requires a better understanding is $^{12}$C($\alpha, \gamma$)$^{16}$O. The reason for this is both, the unmitigated importance of the reaction as it is involved in the production of universal $^{16}$O, and the complexity of its cross section at the relevant energies of static helium burning (300 keV).

As far as the cross-section is concerned the uncertainty is still undesirably large. As a consequence of the fact that, in the energy region of interest, there is no state of natural parity in $^{16}$O near the $\alpha$-threshold to serve as resonance for radiative capture, the total cross section originates from a sum of resonance tails and direct captures, both, to the ground and excited bound states of $^{16}$O. Among the resonance tails contributing are two bound sub-threshold states, i.e., the $1^-$ state of -45 keV and the $2^+$ state of -200 keV below the $\alpha + ^{12}$C threshold [1]. Fig. 1 provides a schematic representation of the $^{12}$C($\alpha, \gamma$)$^{16}$O reaction.

![Figure 1](https://example.com/figure1.png)

Figure 1. Schematic representation of $^{12}$C($\alpha, \gamma$)$^{16}$O reaction.

One of the methods to estimate these contributions consist in determining the reduced $\alpha$-widths of the sub-threshold states by indirect measurements, that are more sensitive to this width than the direct radiative capture measurement. Therefore, the $^{19}$F($p, \alpha\gamma$)$^{16}$O reaction has been used for the purpose of populating $\alpha$-unbound states in $^{16}$O (Fig. 2) [2].

![Figure 2](https://example.com/figure2.png)

Figure 2. Population of unbound states on $^{16}$O by $^{19}$F($p, \alpha\gamma$)$^{16}$O and their possible decay.

2 Experimental Methodology

In order to properly explore the excitation scheme of $^{16}$O, the detection of 2$\alpha$-particles and a $^{12}$C particle in coincidence is required for above threshold levels as well as the de-excitation $\gamma$-rays are relevant for those sub-threshold levels.
A study of the \( ^{19}F(p, \alpha\gamma)\)\(^{16}\)O reaction has been performed at CMAM (Centre for Micro Analysis of Materials) facility (Madrid, Spain), using a 2.6 MeV proton beam, that impacts on a CaF\(_2\) target with a thickness of 0.4 \(\mu\)m on 0.08 \(\mu\)m of Carbon backing.

The detection system (Fig. 3) consist of 14 5x5 cm\(^2\) divided in 2x2 silicon detectors (Si-Ball)[3] and 4 telescopes \(\Delta E-E\) consisting of a 5x5 cm\(^2\) Double-Sided Stripped Silicon Detector (DSSD) as \(\Delta E\) detector and non-segmented silicon detectors (PAD) as E detector. DSSD detector has 16x16 strips, which means they worked as a set of 256 pixels.

The Si-Ball was used in forward angles with respect to the target since it offers a good angular coverage and the possibility of avoiding angles around 0º-30º where the Rutherford elastic scattering dominates. Also at forward angles, two of the telescopes were placed following a configuration that allow the scattered protons from the beam pass through \(\Delta E\) and stop in E detector while all the \(\alpha\)-particles, \(^{16}\)O and \(^{12}\)C ions are stopped in \(\Delta E\) detector. At backwards angles, two telescopes were placed, in this case the protons and \(\alpha_0\) traverse \(\Delta E\) and stops in E detector while the rest of the particles emitted in the reaction reaction stops in \(\Delta E\) detector. Thickness of the detectors used is given in Fig. 3.

In addition, 8 GAGG scintillator detectors and CEPA4 phoswich [4] detector were included in the setup in order to study the de-excitation of the excited states populated in \(^{16}\)O to the ground state. Fig. 3 shows the setup used.

![Figure 3. Scheme of the setup used used to measure the ejectiles produced in \(^{19}F(p, \alpha\gamma)\)\(^{16}\)O reaction.](image)

**3 Analysis procedure**

For a single particle detection in DSSD detectors, the junction (P-side) and the ohmic (N-side) is readout separately. For good event these signals correspond to the same deposited energy. Experimentally a certain deviation between both sides is expected so \(|E_p - E_n| \leq 2\sigma\) condition has been included in the data processing, where \(\sigma\) value is obtained from the gaussian fit applied to \(|E_p - E_n|\) distribution for each detector.

Under those conditions Fig. 4 shows a preliminary identification of the \(\alpha\)-particles produced during the experiment as labeled in Fig. 2. The following step will be to remove proton background by anti-coincidence conditions with E detector and study \(\gamma\) emissions in coincidence with \(\alpha\)-particles.

![Figure 4. Preliminary particle identification as identified for a strip placed at \(\theta = 60^\circ\) in forward telescopes where we can see \(\alpha\)-particles produced due to \(^{19}F(p, \alpha\gamma)\)\(^{16}\)O reaction when populating different levels in \(^{16}\)O, as well as elastic scattered protons that come from the beam with an energy of ~ 2.46 MeV after being scattered and pass through \(\Delta E\), depositing ~ 1.97 MeV.](image)

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**References**