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UNDERGROUND MEASUREMENTS OF THE ^{16}O$(p,\gamma)^{17}$F REACTION AT LUNA[*]

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The ^{16}O$(p,\gamma)^{17}$F nuclear reaction is a key part of the CNO cycle. The rate of this reaction strongly affects the relative abundances of oxygen isotopes formed in low and intermediate mass stars, particularly AGB stars. There are currently few experimental data for this reaction at low energies, and the data that exist have large uncertainties. An experimental campaign has been carried out at the LUNA laboratory in Italy, taking advantage of the ultra-low background rates available in its underground location to measure the weak ^{16}O(p,γ) reaction close to energies of astrophysical interest.

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1. Introduction

The ^{16}O$(p,\gamma)^{17}$F reaction is the slowest proton-induced reaction in the CNO cycle [1]. This is due to the fact that at energies of astrophysical interest it has no resonances, making it an example of a pure direct capture reaction [2].

The ratio of ^{17}O/^{16}O in stars depends strongly on the rate of this reaction. This ratio is an important probe of nucleosynthesis and mixing processes in the interior of stars, as it can be measured directly [3]. At astrophysical energies, *i.e.* centre-of-mass energies below around 500 keV, the existing experimental data is sparse, and generally has large uncertainties. An experimental campaign has been carried out at the LUNA underground accelerator at the Gran Sasso National Laboratory in Italy, aiming to measure the cross section for ^{16}O$(p,\gamma)^{17}$F below 400 keV. The very low background in the underground location combined with lead shielding allows for direct measurements of this weak reaction to be carried out.

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This work will cover the astrophysical motivation for this measurement, as well as detail the characterisation of the setup and some of the data that have been taken.

2. Astrophysical motivation

In stars, the $^{16}O(p,\gamma)^{17}F$ reaction is a part of the CNO cycle, and as such it plays a role in the evolution of intermediate mass main sequence stars and some post-main sequence stars. One of the most important astrophysical sites of this reaction, and the primary motivation for this experiment, is in Asymptotic Giant Branch (AGB) stars.

2.1. AGB Stars

AGB stars are composed of an electron-degenerate carbon–oxygen core, surrounded by a helium shell, a hydrogen shell, and then a convective envelope [4]. Most of the energy production comes from hydrogen-burning, with the helium shell periodically igniting and dominating the energy output. The hydrogen-burning stages proceed primarily via the CNO cycle. During the helium-burning phases, hydrogen-burning is suppressed, and the ashes of the CNO cycle are transported to the surface of the star as the convective envelope extends into the hydrogen shell. This is known as the third dredge-up.

A relatively large amount of material from the surface of AGB stars is ejected via stellar winds. Some of this material ends up as microscopic grains incorporated into meteors which fall to Earth. These are known as pre-solar grains. They are one of the most useful tests of stellar evolution models, as the isotopic ratios of material processed in stars can be directly analysed.

2.2. Pre-solar grains and Hot Bottom Burning

A subset of pre-solar grains, designated group 2, is predicted to have come from AGB stars. However standard stellar nucleosynthesis models are unable to account for all of the isotopic ratios found in those grains. One ratio that has proven particularly difficult to account for is the measured $^{17}O/^{16}O$.

An additional stellar mixing process called Hot Bottom Burning (HBB) has been suggested as a solution to this problem. It states that in massive AGB stars ($M > 4M_{\mathrm{Sun}}$), the base of the convective envelope reaches temperatures high enough to trigger hydrogen burning via the CNO cycle [5]. Whether or not HBB can reproduce the $^{17}O/^{16}O$ ratio of group 2 pre-solar grains depends sensitively on the rates of the two nuclear reactions $^{16}O(p,\gamma)^{17}F$ and $^{17}O(p,\alpha)^{14}N$. As the rates for the two reactions have been refined over the years, HBB has been periodically excluded and re-included as a potential source of group 2 grains [2, 6, 7]. At present, HBB is included when using the ^{17}O$(p,\alpha)^{14}$N reaction rate measured by Bruno *et al.* in 2016 [7, 8]. Further refinement of the ^{16}O$(p,\gamma)^{17}$F reaction rate at low energies is required before the matter can be resolved.

3. State of the art

At low energies, the ^{16}O$(p,\gamma)^{17}$F reaction can proceed in one of two ways: direct capture to the 495 keV first excited state in ^{17}F followed by de-excitation to the ground state; or direct capture straight to the ground state. The Q value of the reaction is 600.27 keV [9].

The ^{16}O$(p,\gamma)^{17}$F reaction has been measured numerous times over the years. However, due to the steep drop in the cross section at low energies, most of the existing data is at energies above 500 keV. The only successful attempt to measure the reaction at energies below 350 keV was by Hester in 1958 [10]. For a full discussion of the various data sets, including why the results from Tanner (1959) [11] and Rolfs (1973) [12] have been discarded, see Iliadis' 2021 review [2]. The current state of the art is shown in figure 1, along with the Gamow window for the typical burning temperatures of massive AGB stars, 60–100 MK [2].

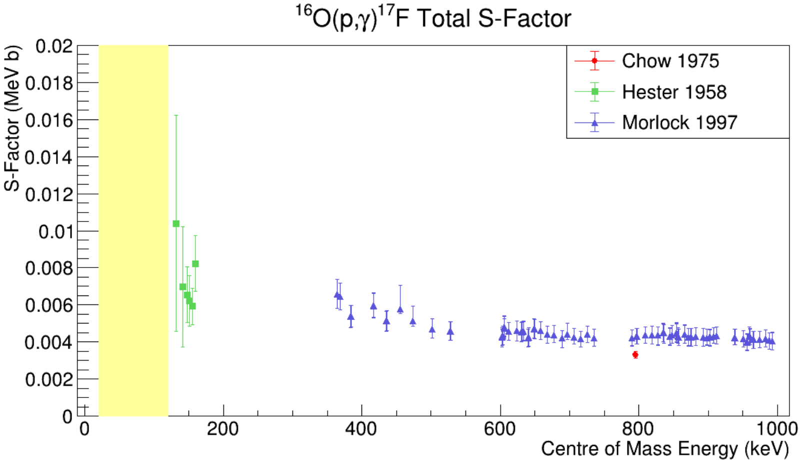

Fig. 1. (Colour on-line) Existing ^{16}O$(p,\gamma)^{17}$F data from [10, 13], and [14], with the Gamow window for massive AGB stars shaded in yellow (grey band).

4. The $^{16}\mathrm{O}(p,\gamma)^{17}\mathrm{F}$ experimental campaign

An experiment was conducted by the LUNA Collaboration at the Gran Sasso National Laboratory in Italy. It consisted of two parts: an activation measurement which concluded in summer 2022; and a prompt gamma measurement which concluded in spring 2023. The prompt gamma experiment will be the focus of the remainder of this work.

4.1. The LUNA facility

The Laboratory for Underground Nuclear Astrophysics (LUNA) is a collaboration based at Laboratori Nazionali del Gran Sasso (LNGS) in Italy. LNGS sits beneath the Gran Sasso mountain in the Apennines, under 1400 m of rock [15], and contains numerous experiments from various fields of particle and nuclear physics. The underground location reduces cosmic radiation flux in the lab by a factor of 10^6, which combined with low quantities of radioactive elements in the rock allows for extremely low gamma-ray background rates to be achieved. LUNA is able to take advantage of the low background to study nuclear reactions at energies where the rates are too low to be measured above ground.

4.2. The prompt gamma experimental setup

The prompt gamma part of the experiment used two different configurations. The first had a HPGe detector at approximately 55° from the beam axis, and two $\mathrm{CeBr_3}$ scintillators at 0° and 90°. The aim of this part was to measure the angular distribution of the two primary gammas. The angular distributions have been measured previously at beam energies above 750 keV [13], but never at the low energies available to this experiment.

The second configuration was focused on measuring the cross section with as high precision as possible. To this end, the $\mathrm{CeBr_3}$ detector at 0° was removed to allow the HPGe to be positioned closer to the target. The higher resolution of this detector compared to the scintillators meant that the reaction peaks from this weak reaction were much clearer in the spectra, and a higher precision could be achieved when calculating the yield. In addition, the secondary gamma, from the de-excitation of the 495 keV first excited state to the ground, could be resolved in the HPGe spectra (see figure 4). This was not possible in the $\mathrm{CeBr_3}$ spectra due to the poorer energy resolution.

For both parts, the setup was contained within a thick lead shield to further reduce the background. The effectiveness of the shield can be seen clearly in figure 2. The detectors were all in as close geometry as possible within the tight constraints of the shielding, to maximise the count rate from this very weak reaction.

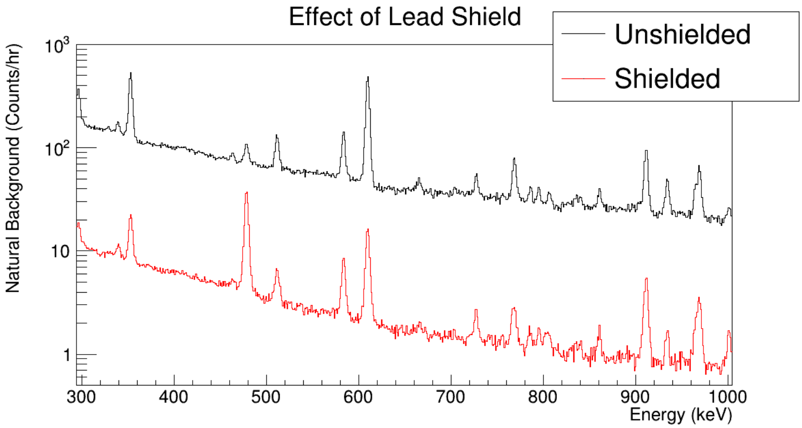

Fig. 2. Effect of the thick lead shield on the natural background rate at LUNA.

For each run, the accelerator was set at the desired energy and focused onto the target for between around 10 and 20 hours. The beam current was constant for each run, with values between approximately 200 and 300 μA. This allowed for between 10 and 20 Coulombs of charge to be accumulated during each run. At the end of each run the target was checked using Nuclear Resonant Reaction Analysis (NRRA), and changed if necessary. This process will be discussed briefly in the following section.

4.3. Targets

Both the prompt gamma and activation parts of the campaign used solid tantalum oxide targets created at LNGS by the anodic oxidation of tantalum backings in water. This is a well-understood technique that produces consistent targets with a well-known stoichiometry of Ta_2O_5 with controllable thickness and isotopic composition. For a detailed explanation of the process and benefits of this technique, see the 2012 paper by the LUNA Collaboration [16]. For this experiment, the water used for the oxidation was enriched in ^{18}O to 8% to allow NRRA to be performed on the narrow resonance of ^{18}O$(p,\gamma)^{19}$F at 151 keV.

A total of six targets were used during the prompt gamma campaign. Before the first run on a target and after each run, a resonance scan was performed to check for degradation. Once the target started showing an appreciable decrease in the width of the scan, it was removed and a new target was used for the next run. A plot of the resonance scans taken on one of the targets is shown in figure 3. A more detailed analysis of the resonance scans will be performed, in order to find the target thicknesses and profiles required for calculating the cross sections and S-factors from the experimental yields.

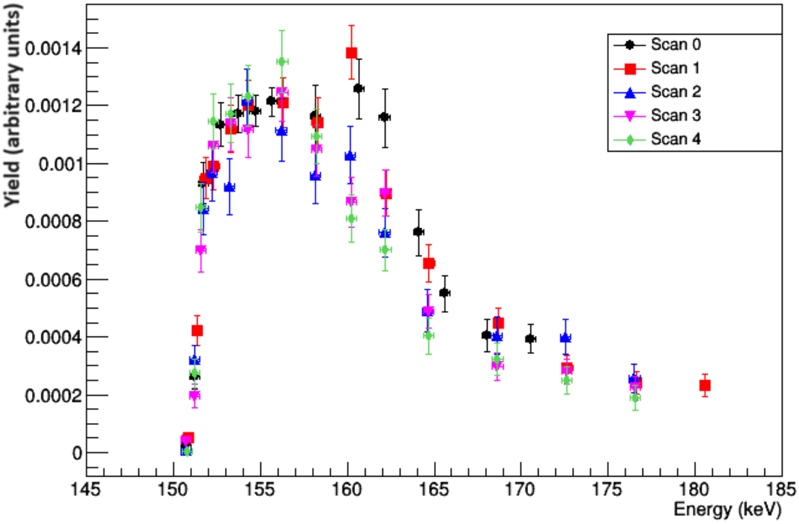

Fig. 3. An example of the resonance scans taken during the $^{16}O(p,\gamma)^{17}F$ campaign.

4.4. Reaction peaks

Due to the very low cross section of the $^{16}O(p,\gamma)^{17}F$ reaction at the low energies studied in this experiment, there were several background or contaminant peaks in the spectra that were of comparable size to the reaction peaks. An example spectrum from a long run at a beam energy of 310 keV is shown in figure 4. The relatively high density of peaks in the region of interest of this experiment led to background peaks overlapping the reac-

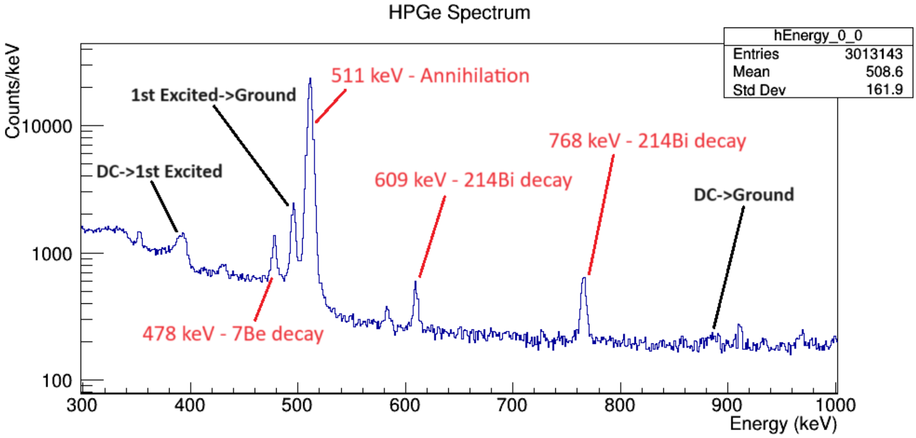

Fig. 4. A spectrum from the HPGe detector taken at $E_{\mathrm{beam}} = 310$ keV, with the $^{16}O(p,\gamma)$ reaction peaks and most prominent background peaks labelled.

tion peaks at some beam energies. This meant that finding the number of counts in the reaction peaks involved fitting the peak plus background, and sometimes an overlapping peak as well.

5. Outlook

The remaining analysis will focus on calculating S-factors from the measured yields. This will involve several steps. The first will be to calculate the efficiency of the detectors as a function of gamma energy, from both calibration measurements and simulations. The targets will then need to be characterised in detail, including their degradation as a function of accumulated charge, and the distribution of ^{16}O atoms throughout the target, called the target profile. From these values and the relevant stopping powers taken from SRIM, the S-factors will be calculated.

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