Feasibility study of the ^{13}C$(\alpha, \mathrm{n})^{16}$O reaction at LUNA

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Abstract. The ^{13}C$(\alpha, \mathrm{n})^{16}$O reaction determines the dominant neutron source of the s-process in thermally pulsing, low-mass, asymptotic giant branch (TP-AGB) stars. The temperature during the s-process in the ^{13}C pocket of 90×10^6 K corresponds to a Gamow window of 140-230 keV. Since this energy is far below the Coulomb barrier, the cross section of this reaction is extremely small and its rate can only be extrapolated from the measurements at higher energies. At present, the cross section at Gamow peak is uncertain by almost one order of magnitude.

An experimental campaign aimed at measuring low energy cross section in ^{13}C$(\alpha, \mathrm{n})^{16}$O is scheduled at the underground LUNA-400 accelerator in Gran Sasso Laboratory, Italy. The unique underground location of this facility offers significant improvement in sensitivity compared with previous investigations. It will allow to establish the interference pattern of the resonances and the absolute scale of this reaction.

1 Introduction

The ^{13}C$(\alpha, \mathrm{n})^{16}$O reaction is the major neutron source for the s-process in thermally pulsing, low mass, asymptotic giant branch (TP-AGB) stars [1]. The energy generation in such stars occurs in the H and He burning shells, separated by a thin He-rich intershell region, surrounding the inert C/O core. During H burning, the He concentration increases to the point of igniting He burning at the bottom of the intershell. Because of the heat generated during the He burning, the intershell becomes convective. The star expands and cools down thus inhibiting H burning in the outer layers. The He flash ends when most of the He has been consumed in the shell. The star contracts again and H burning is reactivated. These alternating H and He burning phases are repeated up to 40 times.

The main s-process is assumed to take place during the phase prior to the He flash when hydrogen is mixed from the convective envelope into the He intershell. The ^{13}C is produced by the reaction sequence ^{12}C$(\mathrm{p}, \gamma)^{13}N(\beta^- \nu)^{13}$C that leads to the formation of the so-called ^{13}C pocket, a thin layer enriched in ^{13}C. The temperature during the s-process in the ^{13}C pocket reaches 90×10^6 K corresponding to a Gamow window of 140-230 keV for the reaction ^{13}C$(\alpha, \mathrm{n})^{16}$O. Since this energy is far below the Coulomb barrier, the cross section is extremely small and not accessible to direct measurements. For this reason, its value has to be determined by extrapolation of measurements at higher energies, as shown in Figure 1.

The extrapolation is complicated by the unknown influence of a broad subthreshold state and by two subthreshold resonances. Our goal is to measure the S-factor at energies closer to the Gamow
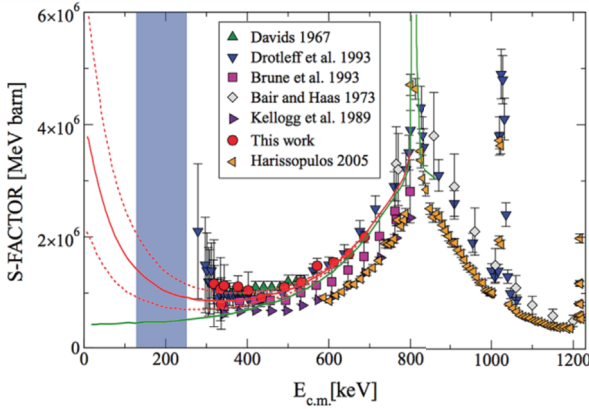
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Figure 1. Astrophysical S-factor of the ^{13}C$(\alpha, n)^{16}$O reaction, the blue area defines the Gamow window [1], [2], [3], [4], [5], [6].

Table 1. ^{13}C$(\alpha, n)^{16}$O reaction rate for a current of 200 μA on a 100% ^{13}C enriched target.

E_α [keV]	cph
400	320
375	100
350	30
300	1.5
275	0.2
250	0.03
200	10^{-4}

window with respect to previous experiments and with high precision in order to facilitate the extrapolations. In Table 1 the rate in counts per hour (cph) for the ^{13}C$(\alpha, n)^{16}$O reaction is shown as a function of beam energy (for a current of 200 μA).

2 LUNA-400

The LUNA experiment is located in the Gran Sasso Underground Laboratory (LNGS) in Italy [7]. This is the largest underground laboratory in the world that hosts experiments in particle physics, particle astrophysics and nuclear astrophysics. The underground facilities have been built at the side of the ten kilometers long highway tunnel crossing the Gran Sasso Mountain, between L'Aquila and Teramo, about 120 km from Rome. The rock overburden of about 1400 m (3800 m water equivalent) reduces the muon component of the cosmic background by a factor of 10^6, the neutron component by a factor of 10^3, and the gamma component by a factor of 10 with respect to a laboratory on the Earth's surface. The reduced rate of low energy neutrons in LNGS, about 10^{-3} n/cm^2 per hour [8], can be compared to the reaction yield shown in Table 1.

The LUNA setup is composed of a 400 kV electrostatic accelerator providing high intensity proton or alpha beams. The beam can be delivered to a solid or gas target system. The low yield expected in this experiment requires targets with high resistance against ion bombardment.

3 Targets

The selection and the production of the ^{13}C target is of primary importance for this measurement, given the high beam intensity that they must withstand without deterioration. Two options are available within the LUNA-400 setup, gaseous or solid targets.

For the gas target, three molecules were considered CH$_4$, CO$_2$, CO all enrichment in ^{13}C up to 99%. The major problems for the gas target is so-called beam heating effect: the density of the target may decrease along the beam path because of heat transfer from the intense ion beam. The tests on
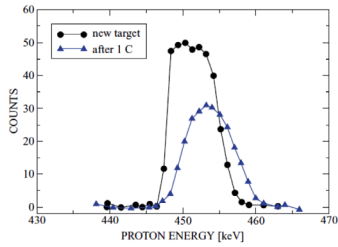
Figure 2. Reaction yield of the ^{13}C(p, γ) resonance at 448.5 keV for a fresh target and after an integrated charge of 1 C [1].
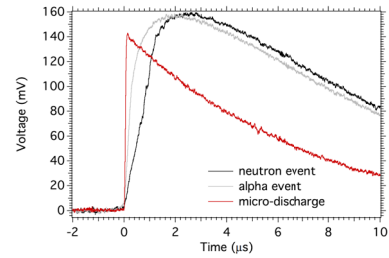

Figure 3. Example of the raw preamplifier traces showing the risetimes from three different sources within a ^{3}He tube: a microdischarge (red), an alpha-particle trace (gray) and a neutron trace (black).
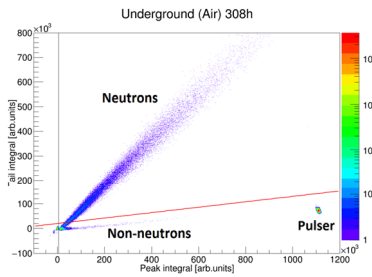

Figure 4. PSD method applied to data acquired underground in air with EJ-426 detector.
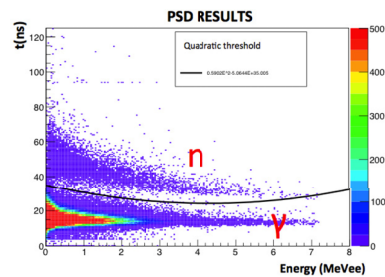

Figure 5. PSD results for BC-501A detector.

beam heating were carried out at LUNA using Nuclear Resonance Analysis (NRA) on a mixture of CH$_4$+N$_2$ (95%+5%). The analysis is still ongoing.

One of the most severe problems related to solid state targets exposed to α beam is the blistering effect: particles implanted into the target are trapped inside the material forming macroscopic bubbles. The bubbles increase in size during the implantation process and built up pressure. Eventually they explode and destroy the involved area of the target. Previous experiment [1] have shown that targets with a typical density of 22 μg/cm^2 can withstand a collected charge of 1 C equivalent to 1.5 h at an intensity of 200 μA (see Figure 2).

Several targets, with ^{13}C enrichment up to 99%, are under consideration with different bulk, substrate and deposition techniques. For the bulk materials we are evaluating Au, Ta, Ni, Cu, sapphire and diamond: the last two are known for their optimal mechanical strength and heat dissipation capabilities, while gold and tantalum do not contribute to beam-induced background in the region of interest. The substrates we are evaluating are Au and graphene or none (deposition directly on the bulk). The available deposition technique are implantation, polymerisation and electron gun evaporation.

A preliminary test on few solid targets will be performed at the Legnaro National Laboratory with the accelerator line *CN-7 MV*: this machine is powered by a Van de Graaff generator capable of providing ion beams with energies up to 7 MeV and currents up to 3 μA. For this tests the collaboration is preparing the following targets: Au + implantation, Ta + evaporation, Ta + polymer and sapphire + Au + evaporation.

3.1 Detectors

Given the low reaction yield, the efficient detection of neutrons is of paramount importance for the measurement of $^{13}C(\alpha, n)^{16}O$ reaction. A secondary requirement is the capability of rejection for non neutron signals. Finally a low-background detector would be desired. Several alternatives are under consideration: plastic scintillator, liquid scintillator and ^{3}He counters.

The most common reaction used for high efficiency thermal neutron detection is ^{3}He(n, p)^{3}H, where both the proton and the ^{3}H are detected by a ^{3}He-filled proportional counters. They offer high detection efficiency with excellent gamma discrimination (Figure 3).

EJ-426-0 plastic scintillator-based detector is a homogeneous matrix of fine particles of Lithium-6-Fluoride (^{6}LiF) and Zinc Sulfide phosphor (ZnS:Ag) compactly dispersed in a colourless binder. Thermal neutrons are captured through the reaction ^{6}Li(n, ^{3}H)α (Q=4.78 MeV). The producer claims that the detector has low intrinsic background, is insensitive to gamma rays, has a 50% intrinsic efficiency for thermal (0.025 eV) neutrons, that falls sharply with increasing neutron energy and can be used with a Pulse Shape Discriminating (PSD) electronic chain to maximise its gamma rejection capability (Figure 4).

The BC501A is a liquid scintillator, made from a mixture of several organic molecules in liquid form with xylene as solvent. This scintillator is particularly effective in separating neutrons from γ-rays using PSD (Figure 5).

4 Conclusions

The proposed experiment will reduce the uncertainties in s-process in AGB stars by precisely measuring the cross-section of the reaction $^{13}C(\alpha, n)^{16}O$ close to the Gamow window. A feasibility campaign has started at LUNA by studying enriched ^{13}C targets, both solid and gaseous, and qualifying low background neutron detectors. A preliminary test on solid targets is already scheduled at Laboratori Nazionali di Legnaro. The $^{13}C(\alpha, n)^{16}O$ measurement in LUNA is scheduled for fall 2017.

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