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# Measurement of very low ( $\alpha, n$ ) cross sections of astrophysical interest

J L Tain<sup>1</sup>, D Jordán<sup>1</sup>, J Agramunt<sup>1</sup>, A Algora<sup>1</sup>, I Bandac<sup>2</sup>, A Bettini<sup>2,3</sup>, R Caballero-Folch<sup>4</sup>, F Calviño<sup>4</sup>, D Cano-Ott<sup>5</sup>, G Cortés<sup>4</sup>, C Domingo-Pardo<sup>1</sup>, L M Fraile<sup>6</sup>, A R García<sup>5</sup>, J J Gomez-Cadenas<sup>1</sup>, J José<sup>4</sup>, R Longland<sup>4</sup>, E Mendoza<sup>5</sup>, A Parikh<sup>4</sup>

<sup>1</sup> Instituto de Física Corpuscular, CSIC-Univ. Valencia, Valencia, Spain

<sup>2</sup> Laboratorio Subterráneo de Canfranc, Canfranc Estación, Spain

<sup>3</sup> Università di Padova and INFN, Padova, Italy

<sup>4</sup> Universitat Politècnica de Catalunya, Barcelona, Spain

<sup>5</sup> Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain

<sup>6</sup> Universidad Complutense de Madrid, Madrid, Spain

E-mail: jose.luis.tain@ific.uv.es

**Abstract.** The reactions  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  are the primary sources of neutrons for the astrophysical  $s$ -process. The feasibility of cross section measurements within the respective Gamow windows is discussed in quantitative terms for a  $4\pi$  neutron counter, based on  $^3\text{He}$  tubes and a neutron moderator, placed in an underground lab.

## 1. Introduction

The astrophysical  $s$ -process is responsible for the production of about half of the abundance of the elements beyond iron in the Universe. The process is described as a succession of neutron captures followed by  $\beta$ -decay taking place along the valley of nuclear stability. Starting with seed nuclei in the iron group, elements up to bismuth can be synthesized. Actually two processes are distinguished [1]: the main  $s$ -process, reaching Pb-Bi, for which the abundance distribution shows the characteristic pattern of formation through a steady flow of neutrons; and the weak  $s$ -process, reaching  $A \sim 90$ , for which the neutron fluence is much lower. The latter is associated with the Red Giant phase of massive stars ( $M > 10M_{\odot}$ ), where the temperature can reach values high enough to activate the reaction  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  during the He burning ( $T \sim 3 \times 10^8\text{K}$ ) and C-shell burning ( $T \sim 10^9\text{K}$ ) stages. This reaction becomes the source of neutrons for the weak  $s$ -process. The main  $s$ -process takes place in thermally pulsing low mass asymptotic giant branch (AGB) stars. Elements are synthesized at the He inter-shell, in the time interval between recurrent ignition events (thermal pulse, TP). The reaction  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  at  $T \sim 10^8\text{K}$  provides the source of neutrons. The so-called  $^{13}\text{C}$  pocket is formed by proton capture reactions on the  $^{12}\text{C}$  formed during TP. In addition to this, during TP when the temperature reaches  $T \sim 3 \times 10^8\text{K}$ , the reaction  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  is activated but contributes little to the final abundances. Although the general picture is well established a detailed description that can be correlated with the different stellar scenarios requires precise knowledge of both ( $\alpha, n$ ) reaction rates at the relevant stellar temperatures. This question is one of the current key issues in nuclear astrophysics.



Experimentally the cross sections at the relevant energies (Gamow window) have not been measured and currently they are estimated from extrapolations. The limiting factor in the measurements has been the relatively high level of neutron background in comparison with the weak reaction rates expected at these energies. All measurements up to now have been performed at surface level, where the natural neutron background flux is about  $10^{-2}\text{cm}^{-2}\text{s}^{-1}$ . The major part of the background has cosmic ray origin, mostly the final product of muon interactions. Since the level of muon flux is reduced by several orders of magnitude underground it has been proposed that future experiments should be pursued at an underground laboratory.

The measurement of these important  $(\alpha, n)$  cross sections is the main objective of the project to build a nuclear astrophysics facility at the Canfranc Underground Laboratory (LSC) in Spain [2]. The project foresees the installation of a MV electrostatic accelerator in a dedicated hall, and the development of the specific instrumentation required for the measurements. As part of this project we are studying the feasibility of the proposed measurements. Apart from the generic argument related to the reduction in background the sensitivity that can be reached with specific setups has not been discussed up to now, to our knowledge. In this contribution we present the results of the work done so far and outline how the work will continue.

## 2. Measurement of very low neutron rates

Over the years a variety of different detection techniques have been applied to the measurement of the  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  cross sections. They included: organic scintillation detectors [3], plastic neutron time-of-flight detectors in conjunction with  $\gamma$ -ray detectors (NaI) [4],  $\text{BF}_3$  neutron counters embedded in a graphite neutron moderator [5],  $^3\text{He}$  neutron spectrometers [6] germanium  $\gamma$ -ray detectors,  $^3\text{He}$  neutron counters embedded in a polyethylene (PE) neutron moderator [7, 8] and a  $4\pi$   $\text{BaF}_2$   $\gamma$ -ray calorimeter with a cadmium loaded paraffin neutron-gamma converter [9].

The lowest energy at which a cross section was measured in the case of  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  [7] is  $E_\alpha \sim 360$  keV with a value  $\sigma \sim 60$  pb. In the case of  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  [8] the lowest point is at about 800 keV with a cross section of about 130 pb. In order to make some rate estimates one can fix the goal reference cross section value for the future measurements at 1 pb, a reduction of two orders of magnitude in the sensitivity limit. Using a realistic value of target thickness:  $n = 10^{-6}\text{b}^{-1}$  (equivalent to about  $20 \mu\text{g}/\text{cm}^2$  or an energy loss of 50 keV in the target) and alpha beam intensity:  $i = 5 \times 10^{14}\text{s}^{-1}$  (80 pμA), one obtains a reaction rate of  $5 \times 10^{-4}\text{s}^{-1}$  or 1.8 per hour. In addition one has to consider the detection efficiency of the neutron detector. Since in general the efficiency is quite sensitive to neutron energy, it is important to note the energy range of the emitted neutrons. The  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  reaction has a positive Q-value of 2.216 MeV. Assuming the beam energy reaches up to about  $E_\alpha = 1.2$  MeV, the range of neutrons to be detected will be around 2.2-3.5 MeV. In the case of  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  the reaction has a negative Q-value of -0.478 MeV and the neutrons will have an energy of less than 1 MeV.

The combination of  $^3\text{He}$  proportional counters with a neutron moderator has been the most frequently used setup until now. In our opinion it is also the best candidate to reach the lowest sensitivity limit because: a) The detection of the thermalized neutrons through the reaction  $^3\text{He} + n \rightarrow ^3\text{H} + n$  (Q=764 keV) provides a very distinctive signature of neutron detection, b) Helium filled proportional tubes are rather insensitive to gamma radiation, c) Large detection efficiencies ( $\geq 50\%$ ) can be achieved using a sufficient number of long  $^3\text{He}$  tubes surrounding the source, and d) The detection efficiency can be made rather independent of neutron energy in the range of interest by an appropriate spatial distribution of tubes. Such devices are commonly used also to measure  $\beta$ -delayed neutron emission probabilities and in fact we have built and used for this purpose one such detector (see Fig 1), named BELEN [10]. In the following we investigate the suitability of the BELEN detector (or a similar one) for the measurement of very low rate  $(\alpha, n)$  reactions. The rate of natural neutron background detected in BELEN measured



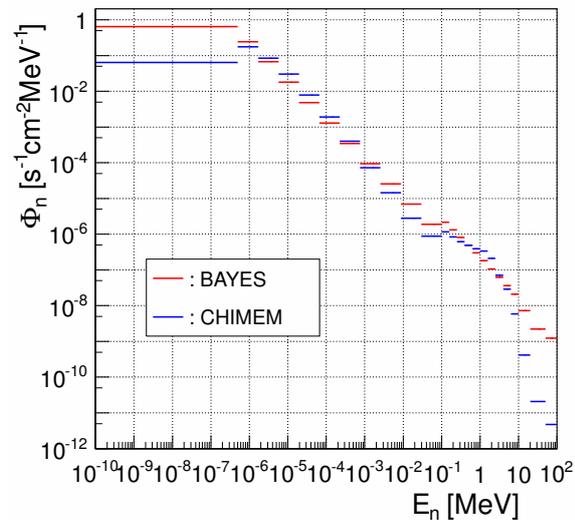
**Figure 1.** View of the BELEN 4 $\pi$  neutron counter.



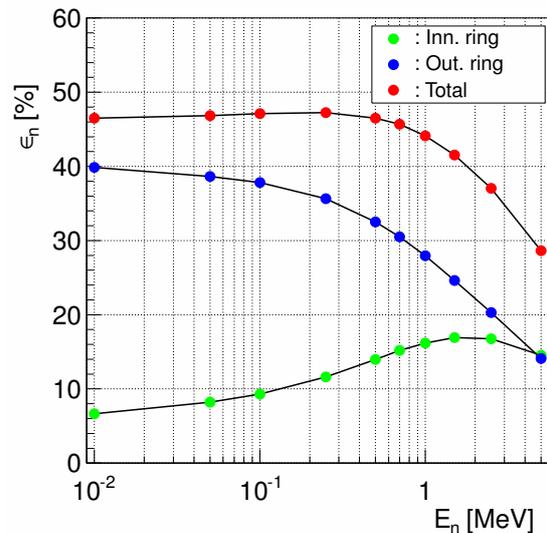
**Figure 2.** View of one of the PE blocks with  $^3\text{He}$  tube used in the neutron background measurement at LSC.

at several surface labs is around  $0.6\text{-}1.2\text{ s}^{-1}$ . For comparison the detector of Ref. [8], which is the most sensitive setup used until now, had a background rate of  $2.8 \times 10^{-2}\text{ s}^{-1}$ . This very low background rate was achieved thanks to the use of massive passive shielding and also an active shield to veto cosmic rays. In order to evaluate the expected rate of detected background neutrons for any experiment in the underground lab it is necessary to know accurately the neutron background flux at the site. More importantly it is necessary to know the energy distribution of the neutron background field, since the cross section for neutron interactions is strongly energy dependent. Accordingly the first step in our work has been the measurement of the neutron flux energy distribution at LSC. The results have been published already [11] and are described briefly here.

The measurement was performed using six  $^3\text{He}$  tubes from the BELEN detector, each enclosed in a PE block of different size (see Fig. 2). The size of the blocks varied between  $4.5\text{cm} \times 4.5\text{cm} \times 70\text{cm}$  and  $27\text{cm} \times 27\text{cm} \times 70\text{cm}$ . The setup was placed in the middle of Hall A at LSC and the measurement lasted for four weeks. The set of neutron counters is treated as a Bonner Sphere Spectrometer (BSS) [12]. The working principle of the BSS is based on the dependence of the number of thermalized neutrons giving a signal in the  $^3\text{He}$  counter on both the initial neutron energy and the thickness of the moderator. The tubes from BELEN have an active volume of  $\varnothing 2.5\text{cm} \times 60\text{cm}$  and a pressure of 20 atmosphere. This provides a gain of two orders of magnitude in sensitivity when compared with conventional BSS systems. The response of the spectrometer was calculated using the MCNPX Monte Carlo simulation code [13] and verified with calibration measurements using a  $^{252}\text{Cf}$  neutron source. The deconvolution of the neutron rates measured in the six detectors with the spectrometer response allows the extraction of the distribution of the flux as a function of the energy. Several codes were used in order to check for systematic deviations. Figure 3 shows the solution obtained with two different codes and corresponds to Fig. 6 of Ref. [11]. The distribution is relatively well determined between 1 eV and 10 MeV but it is rather uncertain at thermal energies and above 10 MeV. As explained in Ref. [11] this reflects the lack of sensitivity of our setup to those energies and is a feature of these kinds of ill-posed inverse problems. The energy integrated flux however is rather insensitive and was determined to be  $\Phi = 3.44(35) \times 10^{-6}\text{cm}^{-2}\text{s}^{-1}$  which is about four orders of magnitude smaller than at earth's surface. Having the flux versus energy distribution, it is now possible to make a realistic estimation of the background rate in a neutron sensitive detector using Monte Carlo simulations. We chose the MCNPX code for this work based on our positive experience when comparing experiment and simulation. The geometry of the BELEN detector consisted of a total of twenty  $^3\text{He}$  tubes distributed in two rings around a central longitudinal hole of



**Figure 3.** Measured neutron flux at LSC obtained with two different deconvolution codes.

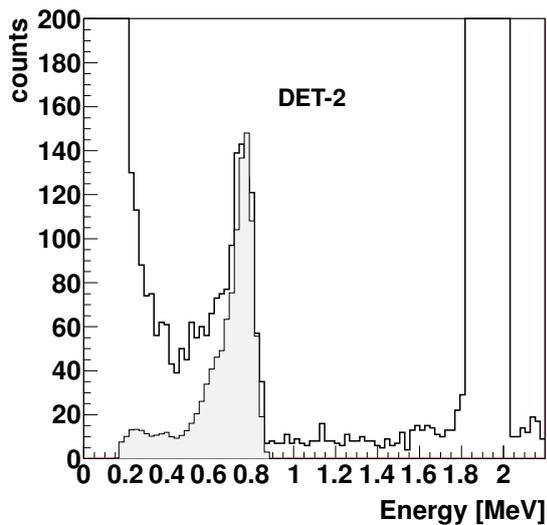


**Figure 4.** Efficiency of the BELEN detector as a function of neutron energy obtained with MCNPX.

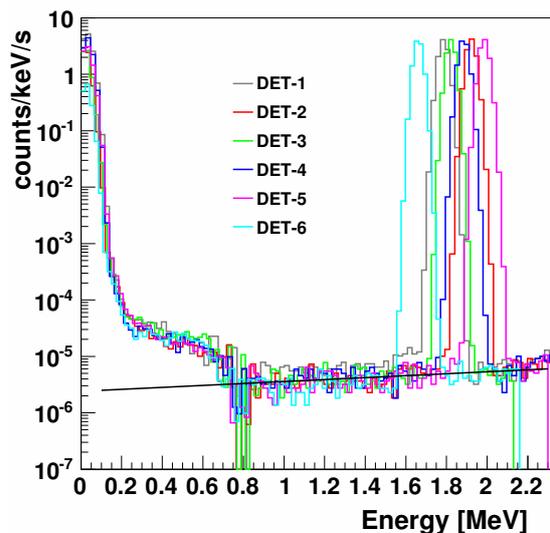
5.5 cm radius in the PE block. Eight tubes were placed at a radius of 9.5 cm and twelve tubes at 14.5 cm. The PE block dimensions were varied to study the shielding effect on the incoming background neutrons. The minimum size was 50cm × 50cm × 80cm (the actual PE size for the BELEN detector is 90cm × 90cm × 80cm.) With this arrangement the efficiency for detecting neutrons emitted randomly from the centre of the detector was calculated as a function of energy as shown in Fig. 4. It can be observed that for this configuration the efficiency is rather constant up to 1 MeV, with a maximum value of 47%, and drops to 37% at 2.5 MeV. To calculate the background rate in this detector, events are simulated with energy sampled from the flux versus energy distribution and a random direction. The neutron initial position is randomly distributed over all outer surfaces of the PE block. The result of the simulation was sensitive to the different flux distributions obtained in Ref. [11]. We found that the rate for the minimal PE block size varied between  $6 \times 10^{-4} \text{s}^{-1}$  and  $9 \times 10^{-4} \text{s}^{-1}$ . Increasing the size of the PE block, which acts as shielding for the background neutrons, has a significant impact. For example an extra layer of 20 cm surrounding the initial PE block reduces the detected rate to a range between  $4 \times 10^{-5} \text{s}^{-1}$  and  $1 \times 10^{-4} \text{s}^{-1}$  depending on the flux distribution used. For a 40 cm layer the rate is in the range  $8 \times 10^{-6} \text{s}^{-1}$  to  $6 \times 10^{-5} \text{s}^{-1}$ . Comparing these numbers with the expected rates for the ( $\alpha$ , n) reactions given above one can conclude that from the point of view of neutron background a PE moderated  $^3\text{He}$  neutron counter array is capable of measuring cross sections of a fraction of a picobarn.

One of the advantages of using the  $^3\text{He}$  tubes from the BELEN detector in this measurement is that we have gained essential information about background signals with an origin different from ambient neutrons. We show in Fig. 5 the count versus amplitude histogram recorded during the whole measuring time for one of the detectors. We should mention that detector operation was very stable during the four week period, except for sporadic sudden increases of noise in some detectors. These noise signals are easily removed in the off-line analysis. Superposed on the spectrum of Fig. 5 is the characteristic spectrum of signals due to thermal neutron capture in  $^3\text{He}$ . The shape of this spectrum, measured with a neutron source, shows the full absorption peak and the tail due to partial deposition of energy by either the triton or proton when the capture happens very close to the walls (wall effect). Fitting this shape

to the measured spectrum provides the number of true neutron counts. As can be observed there are many counts in the spectrum besides those attributable to neutron capture. It is more instructive to look at the spectrum after subtraction of the neutron signals. This is done in Fig. 6 which shows the superposition of the rate spectra belonging to the six neutron detectors. The peak visible in the spectra in the range between 1.6-2.0 MeV corresponds to a fixed frequency (10 Hz) pulse generator signal which was used to measure the lifetime of the data acquisition system (DACQ). It is to be noticed that the six spectra are very similar even if the PE blocks



**Figure 5.** Spectrum registered with one of the neutron detectors. Superposed is the pure neutron response (shaded area).



**Figure 6.** Superposition of the spectra registered with the six neutron detectors after subtraction of the neutron response.

differ greatly in size. This points to a similar origin for the signals which could be the tube itself or the electronics. The counts below 100 keV are associated with electronic noise. We should mention that the data was taken with the self-triggered digital DACQ developed for BELEN. The signals from each counter (conveniently shaped) are sent to one channel of a 100 MHz sampling digitizer. Trapezoidal filters implemented in the firmware are applied to derive time and amplitude information for any signal above a given threshold. Typically the threshold is adjusted to let a certain fraction of noise signals to pass. The counts observed above 800 keV (a flat slightly increasing component) are related to  $\alpha$ -radioactivity present in the walls and other materials of the tube. If the emitter is sufficiently close to the surface, the  $\alpha$ -particle can enter the gas volume after losing part of its initial energy. This produces a continuum component (indicated by the line in Fig. 6) which actually extends down to zero energy. The steep component in the spectra between 100 and 200 keV could be related to the interaction of  $\gamma$ -rays in the tube. The component extending between 200 keV and 800 keV above the flat component is not readily explained and is of unknown origin. This region coincides with the region of neutron signals. The total rate in this energy interval varies between  $5 \times 10^{-4} \text{s}^{-1}$  and  $9 \times 10^{-4} \text{s}^{-1}$  depending on the counter. From this number about 20% could be attributed to the flat  $\alpha$ -component. Such a rate is too high to allow the measurement of the proposed ( $\alpha, n$ ) reaction cross sections of interest. For a twenty tube neutron counter such as the one described here the total background rate will be of the order of  $10^{-2} \text{s}^{-1}$ . The origin of this intrinsic background will be investigated further. However, it should be noted that it has already been demonstrated [14] that  $^3\text{He}$  tubes with a very low intrinsic background can be built. The tubes

were fabricated using very low activity materials and special manufacturing processes, achieving an intrinsic background rate about 1000 times smaller than the present tubes.

### 3. Summary and outlook

We have investigated the issue of the feasibility of the measurement of the important  $^{13}\text{C}(\alpha, n)^{16}\text{O}$  and  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  reaction cross sections at energies in the region of the Gamow window in an underground lab. For this we have measured the energy distribution of the neutron background flux at LSC and used this information to make a realistically simulation of the rate of background events in an existing neutron counter when placed underground. The neutron detector consists of an array of  $^3\text{He}$  tubes embedded in a PE neutron moderator which we believe is the best candidate for this type of measurement. The results show that this type of detector when placed underground can provide two to three orders of magnitude better sensitivity when compared with measurements at earth's surface, thus allowing the measurement of cross sections of a fraction of picobarn. We have also investigated the intrinsic background of the  $^3\text{He}$  tubes from this detector and found that it must be strongly reduced if this application is to be successful.

The work towards the development of a dedicated neutron detector will continue. We plan to perform a new more accurate measurement of the neutron flux energy distribution at LSC. The measurement will use a larger set of neutron detectors than before, including bare tubes to enhance the sensitivity at thermal energies and neutron converter-multipliers to enhance the sensitivity at high energies. A complementary measurement using low background liquid scintillation detectors will be carried out. The issue of the intrinsic background in  $^3\text{He}$  tubes will be further investigated. We plan to use detectors with different characteristics (size, pressure, gas composition and manufacturer). In particular we will study the performance of a new  $^3\text{He}$  detector specially designed to have low intrinsic background rate. The walls of the tube are internally covered with a thin carbon layer to prevent the penetration of charged particle activity from the walls into the gas volume. In addition to this, the accelerator induced neutron background will be investigated.

#### 3.1. Acknowledgments

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