Direct measurement of the $^{2}\H(\alpha,\gamma)^{6}\Li$ cross section at energies of astrophysical interest

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Abstract. The knowledge of the $^{2}\H(\alpha,\gamma)^{6}\Li$ cross section is very important to understand the production of $^{6}\Li$ during the Big-Bang Nucleosynthesis (BBN). Presently, no direct measurement of this reaction in the energy region of interest exists (the only direct measurements actually available are above 1 MeV in the center of mass reference frame and around the 711 keV resonance). The existing data in the energy region of interest for BBN ($40 \text{ keV} < E_{\text{cm}} < 400 \text{ keV}$) have been taken with indirect techniques which are affected by large uncertainties because they strongly depend on theoretical assumptions. The direct measurement is a difficult task because the expected cross section is of the order of a few pico-barn. Thanks to the natural shielding offered by the about 1400 meters of rocks, the cosmic background is reduced by a factor $10^6$ at the Laboratori Nazionali del Gran Sasso (LNGS). Here, at the LUNA (Laboratory for Underground Nuclear Astrophysics) facility it is possible to explore with a direct measurement of the $^{2}\H(\alpha,\gamma)^{6}\Li$ reaction cross section in the BBN energy region. This measurement can be done with a $^4\He$ intense beam hitting a windowless deuterium gas target. The emitted photons are detected with a High-Purity Germanium detector (HPGe) in close geometry. In this paper the experimental setup will be described and the measurement strategy based on the first tests already performed will be discussed.

1. The $^{2}\H(\alpha,\gamma)^{6}\Li$ nuclear reaction

One of the main achievements of the standard Big-Bang model of the Universe is the consistency of the observed light element abundances with the Big-Bang Nucleosynthesis predictions. The primordial nucleosynthesis ended with the creation of the lightest nuclei, $^2\H$, $^3\He$ and $^4\He$. Also some $^7\Li$ was produced and probably $^6\Li$ too. $^6\Li$ has been found in very old low metallicity halo stars, in an unexpectedly high amount (2-3 orders of magnitude higher compared to available BBN network predictions [1]). The only way to produce $^6\Li$ during the BBN is the $^{2}\H(\alpha,\gamma)^{6}\Li$ direct capture, with a very weak expected cross section. The global picture is shaded by the fact that, up to now, direct measurements of this reaction at BBN energies do not exist.

A summary of the $^{2}\H(\alpha,\gamma)^{6}\Li$ available S-factor is shown in Figure 1. Direct measurements cover only the energy region between 1 and 3.5 MeV and the resonance at 711 keV. At BBN energies, only indirect measurements based on Coulomb breakup exist which are affected by large uncertainties. Therefore current estimates differ by about one order of magnitude [7]. For this reason a direct measurement of the $^{2}\H(\alpha,\gamma)^{6}\Li$ S-factor in the BBN energy region is mandatory and the LUNA collaboration is performing this measurement for the first time.
2. The experimental apparatus

Since the expected cross section in the BBN energy region is of the order of few picobarns, the signal-to-noise ratio must be improved as much as possible. The LUNA facility is located underground at the Laboratori Nazionali del Gran Sasso (LNGS) where about 1400 m of rocks (3800 m.w.e.) reduce the muon flux of a factor $10^6$ and the neutron flux of a factor $10^3$ with respect to the surface. At LUNA a custom 400 keV electrostatic accelerator is used to meet requirements of nuclear astrophysics experiments [8]. The machine can provide high intensity (up to 300 $\mu$A) $\alpha$-beams with an excellent energy resolution (less then 100 eV) over long run periods. The setup consists of a $D_2$ windowless differentially pumped gas target. A High-Purity Germanium detector (HPGe) with 135% relative efficiency is used for $\gamma$ detection [9]. The detector is in close geometry, 20 mm far from the beam line. A calorimeter is used for beam intensity measurements. In order to minimize the natural background, all the setup is surrounded by a 4$\pi$ lead shielding. Around the lead shielding an anti-Rn-box is built to keep a constant $^{222}Rn$ daughters $\gamma$ counting rate. The Q-value of the reaction is 1.473 MeV and the Region-of-Interest (RoI) for the $^2H(\alpha,\gamma)^6Li$ reaction with a 400 keV $\alpha$-beam ($E_{cm} \approx 130$ keV) is given by $E_\gamma = Q + E_{cm} + \Delta E_{Doppler} - \Delta E_{Recoil} = 1585 \div 1625$ keV.

The $^2H(\alpha,\alpha)^2H$ Rutherford scattering of the beam inside the gas target is a side effect that has to be dealt with. It induces the $^2H(^2H,n)^3He$ and $^2H(^2H,p)t$ reactions. While the $^2H(^2H,p)t$ reaction is not a problem, the neutrons produced by the $^2H(^2H,n)^3He$ reaction (average neutron energy 2.45 MeV) can induce $(n,\gamma)$ and $(n,n'\gamma)$ reactions on different target atoms like Pb, Ge, Cu, and Fe. These reactions generate a considerable beam-induced background in the $\gamma$-ray spectrum that has to be dealt with. In order to reduce the diffused deuteron mean free path a steel tube with squared cross section is placed on the beam axis, as shown in Figure 2.

The amount of Cu in the setup is reduced as much as possible since a $(n,n'\gamma)$ peak on $^{65}Cu$ at 1623.4 keV is inside the $^2H+\alpha$ RoI. It is possible to monitor the neutron produced by the $^2H(^2H,n)^3He$ reaction by measuring the proton produced by the $^2H(^2H,p)t$ reaction since both fusion reaction cross sections are very well known. For this reason a silicon detector is placed above the steel tube inside the scattering chamber. An aluminum foil is placed between the silicon detector and the deuterium target in order to stop $^3He$, tritium ions and $\alpha$ scattered particles. Figure 3 shows a silicon detector measured spectrum while Figure 4 shows the simulation done with the LUNA Monte-Carlo code based on GEANT3 [10].

Moreover, with a germanium detector, the neutron-induced peaks are usually identifiable.
because their widths are normally larger than that for $\gamma$-ray-induced events. As indicated by Knoll [11], it is possible to calculate the neutron produced by measuring the $\gamma$ counting rate in the neutron inelastic scattering edge on $^{72}$Ge at 693.4 keV. This is a rough estimation of the neutron fluence because the calculation depends on detector and setup geometries but can be compared with the Si detector measurements.

3. Measurements and future outlook

In spite of the natural background reduction offered by LNGS and by the lead shielding, the beam-induced background make this measurement not an easy task. Figure 5 shows a HPGe $^2$H+$\alpha$ spectrum measured with the best experimental conditions and compared with the natural background. The natural background $\gamma$ counting rate in the $^2$H+$\alpha$ RoI is $\sim 55 \frac{\text{counts}}{\text{day}}$, while the total counting rate is $\sim 446 \frac{\text{counts}}{\text{day}}$. According to Hammache $^2$H+$\alpha$ cross section value [6] in these experimental conditions we expect to have $\sim 44 \frac{\text{counts}}{\text{day}}$, ten times lower than the total $\gamma$ counting rate. Therefore the beam-induced background is the dominant $\gamma$ contribution and it should be measured with the best possible accuracy. For this reason a possible solution was studied, that is to produce a similar beam-induced background by measuring the $^2$H($\alpha,\gamma)^6$Li with a 280 keV $\alpha$ beam. The $^2$H($\alpha,\gamma)^6$Li signal is obtained by the subtraction of these two spectra. At this lower energy the $^2$H+$\alpha$ RoI is $1550\div1580$ keV, so there is no overlapping between the two different energy RoIs. The GEANT4 simulation are encouraging in this concern. Measurements will be done during 2011.
Figure 5. HPGe $^2$H+α spectrum measured for 9 days with a 400 keV α beam, 259 μA beam current and 0.2 mbar deuterium gas target pressure (yellow) and natural background spectrum (pink). In the $^2$H+α spectrum are well visible the inelastic scattering n-edges on Ge isotopes. The panel on the top-right corner shows a zoom of both spectra around the Region of Interest of the $^2$H(α,γ)$^6$Li reaction, marked by the light blue box. The black arrow indicate the (n,n′γ) peak on $^{65}$Cu at 1623.4 keV.

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