PROCEEDINGS OF SCIENCE

First direct measurement of the $^{2}H(\alpha,\gamma)^{6}Li$ cross section at Big Bang energies

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The amount of ^{6}Li observed in metal poor stars is three orders of magnitude higher than the one obtained on the basis of Big Bang Nucleosynthesis (BBN) theory. These calculations require the knowledge of the nuclear cross section of the processes involved in the production/destruction of ^{6}Li at the BBN energies. Whereas the destruction process cross sections are well known, the reaction that dominates the ^{6}Li production, that is $^{2}H(\alpha,\gamma)^{6}Li$, has never been directly measured in the BBN energy range. The only information about this cross section come from indirect measurements that however provide only upper limits. Here we show the first direct measurement of the $^{2}H(\alpha,\gamma)^{6}Li$ cross section at BBN energies obtained at LUNA (Laboratory for Underground Nuclear Astrophysics). The experiment has been performed with a 400 kV accelerator located in the deep underground Gran Sasso National Laboratory (LNGS). About 1400 meters of rock provide a huge reduction of the cosmic-ray background giving to LUNA the unique possibility to study thermonuclear cross sections in the astrophysical energy region of interest. For the $^{2}H(\alpha,\gamma)^{6}Li$ study, a 400 keV alpha beam impinged on a deuterium gas target. In order to properly subtract the beam induced background, a 280 keV monitor run has also been performed.

52 International Winter Meeting on Nuclear Physics - Bormio 2014,
27-31 January 2014
Bormio, Italy

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PoS(Bormio2014)020

1. Introduction

During the first minutes of the Universe (*Big Bang Nucleosynthesis* era, BBN), light isotopes such as ^{2}H, ^{3}He, ^{4}He, ^{6}Li and ^{7}Li have been produced by nuclear fusion reactions starting from primitive protons and neutrons as shown in figure 1. Their abundances only depend on Standard Model physics, on baryon-to-photon ratio and on the nuclear cross section of the involved processes.

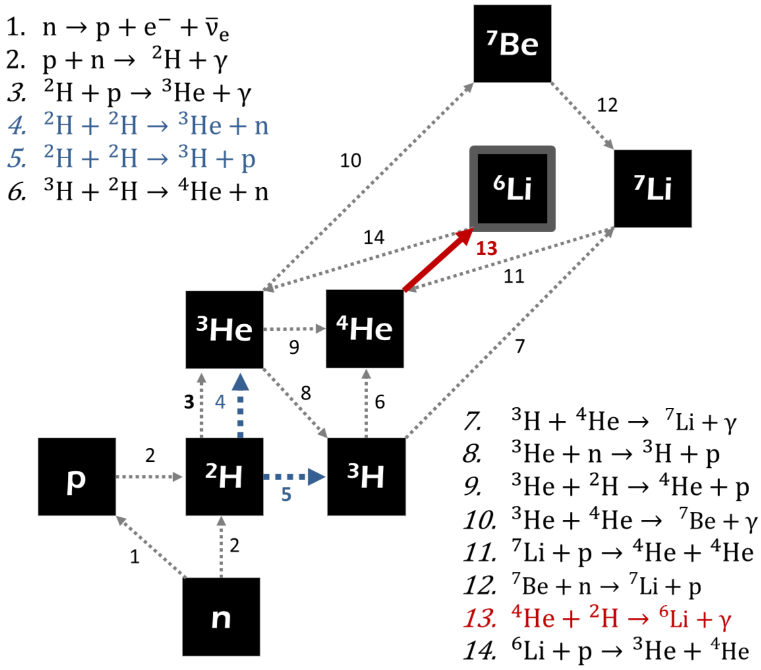

Figure 1: Nuclear reactions involved during the BBN era.

In this paper we will focus on the amount of ^{6}Li produced during BBN through the ^{2}H(α,γ)^{6}Li reaction [1] and observed today as absorption lines in metal-poor stars' electromagnetic spectra [2]. Unfortunately, the ^{2}H(α,γ)^{6}Li nuclear cross section has never been directly measured in the BBN energy range because of its low counting rate [3]. On the basis of the uppers limits provided by indirect measurements, standard BBN provides a ^{6}Li abundance three orders of magnitude lower than the observed one [4].

Thanks to the strong background reduction of the Gran Sasso deep underground laboratory (about 3800 mwe), the LUNA (Laboratory for Underground Nuclear Astrophysics) experiment gives the unique possibility to directly measure the ^{2}H(α,γ)^{6}Li nuclear cross section at BBN energies (between about 30 and 400 keV in the center of mass system).

At the relevant energies for BBN, the ^{2}H(α,γ)^{6}Li reaction proceeds either via electric dipole (E1) or electric quadrupole (E2) direct capture to the ground state of ^{6}Li emitting a single γ-ray. The energy of the emitted gamma ray is given by:

$$E_\gamma(E_\alpha) = Q + E_\alpha \frac{m_d}{m_d + m_\alpha} \pm \Delta E_{Doppler} - E_{recoil} \tag{1.1}$$

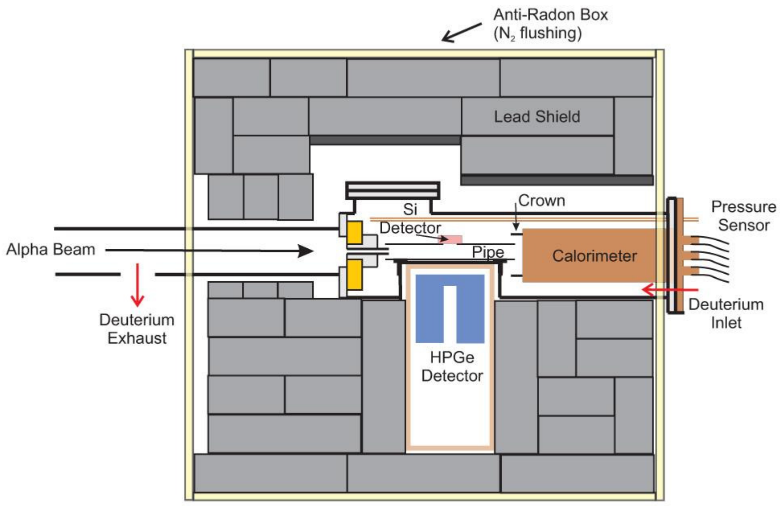

Figure 2: The LUNA experimental setup. See text for a general description and ref. [6] for more details.

where Q = 1473.48 keV is the reaction Q-value, E_α is the α-beam energy (in the lab system), m_d and m_α the deuteron and helium masses, $\Delta E_{Doppler}$ is the Doppler shift of the γ-ray with respect to the detector and E_{recoil} is the ^{6}Li recoil energy. At LUNA the ingoing α particles are provided by a 400 kV linear accelerator [5], able to provide high particle current (about 300 μA), stable in time (5 eV/h) and energy (70 eV spread). These particles, after a series of long, narrow apertures, enter in a windowless gas target filled with 0.3 mbar deuterium gas and stop on a constant temperature gradient calorimeter able to measure the beam current with a 1% precision. In order to reduce the natural background, a lead castle and an anti-radon box have been used. The reaction gammas are detected with a large (137% relative efficiency) high purity germanium detector (HPGe) placed at 90^o angle with respect to the ion beam direction, in very close geometry.

In particular, we measured the ^{2}H(α,γ)^{6}Li reaction at the highest beam energy that the LUNA accelerator can provide, i.e. 400 keV. At this energy, the measurement is affected by a huge beam-induced background due to energetic deuterons coming from elastic scattering of the α beam on the deuterium gas. These deuterons indeed, produce neutrons and protons via ^{2}H(d,n)^{3}He and ^{2}H(d,p)^{3}H reactions, respectively. Subsequent inelastic neutron scattering reactions in the germanium detector and surrounding materials (expecially iron, copper and lead) give rise to a large Compton background that is about one order of magnitude higher than the expected ^{2}H(α,γ)^{6}Li signal in the energy region of interest (ROI) given by equation 1.1. In order to reduce the deuteron elastic scattering a narrow pipe along the beam line has been mounted. The neutron produced are monitored by detecting, through a silicon detector, the protons coming from the ^{2}H(d,p)^{3}H reaction whose cross section is proportional to the ^{2}H(d,n)^{3}He one. Although the induced neutron production rate is very low (less than 10 n/s), an high density polyethylene (5% borated) shielding of the gas target was requested to operate in a low background deep underground laboratory such as LNGS. The experimental setup used for the measurement is shown in figure 2.

2. The ^{2}H(α,γ)^{6}Li reaction at LUNA

Since that shape and rate of the neutron beam-induced background depend only weakly on the beam energy, an irradiation at one beam energy can be used as a background monitor for an irradiation at another beam energy provided that the two ROIs do not overlap. The two selected energies, 280 and 400 keV, fulfil the not-overlapping criterion and have been alternated with an overall collected charge of about 550 C. The total data sample is also divided into two subsamples (RUN1 and RUN2, respectively), acquired in two different periods due to the accelerator availability. The reaction rate at a given beam energy has been obtained by using a minimization procedure. The starting point is that the shape of the two beam-induced background ($BIB_{400}(E)$ and $BIB_{280}(E)$) is the same. If we call β the proportionality constant between the two spectra we have:

$$BIB_{400}(E) = \beta BIB_{280}(E) \tag{2.1}$$

$$R_{400}(E) - BG_{400}(E) - k_{400}N_{400}(E) = \beta\left(R_{280}(E) - BG_{280}(E) - k_{280}N_{280}(E)\right) \tag{2.2}$$

where $R_i(E)$ are the spectral rates as seen by the HPGe detector, BG_i the natural backgrounds and N_i represents the γ-ray contribution from the ^{2}H(α,γ)^{6}Li reaction with i = 280 keV and 400 keV respectively. Aim of the minimization procedure is to obtain the value of the k_i parameters that are proportionals to the reaction cross section σ_{24}. In order to show the ^{2}H(α,γ)^{6}Li signal at 400 keV we plot in figure 3 not only $R_i(E)$ but also the difference $R_{400}(E) - \beta R_{280}(E)$.

In the low energy domain, the reaction cross section $\sigma_{24}(E)$ is usually parameterized as:

$$\sigma_{24}(E) = \frac{S_{24}(E)}{E} e^{(-2\pi\eta)} \tag{2.3}$$

where S(E) is the astrophysical S-factor that includes the cross section's pure nuclear behaviour and η is the Sommerfeld parameter

$$\eta = \frac{31.29}{2\pi} Z_1 Z_2 \sqrt{\frac{\mu}{E}} \tag{2.4}$$

where Z_1 and Z_2 are the atomic numbers, μ is the reduced mass (in atomic mass units) and E is the energy (in keV) in the center-of-mass system (c.m.s.). In our case, σ_{24} has been measured at 400 keV in the laboratory system i.e. 134 keV in the c.m.s and thus the respective S-factor has been extracted. From the minimization procedure is also possible to obtain the σ_{24} value at 280 keV (94 keV in the c.m.s.). The respective S-factors, obtained using equation 2.3, are shown in figure 4. This shows that there are no-resonant processes in the BBN energy domain able to explain a possible overproduction of ^{6}Li. In this context, our measure confirms the theoretical predictions previously obtained using indirect experimental data [11].

3. Conclusions

In conclusion, the cross section (S-factor) of the ^{2}H(α,γ)^{6}Li reaction has been directly measured at LUNA at BBN energies for the first time. Our data rule out a nuclear solution able to explain the huge amount of ^{6}Li observed in in metal-poor stars. Therefore, current astronomical

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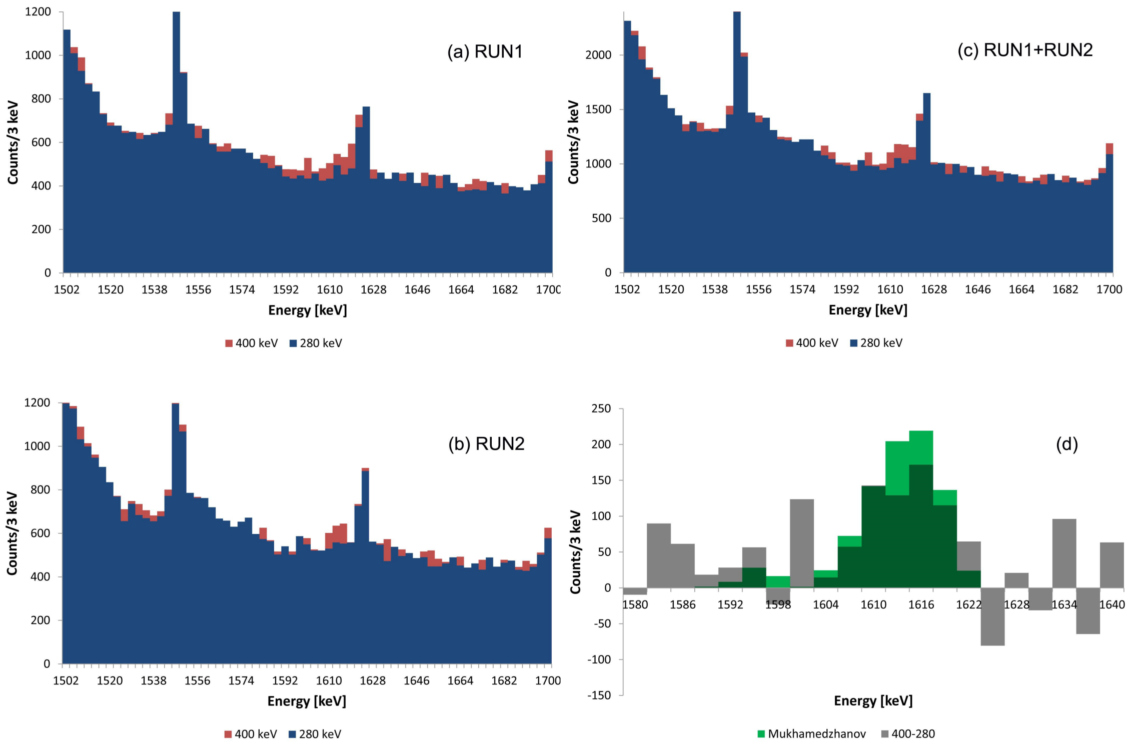

Figure 3: Panels (a)(b) and (c) show relevant parts of the γ-ray spectrum for runs 1, 2 and their sum, after subtraction of natural background. The 400 keV data are shown as filled red histograms, the rescaled 280 keV data as filled blue histograms. Panel (d) shows the 400 keV spectrum, after subtraction of the rescaled 280 keV spectrum. The filled green histogram represents the expected γ-ray line shape based on the Mukhamedzhanov theoretical description of the angular distribution for the ^{2}H(α,γ)^{6}Li reaction [11]

observations and the consequent ^{6}Li abundance estimation should be affected by systematics like, for example, a possible stellar flare in-situ production of ^{6}Li. Another possibility is that the ^{6}Li observed had been produced by non-standard processes like heavy particles decay.

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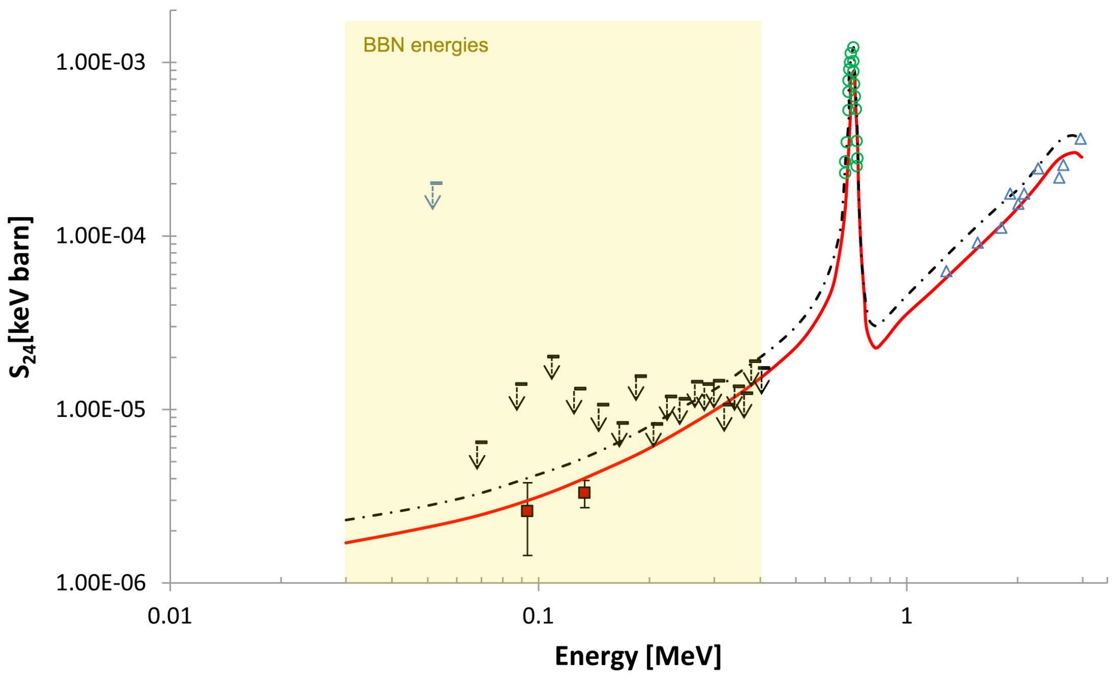

Figure 4: Astrophysical S-factor of the ^{2}H(α,γ)^{6}Li reaction from the present work (red squares) and from the literature (data: blue triangles [7], green circles [8]; upper limits: black arrows [9], blue arrow [10]; theory: red full = E1+E2 [11], black dot-dashed = E1+E2 [3]).