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Study of the $^{2}H(\alpha,\gamma)^{6}Li$ reaction producing ^{6}Li in standard Big Bang Nucleosynthesis

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LUNA (Laboratory for Underground Nuclear Astrophysics) is devoted to measure nuclear cross sections relevant in astroparticle physics and particle physics, such as the solar neutrino flux, the stellar evolution and the Big Bang Nucleosynthesis (BBN). The measurements are performed at the "Laboratori Nazionali del Gran Sasso" (LNGS) where the background induced by cosmic rays is orders of magnitude lower than outside, making possible nuclear cross section measurements at energies well below the Coulomb barrier. The present paper is focused on the study of the $^{2}H(\alpha,\gamma)^{6}Li$ reaction, that is the leading process to produce the ^{6}Li isotope during the BBN. Similarly to the well known Spite plateau of ^{7}Li, the observation of lithium abundance in metal-poor halo stars suggest that there might be a ^{6}Li plateau, whose abundance is in apparent disagreement with the prediction based on the BBN theory and Standard Model physics. This circumstance calls for a reinvestigation of the main production channel for ^{6}Li. In fact, the theoretical prediction of ^{6}Li abundance is affected by a large uncertainty because direct measurements of $^{2}H(\alpha,\gamma)^{6}Li$ reaction have never been previously performed in the BBN energy region. For the first time, $^{2}H(\alpha,\gamma)^{6}Li$ reaction has been studied at Big Bang energies. The LUNA data and their implications for the BBN theory are discussed.

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1. Introduction

Nuclear physics plays a fundamental role in astroparticle physics. In fact, the nuclear reactions regulate the solar neutrino luminosity, determine the evolution of celestial bodies, allow the computation of the abundance of light elements generated during the BBN.
At energies of interest in astroparticle physics ($0.01 \div 1\ MeV$) the cross-section $\sigma(E)$ drops almost exponentially with decreasing energy E, due to the repulsion of charged nuclei. In the low energy domain, the cross section $\sigma(E)$ is parameterized using the astrophysical factor S(E), defined by the formula:

$$\sigma(E) = \frac{S(E)e^{-2\pi\eta}}{E} \qquad (1.1)$$

$S(E)$ contains all the nuclear effects and, for non-resonant reactions, it is a smoothly varying function of energy. The exponential term takes into account the Coulomb barrier. The Sommerfeld parameter η is given by $2\pi\eta = 31.29 Z_1 Z_2 (\mu/E)^{1/2}$. Z_1 and Z_2 are the nuclear charges of the interacting nuclei. μ is their reduced mass (in units of a.m.u.), and E is the center of mass energy (in units of keV).

Due to the low reaction yield, direct measurements at low energy are severely hampered by the background induced by cosmic rays. For this reason the LUNA collaboration carries out its measurements with the world's only underground accelerator facility, operating at the *"Laboratori Nazionali del Gran Sasso"* (LNGS). The ultra-low background at LNGS makes possible to study the nuclear reactions well below the Coulomb barrier [1],[2].
In its standard picture, the Big Bang nucleosynthesis occurs during the first minutes of universe through the reaction chain shown in figure 1. The abundance of light elements such as D, ^3He, ^4He, ^6Li and ^7Li depends on the standard model physics, on the baryon-to-photon ratio η and on the nuclear cross sections of involved processes. As the η parameter has been measured with high precision through the Cosmic Microwave Background (CMB) anisotropies detection [3], the BBN theory makes definite predictions for the abundances of the light elements, as far as the relevant nuclear processes are known. The observed abundances of D, ^3He, and ^4He are in good agreement

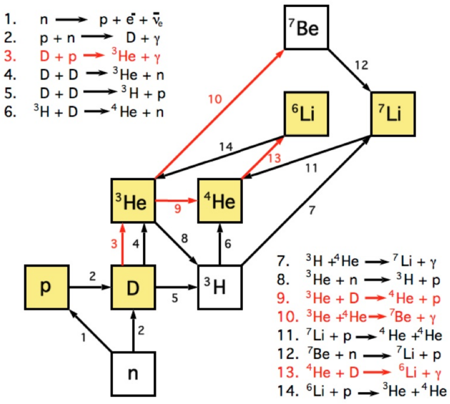

Figure 1: Leading processes of Big Bang Nucleosynthesis. The red arrows show the reactions measured by the LUNA collaboration. Yellow boxes marks stable isotopes.

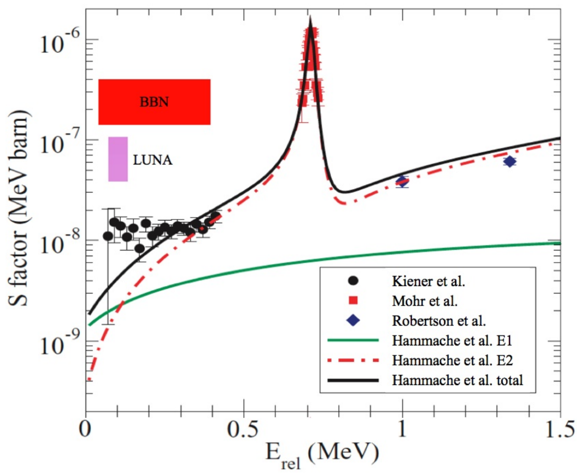

Figure 2: The astrophysical factor of the $^2H(\alpha,\gamma)^6Li$ reaction as a function of the center-of-mass energy. Direct [9],[10] and indirect measurements [11],[12] are reported. The BBN energy region and the energy range studied by LUNA are also reported.

with calculations, confirming the overall validity of BBN theory. On the other hand, the observed abundance of ^7Li is a factor 3 lower than the predicted one, while the amount of ^6Li observed in metal poor stars is unexpectedly large compared to Big Bang Nucleosynthesis (BBN) predictions [4]. The difference between observed and calculated values may reflect unknown post-primordial processes or physics beyond the Standard Model [5]-[8].
The leading process to synthesize ^6Li is the $^2H(\alpha,\gamma)^6Li$ reaction. This process has been experimentally studied only for energies greater than 1 MeV and around the 711 keV resonance [9, 10], while its cross section has never been measured in the BBN region of interest (50 $keV \lesssim E \lesssim 400$ keV). There are also two indirect attempts to determine the $^2H(\alpha,\gamma)^6Li$ cross section at BBN energies, using the Coulomb dissociation technique [11, 12]. In this approach, a ^6Li beam passes close to a target of high nuclear charge to study the time-reversed reaction $^6Li(\gamma,\alpha)^2H$ using virtual photons which are exchanged. All the measurements mentioned above are shown in figure 2. It is worth to point out that the indirect measurements cannot give a reliable determination of the astrophysical factor because in the Coulomb dissociation measurements the nuclear effects are dominant. On the other hand the extrapolation of direct measurements towards BBN energies is affected by a very large uncertainty. The conclusion is that only a direct measurement at low energy can give a solid experimental footing to calculate the ^6Li abundance [13].

2. Experimental set-up

Figure 3 shows the experimental set-up used for the $^2H(\alpha,\gamma)^6Li$ reaction. The measurement is based on the use of the 400 kV accelerator [14], that provides an α beam of high intensity. The α beam impinges a windowless gas target of D_2, with a typical operating pressure of 0.3 $mbar$. The signal is maximized by stretching the beam intensity up to about 350 μA and by using a geometry with the Germanium detector close to the beam line (2 cm apart), to increase its acceptance. The natural background of LNGS is further reduced by means of a 4π lead shield around the reaction

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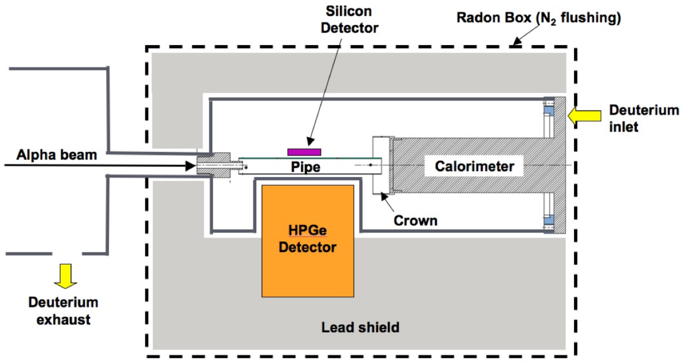

Figure 3: Experimental setup.

chamber and the Germanium detector. Everything is enclosed in a radon box flushed with high purity N_2, to reduce and stabilize the γ activity due to the radon decay chain.
The measurement of the $^2H(\alpha,\gamma)^6Li$ reaction is affected by an inevitable beam-induced background. In fact, the $^2H(\alpha,\alpha)^2H$ Rutherford scattering induces a small amount of $^2H(^2H,n)^3He$ and $^2H(^2H,p)^3H$ reactions. While the $^2H(^2H,p)^3H$ reaction is not a problem in this context, the neutrons produced by the $^2H(^2H,n)^3He$ reaction ($E_{n(cm)} = 2450\ keV$) induce $(n,n'\gamma)$ reactions in the Ge detector and in the surrounding materials (lead, steel, copper), generating a beam-induced background in the $\gamma-ray$ spectrum, in particular around 1.6 MeV, where the capture transition to the ground state of ^6Li is expected. To reduce the neutron production, a tube 17 cm long, with a square cross section of $18 \times 18\ mm^2$ is inserted inside the chamber. This tube strongly reduces the effective path for the scattered deuterons and therefore the neutron yield due to the $^2H(^2H,n)^3He$ reaction is reduced at the level of few neutrons/second. Finally, one silicon detector is faced to the gas target volume to monitor the running conditions through the detection of protons generated in the $^2H(^2H,p)^3H$ reaction ($E_{p(cm)} = 3022\ keV$). In fact, the yield of protons is strictly related to the number of produced neutrons, since the cross sections of the two conjugate $^2H(^2H,n)^3He$ and $^2H(^2H,p)^3H$ reactions are well known [15].
In the center-of-mass system the $^2H(^2H,n)^3He$ reaction produces monochromatic neutrons with $E_{cm}(n) = 2,45\ MeV$. As a consequence, the neutrons produced in the LUNA experiment have a narrow energy distribution, weakly dependent on the beam energy (see figure 4). This in turn implies that spectral shape of the beam-induced background in the Germanium detector is almost unaffected while changing the α-beam energy. Instead, the energy of γs produced in the $^2H(\alpha,\gamma)^6Li$ reaction strongly depends on the beam energy through the following relationship:

$$E_\gamma = 1473,8 + E_{CM} \pm \Delta E_{doppler} - E_{recoil} \tag{2.1}$$

Exploiting the kinematics is then possible to extract the $^2H(\alpha,\gamma)^6Li$ signal with a measurement performed in two steps:
1. Measurement with $E_{beam} = 400\ keV$ on D_2 target. The energy spectrum of the Germanium detector is mainly due to the background induced by neutrons. The γs produced in the $^2H(\alpha,\gamma)^6Li$ reaction are expected in a well defined energy region ($1592 - 1620\ keV$).
2. Same as **1.**, but with $E_{beam} = 280\ keV$. The background is essentially the same as before, while

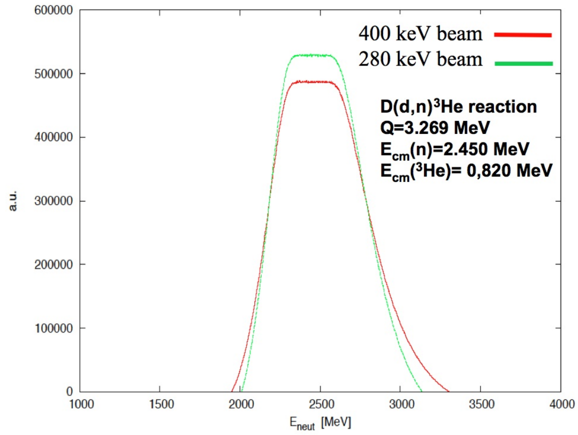

Figure 4: Energy distribution of neutrons produced in the $^2H(^2H,n)^3He$ reaction at $E_\alpha = 400\ keV$ (red line) and $E_\alpha = 280\ keV$ (green line).

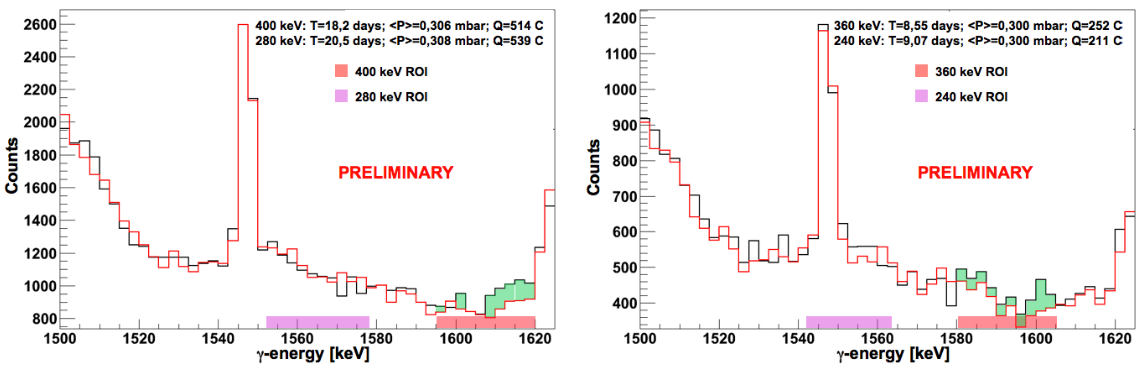

Figure 5: Left: experimental Ge spectra for $E_{beam} = 400\ keV$ (black line) and for $E_{beam} = 280\ keV$ (red line). Right) Experimental Ge spectra for $E_{beam} = 360\ keV$ (black line) and for $E_{beam} = 240\ keV$ (red line). T, $< P >$, Q are respectively the measurement time, the averaged target pressure, the integrated beam current. The bands indicate the full peak detection energy region of γs produced in the $^2H(\alpha,\gamma)^6Li$ reaction (see equation 2.1). Note the counting excess visible in correspondence of the 400 keV RoI. The counting excess at $E_\alpha = 360\ keV$ (figure 5b) is shifted to lower energies, as expected by kinematics.

the γs from the $^2H(\alpha,\gamma)^6Li$ γ reaction are shifted to $1555 - 1578\ keV$.
Figure 5 a) shows the spectra with $E_\alpha = 400/280\ keV$. A counting excess is clearly visible in the $E_\alpha = 400\ keV$ RoI, while at $E_\alpha = 280\ keV$ the very low reaction yield prevents from any conclusion statistically significant. To verify that the counting excess at $E_\alpha = 400\ keV$ is a genuine γ signal coming from the $^2H(\alpha,\gamma)^6Li$ reactions, the measurement has been repeated by shifting the beam energies to $E_\alpha = 360/240\ keV$. As shown in figure 5 b), the counting excess at the higher energy is shifted as expected, even though it has a lower significance due to the worst signal/noise ratio and the shorter measurement time.

3. Conclusion

For the first time the cross section of $^2H(\alpha,\gamma)^6Li$ reaction has been measured at BBN energy, thus providing a solid experimental base to calculate the ^6Li primordial abundance. Although the data analysis is still in progress, the LUNA measurement excludes a nuclear solution for the purported ^6Li problem. Therefore, the observation of a huge amount of ^6Li in metal-poor stars must be explained in a different way, such as systematics in the ^6Li observation, physics beyond the standard Model or unknown post-primordial processes able to produce the fragile ^6Li isotope.

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