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LUNA data on the $^{2}H(\alpha,\gamma)^{6}Li$ reaction and the Big Bang Nucleosynthesis

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The $^{2}H(\alpha,\gamma)^{6}Li$ reaction is the main process responsible for the production of the lithium isotope ^{6}Li in standard Big Bang Nucleosynthesis. Recent observations of lithium isotopic abundances in metal-poor halo stars suggest that there might be a ^{6}Li plateau, similar to the well known Spite plateau of ^{7}Li. This calls for a reinvestigation of the standard production channel for ^{6}Li. The $^{2}H(\alpha,\gamma)^{6}Li$ cross section drops steeply at low energy and has never before been studied directly at Big Bang energies. Previous studies using the Coulomb dissociation of ^{6}Li gave only upper limits due to the dominance of nuclear breakup. Exploiting the ultra-low background at the 400 keV LUNA accelerator, located deep underground in Italy's Gran Sasso laboratory, for the first time the reaction has been studied directly at Big Bang energies. The new data and their implications for Big Bang nucleosynthesis will be shown.

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1. Introduction

In its standard picture, the Big Bang Nucleosynthesis occurs during the first minutes of universe, with the formation of light isotopes such as D, ^{3}He, ^{4}He, ^{6}Li and ^{7}Li, through the reaction chain shown in figure 1. Their abundance depends on the standard model physics, on the baryon-to-photon ratio η and on the nuclear cross sections of involved processes. Cosmic Microwave Background (CMB) experiments provide the η value with high precision (percent level) [1]. Indeed, the BBN theory makes definite predictions for the abundances of the light elements as far as the nuclear cross sections of leading processes are known. The observed abundances of D, ^{3}He, and ^{4}He are in good agreement with calculations, confirming the overall validity of BBN theory. On the other hand, the observed abundance of ^{7}Li is a factor 2-3 lower than the predicted one (see figure 2). The amount of ^{6}Li observed in metal poor stars is unexpectedly large compared to Big Bang Nucleosynthesis (BBN) predictions, about 3 orders of magnitude higher than the calculated value (see figure 2). Even though many of the claimed ^{6}Li detections may be in error, for a very few metal-poor stars there still seems to be a significant amount of ^{6}Li [2]. The difference between observed and calculated values may reflect unknown post-primordial processes or physics beyond the Standard Model.

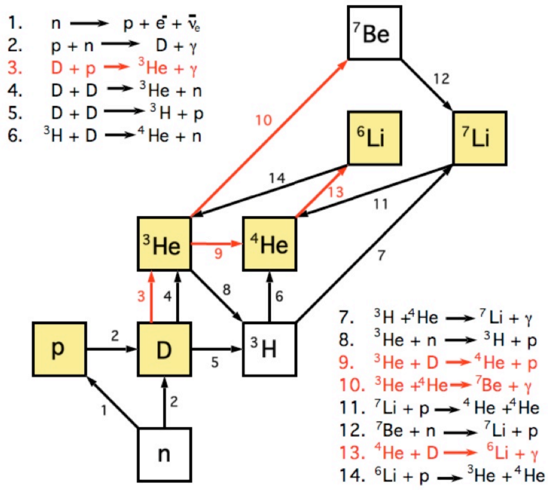

Figure 1: *Leading processes of Big Bang Nucleosynthesis. The red arrows show the reactions measured by the LUNA collaboration. Yellow boxes mark stable isotopes.*

The leading process to synthesize ^{6}Li is the ^{2}H(α,γ)^{6}Li reaction. The ^{2}H(α,γ)^{6}Li cross section is very small at BBN energies (30<E(keV)<400), because electric dipole transition is forbidden for the iso-scalar particles ^{2}H and α at energies below the Coulomb barrier. Therefore, it has never been measured experimentally, and theoretical predictions remain uncertain [3]. This process has been experimentally studied only for energies greater than 1 MeV and around the 711 keV resonance [4,5]. There are two attempts to determine the ^{2}H(α,γ)^{6}Li cross section at BBN energies, using the Coulomb dissociation technique [6,7]. In this approach, an energetic ^{6}Li beam passes close to a target of high nuclear charge. In this way, the time-reversed reaction ^{6}Li(γ,α)^{2}H is studied using virtual photons which are exchanged. The measurements mentioned above are shown in figure 3. As usual in the low energy domain, the cross section σ(E) is parameterized using the astrophysical factor S(E), defined by the formula:

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

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 penetration effect. 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).

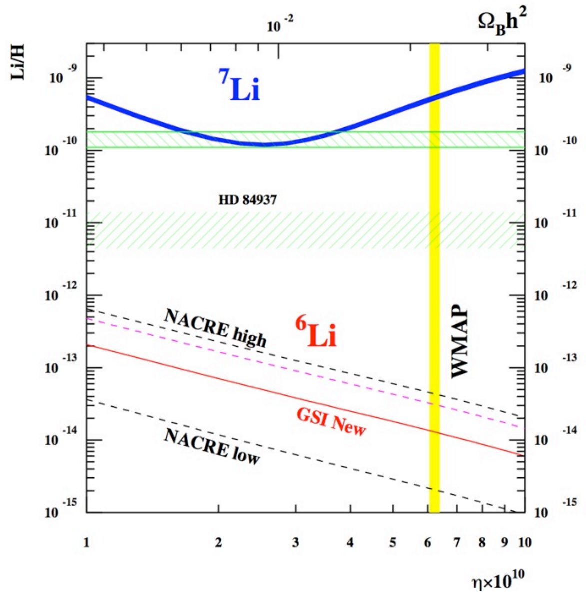

Figure 2: *Abundances of ^{7}Li and ^{6}Li as a function of the η parameter. Observations are represented as green, horizontal dashed bands. The blue band shows the calculated abundance of ^{7}Li. The calculated abundance of ^{6}Li is obtained using the NACRE compilation recommended values (dashed lines). The vertical yellow band indicates the η parameter as measured by the WMAP experiment.*

The result obtained by the two Coulomb dissociation measurements in literature are very different [6,7], reflecting the difficulty to unfold the cross section with this tecnique, mainly because the nuclear effects are dominant and the result strongly depends on the theoretical assumptions. The conclusion is that only a direct measurement of the ^{2}H(α,γ)^{6}Li in the BBN energy region can give a solid experimental footing to compute the ^{6}Li primordial abundance.

The present paper reports on the first direct measurement of the ^{2}H(α,γ)^{6}Li performed by the LUNA collaboration (LUNA=Laboratory for Underground Nuclear Astrophysics). The measurement has been performed with the unique underground accelerator in the world, situated at the LNGS laboratory (LNGS=Laboratorio Nazionale del Gran Sasso) [8]. The "Gran Sasso" mountain provides a natural shielding which reduces the muon and neutron fluxes by a factor 10^6 and 10^3, respectively. The suppression of the cosmic ray induced background also allows an effective suppression of the γ-ray activity by a factor 10^2 - 10^5, depending on the photon energy [9]. As it will be shown in the following, the ^{2}H(α,γ)^{6}Li reaction is affected by an intrinsic beam induced background. In order to extract the weak ^{2}H(α,γ)^{6}Li signal over the relatively high background level, a dedicated set-up has been studied and an innovative method of measurement has been used.

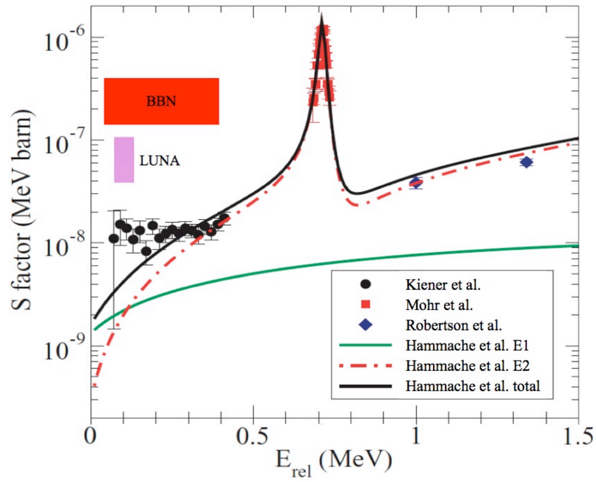

Figure 3: *The astrophysical factor of the ^{2}H(α,γ)^{6}Li reaction as a function of the center-of-mass energy. Direct [4,5] and indirect measurements [6,7] are reported. The BBN energy region (red band) and the energy range studied by LUNA (violet band) are also shown.*

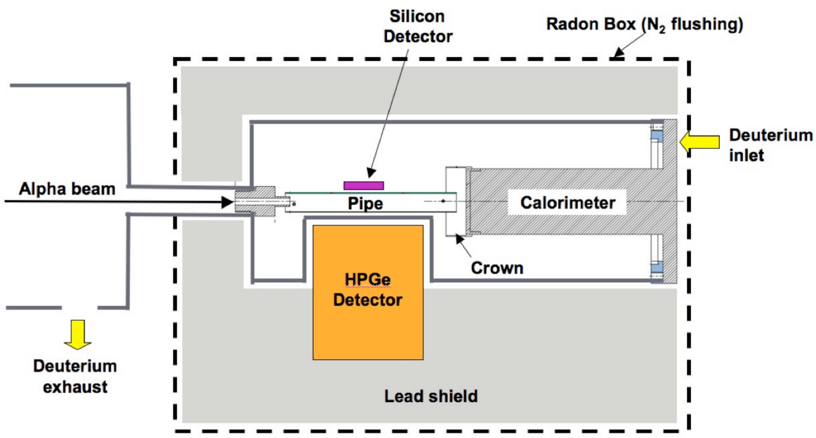

Figure 4: *Experimental set-up.*

2. Experimental set-up

Figure 4 shows the experimental set-up used for the ^{2}H(α,γ)^{6}Li reaction. The measurement is based on the use of the 400 kV accelerator, 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. The natural background of LNGS is further reduced by means of a 4π lead shield around the reaction chamber and the HPGe 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 induce (n,n'γ) reactions in the HPGe detector and in the surrounding materials (lead, steel, copper), generating a beam-induced background in the HPGe spectrum. To reduce the effective path for the scattered deuterons, and therefore the $^2H(^2H,n)^3He$ reaction yield, a 17.8 cm long tube, with a square cross section of 2x2 cm, is placed along the beam line (see figure 4). In this way, the neutron production is limited at the level of few neutrons/second. The set-up is implemented with a silicon detector faced to the gas target volume, to monitor the running conditions through the detection of protons generated in the $^2H(^2H,p)^3H$ reaction ($E_p \sim 3$ MeV). As a matter of fact, the proton rate 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 similar and well known.

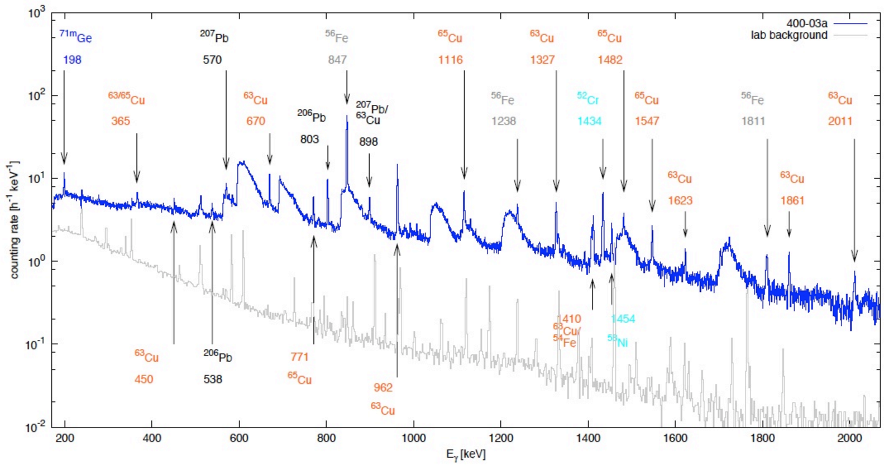

Figure 5: *Spectra taken with the HPGe detector. Blue full line: Beam induced background spectrum at E_α=400 keV and $P_{deuterium}$=0.3 mbar. Grey thin line: laboratory background [10].*

Figure 5 shows the HPGe spectrum at E_α=400 keV and $P_{deuterium}$=0.3 mbar. Various transitions due to the interaction of neutrons with the Germanium and the surrounding materials can be identified [10]. It is worth to point out that the shape and structure of the Beam Induced Background due to the (n,n'γ) reactions weakly depends on the α-beam energy [10]. In fact, the neutrons generated in the $^2H(^2H,n)^3He$ reaction are monochromatic in the center-of-mass system with E_{cm}=2.45 MeV. As a consequence, the neutrons produced in the LUNA experiment have a rather narrow energy distribution, weakly dependent on the beam energy (see figure 6). This in turn implies that the shape and the structure of the BIB is almost unaffected while changing the α-beam energy.

3. Method

The energy of γ-rays coming from $^2H(\alpha,\gamma)^6Li$ reaction depends on the beam energy through the following relationship:

$$E_\gamma = 1473{,}48 + E_{beam}\frac{m_D}{m_D + m_\alpha} \pm \Delta E_{doppler} - E_{recoil}$$

As shown in figure 7, in our set-up the γ-rays fall into a Region of Interest (RoI) of about 30 keV, whose width is due to the doppler broadening. The unknown composition of electric dipole/quadrupole transitions translates into an unknown shape of the γ-peak, but the width and position of the RoI are fully constrained by kinematics. By exploiting the energy dependence of the RoI relative to the $^2H(\alpha,\gamma)^6Li$ reaction, it is possible to extract the signal with a measurement performed in two steps:

1. Measurement with E_{beam}=400 keV on D_2 target. The Ge spectrum is mainly due to the background induced by neutrons. The $^2H(\alpha,\gamma)^6Li$ γ signal is expected in a well defined energy region (1587-1625 keV, see figure 7).

2. Same as **1**, but with E_{beam}=280 keV. The background is essentially the same as before, while the gammas from the $^2H(\alpha,\gamma)^6Li$ reaction are shifted to 1550-1580 keV (see figure 7).

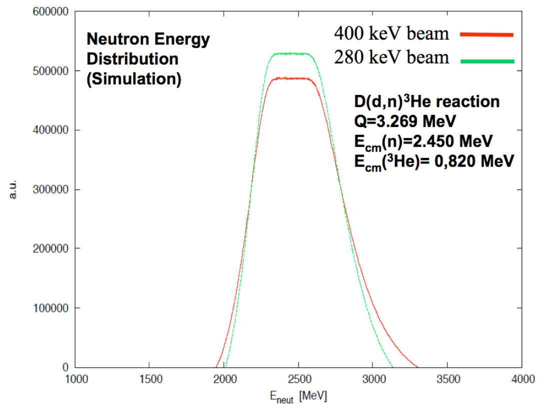

Figure 6: *Energy distribution of $^2H(^2H,n)^3He$ neutrons at E_α=400 keV (red line) and E_α=280 keV (green line).*

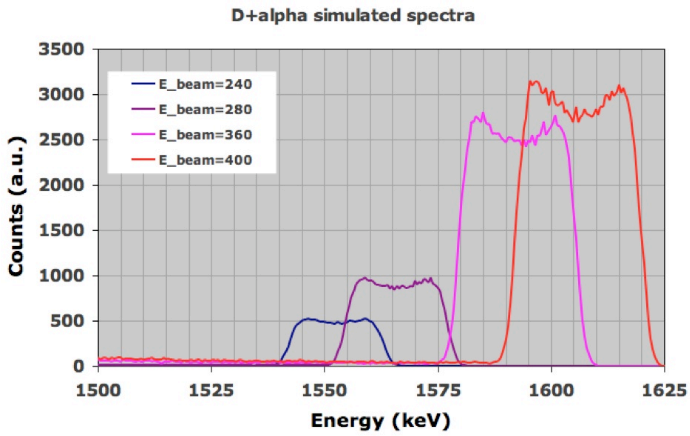

Figure 7: *Simulated full peak detection of γ's from $^2H(\alpha,\gamma)^6Li$ in the LUNA HPGe detector, at different beam energy. Note the doppler broadening of about 30 keV and the dependence with the beam energy.*

Figure 8a shows the spectra with E_α=400 and 280 keV, respectively. A counting excess is visible in the E_α=400 keV RoI. The huge noise/signal ratio at E_α=280 keV prevents from any conclusion statistically significant. A check to verify that the excess is not due to unknown systematics but is a genuine γ signal coming from the ^{2}H(α,γ)^{6}Li reactions has been done by shifting the two energies respectively to E_α=360 and 240 keV. As shown in figure 8b, the counting excess at the higher energy is shifted as expected. The measurement time is shorter with respect to figure 8a because of the occurrence of an accelerator failure.

Figure 9 shows the preliminary result of a blind search of fake "^{2}H(α,γ)^{6}Li like" excess along the HPGe spectra, due to possible statistical fluctuations or unknown systematics. The result of the test shows that only in the true energy region is visible a significant counting excess, while no "^{2}H(α,γ)^{6}Li -like" excess is found along the spectra (see figure 9 caption).

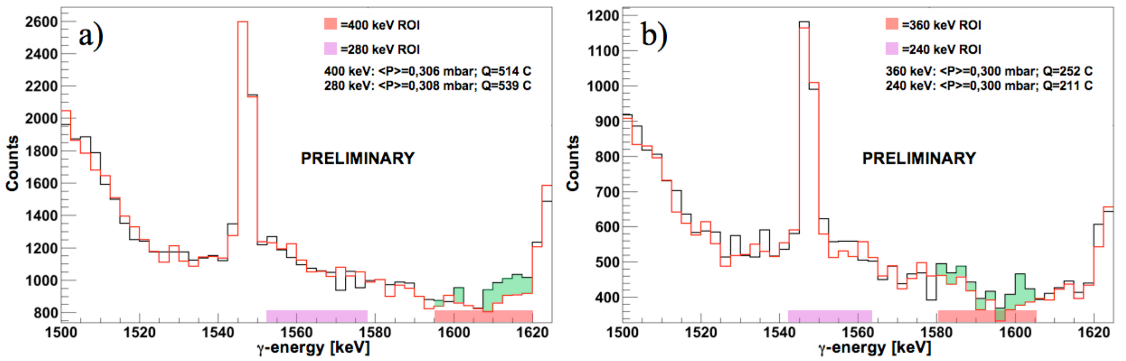

***Figure 8**: a) Experimental spectra for E_α = 400 keV (black line) and for E_α = 280 keV (red line). The red and violet bands indicate the RoI at E_α = 400 keV RoI and E_α = 280 keV, respectively. Note the counting excess visible (green bins) in correspondence to the 400 keV RoI. b) Experimental spectra for E_α = 360 keV (black line) and for E_α = 240 keV (red line). As foreseen, the counting excess shifts to the E_α = 360 keV RoI.*

Energy Region (keV)	RESIDUALS (Counts/Coulomb)	Deviation from zero (# of sigmas)
950-1025	0,59±0,69	0,86
1025-1100	-0,35±0,74	-0,47
1100-1175	0,58±0,66	0,88
1175-1250	-0,23±0,82	-0,29
1250-1325	-0,10±0,53	-0,19
1325-1400	0,03±0,48	0,06
1400-1475	-0,14±0,53	-0,26
1475-1550	0,97±0,53	1,84
1550-1625	1,97±0,39	5,11
1625-1700	-0,14±0,34	-0,41
1700-1775	0,93±0,45	2,07
1775-1850	0,25±0,30	0,83
1850-1925	0,17±0,28	0,59
1925-2000	0,18±0,25	0,74
2000-2075	0,07±0,25	0,29
2075-2150	-0,27±0,23	-1,17
2150-2225	0,31±0,26	1,23

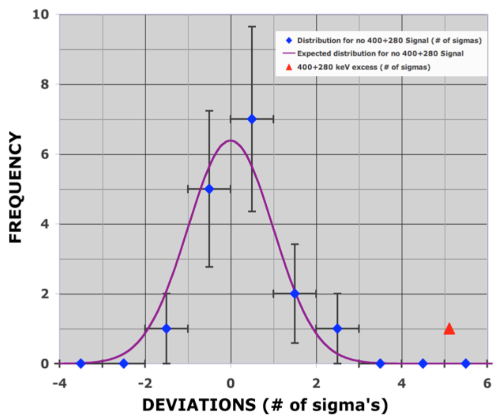

***Figure 9:** The table shows the energy windows considered while subtracting the spectra at E_α = 400 and 280 keV (first column). The second and third columns show the counting difference between the two spectra (excesses at 400 and 280 keV summed up) and their statistical significance (MINUIT). The result of the test (third column in the table) is plotted in the right side. The counting excess in the true ^{2}H(α,γ)^{6}Li energy region is about 5 σ's (red point), while the counting deviations found in the "Off-RoI" energy regions (blue points) are compatible with the statistical expectation (violet curve).*

3. Conclusions

For the first time the $^2H(\alpha,\gamma)^6Li$ reaction has been studied in the BBN region of interest. As a first result, the LUNA data exclude a nuclear solution for the ^6Li problem. When the analysis of data will be completed, the LUNA measurement will substantially reduce the uncertainty of the computed ^6Li primordial abundance.

References

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