PROCEEDINGS OF SCIENCE

Study of the Big Bang Nucleosynthesis reaction D(α,γ)^{6}Li deep underground at LUNA

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The amount of ^{6}Li detected in metal poor stars is unexpectedly large compared to Big-Bang Nucleosynthesis (BBN) predictions. The radiative capture reaction D(α,γ)^{6}Li with a Q-value of 1.474 MeV is the main reaction for ^{6}Li production at temperatures of 0.3×10^9 K. The BBN energy window goes from $E_{\mathrm{BBN}} = 30$ keV up to 300 keV, but direct measurements do not exist below a center-of-mass energy of 650 keV. On the other hand, theoretical calculations for the S-factor differ by more than one order of magnitude.
The LUNA (Laboratory for Underground Nuclear Astrophysics) setup below the Gran Sasso mountain offers measurement conditions with a reduction of the cosmic ray induced μ-flux by six orders of magnitude. Predictions show that the cross section of $\sigma(E_{\mathrm{BBN}}) \approx 2 \times 10^{-11}$ b can be measured with a proper setup using in-beam γ-spectroscopy there. A cross section measurement currently has been started.

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1. Introduction

The lightest nuclei like deuterons, tritons, ^{3}He-nuclei, and α-particles were built up in primordial nucleosynthesis right after the creation of nucleons in the big bang. Also ^{6,7}Li- and ^{7}Be-nuclei had been produced albeit in smaller amounts. Their abundance (ratio) relative to hydrogen (^{1}H) is measured in the spectra from metal-poor stars of white dwarf galaxies [1], the oldest light-emitting objects of the universe.

While the abundance of ^{4}He depends mainly on the ratio n/p, all other nuclides are sensitive to nuclear reaction network calculations [2]. Good agreement between calculations and observations is achieved for D, ^{3}He, and ^{4}He, while problems arise for the abundance of ^{6}Li and ^{7}Li. ^{6}Li is produced practically only by the radiative capture reaction ^{4}He + D $\rightarrow$ ^{6}Li + γ with a very weak cross section. The abundance of ^{6}Li seems to be orders of magnitude higher than the one resulting from model predictions given by the NACRE database [3]. Recently it was suggested [4, 5] that a new line shape analysis of stellar spectra could reduce the abundance ^{6}Li produced in the big bang.

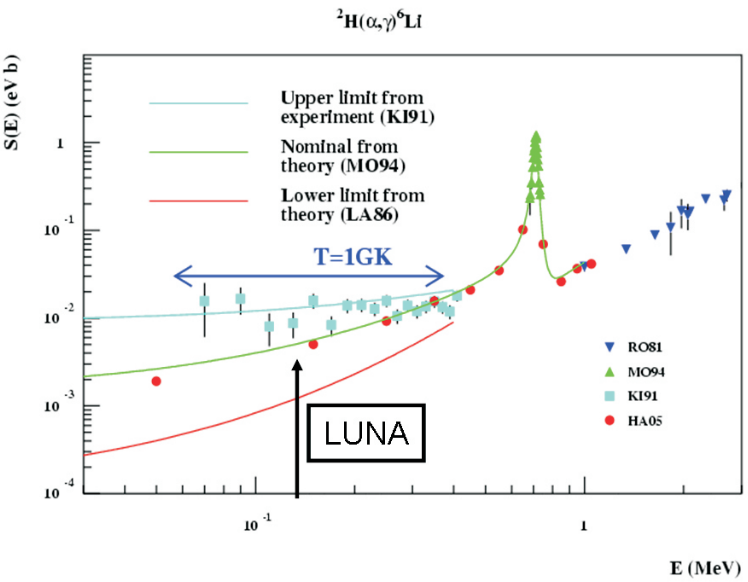

Figure 1: *S*-factor of the D+α-reaction as a function of the center-of-mass energy. Direct measurements: Robertson *et al.* [6] (blue, inverted triangles) and Mohr *et al.* [7] (green triangles). Coulomb dissociation experiments: Kiener *et al.* [8] (cyan squares) and Hammache *et al.* [9] (red points). A lower limit for the cross section below the resonance is given by the theory from Langanke and Rolfs [10] (red curve). Blue arrow: BBN energy window between 50 and 300 keV. Black arrow: energy accessible by LUNA ($E_{\mathrm{c.m.}} \approx 130$ keV).

The *S*-factor of the reaction D(α,γ)^{6}Li is shown in fig. 1. Direct measurements are only available above 1 MeV and around the resonance at 711 keV. At the energy of astrophysical interest at temperatures of about 1 GK, only indirect measurements using Coulomb dissociation of ^{6}Li on ^{208}Pb exist. The elder data of Kiener *et al.* [8] are questionable since the nuclear effect was not taken into account. More accurate data were recently taken by Hammache *et al.* [9], but on the other hand, theoretical estimates are still differing by about one order of magnitude [11]. The aim of LUNA is to measure for the first time the D+α-reaction yield at low energy, in order to have a reliable estimate of ^{6}Li primordial abundance.

2. The experimental setup

Due to the extremely low cross section at the BBN energy window ($\sigma(E_{\mathrm{BBN}}) \approx 10\,\mathrm{fb} - 1\,\mathrm{pb}$) well below the Coulomb barrier it is mandatory to go underground where the cosmic radiation is reduced by orders of magnitudes. Such conditions are offered in the Laboratory for Underground Nuclear Astrophysics (LUNA) [12] which is located inside the Gran Sasso National Laboratory (LNGS). The Q-value of the reaction is 1.473 MeV. A direct measurement below the resonance using an α-beam of $E_\alpha \leq 400\,\mathrm{keV}$ ($E_{\mathrm{c.m.}} \approx 130\,\mathrm{keV}$) can be performed with in-beam γ-spectroscopy. The Region-of-Interest (RoI) is located at $E_\gamma = Q + E_{\mathrm{c.m.}} + \Delta E_{\mathrm{Doppler}} - \Delta E_{\mathrm{recoil}} = 1580 - 1630\,\mathrm{keV}$. It had been planned to perform the experiment using the proven setup from the $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$-experiment [13]. It consists of a windowless gas target and a high-purity germanium (HPGe) detector of 135% rel. efficiency in close geometry [14]. The 400 kV in-line Cockcroft-Walton accelerator can deliver an α-beam with a current of more than 200 μA.

The elastic scattering of α-particles on deuterons turned out to be a large source of beam-induced background since the following D + d reaction produces neutrons with an average energy of 2.5 MeV. The inelastic n-scattering on Ge-isotopes $^A\mathrm{Ge(n,n'}\gamma)^A\mathrm{Ge}$ causes a significant background and distortion in the Ge-spectra.

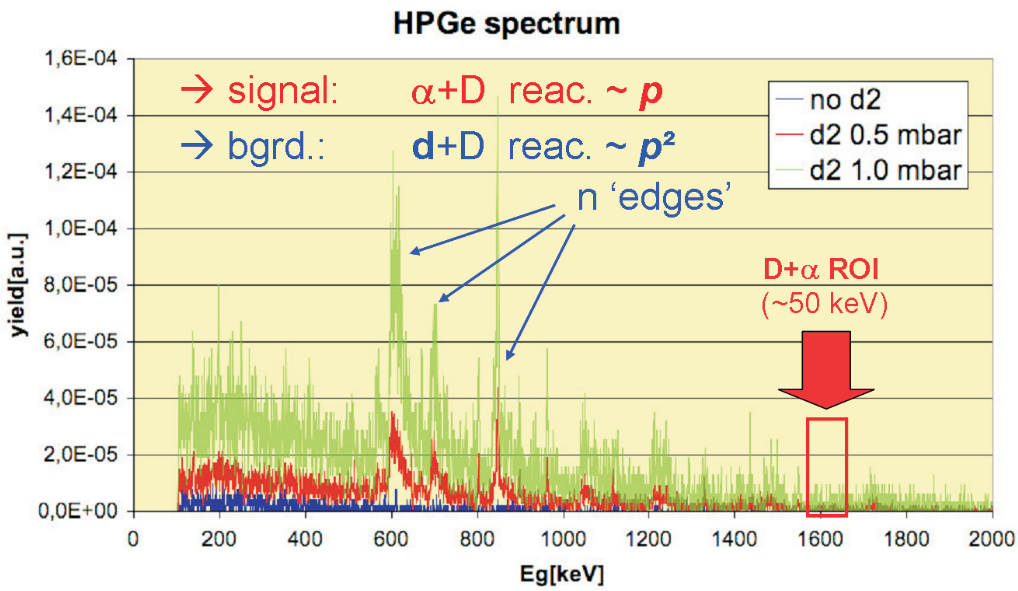

Figure 2: Histograms taken with the HPGe detector at p = 1.0 (green curve) and 0.5 mbar (red curve) pressure in the D_2-gas target. The blue histogram was taken without gas. The region of interest (RoI) is marked by the red rectangle. Clearly visible are the so-called "n-edges" resulting from inelastically scattered neutrons on the isotopes of the Ge-crystal. The signal of the d+α-reaction was expected to be proportional to the pressure while the n-rate depends on the square of the pressure.

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In order to better understand this kind of background the n-induced γ-lines were analyzed under different conditions. According to Knoll's formula [15] the neutron fluence Φ_n in the HPGe-detector, given in n/cm^2, corresponds to the number of counts in the n-edge at 693 keV times 300, divided by the volume of the HPGe-crystal ($V_{\mathrm{HPGe}} = 582\,\mathrm{cm}^3$). As can be seen in fig. 2, the D+α-RoI is not directly affected by γ-transitions from inelastic n-scattering on Ge, but higher lying γs from n-capture in Cu produce an unwished Compton background which has been reduced significantly by replacing the Cu target chamber by a steel chamber.

With nearly the same cross section as the d(d,n)^{3}He reaction, protons are emitted by the d(d,p)t reaction path. The n-flux could be derived by measuring the protons using Si-detectors with a thin Al foil to stop the primary α-particles as well as tritons and ^{3}He-nuclei. Fig. 3 demonstrates that proton peak energy and shape could be well reproduced by simulations with the LUNA Monte-Carlo code [16] based on GEANT3. The n-flux derived at different pressures is in perfect agreement with the independent method using the inelastic n-scattering on Ge.

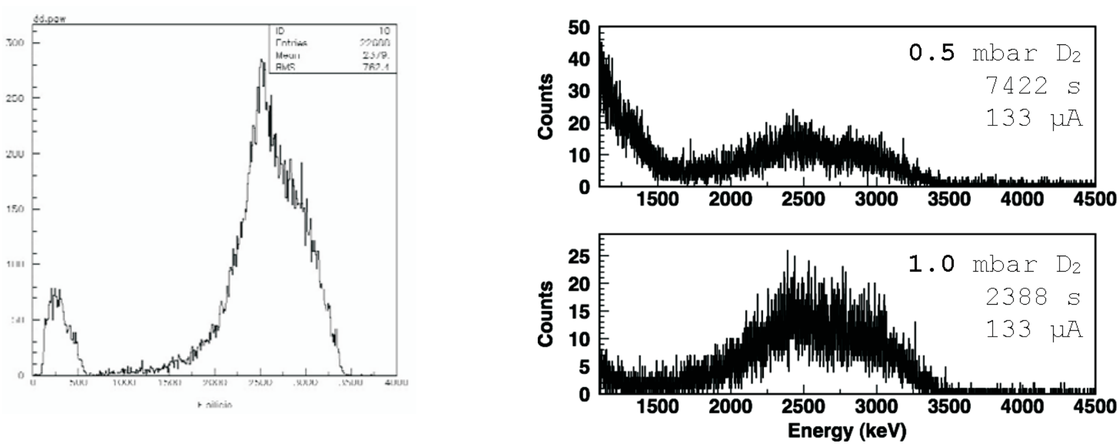

Figure 3: Spectrum of the Si-detectors simulated with the LUNA MC-code (left fig.) and measured Si-spectra at 0.5 (right fig., upper panel) and 1.0 mbar (right fig., lower panel).

A recess in the target chamber allows the HPGe-detector to be 4 cm closer to the beam line to increase the detector efficiency (see fig. 4). The target length optimizes the signal-to-noise ratio. To limit the free path of scattered deuterons in the gas target a rectangular beam tube has been inserted. Due to the low Q-value of the reaction a lead castle has been built around gas target and HPGe-detector and a Pb-wall behind the calorimeter to reduce ^{40}K and U-/Th-decay chain γ-lines from the surrounding rock. Since the Rn-concentration in the tunnel is fluctuating, an anti-Rn-box around the Pb-shielding has been built up to guarantee a stable and low background.

3. Outlook

The setup described above helped to reduce the background by orders of magnitude compared to an unshielded HPGe-detector. The preparation of the experiment has been finished and the measurements will be started soon. In order to keep the n-production below 10 n/s, the best combination was found to run the experiment at a deuterium gas pressure of 0.35 mbar using a beam current of about 200 μA. According to the S-factor given in literature [17] 570 counts can be expected in the

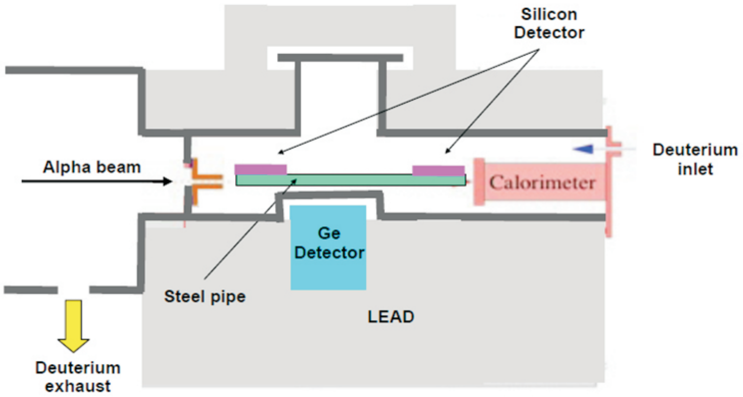

Figure 4: Scheme of the new D+α-setup. With respect to the old setup the new chamber is made from steel instead of Cu, its length is reduced by several cm, a beam tube was inserted to limit the path of the elastically scattered deuterons, and the chamber has a recess to allow the HPGe to be 4 cm closer to the beam.

50 keV wide RoI in already 10 days with 24 h of beam. The signal will be very low under realistic conditions. Therefore the beam-induced background has to be studied carefully during the measurement. One possible tool could be the use of the $D(^3He,p)^4He$-reaction, which induces a similar γ-background but lacks the D+α-signal.

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