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Letter of Intent: SARAF facility, Soreq Nuclear Center, Israel

Measurement of the cross section of the ^{7}Be(n,α)α Reaction and the Problem of Primordial ^{7}Li

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Abstract:

The disagreement of the predicted abundance of primordial ^{7}Li with the observed abundance is a longstanding problem in Big Bang Nucleosynthesis (BBN) theory. While BBN theory correctly predicts the abundances of ^{1}H, ^{2}H, ^{3}He and ^{4}He (that vary over five orders of magnitudes), it over predicts the abundance of primordial ^{7}Li by a factor of approximately 2.5-4.5 (approximately 4-5σ discrepancy). Primordial ^{7}Li is copiously produced directly (e.g. via the ^{6}Li(n,γ) reaction etc.) but later during the first 4-15 minutes approximately 99% of the so produced ^{7}Li is destroyed primarily via the ^{7}Li(p,α) reaction. Hence most of the predicted primordial ^{7}Li is predicted to be produced via the (electron capture beta) decay of the primordial ^{7}Be that is produced primarily in the ^{3}He(α,γ) reaction. We propose to investigate the destruction of ^{7}Be during (the first 10-15 minutes of) BBN via the ^{7}Be(n,α) reaction. If during that time the majority of the primordial ^{7}Be is destroyed (before decaying to ^{7}Li) it will lead to a reduction of approximately 3 of the predicted abundance of the primordial ^{7}Li, hence a resolution of the long standing disagreement. The rate of the 7Be(n,a) reaction relies on unpublished and not very well documented cross section of thermal neutron (only) measured in the 60's and tabulated for the first and last time by Wagoneer *et al.* in the 60's. We propose to measure the cross section of the ^{7}Be(n,α) reaction with neutron beams that mimic a quasi Maxwellian flux at 50 keV. A prototype experiment and the proposed final experiment could be performed at Phase I of SARAF using the LILIT target.

1. Introduction:

The theory of Big Bang Nucleosynthesis (BBN) was first introduced in the 1940's by George Gammow and since then it was successful in predicting the abundances of the primordial ^{1}H, ^{2}H, ^{3}He and ^{4}He that vary over five orders of magnitudes [1]. It also predicted correctly the number of neutrino types and allowed for accurate determination of the baryonic density in the Universe. This latest prediction gave credence to the concept of dark matter that was introduced by Fred Zwicky already in the 1930's. Such cosmological observations brought on the era of precision cosmology [1] and allowed the study of fundamental physics beyond the scope of terrestrial laboratories. Recent accurate determination of the baryon density by the Wilkinson Microwave Anisotropy Probe (WMAP) [2], together with a measurement of the number of neutrino types [3], and several improvement of the nuclear data including neutron half-life [3] and cross-sections of relevant nuclear reactions such as the ^{3}He(α,γ)^{7}Be [4] reaction, allowed for precise predictions by BBN theory of the abundance of primordial elements. These predictions agree quite well with new precise observation of primordial abundances, except for ^{7}Li.

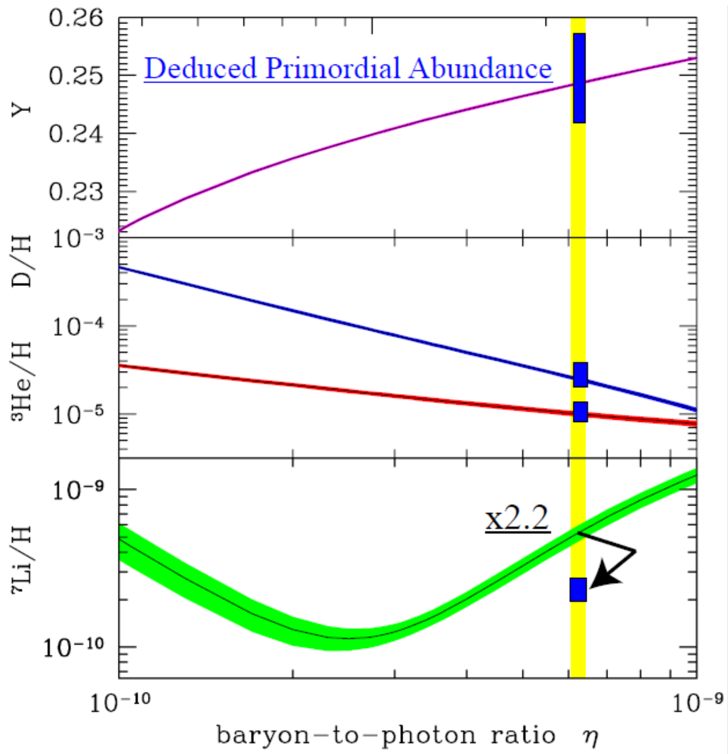

Fig.1: The primordial light element abundances of D, ^{3}He, ^{7}Li (relative to the abundance of H), and the mass fraction of ^{4}He as a function of η. The thickness of the bands represents 1σ uncertainties in the calculated abundance. The yellow band corresponds to the WMAP baryon-to-photon ratio, η of 6.23(17)10^{-10}. The observed elemental abundances are indicated by blue bands. The indicated discrepancy for ^{7}Li is even larger than shown here according to [6].

Prediction of isotopic abundances of the lightest elements presents a stringent test for the BBN theory [5]. The current status is described in Fig. 1 where we observe an excellent agreement between the predicted and the measured abundances of ^{2}H, ^{3}He and ^{4}He at the WMAP value of the baryon to photon ratio (η). However, there is a significant discrepancy between the predictions for ^{7}Li/H ratio (5.24 + 0.71 – 0.62 × 10^{-10}) [6] and the astronomical measurements of: zero metallicity halo stars (1.23 ± 0.06) × 10^{-10}) [7], or globular clusters stars (2.19 ± 0.28) × 10^{-10}) [8]. Hence a discrepancy of a factor 2.4 or 4.2σ (from globular cluster stars) to a factor 4.3 or 5.3σ (from halo stars) [6]. The discrepancy of the predicted ^{7}Li abundance was referred to in the literature as the ^{7}Li problem, puzzle or even crisis.

Several attempts to explain the low ^{7}Li abundance were carried out suggesting physics beyond the Standard Model. We propose to investigate a simple explanation in terms of the destruction of the primordial ^{7}Be. The calculated BBN elemental abundances are shown as a function of time or temperature in Fig. 2. During BBN ^{7}Li is produced via the ^{3}H(α,γ)^{7}Li and the ^{6}Li(n,γ) reactions. The so produced ^{7}Li is later destroyed mostly by the ^{7}Li(p,α) reaction (during the first 4 – 15 minutes) as shown in Fig. 2 by the two orders of magnitude reduction of the abundance of ^{7}Li. BBN theory thus predicts that most of the primordial ^{7}Li is produced by the decay of ^{7}Be ($T_{1/2}$=53.2 days, for atomic nuclei) that in of itself is produced primarily in the ^{3}He(α,γ)^{7}Be reaction. Hence approximately 66% of the primordial ^{7}Li is predicted to be from the decay of ^{7}Be and 34% is due to the direct production (after destruction) of ^{7}Li as discussed above. If in fact the primordial ^{7}Be is subsequently destroyed by for example the ^{7}Be(n,α) reaction, it will lead to a reduction by a factor of approximately 3 of the predicted primordial ^{7}Li abundance and thus a resolution of the long standing primordial ^{7}Li problem that at time was even described as crisis for BBN.

The rate of the ^{7}Be(n,α) reaction was first and last [9] tabulated by Wagoneer *et al.* in the 60's [10]. In Serpico *et al.* [11] we find the following statement: "**To our knowledge, evaluations for the rate of the ^{7}Be(n,α) reaction have only been published in [10], without information on the sources of the data and error estimate. We did not find further analysis in subsequent compilations… For this reason we adopted Wagoner's rate, assuming a factor of ten uncertainty, as he suggested as a typical conservative value. Within this allowed range, this reaction could play a non-negligible role in *direct* ^{7}Be destruction, so it would be fruitful to have a new experimental determination. Apart from the role of unknown or little known ^{8}Be resonances, it is however unlucky that the used extrapolation may underestimate the rate by more than one order of magnitude, as this process mainly proceeds through a p-wave**".

There is no proton-induced reaction with sufficiently large cross section to destroy the ^{7}Be during BBN. It was suggested that ^{7}Be(d,p)2α and ^{7}Be(d,α)^{5}Li may be responsible for destruction of ^{7}Be. However, recent measurements of the cross section of the ^{7}Be(d,p)2α reaction at Louvain-la-Neuve [12] did not indicate that the "^{7}Li problem" can be resolved via this reaction. The destruction of ^{7}Be by ^{3}He-induced reactions that was measured at the Weizmann Institute [13] does not yield to a solution of the ^{7}Li problem.

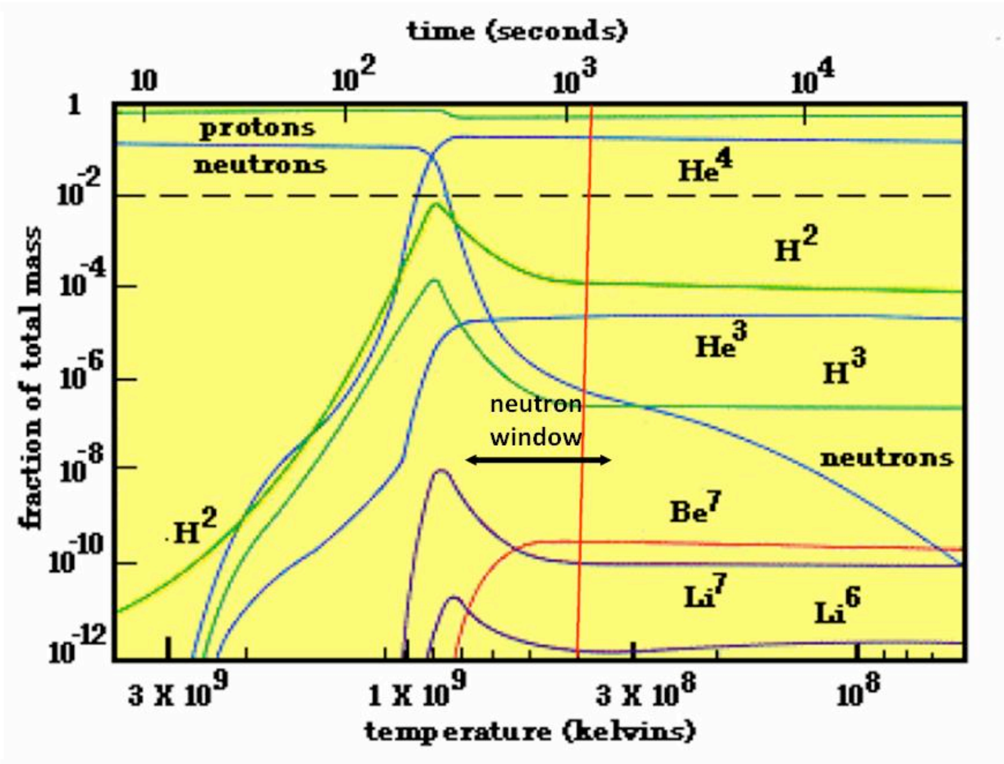

Fig. 2: The calculated abundances of primordial elements as a function of time and temperature [1].

In this letter of intent we propose to measure the cross section of the $^{7}Be(n,\alpha)\alpha$ reaction with neutron beams that mimic a quasi Maxwellian flux at 50 keV at the SARAF facility. For example a measurement of the ratio of the Maxwellian averaged cross sections: $^{7}Be(n,p)/^{7}Be(n,\alpha)$, could be very useful to test the rates published by Wagoneer [10]. In this case one needs to compare the yield for proton peaks at 1.4 MeV with the alpha peak at 9.5 MeV. If the reaction $^{7}Be(n,\gamma\alpha)$ has a large cross section as listed by Wagonner [10], it could be measured in our setup but it leads to a more challenging measurement, as we discuss below.

2. SARAF Phase I and LILIT target

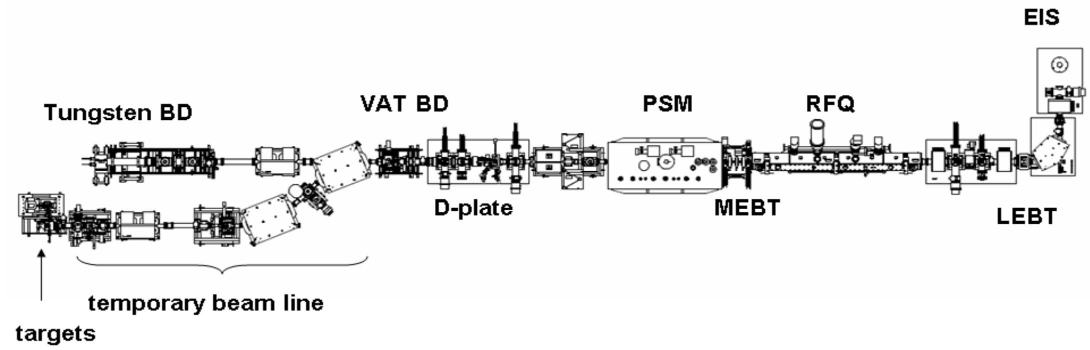

Fig. 3: Layout of SARAF Phase I and the temporary beam line.

Phase I of the Soreq Applied Research Accelerator Facility, SARAF, has been installed and is currently being commissioned at Soreq NRC [14]. Phase I of SARAF consists of a 20 keV/u ECR Ion Source (EIS), a Low Energy Beam Transport (LEBT) section, a 4-rod Radio Frequency Quadrupole (RFQ) injector, a Medium Energy (1.5 MeV/u) Beam Transport (MEBT) section, a Prototype Superconducting Module (PSM), a Diagnostic plate (D-plate) and beam dumps (BD). The main components of the Phase I are shown in Fig. 3. Currently ~1 mA CW proton beams are accelerated at SARAF to the energy of up to 3.5 MeV, though the deuteron operation is limited to a low duty cycle.

The Phase I of SARAF project provides a world unique possibility for astrophysical research. Operation of intense CW proton beams on a lithium target at the energies just above of the nuclear reaction threshold (1.88 MeV) creates the strong source of neutrons with spectrum emulating the astrophysical conditions. A liquid lithium target (LiLiT) is being developed to accommodate the high proton beam power. The main use of the LiLiT target will be for astrophysical research associated with measuring the cross-sections of key s-process reactions [15]. Currently the LiLiT target undergoes a number of landmark off-line tests. It is anticipated that the LiLiT target will be installed at the end of the temporary beam line as shown in Fig. 3 for in-beam operation.

3. The proposed experimental scheme

The proposed experimental scheme for measuring the ^{7}Be(n,α) reaction is shown in Fig. 4. A proton beam with energy of 1.94 Mev bombarding the lithium jet result a neutron cone that mimic a quasi Maxwellian flux at ~ 40 keV temperature. The beam energy will be varied to provide neutron beams that mimic a quasi Maxwellian flux at 30, 40, 50 and 60 keV. A thin ^{7}Be target of a few tens of mCi activity will be placed in close vicinity to the neutron source. The ^{7}Be deposited on a thin foil (e.g. 1-2 mg/cm^{2} nickel foil) will be sandwiched between two thin Mylar foils to minimize energy losses of the outgoing alpha-particles. A ^{7}Be radioactive target (~30 mCi) could be readily produced at the Laboratory of Radiochemistry at the Paul Scherrer

Institute [16]. The alpha-particles will be detected by two large area (400 mm^2) thin (50 μm) Si detectors that will be placed around the target as shown in Fig. 4. The full energy of approximately 19 MeV deposited in the two silicon detectors (in an almost calorimetric geometry) will be measured only for events where sufficient energy is deposited in both silicon detectors.

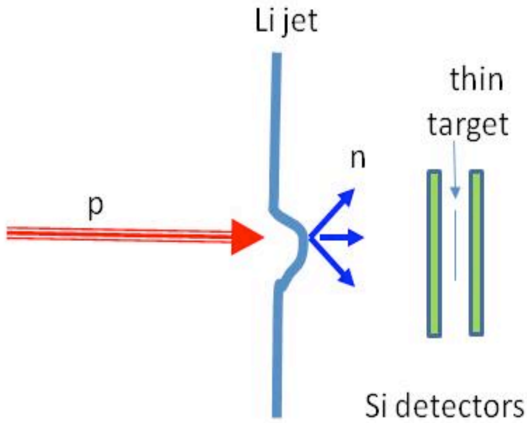

Fig.4: The experimental scheme

The main challenge of the experiment will be the detection of low energy alpha-particles in the presence of large background from epithermal neutrons and the radioactive target. In order to study the background and the feasibility of the final measurement we propose a prototypical experiment using the $^{10}B(n,\alpha)^7Li$ reaction to measure coincidences between the (considerably lower energy) byproducts of ^7Li (0.84 MeV) and the alpha-particle (1.47 MeV), as shown in Fig. 5. The use of a stable boron target rather than ^7Be radioactive target will simplify significantly the experiment and will allow us to test the setup and study neutron induced background. The boron compound will be deposited on a thin foil [17] to allow transmission of the low energy alpha-particles. The geometry of the boron target will be identical to the ^7Be target. The cross-section of the $^{10}B(n,\alpha)^7Li$ reaction is well known hence this reaction could be used for verifying the neutron flux that will be measured independently. In addition the cross section of the $^7Be(n,\alpha)$ reaction can be measured relative to the known cross section of the $^{10}B(n,\alpha)$ by using a two foil target that includes both ^7Be and ^{10}B. Such a ratio measurement will eliminate several systematical uncertainties. Example of a spectrum of the $^{10}B(n,a)$ reaction collected at Yale [17] is shown in Fig. 5. This spectrum was measured with the very same silicon detectors that we propose to use and that are still available at Yale University for use in this study.

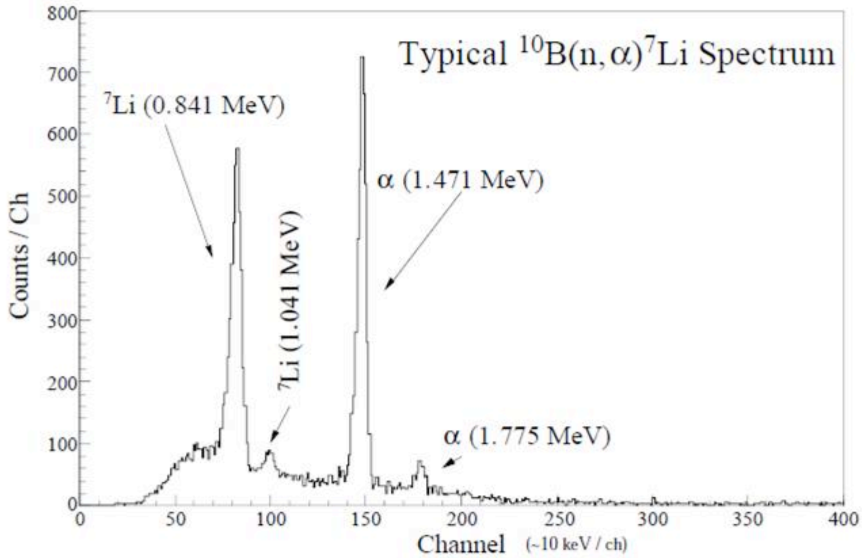

Fig. 5: A typical $^{10}B(n,\alpha)^{7}Li$ single's spectrum measured at Yale with a similar type of arrangement of Si detectors [17].

The detection of the alpha-particles from $^{7}Be(n,\gamma\alpha)$ reaction will involve detecting 1.5 MeV alpha-particles from the decay of the broad (Γ = 1.5 MeV) 2^{+} state at 3.05 MeV in ^{8}Be which are in close proximity to the sharp proton peak at 1.4 MeV from the $^{7}Be(n,p)^{7}Li$ reaction. Thus the investigation of the $^{7}Be(n,\gamma\alpha)$ is indeed more challenging. We note that the same setup can be used to measure the $^{7}Li(n,\gamma)^{8}Li$ by measuring the coincidence between the two beta-delayed alpha-particles. For this experiment the use of pulsed beam will provide further reduction of the background.

4. Conclusion

The combination of Phase I of SARAF linac and the LiLiT target presents a world unique possibility to test our proposed solution of the longstanding BBN ^{7}Li problem. To this end we propose a simple experiment (and a prototype experiment) that will require modest beam time allocation and modest preparation efforts. Efforts are underway at PSI in Switzerland for preparing the necessary ^{7}Be target.

5. Acknowledgement

We acknowledge extensive communication and helpful discussions with Dr. Ken Nollett of the Argonne National Lab.

7. References:

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