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Nuclear Physics Solutions to the Primordial Lithium Problem

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Abstract. The primordial lithium problem is one of the major outstanding issues in the standard model of the Big Bang. Measurements of the baryon to photon ratio in the cosmic microwave background constrain model predictions, giving abundances of ^{7}Li two to four times larger than observed via spectroscopic measurements of metal-poor stars. In an attempt to reconcile this discrepancy, significant effort has been directed at measuring reaction cross sections of light nuclei at astrophysically relevant energies. However, there remain reaction cross sections with large uncertainties, and some that have not yet been measured. Particularly relevant are those involving the destruction of ^{7}Be, a progenitor of ^{7}Li. Key issues that can be improved by nuclear physics input will be highlighted, and the applicability of detectors and event reconstruction techniques recently developed at the ANU will be discussed.

1 Introduction

In the first minutes of the universe, a process known as Big Bang Nucleosynthesis (BBN) occurred. This period of nucleosynthesis was brief - it lasted from when the universe was about three minutes old, when deuterium was no longer photo-disintegrated, to when it was approximately twenty minutes old [1]. Thus only the lightest elements were created in any great abundance - the isotopes of hydrogen, helium, lithium and ^{7}Be (which decays through electron capture to ^{7}Li). 13.8 billion years of stellar and galactic evolution has since enriched the universe with the heavier element abundances observed today.

The abundances of elements produced in BBN provides the initial conditions for the evolution of the oldest stars in the universe. It is thus of great importance to understand the outcomes of BBN - the initial elemental composition of the universe - before we can sensibly talk about the evolution of these stars. Furthermore, by examining the correspondence between predictions of the outcomes of BBN and observations of primordial abundances, the theory of the Big Bang can be examined. When compared to observations, it is found that ^{7}Li is under-abundant by a factor of 2.4 to 4.3 as compared to BBN calculations, on the 4-5 σ level [2]. It is this discrepancy that is known as the "primordial lithium problem", and the search for a solution to this discrepancy motivates this study.

2 Big Bang Nucleosynthesis Calculations

To understand the current status of BBN calculations, a brief overview of how the abundances are calculated is necessary. The modern standard model of BBN is parameter free, relying *only* on experimentally determined reaction rates, as parameters such as the baryon-to-photon ratio have been determined via observations. This relatively new development - previously, the model has been dependent on three parameters - the neutron lifetime, the number of neutrino families, and the baryon-to-photon ratio. The first two are constrained by measurement and theory [3], whilst the latter is constrained by precision observations of the cosmic microwave background (CMB) by the WMAP experiment [4]. Not only does the CMB give information on the age and curvature of the universe, but also the baryon-to-photon ratio, through the relative sizes of the acoustic peaks of its power spectrum [5]. Thus, given nuclear reaction rates and the temperature of the universe, model calculations of BBN can be made. An example of such a calculation is shown in figure 1. To test these predictions primordial element abundances must be measured.

3 Observations

It is a challenge in astronomy to measure primordial abundances of elements in the universe, as the processes of stellar and galactic nucleosynthesis necessarily change elemental abundances. Thus, objects must be found that are both sufficiently close to perform precision measurements on, and have a structure such that the relevant elements have not been modified by nucleosynthesis. Deuterium abundances, for example, are taken from measurements of interstellar hydrogen rich gas clouds. As ^{3}He abundances have only been determined in our own solar system and in metal-rich regions of our galaxy, its primordial abundance has not been determined. To observe primordial ^{7}Li, absorption spectra of population II globular cluster stars and halo field turnoff dwarfs and subgiants are examined [7]. Hydrodynamical models of these stars indicate that they have a very thin surface zone, well isolated from the stars' interior stellar processes. As such, it is expected that the abundances of ^{7}Li are primordial in these stars.

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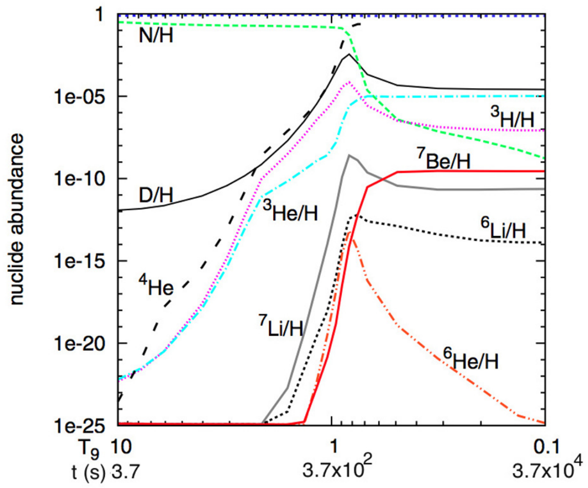

Fig. 1. Prediction of nuclei abundance from a BBN calculation [6]. Abundances are shown as a function of temperature, with the associated age of the universe also shown. Note the log-log scales, and that the abundances (scaled to proton abundance for everything but ^{4}He) span 25 orders of magnitude. Figure adapted from ref [6].

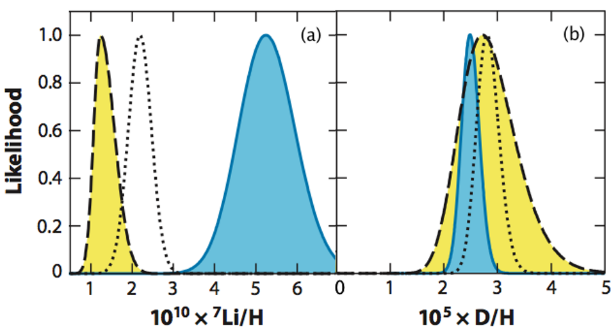

Fig. 2. Comparison of calculated and observed abundances of (a) ^{7}Li and (b) deuterium with respect to proton abundance. The blue curves show predictions from BBN calculations, whereas the yellow show observational abundances, with the dotted and dashed lines showing different analyses of observational data. Figure adapted from ref [8].

As can be seen in figure 2, observed abundances of deuterium are consistent with that predicted in BBN. On the other hand, it is immediately seen that the same cannot be said for ^{7}Li abundances - there is a significant discrepancy between the predicted and observed abundances as discussed above. This problem is generally articulated by examining the abundance of lithium in stellar photospheres as a function of the star's metallicity, as shown in figure 3. Metallicity refers to the abundance of elements heavier than H and He in a star, with Fe usually used as a proxy for all of those elements, and reflects the age of the star. The abundance of ^{7}Li is almost independent of metallicity, and there is low scatter about the line. As such, the natural expectation is that the ^{7}Li abundances are primordial. This line is known as the Spite Plateau, after its discoverers in 1982 [9]. As discussed above, it is clear that this abundance is not that predicted in models of BBN. It has recently come to light that there may exist another lithium problem, this time for ^{6}Li [7]. Instead of abundances lower than that

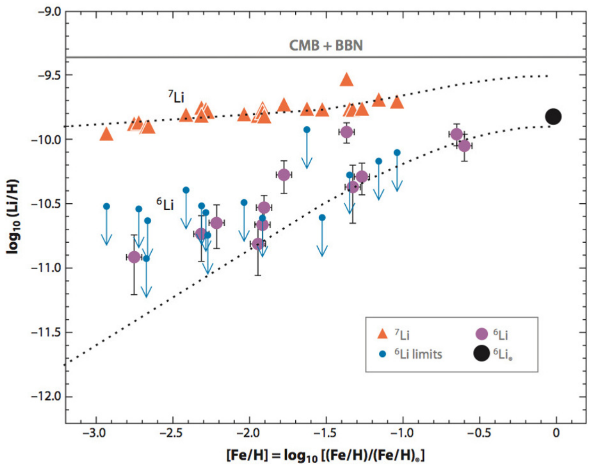

Fig. 3. Abundances of ^{7}Li and ^{6}Li as a function of metallicity, compared to BBN predictions. The line of ^{7}Li abundances is known as the Spite Plateau. Image from Fields 2011 [8], data from Asplund et. al. 2005 [7]

predicted in BBN, observations indicate abundances several orders of magnitude higher than predicted. However, these measurements are challenging, and further observational work is required before the ^{6}Li problem is considered to be as concerning as the ^{7}Li problem. As such, this work focuses on the ^{7}Li problem. For a more detailed discussion of the observational considerations, the reader is referred to [7].

4 Solutions

This large discrepancy between observation and experiment has been the subject of research for many years. The mechanisms through which a solution can be found can be loosely categorised into three groups; new physics solutions, astrophysical solutions and nuclear physics solutions

4.1 New Physics Solutions

If it is the case that both the observations of primordial ^{7}Li abundances are correct and that the nuclear physics behind BBN is correct, it then becomes necessary to consider physics beyond the standard model of particle physics and of cosmology. Such proposed solutions include (but are by no means restricted to) invoking WIMPS and SUSY [10], invoking Axions [11], varying fundamental constants [12], or using non-standard cosmologies such as allowing the universe to be inhomogeneous at Hubble scales [13]. These solutions are necessarily somewhat speculative. It is thus important to consider less speculative solutions, the first of which are astrophysical solutions.

4.2 Astrophysical Solutions

Briefly, astrophysical solutions take the form of examining the measurements of primordial ^{7}Li abundances, assuming that nuclear physics behind BBN predictions are correct. If there are errors in the underlying assumptions behind these measurements, a solution may appear. There are two obvious places in which a solution can be found - through examining the determination of ^{7}Li abundances in stars, and through the assumption that these abundances are primordial.

In order to infer abundances from absorption spectra, it is necessary to know the effective temperature (T_{eff} - the temperature of a black body with the same luminosity per unit area) of the star to some precision, as the ionisation state of Li, and thus the size of the absorption peak is exponentially dependent on this temperature. A systematic increase in T_{eff} determination would alleviate the lithium problem. The temperature scale was however, verified by new methods [14], and significant changes in the T_{eff} scale are unlikely. There is, however, significant scope for solution in the re-examination of stellar models taking into account diffusion and turbulent mixing [15] and rotational mixing [16]. Whilst an astrophysical solution may yet solve the lithium problem, there exist another set of possible solutions: those based on examining the nuclear physics behind BBN.

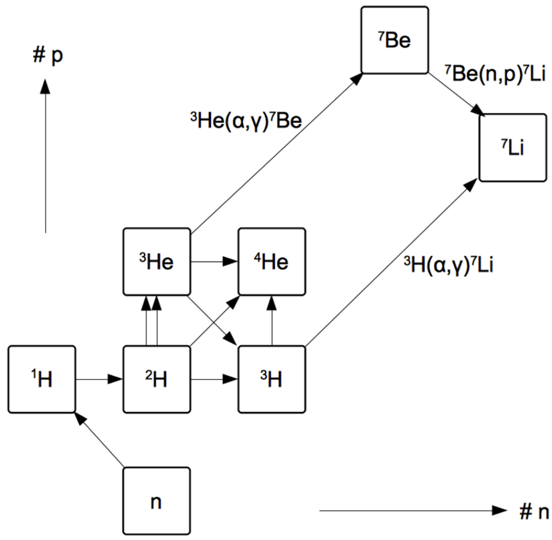

Fig. 4. A simplified nuclear reaction network for ^{7}Li production, showing the 12 most important reactions.

4.3 Nuclear Solutions

Since investigation of astrophysical solutions have not yet resolved the problem, efforts have been made to examine the nuclear physics behind BBN. Reactions during BBN occur at low energies, E, ($0.1 \lesssim E \lesssim 10$ MeV), with light and often unstable nuclei. It is thus unsurprising that there is scope for nuclear physics solutions. Sensitivity studies [6] indicated those reactions which contribute significantly to ^{7}Li yields, and these have directed recent experimental nuclear physics investigations of reaction cross sections.

To examine nuclear physics solutions, the processes by which ^{7}Li is produced must be examined. A simplified nuclear reaction network diagram showing the significant pathways for the production of ^{7}Li is presented in figure 4. At BBN energies, there are two main pathways for ^{7}Li production: (i) direct production in the $t(\alpha,\gamma)^7$Li reaction, and (ii) through the transformation of ^{7}Be to ^{7}Li by the ^{7}Be(n,p)^{7}Li reaction, or by electron capture. During the Big Bang, the production of ^{7}Li through ^{7}Be is dominant. Thus reducing the amount of ^{7}Be during BBN will reduce the ^{7}Li abundance in the Universe.

The first place to turn is naturally the reaction forming ^{7}Be, namely ^{3}He$(\alpha,\gamma)^7$Be . In order to alleviate the ^{7}Li problem, the reaction rate would have to decrease by a factor of three to four. However, solar neutrino production is strongly dependent on this reaction, and thus the reaction rate cannot be changed to an extent that would sufficiently reduce the production of ^{7}Li in BBN calculations [17].

If the ^{7}Li problem cannot be resolved by reducing the production of ^{7}Be, perhaps it can be solved by increasing the destruction of ^{7}Be through reaction channels that do not produce ^{7}Li. Generally, three types of reactions are studied - those with neutrons, deuterons and alpha particles. Reactions with heavier species are generally not studied, as they have lower cross sections due to larger Coulomb barriers, and they are not considered to be sufficiently abundant during BBN, as shown by BBN calculations.

The most studied group of reactions are those with neutrons. The ^{7}Be (n,p)^{7}Li reaction is believed to be the most important, constituting 97% of ^{7}Be destruction through neutron reactions. It has a very large cross section, on the order of 10 barns, at BBN energies and is well studied experimentally with uncertainties about 1% [18,19]. The next significant neutron reaction is believed to be the ^{7}Be(n,α)α reaction, providing the remaining 2.5% of the destruction cross section [19]. There are no data for this reaction at BBN energies. What is used in BBN model calculations is an extrapolation of a 1967 reaction down to BBN energies [20], and this provides a large contribution to uncertainties in ^{7}Li abundance predictions. Investigation of this reaction at BBN energies is necessary to resolve these uncertainties.

The next group of reactions are those with deuterium, where we are mostly concerned with missing resonances, particularly in the ^{7}Be(d,p)2α reaction. The final group of reactions are those with alpha particles, the least studied channel, and again, we are mostly concerned with missing resonances [19]. These kind of reactions have been studied previously (in part, at least), and have not yet yielded solutions to the primordial lithium problem.

An example of such a study can be seen in an experiment by Angulo et. al. in 2005 [21], where the aforementioned ^{7}Be(d,p)2α reaction was investigated. Calculations indicate that if this reaction cross-section was significantly larger than previously assumed, it could resolve the ^{7}Li problem [22]. The results of their experiment indicate a cross section an order of magnitude smaller than previous estimates. However, in the analysis, the assumption was made that the reaction occurred through the ^{8}Be ground and first excited states, and thus all of the energy released in the reaction would be carried by the proton, rather than by the alpha particles. Thus a coincidence analysis was not carried out. Whilst the analysis was appropriate to investigate the assumed scenario, disregarding the case where a resonance ^{8}Be is populated, and the alpha particles rather than the proton carry the energy released in the reaction, will lead to a systematic error in the ^{7}Be destruction rate.

Many studies of reactions in BBN involve making an assumption on the outcome of the reaction, motivating the search for reaction pathways that have not been previously included in BBN calculations. It seems important to obtain a complete picture of reactions in BBN, thus we should measure all of the results of a reaction, without making *a priori* assumptions about the reaction mechanism.

5 A new experimental approach

A new detector array has been developed at the ANU that should be able to address the above challenge. This position sensitive detector array was specifically designed to study the breakup of light nuclei such as ^{6,7}Li. The array consists of four double-sided silicon strip detectors (DSSDs), in a lamp-shade configuration as illustrated in figure 5. As currently configured, the coverage in scattering angle θ and azimuthal angle ϕ is as shown in the figure. This corresponds to a solid angle coverage of more than half of one hemisphere. The array is segmented into 512 pixels, giving the possibility to measure several reaction products in coincidence. The energy resolution for 8 MeV α-particles has been measured to be less than 200 keV. The threshold energy for detection is currently set at $\approx$1.0 MeV, but it is expected that the array can operate with a lower threshold.

Complex kinematical reconstruction software has been developed, allowing extraction of reaction Q-values, and relative kinetic energies, which together gives a complete picture of all breakup reactions.

With these tools, complete characterisation of the different breakup reactions occurring in the collisions of ^{6,7}Li [23] with ^{208}Pb and ^{9}Be [24] at near-barrier energies has been achieved. Surprisingly, nucleon transfer reactions were found to play a dominant role in the destruction of both ^{6}Li and ^{7}Li. Subsequently breakup of ^{6,7}Li in collisions with Zn and Ni isotopes have also been successfully measured.

By stepping to reactions with lighter target nuclei, the trends of transfer-induced breakup will first be investigated. At the same time computer simulations of the astrophysically important reactions will show the best experimental conditions, including the optimal angular coverage, and the possible need for the detector telescope configuration as used in Ref. [23]. It is anticipated that the array will be placed at forward angles, centred around 0°, initially using beams of ^{7}Li then of ^{7}Be incident on light targets. Through these stages, applications of the array and analysis software to the determination of cross sections for the nuclear collisions important in the primordial lithium problem, such as ^{7}Be(d,p)2α, will be developed

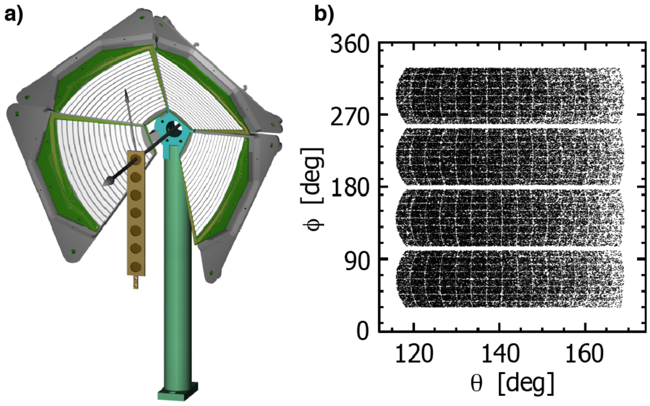

Fig. 5. (a) A high resolution pixelated detector array comprising four DSSDs mounted on a hub in a "lampshade" annular arrangement all angled at 45°, with respect to their bisector, towards the focal point of the hub. The beam (arrow) and target ladder are also shown. (b) The angular coverage, in scattering angle θ and azimuthal angle ϕ, of the detector array's 512 pixels for a typical back-angle breakup measurement.

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