Interaction of Neutrons With $^7$Be; Last Nuclear Physics Attempt to Solve the “Primordial $^7$Li Problem”

Moshe Gai
UConn and Yale
http://astro.uconn.edu
moshe.gai@yale.edu

1. Big Bang Nucleosynthesis (BBN)
2. The “Primordial $^7$Li Problem”
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Letter of Intent: Collaboration Between the n_TOF and ISOLDE at CERN, the Paul Scherrer Institute, Switzerland and the Israel-US SARAF Collaboration

Measurements of Neutron Interactions With $^7$Be and the “Primordial $^7$Li Problem”

D. Berkovits$^1$, E. Berthoumieux$^2$, M. Borge$^3$, E. Chiaveri$^2$, N. Colonna$^4$, G. Feinberg$^{1,5}$, S. Halfon$^{1,5}$, M. Gai$^6$, G.M. Hale$^7$, M. Hass$^8$, K.M. Nollett$^9$, M. Paul$^5$, A. Prygarin$^8$, D. Schumann$^{10}$, C. Seiffert$^3$, A.F. Shor$^2$, Th. Stora$^3$, L. Weissman$^1$

1. Soreq Nuclear Research Center, Nuclear Physics and Engineering Division, Yavne 81800, Israel.


3. ISOLDE, CERN, CH-1211 Geneva, Switzerland.

4. Istituto Nazionale di Fisica Nucleare, 70125 Bari, Italy; for the n_TOF Collaboration, CERN, CH-1211 Geneva, Switzerland.

5. Racah Institute of Physics, The Hebrew University, Jerusalem 91904, Israel.

6. LNS at Avery Point, University of Connecticut, 1084 Shennecossett Rd, Groton, CT06340, USA and Department of Physics, Yale University, 272 Whitney Ave., New Haven, CT 06520-8124, USA.

7. Theoretical Division, Los Alamos National Lab, Los Alamos, NM 87545, USA

8. Department of Particle Physics, Weizmann Inst. of Science, Rehovot 7610, Israel.

9. Department of Physics and Astronomy, Ohio University, Athens, OH 45701, USA.

10. RadWasteAnalytics, Paul Scherrer Institute, CH-5232 Villigen, Switzerland.
Measurement of the cross section of the $^7\text{Be}(n,\alpha)\alpha$ Reaction and the Problem of Primordial $^7\text{Li}$

M. Gai (Yale and UConn) and L. Weissman (Soreq)

Abstract:

The disagreement of the predicted abundance of primordial $^7\text{Li}$ with the observed abundance is a longstanding problem in Big Bang Nucleosynthesis (BBN) theory. While BBN theory correctly predicts the abundances of $^1\text{H}$, $^2\text{H}$, $^3\text{He}$ and $^4\text{He}$ (that vary over five orders of magnitudes), it over predicts the abundance of primordial $^7\text{Li}$ by a factor of approximately 2.5-4.5 (approximately 4-5σ discrepancy). Primordial $^7\text{Li}$ is copiously produced directly (e.g. via the $^6\text{Li}(n,\gamma)$ reaction etc.) but later during the first 4-15 minutes approximately 99% of the so produced $^7\text{Li}$ is destroyed primarily via the $^7\text{Li}(p,\alpha)$ reaction. Hence most of the predicted primordial $^7\text{Li}$ is predicted to be produced via the (electron capture beta) decay of the primordial $^7\text{Be}$ that is produced primarily in the $^3\text{He}(\alpha,\gamma)$ reaction. We propose to investigate the destruction of $^7\text{Be}$ during (the first 10-15 minutes of) BBN via the $^7\text{Be}(n,\alpha)$ reaction. If during that time the majority of the primordial $^7\text{Be}$ is destroyed (before decaying to $^7\text{Li}$) it will lead to a reduction of approximately 3 of the predicted abundance of the primordial $^7\text{Li}$, hence a resolution of the long standing disagreement. The rate of the $^7\text{Be}(n,a)$ 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 $^7\text{Be}(n,\alpha)$ 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.
$^7\text{Li}$ Problem: Cyburt-Fields-Olive; 0808.2818

baryon density $\Omega_y h^2_{10^{-2}}$

Deduced Primordial Abundance

$x \sim 3$
Observation of interstellar lithium in the low-metallicity Small Magellanic Cloud

J. Christopher Howk¹, Nicolas Lehner¹, Brian D. Fields²,³ & Grant J. Mathews¹
K.M. Nollett:
$\Omega_b h^2 (WMAP) \rightarrow 95\%$ of $^7\text{Li}$ Daughter of $^7\text{Be}$
Figure 1. The nuclear network used in BBN calculations.

Olive; astro-ph/0202486
1. $n \leftrightarrow p$
2. $p(n,\gamma)t$
3. $d(p,\gamma)^3He$
4. $d(d,n)^3He$
5. $d(d,p)t$
6. $t(d,n)^3He$
7. $t(a,\gamma)^7Li$
8. $^3He(n,p)t$
9. $^3He(d,p)^4He$
10. $^3He(a,\gamma)^7Be$
11. $^7Li(p,\alpha)^4He$
12. $^7Be(n,p)^7Li$
13. $^7Be(a,\alpha)^4He$
Destruction of $^{7}$Be: $^{7}$Be(n,p)$^{7}$Li(p,a)

FIG. 4. The $^{7}$Be(n,p)$^{7}$Li $(\rho_0 + \rho_1)$ cross section. Data from 25 meV to 13.5 keV are results of the present work (circles). Also shown are the data for this reaction from Ref. 11 (crosses).
THE $^7\text{Be}(d,p)2\alpha$ CROSS SECTION AT BIG BANG ENERGIES AND THE PRIMORDIAL $^7\text{Li}$ ABUNDANCE

C. Angulo, E. Casarejos, M. Couder, P. Demaret, P. Leleux, and F. Vanderbist

Centre de Recherches du Cyclotron and Institut de Physique Nucléaire, Université catholique de Louvain, Chemin du Cyclotron 2, B-1348 Louvain-la-Neuve, Belgium; angulo@cyc.ucl.ac.be

A. Coc, J. Kiener, and V. Tatischeff
Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, IN2P3-CNRS, Université Paris-Sud, Bâtiment 104, F-91405 Orsay Campus, France

T. Davinson and A. S. Murphy
School of Physics, James Clerk Maxwell Building, King’s Buildings, University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, UK

N. L. Achouri and N. A. Orr
Laboratoire de Physique Corpusculaire, ENSICAEN, and Université de Caen, IN2P3-CNRS, 6 boulevard du Maréchal Juin, F-14050 Caen Cedex, France

D. Cortina-Gil
Departamento de Física de Partículas, Universidad de Santiago de Compostela, E-15782 Santiago de Compostela, Spain

P. Figuera
Laboratori Nazionali del Sud, Istituto Nazionale di Fisica Nucleare, via Santa Sofia 62, I-95123 Catania, Italy

B. R. Fulton
Department of Physics, University of York, Heslington, York YO10 5DD, UK

I. Mukha
Instituut voor Kern- en Straling fisica, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium

AND

E. Vangioni
Institut d’Astrophysique de Paris, 98bis boulevard Arago, F-75014 Paris, France

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ABSTRACT

The WMAP satellite, devoted to observations of the anisotropies of the cosmic microwave background radiation, has recently provided a determination of the baryonic density of the universe with unprecedented precision. Using this, big bang nucleosynthesis calculations predict a primordial $^7\text{Li}$ abundance that is a factor of 2–3 higher than that observed in Galactic halo dwarf stars. It has been argued that this discrepancy could be resolved if the $^7\text{Be}(d,p)2\alpha$ reaction rate were around a factor of 100 larger than has previously been considered. We have now studied this reaction, for the first time at energies appropriate to the big bang environment, at the CYCLONE radioactive-beam facility at Louvain-la-Neuve. The cross section was found to be a factor of 10 smaller than derived from earlier measurements. It is concluded therefore that nuclear uncertainties cannot explain the discrepancy between observed and predicted primordial $^7\text{Li}$ abundances, and an alternative astrophysical solution must be investigated.

Subject headings: cosmological parameters — early universe — nuclear reactions, nucleosynthesis, abundances — stars: Population II

1. INTRODUCTION

Using the Wilkinson Microwave Anisotropy Probe (WMAP) determination of the baryonic density (Bennett et al. 2003; Spergel et al. 2003), one obtains predictions of the abundances of the light-element isotopes produced in big bang nucleosynthesis (BBN) (Cyburt et al. 2003; Coc et al. 2002, 2004). While the overall values from theoretical predictions and from the observational determinations of the abundances of D and $^4\text{He}$ are in good agreement, the theory tends to predict a higher $^7\text{Li}$ abundance (by a factor of 2–3) than observed in Galactic halo dwarf stars. It has been argued that this discrepancy could be resolved if the $^7\text{Be}(d,p)2\alpha$ reaction rate were around a factor of 100 larger than has previously been considered. We have now studied this reaction, for the first time at energies appropriate to the big bang environment, at the CYCLONE radioactive-beam facility at Louvain-la-Neuve. The cross section was found to be a factor of 10 smaller than derived from earlier measurements. It is concluded therefore that nuclear uncertainties cannot explain the discrepancy between observed and predicted primordial $^7\text{Li}$ abundances, and an alternative astrophysical solution must be investigated.

 densities obtained from cosmic microwave background observations on the one hand and comparison between BBN calculations and spectroscopic data on the other were only marginally compatible (Coc et al. 2002). In order to improve the nuclear network, Descouvemont et al. (2004) recently performed a reanalysis of low-energy data from the 10 key nuclear reactions involved in BBN, by using R-matrix theory (Lane & Thomas 1958) and evaluating the remaining uncertainties in a statistically robust formalism. Using this improved network, Coc et al. (2004) have calculated BBN light-element productions assuming for the baryonic density the very precise value provided by WMAP (Spergel et al. 2003) and obtained $^7\text{Li}/^4\text{He} = 4.15^{+0.47}_{-0.45} \times 10^{-10}$, compared with the observed value $^7\text{Li}/^4\text{He} \approx (1–2) \times 10^{-10}$, confirming the $^7\text{Li}$ discrepancy.

However, it has been shown that the $^7\text{Be}(d,p)2\alpha$ reaction (which destroys the $^7\text{Be}$ that is the source of $^7\text{Li}$ at high baryonic density) would solve the $^7\text{Li}$ problem if its cross section were much higher than assumed (Coc et al. 2004). Importantly, prior to the present work no direct experimental data at BBN energies were available (for $T = 0.5–1$ GK, the Gamow window...
Search for a resonant enhancement of the $^7$Be + $d$ reaction and primordial $^7$Li abundances


1Department of Physics and Astronomy, Rutgers University, New Brunswick, New Jersey 08903
2Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831
3Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996
4Department of Physics, Sungkyunkwan University, Suwon 440-746, Korea
5Department of Physics, Tennessee Technological University, Cookeville, Tennessee 38505
6Department of Physics and Astronomy, Louisiana State University, Baton Rouge, Louisiana 70803
7Oak Ridge Associated Universities, Oak Ridge, Tennessee 37830

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Big Bang nucleosynthesis calculations, constrained by the Wilkinson Microwave Anisotropy Probe results, produce $^7$Li abundances almost a factor of four larger than those extrapolated from observations. Since primordial $^7$Li is believed to be mostly produced by the beta decay of $^7$Be, one proposed solution to this discrepancy is a resonant enhancement of the $^7$Be$(d, p)\gamma$ reaction rate through the $5/2^+$ 16.7-MeV state in $^8$B. The $^7$H($^7$Be,$d$)$^7$Be reaction was used to search for such a resonance; none was observed. An upper limit on the width of the proposed resonance was deduced.

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One probe of the conditions present in the early universe is the primordial abundances produced during Big Bang nucleosynthesis (BBN). From comparisons of BBN calculations to abundances deduced from observations, constraints on early universe properties can be extracted. BBN calculations constrained by Wilkinson Microwave Anisotropy Probe (WMAP) data estimate the primordial abundances of light nuclei (e.g., D, $^4$He, $^7$Li) [1]. While predictions of the helium and deuterium abundances agree with observations, there exists a discrepancy between the calculated BBN $^7$Li abundance and the primordial abundances deduced from extrapolations to zero metallicity from observations of population II stars, older stars with lower metallicity. Specifically, the inferred primordial abundance of lithium from population II stars is $^7$Li/$^4$H = 1.23$^{+0.34}_{-0.16}$ × 10$^{-10}$, while that calculated with BBN theory using the WMAP baryonic density is $^7$Li/$^4$H = 5.12$^{+0.71}_{-0.60}$ × 10$^{-10}$ [2,3]. This discrepancy is known as the cosmological lithium problem and has been the subject of much interest in recent years [2–7].

Several solutions have been proposed to resolve this discrepancy. A possible astrophysical solution is that the current understanding of the stellar processes that deplete lithium in population II stars needs to be improved [10]. Another possibility is that physics beyond the standard BBN model is required [1]. A proposed nuclear physics resolution is that if $^7$Be is destroyed more quickly in the early universe than was previously thought, less would be available to decay to $^7$Li, reducing the predicted BBN abundance [9]. Recent work by Cyburt et al. showed that if the $5/2^+$ 16.7-MeV state in $^8$B has a $^7$Be + $d$ resonance energy between 170 and 220 keV and a deuteron decay width between 10 and 40 keV, then a resonant enhancement of the $^7$Be$(d, p)\alpha$ or $^7$Be$(d, \gamma)$ reaction could resolve the cosmological lithium problem [3].

A measurement by Angulo et al. using the $^7$Be$(d, p)\alpha$ reaction found no enhancement of the rate compared to prior calculations and early work by Kavanagh [11,12]. However, Cyburt et al. argue that some of the assumptions made in this earlier measurement may not be valid. Furthermore, $(d, p)$ protons populating the 16.63-MeV 2$^+$ state in $^8$Be would have been missed in that study, since they were below the detection threshold [3]. In more recent work, Boyd et al. question whether the resonance would be populated in the $^7$Be + $d$ reaction [7]. Clearly more study of possible resonances in $^7$Be + $d$ reactions and the 16.7-MeV state in $^8$B is needed to resolve these issues.

The $^7$H($^7$Be,$d$)$^7$Be reaction was studied at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL) [8]. The experiment was performed in inverse kinematics using a pure 10-MeV $^7$Be beam with an average intensity of $5 \times 10^6$ $^7$Be/s. The $^7$Be was produced at the Institute of Nuclear Research of the Hungarian Academy of Sciences (ATOMKI) via the $^7$Li$(p, n)^7$Be reaction and shipped to ORNL, where it was chemically isolated from the $^7$Li and pressed into a powder for use in a sputter ion source. A mixed $^7$BeO$^-$/LiO$^-$ beam was extracted from the source and accelerated in the HRIBF tandem accelerator. At the terminal, the oxide molecules were broken up at the carbon stripper foil and the resultant $^7$Be ions accelerated to full energy. The beam was then delivered to a gas-filled ionization counter downstream of the experimental target station where the purity and intensity could be diagnosed. As seen in Fig. 1, a pure beam of $^7$Be was achieved by stripping the beam to charge state $q = 4^+$ at the terminal of the tandem accelerator.

The 10-MeV $^7$Be beam was used to bombard a 1.62-mg/cm$^2$-thick CD$_2$ target. Scattered deuterons from the $^7$H($^7$Be,$d$)$^7$Be reaction were detected in an annular silicon strip detector with an inner radius of 2.4 cm and an outer radius of 4.8 cm divided into 16 1.5-mm strips. It was placed about 23 cm from the target covering forward laboratory angles $\approx 6^\circ$–$12^\circ$. Because the energy of the proposed resonance was low ($E_{m, \alpha} \approx 200$ keV or $E_{lab} \approx 900$ keV), the scattered

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One fewer solution to the cosmological lithium problem

O. S. Kirsebom1,2,* and B. Davids1

1TRIUMF, Vancouver, British Columbia, Canada, V6T 2A3
2Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark

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Data from a recent 7Be(3He,γ)8B measurement are used to rule out a possible solution to the cosmological lithium problem based on conventional nuclear physics.

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The primordial abundance of 7Li inferred from observational data is roughly a factor of 3 below the abundance predicted by the standard theory of big bang nucleosynthesis (BBN) [1] using the baryon-to-photon ratio η = 6.19(15) × 10^{-10} [2] determined mainly from measurements of the cosmic microwave background radiation. In contrast, there is good agreement for 2H and 4He. Taking into account the estimated uncertainties on the observationally inferred and theoretically deduced 7Li abundances, the significance of the discrepancy is (4.2–5.3)σ [3]. This constitutes one of the important unresolved problems of present-day astrophysics and is termed the cosmological lithium problem. Among other possibilities, the discrepancy could be due to new physics beyond the standard model of particle physics [4], errors in the observationally inferred primordial lithium abundance, or incomplete nuclear physics input for the BBN calculations. This Brief Report addresses the last possibility.

In standard BBN theory, assuming η = 6.19(15) × 10^{-10}, most 7Li is produced in the form of 7Be. Only much later, when the universe has cooled sufficiently for nuclei and electrons to combine into atoms, does 7Be decay to 7Li through electron capture. The temperature range of 7Be production is T ≃ 0.3–0.6 GK, where the main mechanism for 7Be production is 3He(α,γ)7Be while the main mechanism for 7Be destruction is 7Be(n,α)4He followed by 7Li(p,α)4He. The rates of these reactions as well as the reactions that control the supply of neutrons, protons, 3He, and α particles are known with better than 10% precision at BBN temperatures [6], resulting in an uncertainty of only 13% on the calculated 7Li abundance [3].

A recent theoretical paper [7] explores the possibility of enhancing 7Be destruction through resonant reactions with p, d, t, 3He, and α, leading to compound states in 8B, 9B, 10B, 10C, and 11C, respectively. The paper concludes that, of the known excited states in these isotopes [8,9], only the 16.8-MeV state in 9B has the potential to significantly influence 7Be destruction.2 (Note that in Ref. [7] this state is referred to as the 16.7 MeV state.) The proposed destruction mechanism is shown schematically in Fig. 1. The

1Corresponding author: oliverk@triumf.ca

2Lithium may be destroyed in metal-poor stars through diffusion and turbulent mixing [5].

2Reference [10] offers a more optimistic view, but only by adopting a somewhat flexible approach to basic principles of nuclear physics.

16.8-MeV state in 9B is formed by the fusion of 7Be with a deuteron and decays by proton emission to a highly excited state in 8Be, 16.626 MeV above the ground state, which subsequently breaks up into two α particles. (The last step is not shown in the figure.) The reason why the decay must proceed by proton emission to the 16.626-MeV state in 8Be and not, for example, the ground state is explained later.

The reaction rate depends critically on the resonance energy, Eγ (i.e., the energy of the 16.8-MeV state relative to the d + 7Be threshold at Sd = 16.490(10) MeV [8]): if too far above the threshold, the tunneling process will be too slow at BBN temperatures. Furthermore, for the proposed destruction mechanism to be efficient, the 16.8-MeV state must have an appreciable width, Γd, for being formed in the d + 7Be channel, but also an appreciable width, Γ − Γd, for not decaying back to d + 7Be. The energetically allowed decay modes competing with deuteron emission are γ, p, α, and 3He. However, γ and 3He can safely be neglected. A deuteron width, Γd, of the required magnitude can only be realized if the 16.8-MeV state is not too close to the threshold. The analysis of Ref. [7] shows that the cosmological lithium problem can be resolved provided Eγ ≃ 170–220 keV, Γd ≃ 10–40 keV, and γ − Γd ≃ Γd. At the time Ref. [7] was written, the known properties of the 16.8-MeV state did not contradict these requirements: The 16.8-MeV state had been observed in two experiments [11,12]. Its energy was determined to be 16.7 MeV with an uncertainty of 100 keV, and only an upper limit of 100 keV existed on its total width. Its spin and parity were not determined, though a tentative 5/2+ assignment was made [13] based on comparison to the mirror nucleus, 9Be. No information existed on its decay properties.

As noted in Ref. [7], the simultaneous requirement of Eγ ≃ 170–220 keV and Γd ≃ 10–40 keV is physically possible, but it implies some rather special properties for the 16.8-MeV state: a reduced deuteron width comparable to the Wigner limit and a very large channel radius of at least 9 fm. In addition, the proposed destruction mechanism could only be reconciled with the direct measurement of Ref. [14] with considerable difficulty: the proton and α decay of the 16.8-MeV state had to be dominated by a single proton-decay branch to the 16.626-MeV, 2+ state in 8Be, because decays to the lower-lying states in 8Be would have produced protons of sufficient energy to be detected by the experimental setup of Ref. [14].
Search for new resonant states in $^{10}\text{C}$ and $^{11}\text{C}$ and their impact on the cosmological lithium problem


1 Institut de Physique Nucléaire d’Orsay, UMR8608, IN2P3-CNRS, Université Paris Sud, 91406 Orsay, France
3 Department of Physics, University of York, Heslington, York YO10 5DD, United Kingdom
5 Nuclear Physics Institute ASCR, 250 68 Rez, Czech Republic
6 GANIL, CEA/DSM-CNRS/IN2P3, Caen, France
7 Departamento de Física i Enginyeria Nuclear, Universitat Politècnica de Catalunya, E-08036 Barcelona, Spain
8 Departamento de Física Aplicada, Universidad de Huelva, E-21071 Huelva, Spain

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The observed primordial $^{7}\text{Li}$ abundance in metal-poor halo stars is found to be lower than its Big-Bang nucleosynthesis (BBN) calculated value by a factor of approximately three. Some recent works suggested the possibility that this discrepancy originates from missing resonant reactions which would destroy the $^{7}\text{Be}$, parent of $^{7}\text{Li}$. The most promising candidate reactions which were found include a possibly missed $^{7}\text{Be}+^{4}\text{He}$ and a state close to 7.8 MeV in the compound nucleus $^{10}\text{C}$ formed by $^{7}\text{Be}+^{4}\text{He}$ and a state close to 7.8 MeV in the compound nucleus $^{10}\text{C}$ formed by $^{7}\text{Be}+^{4}\text{He}$. In this work, we studied the high excitation energy region of $^{10}\text{C}$ and the low excitation energy region in $^{11}\text{C}$ via the reactions $^{10}\text{B}(^{7}\text{He},t)^{10}\text{C}$ and $^{11}\text{B}(^{7}\text{He},t)^{11}\text{C}$, respectively, at the incident energy of 35 MeV. Our results for $^{10}\text{C}$ do not support $^{7}\text{Be}+^{4}\text{He}$ as a possible solution for the $^{7}\text{Li}$ problem. Concerning $^{11}\text{C}$ results, the data show no new resonances in the excitation energy region of interest and this excludes $^{7}\text{Be}+^{4}\text{He}$ reaction channel as an explanation for the $^{7}\text{Li}$ deficit.

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The primordial nucleosynthesis of light elements $^{2}\text{H}$, $^{3}\text{He}$, and $^{7}\text{Li},$ together with the expansion of the Universe and the cosmic microwave background (CMB) are the three observational pillars of the standard Big-Bang model where the last free parameter was the baryonic density of the Universe, $\Omega_b$. A precise value for this free parameter has been deduced from the analysis of the anisotropies of the CMB as observed by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite ($\Omega_b h^2=0.02249\pm0.00560$) [1] and more recently by the Planck mission ($\Omega_b h^2=0.02207\pm0.00333$) [2]. A comparison between the calculations of the primordial abundances of the light nuclei and the observations reveals a good agreement for helium and an excellent agreement for deuterium. In contrast, the theoretical predictions show a discrepancy by a factor of $\sim3$ for $^{7}\text{Li}$ abundance [3, 4]. Indeed, at the baryonic density of the Universe, $\Omega_b h^2$, derived from the CMB anisotropies, the predicted BBN abundance of $^{7}\text{Li}$ is: 

$\left(\frac{^{7}\text{Li}}{^{7}\text{Li}}\right)_{\text{BBN}}=(5.12^{+0.77}_{-0.62})\times10^{-10}$ [3] when using WMAP data or $(4.89^{+0.41}_{-0.39})\times10^{-10}$ [5] with the Planck data. On the other hand, the observed $^{7}\text{Li}$ abundance, derived from the observations of low-metallicity halo dwarf stars, was found to be $\left(\frac{^{7}\text{Li}}{^{7}\text{Li}}\right)_{\text{halo}}=(1.58\pm0.31)\times10^{-10}$ [6]. This significant discrepancy between the observations and the BBN predictions is known as the "lithium problem" [7].

Several ideas were addressed to try to explain this $^{7}\text{Li}$ problem [8]. Some conceived the idea that the $^{7}\text{Li}$ deficit points toward physics beyond the standard model such as decay of super-symmetric particles [8]. Others have suggested that the problem could be due to $^{7}\text{Li}$ stellar destruction in the atmosphere of the halo stars [9]. However, a uniform destruction of $^{7}\text{Li}$ over the so-called Spite-plateau region seems difficult [10]. Finally, several authors investigated the nuclear aspect of the problem concerning the $^{7}\text{Li}$ abundance [11–13]. The main process for the production of the BBN $^{7}\text{Li}$ at $\Omega_b h^2$ is the decay of $^{7}\text{Be}$ which is produced in the reaction $^{7}\text{Be}(^{4}\text{He},\gamma)^{7}\text{Be}$. Direct measurements of this reaction cross-section were performed by several groups resulting in a significant reduction of the thermal reaction rate uncertainty [14], but no solution to the $^{7}\text{Li}$ problem. More generally, the experimental nuclear data concerning the 12 main BBN reactions are sufficient to exclude a solution in this region, so that one has to extend the network to...
Destruction of $^7$Li and $^7$Be in astrophysical environments


$^a$Department of Physics, Unit 3046, University of Connecticut, Storrs, CT 06269, USA
$^b$Department of Chemistry & Physics, Georgia College & State University, CBX 82, Milledgeville, GA 31061, USA
$^c$Department of Particle Physics, Weizmann Institute, Rehovot 76100, Israel
$^d$Institut de Physique Nucleaire, Universite Catholique de Louvain, Chemin du Cyclotron 2, B-1348-Louvain-la-Neuve, Belgique
$^*$Physics Department, 200 Bloomfield Ave., University of Hartford, West Hartford, CT 06117-1599, USA

The destruction of $^7$Li and $^7$Be in astrophysical environments is essential for understanding several stellar and cosmological processes and is not well understood, though earlier $^7$Li + $^3$He experiments have been performed [1]. The primordial abundance of $^7$Li after Big Bang Nucleosynthesis (BBN) plays a major role in our understanding of the early universe [2]. The value of the baryon to photon ratio ($\eta$) deduced from BBN combined with measurements of the cosmic microwave background provide some of the strongest and earliest evidence for the existence of non-baryonic dark matter [2]. The destruction of $^7$Be during the hot-pp cycle may alter our conclusions on the production of carbon in this process, which is thought to compete with the triple-$\alpha$ process for the production of $^{12}$C, as the reaction $^7$Be($^3$He, 2$a$)2p competes with $^7$Be($^4$He, $\gamma$)$^{11}$C and may reduce carbon production [3]. These stellar and cosmological environments involve high temperatures, and thus, effective burning energies (Gamow windows) that are quite high. Experiments using $^7$Be targets inevitably involve interactions with $^7$Li as background due to the $^7$Li daughters from the beta decay of $^7$Be. The experiments were performed at the Weizmann Institute VDG Laboratory using $^3$He beams from 390 keV to 1130 keV on $^7$LiF foil targets and $^7$Be implanted targets. Results from measurements using 10 $\mu$g $^7$LiF foil targets will be discussed.

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$^*$on leave from the National Institute for Physics and Nuclear Engineering, Dept. of Nuclear Physics, Bucharest-Magurele, Romania

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ON THE SYNTHESIS OF ELEMENTS AT VERY HIGH TEMPERATURES*

ROBERT V. WAGONER, WILLIAM A. FOWLER, AND F. HOYLE
California Institute of Technology, Pasadena, California, and Cambridge University
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ABSTRACT

A detailed calculation of element production in the early stages of a homogeneous and isotropic expanding universe as well as within imploding-explosive supermassive stars has been made. If the recently measured microwave background radiation is due to primordial photons, then significant quantities of only D, He³, He⁴, and Li⁷ can be produced in the universal fireball. Reasonable agreement with solar-system abundances for these nuclei is obtained if the present temperature is 3° K and if the present density is \( \sim 2 \times 10^{-41} \text{ gm cm}^{-3} \), corresponding to a deceleration parameter \( q_0 = 5 \times 10^{-3} \). However, massive stars “bouncing” at temperatures \( \sim 10^4 \text{ o K} \) can convert the universal D and He³ into C, N, O, Ne, Mg, and some heavier elements in amounts observed in the oldest stars. The mass gaps at \( A = 5 \) and \( 8 \) are bridged by the reactions \( \text{He}^6(\text{He}^4,\gamma)\text{Be}^7(\text{He}^4,\gamma)\text{C}^{11} \). Bounces at higher temperatures bridge the mass gaps through \( 3 \text{ He}^4 \to \text{C}^{11} \) and mainly produce metals of the iron group, plus a small amount of heavier elements synthesized by a new kind of \( r \)-process (rapid neutron capture). It is found that very low abundances of He³, as recently observed in some stars, can be produced in a universe in which the electron neutrinos are degenerate.

I. INTRODUCTION

In this paper we shall consider the synthesis of elements on short time scales and at very high temperatures. The time scales are typically of the order of \( 10^5 \text{ to } 10^8 \text{ sec} \), while the temperatures range upward of \( 10^9 \text{ o K} \). These conditions are in marked contrast to the situation in stars, where lower temperatures and longer time scales usually obtain. It will appear that synthesis proceeds differently in many respects, and that abundances, particularly with respect to isotopic composition, are different from those which are produced in stellar nucleosynthesis.

The short time scales of the present paper are applicable to systems in rapid dynamical motion. These include the universe itself, if indeed the universe evolved from a hot, dense state, and also large masses of gas that collapse to such a state and subsequently explode. Our investigation deals with masses upwards of \( \sim 10^3 \text{ M}_\odot \).

Nuclear reactions were first applied to the early stages of a Friedmann universe by Alpher, Bethe, and Gamow (1948), and also by Fermi and Turkevich (1950). It was assumed in these investigations that initially all baryons were neutrons, an assumption which placed a severe restriction on the relation between the baryon density \( \rho_b \) and temperature. Writing

\[
\rho_b = \hbar T_9^3 \text{ gm cm}^{-3},
\]

where \( T_9 \) is in units of \( 10^9 \text{ o K} \), the parameter \( \hbar \) had to be set rather precisely \( (10^{-6} \geq \hbar \geq 10^{-7}) \) in order that hydrogen and helium emerged in approximately equal abundances in the final material. A small change of \( \hbar \) was sufficient to make the difference between essentially all hydrogen and essentially all helium.

This situation was changed by Hayashi (1950), who pointed out that at very high temperatures neutrons and protons come into statistical equilibrium through the weak interactions; for example,

\[
e^- + n \leftrightarrow n + \nu_e .
\]

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1 It should be noted that eq. (1) only holds exactly if no net energy is being transferred between the electrons and photons due to pair creation and annihilation (see § II).

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The Reaction $^7\text{Be}(n, \sigma)^4\text{He}$ and Parity Conservation in Strong Interactions (*)

P. Bassi, B. Ferretti and G. Venturini

Istituto di Fisica dell'Università - Bologna
Istituto Nazionale di Fisica Nucleare - Sezione di Bologna

G. C. Bertolini, F. Cappellani, V. Mandl, G. B. Restelli and A. Rota

C. C. R. EURATOM - Ispra

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Summary. — We have studied experimentally the reactions $^7\text{Be}(n, 2\gamma)^4\text{He}$ and $^7\text{Be}(n, \gamma\gamma)^4\text{He}$, produced by thermal neutrons. We have established an upper limit for the first of the two: $\sigma_1 < 0.1$ mb. For the second one we have found $\sigma_2 = 155$ mb. The limit for $\sigma_1$, in the hypothesis of a $2^-$ attribution to the $18.9$ MeV level of $^4\text{Be}$, corresponds to $F^2 < 4 \times 10^{-10}$, where $F$ is the ratio of the amplitudes of the opposite parity wave functions. This result is used to put an upper limit to the strength of a possible parity-violating interaction involving strange particles.

Introduction.

A clean experiment to test if parity is violated in strong interactions at low energy has been suggested by Segel, Kane and Wilkinson (1): it is the study of the reaction

$$^7\text{Be} + n \rightarrow 2\gamma,$$

which is not allowed for thermal neutrons (mainly absorbed in $S$-wave) because the $18.9$ MeV level of $^4\text{Be}$ which is formed has spin 2 and — parity. They

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2. - Experimental results.

Method A. Two Hughes SD1-23-1 cm² solid state counters were used. The source and the detector were placed coaxially at a distance of 9 mm with
move the estimate of the non-resonant contribution upwards by more than a factor of ten, thus further increasing its role. Though sub-leading, it is worthwhile to note that within the actual uncertainties and assuming the WMAP range for $\omega_b$, this process acquires a role comparable to that of $^7\text{Li} + p \rightarrow ^4\text{He} + ^4\text{He}$ and $^4\text{He} + ^3\text{H} \rightarrow \gamma + ^7\text{Li}$ reactions in determining the final prediction of $^7\text{Li}$. The data sets used in our analysis are [160]–[162]. We estimate an overall error of 3% and a large value of the normalization spread parameter, $\varepsilon \sim 0.14$.

### 3.5.4. Reaction $^7\text{Be}n\rightarrow^4\text{He}+^4\text{He}$

To our knowledge, evaluations for the rate of this reaction have only been published in [9] and [23], without information on the sources of the data and error estimate. We did not find further analysis in the subsequent compilations by Fowler et al [10]. The two data sets of the reverse process published in [163, 164] refer to centre of mass energies of the direct one greater than 0.6 MeV, thus leaving a great uncertainty in the BBN window. They seem to be roughly consistent with the old estimate of the rate, and a new one in view of so scarce data would make little sense. 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 $^7\text{Be}$ destruction, so it would be fruitful to have a new experimental determination.

Apart from the role of unknown or little known $^8\text{Be}$ 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.
7Be + n

Figure showing the cross-section $(\sigma v)/v$ in barns as a function of energy $E$ (MeV) for different reactions:

- (n,p) (Smith 93)
- (n,α) (Bassi limit, L=1)
- (n,γα) (s-wave)
- (n,α) ENDF (not MACS)
Figure 3: Energy levels of $^8$Be. For notation see Fig. 2.
- Measurements only for (n,p) [and (p,n)] reactions
- Predictions for (n,n) based on (p,p) data
The $^7\text{Li}(p,n)^7\text{Be}$ reaction for production of stellar neutrons

$E_p = 1912$ keV
$\Delta E = 1$ keV

$Q = -1644$ keV

$E_{th} = 1880$ keV

$\Phi_{MB} \cdot \nu \sim E \cdot e^{-E/kT}$;
$kT = 25$ keV

$I < 100 \mu A$

$\phi \sim 10^9$ neutron/sec

W. Ratynski and F. Kaeppeler,
PR C 37, 595 (1988)
FZ Karlsruhe, Germany
The activation experiment scheme

SARAF phase I

\[ E_p = 1912 \text{ keV} \]
\[ \Delta E > 7 \text{ keV} \]

\( ^7\text{Li}(p,n)^7\text{Be} \)
\[ E_{th} = 1880 \text{ keV} \]

\[ E_n \approx 30 \text{ keV} \]

Secondary activation target

The unique opportunity at SARAF:

High intensity proton beam + Liquid lithium target

High intensity neutron beam
- Liquid lithium jet target
- Proton energy: ~2 MeV.
- Proton current: <3.5 mA.
- Up to $8 \times 10^{10}$ n/sec
- $T \approx 230^\circ$C.
- $T_{\text{max}} \approx 350^\circ$C.

Feinberg et al, Nucl Phys A827 (2009) 590C
Beam lines downstream the linac
Figure 4.6: Typical Spectrum from the $^{10}\text{B}(n,\alpha)^7\text{Li}$ Reaction used to calibrate our alpha array at low energies exhibiting energy resolution of FWHM $= 55$ keV at 1.5 MeV.
Christoph Seiffert et al.; CERN/ISOLDE
Implanted $^{10}\text{B}$ target

$^{10}\text{B}(n,\alpha_1)^7\text{Li}^*$(.477)

$E_\alpha=1477.5\text{keV}$

$A=3180\rightarrow 0.013\text{cps}$
We Need a Thin and Clean $^7$Be Target
(~20 mCi 3 mm diameter)

target: $\sim 5 \times 10^{17}$ $^7$Be/cm$^2$
Beam: $\sim 10^9$ /sec (30-100 keV)
$L = 5 \times 10^{26}$ /cm$^2$ sec
$\varepsilon/4\pi = 15\%$ ($M=2 \rightarrow 30\%$)
$L\sigma\varepsilon > 10$ CPH
$\sigma > 100$ $\mu$b

**Design Goal Sensitivity = 0.1 mb**
(Current limit: $\sim 200$ mb at 50 keV)