The Astrophysical Journal, 630:L105–L108, 2005 September 10

THE ^{7}Be(d, p)2α CROSS SECTION AT BIG BANG ENERGIES AND THE PRIMORDIAL ^{7}Li ABUNDANCE

C. Angulo, E. Casarejos, M. Couder,[1] P. Demaret, P. Leleux,[2] 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 Join, 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[3]
Instituut voor Kern- en Stralingsfysica, Katholieke Universiteit Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
and
E. Vangioni
Institut d'Astrophysique de Paris, 98bis boulevard Arago, F-75014 Paris, France
Received 2005 April 27; accepted 2005 August 1; published 2005 August 26

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}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}Be(d, p)2α 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}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}He are in good agreement, the theory tends to predict a higher ^{7}Li abundance (by a factor of 2–3) than is observed in the atmospheres of halo dwarf stars (Ryan et al. 2000). The NACRE compilation (Angulo et al. 1999) provided a new set of reaction rates that were used to update the predictions of contemporary BBN (Vangioni-Flam et al. 2000). At that time, the baryonic 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}Li/H $= 4.15^{+0.49}_{-0.45} \times 10^{-10}$, compared with the observed value Li/H $\simeq (1–2) \times 10^{-10}$, confirming the ^{7}Li discrepancy.

However, it has been shown that the ^{7}Be(d, p)2α reaction (which destroys the ^{7}Be that is the source of ^{7}Li at high baryonic density) would solve the ^{7}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

[1] Current address: Nuclear Structure Laboratory, Department of Physics, 124 Nieuwland Science Hall, University of Notre Dame, Notre Dame, IN 46556.

[2] Directeur de Recherches, Fonds National de la Recherche Scientifique, Belgium.

[3] On leave from the RRC Kurchatov Institute, Moscow, Russia.

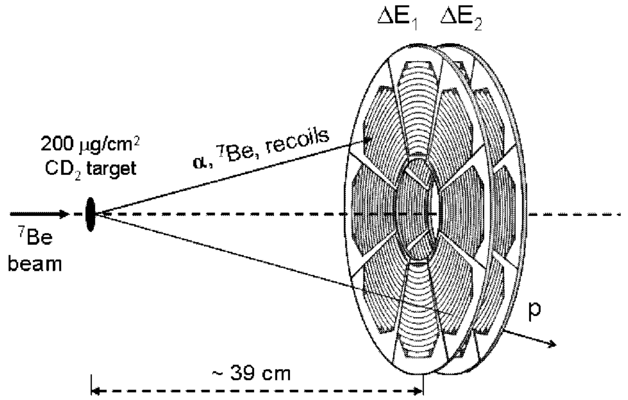

FIG. 1.—Schematic view of the experimental setup.

is $E = 0.11$–0.56 MeV). In fact, the ^{7}Be(d, p)2α reaction rate relied on an extrapolation made by Parker (1972) based on experimental data at center-of-mass (c.m.) energies of 0.6–1.3 MeV from Kavanagh (1960). In this experiment, protons corresponding to the ^{8}Be 0^+ ground state and first excited state (3.03 MeV, 2^+) were detected at 90° using an NaI(Tl) detector. Assuming an isotropic angular distribution, Parker (1972) multiplied the measured differential cross section by 4π and by a further factor of 3 to take into account the estimated contribution of the higher energy ^{8}Be states, not observed by Kavanagh (1960). Consequently, a constant *S*-factor of 100 MeV barn was adopted.

In order to obtain ^{7}Be(d, p)2α reaction cross section at BBN energies, we have performed an experiment at the CYCLONE radioactive-beam facility at Louvain-la-Neuve, Belgium, using an isobarically pure ^{7}Be radioactive beam. The experimental method and results are presented in § 2. The astrophysical consequences are discussed in § 3. The conclusions are given in § 4.

2. EXPERIMENTAL METHOD AND RESULTS

The measurements were performed using a postaccelerated ^{7}Be^{+1} radioactive beam at a nominal energy of 5.8 MeV provided by the CYCLONE110 cyclotron. A detailed description of the production of the ^{7}Be beam can be found in Gaelens et al. (2003). To suppress the contamination from the ^{7}Li isobaric beam, the ^{7}Be beam was completely stripped to ^{7}Be^{+4} by transmission through a thin ^{12}C foil, prior to analysis by a dipole magnet. Before the ^{7}Be(d, p)2α measurement, the beam energy was determined using a calibrated Si detector situated at 0°. A laboratory energy of 5.55 MeV (FWHM ~ 4%) was obtained, including a correction for pulse-height defect. This energy was degraded to 1.71 MeV (FWHM ~ 12%) using a 6 μm Mylar foil located 50 cm upstream of the target. No ^{7}Li contamination was observed, consistent with lithium isotopes' being unable to support a +4 charge state. The target consisted of a 200 μg cm^{-2} (CD$_2$)$_n$ self-supporting foil. With this setup, we were able to investigate the c.m. energy ranges between 1.00 and 1.23 MeV (for a beam energy of 5.55 MeV, without degrader) and between 0.13 and 0.38 MeV (for 1.71 MeV, with degrader). The cross-section measurement was averaged over these energy ranges. In addition to the feeding of the ground and first excited states of ^{8}Be (Kavanagh 1960), we were able to observe the ^{7}Be + d reaction via other kinematically allowed higher energy levels, mainly through a very broad 4^+ state ($\Gamma \simeq 3.5$ MeV)

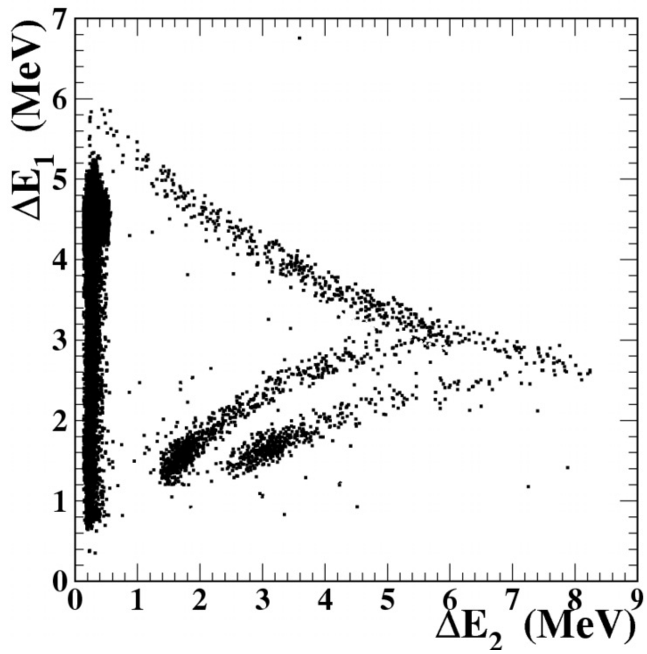

FIG. 2.—The ΔE_1-ΔE_2 spectrum at a beam energy of 5.55 MeV on a 200 μg cm^{-2} (CD$_2$)$_n$ target. The c.m. energy range covered is 1.0–1.23 MeV.

situated at an excitation energy of 11.4 MeV in ^{8}Be (Tilley et al. 2004). At the beam energy of 5.55 MeV, several states in ^{8}Be above the ^{7}Be + d-p threshold are present, but because of the Coulomb barrier in the final state, their contributions are expected to be negligible. The Q-value of the ^{7}Be(d, p)^{8}Be reaction is 16.49 MeV, and thus the laboratory energies of protons and α-particles are high. For example, a 5.55 MeV ^{7}Be beam traversing a 200 μg cm^{-2} (CD$_2$)$_n$ target will lead to the production of protons with energies anywhere between about 7.5 and 22 MeV, for the range of angles covered. Thus, to clearly disentangle the protons from the ^{7}Be + d reaction from those arising from reactions on the C content of the target, a stack of two "LEDA" silicon-strip detector arrays (Davinson et al. 2000) was employed, covering a laboratory angular range of $\theta_{\rm lab} = 7.6°$–$17.4°$. A schematic view of the experimental setup is shown in Figure 1. The ΔE_1 detector consisted of eight sectors of 0.3 mm thickness, while the ΔE_2 detector consisted of four sectors of 0.3 mm thickness and four of 0.5 mm thickness. They were calibrated using a three-line α-particle source (^{239}Pu, ^{241}Am, ^{244}Cm) and a precision pulser. All the particles that are not stopped in the front ΔE_1 detector and that are either stopped or leave energy on the back ΔE_2 detector are protons (having an energy of more than 6.5 MeV) that populated levels up to the 11.4 MeV state in ^{8}Be. We were able to measure the ^{7}Be(d, p)2α cross section up to excitation energies in ^{8}Be of $E_x = 13.8$ MeV for a beam energy of 5.55 MeV and $E_x = 11.5$ MeV for 1.71 MeV. Only about 50% of the contribution of the 4^+ broad state was observed at 1.71 MeV. Other light particles (p, d, ^{3}He, ^{4}He) from ^{7}Be + ^{12}C reactions, as well as recoils and scattered particles, were completely stopped in ΔE_1.

Figures 2 and 3 show the spectra obtained at the two beam energies. The spectrum at 1.71 MeV (Fig. 3) was accumulated over about 26 hr of running time with an averaged ^{7}Be beam intensity of 2×10^6 particles per second. As can be seen, the proton signals are well separated from the background signals

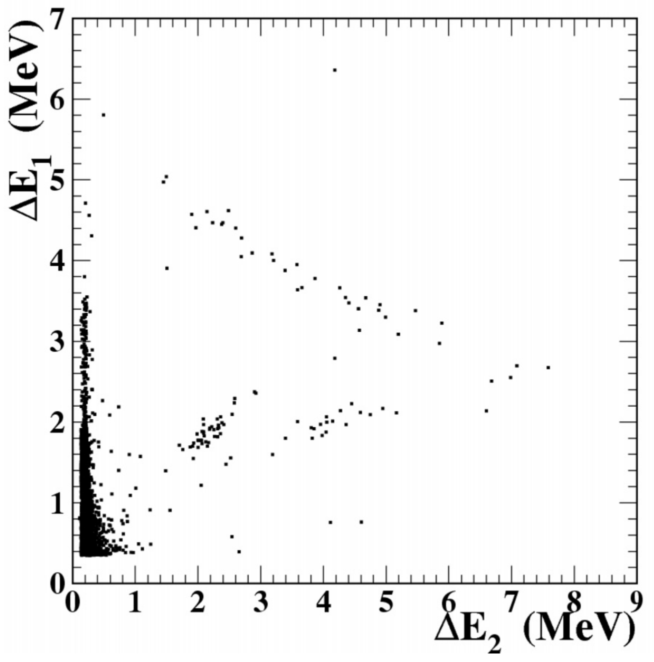

FIG. 3.—Same as Fig. 2, but for a beam energy of 1.71 MeV, corresponding to a c.m. energy range of 0.13–0.38 MeV.

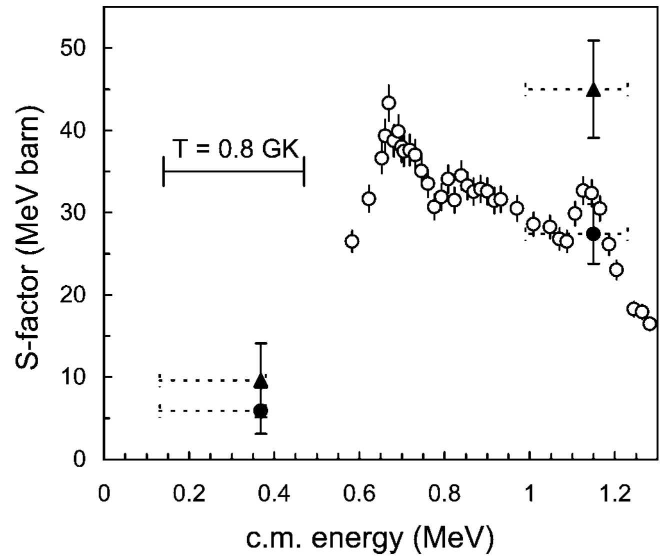

FIG. 4.—Astrophysical S-factor of the ^{7}Be$(d, p)^8$Be reaction. *Open circles*, data from Kavanagh (1960); *filled circles*, present data including contributions from the ground and first excited states of ^{8}Be only; *triangles*, total S-factor. The vertical error bars are the total error. The horizontal dotted bars indicate the energy range covered at each data point. The Gamow window for a typical BBN temperature $T = 0.8$ GK is also shown.

($\Delta E_2 < 1$ MeV), which are produced by random coincidences of α-particles, scattered ^{7}Be, and recoil ions in the ΔE_1 detector with β-particles in ΔE_2. The locus with negative slope contains protons that have passed through the front ΔE_1 detector and stopped in the back ΔE_2 detector. The two loci with positive slope are events in which the proton had sufficient energy to pass through both detectors completely. There are two bands because of the two different-thickness ΔE_2 detectors. The most strongly populated regions at the lower left of these bands correspond to protons losing the least energy in passing through the silicon and, thus, to the highest-energy events. By considering the kinematics and energy losses in silicon using SRIM-2003 (Ziegler et al. 1985), together with the straggling of the beam and experimental energy resolution, one may then identify events on the positive-slope locus up to 2.5 and 3.9 MeV for the 0.3 and 0.5 mm thickness Si wafers, respectively, as corresponding to events in which the recoiling ^{8}Be nucleus is in either the 0^+ ground state or the 2^+ excited state (the energy resolution is insufficient to resolve the two). The total statistical error was 10% for the beam energy of 1.71 MeV and less than 2% for 5.55 MeV (for protons populating the 0^+ and 2^+ states it was 13% and 2.5%, respectively). The absolute normalization was obtained by using events arising from the elastic scattering of the ^{7}Be on the C content of the target (as recorded by the ΔE_1 detector, in which the ^{7}Be is stopped) and assuming that the $^7\text{Be} + {}^{12}\text{C}$ elastic scattering follows the Rutherford law. This assumption is realistic at energies below the Coulomb barrier, as is the case here.

To calculate the average cross section over the energy ranges and angular coverages ($d\bar{\sigma}/d\Omega$), the number of counts was corrected for the detector solid angle (uncertainty $\pm 5\%$), the number of deuterons in the target ($\pm 10\%$), and the total number of incoming beam particles ($\pm 7\%$ and $\pm 26\%$ at the higher and lower beam energies, respectively) and transformed into the c.m. system. The proton angular distribution over the angular range covered here was found to be isotropic at both energies. Thus, we assumed full isotropy and calculated the average cross sections, $\bar{\sigma} = 7.5 \pm 0.8$ (stat.) $\pm$ 2.6 (sys.) mbarn at the effective energy of 0.37 MeV and $\bar{\sigma} = 386 \pm 7$ (stat.) $\pm$ 50 (sys.) mbarn at 1.15 MeV. The summed contribution of the 0^+ and 2^+ states was about 64% of $\bar{\sigma}$ at 1.15 MeV. At 0.37 MeV, $\bar{\sigma}$ includes the contribution of the ground and 2^+ states and about 50% of that of the 4^+ broad state. Because of the low penetration probability ($l = 4$), the contribution of the 4^+ state should be less than 36%. Thus, the $\bar{\sigma}$-value at 0.37 MeV corresponds to more than 80% of the total cross section (for a 4^+ state with $\Gamma \simeq 3.5$ MeV). This was taken into account in the systematic uncertainty.

In nuclear astrophysics it is usual to present the cross section in the form of the astrophysical S-factor $S(E)$, given by

$$S(E) = \sigma(E) \exp(2\pi\eta) E \qquad (1)$$

(Clayton 1983), where η is the Sommerfeld parameter ($\eta = Z_1 Z_2 e^2/\hbar v$, with Z_1 and Z_2 the charge numbers of the target and beam and v the velocity) and E is the effective c.m. energy. In the absence of sharp resonances, the S-factor varies smoothly with energy. Figure 4 shows the ^{7}Be$(d, p)^8$Be astrophysical S-factor $S(E)$ in MeV barn as a function of the c.m. energy. For a comparison with the data of Kavanagh (*open circles*), the present data including only contributions from the 0^+ and 2^+ states of ^{8}Be (*filled circles*) are shown. The agreement with the Kavanagh data at overlapping energies is satisfactory, given the systematic uncertainties. The total S-factor is also shown (*triangles*). These results show that the higher energy states not observed by Kavanagh (1960) contribute about 35% of the total S-factor instead of the 300% estimated by Parker (1972). Hence, the ^{7}Be$(d, p)^8$Be reaction rate is smaller by a factor of about 2 at energies in the range 1.0–1.23 MeV, and by about 10 at energies relevant to BBN, than previously estimated. This excludes a nuclear solution to the primordial lithium abundance problem by means of the ^{7}Be$(d, p)^8$Be reaction, as its effect is completely negligible compared with the 7% (1σ) nuclear uncertainty on the ^{7}Li yield. Nevertheless, these results allow a more accurate determination of the ^{7}Li abundance using BBN models.

3. ASTROPHYSICAL CONSEQUENCES

Since the pioneering work of Spite & Spite (1982), who found a value of Li/H $\approx 1.2 \times 10^{-10}$ independent of Fe/H (for [Fe/H] < -1.3), there have been many independent observations of Li confirming the existence of a plateau and suggesting that this abundance reflects the primordial Li value. However, the Li abundance extracted from observations depends drastically on the assumed surface temperature of the star (Fields et al. 2005). Recent observations (Ryan et al. 2000) have led to Li/H $= 1.23^{+0.68}_{-0.32} \times 10^{-10}$, which is very close to the first evaluation (Spite & Spite 1982). The more recent work studied and quantified the various sources of uncertainty: extrapolation, stellar depletion, and stellar atmosphere parameters. Compared with the *WMAP*-plus-BBN value, the discrepancy is a factor of $\sim$3.4. If it is shown that there is a mechanism by which the outer layers of Population II stars are transported deep into the stellar interior, then there are several ways in which Li abundances might be depleted over the lifetime of the star. In this context, the current estimates for possible depletion factors may be in the range $\sim$0.2–0.4 dex (Vauclair & Charbonnel 1998; Pinsonneault et al. 2002; Richard et al. 2005). However, the data typically show negligible intrinsic spread in the Li abundance, leading to the conclusion that depletion in these stars is on the order of 0.1 dex.

Recently, Meléndez & Ramírez (2004) obtained a higher value for the Li plateau abundance (2.34×10^{-10}), due to a new effective temperature scale that is higher at low metallicity. This new evaluation diminishes the discrepancy, without canceling it. The observation of ^{6}Li is also of interest, since, because it is more fragile than ^{7}Li, it can provide yet more severe constraints upon possible depletion mechanisms (Lambert 2004; Rollinde et al. 2005). Finally, despite the various uncertainties related to Li observations and to the stellar models, it is very difficult to reconcile the BBN ^{7}Li and the Spite plateau, which presents a narrow dispersion all along the metallicity scale.

4. CONCLUSIONS

The existence of the Spite plateau for Li seems to indicate that low-metallicity halo stars are indeed representative of the primordial BBN abundance. In particular, the isotope ^{7}Li plays a key role as a bridge between BBN, stellar evolution, and Galactic cosmic-ray nucleosynthesis. At present there is a significant discrepancy between the BBN-predicted ^{7}Li abundance (assuming a baryon density consistent with the concordance model derived from observations of anisotropies in the microwave background) and the abundance determined from the observations of Li in the atmospheres of halo stars. The experiment reported here demonstrates that the ^{7}Be(d, p)2α S-factor at BBN energies was not underestimated by Parker (1972) but, on the contrary, *overestimated*. The discrepancy cannot therefore be resolved by nuclear physics inputs to BBN calculations. The remaining conventional options (those not invoking physics beyond the standard model) are an adjustment of the stellar input parameters needed to extract the Li abundances from observations, or stellar depletion of ^{7}Li. However, models must be constructed to avoid dispersion in the ^{7}Li abundances over a wide range of stellar parameters, which is a real challenge. Thus, the origin of the discrepancy in the Li abundance remains a challenging issue.

This work was partially supported by the European Commission under contract HPRI-CT-1999-00110, the Belgian Inter-University Attraction Poles program P5/07, the Institut National de Physique Nucléaire et de Physique des Particules (IN2P3, France) through program PICS 1076 (US-CNRS), and the UK Engineering and Physical Sciences Research Council. E. V. is grateful to K. Olive for fruitful discussions.

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