

Direct measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction at astrophysical energies using the ELISSA array

H. Pai^{1,*}, G. L. Guardo², Sk M. Ali³, I. Kuncser^{1,4}, A. Lupoae^{1,5}, T. Petruse¹, C. Matei¹, Y. Xu¹, S. Aogaki¹, D. L. Balabanski¹, S. R. Ban^{1,4}, M. Brezeanu¹, A. Cassisa⁶, M. La Cognata², A. Cvetinović⁷, A. Dhal¹, P. Figuera², A. Kuşoğlu^{1,8}, L. Lamia^{2,9,10}, D. Lattuada^{2,11}, V. Lelasseux¹, Ó. E. López-López¹², C. A. Marin¹, C. V. Nedelcu^{1,4}, A. Pappalardo², I. P. Parlea¹, R. G. Pizzone^{2,13}, G. M. Restifo^{2,11}, R. Roy^{1,14}, P.-A. Söderström¹, S. Niculae¹, N. T. Szegedi², V. A. Toma¹, A. Tumino^{2,11}, G. Turturica¹, T. Tozar¹ and N. Vukman^{15,16,17}

¹*Extreme Light Infrastructure - Nuclear Physics, “Horia Hulubei” National Institute for R&D in Physics and Nuclear Engineering, 30 Reactorului Street, 077125 Magurele, Romania*

²*Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud, Catania 95123, Italy*

³*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*

⁴*Scoala Doctorala de Ingineria si Aplicatiile Laserilor si Acceleratorilor, Universitatea Politehnica, Bucharest, Romania*

⁵*University of Bucharest, Faculty of Physics, 405 Atomistilor Stradă, Măgurele, Romania*

⁶*Nuclear Physics Institute of the Czech Academy of Sciences, 250 68 Řež, Czech Republic*

⁷*Jožef Stefan Institute, Department of Low and Medium Energy Physics (F2), 1000 Ljubljana, Slovenia*

⁸*Department of Physics, Faculty of Science, Istanbul University, Vezneciler/Faith, 34134 Istanbul, Turkey*

⁹*Dipartimento di Fisica e Astronomia “Ettore Majorana”, Università degli Studi di Catania, Catania 95123, Italy*

¹⁰*Centro Siciliano di Fisica Nucleare e Struttura della Materia, CSFNSM, Catania 95123, Italy*

¹¹*Dipartimento di Ingegneria e Architettura, Università degli Studi “Kore”, Enna 94100, Italy*

¹²*Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico*

¹³*Dipartimento di Fisica e Astronomia, Università degli Studi di Catania, Via S. Sofia 64, 95123 Catania, Italy*

¹⁴*Department of Physics, Indian Institute of Technology Ropar (IIT-RPR), Punjab, India*

¹⁵*Istituto Nazionale di Fisica Nucleare, Sezione di Perugia, I-06125 Perugia, Italy*

¹⁶*Ruder Boskovic Institute, 10000 Zagreb, Croatia*

¹⁷*Faculty of Science, University of Split, 21000 Split, Croatia*



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A direct measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction at astrophysical energies was performed at the Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) using a scaled-down version of the ELISSA detector array and the 3 MV Tandem accelerator. This reaction plays a crucial role in both primordial and stellar nucleosynthesis. In Big-Bang Nucleosynthesis (BBN), it is directly linked to the long-standing “Cosmological Lithium Problem,” the discrepancy between observed and predicted primordial ${}^7\text{Li}$ abundances. In stellar environments, it constitutes the final step in the hydrogen-to-helium burning chain. The experiment utilized a ${}^7\text{Li}$ beam incident on a CH_2 target at ten laboratory energies (E_{lab}) corresponding to center-of-mass energies ($E_{\text{c.m.}}$) ranging from 59.5 to 990 keV. The astrophysical S factors were extracted using both the Distorted Wave Born Approximation (DWBA) and polynomial fitting techniques. Updated reaction rates were calculated from the present DWBA results, supplemented by existing experimental data. The impact of the theoretical DWBA calculation on the reaction rate is investigated.

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I. INTRODUCTION

The ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction is of considerable astrophysical importance, playing a key role in both Big-Bang and stellar nucleosynthesis. In the context of the early universe,

this reaction is closely associated with the “Cosmological Lithium Problem,” the longstanding discrepancy between the observed ${}^7\text{Li}$ abundances in metal-poor halo stars and the predictions of standard Big-Bang Nucleosynthesis (BBN) models [1–5]. Indeed, the dominant channel for ${}^7\text{Li}$ destruction, the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction, significantly influences the primordial lithium abundance. Therefore, an accurate determination of its reaction rate at BBN energies is essential for resolving this discrepancy and improving our understanding of primordial nucleosynthesis. However, it is worth mentioning that the bulk of the difference between observed and BBN predicted values seems to be attributed to atomic diffusion [6].

*Contact author: haridas.pai@eli-np.ro; hari.vecc@gmail.com

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TABLE I. Energies used in the experiment (E_{lab}) with the corresponding values in the center-of-mass system ($E_{\text{c.m.}}$). The $E_{\text{c.m.}}$ energies are calculated considering the energy loss in the middle of the used target, whose thickness is also shown.

Beam energy E_{lab} (MeV)	Energy $E_{\text{c.m.}}$ (keV)	Target thickness ($\mu\text{g}/\text{cm}^2$)
0.6	59.5	70
0.75	77	70
0.9	95	70
2	233	70
3	359	70
4	485	71
5	611	70
6	738	70
7	863	70
8	990	71

In the context of stellar nucleosynthesis, the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction is the final step in the hydrogen-to-helium burning chain [7], accounting for $\approx 10\%$ of the energy budget provided by the whole PP chain [7,8]. Eventually, the reproduction of the observation of abundances needs improvement on astrophysical factors. The available astrophysical S -factor data [7,9–18] for the reaction ${}^7\text{Li}(p, \alpha){}^4\text{He}$ at $10 < E_{\text{c.m.}} < 1000$ keV exhibit an exponential increase at low energies due to the effects of electron screening. The $S(0)$ value from various direct and indirect measurements of ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction varies between 40 and 60 keV b (15–40% uncertainty in the direct measurements), while the electron screening potential estimate varies between 200 and 400 keV [8], larger if compared with the adiabatic limit.

The existing ${}^7\text{Li}(p, \alpha){}^4\text{He}$ direct measurement data suffer from large uncertainty, particularly at energies below 500 keV ($E_{\text{c.m.}}$). Thus, a new direct measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reactions at low energies, from 59.5 to 990 keV in the center-of-mass system (energies are calculated considering the energy loss in the middle of the used target) has been carried out using the scaled-down version of the ELISSA array [19–24] to reduce the uncertainty in the $S(E)$ factor.

II. EXPERIMENTAL DETAILS

The experiment was performed using a ${}^7\text{Li}$ beam with an average beam intensity $\approx 2\text{--}4$ pA from the 3 MV Tandem Accelerator [25] at the Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH) in Bucharest-Magurele, Romania. The angular distributions and total cross-section measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction were carried out using the ${}^7\text{Li}$ beam with energies $E_{\text{lab}} = 8, 7, 6, 5, 4, 3, 2, 0.9, 0.75$, and 0.6 MeV (corresponding to center-of-mass energies $E_{\text{c.m.}} = 990, 863, 738, 611, 485, 359, 233, 95, 77$, and 59.5 keV, respectively) and a CH_2 target.

Table I is a detailed list of the beam energies and target (CH_2) thickness used during the experiment. Self-supported, thin polyethylene targets (CH_2) were placed at a 90° angle relative to the beam direction. The spot size of the ${}^7\text{Li}$ beam on

the target was ≈ 1 mm. The experimental setup consisted of a scaled-down version of the ELISSA array [19–24], having 12 X3 position-sensitive strip detectors arranged in a barrel-like configuration.

The X3 detectors were placed at a distance of ≈ 6 cm from the target center. The diameter of the barrel is ≈ 19.54 cm. This configuration resulted in an angular coverage ranging from $\approx 36^\circ\text{--}58^\circ$ in the laboratory system. The absolute differential cross-section of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction has been determined by normalising to the ${}^7\text{Li}(p, p){}^7\text{Li}$ Rutherford scattering cross-section measured in the monitor detector [26]. A Si detector with a 25 mm^2 active area was used as a monitor detector. The monitor detector was placed at a 27.6° angle and located 150 mm away from the target.

The detection system was inserted in the mini-ELISSA reaction chamber, which was operated under high vacuum conditions (better than 10^{-5} mbar). The energy calibration of X3 detectors was carried out with a standard three line α -source (${}^{239}\text{Pu}$, ${}^{241}\text{Am}$, and ${}^{244}\text{Cm}$) having decay energies 5155-keV, 5486-keV and 5805-keV. ${}^7\text{Li}$ elastic scattering at $E_{\text{lab}} = 8, 7, 6, 5, 4, 3, 2, 0.9, 0.75$, and 0.6 MeV was also performed for energy calibration purposes of the detectors through interaction with a gold target. The X3 detectors are position-sensitive resistive detectors. To calibrate the position [19–21,23,24], the detectors were mounted with masks having slit widths of 1 mm in front of the detectors, and three-line α -sources were used. Ballistic deficit correction has also been carried out for the X3 detectors. The angular resolution (FWHM) for the present X3 detectors is found to be $\approx 0.3^\circ - 0.5^\circ$. A standard mvme data acquisition system and electronics modules by mesytec GmbH [27] were used to acquire the data. The acquisition trigger was the OR of all the strips of the experimental setup. For the offline data analysis, the data were converted into the ROOT format using the mvme root client.

In the present experiment, we could clearly identify transfer alpha particles from the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction from the kinematics due to the higher Q value (17.35 MeV) compared to the other possible reaction channels from the CH_2 target. Within the CH_2 target, ${}^{12}\text{C}$ and ${}^1\text{H}$ have higher natural abundance than the other isotopes (e.g., ${}^{13}\text{C}$, ${}^2\text{H}$, and ${}^{16}\text{O}$). Above 4 MeV (E_{lab}), various discrete α -particle bands corresponding to the excited state in ${}^{15}\text{N}$ were identified. These alpha-particle bands are well separated from the alpha band of interest in the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction. During this experiment, data using ${}^{12}\text{C}$ targets were also taken with the ${}^7\text{Li}$ beam for each beam energy to identify the reaction channels between ${}^{12}\text{C}$ and ${}^7\text{Li}$. NPTOOL [28] simulations were used to cross-check the calibration and the proper identification of the emerging alpha particles from the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction. The other reaction channels involving ${}^{13}\text{C}$, ${}^2\text{H}$, and ${}^{16}\text{O}$, which are well separated from the present alpha band of interest, were also cross-checked through NPTOOL simulations. The experimental E vs θ spectrum of one of the X3 detectors with a 3 MeV beam energy (in E_{lab}) is shown in Fig. 1 with blue data points. The red line corresponds to the simulated [28] α transfer. Solid angles of the X3 detectors were determined from the NPTOOL [28] simulation. In the simulation, an isotropic source was used.

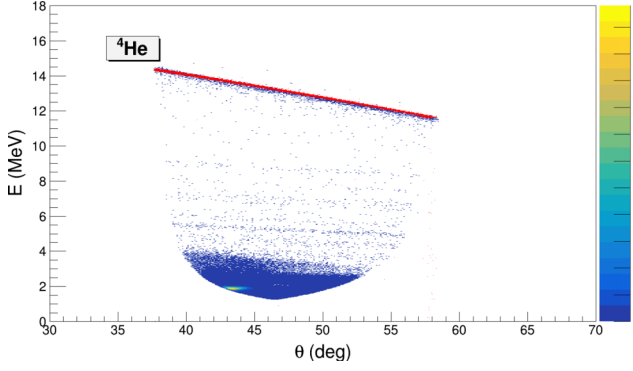


FIG. 1. Comparison of the E vs θ plot (kinematic plot) of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction from the Monte Carlo simulation code NPTOOL [28] (red) with experimental data (blue) for 3 MeV beam energy (in E_{lab}).

III. RESULTS AND DISCUSSION

The direct reaction proceeds via the excitation of only a few degrees of freedom on a much shorter timescale, reflecting the time taken by the projectile to traverse the target. This process has been traditionally associated with energies that are high enough for the mean-free path of the incident particle to be comparable with the size of the nucleus. In these conditions, the particle ejection occurs preferentially at forward angles. It has become clear that the direct reaction process is important, and often dominant, in charged-particle induced reactions at the very low energies of astrophysical interest [29], e.g., ${}^7\text{Li}(p, \alpha){}^4\text{He}$ at $E_{\text{c.m.}} < 1$ MeV [12,18,30]. Given the difficulty of penetrating the Coulomb barrier, the reaction may occur before the projectile can tunnel deep inside the target nucleus.

There are a few different approaches for describing the nuclear reactions of astrophysical interest at sub-Coulomb barrier energies, including phenomenological reaction models involving nuclear potential and microscopic many-body approaches. Obviously, all these models have advantages and disadvantages. In the present work, the Distorted-Wave Born Approximation (DWBA) is adopted to describe the experimental data, and it is expected that the nonresonant contributions to ${}^7\text{Li}(p, \alpha){}^4\text{He}$ cross sections at very low energies could be effectively described by such a direct reaction model. In this work, the pickup process ($p + {}^3\text{H} = \alpha$, ${}^7\text{Li} = {}^4\text{He} + {}^3\text{H}$) is considered for the transfer reaction ${}^7\text{Li}(p, \alpha){}^4\text{He}$, and the zero-range approximation as described in Ref. [18] is adopted.

The potential depth, the radius, and the diffuseness are determined so as to reproduce our experimental cross sections of ${}^7\text{Li}(p, \alpha){}^4\text{He}$ with the DWBA calculation, and this procedure is carried out in the framework of the FRESKO code [31]. It has to be noted that we also treat $S_F D_0^2$ [18] as an adjustable parameter, rather than relying separately on the estimates of spectroscopic factors and of the zero-range interaction strengths found in the literature. In the present calculation, we have adopted $S_F D_0^2$ as $1.98 \times 10^4 \text{ MeV}^2 \text{ fm}^3$, whereas $S_F D_0^2 = 2.32 \times 10^4 \text{ MeV}^2 \text{ fm}^3$ was used in NACRE-II [18].

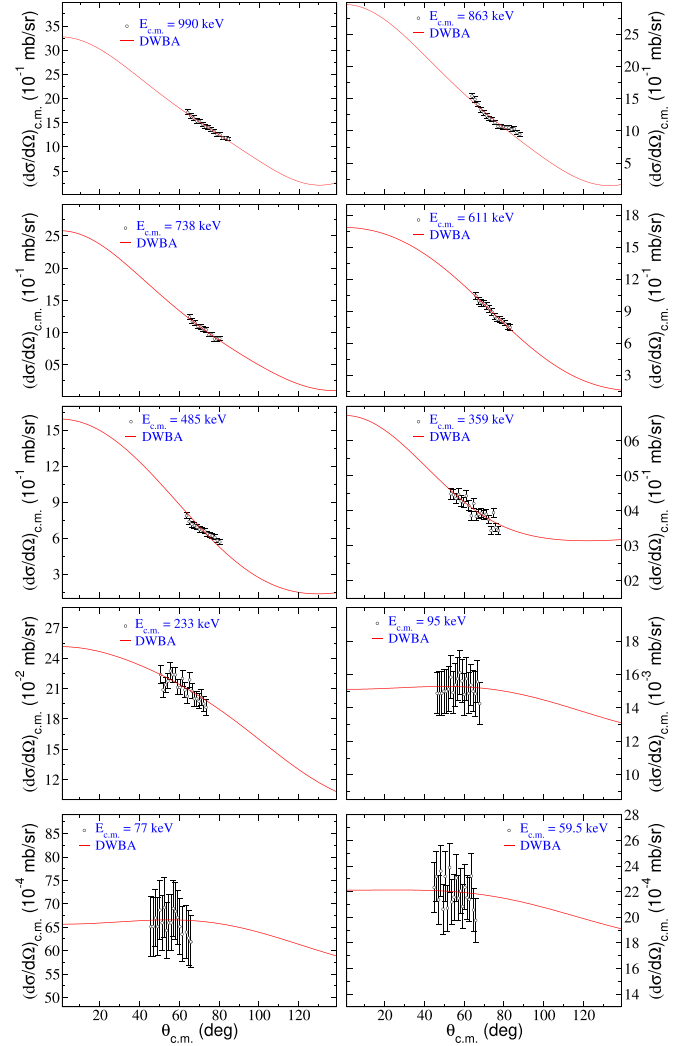


FIG. 2. Angular distributions for ${}^7\text{Li}(p, \alpha){}^4\text{He}$ at 990, 863, 738, 611, 485, 359, 233, 95, 77, and 59.5 keV energies ($E_{\text{c.m.}}$). The solid curves are the DWBA results, and black circles are the experimental data points from the present work.

The present experimental angular distributions for ${}^7\text{Li}(p, \alpha){}^4\text{He}$ at 990, 863, 738, 611, 485, 359, 233, 95, 77, and 59.5 keV energies ($E_{\text{c.m.}}$) are shown by the black circles in Fig. 2. The DWBA fit to the experimental angular distributions is performed using the code FRESKO [31], and the results are shown by the solid curves in Fig. 2. In such DWBA fit, the seed potential parameters are taken from [30]. It can be seen that the experimental angular distributions are well reproduced by the DWBA calculations.

The total cross sections (σ_{total}) at the ten energy points are obtained from the integral of the DWBA angular distributions, and the results are presented in Table II. Note that σ_{total} was divided by 2 to obtain the S factor, so it refers to disintegrations per proton rather than α particles per proton [7,12]. From FRESKO [31] elastic calculations and the literature [32], it is found that between 59.5 and 738 keV beam energy ($E_{\text{c.m.}}$) the proton contributions in the monitor detector are purely Rutherford. However, at 863 and 990 keV beam energy ($E_{\text{c.m.}}$),

TABLE II. Total cross-sections (σ_{total}) results.

Center-of-mass beam energy $E_{\text{c.m.}}$ (keV)	σ_{total}^a (mb)	$\sigma_{\text{total}}^{\text{error}}$ %
59.5	2.6×10^{-2}	9
77	0.08	9.8
95	0.18	9
233	2.3	4
359	4.85	3.5
485	7.0	3.7
611	9.03	3.4
738	10.83	3.7
863	12.88	7.7
990	15.11	19.3

^a σ_{total} is α particles per proton.

they deviate from Rutherford scattering cross section, and the deviation is considered as a systematic uncertainty. These uncertainties are 7% and 19% for $E_{\text{lab}} = 7$ and 8 MeV beam energies (or $E_{\text{c.m.}} = 863$ and 990 keV), respectively. Standard uncertainties associated with the determination of the cross section are statistical uncertainty and uncertainty in the solid angle of the monitor and X3 detectors. In this measurement, statistical uncertainty has a major contribution between 59.5 and 738 keV beam energy ($E_{\text{c.m.}}$), whereas major uncertainty at 863 and 990 keV is due to ${}^7\text{Li}(p, p){}^7\text{Li}$ deviation from the Rutherford scattering cross section at the monitor detector.

A further DWBA fit on the total crosssections (σ_{total}) at nine energy points [59.5 to 863 keV ($E_{\text{c.m.}}$)] is performed. This choice of DWBA fit is justified if the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ transfer reaction is considered, because its total cross sections are experimentally determined at low energies, being dominated by the nonresonant contribution [12]. In practice, the optimal values of the adjustable potential parameters are derived by applying the standard χ^2 fit technique to the total cross sections. The DWBA cross sections calculated by the optimal potential parameters are compared with the present experimental data in Fig. 3, in which the total cross section is represented by the astrophysical S factors. Meanwhile, a polynomial fit of the present experimental total cross sections is also performed. It is found that both the DWBA and polynomial fits reproduce the experimental data well. Furthermore, in Fig. 3 various experimental data sets (CA62 [9], MA64 [10], FI67 [11], SP71 [7], RO86 [12], HA89 [13], EN92 [14], LA01 [15], CR05 [16], and CR09 [17]), as well as the NACRE-II predictions [18], are shown for comparison. Note that some measurements below $E_{\text{c.m.}} \cong 0.05$ MeV look contaminated by electron screening (see [16] for details). From the present DWBA and polynomial fits, $S(0) = 59.8$ and 68.4 ± 4.9 keV b are obtained, respectively. In comparison, the recommended, low, and upper limits of $S(0)$ given by NACRE-II are 52, 44, and 63 keV b, respectively.

The ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction rates at $0.001 \leq T_9 \leq 10$ are calculated using the present DWBA-predicted cross sections and available experimental data [9,10,17] below and above $E_{\text{c.m.}} \cong 0.9$ MeV, respectively. Note that the upper and lower limits of the reaction rates are derived from the uncertainties of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ cross sections. Below

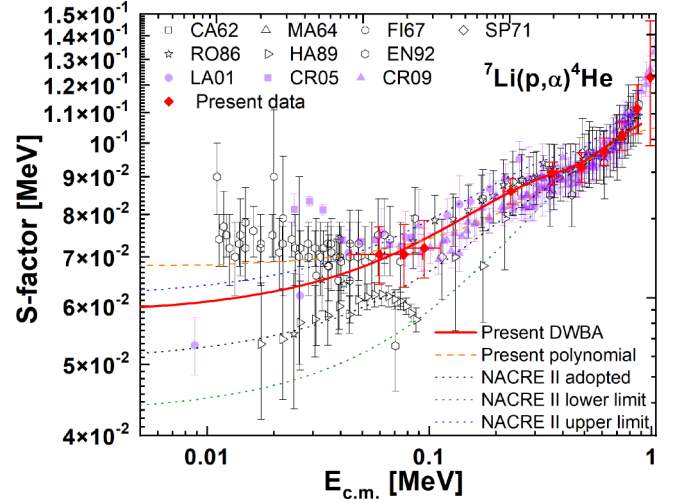


FIG. 3. DWBA fitting of the present experimental data (astrophysical S factor) of ${}^7\text{Li}(p, \alpha){}^4\text{He}$. A polynomial fitting of the present data is presented as well. Available experimental data and NACRE-II results are shown for comparison. Horizontal errors originate from the uncertainty in energy loss at the target.

$E_{\text{c.m.}} \cong 0.9$ MeV, the uncertainty of the lowest point of the present measurement, namely 9%, is considered for the DWBA predicted cross sections, while above $E_{\text{c.m.}} \cong 0.9$ MeV the experimental errors of the data [9,10,17] are taken into account as the cross section uncertainties. The obtained reaction rates are given in Table III. In addition, to demonstrate the impact of the present measurement on the reaction rate, the reaction rate calculated using only the data from Refs. [9,10,17] is presented in Table III as well for comparison. Note that in this calculation, for the low energy side where experimental data are not available, a constant cross section identical to the lowest measured data is assumed. Figure 4 shows that, below $T_9 = 0.2$, the difference between the reaction rates calculated with and without the present DWBA prediction is larger than 5%, and, particularly down to $T_9 = 0.05$, such a difference can reach up to 20%. Above $T_9 = 0.5$, both reaction rates are identical. Further Big Bang

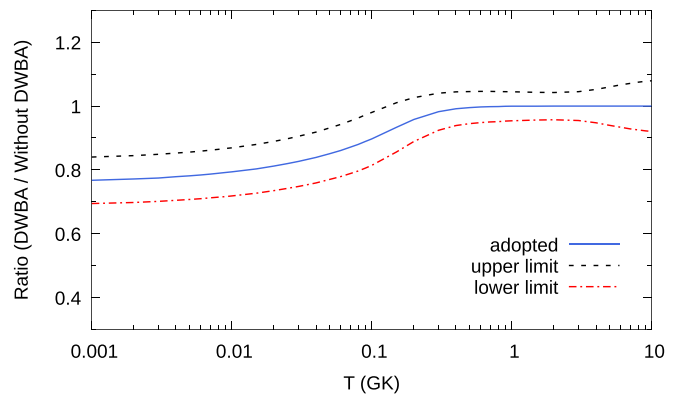


FIG. 4. The ratio of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction rates calculated from DWBA fitting plus experimental data [9,10,17] to those calculated without DWBA result.

TABLE III. The present adopted ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction rates and their uncertainties (in units of $\text{cm}^3 \text{mol}^{-1} \text{s}^{-1}$). The results calculated without the DWBA prediction are also presented for comparison.

T_9	Adopted	Upper limit	Lower limit	Without DWBA
0.001	9.900×10^{-27}	1.084×10^{-26}	8.960×10^{-27}	1.290×10^{-26}
0.002	2.749×10^{-19}	3.010×10^{-19}	2.487×10^{-19}	3.563×10^{-19}
0.003	1.041×10^{-15}	1.141×10^{-15}	9.426×10^{-16}	1.344×10^{-15}
0.004	1.861×10^{-13}	2.038×10^{-13}	1.684×10^{-13}	2.390×10^{-13}
0.005	7.393×10^{-12}	8.096×10^{-12}	6.691×10^{-12}	9.460×10^{-12}
0.006	1.221×10^{-10}	1.337×10^{-10}	1.105×10^{-10}	1.557×10^{-10}
0.007	1.143×10^{-9}	1.252×10^{-9}	1.035×10^{-9}	1.453×10^{-9}
0.008	7.219×10^{-9}	7.905×10^{-9}	6.533×10^{-9}	9.145×10^{-9}
0.009	3.422×10^{-8}	3.747×10^{-8}	3.096×10^{-8}	4.322×10^{-8}
0.01	1.305×10^{-7}	1.429×10^{-7}	1.181×10^{-7}	1.644×10^{-7}
0.015	1.457×10^{-5}	1.596×10^{-5}	1.319×10^{-5}	1.814×10^{-5}
0.02	2.817×10^{-4}	3.085×10^{-4}	2.550×10^{-4}	3.469×10^{-4}
0.025	2.299×10^{-3}	2.517×10^{-3}	2.081×10^{-3}	2.804×10^{-3}
0.03	1.135×10^{-2}	1.243×10^{-2}	1.027×10^{-2}	1.373×10^{-2}
0.04	1.153×10^{-1}	1.262×10^{-1}	1.043×10^{-1}	1.374×10^{-1}
0.05	5.955×10^{-1}	6.521×10^{-1}	5.390×10^{-1}	7.000×10^{-1}
0.06	2.074×10^0	2.271×10^0	1.877×10^0	2.409×10^0
0.07	5.601×10^0	6.132×10^0	5.070×10^0	6.432×10^0
0.08	1.268×10^1	1.387×10^1	1.148×10^1	1.441×10^1
0.09	2.524×10^1	2.760×10^1	2.287×10^1	2.839×10^1
0.1	4.557×10^1	4.978×10^1	4.135×10^1	5.079×10^1
0.15	3.601×10^2	3.898×10^2	3.303×10^2	3.858×10^2
0.2	1.305×10^3	1.398×10^3	1.211×10^3	1.362×10^3
0.3	6.462×10^3	6.843×10^3	6.080×10^3	6.578×10^3
0.4	1.754×10^4	1.848×10^4	1.661×10^4	1.769×10^4
0.5	3.542×10^4	3.721×10^4	3.363×10^4	3.559×10^4
0.6	6.021×10^4	6.316×10^4	5.726×10^4	6.038×10^4
0.7	9.163×10^4	9.601×10^4	8.724×10^4	9.179×10^4
0.8	1.292×10^5	1.353×10^5	1.231×10^5	1.294×10^5
0.9	1.725×10^5	1.804×10^5	1.645×10^5	1.726×10^5
1.0	2.209×10^5	2.309×10^5	2.108×10^5	2.210×10^5
1.5	5.273×10^5	5.502×10^5	5.044×10^5	5.274×10^5
2.0	9.242×10^5	9.636×10^5	8.848×10^5	9.243×10^5
3.0	2.014×10^6	2.105×10^6	1.923×10^6	2.014×10^6
4.0	3.606×10^6	3.795×10^6	3.417×10^6	3.606×10^6
5.0	5.688×10^6	6.030×10^6	5.345×10^6	5.688×10^6
6.0	8.077×10^6	8.615×10^6	7.540×10^6	8.077×10^6
7.0	1.056×10^7	1.131×10^7	9.806×10^6	1.056×10^7
8.0	1.297×10^7	1.394×10^7	1.200×10^7	1.297×10^7
9.0	1.522×10^7	1.640×10^7	1.404×10^7	1.522×10^7
10.0	1.726×10^7	1.863×10^7	1.589×10^7	1.726×10^7

nucleosynthesis calculations are expected by considering the present ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction rates.

IV. CONCLUSION

In summary, a direct measurement of the ${}^7\text{Li}(p, \alpha){}^4\text{He}$ reaction at astrophysical energies was successfully carried out at IFIN-HH using a scaled-down version of the ELISSA detector array. The experiment covered ten beam energies ranging from 0.6 to 8 MeV in the laboratory frame, corresponding to center-of-mass energies between 59.5 and 990 keV. Angular distributions and total cross sections were measured at energies relevant to Big-Bang nucleosynthesis ($0.01 < T_9 < 10$ [33]).

The angular distributions obtained at each energy were analyzed using DWBA calculations with the code FRESKO. From the DWBA calculations, total cross sections and the resultant astrophysical S factors were determined. A polynomial fit to the measured cross sections was also performed for comparison with the DWBA approach. The present analysis provides $S(0)$ values of 59.8 and 68.4 ± 4.9 keV b from the DWBA and polynomial fits, respectively. The present DWBA value lies within the uncertainty bounds of the NACRE-II compilation.

The thermonuclear reaction rates of ${}^7\text{Li}(p, \alpha){}^4\text{He}$ and their uncertainties were computed in the temperature range $0.001 \leq T_9 \leq 10$. It was shown that the present DWBA prediction results in 5%–25% difference in reaction rate below

$T_9 = 0.2$. The calculated reaction rates are expected to be further used in the calculations of Big-Bang nucleosynthesis.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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