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The ^{7}Be$(n,\alpha)^4$He Reaction Studied via THM for the Cosmological Li-Problem

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^{7}Be destruction channels during the Big Bang nucleosynthesis are currently a matter of study because of their influence on the primordial ^{7}Li abundance. We have taken several approaches by means of the Trojan Horse method (THM) to investigate the most important reaction channels ^{7}Be$(n,p)^7$Li and ^{7}Be$(n,\alpha)^4$He. The ^{7}Be$(n,\alpha)^4$He reaction cross sections were firstly determined from the available THM data of the ^{7}Li$(p,\alpha)^4$He reaction with charge-symmetry hypothesis (CSH). We performed another THM experiment using a ^{7}Be RI beam which did not require CSH. We also present the preliminary result of another experiment with an upgraded setup successfully observing both the ^{7}Be$(n,p)^7$Li and the ^{7}Be$(n,\alpha)^4$He reactions. The deduced reaction rates from those studies allows us to evaluate the impact on big bang nucleosynthesis and on the lithium problem.

KEYWORDS: Trojan Horse method, Radioactive isotope beam, Cosmological Li problem, Big Bang Nucleosynthesis

1. Introduction

It has been known that the prediction of the primordial ^{7}Li abundance by the standard Big-Bang Nucleosynthesis (BBN) model [1] is about 3 times larger than the observation [2], the so-called cosmological ^{7}Li problem. As the basis for the solution, nuclear reaction rates involved in the BBN should be accurately reevaluated, as there are still lack or incompletion of data near the BBN energies. Especially, neutron-induced reactions on ^{7}Be are important because the radiogenic ^{7}Li abundance by the BBN strongly depends on the ^{7}Be production and destruction rates. Studying those reactions is experimentally difficult owing to the fact that both species n and ^{7}Be are radioactive. The ^{7}Be$(n,p)^7$Li reaction is considered as the main process to destroy ^{7}Be. Recently, a direct measurement has been performed [3], revising the cross sections upward from the precious direct data [4], yet appearing only below the BBN energies. The derived reaction rate in the BBN temperature region thus has a limited enhancement from the widely-adopted reaction rate [5]. In spite of such a new knowledge about the ^{7}Be$(n,p)^7$Li reaction, the contribution of the transition to the first excited state of ^{7}Li, ^{7}Be$(n,p_1)^7$Li*, at the BBN energies has never been discussed sufficiently, which motivated us to perform a further experiment. Another important neutron-induced reaction channel ^{7}Be$(n,\alpha)^4$He has not been investigated either until recently [6–9], still lacking in direct data at the BBN energies. Thus studies of the both reactions are still needed to determine the total ^{7}Be+n cross section contributing in the BBN energy region. In this article, we report three different Trojan Horse Method (THM) approaches to investigate the neutron-induced reaction on ^{7}Be.

The THM is an indirect technique which allows measurement of the cross section of a two-body reaction A(x,c)C by properly selecting the quasi-free (QF) component of a suitable two-to-three-body reaction a(A, cC)s (see the details in Ref. [10–12]). This picture can be enabled by choosing nucleus a to have a $a = x \oplus s$ configuration with a relatively low x-s binding energy, whose radial wave function of the x-s configuration is well known. The nucleus a represents so-called Trojan-horse nucleus, x takes part in the binary process with A in the pure nuclear field without feeling the Coulomb barrier or screening effects, and the counterpart s acts as the "spectator" which maintains the same momentum distribution as inside a before and after the breakup. Although such a two-to-three-body reaction can be induced at energies well above the Coulomb barrier of the A+a interacting channel, the sub-process A-x can approach astrophysically-relevant low energies thanks to release of the x-s binding energy. In the most simple theoretical description of THM by means of the plane wave impulse approximation, the cross section of the QF a(A, cC)s reaction can be proportional to the one of the binary A(x,c)C processes via the formula [11, 12]

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_C} \propto \mathrm{KF} \cdot |\Phi(p_{\mathrm{xs}})|^2 \cdot \frac{d\sigma}{d\Omega}^{\mathrm{HOES}}_{\mathrm{c.m.}}, \tag{1}$$

where KF represents the kinematical factor, $|\Phi(p_{\mathrm{xs}})|^2$ is the square of the Fourier transform of the radial wave function describing the x–s intercluster motion, and $\frac{d\sigma}{d\Omega}^{\mathrm{HOES}}_{\mathrm{c.m.}}$ is the half-off-energy-shell (HOES) differential cross section for the two-body reaction. Since, ideally, the A+x binary reaction proceeds directly in the pure nuclear field, the THM is free of the Coulomb barrier or screening effects, and has been mainly applied for charged-particle-induced reactions of astrophysical interest. At the same time, in the case of deuteron as the Trojan-horse nucleus a, one can immediately realize that the THM may work for neutron-induced reactions due to its p-n configuration [13, 14]. Here we report our recent application of THM to the neutron-induced reactions ^{7}Be$(n,p)^7$Li and ^{7}Be$(n,\alpha)^4$He via the ^{2}H(^{7}Be,^{7}Lip)^{1}H and the ^{2}H(^{7}Be, $\alpha\alpha$)^{1}H reaction measurements, respectively.

2. ^{7}Be$(n,\alpha)^4$He measurement via ^{7}Li$(p,\alpha)^4$He with charge-symmetry hypothesis

Our first approach before performing THM experiments for neutron induced ^{7}Be+n reactions was derivation of the ^{7}Be$(n,\alpha)^4$He reaction cross section from early available data of the charged-particle-induced reaction ^{7}Li$(p,\alpha)^4$He measured by the THM via the ^{3}He(^{7}Li, 2α)^{2}H and the ^{2}H(^{7}Li, 2α)n reactions [9]. Those data were converted to the ^{7}Be$(n,\alpha)^4$He reaction cross sections with charge-symmetry hypothesis by considering the Coulomb penetrability. The result agrees well with the direct data of the time-reversal reactions ^{7}Li$(p,\alpha)^4$He and ^{4}He$(\alpha,n)^7$Be [6, 8] within the uncertainties.

3. ^{7}Be$(n,\alpha)^4$He reaction measurement at EXOTIC

We also investigated the ^{7}Be$(n,\alpha)^4$He reaction by a more straightforward way without the influence of the CSH. The THM was again applied, but the reaction was studied via the ^{2}H(^{7}Be, $\alpha\alpha$)^{1}H reaction using the ^{7}Be radioactive isotope (RI) beam. One can refer our recently published article [15] for the details. The ^{7}Be beam was produced at the RI beam separator EXOTIC [16] of Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare at the energy of 20.4±1 MeV and the intensity of 5–8×10^5 pps with a purity of about 99%. The beam was bombarded the CD_2 film as the deuteron "Trojan-horse" target with a thickness of 400 μg/cm^2. The schematic view of the

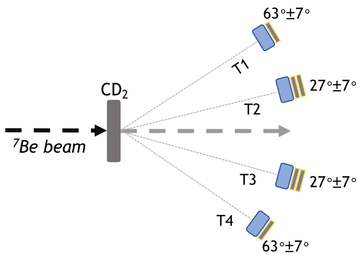

Fig. 1. Setup for the EXOTIC experiment (Section 3).

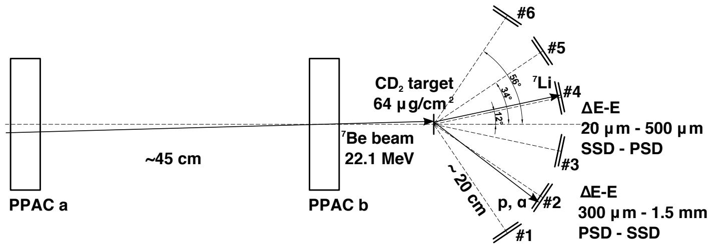

Fig. 2. Setup for the CRIB experiment (Section 4).

experimental setup is shown in Fig. 1. The four ΔE-E telescopes, with ionization chambers for the ΔE stage and position-sensitive silicon detector for the E stage, observed α-α coincidences in T1–T3 and T2–T4 telescope pairs covering the QF angular region. The reconstructed momentum distribution of the "spectator" proton in the exit channel of the ^{2}H(^{7}Be, $\alpha\alpha$)^{1}H reaction well matches that of the squared Hulthén wave function in momentum space representing the s-wave component of the p–n relative motion inside deuteron nucleus, which is the strong evidence of the presence of the QF mechanism. The HOES differential cross section expressed in Eq. 1 was then extracted and converted to the on-energy-shell (OES) cross section by correcting the angular distribution and the centrifugal-barrier penetrability based on the orbital angular momentum of $l = 1$ which arises from the broad p-wave ^{7}Be+n resonances at ^{8}Be excitation energies around 20 MeV [17]. Then the OES cross section was normalized to the data of Ref. [6]. The present data nicely overlap with those of the previous experiments [6, 8] and the one from Section 2 [9], with the uncertainty improved from the [9] work. The derived reaction rate shows a fair agreement with that of Ref. [6]. and significantly improved uncertainty of the present data from those of Ref. [6]. Although the expected ^{7}Li abundance in the BBN network calculation with the present reaction rate using the revised BBN code [18, 19] thus will not vary significantly, the present work may help with a better aspect of its uncertainty.

4. ^{7}Be(n, α)^{4}He and ^{7}Be(n, p)^{7}Li reaction measurement at CRIB

We expanded the idea of the EXOTIC experiment aiming at measurement of another important ^{7}Be+n reaction channel ^{7}Be(n, p)^{7}Li at the CRIB (Center-for-Nuclear-Study RI beam separator [20]) facility. We installed two more ΔE-E telescopes bilaterally symmetrically at the most forward angles with 20-μm-thick silicon detectors at the ΔE stages for heavy-ion detection as shown in Fig. 2. These additional telescopes enabled to detect ^{7}Li-p coincidence in telescope pairs of #3-#5, #3-#6, #4-#2 or #4-#1 in order to observe the ^{2}H(^{7}Be,^{7}Lip)^{1}H reaction for the ^{7}Be(n, p)^{7}Li reaction measurement by the THM. The α-α coincidence measurement were simultaneously available as well with the same setup in telescope pairs of #1-#5 or #2-#6. The present setup allows better angular and energy resolutions by installing Parallel Plate Avalanche Counters (PPACs [21]) enabling event-by-event beam tracking, and a thinner CD$_2$ target of 64 μg/cm^2, and silicon detectors with a better position resolution, and with a higher incident beam energy with smaller energy spread of 22.1±0.1 MeV. The existence of the QF mechanism was confirmed by the momentum distribution of the spectator proton for each coincidence channel by the same manner as the EXOTIC experiment. The preliminary normalized excitation functions for the ^{7}Be(n, p_0)^{7}Li and the ^{7}Be(n, α)^{4}He channels are roughly consistent with the previous studies [3, 4, 6–9, 15, 22–25]. Thanks to the improvement in resolution, we could also extract a possible contribution of the transition to the first excited state of ^{7}Li in the Q-value spectrum of the ^{2}H(^{7}Be,^{7}Lip)^{1}H reaction channel. The present normalized (n, p_1) cross section covering the BBN energy region may smoothly connect to those expected from the results of Ref. [3] and [4] down to the thermal neutron energies, appearing to be one order of magnitude smaller than that of the (n, p_0) channel, but one order of magnitude larger than that of the (n, α) channel. This enhancement

Table I. Summary of the three THM approaches to the ^{7}Be+n reaction cross sections.

Experiment	Performed QF reaction(s)	Aimed two-body reaction(s)	Achievements
CSH	^{3}He(^{7}Li, 2α)^{2}H, ^{2}H(^{7}Li, 2α)n	^{7}Be(n,α)^{4}He	Reduced uncertainty
EXOTIC	^{2}H(^{7}Be, $\alpha\alpha$)^{1}H	^{7}Be(n,α)^{4}He	Reduced uncertainty
CRIB	^{2}H(^{7}Be,^{7}Lip)^{1}H, ^{2}H(^{7}Be, $\alpha\alpha$)^{1}H	^{7}Be(n,p)^{7}Li, ^{7}Be(n,α)^{4}He	First measurement of the ^{7}Be(n,p_1)^{7}Li* channel at BBN energies.

may give a non-negligible extra contribution to the total (n,p) cross section, which may result in a significant reduction of the primordial ^{7}Li abundance. A further data analysis is ongoing.

5. Summary

We presented three different THM approaches to investigated the ^{7}Be+n reactions relevant to the cosmological lithium problem. The present ^{7}Be(n,α)^{4}He reaction cross sections both of the CSH work and the EXOTIC experiment are basically consistent with the previous ones, providing smaller uncertainties. The experiment at CRIB may reveal a possible enhancement of the ^{7}Be(n,p)^{7}Li channel by the (n,p_1) contribution, which might lead a non-negligible reduction of the primordial ^{7}Li abundance in the BBN calculation. The definitive result requires a further data analysis. Table I summarizes the comparison of the three experiments.

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