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Trials for the cosmological ^{7}Li problem with ^{7}Be beams at CRIB and collaborating studies

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Summary. — For many years, the cosmological ^{7}Li problem has been tackled from various aspects. The nuclear reaction data have also been improved, but still there remains some ambiguities. We review our experimental plans to measure the cross sections of three key reactions which act to destroy ^{7}Be during the Big-Bang Nucleosynthesis (BBN). These experiments are all based on ^{7}Be beams produced at Center-for-Nuclear-Study Radioactive Ion Beam separator (CRIB) in collaborations mainly with research groups from INFN-LNS and RCNP. The preliminary result of the previous experiment and the future plan are discussed.

1. – Introduction

The Big Bang theory is one of the most successful achievements of the modern science. There are several evidences such as the cosmic microwave background, Hubble's law of galaxies, and the abundance ratios of the primordial light elements. The respective observation and the theoretical prediction are consistent with high accuracies. With the exception that it has been known that the observed ^{7}Li abundance is about 3 times smaller than that of the theoretical prediction [1], referred to as the cosmological ^{7}Li problem. Although this problem has been examined from various approaches, the main cause is not identified yet.

The ^{7}Li abundance depends on ^{7}Be production rather than that of ^{7}Li itself. This is because ^{7}Be is produced more than ^{7}Li, which eventually decays into ^{7}Li by electron capture after BBN, while ^{7}Li can easily be destroyed by the (p,α) reaction during BBN. We have a couple of experimental projects for three key reactions, ^{7}Be$(n,p)^{7}$Li, ^{7}Be$(n,\alpha)^{4}$He and ^{7}Be$(d,p)^{8}$Be which all act as ^{7}Be destroyer, aiming at a better understanding of their contributions in BBN from the nuclear physics aspect. For these measurements, we use ^{7}Be radioactive (RI) beams produced at CRIB (Center-for-Nuclear-Study RI Beam separator) [2]. Here we report the currently ongoing and the upcoming projects which are carried out in collaboration.

2. – ^{7}Be$(n,p)^7$Li and ^{7}Be$(n,\alpha)^4$He reaction measurements by the Trojan horse method

This project is mainly in collaboration with the nuclear physics group of Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud (INFN-LNS) who have been developing the Trojan horse method (THM) for years. They have promptly performed a THM measurement for the ^{7}Be$(n,\alpha)^4$He reaction at INFN - Laboratori Nazionali di Legnaro, while we plan another THM measurement with some improvements in resolution, and with feasibility of the ^{7}Be$(n,p)^7$Li reaction measurement.

2·1. *Overview.* – The ^{7}Be$(n,p)^7$Li reaction has been considered as the main process to destroy ^{7}Be during the BBN. A recent sensitivity test of the BBN abundance to nuclear reaction rate suggests that the ^{7}Li abundance could be even half if the reaction rate is doubled by p_1 contribution [3]. There is a study by direct measurement using a ^{7}Be target and a neutron beam [4], but it is only done below 13.5 keV. Above this energy up to the initial BBN energy, one has to rely on time-reversal reaction measurements [5-8]. The data basically follows the 1/velocity law of neutron-induced reaction cross section at lower energies, and resonances becomes more significant at BBN energies. On these data, a detailed R-matrix analysis was done [9], which basically reproduced the data well introducing four resonant states. The cross section near the neutron threshold is strongly enhanced by a 2^- state at 27 keV, apart from a small inconsistency between the direct measurement data [4] and the time-reversal reaction data [8]. In addition, there are 2 prominent non-interfering 3^+ states at 0.33 MeV and 2.66 MeV. To fit these higher-energy data, a non-resonant 2^+ state was introduced.

The branching ratio of contribution to the first excited state of ^{7}Li ($1/2^-$, 0.478 MeV), p_1, to that to the ground state ($3/2^-$), p_0, was estimated about 1% in ref. [4], but only up to 100 eV. Such a small contribution in this low-energy region might be because it is close to the Coulomb barrier ($\sim$ 1.1 MeV) from the first excited state, and the p_1 transition can proceed only with d-wave through the 2^- state at 27 keV. At higher energies far from the Coulomb barrier, the p_1 transition could have larger contributions through the 1^-, 0^+ or 2^+ states with s- or p-waves. This possibility has never been discussed in previous works [9, 10] at all. Therefore, the main motivation to measure the ^{7}Be$(n,p)^7$Li reaction is to determine the p_1 contribution at the BBN energies ($\sim$ 25 keV–1 MeV) which was not possible by the time-reversal reaction measurements, as well as to confirm the p_0 excitation function over the different data sets of the previous measurements.

The ^{7}Be$(n,\alpha)^4$He reaction has not been considered in the BBN reaction network until recently, and there are much less studies discussing the contribution of this reaction. In the BBN network calculation [10], the uncertainty of this reaction rate is as much as 1 digit based on the only published rates [11-13], which results in the uncertainty of ^{7}Li abundance about 40%. There is a direct measurement only at the thermal neutron energy [14]. In addition, two data sets of the time-reversal reaction [15, 16] represents the ^{7}Be$(n,\alpha)^4$He reaction cross section only in 0.6–100 MeV, thus leaving a great uncertainty in the BBN window down to 25 keV. There are some improvements by recent studies [17, 18], but it reveals that there is still no consistent explanation for this reaction cross section especially around BBN energies. Due to the spin-parity conservation law, this reaction cannot proceed through s-wave but mainly through p-wave, thus the reaction cross section could be underestimated by extrapolation. Therefore, any new measurement of this reaction in the BBN energy region could drastically reduce the uncertainty of the reaction rate, and thus that of the ^{7}Li abundance.

2˙2. *Method.* – Since both ^{7}Be and neutron are RI, generally it is difficult to measure these reactions directly. The past direct measurements were performed with ^{7}Be target with the half-life of 53 days bombarding white neutron beam at far energies from the BBN energies. We here propose to perform an indirect measurement by the Trojan horse method (THM) [19]. The THM is an indirect technique which can approach a two-body reaction at astrophysical energies via a three-body reaction by selecting quasi-free (QF) kinematics. This is enabled by using a Trojan horse (TH) nucleus in the entrance channel, and observing two recoil particles in coincidence in the three-body exit channel. For this feature, THM is also useful as a "virtual neutron source" for neutron-induced reactions by using deuteron target; deuteron as the TH nucleus involving proton as the spectator and neutron as the participant. Recently, several studies have already shown feasibility of THM for the neutron-induced reactions [20, 21]. On the other hand, THM was also applied to an RI-induced reaction [22] recently at CRIB for the first time. We propose to apply THM to RI + n reaction as one of the first attempts, using a ^{7}Be beam and a deuteron target, which induces the $^{7}\mathrm{Be}(d,{}^{7}\mathrm{Li}p)p$ and $^{7}\mathrm{Be}(d,\alpha\alpha)p$ reactions in inverse kinematics to study the $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$ and $^{7}\mathrm{Be}(n,\alpha)^{4}\mathrm{He}$ reactions. By detecting the coincidence pair of p-^{7}Li or α-α, we can reconstruct these three-body reactions.

2˙3. *Setup.* – A ^{7}Be beam will be produced by CRIB via the $^{7}\mathrm{Li}(p,n)^{7}\mathrm{Be}$ reaction in inverse kinematics with the $^{7}\mathrm{Li}^{2+}$ primary beam at 5.0 MeV/u with 500 pμA. The expected ^{7}Be secondary beam energy is 3.4 MeV/u on target with an intensity up to 1×10^{6} pps. The experimental setup for the simultaneous reaction measurements will consist of two PPACs (Parallel-Plate Avalanche Counters [23]) for beam tracking, a CD_2 target, and six ΔE-E position-sensitive silicon detector telescopes. The thickness of the CD_2 target will be as thin as $50\,\mu\mathrm{g/cm}^2$ in order to minimize the energy spread of the beam particles inside the target. This helps to identify the ^{7}Li first excited state (478 keV) in the reconstructed Q-value spectrum with a resolution of about 100 keV. According to Monte Carlo kinematical simulations, we plan to measure ^{7}Li particle around 8° and in an energy range of 12–24 MeV, protons around 35° and 57° and in 0–12 MeV, and α particles around 35° and 57° and in 10–30 MeV. For this purpose we will use a 300 μm thick position-sensitive silicon detector for the ΔE layer and a 1.5 mm thick single-pad silicon detector for the E layer. This configuration can cover the QF kinematics in a spectator momentum range $p_s < 30\,\mathrm{MeV}/c$. In addition, a 20 μm thick silicon detector will be used in the first layer for identification of ^{7}Li from ^{7}Be at the most forward-angle telescope. We expect the energy resolution about 60 keV for the $^{7}\mathrm{Be}(n,p)^{7}\mathrm{Li}$ reaction and about 200 keV for the $^{7}\mathrm{Be}(n,\alpha)^{4}\mathrm{He}$ reaction in the center-of-mass frame. We expect about 300 events per 50 keV center-of-mass energy bin in 12-day measurement.

3. – $^{7}\mathrm{Be}(d,p)^{8}\mathrm{Be}$ reaction measurement using ^{7}Be-implanted target

Although the $^{7}\mathrm{Be}(d,p)^{8}\mathrm{Be}$ reaction might affect less than the above two reactions, the cross section in the BBN energy range is not well investigated yet. This reaction cross section was previously measured using a ^{7}Be RI beam in inverse kinematics at Louvain-la-Neuve [24], but they deduced only an averaged cross section in the BBN energy region due to the poor energy resolution. The research group from RCNP, Osaka University led by Prof. Tamii proposed an experiment to make a ^{7}Be-implanted target by using a ^{7}Be beam produced at CRIB, which is to be used for a direct measurement of the $^{7}\mathrm{Be}(d,p)^{8}\mathrm{Be}$ reaction with a deuteron beam in normal kinematics. We implanted the ^{7}Be beam with an intensity of about 10^{8} particles per second into a 10 μm thick gold target. Then we measured the radioactivity with a $LaBr_3$ detector, successfully observing 477 keV γ-ray emitted from the ^{7}Li first excited state which originated from electron capture of ^{7}Be. The estimated number of the implanted ^{7}Be particles was 1.3×10^{11}. The ^{7}Be-implanted target was transported to the JAEA-Tokai Tandem accelerator facility, where the direct ^{7}Be$(d,p)^8$Be reaction measurement was performed.

4. – Summary

We reviewed our ongoing and upcoming studies at CRIB to measure cross sections of three key reactions with ^{7}Be nucleus which act as ^{7}Be destroyer in BBN. We plan to measure the ^{7}Be$(n,p)^7$Li and the ^{7}Be$(n,\alpha)^4$He reactions by THM in collaboration mainly with the nuclear astrophysics group of INFN-LNS. The ^{7}Be$(d,p)^8$Be reaction measurement was proposed by the RCNP group, and the direct ^{7}Be+d measurement was enabled with the ^{7}Be-implanted target produced at CRIB. By these different approaches, we aim at better understanding the contribution of these three reactions to the cosmological ^{7}Li problem.

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REFERENCES

[1] Coc A., Uzan J.-P. and Vangioni E., *J. Cosmol. Astropart. Phys.*, **10** (2014) 050.
[2] Yanagisawa Y. *et al.*, *Nucl. Instrum. Methods A*, **539** (2005) 74.
[3] Coc A. and Vangioni E., *J. Phys.: Conf. Ser.*, **202** (2010) 012001.
[4] Koehler P. *et al.*, *Phys. Rev. C*, **37** (1988) 917.
[5] Macklin R. L. and Gibbons J. H., *Phys. Rev.*, **109** (1958) 105.
[6] Borchers R. R. and Poppe C. H., *Phys. Rev.*, **129** (1963) 2679.
[7] Poppe C. H. *et al.*, *Phys. Rev. C*, **14** (1976) 438.
[8] Sekharan K. *et al.*, *Nucl. Instrum. Methods*, **133** (1976) 253.
[9] Adahchour A. and Descouvemont P., *J. Phys. G*, **29** (2003) 395.
[10] Serpico P. D. *et al.*, *J. Cosmol. Astropart. Phys.*, **12** (2004) 010.
[11] Wagoner R. V., *Astrophys. J.*, **148** (1967) 3.
[12] Wagoner R. V., *Astrophys. J. Suppl. Ser.*, **18** (1969) 247.
[13] Wagoner R. V. *et al.*, *Astrophys. J.*, **179** (1973) 343.
[14] Bassi P. *et al.*, *Nuovo Cimento*, **28** (1963) 1049.
[15] King C. *et al.*, *Phys. Rev. C*, **16** (1977) 1712.
[16] Mercer D., Austin S. and Glagola B., *Phys. Rev. C*, **55** (1997) 946.
[17] Hou S. Q. *et al.*, *Phys. Rev. C*, **91** (2015) 055802.
[18] Barbagallo M. *et al.* (2016), arXiv:1606.09420 [nucl-ex].
[19] Spitaleri C. *et al.*, *Phys. Atom. Nucl.*, **74** (2011) 1725.
[20] Gulino M. *et al.*, *J. Phys. G*, **37** (2010) 125105.
[21] Gulino M. *et al.*, *Phys. Rev. C*, **87** (2013) 012801.
[22] Cherubini S. *et al.*, *Phys. Rev. C*, **92** (2015) 015805.
[23] Kumagai *et al.*, *Nucl. Instrum. Methods A*, **470** (2001) 562.
[24] Angulo C. *et al.*, *Astrophys. J.*, **630** (2005) 105.