Background Considerations for the ^{2}H(^{7}Be,^{3}H)^{6}Be Experimental Data II: Three-body Continuum

K. Y. Chae*

Department of Physics, Sungkyunkwan University, Suwon 16419, Korea

V. Guimarães

*Instituto de Física, Universidade de São Paulo, C.P. 66318, 05389-970 - São Paulo, SP, Brazil, and
Institut de Physique Nucléaire d'Orsay, UMR 8608, IN2P3-CNRS, Universite Paris Sud 11, France*

The present article reports second background considerations for the experimentally obtained ^{2}H(^{7}Be,^{3}H)^{6}Be differential cross sections. The one-neutron transfer reaction was measured in inverse kinematics by using radioactive ^{7}Be ($t_{1/2} = 53.2$ days) beams at the Holifield Radioactive Ion Beam Facility of the Oak Ridge National Laboratory in 2004 in order to search for the resonances in the unbound ^{6}Be nucleus. Resonances in this nucleus would affect the ^{3}He(^{3}He,2p)^{4}He reaction rate of the proton-proton chain occurring in stars such as our sun. The result shows, however, that the direct transfer to ^{6}Be resonances is not particularly strong compared to other reaction channels that can produce tritons in the exit channels. The goals of the present work is to better understand the cross section data from transfer reaction measurements by adopting background considerations using the three-body continuum.

I. INTRODUCTION

Experimental nuclear reaction data on differential cross sections obtained by utilizing radioactive ion beams are extremely valuable because not so many rare isotope beams are available. Therefore, investigating the background reaction mechanisms when the nuclear reaction cross section data cannot be fully understood by using mechanism originally desired is worthwhile. For instance, the ^{7}Be(d,t)^{6}Be reaction cross section measurement performed in inverse kinematics by using a radioactive ^{7}Be beam was designed to populate unbound states in ^{6}Be [1]. Depending on the properties of the unbound states, our understandings of the ^{3}He(^{3}He,2p)^{4}He reaction may be enhanced to some extent. The reaction is very important for the proton-proton chain (pp-chain), and the corresponding reaction rate is the key to understanding big-bang nucleosynthesis, stellar burning, and solar neutrino production, as pointed out in Refs. [2–4]. The triton spectra obtained from the ^{7}Be(d,t)^{6}Be reaction measurements were, however, rather featureless. This does not indicate that no resonance is present in

^{6}Be, but that direct transfer to the ^{6}Be unbound states is not particularly strong. Because the reaction cross section measurement has been performed only once, investigating all possible mechanisms involved in the interaction of ^{7}Be+d other than just the direct transfer becomes very important.

II. SUMMARY OF THE PREVIOUS WORKS

To search for the unbound state in the ^{6}Be nucleus, we studied the ^{2}H(^{7}Be,^{3}H)^{6}Be reaction by using a radioactive ^{7}Be beam ($E_{beam} = 100$ MeV), deuterated polyethylene (CD$_2$)$_n$ targets, and a large-area silicon strip detector array (SIDAR, [5]) at the Holifield Radioactive Ion Beam Facility (HRIBF) of the Oak Ridge National Laboratory (ORNL) [1]. Because the silicon detector array is composed of six $\Delta E - E$ telescopes and each detector is segmented into 16 annular strips, the tritons from the (d,t) reactions were identified by using a standard energy-loss technique, and the angular distributions of outgoing tritons were measured at 16 different angles ($14° \leq \theta_{lab} \leq 32°$, $35° \leq \theta_{c.m.} \leq 84°$) simultaneously. The differential cross sections of the ^{2}H(^{7}Be,^{3}H)^{6}Be re-
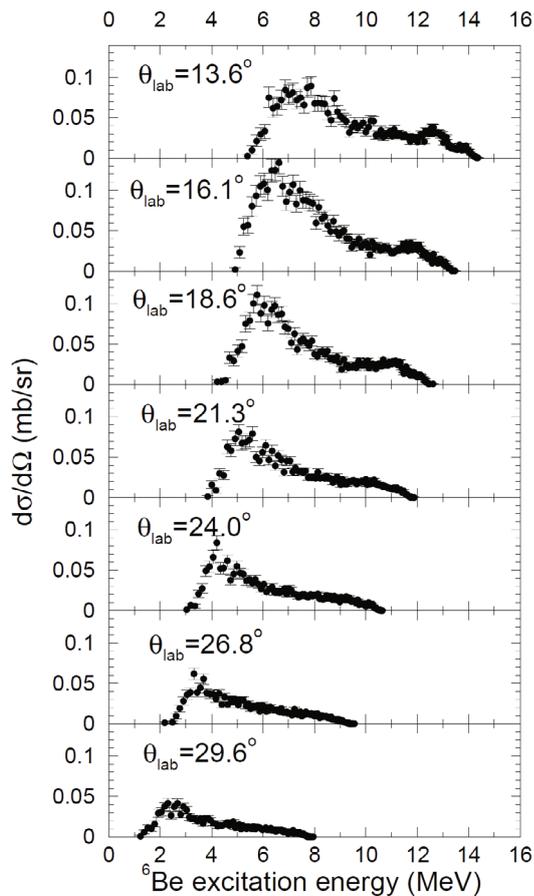
*E-mail: kchae@skku.edu; Fax: +82-31-290-7055

Fig. 1. Differential cross section as a function of ^{6}Be excitation energy taken from Ref. [1].

action as functions of the ^{6}Be excitation energy obtained at seven SIDAR strips (angles) are shown in Fig. 1 which is taken from Ref. [1]. Complete distributions can be found at Fig. 1 of Ref. [6]. The lack of strong sharp peaks in the reaction cross section spectra is a clear indication that the direct transfer to the ^{6}Be levels was not particularly strong.

Because no resonance was evident, the phase space model (PSM) was adopted to better understand the reaction mechanism that could produce tritons in their exit channels other than the direct (d, t) reaction [6]; Three reaction channels, including the $t + p + p + ^4$He, $t + ^3$He $+ ^3$He, and $t + p + ^5$Li, were considered by adopting the PSM with proper normalization constants because those three reaction channels were the only kinematically-allowed channels. As pointed out in Ref. [6], however, the overall PSM distribution was rather featureless in the energy range of the experimental data. In the present work, the three-body continuum is studied to further investigate the triton energy distributions.

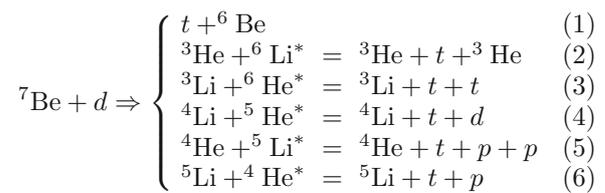## III. THREE-BODY CONTINUUM (SEQUENTIAL DECAY)

When the projectile picks up a light particle such as a nucleon, the projectile may lose some portion of energy by forming an intermediate state that could be a particle-unstable state. Normally, these states are very unstable and, thus, subsequently decay in flight by emitting a particle [7]. This two-step process yields three or more particles in the exit channel. Because the process gives a continuous energy distribution, the process produces a *three-body continuum*. The continuous energy distribution is the result of incomplete reconstruction of the kinematics as indicated in Ref. [8]: The recoil of the emitted particle shifts the energy of the outgoing fragment depending on the emission angle, which causes the broad energy distribution [7].

In order to obtain reliable information on the primary reaction, understanding the mechanisms of the de-excitation process, which is the second step is, therefore, crucial. An example of a three-body continuum process for the ^{7}Be $+ d$ system is

$$^7\text{Be} + d \rightarrow\, ^5\text{Li} +\, ^4\text{He}^* \rightarrow\, ^5\text{Li} + t + p.$$
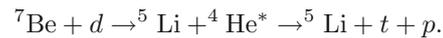
The process consists of two successive steps, each of which can be considered to be two-body reaction: (i) the deuteron picks up a ^{2}H component of ^{7}Be to form an unbound state of the ^{4}He, and (ii) the intermediate, unstable ^{4}He* fragment decays to a proton and a triton. The ^{4}He should be excited to a level above the particle emission threshold in this case.

For the ^{7}Be $+ d$ system, there are several possibilities for the sequential break-up that gives a triton in the exit channel:

$$^7\text{Be} + d \Rightarrow \begin{cases} t +^6\text{Be} & (1) \\ ^3\text{He} +^6\text{Li}^* = ^3\text{He} + t +^3\text{He} & (2) \\ ^3\text{Li} +^6\text{He}^* = ^3\text{Li} + t + t & (3) \\ ^4\text{Li} +^5\text{He}^* = ^4\text{Li} + t + d & (4) \\ ^4\text{He} +^5\text{Li}^* = ^4\text{He} + t + p + p & (5) \\ ^5\text{Li} +^4\text{He}^* = ^5\text{Li} + t + p & (6) \end{cases}$$

Expression (1) is not one of the sequential break-ups, but a direct two-body reaction. The expression is shown for comparison purposes. The expressions from Eqs. (2) to (6) can be schematically summarized as

$$^7\text{Be} + d \rightarrow A + b^* \rightarrow A + x + t,$$
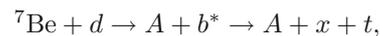
where $b = x + t$, and x is a light pick-up particle.

The triton, t, originates from two major mechanisms in the case of the ^{2}H(^{7}Be,^{3}H)^{6}Be reaction measurement reported in Ref. [1]: the direct two-body reaction and sequential break-ups. A knowledge of sequential break-ups is required, therefore, to better understand the ^{7}Be$(d,t)^6$Be reaction cross section. Due to the kinematics constraints, the reactions labeled (2), (3) and (4) cannot occur in this case, so they are not considered in

the following analysis. For instance, the reaction (2) is not possible because a 100-MeV ^{7}Be beam would populate ^{6}Li* with at most $E_x = 12$ MeV, which is below the $t + {}^3$He threshold. The only two reactions that have been studied by using a three-body continuum mechanism are, therefore, the reactions labeled (5) and (6).

When several decay channels are open, the competition between them can be investigated by considering the particle decay ratio, which can be approximated as [9,10]

$$\frac{\Gamma_2}{\Gamma_1} = \frac{(2s_2 + 1)m_2\sigma_2^0}{(2s_1 + 1)m_1\sigma_1^0} \exp\left[\frac{(S_1 - S_2) + (V_1' - V_2')}{T}\right], \quad (1)$$

where $i = 1, 2$ is the channel index, Γ_i, s_i, m_i, σ_i^0, S_i, V_i', and T are the decay width, spin, mass, inverse capture cross section, separation energy, effective Coulomb barrier, and average temperature, respectively. The three-body continuum calculations for various scenarios are well formalized in Ref. [7] and are summarized below for the case of the mechanism required to analyze the ^{7}Be(d,t)^{6}Be reaction cross section. For the process ^{7}Be $+ d \rightarrow A + b^* \rightarrow A + x + t$, the energy of the emitted nucleus, t, is given by [7,11]

$$E_t' = \frac{t}{b}E_b + \frac{x}{b}\varepsilon + 2\sqrt{\frac{tx}{b^2}E_b\varepsilon}\cos\theta_x, \quad (2)$$

where t, b, and x are the masses of the corresponding particles, respectively, E_b is the kinetic energy of b calculated for the two-body reaction ^{7}Be(d,b)A, and θ_x is the emission angle of x with respect to the direction of b in the rest frame of b. $\varepsilon = E_b^* - E_{t'}^* - S_{bx}$ is the decay energy in $b \rightarrow t + x$ with

E_b^* the excitation energy of b
$E_{t'}^*$ the excitation energy of t after emission of x
S_{bx} the separation energy of x in $b = t + x$.

Particle emission decreases the kinetic energy of fragment b and causes an energy broadening, even if b is monoenergetic. The triton angle is also shifted according to $\theta_{t'} = \theta_b - \Delta\theta$, where

$$\Delta\theta = \sqrt{\frac{x}{t}\frac{\varepsilon}{E_b}}\sin\theta_x\left[1 + \sqrt{\frac{x}{t}\frac{\varepsilon}{E_b}}\cos\theta_x\right]^{-1}. \quad (3)$$

The energy spectrum for the triton in the pick-up and decay processes is expressed as [7]

$$\frac{d^2\sigma}{d\Omega_t dE_t} = \int_0^\infty \int_0^{2\pi} \frac{d^2\sigma}{d\Omega_b dE_b}(\theta_b, E_b^*)\frac{\sin\theta_b}{\sin\theta_t}\Gamma_{bx}$$
$$\times W_x(\Omega_b, \Omega_x)\frac{d\theta_x}{d\varepsilon}\sin\theta_x d\phi_x d\varepsilon. \quad (4)$$

The first factor in the integrand includes all the information about forming the intermediate state, such as the angular distribution, the Q-value dependence, etc. The term can be approximately factorized as

$$\frac{d^2\sigma}{d\Omega_b dE_b} = C_1 \exp\left(-C_2\theta_b\right)\exp\left[-\left(\frac{E_x - C_3}{C_4}\right)^2\right], \quad (5)$$
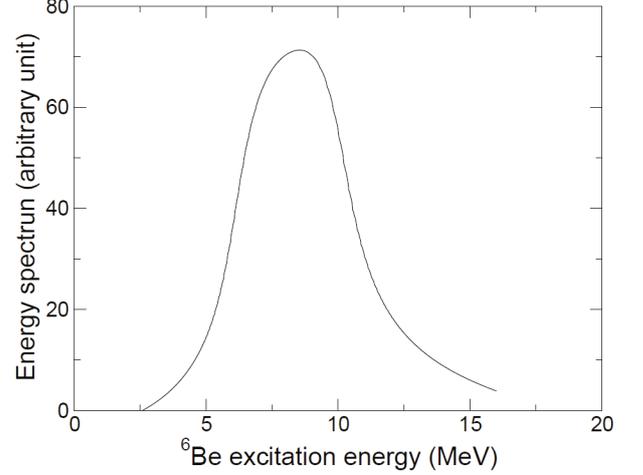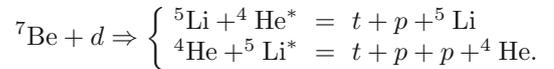

Fig. 2. Energy spectrum for the tritons from the ^{7}Be $+ d \rightarrow t + p + {}^5$Li three-body continuum. $\theta_{lab} = 13.6°$ in this case.

which shows the angular and the energy dependences of the pick-up cross section. In the present work, the angular dependence of the distribution is approximated with an exponential decay, and the Q-value dependence is described by using a Gaussian distribution as suggested in Ref. [7].

The second factor in the exponent of Eq. (4), $\sin\theta_b/\sin\theta_t$, transforms the solid angle of b into that of a deuteron. Γ_{bx} is the branching ratio of the channel $b \rightarrow t + x$, and $W_x(\Omega_b, \Omega_x)$ is the correlation function for the emission of x into the angles θ_x, ϕ_x with respect to θ_b, ϕ_b. Thus, if we assume an isotropic emission in the center-of-mass system of particle b, this factor becomes 1.

IV. RESULTS AND DISCUSSION

The reactions considered by using three-body continuum mechanism in the present work are

$$^7\text{Be} + d \Rightarrow \begin{cases} ^5\text{Li} + {}^4\text{He}^* &= t + p + {}^5\text{Li} \\ ^4\text{He} + {}^5\text{Li}^* &= t + p + p + {}^4\text{He}. \end{cases}$$

These are the only two possible reactions that can be considered by using the three-body continuum due to the kinematics considering the center-of-mass energy of 22.3 MeV.

The three-body continuum distributions for the two channels above were calculated by using Eq. (4). A typical result of the three-body continuum distribution calculation is shown in Fig. 2. In the figure, the energy spectrum for the triton obtained for the ^{7}Be $+ d \rightarrow t + p + {}^5$Li reaction at $\theta_{lab} = 13.6°$ is shown. Triton energies were converted into ^{6}Be excitation energies to be directly compared to the experimentally-obtained cross sections.

The distributions similar to the one shown in Fig. 2 were calculated for the 16 angles corresponding to those
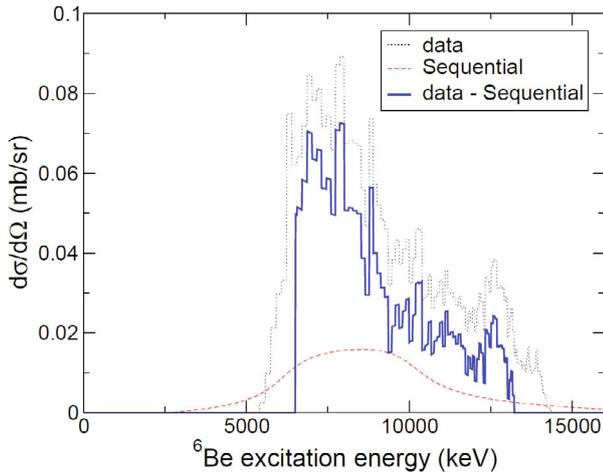
Fig. 3. (Color online) The experimental cross section data and the sequential decay energy spectrum with proper normalization factor. The blue curve shows the difference between two sets (experimental data - sequential decay energy spectrum). $\theta_{lab} = 13.6°$ in this case.

covered by the silicon strips used for the ^{2}H(^{7}Be,^{3}H)^{6}Be reaction measurement. The overall normalization factors were then adjusted in order to fit the experimental data. The normalization parameters were increased until the three-body continuum distributions exceeded the experimental data. The normalized three-body continuum distributions were then subtracted from the ^{7}Be(d,t)^{6}Be reaction cross sections at each angle. One of the background subtraction results obtained at $\theta_{lab} = 13.6°$ is shown in Fig. 3. In the figure, the black dotted curve shows the experimentally-obtained reaction cross section, the red dashed curve represents the three-body continuum distribution, and the blue solid line is the difference between the two sets. For the three-body continuum distribution, both ^{7}Be $+ d \rightarrow t + p +^5$ Li and ^{7}Be $+ d \rightarrow t + p + p +^4$ He reaction channels were included in the calculation.

As shown in the figure, the sudden decrease in the differential cross section observed at the ^{6}Be excitation energy of about 9.5 MeV became clearer by subtracting the three-body continuum distribution from the experimental data. Few peak-like structures are present at $E_{Be} \sim$ 7.1, 7.9, and 8.8 MeV. If the peaks are arose from the unbound states of the radionuclide ^{6}Be, the structures should be observable at the same excitation energies of other angles as well. It was not clear, however, that the peaks are evident at other angles.

In summary, the ^{2}H(^{7}Be,^{3}H)^{6}Be reaction was studied by using the radioactive ^{7}Be beams ($t_{1/2} = 53.2$ days) at the HRIBF of ORNL to search for unbound resonance in radionuclide ^{6}Be [1]. The reaction was measured in inverse kinematics by bombarding the ^{7}Be beams on deuterated polyethylene $(CD_2)_n$ targets. Recoiling tritons were detected at 16 different forward angles by using 18 annular silicon strip detectors. The silicon detector

array was configured as six ΔE-E telescopes backed by veto detectors to identify light charged particles and to reject events from the punching through ^{3}He particles [1]. As shown Fig. 1, however, the observed spectrum was rather featureless indicating that direct transfer to ^{6}Be levels was not particularly strong compared to other reactions that could produce tritons in their exit channels.

Because the resonance in ^{6}Be was not evident, studies of possible background mechanisms were performed to understand the reaction channels that could contribute to the triton spectra. The phase space model of Ref. [6] and the three-body continuum of the present work are the examples of how we can consider alternative sequential reactions as background. Calculations indicate that, however, the observed tritons could not well described by either background consideration. This does not prove that no resonance is present in ^{6}Be radionuclide, but there might be other mechanisms that are not considered in the present work. Moreover, as pointed out in Ref. [1], the observed cross sections were larger than the Distorted Wave Born Approximation calculations indicating that a mixture of reaction mechanisms is involved.

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