Study on the $^8\text{He}$ ground state via $^8\text{He}(p, d)^7\text{He}$ and $^8\text{He}(p, t)^6\text{He}$ reaction at 82.3 MeV/nucleon

J L Lou$^1$, Y L Ye$^1$, D Y Pang$^2$, Z X Cao$^1$, D X Jiang$^1$

$^1$School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China, 100871
$^2$School of Physics and Nuclear Energy Engineering, Beihang University, Beijing, China, 100191

E-mail: yeyl@pku.edu.cn

Abstract. The differential cross sections for reactions $^8\text{He}(p, d)^7\text{He}$ and $^8\text{He}(p, t)^6\text{He}$ were measured by the coincidence of $d + ^6\text{He}$ and $t + ^4\text{He}$ in a wide angular range from 15 to 130 degree in the center-of-mass system. The cross sections of the $^8\text{He}(p, t)^6\text{He}$ reaction were extremely lower than that of $^8\text{He}(p, t)^6\text{He}$, reaction, and was not obtained from the present data. The experimental results were compared to the preliminary theoretical calculations in the frame of adiabatic distorted-wave approximation with the code Fresco. The results show that the configuration of $(1p_{1/2})^2(1p_{3/2})^2$ may have some probability in the ground state wave function of $^8\text{He}$. The cluster structure of $^8\text{He} = ^5\text{H} + ^3\text{H}$ could not be neglected.

1. Introduction
The nucleus $^8\text{He}$ has the largest neutron-to-proton ratio among all the known particle-stable nucleus, exhibiting a neutron halo or thick neutron skin, and is an excellent candidate for the test of nuclear structure models. However, the structure of its ground state is still controversial.

Theoretically, the asymmetry molecule dynamics (AMD) calculation shows that the ground state of $^8\text{He}$ has both a $j - j$ coupling feature ($^4\text{He} + 4n$) and a $L - S$ coupling feature ($^4\text{He} + 2n + 2n$) [1], but the cluster orbital shell model approximation (COSMA) model predicts that the dominant configuration is an alpha particle core surrounded by four valence neutrons filling the $1p_{3/2}$ sub-shell, equal to the pure $j - j$ coupling [2]. At the same time, the AMD model calculations suggest that the "$t + t$ + valence neutrons" structure and the "$^4\text{He}+valence neutrons$" structure[3], as well as the di-neutron structure[1, 4] simultaneously exist in the ground state of neutron-rich He isotopes.

Experimentally, the $1n$ and $2n$ transfer reaction is a sensitive probe for the study of the ground state of $^8\text{He}$[5]. The Spectroscopic Factor(SF) extracted from $^8\text{He}(p, d)^7\text{He}$ reaction and the ratio of SFs of $^8\text{He}(p, t)^6\text{He}_{2+}$ to $^8\text{He}(p, t)^6\text{He}_{0+}$ depend strongly on the assumed structure of $^8\text{He}$ ground state[6]. In this paper, the angular distributions of differential cross sections for reactions $^8\text{He}(p, d)^7\text{He}_{0, s}$ and $^8\text{He}(p, t)^6\text{He}_{2+}$ were measured at a relatively higher incident energy of 82.3 MeV/nucleon. The experimental results were compared to the preliminary theoretical calculations in the frame of adiabatic distorted-wave approximation(ADWA) [7] with the code Fresco.
2. Experimental setup
The experiment was carried out at RIKEN Projectile Fragment Separator (RIPS) radioactive ion beam Line. The secondary beam of $^8$He at 82.3 MeV/nucleon was produced by a 115 MeV/nucleon $^{13}$C primary beam impinged on a $^9$Be target with a thickness of 12 mm. The beam intensity at the physical target amounts to $3 \times 10^6$ pps with a purity of 56% for $^8$He. The schematic experimental setup is shown in Fig.1. The beam was tracked by the gas detector BDC1 and BDC2 placed before the physical target. The out-going angles were detected by the gas detector MDC and silicon strip detector in telescope. The deuterons and tritones were measured by telescope D11 and D12, while the charged particle fragments $^4$He and $^6$He were recorded by the magnetic system and the telescope D2. More detailed description of experimental setup was shown in Ref.[8, 9, 10, 11, 12].

![Schematic view of the experimental setup at RIKEN-RIPS.](image)

3. Data Analysis
The 1n and 2n transfer events were obtained from the coincidence of $d + ^6$He and $t + ^4$He, respectively. The differential cross sections were calculated from the number of incoming $^8$He (about $1.6 \times 10^{10}$), the number of $d(t)$ coincidence with $^8$He($^4$He), and the solid angles. The solid angles were simulated by using the Monte-Carlo method with the beam spot and actual geometry size of each detector. The results for 1n transfer are shown as squares in Fig.2, while that for 2n transfer are shown in Fig.3. Only statistic error resulting from the number of incident $^8$He, the number of coincident $d(t)$ and the background subtraction, is shown in Fig.2 and Fig.3. The systematic error is estimated to be 12%, mainly resulted from the uncertainties of target thickness, selection of transfer event and simulation of the solid angle.

4. Theoretical calculation
The theoretical calculations were carrying out with the code Fresco[15] in the frame of adiabatic distorted-wave approximation(ADWA). The global potential KD02 [16] was adopted for the entrance channel $p + ^8$He. For 1n transfer, the bare potential for exit channel $d + ^7$He was of the Watanabe type, generated by single-folding of the $p,n + ^7$He potentials with the
t the et al [17]. A series calculation suggests that the result is very sensitive to the real part depth of the optical potential parameters of deuteron wave function. The SF extracted from the \( {}^8\text{He}(p, d) {}^7\text{He}_{g.s.} \) reaction is very sensitive to the optical potential parameters of \( d + {}^7\text{He} \). It is found that if the imaginary depth for \( d + {}^7\text{He} \) potential is multiplied by a factor 2.0(OP3,green curve), the consistence between the experimental data and ADWA calculations becomes better than the original calculation without any parameter adjustment(OP1,black curve). However, the best fit for the whole angular distribution is obtained(OP2,red curve) when the re-normalization factor for the real part and imaginary part of \( d + {}^7\text{He} \) potential, respectively. The re-normalization factor of the best fit one is 1.8 and 0.4 for the real part and imaginary part of \( d + {}^7\text{He} \) potential, respectively.

d for 2n transfer, only one-step process was taken into consideration, because the contributions from two-step process was found to be one order of magnitude lower. The potential for the exit channel \( t + {}^6\text{He} \) comes from the \( {}^3\text{He} + {}^6\text{Li} \) optical potential at 72 MeV/nucleon given by Bragin et al [17]. A series calculation suggests that the result is very sensitive to the real part depth of the \( t + {}^6\text{He} \) potential and geometry parameter of 2n-cluster binding potential in \( {}^8\text{He} \). In addition to 2n transfer, the cluster \( {}^5\text{H} \) transfer is necessary for reproducing the angular distribution of differential cross sections, especially for the angles larger than 90 degree. This phenomenon and conclusion is the same as Ref.[6]. The angular distribution of differential cross sections for \( {}^8\text{He}(p, t) {}^6\text{He}_{g.s.} \) reaction were not obtained due to lower statistics.

5. Conclusion

Angular distributions of differential cross sections for \( {}^8\text{He}(p, d) {}^7\text{He} \) and \( {}^8\text{He}(p, t) {}^6\text{He}_{2+} \) reactions at an incident energy of 82.3 MeV/nucleon were measured by using \( d + {}^6\text{He} \) and \( t + {}^4\text{He} \) coincident method. Theoretical calculation in the frame of ADWA were performed with the code Fresco. Although the extracted SF are little different due to different optical

---

**Figure 2.** Experimental data(symbols) and theoretical calculations(curves) of the differential cross sections for \((p, d)\) reaction to \( {}^7\text{He}_{g.s.} \). The OP1,OP2 and OP3 stand for the original calculations without any parameter adjustment(the black curve), the imaginary depth of \( d + {}^7\text{He} \) increases to 2.0 times(the green curve) and the best fit one(the red curve), respectively. The re-normalization factor of the best fit one is 1.8 and 0.4 for the real part and imaginary part of \( d + {}^7\text{He} \) potential, respectively.

**Figure 3.** Experimental data(symbols) and one-step theoretical calculations(curves) of the differential cross sections for \((p, t)\) reaction to \( {}^6\text{He}_{2+} \) at an incident energy of 82.3 MeV/nucleon. The red curve is the coherent summation of 2n(black curve) and \( {}^5\text{H} \)(blue curve) cluster transfer.
potential parameters, they are all smaller than 4.0. Maybe this phenomenon indicates that the configuration of \((1p_{3/2})^2(1p_{1/2})^2\) have some probability in the ground state wave function of \(^8\text{He}\).

In the case of 2n transfer reaction, the \(^8\text{He}(p, t)\; ^6\text{He}_{2+}\) channel is prior to the \(^8\text{He}(p, t)\; ^6\text{He}_{0+}\) channel, similar to this was observed at incident energies of 25 [6] and 61.3 [13] MeV/nucleon. The \(^5\text{H}\) cluster transfer was necessary for reproducing the angular distributions of \(^8\text{He}(p, t)\; ^6\text{He}_{2+}\) reaction at angles larger than 90 degree. Thus, the cluster structure of \(^8\text{He} = ^5\text{H} + ^3\text{H}\) might not be neglected in the ground state of \(^8\text{He}\). In order to get more structure information of the \(^8\text{He}\) ground state, a systemic analysis of all the exist 1n and 2n transfer reaction experimental data of \(^8\text{He}\) is encouraged.

**Acknowledgement**

This work is supported by the National Natural Science Foundation of China (Nos.10905002, 11275001, 11035001, 11275011, 11275018), the National Basic Research Program of China (No. 2007CB815002).

**References**

[1] Yoshiko Kanada-Enyo 2007 *Phys. Rev. C* 76 044323.
[2] M V Zhukov et al 1994 *Phys. Rev. C* 50 R1.
[3] S Aoyama et al 2006 *Phys. Rev. C* 74 017307
[4] N Itagaki et al 2008 *Phys. Rev. C* 78 017306
[5] N Keeley et al 2007 *Phys. Lett. B* 646 222-226
[6] R Wolski et al 2002 in: A. Ohnishi, N. Itagaki, Y. Kanada-Enyo, K. Kato (Eds.), Clustering Aspects of Quantum Many Body Systems, Kyoto, 12-14 November 2001, World Scientific, p 15.
[7] K T Schmitt et al 2012 *Phys. Rev. Lett* 108 192701
[8] Z X Cao et al 2012 *Phys. Lett. B* 707 46-51
[9] J L Lou et al 2011 *Phys. Rev. C* 83 034612
[10] FAISAL Jamil Qureshi et al 2010 *Chin. Phys. Lett* 27 092501
[11] XIAO Jun et al 2012 *Chin. Phys. Lett* 29 082501
[12] L H Lv et al 2012 *J. Phys. G: Nucl. Part. Phys* 39 065102
[13] A A Korseninnikov et al 2003 *Phys. Rev. Lett* 90 082501
[14] F Skaza et al 2006 *Phys. Rev. C* 73 044301
[15] I J Thompson 1988 *Comput. Phys. Rep.* 7 167
[16] A J Koning et al 2003 *Nucl. Phys. A* 713 231
[17] V N Bragin et al 1986 *Sov. J.Nucl.Phys* 44 198