Effect of the breakup process on the direct reaction with a ^{6}Li projectile

W. Y. So
Department of Radiological Science, Kangwon National University, Samcheok 245-711, Korea

Su Youn Lee
Department of Physics, Dong-Eui University, Busan 614-714, Korea

K. S. Kim*
School of Liberal Arts and Science, Korea Aerospace University, Koyang 412-791, Korea
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We investigate the effect of the breakup process on the direct reaction (DR) for ^{6}Li. In order to study this effect, we introduce the experimental and semiexperimental ratio factors $R^{\rm expt}$ and $R^{\rm th}$ by using the semiexperimental and experimental α-production cross sections and DR cross sections. The average values of the ratio $R^{\rm expt}$ ($R^{\rm th}$) for the $^6{\rm Li} + {}^{208}{\rm Pb}$ and $^6{\rm Li} + {}^{209}{\rm Bi}$ systems are 0.90 (0.91) and 0.86 (0.85), respectively. From these results, it can be seen that the α-production cross sections are the main contribution to the DR cross sections.

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Over the last few decades, many groups have experimentally performed and theoretically calculated heavy-ion collisions of loosely bound projectiles such as ^{6}He, ^{6}Li, and ^{9}Be [1–7]. In particular, the characteristic features of loosely bound projectiles at incident energies around the Coulomb barrier have been widely studied. However, breakup processes such as α production and so on are very complicated although the loosely bound projectiles are able to break up in princile.

Because loosely bound projectiles easily break due to their low separation energies (for example, 0.98 MeV for ^{6}He, 1.47 MeV for ^{6}Li, and 1.57 MeV for ^{9}Be), these projectiles are not, in the main, transferred by elastic scattering but by the breakup process. It is necessary when considering the breakup reactions of these projectiles to include various reaction mechanisms such as elastic breakup (EBU), transfer reactions (TR), incomplete fusion (ICF), and complete fusion (CF). The loosely bound nuclei usually produce one or more α particles in the heavy-ion reaction process. Therefore, it is important to investigate the contribution of α-production channels on the direct reaction (DR).

For the $^6{\rm Li} + {}^{208}{\rm Pb}$ reaction at Coulomb barrier energies, the authors in Ref. [4] concluded that a strong stripping breakup process is exhibited due to the large difference between the inclusive and exclusive breakup cross sections. In the same system, Wu *et al.* [5] showed that the effects of ^{6}Li breakup suppress the fusion cross sections at above barrier energies, but the effects of breakup are not clear below the barrier.

On the other hand, for the $^6{\rm Li} + {}^{209}{\rm Bi}$ system, the exclusive breakup cross sections have been measured at $E_{\rm lab} = 36$ and 40 MeV, and the sequential breakup is dominant for the total $\alpha + p$ breakup process as seen by comparing with a resonant state, such as the $(3^+, 2.18\ {\rm MeV})$ state of ^{6}Li [13]. In particular, in Ref. [8], the high precision CF and ICF cross sections has been measured for the $^6{\rm Li} + {}^{209}{\rm Bi}$, $^7{\rm Li} + {}^{209}{\rm Bi}$, and $^9{\rm Be} + {}^{208}{\rm Pb}$ reactions near and below the Coulomb barrier energies. In this paper, a separation of CF from ICF (and TR) is shown to be important for the effect of the breakup of the projectile nuclei on fusion. In our previous paper [9], we calculated α single and α-α coincidence cross sections for the $^9{\rm Be} + {}^{144}{\rm Sm}$ system by using extended optical model analyses. As a result, it was shown that a large proportion of the DR cross section comes from the α-α coincidence cross sections.

In the present work, we investigate the effect of the breakup process on the DR for ^{6}Li by using two different target nuclei, ^{208}Pb and ^{209}Bi. After we study different breakup processes, the theoretical ratios of α production to DR cross sections are obtained and compared with the experimental ratios.

For the typical reaction mechanism processes of a ^{6}Li projectile, the total reaction cross sections can be written as

$$\begin{aligned}\sigma_R^{\rm expt} &= \sigma_{\rm EBU}^{\rm expt} + \sigma_{1n\text{-tr}}^{\rm expt} + \sigma_{1p\text{-tr}}^{\rm expt} + \sigma_{d\text{-capt}}^{\rm expt} + \sigma_{\alpha\text{-capt}}^{\rm expt} + \sigma_F^{\rm expt} \\ &= \sigma_{\rm EBU}^{\rm expt} + \sigma_{\rm tr}^{\rm expt} + \sigma_{\rm ICF}^{\rm expt} + \sigma_F^{\rm expt} \\ &= \sigma_{\alpha\text{-prod}}^{\rm expt} + \sigma_{\alpha\text{-capt}}^{\rm expt} + \sigma_F^{\rm expt}. \qquad (1)\end{aligned}$$

$\sigma_{\rm EBU}^{\rm expt}$, $\sigma_{1n\text{-tr}}^{\rm expt}$, $\sigma_{1p\text{-tr}}^{\rm expt}$, $\sigma_{d\text{-capt}}^{\rm expt}$, $\sigma_{\alpha\text{-capt}}^{\rm expt}$, $\sigma_F^{\rm expt} \equiv \sigma_{CF}^{\rm expt}$, and $\sigma_{\alpha\text{-prod}}^{\rm expt}$ represent EBU, one-neutron TR, one-proton TR, one-deuteron capture, one-α capture, CF, and α-production cross sections, respectively. The EBU process ($^6{\rm Li} + {}^A_ZX \to \alpha + d + {}^A_ZX$ or $\to \alpha + p + n + {}^A_ZX$) is the breakup process such that no particles are captured by the target. The TR cross sections can be written as the sum of a one-neutron transfer [$^6{\rm Li} + {}^A_ZX \to \alpha + p + (n + {}^A_ZX)$] and a one-proton transfer [$^6{\rm Li} + {}^A_ZX \to \alpha + n + (p + {}^A_ZX)$]. The ICF cross sections are composed of one-deuteron capture [$^6{\rm Li} + {}^A_ZX \to \alpha + (d + {}^A_ZX)$] cross sections and α-capture cross sections [$^6{\rm Li} + {}^A_ZX \to d + (\alpha + {}^A_ZX)$ or $\to p + n + (\alpha + {}^A_ZX)$]. The CF cross sections are the sum of $(\alpha + 1p)$-capture cross sections [$^6{\rm Li} + {}^A_ZX \to n + (\alpha + p + {}^A_ZX)$] and $(\alpha + 1p + 1n)$-capture cross sections [$^6{\rm Li} + {}^A_ZX \to (^6{\rm Li} + {}^A_ZX)$].

*kyungsik@kau.ac.kr

TABLE I. Measurements of α-production, DR, and total reaction cross sections for complete fusion, and extracted semiexperimental α-production, DR, and total reaction cross sections for the ^{6}Li + ^{208}Pb system. σ_F^{expt} and $\sigma_{\alpha\text{-prod}}^{\text{expt}}$ are obtained from Refs. [4] and [5], respectively. Note that the α-capture cross sections, $\sigma_{\alpha\text{-capt}}^{\text{expt}}$, are extracted from $\sigma_{\alpha\text{-capt}}^{\text{expt}} = \sigma_d^{\text{expt}} - \sigma_{\text{excl}}^{\text{expt}}$ [12]. Also, σ_d^{expt} and $\sigma_{\text{excl}}^{\text{expt}}$ are obtained from Fig. 6 in Ref. [12], and $\sigma_R^{\text{semiexpt}}$ are obtained from Ref. [3].

$E_{\text{c.m.}}$ (MeV)	σ_F^{expt} (mb)	σ_d^{expt} (mb)	$\sigma_{\text{excl}}^{\text{expt}}$ (mb)	$\sigma_{\alpha\text{-capt}}^{\text{expt}}$ (mb)	$\sigma_{\alpha\text{-prod}}^{\text{expt}}$ (mb)	σ_D^{expt} (mb)	$\sigma_D^{\text{semiexpt}}$ (mb)	σ_R^{expt} (mb)	$\sigma_R^{\text{semiexpt}}$ (mb)	$\sigma_{\alpha\text{-prod}}^{\text{semiexpt}}$ (mb)
30.1	120	81	66	15	249	264	311	384	431	296
32.1	234	111	94	17	397	414	432	648	666	415
34.0	335	144	94	50	467	517	562	852	897	512
37.9	507	260	119	141	594	735	796	1242	1303	655

According to Ref. [4], tritium cannot be produced by a breakup process but only by evaporation because tritium has a breakup threshold of 15.8 MeV, which is much larger than for the other processes in Eq. (1) for loosely bound projectile systems. However, it is well known that tritium can be produced by evaporation from a compound nucleus [10]. The authors in Ref. [11] claimed that inelastic processes are not important for a loosely bound projectile system due to the low binding energy of the projectile. In this work, hence, it is not necessary to include tritium production and inelastic processes.

For the α-production cross sections, the α particle is detected through various processes and the measurement of the α particle is defined as

$$\begin{aligned}\sigma_{\alpha\text{-prod}}^{\text{expt}} &= \sigma_{\text{EBU}}^{\text{expt}} + \sigma_{\text{tr}}^{\text{expt}} + \sigma_{d\text{-capt}}^{\text{expt}} \\ &= \sigma_R^{\text{expt}} - \left(\sigma_F^{\text{expt}} + \sigma_{\alpha\text{-capt}}^{\text{expt}}\right). \end{aligned} \quad (2)$$

From Eqs. (1) and (2), we can obtain the experimental DR cross sections as

$$\begin{aligned}\sigma_D^{\text{expt}} &= \sigma_R^{\text{expt}} - \sigma_F^{\text{expt}} \\ &= \sigma_{\alpha\text{-prod}}^{\text{expt}} + \sigma_{\alpha\text{-capt}}^{\text{expt}}. \end{aligned} \quad (3)$$

To study the breakup processes, it is necessary to obtain the experimental total reaction cross sections σ_R^{expt}. However, it is experimentally difficult to measure all of them because there are many reaction channels. Instead of the experimental total reaction cross sections, we introduce the semi-experimental total reaction cross sections $\sigma_R^{\text{semiexpt}}$ calculated from the measured elastic scattering cross section as

$$\sigma_R^{\text{semiexpt}} = \sigma_C - \sigma_E, \quad (4)$$

where σ_C and σ_E are the angle-integrated total Rutherford and the experimental elastic scattering cross sections, respectively. Since this approach of generating $\sigma_R^{\text{semiexpt}}$ was proven in Refs. [16,17], we use $\sigma_R^{\text{semiexpt}}$ instead of σ_R^{expt}. As a result, the values of $\sigma_{\alpha\text{-prod}}^{\text{semiexpt}}$ in Table I are obtained from

$$\sigma_{\alpha\text{-prod}}^{\text{semiexpt}} = \sigma_R^{\text{semiexpt}} - \left(\sigma_F^{\text{expt}} + \sigma_{\alpha\text{-capt}}^{\text{expt}}\right). \quad (5)$$

If the experimental CF cross sections are available, we generate $\sigma_D^{\text{semiexpt}}$ as follows:

$$\sigma_D^{\text{semiexpt}} = \sigma_R^{\text{semiexpt}} - \sigma_F^{\text{expt}} \quad (6)$$

using $\sigma_R^{\text{semiexpt}}$ extracted from Eq. (4).

In Tables I and II, we present for measured and extracted fusion (CF and ICF), α production, DR, and total reaction cross sections for the ^{6}Li + ^{208}Pb and ^{6}Li + ^{209}Bi systems. For the ^{6}Li + ^{208}Pb system, since the cross sections σ_F^{expt} obtained from Ref. [5] fluctuate with respect to the incident energies, we extract their experimental cross sections using Wong's formula [18]. In this work, one needs to know the α-capture cross sections generated by $\sigma_{\alpha\text{-capt}}^{\text{expt}} = \sigma_d^{\text{expt}} - \sigma_{\text{excl}}^{\text{expt}}$, where the values of σ_d^{expt} and $\sigma_{\text{excl}}^{\text{expt}}$ are obtained from Ref. [12]. σ_d^{expt} and $\sigma_{\text{excl}}^{\text{expt}}$ represent the deuteron-inclusive and the α-exclusive cross sections, respectively. In particular, $\sigma_{\text{excl}}^{\text{expt}}$ is a mix of the α-d and α-p coincidence cross sections. The values of $\sigma_D^{\text{semiexpt}}$

TABLE II. The same as in Table I, but for the ^{6}Li + ^{209}Bi system. σ_F^{expt} and $\sigma_{\alpha\text{-capt}}^{\text{expt}}$ are obtained from Ref. [8], $\sigma_{\alpha\text{-prod}}^{\text{expt}}$ are obtained from Refs. [13,14], and $\sigma_R^{\text{semiexpt}}$ are obtained from Ref. [15].

$E_{\text{c.m.}}$ (MeV)	σ_F^{expt} (mb)	$\sigma_{\alpha\text{-capt}}^{\text{expt}}$ (mb)	$\sigma_{\alpha\text{-prod}}^{\text{expt}}$ (mb)	σ_D^{expt} (mb)	$\sigma_D^{\text{semiexpt}}$ (mb)	σ_R^{expt} (mb)	$\sigma_R^{\text{semiexpt}}$ (mb)	$\sigma_{\alpha\text{-prod}}^{\text{semiexpt}}$ (mb)
29.2	38	11	190	201	208	239	246	197
31.1	113	32	280	312	356	425	469	324
31.9	169	47	360	407	359	576	528	312
33.1	226	62	440	502	341	728	567	279
35.0	345	94	493	587	565	932	910	471
36.9	451	125	470	595	564	1046	1015	439
38.9	558	149	500	649	655	1207	1213	506

and $\sigma_R^{\text{semiexpt}}$ deviate from those of σ_D^{expt} and σ_R^{expt} by about 10% for the ^{6}Li + ^{208}Pb system.

For the case of the ^{6}Li + ^{209}Bi system, the α-capture cross sections are related to the production of Po and At isotopes. In Table VI of Ref. [8], the ^{215}At isotopes are due to xn evaporation and $1p$ evaporation after the $\alpha + {}^{209}\text{Bi} \rightarrow {}^{213}\text{At}^*$ process, which is an α-capture process. However, ^{212}Po isotopes are obtained from $1p + xn$ evaporation and xn evaporation after $\alpha + {}^{209}\text{Bi} \rightarrow {}^{213}\text{At}^*$ or $d + {}^{209}\text{Bi} \rightarrow {}^{211}\text{Po}^*$. Thus, the ICF cross sections for ^{210}Po and ^{211}Po are mixed up in the α-capture cross sections and the d-capture cross sections. In fact, a large fraction of the inclusive α-production cross sections are from the ICF cross sections due to the d-capture ones [14]. As a result, we take the explicitly defined α-capture cross sections, $\sigma_{\sum \text{At}+^{212}\text{Po}}$, as α-capture cross sections and we regard the rest of the incomplete fusion cross sections, $\sigma_{\sum ^{210}\text{Po}+^{211}\text{Po}}$, as α-production cross sections in this work. For the ^{6}Li + ^{209}Bi system, the values of $\sigma_D^{\text{semiexpt}}$ and $\sigma_R^{\text{semiexpt}}$ deviate from those of σ_D^{expt} and σ_R^{expt} by about 10% except for $E_{\text{c.m.}} = 33.1$ MeV. For the case of $E_{\text{c.m.}} = 33.1$ MeV, the experimental α-production cross section is relatively large compared with others [14] and our value of $\sigma_R^{\text{semiexpt}}$ shows this big difference.

On the other hand, since a ^{6}Li nucleus breaks into one α particle and one deuteron in the reaction process, it is important to investigate the contribution of the breakup channels, especially that of the α-production channel on the DR process. To investigate the effects of breakup on the direct reaction quantitatively, we introduce the experimental ratio factor given by

$$R^{\text{expt}} = \sigma_{\alpha\text{-prod}}^{\text{expt}} / \sigma_D^{\text{expt}}. \quad (7)$$

Although the resultant values of $\sigma_{\alpha\text{-prod}}^{\text{semiexpt}}$ show some deviation from $\sigma_{\alpha\text{-prod}}^{\text{expt}}$, we replace the new theoretical ratio factor R^{th} for the experimental ratio factor R^{expt} as follows:

$$\begin{aligned} R^{\text{th}} &= \sigma_{\alpha\text{-prod}}^{\text{semiexpt}} \big/ \sigma_D^{\text{semiexpt}} \\ &\approx R^{\text{expt}} = \sigma_{\alpha\text{-prod}}^{\text{expt}} \big/ \sigma_D^{\text{expt}}. \end{aligned} \quad (8)$$

Actually, we present the average of the R^{expt} (R^{th}) values over the whole energy range, and the values of R^{th} are almost the same as the values of R^{expt} in Table III and as shown in Fig. 1. This means that most of the α particles emitted by the breakup process of ^{6}Li are not captured by the target nuclei. Therefore, a large proportion of σ_D^{expt} ($\sigma_D^{\text{semiexpt}}$) is due to $\sigma_{\alpha\text{-prod}}^{\text{expt}}$ ($\sigma_{\alpha\text{-prod}}^{\text{semiexpt}}$).

One of the most interesting things about these ratios is that the R^{expt} or R^{th} values in the above barrier region are slightly suppressed in comparison with those in the below and near barrier region as shown in Fig. 1. This suppression arises from the capture of an α particle. In particular, Signorini and his colleagues [20] measured α-particle, deuteron, and proton energies emitted by the ^{6}Li + ^{208}Pb reaction at the incident energy $E_{\text{lab}} = 35$ MeV. The average energy of the α particles emitted by the ^{6}Li + ^{208}Pb reaction peaks at 21 MeV, which corresponds to 2/3 of the incident energy of ^{6}Li. The energies of the emitted α particles increase with higher incident energies of ^{6}Li. Consequently, α particles with an emission energy greater than the Coulomb barrier energy easily fuse with the target. This means that the contribution of α-production cross sections at below barrier energies is larger than that of those at the above barrier energies. Hence the suppression of α-production cross sections takes place above the barrier. Note that the Coulomb barrier energy for the $\alpha + {}^{208}$Pb reaction is about $E_{\text{lab}} = 20$ MeV [21].

TABLE III. The average values of the theoretical and experimental ratio factors, $R^{\text{th}} = \sigma_{\alpha\text{-prod}}^{\text{semiexpt}} / \sigma_D^{\text{semiexpt}}$ and $R^{\text{expt}} = \sigma_{\alpha\text{-prod}}^{\text{expt}} / \sigma_D^{\text{expt}}$. Also, we show the Coulomb barrier energies, V_B, for the ^{6}Li + ^{208}Pb and ^{6}Li + ^{209}Bi systems.

System	R^{expt}	R^{th}	V_B
^{6}Li + ^{208}Pb	0.90	0.91	30.10 [5]
^{6}Li + ^{209}Bi	0.86	0.85	29.71 [19]

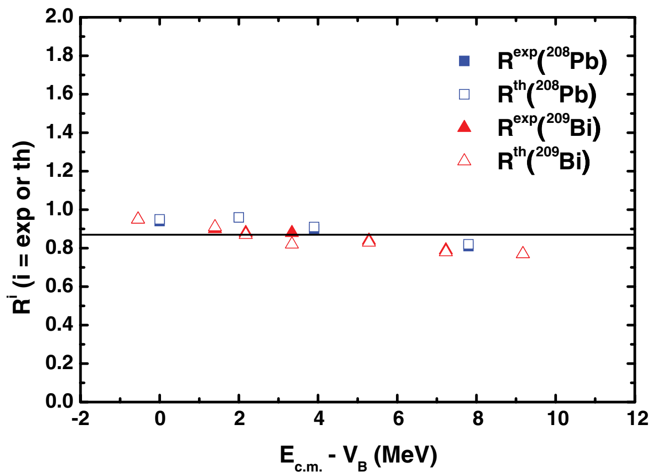

FIG. 1. (Color online) The experimental and theoretical ratio factors R^{expt} and R^{th} as functions of $E_{\text{c.m.}} - V_B$ for the ^{6}Li + ^{208}Pb and ^{6}Li + ^{209}Bi systems. The value of the solid line is 0.87.

In this report, we investigated the effect of the breakup process for the DR of a ^{6}Li projectile. In order to study this effect, we introduced the semiexperimental and experimental ratio factors by using the semiexperimental and experimental α-production cross sections and DR cross sections. Since most α particles emitted by the breakup process of ^{6}Li are not captured by the target nuclei, the values of R^{th} and R^{expt} are smaller than unity. The values of R^{expt} or R^{th} in the above barrier region are gradually suppressed since α particles above the Coulomb barrier energy are able to fuse easily with the target. In conclusion, the α-production cross sections are the main proportion of the DR cross sections. From our R^{th}, one may deduce the contribution of experimental α production.

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[1] J. J. Kolata *et al.*, Phys. Rev. Lett. **81**, 4580 (1998).
[2] E. F. Aguilera *et al.*, Phys. Rev. C **63**, 061603(R) (2001).
[3] N. Keeley, S. J. Bennett, N. M. Clarke, B. R. Fulton, G. Tungate, P. V. Drumm, M. A. Nagarajan, and J. S. Lilley, Nucl. Phys. A **571**, 326 (1994).
[4] C. Signorini *et al.*, Phys. Rev. C **67**, 044607 (2003).
[5] Y. W. Wu, Z. H. Liu, C. J. Lin, H. Q. Zhang, M. Ruan, F. Yang, Z. C. Li, M. Trotta, and K. Hagino, Phys. Rev. C **68**, 044605 (2003).
[6] C. Signorini *et al.*, Phys. Rev. C **61**, 061603(R) (2000).
[7] C. Signorini, Nucl. Phys. A **693**, 190 (2001).
[8] M. Dasgupta *et al.*, Phys. Rev. C **70**, 024606 (2004).
[9] W. Y. So and K. S. Kim, Mod. Phys. Lett. A **26**, 325 (2011).
[10] M. Kildir *et al.*, Phys. Rev. C **51**, 1873 (1995).
[11] C. Signorini *et al.*, Phys. Rev. C **61**, 061603(R) (2000)
[12] C. Signorini, T. Glodariu, Z. H. Liu, M. Mazzocco, M. Ruan, and F. Soramel, Prog. Theor. Phys. Suppl. **154**, 272 (2004).
[13] S. Santra, V. V. Parkar, K. Ramachandran, U. K. Pal, A. Shrivastava, B. J. Roy, B. K. Nayak, A. Chatterjee, R. K. Choudhury, and S. Kailas, Phys. Lett. B **677**, 139 (2009).
[14] S. Santra, S. Kailas, K. Ramachandran, V. V. Parker, V. Jha, B. J. Roy, and P. Shukla, in *Proceedings of the DAE Symposium on Nuclear Physics*, by R. K. Choudhury, D. C. Biswas, and K. Mahata (Birla Institute of Technology & Science, 2010), Vol. 55, p. 248.
[15] S. Santra, S. Kailas, K. Ramachandran, V. V. Parkar, V. Jha, B. J. Roy, and P. Shukla, Phys. Rev. C **83**, 034616 (2011).
[16] G. R. Satchler, *Introduction to Nuclear Reactions* (Wiley, New York, 1980).
[17] R. Bass, *Nuclear Reactions with Heavy Ions* (Springer-Verlag, New York, 1980).
[18] C. Y. Wong, Phys. Rev. Lett. **31**, 766 (1973).
[19] A. Diaz-Torres, I. J. Thompson, and C. Beck, Phys. Rev. C **68**, 044607 (2003).
[20] C. Signorini *et al.*, Eur. Phys. J. A **10**, 249 (2001).
[21] S. M. Lukyanov *et al.*, Phys. Lett. B **670**, 321 (2009).