STUDY OF ^{8}BE TRANSFER IN THE ELASTIC α+^{12}C SCATTERING

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Abstract: Angular distributions of the elastic α + ^{12}C scattering in range of incident energies from 65 to 240 MeV were described well in optical model with folded potentials calculated from effective nucleon-nuclen interaction. The density-dependent interaction CDM3Y6 was used to generate the optical potentials. Enhancements of cross section at large angle in 104 and 110 MeV data were assumed to be due to contributions of the ^{8}Be transfer process. We had perfromed copuled reaction channel (CRC) analyses to estimate the ^{8}Be transfer affects on the elastic α + ^{12}C scattering. Our analysis results had shown that the contrinbutions of both one-step and two-step ^{8}Be transfer process are important and necessary.

1. INTRODUCTION

The elastic α nuclear rainbow scattering attracted much attention in the 1970s because of its important role in determining unambiguously the α-nucleus optical potentials at small distances [1-4]. The elastic nuclear rainbow scattering has firstly observed in the elastic α scattering on the medium and heavy nuclei by Golberg *et al.* [1,5,6]. The appearance of the nuclear rainbow is due to the the refraction of the incident wave caused by strongly attractive nucleus-nucleus potential. Although the optical potentials of the α+^{12}C and α +^{16}O systems are not enough deep to distinguish the airy minimum from the diffractive region of Fraunhofer crossover, some optical model analysis of the elastic α + ^{12}C scattering data with various optical potentials [7,8] have shown the strong refraction with an overwhelming domination of far-side scattering in the range 40^{o}-100^{o} of the center-of-mass angles [7,8]. Such a refractive structure is enough to determine optical potential at small region, but the strong oscillation and enhancement of cross section at the largest angle (near 180°) in 104 MeV data could not describe in the optical model [7,8]. Very interesting are the elastic α +^{12}C data at 110 MeV with high precision recently measured at Jyvaskyla University cyclotron covering a broad angular region (up to $\theta_{c.m.} \approx 180^{o}$) that also demonstrated an evidence of the strong oscillating and enhancing cross section at large angle [9].

Enhancements of the cross section at the largest angles could have been explained to be due to contributions of the elastic ^{8}Be transfer cross section in a coupled reaction channel (CRC) analysis of the elastic α +^{12}C scattering data at 110 MeV by Belyaeva *et al.* [10]. Specially, the contributions of the elastic ^{8}Be transfer process included all three ^{8}Be states (as *S*, *D* and *G* states) in ^{12}C nucleus. However, this CRC analysis has taken the α spectroscopic factor to be too small in comparison with value predicted by microscopic calculations [11-13].

It should be noted that the widely used DWBA and CRC analysis in transfer reactions are assumed that the core-core potential is equal to the optical potential.

2. OPTICAL MODEL ANALYSIS OF THE ELASTIC α+ ^{12}C SCATTERING

The strongly refractive α +^{12}C scattering in the experimental data at Elab = 104, 120, 145 and 172.5 MeV have been described quite well up to center-of-mass of 100° in optical model which using folded potential based on the dependent-density nucleon-nulceon (*NN*) interaction (as CDM3Y6) [8]. In present work, we extend the previous study [8] to widely experimental data of the energies E_{lab}=65-240 MeV [14], especially recent 110 MeV data [9]. The OM calculations of the elastic scattering cross section were performed using the code ECIS97 [15]. The parameters of the WS potential for the imaginary part were adjusted by the best fit the elastic data up to center of mass angle $\theta_{c.m.} \approx 100^\circ$ at which broad bump manifests quite clearly.

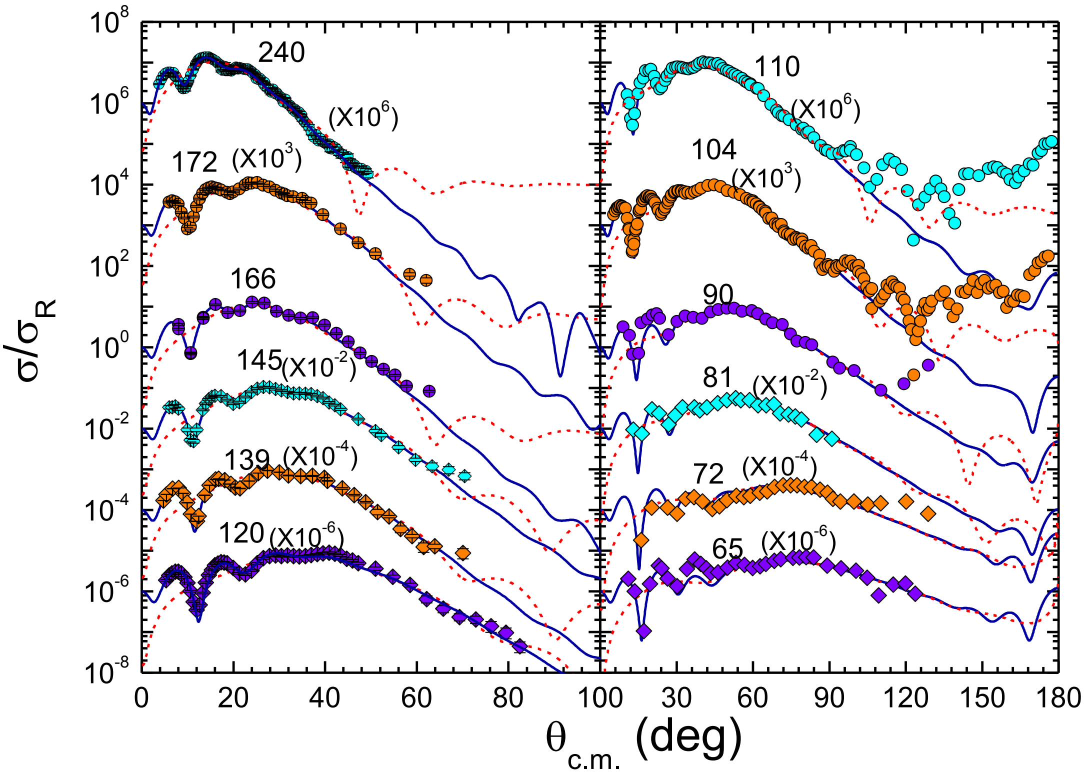

FIG. 1. The angular distribution of the differential α + ^{12}C cross section given by OM calculations (solid lines) using the real folded OP and WS imaginary OP in comparison with the experimental data measured at E_α = 65 − 240 MeV [14]. The far-side scattering cross sections are given by the same OP (dotted lines).

Figure 1 illustrates the present OM descriptions of the elastic α + ^{12}C scattering in comparison with the experimental data measured at incident energies E_{lab} = 65−240 MeV. The analyzed results have shown that the OM describles well the elastic α +^{12}C scattering up to 100° of the center-of-mass angles which cover both the quick Fraunhofer oscillation of the elastic cross section at forward angles and a widely broad of the elastic α + ^{12}C cross section at medium angles ($\theta_{c.m.} \approx$ 40°−100°). In such the strongly refractive systems, the cross section rises to maximum at near rainbow angle, then falls off rapidly and smoothly at larger angle in the most of measured data. However, the 104 and 110 MeV experimental data measured up to 180^o [4,9] had shown that the cross section starts enhancing and strong oscillations appear at the largest angle ($\theta_{c.m.} \geq 100^\circ$). The enhancement of the elastic cross section at backward angles at energies E_{lab} = 104 MeV and 110 MeV seems to result from other contributions which could not be explained in optical model (see Fig. 1). Among numerous explanations of enhancement of cross section at backward angles, an asummation of contributions from the elastic transfer process suggested by von Oertzen and Bohlen [16] is a well appropriate explanation.

3. ^{8}BE TRANSFER CONTRIBUTIONS TO LARGE ANGLE SCATTERING

To take into account the elastic ^{8}Be transfer cross section at E_{lab} = 104, 110 MeV, the optical potentials, $U_{\alpha+\,^{12}C}$, are same the OPs used in above OM analysis of elastic scattering. The core-core potentials, $U_{\alpha+\alpha}$, are adjusted to best fit the data points of the elastic α + α scattering at E_{lab} = 118 MeV [17]. In the ^{8}Be-cluster of the *p*-shell nucleons in ^{12}C, the ^{8}Be-particle can lie at three states: *S* state (L = 0), *D* state ($L=2$) and *G* state ($L=4$) with separation energies to be 7.367, 10.357 and 18.677 MeV, respectively. Therefore, the elastic ^{8}Be transfer proceeds via such a *S* wave should have the highest probability and is necessary to consider firstly. The WS depth of the ^{8}Be binding potential was adjusted to reproduce the α separation energy E_α = 7.367 MeV. The α spectroscopic factors predicted by complex scaling method (CSM) [11] was used to perform CRC calculation of the elastics ^{8}Be transfer cross section. The total elastic α + ^{12}C cross section given by the present CRC calculation in comparison with the elastic α + ^{12}C scattering data measured at E_{lab}= 104 and 110 MeV [4,9] are shown in Fig. 2. One can see that at large angles ($\theta_{c.m.} > 127^\circ$), the elastic scattering cross section is so small in comparison with experimental data that it can be neglected and the elastic ^{8}Be transfer cross section is dominant.

The detailed CRC analysis of the elastic α + ^{12}C scattering data at 104 and 110 MeV have shown that the strong oscillations of the elastic ^{8}Be transfer at backward angle includes the elastic transfer of the ^{8}Be-cluster at the *S*, *D* and *G* states (see Fig. 2). The present percent ratio of the spectroscopic factors with *S*, *D*, and *G* states is very close to the percent ratio predicted by microscopic calculations [11,12]. In particular, this percent ratio is very close to the value which obtained from DWBA analysis of the direct ^{8}Be pickup in the ^{24}Mg(α,^{12}C)^{16}O reaction at E_{lab} = 90.3 MeV [18]. A recent CRC analysis of the data measured at E_{lab} = 110 MeV also showed important contributions of the ^{8}Be-cluster at *S*, *D* and *G* states in the elastic ^{8}Be transfer ^{12}C(^{4}He,^{12}C)^{4}He process [10]. Those α spectroscopic factors are too small in comparison with both obtained from experimental values [18-20] and predicted by theoretical calculations [11-13]. In our CRC analysis, the α spectroscopic factors for each of the ^{8}Be states in ^{12}C are appropriate to the extracted value in the ^{24}Mg(α,^{12}C)^{16}O reaction [18]. We note that ^{8}Be-particle being resonance states at all level is easily disassociated to two α, so the sequential two-step α transfer might has contribution to the elastic ^{8}Be transfer.

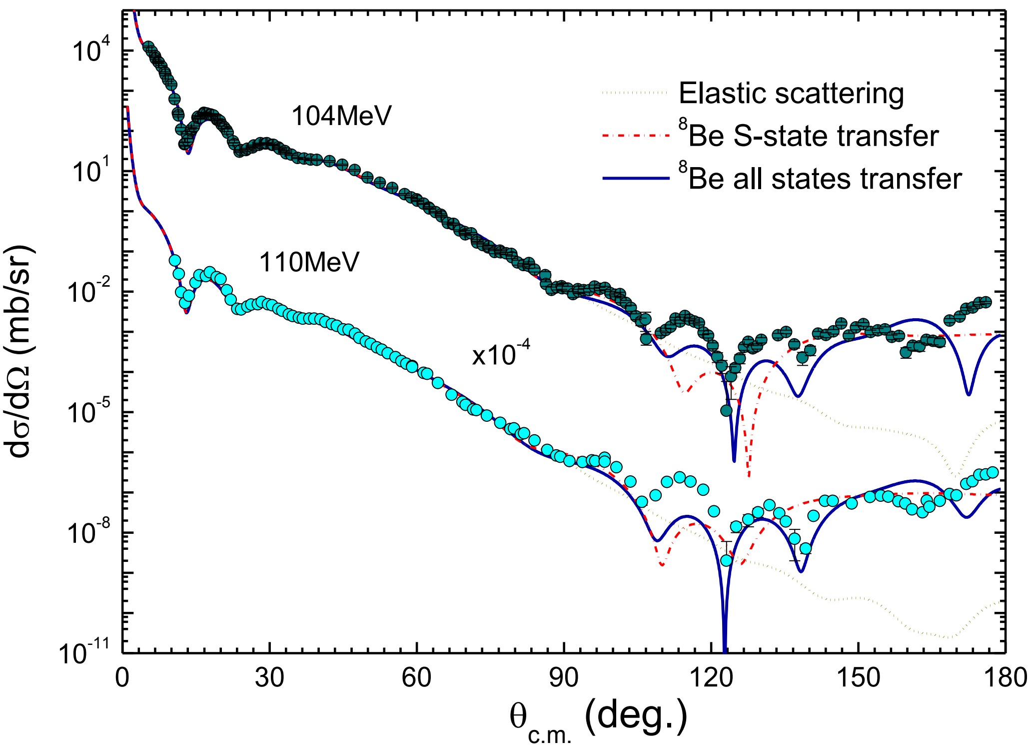

FIG. 2. CRC description (solid lines) of the elastic α + ^{12}C data measured at E_{lab} = 104 and 110 MeV [4, 9]. The elastic scattering cross section (dotted lines) is obtained from OM calculations. The elastic ^{8}Be transfer cross section (dotted-dashed lines) is given by CRC calculations with the *α* spectroscopic factor based on CSM calculations [11].

At the intermediate partition of the sequential two-step *α* transfer process of the α + ^{12}C system, the ^{8}Be-particles might lie at three states (*S*, *D* and *G* states) which corresponding to spin-parity 0^+, 2^+ and 4^+, respectively. Thus, there are total nine channels at the intermediate partition (^{8}Be+^{8}Be) which corresponding to the all states in two ^{8}Be nuclei. In our work the optical potentials of ^{8}Be+^{8}Be system for each channel are taken as WS form with parameters to those of the ^{9}Be+^{8}Be potential [21]. The core-core $U_{\alpha\,+\,8\mathrm{Be}}$ potentials are same geometry as the $U_{\alpha\,+\,9\mathrm{Be}}$ potential at E_{lab} = 65 MeV ($E_{c.m.}$ = 45 MeV) which was adjusted to give the best fit the data points of the differential α + ^{9}Be cross section [22] with strength potential V_0 = 164.2 MeV. The *α*-spectroscopic factor for the *α* + *α* overlap in the ^{8}Be nucleus at 0^+, 2^+ and 4^+ states were taken to be unit. The relative-motion wave functions of the *α*+*α* system in three states of the ^{8}Be were assumed to be same and were generated from the Woods-Saxon (WS) geometry fixed by R_V = 3.75 fm near value of 3.2 fm [23], a_V = 0.65 fm. The WS depth is adjusted to reproduce the quasi-separation energy of 0.01 MeV.

Results of CRC sequential two-step *α* transfer calculations in comparison with experimental data measured at *E*lab = 104 and 110 MeV [4,9] are illustrated in Fig. 3. The dotted lines are the coherent sum of the elastic scattering and the direct (one-step) ^{8}Be transfer cross section. The dashed lines are coherent sum of the elastic scattering and the sequential (two-step) ^{8}Be transfer cross section. The solid lines are coherent sum of the elastics and these two processes. It is seen that the two processes are both quite important. The slope of the angular distributions for one-step process is qualitatively similar to the experimental data, while the contribution of the two-step process enhances the total cross section. Althought the amplitudes corresponding to two processes do interfere destructive oscillatory pattern at center-of-mass angle of 168°, the contribution of the two-step process is necessary to improve the descriptive quality of the elastic α + ^{12}C scattering data especially at 104 MeV [4].

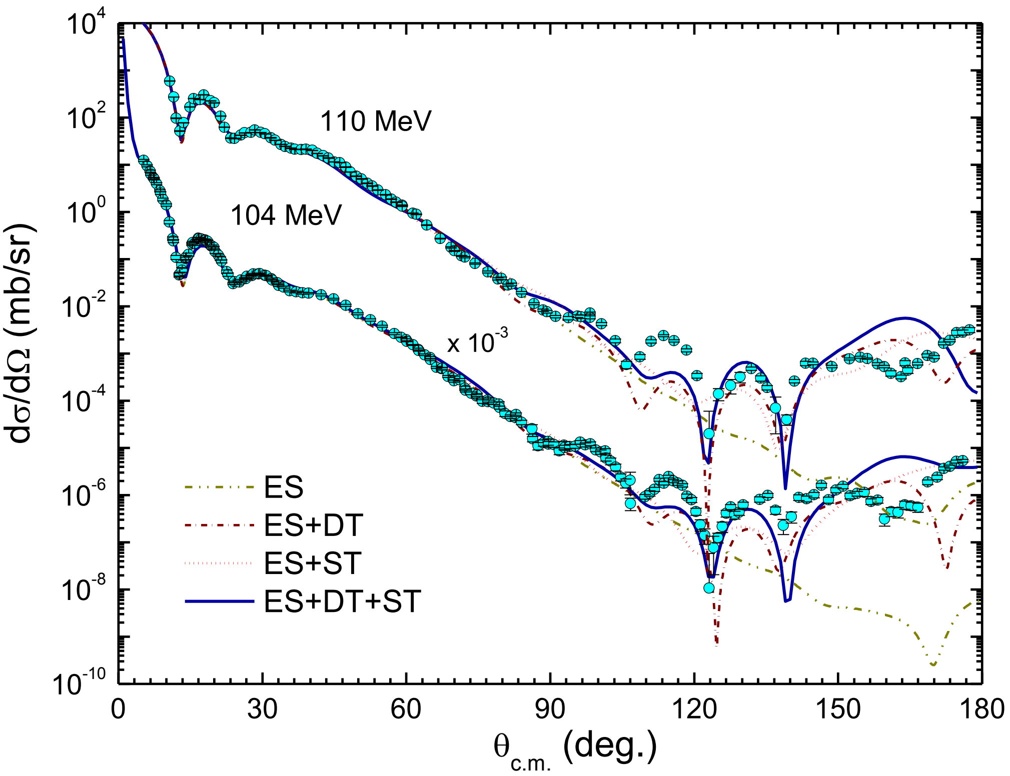

FIG. 3. Results of CRC calculations, with the one-step (direct transfer - DT) and two-step (sequential transfer - ST) ^{8}Be transfer amplitudes added coherently to that of the elastic scattering (ES), in comparison with the elastic α + ^{12}C scattering data measured at E_α = 104 MeV [4] and 110 MeV [9].

4. CONCLUSION

Large-angle scattering of α + ^{12}C system at incident energies of 104 and 110 MeV were described well by adding the elastic ^{8}Be transfer cross section. The calculated CRC results have shown that the enhanced backward-angle oscillations of the elastic α + ^{12}C scattering cross section observed at E_{lab} = 104 and 110 MeV [4, 9] is due to the important contributions of the elastic ^{8}Be transfer cross section, while the elastic scattering cross section at forward angles were described well in double folding model which using the density-dependent nucleon-nucleon interaction CDM3Y6 [8]. In the present CRC calculations the transfer process of ^{8}Be-particle at the *S*, *D* and *G* states were involved in and had large effects on reasonable with experimental points. We also concluded that both the direct one-step transfer and the sequential two-step transfer processes are necessary.

5. ACKNOWLEDGMENTS

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References

[1] D. A. Goldberg and S. M. Smith, *Phys. Rev. Lett.* ***29****, 500 (1972).*

[2] L. W. Put, A. M. J. Paans, *Nucl. Phys A* ***291****, 93 (1977).*

[3] M. Yasue *et al.*, *Nucl. Phys A* ***394****, 29 (1983).*

[4] G. Hauser, R. Lohken, H. Rebel, G. Schatz, G. W. Schweimer, and J. Specht, *Nucl. Phys. A* ***128****, 81 (1969).*

[5] D. A. Goldberg, S. M. Smith, H. G. Pugh, P. G. Roos, *Phys. Rev. C* ***7****, 1938 (1973).*

[6] D. A. Goldberg, S. M. Smith, and G. F. Burdzik, *Phys. Rev. C* ***10****, 1362 (1974).*

[7] A. Ingemarsson, A. Auce, and R. Johansson, *Phys. Rev. C* ***49****, 1609 (1994).*

[8] Dao T. Khoa, *Phys. Rev. C* ***63****, 034007 (2001).*

[9] A. S. Demyanova *et al.*, *Phys. At. Nucl.* ***72****, 1611 (2009)*

[10] T. L. Belyaeva, A. N. Danilov, A. S. Demyanova, S. A. Goncharov, A. A. Ogloblin, and R. Perez-Torres, *Phys. Rev. C* ***82****, 054618 (2010)*

[11] D. Kurath, *Phys. Rev. C* ***7****, 1390 (1973).*

[12] C. Kurokawa and K. Kato, *Nucl. Phys. A* ***792****, 87 (2007).*

[13] Yoshiko Kanada-En'yo, *Progress of Theoretical Physics, vol. 117, No. 4, 655 (2007)*

[14] T. L. Belyaeva, A. N. Danilov, A. S. Demyanova, S. A. Goncharov, A. A. Ogloblin, and R. Perez-Torres, *Phys. Rev. C* ***82****, 054618 (2010)* and references in there.

[15] J. Raynal, in *Computing as a Language of Physics* (IAEA, Vienna, 1972) p.75; J. Raynal, coupled-channel code ECIS97 (unpublished).

[16] W. von Oertzen and H.G. Bohlen, *Phys. Rep.* ***19C****, 1 (1975).*

[17] R. E. Warner *et al.*, *Phys. Rev. C* ***49****, 1534 (1994)*

[18] F. D. Becchetti, K. T. Hecht, J . Janecke and D. Overway, *Nucl. Phys. A* ***339****, 132 (1980).*

[19] MD. A. Rahman and U. Strohbuscha, *Nuovo Cimento A* ***99****,329 (1988).*

[20] C. Dettraz, H. H. Duhm and H. Hafner, *Nucl. Phys. A* ***147****, 488 (1970).*

[21] V. O. Romanyshyn *et al.*, *Phys. Rev. C* ***79****, 054609 (2009).*

[22] Subinit Roy, J. M. Chatterjee, and H. Majumdar, S. K. Datta, S. R. Banerjee, S. N. Chintalapudi, *Phys. Rev. C* ***52****, 1524 (1995).*

[23] G. J. Wozniak, D. P. Stahel, Joseph Cerny, and N. A. Jelley, *Phys. Rev. C* ***14****, 815 (1976).*