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Sub-barrier Fusion and Neutron Transfer with Positive Q-value

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Abstract. Fusion excitation functions of ^{16}O+^{76}Ge and ^{18}O+^{74}Ge have been measured with high precision at energies near and below the Coulomb barrier. Coupled-channels calculations including inelastic excitations well reproduce the experimental fusion excitation functions and the corresponding barrier distributions. There is no evidence that the two-neutron transfer with positive Q-value plays a role in the ^{18}O+^{74}Ge fusion. A systematic investigation on ^{18}O induced fusions has been performed to understand the roles of two-neutron transfers with positive Q-values, but the effects are inconsistent. No definitive conclusion can be made at present and further studies are strongly desired.

1 Introduction

Heavy-ion fusion is a complex process implying the rearrangement of all the nucleons in reactants, which provides an important insight into the dynamics. The coupled-channels (CC) effect plays a crucial role at near- and sub-barrier energy region. Relating transfer reaction to fusion is a complex procedure, which requires one to comprehensively understand the mechanisms of both transfer and fusion. Neutron transfer may take place at a large distance and form a neutron flow, resulting in fusion enhancement. Further, for the positive Q-value neutron transfer (PQNT), the kinetic energy of reaction system may increase, leading to fusion enhancement too. For the above reasons, the effect of the PQNT on fusion, especially at sub-barrier energies, becomes an important topic of current interest.

The idea of PQNT effect dates back to an experimental observation. In 1980, Beckerman *et al.* [1] measured the fusion excitation functions of ^{58,64}Ni+^{58,64}Ni and found that the fusion of the cross system ^{58}Ni+^{64}Ni is strongly enhanced compared to other two systems. Three year later, Broglia *et al.* [2] proposed that two-neutron ($2n$) transfer should be responsible for this enhancement. Later, Ackermann *et al.* [3] confirmed that the direct $2n$ transfer with $Q = 3.9$ MeV, rather than the sequential neutron transfers, takes effect on the fusion enhancement of ^{58}Ni+^{64}Ni. Following these pioneer works, systematic researches into systems of ^{28}Si+^{94}Zr [4], ^{32}S+^{96}Zr, ^{100}Mo, ^{110}Pd [5–7], ^{40}Ca+^{48}Ca, ^{96}Zr, ^{124,132}Sn, ^{134}Te [8–13] and so on, have confirmed fusion enhancements due to the PQNT channels by comparison with their reference systems. Further, the role of multi-nucleon transfers has been extensively discussed in Ref. [14].

However, the relationship between fusion and neutron transfer is actually not clear yet. Theoretically, other mechanisms can also explain the experimental result without including the PQNT effect explicitly. For example, both the fusion enhancement and the shape of barrier distribution (BD) of

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^{40}Ca+^{96}Zr can be well reproduced by a semi-classical model, mainly considering the coupling of the strong 3^- vibrational state of ^{96}Zr [15]. Experimentally, negative results have been also reported. In the systems of ^{18}O+^{92}Mo, ^{118}Sn [16, 17], ^{36}S+^{58}Ni [18], ^{58}Ni+^{100}Mo, ^{124}Sn [19–21], and neutron-rich ^{132}Sn+^{58}Ni [22], the fusion cross sections do not show additional enhancements correlated with the PQNT channels at sub-barrier energies .

In order to further investigate the PQNT effect and to simplify the question, ^{16}O+^{76}Ge and ^{18}O+^{74}Ge systems were selected, considering the main difference in the two systems comes from the transfer reaction channel. The ^{18}O+^{74}Ge system possesses a *2n* transfer channel with positive *Q*-value of 3.75 MeV, while the ^{16}O+^{76}Ge system has no such reaction channel.

2 Experimental procedures

The experiment has been performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy, Beijing, China. Collimated ^{16,18}O ($q = 5^+$) beams with an intensity of 20-30 pnA were used to bombard the ^{76,74}Ge targets. Beam energies were varied only downward in the range of 61-38 MeV in order to reduce the magnetic hysteresis. The ^{74}Ge (99.7% enriched) and ^{76}Ge (99.9% enriched) targets were 120 μg/cm^2 thick evaporated onto 30 μg/cm^2 carbon foil backing and 50 μg/cm^2 thick evaporated onto 20 μg/cm^2 carbon foil backing, respectively. Four silicon detectors, placed symmetrically at 20° (right-left and up-down) with respect to the beam direction, were used to monitor the Rutherford scattering and to provide a normalization of the fusion cross section.

Fusion evaporation residues (ERs) were separated from the beam-like particles (BLPs) by using an electrostatic deflector setup [23]. It is composed of two pairs of electrodes followed by time-of-flight (TOF) versus E detector telescopes with two micro-channel plate (MCP) detectors and a final 48×48 mm^2 square Si detector. Particles from the target were selected before entering the electric fields by an entrance collimator of 2.5 mm in diameter, corresponding to an opening angle of 0.76°.

ER angular distributions were measured in the range from -5° to 13° with a step of 1° for ^{16}O+^{76}Ge at E_{lab} = 44.38 MeV as well as ^{18}O+^{74}Ge at E_{lab} = 45.40 and 40.39 MeV, respectively. Their shapes do not change appreciably with the beam energy and give an overall width of 4.3° symmetrical about 0°. The angular distributions can be fitted by a single Gaussian function. For most of energies, differential cross sections were measured only at 3°. Fusion cross sections were obtained by integration of the angular distribution and normalized by the Rutherford scattering counted by the four Si monitors. Meanwhile, corrections were made for the solid angles and transmission efficiencies.

3 Results and discussions

Fusion excitation functions of ^{16}O+^{76}Ge and ^{18}O+^{74}Ge have been obtained with overall statistical uncertainties of about 1%. In order to understand CC effects in the two systems, CCFULL [24] calculations with all order couplings have been performed by using the well-known Akyüz-Winther (AW) potential [25].

For comparison, reduced fusion excitation functions as a function of reduced energy are plotted in Fig. 1 (left panel). For ^{16}O+^{76}Ge, the low-lying vibrational 2^+ and 3^- one-phonon states of the target, the same ones used in Ref. [26], and their mutual excitations were included in the calculations (see dashed lines in the figure). The higher excitation energy of the 3^- one-phonon state in ^{16}O only produces an adiabatic potential renormalization without affecting the structure in the BD [27], and, consequently, was not included in the CC calculations. For the ^{18}O+^{74}Ge system, the lowest 2^+ two-phonon state as well as 3^- one-phonon vibrational state of the target and the 2^+ state of ^{18}O were included in the CC calculations (solid lines in Fig. 1). In order to check the effect of neutron transfer channel, CC calculations were also performed by including the additional $2n$-pair transfer channel with the Q-value of 3.75 MeV and the nominal coupling strength of 0.7 MeV (dash-dotted lines). It should be pointed out that the CCFULL treats transfer couplings in a very simplified way. Corresponding BDs are also presented in Fig. 1 (right panel). In the second derivative procedure for extracting BD, the energy step was taken as 2 MeV. Details of the analysis can be found in Ref. [28].

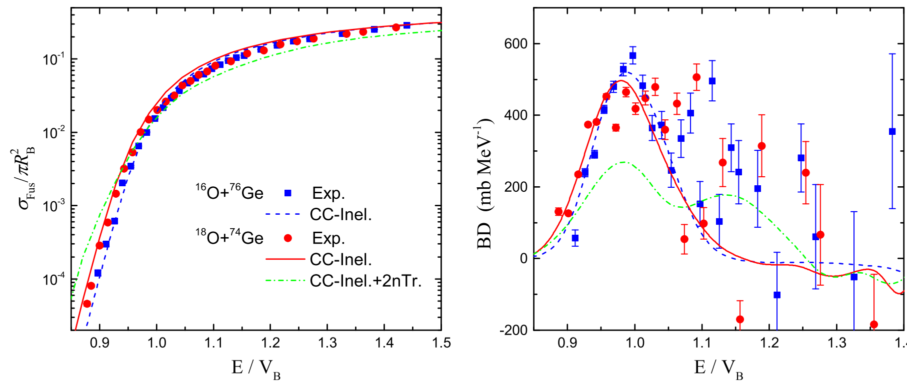

Figure 1. (Color online) Experimental reduced fusion excitation functions (left panel) and barrier distributions (right panel) compared with coupled-channels calculations. See context for details.

From Fig. 1, one can see that: i) both experimental fusion excitation functions and BDs are almost identical for the two systems. ii) CC calculations including only the inelastic coupling (dashed and solid lines for ^{16}O+^{76}Ge and ^{18}O+^{74}Ge, respectively) are in good agreement with experimental fusion excitation functions. iii) CC calculations with an extra $2n$-pair transfer for ^{18}O+^{74}Ge (dash-dotted lines) deviate from the experimental data. From the above analyses, one may conclude that there is no evidence showing the PQNT effect on fusion for ^{18}O+^{74}Ge within the measured energy region.

For ^{74}Ge(^{18}O,^{16}O)^{76}Ge, the experiment performed by Bond *et al.* [29] showed that the transfer mainly populates the ground state at 27° with a beam energy of 75 MeV. It denotes that the $2n$ stripping channel is kinematically matched and should enhance sub-barrier fusion, as expected from ground-state to ground-state transfer at the sub-barrier region [30]. However, the results do not show such an effect by the comparison of the experimental data with CC calculations. Similarly, ^{A}Sn(^{18}O,^{16}O)$^{A+2}$Sn also shows enhanced ground state transition [31], but no corresponding fusion enhancement exists.

For most of ^{18}O induced reactions, there exist $2n$ transfer channels with positive Q-values. Systematic analysis of available data shows that most of the systems show no PQNT effect on fusion except the ^{18}O+^{58}Ni system. It is advantageous to use ^{18}O as projectile to investigate the influence of the $2n$ transfer channel on fusion. To measure fusion excitation functions of these systems with high accuracy may be helpful to clarify the relevant dynamic mechanisms. On the other hand, transfer couplings also depend on the states and Q-values populated by transferred nucleons and transfer form factors. Therefore, direct measurements of $2n$ transfers are also meaningful for correlating the two aspects of fusion and transfer channels and constraining the transfer coupling strengths.

4 Summary

In summary, fusion excitation functions have been measured for ^{16}O+^{76}Ge and ^{18}O+^{74}Ge at energies near and below the barrier. The BDs were extracted from the second derivative of fusion excitation functions. The fusion behaviour of the two systems shows striking similarities and can be reproduced well by the CC calculations with low-lying inelastic states being taken into account. No obvious PQNT effect was observed in the ^{18}O+^{74}Ge system, which exceeds our expectation.

The role of neutron transfer channels in fusion process is complex and still an open question. The controversial PQNT effect on fusion has presented a challenge for the theoretical understanding of the relevant reaction mechanism. It is highly desired to search for the origin of the inconsistency of the PQNT effect on fusion and to achieve a comprehensive description.

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