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Role of Neutron Transfers in Initiating Near-barrier Fusion of Heavy-ions

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Abstract: The effect of neutron transfers on near- and sub-Coulomb-barrier fusion of heavy-ions is still a complicated and controversial problem. This paper reviews the recent experimental results of the fusion excitation functions of several typical systems, which have been measured by using an electrostatic deflector setup at the HI-13 tandem accelerator of CIAE. Both the neutron pickup and stripping effects were studied. Moreover, a self-consistent method to reliably isolate the transfer effect quantitatively based on the coupled-channels calculation is proposed. These studies give a further support for the neutron transfer effect on sub-barrier fusion of heavy-ions and its complexity. Further experimental and theoretical studies are needed for clarifying the relevant reaction mechanisms.

Key words: near-barrier fusion of heavy-ion; reaction dynamic; coupled-channels effect; positive Q-value neutron transfer effect

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1 Introduction

Heavy-ion fusion reaction at the Coulomb-barrier ($V_{\rm B}$) energy region has been widely studied[1−7] but is still not yet completely understood. Fusion is a complicated process that brings two separate nuclei to form a single equilibrated compound nucleus (CN). This process involves the complex mass rearrangement between the two reacting nuclei and therefore the basic problem of quantum tunneling. Besides the fundamental interest in the reaction mechanism, the fusion reaction of heavy-ions is also useful for the synthesization of superheavy elements (SHE)[8−10] and the nucleosynthesis[11] as well as X-ray superburst[12] in nuclear astrophysics.

For lighter heavy-ion reactions, the experimental fusion data can be well described[7] by the one-dimensional barrier penetration model (BPM), stemming from Gamow's explanation[13] for the α-decay of heavy nuclei, with transmission coefficients derived from the Hill-Wheeler formalism[14] where the potential is the sum of repulsive Coulomb and attractive nuclear potentials depending only on the relative distance. Wong extended this approach[15] to take into account target deformation by adopting an approximation of inverted harmonic-oscillator potential, which is usually called Wong model.

Later, the sub-barrier fusion enhancement phenomenon[16] in comparison to the prediction of one-dimensional barrier penetration model was found for the heavier systems. The subsequently proposed structured fusion barrier distribution[17], which is extracted from the precise and smooth fusion excitation function[18], means that the dynamics of heavy-ion reactions at energies near the Coulomb barrier is intimately linked to the structure of the two colliding nuclei, which is usually described by using the coupled-channels (CC) model[19]. This means coupling of the relative motion of the colliding nuclei to several nuclear intrinsic motions. The fusion barrier distribution[17] extracted from the high precision experimental fusion data can more intuitively reflect the specific coupling mechanisms. Thus the sub-barrier fusion of heavy-ions offers a platform for clarifying the general problem of quantum tunneling in the presence of couplings.

Usually, the major coupling factors that have been identified are the permanent deformation[16, 20], low-lying collective excitation[21] and neutron transfer[22−25] for the tightly bound systems. The present hot topics for near-barrier fusion reaction of the medium-mass systems mainly are the following three

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aspects: (1) The nucleon transfer effect, especially for the neutron transfers[22–24]. The theoretical consideration for the transfer effect is difficult due to the complexity of the transfer reaction itself and of the corresponding coupling to transfers. (2) The coupling to the breakup states for the weakly bound systems, the experimental study is difficult and the corresponding conclusions are still inconsistent[1, 4, 26–29] and the theoretical descriptions are still premature and conflicting[30–32]. The most powerful theory to calculate fusion cross sections of the weakly bound system is the Continuum-Discretized Coupled-Channels (CDCC) method[33]. (3) The deep-sub-barrier fusion hindrance[34], compared to the CC calculation, which has great importance for the reaction mechanisms[35, 36] and astrophysics[37].

Up to now, many theoretical models[38–44] have been proposed and applied to study the near-barrier fusion process of heavy-ions. Here we focus on the transfer effect in fusion. Neutral neutron transfer effect is expected to be important at the concerned sub-barrier energies. Compared to the neutron transfer effect, the effect of proton transfer at low energies is expected to be minor due to the Coulomb repulsion and can be ignored[45]. The $+Q$ neutron transfer effect on sub-barrier fusion enhancement was proposed by Broglia *et al.*[46, 47] by analyzing the fusion data of ^{58}Ni+^{64}Ni with a ground-state transfer Q-value ($Q_{\rm gs}$) of Q_{+2n}=3.9 MeV. Measurement of quasi-elastic neutron transfer for ^{58}Ni+^{58,64}Ni[48] also confirmed this suggestion. Afterwards this topic has been widely studied[2]. Nucleon transfer was suggested[49, 50] as an important doorway to fusion by studying the correlation of the fusion and the transfer cross section experimentally. It was pointed out[49] that the transfer reactions which occur at distances not so far from the Coulomb barrier position are the natural candidates to behave as a doorway to fusion.

A schematic model of the influence of transfer on fusion was developed in the early period by Stelson[51]. For the CC method, CCFULL[19] approach with a macroscopic pair-transfer coupling[52, 53] between the ground states is widely used and will be introduced in the following. The refined CC approach that includes the effects of nucleon transfers as an independent degree of freedom was also developed[54]. A different approach is the microscopic time-dependent Hartree-Fock (TDHF) theory[55–57]. TDHF now can make parameter-free predictions of heavy-ion fusion excitation functions, where both the surface excitations and nucleon transfer are automatically considered at the mean field level. TDHF method also allows the response of the reacting nuclei to change self-consistently as the nuclei start to overlap. It is more promising for a comprehensive description of the relevant reaction processes. It should be pointed out that in this calculation the neutron transfers for ^{40}Ca+^{48}Ca occurs mainly inside the Coulomb barrier[58]. Very recently, the first microscopic evidence of the fusion enhancement due to coupling to transfer channels was given by Godbey *et al.*[59], where the effect of isospin (isovector) dynamics results in the thinning of the barrier and thus enhances the sub-barrier fusion cross sections. By the way, the novel superfluidity effect of hindering fusion reaction was shown[60] within symmetry unrestricted time-dependent density functional theory very recently.

The effect of neutron transfers is always interesting since 1980 especially with the advent of the more intense neutron-rich radioactive beams[61–64] in recent years. However, in spite of a longstanding debate[2, 6, 65–67], the experimental conclusions are still inconsistent and the relevance of transfer channels to sub-barrier fusion is not yet clarified. One of the unexpected experimental results is that the near-barrier fusion of Sn+Ni shows a similar trend[68] in spite of their very different neutron transfer $Q_{\rm gs}$-values.

In this contribution, some relevant experimental studies performed at China Institute of Atomic Energy (CIAE) and CC calculations by using the code CCFULL[19] for near-barrier fusion of ^{32}S+^{90,94,96}Zr, ^{18}O+^{74}Ge and ^{18}O+^{58}Ni will be introduced in Sec. 2. Further, a self-consistent method to reliably isolate the neutron transfer effect quantitatively is given in Sec. 3. In Sec. 4, summary and conclusions are presented.

2 Recent fusion experiments at CIAE

For the medium-heavy systems, the formed excited compound nucleus de-excites by evaporating light particles and emitting γ-rays, without fission, at the near-barrier energy region[69]. Therefore, the measured fusion evaporation cross section is equal to the fusion cross section. The corresponding experimental methods[67, 70–72] for measuring the cross sections of the evaporation residues have been developed. Here, the cross sections of fusion evaporation residues have been measured by using an electrostatic deflector[73] at energies near the Coulomb barrier with the beams of the HI-13 tandem accelerator of CIAE.

The electrostatic deflector setup deflects the different reaction products according to the difference in electrical rigidity (η) by using the electrostatic field first, mainly for suppressing the number of beam-like particles to the following detectors. Then to roughly identify the incoming reaction products by using time-of-flight (TOF) detectors of micro-channel plate (MCP) and an energy detector of silicon (Si), that is the usual TOF-E method for mass identification. Usually, the focused beam intensity is about several pnA and the target thickness is about 50 μg/cm^2 with 25 μg/cm^2 carbon backing for a good measurement condition.

2.1 ^{32}S+^{90,94,96}Zr

Sub-barrier fusion enhancement due to multi-neutron pickup has been observed in many systems[22, 23, 74–77]. One of the typical systems that has been studied widely possibly relevant to neutron transfer effect is ^{40}Ca+^{94,96}Zr[77–81]. The fusion excitation function for typical ^{40}Ca+^{96}Zr shows additional enhancement and it was ascribed to the strong influence of neutron transfer channels[77]. Large neutron transfer cross sections are found for ^{40}Ca+^{96}Zr at energies near the Coulomb barrier[78], which support the argument of strong transfer coupling effect. And further, Stefanini *et al.*[79] give a strong support for the neutron transfer effect from a systematic purely experimental comparison. Later, Zagrebaev[80] gives a good description for the data by using a simplified semi-classical model which considers the sequential multi-neutron transfers. However, Pollarolo and Winther[81] ascribe the fusion enhancement to the strong 3^- state of ^{96}Zr based on a semi-classical theory.

^{32}S+^{90,94,96}Zr were studied for further checking this effect, in which ^{32}S+^{90}Zr without $+Q_{\rm gs}$ multi-neutron pickup channels was measured for a comparative study (as a reference). The fusion excitation functions[74, 75] measured at near-barrier energy region are shown in Fig. 1 and the strong isotopic effect can be observed.

The coupled-channels code CCFULL[19] taking into account the multi-dimensional quantum tunneling, due to the collective inelastic channels, is used for the following theoretical calculations. For CCFULL, a vibrational coupling in the harmonic limit and a rotational coupling with a pure rotor are treated and the finite excitation energies is considered. The fusion process is predominantly governed by quantum tunneling over the Coulomb barrier was assumed. The program CCFULL includes the couplings to full order and thus it does not introduce the expansion of the coupling potential. Therefore the no-Coriolis (isocentrifugal) approximation is employed to reduce the dimension of coupled-channels equations. The incoming wave boundary condition inside the Coulomb barrier is employed and a barrier penetrability is calculated for each partial wave.

The single-channel (SC) and CC calculations considering only the inelastic couplings for ^{32}S+^{90,94,96}Zr are shown in Fig. 1. Double-phonon excitations for the reactants are taken into account. It shows that the CC calculations only including the inelastic coupling effect underestimate the sub-barrier fusion cross sections of ^{32}S+^{94,96}Zr, with many $+Q_{\rm gs}$ neutron pickup channels, although it reproduces well for ^{32}S+^{90}Zr. This gives a further evidence for the enhancement effect relating to $+Q_{\rm gs}$ neutron transfers. But, there is also a diverse argument that the sub-barrier fusion enhancement for ^{32}S+^{96}Zr is due to the increased deformation of the intermediate reactants after two-neutron (2n) pickup based on the quantum diffusion approach[82]. The underlying physical mechanism still needs to be confirmed.

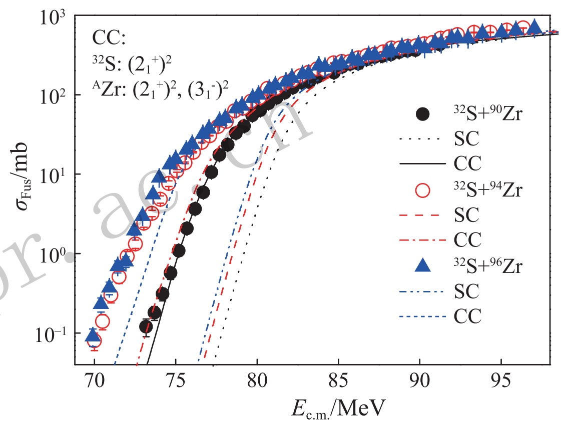

Fig. 1 (color online) The experimental fusion data of ^{32}S+^{90,94,96}Zr, the CC calculations only include the inelastic coupling effects.

Many other systems, such as ^{40}Ca+^{48}Ca[83, 84], ^{40}Ca+^{96}Zr[77], ^{124}Sn[85], ^{132}Sn[86], ^{46}Ti+^{124}Sn[87] and ^{58}Ni+^{64}Ni[22], that the sub-barrier fusion enhancement may be correlated with the positive $Q_{\rm gs}$-value neutron pickup channels have been found. While for some systems, such as ^{58}Ni+^{124,132}Sn[68] and ^{60}Ni+^{100}Mo[88], it was claimed that the fusion cross sections do not show additional enhancement at sub-barrier energies relating to these channels.

2.2 ^{18}O+^{74}Ge

For simplifying the complex problem, we turn to the simpler situation of only a $+Q_{\rm gs}$ 2n stripping channel, which has been studied not so much and therefore has no definite conclusion. The physical considerations for studying this are the suggested pairing enhancement of two-nucleon transfer[89] between heavy nuclei and the expected shorter range for the pair-transfer form factor[2], which may lead to the largest influence on fusion due to coupling to the pair transfer qualitatively.

The most available fusion data, of $^{18}O+^{92}Mo$[90], ^{A}Sn[91] and $^{36}S+^{A}Ni$[92, 93], tend to favor no sub-barrier enhancement effect due to the $+Q$ 2n stripping channel. By the way, good quality experimental fusion data for $^{18}O+^{92}Mo$ is still expected for studying the fusion mechanism. An exception is $^{18}O+^{58}Ni$ which claims strong sub-barrier fusion enhancement due to 2n stripping[80], without good experimental data. Therefore, for further studying the $+Q$ 2n stripping effect on sub-barrier fusion, more lighter systems with little inelastic coupling effect need to be studied.

As a first step, the system of $^{18}O+^{74}Ge$ with +3.75 MeV 2n stripping $+Q_{gs}$-value was selected. Fusion of $^{16}O+^{76}Ge$ was also measured for a reference. For the transfer of $^{18}O+^{74}Ge$, the previous experimental study shows obvious 2n stripping channel to the ground state[94]. Experimentally, the fusion of the two systems $^{16}O+^{76}Ge$ and $^{18}O+^{74}Ge$ was measured for a comparative study. Additionally, the near-barrier fusion of $^{16}O+^{76}Ge$ has already been well measured[95] and can be also used as a check for our data.

The experimental fusion results for the two systems are shown in Fig. 2. The CC calculation only including the inelastic coupling reproduces well the overall experimental trend for $^{18}O+^{74}Ge$. While the CC calculation result (short-dashed line), including a neutron pair-transfer with Q_{gs}-value of +3.75 MeV and a nominal coupling strength (F_{tr}) of 0.7 MeV, deviates from the overall experimental trend for $^{18}O+^{74}Ge$. According to the comparison with the CC calculation result, it shows no sub-barrier fusion enhancement for $^{18}O+^{74}Ge$ at the measured energy region[96].

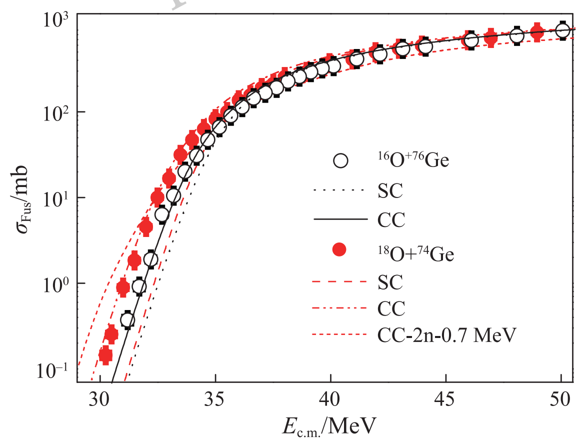

Fig. 2 (color online) The fusion excitation functions for $^{16}O+^{76}Ge$ and $^{18}O+^{74}Ge$.

2.3 $^{18}O+^{58}Ni$

As pointed out before, the near- and sub-barrier fusion behavior of the lighter systems with higher $+Q_{-2n}$-value stripping channel is more intriguing. Compared to $^{18}O+^{74}Ge$, the typical system $^{18}O+^{58}Ni$ has a more higher Q_{-2n}-value of +8.20 MeV and Q_{-2n}/V_B of 0.26, and therefore a strong sub-barrier enhancement effect should be shown if it exists.

The near-barrier nuclear reaction of $^{18}O+^{58}Ni$ has been widely studied[97–100]. The fusion of $^{18}O+^{58}Ni$ has once been measured[97] and seems to show sub-barrier enhancement. An extensive and consistent CC analysis of the elastic, inelastic, one- and two-neutron transfer, and fusion experimental cross sections was also given[98]. Rossi *et al.*[99] found that for $^{18}O+^{58}Ni$ the 2n stripping is strongly inhibited in relation to $1n$ stripping below the barrier. The experimental quasi-elastic (QEL) scattering barrier distribution of $^{18}O+^{58}Ni$ shows some structure and was explained by $1n$ stripping coupled with the 2^+ vibrational excitation of ^{58}Ni[100]. The structure of the barrier distribution also should correspond to a sub-barrier fusion enhancement.

But for a detailed study of fusion mechanism, a good quality fusion data is still needed. To this end, we remeasured the fusion excitation function of $^{18}O+^{58}Ni$ near the Coulomb barrier energy region, which extends to lower energies than the previous data. Fusion of $^{16}O+^{58}Ni$ was also measured for a reference.

The present preliminary experimental fusion excitation function for $^{18}O+^{58}Ni$ is shown in Fig. 3. For comparison, the previous experimental fusion data for $^{18}O+^{58}Ni$ measured by Borges *et al.*[97] is also shown. It can be seen that the CC calculation considering only the inelastic coupling somewhat underestimates the experimental fusion data at lower energies, and the coupling paraments used in the CC calculation are given in Fig. 3. Zagrabev's calculation[80] (not plotted in

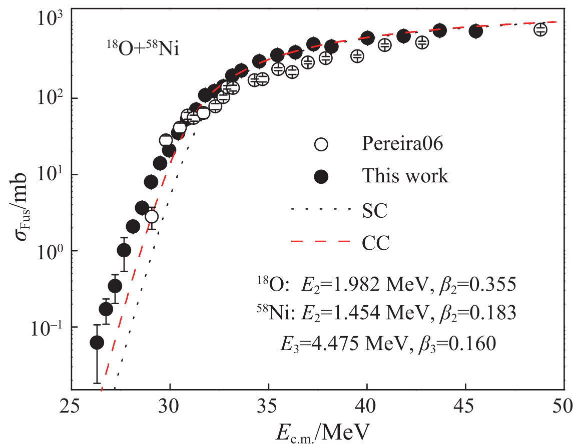

Fig. 3 (color online) The fusion excitation functions of $^{18}O+^{58}Ni$. The present preliminary experimental fusion data (filled circles), previous experimental data[98] (hollow circles) and CC calculation result are shown.

the figure) also supports the view of sub-barrier fusion enhancement for ^{18}O+^{58}Ni, but gives a higher fusion cross section prediction at lower energies based on the previous fusion data above 10-mb by using a simplified semi-classical model. That prediction is higher than the present experimental fusion data at lower-energy region.

Therefore, to solve this problem is still complicated and continuing study will help to understand the underlying reaction dynamics of heavy-ions at near-barrier energy region. To this end, more measurements for the fusion of the relevant systems are needed for a systematic study. At the same time, more experimental data for the final state population and angular distribution of ^{18}O-induced 2n stripping reaction at sub-barrier energies, which have been measured very scarcely up to now, are also needed.

2.4 Discussion

The above analysis shows a rough trend that the effect on the sub-barrier fusion enhancement is more effective for the $+Q_{\rm gs}$ neutron pickup channels compared to the neutron stripping channels. For explaining the absent effect of 2n stripping channel on fusion, Stefanini *et al.*[101] suggest a kinematic mechanism of the importance of the optimum Q-value ($Q_{\rm opt}$) in addition to the $Q_{\rm gs}$-value itself in the comparative study of ^{28,30}Si+^{58,62,64}Ni. At this point, to understand this is still difficult and the reason is not clearly known. But one fact is that after 2n stripping in the reaction ^{18}O+^{58}Ni→^{16}O+^{60}Ni, the mass asymmetry increases, and, thus the Coulomb barrier increases by about $31.50-31.13=0.37$ MeV and therefore the capture cross section should be hindered[82] only from this point.

For clarifying the transfer effect on fusion by using the CC approach, the experimental correlation study of both fusion and transfer was proposed and has been widely performed[85, 102]. Besides the theoretical macroscopic pair-transfer form factor[52, 53] and the parametrized transfer form factor[103, 104], the microscopic transfer form factor was also given[105]. The transfer form factor can be extracted[106, 107] from the experimental transfer angular distribution by using a semi-classical approximation. Normally two-nucleon transfer has a narrower form factor, or angular momentum (l) distribution, than one-nucleon transfer does[108]. That is two-nucleon transfer has a more localized form factor. Moreover, the form factor could be more localized for the the multi-step transfer mechanism[105].

One confusion should be pointed out is the two different physical pictures of two-step process and coupling-channels for explaining the nucleon transfer effect on sub-barrier fusion. From the two-step picture, Broglia *et al.*[46] explained originally the sub-barrier fusion of ^{58}Ni+^{64}Ni by invoking the 2n transfer effect. Later, Zagrebaev introduced a simplified semi-classical model[80] which takes the intermediate sequential neutron transfer channels into account and reproduced some experimental data. For the explanation of transfer reaction, Corradi *et al.*[109] ascribe the loss of transfer flux of ^{32}S+^{101}Ru to feeding more complex channels and/or fusion. This means that the enhanced fusion cross section exhausts part of the transfer cross section that should be observed experimentally.

However, coupled-channels physical picture means that more strong transfer may lead to more fusion enhancement. Recently, a universal correlation between the fusion enhancement and the strength of total neutron-transfer cross sections for systems ranging from light to heavy mass was shown[110]. The correlation of fusion with transfer channels for ^{32}S, ^{37}Cl+^{98,100}Mo, ^{93}Nb[49, 108, 111] was also studied in the CC scheme with the experimentally determined transfer form factor and coupling strength, where the deviation of the two positions of transfer and Coulomb barrier was considered[49] in explaining the transfer effect.

By the way, usually the sub-barrier fusion enhancement is considered to be correlated with the ground-state transfer Q-value, while the real reaction dynamics is that the population to the excited-states for the transfer reaction and the softness of the reactants should be also considered in a theoretical analysis. Anyhow, continuing to study the role of neutron pickup and stripping channels should help to provide insight into the different effects in the fusion.

As pointed out before, the barrier distribution contains information of the coupling mechanism. Besides the barrier distribution extracted from the fusion excitation function, Timmers *et al.*[112] also suggest another method to obtain the barrier distribution from the backward quasi-elastic excitation function, based on the two complementary processes of transmission (fusion) and reflection (QEL). But Zagrebaev[113] indicates that the so-called barrier distribution obtained from QEL is just the total reaction threshold distribution. The difference of the peak positions indeed shows for both the very-heavy systems[114, 115] and the weakly-bound systems[116] between the two processes. Therefore, the intensive comparison of the peak position and sub-barrier shape between the two kinds of barrier distributions should bear some information of the coupling mechanism.

Also isospin equilibration[59] is another important factor that should be considered. The TDHF calculation suggests a fast charge-equilibration mode in reactions of nuclei that have different values of N/Z[117]. Recently a novel argument for fusion is Wolski's simple energy scaling law[118], that is the compound nucleus nature of the heavy-ion sub-barrier fusion without (strong) fusion enhancement. Therefore, the complicated reaction mechanism is still awaiting a final conclusion.

3 Reduction for the experimental fusion data

Since the discovery of sub-barrier fusion enhancement phenomenon, many different theories have been proposed to try to explain the reaction mechanism and the physical conclusions for explaining the experimental data are model dependent. At the same time, some procedures for reducing the experimental fusion data were proposed to study the coupling effects[119–122]. The usual reduction method for the experimental fusion data, to remove the so-called geometrical effects (R_{B}^2, R_{B} is the barrier radius) and barrier height effects[119, 120], reflects the global effect of couplings. More reduction methods can be found[121]. It should be pointed out that all these reductions depend on additional parameters. Therefore, a less model-dependent method to reliably analyze the experimental fusion data is needed.

The aim here is for a reliable self-consistent method to isolate the transfer effect on fusion independent of the inelastic couplings[76], what is called residual enhancement (RE). RE is defined here as the ratio of the experimental fusion cross section (σ_{Exp}) to the CC calculation result (σ_{CC}), that is RE = $\sigma_{\mathrm{Exp}}/\sigma_{\mathrm{CC}}$. In order to avoid the entanglement of the strong breakup effect, the present study is only confined to the tightly bound systems without strong breakup effect at near-barrier energies. Only the experimental data measured by using the same setup are selected for such an analysis. Meanwhile, the same analysis procedure is used for the different data set.

Usually the coupling to the collective inelastic states can be well accounted for in the CC calculations. Therefore, the experimental fusion data of the reference systems without $+Q_{\mathrm{gs}}$ neutron transfer channels provide stringent constraints on the role of nuclear structure within a CC framework considering the mutual excitations. Then the neutron transfer effect for the relevant systems can be disentangled quantitatively based on the extracted coupling information.

The typical ^{40,48}Ca+^{40,48}Ca systems have been studied widely. ^{40}Ca and ^{48}Ca have similar neutron skins and therefore similar charge radii[123]. Therefore, the systematic Akyüz-Winther (AW) potential[124] can be reasonably used for these systems. The vibrational approximation for the excitation of the reactants for the magic ^{A}Ca was used. Here, the ^{40}Ca+^{40}Ca and ^{48}Ca+^{48}Ca systems were used as a standard reference for calibrating the inelastic coupling effect. The relevant coupling parameters considered in the CC calculations, which give the best reproduction for the two symmetric reference systems, are shown in Table 1.

Table 1 The parameters used for the considered low-lying collective excitation states in the CC calculations.

Nucleus	λ^{π}	E_{λ}/MeV	β_{λ}
^{40}Ca	3^-	3.737	0.271
	2^+	3.904	0.119
^{48}Ca	2^+	3.832	0.104
	3^-	4.507	0.175

The result for RE of ^{40,48}Ca+^{40,48}Ca is illustrated in Fig. 4. The insert shows the Q_{gs}-values of the neutron transfer channels, where 'N' represents the number of transferred neutrons. It shows that only ^{40}Ca+^{48}Ca has positive Q_{gs} for the 2n and 4n pickup channels. The RE for the two symmetric systems are almost unity for the whole energy region. The reproduction for the deep-sub-barrier experimental data means that AW potential is also suitable for the deep-sub-barrier energy region, at least for the two analyzed systems. It shows that the RE of the asymmetric ^{40}Ca+^{48}Ca deviate from unity with decreasing energy, then decrease at still lower energies. By the way, the sub-barrier fusion enhancement for ^{40}Ca+^{48}Ca due to transfer coupling was also supported[59] by the microscopic approach. This means that one is able to quantitatively isolate the effect of transfer on the fusion cross section by using such a procedure. More systems

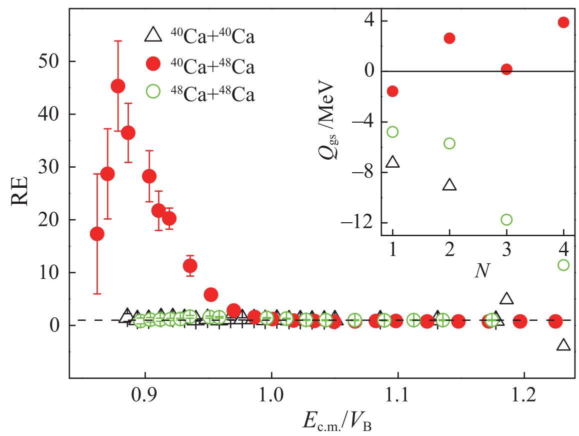

Fig. 4 (color online) RE for ^{40,48}Ca+^{40,48}Ca.

of S,Ca+Zr,Sn have been analyzed[76]. Therefore, RE should offer a quantitative test for the different theoretical models.

Meanwhile, the RE method for the symmetric systems proposes a problem for the inelastic coupling. Here, a smaller β_3=0.27 was obtained by reproducing the experimental fusion data of ^{40}Ca+^{40}Ca. The smaller β_3 of 0.27 for ^{40}Ca was also used[77, 125] for reproducing the experimental fusion data of ^{40}Ca+^{90}Zr,^{192}Os,^{194}Pt. The underlying reason is still unknown and should be studied further. Anyhow, the coming dynamic description is needed to understand the reason for the smaller β_3 value of ^{40}Ca and the complex neutron transfer effect.

4 Summary and conclusions

In summary, the study for near-barrier fusion of heavy-ions keeps a hot topic attracting intense research. The near-barrier fusion studies relevant to the neutron transfer effects at CIAE have been shown. It seems that the $+Q_{\rm gs}$ 2n stripping channel does enhance sub-barrier fusion cross sections for ^{18}O+^{58}Ni, but the enhancement is minor compared to the effect of the 2n pickup channel. Moreover, we propose a new benchmark to isolate the $+Q_{\rm gs}$ neutron transfer effect on fusion by using the extracted inelastic coupling effect from the experimental fusion data based on the CC calculations.

The present study further proves the importance of transfer channels in sub-barrier fusion enhancement in a favorable condition. At present only the static and ground-state Q-value was considered in our study, while the dynamic analysis should give deep understanding for the underlying reaction process in future. More comprehensive experimental data of both fusion and transfer will be in favor of this kind of study, especially for the effect of neutron stripping with $+Q_{\rm gs}$-value. At the same time, a comprehensive theory that can reliably describe the time-dependent dynamics of the fusion process is highly anticipated.

References:

[1] CANTO L F, GOMES P R S, DONANGELO R, *et al.* Phys Rep, 2015, **596**; 1.

[2] BACK B B, ESBENSEN H, JIANG C L, *et al.* Rev Mod Phys, 2014, **86**: 317.

[3] HAGINO K, TAKIGAWA N. Prog Theor Phys, 2012, **128**: 1061.

[4] CANTO L F, GOMES P R S, DONANGELO R, *et al.* Phys Rep, 2006, **424**: 1.

[5] BALANTEKIN A B, TAKIGAWA N. Rev Mod Phys, 1998, **70**: 77.

[6] REISDORF W. J Phys G, 1994, **20**: 1297.

[7] VAZ LOUIS C, ALEXANDER JOHN M, SATCHLER G R. Phys Rep, 1981, **69**: 373.

[8] OGANESSIAN YU TS, *et al.* Phys Rev C, 2011, **83**: 054315.

[9] HOFMANN S, MÜNZENBERG G. Rev Mod Phys, 2000, **72**: 733.

[10] ZHANG Z Y, GAN Z G, MA L, *et al.* Chin Phys Lett, 2012, **29**: 012502.

[11] SPILLANE T, RAIOLA F, ROLFS C, *et al.* Phys Rev Lett, 2007, **98**: 122501.

[12] CUMMING A, BILDSTEN L. Astrophys J Lett, 2001, **559**: L127.

[13] GAMOW G. Nature, 1928, **122**: 805.

[14] HILL D L, WHEELER J A. Phys Rev, 1953, **89**: 1102.

[15] WONG C Y. Phys Rev Lett, 1973, **31**: 766.

[16] STOKSTAD R G, EISEN Y, KAPLANIS S, *et al.* Phys Rev Lett, 1978, **41**, 465.

[17] ROWLEY N, SATCHLER G, STELSON P. Phys Lett B, 1991, **254**: 25.

[18] WEI J X, LEIGH J R, HINDE D J, *et al.* Phys Rev Lett, 1991, **67**: 3368.

[19] HAGINO K, ROWLEY N, KRUPPA A T. Comp Phys Commun 1999, **123**: 143.

[20] STOKSTAD R G, EISEN Y, KAPLANIS S, *et al.* Phys Rev C, 1980, **21**: 2427.

[21] STEFANINI A M, ACKERMANN D, CORRADI L, *et al.* Phys Rev Lett, 1995, **74**: 864.

[22] BECKERMAN M, SALOMAA M, SPERDUTO A, *et al.* Phys Rev Lett, 1980, **45**: 1472.

[23] SONZOGNI A A, BIERMAN J D, KELLY M P, *et al.* Phys Rev C, 1998, **57**: 722.

[24] BOURGIN D, COURTIN S, HASS F, *et al.* Phys Rev C, 2014, **90**: 044610.

[25] PRASAD N V S V, VINODKUMAR A M, SINHA A K, *et al.* Nucl Phys A, 1996, **603**: 176.

[26] WU Y W, LIU Z H, LIN C J, *et al.* Phys Rev C, 2003, **68**: 044605.

[27] DASGUPTA M, HINDE D J, BUTT R D, *et al.* Phys Rev Lett, 1999, **82**: 1395.

[28] HINDE D J, DASGUPTA M, FULTON B R, *et al.* Phys Rev Lett, 2002, **89**: 272701.

[29] FANG Y D, GOMES P R S, LUBIAN J, *et al.* Phys Rev C, 2015, **91**: 014608.

[30] KIM KA-HAE, OTSUKA TAKAHARU, TOHYAMA MITSURU. Phys Rev C, 1994, **50**: R566.

[31] TAKIGAWA N, SAGAWA H. Phys Lett B, 1991, **265**: 23.

[32] HUSSEIN M S, Phys Rev C, 1991, **44**: 446.

[33] DIAZ-TORRES A, THOMPSON I J. Phys Rev C, 2002, **65**: 024606.

[34] JIANG C L, ESBENSEN H, REHM K E, *et al.* Phys Rev Lett, 2002, **89**: 052701.

[35] LIN C J. Phys Rev Lett, 2003, **91**: 229201.

[36] MIŞICU Ş, ESBENSEN H. Phys Rev Lett, 2006, **96**: 112701.

[37] BURBIDGE E M, BURBIDGE G R, FOWLER W A, *et al.* Rev Mod Phys, 1957, **29**: 547.

[38] WANG N, LI Z X, WU X Z. Phys Rev C, 2002, **65**: 064608.

[39] WEN K, SAKATA F, LI Z X, *et al.* Phys Rev Lett, 2013, **111**: 012501.
[40] SIMENEL C, DASGUPTA M, HINDE D J, *et al.* Phys Rev C, 2013, **88**: 064604.
[41] SARGSYAN V V, ADAMIAN G G, ANTONENKO N V, *et al.* Phys Rev C, 2015, **91**: 014613.
[42] LIU Z H, BAO J D. Phys Rev C, 2013, **87**: 034616.
[43] ADAMIAN G G, ANTONENKO N V, SCHEID W, *et al.* Nucl Phys A, 1998, **633**: 409.
[44] SHEN C W, KOSENKO G, ABE Y. Phys Rev C, 2002, **66**: 061602(R).
[45] MUKHERJEE A, DASGUPTA M, HINDE D J, *et al.* Phys Rev C, 2002, **66**: 034607.
[46] BROGLIA R A, DASSO C H, LANDOWNE S, *et al.* Phys Rev C, 1983, **27**: R2433.
[47] BROGLIA R A, DASSO C H, LANDOWNE S, *et al.* Phys Lett B, 1983, **133**: 34.
[48] REHM K E, WOLFS F L H, VAN DEN BERG A M, *et al.* Phys Rev Lett, 1985, **55**: 280.
[49] GOMES P R S, MACIEL A M M, ANJOS R M, *et al.* J Phys G, 1997, **23**: 1315.
[50] HENNING W, WOLFS F L H, SCHIFFER J P, *et al.* Phys Rev Lett, 1987, **58**: 318.
[51] STELSON P H. Phys Lett B, 1988, **205**: 190.
[52] DASSO C H, POLLAROLO G. Phys Lett B, 1985, **155**: 223.
[53] DASSO C H, VITTURI A. Phys Lett B, 1986, **179**: 337.
[54] ESBENSEN H, JIANG C L, REHM K E. Phys Rev C, 1998, **57**: 2401.
[55] DIRAC P A M. Math Proc Cambridge Philos Soc, 1930, **26**: 361.
[56] NEGELE J W. Rev Mod Phys, 1982, **54**: 913.
[57] VO-PHUOC K, SIMENEL C, SIMPSON E C. Phys Rev C, 2016, **94**: 024612.
[58] KESER R, UMAR A S, OBERACKER V E, Phys Rev C, 2012, **85**: 044606.
[59] GODBEY K, UMAR A S, SIMENEL C. Phys Rev C, 2017, **95**: 011601(R).
[60] MAGIERSKI PIOTR, SEKIZAWA KAZAYUKI, WLAZŁOWSKI GABRIEL. Phys Rev Lett, 2017, **119**: 042501.
[61] RAABE R, SIDA J L, CHARVET J L, *et al.* Nature, 2004, **431**: 823.
[62] LEMASSON A, SHRIVASTAVA A, NAVIN A, *et al.* Phys Rev Lett, 2009, **103**: 232701.
[63] CARNELLI P F F, ALMARAZ-CALDERON S, REHM K E, *et al.* Phys Rev Lett, 2014, **112**: 192701.
[64] HINDE D, DASGUPTA M. Nature, 2004, **431**: 784.
[65] BECKERMAN M. Phys Rep, 1985, **129**: 145.
[66] BECKERMAN M. Rep Prog Phys, 1988, **51**: 1047.
[67] REISDORF W, HESSBERGER F P, HILDENBRAND K D, *et al.* Phys Rev Lett, 1982, **49**: 1811.
[68] KOHLEY Z, LIANG J F, SHAPIRA D, *et al.* Phys Rev Lett, 2011, **107**: 202701.
[69] GAVRON A. Phys Rev C, 1980, **21**: 230.
[70] BEGHINI S, SIGNORINI C, LUNARDI S, *et al.* Nucl Instr Meth A, 1985, **239**: 585.
[71] WEI J X, LEIGH J R, WEISSER D C, *et al.* Nucl Instr Meth A, 1991, **306**: 557.
[72] AGUILERA E F, MARTINEZ-QUIROZ E, AMADOR-VALENZUELA P, *et al.* Phys Rev C, 2017, **96**: 024616.
[73] ZHANG H Q, LIN C J, YANG F, *et al.* Chin Phys C, 2010, **34**: 1628.
[74] JIA H M, LIN C J, YANG F, *et al.* Phys Rev C, 2014, **89**: 064605.
[75] ZHANG H Q, LIN C J, YANG F, *et al.* Phys Rev C, 2010, **82**: 054609.
[76] JIA H M, LIN C J, YANG L, *et al.* Phys Lett B, 2016, **755**: 43.
[77] TIMMERS H, ACKERMANN D, BEGHINI S, *et al.* Nucl Phys A, 1998, **633**: 421.
[78] MONTAGNOLI G, BEGHINI S, SCARLASSARA F, *et al.* Euro Phys J A, 2002, **15**: 351.
[79] STEFANINI A M, BEHERA B R, BEGHINI S, *et al.* Phys Rev C, 2007, **76**: 014610.
[80] ZAGREBAEV V I. Phys Rev C, 2003, **67**: 061601(R).
[81] POLLAROLO G, WINTHER A. Phys Rev C, 2000, **62**: 054611.
[82] SARGSYAN V V, ADAMIAN G G, ANTONENKO N V, *et al.* Phys Rev C, 2011, **84**: 064614.
[83] ALJUWAIR H A, LEDOUX R J, BECKERMAN M, *et al.* Phys Rev C, 1984, **30**: 1223.
[84] TROTTA M, STEFANINI A M, CORRADI L, *et al.* Phys Rev C, 2001, **65**: 011601(R).
[85] SCARLASSARA F, BEGHINI S, MONTAGNOLI G, *et al.* Nucl Phys A, 2000, **672**: 99.
[86] KOLATA J J, ROBERTS A, HOWARD A M, *et al.* Phys Rev C, 2012 **85**: 054603.
[87] LIANG J F, ALLMOND J M, GROSS C J, *et al.* Phys Rev C, 2016, **94**: 024616.
[88] STEFANINI A M, MONTAGNOLI G, SCARLASSARA F, *et al.* Euro Phys J A, 2013, **49**: 63.
[89] WU C Y, VON OERTZEN W, CLINE D, *et al.* Annu Rev Nucl Part Sci, 1990, **40**: 285.
[90] BENJELLOUN M, GALSTER W, VERVIER J. Nucl Phys A, 1993, **560**: 715.
[91] JACOBS P, FRAENKEL Z, MAMANE G, *et al.* Phys Lett B, 1986, **175**: 271.
[92] STEFANINI A M, FORTUNA G, PENGO R, *et al.* Phys Lett B, 1985, **162**: 66.
[93] STEFANINI A M, FORTUNA G, PENGO R, *et al.* Nucl Phys A, 1986, **456**: 509.
[94] BOND P D, KORNER H J, LEMAIRE M C, *et al.* Phys Rev C, 1977, **16**: 177.
[95] AGUILERA E F, KOLATA J J, TIGHE R J. Phys Rev C, 1995, **52**: 3103.
[96] JIA H M, LIN C J, YANG F, *et al.* Phys Rev C, 2012, **86**: 044621.
[97] BORGES A M, DA SILVA C P, PEREIRA D, *et al.* Phys Rev C, 1992, **46**: 2360.
[98] PEREIRA D, SILVA C P, LUBIAN J, *et al.* Phys Rev C, 2006, **73**: 014601.
[99] ROSSI E S JR, CHAMON L C, PEREIRA D, *et al.* J Phys

G, 1997, **23**: 1473.
[100] SIMÕES R F, MONTEIRO D S, ONO L K, *et al*. Phys Lett B, 2002, **527**: 187.
[101] STEFANINI A M, FORTUNA G, TIVELLI A, *et al*. Phys Rev C, 1984, **30**: 2088.
[102] CORRADI L, HE J H, ACKERMANN D, *et al*. Phys Rev C, 1996, **54**: 201.
[103] POLLAROLO G, BROGLIA R A, WINTHER A. Nucl Phys A, 1983, **406**: 369.
[104] QUESADA J M, POLLAROLO G, BROGLIA R A, *et al*. Nucl Phys A, 1985, **442**: 381.
[105] ASCUITTO R J, SEGLIE E A. Treatise on Heavy-ion Science[M]. BROMLEY D A, ed. New York: Plenum Press, 1984, Vol. 1, Chap. 5.
[106] CORRADI L, SKORKA S J, LENZ U, *et al*. Z Phys A, 1990, **334**: 55.
[107] REHM K E. Annu Rev Nucl Part Sci, 1991, **41**: 429.
[108] LIANG J F, LEE L L JR, MAHON J C, *et al*. Phys Rev C, 1994, **50**: 1550.
[109] CORRADI L, SKORKA S J, WINKELMANN T, *et al*. Z Phys A, 1993, **346**: 217.
[110] JIANG C L, REHM K E, BACK B B, *et al*. Phys Rev C, 2014, **89**: 051603(R).
[111] MAHON J C, LEE L L JR, LIANG J F, *et al*. J Phys G, 1997, **23**: 1215.
[112] TIMMERS H, LEIGH J R, DASGUPTA M, *et al*. Nucl Phys A, 1995, **584**: 190.
[113] ZAGREBAEV V I. Phys Rev C, 2008, **78**: 047602.
[114] MITSUOKA S, IKEZOE H, NISHIO K, *et al*. Phys Rev Lett, 2007, **99**: 182701.
[115] NTSHANGASE S S, ROWLEY N, BARK R A, *et al*. Phys Lett B, 2007, **651**: 27.
[116] JIA H M, LIN C J, ZHANG H Q, *et al*. Phys Rev C, 2010, **82**: 027602.
[117] SEKIZAWA K, YABANA K. Phys Rev C, 2013, **88**: 014614.
[118] WOLSKI ROMAN. Phys Rev C, 2013, **88**: 041603(R).
[119] BECKERMAN M, SALOMAA M, SPERDUTO A, *et al*. Phys Rev C, 1982, **25**: 837.
[120] DIGREGORIO D E, DITADA M, ABRIOLA D, *et al*. Phys Rev C, 1989, **39**: 516.
[121] CANTO L F, GOMES P R S, LUBIAN J, *et al*. J Phys G, 2009, **36**: 015109.
[122] GOMES P R S, LUBIAN J, PADRON I, *et al*. Phys Rev C, 2005, **71**: 017601.
[123] BIRKHAN J, MIORELLI M, BACCA S, *et al*. Phys Rev Lett, 2017, **118**: 252501.
[124] AKYÜZ Ö, WINTHER A. Nuclear Structure and Heavy-ion Reactions// BROGLIA R A, RICCI R A (Eds.), Proceedings of the International School of Physics "Enrico Fermi," Course LXXVII, Varenna, North-Holland, Amsterdam, 1981.
[125] BIERMAN J D, CHAN P, LIANG J F, *et al*. Phys Rev Lett, 1996, **76**: 1587.

近垒重离子熔合反应中的中子转移效应

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摘要： 近势垒及其以下能区重离子熔合反应中的中子转移耦合道效应是一个复杂且有争议的问题。简要介绍了近年来在中国原子能科学研究院的HI-13串列加速器上，基于静电偏转板装置完成的^{32}S+^{90,94,96}Zr，^{18}O+^{74}Ge和^{18}O+^{58}Ni 等几个典型体系的熔合反应研究情况，并结合耦合道理论对实验数据进行了分析。选取反应体系时同时关注了正Q值的中子拾取和削裂道。另外，基于完全耦合道理论计算，提出了一种能够定量提取熔合反应中中子转移效应的自洽方法。这些研究进一步证实了垒下重离子熔合反应中的中子转移效应，同时指出了其复杂性。需要进一步的实验和理论研究来澄清相关核反应机制。

关键词： 近垒重离子熔合反应；反应动力学；耦合道效应；正Q值中子转移效应

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