Near-barrier fusion of $^{32}\text{S}+^{90,96}\text{Zr}$, $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$

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Abstract. This contribution presents the recent experimental results on heavy-ion near-barrier fusion, mainly aiming at the effect of positive Q-value neutron transfer on the fusion process. Fusion excitation functions of $^{32}\text{S}+^{90,96}\text{Zr}$, $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$ have been measured with an electrostatic deflector setup. The fusion barrier distributions have been extracted from the measured fusion excitation functions. Different conclusions are obtained from the analysis of both the fusion excitation functions and the barrier distributions, that is, $^{32}\text{S}+^{96}\text{Zr}$ shows obvious fusion enhancement related to the positive Q-value neutron transfer channels and was reproduced with Zagrebaev’s semiclassical model, but $^{18}\text{O}+^{74}\text{Ge}$ shows no such effect. More comprehensive reaction dynamics need to be considered than the up-to-date coupled-channels calculations.

1. Introduction
Role of neutron transfer in the fusion process is an important topic of current interest. The importance of neutron transfer on fusion stems from the fact that neutron transfer may occur at a distance beyond the Coulomb barrier, therefore, may have an obvious influence in the sub-barrier fusion reaction. There are some signatures [1] that coupling to the large positive Q-values neutron transfer (PQNT) channels enhances the fusion cross sections at sub-barrier energies. These observations intrigue the conjecture that it may provide a new way to synthesize superheavy elements (SHE) using the neutron-rich beams produced with advanced radioactive ion beam (RIB) facilities, which is of great importance because up to now the superheavy nuclei synthesized all locate in the neutron-deficient side of the SHE “island of stability”. In order to approach the center region, researches for the reaction mechanisms of actinide targets with neutron-rich projectiles are highly required.

However, the relationship between fusion and transfer reaction is actually not quite clear yet and the coupling to the transfer channels can only be qualitatively taken into account in the coupled-channels (CC) calculations up to now. Moreover, other mechanisms, without including the PQNT effect explicitly, also can explain the experimental results. For $^{40}\text{Ca}+^{96}\text{Zr}$, both sub-barrier fusion enhancement and barrier distribution shape can be reproduced within a semiclassical model, mainly considering the strong octupole vibration of $^{96}\text{Zr}$ [2]. A very recent analysis also reproduced qualitatively the fusion excitation function of $^{40}\text{Ca}+^{48}\text{Ca}$ by using the DC-TDHF method [3]. Very recently, Kohley et al. [4] observed that fusion of the neutron-rich $^{132}\text{Sn}+^{58}\text{Ni}$ system, with more PQNT channels, does not cause any fusion enhancement due to
neutron transfer until \(\sim 5\) mb level, by means of a systematic comparison to the experimental results. For \(^{36}\text{S}{}^{+}{^{58}}\text{Ni}\) and \(^{18}\text{O}{}^{+}{^{118}}\text{Sn}\), the fusion behavior of no additional enhancement related to PQNT was ascribed to kinematic mismatches for the transfer reactions [5, 6].

Therefore, the effect of coupling to the neutron transfer channels on fusion is still an open question. It is strongly desired to develop a consistent microscopic approach to clarify unambiguously the PQNT effect on heavy-ion fusion at near-barrier energies. In this talk, we would like to briefly present our experimental results on the PQNT effect in near-barrier fusion.

2. Experiments and results

The experiments have been performed at the HI-13 tandem accelerator of the China Institute of Atomic Energy (CIAE), Beijing. The fusion evaporation residues (ERs) concentrated at forward angles were separated from the incident beam by an electrostatic deflector [7]. Two-dimensional plot of \(E\) vs time of flight (TOF) was used to identify the reaction products. Since fission of the compound nuclei (CN) can be neglected for all the selected systems, the measured ERs cross sections were taken as complete fusion cross sections \(\sigma_F\).

2.1. \(^{32}\text{S}{}^{+}{^{90,96}}\text{Zr}\)

An \(E\) vs TOF detector telescope with a microchannel plate (MCP) detector and a Si(Au) surface barrier detector was used in this experiment [8]. The ERs angular distributions were measured in the range of \(\theta_{\text{lab}}\) from -4° to +10° with a step of 1° at three beam energies (\(E_{\text{Lab}} = 108.3, 116.4,\) and 130.0 MeV) for both systems. The measured angular distributions are symmetrical about 0° and the shapes do not change appreciably with the beam energy. These combined angular distributions and double Gaussian fits were used to obtain the \(\sigma_F\). The fusion excitation functions measured for \(^{32}\text{S}{}^{+}{^{90,96}}\text{Zr}\) are shown in Fig. 1, where the energy scale was corrected for the target thickness and the error bars represent purely statistical uncertainties.

The fusion excitation functions were calculated by means of the CC theory with the code CCDEF [9], considering the quadrupole and octupole vibrations of \(^{32}\text{S}\) and \(^{90,96}\text{Zr}\). The single-channel (SC) and CC calculations without neutron transfers for the \(^{32}\text{S}{}^{+}{^{90}}\text{Zr}\) and \(^{32}\text{S}{}^{+}{^{96}}\text{Zr}\) fusion reaction are also shown in Fig. 1. It can be seen that the CC calculation reproduces the experimental excitation function well without considering neutron transfers for \(^{32}\text{S}{}^{+}{^{90}}\text{Zr}\), but it fails for \(^{32}\text{S}{}^{+}{^{96}}\text{Zr}\) at lower energies. The CCFULL calculation considering the inelastic excitations for \(^{32}\text{S}{}^{+}{^{96}}\text{Zr}\) also underestimates the sub-barrier fusion, shown as the dash-dotted line in Fig. 1. This shows that the enhancement of the sub-barrier fusion cross sections might be caused by PQNT.

To take into account the PQNT effect, the fusion excitation function for \(^{32}\text{S}{}^{+}{^{96}}\text{Zr}\) was calculated by using the following formula according to Zagrebaev’s semiclassical model [10]:

\[
T_I(E_{\text{c.m.}}) = \int f(B) \frac{1}{N_r} \sum_k \int_{-E_{\text{c.m.}}}^{Q_0(k)} \alpha_k(E_{\text{c.m.}}, l, Q) \times P_{\text{HW}}(B, E_{\text{c.m.}} + Q, l) dQ dB,
\]

and

\[
\sigma_F(E_{\text{c.m.}}) = \frac{\pi \hbar^2}{2\mu E_{\text{c.m.}}} \sum_{l=0}^{l_{\text{cr}}} (2l + 1)T_I(E_{\text{c.m.}}),
\]

where \(T_I(E_{\text{c.m.}})\) is the penetration probability, \(B\) and \(f(B)\) are the barrier height and the normalized barrier distribution, which were taken from the calculation with the code CCDEF, \(P_{\text{HW}}\) is the usual Hill-Wheeler formula [11], \(l\) and \(l_{\text{cr}}\) are angular momentum and critical angular momentum. \(\alpha_k(E_{\text{c.m.}}, l, Q)\) is the probability for the transfer of \(k\) neutrons with \(Q \leq Q_0(k)\),
\(Q_0(k)\) is the \(Q\) value for the ground-state to ground-state transfer of the \(k\)th neutron, and \(N_{tr}\) is the normalization of the total probability taking into account the multi-neutron transfers.

The calculation was performed up to the channel \(+4n\) \((k = 4)\) for \(^{32}\text{S} + ^{96}\text{Zr}\) and is shown as the dashed line. It allows a fairly good description of the present experimental data, showing the effect of neutron transfers on sub-barrier fusion. As expected, the correction applied to the calculation at sub-barrier energies by the Zagrebaev model [10] enhances the fusion cross sections further. The result shows that this model can explain the sub-barrier fusion enhancement.

Figure 1. (Color online) Fusion excitation functions (upper panel) and barrier distributions of \(^{32}\text{S} + ^{90,96}\text{Zr}\) (lower panel).

Figure 1 also shows the experimental barrier distributions extracted from fusion and quasielastic (QEL) scattering as well as the calculations for \(^{32}\text{S} + ^{90,96}\text{Zr}\). The experimental values were obtained by double differentiation of \(E_{c.m.}\sigma_F\) versus energy using the three-point difference formula [1]. The QEL barrier distributions were taken from Ref. [12]. It is very interesting to note that the experimental barrier distributions extracted from QEL and fusion are strikingly similar for both systems. Although a fine structure appears visible in the experimental fusion barrier distribution of \(^{32}\text{S} + ^{96}\text{Zr}\), its damping is most probably caused by the strong octupole vibration in \(^{96}\text{Zr}\) [13]. The actual discrepancies between calculated and experimental results are not yet fully understood. Large fluctuations occur in the fusion barrier distributions for \(E_{c.m.} > 83\) MeV owing to the large errors of the fusion cross sections in the higher energy range.

For \(^{32}\text{S} + ^{90}\text{Zr}\), the overall trends of the experimental barrier distributions are similar to the CC calculation, while for \(^{32}\text{S} + ^{96}\text{Zr}\), the experimental barrier distributions are wider and trend to a lower energy range compared with the results for \(^{32}\text{S} + ^{90}\text{Zr}\) and the CC calculation without considering neutron transfers. This shows the PQNT effect on fusion enhancement and is very
Figure 2. (Color online) Fusion excitation functions (upper panel) and barrier distributions (lower panel) of $^{16}$O+$^{76}$Ge and $^{18}$O+$^{74}$Ge. The fusion data for $^{16}$O+$^{76}$Ge from Ref. [16] are also shown as open circles for comparison.

Similar to $^{40}$Ca+$^{96}$Zr [1], for $^{32}$S,$^{40}$Ca+$^{96}$Zr, both the fusion and QEL barrier distributions show significant widening, i.e., they are wider and flatter than those for $^{32}$S,$^{40}$Ca+$^{90}$Zr. This is consistent with the model of Stelson [14] that neutron transfer could act as a doorway state toward fusion.

2.2. $^{16}$O+$^{76}$Ge and $^{18}$O+$^{74}$Ge
In this experiment, $E$ vs TOF detector telescopes were composed of two MCP detectors and a 48 mm × 48 mm quadrant Si detector, with distances of 41.0 cm for MCP1-MCP2 (TOF) and 22.7 cm for MCP2-Si. $E$-TOF1 (TOF1: MCP1-Si) and $E$-TOF2 (TOF2: MCP2-Si) spectra were used to reduce the spurious backgrounds from the random coincidences between the Si and one of the MCPs for these more asymmetric systems, especially for lower fusion cross sections at sub-barrier energies. The ERs angular distributions were measured from $-5^\circ$ to $+13^\circ$ with a step of $1^\circ$ for $^{16}$O+$^{76}$Ge ($E_{\text{lab}}=44.38$ MeV) and $^{18}$O+$^{74}$Ge (45.40 and 40.39 MeV). Their typical shapes do not change appreciably with the beam energy also and give an overall width of 4.3$^\circ$ symmetrical about 0$^\circ$. Single Gaussian well fits the ERs angular distributions resulting from the dominant neutron and proton evaporation for the CN, which is consistent with the calculation of the code PACE2 [15]. The measured fusion excitation functions for $^{16}$O+$^{76}$Ge and $^{18}$O+$^{74}$Ge are shown in Fig. 2, where the energy scale was corrected for the carbon backing and the target thickness.

The data were analyzed with the code CCFULL [17] including all order couplings. The
standard Akyüz-Winther (AW) potential was used, without an attempt to vary them to fit the above-barrier data. For \(^{16}\text{O}+^{76}\text{Ge}\), the low-lying vibrational \(^2+\) and \(^3-\) one-phonon states of \(^{76}\text{Ge}\) as well as their mutual excitations were included in the calculation. The calculations of SC and CC including target excitation only are shown as dotted and solid lines in Fig. 2, respectively. It shows that the CC calculation reproduces the fusion excitation function rather well within the experimental uncertainties, except a small overestimate at higher energies.

In the case of \(^{18}\text{O}+^{74}\text{Ge}\), the calculations of SC and CC including the target \(^2+\) two-phonon and \(^3-\) one-phonon vibrational states and the \(^2+\) state of \(^{18}\text{O}\) are shown in Fig. 2, respectively. The CC calculation gives a good fit to the experimental data. No significant differences in the reduced fusion excitation functions of the two systems emerge at least down to 0.1-mb level. This provides further experimental evidence that in some cases the coupling effect of PQNT channel on fusion is very limited. In order to check the effect of neutron transfer, the CC calculation was also performed by including the additional \(2n\)-pair transfer channel with positive \(Q\)-value of 3.75 MeV and the nominal coupling strength of 0.7 MeV. Result is illustrated by the dash-dotted line in Fig. 2 for a qualitative comparison. One can see that the trend deviates distinctly from the fusion data, suppressed due to flux loss at above-barrier energies and enhanced due to neutron transfer effect at lower energies. It indicates that the effect of neutron transfer on fusion should be negligible for this system at the measured energy range.

The CCDEF calculation considering the inelastic excitations for \(^{18}\text{O}+^{74}\text{Ge}\) also gives a good fit to the fusion data, while the calculation including the neutron transfers overestimates the fusion data at the lowest energies. This is consistent with the conclusion obtained from CCFULL calculations.

The extracted fusion barrier distributions are shown as points in the lower panel of Fig. 2, which were not made normalization due to the large oscillations. Both experimental fusion barrier distributions show only one peak with a width of \(~4\) MeV, centered around the AW barrier with relatively larger oscillations. The corresponding CC calculations are also shown and qualitatively reproduce the experimental barrier distributions.

3. Discussion
For the systems measured in this work, the PQNT effect on fusion is different and a consistent explanation is absent. For physical considerations, we transfer to the reaction systems with less intricate +\(Q\)-value 1\(n\) and/or 2\(n\) transfers in the following, considering the complicated multi-neutron transfer mechanism and subsequent role on near-barrier fusion.

The behavior of \(^{18}\text{O}+^{74}\text{Ge}\) is very different from \(^{18}\text{O}+^{58}\text{Ni}\) \((Q_{-1n}=+0.96\) MeV and \(Q_{-2n} =+8.20\) MeV\) that shows strong fusion enhancement \([18]\), which was thought that collective pair transfer mode plays an important role and was explained well based on the zero-point pairing fluctuations model (pairing vibrations related to 2\(n\) transfer channel). \(^{74}\text{Ge}(^{18}\text{O},^{16}\text{O})^{76}\text{Ge}\) shows that the transfer mainly populates the ground state at \(27^\circ\) at \(E_{\text{Beam}}=75\) MeV \([19]\). So it is expected that there will be kinematically matched for the 2\(n\) stripping channel and neutron transfer should enhance the subsequent fusion at sub-barrier energies, considering the expected ground state to ground state transfer at sub-barrier region. But our results show no such effect. Additionally, the fusion enhancement of \(^{40}\text{Ca}+^{18}\text{O}\) \((Q_{+1n}=-1.58\) MeV and \(Q_{+2n} =+2.62\) MeV\) seems to exclude the possibility that the first neutron transfer with negative \(Q\)-value may severely inhibit the second neutron transfer. On the other hand, although the fusion enhancement observed in \(^{40}\text{Ca}+^{48}\text{Ca}\) has been prevalingly ascribed to the positive \(Q_{+2n}\) transfer coupling, the effect of more and larger positive-\(Q\)-value proton-stripping channels should be considered for clarifying the origin of the fusion enhancement.

As well known, transfer coupling also depends on the states and \(Q\)-values populated by the transferred nucleons as well as the transfer form factors. It is advantageous to investigate the influence of the 2\(n\) transfer channel on fusion using \(^{18}\text{O}\) projectile, considering the more positive
Q-value $2n$ stripping channel for $^{18}\text{O}$ induced reaction. Further, it is quite helpful to research the target dependence of fusion at sub-barrier energies for the lower $Z_{p}Z_{T}$ and higher $Q_{2n}/V_B$ value systems, such as the values for $^{18}\text{O}+^{24}\text{Mg}$, $^{18}\text{O}+^{50}\text{Cr}$ and $^{18}\text{O}+^{58}\text{Ni}$ are $6.24/15.27=0.41$, $9.11/27.16=0.34$ and $8.20/30.95=0.26$, respectively. Therefore, it is useful to measure these fusion excitation functions with high accuracy to clarify the relevant dynamic mechanisms and constrain the transfer coupling strengths, and research the role of $1n$ transfer $Q$-value. On the other hand, a direct measurement of the $2n$ transfer is also meaningful for correlating the two aspects of fusion and transfer.

4. Conclusions
In summary, the fusion excitation functions for $^{32}\text{S}+^{90,96}\text{Zr}$, $^{16}\text{O}+^{76}\text{Ge}$ and $^{18}\text{O}+^{74}\text{Ge}$ at near-barrier energies have been measured and the corresponding fusion barrier distributions have been extracted. For the measured systems, $^{32}\text{S}+^{96}\text{Zr}$ shows additional fusion enhancement, which agrees with previous suggestion \cite{12} that PQNT channels enhance the sub-barrier fusion. But $^{18}\text{O}+^{74}\text{Ge}$ shows no additional fusion enhancement.

The controversial results observed in the fusion reactions have presented a challenge for the theoretical understanding of the reaction mechanism at sub-barrier energies. It is highly desired to search for the underlying reaction mechanism and to improve the CC calculation. In addition to the fusion excitation function, the neutron transfer cross section measurement should provide useful information on the coupling strengths of neutron transfer channels, which will induce a much deeper understanding of the role of neutron transfer.

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