Impacts of the cutoff of CC effects on heavy-ion fusion reactions at extreme sub-barrier energies

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Recently it is reported that an unexpected behavior of heavy-ion fusion reactions occurs at the extreme sub-barrier energies in the ^{60}Ni+^{89}Y system [1], i.e., the experimental excitation function shows an abrupt decrease comparing with the results of Wong formula and its slope ($L(E)=\mathrm{d}[\ln(\sigma E)/\mathrm{d}E]$) shows a drastic change when the bombarding energies are below about 0.91 V_B, where V_B represent the Vaz barrier. The similar phenomena are found in other systems, for example, ^{58}Ni+^{58}Ni, ^{90}Zr+^{90,92}Zr, and so on. In this contribution, I would like to address in the reasons for generating such unexpected behavior. Tow problems are needed to discuss:

First, how to calculate the penetration probability at extreme sub-barrier energies? Jiang et al. used the Wong formula or simple CC code (such as CCFUS, CCDEF). Both of them employ the Hill-Wheeler approximation, i.e., the actual potential barrier is replaced by an inverted parabola. Such an approximation is NOT appropriate at sub-barrier energies, especially at extreme sub-barrier energies. The actual potential barrier has asymmetric shape and has a pocket inside. The parabola potential barrier has symmetric shape without pocket, and it is narrow than the actual one. So it results in high penetration probability at extreme sub-barrier energies. That is the first reason for that the experimental fusion cross sections decrease faster than the theory one. By using the 1D-BPM-WKB calculate, the experimental slope can be well reproduced at very low energies, for example, less than 0.91 V_B. It is means that the CC effects become saturated at such low energies. Of course, 1D-BPM-WKB can not reproduce the cross sections because of the absent of CC effects.

Second, how to take account of the CC effects? Hagino et al. [2] used the full CC code (CCFULL) to analyze the data and showed that both experimental excitation function and its slope can be well reproduced. Obviously, there are some uncertainties in the CCFULL calculation, for example, the choice of potential parameters. So we should seek another way. It well known that the threshold anomaly (TA) [3] observed in the elastic channel is associated with the CC effects. The imaginary potential decreases with the effective close of the reaction channels when the energy decrease and the CC effects accordingly become weaker then saturated at very low energies. Meanwhile, the real part of potential occurs a rapid variation due to the causality principle. By employed this kind TA potential in the 1D-BPM-WKB calculations [4], both experimental cross sections and slope are well reproduced.

In conclusion, I argued that the unexpected behavior observed by Jiang et al. can be well understood in the frame of classical model. Such unexpected behavior comes from the wrong explanation of the experimental data.

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