DOI: 10.21276/sjpms.2016.3.4.4

Scholars Journal of Physics, Mathematics and Statistics **ISSN 2393-8056 (Print)**
Sch. J. Phys. Math. Stat. 2016; 3(4):144-149 **ISSN 2393-8064 (Online)**

Fusion Reactions Induced by 4,6,8He

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Abstract: Fusion cross sections induced by 4,6,8He were studied using different reactions with heavy targets (209Bi, 197Au, 204Pb, 206Pb and 208Pb). The theoretical calculations were done using the Code PACE4 with [r0=1.3 fm, V0=67 MeV, wo=9.5 MeVand lmax=30]. The quantum mechanical transmission probability for one dimensional barrier was used instead of the classical solution to describe the experimental data. Good agreement between theoretical calculations and experimental results are obtained. A study has shown that, the change in evaporation cross sections induced by 6,8He comparing with stable nuclei 4He are produced from the behavior of the weakly bound nuclei 6,8He
Keywords: Fusion reaction, Evaporation residue channels, Cross sections

INTRODUCTION

The development of radioactive nuclear beams allows the study of nuclei with novel and interesting properties. Of particular interest are nuclei such as 6,8He, which are considered as neutron- skin nuclei because the valence neutrons are found well outside the core 4He. Such features should influence the interactions of these exotic species with other nuclei. Several experiments studied have been made from the fusion of 6He near the Coulomb barrier [1–7]. However, there is no consensus about the effects of the various exotic properties of the fusion probability and subsequent decay of the compound nucleus.

Many calculations include a lower barrier due to the larger than normal radius of the beam nucleus and the coupling to the soft E1 mode, which works to enhance the fusion cross section [8]. Other groups include the role of projectile breakup and have concluded that there may be a reduction of the fusion yield and that the excitation function may have structure near the Coulomb barrier [9–10]. This prediction is not universally accepted. The effects on the reaction mechanisms due to the exotic structure of these nuclei are expected to be greatest in 6He because of its halo nature. Furthermore, the effects predicted for 6He are also expected for 8He. (Currently, 6He beams of the appropriate energy are more intense and of higher quality than 8He).

The role of excess neutrons is expected to be a more important infusion of light neutron-rich weakly bound nuclei. Some model calculations predicted that the weak binding energy of such nuclei should significantly suppress the near-barrier fusion cross section. However, the extended “halo” structure of exotic nuclei, such as 6He or 8He, may also influence the fusion probability. In [11–16], some enhancement of the fusion probability for weakly bound nuclei was found due to the excitation of a low-lying soft- dipole mode and due to the strong coupling with the breakup channels.

Neutron transfer cross sections are known to be rather large at near-barrier energies of heavy-ion collisions and there is a prevailing view that coupling with the transfer channels should play an important role in the sub - barrier fusion of heavy nuclei. For weakly bound nuclei (the two-neutron separation energy for 6He is less than 1 MeV) a strong coupling with the breakup channels is also evident and it should influence significantly the fusion probability. However, while the role of collective degrees of freedom (rotation of statically deformed nuclei and/or vibration of nuclear surfaces) in the sub-barrier fusion reactions is well studied in many experiments and well understood theoretically, the role of neutron transfer and breakup channels is not so clear.

The fusion evaporation reactions induced by 6,8He were demonstrated in general terms as enhancement of the fusion probability compared with their stable isotope 4He. However, it is rather difficult to interpret unambiguously the results of these experiments. Such a controversial situation in the experimental data on the sub-barrier reactions are accompanied by serious difficulties. First, experiments with radioactive beams are rather complicated. One problem is the low intensity of the secondary beams. This makes measurements in the region of the Coulomb barrier extremely time consuming, if high statistics are to be obtained. Second, in the experimental study of the effect, we need to compare the fusion cross sections of different combinations of nuclei, which, among other things, have different collective properties, and it is not so easy to single out the role of breakup and/or neutron transfer from the overall effect of sub- barrier fusion enhancement. At last for several reasons, it is very difficult to take into account explicitly the breakup and transfer channels within the consistent channel coupling approach used successfully for the description of collective excitations in the near-barrier fusion processes. As a result, we are still far from a good understanding of the subject and additional experimental and theoretical studies are needed.

In the present article, the fusion evaporation cross sections induced by 6,8He nuclei comparing with 4He were investigated. Experimental data were taken from different references and theoretical calculations were made using the PACE4 Code.

RESULTS AND DISCUSSION

The evaporation residue cross sections induced by 4,6,8He on 209Bi, 204,206,208Pb and 197Au targets, were studied experimentally and theoretically. The experimental data were obtained from several references, and theoretical calculations are made using the Code PACE4.

Our studying is concentrated on the lead and bismuth targets, where lead and bismuth targets have extremely small fission cross sections at the bombarding energies. Bismuth and lead are convenient targets for excitation function work with light projectiles since the resulting polonium and astatine isotopes are alpha emitters. Studying of the reactions 4,6,8He with 209Bi and 197Au targets were done to investigate the effect of targets on the evaporation residue cross sections.

Experimental fusion cross sections for the reaction 4He+209Bi and 6He+209Bi were obtained from [5]. As for the reaction 8He+209Bi, no experimental data were done so far and thus we used only the theoretical calculations in our study. The theoretical calculation for the fusion cross sections are made by using the Code PACE4 with r0=1.3 fm, V0= 67 MeV, the depth of the imaginary nuclear wall wo=9.5 MeV, IMAG(I) imaginary wall is potential volume and lmax=30. A comparison of the PACE4 calculations and the experimental data are shown in Fig.(1).

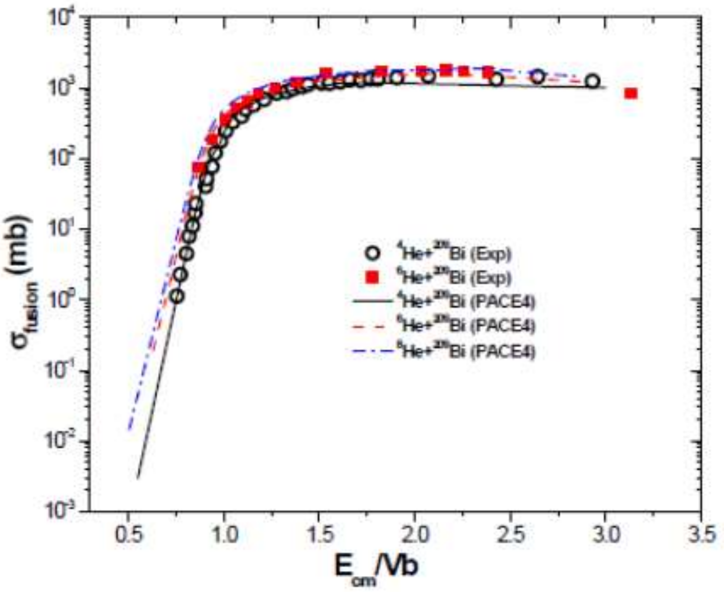

Fig-1: Open circle points are the fusion evaporation cross sections (xn channel) in the reaction 4He+209Bi. Square points are the fusion evaporation cross sections (xn channel) in the reaction 6He+209Bi. The lines represent the fusion evaporation residue cross sections calculations used the Code PACE4.

Experimental fusion cross sections for the reaction 4He+197Au were obtained from [18]. Experimental fusion evaporation residue cross sections for the reaction 6He+197Au are obtained from [3]. Experimental fusion evaporation residue cross sections for the reaction 8He+197Au are obtained from [1].

The theoretical calculation for the fusion cross sections are made by using the Code PACE4 with r0=1.3 fm, V0= 67 MeV, the depth of the imaginary nuclear wall wo=9.5 MeV, IMAG(I) imaginary wall is potential volume and lmax=30. A comparison of the PACE4 calculations and the experimental data are shown in Fig. (2)

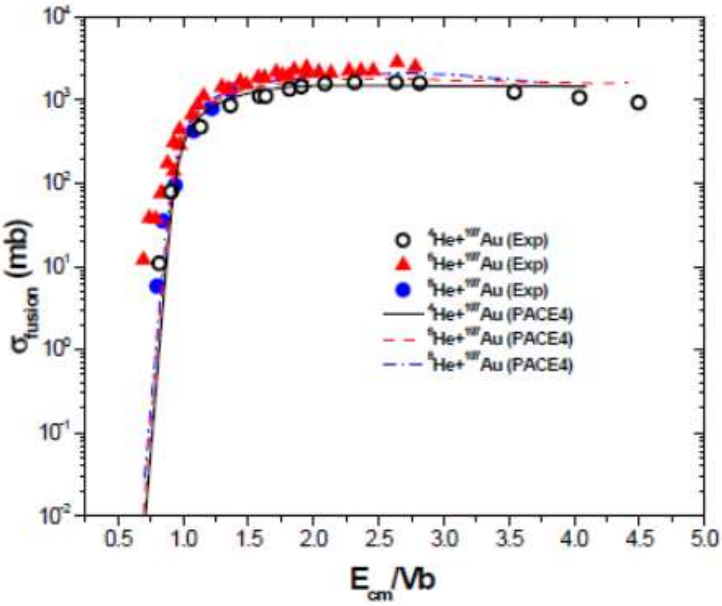

Fig-2: open circle points are the fusion evaporation cross section in the reaction 4He+197Au. Rectangular points are the fusion evaporation cross sections in the reaction 6He+197Au [3]. Closed circle points are the fusion evaporation residue cross sections in the reaction 8He+197Au. The lines represent the fusion evaporation cross sections calculations used the Code PACE4

A comparison of the PACE4 calculations and the experimental data on the reactions induced by the same projectile and different targets ([4He+209Bi, 4He+197Au], [6He+209Bi, 6He+197Au] and [8He+209Bi, 8He+197Au]) are shown in Figs. (3, 4, 5).

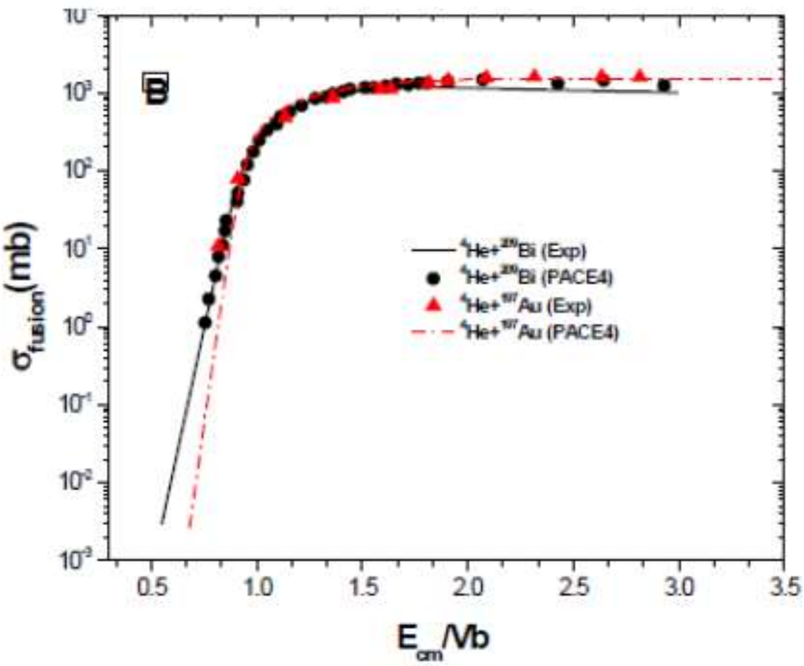

Fig-3: Circle points are the fusion evaporation cross sections (xn channel) in the reaction 4He+209Bi. Triangular points are the fusion evaporation cross sections in the reaction 4He+ 197Au. The lines represent the fusion evaporation cross sections calculations used the Code PACE4

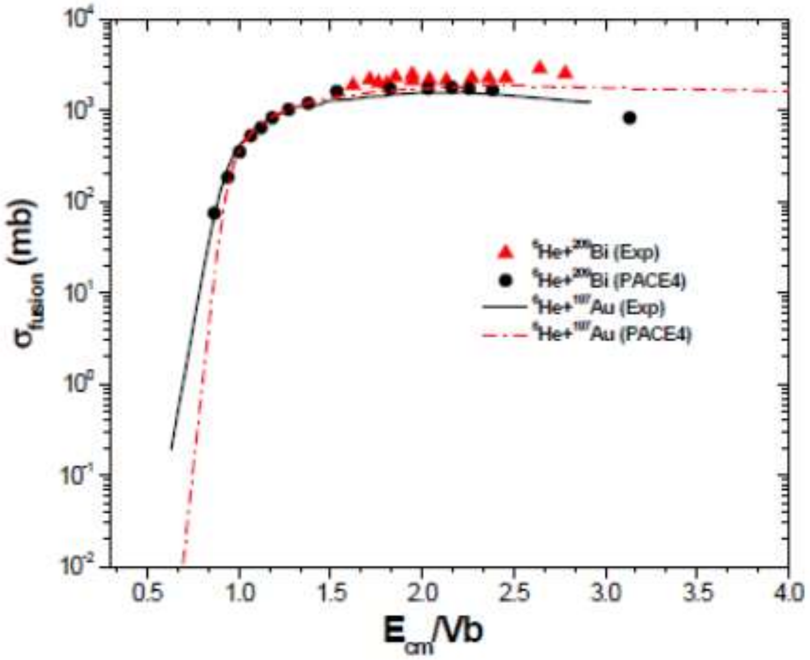

Fig-4: Circle points are the fusion evaporation cross sections (xn channel) in the reaction 6He+209Bi. Triangular points are the fusion evaporation cross section) in the reaction 6He+ 197Au. The lines represent the fusion evaporation cross sections calculations used the Code PACE4

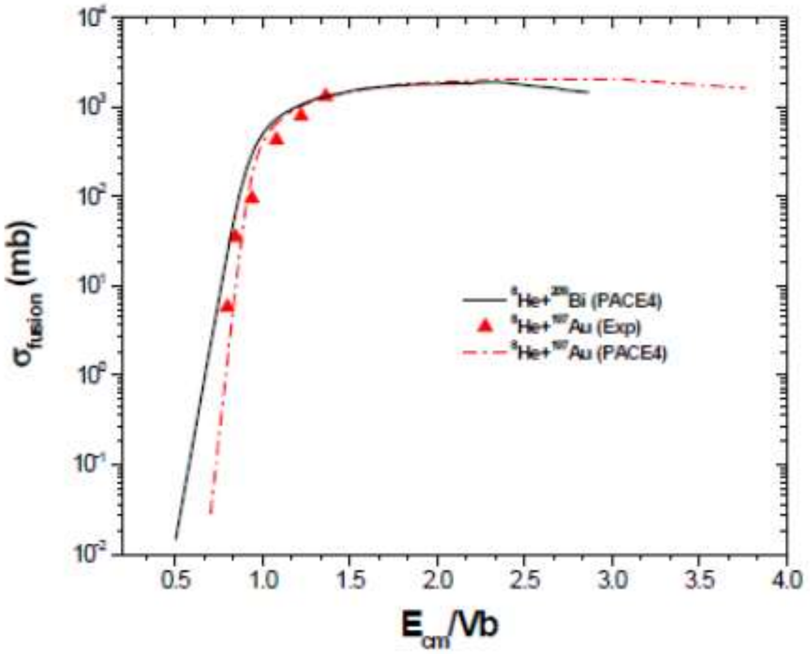

Fig-5: Triangular points are the fusion evaporation cross sections (xn channel) in the reaction 8He+197Au. The lines represent the fusion evaporation cross sections calculations used the Code PACE4

By Comparing the fusion cross sections in the reactions induced by 4,6,8He on 209Bi and 197Au, one has to take into account that these reactions have different excitation energies, different compound nuclei and different decay properties. To avoid additional ambiguities, our study was concentrated on the reactions in which the same compound nuclei are formed, such as 4He+208Pb, 6He+206Pb and 8He+204Pb of the same compound nucleus 212Po. In that case any difference in the evaporation residue cross sections may originate from the difference in the entrance channels of the reactions.

Experimental fusion cross sections for the reaction 4He+208Pb were obtained from 208Pb(4He, 1n)211Po and 208Pb(4He, 2n)210Po [2]. Experimental fusion cross sections for the reaction 6He+206Pb were obtained from [2].

Theoretical calculations of the fusion cross sections were made using the Code PACE4 with r0=1.3 fm, V0= 67 MeV, the depth of the imaginary nuclear wall wo=9.5 MeV, IMAG(I) imaginary wall is potential volume and lmax=30. A comparison of the PACE4 calculations and the experimental data are shown in Fig.(6).

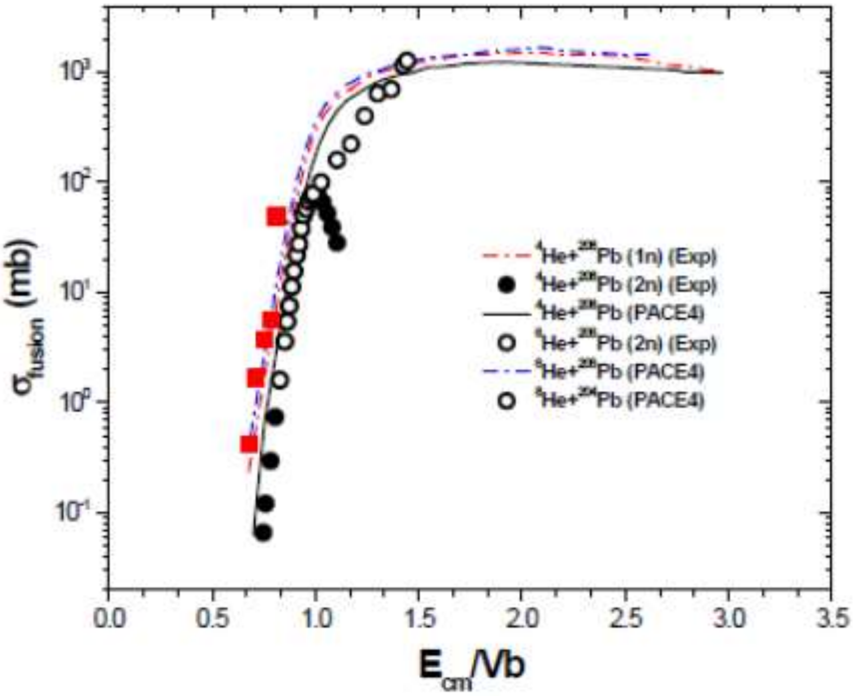

Fig-6: Solid circle points are the fusion evaporation cross section (1n channel) in the reaction 4He+208Pb. Open circle points are the fusion evaporation cross section (2n channel) in the reaction 4He+208Pb. Square points are the fusion evaporation cross section (2n channel) in the reaction 6He+206Pb. The lines represent the fusion evaporation cross sections calculations used the Code PACE4

Large enhancement was obtained in the reaction 6He+206Pb at energies lower than the Coulomb barrier. The experiment on the fusion of 6He with 206Pb target was done at the Joint Institute for Nuclear Research (Dubna) [2] by using the activation method in which a stack of 206Pb targets and Al foils inserted between these targets to reduce the beam energies lower than the Coulomb barrier. Unfortunately, this method gave rather the large energy spread of the 6He beam inside the target; the energy spread may distort significantly the experimental data. Thus, new more accurately experiments are very desirable to measure the fusion cross sections in the reaction 6He+206Pb at energies lower than the Coulomb barrier.

CONCLUSIONS

We were performing theoretical evaporation residue cross section calculations for several systems with weakly bound unstable projectiles and their respective stable projectiles using PACE4 code. Good agreements were obtained between the experimental data and theoretical calculations except for the 6He+206Pb reaction where large enhancement is obtained due to the large energy spread of the 6He beam inside the target. Small apparent enhancement for 6,8He as compared with 4He is obtained at energies lower than the barrier. The mechanism of fusion reactions did not depend on the type of targets and the compound nuclei, but it depended mainly on the structure of the projectile nuclei. As a result, we are still far from a good understanding of the subject and additional experimental and theoretical studies are needed.

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