Studies on excitation functions for the synthesis of heavy and superheavy elements in heavy ion fusion reactions

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Introduction

Nuclear fusion is the process by which two nucleus combine to form a heavier one. In the formation of superheavy elements (SHE), first the colliding nuclei must overcome the Coulomb barrier and captured by the target. Then the projectile and target will evolve from the contact point and form an excited compound nucleus (CN) and finally the compound nucleus cools down by the evaporation of neutrons to produce an evaporation residue (ER) rather than fission. Hence, the ER cross section or ER excitation functions is the product of the capture cross section, the CN formation probability, and the probability of the survival of the CN against fission. Therefore, it is very important to examine carefully these three steps in the study of the synthesis mechanism of superheavy nuclei.

The main aim of the thesis work is to determine the factors that affect the production cross section, to find out the most suitable projectile and target, and to predict the maximum production cross section and corresponding energy for the synthesis of heavy and superheavy elements.

Methodology of the study

A "Phenomenological Model for the Production Cross section (PMPC)" [1] has been developed to study the production cross sections for the synthesis of heavy and superheavy elements. To study the interaction potential and barrier parameter like Coulomb barrier, barrier position and the curvature of the inverted nuclear harmonic potential, we have used the Coulomb potential and nuclear proximity potential of Blocki et al., [2]. The mass excess and shell correction values of heaviest elements are taken form Moller et al.,[3].

Major findings of the study

Probable target-projectile combinations for the superheavy element $^{302}120$, ^{297}Ts and ^{296}Lv have been identified from the cold reaction valleys (Fig 1 of Ref. [4-6]). The interaction barriers for fusion of all the projectile-target combinations identified in the cold valleys of the superheavy $^{302}120$, ^{297}Ts and ^{296}Lv nucleus are studied. At near and above the barrier, the total capture, fusion, and ER cross sections for all the systems also have been calculated. The computed ER cross sections for ^{54}Cr + ^{248}Cm, ^{58}Fe + ^{244}Pu, ^{64}Ni + ^{238}U, and ^{50}Ti + ^{249}Cf combinations are compared with experimental data and other theoretical models. The maximum cross section is obtained for the combination ^{50}Ti + ^{249}Cf (Z=120). For the SHE ^{297}Ts (Z=117), the reaction ^{48}Ca +^{250}Bk → ^{298}Ts gave the maximum probability for the 3*n* channel, and the reaction ^{48}Ca+^{251}Bk→^{299}Ts gave the maximum probability for the 4*n* and 5*n* channels. The system ^{48}Ca + ^{248}Cm is found to be the most suitable projectile-target pair for the synthesis of ^{296}Lv. In addition, we have also calculated the production cross sections for the isotopes $^{291–295,298}$Lv using the ^{48}Ca projectile on $^{243–247,250}$Cm targets [4-6].

Using different mass tables, and the isotopic dependence of the target in the capture, fusion and ER cross sections for the SHE with Z=114 using the fusion reactions ^{48}Ca+$^{236–244}$Pu leading to the CN, $^{284–292}$Fl are studied. From the systematic study of these reactions, it is clear that the reactions ^{48}Ca+$^{243–244}$Pu have maximum production cross sections and these combinations should be the favourable projectile-target pair for the synthesis of isotopes of Fl [7].

The isotopic dependence of both projectile and target reactions in production cross section are studied using the reaction ^{42,44,46,48}Ca + $^{252-255}$Es and $^{46-50}$Ti + $^{246-249}$Bk leading to the CN

$^{292\text{-}303}119$. The calculated result shows that $^{48}Ca + ^{252}Es \rightarrow ^{300}119$ and $^{48}Ca + ^{254}Es \rightarrow ^{302}119$ in the $3n$ channel and the $4n$ channel, respectively, should be the favourable projectile-target pair for the synthesis of $Z = 119$. Among the $^{46\text{-}50}Ti$ induced reactions on $^{246\text{-}249}Bk$ targets, $^{50}Ti + ^{249}Bk$ in the $4n$ channel and $^{50}Ti + ^{248,246}Bk$ in the $3n$-channel are more favourable [8].

The ER cross sections for the fusion reactions $^{48}Ca + ^{249–254}Cf \rightarrow ^{297–302}Og$, $^{45}Sc + ^{247,249}Bk \rightarrow ^{292,294}Og$, $^{50}Ti + ^{242–248,250}Cm \rightarrow ^{292\ 298,300}Og$, $^{51}V + ^{241,243}Am \rightarrow ^{292–294}Og$, $^{54}Cr + ^{238–242,244}Pu \rightarrow ^{292–296,298}Og$, $^{55}Mn + ^{235–237}Np \rightarrow ^{290–292}Og$, $^{58}Fe + ^{232–236,238}U \rightarrow ^{290–294,296}Og$, $^{59}Co + ^{231}Pa \rightarrow ^{290}Og$, and $^{64}Ni + ^{228–230,232}Cm \rightarrow ^{292\ 294,296}Og$ in xn ($x = 3, 4,5$) evaporation channel leading to SHE Z=118 have been systematically calculated. It is found that the reactions $^{48}Ca + ^{251}Cf \rightarrow ^{299}Og$ for 3n channel, $^{48}Ca+^{252}Cf \rightarrow ^{300}Og$ for 4n channel are more favourable for the synthesis of isotopes of Og [1].

With including deformation and orientation effects, the fusion excitation functions for Z=115 have been calculated for the probable reactions $^{48}Ca+^{241,243}Am \rightarrow ^{289,291}Mc$, $^{45}Sc+^{240,242,244}Pu \rightarrow ^{285,287,289}Mc$, $^{50}Ti+^{236,237}Np \rightarrow ^{286,287}Mc$, $^{51}V+^{238}U \rightarrow ^{289}Mc$, $^{36}S+^{253}Es \rightarrow ^{289}Mc$, $^{46}K+ ^{248}Cm \rightarrow ^{294}Mc$ (hot fusion reactions); and $^{78}As+^{208}Pb \rightarrow ^{286}Mc$, $^{76}Ge+^{209}Bi \rightarrow ^{285}Mc$ (cold fusion reactions) with different orientations of the colliding deformed nuclei. The averaged ER excitation functions for different orientations for the reaction $^{48}Ca+^{243}Am \rightarrow ^{291}Mc$ are compared with experimental data. The production cross section for the synthesis of heavy element ^{204}Po and ^{202}Po using $^{40}Ar+^{164}Dy$, $^{48}Ca+^{154}Gd$ and $^{44}Ca+ ^{158}Gd$ are also studied.

The production cross section for the isotopes of SHE with Z=122, and 124 are studied which are not being experimentally confirmed till now. The most suitable reactions to synthesize Z=122 are $^{54}Cr+^{248}Cf$, $^{64}Ni+^{238}Pu$, $^{70}Zn+^{232}U$, $^{50}Ti+^{253}Fm$, $^{54}Cr+^{249}Cf$, $^{58}Fe+^{245}Cm$, and $^{64}Ni+ ^{239}Pu$, for which the calculated ER excitation function are greater than 10 fb. Among these, the reactions $^{54}Cr+^{249}Cf$ and $^{64}Ni+^{238}Pu$ are the most probable to synthesize element with Z=122. By estimating the proton separation energies, it is seen that isotopes $^{298\text{-}301}122$ may decay through proton emission. By comparing the α-decay half-lives with the spontaneous fission half-lives, the isotopes $^{302\text{-}308,310}122$ may decay by 4α chains [9]

Through these predictions, we could emphasize the fact that the isotopes $^{302\text{-}306}122$ can be synthesized in neutron evaporation channel and can detected experimentally via alpha decay. The production cross section for the isotopes of SHE with Z=124 and the most probable reactions to synthesize $^{304}124$, $^{305}124$, $^{306}124$, $^{307}124$, and $^{308}124$ are $^{64}Ni+^{240}Cm$, $^{64}Ni+^{241}Cm$, $^{58}Fe+^{248}Cf$, $^{64}Ni+^{243}Cm$, and $^{58}Fe+^{250}Cf$ respectively. Also we have predicted 4α chains observed for $^{304}124$, 3α chains observed for $^{305}124$, 6α chains observed for $^{306\text{-}307}124$ and 5α chains observed for $^{308\text{-}312,\ 314}124$ [10]

We identified that the production cross section of SHE with neutron number N >184 is less than 2 fb and concluded that SHE with N>184 ($^{307\text{-}308,310}122$ and $^{309\text{-}314}124$) may not be synthesized in near future. The reliability of our model has been proved through the various studies, where our calculated fusion excitation functions are in agreement with experimental values for the SHE with Z=114 to 118 [See table 3 of Ref.8] . Hence we hope that the predicted production cross section of Z=119, Z=120,122 and 124 using the same model will serve as a guide for experimentalist in future experimental investigations.

References

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