Summer 9-28-2017

The study of superheavy elements at the intensity frontier: Reactions and new methods of synthesis

Devaraja H. M

Abstract

Background: The production and study of superheavy elements (SHE) ($Z \geq 103$) is an important area of research in contemporary experimental nuclear physics. The heaviest element produced so far is $Z=118$ (one isotope with $A=294$). The lowest production cross-sections for these SHE are of the order of picobarns, approaching the limit of the measurement capability of the presently available experimental facilities. The SHE island of doubly magic nuclei predicted at $Z=114$, 120, and 126 with $N=184$ has not been reached yet. However, a gap remains in the upper end of the nuclear chart between the Super Heavy Nuclei (SHN) produced in cold fusion (CF) using Pb and Bi targets and hot fusion (HF) reactions with ^{48}Ca with actinide targets. The scarcity of suitable projectile target combinations made the experimental synthesis of these missing nuclides in the gap a challenging task. In addition, the challenges of future SHE research are also to gain a better understanding of the structure and stability against fission and to go beyond $Z=118$ to find the extension of the island of spherical SHE around $Z=114$ or 126 and $N = 184$. Experimental developments such as accelerators for intense heavy-ion beams, advanced detection techniques, and efficient in-flight separators for both complete fusion and deep inelastic transfer products are expected to allow for experiments at high sensitivity and to access new regions of SHE.

Methods and results: The production cross-section strongly depends on the beam energy and the combination of projectile and target. Therefore, theoretical calculations for the production cross-sections for the reactions leading to SHE will provide an important information on the choice of appropriate target-projectile combinations and the corresponding optimal beam energy in assisting

the experimentalists to plan the future experiments. A systematic analysis of the excitation energy (E^*) dependent evaporation residue (ER) cross-sections has been carried out for the HF reactions with a comparison to the experimental ER cross sections related to the synthesis of SHE using the HIVAP code. This analysis enabled us to find a single set of parameters, which when implemented in the HIVAP computer code, describe the experimental production cross-sections for the reactions using a ^{48}Ca beam on actinide targets reasonably well. A simple scaling based on the mass asymmetry of the projectile-target system is introduced for projectiles lighter than ^{48}Ca. It is seen that only three parameters scaled by a constant factor is required to describe the ER cross-section data obtained using lighter than ^{48}Ca projectiles. The projectile dependence on the production cross-section is also studied. From these investigations, suitable projectile target combinations are proposed for the production of unknown heavier isotopes in the gap region for the elements Z = 104 and 106, production of unknown isotopes of the elements Z=116 and 118, and for the synthesis of new SHE with Z = 119 and 120.

The predicted ER cross-sections for the experimentally unexplored isotopes of elements Rutherfordium (^{264}Rf), Seaborgium (^{267,268}Sg), Livermorium ($^{293-295}$Lv), Oganesson ($^{293,295-297}$Og), Z=119 ($^{295-299}$119), and Z=120 ($^{300-302}$120) reveal that the ER cross-sections are varying from a few nanobarns down to 0.09 picobarn. To reach the cross-sections below the picobarn level experimentally, it is essential to upgrade the beam intensity by a few orders of magnitude (up to 10^{14} ions/s). Another added responsibility in the context of SHE research is to further improve the sensitivity of the separation techniques and detection systems, which can enable the experiments to reach the predicted closure shell at Z=114, 120 or 126 with N=184. In this context, in Chapter 3, LISE++ code has been successfully used to simulate and optimize the proposed next generation in-flight separator for high transmission of fusion reaction products. The new generation in-flight separator was proposed in 2010 at Manipal University in collaboration with GSI and Giessen university, aiming at high transmission of fusion and transfer reaction products and including the advanced detection techniques for heavy nuclei, which are presently not accessible with the α decay of parent-daughter correlations.

Due to the extremely small production cross-sections, the heavy and the superheavy isotopes on the neutron-rich side of the stability line are difficult to reach with the heavy ion fusion reactions. This is the main reason for the difficulty of reaching the predicted superheavy "island of stability". It is important to look for different reaction processes to approach the unexplored nuclei in the superheavy mass region. In Chapter 4, deep inelastic multi-nucleon transfer reaction products from collisions of ^{48}Ca+ ^{248}Cm at a beam energy of 270 MeV were separated and identified with the velocity filter SHIP at GSI were analysed. A vast region of reaction products with proton numbers $82 \leq Z \leq 98$ was identified by correlating the implanted residues with subsequent α-decays. Among them, we identified the new neutron-deficient isotopes ^{216}U, ^{219}Np, ^{223}Am, ^{229}Am, and ^{233}Bk. These findings provide the first experimental evidence that establishes deep inelastic multi-nucleon transfer reactions as a means to the production of the new exotic heavy isotopes and possibly a viable way to reach neutron-rich SHN which are not accessible in complete fusion reactions. Additionally, further investigations to understand and interpret these observations were carried out. They include the cross-section extraction for the observed reaction products and the investigation of isotopic distributions.