Observations from evaporation residue cross sections in $^{45}$Sc- and $^{44}$Ca-induced reactions


Recent measurements of evaporation residue (EvR) cross sections [1-3] for nuclei near the N = 126 shell have emphasized the importance of collective enhancements to the level density (CELD) for spherical ground-state nuclei and may have relevance for new superheavy element (SHE) synthesis. The study of $^{45}$Sc-induced reactions on lanthanide targets [3] revealed that proton evaporation competed effectively with neutron evaporation from the compound nuclei (CN) that were produced. The $\gamma n$ cross sections of $^{45}$Sc-induced reactions were also three or more orders of magnitude smaller than cross sections of $^{48}$Ca-induced reactions on the same targets due to the relative neutron deficiency of $^{45}$Sc.

In the last year, we bombarded $^{156,157,159}$Gd targets with $^{45}$Sc projectiles and $^{158}$Gd, $^{159}$Tb, and $^{162}$Dy targets with $^{44}$Ca projectiles as part of a systematic study to produce CN near the N = 126 shell. The beams of $^{45}$Sc$^{6+}$ and $^{44}$Ca$^{6+}$ were provided from the K500 cyclotron, and the unreacted beam and other unwanted reaction products were separated using the Momentum Achromat Recoil Spectrometer (MARS) [4]. Full experimental details are given in Refs. [1, 5].

Combined with previous results, reactions of $^{45}$Sc + $^{156-158,160}$Gd have now been studied and $4n$ cross sections are shown in Fig. 1. As expected, the $4n$ cross sections decrease as the neutron number in the target decreases. As the CN become more neutron-deficient, the fission

![Graph showing $4n$ and $3n$ cross sections](image)

**FIG. 1.** (a) $4n$ and (b) $3n$ cross sections for $^{45}$Sc-induced reactions on $^{156-158,160}$Gd targets. Symbols indicate experimental data and solid lines indicate theoretical calculations.
barriers decrease and the neutron binding energies increase, leading to a higher probability of fission. $^{44}$Ca is of interest because it is only one proton removed from $^{45}$Sc (both are $N = 24$ nuclei). Cross sections for the reactions of $^{44}$Ca on lanthanide targets are approximately two orders of magnitude larger than for reactions of $^{45}$Sc on the same targets as shown in Fig. 2. The $pn\pi$ cross sections in the $^{44}$Ca-induced reactions are also larger than in the $^{45}$Sc-induced reactions. This emphasizes the role of the extra proton in $^{45}$Sc in creating much more fissile CN which have low survival probabilities. A simple theoretical model based on Ref. [6] was developed, and the inclusion of CELD was necessary to reproduce the experimental data. This may have implications for producing SHEs near the predicted $N = 184$ spherical closed shell, as CELD may negate any possible enhancement to the $x\pi$ cross section as a result of producing CN on this shell.

Two reactions with $^{44}$Ca projectiles were cross bombardments for reactions that had been previously studied using either $^{48}$Ca or $^{45}$Sc projectiles. Cross sections for the $4\pi$ EvR of the $^{48}$Ca + $^{154}$Gd and $^{44}$Ca + $^{158}$Gd reactions which produced the $^{202}$Po CN are very similar (see Fig. 2). However, the maximum $4\pi$ EvR cross section of the $^{44}$Ca + $^{159}$Tb reaction which produced the $^{203}$At CN is approximately an order of magnitude larger than in the $^{45}$Sc + $^{159}$Sc reaction which produced the same CN. Some of this discrepancy should be accounted for by differences in the

![Graph showing cross sections for different reactions](image)
fusion probability, but we cannot rule out other effects such as pre-equilibrium emission playing a role [7].

These data demonstrate that the production of neutron-deficient heavy nuclei using $^{44}$Ca and $^{45}$Sc projectiles is relatively difficult compared to similar reactions using $^{48}$Ca projectiles reacting with the same targets.