Projectile influence on EVR production in ^{48}Ca, ^{54}Cr + ^{162}Dy fusion-evaporation reactions and its relation to synthesis of element 120

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While discovery of element 118 is still to be confirmed, pursuits to synthesize an even heavier element are underway [1]. Due to unavailability of targets heavier than Cf, the use of ^{48}Ca beam for production of new elements, though it has been successful in the past, appears exhausted [2]. A move to heavier beams is a new direction in element discovery and the likely first element to be produced in this way is Z = 120, for which ^{54}Cr + ^{248}Cm is a proposed reaction [3].

Challenges of synthesizing Z =120 were investigated by analyzing what factors most influence the cross section of the evaporation residue EVR in switching from ^{48}Ca to ^{54}Cr projectile in reactions with ^{162}Dy and the preliminary results are discussed in this report. Reactions of ^{162}Dy (^{48}Ca, 4n) ^{206}Rn and ^{162}Dy (^{54}Cr, 4n) ^{212}Th were chosen as "model" systems for this study due to similar energetics to ^{48}Ca, ^{54}Cr + ^{248}Cm reactions as shown in Table I. In the experiment, beams of ^{48}Ca^{6+} (214 MeV) and ^{54}Cr^{7+} (273 MeV) were accelerated by the K500 cyclotron and interacted with a ^{162}Dy target having a thickness of 403-µg/cm^2 (deposited onto a ^{nat}C backing). Beam energies were varied using a degrader ladder containing Al foils from 1.2 µm to 8.54 µm, plus a blank. Reaction products of interest were separated from unwanted by-products in the Momentum Achromat Recoil Separator [4] based on magnetic rigidity dispersion in the first dipole (D1) and particle velocity in the Wien filter. An excitation function for production of ^{206}Rn was measured and 84 % upper limit [5] cross sections for the production of ^{212}Th were calculated following three 10-hour irradiations at center-of-target energies of 244.7, 249.1, and 254.1 MeV (see Fig 1. and Table II). Due to ^{205}Rn having a nearly identical E_α as ^{206}Rn, the Rn excitation function is currently treated as the sum of the two isotopes. The contribution of ^{205}Rn to the peak of the ^{206}Rn is assumed to be negligible as the 5n peak cross section is estimated to be at 210 MeV. The difference in peak cross section for the 4n product in each reaction is approximately a factor of $\geq$ 6000

Table I. Summary of energetics of ^{48}Ca and ^{54}Cr reactions on ^{162}Dy and ^{248}Cm. Column 4 shows the difference $E_{cm} - B$, where E_{cm} is the center of mass projectile energy and B is the average interaction (representing sum of Coulomb, centripetal, nuclear potentials) barrier height [8]. E^*_{CN} is the excitation energy of the CN system. Column 6 gives the remaining excitation energy of a nucleus following emission of 4 neutrons each with binding energy S_n. Values calculated based on estimated projectile energy needed to remove 4 neutrons, leaving the residual nucleus with excitation energy below either the S_n or B_f, whichever is lower in energy.

Reaction	Product	N of CN	Energy Above Barrier	E^*_{CN}	$E^*_{CN} - \Sigma(S_{n,i})$
^{162}Dy(^{48}Ca, 4n)	^{206}Rn	124	5.46 MeV	48 MeV	15.63 MeV
^{162}Dy(^{54}Cr, 4n)	^{212}Th	126	10.17 MeV	50 MeV	15.76 MeV
^{248}Cm(^{48}Ca, 4n)	^{292}116	180	9.58 MeV	41 MeV	15.48 MeV
^{248}Cm(^{54}Cr, 4n)	^{298}120	182	12.33 MeV	43 MeV	15.86 MeV

(12.2 ± 4.0 mb for ^{206}Rn and $\leq$ 2 μb for ^{212}Th). Using current theoretical models for fusion reactions, reasons leading to the factor of $\geq$ 6000 were assessed.

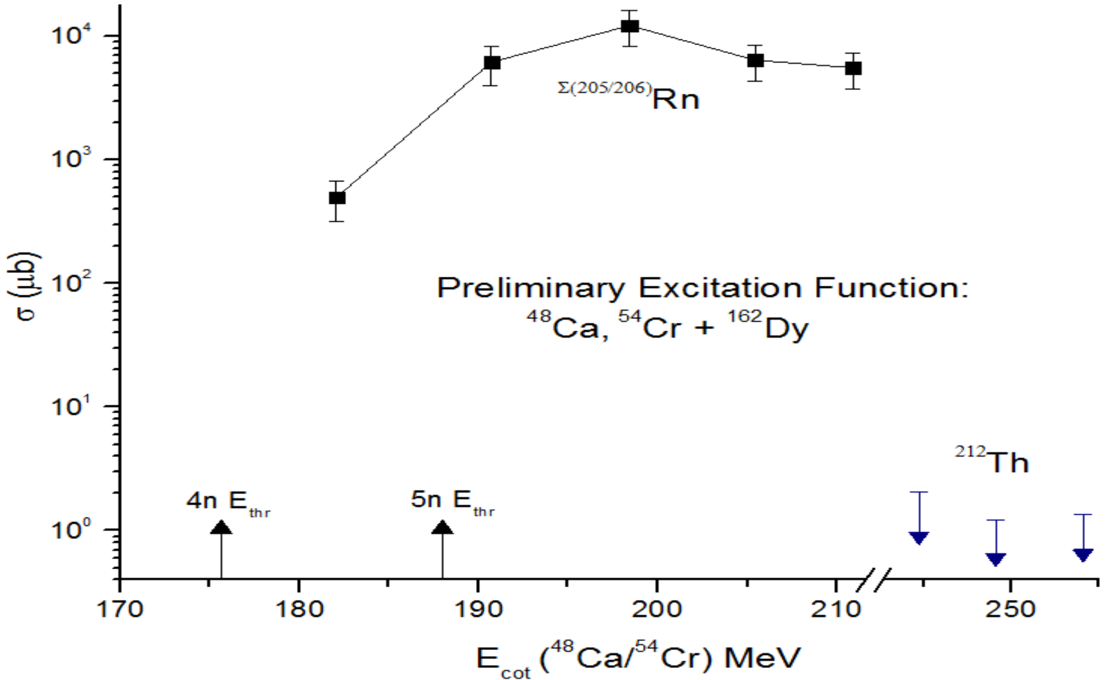

FIG. 1. Preliminary excitation function for ^{162}Dy (^{48}Ca, 4-5n) ^{206,205}Rn and 84% upper limit cross sections for ^{162}Dy (^{54}Cr, 4n) ^{212}Th. E_{cot} is the center-of-target energy. The E_{thr} are the threshold energies for the production of ^{206,205}Rn.

Table II. Summary of estimated and measured 4n peak cross sections and estimated P_{CN} values in the case of ^{48}Ca and ^{54}Cr reactions on ^{162}Dy and ^{248}Cm. Values of column 6 were used for Dy reactions, due to their improved predictions for lighter systems (see main text). Values of Column 7 were used for Cm reactions as prescribed by [3, 11]. The measured cross section for ^{212}Th is an 84% upper limit calculated according to the method described in [4].

Reaction	Product	z	σ_{EVR} meas.	σ_{EVR} est.	P_{CN} [13]	P_{CN} [7]
^{162}Dy(^{48}Ca, 4n)	^{206} Rn	145.3	12.2 mb	78.5 mb^a	0.4208	0.1444
^{162}Dy(^{54}Cr, 4n)	^{212} Th	171.6	$\leq$ 2 μb^b	15.4 μb^a	0.0037	0.0449
^{248}Cm(^{48}Ca, 4n)	^{292} 116	193.6	3.3 pb [16]	1.26 pb^a	8.18×10^{-8}	0.0065
^{248}Cm(^{54}Cr, 4n)	^{298} 120	229.0	—	0.01 pb [3]	1.94×10^{-9}	0.0011

[a] Estimates were made according to [4-6, 8-9, 11], with accuracy of one to two orders of magnitude.
[b] 84% of the distribution lies below the value reported.

Fusion – evaporation cross sections are theoretically modeled by a product of three factors: 1. the cross section corresponding to projectile and target overcoming an interaction barrier and touching (σ_{cap}), 2. the probability that the touching di-nuclear system will fuse into a compound nucleus (P_{CN}), and 3. the survival probability of an excited CN against fission (P_{sur}). The value of σ_{cap} was calculated according to the "diffused barrier formula" as derived in [6] . In cases of very heavy nuclei, the critical angular momentum formula is used for σ_{cap}, where $l_{critical}$ defines the “cut-off” value of angular momentum above which the CN has no fission barrier [7-8]. To estimate CN survival against fission following multiple de-excitation steps resulting in the emission of neutrons, numerical integration over saddle-point decay channels as discussed in [9] was used. The kinetic energy of the neutrons was assumed to be 2T, where T is taken as $(E^*/a)^{1/2}$ and a is calculated according to the parameterization provided in [10], where saddle-point deformation is considered. Estimates of P_{CN} are more challenging, as discussed below. In Table II, the estimated peak cross sections for all reactions of interest in this study are presented.

The greatest uncertainty in theoretical estimates of EVR cross sections lies in making an accurate estimate of P_{CN}. Resolving discrepancies in predicated values of P_{CN} using different methods is a current field of research [11]. P_{CN} is known to decrease exponentially with an increase in z, the Coulomb parameter given by $Z_1Z_2 / (A_1^{1/3}+A_2^{1/3})$, severely hindering fusion of symmetric systems [12]. A simple phenomenological expression as a function of z for P_{CN} was reported in [7] with a downside of having discrepancies of one order of magnitude in some cases. This expression is,

$$P_{CN} = \exp[-\ln(10)\left(\frac{z}{\alpha}\right)^3] \qquad \text{Eq. (1)}$$

where z is the Coulomb parameter and α is determined by the magnitude of $E_{cm} - B$, where E_{cm} is the center-of-mass projectile energy and B is the interaction barrier (see [7] for details). Another approach for estimating P_{CN} cited in [13] considers the fissility of the CN and relates it to a threshold fissility parameter found from fits to a set of hot fusion (generally ≥ 3n products) data. This expression is,

$$P_{CN} = -0.5\exp[-c(x_{eff} - x_{thr})] \qquad \text{Eq. (2)}$$

where x_{eff} is the effective fissility descriptive of the degree of deformation required for a nucleus to fission. The parameters c and x_{thr} are extracted from fits to experimental data (see [13] for details). P_{CN} values from both calculations are given in Table II. The phenomenological expression is prescribed by [3] for heavier systems such as the Cm reactions, as evidenced by its agreeable predictions for formation cross sections of elements 114 – 118 [14]. For the ^{162}Dy reactions, the estimates based on CN fissility were used due to its superior predictions in the case of cross sections in [15], where data for ^{48}Ca + ^{172,173,176}Yb is reported.

The difference in P_{CN} between ^{162}Dy (^{48}Ca, 4n) ^{206}Rn and ^{162}Dy (^{54}Cr, 4n) ^{212}Th is predicted according to Eq. (2) to be a factor of 114. Taking the measured production cross sections from the present work for the same reactions and dividing them by the estimated product $\sigma_{cap}P_{sur}$, estimates of the experimental difference in P_{CN} yields a factor of≥ 19. This treatment is employed realizing that assumptions are made about the level of accuracy in prediction of P_{sur}, however this assumption was validated by successfully predicting the survival probabilities of nuclei formed in hot fusion, for which the P_{CN} was assumed to be 1 due to the extreme asymmetry in the projectile-target pair [10].

The smaller P_{CN} in the less asymmetric ^{54}Cr reactions, as compared to ^{48}Ca reactions with the same target, reduces the overall EVR cross sections. This similar effect is observed in calculations using Eq. (1) for ^{248}Cm (^{48}Ca, 4n) ^{292}116 and ^{248}Cm (^{54}Cr, 4n) ^{302}120 where a difference of a factor of 6 in P_{CN} is predicted. However, the survival probability for ^{302}120 may be enhanced potentially due its proximity to the N = 184 magic neutron shell. Drawing from the results discussed here, one can expect the P_{CN} for ^{54}Cr + ^{248}Cm to be one to two orders of magnitude lower than for the ^{48}Ca + ^{248}Cm reaction [16]. Hence the cross section of 0.01 pb, as predicted in [3], for the synthesis of ^{298}120 is quite reasonable. At such a low cross section, the synthesis of element 120 in the ^{248}Cm (^{54}Cr, 4n) ^{302}120 reaction may not be feasible as it approaches the limits of current production techniques.

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