Production of transuranium isotopes in ^{20}Ne-induced incomplete fusion reactions

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Using a semiclassical dynamical model that combines a classical trajectory model with stochastic breakup with a dynamical fragmentation theory treatment of two-body clusterization and decay of a projectile, results are presented for ^{20}Ne-induced incomplete fusion reactions for the production of superheavy elements. Targets include ^{247,248,250}Cm and ^{251,252,254}Cf, and results include angular, excitation energy, and angular momentum distributions in addition to total integrated cross sections for heavy incomplete fusion products. The results show that at Coulomb energies, the studied Cf isotopes are generally the more favorable choice of target over the studied Cm isotopes for the production of 'colder' and more stable ^{263}Lr, ^{263,264,266}Rf, and ^{265}Db isotopes through the incomplete fusion mechanism. Also presented are evaporation residue cross sections for the dominant primary incomplete fusion products of each of the six reactions: ^{263,264,266}Rf and ^{267,268,270}Sg, as well as for the primary incomplete fusion products ^{269,270,272}Bh.

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I. INTRODUCTION

The production of superheavy elements (SHEs), namely the transactinide elements ($104 \leqslant Z \leqslant 120$), is very challenging due to very small cross sections, with complete fusion (CF) of heavy ions being one of the most successful ways of producing SHEs [1]. The CF mechanism predominantly produces neutron-deficient SHEs, making investigation into new methods of production [2] crucial for further progress in SHE research. The observation of energetic α particles at forward angles in incomplete fusion (ICF) reactions induced by heavy ions at Coulomb energies [3–6] indicates that following projectile breakup, the α particle carries away most of the bombarding energy of the projectile, leaving the remaining projectile fragment to be captured by the target. The result is a fusion product with lower excitation energy than would typically be achieved via the CF mechanism. These cold products from ICF reactions result in both fewer neutrons evaporated and a higher survivability against fission, indicating that this mechanism could be a successful way of producing relatively stable SHE isotopes. Despite a variety of studies mentioned in Ref. [7], ICF dynamics are still not very well understood at energies around 4–7 MeV/nucleon [8,9], and could yet prove to be an effective way of producing stable neutron-rich SHE isotopes.

The ICF dynamics of $^{20}\mathrm{Ne} + {}^{208}\mathrm{Pb}$ collisions at energies above the Coulomb barrier were investigated using a novel semiclassical dynamical model [7], which combined a classical trajectory model with stochastic breakup [10], as implemented in the PLATYPUS code [11], with a dynamical fragmentation theory treatment of two-body clusterization and decay of a projectile [12,13]. A finite-difference method solution to the time-independent Schrödinger equation in the charge asymmetry coordinate was employed by way of diagonalizing a tridiagonal Hamiltonian matrix with periodic boundary conditions. This model has since seen some refinements (detailed in Sec. II) in order to extensively investigate SHE formation via the ICF reaction mechanism. In Sec. III, angular, excitation energy, and angular momentum distributions, as well as total integrated cross sections, are presented for heavy ICF products in ^{20}Ne-induced reactions involving isotopic chains of Cm and Cf targets. Conclusions are drawn in Sec. IV.

II. THEORY

A. Model overview

This novel semiclassical dynamical model [7] is built on the PLATYPUS implementation of a classical trajectory model with stochastic breakup [10,11], which is a powerful tool for quantifying complete and incomplete fusion, as well as breakup in reactions induced by weakly bound two-body projectiles near the Coulomb barrier. As is the case in the PLATYPUS code, the novel model determines the position of projectile breakup on the target-projectile orbit by utilising an experimentally determined breakup function [7] which encodes the effects of the Coulomb and nuclear interactions and defines the probability of breakup as a function of the distance of closest approach by dividing the experimental breakup cross section by the Rutherford scattering cross section [14]. The parameters used here for this breakup function are the same as in Ref. [7]. The PLATYPUS code calculates a wide range of observables including integrated CF and ICF cross sections and breakup observables such as the angle, kinetic energy, and angular momentum distributions of the fragments. All of the observables are calculated using a three-dimensional classical dynamical model merged with Monte Carlo sampled probability-density distributions [10].

TABLE I. ^{20}Ne projectile fragmentation parameters. m_0 is the nucleon mass (938 MeV/c^2).

η_Z	Fragment 1	Fragment 2	$(B^{-1})_{\eta_Z\eta_Z}$ ($10^{-2}m_0^{-1}$fm^{-2})	$V(\eta_z)$ (MeV)
−0.8	^{2}H	^{18}F	1.5349	13.9502
−0.6	^{4}He	^{16}O	1.6078	−5.7166
−0.4	^{7}Li	^{13}N	1.6460	14.7268
−0.2	^{8}Be	^{12}C	1.6665	−0.6184
0	^{11}B	^{9}B	1.6728	15.1328
+0.2	^{12}C	^{8}Be	1.6665	−0.6184
+0.4	^{13}N	^{7}Li	1.6460	14.7268
+0.6	^{16}O	^{4}He	1.6078	−5.7166
+0.8	^{18}F	^{2}H	1.5349	13.9502

Merged with this is a model [12,13] that makes use of the charge asymmetry coordinate, η_Z, which stems from the mass asymmetry coordinate, η [15,16], and is equal to the continuous volume asymmetry coordinate when the two nuclei overlap [15,16]. η_Z is defined as the difference in the charges of the two fragments divided by the sum total of their charges, as per Eq. (1):

$$\eta_Z = \frac{(Z_1 - Z_2)}{(Z_1 + Z_2)}, \tag{1}$$

where Z_1 and Z_2 are the charges of fragments 1 and 2, respectively. The determination of the binary fragmentation configuration is made by solving the time-independent Schrödinger equation in the charge asymmetry co-ordinate with periodic boundary conditions at $\eta_Z = \pm 1$, as shown by Eq. (2):

$$\left[-\frac{\hbar^2}{2}\frac{\partial}{\partial\eta_Z}(B^{-1})_{\eta_Z\eta_Z}\frac{\partial}{\partial\eta_Z} + V(\eta_Z)\right]\psi(\eta_Z) = E\psi(\eta_Z), \tag{2}$$

where $(B^{-1})_{\eta_Z\eta_Z}$ is the inverse inertia coefficient (a mass parameter for the co-ordinate η_Z) (units: nucleon mass^{-1} fm^{-2}), $V(\eta_Z)$ is the driving potential as a function of η_Z, ψ is the wave function, and E is the energy.

The numerical method for solving Eq. (2) is explained in detail in Ref. [7]. The calculation of the ingredients of this equation, the inverse inertia coefficient and the driving potential, are presented in Secs. II B and II C, respectively. The inverse inertia coefficient in the charge asymmetry coordinate is strongly connected with the inertia coefficient in the mass asymmetry coordinate, as discussed in Refs. [12,13,17]. The latter inertia coefficient depends on the number of nucleons in the neck between the two touching fragments, whose determination requires a three-dimensional (3D) spatial integration [Eq. (6)]. Values of the inverse inertia coefficients and the driving potential for ^{20}Ne are presented in Table I.

In the present paper binary configurations of spherical fragments are considered. Both the inverse inertia coefficients and the driving potential are determined at the contact distance between the fragments which is the sum of their radii, i.e., $R_c = 1.1 \times (A_1^{1/3} + A_2^{1/3})$ fm. Whilst binary configurations of deformed fragments in the ^{20}Ne projectile were considered in Ref. [7], the present dynamical reaction model also considers isotropic orientation of the segment joining the two fragments relative to the segment between the center of mass of the projectile and the target. Since this assumption of 'isotropic orientation' diminishes the role of the fragment deformation in the incomplete fusion process, it is considered that the use of spherical fragments is simpler and a good approximation.

B. Inverse inertia coefficient calculation

The inverse inertia coefficient in the charge asymmetry coordinate in Eq. (2) is calculated using the equation [12,17]

$$(B^{-1})_{\eta_Z\eta_Z} = \left(\frac{\partial\eta}{\partial\eta_Z}\right)^{-2}\frac{1}{m_0}\frac{A_{\rm neck}}{2\sqrt{2\pi}b^2A^2}, \tag{3}$$

where A is the total nucleon number of the projectile, $A_{\rm neck}$ is the number of nucleons in the neck between the two projectile fragments, m_0 is the nucleon mass, and b is a parameter that characterizes the size of the 'neck', a region of overlap between the intranuclear nucleon-distribution tails, as visualised by Fig. 2 in Ref. [7]. $\frac{\partial\eta}{\partial\eta_Z}$ is equivalent to $\frac{Z}{A}$, and $A_{\rm neck}$ is given by

$$A_{\rm neck} = \int d^3\mathbf{r}[\rho_1(\mathbf{r}) + \rho_2(\mathbf{R}-\mathbf{r})]\exp\left(-\frac{(z-z_0)^2}{b^2}\right), \tag{4}$$

where $\rho_1(\mathbf{r})$ and $\rho_2(\mathbf{R}-\mathbf{r})$ are the nucleon densities of the two fragments as functions of the distance from the center of mass of each fragment. $\mathbf{R}$ is the distance between the centres of mass of the two fragments, z is the z-axis component of $\mathbf{r}$, and z_0 is the point where these two fragments densities are equal $[\rho_1(z_0) = \rho_2(z_0)]$. This is because $\mathbf{r}$ and $\mathbf{R}-\mathbf{r}$ are the vectors from the center of mass of fragments 1 and 2, respectively. There is no single vector as the two fragments are displaced by $\mathbf{R}$. The origin of the coordinate system is the center of mass of fragment 1, and the z axis is along $\mathbf{R}$. The nucleon densities of the fragments are given by

$$\rho_1(\mathbf{r}) = \frac{\rho_0}{1+\exp\left(\frac{\sqrt{x^2+y^2+z^2}-r_{0_1}A_1^{1/3}}{a_{0_1}}\right)},$$
$$\rho_2(\mathbf{R}-\mathbf{r}) = \frac{\rho_0}{1+\exp\left(\frac{\sqrt{x^2+y^2+(R-z)^2}-r_{0_2}A_2^{1/3}}{a_{0_2}}\right)}, \tag{5}$$

where ρ_0 is the central density of the fragments, A is the corresponding mass number, a_0 denotes diffuseness parameters for the two densities, and x, y, z are Cartesian co-ordinates. These parameters have been set as follows: $\rho_0 = 0.16$ fm^{-3}, r_{0_1} and $r_{0_2} = 1.1$ fm, a_{0_1} and $a_{0_2} = 0.5$ fm, and $b = 0.45$ fm. Using cylindrical co-ordinates, Eq. (4) can be rewritten as

$$A_{\rm neck} = 2\pi\rho_0\int_0^\infty rdr\int_{-\infty}^\infty dz\exp\left(-\frac{(z-z_0)^2}{b^2}\right)$$
$$\times\left[\frac{1}{1+\exp\left(\frac{\sqrt{r^2+z^2}-r_{0_1}A_1^{1/3}}{a_{0_1}}\right)}\right.$$
$$\left.+\frac{1}{1+\exp\left(\frac{\sqrt{r^2+(R-z)^2}-r_{0_2}A_1^{1/3}}{a_{0_2}}\right)}\right]. \tag{6}$$

TABLE II. Results for the heaviest primary ICF products of the reaction $^{20}\mathrm{Ne} + {}^{247}\mathrm{Cm}$.

ICF product	Total cross section (mb)	Mean angle (degrees)	Mean exc. energy (MeV)	Mean angular momentum ($\hbar$)
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.00$		
^{258}Md	42.07	9.28 ± 3.72	21.49 ± 6.81	13.19 ± 5.43
^{259}No	46.79	8.45 ± 3.23	41.69 ± 4.42	11.40 ± 5.54
^{260}Lr	13.85	8.22 ± 2.88	40.30 ± 7.03	10.46 ± 5.31
^{263}Rf	66.74	5.55 ± 2.34	46.21 ± 1.72	11.36 ± 5.20
^{265}Db	27.62	3.75 ± 1.78	55.66 ± 0.85	9.29 ± 4.46
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.10$		
^{258}Md	283.9	13.71 ± 4.79	26.75 ± 7.71	17.44 ± 8.16
^{259}No	556.9	12.74 ± 4.68	46.59 ± 4.41	15.82 ± 7.28
^{260}Lr	397.8	12.33 ± 4.34	43.27 ± 7.44	14.59 ± 6.86
^{263}Rf	1523	10.61 ± 3.82	51.40 ± 3.55	16.57 ± 7.99
^{265}Db	1155	9.22 ± 3.92	62.03 ± 2.77	17.87 ± 8.23
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.20$		
^{258}Md	390.8	17.39 ± 3.94	31.49 ± 8.99	22.40 ± 9.45
^{259}No	1185	15.27 ± 4.62	51.83 ± 5.94	20.78 ± 9.11
^{260}Lr	1099	14.92 ± 4.26	49.34 ± 8.06	19.48 ± 8.88
^{263}Rf	3842	12.17 ± 4.17	59.04 ± 4.74	23.73 ± 10.09
^{265}Db	2655	10.01 ± 4.15	71.26 ± 3.50	26.52 ± 10.73

z_0 is derived from the relation

$$\frac{z_0 - r_{0_1}A_1^{1/3}}{a_{0_1}} = \frac{(R - z_0) - r_{0_2}A_2^{1/3}}{a_{0_2}}, \tag{7}$$

which gives

$$z_0 = \frac{a_{0_2}r_{0_1}A_1^{1/3} + a_{0_1}\left(R_c - r_{0_2}A_2^{1/3}\right)}{a_{0_1} + a_{0_2}}. \tag{8}$$

In the method suggested in Ref. [17] for calculating the inertia coefficients, the phenomenological parameter b controls the size of the neck between two touching fragments. With the standard, adopted values of all the parameters contained in Eq. (6), the number of nucleons in the neck is approximately 2–3 over the range of values of the charge asymmetry coordinate. The standard, adopted value of b has been used in many applications of a dinuclear system model for describing alpha decay, cluster radioactivity and spontaneous fission [12,13].

C. Driving potential calculation

Just as each binary fragmentation configuration of the projectile has its own associated inverse inertia coefficient at the contact distance, so too does it have its own associated

TABLE III. The same results as in Table II, but for the reaction $^{20}\mathrm{Ne} + {}^{248}\mathrm{Cm}$.

ICF product	Total cross section (mb)	Mean angle (degrees)	Mean exc. energy (MeV)	Mean angular momentum ($\hbar$)
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.00$		
^{259}Md	40.61	7.50 ± 3.01	21.93 ± 7.12	12.80 ± 6.05
^{260}No	44.68	6.48 ± 2.69	42.14 ± 3.84	11.51 ± 5.80
^{261}Lr	15.00	5.74 ± 2.12	40.17 ± 5.44	10.92 ± 5.03
^{264}Rf	84.04	4.18 ± 1.72	47.56 ± 1.55	12.37 ± 5.23
^{266}Db	29.30	2.34 ± 1.16	55.55 ± 0.92	10.82 ± 4.57
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.10$		
^{259}Md	294.5	13.87 ± 4.74	26.72 ± 7.64	16.26 ± 7.99
^{260}No	508.2	12.74 ± 4.67	46.88 ± 4.61	15.47 ± 7.32
^{261}Lr	389.7	12.28 ± 4.18	43.28 ± 7.52	13.87 ± 6.63
^{264}Rf	1476	10.66 ± 3.83	52.08 ± 3.53	16.51 ± 7.93
^{266}Db	1068	8.93 ± 3.90	61.72 ± 3.08	17.96 ± 8.28
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.20$		
^{259}Md	352.3	19.43 ± 4.41	31.90 ± 9.44	21.61 ± 9.35
^{260}No	1128	16.92 ± 5.22	52.34 ± 5.69	19.93 ± 8.69
^{261}Lr	1150	16.40 ± 4.96	50.33 ± 7.88	19.79 ± 8.66
^{264}Rf	3695	13.44 ± 4.76	60.38 ± 5.38	23.94 ± 10.36
^{266}Db	2434	11.02 ± 4.77	70.32 ± 4.63	26.42 ± 10.91

TABLE IV. The same results as in Table II, but for the reaction ^{20}Ne + ^{250}Cm.

ICF product	Total cross section (mb)	Mean angle (degrees)	Mean exc. energy (MeV)	Mean angular momentum ($\hbar$)
		$E_{0_{\text{c.m.}}}/V_{CB} = 1.00$		
^{261}Md	35.26	10.97 ± 5.44	24.48 ± 6.69	12.96 ± 6.12
^{262}No	39.58	10.91 ± 4.40	44.28 ± 3.33	11.46 ± 5.40
^{263}Lr	18.09	9.88 ± 3.86	42.59 ± 6.25	10.29 ± 4.43
^{266}Rf	91.88	7.22 ± 3.44	49.76 ± 1.53	12.60 ± 5.59
^{268}Db	27.39	4.38 ± 2.28	57.50 ± 0.98	11.25 ± 4.90
		$E_{0_{\text{c.m.}}}/V_{CB} = 1.10$		
^{261}Md	275.2	9.37 ± 3.04	29.32 ± 7.98	16.78 ± 8.02
^{262}No	498.4	8.33 ± 2.79	48.44 ± 4.46	15.50 ± 7.08
^{263}Lr	389.1	7.60 ± 2.40	45.58 ± 7.60	14.28 ± 6.87
^{266}Rf	1457	5.89 ± 1.87	54.20 ± 3.53	16.78 ± 8.01
^{268}Db	1074	4.56 ± 1.66	63.59 ± 3.12	18.05 ± 8.38
		$E_{0_{\text{c.m.}}}/V_{CB} = 1.20$		
^{261}Md	320.5	11.81 ± 2.78	34.56 ± 9.54	23.19 ± 8.98
^{262}No	1118	9.71 ± 2.80	54.02 ± 5.62	20.11 ± 8.81
^{263}Lr	1068	8.96 ± 2.40	51.39 ± 7.53	19.14 ± 8.49
^{266}Rf	3696	6.46 ± 1.87	62.12 ± 4.98	23.96 ± 10.29
^{268}Db	2552	4.87 ± 1.56	72.41 ± 4.35	26.64 ± 10.74

potential energy:

$$V(\eta_Z) = V_N + V_C + \text{BE}_1 + \text{BE}_2 - \text{BE}_{CN}, \tag{9}$$

where V_N and V_C are the nuclear and Coulomb potentials, respectively, BE_1 and BE_2 are the binding energies of the two fragments and BE_{CN} is the binding energy of the compound nucleus. As in Ref. [7], the nuclear interaction potentials are calculated using the Broglia-Winther approach [18]. Binding energies for the projectile and its constituent fragments were taken from Ref. [19], whilst binding energies for exotic targets and ICF products were taken from Ref. [20].

D. Projectile friction and fragmentation

A refinement of the model described in [7] consists of the addition of a friction term [21] to the target-projectile's Newtonian equations of motion as follows:

$$\frac{d}{dt}(\mu\dot{r}) - \mu r\dot{\phi}^2 + \frac{dV_{NC}}{dr} + K_r\dot{r} = 0. \tag{10}$$

μ is the reduced mass ($\frac{m_P m_T}{m_P+m_T}$), $\dot{r}$ is the radial velocity, $\dot{\phi}$ is the angular velocity, V_{NC} is the interaction potential consisting of nuclear and Coulomb parts, and K_r is the radial friction coefficient, which is proportional to the square of the nuclear

TABLE V. The same results as in Table II, but for the reaction ^{20}Ne + ^{251}Cf.

ICF product	Total cross section (mb)	Mean angle (degrees)	Mean exc. energy (MeV)	Mean angular momentum ($\hbar$)
		$E_{0_{\text{c.m.}}}/V_{CB} = 1.00$		
^{262}Lr	36.29	11.75 ± 5.30	21.65 ± 7.10	12.74 ± 6.19
^{263}Rf	40.76	11.33 ± 4.42	41.83 ± 2.80	11.66 ± 5.65
^{264}Db	20.60	10.11 ± 4.18	40.32 ± 6.28	10.70 ± 4.93
^{267}Sg	90.10	7.32 ± 3.39	46.89 ± 1.69	12.98 ± 5.85
^{269}Bh	24.43	4.57 ± 2.50	55.75 ± 0.98	10.28 ± 4.16
		$E_{0_{\text{c.m.}}}/V_{CB} = 1.10$		
^{262}Lr	254.1	11.64 ± 3.75	26.38 ± 8.53	16.67 ± 8.06
^{263}Rf	502.6	10.59 ± 3.49	46.21 ± 4.48	15.79 ± 7.11
^{264}Db	360.1	10.01 ± 3.12	43.07 ± 7.54	14.54 ± 6.90
^{267}Sg	1444	8.36 ± 2.75	51.28 ± 3.60	16.72 ± 8.06
^{269}Bh	1021	6.77 ± 2.73	62.02 ± 3.26	17.87 ± 8.49
		$E_{0_{\text{c.m.}}}/V_{CB} = 1.20$		
^{262}Lr	391.9	11.79 ± 2.60	31.25 ± 9.24	22.00 ± 9.20
^{263}Rf	1050	9.74 ± 2.96	51.87 ± 5.99	20.27 ± 8.85
^{264}Db	1119	8.97 ± 2.41	49.19 ± 7.73	19.16 ± 8.70
^{267}Sg	3575	6.53 ± 1.94	59.71 ± 5.39	23.88 ± 10.58
^{269}Bh	2400	4.88 ± 1.58	70.94 ± 4.56	26.48 ± 11.05

TABLE VI. The same results as in Table II, but for the reaction $^{20}\mathrm{Ne} + {}^{252}\mathrm{Cf}$.

ICF product	Total cross section (mb)	Mean angle (degrees)	Mean exc. energy (MeV)	Mean angular momentum ($\hbar$)
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.00$		
^{263}Lr	41.78	12.39 ± 5.58	22.36 ± 7.14	13.23 ± 5.67
^{264}Rf	41.40	11.65 ± 4.89	42.16 ± 4.13	11.23 ± 5.32
^{265}Db	11.93	10.44 ± 4.27	40.67 ± 6.44	10.85 ± 5.38
^{268}Sg	74.83	8.15 ± 3.81	47.44 ± 1.65	12.00 ± 5.44
^{270}Bh	27.36	5.59 ± 2.76	55.22 ± 0.92	10.93 ± 4.41
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.10$		
^{263}Lr	257.7	9.54 ± 3.09	26.41 ± 8.22	16.39 ± 8.17
^{264}Rf	473.4	8.31 ± 2.83	47.25 ± 4.32	14.98 ± 6.98
^{265}Db	368.5	7.56 ± 2.56	44.25 ± 7.46	14.36 ± 6.88
^{268}Sg	1361	5.96 ± 2.00	53.39 ± 3.87	17.61 ± 8.50
^{270}Bh	916.8	4.47 ± 1.72	61.73 ± 3.40	18.31 ± 8.42
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.20$		
^{263}Lr	401.6	11.64 ± 2.61	33.13 ± 9.46	23.07 ± 9.59
^{264}Rf	1139	9.71 ± 2.85	52.69 ± 5.90	21.06 ± 9.00
^{265}Db	1087	9.01 ± 2.50	49.57 ± 8.08	20.00 ± 9.09
^{268}Sg	3711	6.41 ± 1.74	60.29 ± 4.74	24.32 ± 10.29
^{270}Bh	2530	4.88 ± 1.38	70.85 ± 3.53	26.91 ± 10.92

force [21]

$$K_r = K_r^0 (\nabla V_N)^2, \tag{11}$$

where $K_r^0 = 4 \times 10^{-23}$ s/MeV. For the sake of simplicity, loss of orbital angular momentum due to tangential friction has been neglected. Including this friction component would be a refinement of the present model. Included here is only radial friction, causing radial kinetic energy dissipation. The last term in Eq. (10) accounts for such a radial kinetic energy dissipation along a projectile-target trajectory. The loss of radial kinetic energy due to the last term in Eq. (10) produces the full energy loss along a projectile-target trajectory and directly determines the excitation energy of the projectile, and by extension the number of summed excited states considered in the calculation of the total probability density function of the projectile's fragmentation in the charge asymmetry coordinate [7], whereas in Ref. [7] the projectile's excitation energy was an input of the model. The eigenstates from Eq. (2) are summed using a Boltzmann factor [22] as shown in Eqs. (23)–(25) in Ref. [7]. The maximal orbital angular momentum between projectile and target considered here is $L_{TP} = 100\hbar$, with 1000 sampled fragmentations per orbital angular momentum.

TABLE VII. The same results as in Table II, but for the reaction $^{20}\mathrm{Ne} + {}^{254}\mathrm{Cf}$.

ICF product	Total cross section (mb)	Mean angle (degrees)	Mean exc. energy (MeV)	Mean angular momentum ($\hbar$)
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.00$		
^{265}Lr	40.92	7.29 ± 2.91	18.28 ± 7.51	13.59 ± 6.10
^{266}Rf	47.46	6.49 ± 2.55	38.63 ± 5.61	11.98 ± 5.53
^{267}Db	14.88	5.73 ± 2.02	36.64 ± 7.95	11.22 ± 5.22
^{270}Sg	58.53	4.05 ± 1.66	43.91 ± 1.80	11.74 ± 5.50
^{272}Bh	20.82	2.55 ± 1.25	51.23 ± 0.89	9.55 ± 4.37
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.10$		
^{265}Lr	282.0	11.54 ± 3.92	22.73 ± 8.45	16.45 ± 8.33
^{266}Rf	513.5	10.48 ± 3.52	44.34 ± 4.40	15.96 ± 7.42
^{267}Db	361.5	10.04 ± 3.28	39.71 ± 7.86	14.71 ± 6.79
^{270}Sg	1479	8.40 ± 2.75	48.96 ± 3.63	16.90 ± 8.09
^{272}Bh	1076	7.07 ± 2.65	57.71 ± 2.78	18.03 ± 8.26
		$E_{0_{\mathrm{c.m.}}}/V_{CB} = 1.20$		
^{265}Lr	346.7	14.13 ± 2.88	28.96 ± 9.66	22.82 ± 9.21
^{266}Rf	1088	12.21 ± 3.37	49.86 ± 5.82	19.96 ± 8.62
^{267}Db	1072	11.53 ± 3.08	46.68 ± 8.06	19.67 ± 8.73
^{270}Sg	3601	9.15 ± 2.84	57.39 ± 5.54	24.31 ± 10.45
^{272}Bh	2340	7.16 ± 2.67	66.84 ± 4.64	26.98 ± 11.03

TABLE VIII. The targets that provide the highest yields of given primary ICF products at varying incident energies in ^{20}Ne-induced reactions.

ICF product	Target that provides highest yield of ICF product				
$E_{0_{\text{c.m.}}}/V_{CB}$	1.00	1.05	1.10	1.15	1.20
^{263}Lr	^{252}Cf	^{252}Cf	^{250}Cm	^{250}Cm	^{250}Cm
^{263}Rf	^{247}Cm	^{247}Cm	^{247}Cm	^{247}Cm	^{247}Cm
^{264}Rf	^{248}Cm	^{248}Cm	^{248}Cm	^{248}Cm	^{248}Cm
^{266}Rf	^{250}Cm	^{250}Cm	^{250}Cm	^{250}Cm	^{250}Cm
^{265}Db	^{247}Cm	^{247}Cm	^{247}Cm	^{247}Cm	^{247}Cm

TABLE X. The targets that provide the primary ICF products with least angular momentum at varying incident energies in ^{20}Ne-induced reactions.

ICF product	Target that provides ICF product with least spin				
$E_{0_{\text{c.m.}}}/V_{CB}$	1.00	1.05	1.10	1.15	1.20
^{263}Lr	^{250}Cm	^{250}Cm	^{250}Cm	^{250}Cm	^{250}Cm
^{263}Rf	^{247}Cm	^{251}Cf	^{251}Cf	^{251}Cf	^{251}Cf
^{264}Rf	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf
^{266}Rf	^{254}Cf	^{254}Cf	^{254}Cf	^{254}Cf	^{254}Cf
^{265}Db	^{247}Cm	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf

E. Dinuclear configurations of the projectile

Using the aforedescribed methods, the projectile fragmentation parameters for ^{20}Ne were calculated and are shown in Table I. Physically this means that ^{16}O + ^{4}He and ^{12}C + ^{8}Be are the most energetically favourable binary fragmentation configurations of ^{20}Ne, followed in order by ^{18}F + ^{2}H, ^{13}N + ^{7}Li, and ^{11}B + ^{9}B. In terms of the mass parameter, the apparent trend is that the more symmetrical the charge distribution of the fragments the greater the inverse inertia coefficient. The isotopic composition of the binary fragments has been chosen with the condition of a N/Z equilibrium in the dinuclear system model [23–28]. The initial, maximal angular momentum between the two fragments is set at $L_{12} = 4\hbar$.

III. RESULTS AND DISCUSSION

A. Model results

Total integrated cross sections, angular, excitation energy and angular momentum distributions and their associated standard deviations were calculated for the primary ICF products of ^{20}Ne-induced incomplete fusion reactions with chains of Cm and Cf targets at varying incident energies. Standard deviations were taken as the square root of the difference between the square of the weighted mean of a distribution and the weighted mean of the squares of a distribution. The targets chosen were ^{247}Cm (Table II), ^{248}Cm (Table III), ^{250}Cm (Table IV), ^{251}Cf (Table V), ^{252}Cf (Table VI), and ^{254}Cf (Table VII). The incident energies chosen were that of the Coulomb barrier for a given projectile-target pairing, and up to 20% above the Coulomb barrier in increments of 5% ($E_{0_{\text{c.m.}}}/V_{CB} = 1.00, 1.05, 1.10, 1.15, 1.20$, where $E_{0_{\text{c.m.}}}$ is the incident energy in the center-of-mass frame and V_{CB} is the Coulomb barrier). Results have been shown only for the ICF of the heavy fragment and target primarily because lighter ICF products are not the focus of this study.

TABLE IX. The targets that provide the primary ICF products with least excitation energy at varying incident energies in ^{20}Ne-induced reactions.

ICF product	Target that provides 'coldest' ICF product				
$E_{0_{\text{c.m.}}}/V_{CB}$	1.00	1.05	1.10	1.15	1.20
^{263}Lr	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf
^{263}Rf	^{251}Cf	^{251}Cf	^{251}Cf	^{251}Cf	^{251}Cf
^{264}Rf	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf
^{266}Rf	^{254}Cf	^{254}Cf	^{254}Cf	^{254}Cf	^{254}Cf
^{265}Db	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf	^{252}Cf

The main integrated total cross section trend that is apparent from Tables II–VII is that at an incident energy sufficiently close to the Coulomb barrier ($E_{0_{c.m.}}/V_{CB} < 1.10$), the second and fourth heaviest ICF products have the highest cross section yields of all. The second and fourth heaviest ICF products have $\eta_Z = 0.6$ and $\eta_Z = 0.2$, respectively, which are the two ^{20}Ne binary fragmentation combinations that have the lowest driving potentials ($U < 0$ MeV). This expected outcome is

TABLE XI. Evaporation residue (EVR) cross sections for the most prevalent primary ICF product of the reaction ^{20}Ne + ^{247}Cm: ^{263}Rf. The total combined cross sections over 100 000 cascades are 66.7 mb, 1.52×10^3 mb and 3.84×10^3 mb at $E_{0_{\text{c.m.}}}/V_{CB} = 1.00$, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{\text{c.m.}}}/V_{CB}$	1.00	1.10	1.20
^{260}Lr	0.329%	0.030%	0.004%
^{260}No	0.002%	0.001%	–
^{259}Lr	6.724%	2.645%	0.152%
^{259}No	0.001%	0.007%	0.002%
^{258}Lr	0.113%	1.577%	2.399%
^{258}No	0.001%	0.001%	0.020%
^{257}Lr	–	0.004%	1.259%
^{257}No	1.548%	0.078%	0.002%
^{257}Md	0.002%	0.001%	–
^{256}No	57.334%	19.687%	0.943%
^{256}Md	0.021%	0.036%	0.015%
^{255}No	7.005%	29.049%	21.970%
^{255}Md	0.001%	0.009%	0.103%
^{254}No	0.002%	0.685%	20.358%
^{254}Md	–	–	0.011%
^{254}Fm	0.039%	0.007%	0.001%
^{253}No	–	–	0.003%
^{253}Fm	0.140%	0.189%	0.042%
^{252}Fm	0.010%	0.172%	0.521%
^{251}Fm	–	0.002%	0.121%
^{249}Cf	–	–	0.001%
Total fission	26.728%	45.820%	52.073%
TOTAL	100.000%	100.000%	100.000%

TABLE XII. The same results as in Table XI, but for the most prevalent primary ICF product of the reaction ^{20}Ne + ^{248}Cm: ^{264}Rf. The total combined cross sections over 100 000 cascades are 84.0 mb, 1.48×10^3 mb, and 3.69×10^3 mb at $E_{0_{\text{c.m.}}}/V_{CB} = 1.00$, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{\text{c.m.}}}/V_{CB}$	1.00	1.10	1.20
^{261}Lr	0.229%	0.017%	–
^{261}No	0.002%	–	–
^{260}Lr	5.510%	2.214%	0.080%
^{260}No	0.002%	0.010%	0.004%
^{259}Lr	1.547%	5.385%	3.351%
^{259}No	–	0.002%	0.010%
^{258}Lr	–	0.007%	0.999%
^{258}No	1.455%	0.125%	0.004%
^{258}Md	0.002%	0.002%	–
^{257}Lr	–	–	0.009%
^{257}No	44.884%	14.090%	0.383%
^{257}Md	0.025%	0.043%	0.012%
^{256}No	25.976%	55.223%	26.383%
^{256}Md	–	0.006%	0.071%
^{255}No	0.007%	0.682%	19.784%
^{255}Md	–	–	0.018%
^{255}Fm	0.021%	0.006%	–
^{254}No	–	–	0.369%
^{254}Fm	0.157%	0.181%	0.043%
^{253}Fm	0.017%	0.131%	0.391%
^{252}Fm	–	–	0.193%
Total fission	20.166%	21.875%	47.896%
TOTAL	100.000%	100.000%	100.000%

TABLE XIII. The same results as in Table XI, but for the most prevalent primary ICF product of the reaction ^{20}Ne + ^{250}Cm: ^{266}Rf. The total combined cross sections over 100 000 cascades are 91.9 mb, 1.46×10^3 mb, and 3.70×10^3 mb at $E_{0_{\text{c.m.}}}/V_{CB} = 1.00$, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{\text{c.m.}}}/V_{CB}$	1.00	1.10	1.20
^{263}Lr	0.118%	0.012%	–
^{262}Lr	5.550%	1.370%	0.042%
^{262}No	0.004%	0.010%	–
^{261}Lr	5.860%	10.205%	3.901%
^{261}No	–	0.005%	0.009%
^{260}Lr	0.003%	0.394%	6.462%
^{260}No	0.383%	0.030%	0.004%
^{260}Md	0.003%	–	–
^{259}Lr	–	–	0.334%
^{259}No	27.309%	5.208%	0.111%
^{259}Md	0.013%	0.020%	0.004%
^{258}No	57.857%	69.788%	17.867%
^{258}Md	–	0.013%	0.056%
^{257}No	0.398%	8.926%	50.667%
^{257}Md	–	–	0.021%
^{257}Fm	0.005%	–	–
^{256}No	–	0.007%	5.552%
^{256}Fm	0.096%	0.085%	0.014%
^{255}Fm	0.021%	0.088%	0.241%
^{254}Fm	–	0.007%	0.172%
^{253}Fm	–	–	0.001%
Total fission	2.380%	3.832%	14.532%
TOTAL	100.000%	100.000%	100.000%

a good indicator of the model's accuracy. At higher incident energies ($E_{0_{\text{c.m.}}}/V_{CB} \geqslant 1.10$), the fourth and fifth heaviest ICF products have the highest cross section yields. The main scattering trend that is apparent from Tables II–VII is that the lighter the ICF product, the greater the scattering angles and the angular distribution's variance. The main excitation energy trend that is apparent from Tables II–VII is that as with the integrated total cross sections, the fourth and fifth heaviest ICF products stand out in that they tend to have the highest mean excitation energy. There is also a trend that the lighter the ICF product, the greater the variance of the excitation energy distribution. The main angular momentum trend that is apparent from Tables II–VII is generally that the lighter the ICF product, the less angular momentum it has, with the exception of the lightest ICF product. A more glaring exception to this rule is the heaviest and third heaviest ICF products at $E_{0_{\text{c.m.}}}/V_{CB} = 1.00$, namely Lr, Db, and Bh isotopes at incident energies equal to the Coulomb barrier. As with the other two distributions' variance, the lighter the ICF product, the greater the angular momentum distribution's variance, however at $E_{0_{\text{c.m.}}}/V_{CB} \geqslant 1.10$ the two heaviest ICF products tend to have the greatest variance.

B. Target comparison

Tables VIII-X summarize the information in Tables II–VII in a format that reveals which of the two respective Cm and Cf targets provides the greatest ICF product yield, the coldest ICF product and the ICF product with least angular momentum, respectively, of ICF products that those targets have in common in ^{20}Ne-induced reactions.

As a general trend Table VIII shows that Cm targets are almost always more favorable than Cf targets when striving to maximize ICF product yield for ^{263}Lr, ^{263,264,266}Rf, and ^{265}Db isotopes in ^{20}Ne-induced reactions at $1.00 \leqslant (E_{0_{\text{c.m.}}}/V_{CB}) \leqslant 1.20$. The exception to this is that ^{252}Cf is preferable to ^{250}Cm for yielding ^{263}Lr at $E_{0_{\text{c.m.}}}/V_{CB} \leqslant 1.05$. Table IX indicates that Cf targets are universally preferable to Cm targets in terms of producing less excited ^{263}Lr, ^{263,264,266}Rf, and ^{265}Db isotopes in ^{20}Ne-induced ICF reactions at $1.00 \leqslant (E_{0_{\text{c.m.}}}/V_{CB}) \leqslant 1.20$. With the exception of some Cm targets at $E_{0_{\text{c.m.}}}/V_{CB} = 1.00$ and when producing ^{263}Lr at any of the chosen incident energies, Table X shows that Cf targets are universally preferable to Cm targets in terms of producing ^{263,264,266}Rf and ^{265}Db isotopes with the least angular momentum in ^{20}Ne-induced ICF reactions at $1.00 \leqslant (E_{0_{\text{c.m.}}}/V_{CB}) \leqslant 1.20$.

C. Evaporation residues

Tables XI contain evaporation residue (EVR) cross sections of the most prevalent primary ICF product of each of the six reactions: ^{263,264,266}Rf, ^{267,268,270}Sg, while

TABLE XIV. The same results as in Table XI, but for the most prevalent primary ICF product of the reaction ^{20}Ne + ^{251}Cf: ^{267}Sg. The total combined cross sections over 100 000 cascades are 90.0 mb, 1.44 × 10^3 mb, and 3.57 × 10^3 mb at $E_{0_{c.m.}}/V_{CB}$ = 1.00, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{c.m.}}/V_{CB}$	1.00	1.10	1.20
^{263}Sg	0.001%	–	–
^{262}Sg	0.003%	0.004%	0.001%
Total fission	99.996%	99.996%	99.999%
TOTAL	100.000%	100.000%	100.000%

Table XVII contains evaporation residue (EVR) cross sections of the second most prevalent primary ICF product of the ^{20}Ne + ^{251}Cf reaction: ^{269}Bh. These EVR cross sections were calculated using the fusion-evaporation code PACE4 [29] with the calculated mean excitation energies and angular momentum distributions as inputs. Fission barrier parameters were sourced from calculations in the macroscopic-microscopic finite-range liquid-drop model [30]. A Fermi gas level density parameter of $a = A/12$ MeV^{-1} was used, with the ratio of this parameter at the saddle point to the ground state value being 1.1 [31].

Table XI shows that for the primary ICF product ^{263}Rf (from the reaction ^{20}Ne + ^{247}Cm), the main EVRs at $E_{0_{c.m.}}/V_{CB}$ = 1.00 is ^{256}No, with a percentage yield of 57%. At $E_{0_{c.m.}}/V_{CB}$ = 1.10, the main EVR is ^{255}No with a percentage yield of 29%, followed by ^{256}No with a percentage yield of 20%. At $E_{0_{c.m.}}/V_{CB}$ = 1.20, the main EVR is ^{255}No with a percentage yield of 22%, followed closely by ^{254}No with a percentage yield of 20%. The percentage total fission of the primary ICF product ^{263}Rf increases with incident energy: 27%, 46%, and 52% at $E_{0_{c.m.}}/V_{CB}$ = 1.0, 1.1, and 1.2, respectively. Table XII shows that for the primary ICF product ^{264}Rf (from the reaction ^{20}Ne + ^{248}Cm), the main EVR at $E_{0_{c.m.}}/V_{CB}$ = 1.0 is ^{257}No, with a percentage yield of 45%, followed by ^{256}No with a percentage yield of 26%. At $E_{0_{c.m.}}/V_{CB}$ = 1.10, the main EVR is ^{256}No with a percentage yield of 55%, followed by ^{257}No with a percentage yield of 14%. At $E_{0_{c.m.}}/V_{CB}$ = 1.20, the main EVR is ^{256}No with a percentage yield of 26%, followed closely by ^{255}No with a percentage yield of 20%. The percentage total fission of the primary ICF product ^{264}Rf also increases with incident energy, albeit at a seemingly delayed rate when compared with ^{263}Rf: 20%, 22%, and 48% at $E_{0_{c.m.}}/V_{CB}$ = 1.0, 1.1, and 1.2, respectively. In Ref. [2], the heaviest observed multinucleon transfer (MNT) products so far in the reaction ^{20}Ne + ^{248}Cm are ^{256}Md and ^{256}Fm [32], which are notably lighter than the heaviest predicted ICF products here. This suggests that it would be possible to produce new isotopes with the ICF mechanism. Table XIII shows that for the primary ICF product ^{266}Rf (from the reaction ^{20}Ne + ^{250}Cm), the main EVR at $E_{0_{c.m.}}/V_{CB}$ = 1.0 is ^{258}No, with a percentage yield of 58%, followed by ^{259}No with a percentage yield of 27%. At $E_{0_{c.m.}}/V_{CB}$ = 1.10, the main EVR is ^{258}No with a percentage yield of 70%. At $E_{0_{c.m.}}/V_{CB}$ = 1.20, the main EVR is ^{257}No with a percentage yield of 51%, followed by ^{258}No with a percentage yield of 18%. The percentage total fission of the primary ICF product ^{266}Rf increases with incident energy at a much more hampered rate than those of ^{263}Rf and ^{264}Rf: 2.4%, 3.8% and 15% at $E_{0_{c.m.}}/V_{CB}$ = 1.0, 1.1, and 1.2, respectively. Tables XIV–XVI show that for the primary ICF products ^{267,268,270}Sg (from the reactions ^{20}Ne + ^{251,252,254}Cf, respectively), almost all EVRs are lost to fission, with only a small handful of lighter Sg isotope yields for the former two, and a slightly larger handful for the latter. The fission barrier of ^{270}Sg is lower than those of ^{267,268}Sg, which explains the discrepancy between the EVR yields of these primary ICF products, however it does not explain why more than 99.9% of events are lost to fission.

TABLE XV. The same results as in Table XI, but for the most prevalent primary ICF product of the reaction ^{20}Ne + ^{252}Cf: ^{268}Sg. The total combined cross sections over 100 000 cascades are 74.8 mb, 1.36 × 10^3 mb, and 3.71 × 10^3 mb at $E_{0_{c.m.}}/V_{CB}$ = 1.00, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{c.m.}}/V_{CB}$	1.00	1.10	1.20
^{264}Sg	0.004%	–	–
^{263}Sg	0.001%	0.002%	0.001%
^{262}Sg	–	0.001%	–
Total fission	99.995%	99.997%	99.999%
TOTAL	100.000%	100.000%	100.000%

TABLE XVI. The same results as in Table XI, but for the most prevalent primary ICF product of the reaction ^{20}Ne + ^{254}Cf: ^{270}Sg. The total combined cross sections over 100 000 cascades are 58.5 mb, 1.48 × 10^3 mb, and 3.60 × 10^3 mb at $E_{0_{c.m.}}/V_{CB}$ = 1.00, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{c.m.}}/V_{CB}$	1.00	1.10	1.20
^{266}Sg	0.057%	0.004%	–
^{265}Sg	0.002%	0.007%	0.001%
^{264}Sg	–	–	0.011%
Total fission	99.941%	99.989%	99.988%
TOTAL	100.000%	100%	100.000%

TABLE XVII. The same results as in Table XI, but for the second most prevalent primary ICF product of the reaction ^{20}Ne + ^{251}Cf: ^{269}Bh. The total combined cross sections over 100 000 cascades are 24.4 mb, 1.02 × 10^3 mb, and 2.40 × 10^3 mb at $E_{0_{c.m.}}/V_{CB}$ = 1.00, 1.10, and 1.20, respectively.

EVR	Percentage yield		
$E_{0_{c.m.}}/V_{CB}$	1.00	1.10	1.20
^{264}Sg	0.001%	–	–
Total fission	99.999%	100.000%	100.000%
TOTAL	100.000%	100.000%	100.000%

Fission likely dominates because the fission barriers of the primary ICF products should be significantly smaller than the barriers involved in n-, p-, and α-decay modes. All the barriers are affected by the angular momenta of the rotating ICF products due to centrifugal effects. For a given angular momentum, the smaller the moment of inertia associated with a decay mode, the larger the corresponding centrifugal barrier. The moments of inertia associated with n, p, and α emissions are smaller than that for fission because the moment of inertia is proportional to the corresponding reduced mass. Table XVII shows that for the primary ICF product ^{269}Bh (from the reaction ^{20}Ne + ^{251}Cf), virtually all EVRs are lost to fission in a similar fashion. The tiny amount of ^{264}Sg produced results from n, p, and γ emission from the primary ^{269}Bh. For the primary ICF products ^{270,272}Bh (from the reactions ^{20}Ne + ^{252,254}Cf, respectively) all EVRs are lost to fission.

IV. CONCLUSIONS

Using a semiclassical dynamical model that combines a classical trajectory model with stochastic breakup with a dynamical fragmentation theory treatment of two-body clusterization and decay of a projectile, results have been presented for ^{20}Ne-induced incomplete fusion reactions for the production of select SHE isotopes. Targets include ^{247,248,250}Cm and ^{251,252,254}Cf, and results include angular, excitation energy and angular momentum distributions in addition to total integrated cross sections for the heaviest primary ICF products. The results have shown that at Coulomb energies, the Cf isotopes are the more favourable choice of target over their respective Cm isotope counterparts for the production of 'colder' and more stable (and more scattered) ^{263}Lr, ^{263,264,266}Rf, and ^{265}Db isotopes through the ICF mechanism. The present model calculations are very useful for planning and interpreting new experiments for SHE research using the ICF reaction mechanism. Also presented and useful for future experiments are EVR cross sections for the dominant primary ICF products of each of the six reactions: ^{263,264,266}Rf and ^{267,268,270}Sg. Moving forward, this model will also be used to calculate cross sections and their distributions for ^{40,48}Ca-induced ICF reactions with a variety of Cm, Cf and Es targets at Coulomb energies, with the aim to study ICF results for even more SHEs.

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