Comparison of complementary reactions for the production of $^{261,262}\text{Bh}$

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Two heavy-ion induced fusion reactions producing $^{261,262}\text{Bh}$ were studied using the Berkeley Gas-filled Separator at the Lawrence Berkeley National Laboratory 88-Inch Cyclotron. An excitation function for the production of ^{262}Bh via the reaction $^{209}\text{Bi}(^{54}\text{Cr}, n)^{262}\text{Bh}$ was measured with a maximum cross section from a fit to the data of 430 ± 110 pb observed at a compound nucleus excitation energy of 15.7 MeV. New data have been measured for the $1n$ exit channel of the $^{208}\text{Pb}(^{55}\text{Mn}, n)^{262}\text{Bh}$ reaction. We present an updated excitation function with an observed maximum cross section of 530 ± 100 pb at a compound nucleus excitation energy of 14.1 MeV. Events corresponding to the $2n$ exit channel for the $^{209}\text{Bi}(^{54}\text{Cr}, 2n)^{261}\text{Bh}$ and $^{208}\text{Pb}(^{55}\text{Mn}, 2n)^{261}\text{Bh}$ reactions were also observed and are presented as partial excitation functions. The measured decay properties correspond well with existing experimental data. We compare these experimental results to cross section predictions from a model by Świątecki *et al.* and discuss entrance channel effects on the magnitude of $1n$ cross sections.

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I. INTRODUCTION

Macroscopic models predict that transactinide (TAN) elements should not exist at all due to instability to fission [1]. Experimental evidence has shown this to not be the case, as many TANs have been produced and identified, with half-lives ranging up to hours (for a review see [2] and references therein). It is now known that TANs owe this enhanced nuclear stability to proton and neutron shell-stabilization [1–3]. Further studies are vital to the understanding of the location and strength of these spherical and deformed shells, production rates, nuclear structure, and to strengthen models used to make predictions about these areas of interest. To gain information about these subjects, these elements and their isotopes must be produced and studied at particle accelerators. Here we present a study of two reactions that produce the same compound nucleus of bohrium (Bh) to better understand the role of the entrance channel, or specific target and projectile combination, on evaporation residue (EVR) cross sections.

For many years, reactions with medium-mass projectiles on spherical, shell-stabilized ^{208}Pb or ^{209}Bi targets have been used in the investigations of TAN elements and their decay properties. At energies at or near the Coulomb barrier these so-called “cold fusion” reactions produce weakly excited (10–15 MeV) [4] compound nuclei that deexcite by emission of one to two neutrons. Until recently, most cold fusion reactions producing odd- Z TANs were studied by using targets of ^{209}Bi instead

of ^{208}Pb . The more asymmetric ^{209}Bi -based reactions were chosen more often because they were expected to have a larger cross section for the $1n$ exit channel product as a result of the lower effective fissility of the reaction [5]. Hence, this preference of a more asymmetric system determined the reactions used in the discoveries of bohrium (Bh, $Z = 107$) [6,7], meitnerium (Mt, $Z = 109$) [8,9], and roentgenium (Rg, $Z = 111$) [10]. Most recently the reaction $^{209}\text{Bi}(^{70}\text{Zn}, n)^{278}113$ was used to synthesize an isotope of element 113 [11].

The first conclusive evidence for the formation of Bh was reported by Münzenberg *et al.*, using the cold fusion reaction $^{209}\text{Bi}(^{54}\text{Cr}, xn)^{263-x}\text{Bh}$ [6,7]. Their data showed that ^{262}Bh has two isomers, both decaying by alpha particle emission. The half-life of the ground state was reported to be 102 ± 26 ms, and several different alpha energies were observed, as expected for an odd-odd nuclide. The half-life of the isomeric state was reported to be 8.0 ± 2.1 ms. Münzenberg *et al.* also reported the discovery of ^{261}Bh , which decays with a half-life of $11.8^{+5.3}_{-2.8}$ ms, again by alpha particle emission. The identification of genetically related alpha-decay chains supported their claims, as these decay chains included previously identified nuclides of Fm and Md.

Recently, Folden *et al.* investigated a different reaction to produce the nuclide ^{262}Bh [12], utilizing an even- Z target instead of the odd- Z ^{209}Bi target previously used. The decay properties of ^{262}Bh observed in the $^{208}\text{Pb}(^{55}\text{Mn}, n)^{262}\text{Bh}$ reaction agreed well with the results from Münzenberg *et al.* where the same compound nucleus was produced in the $^{209}\text{Bi}(^{54}\text{Cr}, n)$ reaction. In addition, an excitation function was measured, using three different lab-frame center-of-target beam energies: 260.0, 264.0, and 268.0 MeV. The maximum measured cross section of 540^{+180}_{-150} pb was a factor of three greater than the largest cross section measured by Münzenberg *et al.* of

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163 ± 34 pb. However, this peak cross section measured by the GSI may not be at the maximum of the excitation function because the compound nucleus excitation energy of 20 ± 2 MeV is significantly higher than expected from experimental systematics for this reaction type.

In addition to the idea that the slightly more asymmetric reactions would give rise to higher cross sections, theoretical predictions have been made about these reactions. Świątecki, Siwek-Wilczyńska, and Wilczyński's "Fusion By Diffusion" model [13–15] employs a three step description of evaporation residue formation. The first step is the capture step, (called "sticking" in their formalism) where the projectile and target nuclei are captured in a pocket in their mutual nuclear and Coulomb potentials to form a dinuclear complex. The second step is the "diffusion" step, where this dinuclear system of touching spheres coalesces to a single spherical compound nucleus, and is treated as one-dimensional diffusion along the elongation coordinate. The final step is the "survival" during deexcitation by emission of one neutron instead of undergoing fission or other competing deexcitation modes, which is treated in a standard statistical model approach. Their model predicts and reproduces experimentally determined $1n$ cross sections typically within a factor of two.

Predictions of the location and magnitude of the $1n$ excitation function for the $^{208}\text{Pb}(^{55}\text{Mn}, n)^{262}\text{Bh}$ reaction were first provided to us by Świątecki prior to Folden's experiment [16]. This prediction indicated the maximum of this excitation function should be approximately 100 pb. Recently updated predictions utilizing a reparametrized model were provided to us, with a peak $1n$ cross section of approximately 400 pb at an excitation energy of ~ 14 MeV for the $^{55}\text{Mn} + ^{208}\text{Pb}$ reaction. A prediction for the $^{54}\text{Cr} + ^{209}\text{Bi}$ reaction suggests a maximum of approximately 500 pb at an excitation energy of ~ 13.5 MeV. The reparametrized model has a second adjustable parameter reflecting drift in the asymmetry during the diffusion stage and it was fitted to 18 measurements, rather than the 12 that were available earlier.

We have undertaken a systematic study of complementary reactions differing only by one proton in the projectile and target which produce the same compound nucleus. By examining the resulting $1n$ cross sections we may determine if there is a preferred entrance channel, and if so, attempt to understand the nuclear physics that govern this phenomenon. By studying both of these reactions at the same facility with the same equipment we assume systematic errors are the same. We have also expanded the range of energies studied to include the $2n$ exit channel. Here we report the results of the reaction pair $^{209}\text{Bi}(^{54}\text{Cr}, xn)^{263-x}\text{Bh}$ and $^{208}\text{Pb}(^{55}\text{Mn}, xn)^{263-x}\text{Bh}$.

II. EXPERIMENTS

Experiments were conducted at the Lawrence Berkeley National Laboratory (LBNL) 88-Inch Cyclotron using the Berkeley Gas-filled Separator (BGS). The BGS has been described in [17,18] and recent improvements are given in [19]. Beams of $^{54}\text{Cr}^{12+}$ and $^{55}\text{Mn}^{13+}$ passed through a $45 \mu\text{g}/\text{cm}^2$ -natC carbon window used to separate the vacuum of the beamline from the 67 Pa of He fill gas of the BGS. Target

wheels consisted of nine arc-shaped targets with an average areal density of $441 \mu\text{g}/\text{cm}^2$ - ^{209}Bi metal on a $35 \mu\text{g}/\text{cm}^2$ -natC backing, or $460 \mu\text{g}/\text{cm}^2$ - ^{208}Pb metal on $35 \mu\text{g}/\text{cm}^2$ -natC. A thin $5\text{--}10 \mu\text{g}/\text{cm}^2$ layer of natC was applied to the downstream side of the targets to improve infrared cooling and prevent target material loss by sputtering. The target wheel rotation speed was approximately 5–10 Hz. Energy loss calculations through the vacuum window, backing, and target were done with SRIM-2003 [20].

Projectile energies expected to be optimal for production of each reaction's $1n$ exit channel in the center of the target were chosen based on calculations from Świątecki *et al.*'s "Fusion By Diffusion" theory [13,14]. Experimental masses were used when available, and tabulated mass defects from the Thomas-Fermi model [21] were used for those nuclides with unknown masses. Table I contains a summary of the beam energies, integrated beam doses, and resulting cross sections for this work as well as for previous studies. The evaporation residues recoiled out of the target with the momentum of the beam and into the BGS. The BGS magnet settings were chosen to guide only products with a magnetic rigidity of 2.16 T-m for both the $1n$ and $2n$ exit channels to the Si-strip focal plane detector (FPD). The magnetic rigidity was determined with data from [12]. Monte Carlo simulations of EVR trajectories through the BGS [22] indicate a total separator efficiency of 0.65 ± 0.06 . To aid in discrimination of alpha-like events from implantation events, a multiwire proportional counter (MWPC) filled with isobutane gas was used upstream of the Si-strip detector array.

The $18 \text{ cm} \times 6 \text{ cm} \times 6 \text{ cm}$ Si-strip FPD array has been described earlier [19]. It was calibrated with a retractable four-point alpha source consisting of ^{148}Gd , ^{239}Pu , ^{241}Am , and ^{244}Cm . The alpha particle energy resolution, determined by the four-point source data prior to each experiment was $\sigma = 31$ keV. The systematic error in the calibration for alpha particles in the Si-strip detector was ± 5 keV, determined by comparing measured and accepted E_α from implanted activity after correction for the detector's dead layer and the recoil of the daughter product. The vertical position was determined by resistive charge division within a single strip [23]. Horizontal position was determined from the FPD strip number.

During the irradiations, the rate of "EVR-like events" ($8.0 < E_{\text{EVR}} < 24.0$ MeV, coincident with MWPC signals and anticoincident with punchthrough or upstream signals) was $1.1\text{--}3.2 \text{ s}^{-1}$. The rate of "alpha decay-like events" ($7.0 < E_{\text{alpha}} < 11.0$ MeV, in the focal plane only, or reconstructed from a focal plane plus an upstream signal, anticoincident with the MWPC and punchthrough signals) was $0.04\text{--}0.10 \text{ s}^{-1}$. $^{261,262}\text{Bh}$ decay chains were identified by searching for time- and position-correlated decays after an EVR implantation event. A fast beam-shutoff system was implemented to reduce the likelihood of random correlations. (See Sec. III D for a discussion of random correlations.) Upon the detection of an EVR correlated to an alpha-like event ($8.3 < E_{\text{alpha}} < 11.0$ MeV, within 3σ of position and 30 s of the EVR), the beam was automatically switched off for 180 s to enable the registration of any subsequent daughter- or granddaughter-like decays under strongly reduced background conditions. The data files were sorted offline, searching for EVR- and

TABLE I. Energies, integrated beam doses, target thicknesses, and cross sections for each reaction. Data from [6,7,12] are presented for comparison.

Laboratory	Reaction	E_{cot} (MeV)	E^* (MeV)	Target thickness (mg/cm ²)	Dose(10 ¹⁶ ions)	²⁶² Bh cross section (pb)	²⁶¹ Bh cross section (pb)
LBNL (Folden [12])	⁵⁵ Mn + ²⁰⁸ Pb	260.0	11.1	0.47	5.7	24 ⁺⁵⁵ ₋₂₀	<41
		264.0	14.3	0.47	4.2	590 ⁺¹⁷⁰ ₋₁₄₀	<56
		268.0	17.4	0.47	7.8	210 ⁺¹⁰⁰ ₋₇₁	32 ⁺⁴³ ₋₂₁
LBNL (this work)	⁵⁵ Mn + ²⁰⁸ Pb	273.0	21.4	0.46	8.1	<49	43 ⁺⁵⁷ ₋₂₈
		278.0	25.3	0.46	7.1	<56	<46
		283.0	29.3	0.46	7.2	30 ⁺⁶⁸ ₋₂₄	<44
LBNL (this work)	⁵⁴ Cr + ²⁰⁹ Bi	253.5	11.3	0.44	3.1	48 ⁺¹¹⁰ ₋₄₀	—
		257.1	14.2	0.44	2.3	260 ⁺²⁰⁰ ₋₁₂₀	—
		260.9	17.2	0.44	1.5	440 ⁺⁴³⁰ ₋₂₄₀	<210
		264.7	20.2	0.44	23	60 ⁺³⁵ ₋₂₄	8 ⁺¹⁸ ₋₇
		268.4	23.2	0.44	6.3	36 ⁺⁸² ₋₃₀	28 ⁺⁶⁵ ₋₂₃
		272.3	26.3	0.44	8.3	<50	67 ⁺⁶⁵ ₋₃₆
GSI [6,7]	⁵⁴ Cr + ²⁰⁹ Bi	258.9	17	0.66	7	93 ⁺⁹³ ₋₅₀	<51
		263.4	20	0.39	71	163 ⁺³⁴ ₋₃₄	36 ⁺²⁵ ₋₁₆
		265.9	24	0.40	18	27 ⁺²⁷ ₋₁₄	36 ⁺²² ₋₁₄
		271.0	28	0.40	14	<56	24 ⁺⁵⁵ ₋₁₉

alpha-like events with the same energy gates as listed above, and >80 MeV spontaneous fission (SF) like events (80 < E_{fission} < 300 MeV, no MWPC signal). Once potential decay chains were identified through the offline searches, more specific searches were carried out to lifetimes of 10⁴ seconds to try to identify $Z = 99$ –100 decays with long half-lives.

III. RESULTS

The known decay properties of ^{261,262}Bh and their associated daughter products can be viewed in Fig. 1. Events attributed to decays of ^{261,262}Bh are depicted in Table II. Distinguishing decay chains of ²⁶²Bh from chains of ²⁶¹Bh presented a challenge due to the strikingly similar alpha particle energies and lifetimes of ^{262m}Bh and ²⁶¹Bh. The ^{257,258}Db daughter products are very similar in alpha particle energies and lifetimes as well, requiring observation of the ^{253,254}Lr granddaughter's alpha decay, or the electron capture (EC) decay of ²⁵⁴Lr and subsequent alpha decay of ²⁵⁴No to conclusively assign a decay chain to a particular mother isotope. For this reason, we have chosen to only assign events fitting strict criteria and have calculated alpha chain detection efficiencies for both the 1n and 2n exit channel products to properly account for the reduced number of unambiguously assigned events. Of the 42 events corresponding to the decay of ^{261,262}Bh, we are only able to conclusively assign 23 of them.

Chain detection efficiencies are calculated by the method described in Section 2.2.3.2 of [24]. The philosophy behind these calculations is that for each EVR of interest, decay and detection paths that result in Z and A identification of the chain (and their corresponding lengths) are determined. In

this work we have calculated alpha chain detection efficiency factors for three different situations: for ²⁶²Bh^{*g,m*} at beam energies where production of ²⁶¹Bh is negligible, for ²⁶²Bh^{*g,m*} when production of ²⁶¹Bh is possible, and for ²⁶¹Bh. The corresponding efficiency values we have calculated are: 0.80, 0.54, and 0.68, respectively. The differences in these values arise from the varied criteria used to conclusively distinguish one isotope from another in light of the similar decay properties mentioned above.

Previous work [7] indicates uncertainty in the true nature of the ground or metastable state assignments of isomer pairs in ²⁶²Bh, ²⁵⁷Db, and ²⁵³Lr, and their associated alpha decay energies and half-lives. Our results are unable to clarify this challenging situation further, so isomeric states were assigned with the most current literature results in mind. Assignments were primarily based on the alpha particle energy (for full energy or reconstructed events), and secondarily on the alpha decay lifetimes. Only two of the 23 chains contain alpha decays that could not be assigned to a ground or metastable state. Because the assignment criteria are partially based on lifetimes, a slight bias is introduced into our half-life values for ²⁶²Bh^{*g,m*}, ²⁶¹Bh, ²⁵⁷Db^{*g,m*}, and ²⁵³Lr^{*g,m*}. Half-life and cross section errors were treated as a special case of the Poisson distribution [25], and our reported error values are at the 68% confidence interval.

A. ²⁶²Bh^{*g,m*}

Sixteen decay chains corresponding to the alpha decay of ²⁶²Bh were identified, 15 of which were from the lowest five energies run in the ⁵⁴Cr + ²⁰⁹Bi reaction. One ²⁶²Bh event was produced in the highest energy run in the ⁵⁵Mn + ²⁰⁸Pb reaction, in experiments designed to extend the excitation

TABLE II. Observed $^{262}\text{Bh}^{g,m}$ and ^{261}Bh decays from the $^{208}\text{Pb}(^{55}\text{Mn}, xn)$ and $^{209}\text{Bi}(^{54}\text{Cr}, xn)$ reactions. Reconstructed energies are listed with the focal plane energy listed first, followed by the calculated energy from a missing signal from either the top or bottom of the strip in parentheses, ending with the energy deposited in the upstream detector. Full decay chains are in supplementary material published online.

Reaction	E_{COT} (MeV)	E^* (MeV)	Event #	Strip #	E_{EVR} (MeV)	Position (mm)	Decay energy (MeV)	Position (mm)	Lifetime	AZ
$^{55}\text{Mn} + ^{208}\text{Pb}$	273	21.4	1	27	18.787	-5.5 ± 0.1	10.054	-7.0 ± 0.3	0.00353 s	^{261}Bh
			2	24	22.452	13.1 ± 0.1	10.331	12.9 ± 0.3	0.00135 s	^{261}Bh
	283	29.3	3	12	17.873	18.2 ± 0.2	Missing	—	—	^{262}Bh
$^{54}\text{Cr} + ^{209}\text{Bi}$	253.5	11.3	4	13	17.121	13.1 ± 0.2	$9.762 = [0.639 + (0.234) + 8.889]$	>0.0	0.08917 s	^{262g}Bh
			5	22	17.77	14.5 ± 0.2	$9.648 = [1.023 + 8.625]$	16.2 ± 2.7	0.28408 s	^{262g}Bh
			6	29	19.223	-4.3 ± 0.1	$9.735 = [0.742 + 8.993]$	-14.0 ± 3.8	0.02422 s	^{262g}Bh
			7	11	16.081	9.0 ± 0.2	0.652	4.4 ± 4.3	0.11001 s	^{262g}Bh
	260.9	17.2	8	15	17.151	-25.6 ± 0.2	9.387	-25.6 ± 0.3	0.01048 s	^{262m}Bh
			9	3	18.33	-0.2 ± 0.2	$10.067 = [1.054 + 9.013]$	0.8 ± 2.7	0.00077 s	^{262m}Bh
			10	31	18.198	-14.2 ± 0.2	0.388	<0.0	0.05295 s	^{262g}Bh
			11	15	18.518	-2.4 ± 0.2	$[0.255 + (0.133)]$	-2.7 ± 1.7	0.02931 s	^{262}Bh
	264.7	20.2	12	22	21.868	-4.8 ± 0.1	7.995	-4.6 ± 0.4	0.12400 s	^{262g}Bh
			13	40	18.568	-10.5 ± 0.2	1.336	-15.1 ± 2.1	0.56130 s	^{262g}Bh
			14	38	20.637	-20.4 ± 0.1	10.096	-20.3 ± 0.3	0.10066 s	^{262g}Bh
			15	39	22.379	-5.6 ± 0.1	$9.540 = [1.017 + 8.523]$	-11.9 ± 2.8	0.03042 s	^{262m}Bh
			16	29	21.647	-2.4 ± 0.1	10.383	-2.8 ± 0.3	0.04972 s	^{262m}Bh
			17	37	17.965	-8.8 ± 0.2	$10.025 = [1.072 + 8.953]$	-14.8 ± 2.6	0.29517 s	^{262g}Bh
			18	23	19.176	-26.9 ± 0.1	$10.285 = [0.960 + (0.087) + 9.238]$	<0.0	0.01954 s	^{261}Bh
	268.4	23.2	19	30	17.176	18.1 ± 0.2	$0.602 = [0.469 + (0.133)]$	>0.0	0.01239 s	^{261}Bh
			20	27	20.038	-1.8 ± 0.1	10.125	-2.1 ± 0.3	0.13698 s	^{262g}Bh
	272.3	26.3	21	36	18.969	-24.0 ± 0.1	10.113	-24.2 ± 0.3	0.01133 s	^{261}Bh
			22	35	19.978	1.7 ± 0.1	10.165	1.2 ± 0.3	0.00588 s	^{261}Bh
			23	29	15.408	12.1 ± 0.2	9.989	11.9 ± 0.3	0.01337 s	^{261}Bh

function first studied by Folden *et al.* [12] The ten full-energy or reconstructed $^{262}\text{Bh}^{g,m}$ alpha decays we observed fit well to previously observed alpha lines [6,7,12]. It is possible that a 9.39 MeV alpha decay is a new, low-energy transition, the result of an alpha decay to an excited state in the daughter. The short lifetime of 10 ms indicates decay from the metastable state. In addition, a 10.13 MeV decay has not been observed before, also potential evidence of a new alpha decay transition.

The measured half-lives of $^{262}\text{Bh}^m$ and $^{262}\text{Bh}^g$ from totals of four and ten alpha decay events are 16_{-5}^{+14} ms and 120_{-29}^{+55} ms, respectively. The metastable state value does not compare very well to the current literature value of 8.0 ± 2.1 ms [6,7,12], and we feel this is a case where increased counting statistics would improve the value greatly. The ground state value compares well with the reported value of 102 ± 26 ms [6,7,12].

We have conservatively re-examined the event assignments from the work of Folden *et al.* [12] and applied the new decay chain assignment restrictions to enable a consistent comparison of all the results. The re-calculated cross sections with the appropriate efficiency factors can be seen in Table I, and remain largely unchanged from the original values [12]. We discuss the resulting updated and expanded excitation function in Sec. IV.

The observed decay properties of daughter products ^{258}Db , ^{258}Rf , ^{254}Lr , ^{254}No , ^{250}Md , and ^{250}Fm all agree well with the most current literature reports [26].

B. ^{261}Bh

Seven decay chains corresponding to the decay of ^{261}Bh were observed in this work. The observed alpha particle

FIG. 1. (Color online) Decay properties of $^{262}\text{Bh}^{g,m}$, ^{261}Bh and their associated daughter products [6,7,23,31–34].

energies match well with known lines, with the exception of one decay at 10.29 MeV. The half life calculated from these seven decays is $6.7^{+3.8}_{-1.8}$ ms, shorter than the published values of $11.8^{+5.3}_{-2.8}$ ms and 10^{+14}_{-5} ms [7,12]. Again we feel this is a case where the value would be improved by a greater number of observed decays. No SF events or decay chains suggesting the EC of ^{261}Bh to ^{261}Sg were observed.

Seven alpha decays of ^{257}Db were observed in this work. Because of the challenge in distinguishing the ground state from the metastable state on an event-by-event basis, we have chosen to not make isomer assignments for these decays. We report an apparent half-life of $0.64^{+0.42}_{-0.18}$ s for the combined lifetimes of the ground and metastable states of ^{257}Db . The alpha-decay granddaughter of ^{261}Bh , $^{253}\text{Lr}^{g,m}$ was observed in these experiments as well. As was the case with ^{257}Db , we have chosen not to make isomer assignments, and report an apparent half-life of $0.93^{+0.60}_{-0.26}$ s for $^{253}\text{Lr}^g$ and $^{253}\text{Lr}^m$.

The observed decay properties of ^{249}Md and ^{245}Es agree well with the published literature values. The complete decay chains are contained in the supplementary material published online.

C. Spontaneous fission

There was also one EVR-SF correlation observed in this work. The decay occurred at a beam energy corresponding to a compound nucleus excitation energy of 17.2 MeV, in focal plane strip number 18 which is near the center of the detector. The event consisted of an EVR pulse height (uncorrected for pulse height defect) of 17.78 MeV followed 737 μs later by a 203 MeV SF registering signals of $176 + 27$ MeV (FPD and

upstream detectors, respectively). The relatively low excitation energy indicates ^{262}Bh because (a) $E^* = 17.2$ MeV, only 2.4 MeV over the threshold for the $^{209}\text{Bi}(^{54}\text{Cr}, 2n)^{261}\text{Bh}$ reaction, and (b) production of ^{262}Sg via $^{209}\text{Bi}(^{54}\text{Cr}, p)$ is unlikely because of the Coulomb barrier against proton emission. This EVR-SF could indicate direct fission of ^{262}Bh . However, we have calculated an SF hindrance factor of ≤ 26 from an interpolation of the partial SF half-lives for ^{260}Sg and ^{264}Hs [27]. This value is several orders of magnitude smaller than what would be expected based on the two odd particles in ^{262}Bh . A more speculative interpretation of this event could be electron-capture delayed-fission (ECDF) in $^{262}\text{Bh}^m$. The Q-value for the EC is approximately 5.9 MeV [21], corresponding to a large probability for delayed fission (see Fig. (4) of [28]). Because of the uncertainty in the nature of this chain, we have excluded it from cross section and half-life calculations.

D. Random rates

A random event correlation analysis was conducted for this work, similar in method to the one described in the appendix of [12]. 65 s was chosen to be the maximum time of decay chain consideration, Δt_{max} , a multiple of five times the longest literature value for the half-life of ^{254}Lr . This time interval covers the decay of Bh, Db, Lr, and No. The focal plane event rates, R_α and N_{EVR} for the rate of alpha-like events and number of EVR-like events, respectively, were determined by integrating over their spectra. Alpha-like events were required to have energies between 8.0–11.0 MeV, and EVR-like events were required to have energies between 8.0–24.0 MeV. The number of randomly correlated decay chains expected was

calculated by multiplying the Poisson probability of observing a certain number of alpha-like events per focal plane pixel within 65 s by the number of EVR-like events. The pixel size was defined as ± 1.5 mm within a single strip. The number of random chains expected over the duration of each experimental beam energy from an EVR followed by three alpha-like events was fewer than 1.3×10^{-3} , and much lower for EVRs followed by greater than three alpha-like events. Though we have stated that an EVR followed by two full energy alpha decays could be acceptable as a decay chain, no events corresponding to this short decay path were assigned in this work. We conclude that the multiple sequential alpha-decay chains observed in this work are true events and not random correlations.

IV. DISCUSSION

Excitation functions for each reaction's $1n$ and $2n$ products are shown in Fig. 2(a) and 2(b). Horizontal error bars represent the energy spread in the target calculated from [20]. The vertical error bars represent statistical error, calculated as in [25]. The black arrow on the abscissa represents the location of the barrier from the “Fusion By Diffusion” model [13,14], with updated parameters [15].

A maximum likelihood fit procedure using a Gaussian function on the low-energy side of the excitation function smoothly joined to an exponential function on the high-energy side as in [29] was used with the $1n$ data. This combination of a Gaussian and exponential function simply reproduces the known general shape of excitation functions. The fit incorporates weighting for numbers of events, cross sections, and also energy spread through the target, which correctly accounts for the variation in cross section over the target's energy thickness. The use of such fits allows us to obtain accurate values of cross sections and energies at the peak of the excitation function.

For the fit to the $^{55}\text{Mn} + ^{208}\text{Pb}$ data, parameters w (Gaussian width) and λ (exponential slope) were fixed at values of 1.349 and 0.183, respectively. These two values were obtained from a fit to the $^{208}\text{Pb}(^{48}\text{Ti}, n)^{255}\text{Rf}$ reaction in [29] that possessed high statistics and multiple bombarding energies, and we are confident that they are applicable in this work. In the fit to the $^{54}\text{Cr} + ^{209}\text{Bi}$ reaction data, the parameters w and λ were allowed to vary, settling at 2.34 and 0.43, respectively. The values for w and λ have little effect on the centroid and amplitude in the fits.

The fits to the data yield a peak $1n$ cross section of 530 ± 100 pb at an excitation energy of 14.1 ± 0.4 MeV, and 430 ± 110 pb at 15.7 ± 0.5 MeV for the $^{55}\text{Mn} + ^{208}\text{Pb}$ and $^{54}\text{Cr} + ^{209}\text{Bi}$ reactions, respectively. The ratio of the $^{55}\text{Mn}/^{54}\text{Cr}$ $1n$ excitation functions' fit maxima is only 1.2 ± 0.4 . This is in marginal agreement with the ratio of 0.8 from the “Fusion By Diffusion” model. The effective fissilities [5] of these reactions are $x_o = 0.847$ and 0.849 for the $^{54}\text{Cr} + ^{209}\text{Bi}$ and $^{55}\text{Mn} + ^{208}\text{Pb}$ reactions, respectively, with $\Delta x_o = 0.002$. Though the fissility values might suggest that the Bi-based reaction should have a higher cross section because of the lower effective fissility, they are so close in value that we assert no real conclusion may be drawn from this argument alone.

FIG. 2. (Color online) Measured excitation functions for the $^{208}\text{Pb}(^{55}\text{Mn}, xn)^{263-x}\text{Bh}$ [2(a)] and $^{209}\text{Bi}(^{54}\text{Cr}, xn)^{263-x}\text{Bh}$ [2(b)] reactions. Points from the $1n$ and $2n$ exit channels are indicated by filled black squares and filled red circles, respectively. Fits to the data as in [29] are indicated by black lines. The fit maxima are 530 ± 100 pb at an excitation energy of 14.1 ± 0.4 MeV, and 430 ± 110 pb at 15.7 ± 0.5 MeV for the $^{55}\text{Mn} + ^{208}\text{Pb}$ and $^{54}\text{Cr} + ^{209}\text{Bi}$ reactions, respectively. The three points lowest in energy in 2(a) are re-evaluated data from Folden *et al.* [12]. Arrows on abscissa indicate barrier location as discussed in the text.

A plot of our $1n$ excitation function for the $^{54}\text{Cr} + ^{209}\text{Bi}$ reaction alongside the previous work from the GSI may be seen in Fig. 3. The GSI data generally agree with that from the present work.

We also compare our results to the “Fusion By Diffusion” model [13–15] predictions provided to us by Świątecki. The $^{55}\text{Mn} + ^{208}\text{Pb}$ reaction was predicted a few years earlier to have a cross section of approximately 100 pb, which has been recently updated to 400 pb based on their reparametrized model [15]. We find that this value compares well to the 530 ± 100 pb observed in this work. The centroids of the

FIG. 3. Measured excitation functions for the $^{209}\text{Bi}(^{54}\text{Cr}, n)^{262}\text{Bh}$ reaction, studied at the LBNL and the GSI [6,7]. Open squares represent data from GSI, filled squares from this work, a horizontal dash represents our upper limit, and the solid line is the fit from the maximum likelihood method.

experiment and prediction compare well also, with our fit yielding a peak at an excitation energy of 14.1 ± 0.4 MeV, compared to the 14.0 MeV from the prediction. Similarly, we compare the results of our $^{54}\text{Cr} + ^{209}\text{Bi}$ reaction to predictions, and we see a peak cross section of 430 ± 110 pb at 15.7 ± 0.5 MeV, comparing somewhat well to the prediction of 500 pb at ~ 13.5 MeV. While the cross sections are fairly close, the centroid of the predicted excitation function is approximately 2 MeV too low. Overall, we find that the “Fusion By Diffusion” model predictions reproduce peak $1n$ cross sections well within a factor of two.

It is also interesting to compare the large differences in $1n$ cross sections in reaction systems differing only by two neutrons in the projectile. The $^{209}\text{Bi}(^{54}\text{Cr}, n)^{262}\text{Bh}/^{209}\text{Bi}(^{52}\text{Cr}, n)^{260}\text{Bh}$ is one such reaction pair. The “Fusion By Diffusion” model predicts the reaction with the heavier projectile to exhibit the larger cross section. In [30] a cross section of 59 pb was measured in the $^{209}\text{Bi}(^{52}\text{Cr}, n)^{260}\text{Bh}$ reaction. The 430 pb measured in this work results in a $^{209}\text{Bi}(^{54}\text{Cr}, n)^{262}\text{Bh}/^{209}\text{Bi}(^{52}\text{Cr}, n)^{260}\text{Bh}$ cross section ratio of $7.3^{+0.75}_{-0.60}$. This supersedes an earlier report of this ratio as 8.2 in a previous paper [30], and we now present finalized results here. Previously no such ratios had been measured in an odd- Z TAN system, and this experimental cross section ratio is close to the cross section ratio of 10 predicted by Świątecki [15]. The resulting lower cross section in the lighter reaction is likely an entrance channel effect due to the ^{52}Cr reaction being more sub-Coulomb barrier than the ^{54}Cr reaction, and we look forward to additional results on these reactions differing only

by two projectile neutrons to see if this effect is observed elsewhere [29].

The partial excitation functions for the $2n$ exit channel can be seen as the filled red circles in Fig. 2(a) and 2(b). We see the onset of the ^{261}Bh product at excitation energies around 17–20 MeV. The maximum $2n$ cross section of approximately 40 pb was observed at a compound nucleus excitation energy of ~ 22 MeV in the $^{54}\text{Cr} + ^{209}\text{Bi}$ reaction. It appears that the $2n$ exit channel of the $^{55}\text{Mn} + ^{208}\text{Pb}$ reaction is unexpectedly much greater in magnitude than the $^{54}\text{Cr} + ^{209}\text{Bi}$ reaction, but in the absence of complete $2n$ excitation functions it is difficult to quantify. Further studies at higher bombarding energies would be required to completely map the $2n$ excitation functions, allowing us to observe the true maxima. This is also of interest to us so that we may gain information about the peak magnitudes of these paired reactions without the potential influence of the Coulomb barrier on the low-energy side.

In conclusion, we have studied the $^{208}\text{Pb}(^{55}\text{Mn}, xn)^{263-x}\text{Bh}$ and $^{209}\text{Bi}(^{54}\text{Cr}, xn)^{263-x}\text{Bh}$ ($x = 1, 2$) reactions with the 88-Inch Cyclotron and Berkeley Gas-Filled Separator at the Lawrence Berkeley National Laboratory. The decay properties of most products agree well with previously published results, along with the new and interesting observation of the first SF decay of ^{262}Bh possibly via delayed fission. We have re-measured the excitation function for the $^{209}\text{Bi}(^{54}\text{Cr}, n)^{262}\text{Bh}$ reaction, expanded the excitation function for the $^{208}\text{Pb}(^{55}\text{Mn}, n)^{262}\text{Bh}$ reaction, and investigated partial $2n$ excitation functions for both reactions. Data suggests that the influence of the entrance channel on $1n$ cross section magnitudes is not significant, as the cross sections of these reactions are identical within their statistical uncertainties. We also confirm the effect that a difference of two neutrons in the projectile has on the cross section by comparing the results of $^{52,54}\text{Cr} + ^{209}\text{Bi}$ reactions to the “Fusion By Diffusion” model, and verify once again that the model predicts and reproduces $1n$ cross section maxima within a factor of two.

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