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# Fusion enhancement in the $^{38}$S + $^{208}$Pb reaction

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The capture-fission cross section was measured for the reaction of $^{38}$S with $^{208}$Pb for center-of-mass projectile energies $E_{\text{cm}}$ of 160–265 MeV. The $^{38}$S beam was prepared by projectile fragmentation at the NSCL at higher energies and degraded to 4–7 MeV/nucleon. The time of flight (energy) of each interacting beam particle was measured along with the fission fragments. The data were compared to previous measurements of the capture-fission excitation function for the $^{32}$S + $^{208}$Pb reaction. The interaction barrier for the $^{38}$S-induced reaction is 16.1 ± 10.1 MeV lower than the $^{32}$S-induced reaction whereas the reduced excitation functions for the two reactions are similar. A discussion of the systematics of barrier shifts in the fusion of $n$-rich nuclei is given and the implications of this shift for the synthesis of heavy nuclei with radioactive beams are discussed.

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## I. INTRODUCTION

One of the projected important uses [1] of modern radioactive beam facilities is the synthesis and study of the heaviest elements. Many interesting possibilities have been suggested [1] that involve the use of neutron-rich radioactive beams. In Fig. 1, we show the predicted half-lives [2,3] of the even-even transactinide nuclei. One observes an overall increase in half-life with increasing neutron number. This increase is thought to involve several orders of magnitude in half-life, which could quantitatively change the character of studies of the atomic physics and chemistry of these elements. Thus attention has been focused on making new neutron-rich isotopes of the heaviest elements as well as the synthesis of new elements.

Enhanced fusion cross sections have been observed for the reactions of neutron-rich $^{38}$S with $^{181}$Ta [4] and $^{29,31}$Al with $^{197}$Au [5]. Liang *et al.* [6] have observed a fusion enhancement in the reaction of neutron-rich $^{132}$Sn with $^{64}$Ni. The enhanced fusion cross sections are due to a well-understood lowering of the fusion barrier for the neutron-rich projectiles. Simply put, in a sharp cutoff model [7], the fusion cross section (in millibarns) can be given as

$$\sigma_{\text{fusion}} = 10\pi R_B^2(1 - V_B/E_{\text{cm}}), \tag{1}$$

where $R_B$ is the fusion barrier radius and $V_B$ is the fusion barrier height. With increasing projectile $N/Z$, $R_B$ increases, $V_B$ decreases, and the fusion cross section increases. Stelson [8] has suggested that neutron flow effects with very neutron-rich projectiles could enhance fusion cross sections beyond a simple fusion barrier shift. Similar neutron flow phenomena have been described by Wang *et al.* [9,10]. Sub-barrier fusion enhancements caused by neutron transfer have also been suggested by Zagrebaev [11] and Kodratyev *et al.* [12]. In addition to enhanced fusion cross sections, one also expects increased survival probabilities for any heavy nuclei formed in these reactions owing to the reduced fissility of the species and the lower excitation energies (resulting from the lowered fusion barriers).

Based upon these experiments and ideas, we have extended the study of the interaction of neutron-rich nuclei with heavy targets to $^{208}$Pb. Reactions involving $^{208}$Pb targets are the basis of the cold-fusion approach to synthesizing heavy nuclei that has led to the successful synthesis of elements 107–113. $^{38}$S was chosen as the neutron-rich projectile for this test as it is readily available and has been used successfully in previous studies [4]. $^{38}$S ($t_{1/2} = 170$ m) can be produced by the fragmentation of $^{40}$Ar at a projectile fragmentation facility such as the National Superconducting Cyclotron Laboratory at Michigan State University. The capture-fission excitation function for the reaction of stable $^{32}$S with $^{208}$Pb has been measured previously [13,14] and can be used to quantitatively evaluate the expected fusion enhancement with $^{38}$S. Although not as neutron rich as fission-fragment radioactive beams, $^{38}$S is sufficiently neutron rich ($N/Z = 1.38$) to allow the suggested possible effects of neutron-rich projectiles to occur [4,5]. The deformation of $^{38}$S is relatively well understood [15] and the inelastic excitations of it and the doubly magic $^{208}$Pb involved in the capture process also should be relatively well understood. In the interaction of $^{32,38}$S with $^{208}$Pb, the probability of complete fusion after the nuclei touch may be less than unity owing to quasifission. The difficult separation [16] of complete fusion and quasifission was not attempted in this work and the measured cross sections correspond to capture cross sections, which are the sum of the complete fusion and quasifission cross sections. The capture cross section is the quantity calculated in coupled-channels calculations and is an important parameter in calculating the probability of synthesizing heavy nuclei [17].

In Sec. II of this paper, we describe the experimental apparatus. Our results are presented and discussed in Sec. III. Conclusions are given in Sec. IV.

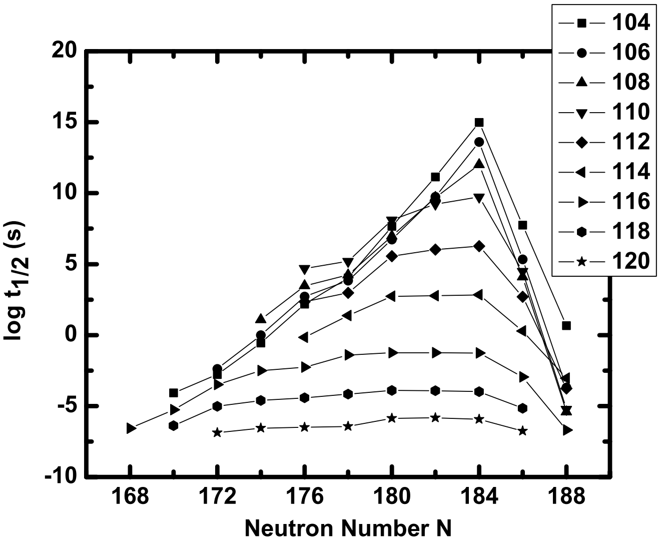

FIG. 1. The predicted [2,3] half-lives of the even-even heavy nuclei vs their neutron number.

## II. EXPERIMENTAL METHODS

The capture-fission excitation function for the radioactive-beam $^{38}$S + $^{208}$Pb reaction was measured in two separate experiments at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University. The first experiment was done in 1998 using the K1200 cyclotron and the A1200 fragment separator. The experimental setup was similar to that used previously [4]. The second experiment was carried out in 2004 using the NSCL coupled cyclotrons (K500/K1200) and the A1900 fragment separator. (The second experiment was performed to check the results of the first experiment, which had indicated that a large shift in interaction barrier height had occurred for this reaction).

In the first experiment, the $^{38}$S beam was generated by fragmenting 40 MeV/nucleon $^{40}$Ar in a Be production target in the A1200 fragment separator. After passage through an achromatic wedge, degrader, and momentum defining slits, the beam was transported to the 92 in. scattering chamber. The on-target beam intensity was 1000–3000 particles/s. The $^{38}$S beam from the A1200 had an energy of 8.18 MeV/nucleon and the energy was degraded to 167–311 MeV by a variable degrader in the 92 in. scattering chamber. The time of flight of each beam particle was measured as it passed through a set of parallel-plate avalanche counters (PPACs) separated by 96 cm in front of the target. The FWHM of the degraded beam energy distributions was about 10%. The $^{208}$Pb target thickness was 920 $\mu$g/cm$^2$. The target was surrounded by an array of Si strip detectors and individual surface barrier detectors that detected fission fragments. Typical solid angles for the strip detectors ranged from 0.5 to 1 sr and the surface barrier detectors subtended solid angles of about 0.06 sr. A valid event consisted of a beam particle that triggered the timing PPACs, causing a fission event in which both fragments were detected with a folding angle corresponding to full linear momentum transfer. Fission cross sections were measured for the interaction of 189.7-, 207.3-, 238.6-, and 311.2-MeV $^{38}$S with $^{208}$Pb.

The efficiency of the fission counting system was calibrated with $^{252}$Cf and the 200- and 302-MeV $^{40}$Ar-induced fission of $^{181}$Ta, $^{197}$Au, and $^{208}$Pb. In this measurement, the solid angles of the detectors were measured using $^{252}$Cf. The geometrical efficiency of the setup for measuring fission cross sections was calibrated by measuring the known fission cross sections for the reaction of 200- and 302-MeV $^{40}$Ar with $^{181}$Ta, $^{197}$Au, and $^{208}$Pb. (The target thicknesses in these measurements were 0.85 mg/cm$^2$, 0.42 mg/cm$^2$, and 0.92 mg/cm$^2$ for $^{181}$Ta, $^{197}$Au, and $^{208}$Pb, respectively.) Direct measurements of these cross sections for the reaction of 200-MeV $^{40}$Ar with $^{197}$Au [18] and $^{208}$Pb [19] exist and the values for the other target-projectile-energy combinations were determined using calculations of the fission cross sections using PACE v.4.13 [20], which adequately fits the known data [18,19] for these reactions.

In the second experiment, a beam of 140 MeV/nucleon $^{40}$Ar was fragmented in a Be production target in the A1900 fragment separator. A beam of 35.0 MeV/nucleon $^{38}$S was produced and transported to the N3 vault. A rotatable Al degrader (168 mg/cm$^2$) was used to reduce the energy of the $^{38}$S beam to ≈8 MeV/nucleon. A rotating-wheel degrader inside the 92 in. chamber was used to reduce the beam energy to 200–310 MeV. The on-target beam intensity was 3500–4500 particles/s. The time of flight of each interacting beam particle was measured as it passed through a set of PPACs separated by 86 cm in front of the target. The $^{208}$Pb target was 880 $\mu$g/cm$^2$ thick. Using a detector array similar to that used in the 1998 experiment, fission cross sections were measured for the interaction of 195-, 239-, 281-, and 311-MeV $^{38}$S with $^{208}$Pb. The efficiency of the fission counting system was calibrated with $^{252}$Cf and the reaction of 243-MeV $^{40}$Ar with $^{208}$Pb. The cross section for this reaction was taken to be 878 mb based upon a PACE v.4.13 [20] extrapolation of the data of [19].

## III. RESULTS AND DISCUSSION

As a background for the discussion of the results of this experiment, we show, in Fig. 2, the previously measured capture-fission cross sections for the reaction of stable $^{32}$S with $^{208}$Pb [13,14]. We display the data in a conventional form and as a $1/E$ plot, which can be extrapolated to give a value of the interaction barrier $V_B$ of 149.4 ± 2.0 MeV and a value of the interaction radius $R_B$ of 9.96 ± 0.09 fm. The data from this experiment involving the reaction of $^{38}$S + $^{208}$Pb are presented in Fig. 3 and Table I. If one treats the two runs (run 1 and

TABLE I. Measured cross sections for the $^{38}$S + $^{208}$Pb reaction.

| $E_{\mathrm{lab}}$ (MeV) | Cross section (mb) | Run number |
|---|---|---|
| 189.7 | 804 ± 80 | 1 |
| 195.3 | 651 ± 87 | 2 |
| 207.3 | 1078 ± 104 | 1 |
| 238.6 | 1163 ± 113 | 1 |
| 238.8 | 1028 ± 164 | 2 |
| 280.8 | 1477 ± 183 | 2 |
| 311.2 | 1600 ± 163 | 1 |
| 311.4 | 1735 ± 177 | 2 |

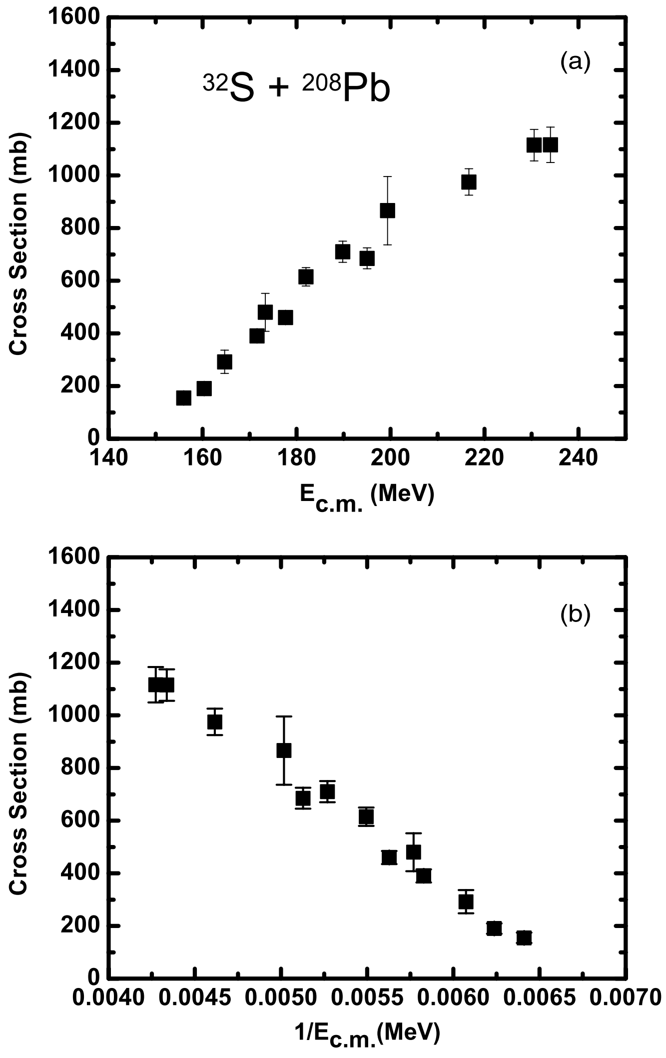

FIG. 2. (a) The capture-fission excitation function for the reaction of $^{32}$S with $^{208}$Pb [13,14]. (b) The data of (a) represented in a $1/E$ plot.

run 2) as separate experiments, the best fits to the $1/E$ plots of the data give $V_B = 112.1 \pm 16.8$ MeV ($R_B = 9.4 \pm 0.7$ fm) and $V_B = 134.6 \pm 15.3$ MeV ($R_B = 10.4 \pm 0.7$ fm), respectively. However, we note that for the energies in common for both experiments,($E_{\text{lab}} = 239$ and 311 MeV), the measured cross sections agree within uncertainties. Therefore, since we do not know any reason a priori to consider one experiment superior to the other, we have combined the data into a single set.

If we attempt to fit the entire data set with a simple plot of $1/E_{\text{cm}}$ versus cross section, the chi-squared value is 7.49 and the goodness of fit (complement of the incomplete $\Gamma$ function) is 0.28. Both of these parameters indicate an unsatisfactory fit to the data at the 95% confidence level. Looking at Fig. 3, we see that the points at $E_{\text{cm}} = 160$ and 175 MeV appear to be outliers with respect to the combined data set. We refit the data, neglecting these outliers using a $1/E$ plot to get $V_B = 133.3 \pm 10.0$ MeV and $R_B = 10.3 \pm 0.4$ fm.

The data from the two reactions can be combined in a reduced excitation function (Fig. 4), where the energies have

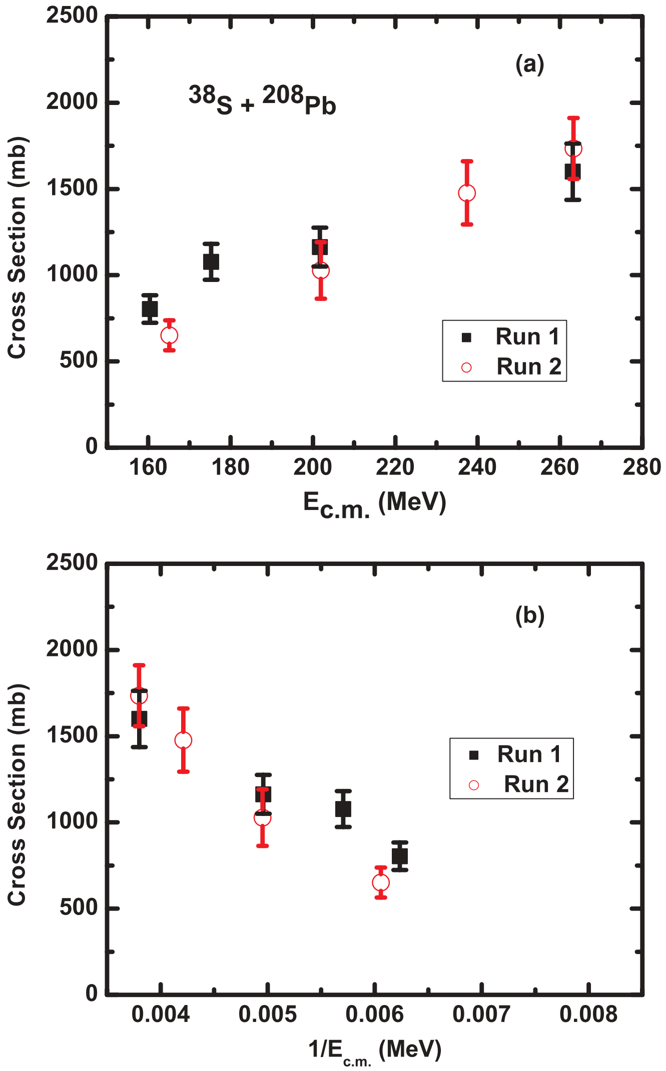

FIG. 3. (Color online) Same as Fig. 2 except for the reaction $^{38}$S + $^{208}$Pb as measured in this work.

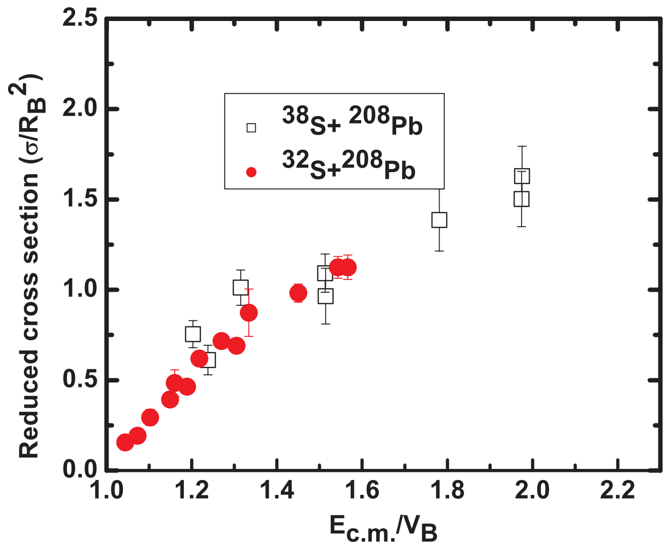

FIG. 4. (Color online) Reduced excitation functions for the $^{32,38}$S + $^{208}$Pb reactions.

TABLE II. Comparison of measured and predicted barrier parameters.

| | $^{32}S + ^{208}Pb$ $V_B$ (MeV) | $R_B$ (fm) | $^{38}S + ^{208}Pb$ $V_B$ (MeV) | $R_B$ (fm) |
|---|---|---|---|---|
| Experimental | $149.4 \pm 2.0$ | $9.96 \pm 0.09$ | $133.3 \pm 10.0$ | $10.3 \pm 0.4$ |
| Bass [21] | 147.4 | 11.9 | 143.7 | 12.3 |
| Moustabchir and Royer [22] | 148.0 | 11.8 | 145.3 | 12.0 |
| Swiatecki *et al.* [17] | 144.5 | | 141.3 | |
| Puri and Gupta [23] | 148.9 | | 145.3 | |
| Dobrowolski *et al.* [24] | 148.9 | | 146.4 | |

been scaled by the deduced interaction barriers and the cross sections have been scaled by the deduced interaction radii. Changes in reduced excitation functions can be used to look for unusual behavior of the cross sections resulting from reaction mechanisms such as pigmy resonances, soft dipole excitations, neutron flow, etc. The two reactions show similar reduced excitation functions insofar as they overlap, indicating no evidence for any enhancement in the capture cross sections apart from a significant shift in the interaction radii and barriers between the neutron-rich $^{38}S$ and the stable $N = Z$ nucleus $^{32}S$. This finding is similar to that of other studies of reactions induced by neutron-rich radioactive beams [4–6].

In Table II, we compare the deduced barrier parameters for the $^{32}S + ^{208}Pb$ and $^{38}S + ^{208}Pb$ reactions with various semi-empirical predictions of these quantities. The data for the $^{32}S + ^{208}Pb$ reaction are reasonably well represented by the semi-empirical predictions, but the large lowering of the barrier height for the $^{38}S$-induced reaction is not. This large shift in interaction barrier heights for neutron-rich radioactive projectiles compared to stable projectiles is also seen, to a lesser extent, in previous studies of the capture cross sections for neutron-rich projectiles [4–6]. In an attempt to gain understanding of these large barrier shifts in reactions induced by neutron-rich projectiles [4–6], we plot, in Figs. 5 and 6 (and tabulate in Table III), the reduced barrier height $B_{\text{measured}}/B_{\text{Bass}}$ versus a number of possible scaling parameters. The Bass barrier [21] is chosen as the normalization quantity for this comparison because it is easily calculated for any system and should represent the average behavior of the nuclear potential in each collision. In Fig. 5(a), the scaling variable is $Z_1Z_2/(A_1^{1/3} + A_2^{1/3})$ [17,23]. As expected, there is no apparent dependence of the reduced barrier heights on this variable because that dependence is already included in the Bass barrier. In Figs. 5(b), 6(a), and 6(b), we use a variety of scaling parameters such as the isospin $T_3$ of the fused system, the reduced isospin of the fused system, $(N - Z)/A$, and the relative symmetry energy of the fused system, $(N - Z)^2/A$. In each case, it appears that there is a rough correlation of

TABLE III. Comparison of deduced barrier heights for fusion reactions involving $n$-rich projectiles.

| Reaction | Reference | $V_B$ (MeV) | $V_{\text{Bass}}$ (MeV) |
|---|---|---|---|
| $^{38}S + ^{208}Pb$ | This work | $133.3 \pm 9.9$ | 143.7 |
| $^{32}S + ^{181}Ta$ | 4 | $130.9 \pm 0.5$ | 134.1 |
| $^{38}S + ^{181}Ta$ | 4 | $125.2 \pm 5.3$ | 130.7 |
| $^{27}Al + ^{197}Au$ | 5 | $111.3 \pm 1.2$ | 117.5 |
| $^{31}Al + ^{197}Au$ | 5 | $107.8 \pm 1.5$ | 115.2 |
| $^{124}Sn + ^{64}Ni$ | 6 | $152.2 \pm 2.2$ | 158.0 |
| $^{132}Sn + ^{64}Ni$ | 6 | $148.6 \pm 2.3$ | 156.1 |

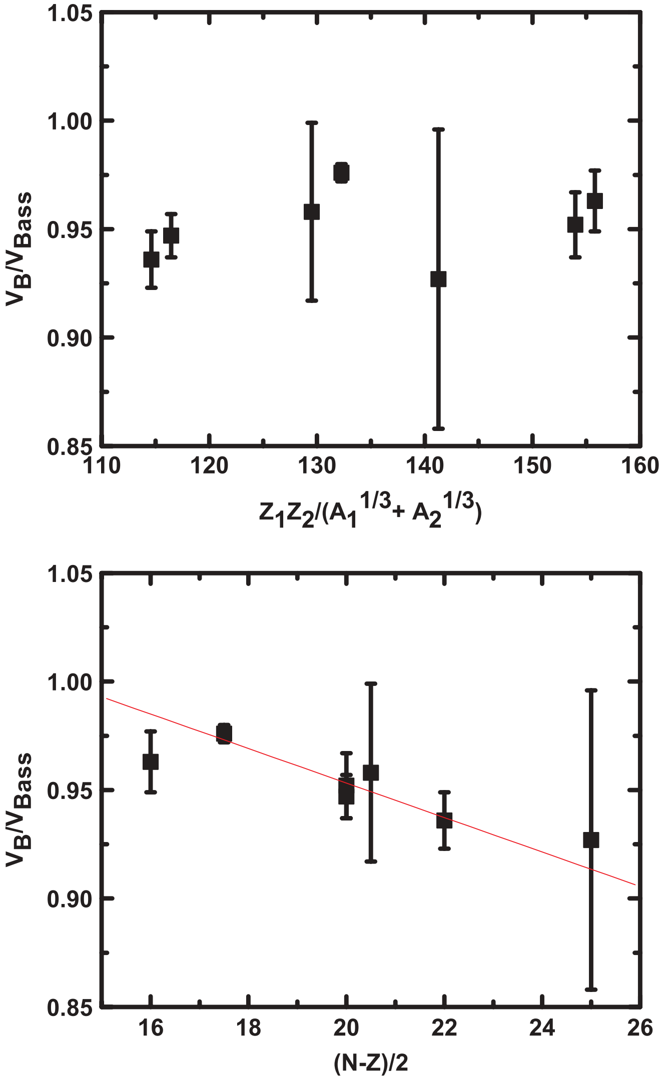

FIG. 5. (Color online) Reduced interaction barrier heights vs various scaling parameters. Data are from [4–6] and this work. See text for details.

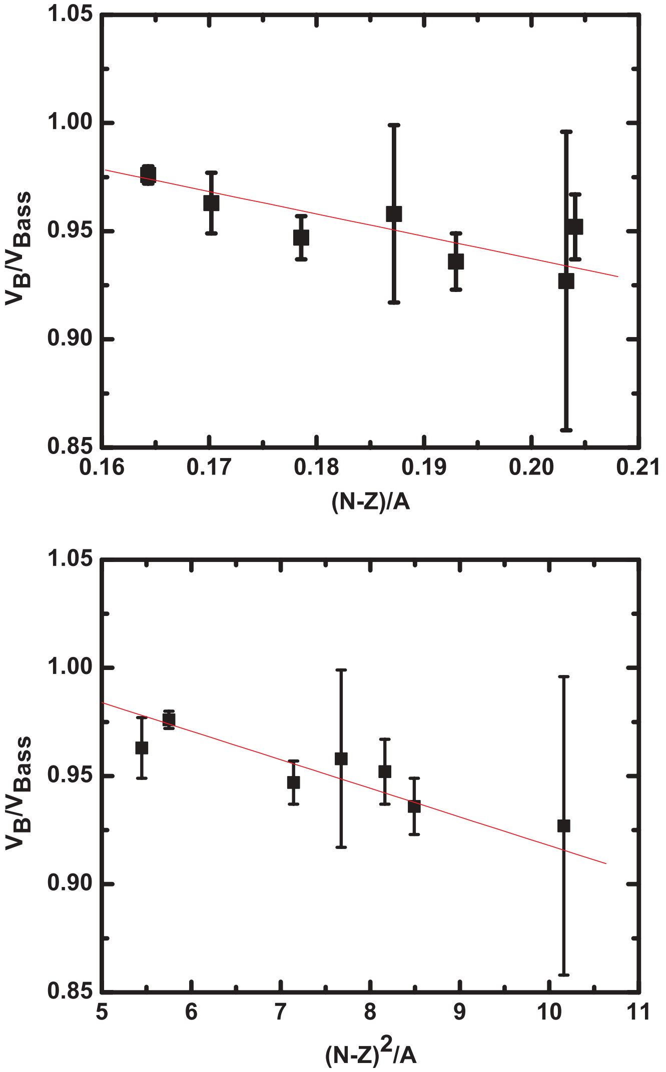

FIG. 6. (Color online) Reduced interaction barrier heights vs various scaling parameters. Data are from [4–6] and this work. See text for details.

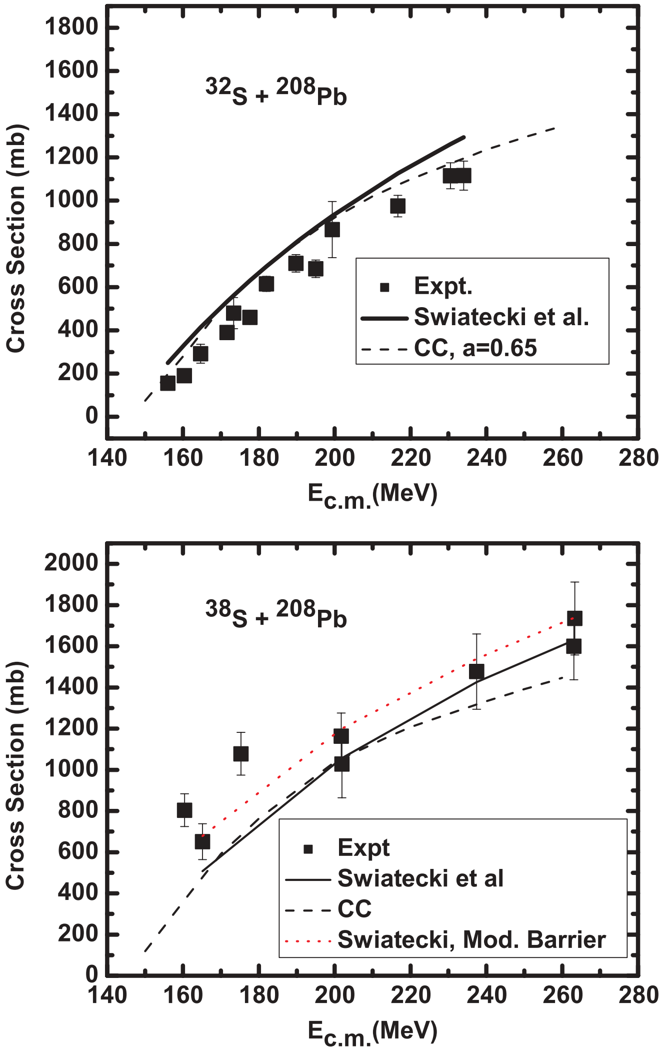

FIG. 7. (Color online) Comparison of the measured cross sections for the (a) $^{32}$S + $^{208}$Pb and (b) $^{38}$S + $^{208}$Pb reactions with the semi-empirical model of Swiatecki *et al.* [16] and the results of a coupled-channels calculation.

the reduced barrier height for neutron-rich systems with the scaling variable, apart from the data for the $^{32}$S + $^{208}$Pb reaction, where we have the unusual situation of having a deduced interaction barrier that is greater than the Bass barrier. A naive view of the data in Figs. 5 and 6 would be that there is a part of the nuclear potential that is related to the neutron excess of the composite system that is not being accounted for in the standard representations of the potentials used in modeling capture cross sections or that there are effects in the interaction that are not included in these potential models.

To make a more detailed comparison of the measurements reported herein with our current understanding of the capture process in collisions involving neutron-rich nuclei, we show, in Fig. 7, a comparison of the measured cross sections with calculations made using a semi-empirical model of the capture cross section relevant for studies of the synthesis of heavy nuclei [17] and the familiar coupled-channels formalism [25].

The semi-empirical formalism of Swiatecki *et al.* [17] does an adequate job (≈10–15% error) of representing the cross sections for the stable beam reactions. This formalism is based upon fitting 45 accurately measured fusion cross sections and has been observed [26] to adequately represent the capture cross section data of [4–6].

The coupled-channels calculation was done using the CCFULL code [25]. Values of the deformation parameter $\beta_2$ of the projectiles were taken from [15] and inelastic excitations of the low-lying vibrational states of the projectile and the target were allowed. The surface diffuseness parameter of the Woods-Saxon potential ($V_0 = 105$ MeV, $r_0 = 1.12$ fm) was fixed at $a = 0.65$ to be consistent with descriptions of elastic scattering [27]. We recognize that it is common to allow the diffuseness parameter to vary to larger values (0.75–1.5)

[27–29] to get the best fit to the data. However, the lack of lower energy data to constrain the fitting and the desire to not conceal any phenomena for the neutron-rich projectiles caused us to use the nominal value of the diffuseness parameter. The coupled-channels calculation also agrees with the stable beam data to within 10%.

Neither calculation agrees well with the measured data for the $^{38}$S + $^{208}$Pb reaction, especially at the lower projectile energies. There are no positive $Q$ value neutron transfer channels for the $^{38}$S system. Because the measured data are for above barrier energies, we thought it would be important to establish whether the deviations between the measurements and predictions involve a breakdown of the functional form of the dependence of the cross section on beam energy. So we arbitrarily set the barrier height in the Swiatecki *et al.* formalism to 133.3 MeV instead of the predicted 141.3 MeV. The resulting prediction (Fig. 7) is in reasonable agreement with the data, indicating the semi-empirical model describes the data given the appropriate parameters. (The data of Fig. 6(b) would suggest the barrier height $B = B_{\mathrm{Bass}}[(1.028 \pm 0.011) - (0.0098 \pm 0.0015)(N-Z)^2/A]$.)

### A. Consequences of these data for heavy-element synthesis

It is interesting to speculate on what the barrier shifts observed with neutron-rich projectiles might mean for the synthesis of heavy nuclei. Consider two reactions, $^{32}\mathrm{S} + {}^{208}\mathrm{Pb} \rightarrow {}^{240}\mathrm{Cf}$ and $^{38}\mathrm{S} + {}^{208}\mathrm{Pb} \rightarrow {}^{246}\mathrm{Cf}$. Assume both reactions are carried out at the nominal interaction barriers, 149.4 and 133.3 MeV, respectively. The excitation energies of the completely fused systems, $^{240}$Cf and $^{246}$Cf, would be 43.6 and 20.6 MeV, respectively, leading to the expectation that the dominant reaction channels would be the 4n and 2n channels, respectively. The products of these reactions would be $^{236}$Cf (an unknown nucleus whose half-life is estimated to be ≈9.4 s [3]) and $^{244}$Cf, whose half-life is 1160 s, a hundred-fold increase in half-life, in accord with the trends suggested in Fig. 1.

The cross section for the production of an evaporation residue, $\sigma_{\mathrm{EVR}}$, can be written as

$$\sigma_{\mathrm{EVR}} = \sigma_{CN} W_{\mathrm{sur}}, \tag{2}$$

where $\sigma_{CN}$ is the complete fusion cross section and $\mathrm{W}_{\mathrm{sur}}$ is the survival probability of the completely fused system. The complete fusion cross section can be written as

$$\sigma_{CN} = \sum_{J=0}^{J_{\max}} \sigma_{\mathrm{capture}}(E_{\mathrm{cm}}, J) \mathrm{P}_{CN}(E_{\mathrm{cm}}, J), \tag{3}$$

where $\sigma_{\mathrm{capture}}(E_{\mathrm{cm}}, J)$ is the capture cross section and $\mathrm{P}_{CN}$ is the probability that the projectile-target system will evolve inside the fission saddle point to form a completely fused system rather than reseparating (quasifission).

Swiatecki *et al.* [17] have developed a semi-empirical formalism for predicting the capture cross sections for collisions leading to heavy nuclei. Using the parametrization of [17] and the measured interaction barrier heights, we calculated $\sigma_{\mathrm{capture}}$ for each reaction. (The quadrupole deformations of the reacting nuclei were determined from [30].) At the barrier, the capture cross sections for the two reactions were essentially the same. The survival probability $\mathrm{W}_{\mathrm{sur}}$ can be written as

$$\mathrm{W}_{\mathrm{sur}} = \mathrm{P}_{xn}(E^*_{CN}) \prod_{i=1}^{i_{\max}} \left( \frac{\Gamma_n}{\Gamma_n + \Gamma_f} \right)_{i,E^*}, \tag{4}$$

where the index $i$ is equal to the number of emitted neutrons and $\mathrm{P}_{xn}$ is the probability of emitting exactly $x$ neutrons [31]. For calculating $\Gamma_n/\Gamma_f$, we have used the classical formalism from Vandenbosch and Huizenga [32]

$$\frac{\Gamma_n}{\Gamma_f} = \frac{4A^{2/3}(E^*_{CN} - B_n)}{k\{2[a(E^*_{CN} - B_f)^{1/2} - 1]\}} \times \exp\{2a^{1/2}[(E^*_{CN} - B_n)^{1/2} - (E^*_{CN} - B_f)^{1/2}]\}. \tag{5}$$

The constants $k$ and $a$ are taken to be 9.8 and $\mathrm{A}_{CN}/12$, respectively. The fission barriers, $B_f$ are written as the sum of liquid drop, $B_f^{\mathrm{LD}}$, and shell correction terms as

$$B_f(E^*_{CN}) = B_f^{\mathrm{LD}} + U_{\mathrm{shell}} \exp\left[\frac{-E^*_{CN}}{E_D}\right], \tag{6}$$

where the shell correction energies $U_{\mathrm{shell}}$ to the LDM barriers are taken from [30], the liquid drop barriers are taken from [33], and the fade-out values of the shell corrections, by using the $E_D$ parameter, are taken from Ignaytuk *et al.* [34]. Neutron binding energies are taken from [30]. Collective enhancement effects are only important for spherical product nuclei and they are neglected here.

Armbruster [35] has suggested the semi-empirical form

$$\mathrm{P}_{CN}(E, J) \approx \mathrm{P}_{CN}(E) = 0.5 \exp[-c(x_{\mathrm{eff}} - x_{\mathrm{thr}})], \tag{7}$$

where the effective fissility is defined as

$$x_{\mathrm{eff}} = \left(\frac{Z_{CN}}{101.8}\right)\left(\frac{1-I}{1-1.78I^2}\right)[1 - \alpha - \alpha f(\kappa)], \tag{8}$$

where $I = (N-Z)/(N+Z)$ and

$$f(\kappa) = \frac{4}{\kappa^2 + \kappa + \frac{1}{\kappa} + \frac{1}{\kappa^2}}. \tag{9}$$

The parameter $\alpha = 1/3$, $\kappa = (A_1/A_2)^{1/3}$, $c = 106$, and $x_{\mathrm{thr}} = 0.79$ [35]. In the Armbruster formalism, $\mathrm{P}_{CN}$ is unity for both systems.

The expected ratio of the two evaporation residue production cross sections ($\sigma_{38}/\sigma_{32}$) is essentially the ratio of the predicted survival probabilities. This ratio is $8.2 \times 10^4$; that is, the expected evaporation residue yield for the reaction induced by $^{38}$S is five orders of magnitude greater than that expected for the $^{32}\mathrm{S} + {}^{208}\mathrm{Pb}$ reaction. This is due primarily to the lower excitation energy in the reaction induced by the neutron-rich projectile. Although this result only applies to the reactions of $^{32,38}$S with $^{208}$Pb, the result does point to and support the larger conclusion [26] that neutron-rich radioactive beams will be useful tools in studying the atomic physics and chemistry of the heaviest elements.

## IV. CONCLUSIONS

What have we learned in this study? We conclude that (a) the interaction barrier for the $^{38}$S + $^{208}$Pb reaction is substantially lower, $16.1 \pm 10.1$ MeV, than that for the $^{32}$S + $^{208}$Pb reaction; (b) the systematics of the interaction barrier heights in reactions induced by very neutron rich projectiles supports the idea that there is a systematic decrease in barrier heights that is correlated to the relative neutron richness of the composite system and this correlation is not included in current models of the capture process; and (c) the measured barrier shifts for reactions induced by neutron-rich radioactive projectiles, such as $^{38}$S, could be very important in the synthesis of new heavy nuclei.

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