

**Suppression of complete fusion due to breakup in the reactions  $^{10,11}\text{B} + ^{209}\text{Bi}$** L. R. Gasques,<sup>\*</sup> D. J. Hinde, M. Dasgupta, A. Mukherjee,<sup>†</sup> and R. G. Thomas<sup>‡</sup>*Department of Nuclear Physics, Research School of Physical Sciences and Engineering,  
Australian National University, Canberra, ACT 0200, Australia*

(Received 17 October 2008; published 10 March 2009)

Above-barrier cross sections of fission and  $\alpha$ -active heavy reaction products were measured for the reactions of  $^{10,11}\text{B}$  with  $^{209}\text{Bi}$ . Systematic analysis showed that the fission originates almost exclusively from complete fusion (CF). Existing measurements of above-barrier fusion products for the  $^{30}\text{Si} + ^{186}\text{W}$  reaction, assumed to proceed exclusively through CF, were extrapolated to the current systems using statistical model calculations. This extrapolation showed that the heavy reaction products from the  $^{10,11}\text{B} + ^{209}\text{Bi}$  reactions include substantial components from incomplete fusion as well as from CF. Compared with fusion calculations without breakup, the CF cross sections are suppressed by 15% for  $^{10}\text{B}$  and 7% for  $^{11}\text{B}$ . A consistent and systematic variation of the suppression of CF for reactions of the weakly bound nuclei  $^{6,7}\text{Li}$ ,  $^9\text{Be}$ , and  $^{10,11}\text{B}$  on targets of  $^{208}\text{Pb}$  and  $^{209}\text{Bi}$  is found as a function of the breakup threshold energy.

DOI: [10.1103/PhysRevC.79.034605](https://doi.org/10.1103/PhysRevC.79.034605)

PACS number(s): 25.70.Jj, 25.70.Mn, 25.60.Gc, 25.60.Dz

**I. INTRODUCTION**

Over the last decade, the effect of the breakup of weakly bound nuclei on fusion and other reaction processes has been widely investigated from theoretical and experimental perspectives [1]. Studies with weakly bound light stable nuclei indicate that complete fusion (CF) cross sections (defined experimentally [2,3] as absorption of all the charge of the projectile) are suppressed at above-barrier energies in comparison with the predictions of both the single barrier penetration model (SBPM) and the coupled-channels (CC) model [2–7]. This is attributed to the low binding energy of the projectiles, which can break up prior to reaching the fusion barrier. In general, the missing CF cross sections are found in yields of incomplete fusion (ICF), which occurs when not all the fragments are captured by the target.

Calculation of CF cross sections, as distinct from ICF, is currently not possible using quantum-mechanical scattering theories such as the continuum discretized coupled-channels model (CDCC), which can only predict total (CF+ICF) fusion. To address this problem, a three-dimensional classical dynamical model was recently developed [8], allowing the calculation of CF and ICF cross sections at energies above the fusion barrier. The model relates above-barrier CF and ICF yields with below-barrier no-capture breakup, where the Coulomb barrier inhibits capture of charged fragments by the target nucleus. This is achieved by the introduction of a stochastically sampled breakup function, which can be obtained experimentally from the measurement of no-capture breakup cross sections at subbarrier energies [9], or from CDCC calculations. A quantitative relationship between the

CF and ICF at energies above the barrier and the below-barrier no-capture breakup opens up a new approach to studying the influence of breakup on fusion [9]. To test and exploit this new approach, both below-barrier and above-barrier measurements are required for light nuclei with a range of breakup threshold energies. Ideally, all significantly populated CF and ICF channels should be measured, to allow detailed comparison with the model predictions.

As part of this development, the present paper describes measurements of CF and ICF cross sections for the  $^{10,11}\text{B} + ^{209}\text{Bi}$  reactions at energies above the fusion barrier  $V_B$ , ranging from  $1.1V_B$  to  $1.5V_B$ . A comparison of the above-barrier CF cross sections with SBPM calculations of fusion without breakup allowed the determination of the suppression of CF due to breakup of the  $^{10}\text{B}$  and  $^{11}\text{B}$  projectiles [2]. The most favorable breakup thresholds are quite different, being 4.461 MeV for  $^{10}\text{B}$  and 8.665 MeV for  $^{11}\text{B}$ . The CF suppression is compared with those obtained for reactions involving other stable but weakly bound projectiles.

**II. EXPERIMENTAL METHOD**

The experiments were performed using pulsed  $^{10,11}\text{B}$  beams from the 14UD tandem electrostatic accelerator at the Australian National University. The beams, with a pulse width of 1 ns and interval of 640 ns, were incident on self-supporting  $^{209}\text{Bi}$  targets of thickness  $480 \mu\text{g cm}^{-2}$ . Fission measurements were made with an unbacked target, while the yield of the heavy CF and ICF products were measured by their  $\alpha$  decay, using four Bi targets backed by  $560 \mu\text{g cm}^{-2}$  Al foils to stop the recoiling evaporation residues (ER). The beam species, beam energy, and target cycling sequence were chosen to minimize the buildup of activity contaminating subsequent measurements. The experimental arrangement was similar to that reported in Ref. [2], and only a brief description is given here. Fission events following fusion were measured using two large-area position-sensitive multiwire proportional counters [10]. Each detector, with an active area of  $28.4 \times 35.7 \text{ cm}^2$ , was located 18.0 cm from the target. To identify the heavy

<sup>\*</sup>Current address: Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal.

<sup>†</sup>Permanent address: Saha Institute of Nuclear Physics, 1/AF, Bidhan Nagar, Kolkata 700064, India.

<sup>‡</sup>Current address: B.A.R.C., Mumbai, India.

reaction products, their characteristic decay  $\alpha$ -particle energies were used, and cross sections were determined using their known  $\alpha$  branching ratios and half-lives. The  $\alpha$  particles from short-lived activities ( $T_{1/2} \leq 24$  min) were detected between the beam pulses by a back-angle annular silicon surface barrier detector.  $\alpha$  decays from long-lived activities were measured using a silicon surface barrier detector placed below the annular counter, close to the plane of the target ladder [2]. For normalization, two Si surface barrier detectors (monitors), symmetrically placed about the beam axis at  $22.5^\circ$ , were used to measure elastically scattered beam particles. Absolute cross sections for fission and ER were determined by performing calibrations at a subbarrier energy in which elastically scattered  $^{58}\text{Ni}$  projectiles of 120 MeV were detected in the fission detectors and the annular  $\alpha$  counter as well as in the two forward-angle monitors. The relative solid angles of the annular and close geometry Si detectors were determined using the 24 min  $\alpha$  activity from  $^{212}\text{Rn}$  [2].

### III. DETERMINATION OF COMPLETE FUSION YIELDS

The identification and determination of the yields of the complete fusion products, among the many possible reaction products, will be described in order of the complexity of the procedure. First, the  $xn$  evaporation products following CF will be discussed, then fission following CF, and finally the products of  $pxn$  and  $\alpha xn$  evaporation following CF. To illustrate the complexity of the analysis, the many possible paths for the production of all  $\alpha$ -active products observed for the  $^{10}\text{B}$ -induced reaction are shown in Fig. 1.

#### A. Evaporation products following complete fusion

Complete fusion of  $^{10,11}\text{B}$  incident on  $^{209}\text{Bi}$  leads to the compound nuclei  $^{219,220}\text{Ra}$ , respectively. Neutron evaporation is the dominant evaporation mode, producing residual Ra evaporation residues, all of which are  $\alpha$ -active (the number of neutrons evaporated in the formation of the observed isotopes following  $^{10}\text{B}$  fusion is indicated in Fig. 1; for example, for  $^{214}\text{Ra}$ , by the label  $5n$ ). Since they can only be produced following complete fusion, interpretation of their measured cross sections is unambiguous. They are shown in Figs. 2(a) and 3(a) for the reactions  $^{10,11}\text{B} + ^{209}\text{Bi}$ , respectively. As expected, each evaporation channel shows a gradual rise and fall with increasing energy, in accordance with expectations from the neutron binding energies and average neutron kinetic energies.

The  $\alpha$  decay of these Ra nuclei produces Rn daughter nuclei, which also undergo  $\alpha$  decay, in turn forming Po daughter nuclei. Decay to daughter nuclei is indicated in Fig. 1 by diagonal shaded arrows. The measured cross sections for the Rn isotopes are presented in Figs. 2(b) and 3(b) as a function of center-of-mass energy  $E_{\text{c.m.}}$ . For both reactions, they can be significantly larger than those predicted from the parent Ra yields, indicating that there are other mechanisms directly populating the Rn nuclei, as might be expected. Subtracting the expected Rn cross sections resulting from the Ra parent decay, the cross sections for the direct production of Rn isotopes are shown for  $^{10}\text{B}$  in Fig. 2(c) and for  $^{11}\text{B}$  in Fig. 3(c). The  $\alpha$  energy spectra also showed the presence of small cross sections for

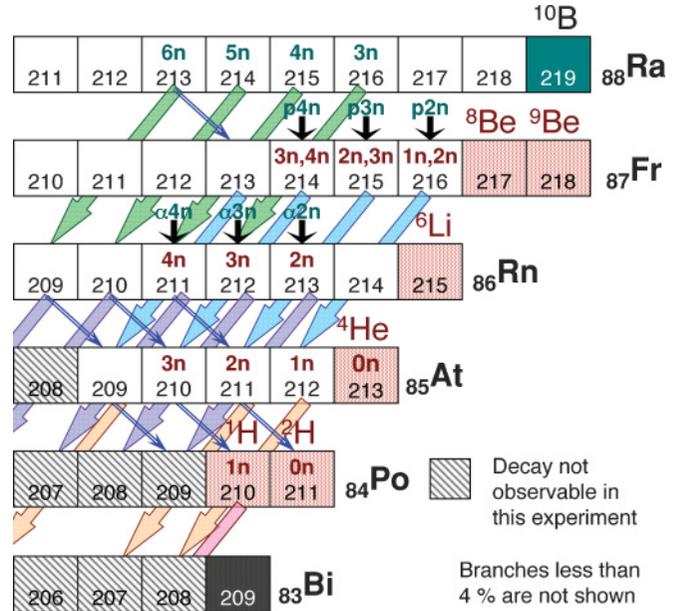


FIG. 1. (Color online) Diagram showing the significant production and decay paths of the isotopes measured for the  $^{10}\text{B} + ^{209}\text{Bi}$  reaction, including production both by CF and ICF. The nucleus captured is shown above the shaded square corresponding to the compound nucleus (CN) on the right. For the isotopes observed, the evaporation channel is labeled assuming only neutron evaporation from each CN. Possible production by charged particle evaporation after CF forming  $^{219}\text{Ra}$  is indicated by the labeled vertical black arrows.  $\alpha$ -particle decays are indicated by the large shaded diagonal arrows, which lead from the parent to the daughter nucleus. Electron capture decay is shown by the narrow diagonal arrows. The assignment of cross sections accounted for all these population and decay pathways.

production of Fr isotopes (not plotted). The origin of Fr and Rn isotopes are discussed next.

#### B. Production mechanisms of Fr, Rn products

The direct production yields of Fr and Rn can result from CF, through  $pxn$  and  $\alpha xn$  evaporation, respectively, in competition with  $xn$  evaporation and fission. These pathways are indicated in Fig. 1 by the vertical arrows, identified with the specific evaporation channel leading to the observed isotope (e.g.,  $p4n$  leading to  $^{214}\text{Fr}$ ). However, this is not the only mechanism available. The  $^{10,11}\text{B}$  projectiles can break up before fusion, into a number of different mass partitions. The most energetically favorable  $^{10}\text{B}$  breakup channel is

$$^{10}\text{B} \rightarrow ^6\text{Li} + ^4\text{He}, \quad Q = -4.461 \text{ MeV}.$$

Less favored breakup channels are

$$\begin{aligned} ^{10}\text{B} &\rightarrow ^8\text{Be} + ^2\text{H}, & Q &= -6.026 \text{ MeV}, \\ &\rightarrow ^9\text{Be} + ^1\text{H}, & Q &= -6.586 \text{ MeV}, \\ &\rightarrow ^4\text{He} + ^4\text{He} + ^2\text{H}, & Q &= -5.934 \text{ MeV}. \end{aligned}$$

Similarly the most favorable  $^{11}\text{B}$  breakup channel is

$$^{11}\text{B} \rightarrow ^7\text{Li} + ^4\text{He}, \quad Q = -8.665 \text{ MeV}.$$

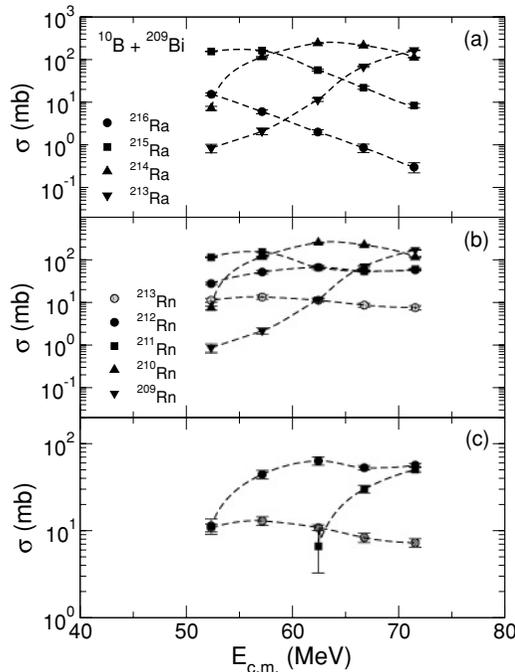


FIG. 2. Measured cross sections for the production of (a) Ra isotopes and (b) Rn isotopes, and (c) yield of Rn isotopes after subtracting the contributions from the decay of Ra isotopes for the reaction  $^{10}\text{B} + ^{209}\text{Bi}$ . The lines guide the eye.

It may also break up into

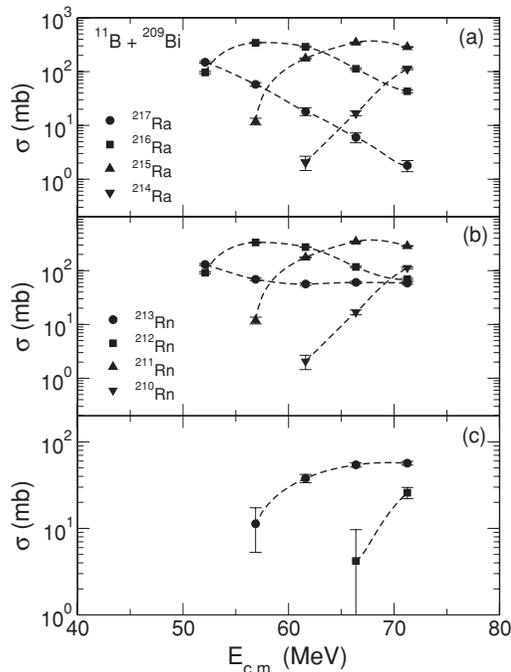
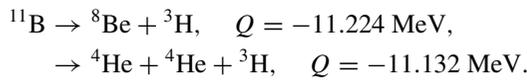


FIG. 3. Same as Fig. 2, but for the reaction  $^{11}\text{B} + ^{209}\text{Bi}$ .

The capture and absorption of one of these fragments by  $^{209}\text{Bi}$  would form one of the compound nuclei  $^{217,218}\text{Fr}$ ,  $^{215,216}\text{Rn}$ ,  $^{213}\text{At}$ , or  $^{210,211}\text{Po}$ . The CN formed by ICF in the  $^{10}\text{B}$  reaction are indicated in Fig. 1 by shading, with the specific captured fragment noted (e.g.,  $^6\text{Li}$ ). Isotopes of Fr and Rn would be produced, as well as isotopes of At and Po, after evaporation of neutrons (the dominant evaporation channel) from these compound nuclei; these are indicated in Fig. 1 by the number of neutrons evaporated, for those isotopes that were observed in the experiment.

Because of the different pathways available in the  $^{10,11}\text{B} + ^{209}\text{Bi}$  reactions, the yields of Rn isotopes originating from  $\alpha xn$  evaporation following complete fusion cannot be directly separated from  $xn$  evaporation following ICF with capture of a  $^{6,7}\text{Li}$ . Equivalently, yields of Fr isotopes produced after  $pxn$  evaporation from the CF compound nuclei  $^{215,216}\text{Ra}$  will be mixed with the same products formed following capture of a  $^{8,9}\text{Be}$  fragment (or two  $^4\text{He}$ ). The resolution of this problem requires the introduction of more experimental information, which will be described after the attribution of the observed fission cross sections is discussed.

### C. Attribution of fission to complete fusion

To investigate whether the contribution of fission following ICF is significant, we define the empirical probability of fission following fusion as

$$P_{\text{fis}} = \frac{\sigma_{\text{fis}}}{\sigma_{\text{fis}} + \sigma_{\text{CF}} + \sigma_{\text{ICF}}}, \quad (1)$$

in which the determination of the observed ICF cross sections ( $\sigma_{\text{ICF}}$ ) will be discussed in the next section. Experimental values of  $P_{\text{fis}}$  are plotted in Fig. 4 as a function of the bombarding energy per nucleon ( $E/A$ ), for the reactions  $^{10,11}\text{B} + ^{209}\text{Bi}$ ,  $^{6,7}\text{Li} + ^{209}\text{Bi}$  [2], and  $^4\text{He} + ^{209}\text{Bi}$  [11]. The latter correspond to the incomplete fusion reactions associated with the most favorable breakup channels. It is clear from the large reduction in  $P_{\text{fis}}$  as the captured mass decreases that the contribution of fission following ICF of  $^{6,7}\text{Li}$  or  $^4\text{He}$

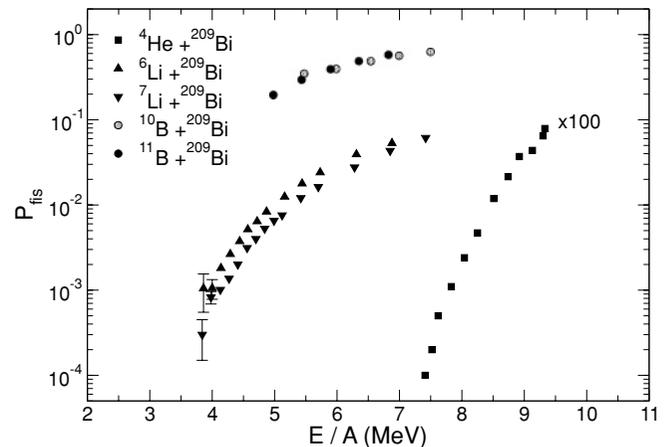


FIG. 4. Measured empirical fission probability as a function of the energy per nucleon of the projectile for the reactions  $^{10,11}\text{B} + ^{209}\text{Bi}$ ,  $^{6,7}\text{Li} + ^{209}\text{Bi}$ , and  $^4\text{He} + ^{209}\text{Bi}$ .

will be negligible compared with that resulting from CF. As an example, we can estimate the maximum contribution to the fission yield from ICF for the  $^{10}\text{B} + ^{209}\text{Bi}$  reaction. From Fig. 4, the maximum probability of fission after a  $^6\text{Li}$  fragment is captured is 7% at the highest value of  $E/A$  (7.5 MeV). It will be found in the next section that approximately 8% of the total fusion (CF+ICF) cross section is attributed to ICF with a  $^6\text{Li}$  fragment, thus the fraction of the total fission is  $0.07 \times 0.08$  divided by the fraction of CF resulting in fission at this energy ( $\sim 0.6$ ), giving less than 1% of the fission yield resulting from ICF of  $^6\text{Li}$ . At lower  $E/A$ , the fraction is even smaller. For the same  $E/A$ , the fission contribution following the capture of a  $^4\text{He}$  fragment is very much lower, as clearly seen in Fig. 4. These calculations are supported by the measured folding angle distributions for fission, which were consistent with complete fusion within experimental uncertainties.

The relatively small contribution of fission following ICF can be understood qualitatively, since the angular momentum and excitation energy brought in by an ICF fragment is on average lower than when the entire projectile fuses with the target, and the compound nucleus itself is less fissile [2]. Despite the heavier projectile, the above quantitative analysis justifies using the same approach as in Ref. [2], and thus the measured fission cross sections are attributed only to CF.

#### D. Separation of complete and incomplete fusion for Fr and Rn products

The origin of the yields of Fr and Rn isotopes was determined making use of measurements of above-barrier fusion cross sections for the  $^{30}\text{Si} + ^{186}\text{W}$  reaction [10], which forms the  $^{216}\text{Ra}$  compound nucleus following fusion. The direct production of Fr and Rn isotopes by ICF for this reaction should be insignificant at all measured energies, as  $^{30}\text{Si}$  is expected to behave as a normal, strongly bound, noncluster-structure nucleus. Thus statistical model calculations [12] that reproduce both the fission probabilities and the relative yields of  $pxn$  and  $\alpha xn$  evaporation for the  $^{30}\text{Si} + ^{186}\text{W}$  reaction should reliably predict the charged particle evaporation for the  $^{10,11}\text{B}$  reactions. It is important to note that our procedure normalizes the statistical model calculations to the data from the  $^{30}\text{Si}$ -induced reaction forming  $^{216}\text{Ra}$ , and uses the model only to make a small extrapolation to the  $^{219}\text{Ra}$  and  $^{220}\text{Ra}$  nuclei formed in the present  $^{10,11}\text{B}$ -induced reactions. Thus the procedure depends only on statistical model calculations that have been normalized to experiment. The first step is to normalize the calculation of the fission channel. The experimental ratios of fission cross sections to  $xn$  evaporation residues (plotted in this way to minimize bias due to ICF) are shown for the three reactions in Fig. 5. The results for  $^{30}\text{Si} + ^{186}\text{W}$  are corrected for the inferred quasifission contribution [10]. It is necessary that the statistical model calculations reproduce these experimental ratios to ensure that the ER calculations are for the correct angular momentum distributions. The calculations, using the code JOANNE2 [12], were matched to experiment by scaling the fission barrier heights by factors of 0.77, 0.83, and 0.85 for the reactions leading to  $^{216}\text{Ra}$ ,  $^{219}\text{Ra}$ , and  $^{220}\text{Ra}$ , respectively. A similar

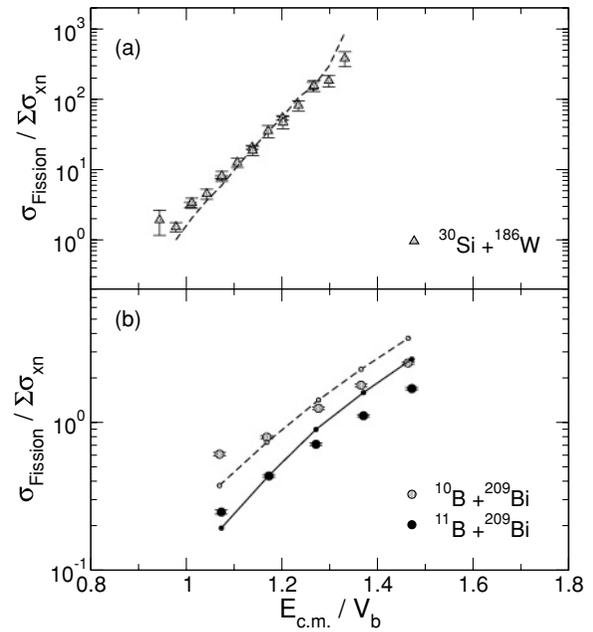


FIG. 5. Ratio of the measured fission cross sections to the summed  $xn$  cross sections for (a)  $^{30}\text{Si} + ^{186}\text{W}$  and (b)  $^{10,11}\text{B} + ^{209}\text{Bi}$ . The lines are the predictions of statistical model calculations (see text).

trend of barrier scaling factors with neutron number has been found previously [13]. Figures 6(a) and 7(a) show the measured ratios [14] of the cross sections for  $pxn$  and  $\alpha xn$  products divided by the  $xn$  cross sections, as a function of the CF excitation energy ( $E^*$ ), for the calibration reaction  $^{30}\text{Si} + ^{186}\text{W}$ . The JOANNE2 calculations were found to give good agreement with the experimental data after multiplying by a factor of 1.8 for  $pxn$  and 1.5 for  $\alpha xn$ . Using these scaling factors, the predicted  $pxn$  and  $\alpha xn$  relative yields for the  $^{10,11}\text{B}$  reactions are shown in Figs. 6(b) and 7(b). Note that the range of  $E^*$  for the three reactions overlap, while the fission competition causes the angular momenta resulting in ER to be similar for all reactions. The predictions lie far below the measurements for the  $^{10,11}\text{B}$  reactions, clearly indicating that a large fraction of the direct production of Fr and Rn isotopes is due to ICF. For the  $^{10}\text{B} + ^{209}\text{Bi}$  reaction, the data are consistent with  $93 \pm 2\%$  of the Fr and  $90 \pm 2\%$  of the Rn yields resulting from ICF, while for the  $^{11}\text{B} + ^{209}\text{Bi}$  reaction,  $85 \pm 4\%$  of the Fr and  $85 \pm 3\%$  of the Rn yields result from ICF. These scaling factors of 1.8 and 1.5 may reflect aspects of the statistical model code such as simplified treatment of level densities and neglect of static deformation, or indeed a contribution from ICF even in the  $^{30}\text{Si} + ^{186}\text{W}$  reaction. If the latter were the case, the predicted  $pxn$  and  $\alpha xn$  yields from CF would be even lower. The conclusion, that the great majority of the observed Fr and Rn yields for the B-induced reactions results from ICF, would be unchanged. Furthermore, because the deduced cross sections of Fr and Rn from CF make such a small contribution to the total CF cross sections, uncertainties in the Fr and Rn CF fractions do not make a significant difference to the deduced CF cross sections.

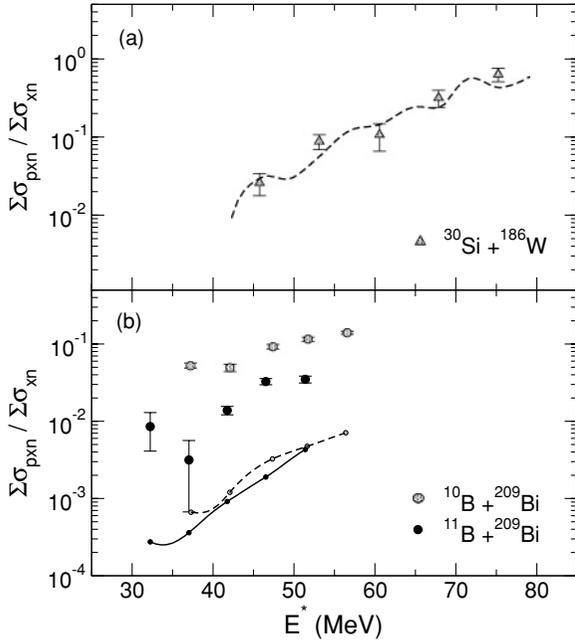


FIG. 6. Ratio of the summed  $pxn$  to  $xn$  cross sections for (a)  $^{30}\text{Si} + ^{186}\text{W}$  and (b)  $^{10,11}\text{B} + ^{209}\text{Bi}$ . The lines are the predictions of statistical model calculations.

### E. Complete fusion cross sections

The CF cross sections were determined by summing the yields for the Ra isotopes, the small fraction of the cross sections for Fr and Rn isotopes associated with CF ( $\sim 8\%$  for  $^{10}\text{B}$  and  $\sim 15\%$  for  $^{11}\text{B}$ -induced reactions), and the full fission cross sections. The total measured yields in each category, together with the deduced CF cross sections are presented in Table I for  $^{10}\text{B} + ^{209}\text{Bi}$  and Table II for  $^{11}\text{B} + ^{209}\text{Bi}$ . The center-of-mass energies have been corrected for energy loss in the target. The errors given in the cross sections only reflect statistical uncertainties. The excitation functions for CF, for both reactions, are shown as filled circles in Fig. 8. Having determined the CF yields, the determination of the suppression of CF by ICF is discussed in the next section.

The yields of other products of ICF, such as At and Po isotopes, together with transfer reactions, whose details do not affect the subsequent analysis, are presented and discussed in

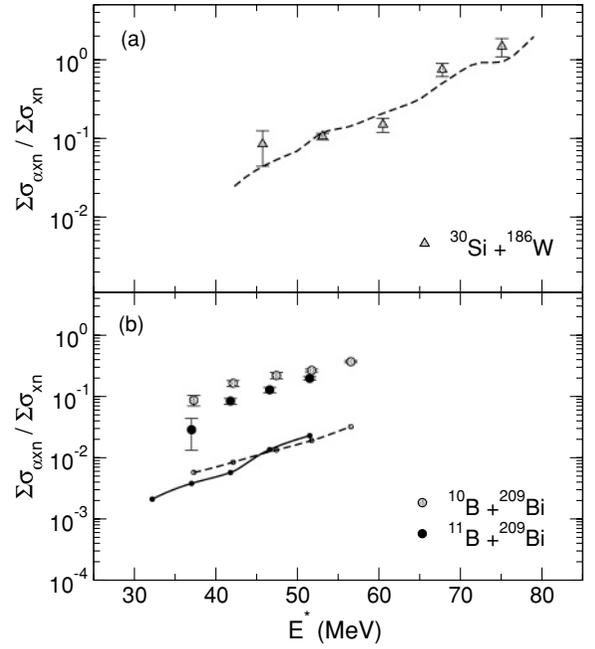


FIG. 7. Ratio of the summed  $\alpha xn$  to the  $xn$  cross sections for (a)  $^{30}\text{Si} + ^{186}\text{W}$  and (b)  $^{10,11}\text{B} + ^{209}\text{Bi}$ . The lines are the predictions of statistical model calculations.

the Appendix. The sum of these cross sections are shown in Fig. 8 by open triangles (multiplied by a factor of 2 for clarity in the figure). The sum of the measured cross sections for Rn and Fr not associated with CF are shown by open circles. Adding these cross sections to the deduced CF cross sections gives the total cross sections for almost all reaction products heavier than the target (indicated by open squares). These exceed the calculated total fusion cross sections as expected, as the cross sections for At and Po must include contributions from transfer reactions.

## IV. SUPPRESSION OF COMPLETE FUSION

To determine the suppression of fusion cross sections at above-barrier energies due to breakup of the  $^{10,11}\text{B}$  projectiles, SBPM calculations were performed using the São Paulo potential (SPP) to give the real part of the nuclear potential

TABLE I. Fission, evaporation residues, and complete fusion cross sections for the  $^{10}\text{B} + ^{209}\text{Bi}$  reaction. The center-of-mass energies  $E_{c.m.}$  are corrected for energy losses in the target. The quoted errors reflect only statistical uncertainties. For the Rn and Fr isotopes, only 7% and 10%, respectively, of the total yields presented in the table contribute to the total complete fusion cross sections (see text).

$E_{\text{beam}}$ (MeV)	$E_{c.m.}$ (MeV)	$\sigma_{\text{fis}}$ (mb)	$\sum \sigma_{\text{Ra}}$ (mb)	$\sum \sigma_{\text{Rn}}$ (mb)	$\sum \sigma_{\text{Fr}}$ (mb)	$\sigma_{\text{CF}}$ (mb)
54.84	52.34	$82 \pm 1$	$134 \pm 3$	$11.4 \pm 2.2$	$6.9 \pm 1.0$	$217 \pm 3$
59.86	57.13	$217 \pm 2$	$273 \pm 5$	$44 \pm 5$	$13 \pm 2$	$494 \pm 5$
65.36	62.38	$400 \pm 4$	$322 \pm 7$	$69 \pm 8$	$29 \pm 3$	$730 \pm 8$
69.87	66.68	$559 \pm 6$	$315 \pm 7$	$82 \pm 8$	$36 \pm 4$	$883 \pm 9$
74.87	71.45	$735 \pm 7$	$294 \pm 5$	$106 \pm 10$	$40 \pm 4$	$1040 \pm 9$

TABLE II. As in Table I, but for the  $^{11}\text{B} + ^{209}\text{Bi}$  reaction. For the Rn and Fr isotopes, only 15% of the total yields presented in the table contributes to the complete fusion cross sections.

$E_{\text{beam}}$ (MeV)	$E_{\text{c.m.}}$ (MeV)	$\sigma_{\text{fis}}$ (mb)	$\sum \sigma_{\text{Ra}}$ (mb)	$\sum \sigma_{\text{Rn}}$ (mb)	$\sum \sigma_{\text{Fr}}$ (mb)	$\sigma_{\text{CF}}$ (mb)
54.84	52.10	$57 \pm 1$	$226 \pm 7$	—	$1.9 \pm 1.0$	$283 \pm 7$
59.87	56.88	$176 \pm 2$	$403 \pm 7$	$11 \pm 6$	$1.3 \pm 1.0$	$581 \pm 7$
64.85	61.61	$329 \pm 3$	$462 \pm 6$	$38 \pm 4$	$6.4 \pm 0.8$	$798 \pm 7$
69.87	66.38	$521 \pm 5$	$471 \pm 7$	$58 \pm 6$	$15.4 \pm 2.0$	$1003 \pm 9$
75.00	71.25	$724 \pm 7$	$430 \pm 7$	$83 \pm 9$	$15.0 \pm 2.0$	$1169 \pm 10$

[15]. In earlier works [16–18], the SPP has proved reliable for reproducing fusion excitation functions for reactions involving both strongly bound and weakly bound projectiles (CF+ICF), and is particularly useful for measurements where experimental fusion barrier distributions are not available. The results of the SBPM calculations (solid lines) are compared with the experimental CF cross sections in Fig. 8. As expected, the measured cross sections lie below the theoretical calculations. The ratios of the observed CF cross sections to those expected without breakup (defined as  $F_{\text{CF}}$ ) are  $F_{\text{CF}} = 0.85 \pm 0.01$  for  $^{10}\text{B}$  and  $F_{\text{CF}} = 0.93 \pm 0.02$  for  $^{11}\text{B}$ . The larger reduction in CF cross sections for the  $^{10}\text{B}$ -induced reaction shows a correlation with the lower breakup energy threshold for  $^{10}\text{B}$  (4.461 MeV) compared with  $^{11}\text{B}$  (8.665 MeV), as might be expected.

A substantial part of the difference between the SBPM calculations and the experimental CF cross sections ( $\sim 70\%$ ) can be found in the measured yields of Fr and Rn isotopes which cannot be associated with CF. The presence of these

unexpectedly large yields supports the conclusion from the SBPM calculations that CF is suppressed in these reactions.

### A. Systematics of fusion suppression

To investigate the systematics of the suppression of fusion due to breakup, Fig. 9 shows the CF suppression  $F_{\text{CF}}$  for reactions involving weakly bound projectiles and heavy target nuclei. These are for the reactions of  $^{6,7}\text{Li}$  incident on  $^{159}\text{Tb}$  [6],  $^{165}\text{Ho}$  [5],  $^{208}\text{Pb}$  [7], and  $^{209}\text{Bi}$  [2] targets;  $^9\text{Be}$  incident on  $^{144}\text{Sm}$  [4] and  $^{208}\text{Pb}$  [2] targets; and  $^{10}\text{B}$  incident on  $^{159}\text{Tb}$  [6]. The present result for  $^{10,11}\text{B} + ^{209}\text{Bi}$  are also shown. For the  $^7\text{Li} + ^{165}\text{Ho}$  reaction, the data [5] have been reanalyzed to incorporate changes in the CC calculations, including rotational couplings for the  $^7\text{Li}$  as in Ref. [2]. This resulted in slightly less suppression of CF (0.73) than the 0.70 reported in Ref. [5].

Understanding systematic behavior is important to clarifying the mechanism of breakup and its effect on the fusion process. The dependence of  $F_{\text{CF}}$  on the charge product of the reaction ( $Z_P Z_T$ ) is illustrated in Fig. 9. The CF suppression for the reactions involving  $^7\text{Li}$  (open circles) and  $^{10}\text{B}$  (filled squares) projectiles are found to be rather independent of  $Z_P Z_T$  within experimental error. The values for  $^7\text{Li}$  lie below those for  $^{10}\text{B}$ , which may be expected because of the lower

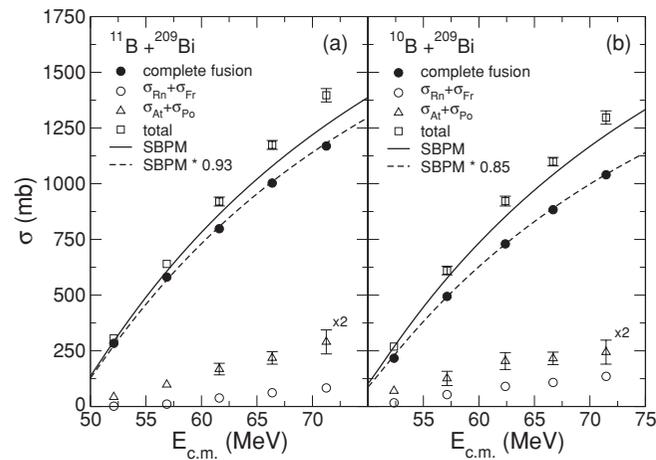


FIG. 8. Complete fusion excitation function (filled circles) for the  $^{10,11}\text{B} + ^{209}\text{Bi}$  reactions. The solid lines are the predictions of a single barrier penetration model, and the dashed lines are the results of these calculations multiplied by the indicated factor. Also shown are the sum of the measured cross sections for Rn and Fr not associated with CF (open circles), the sum of the measured cross sections for At and Po (open triangles), and the total cross sections for almost all reaction products heavier than the target (open squares). For clarity in the figure, the data points plotted as open triangles have been multiplied by a factor of 2.

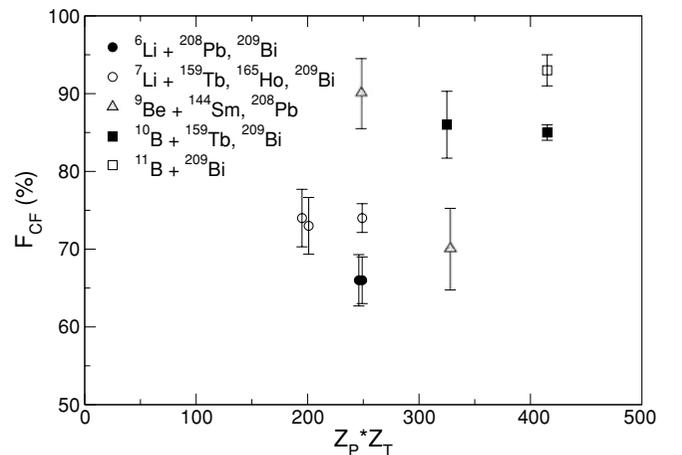


FIG. 9. Complete fusion suppression factor  $F_{\text{CF}}$  for reactions with heavy target nuclei as a function of the charge product of projectile and target.

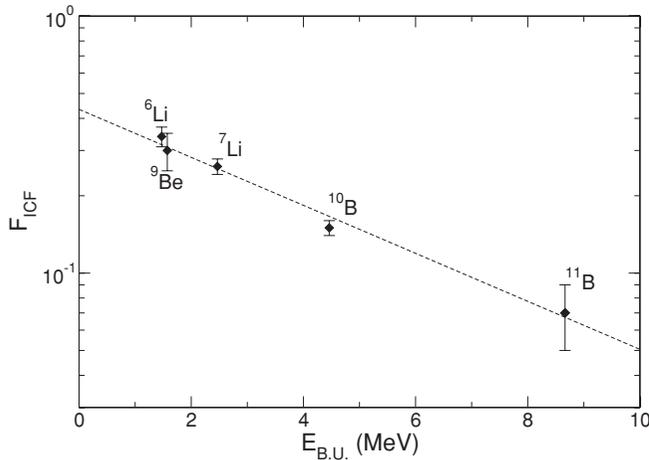


FIG. 10. Approximate fraction of ICF ( $F_{ICF}$ ) as a function of the breakup threshold for reactions on  ${}^{208}\text{Pb}$  and  ${}^{209}\text{Bi}$  (see text). The exponential line is to guide the eye.

breakup energy threshold of  ${}^7\text{Li}$  compared with  ${}^{10}\text{B}$ . For the measurements involving  ${}^9\text{Be}$ , the CF suppression (open triangles in Fig. 9) shows a strong variation with  $Z_P Z_T$ . The origin of this difference is not clear. It may be related to the physical mechanism of fusion suppression or could possibly arise from different experimental techniques used to obtain the CF excitation functions.

This behavior makes it difficult to assess the dependence of the CF suppression on breakup threshold for the full data set. However, taking only the measurements on  ${}^{208}\text{Pb}$  and  ${}^{209}\text{Bi}$  targets, the data are rather consistent. The reactions  ${}^6\text{Li} + {}^{209}\text{Bi}$  [2] and  ${}^6\text{Li} + {}^{208}\text{Pb}$  [7] give the strongest suppression ( $F_{CF} = 0.66$ ). This is expected since the  ${}^6\text{Li}$  nucleus has the lowest threshold against breakup (1.473 MeV). Assuming that the yield of ICF is complementary to that of CF, the ICF fraction  $F_{ICF}$  is given by  $F_{ICF} = 1 - F_{CF}$ ; this is probably only approximately true [2]. This ICF fraction is shown as a function of the projectile breakup threshold in Fig. 10. A remarkably consistent correlation is seen, suggesting the dominant role of the breakup threshold. This may suggest a too simple picture of breakup, as the probability of excitation above the breakup threshold, as well as the threshold energy itself, must play the crucial role. Measurements of breakup at energies below the fusion barrier, where no significant capture of the fragments is expected and the energetics of the breakup process may be reconstructed, are expected to give additional insights into the physical mechanism(s) of breakup [8,9].

## V. SUMMARY AND CONCLUSIONS

Above-barrier cross sections of  $\alpha$ -active heavy reaction products, as well as fission, were measured for the reactions of  ${}^{10,11}\text{B}$  with  ${}^{209}\text{Bi}$ . Due to the many possible paths for the production of the heavy reaction products, separation of the complete fusion and incomplete fusion in the evaporation residues was only possible using experimental information from the  ${}^{30}\text{Si} + {}^{186}\text{W}$  reaction, which allowed normalization of statistical model calculations of the charged particle evaporation channels following CF. Based on this procedure,

the present analysis reveals that  $\geq 85\%$  of the yields of Fr and Rn result from ICF. In contrast, fission was found to originate almost exclusively from CF, as determined by comparing experimental data for fusion reactions of  ${}^4\text{He}$  and  ${}^{6,7}\text{Li}$  with  ${}^{209}\text{Bi}$ . Summing the fission and CF-produced evaporation residue cross sections gave the total CF cross sections for the two reactions. Compared with calculations of fusion without consideration of breakup (using the São Paulo nuclear potential), the CF cross sections are suppressed by  $15 \pm 1\%$  ( ${}^{10}\text{B}$ ) and  $7 \pm 2\%$  ( ${}^{11}\text{B}$ ). Including these new results, for reactions involving light, weakly bound, stable nuclei bombarding targets of  ${}^{208}\text{Pb}$  and  ${}^{209}\text{Bi}$ , a remarkably consistent correlation of the suppression of CF (or equivalently the fraction of ICF) is found with the breakup threshold energy.

Future planned measurements of below-barrier no-capture breakup, in conjunction with the results presented here (and in previous papers) of CF and ICF cross sections for reactions of projectiles with different breakup threshold energies, should be valuable in the development of realistic models describing breakup and fusion (complete and incomplete). In particular, in the near future, a systematic study can test the recently developed three-dimensional classical dynamical model [8], which relates below-barrier no-capture breakup yields with above-barrier CF and ICF cross sections.

## ACKNOWLEDGMENT

This work was supported by a Discovery Grant from the Australian Research Council.

## APPENDIX: OTHER REACTION PRODUCTS

For the  ${}^{10,11}\text{B}$ -induced reactions, ICF could result in the production of many different isotopes of At and Po, as well as the Fr and Rn already discussed. For the At and Po isotopes, similar to the Rn isotopes, their direct production cross sections are obtained by subtracting their feeding through Fr and Rn parent decays (see Fig. 1). The direct production of At and Po isotopes can be associated with ICF and/or transfer reactions. The cross sections for production of both At and Po are given in Table III and shown in Fig. 11 as a function of the center-of-mass energy.

TABLE III. Sum of the individual measured cross sections for At and Po isotopes for the  ${}^{10,11}\text{B}$  reactions. The quoted errors reflect only statistical uncertainties. The center-of-mass energies  $E_{c.m.}$  are corrected for energy losses in the target. The cross sections for  ${}^{209}\text{Po}$ , which may be significant, could not be measured due to its long half-life (102 years).

$E_{\text{beam}}$ (MeV)	$E_{c.m.}$ (MeV)	$\sum \sigma_{\text{At}} + \sum \sigma_{\text{Po}}$ ${}^{10}\text{B}$ (mb)	$\sum \sigma_{\text{At}} + \sum \sigma_{\text{Po}}$ ${}^{11}\text{B}$ (mb)
54.84	52.10	$35 \pm 6$	$21.3 \pm 3.4$
59.87	56.88	$63 \pm 16$	$49 \pm 5$
64.85	61.61	$102 \pm 19$	$84 \pm 13$
69.87	66.38	$108 \pm 14$	$109 \pm 14$
75.00	71.25	$122 \pm 27$	$145 \pm 27$

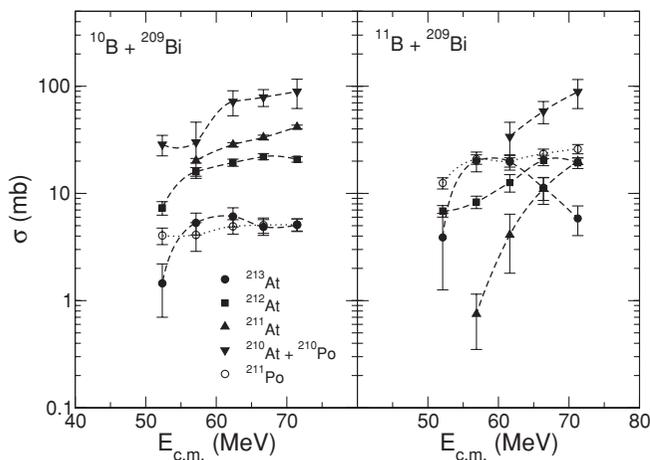


FIG. 11. Measured cross sections for At and Po isotopes for the  $^{10,11}\text{B}$ -induced reactions. The symbols denote the same products in the left and the right panels. The lines guide the eye.

### 1. At isotopes

All Fr isotopes formed have  $\alpha$ -decay half lives short enough to contribute to the prompt yield of At isotopes. However, the feeding of the observed At isotopes is rather small compared with their direct production, so the feeding correction is not large. The observation of decay from the  $^{212}\text{At}$  isomeric state (spin =  $9^-$ ;  $T_{1/2} = 0.119$  s) in the  $\alpha$  spectra, which is not fed

by the decay of  $^{216}\text{Fr}$ , confirms the direct production of this isotope.

The cross sections for  $^{210}\text{At}$  could not be determined individually, since it decays almost completely (99.82%) by electron capture to  $^{210}\text{Po}$ , with  $T_{1/2} = 8.3$  h. Assignment of yields to  $\alpha$  transfer or ICF have not been attempted, as determination of the suppression of CF, the main aim of this work, is independent of this assignment.

### 2. Po isotopes

The total cross sections for production of  $^{210}\text{Po}$  ( $T_{1/2} = 138$  days) were obtained from off-line spectra accumulated over a few days after the irradiations, when all  $^{210}\text{At}$  will have decayed to  $^{210}\text{Po}$ . A significant fraction of the  $^{210}\text{Po}$  yield may be due to transfer of one proton to  $^{209}\text{Bi}$ , with ground-state  $Q$  values of  $-1.60$  MeV ( $^{10}\text{B} + ^{209}\text{Bi}$ ) and  $-6.24$  MeV ( $^{11}\text{B} + ^{209}\text{Bi}$ ). Deuteron transfer reactions are also likely to populate  $^{211}\text{Po}$ . The summed  $^{211}\text{Po}$  ground state and  $^{211}\text{Po}$  isomeric state [spin = ( $25^+/2$ );  $T_{1/2} = 25.2$  s] yields are shown as open circles in Fig. 11. The population of the high-spin isomeric state implies that ICF is a significant route of population. The cross sections for  $^{209}\text{Po}$  could not be measured due to its long half-life of 102 years. Based on the sizable production of  $^{210}\text{Po}$  compared with  $^{211}\text{Po}$ , a substantial yield of  $^{209}\text{Po}$  might be expected. Thus in this work, we could only determine the lower limit of the total cross section of At and Po.

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