Fusion studies with low-intensity radioactive ion beams using an active-target time projection chamber

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Abstract

The total fusion excitation function for $^{10}\text{Be}+^{40}\text{Ar}$ has been measured over the center-of-momentum (c.m.) energy range from 12-24 MeV using a time-projection chamber (TPC). The main purpose of this experiment, which was carried out in a single run of duration 90 hrs using a ≈ 100 particle per second (pps) ^{10}Be beam, was to demonstrate the capability of an active-target TPC to determine fusion excitation functions for extremely weak radioactive ion beams. Cross sections as low as 12 mb were measured with acceptable (50%) statistical accuracy. It also proved to be possible to separate events in which charged particles were emitted from the fusion residue from those in which only neutrons were evaporated. The method permits simultaneous measurement of incomplete fusion, break-up, scattering, and transfer reactions, and therefore fully exploits the opportunities presented by the very exotic beams that will be available from the new generation of radioactive beam facilities.

Keywords: fusion excitation functions, $^{10}\text{Be}+^{40}\text{Ar}$, time projection chamber, very low intensity beams, radioactive ion beams

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31 1. Introduction

32 The study of fusion reactions with radioactive ion beams at energies near
33 the Coulomb barrier has resulted in the discovery of a variety of interesting
34 effects. The coupling of fusion reactions to direct reaction channels such as
35 breakup and transfer often has an important effect on the fusion cross section
36 [1–3]. For example, the total fusion cross sections for exotic ‘neutron halo’
37 nuclei such as ${}^6\text{He}$ typically show a suppression at energies above the Coulomb
38 barrier, with a slight enhancement at sub-barrier energies, when compared with
39 no-coupling one-dimensional barrier penetration models. It appears that these
40 effects result from couplings to the neutron-transfer and breakup channels. To
41 date, however, these studies have concentrated on relatively light nuclei such as
42 ${}^6\text{He}$, ${}^8\text{He}$ [4], and ${}^{11}\text{Li}$ [5] due to the limited availability of heavier projectiles near
43 the neutron or proton drip-line at Coulomb-barrier energies. The new generation
44 of radioactive ion beam facilities, such as the Facility for Rare Isotope Beams
45 (FRIB) currently under construction at Michigan State University, will provide
46 a much wider spectrum of projectiles to choose from. Nevertheless, since the
47 most proton- and neutron-rich nuclei will often be produced at low intensities,
48 and beam-time allocations at these facilities will be very limited, it is imperative
49 to develop highly efficient methods to study nuclear reaction mechanisms using
50 these exotic beams.

51 Recently, we have been carrying out a series of measurements with radioac-
52 tive ion beams produced by the *TwinSol* facility [6] at the University of Notre
53 Dame, using the prototype active-target time projection chamber (pAT-TPC)
54 [7] developed at Michigan State University. The focus of this work was to test
55 design concepts for the full-scale AT-TPC, as well as to develop techniques
56 for analyzing the data produced by this imaging detector. The AT-TPC has
57 a number of important advantages for working with low-intensity beams, in-
58 cluding very high efficiency for detecting reaction products and measuring their
59 angular distributions with virtually 4π solid-angle coverage, much larger avail-
60 able target thickness (since the reaction vertex can be directly imaged), and the

61 ability to measure an excitation function as the projectile slows down in the
 62 target gas [8]. Solid targets may also be used by mounting them within the gas
 63 volume.

64 The first experiments carried out with the pAT-TPC were α -particle scat-
 65 tering measurements to probe cluster structure in the α +projectile system. See,
 66 *e.g.*, Ref. [9] in which α -particle clustering in ^{10}Be was measured via resonant
 67 scattering of ^6He on a ^4He target. In a later experiment in this series, cluster
 68 structure in ^{14}C was studied using a ^{10}Be beam [10]. Although it is radioactive,
 69 ^{10}Be is very strongly bound and so it was anticipated that its fusion excita-
 70 tion function should closely follow expectations for stable nuclei. This makes
 71 it an ideal candidate for developing methods to measure fusion with the pAT-
 72 TPC. In the present work, we report on a measurement of the $^{10}\text{Be}+^{40}\text{Ar}$ fusion
 73 excitation function.

74 2. Experimental method

75 The previous experiments with the pAT-TPC [7, 9, 10] all involved measure-
 76 ments of binary reactions, for which a convenient trigger was the detection of
 77 coincident particle tracks in opposing quadrants of the detector. Fusion prod-
 78 ucts, on the other hand, travel in essentially the same direction as the beam and
 79 also often don't generate secondary tracks (in the case of neutron evaporation),
 80 so a different trigger scheme had to be developed. For this purpose, a multi-
 81 channel-plate (MCP) timing detector was situated in front of the pAT-TPC
 82 (Fig. 2) and the pressure of the gas in the active volume (P10: 90% Ar plus
 83 10% methane) was adjusted to 235 Torr so that the beam stopped just before
 84 the Micromegas [11] at the back of the TPC. Therefore the drift time of the
 85 end of the beam track was minimal. At a bias voltage of 3.3 kV (66 V/cm),
 86 the measured drift velocity was 49 mm/ μs compared with a value of 51 mm/ μs
 87 calculated using Magboltz [12]. A hardware gate on the measured drift time
 88 was imposed so that only events producing tracks that ended upstream of the
 89 location where the beam stopped (*i.e.*, larger drift time) produced a trigger.

90 The secondary ^{10}Be beam was produced using a 45 MeV ^{11}B beam from the
 91 9.5 MV tandem Van de Graaff accelerator in the University of Notre Dame Nu-
 92 clear Science Laboratory. This beam was incident on a $400\text{ }\mu\text{g}/\text{cm}^2$ ^{13}C primary
 93 target. A $10\text{ }\mu\text{m}$ Mylar foil at the crossover point between the two solenoids
 94 (Fig. 1) served to increase the purity of the secondary beam via differential
 95 energy loss. The purity of the resulting 35 MeV ^{10}Be beam was reasonably
 96 good (about 42%) for the resonant-scattering experiment, with contaminants of
 97 $^4\text{He}(2+)$ (50%), $^9\text{Be}(4+)$ (5%), $^{10}\text{B}(4+)$ (3%), $^{11}\text{B}(4+)$ ($\approx 0.25\%$) and $^{10}\text{Be}(3+)$
 98 ($\approx 0.1\%$). The first two of these had a longer range than the main ^{10}Be beam so
 99 they were eliminated by the trigger. However, the remaining contaminants had
 100 a shorter range than the beam and produced a trigger when they stopped in the
 101 counter. Since these events mimic a fusion reaction, methods had to be devised
 102 to eliminate them. The first step was to bunch the primary beam, with a $\approx 1\text{ ns}$
 103 bunch occurring every 100 ns, and place a hardware gate around the measured
 104 time-of-flight from the primary target to the MCP. This yielded a beam purity
 105 of 93% (Fig. 3) which, however, was still insufficient for a fusion measurement.
 106 The remaining beam impurities were eliminated in the subsequent analysis of
 107 those events generating a trigger, as described in Sec. 3.1 below.

108 The data collection electronics for recording the particle tracks (see Ref. [9])
 109 could only handle a trigger rate of $\approx 15\text{ Hz}$ at the time of this experiment. As a
 110 result, the ^{10}Be beam rate had to be limited to 100 Hz since $\approx 15\%$ of the incident
 111 beam particles generated a trigger. As discussed below, this trigger rate was
 112 dominated by contaminant ions stopping in the pAT-TPC, so the efficiency of
 113 the system would have been greatly improved if a pure beam had been available.

114 The absolute normalization was obtained by removing the range gate at
 115 several times during the experiment and pre-scaling the trigger so that the
 116 incident beam rate could be determined from the ion-range spectrum. Problems
 117 encountered with this normalization method are also discussed below.

3. Data analysis

3.1. Isolation of fusion events

The measured ionization densities of the particle tracks (Bragg curves) for several different ions observed during this experiment are shown in Fig. 4. The very large difference in initial ionization of $^{10,11}\text{B}$ vs. ^{10}Be ions is apparent. In order to eliminate the former from the data set, the ionization deposited in the first two centimeters of the track length was plotted vs. the range of the ions in the counter. The result is shown in Fig. 5. Three localized groups corresponding to stopping $^{10,11}\text{B}$ and $^{10}\text{Be}^{[3+]}$ ions, and two continuous bands of events corresponding to ^{10}Be ions scattering in *TwinSol* (and therefore having lower energy and larger dE/dz) or reacting in the counter, can be seen. The latter group contains the actual fusion events but is dominated by scattered ^{10}Be ions. The box in Fig. 5 illustrates the accepted events, which are those having the correct initial ionization. A plot of the observed ranges of these events is shown in Fig. 6. The final step in isolating fusion events is to note that the ionization at the end of the track due to the very-short-range and highly ionizing fusion residue is expected to be both very localized and very intense. A plot of the maximum derivative of the ionization $(dI/dz)_{max}$ vs. its maximum amplitude, for the events in Fig. 6, is shown in Fig. 7. Fusion products are readily separated from ^{10}Be scattering events, which have relatively low ionization that is also not well localized (*i.e.*, low values of the derivative).

Ionization plots for two isolated fusion events are shown in Fig. 8. The left-hand plot illustrates fusion events in which a neutron was evaporated. The very high maximum ionization and strong localization at the end of the track is apparent. The right-hand plot shows the effect of charged-particle evaporation from the fused system. In this case, a secondary α -particle track is observed. Note also that the fusion product recoils after α -particle emission, so that the maximum ionization does not occur on the path of the incident ion as it does for neutron emission (since the momentum of the emitted neutron is much smaller). Also, the fusion-residue track is broader, again due to recoil effects.

148 In principle, these differences could be used to determine the energy distribution
149 of the emitted charged particle(s).

150 3.2. Calculation of the fusion excitation function

151 After elimination of the scattered ^{10}Be events, the range axis (see Fig. 6) was
152 divided into 1 cm bins. (The drift time to distance conversion was obtained from
153 the ^4He tracks, which extend throughout the chamber as seen in Fig. 4). Events
154 occurring near the front of the counter (used for incident particle identification)
155 and near the back of the counter (where the ^{10}Be beam stops) were ignored.
156 Next, the ion range was converted to energy using the code LISE++ [13], which
157 also computed the areal density of the target gas. The input parameters were
158 the type of gas (P10) and the measured gas pressure and temperature. The
159 energy losses in the entrance window of the counter (3.6 μm para-aramid foil;
160 density of 1.4 g/cm^3) and in the MCP (10 $\mu\text{g}/\text{cm}^2$ C foil) were also accounted
161 for. Finally, the number of incident ^{10}Be ions was determined from the pre-
162 scaled trigger rates during the normalization runs, as discussed above.

163 The total fusion excitation function is displayed in Fig. 9. However, the
164 experimental absolute cross sections were actually about 20% greater than those
165 shown in this figure. Since ^{10}Be is tightly bound, its fusion cross section should
166 follow the systematics for stable nuclei, especially at energies well above the
167 Coulomb barrier. The expected cross section was calculated using the PACE4
168 fusion-evaporation code contained within the LISE++ package [13] and is shown
169 by the corresponding curve in Fig. 9. Apart from employing the “quantum-
170 mechanical” option to properly account for near- and sub-barrier fusion, all the
171 default parameters were selected.

172 The most likely cause of the 20% discrepancy is a problem in the pre-scaling
173 procedure used to determine the absolute normalization. However, since we
174 only became aware of this issue well after the experiment was conducted, we
175 were unable to verify this hypothesis. Other possibilities, such as an incorrect
176 measure of the gas pressure, were considered and could be discarded on the basis
177 of the observed range of the ions in the pAT-TPC. As a result, the absolute

normalization of all the data was obtained by scaling the three highest-energy experimental total fusion data points to the cross sections predicted by PACE4.

Since the emission of charged particles from the fused system could be directly observed, as shown in Fig. 8, the cross sections corresponding to charged-particle-associated fusion (CP) and fusion with the emission of only neutrons (NCP) could be separately determined. These excitation functions are also shown in Fig. 9. The absolute normalization in both cases is exactly that used to calculate the total fusion yield, *i.e.*, not the one deduced from the pre-scaled trigger rates during the normalization runs.

3.3. Comparison with theory

The fusion cross sections illustrated in Fig. 9 are compared with the predictions of PACE4 for a P10 gas target, which contains a substantial amount of ^{12}C . In principle, fusion of ^{10}Be with ^{12}C could be separated from that with ^{40}Ar using the range of the recoiling fusion product. However, the $^{10}\text{Be}+^{40}\text{Ar}$ fusion products have a low-enough energy that their stopping power is mainly due to nuclear effects. As a result, their range is similar enough to that of the $^{10}\text{Be}+^{12}\text{C}$ fusion products that it becomes difficult to reliably separate them in practice. As will be discussed in the following paragraph, however, fusion with ^{40}Ar dominates above an incident ^{10}Be energy of about 14 MeV. In this region the comparison between theory and experiment is very good, though there is an indication of a small excess of NCP fusion throughout the range and a deficit of CP fusion above about 27 MeV. It is not clear whether these are experimental effects or deficiencies of the PACE4 predictions.

The ^{12}C and ^{40}Ar fusion cross sections could be approximately separated, though, by comparing the observed ratio of CP fusion to total fusion with the PACE4 prediction, as illustrated in Fig. 10. Above about 16 MeV this ratio is in good agreement with the theoretical prediction, although the above-mentioned excess of NCP fusion throughout the region and the deficit of CP fusion above about 27 MeV are even more clearly seen here. The predicted ratio begins to be dominated by fusion with ^{12}C below 14 MeV, and the experimental data there

are also in good agreement with theory although the error bars are large due to the low cross sections in this region.

4. Summary and conclusions

The fusion excitation function for $^{10}\text{Be}+^{40}\text{Ar}$ has been measured in the c.m. energy range from 12-24 MeV using the prototype active-target time projection chamber (pAT-TPC) developed at Michigan State University. The incident ^{10}Be rate was limited to 100 Hz by the data-collection electronics. Despite that severe constraint, excellent-statistics data were obtained during a single 90-hr run, illustrating the very high efficiency of this detector. Cross sections as low as 12 mb were measured with acceptable (50%) statistical accuracy, and charged-particle-associated evaporation cross sections could also be determined. The count-rate capability of the data-collection electronics has already been improved by a factor of two since this experiment was carried out, and development of a new generation of electronics allowing an anticipated maximum acceptance rate of up to 1000 Hz is underway [14]. It should also be mentioned that, while a ^{10}Be rate of up to $\approx 10^5$ Hz is available from *TwinSol*, a more realistic upper limit of $\approx 10^4$ Hz is imposed by the drift time of the particle tracks. This would imply that the data reported here could be collected in only 1.5 hr with the improved electronics, or even considerably less if a very pure beam were available. However, the focus of this experiment was to illustrate that excellent fusion data can be obtained in a reasonable period of time with very weak beams.

The agreement between evaporation-model theory and experiment in the present experiment was very good, but separating $^{10}\text{Be}+^{40}\text{Ar}$ from $^{10}\text{Be}+^{12}\text{C}$ fusion products proved to be difficult due to the fact that the former were at low energy where nuclear scattering predominates. As a result, both products had comparable ranges and experiments to reliably measure fusion of $^{10}\text{Be}+^{40}\text{Ar}$ in this low energy, below the barrier, regime will likely require a ^{12}C -free target. Ar-H₂ [15] may be a possibility here. A 90% Ar-10% H₂ mixture has a calculated drift velocity of 26 mm/ μs at an electric field of 750 V/cm [12]. However,

237 separation of ^{12}C fusion events is expected to be less of a problem in more
 238 mass-symmetric situations.

239 Fusion of $^6\text{He}+^{40}\text{Ar}$ using a time projection chamber was discussed in Ref.
 240 [16], but only a single ionization plot indicating a fusion event was shown and
 241 no cross sections were determined. Excitation functions for $^{10,13,15}\text{C}+^{12}\text{C}$ were
 242 measured by Carnelli, *et al.* [17] using a Multi-Sampling Ionization Chamber
 243 (MUSIC) [18], which shares a very important advantage with the pAT-TPC over
 244 methods employing thin targets: difficulties in obtaining the point-to-point rel-
 245 ative normalization of the data are eliminated (see also Ref. [19]). Although
 246 excellent-quality data were presented in Ref. [17], a MUSIC detector has a fixed
 247 segmentation so the energy bin-widths could not be adjusted. Also, this detector
 248 doesn't image the tracks so CP and NCP fusion can't be independently mea-
 249 sured. Finally, the pAT-TPC is also capable of imaging binary reactions using
 250 a second trigger [7–10], which permits simultaneous measurement of incomplete
 251 fusion, break-up, scattering, and transfer reactions and therefore fully exploits
 252 the opportunities presented by the very exotic beams that will be available from
 253 the new generation of radioactive ion beam facilities.

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259 5. References

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Figure 1: (Color online) *TwinSol* setup for ^{10}Be beam production. The locations of the chambers containing the production target (^{13}C , $400\text{ }\mu\text{g}/\text{cm}^2$) and mid-plane absorber ($10\text{ }\mu\text{m}$ Mylar) are indicated.

Figure 2: (Color online) Diagram of the MCP and the TPC. The chamber between them (labeled “Si”) contains a Si detector that can be moved into the beam for tuning purposes.

Figure 3: Range plot of the beam, showing also the major contaminants which leak through the time-of-flight gate. (Bin width = 2 mm). For the fusion measurement, a gate on the ion range was adjusted to eliminate the main ^{10}Be peak.

Figure 4: (Color online) Digitized Bragg curves for $^{10,11}\text{B}$, ^{10}Be , and ^4He ions observed in the pAT-TPC. Note that the ^4He ionization never reaches its Bragg peak within the counter due to its very long range. These curves have been inverted for display purposes since the observed ionization is negative. The width of each time bin is 40 ns.

Figure 5: (Color online) The ionization deposited in the first two centimeters of the track (ΔI) vs. ion range, for all ions generating a “fusion” trigger. Note that $|\Delta I|$ decreases toward the top in this plot. The red box indicates the accepted region for ^{10}Be ions reacting in the pAT-TPC. It contains fusion events and also a significant number of ^{10}Be scattering events. The groups corresponding to contaminant ions stopping in the counter are also indicated.

Figure 6: Fusion events plus ^{10}Be scattering projected from the box in Fig. 5. A small number of remaining $^{10,11}\text{B}$ contaminant events can also be seen.

Figure 7: (Color online) Maximum derivative of the ionization $(dI/dz)_{\max}$ vs. the maximum amplitude of the ionization along the track for the events shown in Fig. 6. The accepted fusion events are indicated. A very weak “second branch” containing fusion events appears at higher peak ionization. The exact nature of events in this branch is unknown. They may be due to real physics, or possibly some type of problem in measuring the true width of the fusion peak.

Figure 8: (Color online) Ionization plots (ionization vs. radius and depth in the counter) for two isolated fusion events. The leftmost plot shows a typical neutron-evaporation (NCP) event. The rightmost plot shows the effect of α -particle evaporation from the fused system. Note the deviation of the fusion-residue peak from the beam track, and its larger width, due to recoil effects.

Figure 9: (Color online) Experimental total fusion cross section (triangles), fusion with neutron emission (dots), and fusion with emission of charged particles (squares). The curves are calculations using the PACE4 code. The total fusion cross section and prediction have been multiplied by a factor of three, and the charged-particle associated cross section and prediction have been divided by a factor of five, in order to sufficiently separate the data sets on this plot. See the text for a discussion of the absolute normalization.

Figure 10: (Color online) Observed ratio of charged-particle-associated fusion to total fusion. PACE4 calculations of this ratio for a P10 target, for ^{40}Ar , and for ^{12}C are also shown.