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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 $^{10}Be+^{40}Ar$ has been measured over the center-of-momentum (c. m.) energy range from 12 to 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 h 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.

1. Introduction

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

Recently, we have been carrying out a series of measurements with radioactive ion beams produced by the *TwinSol* facility [6] at the University of Notre Dame, using the prototype active-target time projection chamber (pAT-TPC) [7] developed at Michigan State University. The focus of this work was to test design concepts for the full-scale AT-TPC, as well as to develop techniques for analyzing the data produced by this imaging detector. The AT-TPC has a number of important advantages for working with low-intensity beams, including very high efficiency for detecting reaction products and measuring their angular distributions with virtually 4π solid-angle coverage, much larger available target thickness

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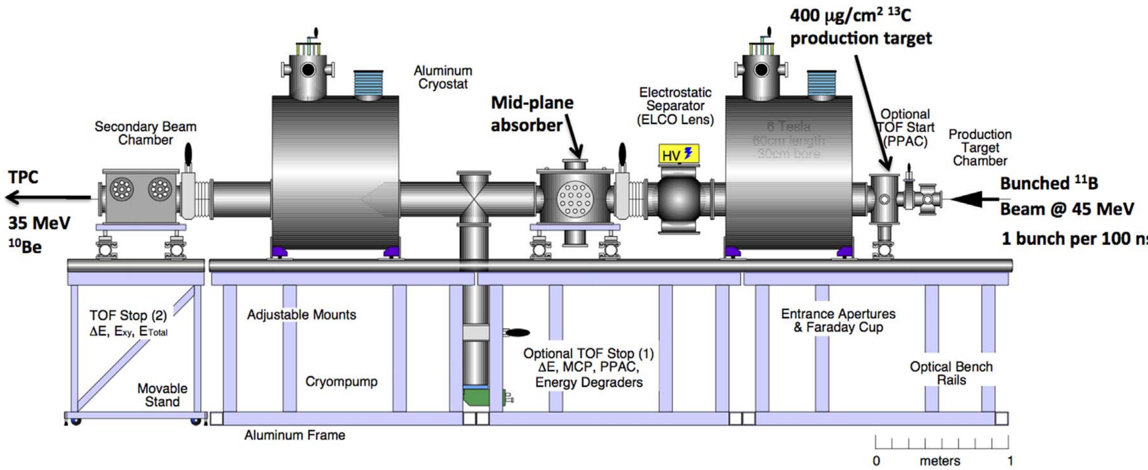

Fig. 1. *TwinSol* setup for ^{10}Be beam production. The locations of the chambers containing the production target (^{13}C, 400 μg/cm^2) and mid-plane absorber (10 μm Mylar) are indicated.

(since the reaction vertex can be directly imaged), and the ability to measure an excitation function as the projectile slows down in the target gas [8]. Solid targets may also be used by mounting them within the gas volume.

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

2. Experimental method

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

The secondary ^{10}Be beam was produced using a 45 MeV ^{11}B beam from the 9.5 MV tandem Van de Graaff accelerator in the University of Notre Dame Nuclear Science Laboratory. This beam was incident on a 400 μg/cm^2 ^{13}C primary target. A 10 μm Mylar foil at the crossover point between the two solenoids (Fig. 1) served to increase the purity of the secondary beam via differential energy loss. The purity of the resulting 35 MeV ^{10}Be beam was reasonably good (about 42%) for the resonant-scattering experiment, with contaminants of ^{4}He(2+) (50%), ^{9}Be(4+) (5%), ^{10}B(4+) (3%), ^{11}B(4+) ($\approx$0.25%) and ^{10}Be(3+) ($\approx$0.1%). The first two of these had a longer range than the main ^{10}Be beam so they were eliminated by the trigger. However, the remaining contaminants had a shorter range than the beam and produced a trigger when they stopped in the counter. Since these events mimic a fusion reaction, methods had to be devised to eliminate them. The first step was to bunch the primary beam, with *a* $\approx$1 ns bunch occurring every 100 ns, and place a hardware gate around the

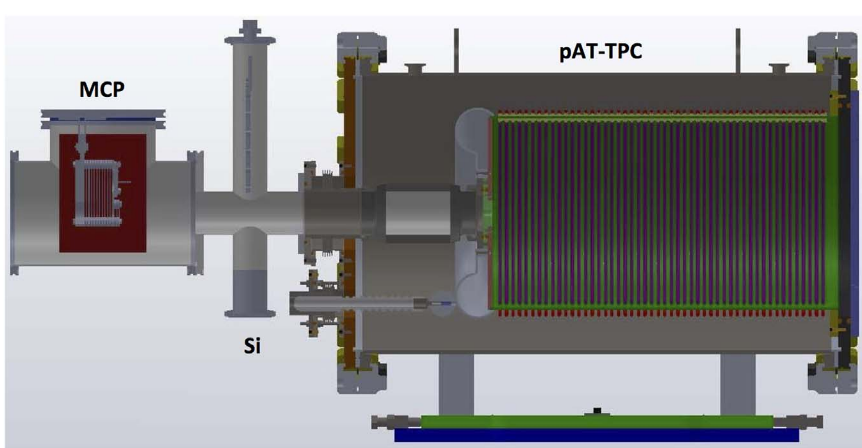

Fig. 2. Diagram of the MCP and the TPC. The chamber between them (labeled “Si”) contains a Si detector that can be moved into the beam for tuning purposes.