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Study of Nuclear Reactions with Intense, High-Purity, Low-Energy Radioactive Ion Beams Using a Versatile Multi-configuration Dual Superconducting-Solenoid System

M.Y. Lee, F.D. Becchetti, T.W. O'Donnell, D.A. Roberts, J.A. Zimmerman
Department of Physics, The University of Michigan, Ann Arbor, MI 48109-1120 USA
V. Guimarães, J.J. Kolata, D. Peterson, P. Santi
Department of Physics, University of Notre Dame, Notre Dame, IN 46556 USA
P.A. DeYoung, G.F. Peaslee
Department of Physics, Hope College, Holland, Michigan 49422-9000 USA
J.D. Hinnefeld
Department of Physics, Indiana University South Bend, South Bend, IN 46634-7111 USA

A new device (TwinSol) installed at the Nuclear Structure Laboratory at the University of Notre Dame implements a pair of large-bore 6-tesla superconducting solenoids for producing relatively pure, high-intensity beams of exotic light nuclei at low-energies (10 to 80 MeV). Typical beams include ^{8}Li and ^{6}He ($T_{1/2}$ < 1 sec.). The device efficiently produces, collects and focuses beams onto (or implants into) suitable target foils and test materials. The system uses various combinations of the following detection schemes: XY position sensitive gas counters for time-of-flight and ion ray-tracing; multiple stacks of silicon surface barrier detector telescopes mounted at various angles on a rotating table; 2D position-sensitive silicon detectors (PSDs) for high precision angular measurements; multi-annular, multi-sectored "CD" detectors for large solid angle (nearly 2π in lab frame), high-collection efficiency (multi-hit) particle detection; and ion-implanted stacks of target foils for off-line detection. Also available are a set of HPGe detectors which will be implemented upon completion of a low-background gamma cave. TwinSol represents an advancement in the application of large-bore superconducting magnet technology, capable of running in persistent mode for weeks without liquid helium (LHe) refill or measurable degradation of magnetic field (< 1%).

1. Introduction

During the last ten years we have developed methods of producing and utilizing radioactive nuclear beams (RNBs) for nuclear physics research through the use of superconducting solenoid magnets [1]. Designed to incorporate features based upon earlier RNB experience with such magnets, the dual superconducting solenoid device

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TwinSol was installed at the University of Notre Dame (UND) Nuclear Structure Laboratory during the summer of 1997 [2]. The original concept of a dual solenoid nuclear spectrometer was developed at IPN-ORSAY [3] but never fully realized. For studying RNB induced reactions, TwinSol is a versatile device with many advantages over earlier systems.

2. Configuration

The TwinSol system is comprised of several vacuum chambers and a beamline which passes through the warm bores of two superconducting solenoids. The solenoids and all other associated components rest atop a set of four optical-bench type aluminum rails. The beamline components are mounted on the inner rails, while the magnets themselves are fastened to the outer rails. The magnets can slide along the beamline without breaking vacuum and are typically set approximately 3 meters apart. Special external cryostat mounts allow for fine adjustment of the magnet XYZ positions. Figure 1 shows a typical layout of the key components of the TwinSol RNB system when configured for single magnet RNB production tests.

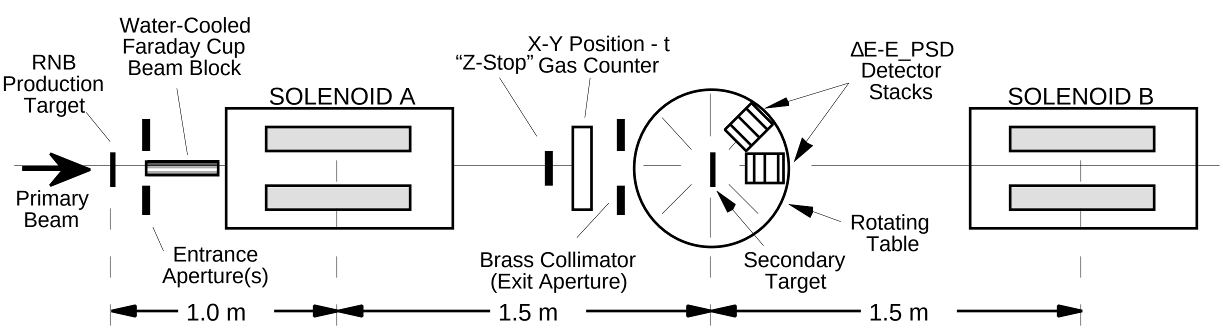

Fig. 1. A schematic of a typical configuration used in producing and measuring the purity of quality RNBs.

Secondary beams are produced in front of the first magnet and collimated by one of several entrance apertures. In the configuration shown in Figure 1, exit angles from the production target range from 2° to 11°. The lower angular limit is defined by a water-cooled Faraday cup which consists of a tungsten alloy rod with a tantalum insert. The Faraday cup is always inserted, stopping the primary beam and most of the fast neutrons. The 11° upper limit is determined by the beam pipe diameter. By comparison, if the primary target was moved to the entrance of the solenoid cryostat, the maximum angle would be 15°. An adjustable entrance aperture system is installed to further limit the angular acceptance. Four fixed-size apertures are available at any given time. Behind the solenoid, a "Z-stop" and exit aperture are used to improve beam purity. The "Z-stop" is a 3 mm thick brass disk of appropriate diameter and position to block ions of lower magnetic rigidity than the secondary beam of interest, while a thick brass collimator serves as the exit aperture, blocking

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high rigidity ions and stray neutrons from entering the scattering chamber which houses the detectors. The scattering chamber in between the two solenoids contains a four-position secondary target ladder and a rotating table for mounting detectors.

3. Tests

Both magnets were tested in the fall of 1996 at the factory [4] and the first magnet has been used in experiments since summer 1997. The second magnet was tested at Notre Dame in the spring of 1998. The cryostats are of a low-loss design with retractable power leads and incorporate a 40° K intermediate shield surrounded by a 100 liter liquid N_2 jacket. When the solenoids are either in persistent mode or not in use, the 300 liter cryostat consumes approximately 15 liters of LHe per week. Due to its off-center bore design, the cryostat requires refilling when only 60 liters remain. This results in an extremely efficient 3 month hold time between refills.

Initial imaging and focusing tests were done using alpha sources at the production target position and a Parallel Plate Avalanche Counter (PPAC) at the focal plane. Magnet current settings predicted using a simulation code typically came within 1% of the experimental values. First RNB tests were conducted using a low-intensity (1 - 5 nA) 30 MeV ^{7}Li primary beam on a 12.7 μm beryllium target. The detector system comprised of a PPAC located 25 cm in front of a silicon ΔE-E_{PSD} detector telescope at the focal plane (Figure 1). The front aperture was set for 5° maximum exit angle to limit the count rate and thus reduce radiation damage to the detectors. A typical ΔE vs. E_{PSD} spectrum is shown in Figure 2.

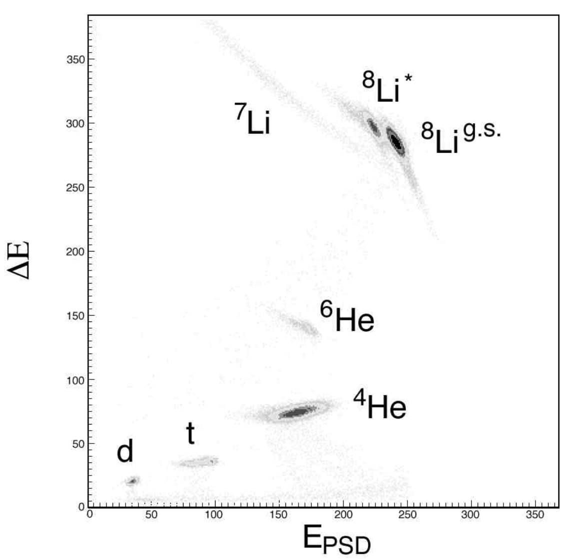

Fig. 2. ΔE vs. E_{PSD} spectrum at the focal plane of first solenoid.

The magnet was tuned to maximize ^{8}Li arriving at the 2.5 cm diameter silicon detector telescope. There is a small amount of ^{8}Li in its first excited state (E_x = 0.98

MeV) produced in this setup. In this particular configuration we could easily produce 4×10^5 ^{8}Li per μA of primary beam. To increase secondary beam, the entrance aperture can be opened up to 11° and thicker targets can be used. (The UND FN-Tandem can deliver up to 5 μA of primary beam). Figure 3 shows the separation between the ground and first excited state of ^{8}Li. This configuration is capable of producing a high quality, high purity (60%) ^{8}Li secondary beam with 300 keV energy resolution. Similarly clean spectra for ^{6}He (85% purity) were obtained at higher magnetic field settings.

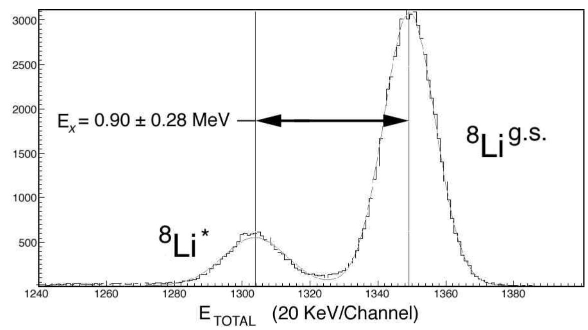

Fig. 3. Total energy spectrum shows a ^{8}Li RNB clearly resolved from its excited state.

4. Radiation Detection

The spectra shown in Figures 2 and 3 were obtained using a ΔE-E_{PSD} detector telescope. This detector arrangement is typically mounted on a rotating table and used most often for particle identification as well as searching for the best combination of magnet setting, aperture size and detector/target position for studying a particular secondary beam. Once the proper settings have been established, these detectors may be removed depending on the specific experiment to be performed. There are instances however, when these detector telescopes serve more than just diagnostic purposes. A stack of thin detectors can be used to study total reaction cross sections in silicon as a function of energy since the detectors themselves act as energy absorbers while the beam traverses the stack. This technique has been used successfully at higher energies (tens of MeV per nucleon) at the National Superconducting Cyclotron Laboratory at Michigan State University [5,6,7] and we hope to extend such measurements to lower energies using the TwinSol system. The position sensitive ability of this detector stack can also be utilized to perform kinematically complete nuclear reaction experiments as described by Fletcher and collaborators [8]. The TwinSol system currently has 5 such position sensitive detector telescopes that can each be set 15° apart on a rotating table.

Several PPACs are available to the TwinSol system and these can be placed at various locations along the beam line for particle tracking as well as time-of-flight measurements. An example of how the PPAC is used is shown in Figure 4.

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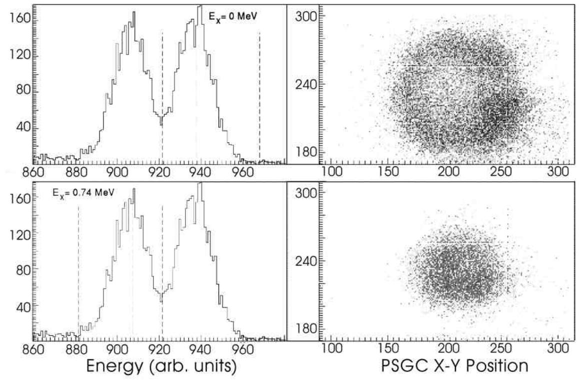

Fig. 4. PPAC spectra of two groups of ^{6}He beam separated by 740 keV.

The PPAC was located as shown in Figure 1, about 25 cm. upstream from the detectors, to study the flight path of ^{6}He produced in front of the first solenoid via the ^{9}Be(^{7}Li,^{6}He)^{10}Be reaction. Due to excited states in the residual ^{10}Be, the ^{6}He beam typically arrives at the focal plane of the solenoid in several energy groups. The two most dominant groups are attributable to the ground and first excited states of ^{10}Be which are separated by 740 keV. As can be seen in Figure 4, the two groups are clearly resolved using only the first magnet. The PPAC image is used to select the appropriate "Z-Stop" in order to eliminate the unwanted group. Alternatively, the "Z-stop" may be omitted and both groups can be studied simultaneously with the PPAC serving as a minimally invasive method of particle identification. We expect to improve the TwinSol setup by using energy degraders in between the two magnets and using the second magnet for further separation of particle groups..

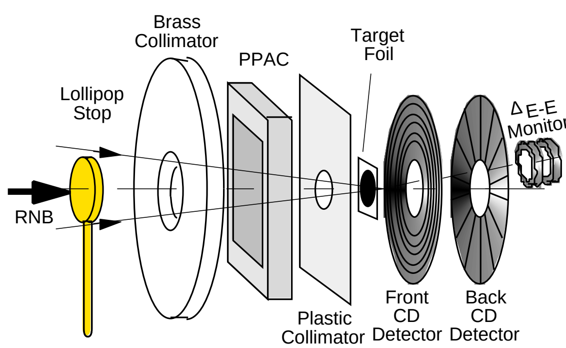

Fig. 5. Setup for elastic scattering of RNBs on a Nickel target using "CD" detectors.

Another versatile detector arrangement employs a pair of "CD" detectors as shown in Figure 5. Named for their resemblance to compact discs, these multi-hit detectors are divided into 16 sectors and 16 annula, thus providing both θ and φ information for outgoing particles ejected from a target. This setup was used to study elastic scattering of 28 MeV ^{8}Li and 26 MeV ^{6}He from a nickel target for a range of θ from

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12° out to 61°. These data are still being analyzed. In a separate experiment, fission fragments from the fusion products of ^{6}He and ^{209}Bi were detected using a similar setup but with the target foil located in between the two detectors in order to cover both forward and backward angles. The results from this experiment [9] showed a significantly lower cross section than previously reported data [10].

The 4n evaporation channel ($T_{1/2}$ = 7 hours) from the aforementioned fusion reaction was studied at several energies using a ^{6}He beam incident upon a stack of ^{209}Bi foils. Each of the foils was then removed and sandwiched between a pair of silicon detectors in order to look for the signature alpha decay following from a 4n evaporation of ^{215}At.

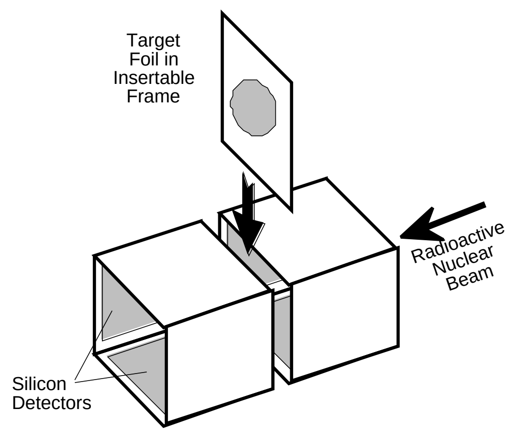

Fig. 6. Eight silicon detectors mounted along the inside of the Hope College Box-Kite array.

A complementary experiment to study the 3n evaporation channel has recently been performed using a box-kite shaped detector arrangement developed by a group from Hope College and shown in Figure 6. In this instance the alpha particles were detected using a pulsed beam with the detectors packed closely together to maximize detection efficiency.

5. Conclusion

New systems are continually being developed for the TwinSol apparatus to improve its capability in studying RNB-induced nuclear reactions. Recent tests with the second magnet indicate that it performs as well as the first one and will allow us to improve beam purity through the use of energy degraders or ion-optical elements in the area between the two magnets. The placement of various PPACs or monitor detectors along the longer RNB flight path afforded to us by the use of the second magnet also allows for greater use of software "apertures" and "beam blocks" for more precise measurements of reactions. The continued development of the TwinSol

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project will also involve the construction of a low-background area behind the second magnet to for gamma spectroscopy experiments.

Acknowledgments

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