

Applications of a superconducting solenoidal separator in the experimental investigation of nuclear reactions

D J Hinde, I P Carter, M Dasgupta, E C Simpson, K J Cook, Sunil Kalkal, D H Luong, E Williams

Department of Nuclear Physics, Research School of Physics and Engineering, Australian National University, ACT 2601, Australia

E-mail: david.hinde@anu.edu.au

Abstract. This paper describes applications of a novel superconducting solenoidal separator, with magnetic fields up to 8 Tesla, for studies of nuclear reactions using the Heavy Ion Accelerator Facility at the Australian National University.

1. Introduction

Heavy ion beams are used at the ANU for nuclear reactions studies, with beam species typically ranging from Li to Ni. These carry substantial linear momentum, meaning that many reaction products are focused around the beam direction. To study the reaction process, or make use of these reaction products, it is often necessary to separate them from the intense background of elastically scattered beam particles, which can be a million times more intense. To make efficient use of the beam, it is desirable to accept reaction products into a large solid angle.

2. Superconducting solenoid

These two goals can be achieved by placing a superconducting solenoid at zero degrees, with the unscattered beam being stopped before entering, and scattered beam particles and reaction products of interest being separated by their different magnetic rigidity, as they pass through the high magnetic

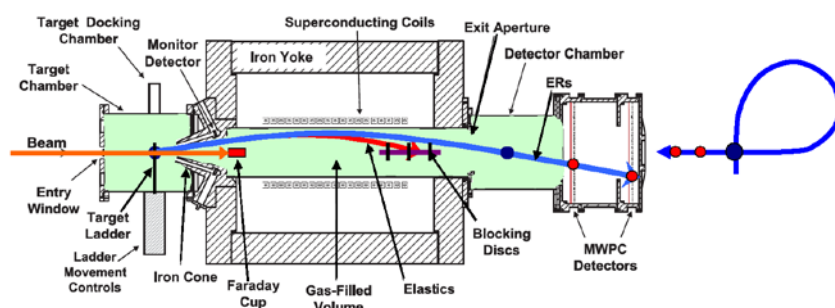


Figure 1. Schematic diagram of SOLITAIRE configured for fusion measurements. A fusion trajectory (blue) is superimposed showing radial separation from the axis (left), and in the perpendicular plane (right). The region filled with 0.7 mbar He gas is indicated in green.

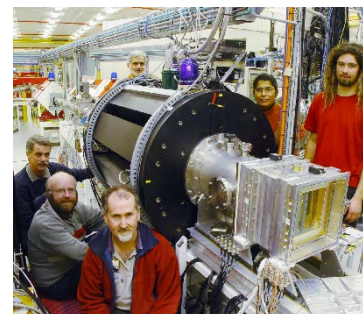


Figure 2. Setting up SOLITAIRE for fusion measurements at the ANU.



fields in the solenoid. This gives helical paths with a focus on axis after the solenoid, with different focal lengths for different magnetic rigidities. By selection of the magnetic field, particles of interest can be transmitted, whilst beam particles are stopped inside the bore of the solenoid, as shown in figure 1. The device at ANU is called SOLITAIRE [1], which is shown in figures 2.

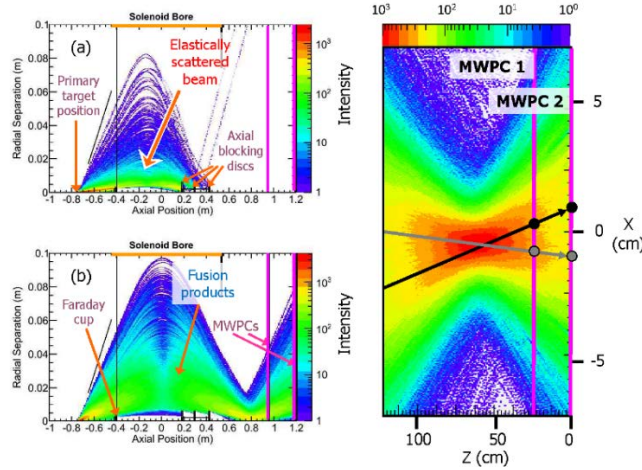


Figure 3. The left panels show simulated trajectories of elastic scattering and fusion products through SOLITAIRE. Beam particles are stopped, whilst fusion products come to a focus and are detected in the two MWPC detectors (see text). The right panel shows experimental trajectories determined by extrapolating the positions measured in the two MWPC detectors (magenta bars).

3. Application to nuclear fusion

Nuclear fusion products carry all the beam momentum. They are deflected from the beam direction by the generally much smaller recoil momentum imparted by evaporated light particles, emitted as they cool to form evaporation residues (ERs). For thick targets, angular scattering in the target can also spread the angles significantly. Nevertheless, fusion products are generally found inside a cone with 10 degree half-angle, centred around zero degrees [2]. Filling the solenoid with low pressure gas effectively collapses the broad fusion product charge state distribution to that of the mean charge state, giving a compact focal point. Figure 3 shows Monte Carlo simulations of particle trajectories, including scattering and charge exchange in the gas, for beam particles (top left) which are stopped on the axial discs, and fusion products (bottom left) which come to a focus before the two Multi Wire Proportional Counters (MWPCs). These detectors are position sensitive, with 1 mm resolution, thus together they can be used to determine the trajectories. Experimental fusion product trajectories in figure 3 (right) show that the focal length is well-determined, allowing the simulation to be matched to the experiment (by adjusting the fusion product mean charge state in the model). To obtain the transmission efficiency, knowledge of the angular distribution from the target is also required, as well as the trajectories through the solenoid. Figure 4 shows the XY position spectrum of fusion products, identified by their energy loss and time information from the MWPCs. From this, information on the angular distribution from the target can be determined, and thus the SOLITAIRE transmission efficiency to the detectors [1]. This allows high precision measurements of fusion cross-sections, essential to give a unique insight into the large effects of quantum coherence [2,3] (and also decoherence and energy dissipation [4]) that controls quantum tunnelling in fusion.

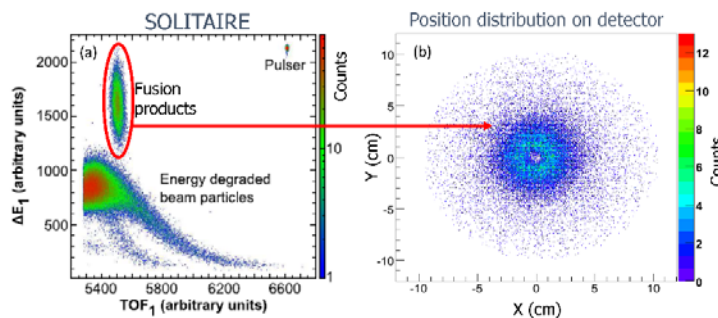


Figure 4. Identification of fusion products from the $^{34}\text{S}+^{89}\text{Y}$ reaction by energy loss (ΔE) and time-of-flight (TOF) from the target to MWPC detector #1. The position spectrum is shown on the right. The width of the image is related to the mean charge state and the shape of the angular distribution from the target before the solenoid.

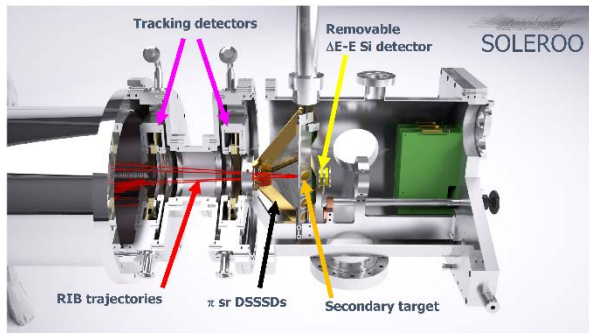


Figure 5. Computer rendering of the secondary target chamber of the SOLEROO radioactive beam facility. Tracking detectors give energy loss, position and timing information about the radioactive ion beam (RIB) particles (red) before they hit the secondary target. This identifies the type of particle, its energy, and impact point and angle of incidence onto the secondary target. A removable Si ΔE -E detector telescope allows checking of beam characteristics (see text).

4. Application to producing radioactive ion beams (RIB)

Radioactive nuclei far from stability are expected to have different properties from stable nuclei. In particular, nuclei with extreme neutron-to-proton ratios show neutron or proton halos (neutron or proton wave-functions extending far from the core) because of their low binding energy. The interactions of halo nuclei may show very different behaviour from well-bound nuclei [5]. It has been suggested that irreversible interactions of the halo nucleon(s) with those in the target nucleus [6] may be important, even at large separations, in contrast with normal expectations for well-bound nuclei.

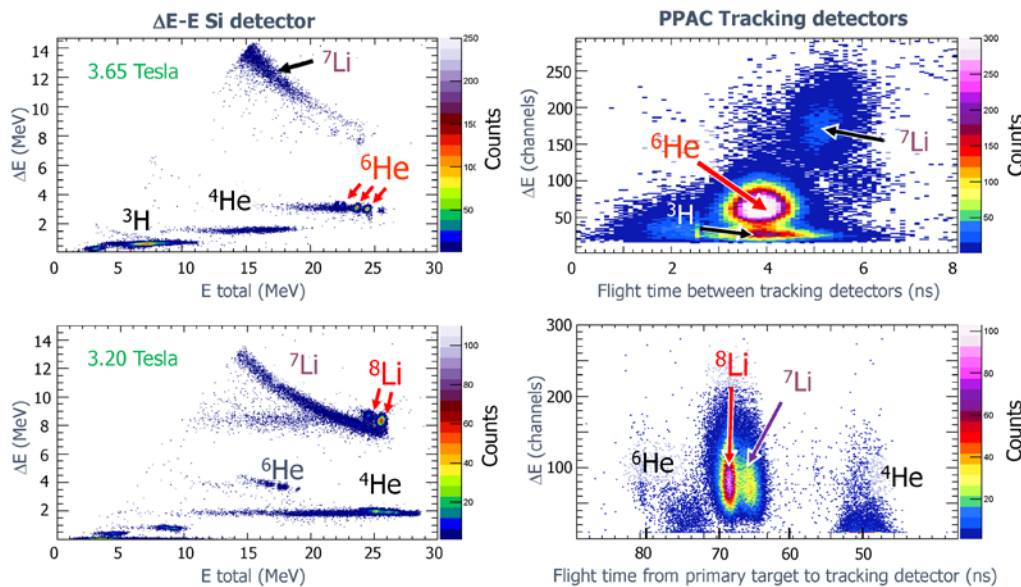


Figure 6. The left panels show spectra from the ΔE -E detector at the secondary target position, for two magnetic fields. The desired exotic beams (with two or more discrete energies) are indicated in red. The right panels show the spectra obtained (at higher beam intensity) derived from the ΔE and timing signals from the thin gas PPAC tracking detectors. The desired products can be cleanly tagged by the information from the tracking detectors.

The development of SOLITAIRE for RIB production (SOLEROO) has been described in [7, 8]. The radioactive nuclei are produced by nuclear reactions upstream of the solenoid, and the purified beam of interest is focused onto a secondary target downstream (shown in figure 5). A key quantity in precision measurements is beam purity and energy definition. To check the beam impurities at low intensity, the secondary target can be removed, and a Si ΔE -E telescope inserted. To identify impurities, two thin gas proportional detectors (PPACs) are located after the solenoid, but before the secondary target. These are capable of operating at count-rates over $10^6/\text{sec}$. Triggered by a signal in one of the detectors viewing the secondary target, the PPACs record the time, energy loss and position of the ion

generating the trigger. The energy loss identifies the atomic number, as shown in figure 6, whilst the flight time gives information on the mass. The position information from the PPACs allows reconstruction of the trajectory. This is illustrated in figure 7, where the X-Y positions of ${}^6\text{He}$ ions are shown in the left panels. The rings in the spectrum from PPAC2, closest to the secondary target, correspond to the discrete ${}^6\text{He}$ energies arising from the production reaction, as seen in figure 6 (top left). By linear extrapolation of the positions registered in the PPACs, the trajectory onto the secondary target is determined, allowing correction for the incidence angle and interaction point of the RIB particle on the target. The closest point of the trajectory to the axis defines the focal length. Measured at low beam intensities, where the Si ΔE -E telescope could be used, the bottom right panel shows the correspondence between the focal length determined from the tracking detectors, and the energy of the ${}^6\text{He}$ as measured in the Si detectors. There is a good correspondence, showing that the focal length information can be used to place cuts on the energy of the radioactive beam. These measurements demonstrate that the thin PPACs, operating at 7 mbar, are able to provide all the information required to define the characteristics of the beam particles passing through them. This now allows measurements of elastic and inelastic scattering, transfer, breakup, fusion and fission in collisions of the light radioactive beams accessible with this device, bombarding any chosen target. Using the large solid angle Si double-sided strip detectors (DSSSDs) illustrated in figure 5, which currently cover a solid angle of π steradians, the beam intensity (several $10^6/\text{sec}$ for ${}^8\text{Li}$, several $10^5/\text{sec}$ for ${}^6\text{He}$) allows a wide range of measurements to be made. A series of measurements is planned for 2016 and onwards.

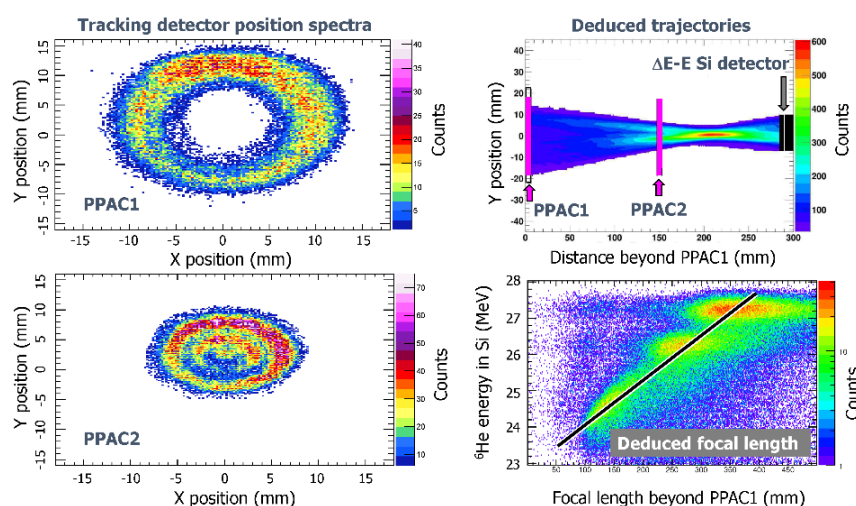


Figure 7. Position spectra for ${}^6\text{He}$ ions measured simultaneously in the two tracking PPACs (left). From them, trajectories are determined (top right), giving the interaction point at the position of the secondary target. The closest distance to the axis is defined as the focal length, which correlates well with the energy measured in the Si detector telescope, showing that identification of all key characteristics is achieved by the tracking detectors

5. Acknowledgments

Support for operations of the ANU Heavy Ion Accelerator Facility through NCRIS is acknowledged. This work was supported by ARC grants DP0879679, FL11010098, DP130101569 and DE140100784.

6. References

- [1] Rodriguez M D *et al* 2010 *Nucl. Instr. Meth. in Phys. Res. A* **614** 119.
- [2] Leigh, J R *et al* 1995 *Phys. Rev. C* **52** 3151
- [3] Dasgupta M *et al* 1998 *Annu. Rev. Nucl. Part. Sci.* **48** 401
- [4] Dasgupta M *et al* 2007 *Phys. Rev. Lett.* **99** 192701
- [5] Tanihata I *et al* 1985 *Phys. Lett. B* **160** 380
- [6] Hinde D J and Dasgupta M, 2004 *Nature* **431** 748
- [7] Rafiei R *et al* 2011 *Nucl. Instr. Meth. in Phys. Res. A* **631** 12
- [8] Horsley A J *et al* 2011 *Nucl. Instr. Meth. in Phys. Res. A* **646** 174