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SSNAP: The Solenoid Spectrometer for Nuclear AstroPhysics

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ABSTRACT

Helical spectrometers, such as the HELIOS device at Argonne National Laboratory, have proven to be a powerful tool for the study of nuclear spectroscopy (Lighthall, 2010). However, due to the expense in procuring a large bohr solenoid, relatively few of these devices exist. However, at the University of Notre Dame, *TwinSol*, is composed of two such magnets. The availability of intense light-ion beams from the Notre Dame Nuclear Science Laboratory (NSL) in combination with a large-bore superconducting solenoids provides an excellent opportunity to develop a new solenoid spectrometer at the University of Notre Dame, one optimized for measurements in normal kinematics.

Contents

1. Motivation

One of the primary research goals in science today is understanding the origin of elements in the universe. Regardless of the environment in which the nucleosynthesis occurs, detailed nuclear structure information is necessary in order to properly model the abundances of nuclear isotopes expected to be produced. In particular, there exists a deficit of nuclear structure data on unstable nuclei that critically affect explosive nucleosynthesis events. One common challenge is that when attempting to measure a key property of some exotic nucleus, many reaction channels are often open and one needs to identify the ejectiles to extract the channel of interest. If the energies of ejectiles are low or the reaction channel is weak, then it can be difficult to identify the particles of interest using the commonly preferred method of ΔE-E (i.e. a particle telescope). The HELIOS solenoid-based spectrometer has demonstrated that particle identification can be done within a helical spectrometer based on the time-of-flight of the particle [1]. This has led to the development of SSNAP at the University of Notre Dame, the Solenoid Spectrometer for Nuclear AstroPhysics.

2. SSNAP: the Solenoid Spectrometer for Nuclear AstroPhysics

SSNAP has been designed to work within one of the solenoids of *TwinSol* [2]. It consists of a series of position-sensitive silicon detectors placed just above the beam axis within a solenoid magnet. After the beam has bombarded a target, the ejectiles will follow a helical path back to the axis, depositing their energy into the detectors. The array would be placed into the second solenoid, using the first to focus the beam onto the primary target placed at the entrance to the solenoid. The radius of curvature and impact position of the particle are determined by its outgoing angle, charge, and momentum. The conversion from z (position along the beam axis where the particle impacted the detector) and center of mass angle is:

$$\theta_{c.m.} = \cos^{-1}\left(\frac{1}{2\pi}\frac{qeBz - 2\pi mV_{cm}}{\sqrt{2mE_{lab} + m^2V_{cm}^2 - mV_{cm}qeBz/\pi}}\right) \quad (1)$$

where $\theta_{c.m.}$ is the center-of-mass angle, q is the charge, B is the magnetic field, z is the position along the beam axis, m is the mass, E_{lab} is the lab energy, and $V_{c.m.}$ is the center-of-mass velocity of the detected particle.

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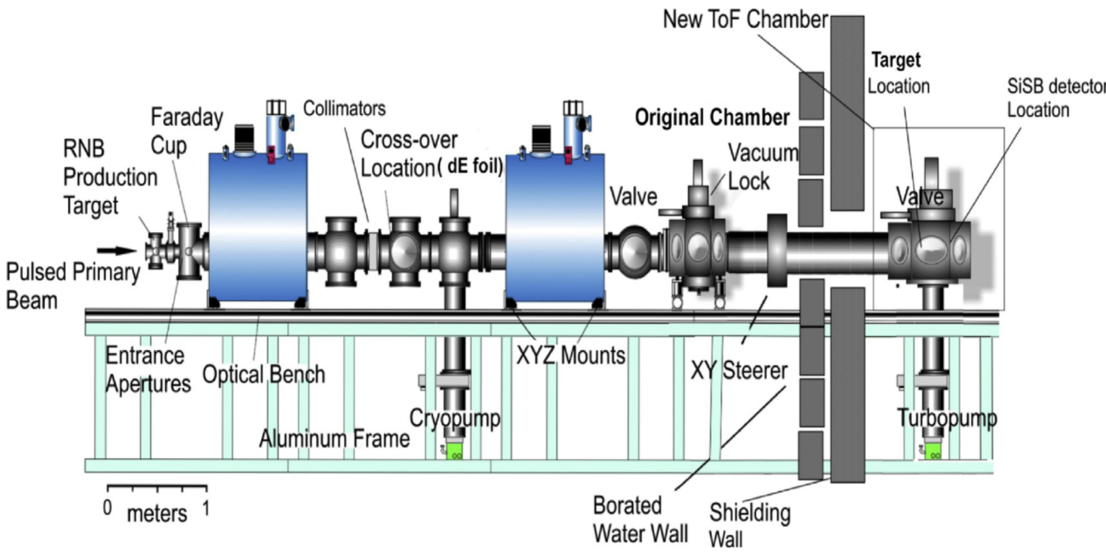

Fig. 1. Schematic drawing of *TwinSol*.

Fig. 2. Schematic drawing of the SSNAP mounting structure.

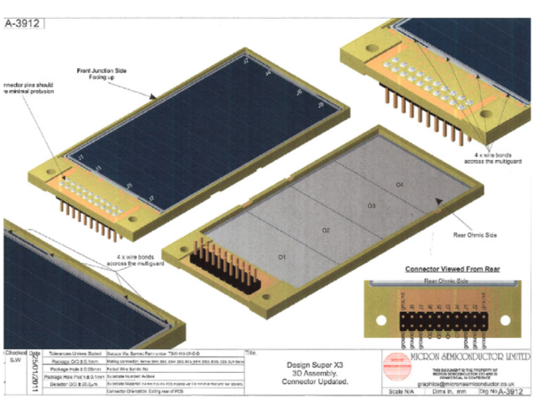

Fig. 3. Schematic drawing of the Super X3 detectors.

Each solenoid is ∼100 cm long with a 30 cm bore and has a liquid-helium cooled coil of superconducting material (NbTi) capable of producing central fields up to 6 T in strength. One challenge in the development of SSNAP is in the limited access to the magnets (see Fig. 1). The array must mount through the access flanges of chambers located upstream and downstream of the solenoids. To accomplish this, aluminum telescopic tubing was implemented, allowing the setup to be assembled within the beamline. The interlocking nature of the segments force the components to remain aligned with each other and thus making the alignment of the overall array a far easier task. Fig. 2 shows a schematic of the support structure. While the main purpose of SSNAP is to detect particles exiting the target at forward laboratory angles, it is also possible to mount the detectors at backward laboratory angles if necessary. Ultimately SSNAP will be used in conjunction with the intense stable light-ion beams (e.g. p, d, ^{3}He, and ^{4}He) available at the NSL to perform measurements in normal kinematics.

For the charged-particle detectors, an array of SuperX3 (SX3) double-sided silicon strip detectors from Micron Semiconductor were chosen (see Fig. 3). The "front" of these detectors consists of 4 resistive strips (1 cm x 7.5 cm) which possess a position resolution of 1.2 mm. The "back" of the detector is comprised of 4 non-resistive segments (4 cm x 1.875 cm) and can achieve an energy resolution of 55 keV FWHM. The detectors are mounted onto PCB boards which interlock and transmit the signals down the pipe to the preamplifier. Up to six SX3 detectors can be mounted together along the central tubing.

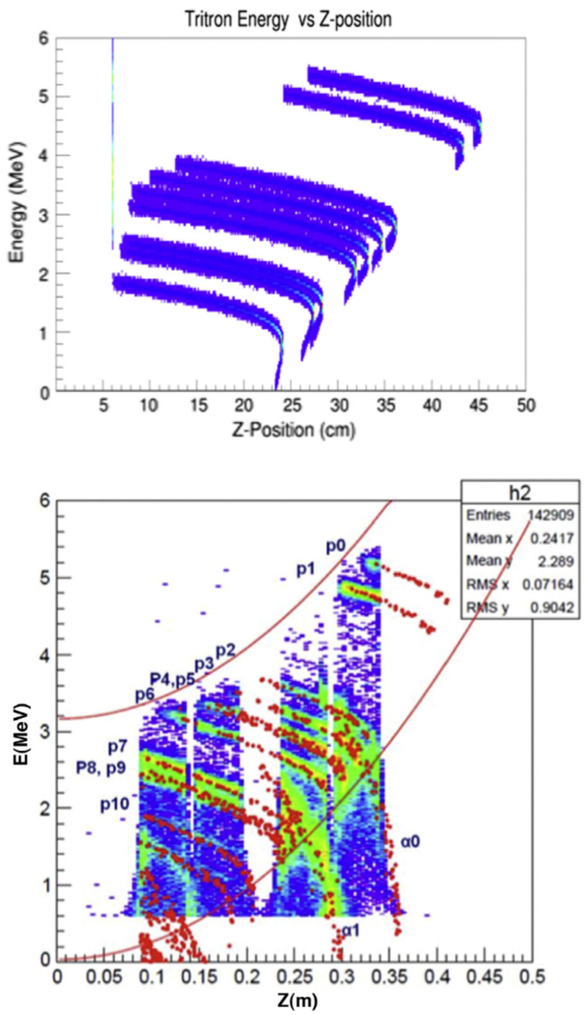

Fig. 4. top A simulation of the ^{12}C+^{12}C reaction (showing only the outgoing proton channels). **bottom** The first test of the SSNAP concept using a beam of 10 MeV ^{12}C on a ^{12}C target foil. Note the different slopes for protons (over-layed with dotted black lines) and alphas (over-layed with dotted red lines).
Source: Adapted from Ref. [3].

3. First reaction data with SSNAP

A Monte Carlo program was created utilizing the known field mapping of the solenoids in order to simulate the trajectories of the emitted ions. This was done to allow for a better determination of the optimal settings for the solenoids and positions of detectors for a given reaction. In addition, these simulations will greatly aid in the interpretation of data. In order to refine and test the simulation data were taken from the ^{12}C+^{12}C reaction utilizing an early implementation of SSNAP. [3] Fig. 4 shows a comparison of the data to simulation.

The next step is a characterize the fully implemented SSNAP system using the ^{12}C(d,p) reaction. Since the angular distributions for this reaction are well known, these data will used to further refine the simulations.

With refined simulations, a further reaction test was needed. The ^{12}C(d,p) reaction is well studied and excellent data exist for $E_d = 7.49$ MeV [4]. A first attempt to study this reaction was performed utilizing the newly enhanced setup shown in Fig. 2. In Fig. 5, a comparison is shown between the data taken and simulation. The detectors were not properly positioned for the high fields (5.7 kg) that were used, but there is good agreement between experiment and simulation. Another study of this reaction is scheduled to further characterize the capabilities of SSNAP for future measurements.

Acknowledgments

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References

[1] J.C. Lighthall, Commisioning of the HELIOS spectrometer, NIMA (2010) 622, pp. 97–106.
[2] F.D. Becchetti, et al., Recent results from the TwinSol low-energy RIB facility, NIMB 376 (2016) 397–401.
[3] X. Fang, et al., J. Phys. G: Conf. Ser. 420 (2013) 012151.
[4] H. Cords, G.U. Din, B.A. Robson, Deuteron-Induced Reactions in ^{12}C at bombarding energies of 5 to 10 MeV, Nucl. Phys. A127 (1969) 95–115.

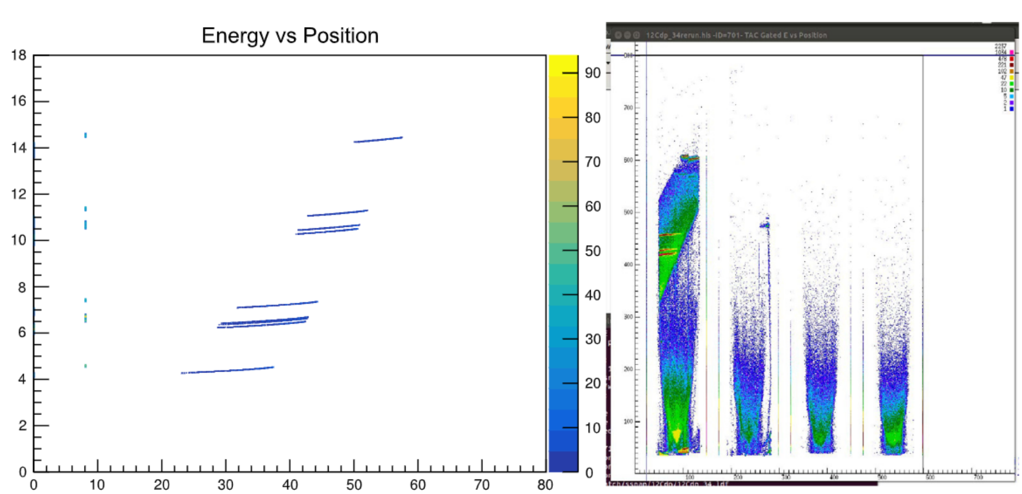

Fig. 5. left Simulation of the ^{12}C(d,p) reaction shown here. Note the agreement between the simulation and experimental measurement. **right** ^{12}C(d,p) data taken at 10 MeV, TAC gated on the (d,p) protons.