Measurement of deuteron- and proton-induced lithium reaction cross sections for SLICS detector efficiency calibration

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Abstract

The Short-Lived Isotope Counting System (SLICS) was developed identify and count beta decays of product nuclei produced by light-ion reactions generated with high-power short-pulse lasers using inertial confinement fusion (ICF) or target normal sheath acceleration (TNSA). An experiment was performed in 2024 to measure the efficiency of this detector by creating a known amount of ^{8}Li at a point in front of the detector, then counting the resulting number of detected beta decays. Unfortunately, previous measurements of the ^{7}Li(d, p)^{8}Li, ^{7}Li(p, α)^{4}He, and ^{6}Li(d, α)^{4}He cross sections needed to predict the amount of ^{8}Li vary widely. To address this problem, an experiment was carried out using the SUNY Geneseo Pelletron in which 1.1 MeV, 1.3 MeV and 1.5 MeV protons and deuterons were incident on a self-supporting 116 nm thick gold foil coated with thin layer of natural lithium. The elastic scattering from the gold, ^{6}Li and ^{7}Li yielded the beam current, and ^{6}Li and ^{7}Li thickness, respectively. Measurement of charged particle energy spectra at angles of 40°, 60°, 90°, 120°, 140°, 160°, and 166° allowed the relevant cross sections to be determined.

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Target Fabrication

In order to have the cleanest possible scattering spectra, it was important to have the ~3 µm thick lithium film deposited onto a very thin (116 nm) yet self-supporting gold foil. To do this, and to keep the lithium from reacting with air, a special ~75 cm long airlock system was designed. A homemade magnetically-coupled linear feedthrough placed the target ladder holding the gold substrate directly above the evaporator inside the deposition chamber. Once the lithium film was created, the target ladder was retracted inside a gate valve, enabling the lithium film to be kept in a vacuum while it was transported to SUNY Geneseo. Once there, the airlock system was attached to the lid of the scattering chamber on the 15R beamline of the 1.7 MV Pelletron accelerator.

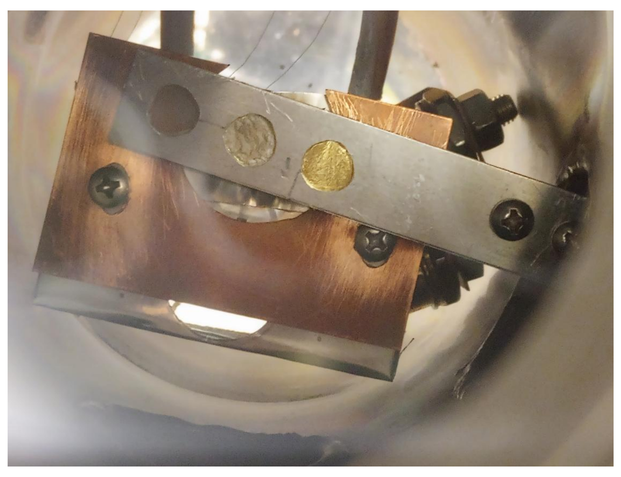


Figure 4 – The target ladder with (from left to right) quartz, lithium on gold foil, and gold foil. It appears that the lithium formed an alloy with the gold and diffused into the substrate.

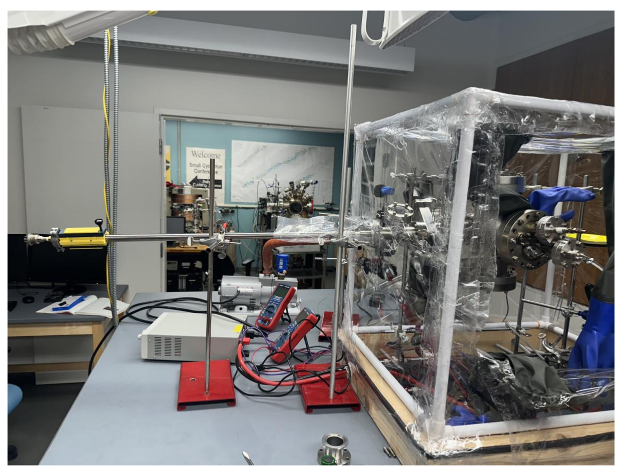


Figure 5 – The deposition chamber (right) with the feedthrough (left) attached. The deposition system is enclosed in an argon-filled glove bag so lithium can be inserted and removed without oxidizing.

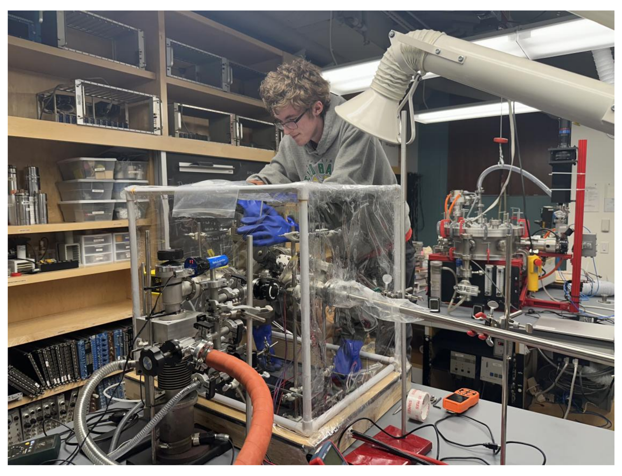


Figure 6 – Lithium pellets were inserted into the evaporator boat using a long aluminum tube. The target ladder was then inserted, placing the gold substrate directly above the boat.

Experiment Design

The SUNY Geneseo 1.7 MV Tandem Pelletron provided an approximately 3 nA deuteron or proton beam at 1.1, 1.3 and 1.5 MeV. These ions struck the lithium coated gold target, which as at an angle of 45° with the gold side upstream. A movable silicon detector was placed at 40°, 60°, 90°, 120°, 140°, and 160°, and a fixed silicon detector was at 166°.

Figure 7 (Upper Right) – The 15R beamline on the 1.7 MV SUNY Geneseo Pelletron. The gate valve and long feedthrough is visible above the scattering chamber lid.

Figure 8 (Lower Right) – A photograph through the scattering chamber viewport.

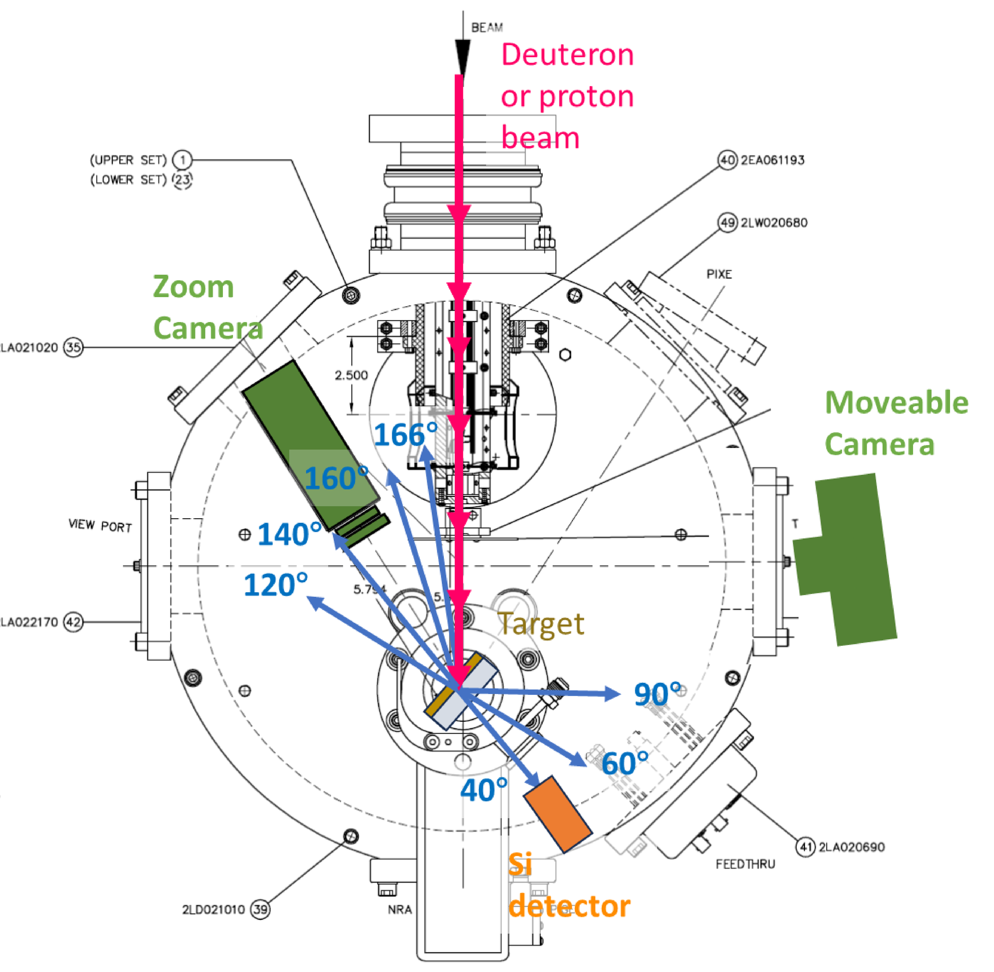
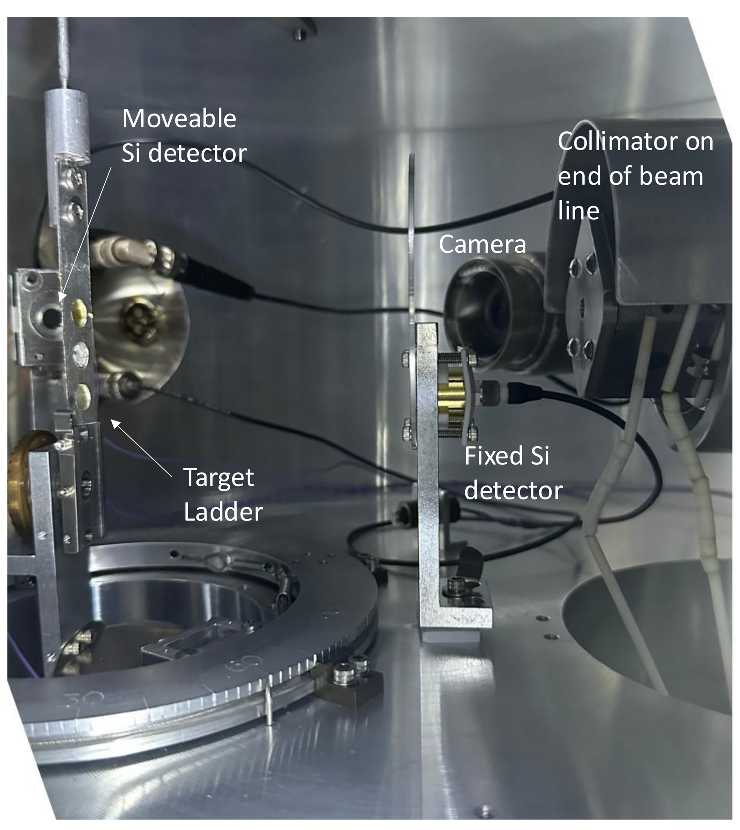


Figure 8 (Above) – Diagram of the scattering chamber. Deuterons or protons first scattered elastically from the gold foil, then, after losing only a tiny amount of energy because of the gold's thinness, they entered the lithium coating where they could scatter elastically from ^{6}Li or ^{7}Li, and the ^{6}Li(d, p)^{8}Li, ^{7}Li(p, α)^{4}He, and ^{6}Li(d, α)^{4}He reactions could occur. The elastic scattering from gold was used to measure the beam current and elastic scattering from ^{6}Li and ^{7}Li provided the target thickness and relative abundances. Outgoing protons and alpha particles from the other reactions allowed the cross sections to thereby be measured.



Motivation

The Short-Lived Isotope Counting System (SLICS) was designed to measure cross sections for light-ion nuclear reactions. A 2024 experiment used the SUNY Geneseo Pelletron to measure the SLICS detector efficiency. The predicted efficiency was consistent with the measurement, which unfortunately had a large uncertainty due to the wide variation in the previously measured ^{6}Li(d, p)^{8}Li, ^{7}Li(p, α)^{4}He, and ^{6}Li(d, α)^{4}He cross sections and ENDF elevations used to measure target thickness and efficiency. A measurement of these cross sections was carried out during Summer 2025 using the SUNY Geneseo Pelletron.

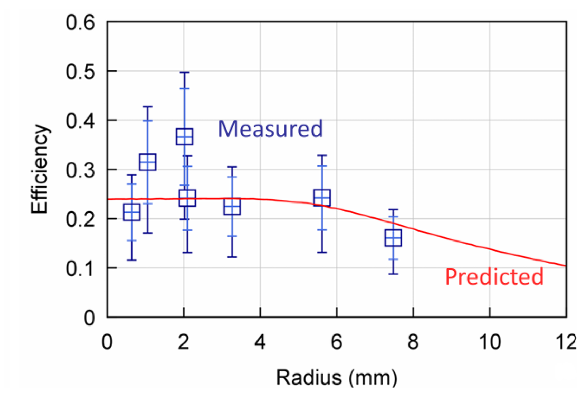


Figure 1 – Measured efficiency (blue squares) as a function of distance from the center of the SLICS detector. The error bars indicate the range in efficiency due to the range of possible target thickness (dark blue) obtained using ^{7}Li(p, α)^{4}He, and ^{6}Li(d, α)^{4}He, and the range of ^{7}Li(d,p)^{8}Li cross sections (light blue).

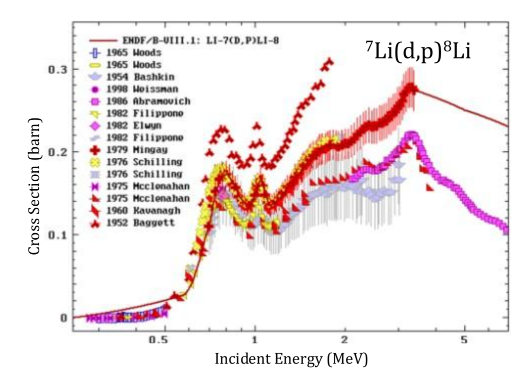


Figure 2 – Previous measurements of the total cross section for ^{7}Li(d,p)^{8}Li as a function of energy disagree by as much as a factor of two. The solid red line is the ENDF/B-VIII.1 evaluated cross section. Figure generated by EXFOR and ENDF.

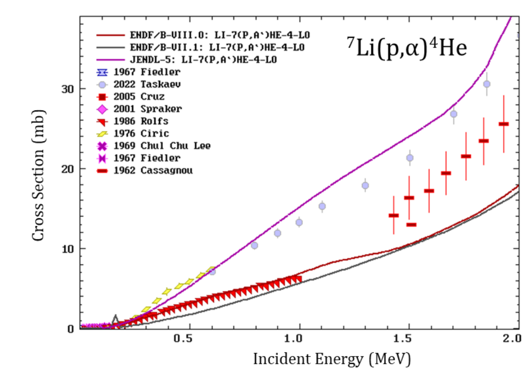


Figure 3 – Previous measurements of the ^{7}Li(p, α)^{4}He total cross section as a function of energy. The solid curves are the ENDF/B-VIII0, ENDF/B-VIII.1 and JENDL-5 evaluaiotns, all of which disagree by as much as a factor of two. Figure generated by EXFOR and ENDF.

Analysis and Preliminary Results

Ion energy spectra were obtained for each angle and energy setting. Peaks corresponding to each reaction were identified based on their predicted energy, and the number of counts in each peak, N_d, was determined.

Figure 9 – The energy spectrum at 166° for 1.51 MeV deuterons incident on the bare gold target (red) and the lithium coated gold target (blue) oriented normal to the beam. Several reaction peaks of interest are labeled. From the shape of the gold peak, it is clear that the gold has migrated into the lithium. The unknown peaks at energies above 1.5 MeV seem to be associated with the gold.

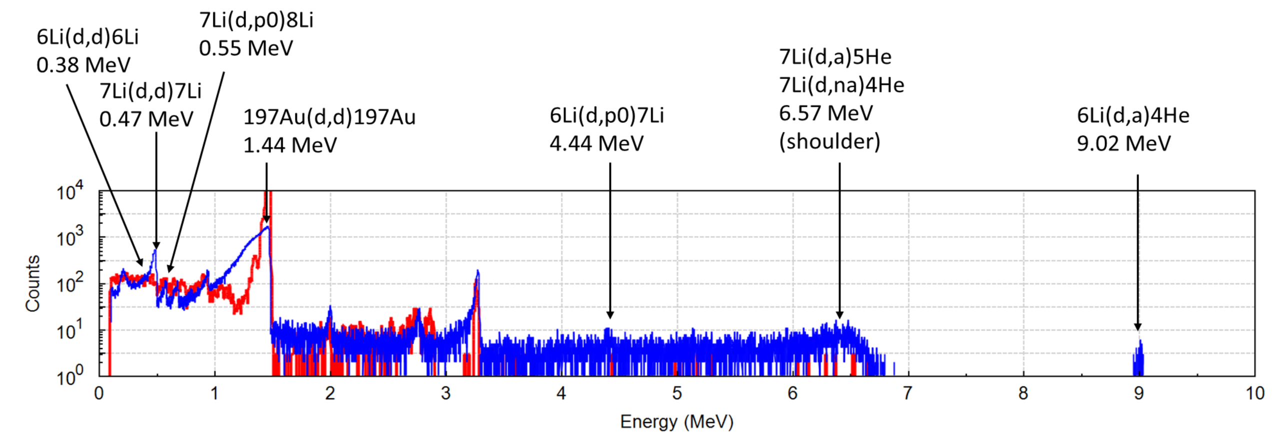
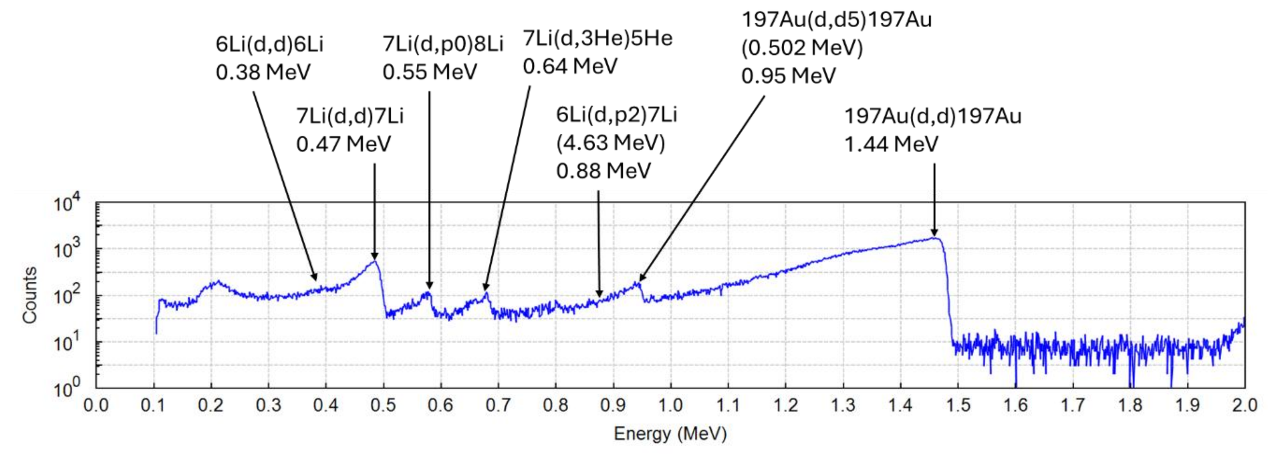


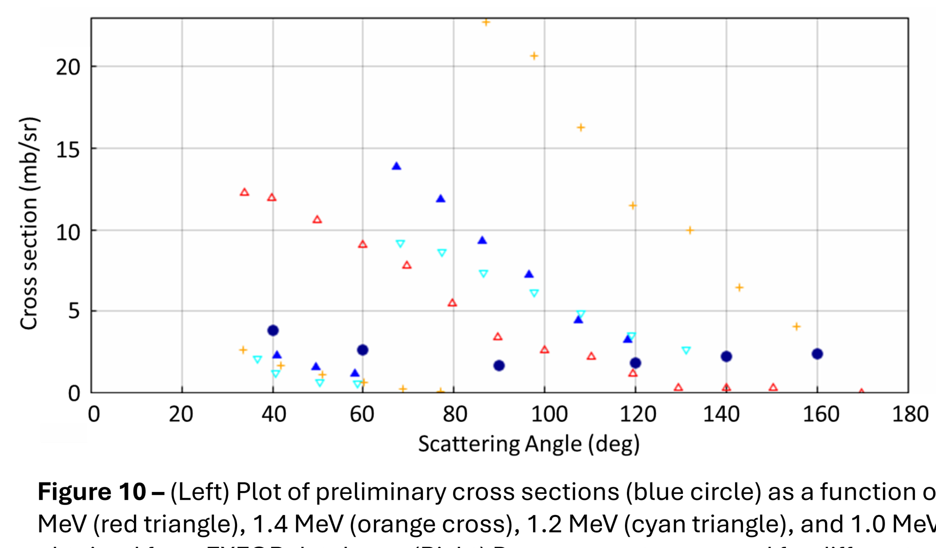
Figure 10 – The region of the 166° energy spectrum below 2 MeV for 1.51 MeV deuterons incident on the lithium coated gold target oriented normal to the beam. Preliminary assignments of reactions of interest to peaks are shown.



The counts are related to the cross section by the equation below. Using the known thickness of the gold foil and known Rutherford scattering cross section for gold allows the beam current N_i to be determined from the number of counts in the elastic gold peak. Using this beam current and the counts in the ^{6}Li and ^{7}Li elastic scattering peaks, with the appropriate known lithium Rutherford scattering cross section, gives the thickness of ^{6}Li and ^{7}Li. Using these thicknesses, the beam current, and the counts in the other peaks allows the cross sections for ^{6}Li(d,p)^{8}Li, ^{7}Li(p,α)^{4}He, and ^{6}Li(d,α)^{4}He to be calculated.

$$N_d = \frac{d\sigma}{d\Omega}(E)\, N_i\, t\, \Delta\Omega$$

$d\sigma/d\Omega$	=	differential cross section (cm²/sr)
N_i	=	number of incident deuterons or protons
t	=	is the target thickness (cm^{-2})
$\Delta\Omega$	=	solid angle (sr)



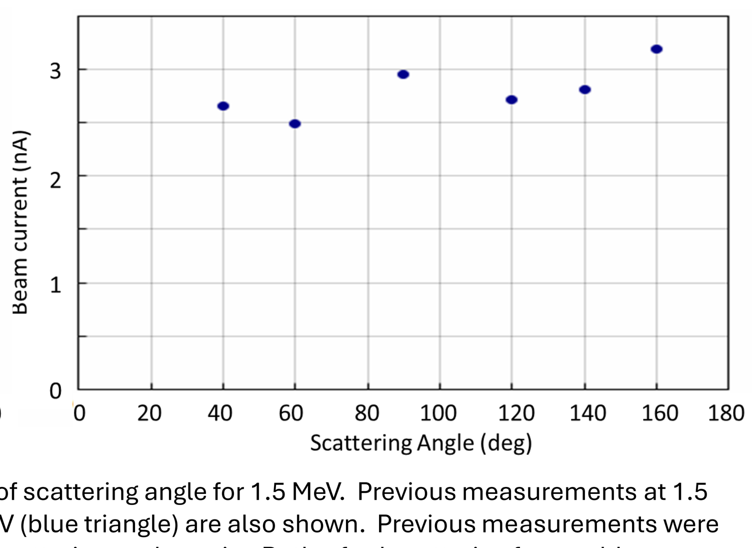


Figure 10 – (Left) Plot of preliminary cross sections (blue circle) as a function of scattering angle for 1.5 MeV. Previous measurements at 1.5 MeV (red triangle), 1.4 MeV (orange cross), 1.2 MeV (cyan triangle), and 1.0 MeV (blue triangle) are also shown. Previous measurements were obtained from EXFOR database. (Right) Beam current measured for different scattering angles using Rutherford scattering from gold.

Future Plans

More careful analysis needs to be carried out before final cross section values can be published. For this initial preliminary analysis the counts in each peak was quickly found by selecting a window around the peak, and calculating the number of events in the window minus the number below a line connecting the window endpoints. Since many of the peaks are quite small, the number of counts is very sensitive to the placement of the window. We plan to go back through the energy spectrum for each angle and more carefully determine the area under each peak.