# Measuring ${}^{nat}$La(p,x) Cross Sections from 35-60 MeV by Stacked Foil Activation

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## Introduction

Proton induced nuclear reactions in the tens of MeV range can be used for the production of radioactive isotopes with minimal contaminants, which makes them a compelling production mechanism for medical diagnostic and therapeudic isotopes [1]. Nuclear data for many of these reactions is scarce, and yet is critical for researchers wishing to optimize irradiation parameters for the production of these radioisotopes [2].

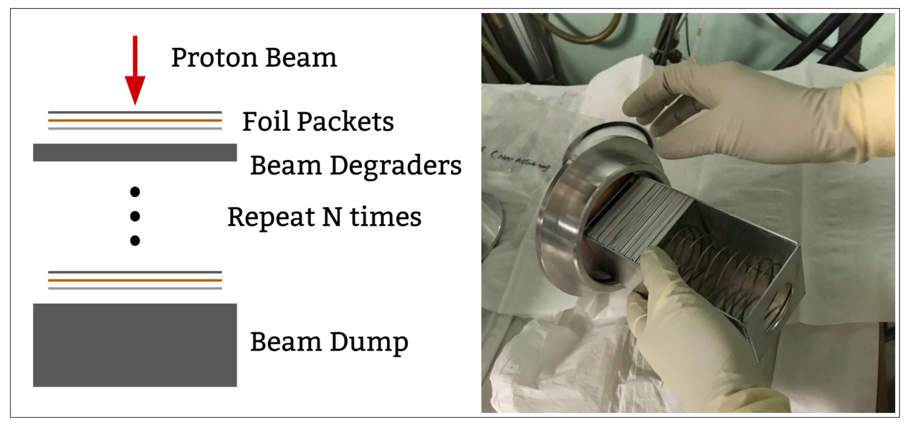


Figure 1:Schematic of the foil stack (left) and photograph of stack prior to irradiation (right).

In this experiment, we measure the ${}^{nat}$La(p,x) reaction cross sections with a particular interest in the (p,6n) reaction on ${}^{139}$La (99.9119% n.a.) [3] for the production of ${}^{134}$Ce, an isotope with applications as a positron emitting analogue of ${}^{225}$Ac. ${}^{225}$Ac is a promising therapeudic isotope, however because it has no $\beta^+$ emissions a chemical analogue such as Ce must be used to study it's bio-kinetics. Data from this experiment is also important to nuclear reaction modelling. Pre-eqillibrium reactions and spin-state distributions influence the cross sections for these reactions, and measuring these cross sections using the stacked foil method will be meaningful to the reaction modelling community.

Measurement of these reaction cross sections can be broken down into a number of discrete steps:

- Calibrate the HPGe $\gamma$-ray detector
- Measure the mass and dimensions of the target foils
- Assemble the stack and secure in the beamline
- Irradiate for fixed duration and proton current
- Count irradiated foils with HPGe detector
- Fit peaks in the monitor and target foil spectra (Fig. 2)
- Determine end-of-beam foil activities ($A_0$)
- Determine beam current and energies
- Calculate cross-sections
- Compare results to EXFOR, TALYS and EMPIRE

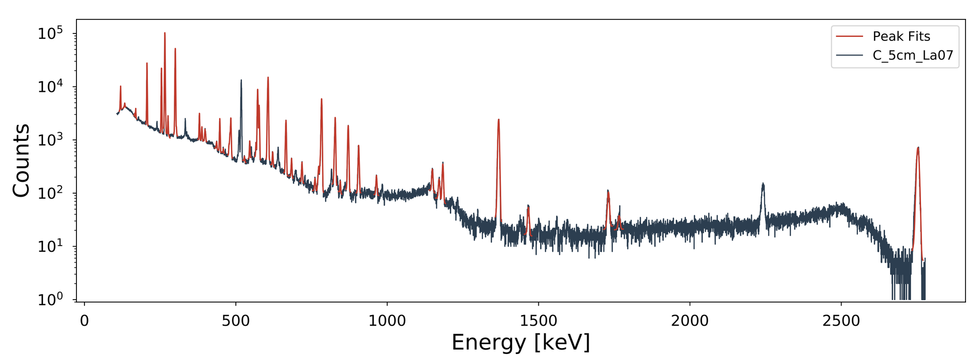


Figure 2:Example of $\gamma$-ray spectrum from the $7^{th}$ lanthanum foil, with peak fits indicated in red.

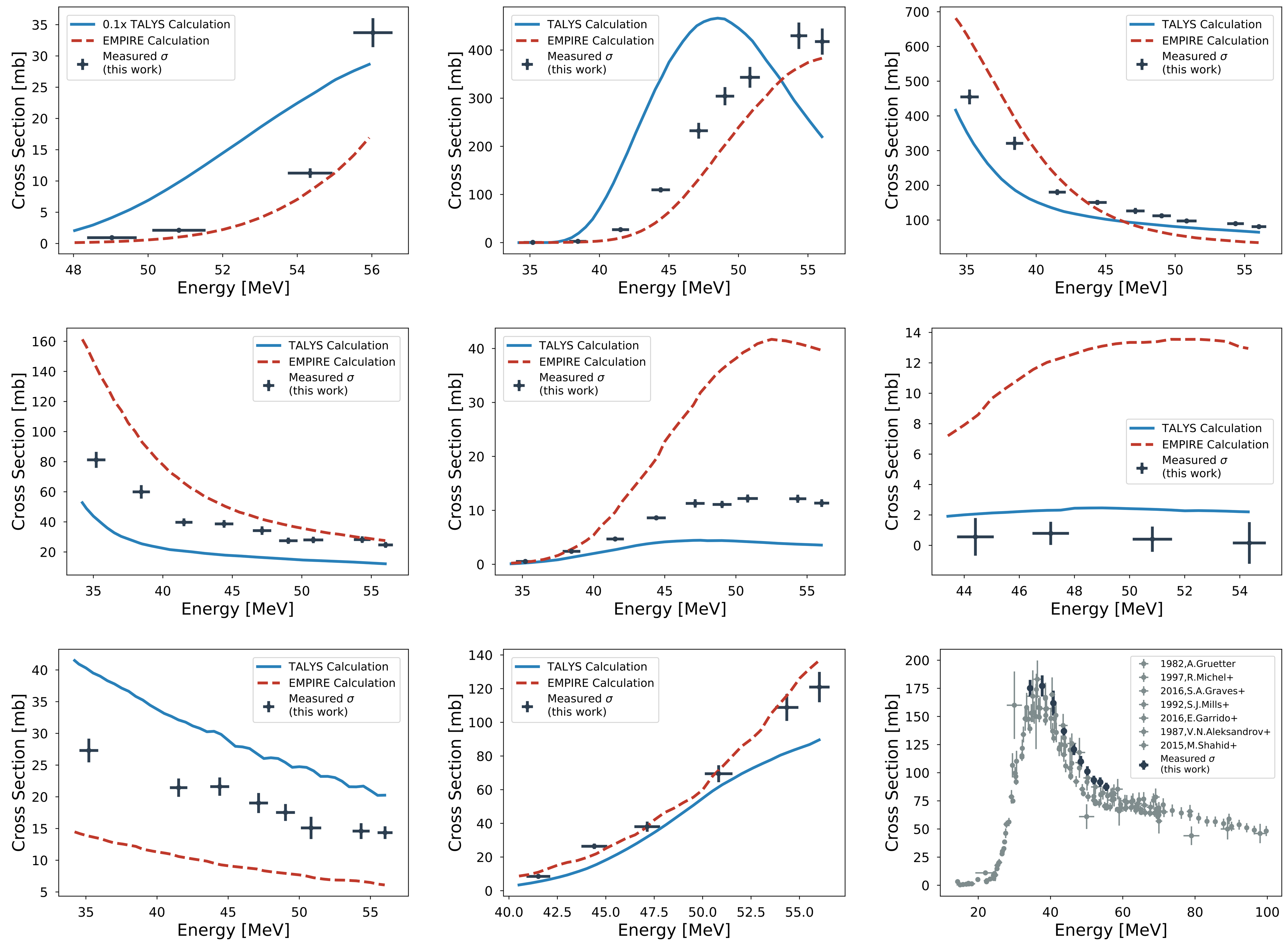


Figure 3:Measured excitation functions in ${}^{nat}$La (first 8) and ${}^{nat}$Cu (lower right). TALYS and EMPIRE calculations shown in solid blue and dashed red, respectively.

## Methodology

The cross section for a given incident beam energy can be calculated using the activation method by the following equation

$$\sigma = A_0[I_p\rho\Delta r(1-e^{-\lambda t_i})]^{-1} \quad (1)$$

where $A_0$ is the activity of a given reaction product at the end of irradiation, $I_p$ is the proton beam current, $\rho\Delta r$ is the areal number density and the factor $(1-e^{-\lambda t_i})$ is the ratio of induced activity to the saturation activity, where $\lambda$ is the decay constant for a given reaction product and $t_i$ is the total irradiation time.

The activity $A_0$ is determined by collecting a spectrum of $\gamma$-ray emissions. If a $\gamma$ spectrum is counted for a measurement time $t_m$, beginning some amount of time $t_c$ after the proton beam was shut off, then the end-of-beam activity measured in a photo-peak having $N_c$ counts will be

$$A_0 = \frac{\lambda N_c}{(1-e^{-\lambda t_m})e^{-\lambda t_c}I_\gamma\epsilon} \quad (2)$$

where $I_\gamma$ is the $\gamma$-emission fraction per decay and $\epsilon$ is the

## Energy Assignments

The energy centroids (and $\sigma_E$) were first estimated using the MCNP output, however there was a large spread in the apparent beam current values seen by each monitor reaction channel. This was indicative of incorrect characterization of the proton energy spectra incident on each monitor foil. In order to correct for this, the areal density of the degrader foils and the incident proton beam energy were treated as free parameters, and were varied in order to find the energy assignments yielding the smallest variance in the beam current.

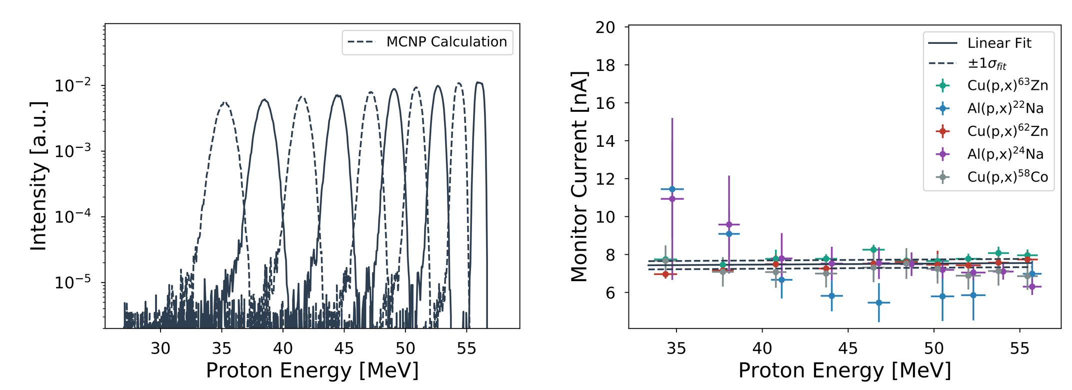


Figure 4:Left: Plot of the proton energy spectra for each lanthanum foil in the target stack. Right: Plot of the beam cur-

## Results and Discussion

Figure 3. shows the measured cross sections for various ${}^{nat}$La(p,x) reactions, using a 57 MeV proton beam at the LBNL 88" cyclotron and a stacked foil target. We also compared these measurements with the outputs of the TALYS and EMPIRE nuclear reaction modelling codes, using default parameters. In most cases neither code accurately predicted the magnitude of the cross sections, but TALYS consistently underpredicted the energy of the peak in the cross section, whereas the EMPIRE predictions agreed with the shape of the measured cross sections quite well. This primarily speaks to the fidelity of the pre-equillibrium models used by the respective codes: the hybrid Monte Carlo simulation model (EMPIRE) typically produced better predictions than the exiton model (TALYS).

Particular attention to detail was taken measuring the production of ${}^{134}$Ce, an isotope with applications as a positron emitting analogue of the medically relevant ${}^{225}$Ac isotope. The results of this study show that a higher energy proton beam will be required to produce ${}^{134}$Ce using this reaction than was previously calculated. The highest energy proton beam availible at the LBNL 88" cyclotron (57 MeV) produces an unacceptable activity of other Cerium isotopes, which will act as impurities in a medical study. A proton beam of at least 70 MeV will be required to produce significant activities of ${}^{134}$Ce without contaminants.

## References

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