Final Report

Advanced Grazing Incidence Neutron Imaging System
for the Location of Non-Terrestrial Water

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Introduction
The purpose of our research was to investigate the potential of using grazing incidence neutron optics as a tool to probe planetary bodies for the presence of water. This research was motivated by the desire to find water in our solar system and expand our presence beyond earth orbit which is a key component NASA's space exploration initiative. During the course of this project, many interesting and confirming results were obtained which will help to further this project as it progresses towards a stage where it can be considered for an actual space mission. The purpose of this report is to summarize the results of our research which are demonstrating the capability to focus neutrons with nickel grazing-incidence optics, investigating the use of a gas scintillation proportional counter to detect neutrons and the simulation of the lunar neutron albedo flux in order to characterize the response of neutron optics to that flux.

Neutron Optics

Neutron Beamline Test
In February of 2007, the National Institute of Standards and Technology's Neutron Research Center (NIST) provided us with one day of beam time on one of their small angle neutron scattering experimental setups. The setup consists of a selectable low-energy neutron beam focused onto a 30m 3He detector. This setup is normally used for SANS testing on samples in order to determine its microstructure. We had to modify the standard setup in order to place our optic in the beamline.

Due to the parameters of the setup, we were not able to get the detector into the focal plane of the optic. Instead we imaged the beam beyond the focal plane at increasing distances to see if the image image would converge. We also obtained neutron flux data from the detector's readout to determine if the theoretical throughput of the detector was comparable with the experimental throughput. Several factors affect this throughput including surface roughness, reflectivity, and optic shape. Before arriving at NIST the optic was tested with x-rays to measure the throughput flux. These test showed that the flux was lower than expected.
The wavelengths used in the experiment were 6 Å, 10 Å and 20 Å. The optic’s geometrical area was measured to be 17.66 mm². The effective areas for the three wavelengths used in the experiment were measured slightly smaller than the geometrical area for the case of 20 Å and 10 Å and much smaller for 6 Å. The reduction in effective area at 6 Å is still being investigated by scientist at NIST and in our group at Marshall Space Flight Center (MSFC).

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>Effective Area (mm²)</th>
<th>Ratio of Effective Area to Geometrical Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>15.1 +/- 1.2</td>
<td>85.5 %</td>
</tr>
<tr>
<td>10</td>
<td>17.1 +/- 0.2</td>
<td>96.8 %</td>
</tr>
<tr>
<td>6</td>
<td>7.1 +/- 0.4</td>
<td>40.2 %</td>
</tr>
</tbody>
</table>

The immediate results of these test were that the concept of focusing neutrons is feasible. We successfully focused neutrons using a nickel grazing incidence optic. It was observed that as the neutron energy increased, the signal decreased as expected. Upon seeing these amazing results, the investigators at NIST invited us back to perform future testing on an assembled optics system. We have submitted a paper detailing this experiment to Nuclear Instruments and Methods in Physics Research.

Future research in this area will include returning to NIST with an optic system in order to perform further test. Also extensive modeling of the optics will be conducted to optimize the shape as well as the material used on a flight instrument. Studies that need to be conducted include understanding the reflectivity of the optics as well as the neutrons response to multi-layered neutron “super-mirrors.” These mirrors utilize multiple coatings of different materials onto the nickel substrate in order to increase the effective area and energy range of the optics. Theoretically, the energy range of the optics can be increased by a factor of 3. The research performed on during this project has provided the experimental evidence to further investigate theses avenues.
He Gas Scintillation Proportional Counter

Modeling
To evaluate the feasibility of a $^3$He/Xe mixture for neutron detection, extensive simulations were designed using the particle transport code, GEANT4. These simulations provided us with the insight to understand the response of our prototype detector to the Am/Be neutron source used in our testing.

![Energy Deposition in He3](image)

*The spectrum from the GEANT4 simulation peaks at 746 KeV which is indicative of thermal neutron detection in $^3$He*

We varied many parameters in the simulation including source location, shielding depth, and detector housing materials. These variations helped to optimize the prototype detector's design and the experiments which were carried out with it. The results of the simulations showed that the idea was sound and we should be able to clearly resolve the 746 KeV peak indicative of neutron detection.

Construction
Following the simulations, a prototype detector was built and tested. The detector consisted of 1 atm of $^3$He and 9 atm of Xe enclosed in a stainless steel chamber. An AM-241 60 KeV x-ray source was used for calibration of the detector's readout. The detection of the scintillation photons was performed using a non-position sensitive photomultiplier tube (PMT). A multichannel analyzer was used to read out the data and locate the 746 KeV peak. No peak was ever discovered. We believe this is due to the one or a combination of three facts. First, the gas could be contaminated causing there to be no light seen by the PMT. The source flux may be too divergent for the detector to gather enough counts within the housing. Finally, the detector may not respond linearly at MeV energies. To remedy this problem, it was decided that a position sensitive PMT should be used in place of the existing PMT. This would allow us to see if the signal from the neutron was concentrated in one part of the detector of spread out and therefore washed out by the...
background flux. This process of designing the detector readout and data acquisition system is currently underway. Once this is completed a full characterization of the detection system can be completed.

**Lunar Neutron Albedo Flux**

**Modeling**

In order to understand how the useful neutron optics would be for observing the lunar neutron albedo flux, simulations of the lunar surface were run with various water/soil mixes. The information we wanted to obtain was whether or not there was enough flux at low energies for the optics to be practical for a lunar mission. Since the optics’ critical angle obeys an inverse power law with energy, we had to find where the lunar flux peaked.

Using GEANT4 the lunar surface was modeled with water/soil mixes varying for 0-100 %. It was clear from these simulations that as water content increased, the number of epithermal neutrons decreased. Unfortunately, without access to a large computing cluster, the computing time needed to gather good statistics at low energies would be immense. Therefore, we obtained data from Dr. David Lawrence of Los Alamos National Lab (LANL) that contained detailed information about the lunar flux at low energies. With this data we were able to fold in the response of our optics to this flux. This showed that there is a substantial amount of flux that can be obtained with optics that are within the current engineering capabilities at MSFC. Through conversations with Dr. Lawrence, he decided to run preliminary simulations based on these results and found that with these optics we may be able to obtain 40% of the energy range.

*The red line indicates the critical angle of the optic while the multicolored lines are the lunar albedo flux for various amounts of water weight*.

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that would be measured using a counting detector such as Lunar Prospector’s Neutron Spectrometer. This is enough to successfully indicate the presence of water on the lunar surface.

The next step in modeling is to design a model of an actual flight instrument to investigate the length of time and type of orbit required for an actual space mission. These simulations will help to optimize the not only orbital parameters, but also the design of the flight instrument itself. These will be completed in the future depending on the outlook of the project.

**Conclusion**

In conclusion, the project has successfully demonstrated that the use of an grazing incidence neutron imaging system is an excellent choice for the a future mission to the moon to find water. Additionally, we have shown that the principle of using grazing incidence optics for focusing neutrons is possible. This opens up several avenues of research for a broad array of applications in medical imaging and homeland security. Through collaborations with scientist at NIST and LANL we have been able to push through to a new paradigm in neutron imaging in which we can have arcsecond resolution of neutrons from a source. The work done has been submitted to a peer reviewed journal for publication.

**Acknowledgments**

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1 B.D. Ramsey et al. Submitted April 2007

2 G.F. Knolls, John Wiley & Sons, Inc. (1992)

3 Lunar neutron flux data provided by Dr. David Lawrence (LANL) through private conversations during 2007