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A DETECTOR ARRAY FOR MEASURING NEUTRON CAPTURE CROSS SECTIONS IN THE KEV REGION

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1. INTRODUCTION

Reactor design and criticality safety calculations require accurate and precise nuclear cross section data in order to minimize the amount of uncertainty in their results. Lower uncertainty allows for tighter safety margins, which is paramount in scenarios where space, weight and cost are at a premium.

Neutron capture reactions are an important component of criticality calculations, and measurements of their cross sections often suffer from significant degrees of experimental uncertainty, particularly in the keV energy region. A program under development at the RPI Gaerttner Linear Accelerator (LINAC) Center aims to address this issue through the use of a new array of deuterated benzene (C_6D_6) liquid scintillators, which have a lower sensitivity to the types of interactions that lead to uncertainty in cross section measurements in the resonance region.

2. THEORY

Neutron capture cross sections are measured at the RPI LINAC via the time-of-flight (TOF) spectroscopy method. The accelerator target acts as a pulsed source of neutrons with a white spectrum of energies, which travel along a 40 meter evacuated flight path. The neutrons then impinge upon a sample, and the prompt gamma rays from capture interactions are detected.

The elapsed time from the LINAC pulse to the detection of the prompt gammas is then used to determine the energy of the neutron that caused the interaction, and the number of events detected at a given time-of-flight is used to determine the overall capture yield.

At neutron energies in the keV range, scattering interactions tend to dominate over radiative capture, sometimes by several orders of magnitude. Neutrons that scatter off the sample under investigation can be subsequently captured in nearby materials, resulting in a false signal [1, 2]. This phenomenon ultimately leads to a higher background and an overestimation in the capture cross section.

The sensitivity of the detection system to the false capture phenomenon can be mitigated by using detector materials with low masses and low neutron capture cross sections. The new detector array at RPI incorporates C_6D_6 liquid scintillators with thin-walled aluminum construction, operating under the total energy detection principle.

2.1. The Total Energy Detection Method

In the total energy detection method (Fig. 1), only one photon per capture reaction is detected per capture event in order to ensure that there is no sensitivity to the cascade pathway [1, 3].

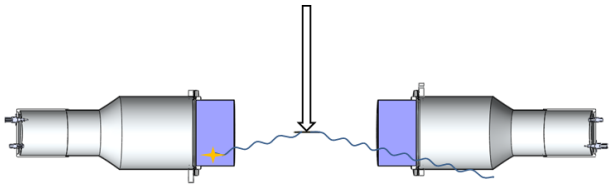

Figure 1. Diagram of the total energy principle, shown to scale

Assuming a single detector with detection efficiency $\varepsilon_\gamma << 1$ and that only one gamma per cascade it detected, the efficiency for registering the capture event is the sum of the detection efficiencies of the total number (n) of photons in the cascade:

$$\varepsilon_c = 1 - \prod_{i=1}^{n}(1 - \varepsilon_{\gamma i}) \approx \sum_{i=1}^{n} \varepsilon_{\gamma i} \qquad (1)$$

Additionally, this method requires that the detection efficiency be proportional to the energy of the gamma ray (E_γ) striking the detector:

$$\varepsilon_{\gamma i} = kE_{\gamma i} \qquad (2)$$

This then allows the capture detection efficiency to be directly proportional to the total excitation energy of the capture reaction (E_x), which is sum of the neutron separation energy (S_n) and the neutron kinetic energy ($E_{n,C}$) in the center-of-mass system [1]:

$$\varepsilon_c \approx k \sum_{i=1}^{n} E_{\gamma i} \approx kE_x = k(S_n + E_{n,C}) \qquad (3)$$

In practice, the efficiency to detect a gamma ray is not necessarily proportional to its energy. To achieve the required proportionality, an energy and geometry dependent weighting function $W(E_d)$ is determined through Monte Carlo simulation [2, 3, 4] and subsequently applied to each detected gamma event.

$$kE_\gamma = \int_0^\infty R_d(E_d, E_\gamma) W(E_d) dE_d \qquad (4)$$

For an individual detector module, the intrinsic efficiency (ε_γ) is on the order of a few percent to avoid detecting multiple photons per capture cascade. An array of 4 detectors, combined with a coincidence rejection algorithm, is used to improve the solid angle efficiency and yield better counting statistics.

3. METHODS & MATERIALS

Preliminary tests were conducted with a single prototype detector module (Fig. 2). To reduce the likelihood of false captures within the detector, construction materials were made as light and thin as practical. The C_6D_6 liquid scintillator is housed within a 127mm diameter, 76mm thick aluminum cell with 0.75mm thick walls. This cell is optically coupled to a 127mm diameter fast photomultiplier tube with a quartz window to reduce the false capture background that would be experienced with conventional PMT window materials (e.g. borosilicate glass).

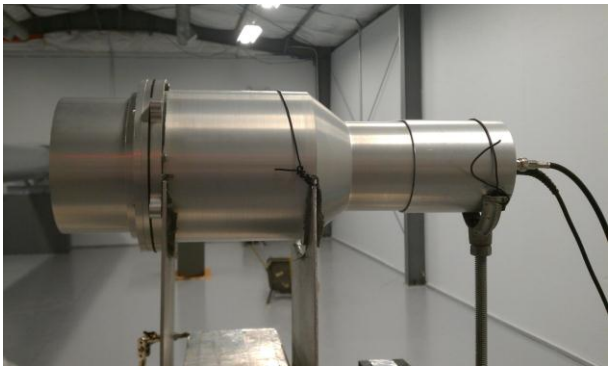

Figure 2. A single detector module shown at the experimental station

A short TOF experiment was conducted with a manganese/copper (80%Mn, 20% Cu) sample and the prototype detector module located on a flight path 38m from the LINAC target. A sample of B_4C enriched to 91% ^{10}B was used to determine the neutron flux and allow for capture yield calculations.

While existing analog electronics were used during the data collection, future data acquisition efforts will be achieved with the use of a Struck Innovative Systems SIS3305 fast digitizer board, which has 10-bit resolution, 8-channel capability and a 1.25 GHz sample rate. Although extensive software development is needed to take full advantage of the capabilities of the SIS3305, it allows for a significant reduction in dead time compared to a purely analog TOF system, as well as providing the data needed for offline pulse-shape analysis, coincidence rejection, and pulse height weighting.

4. RESULTS & FUTURE WORK

The capture yield results from the preliminary experiment are shown in Fig. 3. While the resonances observed are largely dominated by scattering, the results are consistent with analytical capture yield calculations performed using the ENDF 6.8 and 7.1 data libraries. This consistency shows that there is no evidence in the data to indicate sensitivity to scattered neutrons.

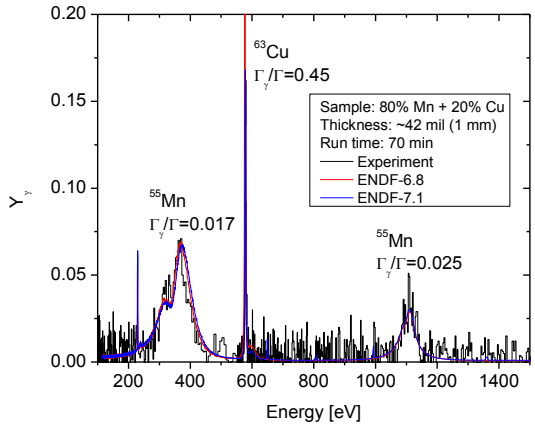

Figure 3. Unweighted capture yields (Y_γ) in an Mn/Cu sample using a single detector module and analog TOF system

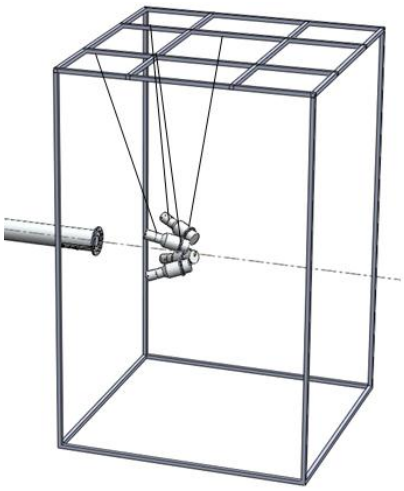

Figure 4. CAD model of future experimental setup showing flight path entering from the left and detector array mounted around the sample at center

These initial results are promising, and future measurements using 4 detectors in an array (Fig. 4), higher LINAC beam currents and longer run times are expected to yield greatly improved statistics. Additionally, switching to the SIS3305 digitizer will significantly reduce the dead time in the system and also allow for higher timing resolution and application of weighting functions during post-processing of the data.

It is estimated that due to systematic effects and due to uncertainty in determining the weighting function [1], the overall uncertainty in future measurements will be on the order of 2-4%.

CONCLUSION

Preliminary tests with a prototype module have shown that the total energy detection principle, when combined with C_6D_6 liquid scintillators, holds promise for obtaining capture cross section measurements in the keV region with low sensitivity to scattered neutrons. This would significantly extend the range of capture measurement capabilities of the RPI LINAC Center. Future measurements incorporating the use of the SIS3305 digitizer and all four detector modules are expected to produce results with 2-4% uncertainty after accounting for systematic effects and uncertainty in determining the detector weighting function.

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