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Abstract

GEANIE is the first large-scale Ge detector array used in conjunction with a high-energy neutron spallation source. GEANIE consists of eleven Compton-suppressed planar detectors, nine suppressed and six unsuppressed co-axial detectors. Spallation neutrons are provided by the LANSCE/WNR facility, and reaction neutron energies are determined via time-of-flight. Neutron flux is monitored in-beam with a fission chamber. GEANIE at LANSCE/WNR currently emphasizes the measurement of partial gamma-ray cross sections as a function of neutron energy.

Absolute cross section measurements require a complete understanding of array performance. Important effects include intrinsic detector efficiency, beam and detector geometry corrections, target attenuation, and deadtime. Measurements and calculations of these effects will be presented for the specific cases of iron and actinide targets.

The use of radioactive targets incurs a large deadtime penalty. In order to increase data throughput we are making plans to move to a triggerless data acquisition system. These modifications and other improvements to the electronics for better timing will be discussed.

PACS number(s):

1. Introduction

GEANIE is the first large-scale Ge detector array used in conjunction with a high-energy neutron spallation source. GEANIE consists of eleven Compton-suppressed planar detectors, and nine suppressed and six unsuppressed coaxial detectors. Spallation neutrons are provided by the LANSCE/WNR facility, and reaction neutron energies are determined via time-of-flight. Neutron flux is monitored in-beam with a fission chamber [1]. GEANIE at LANSCE/WNR currently emphasizes the measurement of partial gamma-ray cross sections as a function of incident neutron energy. These measurements allow us to probe pre-compound reaction mechanisms which occur for neutron interactions at incident energies $E_n \gtrsim 10$ MeV.

LANSCE/WNR has an 800-MeV pulsed proton beam with a 6% duty cycle. Each macro pulse consists of approximately 350 micro pulses spaced by 1.8μs. The secondary neutrons are collimated and also hardened with a polycarbonate absorber. Each proton pulse produces bremsstrahlung photons that are attenuated with a lead absorber. We use this initial photon flash as our reference point for determining the neutron time-of-flight which induce prompt γ rays in the GEANIE array target. Because of the low duty cycle and collimation requirements, the neutron beam currents delivered to GEANIE are fairly low. At neutron energies above 5 MeV, which are the most relevant energies for our measurements, the beam current is less than 10K neutrons MeV^{-1} s^{-1}.

Younes *et al.* [2] has given a contribution earlier in this conference on some of the nuclear structure work that has been done at GEANIE during the last year. The present contribution focuses on the measurement of neutron-induced reaction cross sections for applications, which has been a major emphasis of the research effort at GEANIE. While γ rays provide only part of the channel cross section, they serve as a useful proxy for a direct measurement of the channel cross section when other techniques are not available. For example, the ^{239}Pu(n,2n) reaction has a large fission neutron background that makes neutron counting problematic. In addition, the target purity required for a radio-chemical measurement is difficult to attain. Another feature of LANSCE/WNR which is exploited at GEANIE is that incident neutron energies are simultaneously available from 1 MeV to 200 MeV.

Cross section measurements over this energy range can be directly compared to model predictions of neutron-induced cross-sections, *e.g.* GNASH [3] and ALICE [4]. In particular, information on cross section as a function of spin is available from the observation of γ-rays depopulating the yrast levels. Such detailed cross section measurements require an understanding of pre-equilibrium effects, in particular the spin transfer in pre-equilibrium events, as well as an excellent understanding of the ensuing γ-ray cascade to the ground state.

A good example of applied research work that can be carried out at GEANIE is the measurement of partial γ-ray cross sections for ^{209}Bi(n,xn) reactions. Bismuth is likely to be a target constituent for an Accelerator for Transmutation of Waste (ATW) facility. In addition, bismuth is mono-isotopic and as a result is a good candidate for use in a high-energy neutron fluence monitor. Both of these applications require an accurate knowledge of the neutron channel cross sections. With GEANIE at LANSCE/WNR, each channel can be simultaneously measured with signature decay γ rays. Some recent RIKEN data on the ^{209}Bi(n,9n) cross section [5] shows substantial disagreement with current calculations in ENDF-B/VI. Bernstein *et al.* [6] has made measurements at GEANIE with a ^{196}Pt target which shows that high-neutron multiplicity events are observable with GEANIE.

2. Characterization of GEANIE array

Absolute cross section measurements require a complete understanding of array performance. The characterization of GEANIE is broken down into four parts: (1) point source efficiency, (2) deadtime corrections, (3) corrections which arise from the fact that our neutron beam is too large to be approximated as point source, and (4) attenuation of γ-rays in the target.

2.1. Point source efficiency

The point source efficiency has been measured with a NIST-traceable, mixed γ- ray source. The activity quoted by the vendor was verified with a calibrated detector at LLNL. The efficiency was measured at several different times under a variety of different deadtime scenarios. A statistical analysis of the results indicates that the point source efficiency is repeatable to within 1.4%.

2.2. Deadtime correction

Many experiments at GEANIE are singles measurements in a high-background environment. Background counts come from (1) scattered neutrons, (2) the initial photon flash from the primary target, and (3) radioactive target constituents. Deadtimes are often in the neighborhood of $\approx 50\%$ and hence are an important area of concern for two reasons: (1) high deadtime reduces throughput and (2) deadtime must be well-characterized to extract absolute cross sections. However, our beam-induced detector rates are so low that energy-dependent deadtime effects are negligible ($\approx 0.1\%$), so only rate- and system-dependent effects need to be considered.

For an in-beam cross-section measurement, the γ-ray counts are normalized to neutron flux. The fission chamber and Ge detectors are processed with the same electronics to eliminate systematic differences. Even so, the counting rates are different and there is a rate-dependent deadtime for each detector. We measure the deadtime by comparing the throughput to the number of unsuppressed fast amplifier signals, which are scaled. We can also calculate the rate-dependent deadtime based on detector rates. The measured and calculated values agree to within 2%.

2.3. Beam spot

The beam spot at GEANIE is roughly 2 cm in diameter, too large to be considered a point source. The beam profile has been measured with a Fuji image plate with which we achieved a dynamic range of 10^4. In order to understand the effect of the extended beam spot, the GEANIE array has been modeled with MCNP [8], a Monte Carlo particle transport code. The calculated efficiency of the array as a function of radial distance is is compared to the beam profile in Fig. 1. It is immediately apparent that the majority of the neutron flux is about 0.5 cm from the center of the array. As a result, our efficiency for detecting γ rays is decreased by about 10% compared with the measured point source efficiency at the center of the array.

One of the most important requirements in doing an accurate MCNP calculation for this purpose is that the detector crystals and detector collimators had to be precisely aligned. Each crystal and collimator axis passes within ±1 mm of the array center. In addition, the Ge crystal dimensions provided by Ortec were varied within measurement uncertainties to give optimal agreement with source measurements..

Fig. 2 the results of an MCNP calculation of the point source efficiency of GEANIE is compared with our measurements. In fact, we use MCNP to interpolate the measured efficiency to other γ-ray energies.

2.4. Target attenuation

As mentioned earlier, some γ-rays are significantly attenuated in the target. For example, in ^{234}U, the $6^+ \rightarrow 4^+$ transition has an energy of 157 keV. The attenuation correction can be calculated by integrating the standard attenuation equation, assuming that all γ rays pass through the center of the target. This simple approach compares well to the doing an MCNP calculation for the measured beam spot and GEANIE array. In this example, the fraction of γ-rays escaping the target is calculated with both approaches for both a 12-mil and 24-mil thick targets as a function of detector-target angle. The fraction escaping a 12-mil target is about 60% larger than the fraction escaping a 24-mil target.

In Fig. 3, the excitation function for the 157-keV γ ray is shown as derived from both thin and thick target data, after the counts have been scaled by the attenuation correction, target thickness, and neutron flux. While there is clearly a small systematic difference between the results, the data agree within the uncertainty which in this particular instance is dominated by the target thickness.

3. Benchmark: ^{56}Fe(n,n′γ)

The ^{56}Fe(n,n′γ) where $E_\gamma = 0.847$ MeV a benchmark for γ-ray cross-section measurements. Even so there is substantial disagreement over the correct cross section value. An IAEA evaluation of the existing data [9] gives 856(52) mb as the accepted cross section at $E_n = 14.5$ MeV. The value obtained in this measurement is 840(76) mb. For energies from 2-20 MeV, our preliminary results are in agreement with higher measurements, for example, measurements made by Nelson [10], Savin [11], and Drake [12]. Our measured excitation function also has very similar features to the Dickens *et al.* [13], however, our cross section values are 10-15% larger. The shape of the excitation function and cross section values are in substantial disagreement with the Voss [14] measurements, with the disagreement increasing as the incident neutron energy increases. This measurement has one thing in common with the previous Nelson measurement — the same fission chamber for is used as the neutron flux monitor. Because of this, we plan to re-measure the thickness of the fission foils via Rutherford backscattering.

Because our detectors are positioned at six distinct angles with respect to the beam, the angular distribution of the γ-ray emission must be taken into account. The A_0 term of the distribution is the cross section. In addition to the A_0 term, the A_2 and A_4 coefficients of the angular distribution as a function of incident neutron energy are plotted in Fig. 4. These measurements are in reasonable agreement with a CINDY calculation. This indicates that the deadtime corrections and efficiency measurements on a detector-by-detector basis are substantially correct.

4. Conclusions

Because of the small duty cycle and limited beamtime available at LANSCE/WNR, we plan to move to a triggerless data acquisition system to substantially reduce deadtime. Recently, the quad-channel AD413 ADCs were replaced with single-channel AD114s, which also have better dispersion. In addition to upgrading our gated integrators to Tennelec TC245s, we also have plans to upgrade our constant fractions with a CAMAC module designed by Michael Maier, with the hope of improving our low γ-energy timing. After that upgrade, we will make the shift to a triggerless data acquisition by putting in a buffered memory for each channel, and an absolute clock time stamp in order to properly analyze our events offline.

The measurements and tests discussed above indicate that γ-ray cross section measurements can be done at GEANIE. Some further test measurements are being analyzed and further array improvements ongoing. An improved ^{56}Fe(n,n$'\gamma$) is currently in progress. In summary, GEANIE and LANSCE/WNR is a unique combination for studying neutron-induced reactions.

5. Acknowledgments

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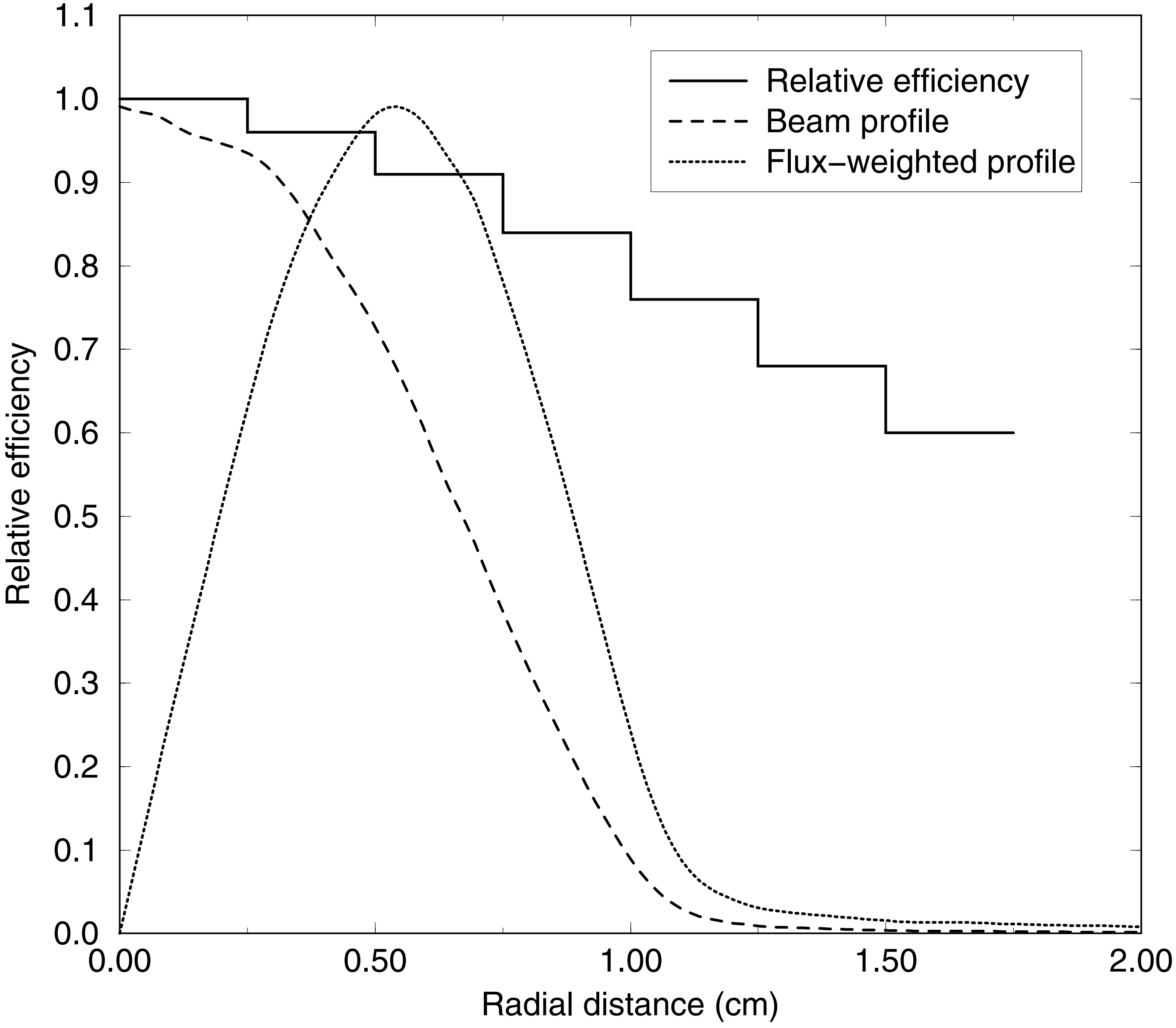
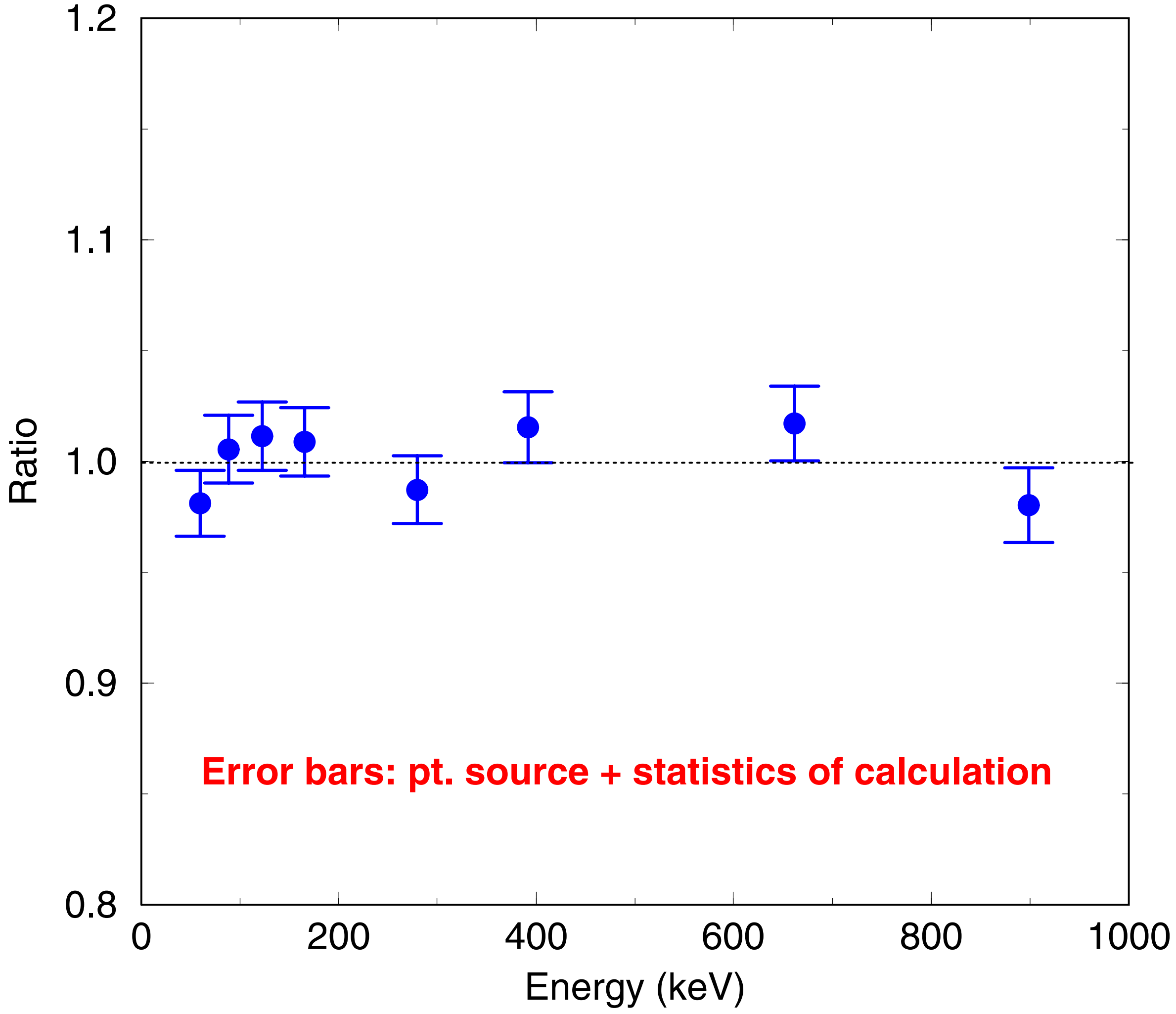
Fig. 1: A line out of the measured beam profile (dashed) is scaled by the circumference or r, the radial distance, to give the flux-weighted profile (dotted). This can be compared to the relative efficiency of the GEANIE array as a function of radial distance from the array center (solid).

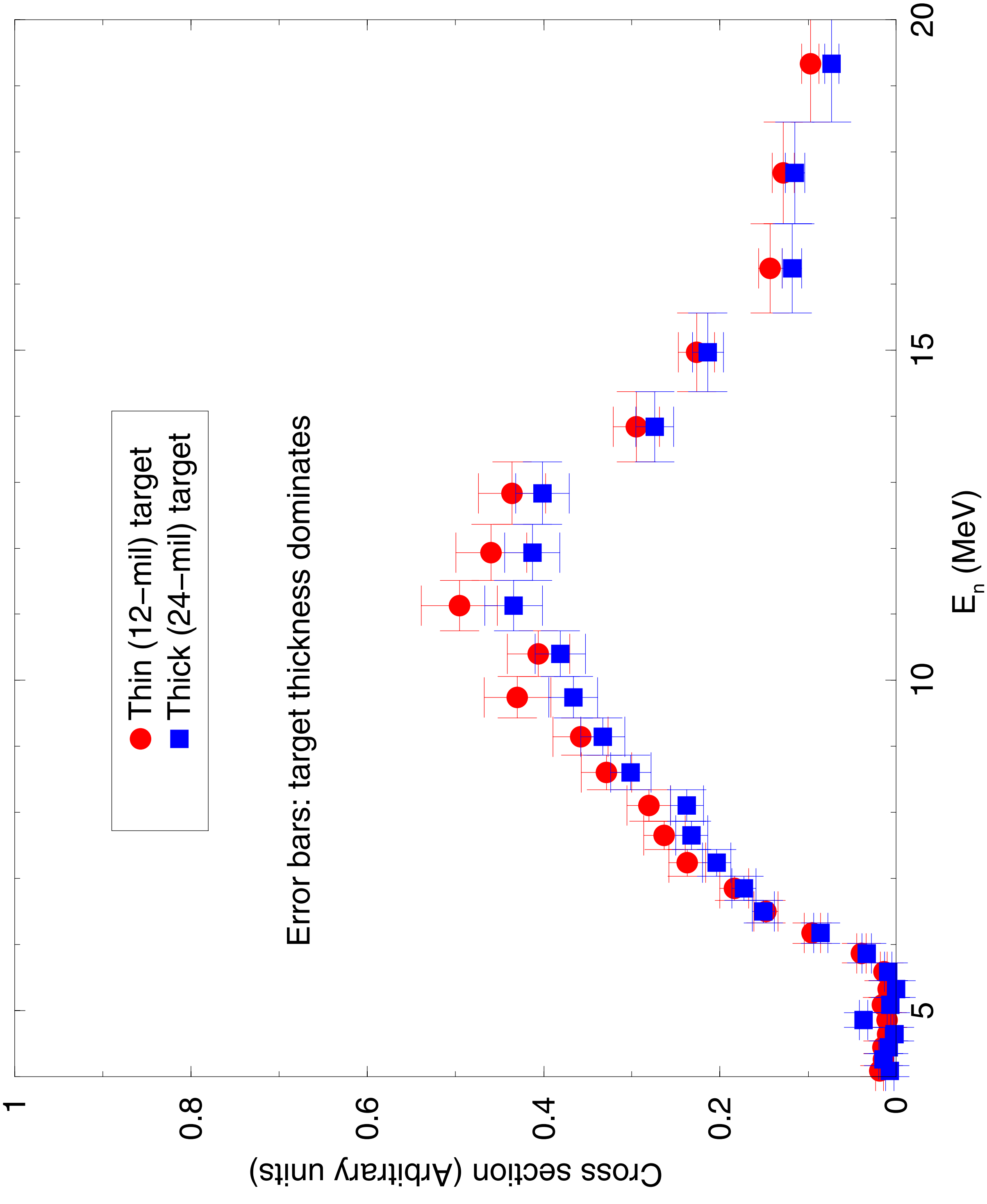
Fig. 2: The results of an MCNP calculation of the total point source efficiency of the planar detectors in GEANIE are compared to the measured values.

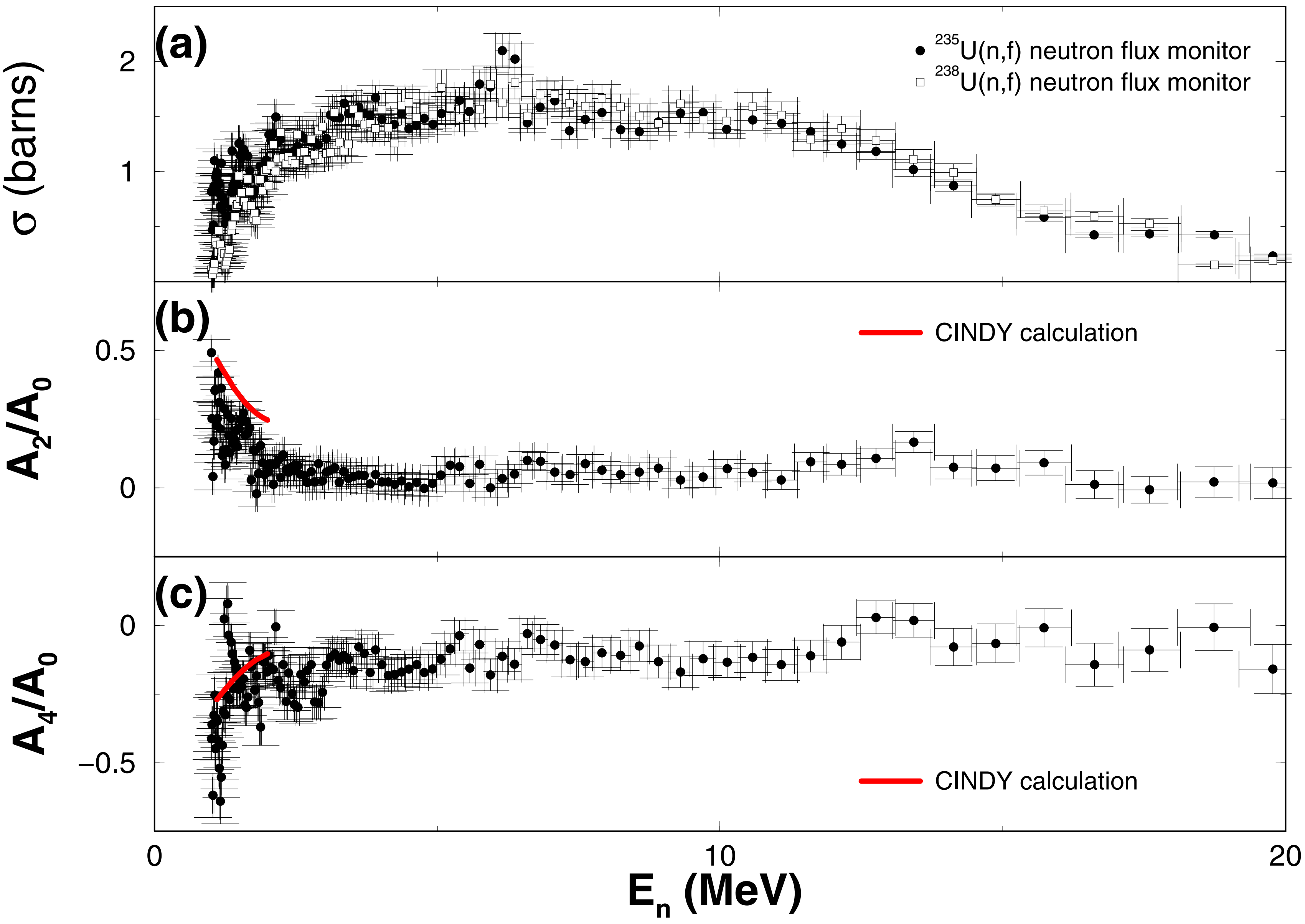
Fig. 3: The excitation function of the ^{235}U(n,2nγ), with $E_\gamma = 157$ keV ($6^+ \rightarrow 4^+$) is shown for thin and thick target cases. The agreement within uncertainties indicates that the attenuation correction applied in both cases is consistent.

Fig. 4: The A_0, A_2, and A_4 coefficients of the angular distribution are plotted for the ^{56}Fe(n,n$'\gamma$) where $E_\gamma = 0.847$ MeV reaction.


Relative efficiency
Beam profile
Flux−weighted profile
Relative efficiency
Radial distance (cm)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.00
0.50
1.00
1.50
2.00


1.2
1.1
1.0
0.9
0.8
Ratio
0
200
400
600
800
1000
Energy (keV)
Error bars: pt. source + statistics of calculation


Thin (12−mil) target
Thick (24−mil) target
Error bars: target thickness dominates
Cross section (Arbitrary units)
0
0.2
0.4
0.6
0.8
1
E_n (MeV)
5
10
15
20


(a)
(b)
(c)
σ (barns)
A_2/A_0
A_4/A_0
2
1
0.5
0
0
−0.5
0
10
20
E_n (MeV)
^{235}U(n,f) neutron flux monitor
^{238}U(n,f) neutron flux monitor
CINDY calculation
CINDY calculation