New (n, γ) Measurements on Elemental Iron from 850 to 2500 keV

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ABSTRACT

Few experimental measurements of the (n, γ) cross section exist for iron above the first inelastic state of ^{56}Fe at 847 keV. Because capture measurements rely on the detection of prompt photon cascades emitted by the de-excitation of the compound nucleus, it is challenging to separate the capture signal from photons generated in inelastic scattering events. A new array of C_6D_6 detectors at the Gaerttner Linear Accelerator Center at Rensselaer Polytechnic Institute has enabled the straightforward separation of the radiative capture and inelastic scattering signals in a sample of natural iron through the use of digital filtering and analysis. These techniques have enabled the extension of iron experimental data to energies of 2500 keV. Results show good agreement with the ENDF/B-VII.1 and JEFF-3.2 evaluations to 1500 keV.

KEYWORDS
Cross Sections, Neutron Capture, C_6D_6, Time of Flight, Iron

1. INTRODUCTION

Iron's ubiquitous role as a structural material necessitates accurate and complete cross section data over a wide range of incident neutron energies. In particular, radiative capture cross section data are needed in the keV range in order to support accurate and robust neutron transport calculations for reactor and criticality safety applications. In the case of iron, most experimental capture data from which evaluated nuclear libraries are derived are limited to energies below the first inelastic level in ^{56}Fe at 847 keV.

Energy-dependent (n, γ) cross section measurements rely on the detection of the prompt cascade of de-excitation photons emitted at the time of capture. Above the inelastic scattering threshold; however, additional photon production from inelastic interactions competes with capture reactions, contaminating the signal and making accurate measurements challenging.

A new experimental apparatus has been developed and installed at the Gaerttner Linear Accelerator Center at Rensselaer Polytechnic Institute[1] with the capability of measuring capture cross sections above the inelastic threshold. A digital data acquisition system saves the raw waveforms of every detector

event, allowing for multiple analyses of the data with different post-processing algorithms that can separate the capture signal from the inelastic contribution.

2. THEORY OF OPERATION

2.1. Total Energy Method

The primary design criterion for a capture detection system is that its efficiency to detect a capture event be independent of the cascade pathway [2]. That is, it should be dependent only on the total excitation energy of the compound nucleus and not on the energy spectrum or photon multiplicity of the de-excitation cascade. This is achieved by either employing a large 4π detector that absorbs all cascade photons (the Total Absorption Method), or by using a detector whose detection efficiency is proportional to the incident photon energy (the Total Energy Method [3]).

For a γ-ray detector with a low detection efficiency ($\epsilon_\gamma << 1$) such that only a single photon per capture cascade is detected, the efficiency to detect a capture event (ϵ_c) is given by the sum of the individual detection efficiencies of all the photons in the cascade. This approximation is shown in Eq. 1.

$$\epsilon_c = 1 - \prod_i (1 - \epsilon_{\gamma,i}) \approx \sum_i \epsilon_{\gamma,i} \quad (1)$$

The assertion that the detection efficiency ϵ_γ be proportional to incident photon energy $E_{\gamma,i}$ is made in Eq. 2. This is the primary principle of the total energy method.

$$\epsilon_{\gamma,i} = kE_{\gamma,i} \quad (2)$$

By combining the approximation in Eq. 1 and assertion in Eq. 2, it can be shown that the efficiency to detect a capture event is proportional to the total excitation energy (E_{ex}) of the compound nucleus, which is the sum of the neutron separation energy (S_n) and incident neutron energy in the center-of-mass system ($E_{n,cm}$), and thus independent of the cascade pathway.

$$\epsilon_c \approx k \sum_i E_{\gamma,i} \approx kE_{ex} = k(S_n + E_{n,cm}) \quad (3)$$

2.2. Pulse Height Weighting Technique

For most detectors, the γ-ray detection efficiency is not proportional to the incident γ-ray energy. In order to maintain the validity of the Total Energy method, the detector's response function needs to be corrected *a posteriori* using a mathematical weighting function[4].

For an incident γ-ray of energy E_γ, the probability that it deposits energy E_d within the detector is governed by the response function $R(E_d, E_\gamma)$. The integral of the response function from a lower level discriminator (E_L) to an arbitrary maximum energy is equal to the total detection efficiency of photons of E_γ (Eq. 4).

$$\epsilon_\gamma = \int_{E_L}^{\infty} R(E_d, E_\gamma) dE_d \quad (4)$$

In order to preserve the proportionality of efficiency to incident photon energy, a weighting function is used to modify the response function of the detector (Eq. 5). In practice, the weighting function has the form of a 5^{th} – order polynomial[2] for computational convenience.

$$E_\gamma = k\epsilon_\gamma = \int_{E_L}^{\infty} R(E_d, E_\gamma) W(E_d) dE_d \quad (5)$$

The weighting function is dependent on the sample-detector geometry, sample material and thickness, detector resolution, and photon energy, and is determined via detailed Monte Carlo simulation of the experimental setup. Response functions to monoenergetic photons emitted from within the sample are tallied in the simulations, and a weighting function is determined via least-squares fit of the function's polynomial coefficients to Eq. 5 for each simulated photon energy[2], [5].

2.3. Inelastic Filtering

Inelastic scattering reactions occur when a neutron scatters off a target nucleus, exciting the nucleus in the process. The scattered neutron is accompanied by photon emission from the subsequent de-excitation of the inelastic state. The key to separating the capture signal from data taken above the inelastic threshold is the use of a lower-level energy discriminator that can window out the monoenergetic inelastic photons while preserving the signal from higher energy transitions. In the case of iron, over 90% of its de-excitation photons have energies in excess of 7 MeV. This makes applying a lower-level energy discriminator to the data a fairly straightforward task, with minimal bias due to the removal of low-energy cascade transitions.

3. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup consists of an array of four C_6D_6 detector modules mounted to a low-mass aluminum structure and placed on a 125° back angle with respect to the incident neutron beam. Samples of B_4C (enriched to 91% ^{10}B), elemental lead, and elemental iron were mounted to a stepper-motor controlled sample changer, along with an open sample holder.

Time-of-Flight (TOF) measurements were performed on the samples at a flight path of 45.277 m. Data were collected for approximately 100 hours using a LINAC pulse width of 10 ns and a pulse repetition rate of 400 Hz. Data acquisition was handled with a 10-bit, 1.25 GHz Struck Systems SIS3305 digitizer board, which saved the raw detector waveforms directly to a file with no additional signal conditioning required.

4. RESULTS & DISCUSSION

Approximately 100 GB of digitized waveforms were saved over the course of the experiment. Custom software applications were used to bin the data in TOF, as well as to investigate the γ-ray spectra at different incident neutron energy ranges.

Fig. 1 shows the measured γ-ray spectrum from the iron sample at incident neutron energies from 1000-2500 keV and from 400-600 keV, which are energy ranges above and below the inelastic threshold, respectively. The deposited photon energy, E_d, is determined from the pulse integral of each digitized event. The Compton edges of the 847 and 1408 keV photons from the first inelastic states of ^{56}Fe and ^{54}Fe, respectively, are prominently visible in the higher energy spectrum. By applying cutoffs above 1000 keV and 1750 keV, these signals can be filtered out.

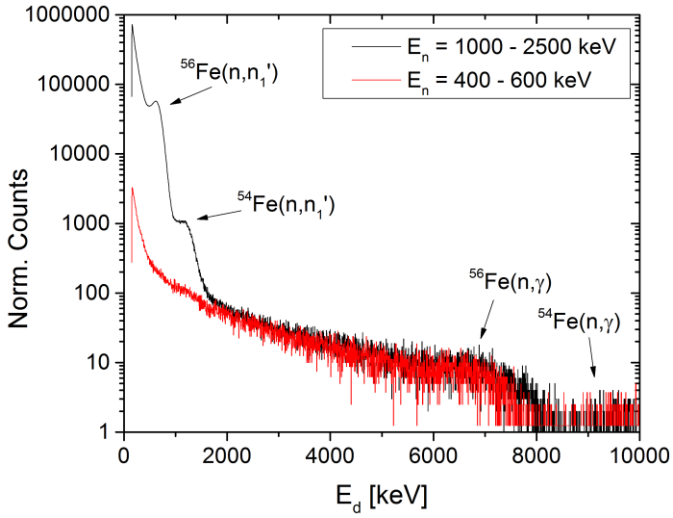

Figure 1. Photon energy spectra above and below the inelastic thresholds of ^{54,56}Fe.

Experimental yields were determined from the ratio of the weighted, monitor-normalized,background-corrected counting rate of the iron sample ($\dot{C}_{Fe} - \dot{C}_{bkg}$) to that of the B_4C sample ($\dot{C}_{B4C} - \dot{C}_{bkg}$). This ratio was corrected for the energy-dependent shape of the B_4C photon-production yield (Y_{B4C}) to determine the effective energy-dependent flux shape, and normalized to the saturated 1.15 keV resonance in ^{56}Fe (f).

$$Y_{exp} = f \cdot Y_{B4C} \cdot \frac{\dot{C}_{Fe} - \dot{C}_{bkg}}{\dot{C}_{B4C} - \dot{C}_{bkg}} \qquad (7)$$

Above neutron energies of 847 keV, a lower-level discriminator of 1 MeV was used to window out the inelastic contribution of ^{56}Fe. Similarly, above 1408 keV, a 1.75 MeV discriminator was used to remove the inelastic contributions of ^{54}Fe. The effects of applying these different discriminators are shown in Fig. 2.

At lower energies within the resolved resonance region, the data show good agreement with SAMMY [6] calculations performed with existing evaluated libraries (Fig. 3a). At higher energies, in the vicinity of the inelastic threshold, Fig. 3b shows a comparison of the data from this measurement compared with current evaluations and all relevant experimental data known to exist in this energy region.

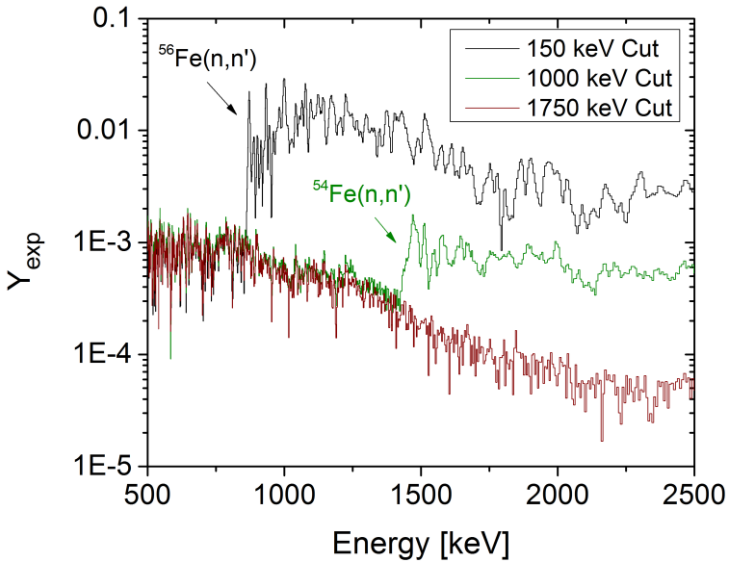

Figure 2. Capture yields in iron from 500-2500 keV, showing the effects of applying energy discriminators above the inelastic thresholds of ^{54,56}Fe.

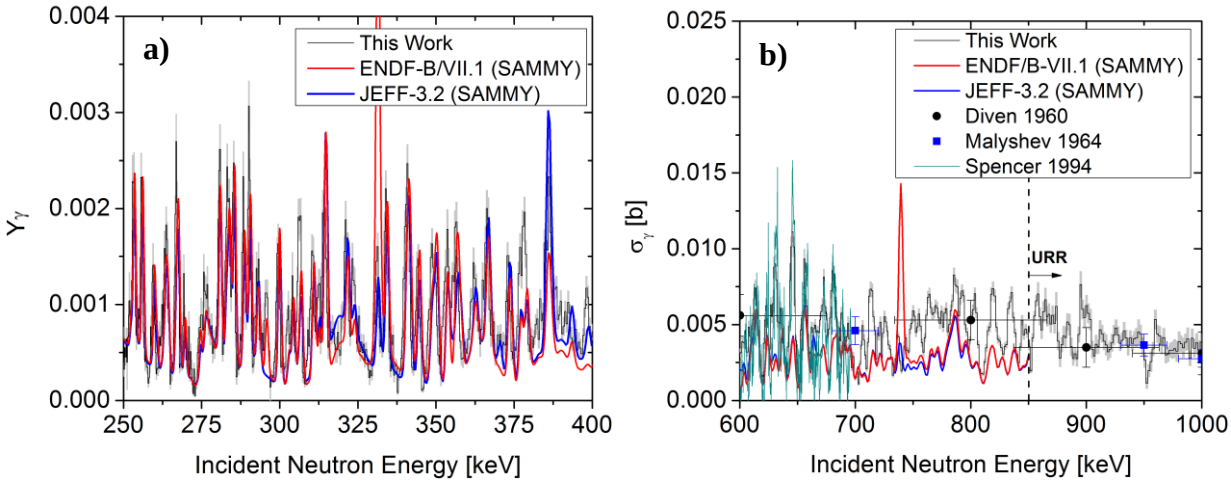

Figure 3. Comparison of capture yields in elemental iron from experimental data and existing evaluations in the energy ranges a) 250-400 keV; b) 600-1000 keV.

The data taken in this experiment show good agreement with previous measurements by Spencer, Diven, and Malyshev up to 1.5 MeV. There are also significant differences between the ENDF/B-VII.1 and JEFF-3.2 libraries, notably on the ^{56}Fe resonances at ~330, 380 and 740 keV. At energies above 1500 keV, it was discovered that there is a significant systematic uncertainty due to non-1/v nature of the B_4C photon production cross section, and capture yield measurements above this energy require an alternate method of flux measurement.

5. CONCLUSION

The new capture detection system at the RPI LINAC Center has the capability to separate the capture signal from mixed capture and inelastic reactions by applying energy discriminators to the digitized waveforms stored over the course of an experiment. This method can be applied to other isotopes with similar characteristics and provide new capture data in energy regions where it was previously not available.

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