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Neutron-induced Cross Section Measurements of Calcium

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To support the US Department of Energy Nuclear Criticality Safety Program, neutron-induced cross section experiments were performed at the Geel Electron Linear Accelerator of the Institute for Reference Material and Measurements of the Joint Research Centers, European Union. Neutron capture and transmission measurements were carried out using a metallic calcium sample. The measured data will be used for a new calcium evaluation, which will be submitted with covariances to the ENDF/B nuclear data library.

I. INTRODUCTION

Among its many applications, calcium is a constituent of concrete and is very frequently found in combination with uranium. This could be for the construction of a nuclear power plant or storage facilities for nuclear waste. Liquid radioactive waste is frequently solidified by mixing it with concrete. In addition to that, the ^{40}Ca (94.94% abundance) neutron capture cross section is of interest to nuclear astrophysics. Due to its massive solar abundance, it is considered to be a "neutron poison" in the *s*-process nucleosynthesis, which mainly occurs in asymptotic giant branch stars.

Evaluated data for calcium found in the nuclear data libraries such as ENDF/B, JEFF, or JENDL do not perform well in criticality calculations [1]. For this reason, the US Department of Energy Nuclear Criticality Safety Program (NCSP) has identified calcium as a nuclide needing improvement for supporting criticality safety analyses. In particular, a consistent set of covariance data is needed to support sensitivity/uncertainty analyses. Criticality safety calculations for storage of nuclear material outside reactors frequently encounter neutron spectra different from nuclear power plants. In fact, a significant contribution to the neutron spectrum results from the epithermal energy region (keV region), where the neutron cross section is sometimes not well known or nonexistent. As a result, the NCSP initiated new neutron-induced cross section measurements at the Geel Electron Linear Accelerator (GELINA) on calcium to support the development of a new cross-section evaluation in the resonance region.

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II. EXPERIMENTS AT GELINA

The time-of-flight (TOF) facility GELINA [2] was used to perform neutron capture and transmission measurements. GELINA is the only TOF facility left with excellent resolution over a broad neutron energy range. Bremsstrahlung from a pulsed electron beam impinging on a rotating depleted uranium target produces neutrons via photo-nuclear and -fission reactions. The GELINA electron beam with a maximum energy of 150 MeV is compressed using a bunching magnet to 1 ns pulse width. Two beryllium canned water containers mounted above and below the mercury-cooled neutron production target are used for neutron moderation. Thus, the produced neutron spectrum ranges from thermal up to several MeV; consequently, only few experiments are needed to determine the cross section in the resolved and unresolved resonance region. The small neutron production target, short neutron pulse, and long flight paths up to 400 m result in an excellent TOF- and thus neutron energy resolution. This facilitates resolving individual resonances in the neutron cross sections. For the reported experiment, GELINA operated at 800 Hz repetition rate and 1 ns pulse width.

Many of the previous experiments on which the actual evaluation rely were performed with calcium carbonate samples. In these experiments, for each calcium nucleus there are in total four nuclei of carbon and oxygen that scatter mainly neutrons and can produce an unwanted prompt background in the capture experiments, which is very difficult to correct. For this reason a metallic calcium sample was chosen, which was encapsulated in a thin-walled aluminum can to prevent reaction with air. While producing the metallic samples it was found that even though the calcium metal looked shiny on the outside, it could still be oxidized on the inside. As a consequence, all calcium was distilled to remove the oxide before producing the metallic disk. Two disks with diameters of 6 cm and a thickness of 5 cm or 1 cm, respectively, were produced for the transmission experiments. A 7.62 cm diameter disk with 0.635 cm thickness was additionally used in the capture experiments. To compensate for the effect of the metallic can, data were taken with corresponding empty containers.

A. Transmission Experiments

The data for neutron capture cross sections are usually obtained with a rather thick sample, which has the drawback that corrections have to be applied by the data analysis programs. These corrections such as self-shielding and multiple scattering require reliable neutron widths as input to the data analysis programs. The lack of this information can result in erroneous capture cross section data [3]. Thus, neutron total cross sections were obtained from neutron transmission data on 5 cm metallic calcium sample using the flight path 4 experimental setup at a distance of 49.33 m from the neutron production target.

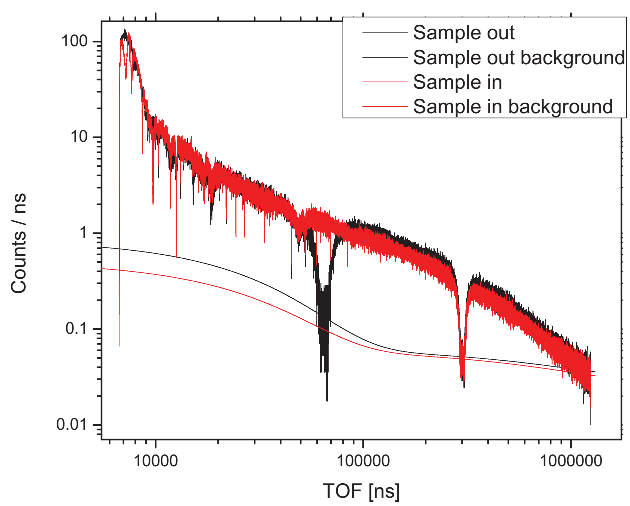

FIG. 1. Background correction for natural calcium transmission data.

The black resonance filter technique [4] is used to determine the time-dependent and -independent backgrounds. In 2012, this setup had undergone changes to better handle the gaps in the data resulting from the black resonance filters used to determine the background. A third sample position with various combination of black filters was added to the setup. In this way the background can be continuously monitored without interfering with the transmission data. A typical transmission spectrum for the natural calcium sample, open beam and corresponding backgrounds, is shown in Fig. 1. A 0.635 cm thick ^{6}Li-glass detector was used to detect the transmitted neutron. A pre-sample collimator limited the neutron beam to 4.5 cm diameter at the sample position in the 30 m flight station and made sure that the photomultiplier mounted on one side of the scintillation glass was not affected by neutrons. The samples, their corresponding empty containers, and background filters were cycled periodically through the neutron beam to reduce the systematic uncertainties. For each sample and cycle, the neutron flux was recorded and used for normalization. The transmission spectrum for natural calcium from 1 to 300 keV is shown in Fig. 2.

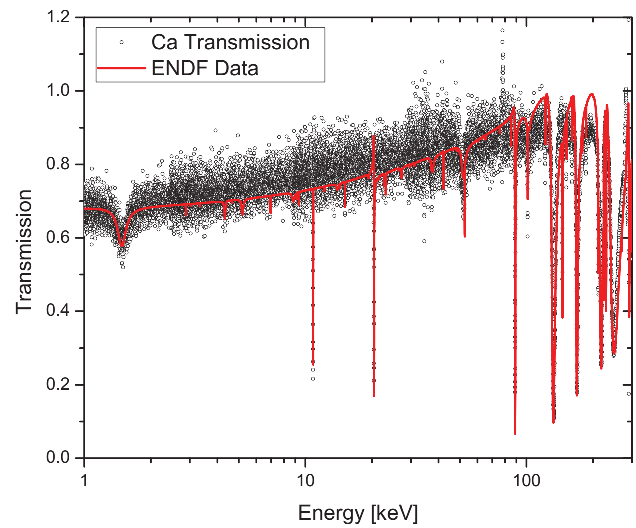

FIG. 2. Transmission for natural calcium compared to calculated transmission from ENDF/B-VII.1 resonance parameters.

B. Neutron Capture Experiments

The experimental (n,γ) cross section for natural calcium in the neutron energy range from 14 to 150 keV is compared to the ENDF/B-VII.1 evaluation in Fig. 3. The calculated cross section includes all experimental effects. The neutron capture data were obtained with four C_6D_6-detectors mounted at an angle of 125° to the neutron beam at the 60 m flight station on flight path 14 of the GELINA facility. The pulse-height weighting method is applied to these so-called total energy detectors using MCNP to calculate the weighting function. The calcium samples and corresponding empty container were mounted in the well-collimated beam on a low mass sample holder at a distance of 58.56 m from the neutron production target. Located in front of the sample was a ^{10}B ionization chamber to record the neutron flux simultaneously. Normalization runs were made with a 80 mm diameter natural Fe sample, and the well-known 1.15 keV resonance in ^{56}Fe was used to normalize the calcium capture data. A scattering sample was used to determine