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# Inelastic neutron scattering cross-section measurements on $^{7}$Li and $^{63,65}$Cu

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**Abstract.** The $\gamma$-ray production cross section for the 477.6-keV transition in $^{7}$Li following inelastic neutron scattering has been measured from the reaction threshold up to 18 MeV. This cross section is interesting as a possible standard for other inelastic scattering measurements. The experiment was conducted at the Geel Electron LINear Accelerator (GELINA) pulsed white neutron source with the Gamma Array for Inelastic Neutron Scattering (GAINS) spectrometer. Previous measurements of this cross section are reviewed and compared with our results. Recently, this cross section has also been calculated using the continuum discretized coupled-channels (CDCC) method. Experiments for studying neutrinoless double-$\beta$ decay ($2\beta0\nu$) or other very rare processes require greatly reducing the background radiation level (both intrinsic and external). Copper is a common shielding and structural material, used extensively in experiments such as COBRA, CUORE, EXO, GERDA, and MAJORANA. Understanding the background contribution arising from neutron interactions in Cu is important when searching for very weak experimental signals. Neutron inelastic scattering on $^{\mathrm{nat}}$Cu was investigated with GAINS. The results are compared with previous experimental data and evaluated nuclear data libraries.

## 1. Introduction

In experiments involving neutron beams, the flux is often measured with a transmission fission chamber, containing e.g., $^{235}$U, $^{238}$U, or $^{239}$Pu. The disadvantage of such a system is the low counting rate of the fission events, which necessitates long acquisition times for collecting adequate statistics. An alternative method for neutron fluence determination could be the measurement of $\gamma$ rays following inelastic scattering, provided that the $\gamma$-ray production cross section is known sufficiently well. Several possibilities for a reference cross section have been considered in [1,2], where the 477.6-keV $1/2^{-} \rightarrow 3/2^{-}_{\mathrm{g.s.}}$ transition in $^{7}$Li was concluded to be one of the best candidates. Factors making this transition favorable include isotropic $\gamma$-ray emission, negligible internal conversion coefficient, low inelastic threshold (546 keV), and fairly smooth energy dependence of the cross section. Lithium and beryllium fluorides are also interesting as coolants for Molten Salt Reactor Systems, as described in the Technology Roadmap for Generation IV Nuclear Energy Systems [3]. Additionally, in deuterium-tritium fusion reactors the fuel cycle requires breeding of tritium from $^{6,7}$Li. The interactions between neutrons and lithium affect the tritium breeding ratio, nuclear heating, and radiation damage. Thus good quality nuclear data on neutron- and proton-induced reactions of $^{6,7}$Li are necessary.

Copper is largely used in tokamaks in heat sink components, magnets, diagnostics, waveguides and mirrors. A lack of good quality data affects the analysis required for fusion applications as it relies on the use of validated nuclear data and calculation tools. Copper is also commonly used as a shielding material e.g., in experiments studying very rare phenomena, such as neutrinoless double-beta decay. To reduce the background, the experiments are performed deep underground. Also the detectors are made using very high-purity materials, even with activities below 1 $\mu$Bq/kg. Major sources of neutron-induced background are secondary neutrons produced by cosmic muons, and $(\alpha, n)$ or fission reactions occurring in rocks. Neutrons are a concern as they produce $\gamma$ rays through inelastic scattering and other neutron-induced nuclear reactions. Background in $2\beta0\nu$ experiments due to inelastic neutron scattering in various materials has been investigated before, see e.g., [4] and references therein. There are several experimental efforts currently ongoing to search for neutrinoless double-$\beta$ decay, such as COBRA, CUORE, EXO, GERDA, KamLAND-Zen, MAJORANA, and SuperNEMO. Most of the experiments mentioned above use copper as a structural or shielding material.

## 2. Experimental setup

The experiments studying inelastic scattering on $^{7}$Li and $^{63,65}$Cu were conducted at JRC Geel in 2015. The neutrons were produced using the GELINA pulsed white neutron source with a 800-Hz repetition rate, and the GAINS spectrometer was used for $\gamma$-ray detection. Currently, GAINS consists of 12 large-volume high-purity germanium (HPGe) detectors manufactured by

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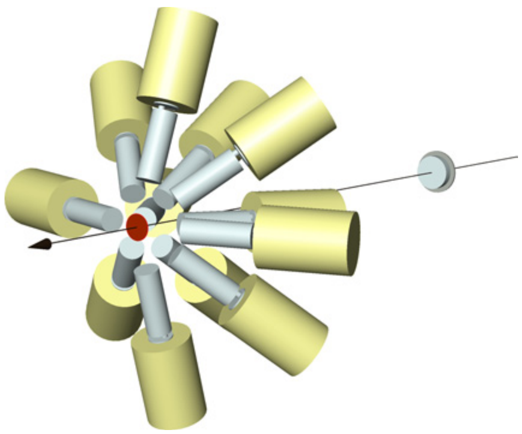

**Figure 1.** A schematic representation of the GAINS array. The direction of the neutron beam is indicated with the arrow. The $^{235}$U fission chamber can be seen behind the HPGe-detector array.

CANBERRA, mounted at 110°, 125°, and 150° with respect to the beam direction, with four detectors at each angle. A schematic of the array is presented in Fig. 1. The neutron flux was measured with a $^{235}$U fission chamber. The chamber contains 8 $UF_4$ deposits of 70 mm diameter, placed on five aluminum foils (20 $\mu$m thickness). Details on the chamber are presented in [5,6]. The data acquisition system for the HPGe detectors uses Acquiris DC440 digitizers, which have a 12-bit amplitude resolution and a sampling rate of 420 million samples/s. A more detailed description of the data acquisition system is provided in [7]. The lithium sample was an optical-quality lithium fluoride (LiF) disk with an areal density of 0.5410(2) g/cm$^2$. The copper sample was a stack of six disks of natural isotopic composition, 2.1360(2) g/cm$^2$ in total.

There were two experiments devoted to $^7$Li and one for $^{63,65}$Cu. The $^{63,65}$Cu experiment and the first $^7$Li experiment were conducted at GELINA flight path 3, 200-m measurement cabin. The sample position of GAINS was located 198.757(5) m from the neutron source, and the fission chamber was positioned 146.8 cm upstream. The second $^7$Li measurement was carried out at flight path 3, 100-m measurement cabin. There the sample is at 99.676(5) m from the neutron source, and the fission chamber is 211.5 cm upstream.

The determination of the absolute $\gamma$-ray detection efficiency of the GAINS spectrometer relies on Monte Carlo simulations, where experimentally determined $^{152}$Eu point- source efficiencies are compared with MCNP5 [8] simulations. When a satisfactory agreement exists between the experimental and simulated efficiencies, the final efficiencies are then determined by introducing the sample with proper size and material into the simulation. The method to determine the fission chamber efficiency is described in [6]. It includes corrections for neutron flux attenuation between the fission chamber and the sample and multiple neutron scattering in the sample itself. A correction factor is determined by comparing MCNP5 simulations of the actual experimental setup and of the same configuration with the sample and all materials between the fission chamber and the sample voided. Finally, the extraction of $\gamma$-production, level population,

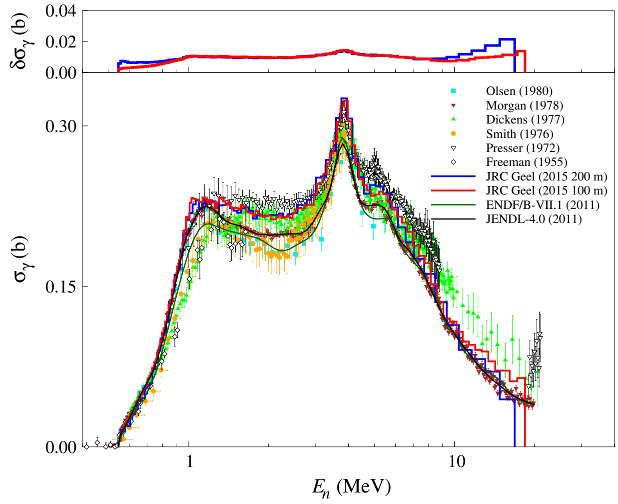


**Figure 2.** The $\gamma$-ray production cross section, $\sigma_\gamma$, for the 477.6-keV transition in $^7$Li, from the reaction LiF$(n, n'\gamma)$LiF, compared with selected previous experimental data sets and the ENDF/B-VII.1, and JENDL-4.0 libraries. The total experimental uncertainties of the JRC Geel data are displayed on the top panel.

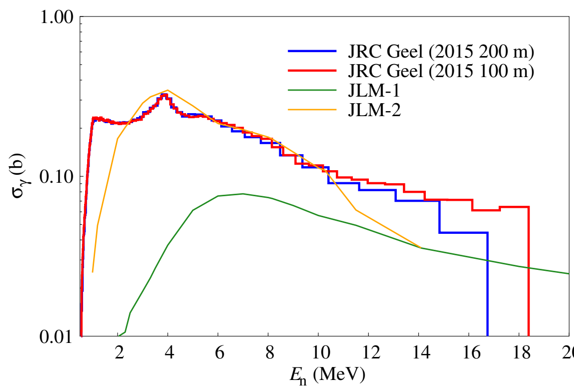


**Figure 3.** Comparison between our experimental data and a recent calculation [10] using the CDCC method with two different parameter sets.

and inelastic scattering cross sections from GAINS data is described in [9].

## 3. Results

### 3.1. Inelastic neutron scattering by $^7$Li

The results of the two $^7$Li experiments have been published in Ref. [11]. They will briefly be reviewed here. The $\gamma$-ray production cross section for the 477.6-keV transition in $^7$Li is displayed in Fig. 2 along with selected previous experimental data sets and the ENDF/B-VII.1, and JENDL-4.0 libraries. From the inelastic threshold up to about $E_n = 0.8$ MeV there is a reasonably good agreement between the different data sets. Above 1.2 MeV, the JRC Geel results agree best with the data of Dickens *et al*. and Presser. Typically, our results are consistently higher than all the others. Above 8 MeV our data agrees well with those of Morgan. From the two evaluated libraries, JENDL-4.0 is in a slightly better agreement with our data.

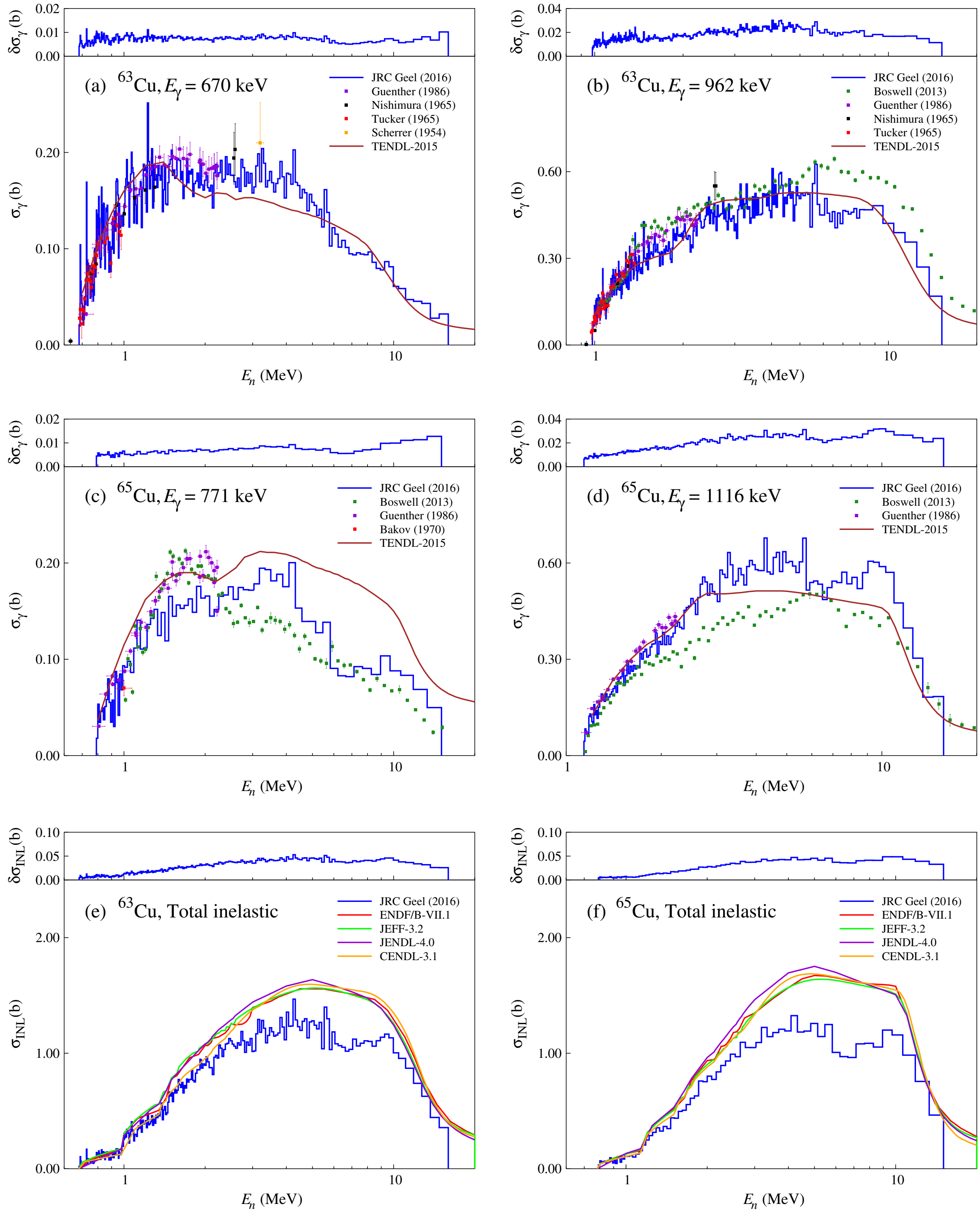


**Figure 4.** The $\gamma$-ray production cross sections, $\sigma_\gamma$, for the first two transitions feeding the ground state in $^{63}$Cu [(a) and (b)], and $^{65}$Cu [(c) and (d)]. Data from previous experiments and from the TENDL-2015 data library are also included. The total inelastic cross sections for $^{63}$Cu and $^{65}$Cu are shown in panels (e) and (f), respectively. Data from several evaluated libraries is provided for comparison. Above 2 MeV neutron energy the total inelastic cross sections from the present experiment are lower limits. The total experimental uncertainties, $\delta\sigma_\gamma$, of the JRC Geel data are displayed on the top of each panel.

Recently, the elastic neutron scattering cross section and the inelastic cross sections to the first and second excited states in $^7$Li have been calculated by Ichinkhorloo et al. [10]. A comparison between the calculated $^7$Li$(n,n_1)$ cross section, using two different parametrizations (JLM-1 and JLM-2), and the JRC Geel experimental data is shown in Fig. 3. In the JLM-1 calculation normalization factors are taken to reproduce the integrated elastic scattering cross section. The normalization is then adjusted at each incident neutron energy below 11.5 MeV (JLM-2). The inelastic scattering cross section is then calculated using these parameter sets. The JLM-1 calculation clearly underestimates the cross section, but JLM-2 quite successfully reproduces the experimental data, especially from 2 MeV to 10 MeV.

### 3.2. Inelastic neutron scattering by $^{63,65}$Cu

The $\gamma$-ray production cross sections for the first two transitions feeding the ground state in $^{63,65}$Cu are displayed in Fig. 4 [panels (a)–(d)], as well as available previous experimental data. The agreement with the JRC Geel data is typically quite good, although there are discrepancies with the data by Boswell et al. Along with the experimental data, the TENDL-2015 nuclear data library [12] is presented. TENDL-2015 is based on calculations with the TALYS nuclear model code system.

The total inelastic cross sections for $^{63,65}$Cu are shown in panels (e) and (f) of Fig. 4, and compared with data from several evaluations: ENDF/B-VII.1, JEFF-3.2, JENDL-4.0, and CENDL-3.1. The measured total inelastic cross sections are accurate only to a maximum energy up to which excited states have been observed. Any contributions from higher levels are not included, so above this energy the cross section is only a lower limit. In the case of the JRC Geel data this energy is about 2 MeV, which explains the discrepancies at higher neutron energies.

## 4. Conclusions

Neutron inelastic scattering by $^{7}$Li was studied with the GAINS setup at the GELINA time-of-flight facility. The $\gamma$-ray production cross section for the 477.6-keV transition was measured with a total relative uncertainty less than 5% for $1\,\text{MeV} < E_n < 8\,\text{MeV}$. The two JRC Geel data sets were well consistent with each other, but some discrepancies exists between previously measured data. Inelastic neutron scattering by $^{63,65}$Cu has been investigated using GAINS with a natural Cu sample, allowing the determination of $\gamma$-ray production, level population, and total inelastic cross sections. The total relative uncertainties for the highest-intensity $\gamma$-rays are similar to that of the $^{7}$Li experiment. Fairly good agreement when compared with previous experimental data and evaluated libraries is found.

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