

A substitution measurement for cross section of $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction using natCu and ^{63}Cu targets by quasi-monoenergetic γ beams at SLEGS*

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Abstract

To overcome the difficulty and expensive cost for some specific isotopic targets, a substitution method was proposed to measure the cross section of (γ, n) reactions. Considering that the natural copper element (natCu) only has ^{63}Cu and ^{65}Cu isotopes, the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction was taken as an example to test the substitution method. Using quasi-monoenergetic γ beams provided by the Shanghai Laser Electron Gamma Source (SLEGS) of the Shanghai Synchrotron Radiation Facility (SSRF), the natCu(γ, n) was measured from $E_\gamma = 11.09$ to 17.87 MeV. Furthermore, based on the previously measured $^{63}\text{Cu}(\gamma, n)$ reaction using the same experimental setup at SLEGS, the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ was extracted using the substitution method, which was compared to the existing experimental data measured by bremsstrahlung and positron annihilation in-flight light sources, and the Talys2.0 toolkit predictions. The γ strength function (γSF) of ^{65}Cu is obtained from the $^{65}\text{Cu}(\gamma, n)$ data, and the reaction cross section of $^{64}\text{Cu}(n, \gamma)$ was further calculated.

Full Text

Preamble

A Substitution Measurement for the Cross Section of the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ Reaction Using natCu and ^{63}Cu Targets with Quasi-Monoenergetic γ Beams at SLEGS

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To overcome the difficulties and high costs associated with obtaining specific isotopic targets, a substitution method was proposed for measuring the cross sections of (γ , n) reactions. Considering that natural copper (natCu) contains only ^{63}Cu and ^{65}Cu isotopes, the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction was selected as a test case for this substitution method. Using quasi-monoenergetic γ beams provided by the Shanghai Laser Electron Gamma Source (SLEGS) at the Shanghai Synchrotron Radiation Facility (SSRF), the natCu(γ , n) reaction was measured from $E_\gamma = 11.09$ to 17.87 MeV. Furthermore, based on previously measured $^{63}\text{Cu}(\gamma, n)$ reaction data obtained with the same experimental setup at SLEGS, the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ cross section was extracted using the substitution method. The results were compared with existing experimental data measured using bremsstrahlung and positron annihilation in-flight light sources, as well as with predictions from the Talys2.0 toolkit. The γ strength function (γSF) of ^{65}Cu was obtained from the $^{65}\text{Cu}(\gamma, n)$ data, and the reaction cross section for $^{64}\text{Cu}(n, \gamma)$ was subsequently calculated.

Keywords: photoneutron cross section, flat efficiency detector, laser Compton scattering, γ rays, SLEGS, cross-section subtraction method

Introduction

The $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction has important applications in both medical and scientific research. In medicine, ^{64}Cu is a short-lived β^+ emitter ($T_{1/2} = 12.7$ h; β^+ with 278 keV mean energy, 61.5%; β^- with 191 keV mean energy, 38.5%), making this reaction an important method for producing the radioisotope ^{64}Cu [?, ?], which is widely used in nuclear medical imaging techniques such as positron emission tomography (PET) [?, ?] and single photon emission computed tomography (SPECT) [?]. It plays a significant role in cancer diagnosis and treatment. For example, ^{64}Cu -labeled peptides such as ^{64}Cu -DOTATATE [?, ?] are used for diagnosing neuroendocrine tumors [?], ^{64}Cu -labeled oxygen depletion probes such as ^{64}Cu -ATSM [?] are employed to detect hypoxic regions in tumors, and ^{64}Cu -labeled prostate specific membrane antigen (PSMA) [?] ligands are utilized in PET imaging of prostate cancer for precise tumor cell localization. Additionally, ^{64}Cu can be used in radionuclide therapy to destroy tumor cells through its β^+ and β^- decay properties [?]. In scientific research, the $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction is also of great importance, as it enables studies of nuclear structure, properties of atomic nuclei, and nuclear reaction mechanisms.

During the last century, laboratories worldwide conducted experimental studies on the photoneutron reaction of ^{65}Cu using bremsstrahlung (BR) light sources [?, ?] and positron annihilation in-flight (PAIF) light sources [?] through the activation method. Due to the low natural abundance of ^{65}Cu , it is difficult to obtain high-purity experimental target materials. Consequently, very little experimental data exist for ^{65}Cu , and the available data show large discrepancies. In response to this situation, Varlamov et al. [?] evaluated the existing data. By comparing the evaluated and experimental reaction cross sections, they found that the results from BR and PAIF sources agree within the low incident γ energy range but differ significantly at high γ energies, reflecting systematic errors in experiments caused by misclassification of neutron channels [?]. The quasi-monochromatic γ -ray source generated by laser Compton scattering provides an opportunity for measuring the (γ, n) reaction with improved precision, which helps to resolve discrepancies in existing data.

In this study, the cross sections for the $\text{natCu}(\gamma, n)$ reaction were measured within the Giant Dipole Resonance (GDR) energy region using the SLEGS beamline [?] at the Shanghai Synchrotron Radiation Facility (SSRF) [?]. The $^{65}\text{Cu}(\gamma, n)$ cross sections were determined via the subtraction method, and the neutron capture cross sections for ^{64}Cu were extracted. The structure of this article is organized as follows. Section III describes the experimental procedure for measuring the $\text{natCu}(\gamma, n)$ cross sections. Section IV presents the results for the monochromatic $\text{natCu}(\gamma, n)$ cross sections and the $^{65}\text{Cu}(\gamma, n)$ cross sections obtained via the subtraction method. Section V discusses the discrepancies among existing experimental data and presents cross-sectional data for the $^{64}\text{Cu}(n, \gamma)$ reaction. Finally, a brief conclusion is given in Section VI.

II. Cross-Section Substitution Measurement Method for (γ , N) Reactions

The use of pure isotopic targets in experiments typically faces difficulties related to low purity and high cost. Appropriate substitution measurement technology provides an indirect measurement approach for isotopes that have extremely low natural abundances, require exorbitantly high purification costs, or are extremely difficult to fabricate into target materials under natural conditions. For a metallic elemental target containing n types of isotopes, the total photonuclear reaction cross section σ_{total} obeys the principle of linear superposition, which can be expressed by the following formula:

$$\sigma_{\text{total}} = \sum w_j \cdot \sigma_j,$$

where w_j represents the effective mass weight coefficient of the j -th isotope, defined as

$$w_j = \frac{m_j \cdot f_j}{\sum_{k=1}^n m_k \cdot f_k},$$

where m_j is the atomic mass of the j -th isotope and f_j is its natural abundance (or artificially enriched fraction). This weight model rigorously accounts for the effects of mass differences and abundance distributions among isotopes on the macroscopic cross section.

To solve for the cross section of the target isotope i , the above formula can be transformed to yield:

$$\sigma_i = \frac{\sigma_{\text{total}} - \sum_{j \neq i} w_j \cdot \sigma_j}{w_i}.$$

To ensure the validity of this equation, two crucial conditions must be met. First, the cross sections $\sigma_{\{j \neq i\}}$ of all isotopes other than the target isotope i must have been determined by independent and reliable experiments. Second, the isotopic composition parameters w_j need to be determined with high accuracy to guarantee the reliability of the calculation results.

Compared to the traditional single-isotope target measurement method, the cross-section substitution measurement (CSSM) method demonstrates remarkable advantages. Firstly, it excels in cost-effectiveness. By using the substitution method for cross-section measurements, researchers can avoid purchasing expensive isotopic target materials, thereby significantly reducing experimental costs. This allows researchers to conduct more studies under constrained funding conditions. Secondly, this method exhibits extremely high universality and can be widely applied to substitution measurements of various isotopes with natural

abundances less than 100%, providing more flexible and diverse experimental means for research in related fields.

However, when applying the CSSM method, some potential issues require special attention. When the target isotope abundance is extremely low, the CSSM data may suffer from significant systematic errors, compromising the accuracy and reliability of the experimental results.

III. Experiment

This experiment was carried out at the Shanghai Laser Electron Gamma Source (SLEGS) beamline station [?, ?] located at the Shanghai Synchrotron Radiation Facility (SSRF). The SLEGS beamline employs inverse Compton scattering technology, where 3.5 GeV electrons in the SSRF storage ring collide with photons from a CO₂ laser (wavelength 10.64 μm, power 100 W) to generate quasimonochromatic gamma rays with tunable energies from 0.66 to 21.7 MeV.

The energy of the γ beam is adjusted in slant-scattering mode with a minimum step of 10 keV. For details on measurements of (γ , n) reactions at SLEGS, see Refs. \cite{21-25}. The cross sections for the natCu(γ , n) reaction were measured at 37 energy points ranging from 10.9 to 17.8 MeV.

The laser Compton scattering (LCS) γ beam, after passing through the collimation system, irradiated the experimental target positioned at the center of the ³He flat efficiency detector (FED) [?]. A large-volume BGO detector downstream of the FED monitored the in-beam gamma flux. The incident gamma spectrum was reconstructed using the direct unfolding method combined with a Geant4-simulated detector response matrix (Fig. 2 [Figure 2: see original paper]), as described in Refs. \cite{27-29}.

A. Targets

The natCu target, weighing 3.15 g, was placed in polyethylene target holders and irradiated using LCS γ beams. The alignment of the target and the FED with the LCS γ -ray beam was adjusted using a MiniPIX X-ray camera for collimation. Detailed specifications can be found in Table 1 .

Table 1. Information for natCu targets used in experiments.

Target	Weight	Diameter	Total thickness	Density
natCu	3.15 g	10.00 mm	4.48 mm	9.69 g/cm ³

Total chemical impurity: natCu > 99.99%

The target holder has a 10 mm diameter window. Considering that the size of the LCS γ -ray beam was approximately 4 mm in diameter at the target position, the 10 mm diameter window was sufficient to ensure that the target could be measured without influence from neutrons originating in the polyethylene.

B. Measurements

The SLEGS facility features a new FED with 26 proportional counters arranged in three concentric rings within a polyethylene moderator shielded by 2 mm of Cd. The counters, 500 mm long and filled with 2 atm of ^3He , were read out through CAEN SY4527LC/Mesytec MDPP-16 systems.

Geant4 simulations indicate that the efficiency decreases from 35.6% at 50 keV to 42.3% at 1.65 MeV [?], then drops to 40.7% at 3 MeV. The ^{252}Cf calibration resulted in an efficiency of $42.1 \pm 1.3\%$ at 2.13 MeV (Fig. 3 [Figure 3: see original paper]). The uncertainty of the efficiency was assessed by varying the density of the moderator, the pressure of the gas, and the counter geometry. Weighted average efficiency corrections were applied based on neutron energy profiles [?, ?].

IV. Data Analysis

The total detector efficiency and the efficiencies of individual rings are shown in Fig. 3 [Figure 3: see original paper]. The detector efficiency curves were simulated using neutron-evaporation spectra and monochromatic neutrons. The red dots correspond to the neutron spectrum described by a Maxwell-Boltzmann distribution at the average neutron energy ($T = 1.42$ MeV) of ^{252}Cf [?].

The photoneutron cross section in the monochromatic approximation is calculated by the integral equation [?]:

$$\int E_{\max} n_{\gamma}(E) \sigma(E) dE = N_{\gamma} N_t \xi \epsilon_n,$$

where $n_{\gamma}(E)$ is the energy distribution of LCS γ -ray beams, normalized in the integration region; $\sigma(E)$ represents the photoneutron cross section; N_n is the number of detected neutrons; N_t is the number of target nuclei per unit area; N_{γ} is the number of incident γ particles with energies above the neutron threshold; and ϵ_n is the self-attenuation coefficient given by $1 - e^{-\mu t}$, where μ is the linear attenuation coefficient of the sample and t is the sample thickness.

In the monochromatic approximation, the photoneutron cross section can be expressed as:

$$\sigma_{E_{\max}}(\gamma, n) = \frac{N_n}{N_{\gamma} N_t \xi \epsilon_n}.$$

In the experiment, the laser pulse cycle was 1000 μs (50 μs on + 950 μs off). Due to the energy dispersion of LCS γ -ray beams, the monochromatic approximation is insufficient for determining photoneutron cross sections. When neutrons were counted with the FED array, flat-efficiency regions for each detector ring were determined, considering neutron energy and detector parameters. The median

method was used to establish optimal efficiency points and improve neutron count statistics.

To solve the unfolding problem, the integral in Eq. (4) is approximated as a summation for each γ beam profile, resulting in a system of linear equations $\sigma_f = D\sigma$ [?, ?]. The folding iteration method was used to solve this underdetermined system. Starting with a constant trial function σ_0 , the folded vector $\sigma_0^f = D\sigma_0$ was calculated [40–43]. The next trial input function σ_1 was obtained by adding the difference between the experimental spectrum σ_{exp} and the folded spectrum σ_0^f to $D\sigma_0$, after spline interpolation to match vector dimensions. The iteration proceeds with [?, ?]:

$$\sigma_{i+1} = \sigma_i + (\sigma_{\text{exp}} - \sigma_i^f).$$

The iteration continues until convergence when σ_{i+1} approximates σ_{exp} within statistical errors. Convergence was assessed by calculating the reduced χ^2 between σ_{i+1} and σ_{exp} , with typical convergence achieved in about three iterations, making the reduced χ^2 value approximately 1.

The monochromatic cross sections of the $\text{natCu}(\gamma, n)$ reaction were derived using the unfolding iteration method. Fig. 4 [Figure 4: see original paper] compares the quasimonochromatic and monochromatic cross sections for $\text{natCu}(\gamma, n)$. Statistical uncertainties are attributed solely to neutron counts, as the high number of γ -ray counts contributes negligible uncertainties. Experiments for the reactions $^{197}\text{Au}(\gamma, n)$ [?] and $^{27}\text{Al}(\gamma, n)$ [?] have been performed at SLEGS. A comparison of the $^{197}\text{Au}(\gamma, n)$ reaction data with the findings of Itoh et al. [?] reveals an integrated cross-section difference of approximately 0.4%, which underscores the reliability of SLEGS in both measurement procedures and data analysis. The cross sections from the SLEGS experiment are of comparable or even higher quality than some datasets in the EXFOR database. A summary of uncertainties is presented in Table 2.

Table 2. Summary of uncertainties for measurements at SLEGS.

Error Source	Process	Type	Uncertainty
FED efficiency	Data processing	Systematic	3.02%
External copper	Data processing	Systematic	0.50%
Target thickness	Data processing	Systematic	<0.10%
N _n extraction algorithm	Data processing	Systematic	2.00%
Unfolding method	Data processing	Systematic	1.00%

In this experiment, the measured natCu target material had isotopic abundances of 69.15% for ^{63}Cu and 30.85% for ^{65}Cu . The one-neutron (S_n) and two-neutron (S_{2n}) separation energies for ^{63}Cu are 10.86 MeV and 19.74 MeV, respectively, while for ^{65}Cu they are 9.91 MeV and 17.83 MeV, respectively [?, ?].

In light of this, during the data processing phase of this experiment, a subtraction calculation was carried out in the energy interval where the one-neutron separation thresholds of ^{65}Cu and ^{63}Cu overlap. To obtain high-precision photonuclear reaction cross-section data for ^{65}Cu , it is necessary to account for and subtract the contribution from the reaction cross section of ^{63}Cu [?]. Substituting these parameters into Eq. (1), the total cross section of the photonuclear reaction for natCu can be expressed as:

$$\sigma_{\text{natCu}} = w_{63\text{Cu}} \cdot \sigma_{63\text{Cu}} + w_{65\text{Cu}} \cdot \sigma_{65\text{Cu}}.$$

The effective mass-weight coefficients for the two isotopes, $w_{\{^{63}\text{Cu}\}}$ and $w_{\{^{65}\text{Cu}\}}$, are calculated using Eq. (2) and then substituted into Eq. (3):

$$\sigma_{65\text{Cu}} = \frac{\sigma_{\text{natCu}} - w_{63\text{Cu}} \cdot \sigma_{63\text{Cu}}}{w_{65\text{Cu}}}.$$

In this equation, the cross-section data for natCu were precisely determined through the aforementioned independent experiments, and the benchmark cross-section data for ^{63}Cu were derived from the precise measurement results reported in Ref. [?]. The results for the ^{65}Cu photonuclear neutron cross sections obtained via the subtraction method are shown in Fig. 5 [Figure 5: see original paper].

V. Results and Discussion

^{65}Cu Photoneutron Reaction Cross Section

To ensure the quality of the cross-section data for ^{65}Cu obtained via the subtraction method, the measured (γ, n) results for natCu and ^{63}Cu [?] from SLEGS were selected, which have the same measured energy points in the experiments. The selected energy points fall within the (γ, n) energy intervals for both ^{63}Cu and ^{65}Cu , and a total of 35 such data points met these criteria. These data were then substituted into Eq. (9), and the results are shown in Fig. 5 [Figure 5: see original paper].

The photoneutron cross-section data for $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ measured at SLEGS are compared with existing data from the EXFOR database in Fig. 5. Although the overall trends align, significant discrepancies are observed in the absolute values. The experiment by Fultz et al. [?] at Lawrence Livermore National Laboratory (LLNL) is closest to our results. They used BF_3 neutron detectors and measured in the energy range of 9.34 to 27.78 MeV. Data from Katz et al. [?], obtained using bremsstrahlung radiation at the BETAT accelerator in Canada with a 22 MeV endpoint energy, are notably higher than the LLNL data. Antonov's measurements [?] at JINR using bremsstrahlung radiation are significantly higher than other datasets in both neutron threshold and cross-section values.

We further investigated the effects of varying isotopic abundances on cross sections, as such variations can induce discrepancies in the results. As illustrated in Fig. 5, an increase in the abundance of the target isotope leads to a corresponding decrease in the cross section; conversely, a decrease in the abundance of the target isotope results in a corresponding increase in the cross section. Consequently, it is imperative to precisely determine the isotopic abundances in the target material before commencing the experiment.

As discussed in Ref. [?], the ratios of integral cross sections provide a clear indication of systematic differences among various data compilations. The integral cross sections in the S_n and $S_{\{max\}}$ regions are calculated as:

$$\sigma_{\text{int}} = \int_{S_n}^{S_{\text{max}}} \sigma(E) dE.$$

Based on these experimental data, the integral ratios of the photoneutron reaction cross section were calculated for energy ranges from S_n to 15 MeV, 15 MeV to $S_{\{2n\}}$, and S_n to $S_{\{2n\}}$, with results presented in Table 4. In the S_n to 15 MeV energy range, the experimental results of this work show a difference of only 0.4% from the Fultz data and a discrepancy of less than 1% from TALYS theoretical calculations, while discrepancies with other datasets exceed 40%. In the 15 MeV to $S_{\{2n\}}$ range, the minimum difference between this work and the Katz [?] data is 14%, and differences with other datasets exceed 20%. Overall, the neutron threshold and cross-section peak position demonstrate good consistency with the Fultz [?] data and TALYS-2021 calculations; the neutron threshold shows favorable agreement with the Katz data; however, there are notable differences in both the neutron threshold and peak position compared to the Antonov [?] data. Collectively, these structural differences in the data are of significant importance for refining nuclear data evaluations and optimizing theoretical model parameters.

Table 3. The monochromatic cross sections of $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$.

	natCu(γ , n) Cross sections [MeV][mb]	natCu(γ , n) Total uncer- tainty [mb]	$^{63}\text{Cu}(\gamma$, n) Cross sections [mb]	$^{63}\text{Cu}(\gamma$, n) Total un- certainty [mb]	$^{65}\text{Cu}(\gamma$, n) Cross sections [mb]	$^{65}\text{Cu}(\gamma$, n) Total un- certainty [mb]

Table 4. Integral cross-section ratio.

Ratio relation	$\sigma_{n,15\text{ MeV}}^{\text{int}} \text{ ratio}$	$\sigma_{15\text{ MeV}}^{\text{int}} S_{2n}$	$\sigma_{n,15\text{ MeV}}^{\text{int}} S_{2n} \text{ ratio}$
SLEGS/TALYS	0.996	1.140	1.050
SLEGS/Fultz	1.004	1.210	1.090
SLEGS/Katz	0.580	1.140	0.790
SLEGS/Antonov	0.410	0.790	0.540

⁶⁴Cu Radiative Neutron Capture Cross Section

The gamma strength function (γ SF) [?] is used to describe the average probabilities of gamma decay and absorption in nuclear reactions and represents an important parameter for characterizing nuclear reaction processes. When research involves reactions with gamma rays, such as (n, γ) and (γ , n), the precision of the γ SF is particularly crucial. According to the principle of detailed balance [?] and the generalized Brink assumption [?, ?], it is believed that the upward γ SF $f_{X}(E_{\gamma})$ is approximately equal to the downward γ SF $f_{X}(E_{\gamma})$. Therefore, it can be considered that $f_{X}(E_{\gamma}) = f_{X}(E_{\gamma})$. Connecting the (upward) photoneutron cross section to the (downward) γ SF [?]:

$$f_{X1}(E_{\gamma}) = \frac{3\pi^2 \hbar^2 c^2}{\sigma_{\gamma n}(E_{\gamma})}$$

The constant is $1/(3\pi^2 \hbar^2 c^2) = 8.674 \times 10^{-8} \text{ mb}^{-1} \text{ MeV}^{-2}$, and using this relationship, the experimentally constrained γ SF can be obtained from the measured photoneutron reaction cross-section data. The γ SF model in TALYS is then compared with the experimentally constrained γ SF, and the model closest to the experimentally obtained γ SF is selected. Furthermore, the γ SF model is constrained using the normalization parameter G_{norm} in the TALYS 2.0 toolkit, and the optimization of G_{norm} is achieved by minimizing the χ^2 value, thus making the theoretical calculation results of the constrained γ SF model more consistent with the experimentally obtained γ SF values.

The γ SF of ⁶⁵Cu(γ , n) constrained by the measured (γ , n) data is shown in Fig. 6 [Figure 6: see original paper], with the expression for χ^2 being:

$$\chi^2 = \sum_{i=1}^N \left(\frac{\sigma_{\text{th},i} - \sigma_{\text{exp},i}}{\sigma_{\text{err},i}} \right)^2,$$

where N represents the total number of experimental data points, and $\sigma_{\text{th},i}$, $\sigma_{\text{exp},i}$, and $\sigma_{\text{err},i}$ denote the theoretical value, experimentally measured value, and experimental error of the γ SF at the i-th data point, respectively.

The neutron capture cross section of ⁶⁴Cu, after adjustment with the optimal G_{norm} value, is shown in Fig. 7 [Figure 7: see original paper]. Specifically, in the Kopecky-Uhl generalized Lorentzian model [?], G_{norm} is set

to 1.2; in the Goriely hybrid model, its value is 1.4. Notably, when constrained by G_{norm} , the χ^2 value of the hybrid mode [?] is the smallest among all investigated models, showing the best agreement with this set of experimental data.

Similarly, Utsunomiya et al. [?] and Z.C. Li et al. [?] previously conducted related research and measured the (n, γ) radiative reaction cross sections for the $^{136, 137}\text{Ba}$ and ^{62}Cu isotopes. In this study, due to the lack of experimental data on the low-lying excited states and neutron resonance spacings of ^{65}Cu , constraints on the nuclear level density (NLD) model are limited, resulting in substantial theoretical uncertainties.

VI. Summary

The reaction cross sections of $\text{natCu}(\gamma, n)$ were measured in the incident energy range of 10.89 to 17.87 MeV using the ^3He FED system developed at SLEGS. Based on the measured photoneutron cross-section data, the reaction cross sections of $^{65}\text{Cu}(\gamma, n)$ were obtained using the cross-section substitution method. Compared with existing experimental data, the reliability of this method was demonstrated, providing a new approach for photoneutron cross-section measurements. Based on the $^{65}\text{Cu}(\gamma, n)$ data obtained in this work, the experimentally constrained γSF of ^{65}Cu was extracted and compared with TALYS 2.0 calculation results considering different models. In addition, the cross-section curve of its inverse reaction, $^{64}\text{Cu}(n, \gamma)$, was calculated. This provides a new approach for extracting (n, γ) cross sections for some unstable nuclides.

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References

- [1] I. M. Jackson, P. J. H. Scott, S. Thompson, Clinical applications of radiolabeled peptides for PET. *Semin. Nucl. Med.* 47, 493–523 (2017). doi:10.1053/j.semnuclmed.2017.05.007.
- [2] M. Brandt, J. Cardinale, M. L. Aulsebrook et al., An overview of PET radiochemistry, part 2: Radiometals. *J. Nucl. Med.* 59, 1500–1506 (2018). doi:10.2967/jnumed.117.190801.
- [3] O. O. Krasnovskaya, D. Abramchuck, A. Erofeev et al., Recent advances in $^{64}\text{Cu}/^{67}\text{Cu}$ -based radiopharmaceuticals. *Int. J. Mol. Sci.* 24, 9154 (2023). doi:10.3390/ijms24119154.
- [4] G. A. Follacchio, M. S. De Feo, G. De Vincentis et al., Radiopharmaceuticals labelled with copper radionuclides: clinical results in human beings. *Curr. Radiopharm.* 11, 22–33 (2018). doi:10.2174/1874471011666171211161851.
- [5] A. Boschi, P. Martini, E. Janevik-Ivanovska et al., The emerging role of copper-64 radiopharmaceuticals as cancer theranostics. *Drug Discov. Today*

- 23, 1489–1501 (2018). doi:10.1016/j.drudis.2018.04.002.
- [6] M. Bobeica, D. Niculae, D. Balabanski et al., Radioisotope production for medical applications at ELI-NP. *Rom. Rep. Phys.* 68, 847–883 (2016). doi:10.1140/epjp/i2016-16094-2.
- [7] W. Luo, Production of medical radioisotope ^{64}Cu by photoneutron reaction using ELI-NP γ -ray beam. *Nucl. Sci. Tech.* 27, 96 (2016). doi:10.1007/s41365-016-0094-6.
- [8] W. Luo, D. L. Balabanski, D. Filipescu, A data-based photonuclear simulation algorithm for determining specific activity of medical radioisotopes, *Nucl. Sci. Tech.* 27, 113 (2016). doi:10.1007/s41365-016-0111-9.
- [9] B. Grubmüller, R. P. Baum, E. Capasso et al., ^{64}Cu -PSMA-617 PET/CT imaging of prostate adenocarcinoma: first in-human studies. *Cancer Biother. Radiopharm.* 31, 277–286 (2016). doi:10.1089/cbr.2015.1964.
- [10] H. E. Johns, L. Katz, R.E.A. Douglas et al., Gamma-neutron cross sections. *Phys. Rev.* 80, 1062 (1950). doi:10.1103/PhysRev.80.1062.
- [11] A. D. Antonov, N. P. Balabanov, Yu. P. Gangrskii et al., Studies of photonuclear reactions with emission of α particles in the region of the giant dipole resonance. *Soviet Journal of Nuclear Physics.* 51, 193–196 (1990).
- [12] S. C. Fultz, R. L. Bramblett, J. T. Caldwell et al., Photoneutron cross sections for natural Cu, Cu^{63} , and Cu^{65} . *Phys. Rev.* 133, B1149 (1964). doi:10.1103/PhysRev.133.B1149.
- [13] F. Cantiello, V. Gangemi, G. L. Cascini et al., Diagnostic accuracy of ^{64}Cu prostate-specific membrane antigen positron emission tomography/computed tomography for primary lymph node staging of intermediate-to high-risk prostate cancer: our preliminary experience. *Urology.* 106, 139–145 (2017). doi:10.1016/j.urology.2017.04.019.
- [14] A. V. Varlamov, V. V. Varlamov, D. S. Rudenko et al., Atlas of giant dipole resonances. Parameters and graphs of photonuclear reaction cross sections. IAEA NDS, Vienna, Austria. 1–311 (1999). (NDS)-394, doi:10.18036/nsd.indc.nds.0394.
- [15] W. J. Huang, M. Wang, F. G. Kondev et al., “The AME 2020 atomic mass evaluation (I). Evaluation of input data, and adjustment procedures,” *Chinese Physics C.* 45, no. 3, p. 030002, 2021, IOP Publishing. doi:10.1088/1674-1137/abddb0.
- [16] M. Wang, W. J. Huang, F. G. Kondev et al., “The AME 2020 atomic mass evaluation (II). Tables, graphs and references,” *Chinese Physics C.* 45, no. 3, p. 030003, 2021, IOP Publishing. doi:10.1088/1674-1137/abddaf.
- [17] L. X. Liu, H. W. Wang, G. T. Fan et al., The SLEGS beamline of SSRF, *Nucl. Sci. Tech.* 35, 111 (2024). doi:10.1007/s41365-024-01414-2.
- [18] H. W. Wang, G. T. Fan, L. X. Liu et al., Commissioning of laser electron gamma beamline SLEGS at SSRF, *Nucl. Sci. Tech.* 33, 87 (2022). doi:10.1007/s41365-022-01076-0.
- [19] K. J. Chen, L. X. Liu, Z. R. Hao et al., Simulation and test of the SLEGS TOF spectrometer at SSRF. *Nucl. Sci. Tech.* 34(3), 47 (2023). doi:10.1007/s41365-023-01194-3.
- [20] Z. R. Hao, G. T. Fan, H. W. Wang et al., Collimator system of SLEGS

- beamline at Shanghai Light Source, Nucl. Instrum. Meth. A 1013, 165638 (2021). doi:10.1016/j.nima.2021.165638.
- [21] H. H. Xu, G. T. Fan, H. W. Wang et al., Interaction chamber for laser Compton slant-scattering in SLEGS beamline at Shanghai Light Source, Nucl. Instrum. Meth. A 1033, 166742 (2022). doi:10.1016/j.nima.2022.166742.
- [22] Z. R. Hao, H. H. Xu, G. T. Fan et al., Gamma spot monitor at SLEGS beamline, Nucl. Instrum. Meth. A 1068, 169748 (2024). doi:10.1016/j.nima.2024.169748.
- [23] Z. C. Li, Y. X. Yang, Z. W. Cao et al., Effective extraction of photoneutron cross-section distribution using gamma activation and reaction yield ratio method, Nucl. Sci. Tech. 34, 170 (2023). doi:10.1007/s41365-023-01330-z.
- [24] M. D. Zhou, G. T. Fan, C. W. Ma et al., Measurement of $^{59}\text{Co}(\gamma, n)^{58}\text{Co}$ using a new flat-efficiency neutron detector at SLEGS, Phys. Rev C. (Submitted).
- [25] X. Pang, B. H. Sun, L. H. Zhu et al., Progress of photonuclear cross sections for medical radioisotope production at the SLEGS energy domain, Nucl. Sci. Tech. 34, 187 (2023). doi:10.1007/s41365-023-01339-4.
- [26] S. Amano, K. Horikawa, K. Ishihara et al., Several-MeV γ rays generation at NewSUBARU by laser Compton backscattering, Nucl. Instrum. Meth. A 602, 337 (2009). doi:10.1016/j.nima.2009.01.010.
- [27] L. X. Liu, H. Utsunomiya, G. T. Fan et al., Energy profile of laser Compton slant-scattering γ -ray beams determined by direct unfolding of total-energy responses of a BGO detector, Nucl. Instrum. Meth. A 1063, 169314 (2024). doi:10.1016/j.nima.2024.169314.
- [28] W. Luo, H. Y. Lan, Y. Xu et al., Implementation of the n-body Monte-Carlo event generator into the Geant4 toolkit for photonuclear studies, Nucl. Instrum. Meth. A 849, 49 (2017). doi:10.1016/j.nima.2017.01.010.
- [29] S. Agostinelli, J. Allison, K. A. Amako et al., Geant4—a simulation toolkit, Nucl. Instrum. Meth. A 506, 250 (2003). doi:10.1016/S0168-9002(03)01368-8.
- [30] Z. R. Hao, L. X. Liu, Y. Zhang et al., Photoneutron dataset generation and analysis at SLEGS. ChinaXiv:202412.00386. doi:10.12074/202412.00386.
- [31] Z. R. Hao, G. T. Fan, L. X. Liu et al., Design and simulation of 4π flat-efficiency ^3He neutron detector array, Nucl. Tech. (in Chinese) 43, 9 (2020). doi:10.11889/j.0253-3219.2020.hjs.43.110501.
- [32] P. Jiao, Z. R. Hao, Q. K. Sun et al., Measurements of $^{27}\text{Al}(\gamma, n)$ reaction using quasi-monoenergetic γ beams from 13.2 to 21.7 MeV at SLEGS. Nucl. Sci. Tech. 36, 66 (2025). doi:10.1007/s41365-025-01662-y.
- [33] Z. C. Li, Z. R. Hao, Q. K. Sun et al., New measurement of $^{63}\text{Cu}(\gamma, n)^{62}\text{Cu}$ cross-section using quasi-monoenergetic γ -ray beam. Nucl. Sci. Tech. 36, 34 (2025). doi:10.1016/j.nimb.2024.165595.
- [34] B. Berman, J. Caldwell, R. Harvey et al., Photoneutron cross sections for ^{90}Zr , ^{91}Zr , ^{92}Zr , ^{94}Zr , and ^{89}Y , Phys. Rev. 162, 1098 (1967). doi:10.1103/PhysRev.162.1098.
- [35] O. Itoh, H. Utsunomiya, H. Akimune et al., Photoneutron cross sections for Au revisited: measurements with laser Compton scattering γ -rays and data reduction by a least-squares method, J. Nucl. Sci. Technol. 48, 834 (2011).

doi:10.1080/18811248.2011.9711766.

- [36] J. W. Jury, B. L. Berman, D. D. Faul et al., Photoneutron cross sections for C^{13} . *Phys. Rev. C.* 19, 1684 (1979). doi:10.1103/PhysRevC.19.1684.
- [37] National Institute of Standards and Technology (NIST), X-ray mass attenuation coefficients. Online resource, NIST X-ray Mass Attenuation Coefficients (2025).
- [38] Y. L. Dang, L. F. Long, F. G. Yong et al., New measurement of thick target yield for narrow resonance at $E_x = 9.17$ MeV in the $^{13}C(p, \gamma)^{14}N$ reaction. *Chin. Phys. B.* 28, 060706 (2019). DOI:10.1088/1674-1056/ab96a0.
- [39] F. L. Liu, W. S. Yang, J. H. Wei et al., Study on γ -ray source from the resonant reaction $^{19}F(p, \alpha\gamma)^{16}O$ at $E_p = 340$ keV. *Chin. Phys. B.* 29, 070702 (2020). DOI:10.1088/1674-1056/ab96a0.
- [40] M. Guttormsen, T. S. Tveter, L. Bergholt et al., The unfolding of continuum γ -ray spectra. *Nucl. Instrum. Meth. A.* 374, 3 (1996). doi:10.1016/0168-9002(96)00197-0
- [41] H. Utsunomiya, I. Gheorghe, D. M. Filipescu et al., Direct neutron-multiplicity sorting with a flat-efficiency detector. *Nucl. Instrum. Meth. A.* 871, 135 (2017). doi:10.1016/j.nima.2017.08.001
- [42] I. Gheorghe, H. Utsunomiya, S. Katayama et al., Photoneutron cross-section measurements in the $^{209}Bi(\gamma, xn)$ reaction with a new method of direct neutron-multiplicity sorting. *Phys. Rev. C.* 96, 044604 (2017). doi:10.1103/PhysRevC.96.044604
- [43] I. Gheorghe, H. Utsunomiya, K. Stopani et al., Updated neutron-multiplicity sorting method for producing photoneutron average energies and resolving multiple firing events. *Nucl. Instrum. Meth. A.* 1019, 165867 (2021). doi:10.1016/j.nima.2021.165867
- [44] T. Renstrøm, H. Utsunomiya, H. T. Nyhus et al., Verification of detailed balance for γ absorption and emission in Dy isotopes, *Phys. Rev. C.* 98, 054310 (2018). doi:10.1103/PhysRevC.98.054310.
- [45] G. C. Yang, L. M. Hua, F. Lu et al., Response functions of a 4π summing gamma detector in β -Ols method, *Nucl. Sci. Tech.* 33, 68 (2022). doi:10.1007/s41365-022-01058-2
- [46] V. Varlamov, B. Ishkhanov, V. Orlin, Reliability of $(\gamma, 1n)$, $(\gamma, 2n)$, and $(\gamma, 3n)$ cross-section data on ^{159}Tb , *Phys. Rev. C.* 95, 054607 (2017). doi:10.1103/PhysRevC.95.054607.
- [47] G. Bartholomew, E. Earle, A. Ferguson et al., Gamma-ray strength functions. *Adv. Nucl. Phys.* 7, 229-324 (1973). doi:10.1007/978-1-4615-9044-6-4.
- [48] J. M. Blatt, V. F. Weisskopf, F. J. Dyson et al., Theoretical nuclear physics. American Institute of Physics. (1953). doi:10.1063/1.3061164.
- [49] H. Utsunomiya, T. Renstrøm, G. M. Tveten et al., Photoneutron cross sections for Ni isotopes: Toward understanding (n, γ) cross sections relevant to weak s-process nucleosynthesis. *Phys. Rev. C.* 98, 054619 (2018). doi:10.1103/PhysRevC.98.054619.
- [50] D. Filipescu, I. Gheorghe, H. Utsunomiya et al., Photoneutron cross sections for samarium isotopes: Toward a unified understanding of (γ, n) and (n, γ) reactions in the rare earth region. *Phys. Rev. C.* 90, 064616 (2014).

doi:10.1103/PhysRevC.90.064616.

[51] R. Capote, M. Herman, P. Obložinský et al., RIPL-reference input parameter library for calculation of nuclear reactions and nuclear data evaluations. Nucl. Data Sheets. 110, 3107-3214 (2009). doi:10.1016/j.nds.2009.10.004.

[52] A. Koning, TASMANT-2.0. <https://nds.iaea.org/talys/tutorials/tefal.pdf> (2023).

[53] S. Goriely, V. Plujko. Simple empirical E1 and M1 strength functions for practical applications. Phys. Rev. C. 99, 014303 (2019). doi:10.1103/PhysRevC.99.014303

[54] E. B. Balbutsev, I. V. Molodtsova, P. Schuck. Spin scissors mode and the fine structure of M1 states in nuclei. Nucl. Phys. A. 872, 1 (2011). doi:10.1016/j.nuclphysa.2011.09.016

[55] T. Renstrøm, H. Utsunomiya, H. T. Nyhus et al., Verification of detailed balance for γ absorption and emission in Dy isotopes. Phys. Rev. C. 98, 054310 (2018). doi:10.1103/PhysRevC.98.054310.

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