Progress of photonuclear cross-sections for medical radioisotope production at the SLEGS energy domain

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Abstract

Photonuclear reactions using a laser Compton scattering (LCS) gamma source provide a new method for producing radioisotopes for medical applications. Compared with the conventional method, this method has the advantages of a high specific activity and less heat. Initiated by the Shanghai Laser Electron Gamma Source (SLEGS), we conducted a survey of potential photonuclear reactions, (γ, n), (γ, p), and (γ, γ) whose cross sections can be measured at SLEGS by summarizing the experimental progress. In general, the data are rare and occasionally inconsistent. Therefore, theoretical calculations are often used to evaluate the production of medical radioisotopes. Subsequently, we verified the model uncertainties of the widely used reaction code TALYS-1.96, using the experimental data of the 100Mo(γ, n) 99Mo, 65Cu(γ, n) 64Cu, and 68Zn(γ, p) 67Cu reactions.

Full Text

Preamble

Progress of Photonuclear Cross-Sections for Medical Radioisotope Production at the SLEGS Energy Domain

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Photonuclear reactions using a laser Compton scattering (LCS) gamma source provide a new method for producing radioisotopes for medical applications.

Compared with conventional methods, this approach offers advantages of high specific activity and reduced heat generation. Motivated by the Shanghai Laser Electron Gamma Source (SLEGS), we surveyed potential photonuclear reactions—(γ, n), (γ, p), and (γ, γ)—whose cross-sections could be measured at SLEGS by reviewing experimental progress. In general, the available data are scarce and occasionally inconsistent. Therefore, theoretical calculations are frequently employed to evaluate medical radioisotope production. Subsequently, we verified the model uncertainties of the widely used reaction code TALYS-1.96 using experimental data from the ^{100}Mo(γ, n)^{99}Mo, ^{65}Cu(γ, n)^{64}Cu, and ^{68}Zn(γ, p)^{67}Cu reactions.

Keywords: Medical radioisotope, Photonuclear reaction, LCS, Cross section

Introduction

Radioisotopes are widely used for the diagnosis and therapy of various diseases due to their nuclear-physical properties [**?**, **?**]. Diagnostic radioisotopes can provide functional and metabolic information for early treatment of diseased regions that have not yet undergone morphological or structural changes. Currently, positron emission tomography (PET) [**?**] and single-photon emission computed tomography (SPECT) [**?**] represent the two major diagnostic techniques. Short-lived β^+-emitting radioisotopes are commonly used for PET, with typical examples including ^{11}C, ^{13}N, ^{15}O, and ^{18}F, which have half-lives of 20, 10, 2, and 110 minutes, respectively. For SPECT, γ-ray emitting radioisotopes are frequently employed, among which ^{99} Tc with a half-life of 6 h [**?**] is the most common radioisotope tracer. Therapeutic radioisotopes can be combined with targeted drugs to achieve precise removal of small diseased regions without excessive doses to normal tissues. Consequently, radioisotopes that emit low-range, highly ionizing radiation are of significant interest. The β^--particle emitting radioisotopes (e.g., ^{32}P, ^{89}Sr, ^{90}Y, ^{131}I, ^{177}Lu, and ^{188}Re), Auger electron cascades (e.g., ^{103}Pd and ^{125}I), and α-particle emitting radioisotopes (e.g., ^{211}At, ^{212}Bi, ^{223}Ra, ^{225}Ac, and ^{227}Th), with high linear energy transfer in tissue, are suitable for therapy.

More than 40 million nuclear medicine procedures are performed annually, with demand for radioisotopes increasing by 5% each year [**?**]. Currently, medical radioisotope production relies primarily on nuclear reactors and cyclotrons. Thermal neutron-induced fission produces neutron-rich radioisotopes in nuclear reactors. The advantage of this method is the possibility of producing high levels of total and specific activities. However, the production of desired radioisotopes is accompanied by considerable amounts of long-lived radioactive waste, raising numerous safety and security concerns. In addition, many nuclear reactors used for medical radioisotope production are more than 50 years old and may be shut down in the near future [**?**]. For example, a vast majority of reactors producing ^{99}Mo are expected to shut down by 2030.

Compared with reactors, cyclotrons typically produce neutron-deficient radioiso-

topes via charged particle reactions accompanied by less radioactive waste. They also offer the advantage of being more compact, allowing placement near hospitals, and making them useful tools for producing radioisotopes with short half-lives ranging from several minutes to hours.

Another promising method for radioisotope production involves photonuclear reactions, mainly including (γ, n), (γ, p), and (γ, γ). This is considered an alternative to radioisotope production in reactors and cyclotrons, or the only method of production for certain radioisotopes. (γ, n) reactions can produce β^+-emitting radioisotopes for PET imaging, such as ^{11}C, ^{13}N, ^{15}O, and ^{18}F, which are conventionally produced by cyclotron-based (p, n) or (p, γ) reactions. (γ, p) reactions are suitable for producing β^--emitting radioisotopes that are currently mostly produced in reactors. High-intensity γ beams are required to obtain adequate yield using this method. With the development of laser Compton scattering (LCS) gamma sources, the production of radioisotopes via photonuclear reactions has attracted considerable attention [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**].

In contrast to conventional bremsstrahlung gamma sources based on electron linear accelerators, LCS gamma sources offer advantages of high photon flux and excellent monochromaticity. The advantages of photonuclear reactions using LCS gamma sources for radioisotope production are as follows: First, unlike bremsstrahlung gamma sources, LCS gamma sources significantly reduce heat per useful reaction rate because γ-rays in the energy range of interest are not accompanied by an intense low-energy tail. Moreover, LCS gamma sources can selectively tune photons to energies of interest, enabling high specific activity by matching the photon energy to the giant dipole resonance (GDR) peak. Second, unlike charged-particle induced reactions, photonuclear reactions generate less heat as their energy deposition in targets via gamma-matter interactions is significantly smaller. Thus, the target can be thicker and requires considerably less cooling [**?**]. Moreover, photonuclear reactions can simultaneously irradiate multiple targets, maximizing the utilization of γ beams and enabling simultaneous production of multiple radioisotopes [**?**].

The Shanghai Laser Electron Gamma Source (SLEGS) employs the LCS technique to generate γ beams ranging from 0.25–21.7 MeV with a full-spectrum flux of 10^5–10^7 s^{-1} [**?**] and the best possible bandwidth of γ beams of 5%–15% after passing through a dual collimation system [**?**]. Using collimation technology, the size of a γ beam can be continuously adjusted to within Φ25 mm [**?**]. The monochromaticity and high intensity of γ beams combined with detector spectrometers can be used to measure photonuclear reaction cross-sections [**?**, **?**, **?**, **?**]. One of the main topics at SLEGS is the measurement of key photonuclear reaction cross-sections relevant for medical radioisotope investigations, providing crucial nuclear data for the photonuclear method.

In this study, we aim to estimate the production of medical radioisotopes in the energy range of 0.25–21.7 MeV in the SLEGS domain. The remainder of this paper is organized as follows. In Sect. II, we summarize the radioisotopes

that can be produced via (γ, n), (γ, p), and (γ, γ) reactions and discuss their experimental feasibility. Owing to the scarcity of cross-sectional data regarding photonuclear reactions, theoretical calculations are often used to assess the yields of medical radioisotopes. In Sect. III, we investigate the cross-sectional data of the ^{100}Mo(γ, n), ^{65}Cu(γ, n), and ^{68}Zn(γ, p) reactions in the SLEGS energy region to produce ^{99}Mo, ^{64}Cu, and ^{67}Cu radioisotopes. Finally, we provide a summary in Sect. IV.

II. Medical Radioisotopes Produced in Photonuclear Reactions

In this section, we discuss potential (γ, n), (γ, p), and (γ, γ) reactions for the production of medical radioisotopes. Crucial considerations include the natural abundance of the target isotopes, half-life of the radioisotopes, and available experimental data. Generally, it is preferable to have a target isotope with dominant abundance (e.g., greater than 10%) and a suitable half-life (several tens of minutes to days) for the produced radioisotope. However, the lack of experimental data may limit the medical applications of radioisotopes.

(γ, n) Reactions

Radioisotopes can be most efficiently produced by exciting the target nuclide into a GDR using photons. The GDR is characterized by a large peak cross-section and broad width, resulting in a large integral cross-section. The shape of the GDR follows a Lorentzian distribution with a spreading width of approximately 5 MeV [**?**, **?**, **?**]. Generally, a considerable portion of the total photonuclear cross-section originates from (γ, n) reactions, which increases as the charge number of the target nuclide increases, making subsequent chemical separation easier. For example, the ^{100}Mo(γ, n) reaction accounts for more than 70% of the total photonuclear reactions within the energy range of 8.4–15 MeV. Therefore, medium- and heavy-mass nuclei are ideal for production via (γ, n) reactions [**?**].

Table 1 summarizes 15 medical radioisotopes produced by (γ, n) reactions [**?**, **?**, **?**, **?**, **?**]. Excluding ^{100}Mo, the natural abundance of these reaction targets exceeds 10%. Higher natural abundance results in higher yield and lower impurity content. The seventh column indicates the current status of the EXFOR database [**?**]. Experimental data for only nine radioisotopes are presented in the Appendix. Among these, the ^{19}F(γ, n) reaction has only one dataset measured in the 1960s. The data for the ^{90}Zr(γ, n), ^{100}Mo(γ, n), and ^{187}Re(γ, n) reactions do not cover the entire GDR energy region. There is a significant discrepancy between the two datasets for the ^{65}Cu(γ, n) reaction, making it possible to determine the relevant cross-sections at SLEGS.

(γ, p) Reactions

Despite the nucleus being excited beyond the proton separation energy by photons, it does not necessarily lose a proton. Only for excitations well beyond the proton separation energy can the proton acquire sufficient kinetic energy to effectively cross the Coulomb barrier. However, in these cases, the excitation energy typically exceeds the separation energies of one or two neutrons, causing the neutron emission channel to compete with the proton emission channel. For light and certain medium-mass nuclei, the cross-sections of (γ, p) reactions are comparable to and occasionally exceed those of (γ, n) reactions due to nuclear shell structure. Certain heavier β^- emitters for radionuclide therapy can also be produced by (γ, p) reactions, but the increasing Coulomb barrier leads to smaller cross-sections. (γ, p) reactions result in the daughter and parent isotopes being chemically different, but several advanced chemical-separation techniques have been developed for this purpose. For example, a simple and reproducible three-ion exchange matrix approach was developed to separate ^{67}Cu from ^{68}Zn [**?**], and separation techniques exist for other pairs such as Ti/Sc, Zr/Y, and Hf/Lu [**?**, **?**, **?**].

The potential (γ, p) reactions used for nuclear medicine are listed in Table 2 . However, experimental data regarding this topic are scarce. Only limited data for ^{43}K, ^{67}Cu, and ^{177}Lu have been obtained using bremsstrahlung gamma sources, as detailed in the Appendix. No error bars are shown for the ^{43}K data, whereas relatively large errors ranging from typically 10% to 100% for ^{67}Cu and ^{177}Lu have been reported.

(γ, γ) Reactions

A nuclear isomer is the metastable state of an atomic nucleus in which one or more nucleons occupy higher energy levels than the ground state of the same nucleus. The lifetime and excitation energy are two important properties of nuclear isomers. The excitation energy between the isomer and ground state is characteristic and can be used to identify nuclides. Nuclear isomers can be de-excited by emission of γ-rays and/or conversion electrons to the ground state. γ-emitting isomers can be used as radioactive labels for SPECT imaging, while nuclear isomers emitting low-energy Auger electrons are potential radioisotopes for targeted therapy.

Conventional production methods such as (n, γ) reactions have relatively low yields because the dominant production pathway proceeds directly to the nuclear ground state with a spin closer to that of the target isotope. Using monochromatic, small-bandwidth LCS photons, transitions from a stable or long-lived nuclear ground state to higher energy levels can be selectively excited. Such levels serve as gateway states, which then partially decay to the isomeric state directly or via a cascade. The (γ, γ) reaction is equivalent to storing the energy of an incident photon in an isotope that acts as a container.

Table 3 lists six isomers that can be produced by (γ, γ) reactions for medical

applications. Excluding ^{117} Sn and ^{176} Lu, experimental data for the other radioisotopes are detailed in the Appendix. The dataset for ^{103} Rh lacks error bars, and two different results were reported from 6 to 23 MeV. For ^{113} In, two cross-sectional datasets differ by more than 300 times at 8 MeV. For ^{115} In, significant discrepancies exist between multiple datasets. The data for ^{195} Pt have large relative errors as high as 100% at 3.5, 7.5, and 8 MeV.

III. Evaluation of Cross-Sections for ^{99}Mo, ^{64}Cu, and ^{67}Cu Production

Cross-section data are used to calculate the expected yield of radioisotopes for a given thickness and enrichment of the target material, and to determine the optimum energy range for production of the desired radioisotope and the level of radioisotopic impurities. However, the slow development of gamma sources and small cross-sections of photonuclear reactions have resulted in relatively few experimental studies of cross-sectional data, with frequent scattering between different experimental datasets. Consequently, cross-sections predicted by theoretical models play a key role in medical radioisotope production.

The TALYS code [**?**] offers a unified approach for calculating nuclear reactions involving neutrons, photons, protons, deuterons, tritons, ^{3}He, and α particles in the keV–200 MeV energy range for target nuclides with masses from 5 to 339. The code outputs reaction data including cross-sections, energy spectra, and angular distributions of emitted particles. Numerous studies have tested the TALYS code and demonstrated its reliable predictive power for nuclear reaction calculations [**?**, **?**, **?**]. In the TALYS code, decay of the compound nuclear state from photonuclear reactions is treated using the Hauser-Feshbach (HF) statistical model [**?**], with nuclear-level density and γ strength function as the main input parameters.

In this study, we employed the TALYS-1.96 code, which implements six different nuclear level density (NLD) models and nine different models of γ strength functions (γSF), as shown in Table 4 . The NLD and γSF models employ phenomenological and microscopic approaches, respectively. We selected ^{99}Mo, ^{64}Cu, and ^{67}Cu radioisotopes as examples to compare model calculations with experimental data. The ^{99} Tc decayed from ^{99}Mo is the most frequently used radioisotope in nuclear medicine. ^{68}Zn is of interest due to its applications in production of the medical radioisotope ^{67}Cu. ^{67}Cu and ^{64}Cu can form a "matched pair" [**?**, **?**], where therapeutic ^{67}Cu, along with positron-emitting ^{64}Cu, can measure uptake kinetics in a patient's organ via PET imaging, allowing for precise dosimetric calculation. We used the default values of NLD and γSF models in the following calculations.

^{99}Mo/^{99} Tc

With a half-life of 6 h and 140 keV γ-rays, ^{99} Tc is nearly ideal for SPECT imaging. The most common method to obtain ^{99} Tc is by elution from ^{99}Mo

generators. The ^{100}Mo(γ, n) reaction has sufficient potential to produce ^{99}Mo. The excitation functions are presented in Fig. 1 [Figure 1: see original paper], covering the entire GDR energy range. The cross-sections of ^{100}Mo(γ, n)^{99}Mo were experimentally measured by Utsunomiya et al. [**?**], Crasta et al. [**?**], and Ejiri et al. [**?**] using LCS and bremsstrahlung gamma sources. All experimental results were distributed in the low-energy region of the GDR and did not exceed the peak.

Fig. 1(a) demonstrates that the shape and value of the excitation function are highly sensitive to the choice of γSF model, particularly at the GDR peak position. Excluding Strength 2 and 3, the remaining γSF models yield relatively similar results close to experimental data. Different γSF models produce similar predictions for energies above the GDR peak. Overall, cross-sections estimated using Strength 8 achieve the best agreement with experimental data. As shown in Fig. 1(b), calculation results from all NLD models below the peak are consistent but significantly higher than experimental data, whereas those above the peak differ substantially. The data predicted by models at energies above 14 MeV are highly valuable, and new experiments can be conducted at SLEGS to verify these predictions.

^{64}Cu

As listed in Table 1, the decay characteristics of ^{64}Cu render it useful for nuclear medicine [**?**], combining PET diagnostic capabilities with radiotherapy through average electron emissions of 190 keV. Currently, ^{64}Cu is mainly produced by small cyclotrons via ^{64}Ni(p, n) reactions [**?**, **?**, **?**, **?**]. Alternative production using ^{65}Cu(γ, n) does not require rare or expensive ^{64}Ni targets and simplifies the chemical separation step. Experimental data for cross-sections of the ^{65}Cu(γ, n)^{64}Cu reaction are presented in Fig. 2 [Figure 2: see original paper] along with TALYS calculations. Measurements by Katz et al. [**?**] and Antonov et al. [**?**] were performed using bremsstrahlung gamma sources but differed significantly in shape and magnitude. Coote et al. [**?**] obtained a single cross-section at 17.6 MeV using monochromatic γ-rays from the ^{7}Li(p, γ)^{8}Be reaction, which is consistent with calculations but lower than other experimental data by 80–120 mb. The cross-sections of ^{65}Cu(γ, n)^{64}Cu vary significantly with the choice of γSF models but not with NLD models. However, discrepancies between experiments and models cannot be compensated by varying γSF models. Future experiments on the ^{65}Cu photoneutron reaction using a monochromatic LCS gamma source will be useful for resolving these discrepancies and providing assurance for medical applications.

^{67}Cu

^{67}Cu is a promising β^{-}-particle emitter with an average energy of 141 keV for targeted radiotherapy. The range of these particles in tissue is of the same order as cell diameter, reducing unwanted dose burden on patients [**?**]. With a half-life of 61.83 h and low-energy γ emissions (91.266 keV, 7%; 93.311 keV,

16.1%; 184.577 keV, 48.7%), ^{67}Cu can provide long therapeutic effects. ^{67}Cu and its stable daughter ^{67}Zn are nontoxic to the body, and both Cu and Zn are prevalent trace elements. Along with the PET imaging radioisotope ^{64}Cu, it forms a "matched pair." However, widespread clinical use of ^{67}Cu-based radiopharmaceuticals has been limited by availability, quantity, and quality. Experiments [**?**, **?**, **?**, **?**, **?**] have shown that the ^{68}Zn(γ, p) reaction has potential to produce sufficient quantities of ^{67}Cu with adequate purity for medical use, and various Cu and Zn separation methods have been employed in radiochemical processing [**?**, **?**, **?**, **?**].

Figure 3 [Figure 3: see original paper] presents the excitation function of the ^{68}Zn(γ, p)^{67}Cu reaction. Experimental data regarding this reaction are scarce, with only one group providing two points in the SLEGS energy region [**?**]. These data are significantly inconsistent with any calculations and hardly constrain NLD and γSF models. In contrast to (γ, n) reactions with cross-sections of several hundred mb, (γ, p) reactions are typically several mb in medium-heavy nuclei. Additionally, protons can easily stop in the target and are difficult to detect. If the product nuclei of (γ, p) reactions are unstable with moderate half-life, cross-sections can be determined by offline measurements of characteristic γ-rays during decay. For the ^{68}Zn(γ, p) reaction, an offline measurement technique can be employed to determine its cross-sections.

IV. Summary

In this study, we summarized medical radioisotopes that can be produced by (γ, n), (γ, p), and (γ, γ) reactions, along with experimental data for these production pathways. We investigated photonuclear reaction cross-sections for production of ^{99}Mo, ^{64}Cu, and ^{67}Cu. Experimental data for ^{99}Mo and ^{67}Cu did not cover the entire GDR energy region, whereas data for ^{64}Cu exhibited significant discrepancies. To better constrain the NLD and γSF models in TALYS, additional experimental measurements at SLEGS in the GDR energy region are necessary in the future.

Appendix

Experimental data for production of medical radioisotopes by (γ, n), (γ, p), and (γ, γ) reactions are summarized. Table 5 lists relevant information on these reactions, with all data and information obtained from the EXFOR database [**?**].

To compare productivity of the photonuclear method with traditional methods, we consider production of ^{99}Mo/^{99} Tc as an example. The highest flux currently available for SLEGS is 10^7 s^{-1}. We adopted calculated results from the TALYS-1.96 code using the Strength 8 model for yield calculations, which provided a maximum 145 mb cross-section for the ^{100}Mo(γ, n) reaction at an incident photon energy of 14.4 MeV. After irradiating a $^{100}MoO_3$ target with a radius of 2 mm and thickness of 1 cm for 5 times the half-life of ^{99}Mo, the saturation

specific activity of ^{99}Mo and ^{99} Tc can reach 4.76 and 4.74 μCi/g, respectively. Use of stacked targets can further enhance production. When energy regions corresponding to maximum cross-sections of targeted nuclear reactions are close, multiple radioisotopes can be simultaneously produced. For example, ^{62}Cu, ^{64}Cu, and ^{89}Zr radioisotopes can be produced simultaneously when the incident photon energy is approximately 17 MeV.

Currently, ^{99}Mo is primarily produced by the (n, f) reaction in high-flux reactors using enriched ^{235}U targets, with specific activity reaching 185 TBq/g (5000 Ci/g) [**?**]. However, most reactors will gradually shut down by 2030 [**?**]. Medical cyclotrons can directly generate ^{99} Tc via the ^{100}Mo(p, 2n) reaction. According to experimental data, an enriched ^{100}Mo target irradiated with a 16.5 MeV proton beam at 130 μA for 6 h yielded 116 GBq/g (3.13 Ci/g) of ^{99} Tc [**?**]. Recently, a subcritical ^{99}Mo production system was developed, driven by an accelerator-based deuterium–deuterium (D–D) neutron source. The D–D fusion reaction generates neutrons that irradiate a low-enriched uranium solution and induce fission in ^{235}U. This system can generate 47.8 mCi/g of ^{99}Mo during stable 24 h operation with a neutron intensity of 1$×10^{14}$ n/s [**?**].

Bremsstrahlung gamma sources based on linear electron accelerators are often used to produce ^{99}Mo radioisotopes. Using a $^{100}MoO_3$ target irradiated with a 35 MeV electron beam at 100 μA for 20 h, the specific activity can achieve 4.4 GBq/g (119 mCi/g) [**?**]. NorthStar Medical Radioisotopes developed a ^{99}Mo production system using an electron linear accelerator. This system based on (γ, n) reactions produces approximately 30% more ^{99}Mo per gram of target material compared with the traditional neutron capture route [**?**, **?**].

In comparison, the specific activity produced by the photonuclear method based on SLEGS is currently low. However, with further increase in γ beam flux from 10^7 s^{-1} to 10^{15} s^{-1} [**?**], the specific activity of ^{99}Mo can reach up to 4$×10^{2}$ Ci/g. For a 2-day protocol, the activity of ^{99} Tc-labeled tracers required for one myocardial perfusion imaging is 24 mCi [**?**]. The total yield from stacked targets in one year can provide 400,000 myocardial perfusion images. As the flux of SLEGS increases in the future, this method is promising for producing medical radioisotopes and will become feasible in China.

Table 5. Information regarding experimental data for production of medical radioisotopes by photonuclear reactions. The cross-sectional data for production of ^{11}C, ^{13}N, ^{15}O, ^{18}F, ^{62}Cu, ^{64}Cu, ^{89}Zr, ^{99}Mo, and ^{186}Re radioisotopes by (γ, n) reactions are shown in the following figures: Fig. 4 [Figure 4: see original paper] (^{12}C(γ, n)^{11}C), Fig. 5 [Figure 5: see original paper] (^{14}N(γ, n)^{13}N), Fig. 6 [Figure 6: see original paper] (^{16}O(γ, n)^{15}O), Fig. 7 [Figure 7: see original paper] (^{19}F(γ, n)^{18}F), Fig. 8 [Figure 8: see original paper] (^{63}Cu(γ, n)^{62}Cu), Fig. 9 [Figure 9: see original paper] (^{65}Cu(γ, n)^{64}Cu), Fig. 10 [Figure 10: see original paper] (^{90}Zr(γ, n)^{89}Zr), Fig. 11 [Figure 11: see original paper] (^{100}Mo(γ, n)^{99}Mo), and Fig. 12 [Figure 12: see original paper] (^{187}Re(γ, n)^{186}Re). The cross-sectional data for production of ^{43}K, ^{67}Cu, and ^{177}Lu radioisotopes by (γ, p) reaction are shown in Fig. 13 [Figure 13: see original paper] (^{44}Ca(γ,

p)^{43}K), Fig. 14 [Figure 14: see original paper] (^{68}Zn(γ, p)^{67}Cu), and Fig. 15 [Figure 15: see original paper] (^{178}Hf(γ, p)^{177}Lu). The cross-sectional data for production of ^{103} Rh, ^{113} In, ^{115} In, and ^{195} Pt radioisotopes by (γ, γ) reaction are shown in Fig. 16 [Figure 16: see original paper] (^{103}Rh(γ, γ)^{103} Rh), Fig. 17 [Figure 17: see original paper] (^{113}In(γ, γ)^{113} In), Fig. 18 [Figure 18: see original paper] (^{115}In(γ, γ)^{115} In), and Fig. 19 [Figure 19: see original paper] (^{195}Pt(γ, γ)^{195} Pt). All data and information were obtained from the EXFOR database [**?**].

Note: Figure translations are in progress. See original paper for figures.