

Photonuclear reactions on stable isotopes of platinum at bremsstrahlung end-point energies of 10–23 MeV

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In this work, experiments with a beam from the MT-25 microtron at bremsstrahlung end-point energies of 10–23 MeV were carried out using the γ activation method. Theoretical results based on TALYS-2.0 with standard parameters and a combined model of photonucleon reactions were compared with experimental values of relative yields. Experimental data in the energy range 19–23 MeV can be described with the combined model of photonucleon reactions due to the inclusion of isospin splitting of the giant dipole resonance.

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I. INTRODUCTION

Photonuclear reaction studies provide valuable information on the structure and characteristics of atomic nuclei. These reactions have a substantial advantage over those caused by nucleons since the electromagnetic interaction of photons and nuclei is well understood theoretically. The interaction of γ quanta and atomic nuclei leads to a broad maximum in the absorption cross section of γ quanta located in the range of nuclear excitation energies of 10–30 MeV, known as a giant dipole resonance (GDR) [1].

Natural platinum consists of six stable isotopes with the following mass numbers and isotopic abundances: ^{190}Pt (0.012%), ^{192}Pt (7.82%), ^{194}Pt (32.864%), ^{195}Pt (33.775%), ^{196}Pt (25.211%), and ^{198}Pt (7.365%). Although all of these isotopes can undergo photodisintegration via different reaction channels, only a small number have been studied thus far, namely, photoneutron reactions [2–6]. The cross sections for the $(\gamma, n) + (\gamma, pn) + (\gamma, 2n)$ [2] and $(\gamma, n) + (\gamma, 2n)$ [3] reactions induced by bremsstrahlung photons on the isotopes $^{194,195,196,198}\text{Pt}$ were determined by detecting neutrons in the energy range of γ quanta 8–21 MeV with the step of 0.2 MeV. The $^{198}\text{Pt}(\gamma, n)^{197m}\text{Pt}$ reaction cross sections in energy range 8–17 MeV have been measured in Ref. [4]. Isomeric ratios of $^{197m,g}\text{Pt}$ in energy range 9.5–30 MeV have been measured in Refs. [4–9].

The objective of the present study is to get new information about basic photoneutron and photoproton reactions on platinum isotopes using a beam of bremsstrahlung γ radiation at the energy range from 10 to 23 MeV. Despite the small reaction cross section (γ, p) , the decay of GDR with proton emission makes it possible to examine isospin splitting of GDR. We obtained our experimental data using the electron accelerator's γ activation method with bremsstrahlung photons, and we performed calculations using the program code TALYS-2.0 [10] and the combined model of photonucleon reactions [11]. Also particular reaction products, such as ^{193m}Pt [12] and ^{195m}Pt [13,14], have potential as medicinal isotopes. Therefore, analyzing reaction yields is beneficial for both research and application.

II. EXPERIMENTAL SETUP AND PROCEDURES

This experiment was carried out using the MT-25 microtron's output electron beam [15]. The electron energies ranged from 10 to 23 MeV, with an energy step of 1 MeV. To generate bremsstrahlung γ radiation, a radiator target constructed of tungsten, a common converter material, was employed. The tungsten target was thick enough (3 mm) to maximize the quantity of photons in the energy range of the GDR, which dominates the photonuclear cross section between the reaction threshold and 20–30 MeV. To eliminate the leftover electrons from the bremsstrahlung beam, a 30-mm-thick aluminium absorber was positioned behind the tungsten converter. The natural platinum target measured $10 \times 10 \times 0.4$ mm (at 10–19 MeV) and $4 \times 4 \times 0.3$ mm (at 20–23 MeV) and was located 1 cm away from the converter.

In the experiments, a bremsstrahlung flux created in the tungsten converter was used to irradiate metallic natural

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TABLE I. Main parameters of the experiments.

Energy of electrons (MeV)	Mass of platinum target (mg/cm ²)	Integral charge (mC)	Integral number of electrons incident on the tungsten converter ($\times 10^{16}$ particle)	Irradiation time (min)	Total measuring time of spectra (h)
10	1108.0	10 ± 1	6.3 ± 0.7	44	14
11	1018.9	10 ± 1	6.3 ± 0.7	42	14
12	984.7	10 ± 1	6.3 ± 0.7	31	14
13	967.3	10 ± 1	6.3 ± 0.7	33	20
14	814.0	4.0 ± 0.4	2.6 ± 0.3	18	14
15	844.1	4.0 ± 0.4	2.6 ± 0.3	13	35
16	814.6	4.0 ± 0.4	2.6 ± 0.3	25	18
17	824.7	4.0 ± 0.4	2.6 ± 0.3	78	18
18	850.4	4.0 ± 0.4	2.6 ± 0.3	17	14
19	769.7	4.0 ± 0.4	2.6 ± 0.3	28	14
20	1193.7	4.0 ± 0.4	2.6 ± 0.3	34	14
21	737.5	4.0 ± 0.4	2.6 ± 0.3	15	21
22	637.5	4.0 ± 0.4	2.6 ± 0.3	15	15
23	241.2	4.8 ± 0.5	3.1 ± 0.3	26	36

platinum samples. In addition to the ionization chamber and Faraday cup, the electrical charge gathered on the target was digitized and used to determine the beam current. The electron current of the accelerator was measured during irradiation with a Faraday cup [16]. The accelerator current was calibrated based on the experimentally observed yield of the reaction $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$. The yield was calculated using the estimated cross section, whereas the bremsstrahlung spectrum was obtained using GEANT4 [17]. A 0.15-mm-thick copper monitor was positioned behind the irradiation Pt target. Copper was chosen because the cross section of the reaction $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ was determined with sufficient precision [18]. Table I lists the main experimental parameters.

After irradiation, when the radiation levels in the experimental hall were safe, the targets were moved to a separate measuring room, where the induced activity in the irradiated target was determined. We utilized a high purity germanium (HPGe) γ detector with a resolution of 16 keV at 1332 keV, together with standard measurement electronics and a 16K ADC/MCA (Multiport II Multichannel Analyser, CANBERRA). The energy and efficiency calibrations of the HPGe detector were performed with conventional γ -ray sources. The approach for γ activation measurements utilized in this study is detailed in Refs. [16,18–20]. The spectra of each sample were measured many times during a period of 0.5, 1, 6, and 12 h. Figure 1 depicts typical γ -ray spectra of ^{nat}Pt -produced reaction products. The sample received bremsstrahlung radiation with an end-point energy of 23 MeV. A background spectrum (red line) is also shown in Fig. 1. The upper and lower limits of the integrated peak areas are 350 000 and 150, respectively.

The γ -ray spectra were processed using the DEIMOS32 algorithm [21], which applies the Gaussian function to the count area of the full-energy peaks. The radionuclides were identified using their γ -ray energies and half-lives. Table II shows the principal γ -ray energies and intensities used to determine the yield of reaction products. The spectroscopic data for the photonuclear reaction products shown in columns 4–5 of Table II are sourced from Ref. [22].

The half-lives of previously examined radionuclides range from 95.41 min (^{197m}Pt) to 4.33 days (^{193m}Pt). A number of γ -ray spectra were obtained at varied waiting durations, from tens of minutes to 1 day following irradiation, to calculate the half-lives of certain radionuclides and pick the suitable spectra for each isotope's activity. The activity is often measured with the most intense, well-separated, interference-free, and correctable γ ray.

III. DATA ANALYSIS

The experimental yields of the reactions Y_{exp} per one electron of the accelerated beam incident on the bremsstrahlung target were determined using the following formula:

$$Y_{\text{exp}} = \frac{S_p C_{\text{abs}}}{\varepsilon I_\gamma} \frac{t_{\text{real}}}{t_{\text{live}}} \frac{1}{N} \frac{1}{N_e} \frac{e^{\lambda t_{\text{cool}}}}{(1 - e^{-\lambda t_{\text{real}}})} \frac{\lambda t_{\text{irr}}}{(1 - e^{-\lambda t_{\text{irr}}})}, \quad (1)$$

where S_p is the full-energy-peak area; ε is the full-energy-peak detector efficiency; I_γ is the γ emission probability; C_{abs} is the correction for self-absorption of γ rays in the sample; t_{real} and t_{live} are the real time and live time of the measurement, respectively; N is the number of atoms in the activation sample; N_e is the integral number of incident electrons; λ is the decay constant; t_{cool} is the cooling time; and t_{irr} is the irradiation time.

For the γ activity measurements, the activated sample was placed at 5 cm from the detector surface to maintain the detector dead time at approximately 3% and to reduce counting losses due to the coincidence summing effect. The Compton background has been missed about 2 h after irradiation, so the target was located on the detector surface for measuring γ rays of long-lived isotopes in the target. Energy and efficiency calibrations of the HPGe detector were carried out using the standard γ -ray sources ^{60}Co , ^{109}Cd , ^{134}Cs , ^{137}Cs , ^{152}Eu , and ^{241}Am . Figure 2 shows the efficiency calibration curves. Higher efficiency is achieved when measurements are made under conditions of close geometry. In this case, for all measurements with irradiated samples and calibration sources located on the detector surface under conditions of

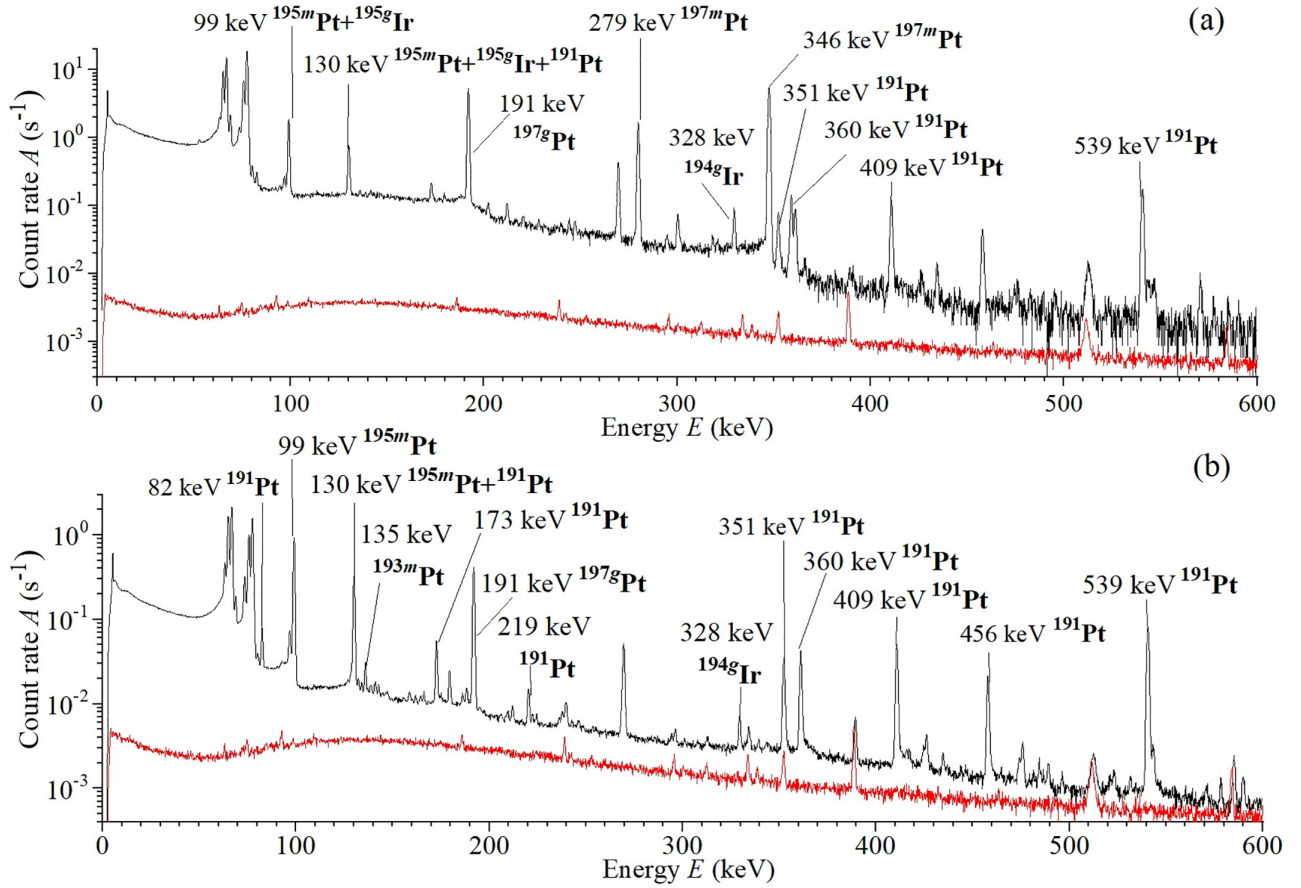


FIG. 1. Spectra of residual activity of the irradiated sample of ^{nat}Pt (top-to-bottom) 4 h (a) and 6 days (b) after irradiation. The spectra measurement duration was 1 h (a) and 1 day (b). The bremsstrahlung end-point energy used for the irradiation was 23 MeV.

close geometry, it is necessary to make corrections for the summation of coincidences [23,24]. Table III presents the calculated values of the coincidence summing correction factors. These correction factors are defined as the ratios of the true gamma-ray counts to the corresponding measured counts.

The yields Y_{theor} of photonuclear reactions representing the convolution of the photonuclear reactions cross section $\sigma_i(E)$ and the distribution density of the number of bremsstrahlung photons over energy per one electron of the accelerator $W(E, E_{\gamma\text{max}})$ were determined as a result of the experiment. For the yield measurement of a natural mixture of isotopes, the result

is the yield of isotope production in all possible reactions on a natural mixture:

$$Y_{\text{theor}} = \sum_i \eta_i \int_{E_{\text{th}}}^{E_{\gamma\text{max}}} \sigma_i(E) W(E, E_{\gamma\text{max}}) dE \quad (2)$$

where $E_{\gamma\text{max}}$ is the kinetic energy of electrons hitting the tungsten radiator, E is the energy of bremsstrahlung photons produced on the radiator, E_{th} is the threshold of the studied photonuclear reaction, η_i is the percentage of the studied isotope in a natural mixture of platinum isotopes, and the index i

TABLE II. Spectroscopic data from Ref. [22] for the product nuclei from the photonuclear reactions on stable isotopes of platinum.

Nucleus	Half-life $T_{1/2}$	Decay mode (%)	γ -ray energy E_γ (keV) (I_γ (%))	Reaction	E_{th} (MeV)
^{189}Pt	10.87 h	EC: 100	721.38 (7.9)	$^{190}\text{Pt}(\gamma, n)^{189}\text{Pt}$	8.91
^{191}Pt	2.83 d	EC: 100	538.90 (14.4)	$^{192}\text{Pt}(\gamma, n)^{191}\text{Pt}$	8.67
^{193m}Pt	4.33 d	IT: 100	135.5 (0.114)	$^{194}\text{Pt}(\gamma, n)^{193m}\text{Pt}$	8.50
^{195m}Pt	4.01 d	IT: 100	98.90 (11.7), 129.79 (2.90)	$^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$	8.18
^{197g}Pt	19.89 h	β^- : 100	77.35 (17), 191.44 (3.7)	$^{198}\text{Pt}(\gamma, n)^{197g}\text{Pt}$	7.55
^{197m}Pt	95.41 m	β^- : 3.3 IT: 96.7	346.5 (11.1)	$^{198}\text{Pt}(\gamma, n)^{197m}\text{Pt}$	7.96
^{194}Ir	19.18 h	β^- : 100	328.47 (13.1)	$^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$	7.55
^{195g}Ir	2.29 h	β^- : 100	98.83 (10), 129.7 (1.4), 211.3 (2.5)	$^{196}\text{Pt}(\gamma, p)^{195g}\text{Ir}$	8.24
^{195m}Ir	3.67 h	IT: 5 β^- : 95	684.88 (9.8)	$^{196}\text{Pt}(\gamma, p)^{195m}\text{Ir}$	8.34

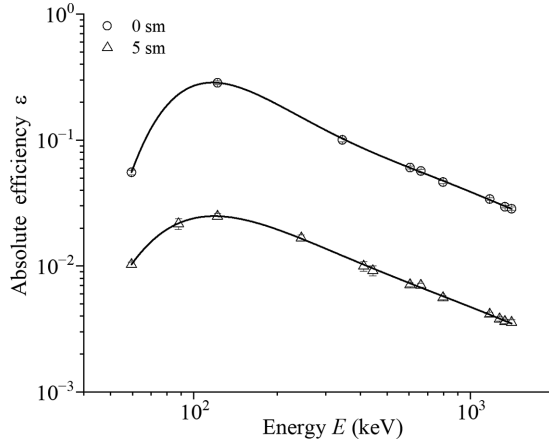


FIG. 2. The efficiency calibration curves.

corresponds to the number of the reaction contributing to the production of the studied isotope.

The photon beam flux $W(E, E_{\gamma\max})$ distribution was simulated by the GEANT4 code [17] and used for the renormalization of the experimental flux based on the monitor $^{65}\text{Cu}(\gamma, n)^{64}\text{Cu}$ reaction. Figure 3 shows the distribution density of the number of bremsstrahlung photons $W(E, E_{\gamma\max})$ per one electron of the accelerator for accelerated electron energies from 10 to 23 MeV, calculated using GEANT4 for the bremsstrahlung target from tungsten with a thickness of 3 mm.

The total and partial cross sections $\sigma(E)$ of the photonuclear reactions on the platinum isotopes were computed for the monochromatic photons with the TALYS-2.0 code [10] with the standard parameters and CMPR [11]. The TALYS software examines all processes in the nucleus and transitions between states. As a result, it is feasible to calculate not only the overall cross sections of photonuclear reactions, but also the cross sections of reactions involving the production of certain states, particularly isomeric states. The CMPR code estimates the cross sections of photonuclear reactions that produce an

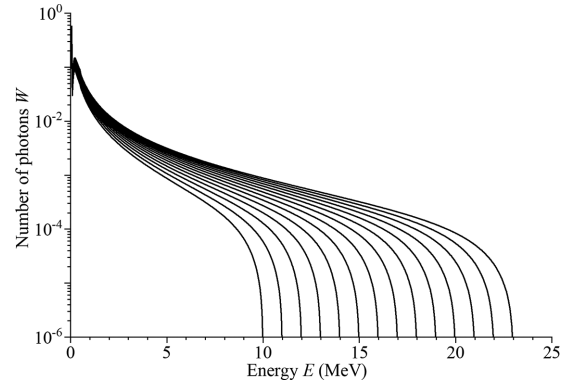


FIG. 3. The distribution density of the number of bremsstrahlung photons at the energies of 10–23 MeV.

investigated isotope, which are the sums of the ground and isomeric states.

Since the experiment was performed with a natural mixture of isotopes, several reactions with appropriate thresholds contribute to production of Pt and Ir isotopes, except for $^{197m,g}\text{Pt}$. A section of the nuclear chart in the Pt region is shown in Fig. 4. The experimental yield includes all possible reaction channels on stable isotopes of a natural mixture of Pt.

The fundamental problem of bremsstrahlung beam experiments is that the yield of the photonuclear reaction depends on both the investigated cross section of the reaction $\sigma_i(E)$ and the form of the bremsstrahlung spectrum $W(E, E_{\gamma\max})$, which is often known with inadequate accuracy. The use of the relative yields makes it possible to obtain the dependence of the probability of photonuclear reactions on the maximum energy of bremsstrahlung under different experimental conditions. The calibration with respect to the yield of the most probable reaction excludes the influence of the total photon absorption cross section. The $^{198}\text{Pt}(\gamma, n)^{197}\text{Pt}$ reaction is chosen as a main reaction because the cross section of the reaction was determined with sufficient precision [3]. Theoretical values of the relative yields can be calculated using the following formula:

$$Y_{\text{rel},i} = \frac{\sum_{i=1}^6 \eta_i \int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma_i(E) W(E, E_{\gamma\max}) dE}{\eta_{\text{Pt-198}} \int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma_{(\gamma,n)}(E) W(E, E_{\gamma\max}) dE} \quad (3)$$

where $\eta_{\text{Pt-198}}$ is the percentage of the ^{198}Pt in a natural mixture of platinum isotopes (7.356%). In order to compare results of different experiments, it is necessary to assume that the shapes of the bremsstrahlung spectra in the compared experiments do not differ. Owing to the assumption on the unchanged shape of the bremsstrahlung spectrum, the bremsstrahlung photon production cross section $\sigma(E, E_{\gamma\max})$ should be taken as the function $W(E, E_{\gamma\max})$:

$$Y_{\text{rel},i} = \frac{\sum_{i=1}^6 \eta_i \int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma_i(E) \sigma(E, E_{\gamma\max}) dE}{\eta_{\text{Pt-198}} \int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma_{(\gamma,n)}(E) \sigma(E, E_{\gamma\max}) dE}, \quad (4)$$

TABLE III. The calculated values of the summing correction factor.

Nucleus	γ -ray energy (keV)	Intensity (%)	Summing coincidence correction
^{189}Pt	721.38	7.9	0.8188
^{191}Pt	538.90	14.4	0.8376
^{193m}Pt	135.5	0.114	1.0000
^{195m}Pt	98.90	11.7	0.4941
	129.79	2.90	0.9503
^{197g}Pt	77.35	17	0.9531
	191.44	3.7	0.9082
^{197m}Pt	346.5	11.1	0.9974
^{194}Ir	328.47	13.1	0.8584
^{195g}Ir	98.83	10	1.0000
	129.7	1.4	1.0000
	211.3	2.5	1.0000
^{195m}Ir	684.88	9.8	0.6871

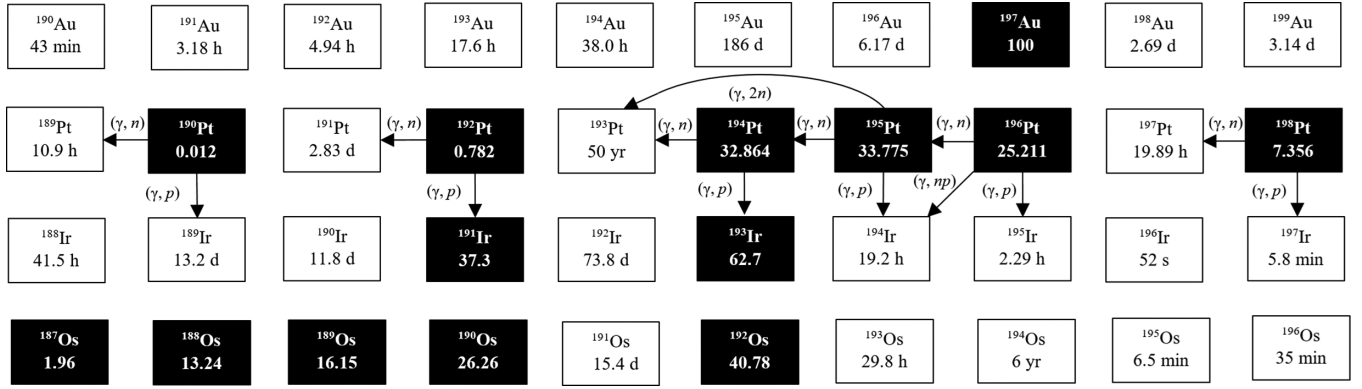


FIG. 4. A section of the nuclear chart in the Pt region.

where $\sigma(E, E_{\gamma\max})$ is calculated based on the Seltzer-Berger tables [25].

To represent the experimental photonuclear reaction data, the cross section per equivalent quantum σ_q is determined by the expression

$$\sigma_q = \frac{\int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma(E) \sigma(E, E_{\gamma\max}) dE}{\frac{1}{E_{\gamma\max}} \int_0^{E_{\gamma\max}} E \sigma(E, E_{\gamma\max}) dE}. \quad (5)$$

The cross section per equivalent quantum for a natural mixture of isotopes includes all possible channels of the final isotope production with account for the percentage of initial nuclei:

$$\sigma_q^{\text{nat}} = \frac{\sum_{i=1}^6 \eta_i \int_{E_{\text{th}}}^{E_{\gamma\max}} \sigma_i(E) \sigma(E, E_{\gamma\max}) dE}{\frac{1}{E_{\gamma\max}} \int_0^{E_{\gamma\max}} E \sigma(E, E_{\gamma\max}) dE}. \quad (6)$$

The comparison between two types of the cross sections shows the advantage of using σ_q in the case when several reaction channels appear with different thresholds E_{th} with a certain $E_{\gamma\max}$ value.

The experimental values for the cross section per equivalent quantum was calculated using the normalization of yields to the number of γ quanta based on the bremsstrahlung spectra obtained in the GEANT4 program. The Seltzer-Berger tables

were used in the theoretical calculations of relative yield and the cross section per equivalent quantum.

IV. RESULTS AND DISCUSSION

In addition to theoretical calculations with the use of the TALYS and CMPR codes and previously published data, the measured relative yields and cross section per equivalent quantum are displayed in Figs. 5–10. The square root of the quadratic sum of all independent statistical and systematic uncertainties allowed one to determine the general uncertainty in the results.

A. Photoneutron reactions

Six platinum isotopes are directly generated by $^{\text{nat}}\text{Pt}(\gamma, n)$ reactions when natural platinum is irradiated with bremsstrahlung radiation with end-point energy of 10–23 MeV. In this study, the relative yields and cross section per equivalent quantum ns of the $^{\text{nat}}\text{Pt}(\gamma, n)^{189,191,193m,195m,197g,197m}\text{Pt}$ reactions at the bremsstrahlung end-point energies of 10–23 MeV are determined for the first time and presented in Table IV. For $^{\text{nat}}\text{Pt}(\gamma, n)^{197}\text{Pt}$ the relative yield line remains empty due to normalization to this reaction.

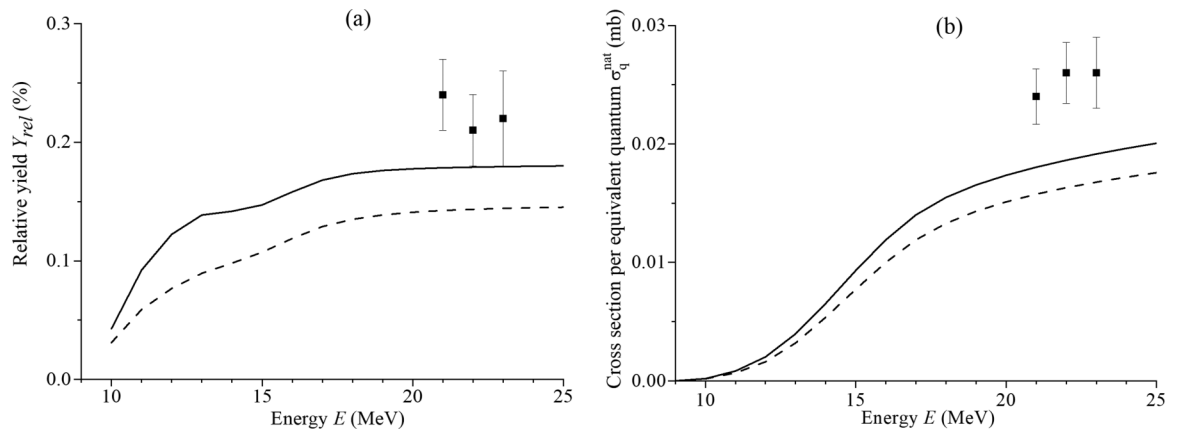


FIG. 5. Relative yield (a) and cross section per equivalent quantum (b) of reaction $^{190}\text{Pt}(\gamma, n)^{189}\text{Pt}$ as a function of bremsstrahlung end-point energy from the present work (solid rectangles) and simulated values using the CMPR (solid lines) and TALYS code (dashed lines).

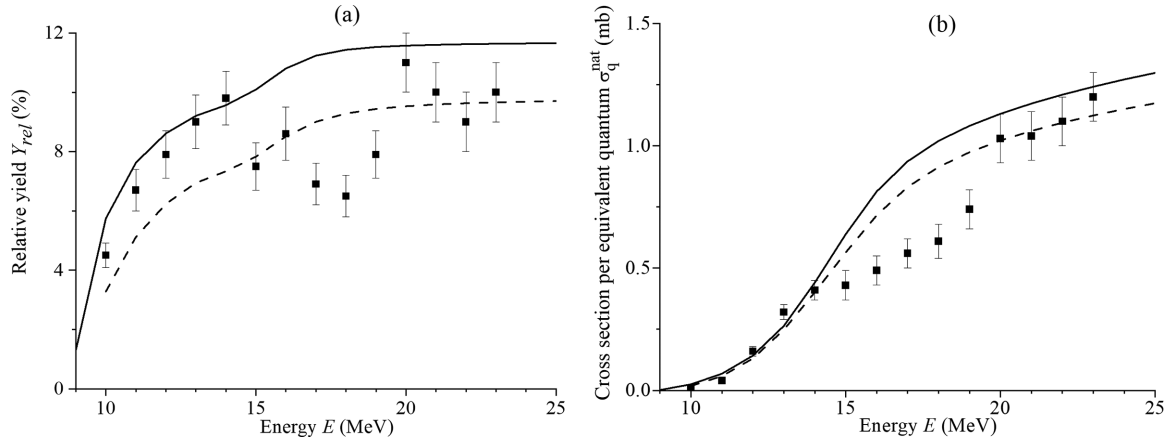


FIG. 6. Relative yield (a) and cross section per equivalent quantum (b) of reaction $^{192}\text{Pt}(\gamma, n)^{191}\text{Pt}$ as a function of bremsstrahlung end-point energy from the present work (solid rectangles) and simulated values using the CMPR (solid lines) and TALYS code (dashed lines).

1. $^{190}\text{Pt}(\gamma, n)^{189}\text{Pt}$ reaction

The activity of the ^{189}Pt ($T_{1/2} = 10.87$ h) radionuclide was measured using γ rays of 721.38 keV (7.9%). The measured results for the $^{190}\text{Pt}(\gamma, n)^{189}\text{Pt}$ reaction are compared to theoretical values obtained using TALYS-2.0 and CMPR (Fig. 4). There are no published data on the $^{190}\text{Pt}(\gamma, n)^{189}\text{Pt}$ reaction. In this work three points were measured at energies between 21 and 23 MeV. As seen in Fig. 5, the points are nearer the curve according to CMPR.

2. $^{192}\text{Pt}(\gamma, n)^{191}\text{Pt}$ reaction

The activity of the ^{191}Pt ($T_{1/2} = 2.83$ d) radionuclide was measured using γ rays of 538.897 keV (14.4%). Since no literature data have been discovered, the measured $^{192}\text{Pt}(\gamma, n)^{191}\text{Pt}$ reaction results could only be compared with the theoretical calculations, as illustrated in Fig. 6.

It is clear from the graphic that in the region from 10 to 14 MeV there is good agreement between the theoretical and currently measured values in terms of both form and magnitude. At energies of 15–23 MeV, the experimental points along the

relative yields are scattered, and measured cross sections per equivalent quantum are lower than the theoretical curves.

3. $^{194}\text{Pt}(\gamma, n)^{193m}\text{Pt}$ and $^{195}\text{Pt}(\gamma, 2n)^{193m}\text{Pt}$ reactions

The ^{193}Pt radionuclide exists in both isomeric and unstable ground states. The activity of ^{193g}Pt ($T_{1/2} = 50$ y) cannot be measured directly because it does not emit γ rays. The activity of ^{193m}Pt ($T_{1/2} = 4.33$ d) was measured using γ rays of 135.5 keV (0.114%). The measurements for the $^{194}\text{Pt}(\gamma, n)^{193m}\text{Pt}$ reaction were conducted for the first time and could only be compared to theoretical values. The measured values for the reaction are higher than the calculated values, as seen in Fig. 7.

4. $^{195}\text{Pt}(\gamma, \gamma')^{195m}\text{Pt}$ and $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ reactions

The ^{195m}Pt nuclide emits two γ rays [98.90 keV (11.7%) and 129.79 keV (2.90%)] of suitable energy and intensity for corresponding activity measurements; however, there was an interference problem with both of them. The value of 129.7 keV is not suitable for determining activity of ^{195m}Pt , because the nuclei ^{191}Pt ($T_{1/2} = 2.83$ d), ^{195g}Ir ($T_{1/2} = 2.29$ h), and

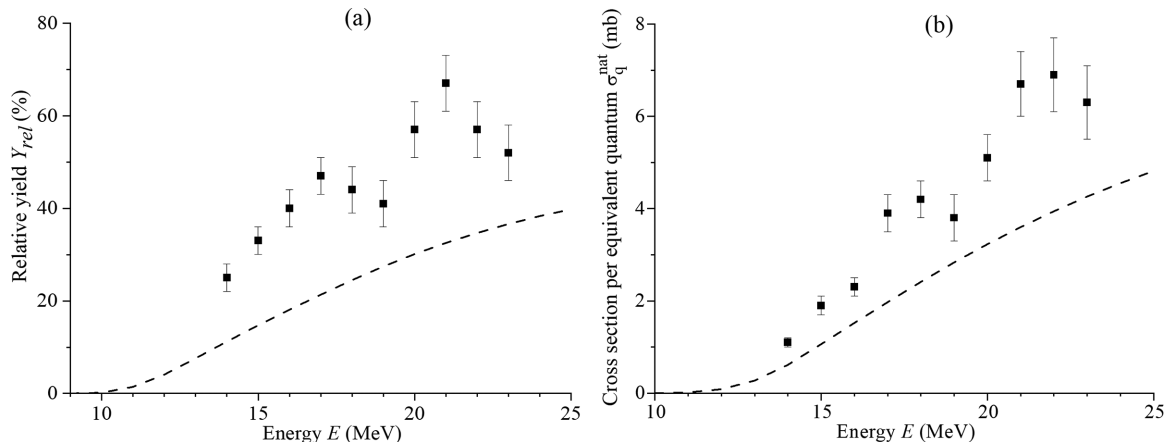


FIG. 7. Relative yield (a) and cross section per equivalent quantum (b) of $^{194}\text{Pt}(\gamma, n)^{193m}\text{Pt}$ and $^{195}\text{Pt}(\gamma, 2n)^{193m}\text{Pt}$ reactions as a function of bremsstrahlung end-point energy from the present work (solid rectangles) and simulated values using TALYS code (dashed lines).

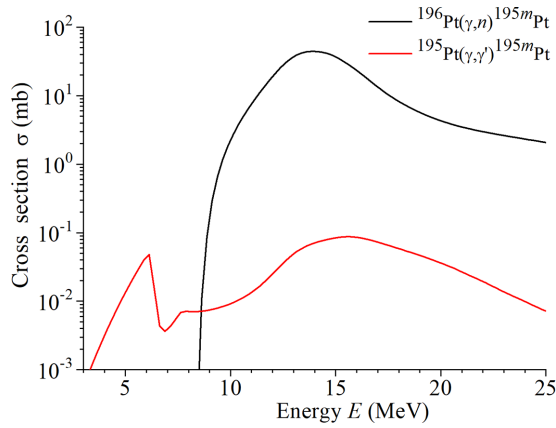


FIG. 8. The cross sections of $^{195}\text{Pt}(\gamma, \gamma')^{195m}\text{Pt}$ and $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ reactions.

^{195m}Ir ($T_{1/2} = 3.67$ h) also emit γ rays of 129.4 keV (3.0%), 129.7 keV (1.4%), and 129.7 keV (1.7%), respectively. An interference problem with γ rays of 98.857 keV is due to the fact that the ^{195g}Ir ($T_{1/2} = 2.29$ h) also emits γ rays of 98.83 keV (10%). Therefore, in the first spectra it is impossible to extract information about the activity of the ^{195m}Pt . To determine the activity of the ^{195m}Pt we use spectra taken 1 day (it is $10T_{1/2}$ of the ^{195g}Ir) after irradiation (we can assume that at this time the ^{195g}Ir completely decays, $10T_{1/2}$).

The ^{195m}Pt radionuclide can be formed as a result of $^{195}\text{Pt}(\gamma, \gamma')^{195m}\text{Pt}$ and $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ reactions. Figure 8 shows the cross sections of $^{195}\text{Pt}(\gamma, \gamma')^{195m}\text{Pt}$ and $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ reactions. The cross section of the $^{195}\text{Pt}(\gamma, \gamma')^{195m}\text{Pt}$ reaction is smaller almost 300 times than the cross section of $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ reaction in the energy range from 10 to 25 MeV. Therefore, the contribution of the $^{195}\text{Pt}(\gamma, \gamma')^{195m}\text{Pt}$ reaction in the formation of the nucleus ^{195m}Pt can be neglected.

Since there were no literature data on the $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ reaction, its measurements were simply compared to theoretical calculations. In Fig. 9, the measured values are greater

than the estimated values; yet, both follow a similar trend as the incident photon energy increases.

5. $^{198}\text{Pt}(\gamma, n)^{197}\text{Pt}$ reaction

The ^{197}Pt radionuclide exists in both isomeric and unstable ground states. The activity of ^{197m}Pt ($T_{1/2} = 95.41$ min, $13/2^+$) was measured using γ rays of 346.5 keV (11.1%). For the ground state ^{197g}Pt ($T_{1/2} = 19.89$ h, $1/2^-$), the interference-free γ rays of 77.35 keV (17%) and 191.44 keV (3.7%) were suitable for the activity measurement. Here, given that ^{197m}Pt decays to ^{197g}Pt with an IT coefficient of 96.7%, the measurement using 77.35- and 191.44-keV γ rays represents the cumulative activity for $^{197(0.967m+g)}\text{Pt}$. To determine the activity of the ^{197g}Pt we use spectra taken 13 h (it is $8T_{1/2}$ of the ^{197m}Pt) after irradiation (we can assume that at this time the ^{197m}Pt completely decays).

The metastable state has a lower production probability than the ground state because of its higher nuclear spin. Figure 10 displays a comparison between the current measured and theoretical values. Figure 10 shows that the measured values for the $^{198}\text{Pt}(\gamma, n)^{197g}\text{Pt}$ reaction are in good agreement with TALYS calculations in terms of shape and magnitude.

For the production of ^{197m}Pt from the Pt target, only one previous experimental data set in the GDR energy region based on bremsstrahlung photons was available [4]; these data were found to be higher than the theoretical values obtained using the TALYS-2.0 codes as shown in Fig. 10 and this shows that the current results follow the shape but are higher than the theoretical curve. Starting from 14 MeV, the literature data began to differ from our measured values.

The experimental points along the cross sections of reactions $(\gamma, n) + (\gamma, 2n)$ [3] and $^{198}\text{Pt}(\gamma, n)^{197m}\text{Pt}$ [4] were approximated by the Lorentz function, and the relative yields Y_{rel} and cross sections per equivalent quantum σ_q were calculated based on the least squares approximation. In Fig. 9 these points are indicated by open black rectangles [3] and open red rectangles [4], respectively.

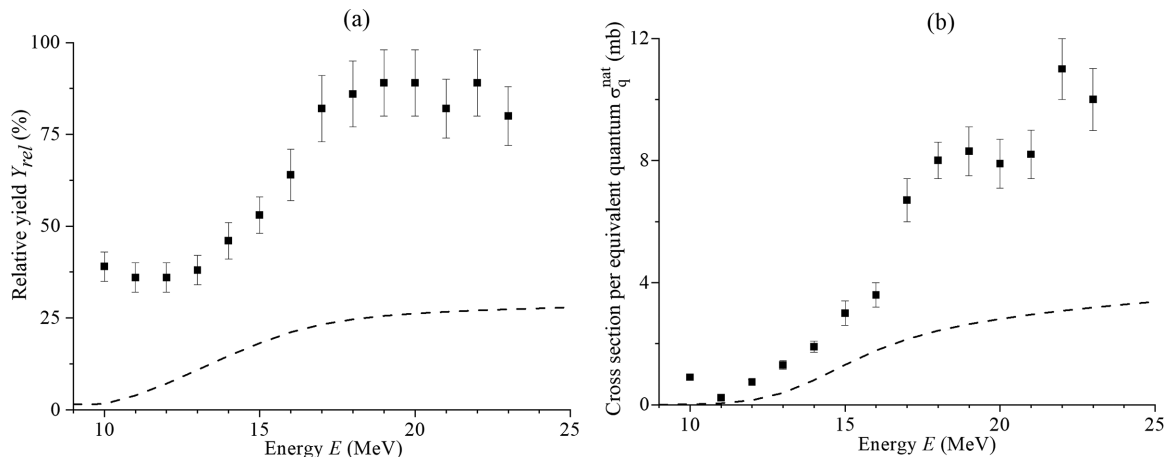


FIG. 9. Relative yield (a) and cross section per equivalent quantum (b) of reaction $^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$ as a function of bremsstrahlung end-point energy from the present work (solid rectangles) and simulated values using TALYS code (dashed lines).

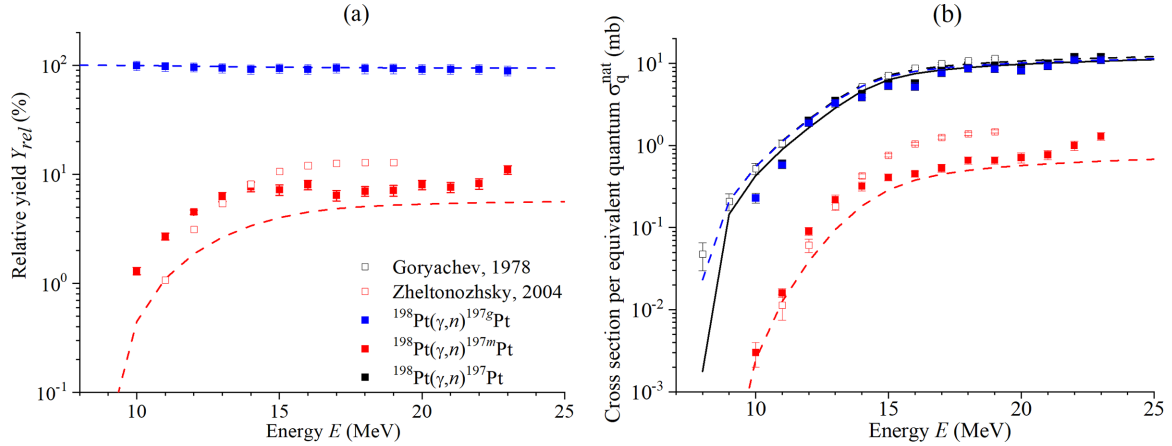


FIG. 10. Relative yield (a) and cross section per equivalent quantum (b) of reaction $^{198}\text{Pt}(\gamma, n)^{197}\text{Pt}$ as a function of bremsstrahlung end-point energy from the present work (solid rectangles), literature data [3] (open black rectangles), Ref. [4] (open red rectangles), as well as simulated values using TALYS code (dashed lines) and CMPR (solid line).

The experimental values from this study for the $^{198}\text{Pt}(\gamma, n)^{197}\text{Pt}$ reaction and the literature data in the GDR region [3] are shown in Fig. 10. In the figure, it is clear that the measured and theoretical values are in good agreement, in terms of not only shape but also magnitude.

B. Photoproton reactions

Iridium (^{194g}Ir , ^{195g}Ir , ^{195m}Ir) radioisotopes were directly produced by $^{\text{nat}}\text{Pt}(\gamma, p)$ reactions. In this study, the relative yields and cross sections per equivalent quantum of the $^{\text{nat}}\text{Pt}(\gamma, p)^{194g, 195g, 195m, 195}\text{Ir}$ reactions at the bremsstrahlung end-point energies of 10–23 MeV are determined for the first time and presented in Table V.

1. $^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$ reaction

The ^{194}Ir radionuclide exists in both isomeric and unstable ground states. Because the half-life of the isomeric state of ^{194m}Ir ($T_{1/2} = 31.85$ ms) is short, its activity could not be measured, whereas the activity of the unstable ground state of ^{194g}Ir ($T_{1/2} = 19.18$ h) could be measured using the interference-free γ rays of 328.467 keV (13.1%). Given that ^{194m}Ir decays to ^{194g}Ir with an IT coefficient of 100%, the activity measured from the γ rays of 762.65 keV was accumulated and used to determine the yield of ^{194}Ir . Figure 11 displays the measured data as well as the computed values. It is evident from Fig. 11 that there is good agreement between the theoretical values on the basis of CMPR and currently measured values in terms of both form and magnitude.

2. $^{196}\text{Pt}(\gamma, p)^{195}\text{Ir}$ reaction

The ^{195}Ir radionuclide exists in both isomeric and unstable ground states. The activity of ^{195m}Ir ($T_{1/2} = 3.67$ h, $11/2^-$) was measured using γ rays of 684.88 keV (9.8%). The ^{195g}Ir ($T_{1/2} = 2.29$ h, $3/2^+$) emits three γ rays [98.83 keV (10%), 129.71 keV (1.4%), and 211.41 keV (2.5%)] of suitable energy and intensity for corresponding activity measurements; however, there was an interference problem with two of these, as ^{195m}Pt ($T_{1/2} = 4.01$ d) also emits γ rays of 98.857 keV (11.7%) and 129.7 keV (2.83%). That is why the activity of

the ^{195g}Ir could be measured using the interference-free γ rays of 211.41 keV. Given that ^{195m}Ir decays to ^{195g}Ir with an IT coefficient of 5%, the activity measured from the γ rays of 211.41 keV was accumulated and used to determine the yield of $^{195(0.05m+g)}\text{Ir}$. Since only 5% of ^{195m}Ir decays into ^{195g}Ir , the contribution of ^{195g}Ir formation from the isomeric transition of ^{195m}Ir does not exceed the error margin. Because literature data were unavailable, these measurements were solely compared to the theoretical values (Fig. 12). The figures also show that the current results follow the shape but are higher than the theoretical values; they are the closest to the values calculated using the CMPR code.

In the case of photoproton reactions on the heavy platinum isotopes (see Figs. 11 and 12), the theoretical values calculated using the CMPR code are much larger than the TALYS results. For photoproton reactions on the isotopes of ^{195}Pt and ^{196}Pt , the cross sections per equivalent quantum $\sigma_{q\text{CMPR}}$ and $\sigma_{q\text{TALYS}}$ differ by one order of magnitude. The experimentally obtained results lie closer to the theoretical curve according to CMPR. CMPR allows us to describe experimental data on photoproton reactions in the energy range from 19 to 23 MeV by accounting for isospin splitting of the giant dipole resonance.

The only parameter in TALYS that describes the excitation of the nucleus in the used model of the GDR is the energy of the absorbed gamma quantum E_γ , which is redistributed among the nucleons of the nucleus, and the emission is calculated as a proton or neutron at each stage of energy dissipation. The number of decay channels and particle energy determine the competition between proton and neutron emission. The TALYS program does not take into account the isospin values $T_- = T_0 = (N - Z)/2$ and $T_+ = T_0 + 1$, nor the characteristics of their decay with proton and neutron emission.

The excitation of the nucleus in CMPR is described by the deformation parameters of the nucleus and the energy of the absorbed γ quantum E_γ . Level densities are computed in CMPR using a constant temperature model, which is the same as ldmodel 1 in TALYS. In contrast to the TALYS program, the magnitude of the isospin splitting of the GDR is taken into account along with the splitting of the GDR due

TABLE IV. Experimental results of photoneutron reactions.

Reaction	$E_{\gamma\text{max}}$ (MeV)	Y_{rel} (%)	σ_q (mb)
$^{190}\text{Pt}(\gamma, n)^{189}\text{Pt}$	21	0.24 ± 0.03	0.024 ± 0.003
	22	0.21 ± 0.03	0.026 ± 0.003
	23	0.22 ± 0.04	0.026 ± 0.004
$^{192}\text{Pt}(\gamma, n)^{191}\text{Pt}$	10	4.5 ± 0.4	0.010 ± 0.001
	11	6.7 ± 0.7	0.040 ± 0.003
	12	7.9 ± 0.8	0.16 ± 0.02
	13	9.0 ± 0.9	0.32 ± 0.03
	14	9.8 ± 0.9	0.41 ± 0.04
	15	7.5 ± 0.8	0.43 ± 0.06
	16	8.6 ± 0.9	0.49 ± 0.06
	17	6.9 ± 0.7	0.56 ± 0.06
	18	6.5 ± 0.7	0.61 ± 0.07
	19	7.9 ± 0.8	0.74 ± 0.08
	20	11 ± 1	1.0 ± 0.1
	21	10 ± 1	1.0 ± 0.1
	22	9 ± 1	1.1 ± 0.1
	23	10 ± 1	1.2 ± 0.1
$^{194}\text{Pt}(\gamma, n)^{193m}\text{Pt}$	14	25 ± 3	1.1 ± 0.1
	15	33 ± 3	1.9 ± 0.2
	16	40 ± 4	2.3 ± 0.2
	17	47 ± 4	3.9 ± 0.4
	18	44 ± 5	4.2 ± 0.4
	19	41 ± 5	3.8 ± 0.5
	20	57 ± 6	5.1 ± 0.5
	21	67 ± 6	6.7 ± 0.7
	22	57 ± 6	6.9 ± 0.8
	23	52 ± 6	6.3 ± 0.8
$^{196}\text{Pt}(\gamma, n)^{195m}\text{Pt}$	10	39 ± 4	0.09 ± 0.01
	11	36 ± 4	0.22 ± 0.04
	12	36 ± 4	0.74 ± 0.08
	13	38 ± 4	1.3 ± 0.1
	14	46 ± 5	1.9 ± 0.2
	15	53 ± 5	3.0 ± 0.4
	16	64 ± 7	3.6 ± 0.4
	17	82 ± 9	6.7 ± 0.7
	18	86 ± 9	8.0 ± 0.8
	19	89 ± 9	8.3 ± 0.8
	20	89 ± 9	7.9 ± 0.8
	21	82 ± 8	8.2 ± 0.8
	22	89 ± 9	11 ± 1
	23	80 ± 8	10 ± 1
$^{198}\text{Pt}(\gamma, n)^{197g}\text{Pt}$	10	99 ± 10	0.23 ± 0.03
	11	97 ± 9	0.58 ± 0.06
	12	96 ± 9	1.9 ± 0.2
	13	94 ± 9	3.3 ± 0.4
	14	92 ± 9	3.9 ± 0.4
	15	93 ± 9	5.3 ± 0.5
	16	92 ± 9	5.2 ± 0.5
	17	94 ± 9	7.6 ± 0.7
	18	93 ± 9	8.7 ± 0.9
	19	93 ± 9	8.6 ± 0.9
	20	92 ± 9	8.2 ± 0.8
	21	92 ± 9	9.3 ± 0.9
	22	92 ± 9	11 ± 1
	23	89 ± 9	11 ± 1

TABLE IV. (Continued.)

Reaction	$E_{\gamma\text{max}}$ (MeV)	Y_{rel} (%)	σ_q (mb)
$^{198}\text{Pt}(\gamma, n)^{197m}\text{Pt}$	10	1.3 ± 0.1	0.003 ± 0.001
	11	2.7 ± 0.2	0.016 ± 0.002
	12	4.5 ± 0.2	0.09 ± 0.01
	13	6.2 ± 0.5	0.22 ± 0.03
	14	7.7 ± 0.6	0.32 ± 0.04
	15	7.2 ± 0.6	0.41 ± 0.04
	16	8.0 ± 0.7	0.45 ± 0.04
	17	6.4 ± 0.5	0.53 ± 0.06
	18	7.0 ± 0.6	0.66 ± 0.07
	19	7.1 ± 0.6	0.66 ± 0.07
	20	8.0 ± 0.7	0.71 ± 0.10
	21	7.6 ± 0.7	0.77 ± 0.10
	22	8.2 ± 0.7	1.0 ± 0.1
	23	11 ± 1	1.3 ± 0.1
$^{198}\text{Pt}(\gamma, n)^{197}\text{Pt}$	10		0.23 ± 0.03
	11		0.60 ± 0.06
	12		2.0 ± 0.2
	13		3.5 ± 0.3
	14		4.2 ± 0.4
	15		5.7 ± 0.6
	16		5.7 ± 0.6
	17		8.2 ± 0.8
	18		9.4 ± 0.9
	19		9.3 ± 0.9
	20		8.9 ± 0.9
	21		10 ± 1
	22		12 ± 1
	23		12 ± 1

to nuclear deformation. The photoabsorption cross section at medium and heavy nuclei is approximated by the sum of four Lorentz curves corresponding to dipole excitations of nuclei with isospin $T_< = T_0 = (N - Z)/2$ and $T_> = T_0 + 1$ with neutron-proton vibrations along and perpendicular to the symmetry axis of the nucleus.

TABLE V. Experimental results of $^{\text{nat}}\text{Pt}(\gamma, p)$ reactions.

Reaction	$E_{\gamma\text{max}}$ (MeV)	Y_{rel} (%)	σ_q (mb)
$^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$	19	0.11 ± 0.01	0.010 ± 0.001
	20	0.24 ± 0.02	0.021 ± 0.002
	21	0.37 ± 0.03	0.037 ± 0.005
	22	0.59 ± 0.06	0.072 ± 0.007
	23	0.66 ± 0.08	0.080 ± 0.009
$^{196}\text{Pt}(\gamma, p)^{195g}\text{Ir}$	21	0.25 ± 0.06	0.025 ± 0.004
	22	0.23 ± 0.05	0.028 ± 0.005
	23	0.30 ± 0.06	0.035 ± 0.005
$^{196}\text{Pt}(\gamma, p)^{195m}\text{Ir}$	21	0.05 ± 0.01	0.005 ± 0.001
	22	0.05 ± 0.01	0.006 ± 0.001
	23	0.07 ± 0.01	0.008 ± 0.001
$^{196}\text{Pt}(\gamma, p)^{195}\text{Ir}$	21	0.30 ± 0.06	0.030 ± 0.004
	22	0.28 ± 0.06	0.034 ± 0.005
	23	0.36 ± 0.07	0.044 ± 0.006

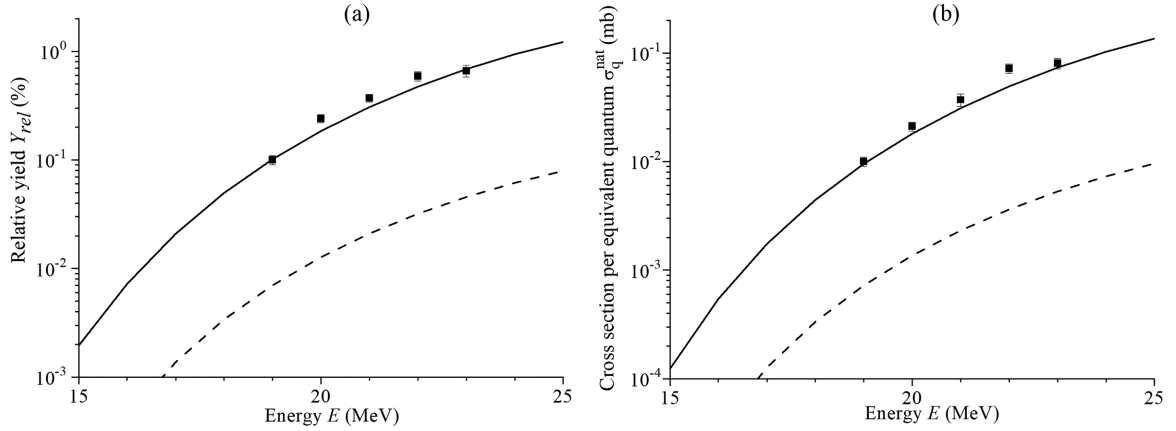


FIG. 11. Relative yield (a) and cross section per equivalent quantum (b) of reaction $^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$ as a function of bremsstrahlung end-point energy from the present work (solid rectangles) and simulated values using TALYS code (dashed lines).

The essential components for TALYS computations to calculate photonuclear reaction cross sections are the nuclear level densities and γ -ray strength functions. The cross section of the reactions is computed in this work using TALYS with standard parameters. For the reaction $^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$, the effects of altering a number of input parameters are examined, including level densities [constant Temperature + Fermi gas model (*LD1*), back-shifted Fermi gas model (*LD2*), generalized superfluid model (*LD3*), Skyrme-Hartree-Fock-Bogolyubov level densities from numerical tables (*LD4*), Skyrme-Hartree-Fock-Bogolyubov combinatorial level densities from numerical tables (*LD5*), and temperature-dependent Gogny-Hartree-Fock-Bogolyubov combinatorial level densities from numerical tables (*LD6*)] and the selection of the γ -strength function form (Kopecky-Uhl generalized Lorentzian, Brink-Axel Lorentzian, Hartree-Fock BCS tables, Hartree-Fock-Bogolyubov tables, Goriely's hybrid model, Goriely T-dependent HFB, T-dependent RMF, Gogny D1M HFB+QRPA, simplified modified Lorentzian model, and Skyrme HFB+QRPA).

The cross section and cross section per equivalent quantum for the reaction $^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$ are displayed in Figs. 13

and 14. Changing the parameters of level density models and gamma strength functions leads to 54 different results of the theoretical value of $\sigma(E)$, and the observed spread of cross sections reaches a factor of ≈ 4.5 (see Fig. 13). The minimum value was obtained for the case of a combination of parameters *LD3* and Gogny D1M HFB+QRPA, and the maximum *LD6* and T-dependent RMF. Changing these input parameters has no impact on the TALYS results, as can be seen in Figs. 13 and 14.

Thus, it was confirmed that the difference between the results of TALYS and CMPR is due to the consideration of isospin splitting in CMPR. A brief description of isospin splitting is given below.

In nuclei with $N \neq Z$, upon absorption of electric dipole γ photons, two branches of the GDR are excited, $T_{\leq} T_0$ and $T_{\geq} T_0 + 1$, where $T_0 = \frac{|N-Z|}{2}$. Figure 15 shows the excitations of the isospin components $T_{\leq}$ and $T_{\geq}$ of the GDR in the initial nucleus (N, Z) and their decay according to the proton ($N, Z - 1$) and neutron ($N - 1, Z$) channels. From Fig. 15, it can be observed that the decay of excited GDR states with isospin $T_{\geq} T_0 + 1$ according to the neutron channel to low-lying states $T = T_0 - 1/2$ with neutron emission is forbidden,

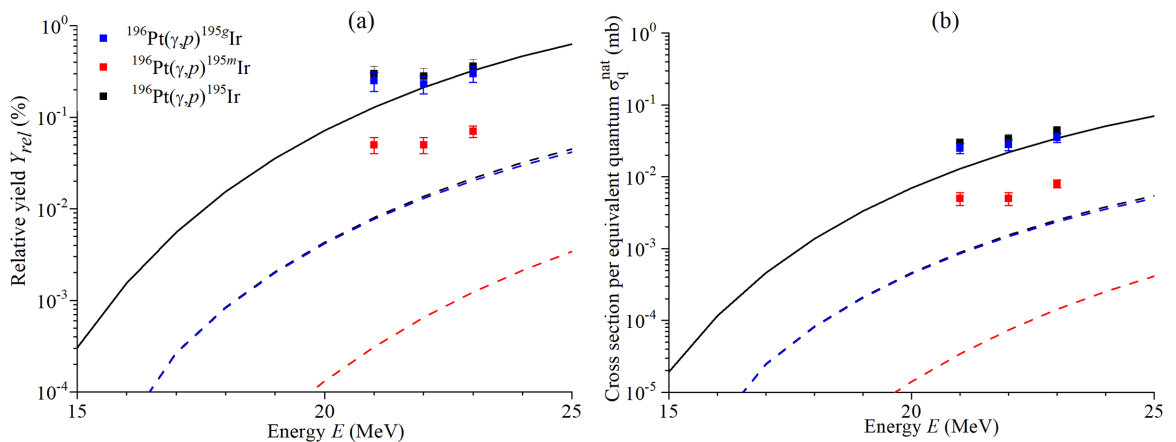


FIG. 12. Relative yield (a) and cross section per equivalent quantum (b) of reaction $^{196}\text{Pt}(\gamma, p)^{195}\text{Ir}$ as a function of bremsstrahlung end-point energy from the present work (solid rectangles) as well as simulated values using TALYS code (dashed lines) and CMPR (solid lines).

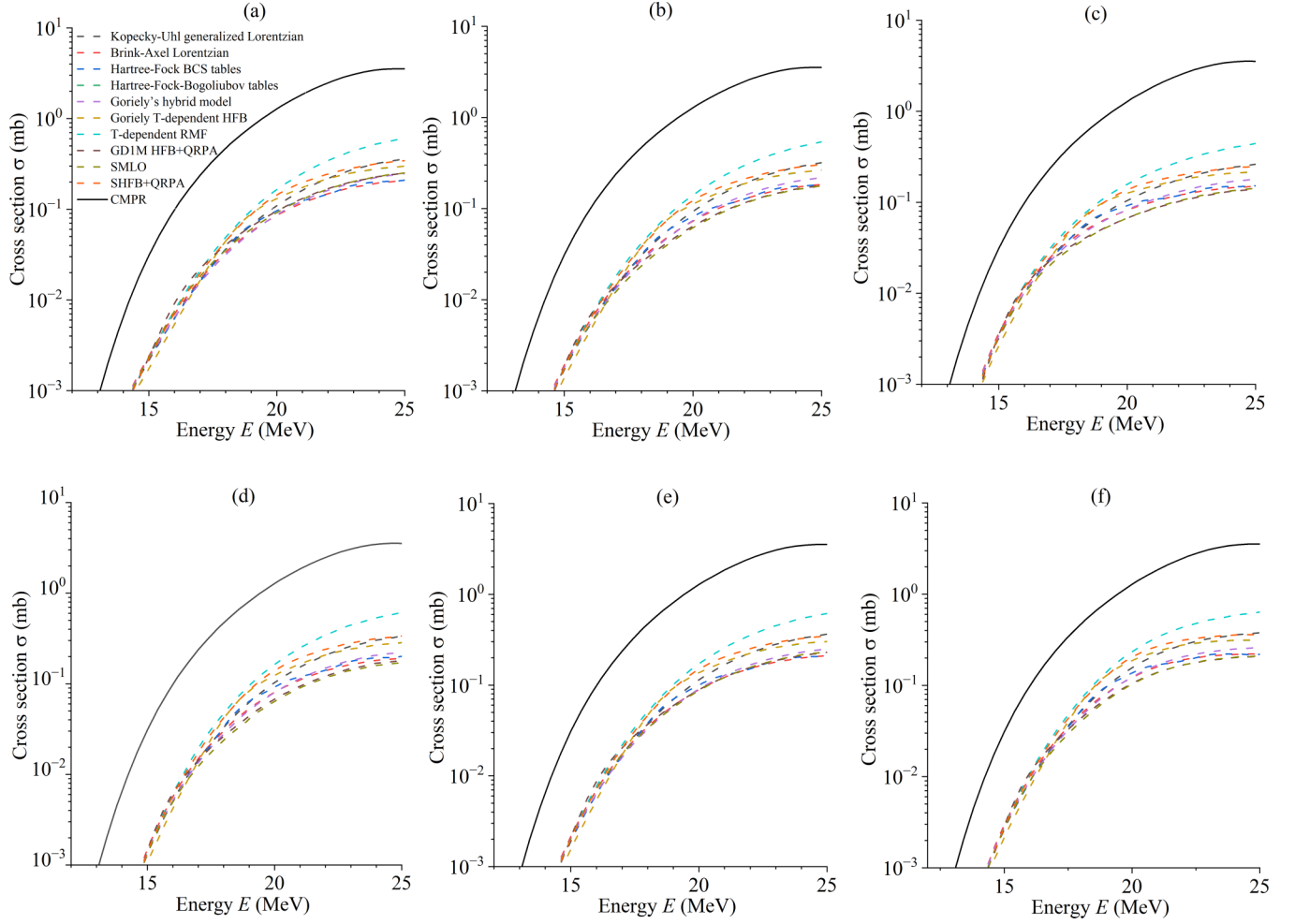


FIG. 13. Cross sections $\sigma(E)$ for the $^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$ reaction calculated with the TALYS code for six level density models $LD1-LD6$ (a-e) and ten gamma strength functions (dashed lines) as well as simulated values using the CMPR (solid lines).

which leads to an increase in the reaction cross section $(\gamma, 1p)$ and to a maximum shift of the reaction cross section $(\gamma, 1p)$ with respect to reactions $(\gamma, 1n)$ towards higher energies in the nucleus (N, Z) .

The value of isospin splitting of the GDR is determined by the following relation (7):

$$\Delta E = E(T_>) - E(T_<) = \frac{60}{A}(T_0 + 1). \quad (7)$$

For isotopes $^{\text{nat}}\text{Pt}$, the isospin increases from 17 to 21, which leads to an increase in the isospin splitting of the GDR for these isotopes from 5.68 to 6.67 MeV.

The ratio of the probabilities of excitation of states $T_>$ and $T_<$ is described by the following relation (8):

$$\frac{s(T_>)}{s(T_<)} = \frac{1}{T_0} \frac{1 - 1.5T_0A^{-2/3}}{1 + 1.5T_0A^{-2/3}}. \quad (8)$$

The combined model of photonuclear reactions considers not only the giant dipole resonance and the quasideuteron photoabsorption mechanism, but also the contribution into the cross section of isovector quadrupole resonance (QR) and the GDR overtone (GDR2) in calculation of the photoabsorption cross section. Figure 16 shows the contributions of the cross

sections of QR, GDR2, and the quasideuteron mechanism (QD) into the total absorption cross section in the energy region below 40 MeV on platinum isotopes $^{190,198}\text{Pt}$. The corresponding integral cross sections of photonuclear reactions on isotopes $^{\text{nat}}\text{Pt}$ are given in Table VI.

TABLE VI. The integral cross sections of total absorption $\sigma_{\text{int}}(\gamma, \text{abs})$, giant dipole resonance $\sigma_{\text{GDR}}^{\text{int}}$, quadrupole resonance $\sigma_{\text{QR}}^{\text{int}}$, overtone $\sigma_{\text{GDR2}}^{\text{int}}$, and quasideuteron mechanism $\sigma_{\text{QD}}^{\text{int}}$ for isotopes $^{\text{nat}}\text{Pt}$, calculated according to CMPR in the γ energy region below 40 MeV.

A	Integral cross section σ_{int} (MeV mb)					
	$\sigma_{\text{int}}(\gamma, \text{abs})$	$\sigma_{\text{GDR}}^{\text{int}}$		$\sigma_{\text{QR}}^{\text{int}}$	$\sigma_{\text{GDR2}}^{\text{int}}$	$\sigma_{\text{QD}}^{\text{int}}$
		$T_<$	$T_>$			
190	3685	3190	38	233	57	167
192	3688	3213	31	222	54	168
194	3693	3221	23	227	55	169
195	3739	3263	20	227	58	170
196	3727	3258	16	228	56	170
198	3740	3266	12	232	59	171

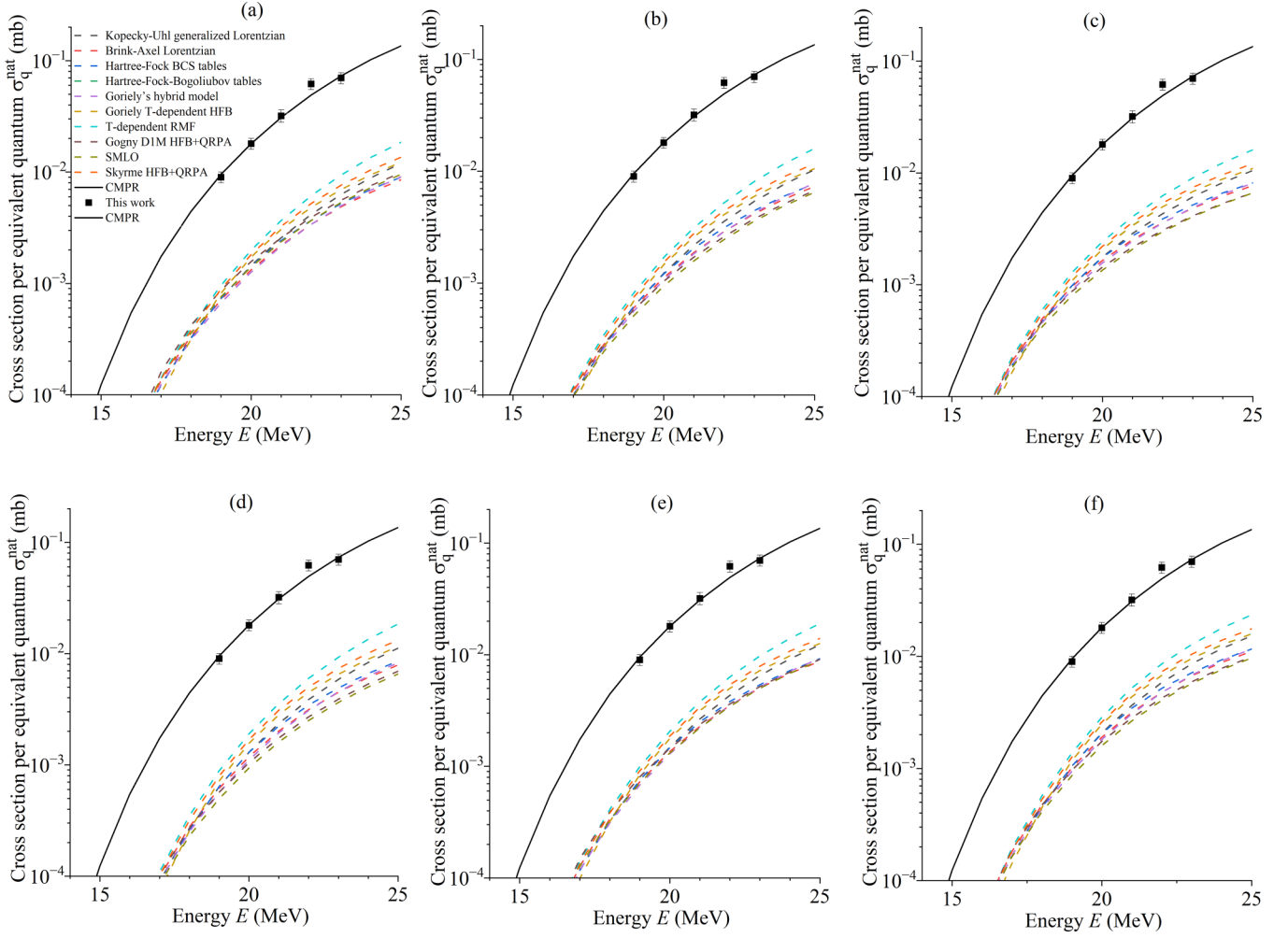


FIG. 14. Cross sections per equivalent quantum $\sigma_q^{\text{nat}}(E)$ for the $^{195}\text{Pt}(\gamma, p)^{194}\text{Ir}$ reaction calculated with the TALYS code for six level density models LD1–LD6 (a–e) and ten gamma strength functions (dashed lines) as well as simulated values using the CMPR (solid lines).

Figure 17 shows all of the contributions of the cross sections into the total absorption cross section in the energy region below 40 MeV to the theoretical cross sections for the reaction (γ, p) on $^{192, 194, 196, 198}\text{Pt}$ isotopes. Table VII shows the values of the energy of the isospin splitting of the GDR,

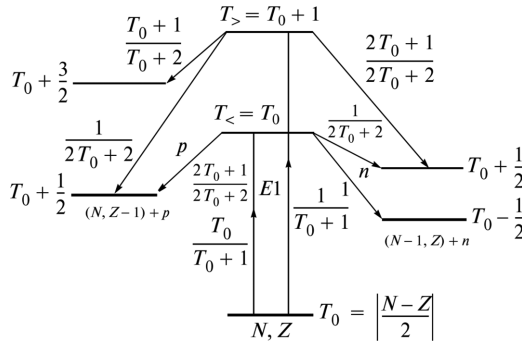


FIG. 15. Scheme of excitation of states $T_<$ and $T_>$ in the nucleus (N, Z) and their decay along the proton channel $(N, Z - 1)$ and neutron channel $(N - 1, Z)$.

calculated on the basis of relations (7) for isotopes $^{\text{nat}}\text{Pt}$. Also Table VI contains integral cross sections $\sigma_{<}^{\text{int}}$ and $\sigma_{>}^{\text{int}}$ of the isospin component reactions $(\gamma, sn) = (\gamma, n) + (\gamma, np) + (\gamma, 2n)$ and $(\gamma, sp) = (\gamma, p) + (\gamma, np) + (\gamma, 2p)$ in the energy region below 40 MeV, and the ratio of the reaction cross sections $\frac{\sigma_{>}^{\text{int}}}{\sigma_{<}^{\text{int}}}$, calculated on the basis of CMPR for isotopes $^{\text{nat}}\text{Pt}$. It can be seen from the Table VI that with a decrease in the mass number A from 190 to 198, the value of the isospin splitting decreases by the value ≈ 1.01 MeV. The isospin splitting leads to the shift of the proton cross section of the relative neutron in the high energy side.

C. Isomeric ratios

The E1 photon absorption by isotopes of the ^{196}Pt ($J^\pi = 0^+$) nucleus leads to the excitation of the giant dipole resonance. Upon the decay of the giant dipole resonance via a reaction involving the emission of protons, there arises a ^{195}Ir nucleus in the ground or excited state. Cascades of γ transitions from excited states lead to the production of the isomeric or ground state of ^{195}Ir . The ^{195m}Ir isomeric state decays through the β^- decay (95%) or isomer transition (5%)

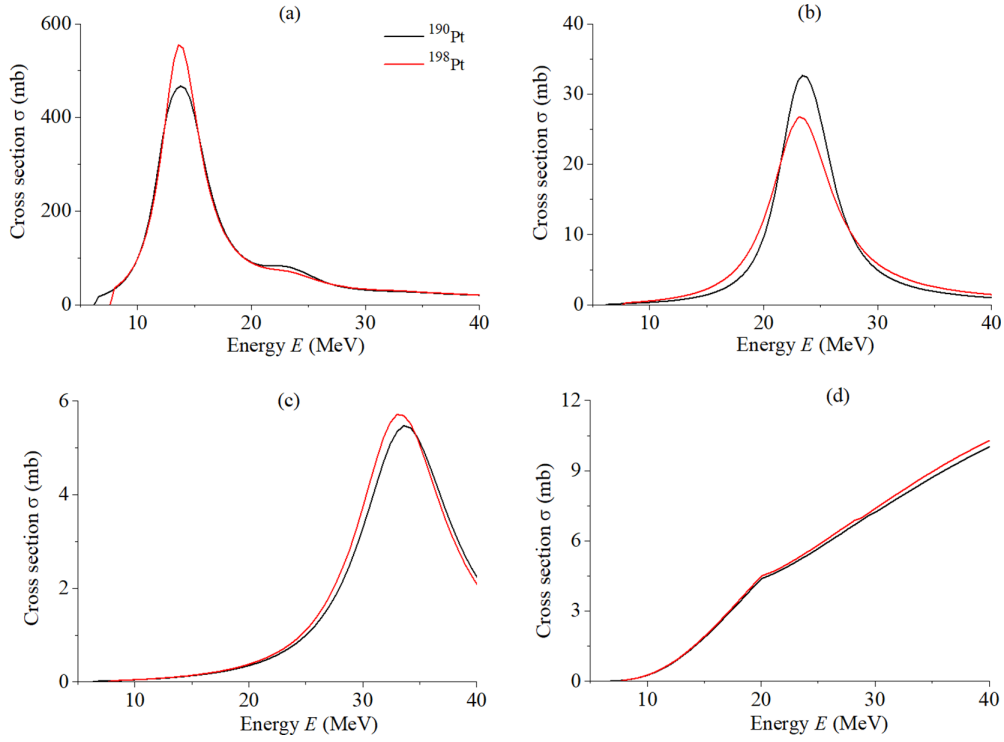


FIG. 16. (a) The total photoabsorption cross section $\sigma(\gamma, \text{abs})$, (b) the contribution of overtone GDR2, (c) the contribution of quadrupole resonance (QR), and (d) contribution of the QD mechanism in the total photoabsorption cross section for isotopes ^{190}Pt (solid blue line) and ^{198}Pt (dashed red line), calculated according to CMPR.

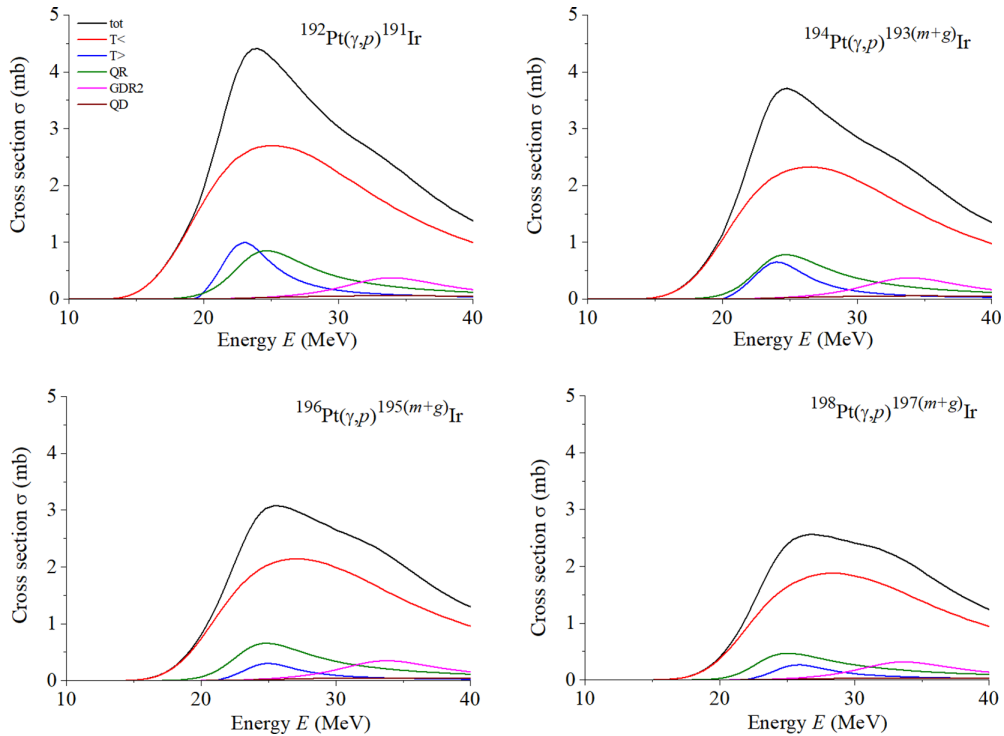


FIG. 17. Cross section reactions (black line) and cross sections of the GDR components $T_{<} = T_0$ (red line) and $T_{>} = T_0 + 1$ (blue line), QR (olive line), GDR2 (magenta line), and QD (wine line) for the reaction (γ, p) on $^{192,194,196,198}\text{Pt}$ isotopes.

TABLE VII. The values of the isospin splitting of the GDR, integral cross sections $\sigma_{<}^{\text{int}}$ and $\sigma_{>}^{\text{int}}$ of the isospin components reactions (γ , sn) and (γ , sp), and the ratio of the reaction cross sections $\frac{\sigma_{>}^{\text{int}}}{\sigma_{<}^{\text{int}}}$, calculated on the basis of CMPR for isotopes $^{\text{nat}}\text{Pt}$.

A	T_0	$E(T_+) - E(T_-)$	(γ, sn)			(γ, sp)		
			$\sigma_{<}^{\text{int}}$ (MeV mb)	$\sigma_{>}^{\text{int}}$ (MeV mb)	$\frac{\sigma_{>}^{\text{int}}}{\sigma_{<}^{\text{int}}}$	$\sigma_{<}^{\text{int}}$ (MeV mb)	$\sigma_{>}^{\text{int}}$ (MeV mb)	$\frac{\sigma_{>}^{\text{int}}}{\sigma_{<}^{\text{int}}}$
190	17	5.68	3035	31	0.010	50	14	0.28
192	18	5.94	3110	25	0.008	48	11	0.22
194	19	6.19	3149	19	0.006	41	6	0.15
195	19.5	6.31	3222	17	0.005	42	5	0.11
196	20	6.43	3558	14	0.004	37	3	0.09
198	21	6.67	3130	9	0.003	31	2	0.06

channel. Usually, the isomeric and ground states strongly differ in spins; therefore, the isomeric ratio is represented in most cases through the yields of high- to low-spin states. In the case of $^{195m,g}\text{Ir}$, the spin of the isomeric state of ^{195m}Ir is $11/2^-$ (high-spin state) and that of the unstable ground state of ^{195g}Ir is $3/2^+$ (low-spin state). Therefore, the isomeric ratio of $^{195m,g}\text{Ir}$ was computed as the ratio of the high- to low-spin states. The isomeric ratios for the production of the $^{196}\text{Pt}(\gamma, p)^{195m,g}\text{Ir}$ reaction at different bremsstrahlung end-point energies are given in Fig. 18 and Table VIII. In the experiments we were able to determine only three points for the isomeric ratio of the $^{195}\text{Pt}(\gamma, p)^{194m,g}\text{Ir}$ reaction. It is impossible to draw a conclusion based on three points with a step of 1 MeV. The theoretical curve calculated using the TALYS program lies much lower than our experimental data.

The $E1$ photon absorption by isotopes of the ^{198}Pt ($J^\pi = 0^+$) nucleus leads to the excitation of the giant dipole resonance. Upon the decay of the giant dipole resonance via a reaction involving the emission of neutrons, there arises a ^{197}Pt nucleus in the ground or excited state. Cascades of γ transitions from excited states lead to the production of the isomeric or ground state of ^{197}Pt . The ^{197m}Pt isomeric state decays through the β^- decay (3.3%) or isomer transition (96.7%) channel. In the case of $^{197m,g}\text{Pt}$, the spin of the isomeric state of ^{197m}Pt is $13/2^+$ (high-spin state) and that of the unstable

ground state of ^{197g}Pt is $1/2^-$ (low-spin state). Therefore, the isomeric ratio of $^{197m,g}\text{Pt}$ was computed as the ratio of the high- to low-spin states. The isomeric ratios for the production of the $^{198}\text{Pt}(\gamma, n)^{197m,g}\text{Pt}$ reaction at different bremsstrahlung end-point energies are given in Fig. 19 and Table VIII.

There are very few data available in the current literature on the isomeric ratios in photoneutron reactions with natural platinum in the GDR region as well as in the higher energy range. We found only five experimentally measured data for the $^{198}\text{Pt}(\gamma, n)^{197m,g}\text{Pt}$ reaction [4–9]. The authors in Ref. [7] have measured for the region from 11 to 14 MeV, in Ref. [4] from 11 to 17 MeV, in Ref. [5] from 10 to 24 MeV, and in Refs. [8,9] for 30 MeV. Our data were measured for the region from 10 to 23 MeV. One can see that for energy 14 MeV the data in Ref. [7] are insignificantly lower than in Refs. [4] and in agreement with our result and the result in Ref. [5]. Our data from 14 to 23 MeV are insignificantly lower

TABLE VIII. Isomeric ratios of the $^{196}\text{Pt}(\gamma, p)^{195m,g}\text{Ir}$ and $^{198}\text{Pt}(\gamma, n)^{197m,g}\text{Pt}$ reactions at the bremsstrahlung end-point energies of 10–23 MeV from the present work and simulated data using TALYS.

Bremsstrahlung			
Reaction	end-point energy (MeV)	Experiment	TALYS
$^{198}\text{Pt}(\gamma, n)^{197m,g}\text{Pt}$	10	0.013 ± 0.004	0.004
	11	0.030 ± 0.005	0.011
	12	0.047 ± 0.007	0.019
	13	0.067 ± 0.013	0.027
	14	0.082 ± 0.014	0.035
	15	0.077 ± 0.011	0.042
	16	0.086 ± 0.015	0.047
	17	0.070 ± 0.011	0.051
	18	0.076 ± 0.011	0.053
	19	0.077 ± 0.012	0.055
	20	0.087 ± 0.012	0.056
	21	0.083 ± 0.011	0.057
	22	0.091 ± 0.016	0.058
23	0.118 ± 0.018	0.058	
$^{196}\text{Pt}(\gamma, p)^{195m,g}\text{Ir}$	21	0.20 ± 0.03	0.040
	22	0.18 ± 0.04	0.049
	23	0.23 ± 0.05	0.060

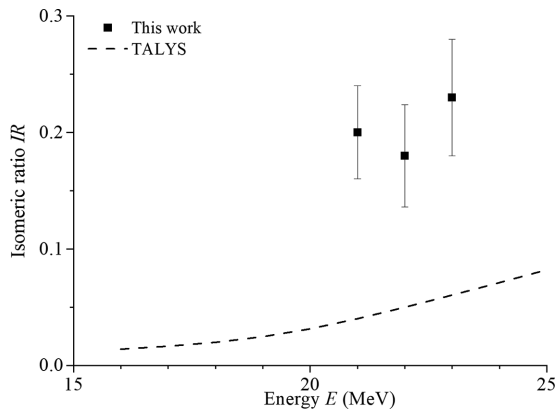


FIG. 18. Isomeric yield ratios of the pairs $^{195m,g}\text{Ir}$ produced in the $^{196}\text{Pt}(\gamma, p)$ reaction as a function of the bremsstrahlung end-point energy from the present work (solid squares) and simulated values using TALYS code (dashed lines).

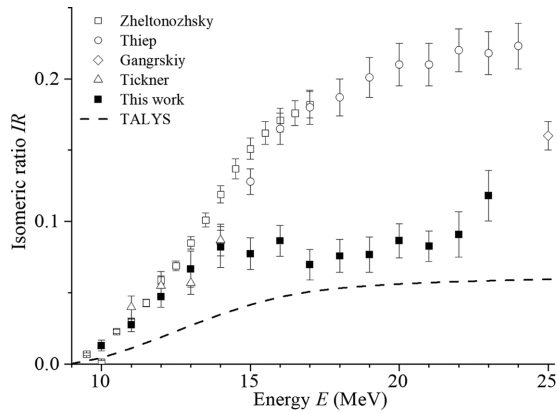


FIG. 19. Isomeric yield ratios of the pairs $^{197m,g}\text{Pt}$ produced in the $^{198}\text{Pt}(\gamma, n)$ reaction as a function of the bremsstrahlung end-point energy from the present work (solid squares), literature data [4] (open squares), Ref. [5] (open circles), Ref. [6] (open diamonds), Ref. [7] (open triangles), and simulated values using TALYS code (dashed lines).

than in Refs. [4,5]. In general the isomeric ratio of pair $^{197m,g}\text{Pt}$ increases with the increase of end-point bremsstrahlung energy. As it is seen from our data, the isomeric ratio slightly changes for energy higher than 14 MeV. The theoretical curve calculated using the TALYS program lies much lower than the experimental data.

V. CONCLUSION

The current work measured relative yields, cross sections per equivalent quantum, and flux-averaged cross sections

for photonuclear reactions on a natural platinum mixture at bremsstrahlung end-point energies ranging from 10 to 23 MeV. The bremsstrahlung photon flux was calculated using the GEANT4.11.1 algorithm. The experimental results were compared to calculations performed with the TALYS model with standard parameters and the CMPR code. The resulting photoneutron reactions showed a high agreement between the experimental data and computations using the TALYS-2.0 program and the CMPR framework. On the heavy isotopes ^{195}Pt and ^{196}Pt , the theoretical relative yield computed using CMPR was much higher than the TALYS values. CMPR allows us to describe experimental data on photoproton reactions in the energy range from 10 to 23 MeV by taking into account isospin splitting of the giant dipole resonance. In addition, new data on the yields of photonuclear reactions on natural platinum obtained in this work are important for the photonuclear production of medical isotopes.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [26].

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