Multi-particle Photonuclear Reactions behind Giant Dipole Resonance

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Experimental data on yields of multi-particle photonuclear reactions (involving the emission of up to seven neutrons from the nucleus involved) on $^{197}$Au, $^{203}$Tl, and $^{209}$Bi nuclei in the region extending from the giant dipole resonance to an energy of 67.7 MeV are presented. These data are compared with the results of modern theoretical calculations that take into account both the excitation of a giant dipole resonance (GDR) in a nucleus and the photodisintegration of quasideutrons (QD) in it. By and large, experimental data confirm the results of theoretical calculations – that is, only upon taking simultaneously into account both alternative photodisintegration mechanisms (GDR excitation and QD photodisintegration) can one describe these experimental data. The contribution of QD photodisintegration grows with increasing photon energy and neutron multiplicity and becomes dominant for reactions with the emission of not less than five neutrons from the nucleus being considered.

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I. INTRODUCTION

The region of photodisintegration of nuclei extends from the nucleon threshold (5 to 10 MeV) to the threshold for meson production on nuclei (135 MeV). In this energy range, whose width is about 100 MeV, the attention of experimentalists and theorists over more than 60 years of their investigations has been focused primarily on the giant dipole resonance (GDR), which dominates cross sections for photon absorption by nuclei in the energy range 10 – 40 MeV. At the present time, it can be stated that the physics of this unique nuclear phenomenon has been understood quite well. For a long time, the region of energies above that of the GDR maximum had been as if overshadowed by investigations into this resonance phenomenon. Methodological differences were the main reason for this. In the region of energies above the GDR energy, excited nuclear states decay predominantly via the emission of several (up to ten) nucleons, mostly neutrons. As a matter of fact, methods for a direct photonucleon detection, which are usually used in the region of the giant dipole resonance, which decays via the emission of one nucleon (more rarely two nucleons), therefore prove to be inappropriate. At the same time, investigation of photodisintegration in the region of energies above the GDR energy up to the meson-production threshold is of considerable interest. A change in the mechanism of photon interaction with nuclei occurs in this energy region. In contrast to what occurs in the GDR region, where photons interact with a nucleus as a structureless unit, photons in the region above this resonance interact, because of a decrease in the wavelength and because of kinematical constraints associated with momentum conservation, with few-nucleon systems formed within the nucleus being considered – first of all, with quasideuteron (QD) [1-3]. Thus, there is the competition between two photodisintegration mechanisms: a traditional resonance one realized via GDR excitation and a nonresonance (QD) one. This circumstance brings about the problem of studying the competition of these two mechanisms.

As a matter of fact, investigation of the photodisintegration of nuclei in the energy region above the GDR energy amounts to studying multiparticle photonuclear reactions. By them, we mean photonuclear reactions with the emission of several nucleons from the participant nucleus – that is, reactions like $(\gamma,2n)$, $(\gamma,2p)$, $(\gamma,3n)$, $(\gamma,pn)$, and $(\gamma,4n)$. By the reaction multiplicity in turn, we mean the number of nucleons leaving the nucleus in a reaction event. The reactions in question are induced by photons of energy in excess of the energy corresponding to the GDR maximum. Their cross sections also have the shape of rather broad resonance curves lying in the region of the tail of this resonance. We emphasize that the cross sections for multiparticle photonucleon reactions decrease fast with increasing multiplicity (number

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of emitted nucleons). This situation is aggravated by the fact that, in addition to existing instrumental and methodological difficulties, the technique of directly detecting reaction products (neutrons and protons in the case being considered), which is usually used in modern physics, gives no way to separate channels characterized by different multiplicities, especially in the case where the target used is monoisotopic. Nevertheless, the availability of intense photon beams whose energies extend up to 50 or 70 MeV, together with the use of efficient activation procedures for separating a specific reaction channel, makes it possible to study multiparticle photonuclear reactions involving the emission of up to seven or eight nucleons.

The present study is devoted to performing an experimental investigation and a global analysis of photodisintegration at energies above the GDR energy in heavy nuclei containing about 200 nucleons. Specifically, we have studied the $^{197}$Au, $^{203,205}$Tl, and $^{209}$Bi nuclei. Experimental data on individual nuclei can be found in [4-6].

II. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The experiments were performed in a bremsstrahlung photon beam from the pulsed racetrack microtron RTM-70 in Skobeltsyn Institute of Nuclear Physics at Moscow State University, the electron maximum energy and current being, respectively, 67.7 MeV and 40 mA [7,8].

We applied the method of induced gamma activity. In order to separate various photonuclear reaction channels, the spectra of gamma rays accompanying the $\beta^+$ decay of isotopes produced in the target were analyzed off the beam. On the basis of the results of one such experiment, one can obtain information about all photonuclear reactions proceeding on the isotope under study. The use of efficient HPGe gamma spectrometers and the availability of international nuclear databases systematizing extensive and reliable data on the schemes of induced-activity levels and nuclear properties contribute to the success of this method of investigations. More details on the experimental procedure used and the principles of experimental data analysis can be found in [4-6]. The same applies to experimental data on $^{197}$Au, which were described in detail in [4]. They will be included in our global analysis in the concluding sections of the present article.

We now report on the special features of our experiments with $^{209}$Bi and $^{203,205}$Tl. For the $^{209}$Bi target, we used a metallic-bismuth plate 5 cm in diameter and 3 mm in thickness. The content of the isotope $^{209}$Bi in the natural mixture of isotopes is 100%. The $^{209}$Bi sample was irradiated for 4.3 h. In all, 314 series of measurements were performed for the gamma spectra of residual activity of the irradiated sample. The total exposure time was 245 days. Upon processing the induced-activity gamma spectra for the irradiated bismuth sample, we separated the photoneutron reaction channels ($\gamma,2n$) – ($\gamma,7n$) (we did not observe proton emission, since the Coulomb barrier suppressed it strongly). An observation of the reaction involving the emission of only one neutron, ($\gamma,n$), was impossible in the present investigations because of a long half-life of the residual nucleus $^{208}$Bi (3.68 × 10$^9$ yr). In order to study the photodisintegration of $^{203,205}$Tl, we employed a thallium sulfate (Tl$_2$SO$_4$) sample that had a natural composition of thallium isotopes. It was packed into a plastic ampule. The target dimensions were 1 × 1 × 1 cm$^3$. The natural mixture of thallium isotopes contains two stable isotopes $^{203}$Tl (29.5%) and $^{205}$Tl (70.5%). The thallium sample was also irradiated at the bremsstrahlung photon endpoint energy of 67.7 MeV. The duration of the irradiation was four hours. The time interval between the completion of the irradiation and the commencement of the measurements of induced-activity gamma spectra was one minute. In all, we performed 654 series of measurements of the induced-activity gamma spectra. The total duration of the exposure of the spectra was 202 days. The ($\gamma,in$) reaction on the isotope $^{203}$Tl and the reaction ($\gamma,(i+2)n$) on the isotope $^{205}$Tl (where $i = 1, 2, 3, \ldots$) lead to the production of the same final-state radioactive thallium isotopes. Therefore, the respective experimental data only make it possible to measure the total yields of the above reactions on two stable thallium isotopes $^{203,205}$Tl – that is, the total yields of the pair of the interfering reactions $^{203}$Tl($\gamma,in$)$^{203-4}$Tl and $^{205}$Tl($\gamma,(i+2)n$)$^{205-1-2}$Tl. In our experiment, we observed the photoneutron reactions occurring on thallium isotopes and leading to the production of the isotopes $^{197-202}$Tl, as well as the reaction $^{205}$Tl($\gamma,np$)$^{203}$Hg. We did not aim at observing the reaction $^{205}$Tl($\gamma,n$)$^{204}$Tl since the beta decays of the $^{204}$Tl nucleus appearing in the reaction final state do not involve gamma-ray emission or characteristic X-ray emission.

III. RESULTS

The yields $Y(E_m)$ of photoneutron reactions of various multiplicity that occur in the nuclei under study are the main result of the present study (in heavy nuclei, the proton yield is suppressed by the Coulomb barrier). The reaction yield is defined as the convolution of the reaction cross section $\sigma(E)$ with the bremsstrahlung spectrum $W(E,E_m)$ (here, $E_m$ is the bremsstrahlung spectrum endpoint energy; in our case, $E_m = 67.7$ MeV); that is,

$$Y(E_m) = M \int_{E_{\text{br}}}^{E_m} \sigma(E)W(E,E_m)dE,$$

where $M$ is the number of irradiated nuclei under study and $W(E,E_m)$ is the number of bremsstrahlung photons of energy $E$ per unit energy interval. The yields of multiparticle photonuclear reactions were normalized...
Table 1. Experimental and theoretical yields (rel. un.) of photonuclear reactions in $^{197}$Au nucleus.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Experiment</th>
<th>Theory [9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{197}$Au($\gamma$,n)$^{196}$Au</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>$^{197}$Au($\gamma$,2n)$^{196}$Au</td>
<td>0.16 ± 0.01</td>
<td>0.20</td>
</tr>
<tr>
<td>$^{197}$Au($\gamma$,3n)$^{194}$Au</td>
<td>0.023 ± 0.002</td>
<td>0.021</td>
</tr>
<tr>
<td>$^{197}$Au($\gamma$,4n)$^{193}$Au</td>
<td>0.0074 ± 0.0013</td>
<td>0.0097</td>
</tr>
<tr>
<td>$^{197}$Au($\gamma$,5n)$^{192}$Au</td>
<td>0.0025 ± 0.0002</td>
<td>0.0027</td>
</tr>
<tr>
<td>$^{197}$Au($\gamma$,6n)$^{191}$Au</td>
<td>0.00050 ± 0.00007</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

Table 2. Experimental and theoretical yields (rel. un.) of photonuclear reactions in $^{203,205}$Tl nuclei.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Experiment</th>
<th>Theory [9]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{203}$Tl($\gamma$,n)$^{202}$Tl + $^{205}$Tl($\gamma$,3n)$^{202}$Tl</td>
<td>1.00 ± 0.03</td>
<td>1.0000</td>
</tr>
<tr>
<td>$^{203}$Tl($\gamma$,2n)$^{202}$Tl + $^{205}$Tl($\gamma$,4n)$^{202}$Tl</td>
<td>0.18 ± 0.06</td>
<td>0.211</td>
</tr>
<tr>
<td>$^{203}$Tl($\gamma$,3n)$^{200}$Tl + $^{205}$Tl($\gamma$,4n)$^{200}$Tl</td>
<td>0.029 ± 0.003</td>
<td>0.032</td>
</tr>
<tr>
<td>$^{203}$Tl($\gamma$,4n)$^{199}$Tl + $^{205}$Tl($\gamma$,5n)$^{199}$Tl</td>
<td>0.011 ± 0.002</td>
<td>0.013</td>
</tr>
<tr>
<td>$^{203}$Tl($\gamma$,5n)$^{198}$Tl + $^{205}$Tl($\gamma$,6n)$^{197}$Tl</td>
<td>0.004 ± 0.001</td>
<td>0.003</td>
</tr>
<tr>
<td>$^{203}$Tl($\gamma$,6n)$^{197}$Tl + $^{205}$Tl($\gamma$,7n)$^{197}$Tl</td>
<td>0.00012 ± 0.00005</td>
<td>0.0008</td>
</tr>
<tr>
<td>$^{205}$Tl($\gamma$,np)$^{203}$Hg</td>
<td>0.0035 ± 0.0012</td>
<td>0.0040</td>
</tr>
</tbody>
</table>

to the yields of experimentally observable photonucleon reactions of lowest multiplicity: ($\gamma$,n) for $^{197}$Au, ($\gamma$,n)+($\gamma$,3n) for $^{203,205}$Tl, and ($\gamma$,2n) for $^{209}$Bi. The results obtained here for the relative yields are given in Tables 1 – 3 along with the results of theoretical calculations discussed in the next section.

IV. DISCUSSION OF THE RESULTS

The interaction of an electromagnetic field with a nucleus proceeds predominantly through its E1 component. At low energies of the absorbed photon ($E_\gamma < 30$ MeV), in which case the long-wavelength approximation is valid, this leads to GDR excitation since self-sustaining synchronous vibrations of all protons with respect to all neutrons arise under the effect of an external E1 field. As the energy of the incident photon increases, its wavelength decreases, with the result that the photoabsorption process comes (from $E_\gamma > 30 – 40$ MeV and up to the pion-production threshold) to be dominated by the quasideuteron mechanism, which is different from the GDR mechanism and which involves the transfer of a dipole excitation to individual spatially correlated neutron-proton pairs rather than to the entire nucleus as a structureless unit [1].

We now summarize the fundamentals of the theoretical model used:

(i) One takes into account two independent modes of the photoexcitation of a nucleus; this is GDR formation and QD photoabsorption at energies in excess of 30 MeV.

(ii) One describes the cross sections for the formation of these excitations on the basis of the semimicroscopic GDR model [10] and on the basis of the QD model [3].

(iii) In calculating the GDR component of photonucleon reactions, one takes into account only the neutron-evaporation process.

(iv) In describing the QD component of photonucleon reactions, one considers both equilibrium and preequilibrium nucleon-emission processes; in order to describe preequilibrium processes, one employs the exciton-model version that relies on the Fermi gas densities of particle-hole states [9], and this makes it possible to take into account the effect of the energy dependence of densities of single-particle and single hole states on the dynamics of the preequilibrium cascade.

The theory predicts that, without allowing for the QD mechanism, one cannot explain the cross section of nuclear photoabsorption in the region of energies above the GDR energy. If this mechanism is disregarded, the cross section being discussed will be strongly underestimated. Moreover, the deficiency of the cross section will grow with increasing photon energy – that is, with increasing neutron multiplicity. The experimental data obtained in the present study for the multiparticle neutron photodisintegration of heavy nuclei make it possible to test quantitatively the role of the QD photoexcitation mechanism supplemented with the model of nucleon emission from an excited nucleus [9]. Information necessary for such a test is contained in Tables 1 – 3. In these tables, the relative yields of multinucleon photonuclear reactions for all nuclei studied in our experiments are contrasted against their calculated counterparts. We present the results of the calculations in which we take into account the two possible photodisintegration mechanisms (GDR + QD) and those in which we take into account only the GDR mechanism. The data that we quote prove compellingly that the description of multinucleon photodisintegration with allowance for the GDR and QD mechanisms yields results that agree well with experimental data for the
photonucleon reactions of all multiplicities. If, however, QD photodisintegration is disregarded, the yields from photonucleon reactions involving the emission of more than two or three neutrons prove to be below the experimental results. For high multiplicity \((i \geq 4)\) reactions, they are underestimated by a factor of two or more. One can clearly see the trend toward the growth of the contribution from the QD mechanism as the photonucleon multiplicity (excitation energy of the nucleus) increases. For \(i \geq 5\), the QD mechanism comes to be dominant.

Since photonucleon reactions of high multiplicity form the segment of the photoabsorption cross section in the region \(E_{\gamma} > 30\) MeV, the role of the QD photodisintegration is obvious in this energy region. These conclusions are identical for the four heavy nuclei considered here, \(^{197}\text{Au}\), \(^{203,205}\text{Tl}\), and \(^{209}\text{Bi}\), and suggest that the mechanisms of the multiparticle photonuclear reactions are common in them; that is, they are inherent in heavy nuclei featuring about 200 nucleons.

V. CONCLUSIONS

We will now formulate the basic results of the present study:

(i) We have presented experimental data on the yields from multiparticle photonuclear reactions occurring on \(^{197}\text{Au}\), \(^{203,205}\text{Tl}\), and \(^{209}\text{Bi}\) nuclei in the region of energies from the GDR energy to 67.7 MeV. We have performed a simultaneous analysis of these data. We have established that they have common features that are indicative of the universality of the mechanism of photodisintegration of heavy nuclei at energies in excess of that which corresponds to the GDR maximum.

(ii) We have compared the experimental data in question with the predictions of the modern theoretical photodisintegration model developed in [9] and based on taking into account both photodisintegration via GDR excitation and the QD photodisintegration mechanism. The results of the respective theoretical calculations describe successfully, for all of the nuclei considered above, the relationship between the yields from photonucleon reactions of different multiplicity. This is indicative of the validity of the model in question and makes it possible to draw the following conclusions:

(a) Only upon taking simultaneously into account the two photodisintegration mechanisms (that is, photodisintegration via GDR excitation and the mechanism of QD photodisintegration) can one describe adequately relevant experimental data.

(b) The contribution of QD photodisintegration grows with increasing photon energy and, accordingly, the neutron multiplicity, becoming dominant for reactions involving the emission of not less than five neutrons from the nucleus being considered.

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