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Energy Resolution of Experiments Quasimonoenergetic Experiments Annihilation Photons and Structure of Giant Dipole Resonances

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Abstract—Reasons behind the known systematic discrepancies between the results of photonuclear experiments performed with different photon beams are investigated in detail. Information about the cross sections obtained for the reactions ^{63}Cu$(\gamma,n)^{62}$Cu and ^{197}Au(γ,xn) at all stages of experiments with quasimonoenergetic photons from relativistic positrons annihilating in flight is studied, and a comparison with the data of experiments with beams of bremsstrahlung gamma radiation is performed. Data obtained in experiments of both types for the reaction ^{16}O(γ,xn) are used in the present analysis. It is shown that the typical difference procedure of experiments with quasimonoenergetic annihilation photons hinders the estimation of the actual energy resolution substantially, this leading to a considerable distortion of information about the structure of cross sections for photonuclear reactions. © *2004 MAIK "Nauka/Interperiodica"*.

INTRODUCTION

It is well known that investigation of photon-induced reactions and of the properties of giant dipole resonances in nuclei has played an extremely important role in evolving currently prevalent ideas of the structure and dynamics of nuclei and in clarifying the mechanisms of nuclear reactions. The discrepancy between the experimentally observed properties of giant dipole resonances and their theoretical counterparts from shell-model calculations, which was firmly established in the mid-1950s, led to discovering collective nuclear states and the mechanism of their formation in the shell model. The ensuing development of nuclear physics was associated to a considerable extent with the investigation of collective nuclear states, their role in various reactions, their interaction with single-particle degrees of freedom, their decay modes, and other similar phenomena involving these degrees of freedom. It should be noted in this connection that, while the position of giant dipole resonances on the energy scale and their shape are well described within the simplest collective nuclear model both in spherical and in deformed nuclei, attempts at describing, on the basis of this model, the features of the decay of highly excited nuclear states ran into some difficulties. To overcome these difficulties, it was required to develop first the single-particle and then the multiparticle shell model. The latter, which predicts the appearance of strong coherent $E1$ excitations in the region of energies substantially higher than the energies of single-particle electric-dipole vibrations, was able to describe correctly the position of a giant dipole resonance on the energy scale but not its shape. As a matter of fact, the theoretical spectrum of $E1$ excitations is much poorer than its experimental counterpart, the special features of the latter including the following:

(i) The gross structure (structural features of width about 1 MeV) and the width (size of the region over which the strongest $E1$ nuclear excitations are spread) of photoabsorption cross sections are determined by single-particle—single-hole ($1p1h$) states.

(ii) The intermediate structure (structural features of width about 0.1 MeV) of giant dipole resonances is formed owing to the coupling of doorway states to more complicated states of a collective character.

(iii) The fine structure (structural feature of width about 0.01 MeV) of giant dipole resonances arises owing to the coupling of doorway states to noncollective multiparticle—multihole states.

Effects caused, for example, by the difference in the configuration structure of nuclear shells and by isospin selection rules also complicate significantly the shape of giant dipole resonances.

The overwhelming majority of data presented in the literature [1–5] for photonuclear-reaction cross sections were obtained by using bremsstrahlung gamma rays or quasimonoenergetic photons produced upon the in-flight annihilation of relativistic positrons. As soon as the first data obtained by the

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two methods in question appeared, it became clear—presently, this is well known—that they disagree systematically to a considerable extent (in shape, magnitude, and position on the energy scale), and this complicates significantly the application of such data in practice. The main distinction here is that, in the overwhelming majority of cases, the reaction cross sections are much smoother in data from experiment with quasimonoenergetic annihilation photons [1, 5] than in data from experiments with bremsstrahlung gamma rays. As a rule, cross sections obtained by using bremsstrahlung photons involve distinct structural features (changing sizably from one nucleus to another), resonances having various widths. For almost all nuclei (with the exception of light ones), cross sections obtained with quasimonoenergetic annihilation photons have the form of a smooth resonance (two smooth resonances in the case of deformed nuclei), despite the fact that the energy resolutions quoted by the authors of the corresponding experimental studies (about 250 to 400 keV) are quite sufficient for isolating, in reaction cross sections, resonances of not only the gross but also the intermediate structure.

In view of these discrepancies, the problem of assessing the reliability of the observation of resonances in the structure of giant dipole resonance (especially in medium-mass and heavy nuclei) and the problem of finding out why such resonances are present within one method and why they are absent within the other method are of great interest. Although the experiments being discussed were performed rather long ago (about 10 to 15 years ago), the problem of studying the reasons behind the above discrepancies and the more important problem of developing methods for removing these discrepancies are quite pressing even now for a number of reasons, including that associated with the extensive use of the respective results, which are included in numerous databases, in fundamental and applied investigations. A great number of studies[6–14] were devoted to various aspects of these problems. For a large number of nuclei, these efforts resulted in constructing systematics of various parameters that characterize the discrepancies being discussed and in revealing basic regularities in the relation between these discrepancies and conditions of specific experiments and of the interpretation of their results. It was found that the main distinction in the conditions of experiments aimed at extracting reaction cross sections consisted in the difference of effective photon spectra. It was shown that a rather complex shape of such spectra in experiments with quasimonoenergetic annihilation photons complicates (renders unjustified), in many cases, the interpretation of the results as the sought cross sections proper. Special methods were developed for recasting the results of different experiments into a unified representation that admits their interpretation in terms of reaction cross sections obtained with a specific energy resolution.

The present study is devoted to a detailed investigation of the energy resolution actually achieved at all stages of typical experiments with quasimonoenergetic annihilation photons and to analyzing the reasons behind the discrepancies between their results and traditional estimates based on the width of the annihilation line in the spectrum of photons inducing the reaction being considered. Our investigations were performed on the basis of processing not only well-known ultimate results of experiments with quasimonoenergetic annihilation photons but also their intermediate results that are close to the results of typical experiments with bremsstrahlung photons in what is concerned with the conditions of the derivation of data and which are published very rarely. In particular, we use data of Sund *et al.* [15] and Fultz *et al.* [16], whose facilities for determining, according to the scheme of a typical experiment with quasimonoenergetic annihilation photons, the cross sections for the reactions ^{63}Cu$(\gamma, n)^{62}$Cu and ^{197}Au(γ, xn), respectively, are virtually identical from the point of view of the problems being discussed.

1. BASIC FEATURES OF THE METHODS FOR OBTAINING INFORMATION ON THE CROSS SECTIONS FOR PHOTONUCLEAR REACTIONS IN DIFFERENT EXPERIMENTS

1.1. Experiments with Beams of Bremsstrahlung Gamma Rays

Historically, the first experiments that provided data on a large width of a giant dipole resonance and its complicated shape were based on measurements in beams of bremsstrahlung photons. Since the photon spectrum is continuous in such experiments and is described by expressions obtained by various authors, including Schiff, Seltzer and Berger, and Bethe and Heitler, one cannot measure directly the reaction cross section σ itself. Instead, the result is obtained in the form of its convolution with the photon spectrum (integral of their product)—that is, the reaction yield Y,

$$Y(E_{jm}) = \frac{N(E_{jm})}{\varepsilon D(E_{jm})} = \alpha \int\limits_{E_{\text{th}}}^{E_{jm}} W(E_{jm}, E)\sigma(E)dk, \quad (1)$$

where $\sigma(E)$ is the cross section at a photon energy E for the reaction having an energy threshold E_{thr},

$W(E_{jm}, E)$ is the bremsstrahlung-photon spectrum having an endpoint energy E_{jm}, $N(E_{jm})$ is the number of reaction events, $D(E_{jm})$ is the gamma-radiation dose, ε is the detector efficiency, and α is a normalization factor.

Information about the reaction cross section σ is extracted from data on the reaction yield Y by using one of numerous mathematical methods specially developed for this purpose (these include the photon-difference method, the inverse-matrix method, the Penfold–Leiss method, the method of smallest Cook structure, Tikhonov's regularization method, and the reduction method). Within these methods, procedures used to treat values of Y are constructed in such a way that the effective spectrum $F(E_{jm}, E)$ of photons causing the reaction in question (instrumental function characterizing the method or its resolution function) would be rather well localized (see Fig. 1). In the majority of relevant experiments, the width of the quasimonoenergetic line in the instrumental function near photon energies at which one evaluates the cross section σ is 100 to 200 keV. Thus, the use of one of the above methods for determining the reaction cross section $\sigma(E)$ from the experimental reaction yield $Y(E_{jm})$ actually provides information about the estimated cross section

$$\sigma^{\text{est.}}(E) = \int F(E_{jm}, E)\sigma(E)dE, \qquad (2)$$

its deviation from the sought cross section $\sigma(E)$ being controlled by the deviation of $F(E_{jm}, E)$ from a delta function.

Of particular importance for the ensuing discussion are the following two circumstances:

(i) Complicated shapes of the instrumental functions in the methods for extracting information about the reaction cross section from the experimental reaction yield introduce distortions in the cross section to be determined and errors in the estimate of the energy resolution that is actually achieved.

(ii) Since the basic lines of the instrumental functions in experiments with bremsstrahlung photons are rather well localized on the energy scale, the results obtained in such experiments can be interpreted, despite some obvious flaws, as precisely the sought reaction cross section.

1.2. Experiments with Quasimonoenergetic Photons Obtained upon the In-Flight Annihilation of Relativistic Positrons

Since the beginning of photonuclear investigations, the need for solving an unstable inverse problem [integral Eq. (1)] has given impetus to searches for alternative methods that would make it possible to create conditions under which a quasimonoenergetic character of the effective spectrum of photons causing the reaction under study is achieved directly in an experiment. The method of obtaining quasimonoenergetic photons upon the in-flight annihilation of accelerated positrons became one of such alternatives. The method is based on the fact that, in the case of relativistic-positron annihilation in a converter target, photons of energy localized within quite a narrow interval are emitted into the forward hemisphere. Such photons are inevitably accompanied by positron-bremsstrahlung photons having a spectrum similar (there are reasons to believe that it is identical) to the spectrum of electron-bremsstrahlung photons. In view of this, a difference scheme of an experiment was proposed for determining the cross section for the reaction induced by such photons. This scheme includes three steps of measurements (see Fig. 2):

(i) measurement of the yield $Y_{e^+}(E_j)$ (1) in the reaction induced by a beam formed by positron-bremsstrahlung photons and quasimonoenergetic positron-annihilation photons;

(ii) measurement of the yield $Y_{e^-}(E_j)$ (1) in the reaction induced by electron-bremsstrahlung photons;

(iii) evaluation (after the corresponding normalization) of the difference of the measured yields,

$$Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(E). \qquad (3)$$

Assuming that the positron- and electron-bremsstrahlung spectra are identical and considering that the calculated width of the annihilation line is relatively small, one interprets this difference as the cross section $\sigma(E)$.

By definition, the reaction-yield difference (3) corresponds to an experiment where the instrumental function $F(E_{jm}, E)$ (2) is the difference of the two corresponding experimental photon spectra; under the assumption that the positron- and the electron-bremsstrahlung spectra are identical, this is the line associated with annihilating positrons. It is obvious, however, that, in contrast to what we have in experiments with bremsstrahlung photons, where the instrumental function for the method used is calculated irrespective of the conditions of a specific experiment (moreover, precisely those conditions for which the bremsstrahlung spectrum was calculated are created in an experiment, as a rule), the instrumental function in experiments with quasimonoenergetic annihilation photons is actually determined anew each time. It should also be noted that, while the shape of the calculated annihilation line [1, 5, 17] depends only on the geometric and energy conditions of in-flight positron annihilation, the shape of the instrumental function for the whole experiment depends on the accuracy in determining the experimental reactions yields (3) and on the accuracy to which these yields

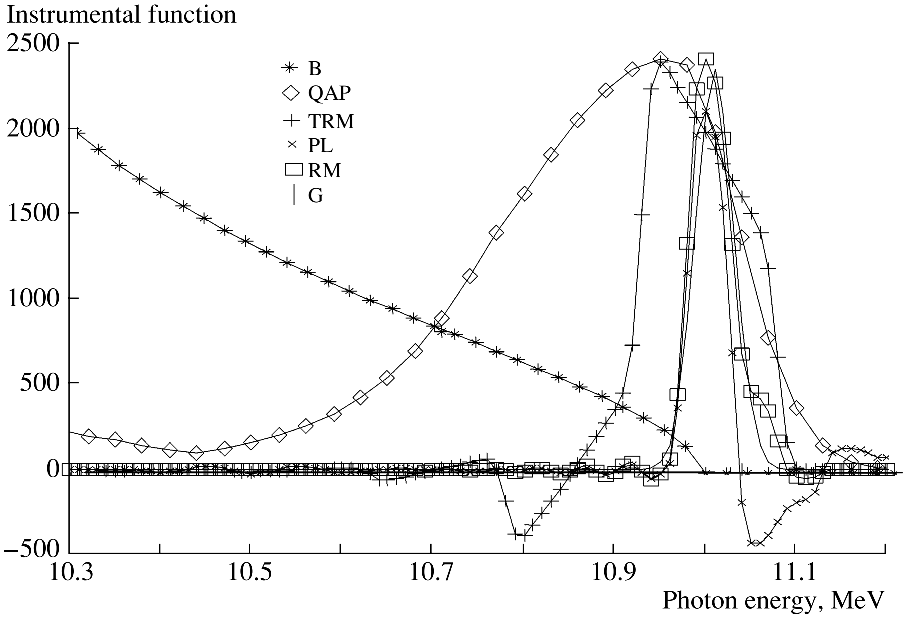

Fig. 1. Comparison of instrumental functions (effective photon spectra) corresponding to various methods for deriving information about cross sections for photonuclear reactions: (B) spectrum of bremsstrahlung photons (example for $E_\gamma^{\max} =$ 11 MeV), (QAP) spectrum of quasimonoenergetic annihilation photons (the width of the annihilation line is 350 keV), (PL) instrumental function in the Penfold–Leiss method (the step of processing is 100 keV); (TRM) instrumental function in Tikhonov' regularization method (the step of processing is 50 keV), (RM) instrumental function in the reduction method (the resolution is 50 keV), and (G) Gaussian function of width 50 keV.

are normalized with respect to one another. However, the latter accuracy is quite poor, since annihilation photons originate from a multistep process (which involves the production of bremsstrahlung photons by electrons in a special target, $e^- + A \to A + e^- + \gamma$; the production of bremsstrahlung gamma radiation from electron–positron pairs by photons, $\gamma + A \to A + e^- + e^+$; and the annihilation of product positrons, $e^+ + e^- \to 2\gamma$); as a result, the intensity of the "beam" of quasimonoenergetic photons is rather low.

The above circumstances result in that the instrumental function $F(E_{jm}, E)$ (see Figs. 1, 2) in experiments with quasimonoenergetic annihilation photons differs in shape substantially from a simple symmetric annihilation line [1, 5, 17]. The main distinctions are the following:

(i) Since the annihilation target is insufficiently thin, the line is highly asymmetric (the decrease toward the region of low energies is strongly extended).

(ii) By and large, the instrumental function is actually not localized on the energy scale (in addition to the annihilation line, the spectrum involves alien contributions extended in energy—a pedestal and a bremsstrahlung tail).

Not only do the above alien contributions complicate substantially the estimation of the actually achieved energy resolution, but, in view of the presence of extra photons in the spectrum near the annihilation line, they also lead to considerable distinctions in amplitude between the reaction cross sections from experiments with bremsstrahlung photons and from experiments with quasimonoenergetic annihilation photons and, because of the shift of the centroid of the spectrum away from the annihilation-line maximum, to distinctions between their positions on the energy scale. It appears to be rather difficult to estimate the resolution actually achieved for such a "cross section," and the problem of assessing the degree to which it agrees with the respective estimate based on the calculated width of the annihilation line in the photon spectrum remains in fact unclear.

Concurrently, the following circumstance is worthy of note: in the majority of the experiments performed thus far, the annihilation-line width was significant, about 250 to 400 keV (sometimes, it was as large as 500 keV, more rarely falling between 150 and 300 keV), because of the use of rather thick annihilation targets, which were dictated by the low intensity of the multistep annihilation-photon-production process. All of the aforesaid affects significantly the spectrum of quasimonoenergetic annihilation photons.

2. SYSTEMATIC DISTINCTIONS BETWEEN THE PHOTONUCLEAR-REACTION CROSS SECTIONS OBTAINED IN EXPERIMENTS WITH BREMSSTRAHLUNG PHOTONS AND IN EXPERIMENTS WITH QUASIMONOENERGETIC ANNIHILATION PHOTONS

As a matter of fact, the distinction between the instrumental functions in the different methods means the difference of the conditions under which one obtains results in experiments with bremsstrahlung photons and in experiments with quasimonoenergetic annihilation photons, this being interpreted in either case as reaction cross sections. Naturally, this is reflected in that the results of experiments with bremsstrahlung photons and experiments with quasimonoenergetic annihilation photons, where the overwhelming majority of data on the cross sections for photonuclear reactions have been obtained thus far, differ systematically [1, 5].

As a typical example of the manifestation of the aforementioned distinctions, a comparison of data on the cross section for the reaction $^{16}O(\gamma, xn)$ that were obtained in an experiment with bremsstrahlung photons [18] and in the experiments with quasimonoenergetic annihilation photons in Saclay [19] and in Livermore [20] is illustrated in Fig. 3. Strong resonances are clearly seen in the reaction cross sections, for which a rather high energy resolution was claimed in those experimental studies (200 keV [18], 180–280 keV [19], and 200–300 keV [20]). This figure shows that, although almost all of the special features (maxima and minima) are present in all three of the cross sections under comparison, they differ in shape, fully in accord with the foregoing. Although, in the case being considered, the estimates of the energy resolution that are presented in [19, 20] for experiments with quasimonoenergetic annihilation photons are close to the resolution of the above experiment with bremsstrahlung photons, the cross sections produced by the former method look like smoothed versions of the cross section from the experiment with bremsstrahlung photons in [18]: in them, the resonances have much smaller amplitudes and larger widths. This must also be reflected in the relationship between the integrated cross sections. By way of example, we indicate that, in the common energy region, which extends up to 25 MeV, the integrated cross sections from [18, 19] are quite close to each other (36.91 and 34.6 MeV mb, respectively). At the same time, the integrated cross section in [20], 27.92 MeV mb, differs from the above values significantly. According to the results obtained from an analysis [7, 8] of a vast set of data on the absolute values of the cross section for the total photoneutron reaction, (γ,xn), an additional normalization of the data obtained in Livermore from an experiment with quasimonoenergetic annihilation photons is required for bringing them in correspondence with a global systematics. The normalization factor of 1.12, which was determined on the basis of the global systematics, leads to the value of 31.27 MeV mb for the integrated cross section from [20], this result being in much better agreement with the data quoted in [18, 19].

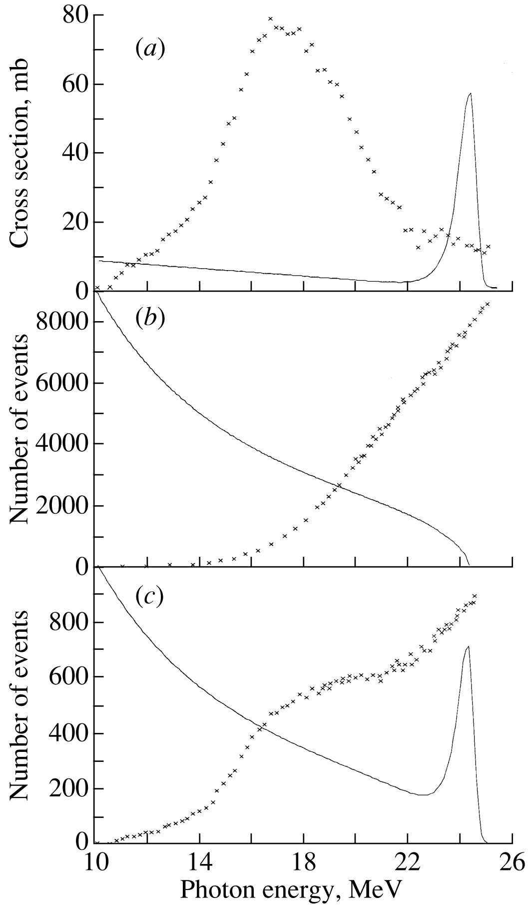

Fig. 2. Experimental data from [15] on the yields from the reaction $^{63}Cu(\gamma, n)^{62}Cu$, (crosses) and simulated effective photon spectra (curves): (*a*) results of an experiment with quasimonoenergetic annihilation photons [yield difference $Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(E)$ (2)] and corresponding difference of the spectra of photons produced by positrons and electrons, (*b*) yield $Y_{e^-}(E_j)$ (2) in an experiment with electron-bremsstrahlung photons and corresponding photon spectrum, and (*c*) yield $Y_{e^+}(E_j)$ (2) in an experiment with a photon beam formed by positron-bremsstrahlung photons and quasimonoenergetic positron-annihilation photons and corresponding total spectrum of photons.

A detailed comparison [21] of the amplitude ratios (A_B/A_{QAP}) and of the width ratio (Γ_B/Γ_{QAP}) for all resonances that were identified in the reaction cross sections for a different oxygen isotope,

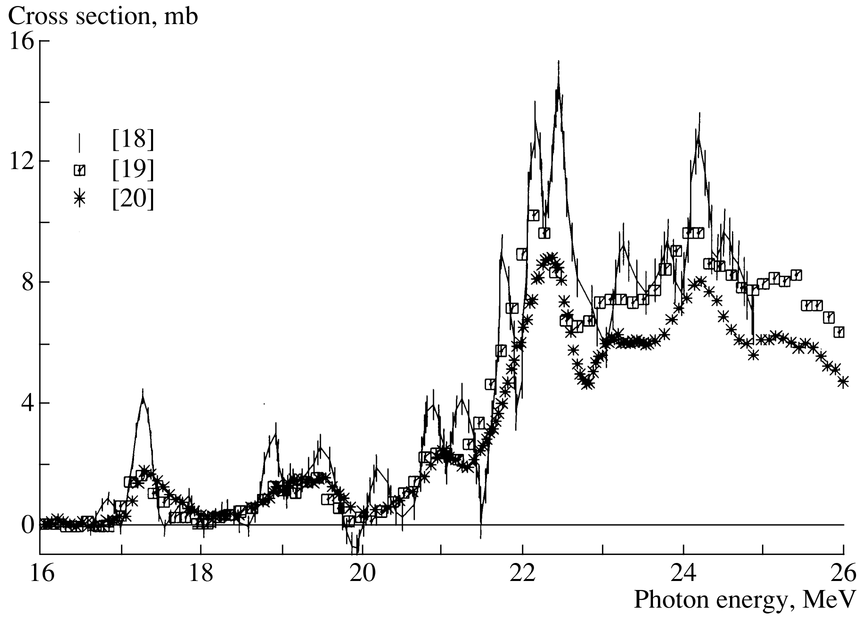

Fig. 3. Cross sections for the reaction $^{16}O(\gamma, xn)$ according to data from an experiment with bremsstrahlung photons (the energy resolution there was 200 keV) [18] and from two experiments performed with quasimonoenergetic annihilation photons in Saclay [19] and in Livermore [20] (the resolution claimed in those studies was 180–280 and 200–300 keV, respectively).

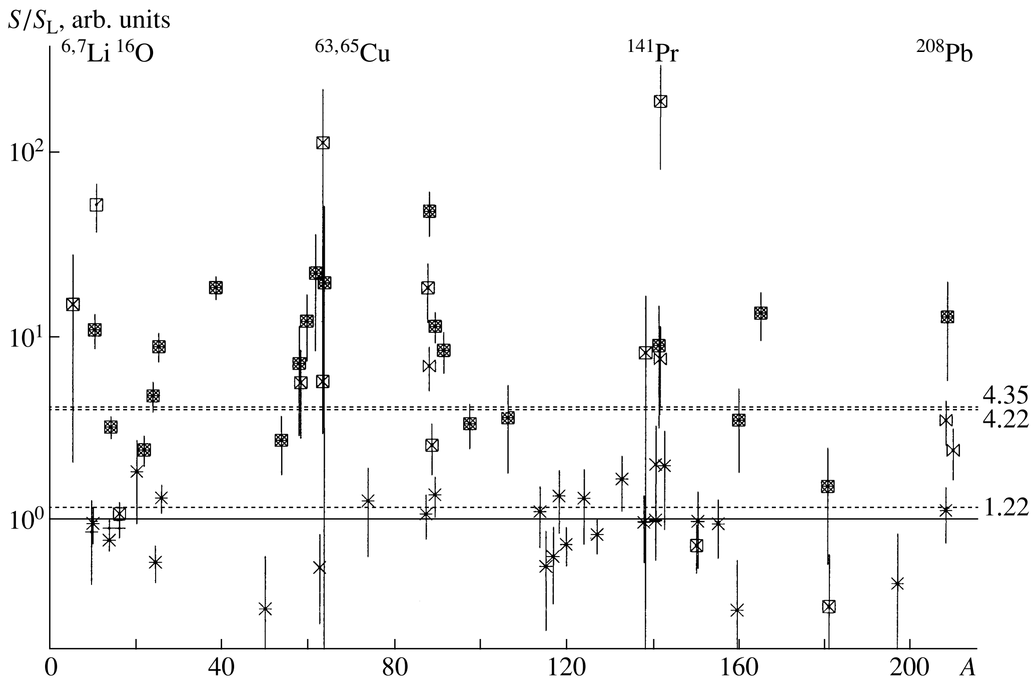

Fig. 4. Systematics of data on the parameter S/S_l of the photonuclear-reaction cross sections for various nuclei: data from experiments with bremsstrahlung photons [(⊠) Moscow, (⊠) Melbourne, and (⊡) other experiments], data from experiments with quasimonoenergetic annihilation photons [(✳) Saclay, (+) Hessen, and (×) other experiments], and tagged-photon data [(⋈) Illinoice].

$^{18}O(\gamma, xn)$, that were obtained in experiments with bremsstrahlung photons (Melbourne, [21]) and with quasimonoenergetic annihilation photons (Livermore, [22]) provides more precise quantitative information about the scale of the discrepancies being discussed. Although procedures for determining the widths and amplitudes of resonances in cross sections having a complicated structure involves a considerable degree of arbitrariness, almost all of the resonances in the cross section from the experiments with quasimonoenergetic annihilation photons have a smaller amplitude and a larger width than their counterparts from the experiments with bremsstrahlung photons ($\langle A_{\rm B}/A_{\rm QAP}\rangle = 1.17$ and $\langle \Gamma_{\rm QAP}/\Gamma_{\rm B}\rangle = 1.35$, respectively).

The general character of the dependence of the manifestation of structural features in cross sections on the method used to determine these cross sections can be illustrated by the systematics of the specially introduced structure parameter S describing, on the whole, deviations of each cross section from that which was strongly smoothed (with a step of $\Delta =$ 1 MeV),

$$S = \frac{1}{N}\sum_{i=1}^{N}\frac{(\sigma_i - \langle\sigma_i\rangle)^2}{\langle\langle\sigma\rangle\rangle^2}, \qquad (4)$$

$$\langle\sigma_i\rangle = \frac{1}{\Delta}\int\limits_{E_i-\Delta/2}^{E_i+\Delta/2}\sigma(E)dE, \qquad (5)$$

$$\langle\langle\sigma\rangle\rangle = \frac{1}{D}\int\limits_{D}\sigma(E)dE, \qquad (6)$$

where D is the common energy region of the cross sections under comparison.

Figure 4 shows the ratios S/S_l (the values of S were calculated on the basis of data from various laboratories, while the values of S_l were determined by using the data from the Livermore experiment with quasimonoenergetic annihilation photons; for some nuclei, there are no Livermore data, in which case the ratios S/S_s and S/S_g were calculated on the basis of data from the experiments performed with quasimonoenergetic annihilation photons in Saclay and Hessen). It can be seen that, among all data subjected to analysis, two data sets stand out distinctly in what is concerned with the manifestation of structural features: they are formed by cross sections measured in experiments with quasimonoenergetic annihilation photons (the mean value is $\langle S/S_l\rangle = 1.22$) and by cross sections determined in experiments with bremsstrahlung photons ($\langle S/S_l\rangle =$ 4.35). It should be emphasized that, for all cross sections from experiments with quasimonoenergetic annihilation photons, the values of the parameter S/S_l (S/S_s and S/S_g) are concentrated quite closely around unity. This means that, in all three laboratories employing quasimonoenergetic annihilation photons (Livermore, Saclay, Hessen), the estimation of the experimental energy resolution on the basis of the annihilation-line width (in the majority of cases, 250–400 keV; sometimes, 500 keV; more rarely, 150–300 keV) does lead to revealing the actual structure of a giant dipole resonance: all cross sections from the experiments with quasimonoenergetic annihilation photons are significantly oversmoothed (with a resolution of about 1 MeV).

This is also confirmed by the fact that, for the parameter being discussed, data obtained in Illinoice [23] by using a beam of tagged photons yield a value ($\langle S/S_l\rangle = 4.22$) that exceeds considerably its counterpart in the experiments with quasimonoenergetic annihilation photons and which is close to that in the experiments with bremsstrahlung photons. Since, in the experiments with tagged photons, the instrumental function is in fact a regular Gaussian line, the above indicates that data from experiments with bremsstrahlung photons reflect the actual structure of the cross sections much better than data from experiments with quasimonoenergetic annihilation photons.

3. CORRECTION OF THE RESULTS OF EXPERIMENTS WITH QUASIMONOENERGETIC ANNIHILATION PHOTONS FOR THE SHAPE OF THE EFFECTIVE PHOTON SPECTRUM AND ESTIMATION OF THE ENERGY RESOLUTION ACTUALLY ACHIEVED IN SUCH EXPERIMENTS

As was indicated above, it was shown previously [6–14] that, instead of the reaction cross section, a specific experiment where the instrumental function differs significantly from that which is close to an ideal one (for example, a Gaussian line of small width) yields the convolution (2) of the cross section with the effective photon spectrum $F(E_{jm}, E)$. Obviously, the possibility of interpreting this convolution as a cross section depends on the shape of the effective photon spectrum.

For instance, the convolution of the cross section from an experiment employing bremsstrahlung photons with the instrumental function for one of the most popular methods for reconstructing the cross section on the basis of the experimental yield (see Fig. 1) can be interpreted, owing to a strong localization of this instrumental function, as the cross section itself, although this cross section is somewhat distorted, since the shapes of the instrumental functions used deviate from regular shapes—say, Gaussian ones. As a matter of fact, the reaction yield (1) itself in an experiment with bremsstrahlung photons can also be interpreted as the reaction cross section as measured with an instrumental function whose width is very large (tends to infinity).

At the same time, the situation around the results of experiments with quasimonoenergetic annihilation photons is much more intricate: in view of the definition in (3) and in view of the existence of extended alien contributions (see Figs. 1, 2) to the instrumental function, these results are again only the reaction yields rather than the cross sections proper localized in energy. In order to obtain data on the reaction cross section, it is necessary to correct the results for the shape of this instrumental function. The authors of [6–14] employed the reduction method for introducing such a correction [24, 25]. Not only does this method make it possible to transform quite straightforwardly the reaction cross section from its form for a specific shape of the effective photon spectrum $F(E_{jm}, E)$ to a form that this cross section would have for a different shape of the effective photon spectrum (for example, in the form of a regular Gaussian curve), but it also permits calculating errors in the estimated cross section.

3.1. Reduction Method

Briefly, the fundamentals of the reduction method [24, 25] are as follows. The integral Eq. (1) for various photonuclear experiments is represented in a matrix form ([A, Σ] model), the relation between the reaction yield and the reaction cross section being taken in the form

$$y = A\sigma + \nu, \tag{7}$$

where y is the experimental reaction yield, A is the instrumental function such that it transforms the input signal σ into the output signal y, σ is the reaction cross section, ν is a noise, and ν_i stands for random errors in Y_i such that $\Delta Y_i^2 = M(\nu_i)^2 = M((\nu_i - M\nu_i)^2)$ is the mathematical expectation value. The error vector is characterized by the correlation matrix

$$\Sigma = \begin{pmatrix} \Delta Y_1^2 & & \dots & 0 \\ & \Delta Y_2^2 & \dots & \\ & & \dots & \\ 0 & & \dots & \Delta Y_n^2 \end{pmatrix} \tag{8}$$

Within the model where the error is minimized, the reduction method [24, 25] makes it possible to find the operator R [hereafter, the symbol $(\ )^-$ denotes the pseudoinversion operator],

$$R = U(\Sigma^{-1/2}A)^-\Sigma^{-1/2} = U(A^*\Sigma^{-1}A)^-A^*\Sigma^{-1}, \tag{9}$$

such that, for a minimum level of errors,

$$M||Ry - U\sigma|| = \min, \tag{10}$$

and under the condition that a solution exists for any σ,

$$RA = U, \tag{11}$$

it enables one to obtain the vector

$$Ry = R(A\sigma + \nu) = U\sigma + (RA - U)\sigma + R\nu = \sigma^{\text{est.}}, \tag{12}$$

which is interpreted as the result obtained by measuring the cross section σ with an instrument of preset quality U and distorted by the noise $\nu^{\text{est.}} = R\nu$:

$$\sigma^{\text{оцен.}} = Ry = U\sigma + R\nu. \tag{13}$$

The error in the estimated cross section,

$$\nu^{\text{est.}} = R\nu = G^{1/2} \tag{14}$$

is determined by the covariation matrix Σ:

$$G = R\Sigma R^* = (A^*\Sigma^{-1}A)^-. \tag{15}$$

A comparison of relations (13) and (2) reveals that, for an instrument of preset quality U, one can take, for example, an instrument whose instrumental function (resolution function) is a Gaussian function of width $U = \int F(E_{jm}, E)dE$.

Relations (12)–(15) specify a solution to the reduction problem formulated as follows: it is necessary to find an optimum monoenergetic representation of the reaction cross section on the basis of information contained in the reaction yield—that is, the reaction cross section for monoenergy effective photon spectrum with a specific energy resolution. Obviously, the reduction method is not a method for solving the unstable inverse problem specified by the integral Eq. (1). This is a method that makes it possible to recast the reaction cross section “measured” with the aid of an “instrument” having an instrumental function A into a form that this cross section would have if it were “measured” by another “instrument” having a different (better) instrumental function U [as applied to experiments with bremsstrahlung photons, the yield Y is the cross section “measured by an instrument” whose instrumental function is W (1)].

3.2. New Data on the Cross Sections for the Reactions $^{63}Cu(\gamma,n)^{62}Cu$ and $^{197}Au(\gamma,xn)$ According to an Analysis of the Results of Experiments with Quasimonoenergetic Annihilation Photons by the Reduction Method

As was shown above, the result of an actual experiment with quasimonoenergetic annihilation photons is the difference (2) of two independent measurements, each being close a measurement in a typical experiment with bremsstrahlung photons. In this connection, a solution to the problem of assessing the degree to which the actual resolution in an experiment with quasimonoenergetic annihilation photons differs from the traditional estimate based on the annihilation-line width can be obtained from a detailed comparison of the results of such measurements with one another and with the results of a typical experiment with bremsstrahlung photons. Upon scanning all possible sources in the literature [1–4] and available databases [26], we found only two such studies [15, 16]. With the aid of virtually identical facilities (only the methods used to detect reaction products were different), the cross sections for the reactions ^{63}Cu(γ, n)^{62}Cu and ^{197}Au(γ, xn) were determined in San Diego and Livermore, respectively, according to the scheme of a typical experiment with quasimonoenergetic annihilation photons.

All published intermediate and ultimate [in the sense of Eq. (2)] experimental results used to derive information about the cross sections for the reactions ^{63}Cu(γ, n)^{62}Cu [15] (they are presented in Fig. 2, along with the instrumental functions corresponding to the measurements) and ^{197}Au(γ, xn) [16] were individually processed by the reduction method [see Eqs. (8)–(11)] [24, 25]. These data include

(i) the reaction yield $Y_{e^-}(E_j)$ measured in a beam of electron-bremsstrahlung photons (result of a typical experiment with bremsstrahlung photons);

(ii) the reaction yield $Y_{e^+}(E_j)$ measured in a beam formed by photons of bremsstrahlung gamma radiation and photons from positron annihilation (result close to the result of a typical experiment with bremsstrahlung photons);

(iii) the difference $Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$ (3) of the yields, which, in a traditional experiment with quasimonoenergetic annihilation photons, is interpreted as the sought reaction cross section.

For both nuclei, all three reaction cross sections estimated with the aid of the reduction method on the basis of the intermediate and ultimate [in the sense of Eq. (3)] results of the experiments under identical conditions (the same form of the instrumental function with a precisely determined resolution) were compared with one another (and with the results obtained in typical experiments with bremsstrahlung photons [30, 31] and also rescaled to the corresponding resolution). For a detailed comparison, we used a number of generalized parameters [27–29]. These include

(a) the integrated cross section $\sigma^{\text{инт}}$;

(b) the energy centroid $E_{\text{c.}}$;

(c) the sum of errors, Σ;

(d) the structure parameter S [see Eqs. (4)–(6)];

(e) the informativeness I [this is a parameter that, in a sense, describes an increase in the amount of information in the cross section as the errors ν in it decrease and as the energy resolution is improved (that is, the quantity ΔE is reduced)]:

$$I = \frac{1}{N\Delta E}\sum_{i=1}^{N}\frac{1}{\nu_i}. \qquad (16)$$

On the basis of the data in Table 1, the generalized features of the reaction cross sections from the experiments with quasimonoenergetic annihilation photons [15, 16] prior to and after processing them by the reduction method can be compared in detail with the features of the corresponding experimental cross sections from the experiments with bremsstrahlung photons [30, 31]. This makes it possible to draw some specific conclusions [27–29] concerning the actual experimental resolution in the relevant experiments.

Among the conclusions that can be drawn from the results presented in Table 1, the most important are the following [27–29] (the quantities Σ, I, and S are given in, respectively, mb, (MeV mb)$^{-1}$, and arbitrary units):

(i) Upon treatment by the reduction method, strongly different results of different experiments appear to be close to one another in all of the parameters being considered [variations in some of the parameters are the following: from 35 to 39 in Σ for Cu (rows 2–4) and from 212 to 247 in Σ for Au (rows 7–9), from 371 to 435 in I for Cu (rows 2–4) and from 96 to 103 in I for Au (rows 7–9), and from 264 to 308 in for Cu (rows 2–4) and from 175 to 301 in S for Au (rows 7–9)].

(ii) Upon treatment by the reduction method, the results (2) of the experiments with quasimonoenergetic annihilation photons are virtually indistinguishable, in all of the parameters, from all other results of similar treatments for Cu [15], $\Sigma = 36$, $I = 426$, and $S = 272$ (row 4), while, for Au [16], $\Sigma = 212$, $I = 98$, and $S = 175$ (row 9), the levels of errors being commensurate.

(iii) The main conclusion is that, in all of the parameters, the published results (2) of the experiments with quasimonoenergetic annihilation photons differ dramatically from the results of treatment by the reduction method for Cu [15], $\Sigma = 32$, $I = 77$, and $S = 67$ (row 5), while, for Au [16], $\Sigma = 244$, $I = 49$, and $S = 74$ (row 10), the levels of errors being commensurate.

(iv) In all of the parameters subjected to analysis, data for the Cu nucleus that were deduced with the aid of the reduction method are commensurate with the results obtained in the experiment of Sund *et al.* [15] with bremsstrahlung photons and rescaled to a rather high energy resolution of $\Delta E = 210$ keV; in the case of the Au nucleus, the resulting data appear

Table 1. Generalized features of the cross sections obtained for the reactions ^{63}Cu(γ, n)^{62}Cu and ^{197}Au(γ, xn) in [15] and [16], respectively, by using various effective photon spectra

№ п/п	Results subjected to analysis	$E_{c.}$, MeV	σ^{int}, MeV mb	Σ, mb	I, 1/(MeV mb)	S, arb. units	ΔE, MeV
	^{63}Cu(γ, n)^{62}Cu						
1	Result of the experiment reported in [30] and performed in a beam of bremsstrahlung gamma radiation (Fig. 5*a*)	17.8	658	34	422	319	0.21
2	Result obtained by processing the yield $Y_{e^-}(E_j)$ (Fig. 5*b*)	18.0	497	39	371	308	0.21
3	Result obtained by processing the yield $Y_{e^+}(E_j)$ (Fig. 5*c*)	17.9	497	35	435	264	0.21
4	Result of processing the yield $Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$ (Fig. 5*d*)	17.8	497	36	426	272	0.21
5	Result from [15] in the form of the yield $Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$ (Fig. 5*e*)	17.8	497	32	77	67	0.2–0.4*
	^{197}Au(γ, xn)						
6	Result of the experiment reported in [31] and performed in a beam of bremsstrahlung gamma radiation	15.4	3660	288	45	193	0.5
7	Result of processing the yield $Y_{e^-}(E_j)$	15.2	2970	235	96	301	0.24
8	Result of processing the yield $Y_{e^+}(E_j)$	15.6	2970	247	103	229	0.24
9	Result of processing the yield $Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$	15.4	297	212	98	175	0.24
10	Result from [16] in the form of the yield $Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$	15.3	2970	244	49	74	0.4**

* Energy resolution claimed by the authors of [15].

** Energy resolution claimed by the authors of [16].

to be much better than the results of the experiment of Fultz *et al.* [16] with bremsstrahlung photons, this being quite natural since the energy resolution there was as poor as $\Delta E = 500$ keV.

Thus, we see that, for commensurate levels of errors, the original results (2) of experiments with quasimonoenergetic annihilation photons are characterized by substantially (severalfold) lower values of the structure parameter S and of the informativeness I in relation to the results of treatment by the reduction method for the same energy resolution as that which was claimed for the original data. From here, it obviously follows that the resolution actually achieved in [15, 16] was poorer by an approximately the same factor [5.5 (= 426/77) for Cu and 2 (= 98/49) for Au].

With the aim of more precisely determining the actual values of the energy resolution in experiments with quasimonoenergetic annihilation photons, all four cross sections under comparison for both nuclei (for each nucleus, one cross section from the experiments with bremsstrahlung photons [30, 31] and three results obtained by processing, by means of the reduction method, the cross sections from the experiments with quasimonoenergetic annihilation photons [15, 16]) were smoothed by using Gaussian functions of various width (ΔE) until each of these appeared to be in the best agreement ($\chi^2 = \min$) with the fifth cross section under discussion, the result (2) of the corresponding experiment with quasimonoenergetic annihilation photons [15, 16]. For the Cu nucleus, the best agreement with the cross section from [15] was achieved with a smoothing Gaussian function of width $\Delta E = 1.2$–1.3 MeV at $\chi^2_{\min} = 0.03$–0.05. For the Au nucleus [16], the corresponding values are $\Delta E = 1.6$ MeV and $\chi^2_{\min} = 0.11$–0.18. From these data, we can draw the conclusion that it is the width ΔE of the smoothing Gaussian function that controls the energy resolution actually achievable in an experiment with quasimonoenergetic annihilation photons. It is three to four times greater than the estimate obtained by the authors of [15, 16] on the basis of the calculated width of the annihilation line in the spectrum of photons produced by a positron beam and agrees with the systematics from [6] (see Fig. 4). A low (1.2–1.6 MeV) actual energy resolution of experiments with quasimonoenergetic annihilation photons is the reason why structural features similar to those observed in experiments with bremsstrahlung photons cannot be revealed in the reaction cross sections obtained in [15, 16], despite the proximity of values claimed for the energy resolution (about 200 keV). It is obvious that such structural features can manifest themselves only in cross sections determined with an energy resolution close to 200 keV, and this is what one observes in cross sections obtained upon treatment by the reduction method.

In Fig. 5, one can clearly see which structural features manifest themselves [27–29] in the cross section obtained for the reaction ^{63}Cu$(\gamma, n)^{62}$Cu from the result (2) of the experiment of Sund *et al.* [15] with quasimonoenergetic annihilation photons by using the reduction method for the instrumental function in the form of a Gaussian line of width 0.21 MeV. All three cross sections obtained with the aid of the reduction method have quite distinct structural features, whose properties are quite consistent (see Table 2), their positions on the energy scale being also in agreement with the positions of the resonances in the cross section obtained in [30] and smoothed to achieve the same resolution (the absolute normalization was not performed). The structural features of the corresponding cross sections for the reaction ^{197}Au(γ, xn) that were obtained with the aid of the reduction method are also in fairly good agreement [27, 28].

From all of the aforesaid, it is obvious why the structural features being discussed are not manifested in the results reported in [15, 16]: these results cannot be interpreted as cross sections for the energy resolution claimed there (0.2–0.4 MeV). The results presented in [15, 16] should be interpreted either as yields (that is, as the convolutions of cross sections with effective photon spectra of a complicated form and, hence, as results corresponding to a much poorer resolution) or as cross sections obtained with a resolution as low as about 1.2 to 1.6 MeV. It should be emphasized once again that, upon the relevant treatment of these results (that is, upon the application of the procedure recasting them into a form that they would have for the claimed resolution), they also exhibit [for the example of the reaction ^{63}Cu$(\gamma, n)^{62}$Cu, see Fig. 5 and Table 2] the corresponding structural features distinctly.

Obviously, the revealed considerable (severalfold) distinction between the actual resolution of experiments with quasimonoenergetic annihilation photons and the estimate on the basis of the calculated width

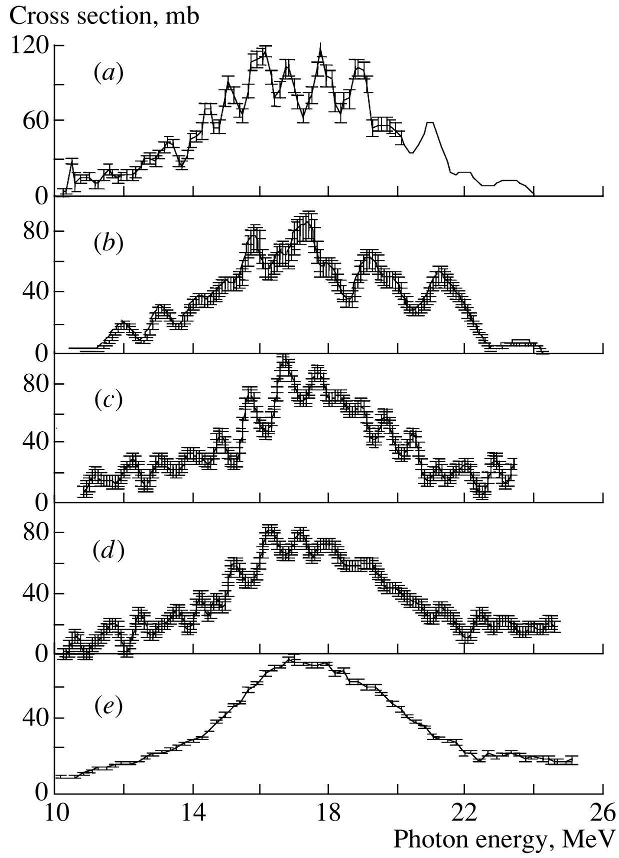

Fig. 5. Comparison of the cross sections for the reaction ^{63}Cu$(\gamma, n)^{62}$Cu that were obtained by various methods: (*a*) result of the experiment with bremsstrahlung photons that was reported in [30] (the energy resolution there was 210 keV); (*b*) result derived by processing, according to the reduction method at a resolution of 210 keV, an intermediate result of Sund *et al.* [15] that is the reaction yield $Y_{e^-}(E_j)$ within the procedure employing quasimonoenergetic annihilation photons; (*c*) result derived by processing, according to the reduction method at a resolution of 210 keV, an intermediate result of Sund *et al.* [15] that is the reaction yield $Y_{e^+}(E_j)$ within the procedure employing quasimonoenergetic annihilation photons; (*d*) result derived by processing, according to the reduction method at a resolution of 210 keV, an ultimate result [see Eq. (2)] of Sund *et al.* [15] that is the yield difference $Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j)$; and (*e*) an ultimate result [see Eq. (2)] for Sund *et al.* [15] that is the yield difference $Y_{e^+}(E_j) - Y_{e^-}(E_j) = Y(E_j) \approx \sigma(E)$, the resolution claimed for this result being between 200 and 400 keV.

of the annihilation line in the effective photon spectrum leads to a considerable distortion (as a matter of fact, to a loss) of information about the structure of cross sections for photonuclear reactions, information that should have been contained in experiments of claimed resolution. Thus, we see that the reason behind the well-known systematic discrepancies between the results of experiments employing

Table 2. Positions of the structural features of the cross sections for the reaction ^{63}Cu(γ, n)^{62}Cu on the energy scale and amplitudes of these features according to the results of various experiments upon treatment by the reduction method for the energy resolution of $\Delta E = 0.21$ MeV

Resonance energy E_γ, MeV	Reaction cross sections obtained by the reduction method, mb			
	Cross section from the experiment of Ishkhanov *et al.* [30]*	Yield $Y_{e^-}(E_j)$ in the experiment of Sund *et al.* [15]	Yield $Y_{e^+}(E_j)$ in the experiment of Sund *et al.* [15]	Yield difference $Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$ in the experiment of Sund *et al.* [15]
15.8–16.1	112	61	57	53
16.7–16.9	95	55	70	70
17.7–18.0	104	68	64	68
19.3–19.5	94	51	50	52
21.7–22.0	50	45	20	28

* The absolute value of the reaction cross section was not normalized.

Table 3. Structure parameter S (in arbitrary units) for the ^{16}O(γ, xn) cross sections obtained with the aid of the reduction method for various values of the energy resolution ΔE

ΔE, keV	Experiment with bremsstrahlung photons [18]	Experiment with quasimonoenergetic annihilation photons [19]	Experiment with quasimonoenergetic annihilation photons [20]
Original (claimed) resolution:			
150	270	–	
200–300		95	
180–280		80	
Achieved resolution:			
250		180	154
200		212	192
150		246	239

different photon beams proves to be quite simple: data from experiments with quasimonoenergetic annihilation photons are oversmoothed in relation to data from experiments with bremsstrahlung photons.

3.3. Manifestation of the Structural Features of the Photonuclear-Reaction Cross Sections versus the Energy Resolution for the Example of Data on ^{16}O(γ, xn) Reactions

The results of our investigations directly relate the problem of manifestations of structural features in experimental reaction cross sections to an actually achievable energy resolution. In order to trace this relationship quantitatively, we processed, by means of the reduction method, two ^{16}O(γ, xn) cross sections obtained in [19, 20] from experiments with quasimonoenergetic annihilation photons, these cross sections being given in Fig. 3 as an illustration of typical discrepancies between the results of different experiments. Both cross sections for a relatively light nucleus from the experiments with quasimonoenergetic annihilation photons involve distinct and readily identifiable structural features that make it possible to trace their shape quite reliably versus the width of the corresponding instrumental function. In Fig. 6 (and in Fig. 3 as well), the reaction cross sections obtained for various values of the energy resolution are compared with the result of the experiment of Ishkhanov *et al.* [18], who employed bremsstrahlung photons. Both from the shape of the emerging resonances and from the values of the structure parameter S [see Eq. (4)–(6)] that are quoted in Table 3, one can get the idea of the form (Figs. 6*c*, 6*g*) that the results of the two experiments in [19, 20] with quasimonoenergetic annihilation photons would have had if the energy resolution actually achieved in them had been close to that which was claimed there. Thus, we see that a unified interpretation (an optimum single-energy representation at close values of the energy resolution) of the different experiments removes almost completely the problem of their systematic discrepancies and the related problem of the reliability of the structural features revealed in the reaction cross sections, and these structural features were precisely the subject of the present study.

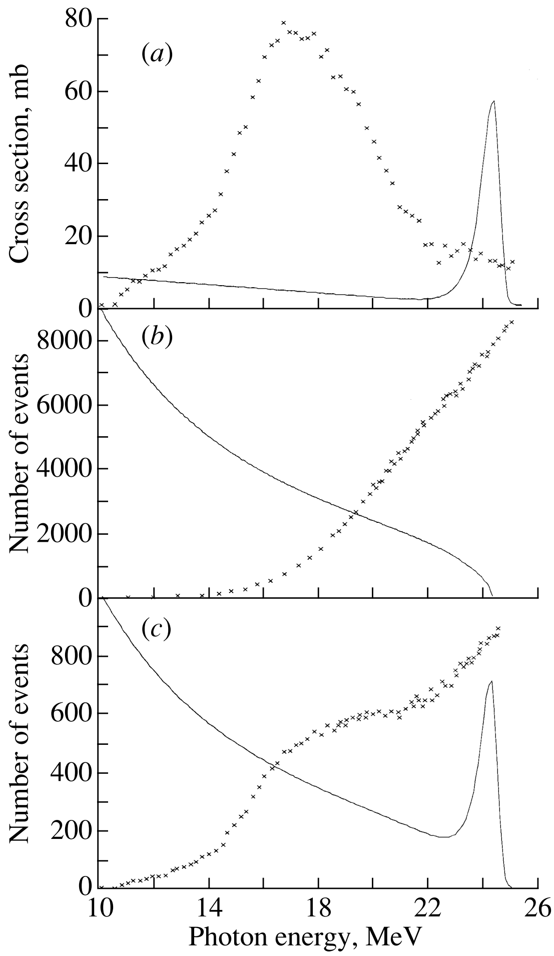

Fig. 6. (×) $^{16}O(\gamma, xn)$ cross sections derived by the reduction method from the results (2) obtained by the authors of (left panels) [19] and (right panels) [20] from experiments with quasimonoenergetic annihilation photons, along with (solid curves) the results of the experiment with bremsstrahlung photons that was reported in [18] (the energy resolution there was 200 keV): (*a*, *e*) results for the energy resolution claimed in the experiments with quasimonoenergetic annihilation photons ($\Delta E = 200$–300 keV in [19] and $\Delta E = 180$–280 keV in [20]), (*b*, *f*) results for the achieved energy resolution of $\Delta E = 250$ keV, (*c*, *g*) results for the achieved energy resolution of $\Delta E = 200$ keV, and (*d*, *h*) results for the achieved energy resolution of $\Delta E = 150$ keV.

CONCLUSIONS

The main results of our present investigations have cast some doubt on the statement that the energy resolution of experiments with quasimonoenergetic annihilation photons is determined by the calculated width (Figs. 1, 2) of the annihilation line in the effective photon spectrum and lead to the following conclusions:

(i) In the majority of the experiments with quasimonoenergetic annihilation photons, the actually achieved energy resolution is substantially (severalfold) poorer than that which was claimed for this quantity and which was estimated on the basis of the calculated annihilation-line width; it is in fact between 1.2 and 1.6 MeV.

(ii) The reason behind the well-known systematic discrepancies between the results of experiments employing different photon beams is quite simple: reaction cross sections from experiments with quasimonoenergetic annihilation photons are overly smoothed in relation to the results of experiments with bremsstrahlung photons—quasimonoenergetic photons are insufficiently "monoenergetic" for performing detailed investigations into cross sections for photonuclear reactions.

(iii) That the actually achieved energy resolution is rather low leads to a significant distortion (loss) of information about the structure of cross sections for photonuclear reactions in relation to what is expected to be manifested in experiments characterized by the claimed resolution.

(iv) Information about reaction cross sections that is lost in the ultimate result (2) $[Y_{e^+}(E_j) - Y_{e^-}(E_j)]$ of a typical difference experiment with quasimonoenergetic annihilation photons can be recovered upon treatment (for example, by means of the reduction method) by introducing additional information about the shape of the actual photon spectrum.

(v) Upon such a treatment, reaction-cross-section data that are close in shape, magnitude, and energy resolution at the claimed (about 300 keV) or even higher energy resolution can be obtained not only from the ultimate result [difference $\sigma(E) \approx Y(E_j) = Y_{e^+}(E_j) - Y_{e^-}(E_j)$ (2)] but also from both intermediate results $[Y_{e^+}(E_j)$ and $Y_{e^-}(E_j)]$ of measurements.

It should be emphasized that one of the aforementioned intermediate results (2) $[Y_{e^-}(E_j)]$ of an experiment with quasimonoenergetic annihilation photons is nothing but the reaction yield in a conventional experiment with bremsstrahlung photons. A slight distinction consists in that the former type of experiments employs, for a photon source, a target (it also plays the role of a converter for positron annihilation) from a light rather than from a heavy element. This distinction reduces substantially the intensity of the photon beam used and, hence, the statistical accuracy in measuring the reaction yield $Y_{e^-}(E_j)$. Here, it is reasonable to mention once again that the intensity of the beam of photons from positrons is very low (annihilation is a multistep process); as a result, the statistical accuracy in determining the yield $Y_{e^+}(E_j)$ also proves to be quite low. The consequences of interpreting, as the sought reaction cross section, the difference $Y_{e^+}(E_j) - Y_{e^-}(E_j)$ of the experimental yields measured under such conditions have been demonstrated in the present study above.

All of the aforesaid, together with the results of previous investigations reported in [6–14, 27–29] and devoted to studying the effect of the instrumental function (effective photon spectrum) in an experiment with quasimonoenergetic annihilation photons on the parameters of the resulting cross section, leads to a reappraisal of advantages and disadvantages of the two basic methods for experimentally studying photonuclear reactions. Our results make it possible to conclude that, in performing detailed investigations into cross sections for photonuclear reactions, the complicated and expensive procedure of measurements in beams of quasimonoenergetic annihilation photons does not have any advantages in the energy resolution over the procedure of measurements in beams of bremsstrahlung gamma radiation; on the contrary, it is far inferior to it in this respect. Moreover, the former is also inferior to the latter in statistical accuracy as well, because of a much lower intensity of the beam of quasimonoenergetic annihilation photons inducing the reactions being studied.

In addition, we note that, apart from the absence of advantages of applying, in practice, the procedure employing quasimonoenergetic annihilation photons, it is much more complicated and expensive than the well-developed procedure of measurements in beams of bremsstrahlung photons.

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