Energy Resolution of Experiments with Quasimonoenergetic Annihilation Photons and Structure of a Giant Dipole Resonance

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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 \( ^{63}\text{Cu}(\gamma,n)^{62}\text{Cu} \) and \( ^{197}\text{Au}(\gamma,xn) \) 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 \( ^{16}\text{O}(\gamma,xn) \) are used in the present analysis. It is shown that the difference procedure typically used experiments with quasimonoenergetic annihilation photons hinders the estimation of the actual energy resolution substantially, thus 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 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 features 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 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 experiments 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 a 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 \(^{63}\text{Cu}(\gamma, n)^{62}\text{Cu}\) and \(^{107}\text{Au}(\gamma, xn)\), respectively, are virtually identical from the point of view of the problems being discussed.

1. BASIC FEATURES OF THE METHODS FOR OBTAINING INFORMATION ABOUT 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 \(\sigma\) 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 \(Y\),

\[
Y(E_{jm}) = \frac{N(E_{jm})}{\varepsilon D(E_{jm})} = \alpha \int_{E_{thr}}^{E_{jm}} W(E_{jm}, E)\sigma(E) dE, \tag{1}
\]

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