PROBING THE $X(6900)$ VIA TWO-PHOTON PRODUCTION IN ULTRAPERIPHERAL COLLISIONS*

Longjie Chen [a], Wolfgang Schäfer [a], Antoni Szczurek [a,b]

[a]Institute of Nuclear Physics Polish Academy of Sciences
Radzikowskiego 152, 31-342 Kraków, Poland
[b]Institute of Physics, University of Rzeszów
Pigonia 1, 35-959 Rzeszów, Poland

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Studies of the internal structure of hadrons have been a main focus in particle physics since perturbative Quantum Chromodynamics (p-QCD) was established as the theory of the strong interaction. While the constituent quark model provided a successful framework for the investigation of many hadrons, recent decades have unveiled exotic states that defy simple classification. An example is the $X(6900)$ resonance, identified in the di-J/ψ mass spectrum by LHCb, ATLAS, and CMS. As a tetraquark composed of $c\bar{c}c\bar{c}$, its existence confirms the possibility of such multi-quark states. Its fundamental nature — whether it is a compact diquark–antidiquark entity or a diffuse molecule of two charmonia — remains an open question. We propose a study for the exclusive $\gamma\gamma \to X(6900)$ process, accessible in ultraperipheral heavy-ion collisions (UPCs), which serves as a clean probe to differentiate between these inner structures. In this work, we calculate the respective two-photon decay width, $\Gamma_{\gamma\gamma}$, using a leading-order Non-Relativistic QCD (NRQCD) framework. The long-distance matrix elements are determined from the wave functions at origin obtained in an extended relativized quark model. For the $X(6900)$ as a radially excited ($2s$) compact state, we predict sizable widths of $\Gamma_{\gamma\gamma}(2^{++}_{2s}) \approx 0.22$ keV and $\Gamma_{\gamma\gamma}(0^{++}_{2s}) \approx 0.15$–$0.69$ keV. These values are significantly larger than expected for a molecular state, providing a clear experimental discriminant.

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1. Introduction

The observation of the $X(6900)$ resonance in the di-J/ψ mass spectrum by the LHCb, ATLAS, and CMS collaborations has confirmed the existence of fully charmed tetraquark (T_{4c}) states [1–3]. However, its fundamental

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structure remains an open question, with two primary competing hypotheses: a compact diquark–antidiquark state, $[cc]_{\bar{3}_c}[\bar{c}\bar{c}]_{3_c}$ or $[cc]_{6_c}[\bar{c}\bar{c}]_{\bar{6}_c}$ *versus* a loosely bound meson molecule, $[c\bar{c}]_{1_c}[c\bar{c}]_{1_c}$.

While hadroproduction in pp collisions, for instance via fragmentation processes [4], has been the primary mode of discovery, the corresponding hadronic environment and the possible role of double parton scattering [5] complicate the theoretical interpretation. We propose that the exclusive $\gamma\gamma \to T_{4c}$ process serves as a clean probe which is highly sensitive to the internal structure. This process is accessible via photon–photon scattering in ultraperipheral heavy-ion collisions (UPCs).

In UPCs, the colliding nuclei pass each other at impact parameters larger than the sum of their radii; therefore, the strong hadronic interactions are strongly suppressed. The intense electromagnetic fields of the relativistic ions can be treated as a flux of quasi-real photons, described within the equivalent photon approximation. The $\gamma\gamma \to T_{4c}$ cross section therefore factorizes into the convolution of the photon fluxes of the two nuclei with the elementary $\gamma\gamma$ cross section, the latter being directly proportional to the two-photon decay width $\Gamma_{\gamma\gamma}$ of the produced resonance. Since the final state is produced in an otherwise empty rapidity region, UPCs provide an exceptionally clean environment, free from the underlying event and multiple parton interactions that obscure the interpretation in hadronic collisions.

A measurement of the exclusive production rate can therefore help discriminate between the compact and molecular structural configurations.

2. Theoretical formalism

2.1. NRQCD factorization

To perform the calculation of two-photon decay width for the selected channel, we apply the Non-Relativistic QCD (NRQCD) factorization, which is the standard effective theory for systems containing heavy quarks [6–8]. Within NRQCD, the decay width is factorized into components that describe different physical scales as [7]

$$\Gamma(T_{4c} \to \gamma\gamma) = \sum_n \hat{F}_n(m_c) \cdot |\langle 0|\mathcal{O}_n|T_{4c}\rangle|^2 \,, \tag{1}$$

where $\hat{F}_n$ denotes the perturbatively calculable short-distance coefficients (SDCs), while the $\langle 0|\mathcal{O}_n|T_{4c}\rangle$ represents the long-distance matrix elements (LDMEs), which encode the non-perturbative physics of the hadron's structure. In this work, we have calculated the SDCs at leading order (LO) for the dominant S-wave configurations, some of the 40 Feynman diagrams are shown in Fig 1.

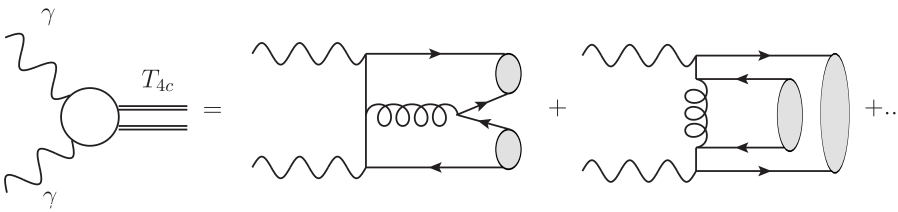

Fig. 1. Representative LO Feynman diagrams for the $c\bar{c}c\bar{c} \to \gamma\gamma$ process.

2.2. LDMEs from a relativized quark model

Within this framework, the non-perturbative effect is modeled by LDMEs, which are directly proportional to the square of the tetraquark wave function at the origin, $|\psi(0)|^2$. To determine this quantity, we employ an extended relativized quark model from Lü *et al.* [9], which solves the four-body Schrödinger equation numerically. This model's Hamiltonian includes relativistic kinetic terms as well as a potential with both linear confinement and one-gluon-exchange (OGE) interactions. Using the model parameters and Gaussian basis [9, 10] from this work, we have computed the necessary wave functions at the origin for various candidate states, which are presented in Table 1 [11].

Table 1. Calculated wave functions at the origin for various candidate tetraquark states [11]. Units are MeV for mass and $\mathrm{GeV}^{\frac{9}{2}}$ for wave functions.

Mass (J^{PC})	State	Eigenvector	$\psi_{\bar{3}3}(0)$	$\psi_{6\bar{6}}(0)$	$\psi_{\rm phys}(0)$
6435 (0^{++})	$1s$	$[0.62, 0.79]$	0.0466	0.0283	0.0510
6542 (0^{++})	$1s$	$[0.79, -0.62]$	0.0466	0.0283	0.0189
6849 (0^{++})	$2s$	$[0.50, 0.87]$	0.0721	0.0466	0.0764
6940 (0^{++})	$2s$	$[0.87, -0.50]$	0.0721	0.0466	0.0391
6543 (2^{++})	$1s$	1	0.0300	—	0.0300
6928 (2^{++})	$2s$	1	0.0471	—	0.0471

3. Results and phenomenological discussion

Combining the perturbatively calculated SDCs with the non-perturbative LDMEs allows us to arrive at our predictions for the decay widths. Since the $X(6900)$ is widely considered to be a first **radially** excited ($2s$) state, we focus on the predictions for these states, presented in Table 2. This calculation yields our central predictions: a width of $\Gamma_{\gamma\gamma}(2^{++}_{2s}) \approx 0.22$ keV and a range for the scalar state of $\Gamma_{\gamma\gamma}(0^{++}_{2s}) \approx 0.15$–$0.69$ keV. These values, derived from a model that resolves the internal structure of the diquarks, are notably more moderate than predictions from frameworks that treat the diquarks as point-like objects [12].

The key phenomenological insight that emerges from these results is the clear distinction between the compact and the molecular pictures. Our predicted widths of $\mathcal{O}(0.1$–1.0 keV) are characteristic of a compact object. In a molecular state, however, annihilation is suppressed by the spatial separation of the constituent mesons, leading to an expectation that $\Gamma_{\text{molecule}} \ll \Gamma_{\text{compact}}$ by at least an order of magnitude. An experimental measurement is thus a powerful arbiter between these two competing scenarios.

Table 2. Final predictions for masses [MeV], root of mean square (RMS) radii [fm], LDMEs [GeV^9], and two-photon decay widths [keV] [11]. Uncertainties are dominated by scale variation and truncations of higher-order renormalization evolution.

Mass (J^{PC})	State	Eigenvec.	$\langle r^2 \rangle^{\frac{1}{2}}$ [fm]	LDMEs $\bar{3}3$	LDMEs $6\bar{6}$	LDMEs mix	$\Gamma_{\gamma\gamma}$ [keV]
6435 (0^{++})	$1s$	[0.62, 0.79]	0.265	0.01323	0.00794	0.010	$0.106^{+0.03}_{-0.02}$
6542 (0^{++})	$1s$	[0.79, −0.62]	0.281	0.02152	0.00488	−0.010	$0.245^{+0.07}_{-0.05}$
6849 (0^{++})	**$2s$**	**[0.5, 0.87]**	**0.351**	**0.02078**	**0.02605**	**0.023**	**$0.149^{+0.05}_{-0.03}$**
6940 (0^{++})	**$2s$**	**[0.87, −0.50]**	**0.452**	**0.06234**	**0.00868**	**−0.023**	**$0.688^{+0.21}_{-0.15}$**
6543 (2^{++})	$1s$	1	0.321	0.01442	—	—	$0.088^{+0.03}_{-0.02}$
6928 (2^{++})	**$2s$**	**1**	**0.520**	**0.03546**	—	—	**$0.217^{+0.07}_{-0.05}$**

4. Conclusion

In this work, we have argued that the two-photon decay width of the $X(6900)$ is a powerful probe of its internal structure. By performing a leading-order calculation in the NRQCD factorization, complemented by a relativized quark model for the non-perturbative inputs, we have derived predictions for the decay width under the compact diquark–antidiquark configuration. Our results indicate sizable decay widths in the range of 0.15–0.69 keV for the candidate of radially excited $2s$ states. These values are testable in ultraperipheral collisions at the LHC and serve as a benchmark in contrast to the small decay width expected from the molecular picture.

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