Manipulation of Giant Multipole Resonances via Vortex γ Photons

Zhi-Wei Lu,[1,*] Liang Guo,[2,3,*] Zheng-Zheng Li,[2,3] Mamutjan Ababekri,[1] Fang-Qi Chen,[2,3] Changbo Fu,[4] Chong Lv,[5]
Ruirui Xu,[6] Xiangjin Kong,[4] Yi-Fei Niu,[2,3,†] and Jian-Xing Li[1,5,‡]
[1]*Ministry of Education Key Laboratory for Nonequilibrium Synthesis and Modulation of Condensed Matter,*
Shaanxi Province Key Laboratory of Quantum Information and Quantum Optoelectronic Devices, School of Physics,
Xi'an Jiaotong University, Xi'an 710049, China
[2]*School of Nuclear Science and Technology, Lanzhou University, Lanzhou 730000, China*
[3]*Frontiers Science Center for Rare Isotopes, Lanzhou University, Lanzhou 730000, China*
[4]*Key Laboratory of Nuclear Physics and Ion-beam Application (MoE), Institute of Modern Physics,*
Fudan University, Shanghai 200433, China
[5]*Department of Nuclear Physics, China Institute of Atomic Energy, P.O. Box 275(7), Beijing 102413, China*
[6]*China Nuclear Data Center, China Institute of Atomic Energy, P.O. Box 275(41), Beijing 102413, China*

(Received 14 June 2023; revised 5 August 2023; accepted 15 September 2023; published 14 November 2023)

Traditional photonuclear reactions primarily excite giant dipole resonances, making the measurement of isovector giant resonances with higher multipolarities a great challenge. In this Letter, the manipulation of collective excitations of different multipole transitions in even-even nuclei via vortex γ photons is investigated. We develop the calculation method for photonuclear cross sections induced by the vortex γ photon beam using the fully self-consistent random-phase approximation plus particle-vibration coupling (RPA + PVC) model based on Skyrme density functional. We find that the electromagnetic transitions with multipolarity $J < |m_\gamma|$ are forbidden for vortex γ photons due to the angular momentum conservation, with m_γ being the projection of total angular momentum of γ photon on its propagation direction. For instance, this allows for probing the isovector giant quadrupole resonance without interference from dipole transitions using vortex γ photons with $m_\gamma = 2$. Furthermore, the electromagnetic transition with $J = |m_\gamma| + 1$ vanishes at a specific polar angle. Therefore, the giant resonances with specific multipolarity can be extracted via vortex γ photons. Moreover, the vortex properties of γ photons can be meticulously diagnosed by measuring the nuclear photon-absorption cross section. Our method opens new avenues for photonuclear excitations, generation of coherent γ photon laser and precise detection of vortex particles, and consequently, has significant impact on nuclear physics, nuclear astrophysics and strong laser physics.

DOI: 10.1103/PhysRevLett.131.202502

The collective excitation modes of quantum many-body systems are pervasive in a diversity of physics subdisciplines [1], such as condensed matter physics [2,3], atomic physics [4–6], nuclear physics [7–10], and particle physics [11,12]. In atomic nuclei, the giant resonances (GRs) appear to be a global feature of nuclei arising from the collective motion of the nucleons within the nucleus [7]. GRs not only play a fundamental role in nuclear structure research, but also serve as a means of constraining the nuclear equation of state [13], which is crucial for understanding a host of astrophysical phenomena [14–17], such as supernova explosions [17] and the structure of neutron stars [14,16].

GRs have been found to exist in the energy range of approximately 10–30 MeV, and their modes are characterized by the quantum numbers related to multipolarity, spin, and isospin [7]. The isovector giant dipole resonance, in which neutrons oscillate against protons [7], was first discovered in 1937 via photonuclear reaction [18,19]. While photons can provide transition strengths in a model-independent way, owing to the well-known excitation mechanism of electromagnetic force, they generate primarily the giant dipole resonance (GDR) [20]. The giant quadrupole resonance (GQR), in which the nucleons undergo quadrupole deformation [21], was the next fundamental mode discovered in the 1970s [22–25]. It has been systematically studied over the nuclear chart using inelastic scattering of charged particles [26]; however, these probes, such as alpha particles, protons, and ^{3}He, mainly induce isoscalar excitations [26]. The study of the isovector giant quadrupole resonance (IVGQR) has always been a challenge due to the lack of a highly selective experimental probe. Detailed studies on IVGQR are invaluable for nuclear structure and nuclear astrophysics, for instance, to constrain the nuclear effective mass, the isovector channel of the nuclear effective interaction, the density dependence of the nuclear symmetry energy [13,27,28], etc. At present, the main experimental studies are based on electron scattering, which displays a large spread in the reported parameters (e.g., transition strengths and resonance widths [21,29]) due to the difficulty in disentanglement of different GR modes [7]. In photonuclear reactions, IVGQR is only a minor component and extracted by observing the electric dipole ($E1$)-electric quadrupole ($E2$) interference term using the intense, nearly monoenergetic, ~100% linearly polarized γ-ray beams [29,30]. These difficulties in detecting IVGQR are attributed to the preference of $E1$ excitations over higher multipolarities by several orders of magnitudes from photon excitations. Nevertheless, the introduction of nonzero orbital angular momenta (OAM) to photons could potentially alter the selection rule and enable the unique extraction of higher multipole excitations. This would completely broaden the conventional understanding of photonuclear reactions and unlock new horizons in nuclear physics [31,32].

Vortex photons, described by wave functions with helical phases and carrying intrinsic OAM along the propagation direction [33,34], have given rise to new phenomena in various fields of physics, such as optical physics [35,36], astrophysics [37,38], and atomic physics [39,40]. Currently, vortex photons spanning from visible to x-ray regimes have been generated experimentally through optical mode conversion techniques, high harmonic generation, or coherent radiation in helical undulators and laser facilities [41–46]. With the rapid developments of ultraintense, ultrashort laser techniques [47,48], the generation of vortex γ photons is extensively proposed theoretically, where most of the studies consider Compton scattering to attain high energy and OAM [32,49–61]. Studies of atomic excitation using vortex photons [39,40,62–72] have shown that absorption of photons with nonzero OAM by atoms can excite multipole transitions that are otherwise suppressed for plane wave photons, due to modifications of the atomic transition selection rules on the beam axis. In nuclear physics, cross sections of deuteron photodisintegration by vortex photons [73] via ${}^3S_1 \to {}^1S_0$ magnetic dipole ($M1$) transition have been compared with those by plane wave photons. Nonetheless, the excitations of higher multipole transitions in nuclei via vortex photons are still an open question.

In this Letter, we investigate the collective excitations of different multipole transitions in even-even nuclei ($J_i = 0$) via vortex γ photons. We develop the calculation method for photonuclear cross sections induced by the vortex γ photon beam using the fully self-consistent RPA + PVC model based on Skyrme density functional [74–77]. According to the interaction scenario illustrated in Fig. 1, the electromagnetic transitions are unrestricted for plane wave γ photons since the selection rule of plane wave is $|J_i - J_f| \leqslant J \leqslant J_i + J_f$, $M_f - M_i = \Lambda$. However, for vortex γ photons, when the nucleus is positioned on the beam axis, the selection rule is modified to $M_f - M_i = m_\gamma$ due to the conservation laws of angular momentum, with m_γ being the projection of the total angular momentum (TAM) of γ photon on its propagation direction. Therefore, the electromagnetic transitions with multipolarity $J < |m_\gamma|$ are forbidden (indicated as the forbidden transitions). Because of the dependence on polar angle θ_k, the electromagnetic transition with $J = |m_\gamma| + 1$ could vanish at a specific polar angle, thus transitions almost entirely come from $J = |m_\gamma|$ case (indicated as the quasipure transitions). Manipulating GRs with different multipolarities via vortex γ photons with different m_γ enables investigating isovector giant resonances of higher multipolarities without interference from other transitions, which broadens the research scope of photonuclear reaction compared with plane wave γ photons, and provides valuable insights into the nuclear structure and nuclear astrophysics [17,20,28]. Additionally, the forbidden and quasipure transitions excited by vortex γ photons might construct a three-level system for coherent zeptosecond γ photon laser [78–80].

Meanwhile, exploring the vortex properties of single γ photon is a fascinating area of research [32,41]. Vortex photons, ranging from visible to x-ray frequencies, have been successfully detected through interference with a reference beam [42–46]. However, detecting the vortex γ photons remains a challenge. We find that the vortex properties of γ photons can be determined accurately by measuring the nuclear photon-absorption cross section.

In the RPA + PVC model, the coupling of single-nucleon states to low-lying phonons (1 particle-1 hole-1 phonon configurations) is taken into account. While the RPA model provides a good description of GRs' energies, the PVC effect is crucial for describing the damping width of GRs [81]. Using the strength function $S_{\mu J}$ (electric, $\mu = E$; magnetic, $\mu = M$) obtained by RPA + PVC model, we can derive the nuclear photon-absorption cross section $\sigma^{(pl)}$ of a plane wave γ photon beam interacting with nucleus [see Eq. (8) in Supplemental Material (SM) [82]].

Different vortex modes exhibit similar characteristics in the vicinity of beam axis and different asymptotic behavior in the region far away from the beam axis (see Sec. III of SM [82]). Take the Bessel mode for example, the nuclear photon-absorption cross section $\sigma^{(tw)}$ of a vortex γ photon beam, interacting with nucleus, differs from the case of plane wave due to the vortex state's vector potential $\boldsymbol{A}^{(tw)}_{\varkappa m_\gamma k_z \Lambda}$ [34,82] and its ensuing change in the flux density and transition amplitude. The vortex state can be characterized by a definite transverse momentum $\varkappa = |\boldsymbol{k}_\perp|$, longitudinal momentum k_z, m_γ, and helicity Λ. In momentum space, the vortex state can be interpreted as a coherent superposition of plane waves, arranged on a cone defined by the polar angle $\theta_k = \arctan(\varkappa / k_z)$. In general, vortex γ photon is the superposition of spin eigenstates, thus one can get $m_s = 0, \pm\Lambda$ and $m_l = m_\gamma, m_\gamma \mp \Lambda$. When $\theta_k \to 0$, the vortex γ photon is approaching the limit of plane wave γ photon, and is almost in the spin eigenstate, thus one has $m_s \simeq \Lambda$ and $m_l \simeq m_\gamma - \Lambda$. To normalize the nuclear photon-absorption cross sections of vortex γ photon to the plane wave case, we assume that the average flux density of

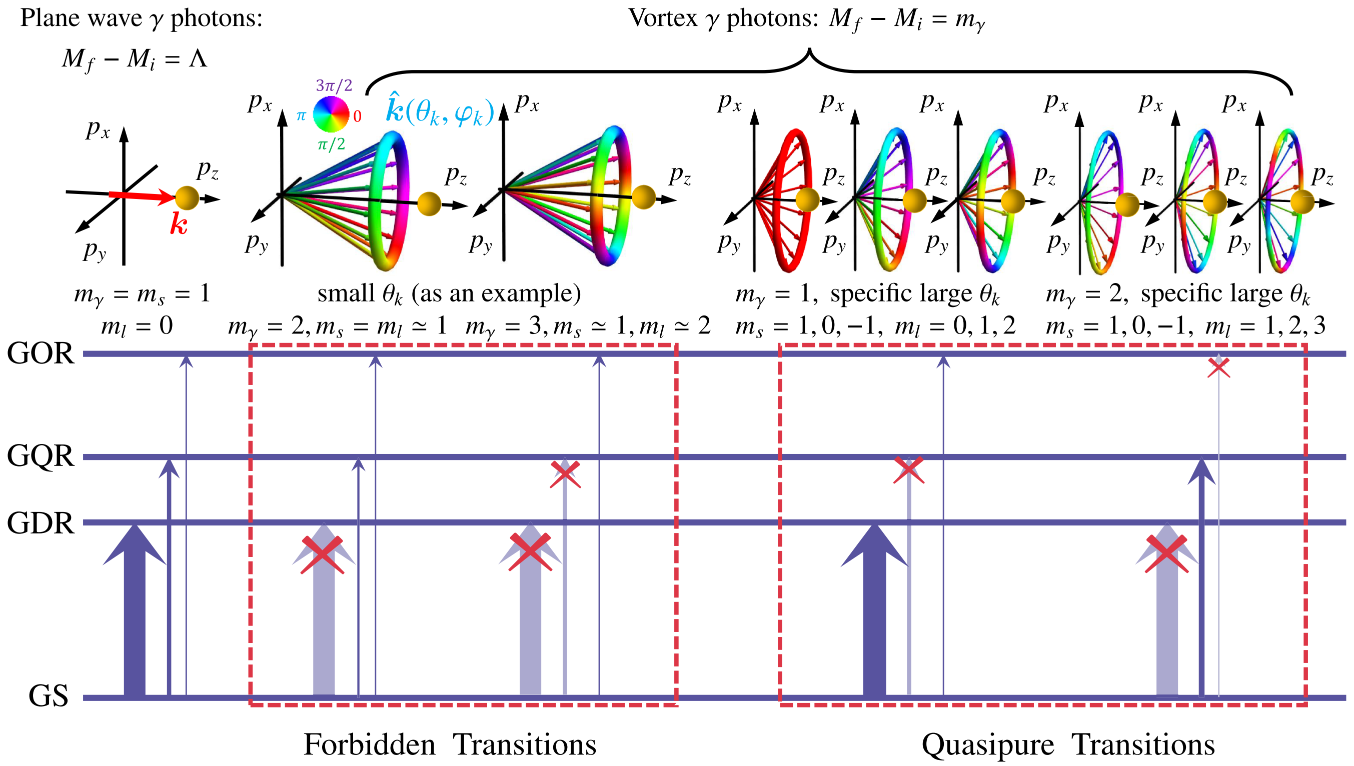

FIG. 1. Scenario of nuclear responses for even-even nuclei excited either by plane wave or vortex γ photons on the beam axis. In the momentum space, the vortex state consists of multiple plane waves with conically distributed $\boldsymbol{k}$ vectors characterized by the polar angle θ_k and the azimuth angle φ_k. The mutual phases (color coded) of the plane waves in the spectrum increase by $2\pi m_l$ around the circle, where m_l (m_s) is the projection of the OAM (spin) of γ photon on its propagation direction with $m_l = m_\gamma - m_s$ and the helicity $\Lambda = 1$. M_i (M_f) is the projection of the total angular momentum on the γ photon's propagation direction for the initial (final) state of the nucleus. The arrows linking the ground state (GS) to GDR, GQR, and giant octupole resonance (GOR) symbolize electromagnetic transitions with multipolarities $J = 1$, 2, 3, respectively. The "Forbidden Transitions" represent that electromagnetic transitions with $J < |m_\gamma|$ are forbidden (for all θ_k), and the "Quasipure Transitions" indicate electromagnetic transitions predominantly contributed by $J = |m_\gamma|$ (for specific θ_k).

vortex γ photons along its propagation direction is equivalent to that of plane wave multiplied by $\cos\theta_k$ [70,83]. We introduce a quantity $r^{(tw)}$, which represents the ratio of vortex and plane wave cross section for nuclear excitation, i.e., $r^{(tw)} = \sigma^{(tw)}/\sigma^{(pl)}$,

$$r^{(tw)} = \frac{\sum_{M_i M_f} J^2_{m_\gamma + M_i - M_f}(\varkappa b) |\sum_{M'_i M'_f} d^{J_i}_{M_i M'_i}(\theta_k) d^{J_f}_{M_f M'_f}(\theta_k) M^{(pl)}_{M'_i M'_f}|^2}{\cos\theta_k \sum_{M'_i M'_f} |M^{(pl)}_{M'_i M'_f}|^2}. \tag{1}$$

The ratio $r^{(tw)}$ exhibits two supplementary features being dependent upon the vortex properties of the incoming γ photons (i.e., m_γ and θ_k). One is the Bessel function $J_{m_\gamma + M_i - M_f}(\varkappa b)$ (with the impact parameter b) that stems from the transverse structure of vortex γ photons with a Bessel mode. The other is the Wigner d function $d^{J_f}_{M_f M'_f}(\theta_k)$ [$d^{J_i}_{M_i M'_i}(\theta_k)$], which arises from the transformation of the projection of the nuclear TAM from the propagation axis of vortex γ photon to the orientation of its plane wave component $\boldsymbol{k}$, in order to express the transition amplitude in terms of the plane wave case $M^{(pl)}_{M'_i M'_f}$ (with the selection rule $M'_f - M'_i = \Lambda$). With the property of Bessel function [84], the selection rule is modified as $M_f - M_i = m_\gamma$ on the beam axis, which indicates that the full projection of the TAM of γ photon along its propagation direction can be transferred to the nuclear degrees of freedom. This results in the forbidden transitions in Fig. 1. For even-even nuclei, the TAM and its projection are $J_i = M_i = M'_i = 0$. Because of the selection rules for vortex and plane wave γ photons mentioned above, the ratio $r^{(tw)}$ on the beam axis ($b = 0$) becomes

$$r^{(tw)} = |d^{J_f}_{m_\gamma \Lambda}(\theta_k)|^2 / \cos\theta_k. \tag{2}$$

For specific θ_k with $d^{J_f}_{m_\gamma \Lambda}(\theta_k) = 0$, the ratio $r^{(tw)}$ vanishes, which results in the quasipure transitions in Fig. 1. In this Letter, we focus on the interaction between vortex γ photon beam and a single nucleus, which results in the b

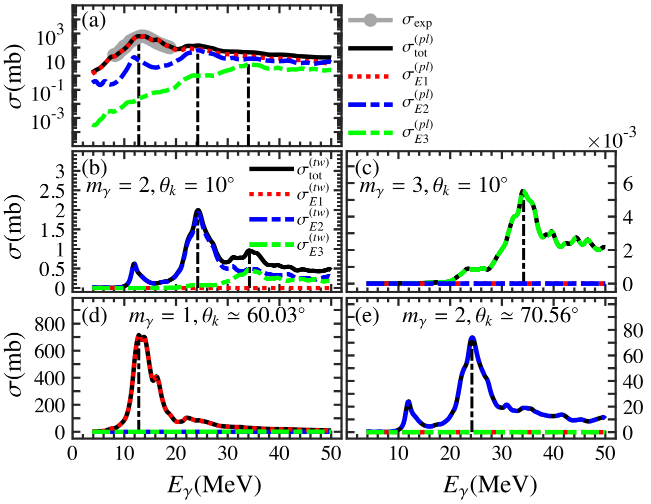

FIG. 2. (a) The experimental [85] and theoretical photon-absorption cross sections of ^{208}Pb for plane wave γ photons. (b)–(e) The theoretical photon-absorption cross sections of ^{208}Pb on the beam axis for vortex γ photons with various m_γ and θ_k, respectively. Here, $\Lambda = 1$, $\sigma_{\mathrm{tot}}^{(pl)} = \sigma_{E1}^{(pl)} + \sigma_{E2}^{(pl)} + \sigma_{E3}^{(pl)}$, and $\sigma_{\mathrm{tot}}^{(tw)} = \sigma_{E1}^{(tw)} + \sigma_{E2}^{(tw)} + \sigma_{E3}^{(tw)}$.

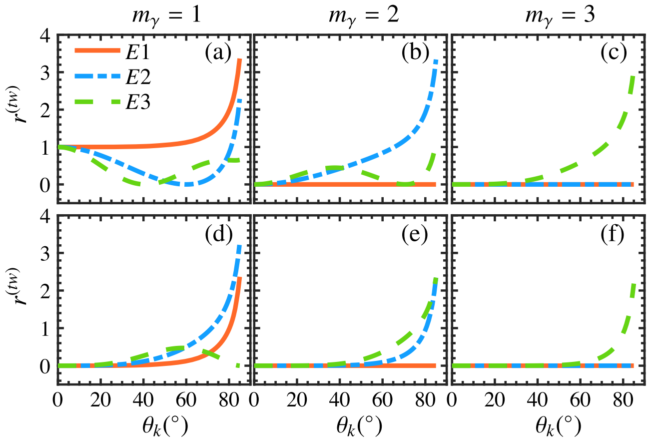

FIG. 3. The ratio of $E1$, $E2$, and $E3$ transitions ($r_{E1}^{(tw)}$, $r_{E2}^{(tw)}$, and $r_{E3}^{(tw)}$) vs the polar angle θ_k on the beam axis. (a)–(c): $\Lambda = 1$ with $m_\gamma = 1$, $m_\gamma = 2$, $m_\gamma = 3$, respectively. (d)–(f) are similar but for $\Lambda = -1$.

dependence of $r^{(tw)}$, and the realistic feasibility about this reaction is discussed later. The effects of macroscopic and mesoscopic target are discussed in Sec. IV of SM [82].

Vortex effects on the nucleus are the same for electric and magnetic transitions since the ratio $r^{(tw)}$ is parity independent and angular momentum dependent. For convenience, we perform calculations of the electric transitions ($E1$, $E2$, and $E3$) in nucleus ^{208}Pb using both plane wave γ photons and vortex γ photons with Bessel mode, and the nuclear photon-absorption cross sections are shown in Fig. 2. We choose ^{208}Pb due to the availability of experimental data [85], the large photon-absorption cross section, and ongoing challenges in IVGQR [29,30]. The excitation of other even-even nuclei by vortex γ photons is similar, albeit with changes in the characteristic photon-absorption cross sections. For plane wave γ photons [Fig. 2(a)], we find that the theoretical results are in good agreement with the experiment. It is also found that the $E1$, $E2$, and $E3$ photon-absorption cross sections of plane wave exhibit characteristic peaks. Below photon energy 20 MeV, the total cross section $\sigma_{\mathrm{tot}}^{(pl)}$ is dominated by the $E1$ cross section $\sigma_{E1}^{(pl)}$. While the photon energy E_γ exceeds 20 MeV, the contribution from $\sigma_{E1}^{(pl)}$ is a bit larger than that of $\sigma_{E2}^{(pl)}$. For $\sigma_{E3}^{(pl)}$, its contribution is always negligible. Thus, studying $E2$ and $E3$ cross sections using plane wave γ photons is challenging.

However, when the nucleus is positioned on the beam axis ($b = 0$), the contribution of $E2$ cross section can be distinguished by vortex γ photon with $m_\gamma = 2$ due to the forbiddance of $E1$ transition and the dominance of $E2$ transition, as shown in Fig. 2(b) ($\theta_k = 10°$ as an example) and corresponding to the forbidden $E1$ transition in Fig. 1. Similarly, the contribution of $E3$ cross section can be distinguished by vortex γ photon with $m_\gamma = 3$, as shown in Fig. 2(c) corresponding to the forbidden $E1$ and $E2$ transitions in Fig. 1. As a result, we can find that vortex γ photons with $m_\gamma = 1$, $m_\gamma = 2$, and $m_\gamma = 3$ are with the different peak energies of the photon-absorption cross section corresponding to the peak energies of $E1$, $E2$, and $E3$ transitions of plane wave, respectively [Figs. 2(b)–(d)]. Thus, the projection of TAM m_γ of vortex γ photons can be determined by the measurement of the peak energy. Furthermore, the transitions with $J = |m_\gamma| + 1$ could vanish at specific θ_k (see Fig. 3), so we take these angles to plot the corresponding cross sections in Figs. 2(d) and (e), where vortex γ photons with $m_\gamma = 1$ and $m_\gamma = 2$ can result in the occurrence of the quasipure $E1$ and $E2$ transitions, respectively, with a cross section comparable to that of the plane wave. In principle, the quasipure $E3$ transition can also be induced by vortex γ photon with $m_\gamma = 3$, and specific θ_k (Fig. 4 in SM [82]).

In order to understand the occurrence of the quasipure transition, the ratios $r_{E1}^{(tw)}$, $r_{E2}^{(tw)}$, and $r_{E3}^{(tw)}$ on the beam axis ($b = 0$) as a function of θ_k [see Eq. (2)] are shown in Fig. 3. In Fig. 3(a), $E2$ transition is forbidden for vortex γ photon with $m_\gamma = 1$ at $\theta_k \simeq 60.03°$ [$d_{11}^2(\theta_k) = 0$], resulting in a quasipure $E1$ cross section and $r_{E1}^{(tw)} = 1.13$, which corresponds to Fig. 2(d). Similarly, in Fig. 3(b), $E3$ transition is forbidden for a vortex γ photon with $m_\gamma = 2$ at $\theta_k \simeq 70.56°$ [$d_{21}^3(\theta_k) = 0$], resulting in a quasipure $E2$ cross section and $r_{E2}^{(tw)} = 1.19$, which corresponds to Fig. 2(e). We can see that in Figs. 3(b),(c),(e),(f), transitions with $J < |m_\gamma|$ are always forbidden independent of θ_k and Λ due to the angular momentum selection rule. Besides, $r^{(tw)}$ becomes

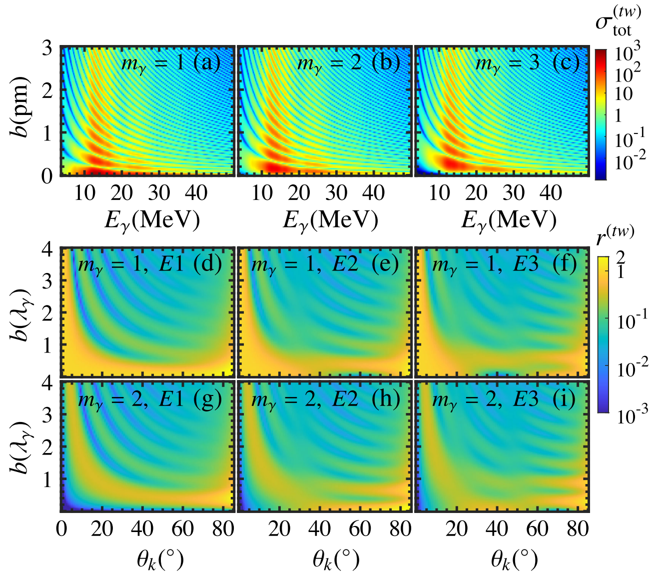

FIG. 4. (a)–(c): Distributions of total vortex photon-absorption cross section $\sigma_{\rm tot}^{(tw)}$ (mb) in the plane of the impact parameter b and the energy E_γ with the polar angle $\theta_k = 10°$ and $m_\gamma = 1$, $m_\gamma = 2$ and $m_\gamma = 3$, respectively. (d)–(i): Distributions of the ratio $r^{(tw)}$ in the plane of the impact parameter b and the polar angle θ_k at the energy $E_\gamma = E_{\gamma,1}$ with its corresponding photon wavelength λ_γ, where $m_\gamma = 1$ for panels (d)–(f) and $m_\gamma = 2$ for panels (g)–(i). Here, $E_{\gamma,1}$ is the peak energy of the $E1$ transition for the plane wave case [see Fig. 2(a)].

extremely large at the large polar angle (near 90°), which is due to $\cos\theta$ dependence of the corresponding effective flux density of vortex γ photon along its propagation direction. Furthermore, the polar angle θ_k of vortex γ photon can be determined by the measurement of $r^{(tw)}$, and the vortex topological charge m_l can be further inferred as $m_l = m_\gamma$, $m_\gamma \pm \Lambda$ with probabilities $|d^1_{0\Lambda}(\theta_k)|^2$, $|d^1_{\mp 1,\Lambda}(\theta_k)|^2$, respectively.

In the region far away from the beam axis (the impact parameter $b \neq 0$), the photon energy E_γ dependence of $\sigma_{\rm tot}^{(tw)}$ and the polar angle θ_k dependence of $r^{(tw)}$ are shown in Fig. 4. There is no specific selection rule since the system has no axial symmetry, thus there are no forbidden transitions. Moreover, the 1^- (GDR), 2^+ (GQR), and 3^- (GOR) states come from the superposition of $M_f = 0, \pm 1$, $M_f = 0, \pm 1, \pm 2$, and $M_f = 0, \pm 1, \pm 2, \pm 3$, respectively. In contrast, for vortex γ photon at $b = 0$, $M_f = m_\gamma$, and for plane wave γ photon, $M_f = \Lambda$. At the small polar angle θ_k, $\sigma_{E1}^{(tw)}$, $\sigma_{E2}^{(tw)}$, and $\sigma_{E3}^{(tw)}$ are dominated by $M_f = \Lambda$, which returns to the selection rule of plane wave. With increasing θ_k, the contributions from $M_f \neq \Lambda$ increase (Figs. 5–7 in SM [82]). From the peak position in Figs. 4(a)–(c) as well as Fig. 8 in SM [82], one can see the cross section from $E1$ is dominated, just as the plane wave case. The vortex photon-absorption cross section $\sigma^{(tw)} \propto J_z^{(tw)}$ [Eq. (17) in SM [82]] due to the dominated $E1$ transition, thus the dependence of cross section on impact parameter b and m_γ in Fig. 4 follows the behavior of Bessel function $J_{m_\gamma - m_s}(\varkappa\rho)$ in $J_z^{(tw)}$. We also find that, as the impact parameter b increases, $r^{(tw)}$ decreases. For typical interatomic distances in crystals (0.1 nm), $r^{(tw)}$ is $\simeq 10^{-4}$ for vortex state with Bessel mode and $\simeq 0$ with Bessel-Gauss mode (details in Fig. 9 of SM [82]), which means that the absorption of the vortex beam by other nuclei being offset ($\gtrsim$0.1 nm) from the vortex beam axis can be neglected. Furthermore, the superposition of vortex γ photons with different m_γ could make the vortex photon-absorption cross sections azimuth-dependent (Figs. 10 and 11 in SM [82]).

In order to selectively observe the quasipure GR transitions of different multipolarities, the target nuclei should be located near the beam axis, and there are two possible options: one involves interacting the vortex beam with a single, trapped ion [40,62], while the other involves interaction with a solid target, such as a single crystal. The former offers the advantage of easier manipulation of the alignment and offset of the vortex beam with respect to the nucleus, but it has the disadvantage of low probability, necessitating the time accumulation and highly brilliant vortex γ beams, which are promising based on the interaction of ultraintense lasers with material [86] and are discussed in Refs. [53,54,56,57,60,87]. The latter offers the advantage of a relatively large reaction rate, but it presents the difficulty of achieving synchronous alignment of the vortex beam axis with the nuclei.

In conclusion, we demonstrate the ability of vortex γ photons to manipulate the population of giant multipole resonance, enabling the occurrence of the forbidden and quasipure transitions and ensuing the extraction of isovector giant resonances with specific multipolarity. Moreover, measuring nuclear photon-absorption cross sections can meticulously diagnose the vortex γ photons. Our findings may have significant implications for the studies of nuclear physics, nuclear astrophysics, and strong laser physics. For instance, our method would open a completely new avenue for experimental nuclear spectroscopy that makes previously unexplored nuclear high-energy states measurable in an exclusive way, provide new opportunities for constraining nuclear equation of state, enable highly accurate detection for the properties of vortex particles, unlock new possibilities for designing coherent γ photon laser, etc.

We thank V. G. Serbo, L. Zou, P. Zhang, and I. P. Ivanov for helpful discussions. The work is supported by the National Key Research and Development (R&D) Program under Grant No. 2021YFA1601500, the National Natural Science Foundation of China (Grants No. 12022506, No. U2267204, No. 12075104), the Foundation of Science and Technology on Plasma Physics Laboratory (No. JCKYS2021212008 and No. 6142A04220107), the

Open Fund of the State Key Laboratory of High Field Laser Physics (Shanghai Institute of Optics and Fine Mechanics), the Open Foundation of Key Laboratory of High Power Laser and Physics, Chinese Academy of Sciences (SGKF202101), and the Shaanxi Fundamental Science Research Project for Mathematics and Physics (Grant No. 22JSY014).

[*]These authors have contributed equally to this work.
[†]niuyf@lzu.edu.cn
[‡]jianxing@xjtu.edu.cn

[1] J.-P. Connerade, J.-M. Esteva, and R. Karnatak, *Giant Resonances in Atoms, Molecules, and Solids* (Springer, New York, 2013), Vol. 151.

[2] A. Rodin, M. Trushin, A. Carvalho, and A. Castro Neto, Collective excitations in 2D materials, Nat. Rev. Phys. **2**, 524 (2020).

[3] L. Venema, B. Verberck, I. Georgescu, G. Prando, E. Couderc, S. Milana, M. Maragkou, L. Persechini, G. Pacchioni, and L. Fleet, The quasiparticle zoo, Nat. Phys. **12**, 1085 (2016).

[4] M. Edwards, P. A. Ruprecht, K. Burnett, R. Dodd, and C. W. Clark, Collective Excitations of atomic Bose-Einstein condensates, Phys. Rev. Lett. **77**, 1671 (1996).

[5] L. W. Clark, A. Gaj, L. Feng, and C. Chin, Collective emission of matter-wave jets from driven Bose–Einstein condensates, Nature (London) **551**, 356 (2017).

[6] P. Jurcevic, B. P. Lanyon, P. Hauke, C. Hempel, P. Zoller, R. Blatt, and C. F. Roos, Quasiparticle engineering and entanglement propagation in a quantum many-body system, Nature (London) **511**, 202 (2014).

[7] M. N. Harakeh and A. Woude, *Giant Resonances: Fundamental High-Frequency Modes of Nuclear Excitation* (Oxford University Press on Demand, New York, 2001), Vol. 24.

[8] J. Wambach, Damping of small-amplitude nuclear collective motion, Rep. Prog. Phys. **51**, 989 (1988).

[9] P. Ring and P. Schuck, *The Nuclear Many-Body Problem* (Springer Science & Business Media, New York, 2004).

[10] J. D. Walecka, *Theoretical Nuclear and Subnuclear Physics* (World Scientific, Singapore, 2004).

[11] H. Stoecker, Collective flow signals the quark–gluon plasma, Nucl. Phys. **A750**, 121 (2005).

[12] H. Stoecker and W. Greiner, High energy heavy ion collisions–probing the equation of state of highly excited hardronic matter, Phys. Rep. **137**, 277 (1986).

[13] X. Roca-Maza and N. Paar, Nuclear equation of state from ground and collective excited state properties of nuclei, Prog. Part. Nucl. Phys. **101**, 96 (2018).

[14] J. Lattimer and M. Prakash, Neutron star structure and the equation of state, Astrophys. J. **550**, 426 (2001).

[15] F. J. Fattoyev, C. J. Horowitz, J. Piekarewicz, and G. Shen, Relativistic effective interaction for nuclei, giant resonances, and neutron stars, Phys. Rev. C **82**, 055803 (2010).

[16] N. Paar, C. C. Moustakidis, T. Marketin, D. Vretenar, and G. A. Lalazissis, Neutron star structure and collective excitations of finite nuclei, Phys. Rev. C **90**, 011304(R) (2014).

[17] M. Oertel, M. Hempel, T. Klähn, and S. Typel, Equations of state for supernovae and compact stars, Rev. Mod. Phys. **89**, 015007 (2017).

[18] W. Bothe and W. Gentner, Atomumwandlungen durch γ-Strahlen, Z. Phys. **106**, 236 (1937).

[19] B. L. Berman and S. Fultz, Measurements of the giant dipole resonance with monoenergetic photons, Rev. Mod. Phys. **47**, 713 (1975).

[20] P. F. Bortignon, A. Bracco, and R. A. Broglia, *Giant Resonances: Nuclear Structure at Finite Temperature* (CRC Press, London, 2019).

[21] F. E. Bertrand, Giant multipole resonances–perspectives after ten years, Nucl. Phys. **A354**, 129 (1981).

[22] R. Pitthan and T. Walcher, Inelastic electron scattering in the giant resonance region of La, Ce and Pr, Phys. Lett. B **36**, 563 (1971).

[23] R. Pitthan, F. Buskirk, E. Dally, J. Dyer, and X. Maruyama, electroexcitation of giant multipole resonances in ^{197}Au and ^{208}Pb between 5 and 40 MeV excitation energy with 90-MeV electrons, Phys. Rev. Lett. **33**, 849 (1974).

[24] M. Lewis, Giant resonances in the high-energy unelastic scattering continuum, Phys. Rev. Lett. **29**, 1257 (1972).

[25] M. Lewis and F. Bertrand, Evidence from inelastic proton scattering for a giant quadrupole vibration in spherical nuclei, Nucl. Phys. **A196**, 337 (1972).

[26] F. E. Bertrand, Excitation of giant multipole resonances through inelastic scattering, Annu. Rev. Nucl. Part. Sci. **26**, 457 (1976).

[27] M. Baldo and G. Burgio, The nuclear symmetry energy, Prog. Part. Nucl. Phys. **91**, 203 (2016).

[28] X. Roca-Maza, M. Brenna, B. K. Agrawal, P. F. Bortignon, G. Colò, L.-G. Cao, N. Paar, and D. Vretenar, Giant quadrupole resonances in ^{208}Pb, the nuclear symmetry energy, and the neutron skin thickness, Phys. Rev. C **87**, 034301 (2013).

[29] S. S. Henshaw, M. W. Ahmed, G. Feldman, A. M. Nathan, and H. R. Weller, New method for precise determination of the isovector giant quadrupole resonances in nuclei, Phys. Rev. Lett. **107**, 222501 (2011).

[30] D. S. Dale, R. M. Laszewski, and R. Alarcon, Isovector $E2$ Resonance in ^{208}Pb, Phys. Rev. Lett. **68**, 3507 (1992).

[31] I. P. Ivanov, Promises and challenges of high-energy vortex states collisions, Prog. Part. Nucl. Phys. **127**, 103987 (2022).

[32] Y. Taira, T. Hayakawa, and M. Katoh, Gamma-ray vortices from nonlinear inverse Thomson scattering of circularly polarized light, Sci. Rep. **7**, 5018 (2017).

[33] L. Allen, M. W. Beijersbergen, R. J. C. Spreeuw, and J. Woerdman, Orbital angular momentum of light and the transformation of Laguerre-Gaussian laser modes, Phys. Rev. A **45**, 8185 (1992).

[34] B. A. Knyazev and V. Serbo, Beams of photons with nonzero projections of orbital angular momenta: New results, Phys. Usp. **61**, 449 (2018).

[35] C. Hernández-García, J. Vieira, J. T. Mendonca, L. Rego, J. San Román, L. Plaja, P. R. Ribic, D. Gauthier, and A. Picón, Generation and applications of extreme-ultraviolet vortices, in *Photonics* (MDPI, Basel, 2017), Vol. 4, p. 28.

[36] M. J. Padgett, Orbital angular momentum 25 years on, Opt. Express **25**, 11265 (2017).

[37] M. Harwit, Photon orbital angular momentum in astrophysics, Astrophys. J. **597**, 1266 (2003).

[38] F. Tamburini, B. Thidé, G. Molina-Terriza, and G. Anzolin, Twisting of light around rotating black holes, Nat. Phys. **7**, 195 (2011).

[39] M. Babiker, D. L. Andrews, and V. E. Lembessis, Atoms in complex twisted light, J. Opt. **21**, 013001 (2018).

[40] R. Lange, N. Huntemann, A. A. Peshkov, A. Surzhykov, and E. Peik, Excitation of an electric octupole transition by twisted light, Phys. Rev. Lett. **129**, 253901 (2022).

[41] T. Maruyama, T. Hayakawa, T. Kajino, and M.-K. Cheoun, Generation of photon vortex by synchrotron radiation from electrons in Landau states under astrophysical magnetic fields, Phys. Lett. B **826**, 136779 (2022).

[42] Y. Shen, X. Wang, Z. Xie, C. Min, X. Fu, Q. Liu, M. Gong, and X. Yuan, Optical vortices 30 years on: Oam manipulation from topological charge to multiple singularities, Light Sci. Appl. **8**, 90 (2019).

[43] A. G. Peele, P. J. McMahon, D. Paterson, C. Q. Tran, A. P. Mancuso, K. A. Nugent, J. P. Hayes, E. Harvey, B. Lai, and I. McNulty, Observation of an x-ray vortex, Opt. Lett. **27**, 1752 (2002).

[44] B. Terhalle, A. Langner, B. Päivänranta, V. A. Guzenko, C. David, and Y. Ekinci, Generation of extreme ultraviolet vortex beams using computer generated holograms, Opt. Lett. **36**, 4143 (2011).

[45] G. Gariepy, J. Leach, K. T. Kim, T. J. Hammond, E. Frumker, R. W. Boyd, and P. B. Corkum, Creating high-harmonic beams with controlled orbital angular momentum, Phys. Rev. Lett. **113**, 153901 (2014).

[46] E. Hemsing, A. Knyazik, M. Dunning, D. Xiang, A. Marinelli, C. Hast, and J. B. Rosenzweig, Coherent optical vortices from relativistic electron beams, Nat. Phys. **9**, 549 (2013).

[47] C. N. Danson, C. Haefner, J. Bromage, T. Butcher, J.-C. F. Chanteloup, E. A. Chowdhury, A. Galvanauskas, L. A. Gizzi, J. Hein, D. I. Hillier *et al.*, Petawatt and exawatt class lasers worldwide, High Power Laser Sci. Eng. **7**, e54 (2019).

[48] J. W. Yoon, Y. G. Kim, I. W. Choi, J. H. Sung, H. W. Lee, S. K. Lee, and C. H. Nam, Realization of laser intensity over 10^{23} W/cm^2, Optica **8**, 630 (2021).

[49] M. Ababekri, R.-T. Guo, F. Wan, B. Qiao, Z. Li, C. Lv, B. Zhang, W. Zhou, Y. Gu, and J.-X. Li, Vortex γ photon generation via spin-to-orbital angular momentum transfer in nonlinear Compton scattering, arXiv:2211.05467.

[50] Y. Taira and M. Katoh, Gamma-ray vortices emitted from nonlinear inverse Thomson scattering of a two-wavelength laser beam, Phys. Rev. A **98**, 052130 (2018).

[51] X.-L. Zhu, T.-P. Yu, M. Chen, S.-M. Weng, and Z.-M. Sheng, Generation of GeV positron and γ-photon beams with controllable angular momentum by intense lasers, New J. Phys. **20**, 083013 (2018).

[52] B. Feng, C. Qin, X. Geng, Q. Yu, W. Wang, Y. Wu, X. Yan, L. Ji, and B. Shen, The emission of γ-ray beams with orbital angular momentum in laser-driven micro-channel plasma target, Sci. Rep. **9**, 18780 (2019).

[53] J. Wang, X. B. Li, L. F. Gan, Y. Xie, C. L. Zhong, C. T. Zhou, S. P. Zhu, X. T. He, and B. Qiao, Generation of intense vortex gamma rays via spin-to-orbital conversion of angular momentum in relativistic laser-plasma interactions, Phys. Rev. Appl. **14**, 014094 (2020).

[54] C.-W. Zhang, M.-A. Bake, H. Xiao, H.-B. Sang, and B.-S. Xie, Generation of bright collimated vortex γ-ray via laser driven cone-fan target, Phys. Plasmas **30**, 023105 (2023).

[55] C. Liu, B. Shen, X. Zhang, Y. Shi, L. Ji, W. Wang, L. Yi, L. Zhang, T. Xu, Z. Pei *et al.*, Generation of gamma-ray beam with orbital angular momentum in the QED regime, Phys. Plasmas **23**, 093120 (2016).

[56] H. Zhang, J. Zhao, Y. Hu, Q. Li, Y. Lu, Y. Cao, D. Zou, Z. Sheng, F. Pegoraro, P. McKenna *et al.*, Efficient bright γ-ray vortex emission from a laser-illuminated light-fan-in-channel target, High Power Laser Sci. Eng. **9**, e43 (2021).

[57] Y.-Y. Liu, Y. I. Salamin, Z.-K. Dou, Z.-F. Xu, and J.-X. Li, Vortex γ rays from scattering laser bullets off ultrarelativistic electrons, Opt. Lett. **45**, 395 (2020).

[58] U. D. Jentschura and V. G. Serbo, Generation of high-energy photons with large orbital angular momentum by Compton backscattering, Phys. Rev. Lett. **106**, 013001 (2011).

[59] Y.-Y. Chen, J.-X. Li, K. Z. Hatsagortsyan, and C. H. Keitel, γ-ray beams with large orbital angular momentum via nonlinear Compton scattering with radiation reaction, Phys. Rev. Lett. **121**, 074801 (2018).

[60] Y.-T. Hu, J. Zhao, H. Zhang, Y. Lu, W.-Q. Wang, L.-X. Hu, F.-Q. Shao, and T.-P. Yu, Attosecond γ-ray vortex generation in near-critical-density plasma driven by twisted laser pulses, Appl. Phys. Lett. **118**, 054101 (2021).

[61] D. Younis, B. Hafizi, and D. Gordon, Generation of collimated vortex gamma-rays from intense poincaré beam–plasma interaction, Phys. Plasmas **29**, 093106 (2022).

[62] C. T. Schmiegelow, J. Schulz, H. Kaufmann, T. Ruster, U. G. Poschinger, and F. Schmidt-Kaler, Transfer of optical orbital angular momentum to a bound electron, Nat. Commun. **7**, 12998 (2016).

[63] A. Afanasev, C. E. Carlson, C. T. Schmiegelow, J. Schulz, F. Schmidt-Kaler, and M. Solyanik, Experimental verification of position-dependent angular-momentum selection rules for absorption of twisted light by a bound electron, New J. Phys. **20**, 023032 (2018).

[64] M. Solyanik-Gorgone, A. Afanasev, C. E. Carlson, C. T. Schmiegelow, and F. Schmidt-Kaler, Excitation of E1-forbidden atomic transitions with electric, magnetic, or mixed multipolarity in light fields carrying orbital and spin angular momentum, J. Opt. Soc. Am. B **36**, 565 (2019).

[65] S.-L. Schulz, S. Fritzsche, R. A. Müller, and A. Surzhykov, Modification of multipole transitions by twisted light, Phys. Rev. A **100**, 043416 (2019).

[66] Y. Duan, R. A. Müller, and A. Surzhykov, Selection rules for atomic excitation by twisted light, J. Phys. B **52**, 184002 (2019).

[67] S.-L. Schulz, A. A. Peshkov, R. A. Müller, R. Lange, N. Huntemann, C. Tamm, E. Peik, and A. Surzhykov, Generalized excitation of atomic multipole transitions by twisted light modes, Phys. Rev. A **102**, 012812 (2020).

[68] H. M. Scholz-Marggraf, S. Fritzsche, V. G. Serbo, A. Afanasev, and A. Surzhykov, Absorption of twisted light by hydrogenlike atoms, Phys. Rev. A **90**, 013425 (2014).

[69] A. Surzhykov, D. Seipt, V. G. Serbo, and S. Fritzsche, Interaction of twisted light with many-electron atoms and ions, Phys. Rev. A **91**, 013403 (2015).

[70] A. Afanasev, C. E. Carlson, and A. Mukherjee, High-multipole excitations of hydrogen-like atoms by twisted photons near a phase singularity, J. Opt. **18**, 074013 (2016).

[71] A. Peshkov, V. Serbo, S. Fritzsche, and A. Surzhykov, Absorption of twisted light by a mesoscopic atomic target, Phys. Scr. **91**, 064001 (2016).

[72] A. Afanasev, C. E. Carlson, and A. Mukherjee, Recoil momentum effects in quantum processes induced by twisted photons, Phys. Rev. Res. **3**, 023097 (2021).

[73] A. Afanasev, V. G. Serbo, and M. Solyanik, Radiative capture of cold neutrons by protons and deuteron photodisintegration with twisted beams, J. Phys. G **45**, 055102 (2018).

[74] X. Roca-Maza, Y. Niu, G. Colò, and P. Bortignon, Towards a self-consistent dynamical nuclear model, J. Phys. G **44**, 044001 (2017).

[75] S. Shen, G. Colò, and X. Roca-Maza *et al.*, Particle-vibration coupling for giant resonances beyond the diagonal approximation, Phys. Rev. C **101**, 044316 (2020).

[76] W. L. Lv, Y. F. Niu, and G. Colò *et al.*, Learning about the structure of giant resonances from their γ decay, Phys. Rev. C **103**, 064321 (2021).

[77] Z. Li, Y. Niu, and G. Colò, Towards a unified description of isoscalar giant monopole resonances in a self-consistent quasiparticle-vibration coupling approach, Phys. Rev. Lett. **131**, 082501 (2023).

[78] E. V. Tkalya, Proposal for a nuclear gamma-ray laser of optical range, Phys. Rev. Lett. **106**, 162501 (2011).

[79] G. C. Baldwin and J. C. Solem, Recoilless gamma-ray lasers, Rev. Mod. Phys. **69**, 1085 (1997).

[80] H. A. Weidenmüller, Nuclear excitation by a zeptosecond multi-MeV laser pulse, Phys. Rev. Lett. **106**, 122502 (2011).

[81] G. Bertsch, P. F. Bortignon, and R. Broglia, Damping of nuclear excitations, Rev. Mod. Phys. **55**, 287 (1983).

[82] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.131.202502 for more details on the derivations of the photon-absorption cross sections for plane wave and vortex γ photons, the impact of other parameters of γ photons and target on the giant multipole resonances, and the comprehensive analysis on the results in the Letter.

[83] V. Ivanov, A. Chaikovskaia, and D. Karlovets, Study of highly relativistic vortex electron beams by atomic scattering, arXiv:2305.12419.

[84] F. Bowman, *Introduction to Bessel functions* (Courier Corporation, London, 2012).

[85] V. Varlamov, M. Stepanov, and V. Chesnokov, New data on photoabsorption reaction cross sections, Bull. Russ. Acad. Sci. Phys. **67**, 656 (2003).

[86] A. Di Piazza, C. Müller, K. Z. Hatsagortsyan, and C. H. Keitel, Extremely high-intensity laser interactions with fundamental quantum systems, Rev. Mod. Phys. **84**, 1177 (2012).

[87] L. B. Ju, C. T. Zhou, T. W. Huang, K. Jiang, C. N. Wu, T. Y. Long, L. Li, H. Zhang, M. Y. Yu, and S. C. Ruan *et al.*, Generation of collimated bright gamma rays with controllable angular momentum using intense Laguerre-Gaussian laser pulses, Phys. Rev. Appl. **12**, 014054 (2019).