Photonuclear Reactions by Photon Vortex with Bessel Waves in Astronomical System

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Collaborators

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Effect on stellar nucleosynthesis by Photon Vortex

T.M., T. Hayakawa, M.K.Cheoun, T.Kajino, ApJ 975, 51 (2024)

§ 1 Introduction

Optical Vortices L.Allen et al., PRA45, 8185 (‘94)

Optical vortices can bring large angular momentum.

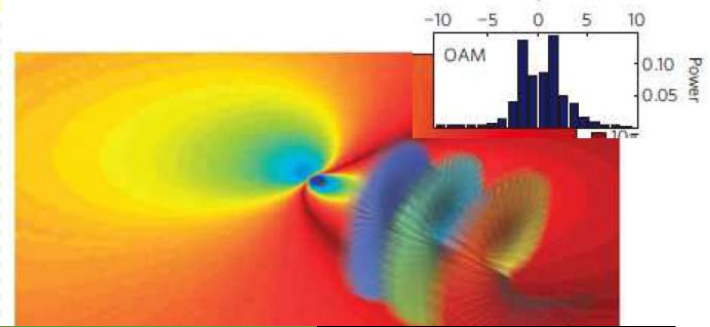
This concept is applied to quantum mechanics

Photon Vortex : Eigen States of **z-Comp. of Total Ang. Mom.** (zTAM)

Strong Gravity (BH) ⇒ Optical Vortex

F. Tamburini et al., Nat.-Phys., Vol.7, 195 (`11),

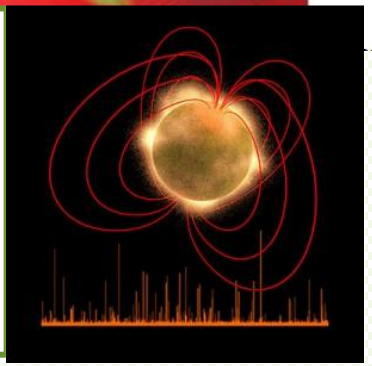
MNRAS **492,** L22 (’20)



Magnetar

- Strong Mag. Field $B \sim 10^{14-15}$ G (normal $B \sim 10^{12-13}$ G)
- Emitting High Energy γ **Soft Gamma Repeater (SGR)**

T.M, T. Hayakawa, M.K.Cheoun, T.Kajino, PLB826, 136779 (22)



Photon Vortex carrying zTAM

⇒ **Different Multipole** of Giant Resonances, Zhi-Wei Lu et al., PRL 131, 202502 (‘23)

Photon Vortex Generation in Strong Magnetic Field

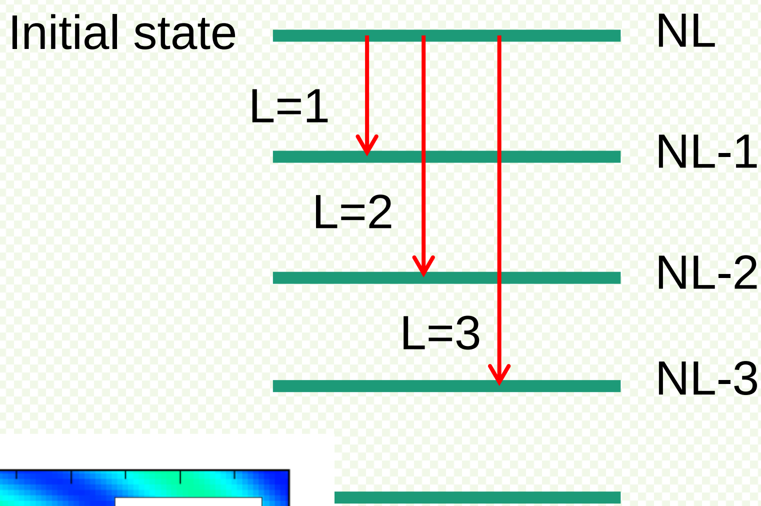
T.M, T. Hayakawa, M.K.Cheoun, T.Kajino, PLB826, 136779 (22)

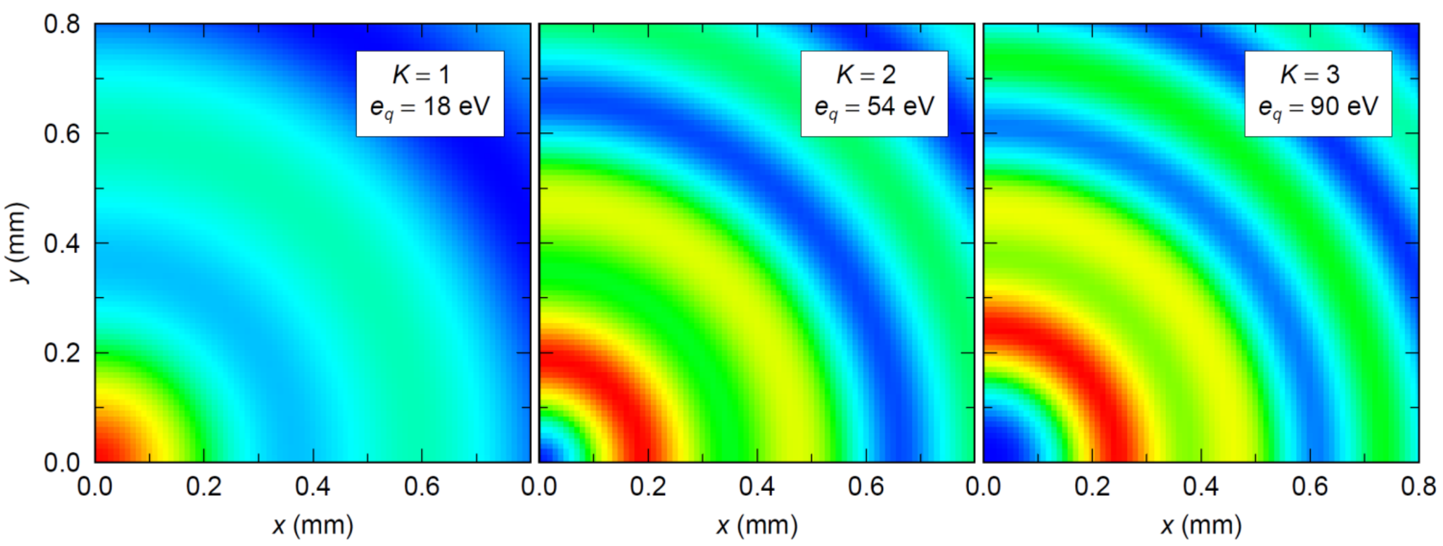
In Strong Magnetic Field, $\boldsymbol{B} = B\hat{\boldsymbol{z}}$

Electrons ⋯ Helical Motions

→ Landau Level States

Eigen States of z-Component of Total Ang. Mom. (zTAM) and Momentum (p_z)





Emitted Photons are Photon Vortex (Bessel Wave)

Stron Mag. Fld ⇒ Phton Vortex ⇒ Photoreaction → Nucleosynthesis?

§ 2 Nuclear Photoreaction with Photon Vortex

Photon Vortex carrying zTAM

Its Interaction with Matter is different from that of Plane Wave Photon

Change of **Selection Rule** for **H-atom** A. Afanasev et al., PRA 88, 033841 (03)

A.Picón, et al. New J. of Phys. 12, 083053 (10)

Exp.: C.T.Schmiegelow, et al., Nat. Commun. 7, 12998 (16)

R.Lange, e al., PRL129, 253901 (22)

Photon Vortex in Super Novae

Photo-Absorption Reaction : Selection Rule is changed (?)

zTAM ($J_z \geq 2$) + OAM ($\perp$ Beam Dir.) = Total AM ($J \geq 2$)

***E1* Transition does not occur?** Influencing to Nuclear Synthesis？

Y. Taira,at al., Sci. Rep. 7, 5018 (2017).

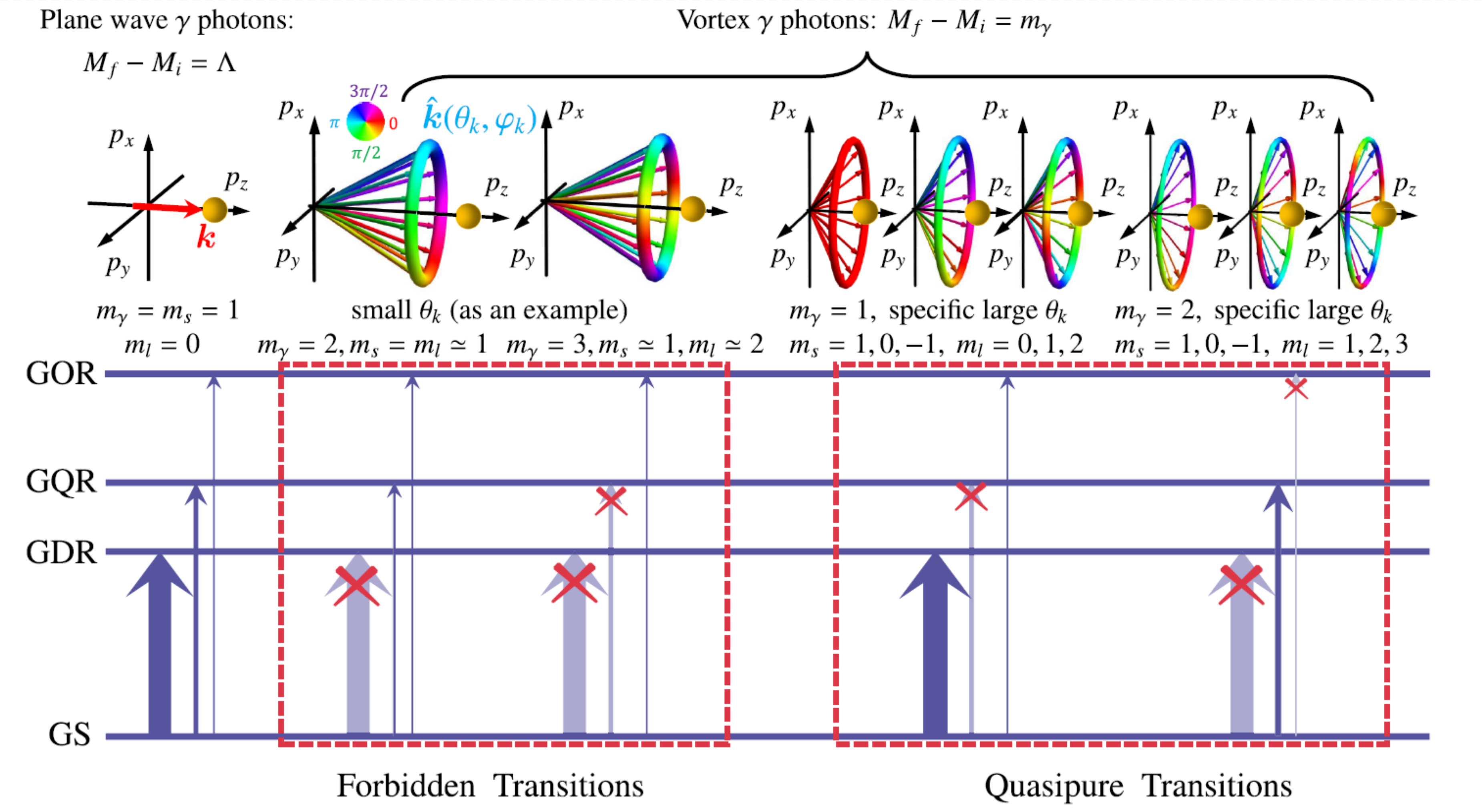
$n + p \rightarrow \gamma + d, \quad \gamma + d \rightarrow n + p$ A. Afanasev et al., J. Phys. G **45** 055102

Different Multipole of Giant Resonances, Zhi-Wei Lu et al., PRL 131, 202502 (23)

Y. Xu, et al., PLB 852,138622 (24)

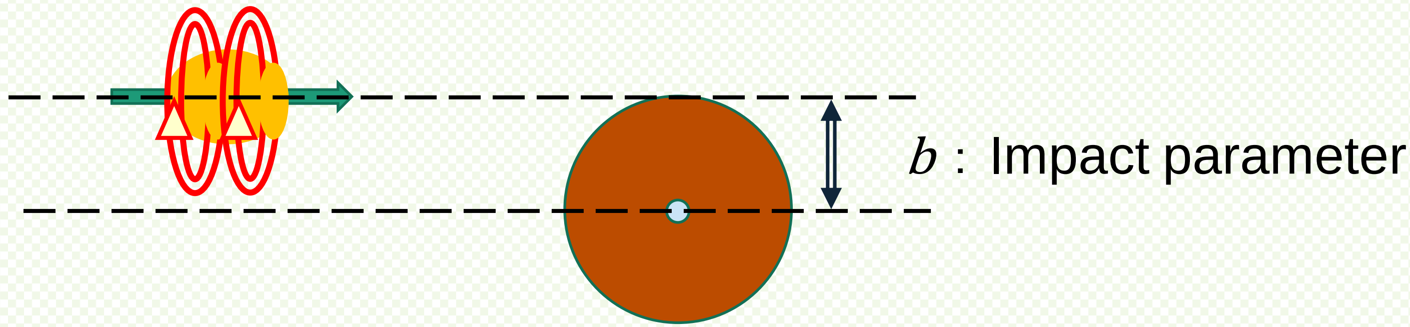
Giant Resonance States excited by Bessel Wave Photons

Zhi-Wei Lu, et al. Phys. Rev. Lett. 131, 202502 (2023)



Changing Selection Rule ⇒ Nuclear Synthesis (?)

Impact Parameter Dependence



In Previous Works, $b = 0$ or Small b

In Nature, No Restriction ⇒ Integrating Results Over b

In Lab., Dependent on Technology

Photon Vortex ⇒ Changing Selection Rule

⇒ Nuclear Synthesis (?) after averaging over b

⇒ Observing Excitation with $J \geq 3$ (?) in Lab.

Difficult to be observed at Present

§ 3 Results in Photo-Absorption with Photon Vortex

Theoretical Calculations

Target : Spin = 0 (Spherical Symmetry)

Excited Sates : Eigen States of J and J_z

Photo-Absorption ⇒ Multipole Expansion

Ratio : (Photon Vortex) / (Plane Wave Photon)

⇒ Impact Parameter Dependence

§ 3-1 Transition Strength with Plane Wave (PW)

$$\boldsymbol{e}_h e^{ie_q z} = \sum_{J=1}^{\infty} \sqrt{2\pi(2J+1)}(i)^J \left[h\boldsymbol{T}_{Jh}^{mag} + \boldsymbol{T}_{Jh}^{el} \right]$$

$$\boldsymbol{e}_h = -h(1, ih, 0)/\sqrt{2},$$

$$\boldsymbol{T}_{JM}^{mag} = j_J(e_q r)\mathcal{Y}_{JJ1}^h(\Omega_r)$$

$$\boldsymbol{T}_{JM}^{el} = -\frac{i}{e_q}\boldsymbol{\nabla} \times \left[j_J(e_q r)\mathcal{Y}_{JJ1}^h(\Omega_r) \right]$$

Trans. Amp.

$$\hat{T}_{JM}^{\kappa} \equiv \int d^3r \hat{\boldsymbol{J}} \cdot \boldsymbol{T}_{JM}^{\kappa},$$

Current Op.

$$T_{JM}^{\kappa} \equiv < J, M, \kappa | \hat{T}_{JM}^{\kappa} | 0 >$$

Excited States with (J, M)

Parity : κ

$$\boldsymbol{T}_{JM}^{\kappa} = h\boldsymbol{T}_{JM}^{mag} \quad (\kappa = (-)^J), \qquad \boldsymbol{T}_{JM}^{\kappa} = \boldsymbol{T}_{JM}^{el} \quad (\kappa = (-)^{J+1}).$$

$$T_{JM}^{\kappa} = < 00JM | JM > < J, \kappa \| \int d^3r \hat{\boldsymbol{J}} \cdot \boldsymbol{T}_{JM}^{\kappa} \| 0 > = < J, \kappa \| \hat{T}_{JM}^{\kappa} \| 0 >$$

Transition Probability

$$\mathcal{P}_{J\kappa}^{(0)} = \left| < J, h, \kappa | \int d^3r \left(\hat{\boldsymbol{J}} \cdot \boldsymbol{e}_h \right) e^{ie_q z} | 0, 0, + > \right|^2 = 2\pi \| T_{Jh}^{\kappa} \|^2$$

Only for $M = h = \pm 1$ (helicity)

Calculation in Nuclei

§ 3-2 Transition Strength with Bessel Wave

Photon Wave Func. Bessel Wave

$$\boldsymbol{A}^h_K(\boldsymbol{r}) = e^{iq_z z}\left[\frac{i(e_q + hq_z)}{2e_q}\tilde{J}_{K-1}\boldsymbol{e}_+ + \frac{i(e_q - hq_z)}{2e_q}\tilde{J}_{K+1}\boldsymbol{e}_{-1} + \frac{hq_T}{\sqrt{2}e_q}\tilde{J}_K\boldsymbol{e}_0\right]$$

$$\tilde{J}_M(q_T\boldsymbol{r}_T) = J_M(q_T r_T)e^{iM\phi}$$

Fourier Transformation

$$\boldsymbol{A}^h_K(\boldsymbol{p}) = \int d^3r e^{-i\mathbf{p}\cdot\mathbf{r}}\boldsymbol{A}^h_K(\boldsymbol{r}) = \frac{(2\pi)^2}{q_T}\delta(p_z - q_z)\delta(p_T - q_T)(-i)^{K-h}e^{i(K-h)\phi_p}\boldsymbol{e}(\boldsymbol{p}, h)$$

$$\boldsymbol{e}(\boldsymbol{p}, h) = \frac{(1 + h\cos\theta_p)}{2}e^{-i\phi_p}\boldsymbol{e}_+ + \frac{(1 - h\cos\theta_p)}{2}e^{i\phi_p}\boldsymbol{e}_- + \frac{h\sin\theta_q}{\sqrt{2}}\boldsymbol{e}_0,$$

Polarization Vector $\perp \boldsymbol{p}$

Multipole Expansion

$$\boldsymbol{e}(\boldsymbol{p}, h)e^{i\mathbf{q}\cdot\mathbf{r}} = \sum_{JM,\kappa}\sqrt{2\pi(2J+1)}(i)^J\mathcal{D}^J_{M,h}(\phi_p, \theta_p, 0)\boldsymbol{T}^\kappa_{JM},$$

Wigner D-Function

$$\mathcal{D}^J_{M,h}(\phi_p, \theta_p, 0) = \exp(-iM\phi_p)d_{Mh}(\theta_p)$$

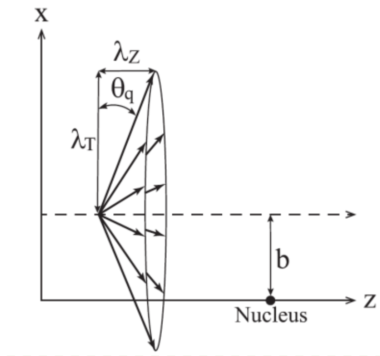
Excitation to Various ***M***

Wigner d-Matrix

Transition Strength with Bessel Wave 2

Shifting Central Axis of BW with b

$$\mathcal{A}^{Kh}_{JM\kappa}(b) = < J, M, \kappa| \int d^3r \hat{\boldsymbol{J}}(\boldsymbol{r}) \cdot \boldsymbol{A}^h_K(\boldsymbol{r} - \boldsymbol{b})|00 >$$
$$= \int \frac{d^3p}{(2\pi)^3} e^{-i\mathbf{p}\cdot\mathbf{b}} \frac{(2\pi)^2}{q_T} \delta(p_z - q_z)\delta(p_T - q_T)(i)^{J-K+h} e^{i(K-h-M)\phi_p}$$
$$\times \sqrt{2\pi(2J+1)} d^J_{M,h}(\theta_p) \|T^\kappa_J\|.$$



Transition Probability at fixed b

$$P^{Kh}_{JM\kappa}(b) = \left| \left\langle J,\, M,\, \kappa \right| \int d^3r \hat{\boldsymbol{J}}_{\text{nuc}}(\boldsymbol{r}) \cdot \boldsymbol{A}^h_K(\boldsymbol{r} - \boldsymbol{b}) \left|0,\, 0,\, + \right\rangle \right|^2$$
$$= 2\pi\, |d^J_{M,h}(\theta_q)|^2 \, [J_{M-K}(q_T b)]^2 \, \|T^\kappa_J\|^2 .$$

Ratio between PW and BW

$$R_K(b) = \sum_{M=-J}^{J} \frac{P^{Kh}_{JM\kappa}(b)}{\mathcal{P}^{(0)}_{J\kappa}} = \sum_{M=-J}^{J} |d^J_{M,h}(\theta_q)|^2 \, [J_{M-K}(q_T b)]^2$$

when $q \sim 0$, Only $(M = K)$ contributes

Actual Transition Calculation is not Needed

Transition Strength with Bessel Wave 3

Integrating over Impact Parameters

$$\mathcal{P}^{Kh}_{JM\kappa} = \frac{1}{S_T} \int d\boldsymbol{b} \left| \int d^3r < J, M, \kappa | \hat{\boldsymbol{J}}(\boldsymbol{r}) \cdot \boldsymbol{A}^h_K(\boldsymbol{r} - \boldsymbol{b}) | 0 > \right|^2$$

S_{T}: Cross-Section in System

$$S_T = \frac{2\pi}{q_T} \delta(p_T - q_T)$$

$$\mathcal{P}^{Kh}_{JM\kappa} = 2\pi \left| d^J_{M,h}(\theta_q) \right|^2 \|T^\kappa_J\|^2.$$

$$\int dr\, r J_n(qr) J_n(pr) = \frac{1}{q} \varepsilon(p - q)$$

$$\mathcal{P}^{K}_{J\kappa} = \sum_M \mathcal{P}^{Kh}_{JM\kappa} = 2\pi \|T^\kappa_J\|^2.$$

Same as that in PW

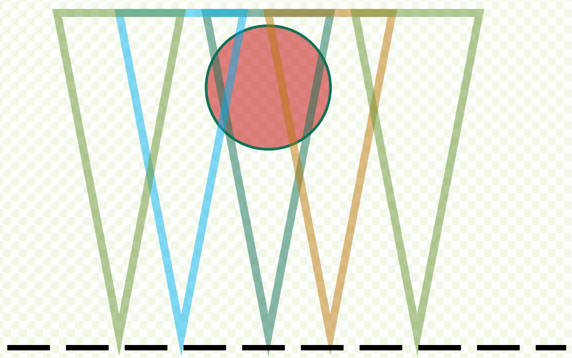
No BW Effect for Total Excitation Probability

Transition by BW Photons

Trans. Prob. ： Averaging Over Impact Parameter (IP)

$\Rightarrow$ Same Results of PW

In Nature Selection Rule is not Changed



Changing Selection Rule is Observed for Atom

Restriction for Impact Parameter in Laboratory?

Experimental Projects of Gamma-ray Vortex Generation

Can we get New Information by controlling IP in Experiments?

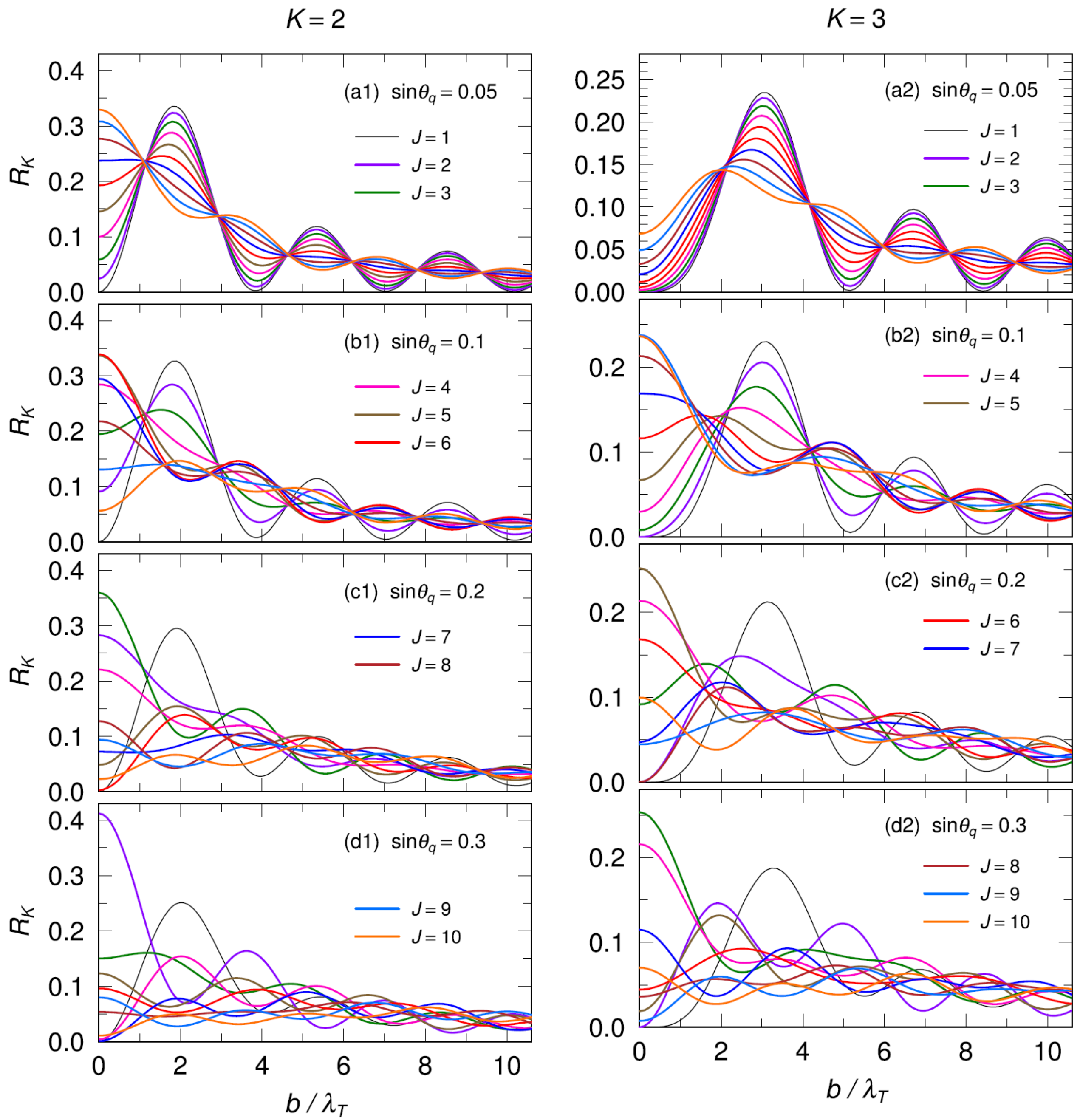
Impact Parameter (IP) Dependence

$$\frac{\text{Exc. Prob. In BW}}{\text{Exc. Prob. In PW}}$$

$$\sin\theta_q = q_T/|\boldsymbol{q}|$$

This value is fixed for BW

In small b, Contrs. from $J < K$ are small

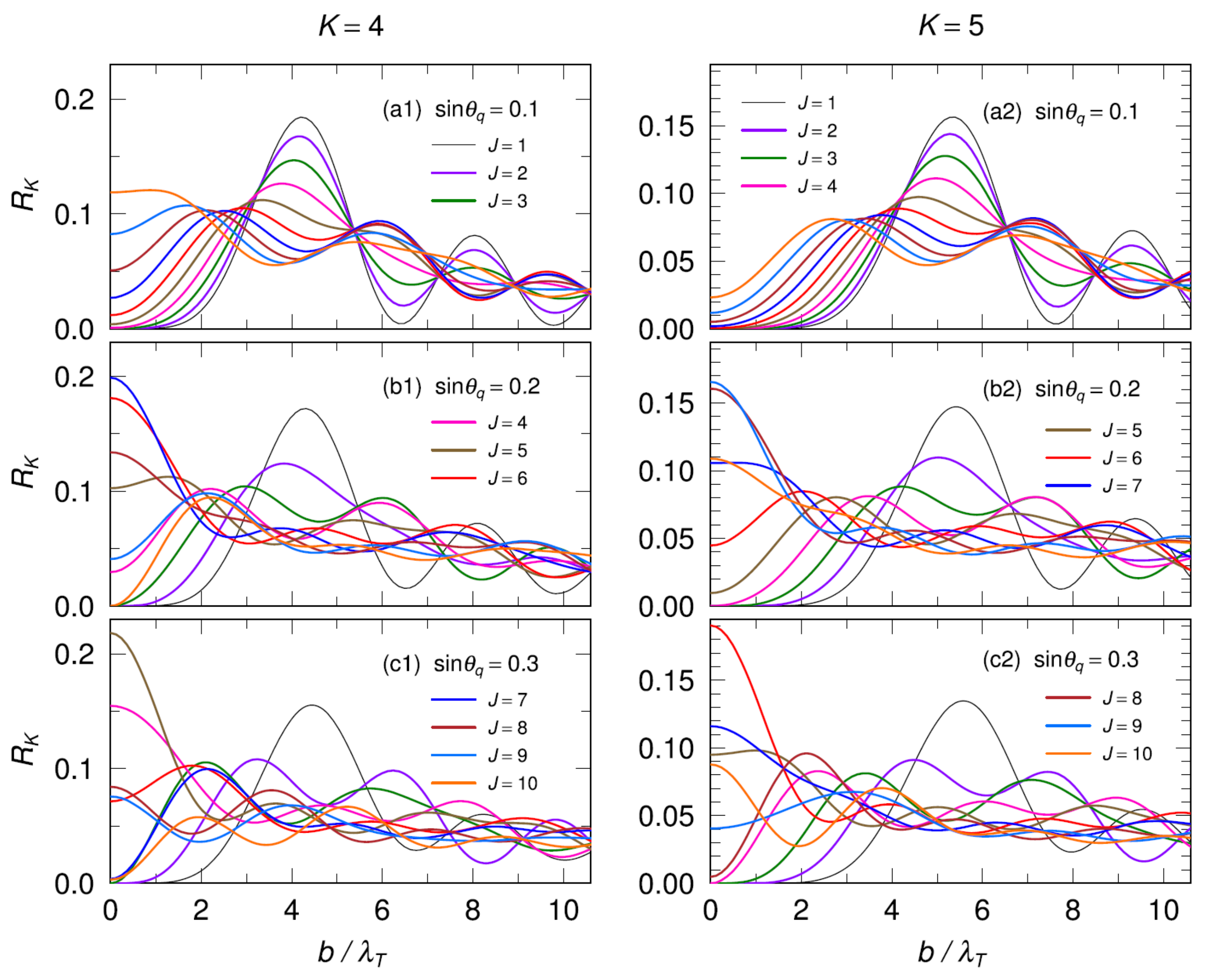


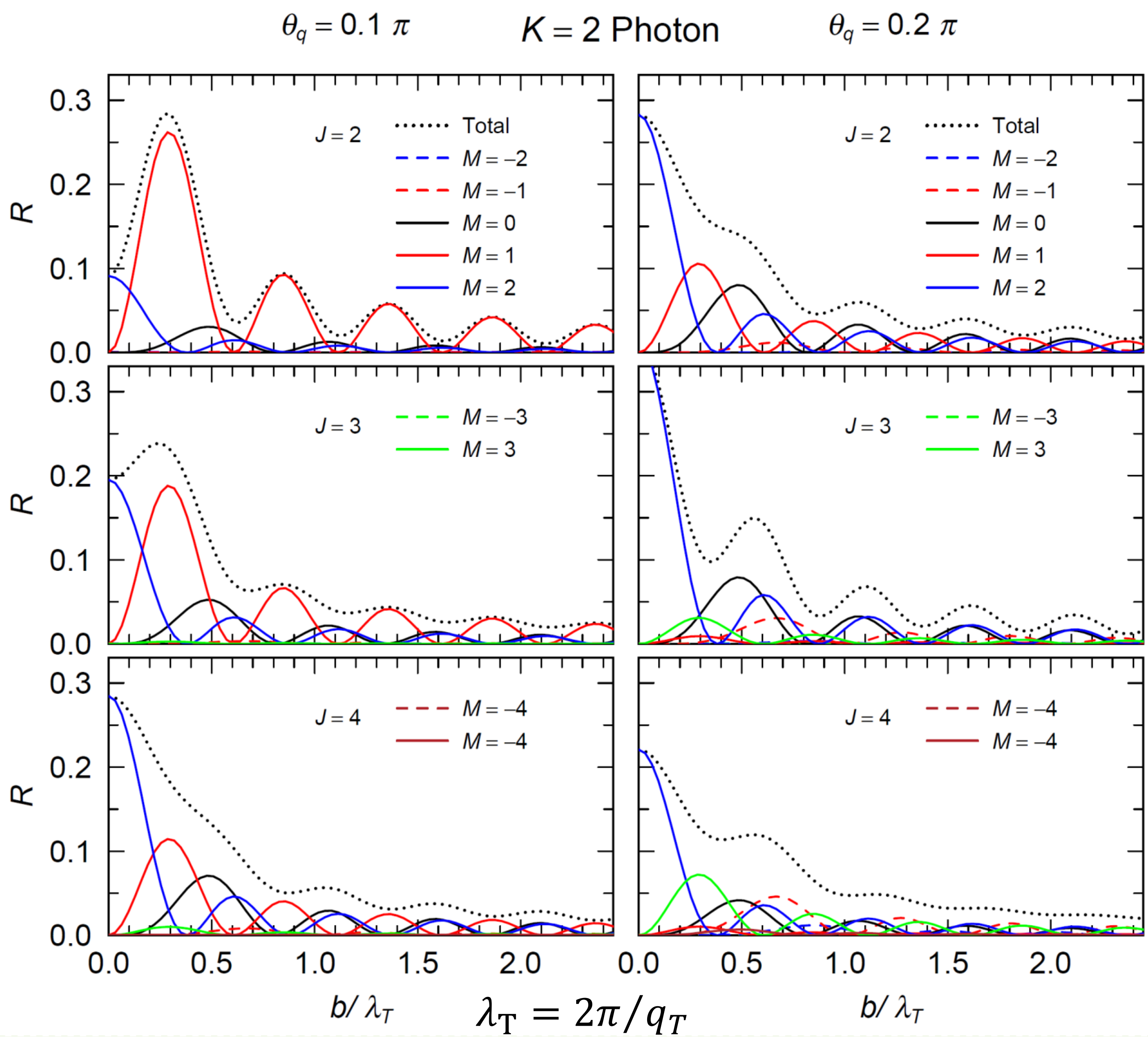
Impact Parameter (IP) Dependence

Orderly for small θ_q

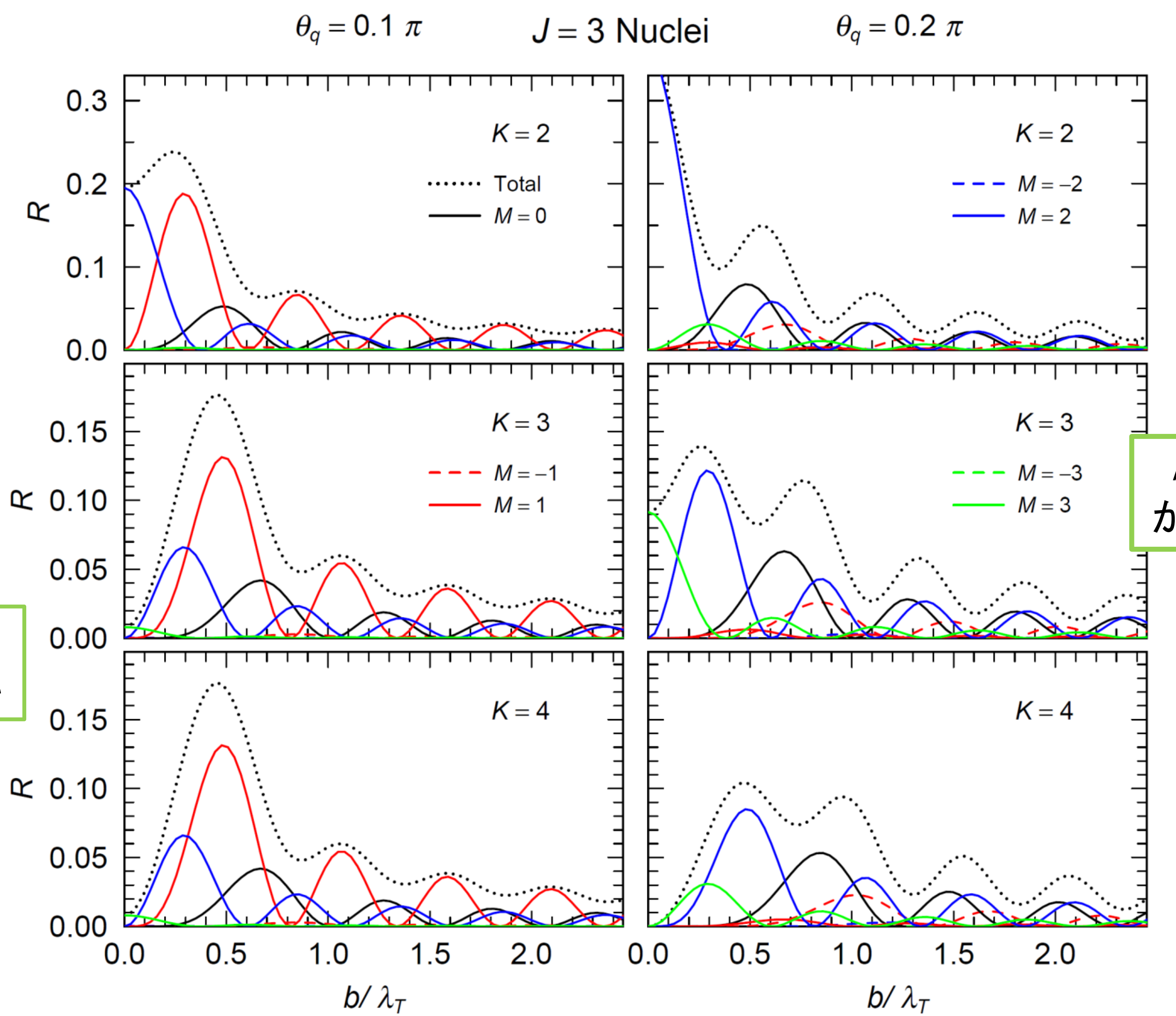
Chaos for large θ_q

Special Regularities are Hard to see.





$\theta_q = 0.1\ \pi$
$K = 2$ Photon
$\theta_q = 0.2\ \pi$
$J = 2$
Total
$M = -2$
$M = -1$
$M = 0$
$M = 1$
$M = 2$
$J = 3$
$M = -3$
$M = 3$
$J = 4$
$M = -4$
$M = -4$
R
b/λ_T
$\lambda_T = 2\pi/q_T$



$K = M$
が大きい

$K = M$
が小さい

$\lambda_{\mathrm{T}} = 2\pi / q_T$

Nuclear Photoreaction with Bessel Wave

In Nature, Selection Rule is Not Changed

IP cannot be controlled → Same in PW

BW → Various J_z, PW → Only $J_z = \pm 1$

Different Angular Distribution for Emitted Particles

Changing Selection Rule is observed for Atom with LG Wave, whose intensity distribution is concentrated around the symmetry axis.

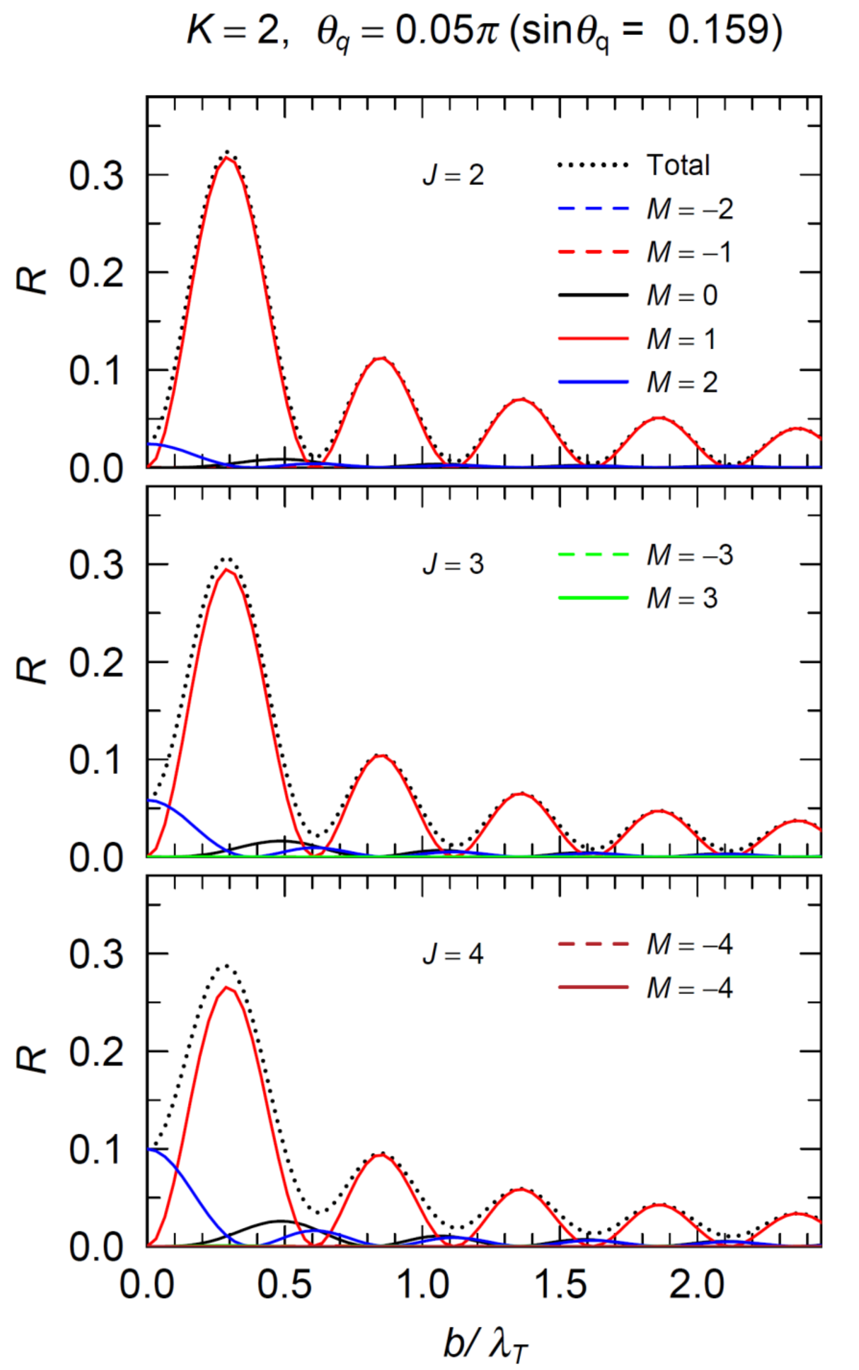
In Laboratory, BW cannot be created.

Controlling Width of LG Wave ↔ Controlling IP ?

Contributions from ($J \geq K$) are Large

We expect to find a method to observe high AM excitations that are difficult to observe with PW.

Thank You!



小さい θ_q

→ $M = 1$ のみ

平面波と同じ

§ 4 Summary

Synchrotron Radiation ⇒ **Photon Vortex** in Dir. parallel to Mag. Fld.

T.M, T. Hayakawa, M.K.Cheoun, T.Kajino, PLB826, 136779 (2022)

Nuclear Photoreaction with Bessel Wave

In Nature, IP is uncontrolled ⟶ Same in PW

Selection Rule is **Not Changed**

BW ⟶ Various J_z, PW ⟶ Only $J_z = \pm 1$

Different Angular Distribution when $\theta_q \gtrsim 0.1\pi$

Application to Experiments

1) Limiting Impact Parameter
2) Concentrating Strenghth around Symmetry Axis

Changing Selection Rule is observed for **Atom** with **LG Wave**, whose intensity distribution is concentrated around the symmetry axis.

But Nuclei are too Small (?)

Thank You!

§ 4 Summary

In Nature, Selection Rule is Not Changed

IP cannot be controlled → Same in PW

BW → Various J_z, PW → Only $J_z = \pm 1$

Different Angular Distribution for Emitted Particles

Changing Selection Rule is observed for Atom with LG Wave, whose intensity distribution is concentrated around the symmetry axis.

In Laboratory, BW cannot be created.

Controlling Width of LG Wave ↔ Controlling IP ?

Contributions from $(J \geq K)$ are Large

We expect to find a method to observe high AM excitations that are difficult to observe with PW.

Thank You!

§ 4 Summary

Electron in Strong Mag. Fld. is in Eigen State of a **Landau Level**

Eigen State of zTAM

Trans. Between two Landau Levels → 1-Photon Emission

→ **Bessel Wave** (γ-Ray Vortex with $L_z \geq 1$)

Harmonic Photons with zTAM $K \geq 2$ ($L_z \geq 1$) are Emitted

to Direction of Magnetic Field (Arctic or Antarctic)

in Different Energy Region

Synchrotron Radiation

Linear Polarization in the Dir. perpendicular to Mag. Fld.

Circular Polarization to the Dir. parallel to Mag. Fld.

\+ **Vortex Wave** in Strong Magnetic Field

This phenomena can be examined in Laboratory

T.M. et al., Phys. Rev. Res. **5**, 043289 (2023)

Giant Resonance States excited by Bessel Wave Photons 2

Y. Xu, et al., Phys. Lett. B 852,138622 (2024)

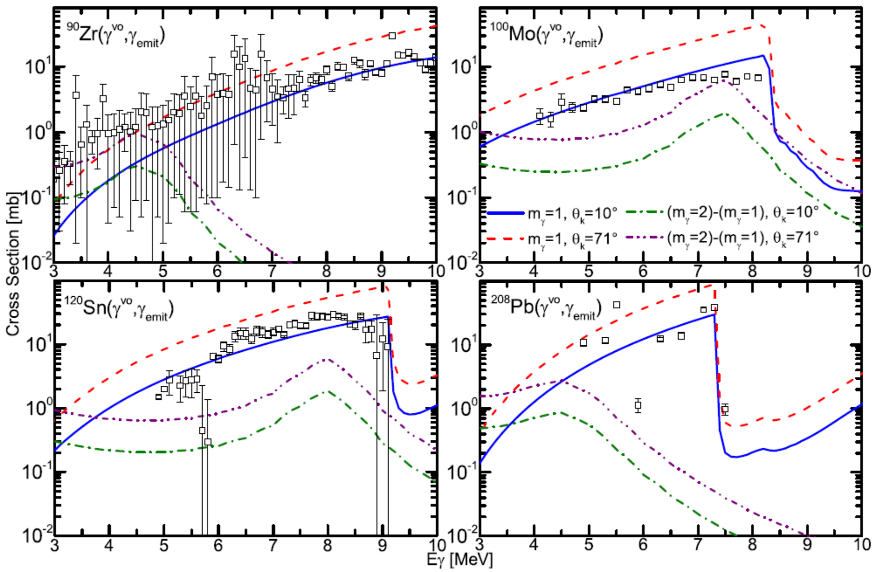


Fig. 2. The calculated cross-section $\sigma^{vo}_{\gamma_{emit}}$ $(m_\gamma = 1)$ (blue solid and red dashed lines) and the cross-section difference $\sigma^{vo}_{\gamma_{emit}}$ $(m_\gamma = 2) - \sigma^{vo}_{\gamma_{emit}}$ $(m_\gamma = 1)$ (green dash-dotted and purple dash-dot-dotted lines) for the $(\gamma^{vo}, \gamma_{emit})$ reaction on ^{90}Zr, ^{100}Mo, ^{120}Sn, and ^{208}Pb at θ_k = 10 and 71 deg, respectively. The available γ-scattering data measured by normal photons are shown for comparison.

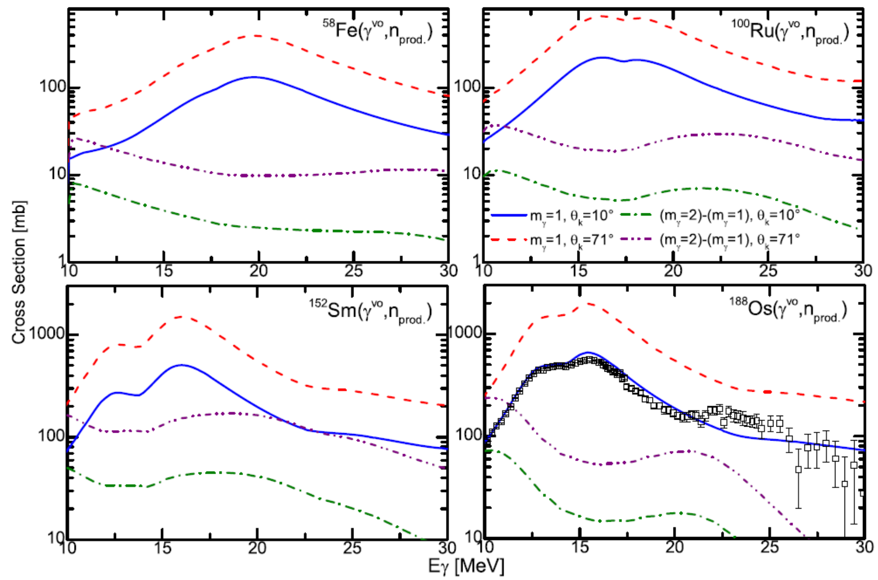


Fig. 3. The calculated cross-section $\sigma^{vo}_{n_{prod.}}$ $(m_\gamma = 1)$ (blue solid and red dashed lines) and the cross-section difference $\sigma^{vo}_{n_{prod.}}$ $(m_\gamma = 2) - \sigma^{vo}_{n_{prod.}}$ $(m_\gamma = 1)$ (green dashed-dotted and purple dashed-dotted-dotted lines) for the $(\gamma^{vo}, n_{prod.})$ reaction on ^{58}Fe, ^{100}Ru, ^{152}Sm, and ^{188}Os at θ_k = 10 and 71 deg, respectively. The experimental data of ^{188}Os$(\gamma, n_{prod.})$ are shown for comparison.

zTAM m_γ $(m_\gamma = 2) - (m_\gamma = 1)$: Significant Difference

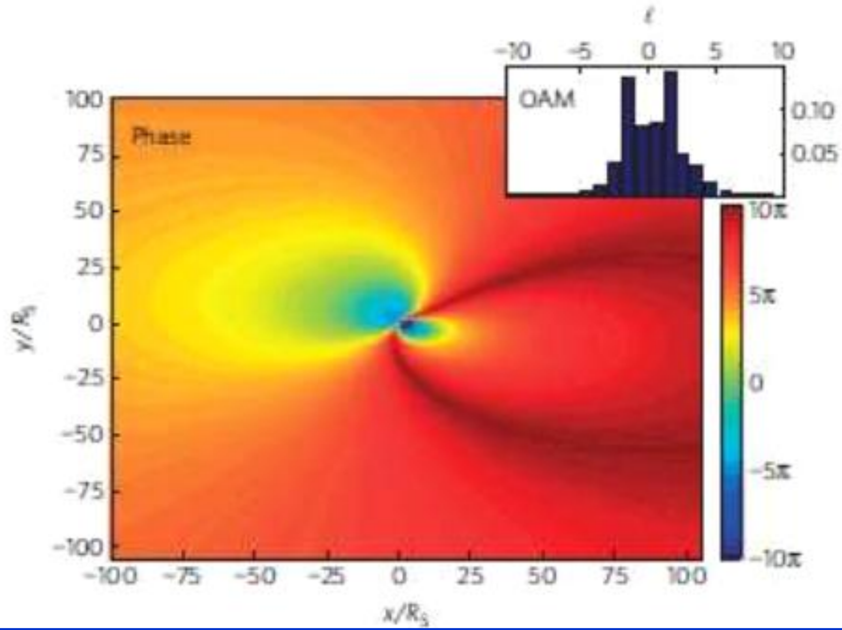
Integrated over IP, *b*, in Small Region

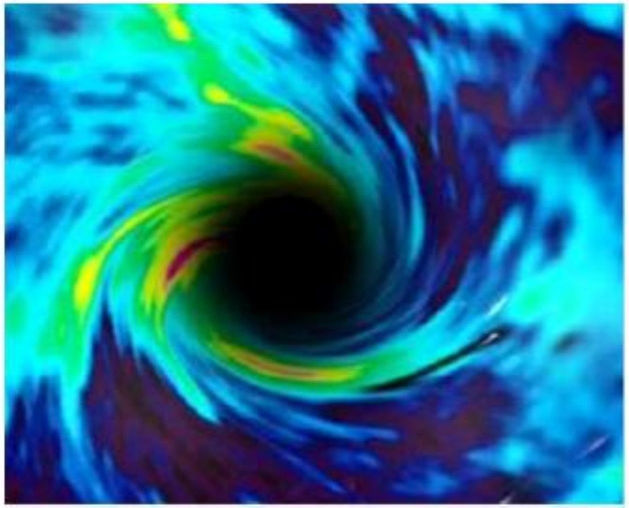
nature physics
LETTERS
PUBLISHED ONLINE: 13 FEBRUARY 2011 | DOI: 10.1038/NPHYS1907

Twisting of light around rotating black holes

Fabrizio Tamburini[1], Bo Thidé[2]*, Gabriel Molina-Terriza[3] and Gabriele Anzolin[4]

Kerr black holes are among the most intriguing predictions of Einstein's general relativity theory[1,2]. These rotating massive astrophysical objects drag and intermix their surrounding space and time, deflecting and phase-modifying light emitted near them. We have found that this leads to a new relativistic effect that imprints orbital angular momentum on such light.





Black holes put a twist on light passing by.

Fabrizio Tamburini

Optical Vortex Generation from Rotating BH

Fabrizio Tamburini et al.

Nature-Phys., Vol.7, **195 (2011)**

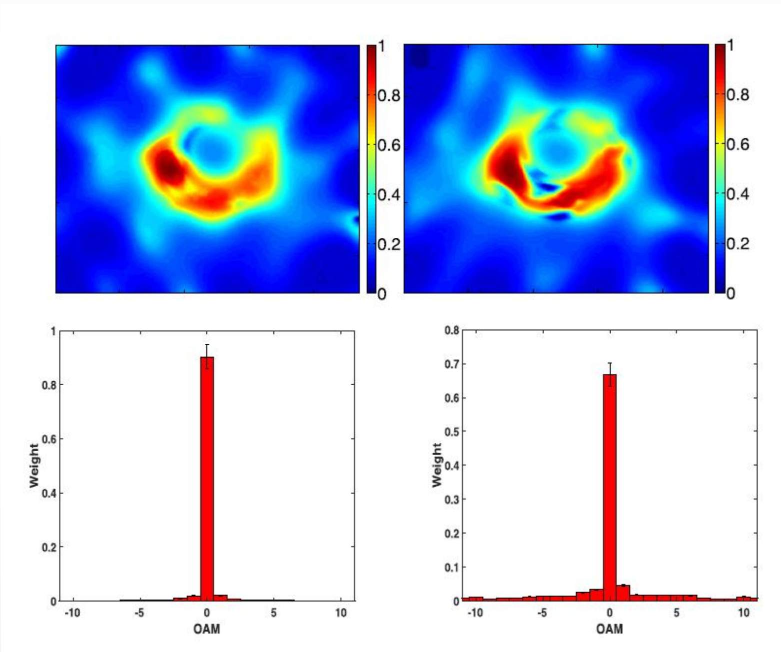
13 February 2011 | Nature | doi:10.1038/news.2011.90

Observation of Optical Vortex from Universe

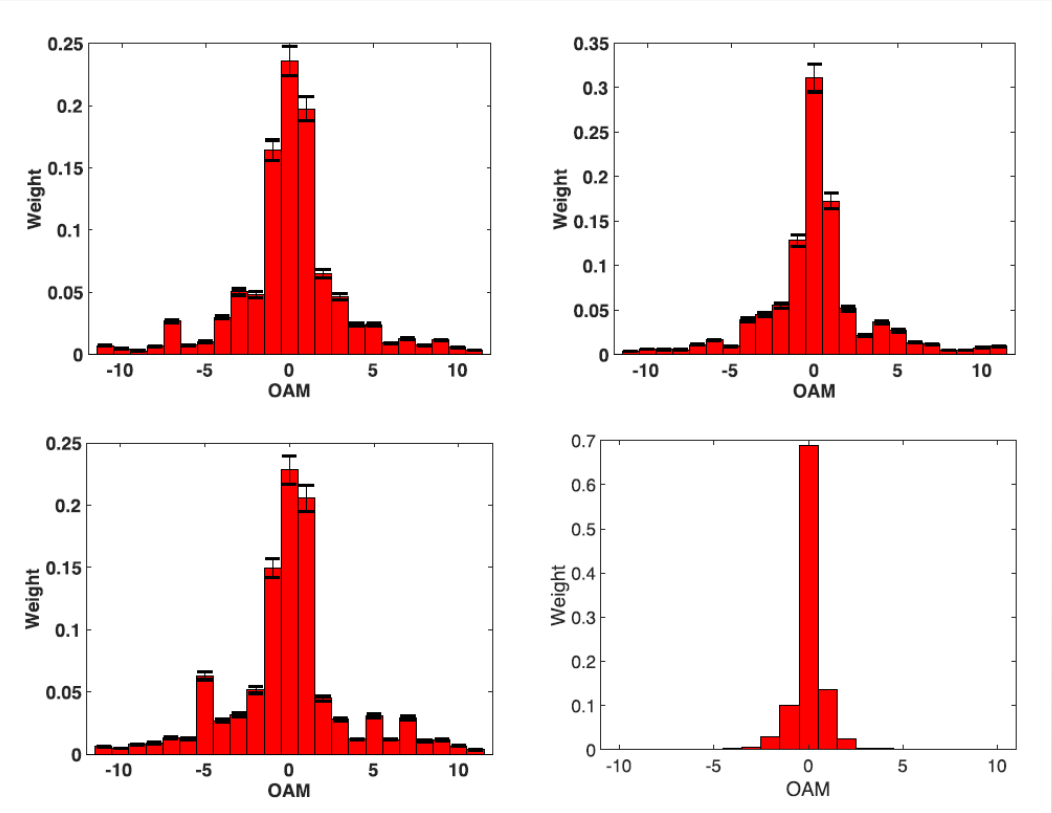
Measurement of the spin of the M87 black hole from its observed twisted light

F.Tamburini et al., MNRAS **492,** L22 (2020)

Experiment with Plasma



Observation from BH

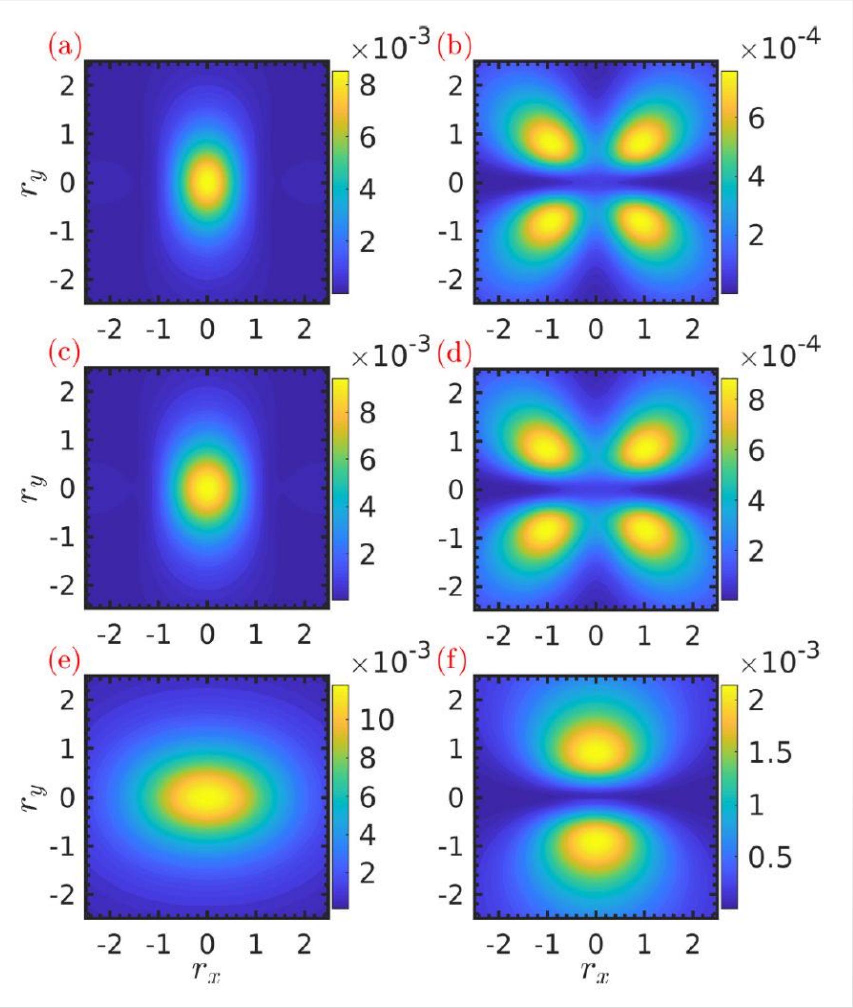


Distribution of OAM

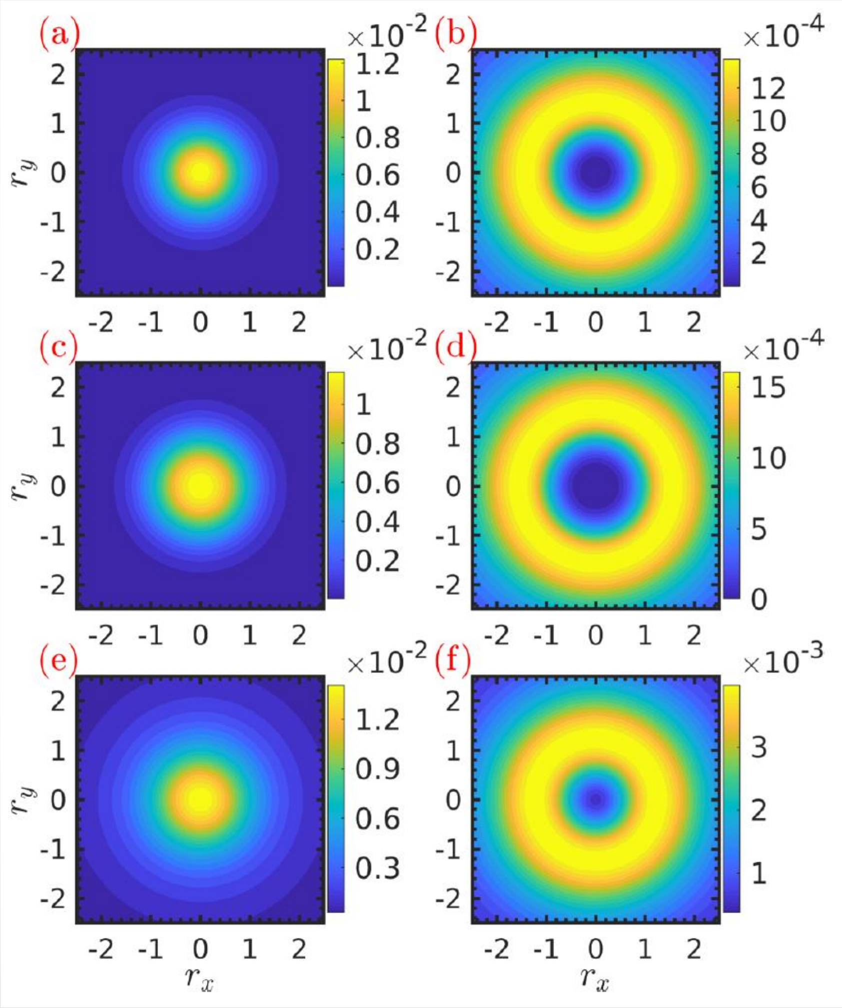
Theoretical Calculation Results

Emitted Photon Density

B.King, S.Tang, PRA **102**, 022809 (2020)

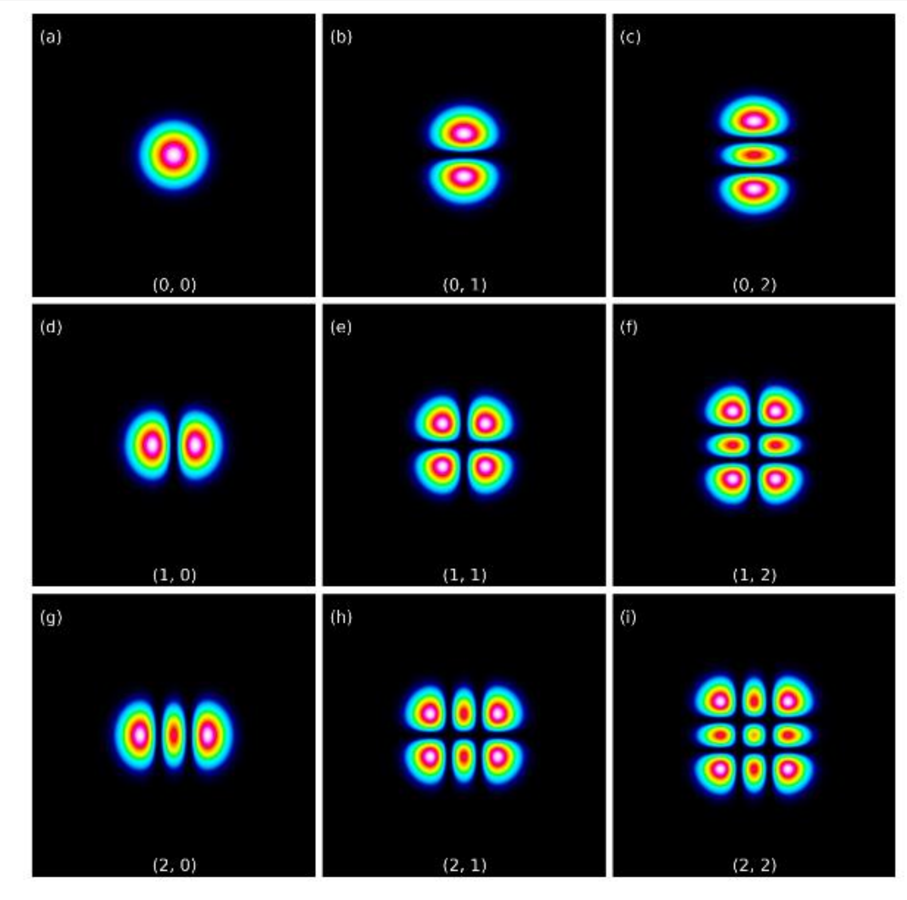


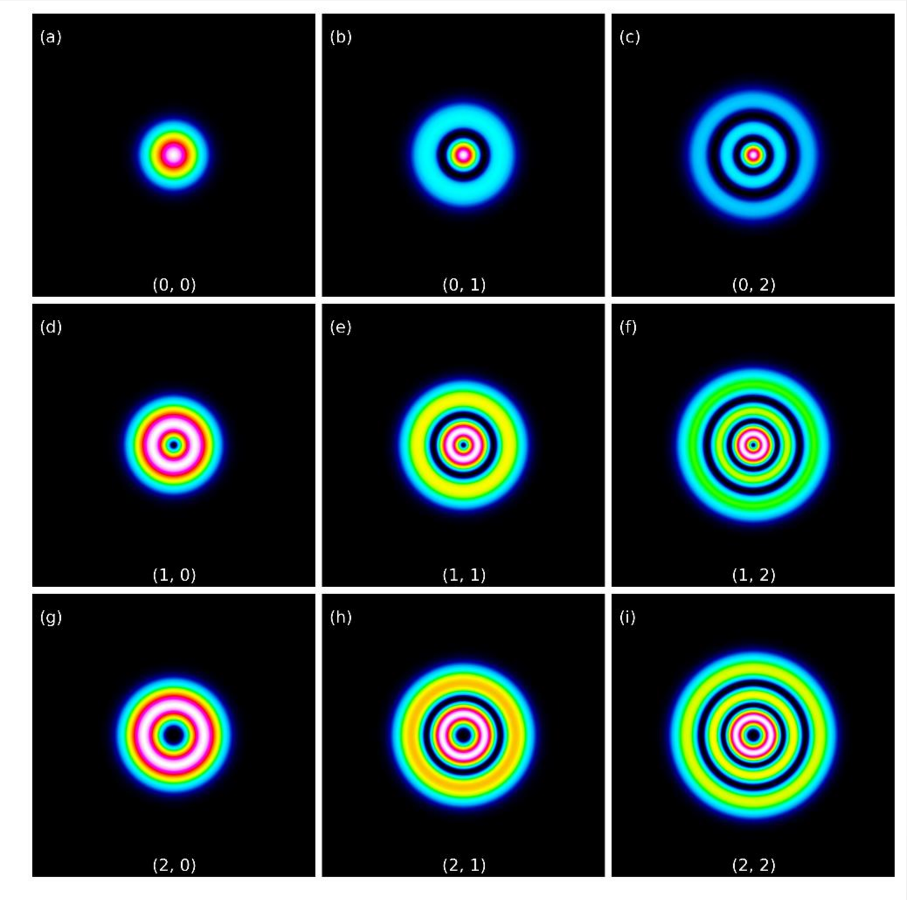
Initial Photon   Linear Polarization



Circular Polarization

Hermit-Gaussian and Laguerre-Gaussian Mode





http://www.dataray.com/blog-m2-high-order-modes.html

Shape of Wave is equivalent to tPhoton Wave Function