Photon science using gamma-ray in future linear colliders

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Delbrück scattering : non-linear effect of QED

J. Koga and T. Hayakawa, Phys. Rev. Lett. 118, 204801 (2017).

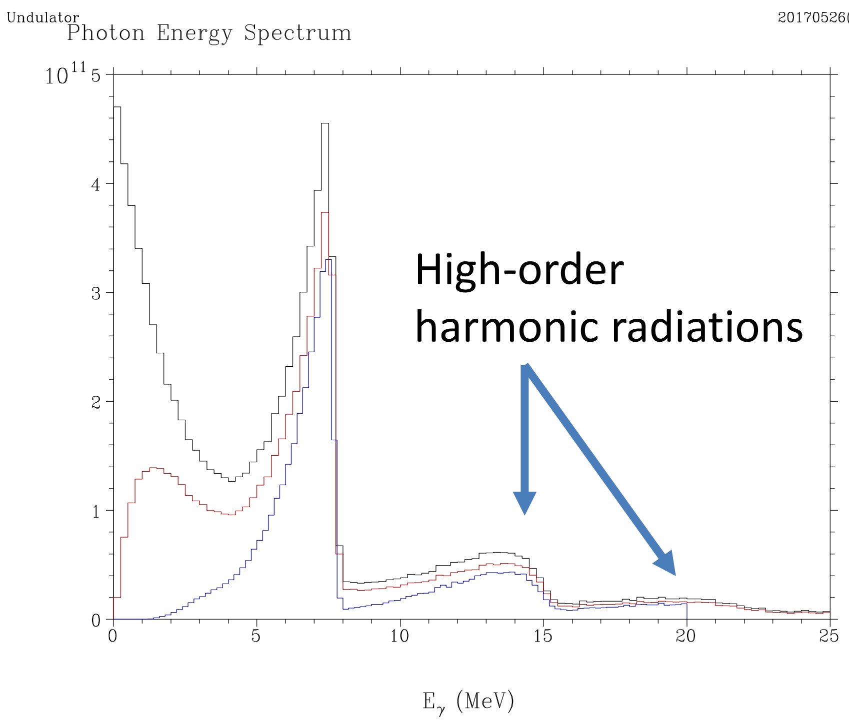
Photon vortex generation and detection : photon as the eigen state of angular moment

Y. Taira, T. Hayakawa, M. Katoh, Sci.c Rep. 7, 5018 (2017).
T. Maruyama, T. Hayakawa, T. Kajino, Sci. Rep. 9, 51 (2019)
T. Maruyama, T. Hayakawa, T. Kajino, Sci. Rep. 9, 7998 (2019)
T. Maruyama, T. Hayakawa, T. Kajino, M.-K. Cheoun, arXiv:1908.11545 [astro-ph.HE]

How generate gamma-rays in future linear colliders

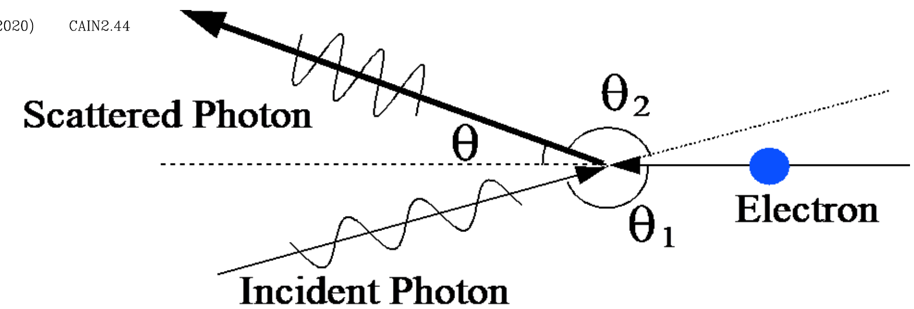
Expected gamma-ray energy spectrum from undulator to produce positrons.

Synchrotron radiations.



2017/5/31 PositronWG, Yokoya

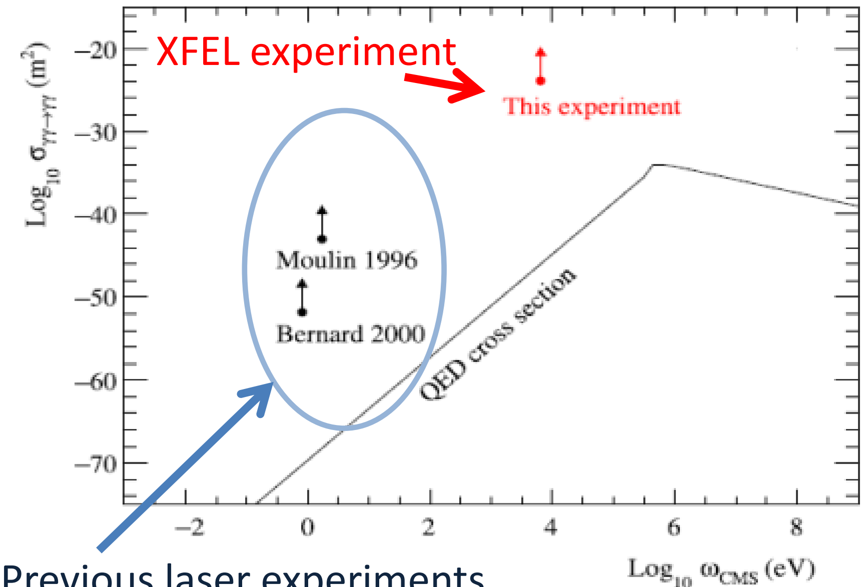
Inverse Compton scattering with laser



Non-linear inverse Compton scattering with high intense laser

Photon-photon scattering

Scattering using laser lights

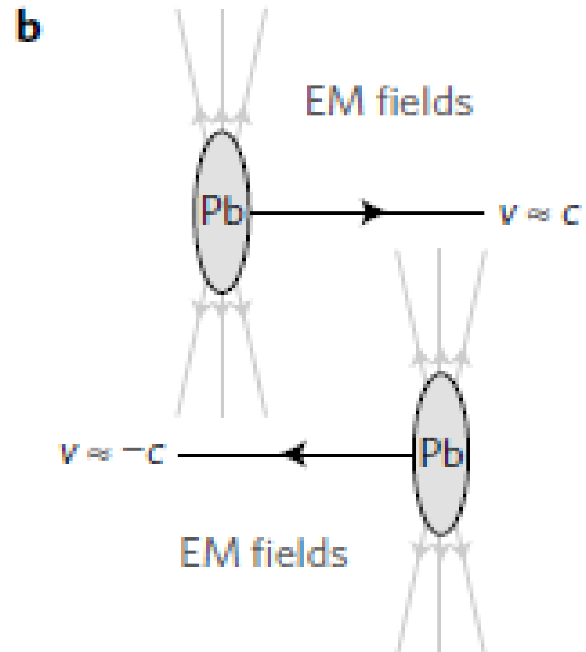


Previous laser experiments

T. Inada, Phys. Lett. B, 732, 356 (2014)
T. Yamaji, Phys. Lett. B 763, 454 (2016)

The calculated cross section is lower than experimental upper limit by about 20 orders of magnitudes.

Experiment using LHC



First measurement of virtual photon-virtual photon scattering.

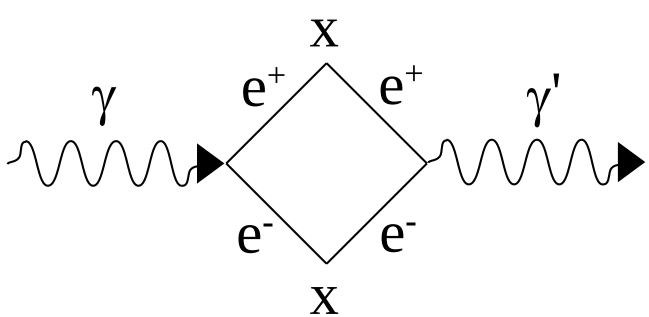
5 TeV gamma-rays with uncertainty of 25%
Only 13 events.

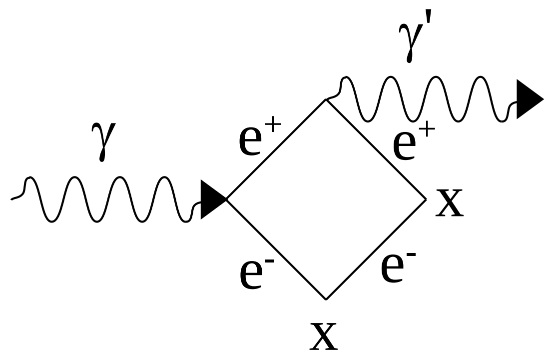
ATLAS Collaboration, Nat. Phys. 13, 852 (2017);
Phys. Rev. Lett. 123,052001 (2019) 59 events

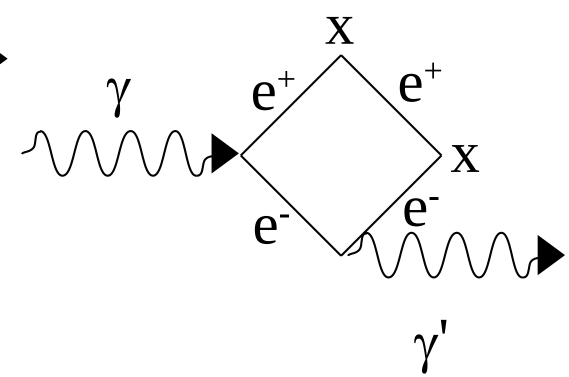
Delbrück scattering

Lowest order Feynman diagrams

X： Interaction with Coulomb filed



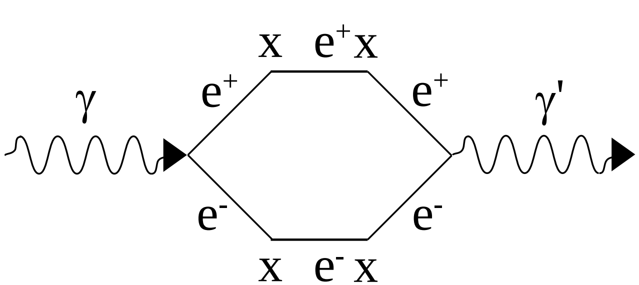


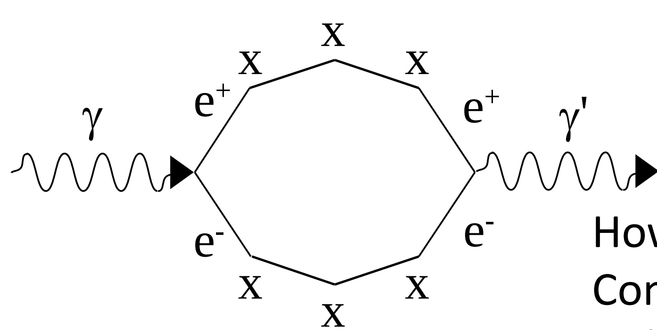


lowest order $(Z\alpha)^2$

An electron and positron pair is created by an incident photon and subsequently generate again a gamma-ray by an annihilation

Higher order Feynman Diagrams

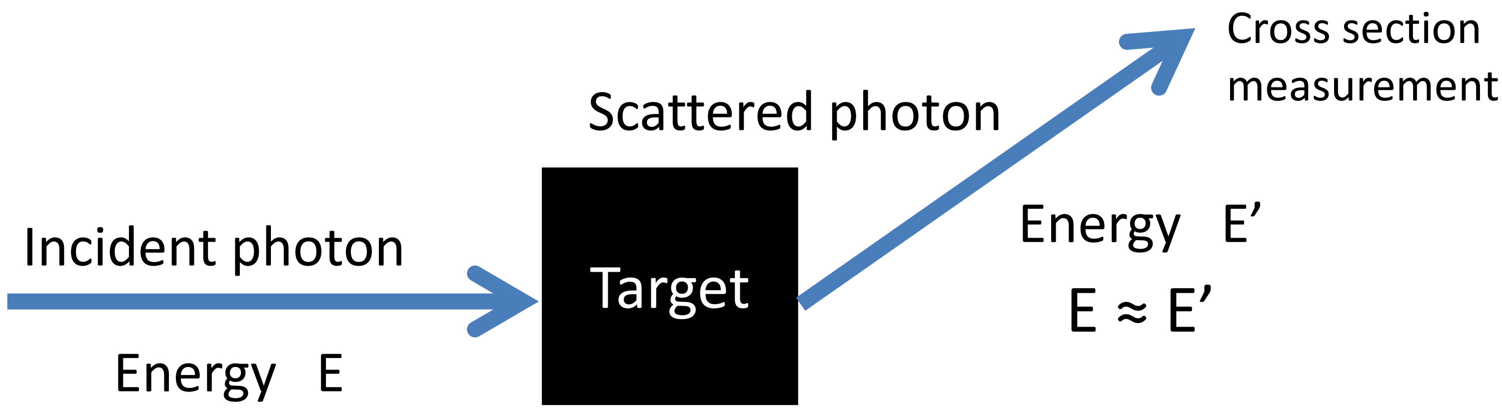




Higher order $(Z\alpha)^{2n}$ n=2,3,4

However, with the present Computing power, Delbruck scattering cannot be calculated exactly.

Elastic scattering



Experiments are very simple. Elastic scattering of gamma-rays using extremely strong radioactivity produced from nuclear reactors were measured in 1970-1990's

However, there are some elastic scattering processes

- atomic Rayleigh (R)
- nuclear Thomson (T)
- Giant Dipole Resonance (G)
- Delbrück (D)

Amplitude

$$A = A^R + A^T + A^G + A^D$$

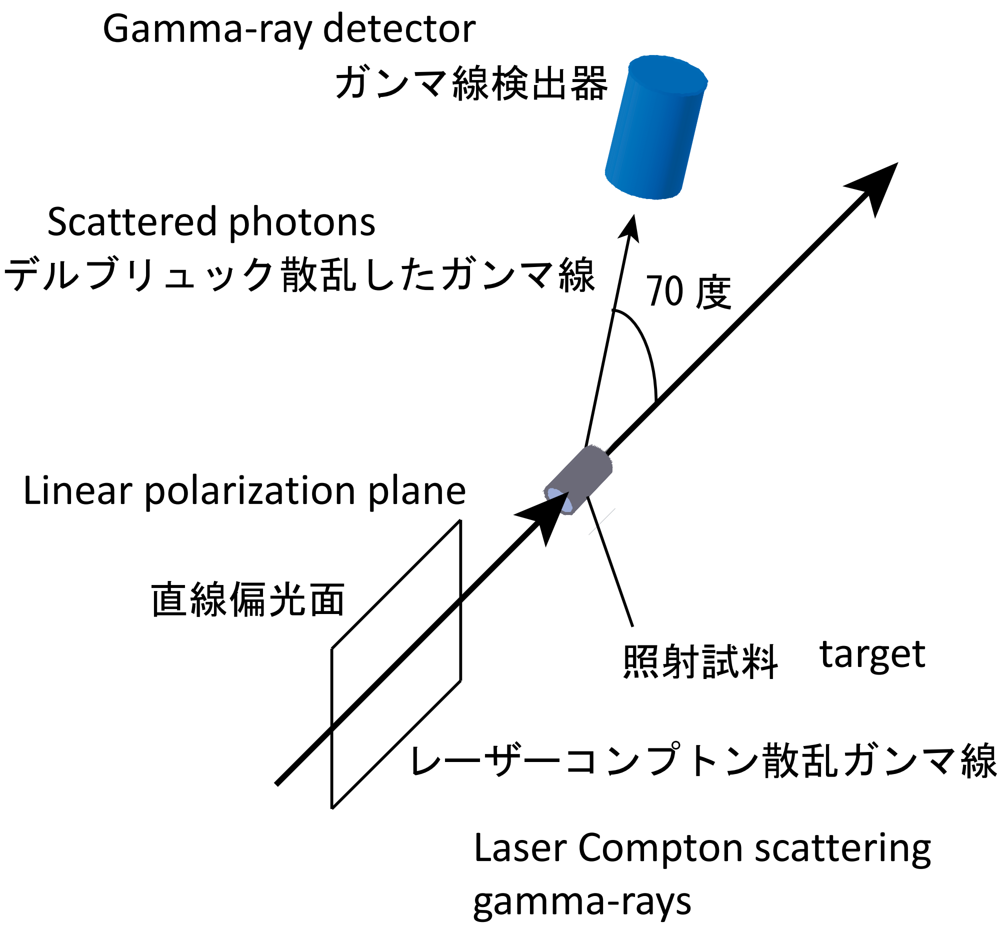
Cross section

$$\sigma \propto A^2$$

Because there is the interference between several elastic scattering, it is impossible to measure selectively the amplitude of Delbrück scattering.

Our proposal to measure the amplitude of Delbrück scattering

We have proposed the use of linearly polarized gamma-rays.



Differential cross sections depends on the angle between the scattered plane and the linear polarization plane.

We search a specific condition at which we can observe selectively the amplitude of Delbrück scattering .

J. Koga and T. Hayakawa, Phys. Rev. Lett. 118, 204801 (2017).

Calculation

・Nuclear Tomson scattering

$$A_{\perp}^{T} = -\frac{Z^2 e^2 m_e}{Mc^2}\left(1 - \frac{1}{3}k^2\langle r^2\rangle\right),$$

$$A_{\parallel}^{T} = A_{\perp}^{N}\cos\theta,$$

・Giant Dipole Resonance in nuclei

$$A_{\perp}^{\mathrm{GDR}} = \frac{E^2}{4\pi\hbar c r_e}\sum_{j=1}^{2}\sigma_j\Gamma_j\frac{E_j^2 - E^2}{(E_j^2 - E^2)^2 + E^2\Gamma_j^2},$$

$$A_{\parallel}^{\mathrm{GDR}} = A_{\perp}^{\mathrm{GDR}}\cos\theta,$$

Well known

・Rayleigh scattering

Approximation:
The second order s-matrix calculation

At present, there is no researcher for Rayleigh scattering. The last researcher, L. Kissel, was retired 20 years ago.
We obtained the code from L. Kissel.

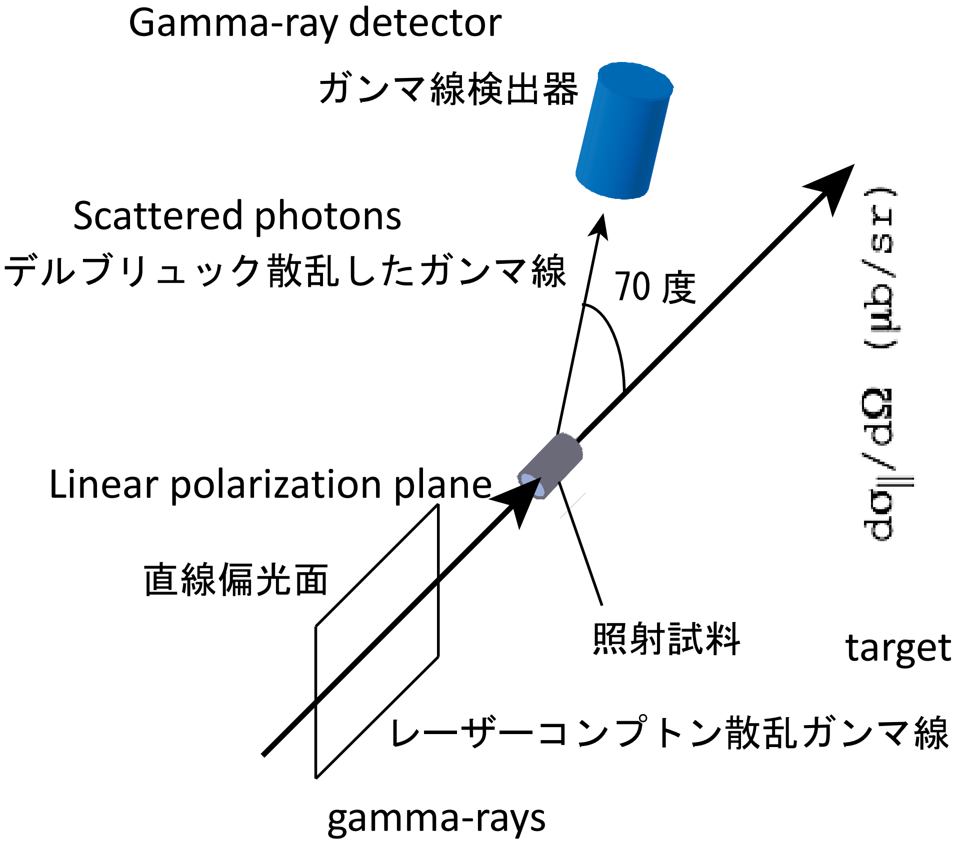
・Delbrück scattering

Calculation using the approximation proposed by B. De Tollis.

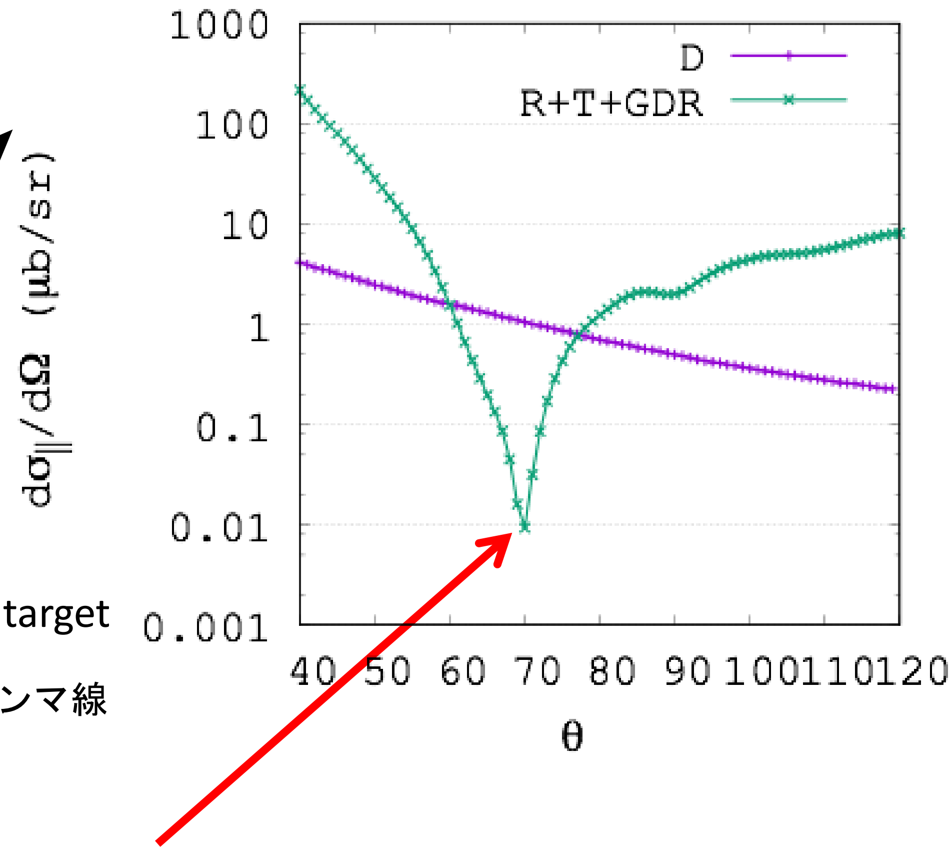
The model was made to reproduce the experimental data.

Proposal of a new experiment

Proposed experiment



Cross sections



If we use a linearly polarized gamma-rays as the incident beam, we can selectively measure the cross section of the Delbruck scattering at 70 degree.

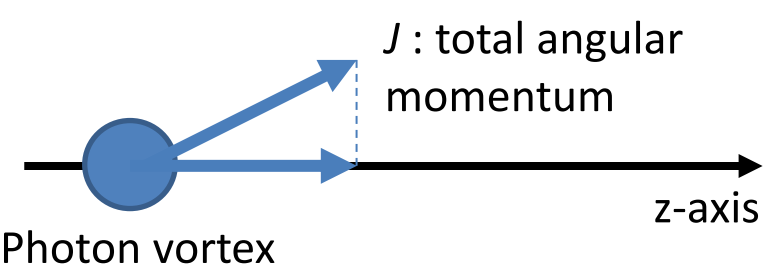
J. Koga and T. Hayakawa, Phys. Rev. Lett. 118, 204801 (2017).

Light vortex and photon vortex

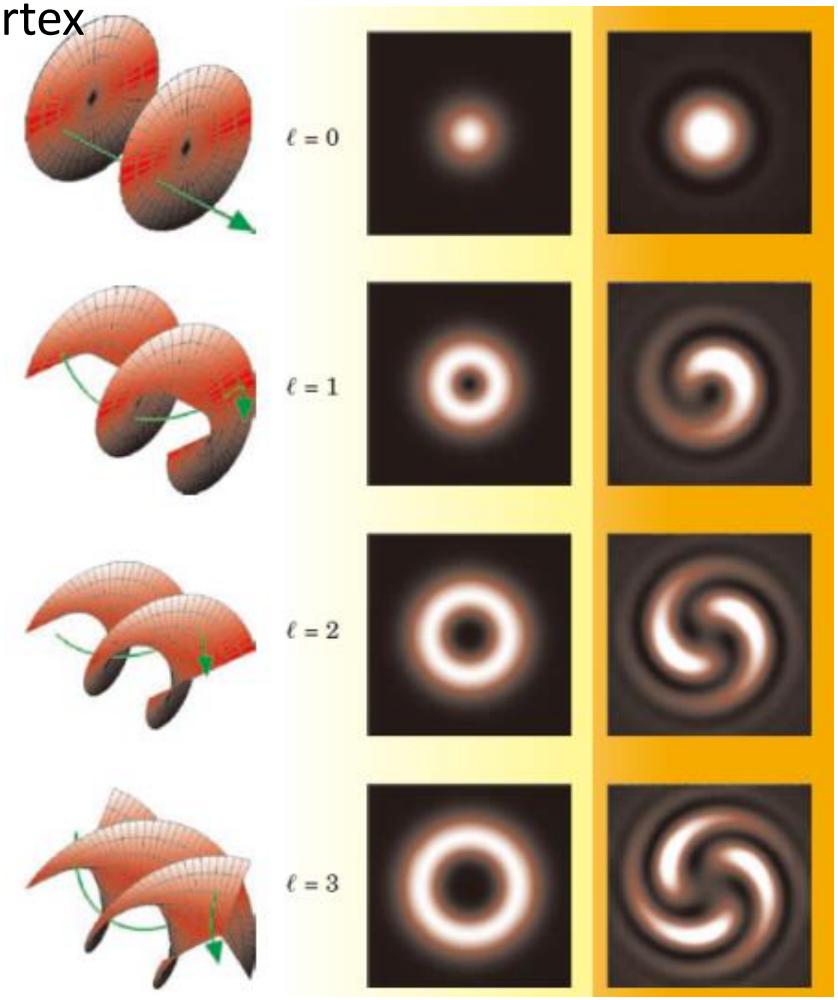
L. Allen, et al. Phys. Rev. A, 45, 8185 (1992)

They showed that “photon vortex” in addition to “light vortex” can be generated.

The wavefunction of photon vortices is the eigen states of z-component of the total angular momentum when the photon propagates along z-axis.



Light vortex

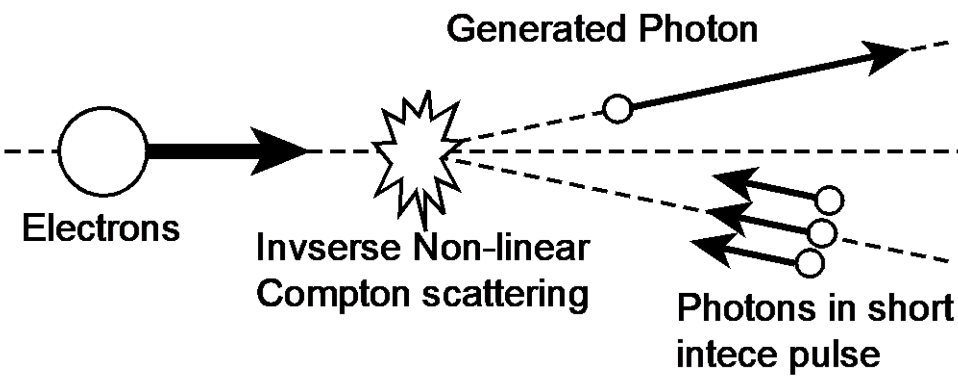


M. Padgett et al., Phys. Today 57 (2004) 35

Light vortex generation by Non-linear inverse Compton scattering

Proposal of photon vortex generation by non-linear inverse Compton scattering with circularly polarized intense laser pulse

Y. Taira, T. Hayakawa, M. Katoh,
Scientific Reports, 7, 5018 (2017).

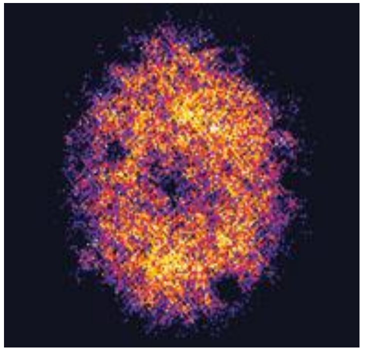


Calculation by classical electromagnetism

Y. Chen, et al. Phys. Rev. Lett. 121, 074801 (2018)
Semi-classical calculation
with simulation

Y. Sakai, et al. Phys. Rev. STAB, 18, 060702 (2015)

Non-linear inverse Compton experiment



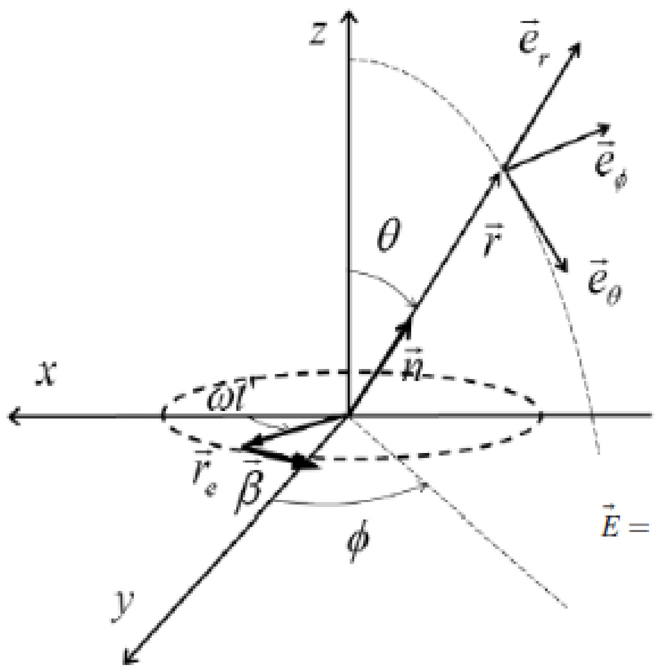
BNL ATF
+
CO2 laser

Observation of 2nd harmonics

However, in quantum theory, this problem has been unresolved.

Light vortex generation by synchrotron radiation

M. Katoh, et al. Phys. Rev. Lett. 118, 094801 (2017).
Angular Momentum of Twisted Radiation from an Electron in Spiral Motion



$$\vec{E} = E_{lx}^{(1)}\vec{e}_x + E_{ly}^{(1)}\vec{e}_y + E_{lz}^{(1)}\vec{e}_z = \frac{(E_{lx}^{(1)} - iE_{ly}^{(1)})}{\sqrt{2}}\frac{\vec{e}_x + i\vec{e}_y}{\sqrt{2}} + \frac{(E_{lx}^{(1)} + iE_{ly}^{(1)})}{\sqrt{2}}\frac{\vec{e}_x - i\vec{e}_y}{\sqrt{2}} + E_{lz}^{(1)}\vec{e}_z$$

$$\equiv E_{l+}^{(1)}\vec{e}_+ + E_{l-}^{(1)}\vec{e}_- + E_{lz}^{(1)}\vec{e}_z = \frac{e}{c} l\omega \frac{e^{i(kr-l\omega t)}}{r}\begin{pmatrix} \left\{\frac{\cos^2\theta}{\sin\theta} J_l(l\beta\sin\theta) + \beta J_l'(l\beta\sin\theta)\right\} e^{i(l-1)\varphi}\vec{e}_+ \\ +\left\{-\frac{\cos^2\theta}{\sin\theta} J_l(l\beta\sin\theta) + \beta J_l'(l\beta\sin\theta)\right\} e^{i(l+1)\varphi}\vec{e}_- \\ -i\cos\theta J_l(l\beta\sin\theta) e^{il\varphi}\vec{e}_z \end{pmatrix}.$$

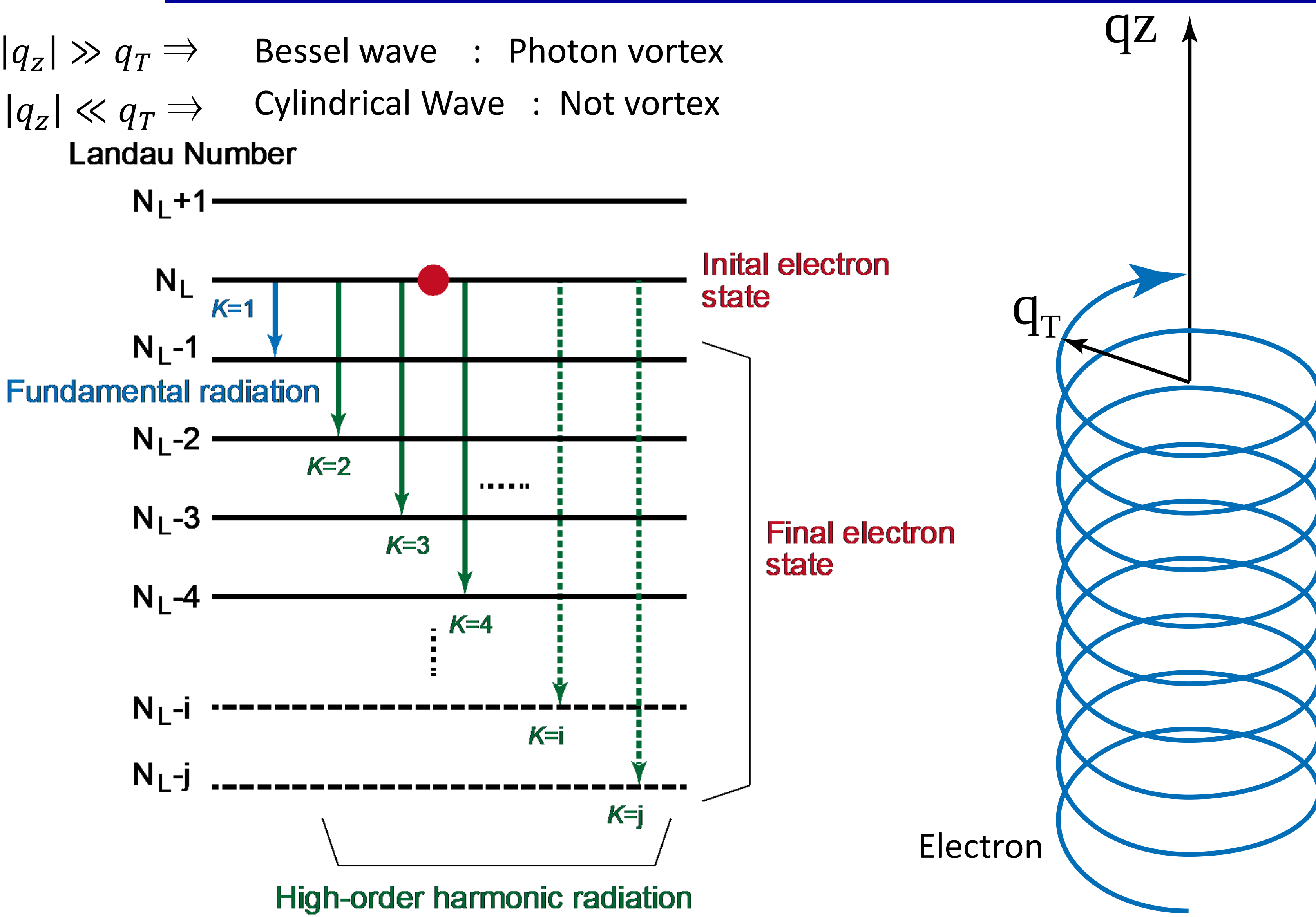
The average angular momentum per photon was calculated suing classical electromagnetism. The result suggests that photon generated by high-order harmonic radiations may be photon vortex.

However, this problem has not been resolved in Landau quantization.

Photon vortex generation by High-order harmonic radiation

$|q_z| \gg q_T \Rightarrow$ Bessel wave : Photon vortex

$|q_z| \ll q_T \Rightarrow$ Cylindrical Wave : Not vortex



T. Maruyama, T. Hayakawa, T. Kajino, M.-K. Cheoun, arXiv:1908.11545 [astro-ph.HE]

Obtained wave-function of emitted photon

$$\boldsymbol{\nabla} \cdot \boldsymbol{A} = 0$$

$$\boldsymbol{A}_{Lh}(\boldsymbol{r}; q_z, k) \propto e^{i(q_z z - e_q t)} \left[q_z J_L(q_T r) e^{iL\phi}, ihq_z J_L(q_T r) e^{iL\phi}, \underline{ihq_T J_{L+h}(q_T r) e^{i(L+h)\phi}} \right]$$

We take two states as eigen states

$$\boldsymbol{A}(h = +1) - \boldsymbol{A}(h = -1) \quad \text{State-1}$$

$$\boldsymbol{A}(h = +1) + \boldsymbol{A}(h = -1) \quad \text{State-2}$$

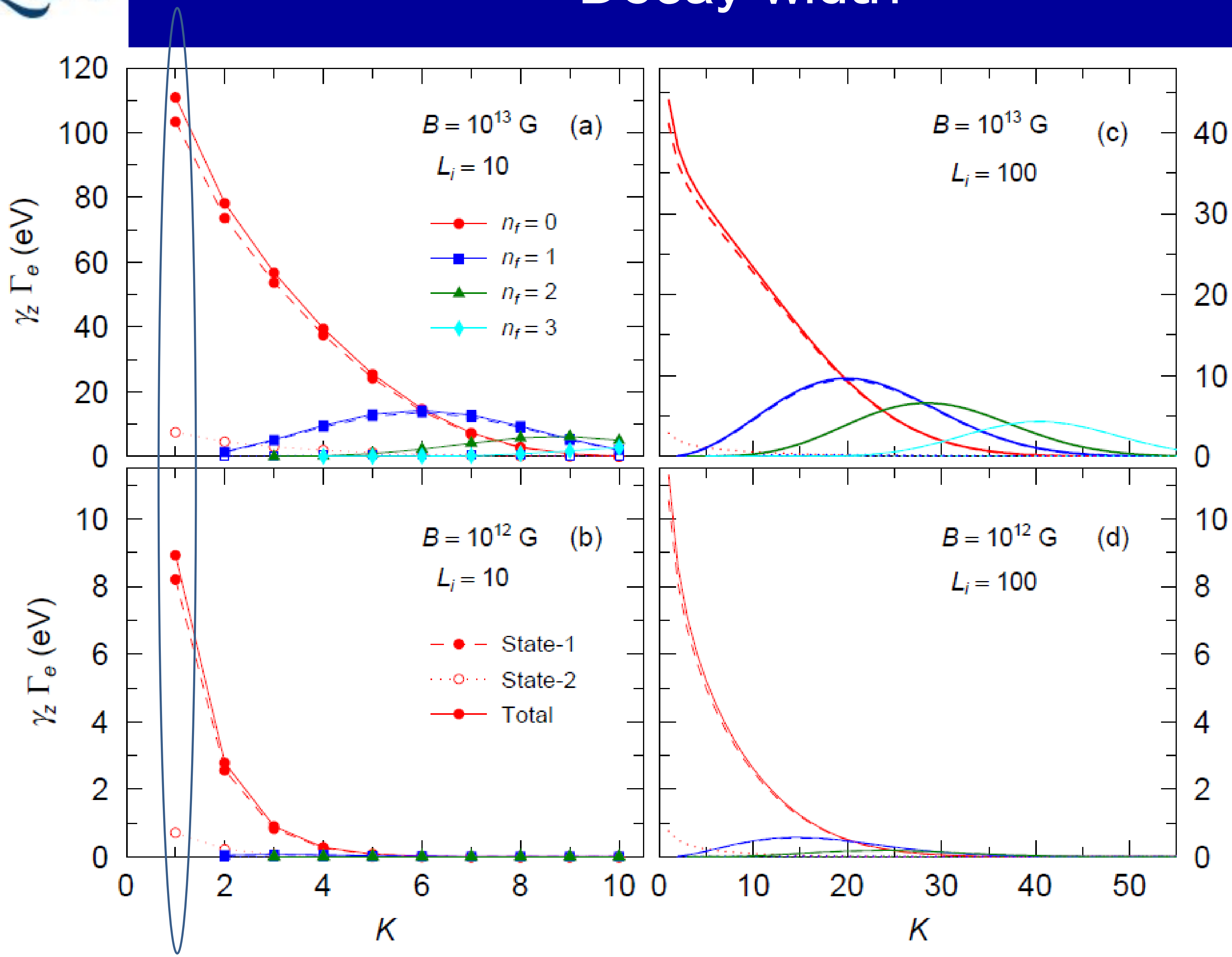
Final photon wave-functon

$$\boldsymbol{A}^{(1)}_K = \frac{1}{2e_q} e^{i(q_z z - e_q t)} \left[iq_z \left(\tilde{J}_{K+1} - \tilde{J}_{K-1} \right), q_z \left(\tilde{J}_{K+1} + \tilde{J}_{K-1} \right), 2q_T \tilde{J}_K \right]$$

$$\boldsymbol{A}^{(2)}_K = \frac{1}{2} e^{i(q_z z - e_q t)} \left[i \left(\tilde{J}_{K+1} + \tilde{J}_{K-1} \right), \left(\tilde{J}_{K+1} - \tilde{J}_{K-1} \right), 0 \right],$$

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

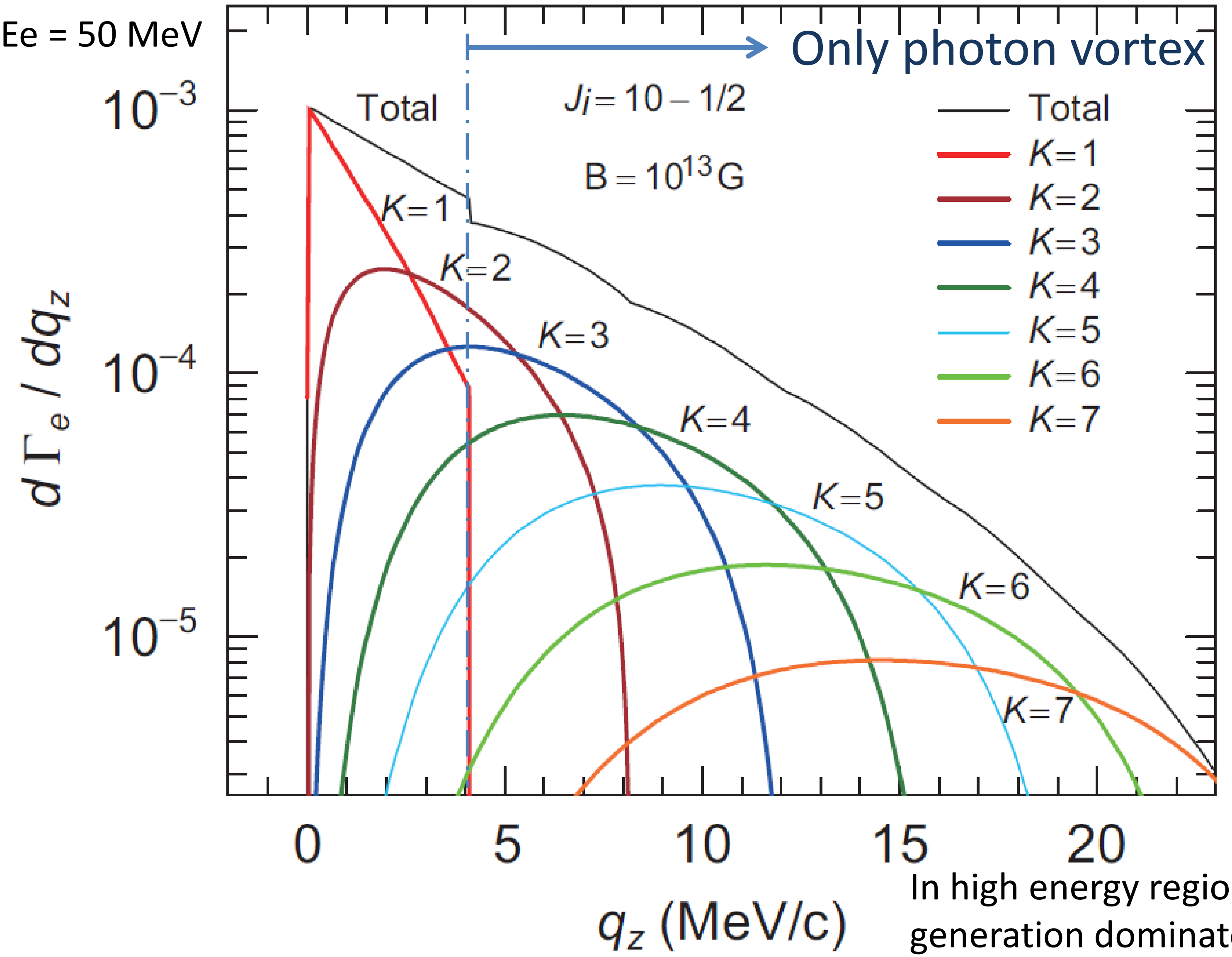
Decay width



K = 1 : Fundamental radiation

Energy spectrum

Ee = 50 MeV

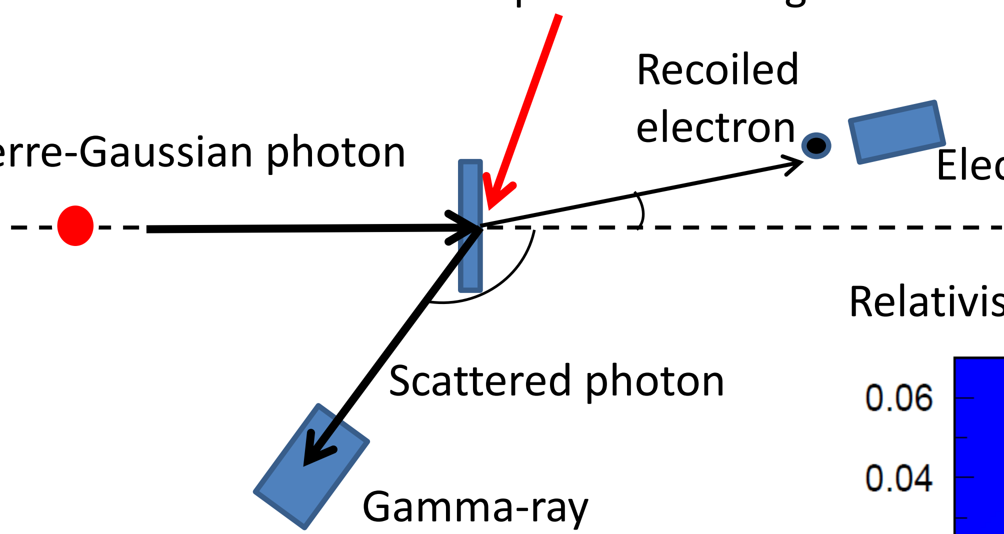


In high energy region, photon vortex generation dominates.

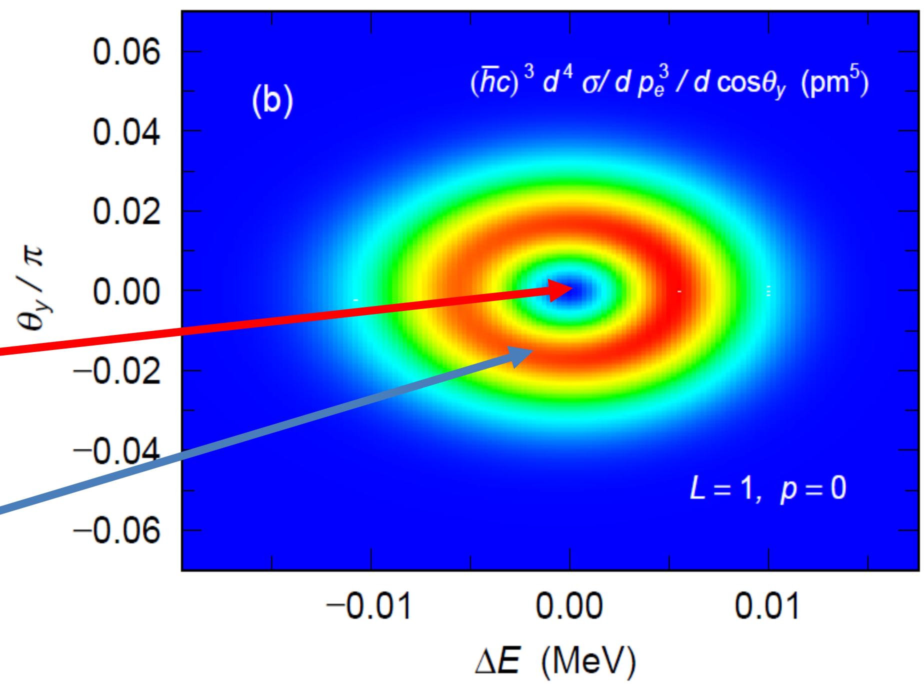
T. Maruyama, T. Hayakawa, T. Kajino, M.-K. Cheoun, arXiv:1908.11545 [astro-ph.HE]

Identification of photon vortex using Compton scattering

Coincidence measurement of scattered photon and electron from Compton scattering



Relativistic quantum mechanics calculation

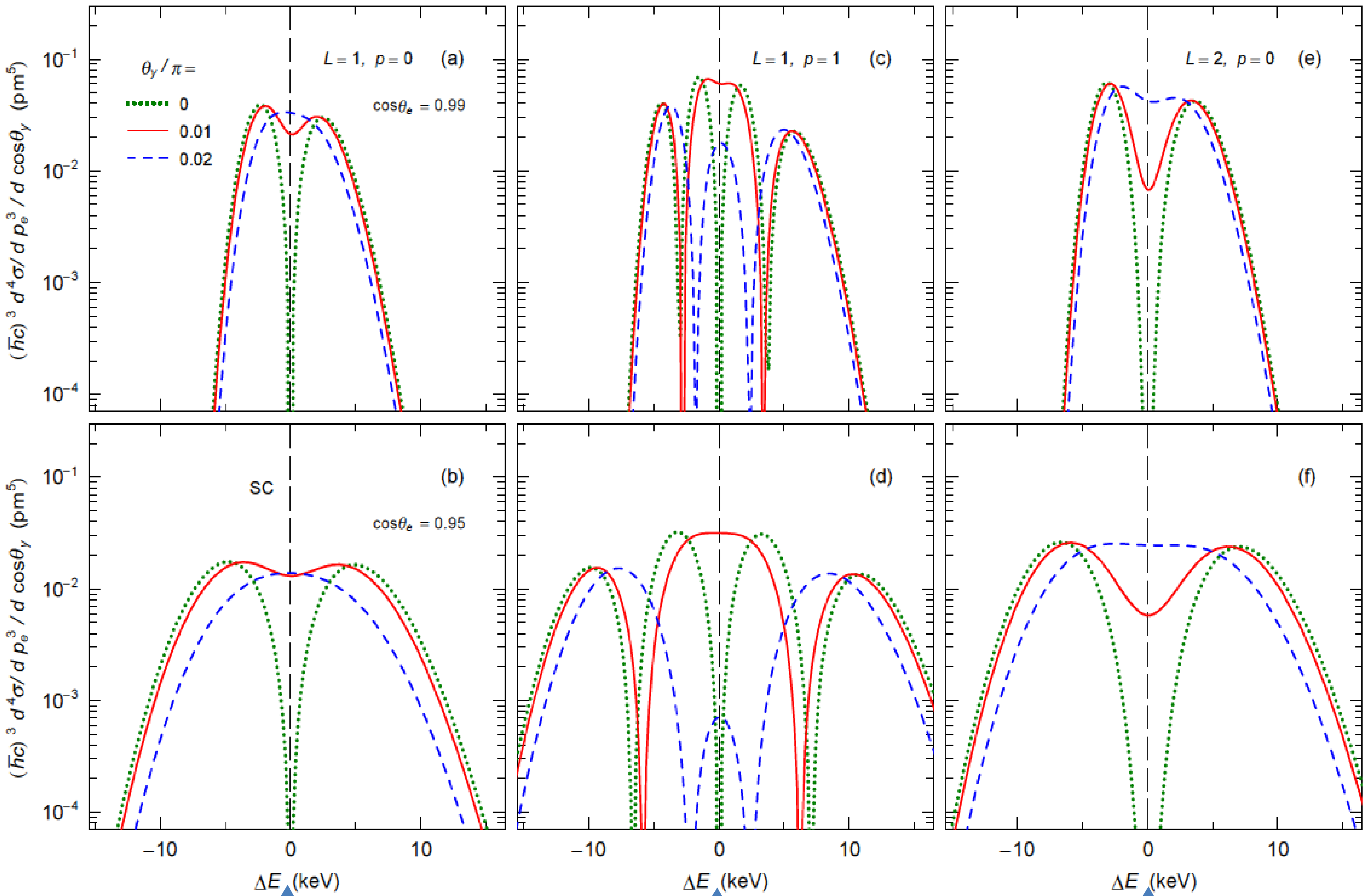


Plane wave photon

Energy and/or scattered angle for LG photon shifts from that for plane wave photon.

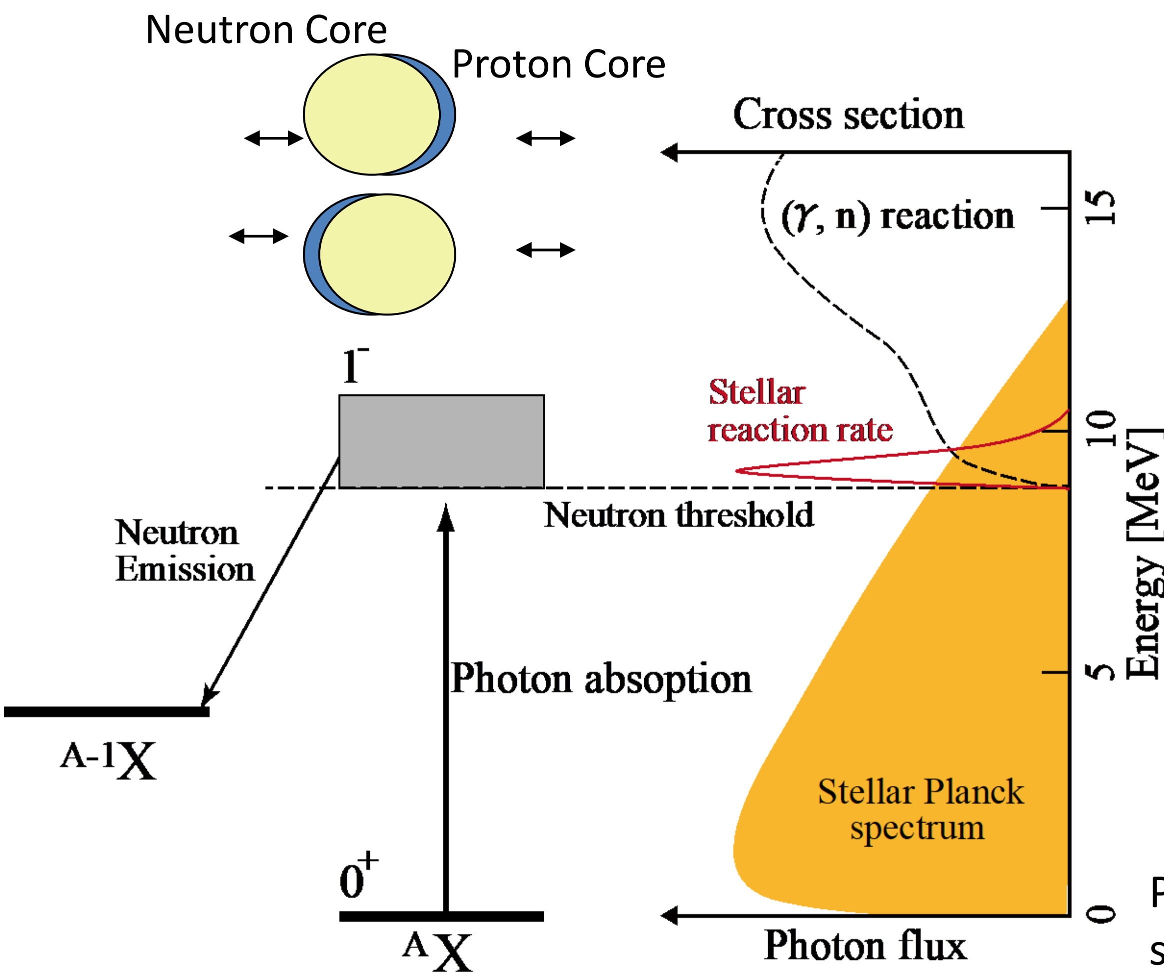
T. Maruyama, T. Hayakawa, T. Kajino, Sci. Rep. 9、51 (2019)

Energy of scattered photon



Standard photon Standard photon Standard photon

“photon vortex” on nuclear reactions



Conservation law of angular momentum

| Ji-Jp | ≤ Jf ≤ |Ji+Jp |

When the total angular momentum of an incident photon is higher than 1, GDR on even-even nucleus with J=0 is forbidden.

Photodisintegrations in supernovae with strong magnetic fields should be affected.

Y. Taira, T. Hayakawa, M. Katoh, Scientific Reports, 7, 5018 (2017).

Summary

It is expected to generate strong gamma-rays in future linear colliders.
They can be used for photon science.

Delbrück scattering : non-linear effect of QED

J. Koga and T. Hayakawa, Phys. Rev. Lett. 118, 204801 (2017).

Photon vortex generation and detection : photon as the eigen state of angular moment

Proposal of light vortices by non-linear inverse Compton scattering

Y. Taira, T. Hayakawa, M. Katoh, Sci.c Rep. 7, 5018 (2017).

Theoretical calculation of photon vortex generation in high-order harmonic radiations in synchrotron radiations.

T. Maruyama, T. Hayakawa, T. Kajino, M.-K. Cheoun, arXiv:1908.11545 [astro-ph.HE]

Calculation of Compton scattering with photon vortex

T. Maruyama, T. Hayakawa, T. Kajino, Sci. Rep. 9, 51 (2019)