Beam Polarization Group Meeting

Monte Carlo simulation method of polarization effects in Laser Compton Scattering on relativistic electrons

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Outline

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Monte Carlo simulation method of polarization effects in Laser Compton Scattering on relativistic electrons

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课题背景:

- X或者伽马束流的偏振信息,在材料物理、核物理、实验室天体物理等基础研究领域以及工业探伤、聚变等离子体诊断等应用上具有重要意义。
- keV 能量的X射线探针光用于高温高密等离子体诊断,其偏振信息变化可以有效反映出被测 等离子体的磁场分布;
- MeV 能量的伽马射线用以巨核共振研究,不同的偏振性可以用来诱导产生不同的激发态;
- CT:偏振X射线穿过样本中心,荧光光子和康普顿散射光子同时产生,且两者强度相近。对 荧光光子探测时,康普顿散射光子会产生较强的干扰。

Ref: [1] 温树槐,丁永坤,激光惯性约束聚变诊断学[M, 国防工业出版社(2012). [2] Ch.Fuchs, and H.J.Hartfuss, Cotton-Mouton Effect Measurement in a Plasma at the W7-AS Stellarator, Phys.Rev.Lett.81(8):1626-1629(1998) [3] J.A.Stamper, and B.H.Ripin, Faraday-Rotation Measurements of Mega gauss Magnetic Fields in Laser-Produced Plasmas, Phys.Rev.Lett.34,138(1975).

偏振-物理基础

- > The wave function and density matrix
- 1. The wave function describing the state of polarization for electromagnetic radiation can be expanded in a complete set of orthonomal eigenfunctions with only two terms:

$$\psi = a_1\psi_1 + a_2\psi_2,$$

- ψ_1 and ψ_2 can either represent two orthogonal states pf plane polarization or two states of circular polarization .
- $|a_1|^2$ and $|a_2|^2$ give the probabilities of detecting of quanta by a detector sensitive only to the ψ_1 and ψ_2 state.



$$\rho = \begin{pmatrix} a_1 a_1^* & a_1 a_2^* \\ a_2 a_1^* & a_2 a_2^* \end{pmatrix},$$

- the diagonal elements give the <u>intensities</u> of the two polarization states
- the offdiagonal elements give the <u>relative phase</u> between the two states





> The beam polarization

1. Beam intensity

3.

$$I = \rho_{11} + \rho_{22} = \begin{pmatrix} a_1^* & a_2^* \end{pmatrix} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix},$$

2. The degree of plane polarization with respect to two arbitrary orthogonal axes e_1 and e_2

$$P_1 = \rho_{11} - \rho_{22} = \left(a_1^* \ a_2^*\right) \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

- $P_1 = +1$ for plane polarization aligned with e_1
- $P_1 = -1$ for plane polarization aligned with e_2

$$P_2 = \rho_{12} + \rho_{21} = \begin{pmatrix} a_1^* & a_2^* = \end{pmatrix} \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

- $P_2 = +1$ for plane polarization aligned with e_1 rotated by 45°
- $P_2 = -1$ for plane polarization aligned with e_2 rotated by 45°

4. The degree of circular polarization

$$P_3 = i(\rho_{21} - \rho_{12}) = \begin{pmatrix} a_1^* & a_2^* \end{pmatrix} \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}.$$

- $P_3 = +1$ for right circular polarization
- $P_3 = -1$ for left circular polarization



偏振-物理基础

- > The properties of the Stokes parameters
 - It is customary to write the Stokes parameters in the form of a four vector:

$$\begin{pmatrix} I \\ P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} I \\ \mathbf{P} \end{pmatrix}.$$

• The beam polarization is defined as:

$$P = \frac{\sqrt{P_1^2 + P_2^2 + P_3^2}}{I}.$$

 $\begin{pmatrix} I' \\ \mathbf{P'} \end{pmatrix} = M \begin{pmatrix} I \\ \mathbf{P} \end{pmatrix}.$

• The initial and the rotated system, define **M** rotation matrix:

tationin the new system of coordinates, the Stokesparameters of the same beam are

$$\begin{bmatrix} I \\ P_1 \cos 2\phi + P_2 \sin 2\phi \\ -P_1 \sin 2\phi + P_2 \cos 2\phi \\ P_3 \end{bmatrix}.$$



截面-物理基础

- Using the Stokes parameters formalism, we now move on to describe the particular case of Compton scattering of polarized photons on unpolarized electrons at rest.
- Following energy and momentum conservation in Compton scattering, one obtains the well known expression
- 1. Klein-Nishina[1]

2. the general treatment of Compton scattering with consideration of polarization for the incident and scattered photons and electrons has been given by Wightman in ref. [2] and brought into a convenient form by Fano in ref. [3].

$$\frac{1}{k_f} - \frac{1}{k_i} = 1 - \cos\theta,$$

- $k_i = E_i/mc^2$ and $k_f = E_f/mc^2$ are the initial and final photon energies in units of mc^2
- θ is the photon scattering angle.

Ref: [1] [30] Y. Nishina, Die Polarisation der Comptonstreuung nach der Diracschen Theorie des Elektrons, Zeits. f. Physik. 52 (1929) 869.
[2] A. Wightman, Note on Polarization Effects in Compton Scattering, Physical Review 74 (1948) 1813.
[3] U. Fano, Remarks of the Classical and Quantum-Mechanical Treatment of Partial Polarization, Journal of the Optical Society of America 39 (1949) 859.

截面-物理基础



- φ is azimuthal spherical angle defining the k_f direction of scattered photon after Compton interaction;
- Φ is the rotation angle of e_{\perp} vector to the right of ε_i

$$\Phi = \varphi + \frac{\pi}{2}$$

- The angle differential Compton scattering cross section
- Stokes parameters of incident gamma beam (1 $P_1 P_2 P_3$)
- The probabilities of detecting a photon characterized by the Stokes parameters is $(1 P'_1 P'_2 P'_3)$



• The energy differential Compton scattering cross section

$$\boxed{\frac{\mathrm{d}\sigma}{\mathrm{d}E_f\,\mathrm{d}\phi} = \frac{1}{2}r_0^2 \frac{mc^2}{E_i^2} \left\{ \frac{k_i}{k_f} + \frac{k_f}{k_i} + (1 - P_1) \left[2\left(\frac{1}{k_i} - \frac{1}{k_f}\right) + \left(\frac{1}{k_i} - \frac{1}{k_f}\right)^2 \right] \right\}}$$

散射光子极化-MC results (1)



Conclusion:

- 1. it is clear that polarization degree is very high (> 99.5%) over the entire angular region, with the exception of (θ, ϕ) pairs of (90, 90) and (90, 270) which are anyhow restricted by the differential Compton cross section.
- 2. By analyzing these figures, it is clear that the polarization degree decreases significantly for backscattered photons at values ranging from 98% to less than 40%.

Figure 3. Theoretical dependence of the polarization degree with polar scattering angles θ and ϕ for polarized photon incident on unpolarized electron at rest. Incident photon energies: (a) 5 keV, (b) 15 keV, (c) 30 keV, (d) 50 keV, (e) 500 keV, (f) 1000 keV.

散射光子极化-MC results (2)

Inverse Compton Scattering



Figure 6. Simulations for Compton scattering of a Gaussian 1064 nm laser beam with 95% linear polarization on realistic 974 MeV electron beam.

Laboratory frame system representations:

- (a) γ -ray beam intensity spatial distribution at collimator position; (b) $P_1^{(LAB)}$ and (c) $P_2^{(LAB)}$ Stokes parameters distributions as function of γ -ray energy;
- (d) γ -ray energy distributions of polarization vector azimuthal angle; (e) $P_1^{(LAB)}$ and (f) $P_2^{(LAB)}$ spatial distribution;

Electron rest frame system representations:

(g) distribution of $\theta \& \varphi$ spherical angles defined in fig. 2; (h) distribution of ratio $p = d\sigma_{\perp}(\Omega)/d\sigma_{\parallel}(\Omega)$ between perpendicular and parallel polarization cross sections relative to the Compton scattering plane (Fano reference system) defined in (3.21) as function of spherical angles;

(i) distribution of the scattered photon polarization degree P_T defined in (2.9) as function of spherical angles.

(j) *Laboratory frame system representation* for 2D distribution of the linear polarization degree *PT* as function of the γ -ray energy.

散射光子极化-MC results (3)



(c) $\tau = 90^{\circ} \& 270^{\circ}$

(d) $\tau = 135^{\circ} \& 315^{\circ}$

Stokes 2

8 10 12 Energy (MeV)

Stokes2 Surt

Stokes 2

Stokes2 Surf

全光逆康普顿散射源偏振特性与 CT 成像应用研究

取电子束能量为 100MeV,则可由式 (2-34) 得到此时逆康普顿散射电场的空间分布,进一步可以得到 S₃ 的分布如下图:



图 2.3 线偏振逆康普顿散射光子 S₃ 分布。

可以看出在散角小于 1/γ 的锥角内, 散射光子的偏振性与散射激光相同, 且靠 近轴线处偏振度接近 100%。

全光逆康普顿散射源偏振特性与 CT 成像应用研究

当电子与圆偏振激光发生逆康普顿散射时,散射光子的偏振度由斯托克斯参数 S₂ 来表示:



图 2.5 (a) 为圆偏振逆康普顿散射光子 S₂ 空间分布, (b) 为线偏振逆康普顿散射光子 S₃ 空间分布, 图中红色虚线圆圈表示 1/γ 的锥角范围。

CAIN

		initial e^{\pm}	laser	final e^{\pm}	final γ
Beamstrahlung	$e^{\pm} \rightarrow e^{\pm} + \gamma$	LT	_	\mathbf{LT}	LT
Linear laser-Compton	$e^{\pm} + laser \rightarrow e^{\pm} + \gamma$	\mathbf{LT}	LT	LT	LT
Nonlinear laser-Compton	$e^{\pm} + n \cdot laser \rightarrow e^{\pm} + \gamma$	\mathbf{L}	L^*	\mathbf{L}	\mathbf{L}
	or	Ν	T^*	Ν	Т
		initial γ	laser	final e^{\pm}	
Coherent pair	$\gamma \rightarrow e^+ + e^-$	\mathbf{LT}	_	\mathbf{LT}	
Linear laser-Breit-Wheeler	$\gamma + \text{laser} \rightarrow e^+ + e^-$	\mathbf{LT}	LT	\mathbf{LT}	
Nonlinear laser-Breit-Wheeler	$\gamma + n \cdot \text{laser} \rightarrow e^+ + e^-$	\mathbf{L}	L^*	\mathbf{L}	
		initial	final pair		
Incoherent Breit-Wheeler	$\gamma + \gamma \rightarrow e^+ + e^-$	\mathbf{L}	Ν		
Incoherent Bethe-Heitler	$\gamma + e \rightarrow e + e^+ + e^-$	N	Ν		
Incoherent Landau-Lifshitz	$e + e \rightarrow e + e + e^+ + e^-$	N	Ν		
		initial	final		
Bremsstrahlung	$e + e \rightarrow e + e + \gamma$	Ν	Ν		

L Longitudinal spin of electron/positron (or circular polarization of photon).

- T Transverse spin of electron/positron (or linear polarization of photon).
- * $\pm 100\%$ polarization only.
- **N** Not computed. (No change for existing particles, zero for created particles)
- Irrelevant.

Summary



- First principle: Klein-Nishina
- Software: cain ,mccmpt, cmcc , mclcss , Geant4

backup