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SYMMETRIC COMPTON SCATTERING: A WAY TOWARDS PLASMA HEATING AND TUNABLE MONO-CHROMATIC GAMMA-RAYS

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Abstract

We analyze the transition between Compton Scattering and Inverse Compton Scattering (ICS), characterized by an equal exchange of energy and momentum between the colliding particles (electrons and photons). In this Symmetric Compton Scattering (SCS) regime, the energy-angle correlation of scattered photons is cancelled, and, when the electron recoil is large, monochromaticity is transferred from one colliding beam to the other. Large-recoil SCS or quasi-SCS can be used to design compact intrinsic monochromatic γ-ray sources based on compact linacs, thus avoiding the use of GeV-class electron beams and powerful laser/optical systems as required for ICS sources. At very low recoil and energy collisions (about 10 keV energy range), SCS can be exploited to heat the colliding electron beam, which is scattered with large transverse momenta over the entire solid angle, offering a technique to trap electrons into magnetic bottles for plasma heating.

INTRODUCTION

The Inverse Compton Scattering (ICS) effect regards the interaction between highly relativistic electrons and laser beams, within an inverse kinematics set-up where the electron loses energy and momentum in favor of the incident photon, that is back-scattered and up-shifted to much larger energies. Compton sources are devices developed and operating in many laboratories [1] with plenty of applications. In this paper, we analyze the transition between direct Compton (DC) effect, occurring when the electron is at rest, and ICS. In this case, the colliding particles exchange an equal amount of energy and momentum, and we call this regime Symmetric Compton Scattering (SCS). Unlike in all other radiations emitted with a Lorentz boost, SCS scattered photon energy indeed no longer depends on the scattering angle, so that the back-scattered radiation beam becomes intrinsically monochromatic. SCS is characterized by the transfer of monochromaticity from one colliding beam to the other, so that when a large bandwidth photon beam collides under SCS conditions with a monoenergetic electron beam, the back-scattered photon beam results to be monochromatized. The possible applications ranges in many fields. SCS or quasi-SCS at large recoil could allow to design compact sources of intrinsic monochromatic γ-rays alimented by low energy MeV electron bunches, thus avoiding the use of GeV-class accelerators and powerful laser/optical systems, actually needed by ICS sources [2]. On the other hand, the SCS effect at low recoil can provide an electron heater based on X-rays.

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SYMMETRIC COMPTON SCATTERING

In the Compton scattering, the photon energy ($E'_{\rm ph} = \hbar\omega'$, with ω' being the photon angular frequency and $\hbar$ the reduced Planck constant) scattered at an angle θ is given by:

$$E'_{\rm ph}(\theta) = \frac{(1+\beta)\gamma^2}{\gamma^2(1-\beta\cos\theta) + \frac{X}{4}(1+\cos\theta)} E_{\rm ph}, \qquad (1)$$

where the incident photon energy is $E_{\rm ph} = \hbar\omega$, $\beta = v_e/c$ is the dimensionless electron velocity v_e (c being the speed of light), $\gamma = 1/\sqrt{1-\beta^2}$ is electron Lorentz factor and X is the electron recoil factor,

$$X = \frac{4E_e E_{\rm ph}}{(m_0c^2)^2} = \frac{4\gamma E_{\rm ph}}{m_0c^2} = 4\gamma^2\frac{E_{\rm ph}}{E_e}, \qquad (2)$$

with m_0 the electron rest mass and $E_e = \gamma m_0 c^2$.

We call Symmetric Compton Scattering (SCS) the regime of transition between DC and ICS [3], where the energy/momentum transfer between photons and electrons is balanced. The maximum photon energy closely approaches the electron energy. Referring to Eq. (1), the dependence on θ of $E'_{\rm ph}$ cancels when: $\frac{X}{4} = \beta\gamma^2$, a condition valid when the photon and electron energies satisfy the relation $E_{\rm ph} = \beta E_e$, corresponding to equal electron and photon momenta with opposite directions $\vec{p}_e = -\vec{p}_{\rm ph}$. Moreover, we can introduce an asymmetry factor $A = \beta\gamma^2 - \frac{X}{4}$, that vanishes ($A = 0$) in SCS regime, assumes large positive values ($A \to \gamma^2$) in ICS regime (that is indeed characterized by $X \ll 4\beta\gamma^2$) and negative values in DC when $\beta = 0$.

The energy of the scattered photons is $E'_{\rm ph} = E_{\rm ph}$, uniformly in θ.

The asymmetry factor A is negative in DC regime, where $\beta = 0$ and $\gamma = 1$, and $A = -\lambda_C/\lambda$. In ICS regime the asymmetry factor A is positive and scales like γ^2.

Figure 1 shows the dependence of E'_0 vs. T_e and of the recoil factor X in different regimes (DC, SCS, ICS).

Another unique characteristic of Symmetric Compton Scattering, that does not occur in any other electron-photon collision, is that: $E_{\rm ph} = \beta E_e$, $E'_{\rm ph} = E_{\rm ph}$ and $E'_e = E_e$, i.e., the energies of electron and photon do not change before and after SCS. This is represented by the $A = 0$ line plotted in Fig. 1.

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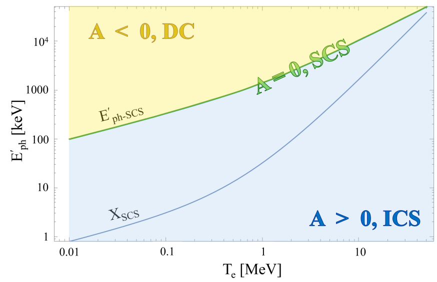

Figure 1: Plane of the scattered photon energy in SCS regime vs electron kinetic energy T_e. Direct Compton in yellow ($A < 0$), ICS in blue ($A > 0$) and in green the SCS divide line ($A = 0$).

The symmetry condition can be satisfied in a regime of low or large recoil, depending on the electron's energy. When $X \leq 1$, namely when $\gamma \leq 1.03$ or $\beta < 0.24$, the angular distribution of photons and electrons after the scattering is almost flat, with the scattered particles spread on the whole solid angle. When the recoil is strong ($X_{SC} \gg 1$), corresponding to β close to 1 and larger Lorentz factor, the angular distribution of photons and electrons is peaked close to $\theta = 0$.

Figure 2 illustrates the variation in the angular distribution of the photons as a function of the recoil factor X_{SC}. In the figure, the peak value of the zenithal angle distribution θ_{peak} (in red) and the full width half maximum θ_{FWHM} (in blue) vs X_{SC} are represented. The inner windows show the photon distribution shape for X_{SC}=1, 5, 50 and 250. The distribution of the scattered electrons appears to be similar to that of photons but rotated towards $\theta = \pi$.

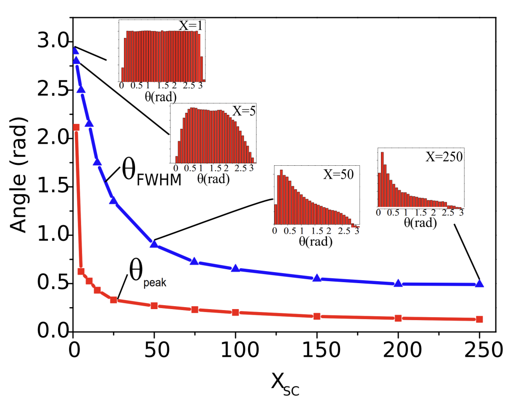

Figure 2: Peak value of the distribution of the zenithal momentum angle θ_{peak} (in red) and the full width half maximum θ_{FWHM} in SCS vs X_{SC} in the unpolarized case. The inner windows show the photon distribution shape for X_{SC}=1,5,50 and 250.

SYMMETRIC COMPTON SCATTERING SIMULATION

We used the WHIZARD code [4], a universal parton-level Monte Carlo event generator, to perform simulations of SCS.

An almost monochromatic (with an rms energy spread of the order of 10^{-4}) 10 MeV electron beam ($\beta \to 1$) collided head-on with an incoming photon beam characterized by large bandwidth (20% rms spread). The recoil in this interaction is $X = 1533$. In Fig. 3 the outgoing photons showed no correlation between energy and emission angle and featured a significant narrowing of the bandwidth ($2 \cdot 10^{-4}$ rms spread, i.e., a reduction of the energy spread by about 3 orders of magnitude from incident photon beam to the scattered photon beam). The electron beam emerging from the interaction inherited an high energy spread (of the order of 10^{-1}) from the original interacting photon beam, displaying an entropy exchange.

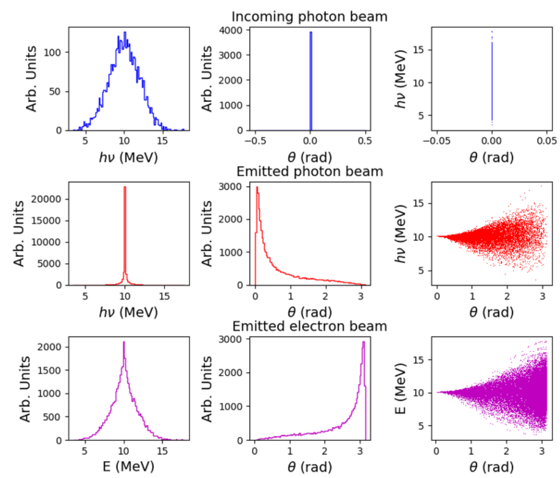

Figure 3: Simulations of SCS. First row: incident photons. Second row: outgoing photons. Third row: and outgoing electrons. First column, energy distributions. Second column, angular distributions. Third column, energy vs angle θ. Average initial photon energy $\langle E_{\text{ph}} \rangle = 10$ MeV, rms relative width of the distribution $\Delta E_{\text{ph}}/E = 0.2$. Initial electron beams with average energy $\langle E_e \rangle = 10$ MeV and $\Delta E_e/E = 0$. Recoil factor: $X = 1533$.

A home made multitasking Monte Carlo code has been also developed, validated for different type of collisions and applied to the Compton scattering process . As an additional internal feature, the code allows to consider the energy and angular (polar and azimuth) spread of both incident beams. To confirm the occurrence of the effect, we performed the same simulation of the deep recoil SCS interaction (at $X = 1533$) made with Whizard. Our findings confirm the exchange of entropy, resulting in a reduction of the bandwidth of the emitted radiation and an enlargement of the electron's bandwidth.

Furthermore, we examined the transition from the SCS regime to the ICS regime, with a particular focus on the angular distribution of the scattered radiation. To explore the transition regime, we started with the deep recoil SCS interaction ($X = 1533$) and slightly increased the energy of the incident electron bunch, while reducing the energy of the photon bunch. We investigated three cases, specifically with electron-photon energies of ($E_e \simeq E_{ph} = 10$ MeV), ($E_e = 11$ MeV, $E_{ph} = 9.08$ MeV), and ($E_e = 12$ MeV, $E_{ph} = 8.33$ MeV). The results, depicted in Fig. 4, show the

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distribution shifting from an uncorrelated energy-angle pattern to a more correlated one, resembling the typical "mustache" shaped curve observed in ICS experiments, typical of the well known $(\gamma\theta)^2$ dependence shown in the denominator of Eq. (1).

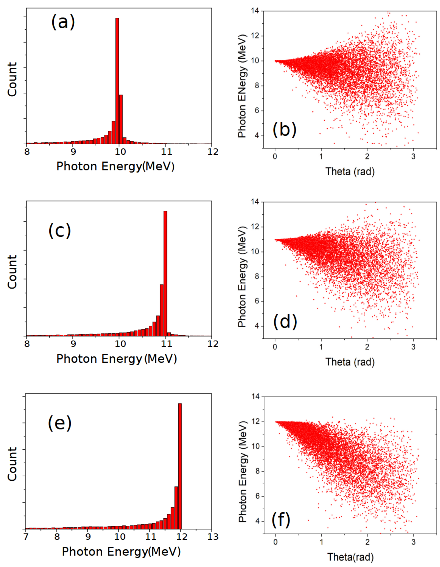

Figure 4: Transition regime between SCS and ICS for three different sets of photons and electrons energy. Left: produced photon energy distribution and right: angular photon distribution (i.e., energy as a function of emission angle) (a) and (b) initial electron energy of 10.013 MeV and initial photon energy of 10 MeV. (c) and (d) initial electron energy of 11 MeV and initial photon energy of 9.08 MeV. (e) and (f) initial electron energy of 12 MeV and initial photon energy of 8.33 MeV.

The Symmetric Compton Scattering at large recoil can transfer monochromaticity from the beam of electrons to the beam of photons, in such a way that broad band incident photon beams are transformed into narrow band photon beams by the scattering. This mechanism can be considered sort of a photon cooling effect via SCS by monoenergetic electron beams, while the electron beam is heated up to a larger energy spread. The electron energy angular distribution is peaked forward in case of large recoil, see Fig. 2, due to the angular cross section dependence, that is forward peaked when the recoil parameter X is large. On the other hand, if SCS takes place at low recoils the two scattered beams of photons and electrons are almost isotropically diffused over the entire solid angle. This is an effective heating of the transverse electron emittance, with a complete transfer of its initial dominant longitudinal momentum into prevalent transverse momentum. The part of electron beam undergoing scattering is blown all over the solid angle.

Such an effect, that does not occur in ICS, could be exploited to capture an electron beam inside a MB. SCS at a low recoil factor is the only mechanism to transfer large transverse momentum from the photon beam to the scattered electrons. A natural application of this mechanism would be the capture of an electron beam of suitable energy into a Magnetic Bottle (MB), transforming the beam into a plasma stored inside the bottle: this would be achieved by injecting the beam on-axis and colliding it with a beam of photons under SCS conditions.

As discussed above the scattered electrons would have a dominant transverse momentum and they would comply with the well known capture condition of a MB, i.e., in terms of the angle θ : $|\tan\theta| > \left(\frac{B_{\max}}{B_{\min}} - 1\right)^{-\frac{1}{2}}$.

We take as an example a SCS performed at the center of a MB, between an injected electron beam of 5 keV kinetic energy and a counter propagating photon beam of 72 keV (so to comply with SCS condition stated by $\frac{X}{4} = \beta\gamma^2$. Given the low β of the electrons, the differential cross section is almost flat. The recoil factor is in this case small, i.e., $X = 0.57$.

The capture condition for this MB is evaluated applying condition for $|\tan\theta|$ so to find the minimum θ angle for a captured particle $\theta_{\min} = 0.674$ rad that translates to the following percentage of electrons emitted uniformly over the solid angle: $(\pi - 2\theta_{\min})/\pi \cdot 100 \sim 57\%$.

The electrons undergoing a SCS collision in the inner region of the MB are spread all over the solid angle, converting their longitudinal momentum into transverse momentum. Tracking the scattered electrons, we find that a large majority of them (60 over 100 tracked) are trapped in the bottle.This result is in accordance with the predictions. This clearly represents a possible mechanism of plasma heating by electrons trapped into the MB generated by a SCS interaction of the injected beam into the bottle and a counter-propagating photon beam of equal momentum.

CONCLUSIONS

We explore the transition between Compton Scattering and Inverse Compton Scattering (ICS), a regime characterized by an equal exchange of energy and momentum between the colliding particles. This regime of Symmetric Compton Scattering (SCS) has the unique property of transferring monochromaticity from one beam to the other, resulting in back-scattered photons that are intrinsically monochromatic. The paper suggests that large recoil SCS or quasi SCS can be used to design compact intrinsic monochromatic γ-ray sources, thus avoiding the use of GeV-class electron beams and powerful laser/optical systems typically required for ICS sources.

The capability of SCS regime to vanish the photon energy-angle correlation, married to the large recoil beneficial effects on the scattered photon energy spread, makes possible to conceive a monochromatic gamma ray beam source based on the collision between a bremsstrahlung radiation beam (or a coherent bremsstrahlung beam from a channeling source, [5]) and a monoenergetic electron beam of similar energy, say in the 2-10 MeV range. A compact source, developed on this concept, is much more sustainable than typical ICS sources for nuclear physics/photonics like ELI-NP-GBS [6], which envisages the use of GeV-class linear accelerators.

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