Effect of differential cross section in Breit–Wheeler pair production

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Received 21 May 2018, revised 4 July 2018
Accepted for publication 30 July 2018
Published 17 August 2018

Abstract

The possibility of achieving a pair beaming in the Breit–Wheeler (BW) electron/positron pair creation process is investigated in this paper. We examine the effect of the BW differential cross section on the pair’s angular and energy distributions. Although this study is relevant for laser induced intense gamma-ray source collision experiments, we apply this pair beaming effect in an astrophysical context, in particular for active galactic nuclei (AGN).

Keywords: gamma-ray sources, Breit–Wheeler process, pair electron-positron, active galactic nuclei

(Some figures may appear in colour only in the online journal)

1. Introduction

Electron/positron pair production in the collision of two photons is a fundamental physical process predicted by quantum electrodynamics (QED) [1]. The electron/positron pair annihilation in two photons: \( e^+ + e^- \rightarrow \gamma + \gamma \) was theoretically predicted by Dirac [2] and has obtained extremely accurate experimental verification [3]. But the reverse process: \( \gamma + \gamma \rightarrow e^+ + e^- \), theoretically predicted by Breit–Wheeler (BW) [4], although conceptually simple, has been much more difficult to verify experimentally, by comparison.

The photon–photon collision in physics was first studied in the 1970s by Novosibirsk [5] and Frascati [6]. In these experiments the pairs were created by the collision of electron and positron beams: \( e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^- \) in the so-called Landau–Lifshitz process. The photons in this process are virtual, they present an intermediate step of the pair creation: \( \gamma^+ + \gamma^- \rightarrow e^+ + e^- \). Another similar QED process, which has been verified experimentally, is the Bethe-Heitler process [7], \( \gamma + \gamma^\ast \rightarrow e^+ + e^- \), where a real photon collides with a virtual photon produced in the Coulomb electric field of an ion. Concerning the collision of real photons only the non-linear or multi-photon BW process [8] has been observed [9], where a real photon is coupled to several (4–5) low energy laser photons. The two-photon collision process is still awaiting direct observational verification. Only recently, thanks to high-power laser technology, have first schemes for its direct observation been proposed [10–12].

In the astrophysical context, the BW process plays an important role in high-energy phenomena [13]. According to Nikishov [14], the background photons put a stringent limit on the maximum energy of photons coming from hard x-ray sources. The BW process also takes place in active galactic nuclei (AGN) [15, 16], where the gamma rays near the central black hole (BH) are converted into electron/positron pairs, which are further accelerated by the radiation pressure of the x-ray flux emission from the disk.

Electron/positron pair production by two gamma photon beams was studied in [17] by considering only the pairs’ kinematics in the BW process. The pair angular distribution in the center of mass (CM) frame was assumed to be uniform, i.e. the pairs were emitted isotropically. The effect of pair beaming in the laboratory frame was explained by the directed motion of the CM frame. This effect may facilitate the experimental observation of the BW process.

In this paper, we account for the effect of the BW differential cross section anisotropy on pair beaming. This effect changes the angular and energy distribution of the pairs in the laboratory frame. In section 2 we recall the main features of the pair beaming assuming an anisotropic pair distribution in the CM frame. Section 3 is devoted to the analysis of the effect of the BW differential cross section anisotropy on pair beaming. The BW differential cross section is derived in section 3.1, and the pair’s angular and energy distributions are studied in section 3.2. Section 4 presents an analysis of the
BW process in the astrophysical context, in particular, for AGN. Section 5 contains our conclusions.

2. Kinematics of $e^+$, $e^-$ pairs and pair beaming

In this section we recall the main results obtained in [17], were we demonstrated the pair beaming effect in the collision of two photon beams. We use a unit system where the speed of light $c = 1$ and the electron mass $m_e = 1$. We consider two colliding photons with momenta $p_1^\gamma$, $p_2^\gamma$ and energies $E_1^\gamma$, $E_2^\gamma$, respectively, where $\theta_p$ is the angle between them. The scalar product, of the four-momenta of two photons, is a Lorentz invariant:

$$ q^- = g_{\mu\nu} (E_1^\gamma E_2^\gamma \cos \theta_p) $$

where $E_{cm}$ is the total energy in the CM frame. The pair’s creation threshold is defined by the condition $E_{cm} \geq 2$ and electrons and positrons are created at rest if $E_{cm} = 2$. In the general case this condition writes: $E_1^\gamma E_2^\gamma (1 - \cos \theta_p) \geq 2$. For a given energy of the two photons, the threshold angle $\theta_{th}$ is defined by: $\theta_p \geq \theta_{th}$ where $\theta_{th} = \arccos(1 - 1/E_1^\gamma E_2^\gamma)$. From the Lorentz transformation of the $e^+$, $e^-$ pair momenta and energy, one finds a condition in which all pair momenta are aligned in the direction of the CM frame velocity. This condition is referred to as the pair beaming condition. This condition writes:

$$ \theta_p \leq \theta_{p, beam} $$

where:

$$ \theta_{p, beam} = \arccos(1 - [E_1^\gamma + E_2^\gamma]/E_1^\gamma E_2^\gamma) $$

Moreover, in the case where $(E_1^\gamma + E_2^\gamma)/2E_1^\gamma E_2^\gamma > 1$, there is beaming for $\theta_p \geq \theta_{th}$. This latter beaming condition is relevant for collisions between very high and very low energy photons. For $\theta_p = \pi$ and equal photon beam energies, there is no beaming because the laboratory frame and the CM frame.

![Figure 1. Pair emission in the laboratory frame for $E_1^\gamma = E_2^\gamma = 4$ MeV and $\theta_p = 40^\circ$. (a) Angular distribution of pair emission, $\theta_e$ and $\phi_e$ are the polar and azimuthal angles. Red and blue arrows delimit the pair emission directions, black arrow the direction of CM frame velocity. (b) Pair angular distribution in the direction of the CM frame velocity, blue and black points show the positrons and electrons, respectively. (c) Angular histogram ($\theta_{ex}$) in the plane of incidence of photons. (d) Angular histogram ($\theta_{ey}$) in the direction perpendicular to the incidence plane.](image-url)
are identical, and the pairs $\gamma^-, \gamma^+$ are emitted in opposite directions. When the pair beaming conditions apply, the emission cone aperture $\theta_{e, \text{beam}}$ writes:

$$\tan \theta_{e, \text{beam}} = \pm \frac{E_{cm} \sqrt{E_{cm}^2 - 4}}{4(E_{\gamma^1} + E_{\gamma^2})^2 - E_{cm}^4}.$$  

However, the results in [17] are obtained assuming that in the CM frame, the pair emission probability is isotropic, that is, the differential cross section $d\sigma/d\Omega_{cm} = 1$ is constant. The pair beaming is then possible for $\theta_{th} < \theta_p < \theta_{p, \text{beam}}$. An example of the beaming effect, is shown in figure 1 for the case of two photon beams with the same energy: 4 MeV crossing at an angle $\theta_p = 40^\circ$, which satisfies the beaming condition: $\theta_{p, \text{beam}} \approx 42^\circ$, $\theta_{th} \approx 15^\circ$. In this case 5 000 pairs are emitted isotropically in the CM frame and their distribution in the laboratory frame is shown in figure 1. Figure 1(a) shows the angular pair distribution versus the polar and azimuthal angles ($\theta_e, \phi_e$). The pairs are emitted along the CM frame velocity. The pairs are distributed inside a cone angle $\theta_{e, \text{beam}} = \pm 64.7^\circ$ (see figure 1(b)). Figures 1(c) and (d) present the angular distribution in the photon incidence plane and in the direction perpendicular to this plane, respectively. The pair distribution has an azimuthally symmetric bell shape.

According to the Lorentz transformation the minimum and maximum pair energies are [17]:

$$E_{\text{max}, \text{min}} = \frac{(E_{\gamma^1} + E_{\gamma^2})}{2} \pm \sqrt{\left(E_{\gamma^1} + E_{\gamma^2}\right)^2 - E_{cm}^2} \sqrt{E_{cm}^2 - 4}. $$

The pair energy distribution is presented in figure 2(a). The spectrum is uniform between the two energy values given before. The effect of anisotropy of pair emission is discussed in the next section.
3. Effect of the cross section anisotropy on pair beaming

3.1. BW differential cross section

The Feynman diagram technique for the differential cross section calculation is described in [1]. Figure 3 shows the two first order Feynman diagrams of the BW process: the production of an $e^-$, $e^+$ pair from the collision of two real photons. In the BW process two Feynman diagrams are possible because the photon is an indiscernible particle and the photon can be associated with one of the two diagram vertices. For each Feynman diagram the initial and final states are given by a plane wave function. The probability current is calculated for each branch of each Feynman diagram. Then the diffusion matrices $\mathcal{M}_1$ and $\mathcal{M}_2$ are obtained by the use of the probability current and the Fermion propagator. The total scattering matrix $\mathcal{M}$ is the sum of the two scattering matrices $\mathcal{M}_1$ and $\mathcal{M}_2$ corresponding to the processes shown in figure 3. The module of $\mathcal{M}$ averaged over all spin and polarization configurations can be written as:

$$\langle |\mathcal{M}|^2 \rangle = \frac{1}{4} \sum_{\text{state}} |\mathcal{M}_1 \mathcal{M}_1^* + \mathcal{M}_2 \mathcal{M}_2^* + 2 \text{Re} (\mathcal{M}_1 \mathcal{M}_2^*)|.$$

The pairs are characterized by their four-momenta $P$ and $P'$ and photons by their four-momenta $K$ and $K'$. The kinematic invariants called the Mandelstam variables are then given by: $s = (P + P')^2 = (K + K')^2$, $t = (P - K)^2 = (P' - K')^2$, and $u = (P - K')^2 = (P' - K)^2$. Specifically, $\sqrt{s} = E_{cm}$ is the total energy in the CM frame.

$$\langle |\mathcal{M}|^2 \rangle = 2e^4 \left[ \frac{u - 1}{t - 1} + \frac{t - 1}{u - 1} - 4 \left( \frac{1}{t - 1} + \frac{1}{u - 1} \right) \right] - 4 \left( \frac{1}{t - 1} + \frac{1}{u - 1} \right)^2,$$

where $e$ is the electron electric charge. The BW differential cross section in the CM frame can be written as follows [18]:

$$\frac{d\sigma}{d\Omega_{cm}} = \left[ \frac{2|\vec{p}|}{64\pi s \sqrt{s}} \right] |\mathcal{M}|^2,$$

where, $\vec{p}$ is the momentum of the positron or electron. Expressing the Mandelstam variables through the CM frame velocity $\beta_{cm}$ and the angle between the photon direction and electron emission direction $\theta_e$, one finds:

$$\frac{d\sigma}{d\Omega_{cm}} = \frac{r_e^2 \beta_{cm}}{s} \left[ \frac{\beta_{cm}}{2} \left( 1 + \frac{3 - \beta_{cm}^2}{1 - \beta_{cm}^2} \right) \right] \times \left\{ \frac{1}{1 - \beta_{cm}^2} + \frac{1}{1 + \beta_{cm}^2} \right\} \left[ \frac{1}{1 - \beta_{cm}^2} + \frac{1}{1 + \beta_{cm}^2} \right],$$

where, $r_e$ is the electron classical radius, $x = \cos \theta_e$ and $d\Omega_{cm} = dxd\phi$. Figure 4(a) shows the BW differential cross section in the CM frame for the collision of photons with equal energies of 4 MeV and $\theta_p = 40^\circ$. The energy dependence of the differential cross section is shown in panel (b).
The probability of pair emission is symmetric along the photons’ directional axis and achieves a maximum in the photon beam direction, see figure 4(a). The anisotropy increases with the CM energy and appears clearly for \( \sqrt{s} > 3 \), which is very close to the pair creation threshold \( \sqrt{s}_c \).

To obtain the pair distribution in the laboratory frame we used the following calculation method:

1. Choose the number of pairs emitted in the CM frame.
2. In the CM frame the photons and pairs are in counter propagation. In this frame the pair distribution is given by the BW differential cross section. This function depends only on \( x \) (see equation (1)) and \( \beta_{cm} \) (CM frame velocity). \( \beta_{cm} \) depends only on the initial energy of the photons and their angle of collision \( \theta_{\gamma} \). \( x \) depends only on the emission polar angle of the electron or positron \( (x = \cos(\theta_e)) \). Then we impose to the \( x \) distribution to follow equation (1) assuming that pair emission in the azimuthal angle \( \phi \) is isotropic (because equation (1) is independent of \( \phi \)).

3. Once we obtain the angular distribution of the pairs in the CM frame, we operate a change of reference frame in which the pair distribution is identified in new spherical coordinates, where the polar direction is along the CM frame velocity direction \( (\beta_{cm}) \). Then the pair distribution in \( \theta \) and \( \phi \) is obtained in the CM frame (see [18]).

4. From the total energy in the CM frame \( E_{cm} \), which depends on the energy of the two initial photons and the angle between them, the energies and momenta of all pairs are calculated. The CM frame velocity \( \beta_{cm} \) can also be calculated (see [17]).

5. From the Lorentz transformation, we obtain the pair distribution (momenta and energy) in the laboratory frame.

Figure 5. Pair emission in the laboratory frame for \( E_{\gamma_1} = E_{\gamma_2} = 4 \) MeV and \( \theta_{\gamma} = 40^\circ \) with anisotropic differential cross section. (a) Angular distribution of pair emission, \( \theta_e \) and \( \phi_e \) are the polar and azimuthal angles. Red and blue arrows delimit the pair emission directions, and the black arrow shows the direction of the CM frame velocity. (b) Pair angular distribution in the direction of the CM frame velocity, blue and black points show the positrons and electrons, respectively. (c) Angular histogram \((\theta_e)\) in the plane of incidence of the photons. (d) Angular histogram \((\theta_{e,y})\) in the direction perpendicular to the incidence plane.
3.2. Pairs kinematics and energy distributions

By using the Lorentz transformations the pair emission distribution is obtained in the laboratory frame. The pair distribution has been calculated by a random generation of 5000 pairs in the CM frame with the probability given in equation (1). Figure 5 shows the pair emission characteristics for the same set of parameters as in figure 1, with $E_{cm} = \sqrt{s} = 5.3$. The pair angular distribution is much more affected by the anisotropy of the differential cross section. This is expected as according to figure 4, the pairs emission is much more anisotropic for $\sqrt{s} > 3$. This can be seen in figures 5(c) and (d) where the pair beam in the collision plane is larger than in the perpendicular direction. In particular, the angular pair distribution shows two peaks in the photon beam direction. The pair energy distribution is shown in figure 2(b). Compared to figure 2(a), the maximum of the energy distribution is shifted to higher energies.

To further investigate the effect of the BW differential cross section on pair beaming, we varied the incoming photon energies. Two different cases are considered: 4–1 MeV, 47 MeV, while keeping the same crossing angle, $\theta_p = 40^\circ$. For the two cases the values of $\sqrt{s}$ are: ~3 and ~7 corresponding to a decreasing and increasing anisotropy, respectively, according to figure 4(b).

Figure 6 shows the pair emission characteristics for 4 MeV and 1 MeV photon beam collisions. The pair angular distribution (see figure 6(a)) shows a stronger beaming than in figure 5, indeed, the pair beaming condition gives: $\theta_{beam} = \pm 14.7^\circ$. Moreover, because of the unbalanced photon energy beams, the CM frame velocity is almost aligned along the high-energy photon beam direction. Then most of the pairs are emitted in the
direction of the highest photon beam energy. The pairs energy distribution is shown in figure 7(a). Compared to figure 2(b), the maximum of the energy distribution is shifted to higher energies and is uniform as in figure 2(a).

For 4 and 7 MeV photon energies, the pair emission characteristics are shown in figure 8. The angular distribution presented in figure 8(a) shows that the CM frame velocity direction is aligned toward the high-energy photon direction. Because, the beam angle \( \theta_{\text{beam}} = 37^\circ \), the beaming condition is not totally satisfied, some pairs are emitted backwards compared to the CM frame velocity direction. Figures 8(b)–(d) show that the pair beam is split in two parts as in figure 5(c). However, the pair beam presents an asymmetry in the photon incidence plane and more pairs are emitted in the direction of the highest photon energy beam. The pair energy distribution is shown in figure 7(b). The shape of the energy distribution shown in figure 7(b) is close to the energy distribution plotted in figure 2(b), but shifted to higher energies.

In summary, to investigate the BW differential cross section effect on pair beaming, three cases are considered in terms of photon beam energies: 4–4 MeV, 4–1 MeV and 4–7 MeV, all cases with \( \theta_p = 40^\circ \). In the case of 4–4 MeV, the influence of the differential cross section are important regarding the pair angular distribution as well as the energy distribution. The pairs are emitted mainly in the photon beam directions. Then, less pairs are emitted in the bisector between the photon beam directions compared to the case of the isotropic differential cross section. The pair energy distribution achieves a maximum at the mean energy of the two photon beams. Concerning the two last cases, 4–1 MeV and 4–7 MeV, the pair beam is emitted mainly along the CM frame velocity direction. Because of the photon beams energy difference, less pairs are emitted on the bisector between the two photon beams. However, for the 4–1 MeV photon beam collision, the effect of the BW differential cross section on the pair’s angular and energy distributions are weak. In the case of the 4–7 MeV photon beams, the effect becomes important and the pair distribution is beamed in the direction of the most energetic photon beam. The energy distribution is shifted to higher energies and achieves a maximum for the mean energy of the two photon beams.

4. Application of pair production in AGN

In this section we present an analysis of the BW process in the astrophysical context, in particular in AGN. An AGN produces jets of relativistic particles [19]. The relativistic flows are characterized by their bulk Lorentz factor \( \Gamma_b \) (equivalent to \( E \) in the pair energy distribution, see the previous section).

As stated in [20] ‘AGN is capable of launching relativistic outflows, although the exact mechanism is not yet clear’. In this reference two different models are proposed for the broadband AGN emission: leptonic, hadronic or a mix of the two. Here we assume the leptons are making a significant contribution to the AGN spectral emission distribution. However, emission of high-energy and very high-energy photons requires the acceleration of particles to GeV and even TeV (see [20]). Such high luminosity combined with the small size of the source should result in a strong depletion of gamma rays by pair absorption, contradictory to their detection at high levels of energy emission. This contradiction can be solved if the emission is beamed by a relativistic bulk motion of particles. Thus the idea was proposed that gamma emission takes place in the relativistic jet, with an internal Lorentz factor in the range \( 10^5-10^7 \). The \( e^+ - e^- \) plasma is confined by the magnetohydrodynamical (MHD) structure of the jet, with bulk Lorentz factors between 3 and 20. The pair plasma emits two main spectral components at low energy by synchrotron emission and at high-energy by inverse Compton
scattering (for the leptonic model). In our case we are interested in the $e^+, e^-$ plasma production mechanism near the central super massive BH by the radiation emitted from the accretion disks. We assume that the pair are created and beamed on the AGN axis with maximum Lorentz factors around 10, boosted by the BW process. This assumption has been discussed by Ghisellini G [21]. The author assumes that copious pair creation could occur in the inner zone of the still accelerating jet, where the bulk Lorentz factor is small. Further, at a large distance from the central BH, we assume that the pair plasma will be heated to a higher Lorentz factor ($10^2$–$10^3$) and accelerated by the Compton rocket [22] to achieve a higher bulk Lorentz factor $\Gamma_b$.

The observations show that in AGN the bulk Lorentz factor for jet flows is in the range: $\Gamma_b = 2–10$. It is mainly assumed that the relativistic flow is dominated by an $e^-, e^+$ pair plasma. Moreover, the idea of two flow structures was proposed. The jet is composed by a mildly relativistic sheath composed of $e^-/p^+$ and driven by MHD forces and an ultra-relativistic flow composed of $e^-, e^+$ pairs, which is responsible for most of the emission (see figure 9). It is assumed that the AGN is composed of a central rotating BH, with two different accretion disks: around the central BH for radius $R < 10r_g$, an advection-dominated accretion flow (ADAF) ($r_g$ is the Schwarzschild radius, $r_g = 2MG/2c^2$, $M$ is the BH mass, $G$ the gravitational constant and $c$ the speed of light) and an external standard accretion disk (SAD). The SAD emits photons mainly in ultra-violet and x-rays and the ADAF emission is between the radio and gamma-ray range [23].

The mechanisms of $e^-, e^+$ pair plasma production and acceleration are not well understood, however we will assume that the pair plasma is produced from the BW process. As

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**Figure 8.** Pair emission in the laboratory frame for $E_{\gamma_1} = 4\,\text{MeV}$, $=E_{\gamma_2} = 7\,\text{MeV}$ and $\theta_p = 40^\circ$ with anisotropic differential cross section. (a) Angular distribution of pair emission, $\theta_e$ and $\phi_e$, are the polar and azimuthal angles, respectively. Red and blue arrows delimit the pair emission directions, the black arrow shows the direction of the CM frame velocity direction. (b) Pair angular distribution in the direction of the CM frame velocity, blue and black points show the positrons and electrons, respectively. (c) Angular histogram ($\theta_e$) in the plane of incidence of the photons. (d) Angular histogram ($\theta_e$) in the direction perpendicular to the incidence plane.
shown in figure 9, the gamma rays emitted from the ADAF collide along the BH rotation axis. Once the pair plasma is created by the BW process, the anisotropy of the high-energy photons emitted from the accretion disk can transfer a strong momentum to the pair plasma via the inverse Compton process. This mechanism is know as a Compton rocket \cite{22}. We propose to study direct pair plasma creation and acceleration by the BW process, and show that this flow can be produced with a high Lorentz factor $\Gamma_b \sim 10$ without the requirement of the Compton rocket mechanism.

The characteristics of the photon energy distribution emitted from the ADAF were calculated in \cite{23}, the photons are emitted from the radio to gamma-ray range, with an energy cutoff at 4 MeV (see figure 2 in \cite{23}). From the pair threshold production definition, only photons between 0.065–4 MeV energies can participate in the BW pair
production (see section 2). We propose to study the photon beam collision at different angles of $\theta_p$, in two different cases: for 4–4 MeV and 4–0.5 MeV photon beam energies. For the second situation, 0.5 MeV has been chosen to highlight the beaming effect and the consequence of an energy difference between the two photon beams.

Figure 10 shows for $\theta_p = 180^\circ$, 90°, 40° and 16° the pair momenta distributions for 4–4 MeV photon beams collision. From the pair beaming criteria, only the pairs corresponding to $q \in [14.7°, 41.9°]$ are beamed. For $\theta_p = 180^\circ$ the pairs are emitted toward the photon beam directions and the energy distribution is mono-energetic (see figure 10(c)), all the pairs are emitted with a Lorentz factor $\Gamma_b \approx 8$. For $\theta_p = 90^\circ$ most of the pairs are emitted in the CM frame velocity direction, however, a small fraction are emitted towards the BH. The pair energy distribution peaks around $\Gamma_b \approx 8$, with a maximum $\Gamma_b \approx 13$ (see figure 10(d)). For $\theta_p = 40^\circ$ the pairs are beamed, all the pairs propagate along the CM frame velocity direction. The pair angular distribution is shown in figure 10(a) and the inner beam pair structure is due to the BW differential cross section (see previous section). For the beaming angle, the pair beam achieves the maximum energy: $\Gamma_b \approx 15$. Between $\theta_p = 40^\circ - 16^\circ$ the pair beaming increases (see figure 10(b)) and at the same time the pair energy distribution range decreases (see figure 10(f)).

Figure 11 shows the pair distribution characteristics for 4–0.5 MeV photon beams collision. We represent the momenta distributions for $\theta_p = 180^\circ$, 90° and 45°. Because of the different photon energies (see the previous section), the pair beam is emitted mainly along the higher photon energy direction. For $\theta_p = 180^\circ$ the pair momenta distribution is preferentially emitted in the direction of the CM frame velocity, that is the direction of the maximum photon energy beam. The corresponding energy distribution in figure 11(c) shows that the energy distribution is no longer a Dirac distribution. As in the previous case, the distribution is enlarged between $\Gamma_b \sim 1 - 7.5$ and the pair beam is preferentially at low and high energies. The beaming condition is satisfied for $\theta_p \in [42.4°, 98.6°]$, then all the pairs are emitted in the CM frame velocity direction. However, the pair beam axis is no longer on the AGN symmetry axis, but with an angle of 45° from the symmetry axis. On figure 11(a) the pair angular distribution is peaked due to the BW differential cross section effect. The energy distribution is more uniform and achieves the maximum extent, as we observed in the previous case, with $\Gamma_b 1-8$ (see figure 11(d)). Finally, for $\theta_p = 45^\circ$ the
pair momenta distribution is pinched along the CM frame velocity direction (see figure 11(b)). The pair beam is emitted with an average angle of ~20° from the AGN symmetry axis and pairs are beamed inside ±5°. The corresponding energy distribution varies between $\Gamma_b \sim 3$–6 (see figure 11(e)).

In summary, the two different photon collision situations allow us to observe that for $4$–$4$ MeV photon beam energies, the pair beam is aligned along the AGN symmetrical axis, with the maximum Lorentz factor $\Gamma_b \sim 15$ when the beaming criteria is reached. The pair beam is more collimated due to the BW differential cross section effect. While in the $4$–$0.5$ MeV case the pair beam is off-axis with a lower Lorentz factor $\Gamma_b < 8$ and is less collimated.

5. Conclusions

The pair beaming condition in the BW process has been previously studied in [17]. In this paper, we go further to investigate in detail the effect of the BW differential cross section on pair beaming. We show that, for equal photon beam energies, this effect is weak, i.e. for $\sqrt{s} < 3$, the pairs are emitted mainly on the bisector of the initial photon beam directions. However, for different photon beam energies, the pairs are beamed in the CM frame velocity direction. For $\sqrt{s} > 3$, the effect of the BW differential cross section becomes important. Two peaks in the pair angular distribution appear in the photon incident plane along the photon beam directions. In the case of equal photon energy beams, the two peaks are symmetric and for unbalanced energies more pairs are emitted toward the highest photon energy direction. The energy distributions are modified in consequence. This study shows that from an experimental point of view for photon collisions in the MeV energy range, the angle between the two photon beams has an important effect on pair beaming. This effect could be useful for pair detection, because all the pairs can be emitted in a different direction from the initial photon beams and in a controllable divergence angle. The pair beaming allows us to increase the detection probability. Moreover, for a collision between GeV–keV photon beams the pair beaming is extreme in the GeV photon direction below 0.1° [10].

The application of the BW process in an astrophysical situation, in particular to AGN, shows that the pair beam achieves the maximum Lorentz factor when the beaming conditions are satisfied. For the $4$–$4$ MeV photon collision situation, Lorentz factors $\Gamma_b$ greater than 10 can be reached. In this case $\Gamma_b$ values obtained are close to the AGN jet observations and the BW differential cross section effect is important. For the $4$–$0.5$ MeV photon collision situation, the pair beam is off-axis and the pair beam energy distribution is shifted to lower energies. Then, this study suggests that the BW process could be taken into account in initial conditions or in addition to the Compton rocket pair acceleration process.

Acknowledgments

We thank J C Caillon for helpful discussions. We acknowledge the financial support from the French National Research Agency (ANR-17-CE30-0033-01) - TULIMA Project and US Air Force project AFOSR No. FA9550-17-1-0382. This work is partly supported by the Aquitaine Regional Council.

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