Enhancement of low-mass dileptons in ultraperipheral collisions (continued)

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21ISMD, 13 July 2021

Spectra of dilepton pairs created in ultraperipheral nuclear collisions are calculated. It is shown that production of low-mass e+e- pairs is strongly enhanced (compared to perturbative estimates) due to the Sommerfeld-Gamow-Sakharov (SGS) factor. Coulomb attraction of the non-relativistic components of such pairs leads to the finite value of the ultraperipheral cross section at the very threshold. This can result in the increased intensity of 511 keV photons. It can be recorded at the NICA collider and has important astrophysical implications regarding the 511 keV line emitted from the Galactic center. The analogous effect can be observed in dilepton production at LHC.

Ultraperipheral $\equiv$ interaction of e.m. fields of colliding ions.

The distribution of equivalent photons with a fraction of the nucleon energy x generated by a moving nucleus with the charge Ze can be obtained from the expression for the Poynting vector as

$$\frac{dn}{dx} = \frac{2Z^2\alpha}{\pi x} \ln \frac{u(Z)}{x} \tag{1}$$

if integrated over the transverse momentum up to some value. The physical meaning of the ultraperipherality parameter $u(Z)$ is the ratio of the maximum adoptable transverse momentum to the nucleon mass as the only massless parameter of the problem. Its value is determined by the form factors of colliding ions. It is clearly seen from Eq. (1) that soft photons with small fractions x of the nucleon energy dominate in these fluxes.

According to the equivalent photon approximation, the spectra of dileptons created in ultraperipheral collisions can be obtained from the general expression for the total cross section

$$\sigma_{up}(X) = \int dx_1 dx_2 \frac{dn}{dx_1}\frac{dn}{dx_2}\sigma_{\gamma\gamma}(X). \tag{2}$$

$$\sigma_{\gamma\gamma}(X) = \sigma_{\gamma\gamma}^{BW}(X)T. \tag{3}$$

$$\sigma_{\gamma\gamma}^{BW}(X) = \frac{2\pi\alpha^2}{2m^2}(1-v^2)[(3-v^4)\ln\frac{1+v}{1-v} - 2v(2-v^2)], \tag{4}$$

where $v = \sqrt{1-\frac{4m^2}{M^2}}$ is the velocity of the pair components in the pair rest system, m and M are the electron and dielectron masses, correspondingly. The perturbative Breit-Wheeler cross section tends to 0 at the threshold of pair production $M = 2m$ ($v = 0$) and decreases as $\frac{1}{M^2}\ln M$ at very large M ($v \to 1$). The non-perturbetive SGS-factor is $1/v$-divergent at small v:

$$T = \frac{2\pi\alpha}{v(1-\exp(-2\pi\alpha/v))}, \tag{5}$$

The differential distributions of leptons are easily computed from the integrands of (2). For example, the distribution of the relative velocity v is

$$\frac{d\sigma}{dv^2} = \frac{16(Z\alpha)^4}{3m^2}[(3-v^4)\ln\frac{1+v}{1-v} - 2v(2-v^2)]\frac{\alpha}{v(1-\exp(\frac{-2\pi\alpha}{v}))} \ln^3\frac{u\sqrt{s_{nn}(1-v^2)}}{2m}. \quad (6)$$

Here s_{nn} is the total energy of two colliding nucleons squared. It can be represented by the following expressions $s_{nn} = 4m_n^2\gamma_c^2 = 2m_n^2(\gamma_r + 1) = 2m_n(E_k + 2m_n)$ where m_n is a nucleon mass, γ_c and γ_r are the Lorentz-factors of the nucleon in the center of mass and rest (of another nucleon) systems and E_k corresponds to the nucleon kinetic energy in the non-relativistic domain. The threshold of pair creation in the rest system of one of the nucleons is $E_{k,t} = 4m(1+\frac{m}{2m_n}) \approx 2.05$ MeV.

The distribution is shown in the left-hand side of Fig. 1.

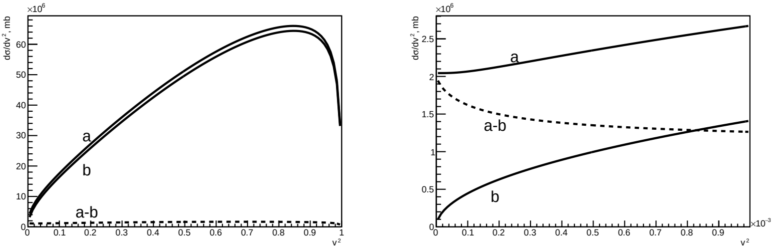

Fig. 1. The distribution of the relative velocities in dielectrons produced in ultraperipheral collisions at NICA energy $\sqrt{s_{nn}}$=11 GeV with (a) and without (b) account of the SGS-factor. Their difference (a-b) is shown by the dashed line. The velocities for the region of small masses are shown in the right-hand side. Note the factor 10^{-3} at the abscissa scale.

Its most interesting feature at small v is deciphered at the larger scale in the right-hand side of the same Figure. It demonstrates the crucial difference between the distributions with (a) and without (b) account of the SGS factor. At low velocities v (i.e. small pair masses M) the two curves tend to different values. It is finite with account of SGS factor and vanishes without it. This is a clear signature of its $1/v$-law. The non-relativistic nature of the pair of annihilating particles separates the short-distance annihilation process (taking place at distances up to $O(1/m)$) from the long-distance interactions (characterized by the Bohr radius of the pair $O(1/m\alpha)$), responsible for the SGS-effect.
The same peculiar feature is seen in the energy behaviour of the total cross section of the ultraperipheral processes (2). They do not vanish at the very threshold $M_t = 2m$ but stay constant. This remarkable effect of the mutual attraction of the created components is well known and described in the textbooks on non-relativistic quantum mechanics (see, e.g., the 4-th and later editions of the Landau-Lifshitz books).

The energy distributions of electrons and positrons created in ultraperipheral processes coincide with the corresponding distributions of photons in the clouds around colliding nuclei. Therefore they are directly obtained from Eq. (2) by omitting the x_i-integrations. One gets

$$\frac{d^2\sigma}{dE_1 dE_2} = \frac{4(Z\alpha)^4}{m^4} \frac{\alpha(1-v^2)^2[(3-v^4)\ln\frac{1+v}{1-v} - 2v(2-v^2)]}{v(1-\exp(\frac{-2\pi\alpha}{v}))} \ln\frac{u\sqrt{s_{nn}}}{E_1} \ln\frac{u\sqrt{s_{nn}}}{E_2}. \quad (7)$$

As usual, here $v = \sqrt{1-\frac{4m^2}{M^2}} = \sqrt{1-\frac{m^2}{E_1 E_2}}$.

The transverse momentum p_t-distribution of leptons can also be obtained from the general formula (2) if the differential Breit-Wheeler distribution is inserted there:

$$\frac{d\sigma^{BW}}{dp_t} = \frac{2\pi\alpha^2(1-v^2)}{m^2 p_T}\frac{1-p_t^2(1-v^2)/2m^2}{\sqrt{1-p_t^2(1-v^2)/m^2}}. \tag{8}$$

The transverse momenta of leptons are strongly limited in ultraperipheral production for $p_t \geq m$ as

$$\frac{d\sigma^{up}}{dp_t} = \frac{16(Z\alpha)^4}{9\pi p_t^3}\ln^3\frac{u^2 s_{nn}}{p_t^2}. \tag{9}$$

Summarizing, it is shown how the total cross sections and differential distributions of lepton production in ultraperipheral nuclear collisions can be calculated with account of both perturbative (Breit-Wheeler) and non-perturbative (Sommerfeld-Gamov-Sakharov) contributions. The fast energy increase and the constant cross sections at the threshold are the most peculiar features of these processes. Their particular values are much larger for heavy nuclei with large charge Ze surrounded by stronger electromagnetic fields. It results in the factor $(Z\alpha)^4$ for cross sections.