Vladimir Nikolaevich Baier

Vladimir Baier, professor of physics and an eminent Russian scientist, was born on 27 September 1930. Last week we commemorated the 80 anniversary of his birthday. He died on 19 February in his car when he had come the Institute in the morning as usual. His heart stopped.

I collaborated with him within 46 years. Three monographs, some reviews and more than 100 articles were published by us during this time. And so I will tell about him.

Baier started his academic career in 1955 as a postgraduate student in the Lebedev Physical Institute of the USSR Academy of Sciences in Moscow. He worked there under the supervision of Nobel laureate Igor Tamm. After receiving his PhD in 1959, Baier joined the newly founded Institute of Nuclear Physics in Novosibirsk, led

by Gersh Budker.
Baier was one of the first to envision the electron-positron colliders. He shared his idea with Budker, who initially considered it insane. Attitudes soon changed and Baier
took an active part in making his idea a reality. Together with his colleagues Baier obtained a number of fundamental results in QED.
His works were devoted to single and double bremsstrahlung and electroproduction in collisions of high-energy electrons, radiative corrections to cross-sections at high-energy, radiative polarization and radiative-return theory. Baier did much to advance the quasi-real photon /electron method, which lies at the root of the parton model - one of the main tools in the modern theory of strong interactions at high energy.
The operator approach to QED

in an external field became a clue to the construction of the general theory of QED processes in periodic structures such as the laser wave, undulator, and monocrystal.
For many years Baier combined intensive research and teaching. He made a significant contribution to the establishment and development of Novosibirsk State University. Many generations of students have vivid memories of him and his QED textbooks are still in demand.
Vladimir Baier will remain in the memory of those who knew him personally, while his scientific works and methods will continue in physics for a long time.

Exact Theory of the Photoproduction of Charged Particles in External Fields

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1 General expressions for the probability of process

Our analysis is based on the the polarization operator (Baier, Katkov, Strakhovenko, 1975).

Magnetic field purely (Baier, Katkov, 2007). Electric field purely (Baier, Katkov, 2010).

The imaginary part of this operator on the mass shell ($k^2 = 0$) determines W

$$W = \frac{\alpha m^2 r}{2\pi \mathrm{i}\omega}\mu\nu \int\limits_{-1}^{1} dv \int\limits_{-\infty - \mathrm{i}0}^{\infty - \mathrm{i}0} f(v,x)\exp(\mathrm{i}\psi(v,x))x dx; \tag{1}$$

$$r = \frac{\omega^2 - k_3^2}{4m^2}, \quad \nu = eE/m^2, \quad \mu = eH/m^2. \tag{2}$$

Here

$$f(v,x) = \frac{\cosh(\nu x)(\cos(\mu x) - \cos(\mu x v))}{\sinh(\nu x)\sin^3(\mu x)} + \frac{\cos(\mu x)(\cosh(\nu x) - \cosh(\nu x v))}{\sin(\mu x)\sinh^3(\nu x)}, \tag{3}$$

$$\psi(v,x) = 2r\frac{\cosh(\nu x) - \cosh(\nu x v)}{\nu \sinh(\nu x)} + 2r\frac{\cos(\mu x) - \cos(\mu x v)}{\mu \sin(\mu x)} - x. \tag{4}$$

We can return to a covariant form of the process description using the following expressions

$$E^2, H^2 = \left(\mathcal{F}^2 + \mathcal{G}^2\right)^{1/2} \pm \mathcal{F}, \tag{5}$$

$$\mathcal{F} = \left(\mathbf{E}^2 - \mathbf{H}^2\right) / 2, \quad \mathcal{G} = \mathbf{EH}. \tag{6}$$

The SQA is valid for $r \gg 1$ and can be derived by expanding the functions $f(v,x)$, $\psi(v,x)$ over x powers.

$$W^{(SQA)} = \frac{\alpha m^2}{3\sqrt{3}\pi\omega} \int\limits_0^1 \frac{9 - v^2}{1 - v^2} K_{2/3}(z)\, dv,$$

$$z = \frac{8}{3\left(1 - v^2\right)\kappa},$$

$$\kappa^2 = 4r(\mu^2 + \nu^2) = -\frac{e^2}{m^6}\left(F^{\mu\nu}k_\nu\right)^2. \tag{7}$$

To get the correction to the probability in SQA we shall keep leading to leading powers of x. We have

$$W^{(1)} = -\frac{\alpha m^2 \widetilde{\mathcal{F}}}{30\sqrt{3}\pi\omega\kappa} \int\limits_0^1 \frac{dv}{1 - v^2} G(v, z), \tag{8}$$

$$\widetilde{\mathcal{F}} = \frac{e^2 \mathcal{F}}{m^4} = \frac{\nu^2 - \mu^2}{2},$$

where

$$G\left(v,z\right) = 2\left(1+v^2-27z^2\right)K_{1/3}\left(z\right) + 3\left(7-v^2\right)zK_{2/3}\left(z\right). \tag{9}$$

$$W^{(1)} = \frac{6\alpha m^2\widetilde{\mathcal{F}}}{5\omega\kappa^2}\sqrt{\frac{2}{3}}\exp\left(-\frac{8}{3\kappa}\right), \ \kappa \ll 1 \tag{10}$$

$$\frac{W^{(1)}}{W^{(SQA)}} = \frac{64\widetilde{\mathcal{F}}}{15\kappa^3},$$

2 Region of intermediate photon energies

If $E/E_0 = \nu \ll 1$ ($E_0 = 1.32 \cdot 10^{16}\,\mathrm{V}\,/\,\mathrm{cm}$), $H/H_0 = \mu \ll 1$ ($H_0 = 4.41 \cdot 10^{13}\,\mathrm{G}$) and $r \lesssim \nu^{-2/3}$ the SQA is non-applicable. If $r \gg \nu^2$ is fulfilled, the method of stationary phase can be applied at integration over x. In this case the small values of v contribute to the integral over v.

So one can expand the phase $\psi(v,x)$ over v and extend the integration limit to the infinity. We get

$$W=\frac{\alpha m^2 r\mu\nu}{2\mathrm{i}\sqrt{\mathrm{i}\pi\chi\left(x\right)}\omega}\int\limits_{-\infty}^{\infty} f(0,x)\exp\left\{-\mathrm{i}\varphi\left(x\right)\right\}xdx, \tag{11}$$

where

$$\varphi\left(x\right)=2r\left(\frac{1}{\mu}\tan\frac{\mu x}{2}-\frac{1}{\nu}\tanh\frac{\nu x}{2}\right)+x, \tag{12}$$

$$\chi\left(x\right)=rx^2\left(\frac{\nu}{\sinh(\nu x)}-\frac{\mu}{\sin(\mu x)}\right). \tag{13}$$

From the equation $\varphi'(x_0)=0$ we find the saddle point x_0

$$\tan^2\frac{\nu s}{2}+\tanh^2\frac{\mu s}{2}=\frac{1}{r},\quad x_0=-\mathrm{i}s. \tag{14}$$

At $r\gg 1$ we have

$$W=\frac{3\alpha m^2\kappa}{16\omega}\sqrt{\frac{3}{2}}\exp\left(-\frac{8}{3\kappa}+\frac{64\widetilde{\mathcal{F}}}{15\kappa^3}\right) \tag{15}$$

This expression coincides with Eq.(10) for $\widetilde{\mathcal{F}}\ll\kappa^3\ll 1$.

So the overlapping region of both approximations exists.

At energy $r \ll 1$ ($\nu^2 \ll r \ll \nu^{2/3}$) we have $\nu s \simeq \pi - 2\sqrt{r}$,

$$W = \frac{\alpha m^2 \mu}{4\omega\sqrt{r}} \coth(\pi\eta) \tag{16}$$

$$* \exp\left(-\frac{1}{\nu}\left(\pi - 4\sqrt{r} + \frac{2r}{\eta}\tanh\frac{\pi\eta}{2}\right)\right), \tag{17}$$

At $\eta \gg 1$ the probability W has been increased by the factor $\eta\pi \exp(\pi r/\nu)$ in comparison with the case of the absence of magnetic field.

3 Approximation at low photon energy

At $r \sim \nu^2$ another approach has to be. We close the integration over x contour in the lower half-plane and represent this equation in the following form

$$W=\frac{\alpha m^2 r}{2\pi \mathrm{i}\omega}\mu\nu\int\limits_{-1}^{1}dv\sum_{n=1}^{\infty}\oint f(v,x)\exp(\mathrm{i}\psi(v,x))xdx, \tag{18}$$

where the path of integration is any simple closed contour around the point $-\mathrm{i}\pi n/\nu$. Let us choose the contour near this point in the following way $\nu x=-\mathrm{i}\pi n+\xi_n,\quad |\xi_n|\ \sim\sqrt{r}\sim\nu$ and expand the function entering in over the variables ξ_n. In the case $\nu\ll 1$, because of appearance of the factor $\exp\left(-\mathrm{i}\pi n/\nu\right)$, the main contribution to the sum gives the term $n=1$. Near the point $-\mathrm{i}\pi/\nu$ the main terms of expansion such as $(\xi\equiv\xi_1)$

$$f=\frac{2\mathrm{i}}{\xi^3}\coth(\pi\eta)\cos^2\frac{\pi v}{2}, \tag{19}$$

$$\psi=\frac{4r}{\xi\nu}\cos^2\frac{\pi v}{2}-\frac{\xi}{\nu}+\frac{\mathrm{i}\pi}{\nu}.$$

We find after integgration over ξ and v

$$W=\frac{\alpha m^2}{\omega}\eta\pi\coth(\pi\eta)\ \exp\left(-\frac{\pi}{\nu}\right)I_1^2\left(z\right), \tag{20}$$

$$z=\frac{2\sqrt{r}}{\nu},$$

where $\mathrm{I}_n(z)$ is the Bessel function of imaginary argument. The found probability is applicable for $r \ll \nu$.

For $r \gg \nu^2$ the asymptotic representation $\mathrm{I}_n(z) \simeq \exp(z) \big/ \sqrt{2\pi z}$ can be used. As a result one obtains the probability (16) if in the exponent of the last to leave out the term $\propto r/\nu$. At very low photon energy $r \ll \nu^2$, using the expansion of the Bessel functions for the small value of argument, we have

$$W = \frac{\alpha m^2 r}{\omega \nu^2} \eta\pi \coth(\pi\eta) \exp\left(-\frac{\pi}{\nu}\right). \tag{21}$$

The probability under consideration is of interest of theoretics for arbitrary values μ and ν. For $r \ll \nu^2 \big/ \left(1+\nu^2\right)$ one can conserve in the phase $\psi(v,x)$ the term $-x$ only. After integrating over v we get the following equation for the probability

$$
\begin{aligned}
W &= \frac{\alpha m^2 r}{\mathrm{i}\pi\omega} \sum_{n=1}^{\infty} \oint F(y_n) \exp\left(-\mathrm{i}\frac{y_n}{\nu}\right) dy_n, \quad (22)\\
y_n &= -\mathrm{i}n\pi + y;\\
F(y) &= \frac{\cosh(y)\left(\eta y \cos\left(\eta y\right) - \sin\left(\eta y\right)\right)}{\sinh y \sin^3 \eta y} \qquad (23)\\
&\quad + \frac{\eta \cos(\eta y)\left(y \cosh y - \sinh y\right)}{\sinh^3 y \sin(\eta y)}.
\end{aligned}
$$

Summing the residues in the points $y_n = -\mathrm{i}n\pi$ one obtains

$$
\begin{aligned}
W &= \frac{\alpha m^2 r}{\omega} \sum_{n=1}^{\infty} \exp\left(-\frac{\pi n}{\nu}\right) \Phi\left(z_n\right), \qquad (24)\\
z_n &= \eta\pi n,\\
\Phi\left(z_n\right) &= \frac{z_n}{\nu^2} \coth z_n \qquad (25)\\
&\quad + \frac{2}{\sinh^2 z_n}\left[\frac{\eta z_n}{\nu} + \left(1+\eta^2\right) z_n \coth z_n - 1\right].
\end{aligned}
$$

At $\eta \to 0$, $z_n \to 0$ we have

$$\Phi = \frac{1}{\nu^2} + \frac{2}{\nu\pi n} + \frac{2}{\pi^2 n^2} + \frac{2}{3}, \tag{26}$$

$$W = \frac{\alpha m^2 r}{\omega}[\left(\frac{1}{\nu^2} + \frac{2}{3}\right)\frac{1}{e^{\pi/\nu} - 1} \tag{27}$$
$$- \frac{2}{\pi\nu}\ln\left(1 - e^{-\pi/\nu}\right) + \frac{2}{\pi^2}\mathrm{Li}_2\left(e^{-\pi/\nu}\right)]$$

where $\mathrm{Li}_2(z)$ is the Euler dilogarithm. In the opposite case $\eta \to \infty$, $z_n \to \infty$ one obtains

$$\Phi = \frac{\pi\eta n}{\nu^2}, \quad W = \frac{\alpha m^2 r}{\omega\nu^2}\frac{\pi\eta}{4}\sinh^{-2}\frac{\pi}{2\nu}. \tag{28}$$

4 Conclusion

The probability of the process has been calculated using three different overlapping approximation. In the region of SQA applicability the created by a photon particles have ultrarelativistic energies. The role of fields here is to transfer the required transverse momentum and the electric and magnetic field actions are equivalent. But even in this case it is necessary to note a special significance of a weak electric field in the removal of the root divergence of the probability when the particles of pair are created on the Landau levels.

In the region $\omega \lesssim 2m$ ($r \lesssim 1$) the energy transfer from electric field to the created particles becomes appreciable and for $\omega \ll m$ it determines the probability of the process mainly. At $\omega \ll eE/m$ the photon assistance in the pair creation comes to the end and the probability under consideration defines the probability of photon absorption by the particles created by electromagnetic fields. In this case the influence of a magnetic field on the process is connected with the interaction of the magnetic moment of the created particles and magnetic field. This interaction, in particular, has appeared in the distinction of the pair creation probability by field for scalar and spinor particles (Schwinger, 1951).


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