FORMATION OF POSITRONIUM UPON COLLISION OF FAST PARTICLES, AND ITS DECAY

G.V. Meledin, V.G. Serbo, and A.K. Slivkov
Novosibirsk State University
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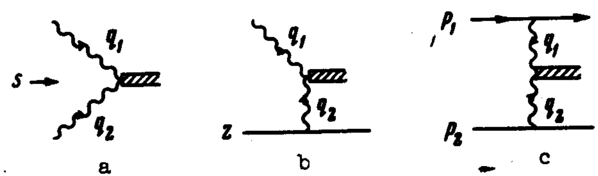
1. When a high-energy γ quantum collides with a nucleus or when two charged particles collide, there may be produced, besides an electron-positron pair, also a positronium in accordance with the two-photon scheme indicated in the figure (we are dealing with parapositronium - the bound state e^+e^- with spin S = 0). However, the cross section for the production positronium is smaller by a factor of α^3 than the cross section for the production of the e^+e^- pair, since, roughly speaking, it is necessary to fall in the momentum space in the momentum-value interval $(\Delta p)^3 \sim (m\alpha)^3$. The cross section for the production of positronium by two photons with momenta q_1 and q_2 (Fig. a) can be expressed in terms of the width of the positronium decay Γ [1]

$$\sigma_a = \frac{4\pi^2\Gamma}{m}\,\delta(s - 4m^2) = 2\pi^2\alpha^5\delta(s - 4m^2), \tag{1}$$

where $s = (q_1 + q_2)^2$, m is the electron mass, and $\alpha = 1/137$. In writing down (1) we took into account the fact that the decay width

$$\Gamma = \frac{1}{2} m\alpha^5 \tag{2}$$

is much smaller than the binding energy of the positronium $m\alpha^2/4$.



Using (1), we obtain in the Weizsacker-Williams approximation the cross section for the production of positronium in the field of a nucleus Ze by a photon with energy $\omega \gg m$ (Fig. b).

$$\sigma_6 = \int \sigma_g n(s)\, ds = \frac{\pi \alpha^6 Z^2}{m^2} \ln \frac{\omega}{m} = 7{,}1 \cdot 10^{-34} \ln \frac{\omega}{m} \ (\mathrm{cm}^2) \tag{3}$$

Here [3]

$$n(s)ds = \frac{Z^2\alpha}{\pi} \frac{ds}{s} \int_{|q_2^2|_{min}}^{s} \left(1 - \frac{|q_2^2|_{min}}{|q_2^2|}\right) \frac{dq_2^2}{q_2^2} \tag{4}$$

is the spectrum of the equivalent photons, and $|q_2^2|_{min} = s^2/4\omega^2$.

If we do not integrate with respect to q_2^2 in (3), then we obtain the angular distribution (the positronium emission angle is $\theta \ll m/\omega$), which coincides with [4]

$$\frac{d\sigma_6}{d\Omega} = \frac{Z^2\alpha^6\theta^2}{2m^2[\theta^2 + 4m^4\omega^{-4}]^2} \ . \tag{5}$$

The cross section (3) differs only by a factor $9\pi\alpha^3/28$ from the cross section for the production of an e^+e^- pair in the same process. Therefore the cross section for the production of positronium in collisions of two fast particles with charges Z_1e and Z_2e and masses M_1 and M_2 (Fig. c) should also differ only by this factor from the cross section obtained by Landau and Lifshitz [5] for the production of the e^+e^- pair. Thus, this cross section is

$$\sigma_6 = \frac{(Z_1Z_2)^2\alpha^7}{3m^2} \ln^3\gamma = 5{,}5 \cdot 10^{-37} (Z_1Z_2)^2 \ln^3\gamma \ (\mathrm{cm}^2), \tag{6}$$

where $\gamma = (p_1p_2)/M_1M_2$ is the Lorentz factor of the relative velocity of the colliding particles. This result can be obtained from the general formula (3) for the production of reasonances by the two-photon mechanism, obtained by Budnev and Slivkov [6], by substituting in it the value of Γ (2) (the result of [6] must also be multiplied by 2. This factor of 2, which takes into account the identity of the decay photons, has been left out from [6]).

We note that at the energies reached in modern accelerators, the cross sections (3) and (6) are of the same order as the cross section for the production of hadron resonances [6].

2. In some experiments (e.g., with colliding beams), the positronium produced with momentum $\vec{p}$ ($\tilde{\gamma} = |\vec{p}|/2m$) stays for a certain time Δt in the region of the magnetic field H. This can lead to new positronium decay channels. If in the system connected with the positronium the electric field $E \simeq \tilde{\gamma}H$ is sufficiently large, then it can lead to a decay of the positronium (autoionization) into e^+ and e^- (with energies that are practically equal in the laboratory frame). This uncovers a new possibility of registering free positronium. The probability of such a decay is equal to [7]

$$W = 2\frac{\Delta t}{\tilde{\gamma}T_0} \frac{E_0}{E} \exp\left(- \frac{E_0}{6E}\right), \tag{7}$$

where $T_0 = (m\alpha^2)^{-1} = 2.3 \times 10^{-17}$ sec and $E_0 = m^2\alpha^{5/2} = 1.7 \times 10^7$ Oe. At $\gamma \sim 10^2 - 10^3$ and at a field dimension $\sim$1 m, the probability is $W \sim 1$ at

$\tilde{\gamma}H = E_0/120 = 1.4 \times 10^5$ Oe (without the magnetic field, the path of the positronium increases to $\tilde{\gamma}/\Gamma \sim 4 - 40$ m). We note that W is not very sensitive to changes of Δt, but decreases very sharply with decreasing $\tilde{\gamma}H$. Thus, when $\tilde{\gamma}H$ decreases by 30% from the value corresponding to $W \sim 1$, the probability (7) drops by more than three orders of magnitude.

In weaker fields, where there is practically no ionization, positronium can go over into orthopositronium (with spin S = 1), the lifetime of which is larger by three orders of magnitude. To obtain an appreciable orthopositronium yield, it is necessary to have $\tilde{\gamma}H \sim (\varepsilon_{ortho} - \varepsilon_{para})/\mu \sim 10^5$ Oe (there is no ionization in such fields). The characteristic transition length is

$$\tilde{\gamma}/(\epsilon_{ortho} - \epsilon_{para}) \sim 2\cdot 10^{-2}\,\tilde{\gamma}(\mathrm{cm})$$

Thus, by varying the field it is possible, in principle, to obtain free positronium in the para- and ortho-states.

All the obtained formulas are valid also for the production of the dimuon ($\mu^+\mu^-$ in the bound state), with the obvious replacement of the electron mass m by the muon mass. The corresponding cross sections are smaller by almost four orders of magnitude than for positronium.

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