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ON PRODUCTION AND DETECTION OF AXIONS AT PASSING ELECTRONS THROUGH MATTER

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A b s t r a c t

The bremsstrahlung mechanism of axion production at electron scattering on a nucleus is studied in detail. The cross sections of the reactions allowing to detect axions at their passing through matter are calculated.

1. INTRODUCTION

At the recent time the question of the existence of a light pseudoscalar particle, 'the axion', has been widely discussed. A necessity to introduce the axion into a theory is that there are pseudoparticle solutions in the non-Abelian gauge theories. Due to these solutions the P and CP invariances in quantum chromodynamics can be broken[1]. Invariance is conserved, by introducing a global U(1) symmetry[2]. Then, as shown by Weinberg[3] and Wilczek,[4] a light pseudoscalar particle must exist.

In connection with this, the question arises on a possibility to observe this particle in experiments. One of the axion production method is a process of their emission in the reaction $e+Z \to e+Z+a$ [5]. In the present paper the analytical expressions for the differential and total cross sections of this process are obtained. We also discuss some possible methods for detecting the axions at their passing through matter. Such processes are: the Compton-effect $e+a \to e+\gamma$, the electron-positron pair production in a field of nucleus $a+Z \to e^+ + e^- + Z$ by axions, and the process similar to the photoeffect where the atomic electron transits to continous spectrum when axion absorption occurs. For these reactions the accurate expressions for the differential and total cross sections are obtained.

Some of the questions of axion production and detection being considered here have been previously discussed in[5,6,7].

We write the electron-axion interaction in the form $ig\bar{e}\gamma_5 e a$, where $g = 2^{1/4} G^{1/2} m_e C$, $C \sim 1$; while in the numerical results below we take $C = 1$.

2. Axion Production

Let us consider the process $e+Z \to e+Z+a$. The conditions of Borh approximation applicability is assumed to be fulfilled, i.e. $Z\alpha/v_1 \ll 1$, $Z\alpha/v_2 \ll 1$, where v_1 and v_2 are the velocities of the initial and finite electrons, respectively. In addition, we assume that the initial electron state is unpolarized, and we are not interested of polarization of the electron in its finite state. With these assumptions, the differential cross section for the process under consideration with the axion emission at a given energy and in a given direction, as well as with the secondary electron emission in a given direction has the form:

$$d\sigma = \sqrt{2}\,\frac{Z^2\alpha^2 G m^2 c^2}{8\pi^3}\,\frac{p_2 K}{p_1}\,d\Omega_a\,d\Omega_e\,d\omega\,\frac{1}{\vec{q}^{\,4}}\,\times$$
$$\times\Big\{\Big[1+\frac{1}{2}\frac{\alpha_1}{\alpha_2}+\frac{1}{2}\frac{\alpha_2}{\alpha_1}\Big]+\frac{1}{2}\mu^2\vec{q}^{\,2}\Big[\frac{1}{\alpha_1}+\frac{1}{\alpha_2}\Big]^2-\frac{2\omega^2\vec{q}^{\,2}}{\alpha_1\alpha_2}- \qquad (1)$$
$$-2\mu^2\Big[\frac{\varepsilon_1}{\alpha_2}+\frac{\varepsilon_2}{\alpha_1}\Big]^2\Big\}$$
$$\alpha_1 = -2\varepsilon_1\omega+2\vec{p}_1\vec{K}+\mu^2;\quad \alpha_2 = 2\varepsilon_2\omega-2\vec{p}_2\vec{K}+\mu^2$$
$$\vec{q} = \vec{p}_2+\vec{K}-\vec{p}_1,\quad p_1=|\vec{p}_1|,\; p_2=|\vec{p}_2|,\; K=|\vec{K}|$$

Here $\varepsilon_1, \vec{p}_1$ and $\varepsilon_2, \vec{p}_2$ are the energy and the momentum of the initial and finite electrons, respectively; $\omega, \vec{K}$ are the energy and the momentum of axion; m and μ are the masses of electron and axion, respectively.

The result of integration over the secondary electron angle is a very cumbersome expression, therefore we shall confine ourselves to an anlysis of the angular distribution of axions in the ultrarelativistic case, that is at $\varepsilon_1, \varepsilon_2, \omega \gg m, \mu$. Within this limit the angular distribution of axions has a sharp ma-

ximum near the direction of the incident electron momentum. The axions are mainly emitted in the cone at an angle $\sim m/\varepsilon_1$. It is easy to understand a qualitative character of the angular distribution of axions at a given energy, examining the appropriate formulae at $\mu = 0$; at $\mu \neq 0$ formulae become cumbersome, however, a qualitative behaviour is not changed essentially. In the ultrarelativistic case, when $\mu = 0$, the angular distribution of axions at a given energy, irrelative of the direction of the secondary electron emission, has the form:

$$d\sigma = \frac{\sqrt{2}\,G c^2}{2\pi}\,\alpha^2 Z^2\,\frac{\omega}{\varepsilon_1^2}\Big[\ln\frac{2\varepsilon_1\varepsilon_2}{m\omega}-\frac{1}{2}\Big]\frac{d\tau_1^2\,d\omega}{(1+\tau_1^2)^2} \qquad (2)$$

where $\tau_1 = \frac{\varepsilon_1}{m}\theta_1$, $\cos\theta_1 = \frac{\vec{p}_1\vec{K}}{p_1 K}$, $\theta_1 \ll 1$

Integration (1) over directions of escape of the axion and the secondary electron leads to the following expressions for the spectral distribution of axion emission:

$$\frac{d\sigma}{d\omega} = \sqrt{2}\,\frac{Z^2\alpha^2 G m^2 C^2}{2\pi}\,\frac{p_2 K}{p_1}\Big\{-\frac{2\omega^2(\varepsilon_1\varepsilon_2+m^2)}{p_1^2 p_2^2\,\Omega}-\frac{2\mu^2}{\Omega}\Big(\frac{1}{p_1^2}+$$
$$+\frac{1}{p_2^2}\Big)-\frac{8\mu^2\omega^2}{\Omega^2}-\frac{1}{4K}\Big(\frac{l_1}{p_1^3}-\frac{l_2}{p_2^3}\Big)+\frac{\mu^2\omega}{2K\Omega}\Big(\frac{l_1\varepsilon_1}{p_1^3}+\frac{l_2\varepsilon_2}{p_2^3}\Big)+$$
$$+\frac{\mu^4}{4K\Omega}\Big(\frac{l_2}{p_2^3}-\frac{l_1}{p_1^3}\Big)+\frac{128}{3}\frac{\mu^2K^2}{\Omega^3}\big(m^2\omega^2+\mu^2\varepsilon_1\varepsilon_2\big)+$$
$$+\frac{L}{p_1 p_2}\Big[-\frac{\omega}{8K}\Big(\frac{\varepsilon_1 l_1}{p_1^3}+\frac{\varepsilon_2 l_2}{p_2^3}\Big)+\frac{1}{4}\Big(\frac{1}{p_1^2}+\frac{1}{p_2^2}\Big)+\frac{\mu^2}{8K}\Big(\frac{l_1}{p_1^3}-$$
$$-\frac{l_2}{p_2^3}\Big)+\frac{\mu^2}{4\Omega}\Big(\frac{1}{p_1^2}+\frac{1}{p_2^2}\Big)\big(2\varepsilon_1\varepsilon_2-2m^2+\mu^2\big)+ \qquad (3)$$
$$+\frac{2\omega^2-\mu^2}{\Omega}-\frac{8}{3}\frac{\mu^2K^2\varepsilon_1\varepsilon_2}{\Omega^2}\Big]\Big\},$$

where

$$l_1 = \ln \frac{2\varepsilon_1\omega + 2p_1\kappa - \mu^2}{2\varepsilon_1\omega - 2p_1\kappa - \mu^2}, \quad l_2 = \ln \frac{2\varepsilon_2\omega + 2p_2\kappa + \mu^2}{2\varepsilon_2\omega - 2p_2\kappa + \mu^2},$$

$$L = \ln \frac{2\varepsilon_1\varepsilon_2 + 2p_1p_2 - 2m^2 + \mu^2}{2\varepsilon_1\varepsilon_2 - 2p_1p_2 - 2m^2 + \mu^2}, \quad \Omega = 4m^2\kappa^2 + 4\mu^2\varepsilon_1\varepsilon_2 + \mu^4$$

The diagrams for spectral distribution at some values of the axion'mass and of the incident electron energy aro presented in Figs. 1 and 2. From (3) it is easy to see that $\frac{d\sigma}{d\omega} \sim \kappa$ at $\kappa \to 0$. This result becomes clear if one takes into consideration the fact that the axion-electron vertex has an additional degree κ in the numerator, compared to the photon-electron one, hence, at $\kappa \to 0$

$$\frac{d\sigma_a}{d\omega} \sim \frac{d\sigma_\gamma}{d\omega}\kappa^2 \sim \kappa$$

In the ultrarelativistic case, expression (3) is essentially simplified and takes the visible form:

$$\frac{d\sigma}{d\omega} = \sqrt{2}\,\frac{Z^2\alpha^2 G c^2 m^2}{2\pi}\,\frac{\omega^3}{3\varepsilon_1^2\Phi}\left[1 + \frac{m^2\omega^2}{2\Phi}\right]\left[\ln\frac{4\varepsilon_1^2\varepsilon_2^2}{\Phi} - 1\right] \qquad (4)$$

where $\Phi = m^2\omega^2 + \mu^2\varepsilon_1\varepsilon_2$

The total cross section is obtained by integration of exp.(3). The results for some values of μ are given in Fig.3. They coincide, with an accuracy of 4%, with the values given in the paper /5/ for the total cross section of the process under consideration.

In the ultrarelativistic case, at $\mu = 0$ the total cross section has a simple form:

$$\sigma = \sqrt{2}\,\frac{Z^2\alpha^2 G c^2}{4\pi}\left(\ln\frac{2\varepsilon_1}{m} - \frac{3}{2}\right) \qquad (5)$$

Proceed now to another method of axion production: the decay of orthopositronium to produce an axion and a photon. B.A.Swarts drew our attention to a possibility to use this process for axion production. The decay rate under study is equal to:

$$W = \frac{G m^3 c^2 \alpha^4}{6\pi\sqrt{2}}\left(1 - \frac{\mu^2}{4m^2}\right) \qquad (6)$$

$$\mu < 2m.$$

When our work had completed, we have acquainted ourselves with the preprint /7/ wherein the decay rate is calculated as well. Our result differs from that in /7/ by a factor of 2.

3. Methods of Axion Detection

One of possible methods for detecting the axions is the Compton-effect $a + e \to e + \gamma$. The spectral distribution of the photon emission in the system of rest initial electron is the following:

$$\frac{d\sigma}{d\omega_1} = \frac{\sqrt{2}\,G m^2 \alpha c^2}{2(\omega^2 - \mu^2)}\left\{\frac{\mu^2(\omega_1 - \omega)}{m\omega_1(2m\omega + \mu^2)} + \right.$$

$$\left. + \left(\frac{1}{2m\omega + \mu^2} - \frac{1}{2m\omega_1}\right)^2 (m\mu^2 + \omega_1\mu^2 + 2m\omega\omega_1)\right\} \qquad (7)$$

where ω and ω_1 are the axion and photon energies, respectively. The total cross section for this process has the form:

$$\sigma = \frac{\alpha G c^2}{\sqrt{2}}\,\frac{1}{\gamma^2}\left[\frac{x^2 - 2\lambda\delta}{x}\ln\left|\frac{\gamma + \delta}{\gamma - \delta}\right| + \frac{x\gamma\delta}{2(x+1)^2} + \right.$$

$$\left. + \frac{2\lambda\gamma}{x} + 2\left(\frac{2}{\gamma} - x + \lambda\right)\frac{\gamma}{x+1}\right] \qquad (8)$$

$$\gamma = \sqrt{(x-\lambda)^2 - 4\lambda}, \quad \delta = x + 2 - \lambda, \quad \lambda = \mu^2/m^2, \quad x = \frac{s - m^2}{m^2}, \quad s = (p_1 + \kappa)^2$$

Here p_1 and κ are the 4-momenta of initial electron and axion, respectively. In the case when $\mu = 0$, formula (4) for a cross section is transformed into the following expression:

$$\sigma = \frac{\alpha G c^2}{\sqrt{2}} \frac{1}{x} \left[\ln(1+x) - \frac{x(3x+2)}{2(x+1)^2} \right] \qquad (9)$$

The dependence of a cross section on the incident axion energy, when the initial electron is at rest, is shown in Fig.4.

Let us consider now the process analogous to the photoeffect $a+e+Z \to e+Z$. The cross section is calculated for the atoms with $Z \ll 137$. With the restrictions on the axion mass [3,4] taken into account, the axion energy is always high in comparison to the coupling energy of the K-electron. For this reason, we calculate the cross section for this case only. Under the above assumptions, the cross section for the process in question on the K-electron has the following form:

$$\sigma = \frac{2\sqrt{2}\, G c^2 (Z\alpha m)^5}{\kappa} \left\{ \frac{4\omega(\omega^2+\mu^2)}{(\kappa^2-p^2)^4} - \frac{2\omega}{(\kappa^2-p^2)^3} - \frac{64}{3} p^2\kappa^2 \frac{m\mu^2}{(\kappa^2-p^2)^6} - \frac{16\mu^2\kappa^2\varepsilon}{(\kappa^2-p^2)^5} - \frac{\omega}{p\kappa}\frac{1}{(p^2-\kappa^2)^2} \ln\left|\frac{p+\kappa}{p-\kappa}\right| \right\} \qquad (10)$$

where ω, κ and ε, p are the energy and the absolute value of the axion momentum and electron one, respectively. The dependence of a cross section on the incident axion energy is given in Fig.5.

And finally, we would like to dwell upon the electron-positron pair production in a field of nucleus by axions. The differential cross section for this reaction is defined from formula (1) by substitution:

$$(\omega, \vec{k}) \to (-\omega, -\vec{k}), \quad (\varepsilon_1, \vec{p}_1) \to (-\varepsilon_+, \vec{p}_+),$$

$$(\varepsilon_2, \vec{p}_2) \to (\varepsilon_-, \vec{p}_-), \quad d\omega \to d\varepsilon_+ \frac{p_+^2}{\kappa^2}, \quad d\Omega_1 d\Omega_2 \to d\Omega_+ d\Omega_-$$

where $\varepsilon_-, \vec{p}_-; \varepsilon_+, \vec{p}_+$ are the energy and the momentum of electron and positron, respectively. The energy distribution of the pair components is readily defined from (3) by the same transformation. The total cross section for the electron-positron pair production by axions in a field of nucleus is presented in Fig.6. In the ultrarelativistic case at $\mu = 0$ this cross section has the simple form:

$$\sigma = \sqrt{2}\, \frac{G \alpha^2 c^2 Z^2}{\pi} \left(\ln\frac{2\omega}{m} - \frac{5}{2} \right) \qquad (11)$$

In Ref. [5] the total cross section of the $\mu^+\mu^-$-pair production by axions in a field of nucleus was calculated. Our result strongly differ from the result of [5] (see Table 1).

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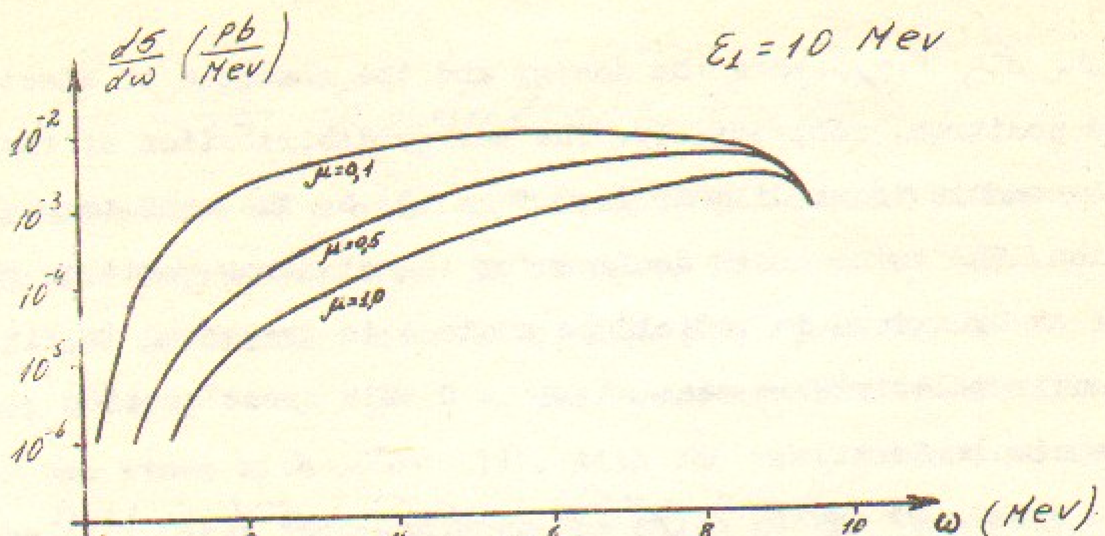
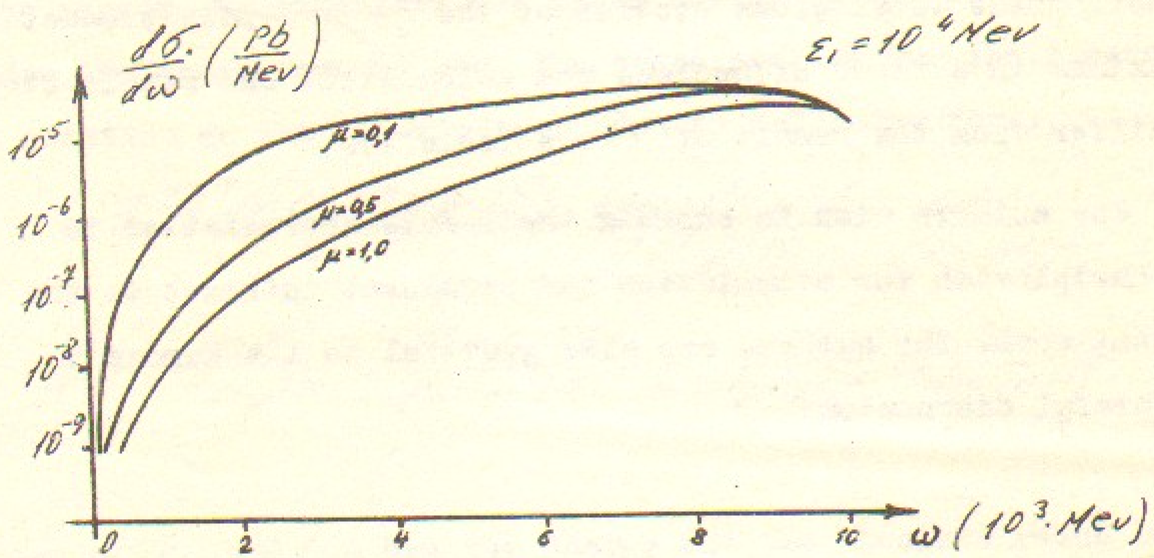


Рис 1



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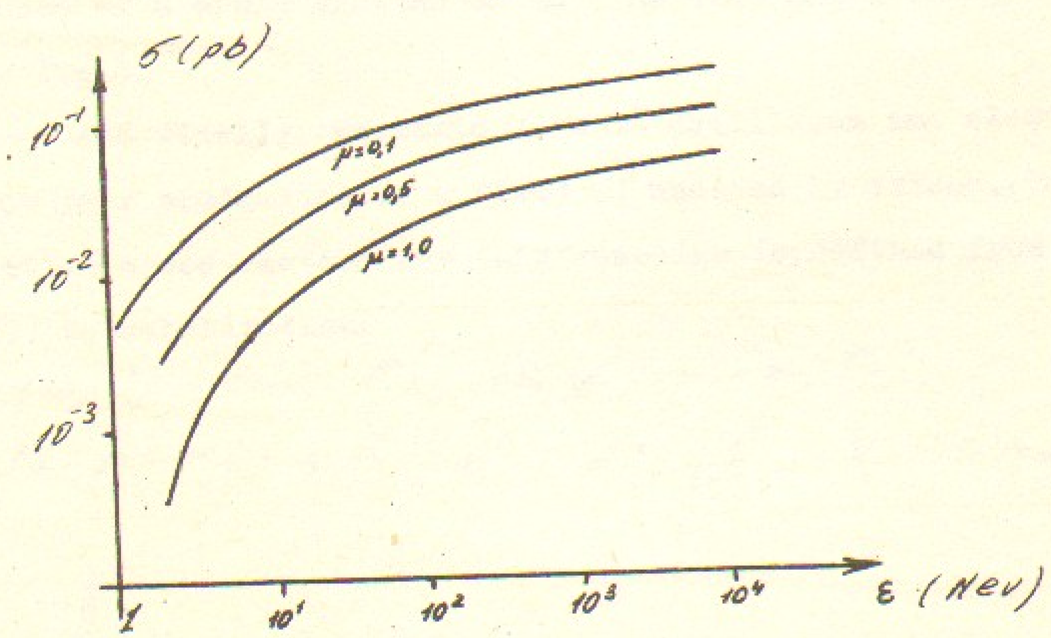

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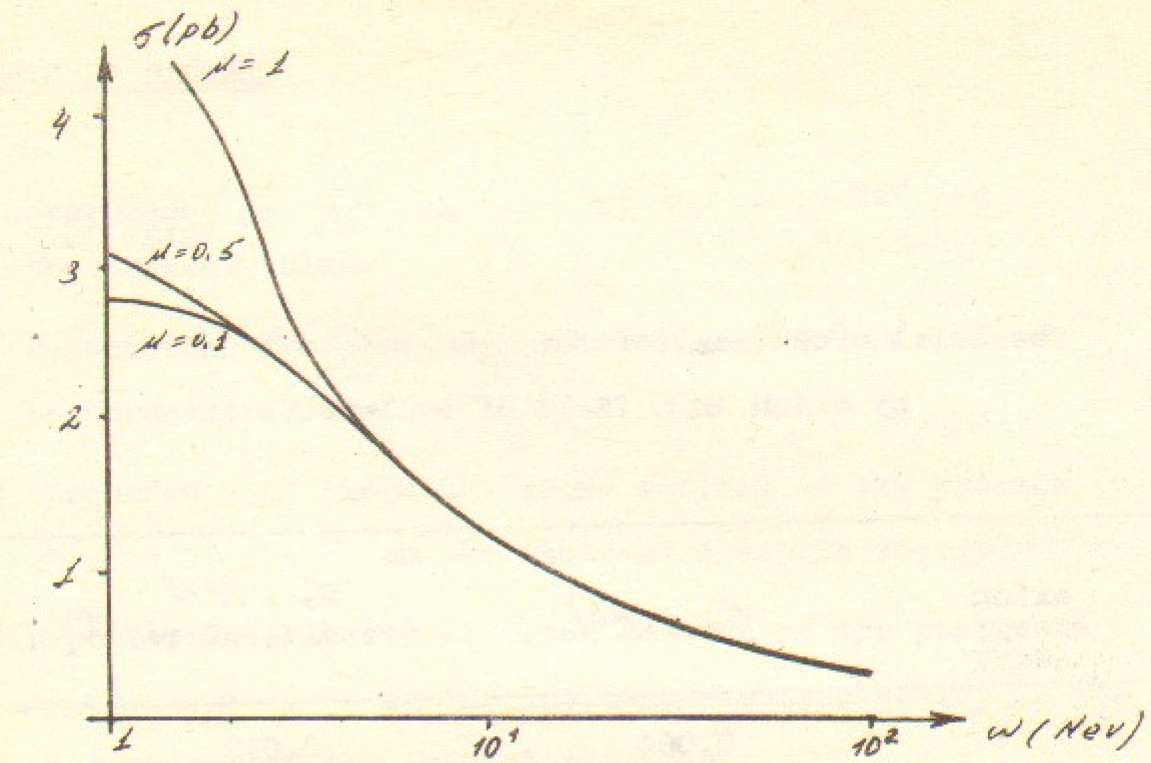

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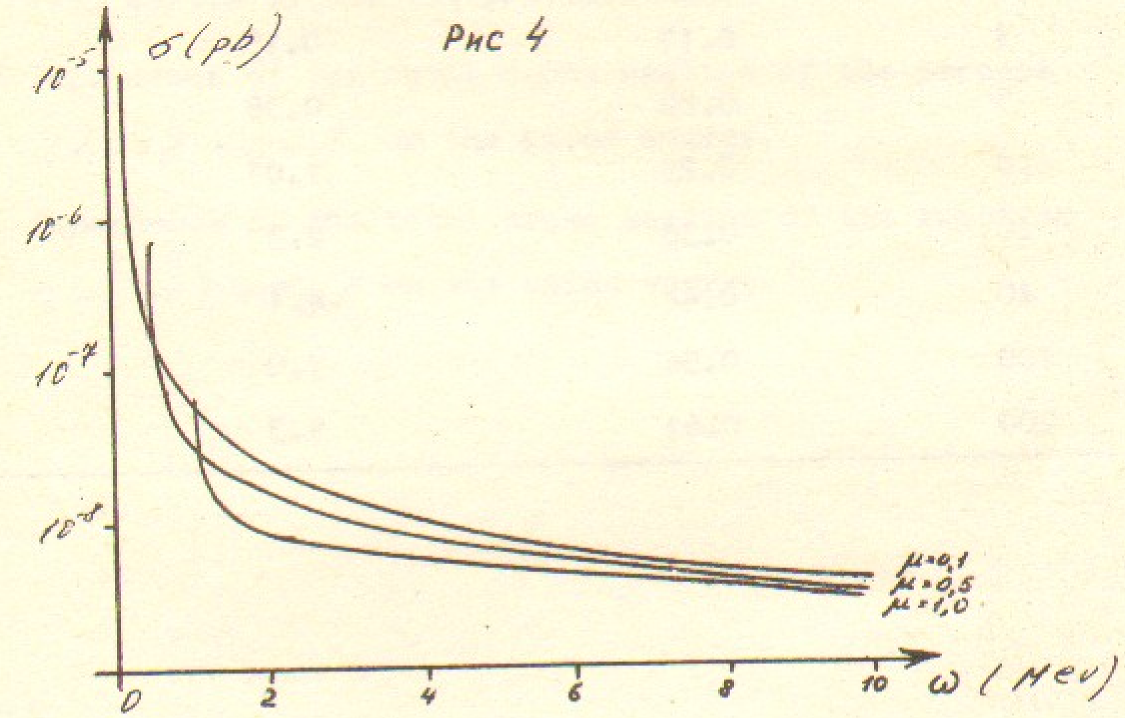

Рис 5

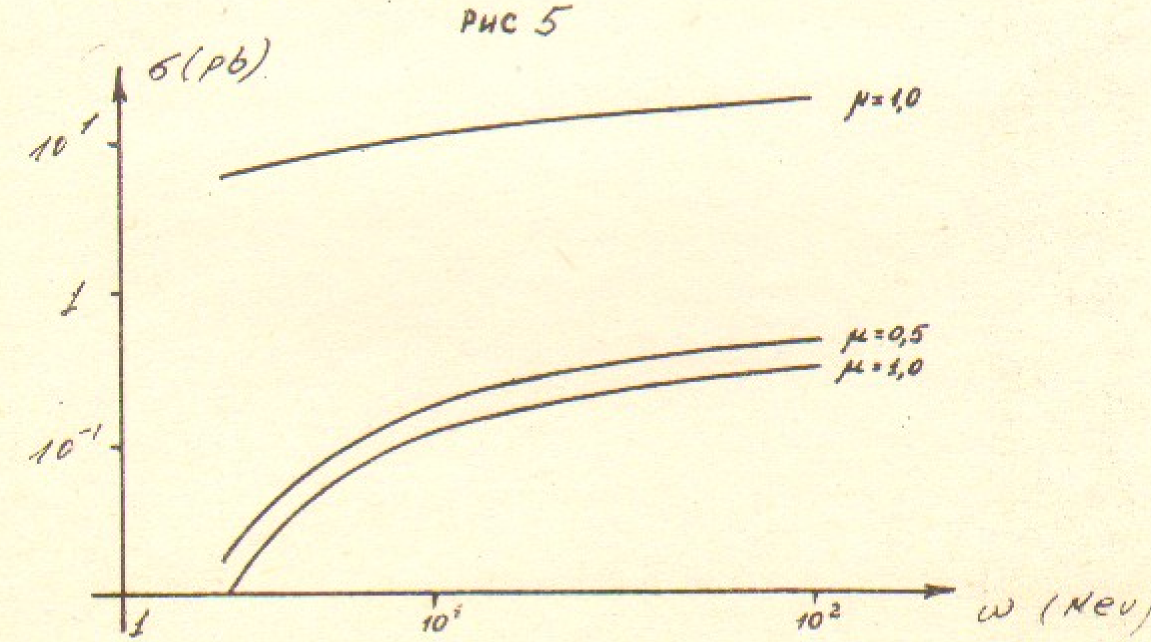

Рис. 6

Table 1.

The total cross section for $\mu^+\mu^-$-pair production by axion in a field of nucleus

axion energy (GeV)	$\sigma_{Z=1}$ (pb)	$\sigma_{Z=1}$ (pb) (results of ref. /5/)
1	0.064	0.012
3	0.17	0.15
5	0.22	0.38
10	0.29	1.01
20	0.36	2.3
40	0.44	4.1
100	0.54	7.0
200	0.61	9.3

CAPTIONS TO FIGURES

Fig.1 Dependence of $\frac{d\sigma}{d\omega}$ on ω at $\mathcal{E}_1$ = 10 MeV for the bremsstrahlung.

Fig.2 Dependence of $\frac{d\sigma}{d\omega}$ on ω at $\mathcal{E}_1$ = 10^4 MeV for the bremsstrahlung.

Fig.3 Dependence of the total cross section of the process $e+Z \to a+e+Z$ on the incident electron energy.

Fig.4 Dependence of the total cross section of the process $a+e \to e+\gamma$ on the incident electron energy in the rest system of the initial electron.

Fig.5 Dependence of the total cross section of the process $a+e+Z \to e+Z$ on the axion energy.

Fig.6 Dependence of the total cross section of the reaction $a+Z \to e^+ + e^- + Z$ on the axion energy.

R e f e r e n c e s

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