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LEPTON-PAIR PRODUCTION OF A LIGHT PSEUDOSCALAR PARTICLE

VIA THE BETHE-HEITLER PROCESS

B.R. Kim and Ch. Stamm

III. Physikalisches Institut
Technische Hochschule Aachen
Abteilung für Theoretische Elementarteilchenphysik
D-5100 Aachen, Federal Republic of Germany

and

R. Rodenberg
CERN - Geneva

A B S T R A C T

Bethe-Heitler processes of light pseudoscalar particles of nuclei are at present very important experimentally. For these processes we present our results which seem to differ from previous theoretical calculations found in the literature.

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**) On leave from III. Physik. Institute, TH Division, Aachen.

In recent years, notably since the advent of the standard axion model¹⁾, light pseudoscalar particles, for example the axion, the majoron²⁾ or the longitudinally polarized state of the supersymmetric U particle³⁾ in the limit of vanishing coupling constant and mass, have attracted not only the attention of theorists but also that of experimentalists. Several groups⁴⁾ looked and others are still looking for axions. The best candidate for detecting axions would be their decay into electron-positron pairs. But all available experiments seem to indicate that the axion mass must be smaller than two electron masses if it really exists. In this case the most suitable reaction will be its lepton-pair production via the Bethe-Heitler process⁵⁾ off a nucleus as shown in Fig. 1. An Aachen group⁶⁾ and a group of CDHS⁷⁾ have been looking for $\mu^+\mu^-$ -pairs, which might originate from lepton-pair production of a light pseudoscalar particle via the Bethe-Heitler process.

On the theoretical side there exist, to our knowledge, two published papers on this subject, namely Bardeen et al.⁸⁾ and Zhitnitskii et al.⁹⁾. In Ref. 8 the authors do not mention any details about their calculations, but present just numbers for the total cross section of the process given in Fig. 1 in the case of Fe, whereas in Ref. 9 the calculations were done on pointlike nuclei, that is without any form factor.

The problem consists in that the discrepancy between Ref. 8 and Ref. 9 is so big that it cannot be explained by form factor effects alone. This point was already stressed in Ref. 9.

Confronted with the question by the experimental groups, as to which numbers they should use, those of Ref. 8 or of Ref. 9, we investigated this problem.

We did the calculations analytically up to numerical calculations and used form factors given by Tsai¹⁰). We found that our results differ considerably from those of Ref. 8, but are compatible with those of Ref. 9 in the sense that the difference can be understood as form factor effects.

In the following we use the notation of Ref. 10. The cross section for coherent lepton-pair-production of a pseudoscalar particle off a nucleus via the Bethe-Heitler process is given as

$$d\sigma = - \frac{e^4 g^2}{4m_i} \frac{1}{(2\pi)^5} \frac{1}{q^4} \frac{1}{(kp)(kp_+)} \left\{ q^2(kp_i)^2 - 2(kp_i)(kq)(p_i q) + (kq)^2 m_i^2 \right\} \cdot W_2 \cdot \frac{d^3 p}{E} \cdot \frac{d^3 p_+}{E_+} \quad (1)$$

with

g: coupling constant of the pseudoscalar particle to the lepton

$$g = i2^{1/4} G^{1/2} m_l \frac{1}{X} \quad \text{for the axion}$$

k: 4-momentum of the pseudoscalar particle

p_i : 4-momentum of the incident nucleus

q: 4-momentum transfer

p: 4-momentum of l^-

p_+ : 4-momentum of l^+

E: energy of l^-

E_+ : energy of l^+

As we are interested in coherent production, the form factor W_1 is zero, whereas W_2 depends both on the nucleus concerned and on the mass of the produced leptons. To be

explicit, one must use an atomic form factor for electron-positron-pair production, but for $\mu^+\mu^-$ -production a nucleonic form factor is required (in the energy range we are interested in).

The reason is as follows:

If one integrates $d\sigma$ of eq. (1) over q^2 , one observes that the integral is dominated by the minimum value of q^2 , $q_{\min}^2$, which has approximately the following form

$$-q_{\min}^2 \approx \frac{4m^4}{E_a^2} \quad (2)$$

with m : mass of the lepton

E_a : energy of the pseudoscalar particle.

This relation shows that $-q_{\min}^2$ is much smaller for e^+e^- than for $\mu^+\mu^-$.

To illustrate, let us put $E_a = 1$ GeV. Then we obtain

$$-q_{\min}^2 = 2.73 \cdot 10^{-13} \text{ GeV}^2, \quad \frac{1}{|q_{\min}^2|^{1/2}} = 4 \cdot 10^{-8} \text{ cm for } e^+e^- \quad (3)$$

$$-q_{\min}^2 = 5 \cdot 10^{-4} \text{ GeV}^2, \quad \frac{1}{|q_{\min}^2|^{1/2}} = 10^{-12} \text{ cm for } \mu^+\mu^-$$

That is, in the case of e^+e^- the virtual photon sees the whole atom, whereas in the case of $\mu^+\mu^-$ it sees just the nucleus.

In our calculation we used the following form factors¹⁰⁾

$$W_2 = 2m_i \delta(m_f^2 - m_i^2) \frac{Z^2}{(1 - q^2/d)^2} \quad \text{for } \mu^+\mu^- \quad (4)$$

with $d = 0.164 \text{ A}^{-2/3} \text{ GeV}^2$

and

$$W_2 = 2m_i (m_f^2 - m_i^2) \frac{Z^2 q_a^4}{(1 - a^2 q^2)} \quad \text{for } e^+e^- \quad (5)$$

with

$$a = 184.15 (2.718)^{-1/2} Z^{-1/3} / m_e$$

m_e = electron mass

The integrated expression of eq. (1) is very lengthy and will be published in a separate paper. Here we present the results only¹¹⁾.

In Table 1 we listed our results, those of Ref. 8 and Ref. 9 for $\mu^+\mu^-$ production off Fe.

In Table 2 our results for e^+e^- production off Al are listed.

As already mentioned the discrepancy between the results of Ref. 8 on the other hand and our results and those of Ref. 9 on the other hand is considerably large, in particular for $E < 20$ GeV.

In conclusion we want to make a remark about the asymptotic behaviour of the cross section. Both Ref. 8 and Ref. 9 predict a logarithmic behaviour:

$$\sigma \underset{E_a \rightarrow \infty}{\sim} C_1^2 G \ln \frac{s}{m_e^2} \quad (\text{Ref. 8}) \quad (6)$$

$$\sigma \underset{E_a \rightarrow \infty}{=} \sqrt{2} \frac{G \alpha^2 Z^2}{\pi} \left(\ln \frac{2E_a}{m_e} - \frac{5}{2} \right) \quad (\text{Ref. 9}) \quad (7)$$

In the case of Ref. 9 this behaviour is understandable because they use pointlike nuclei. In the case of Ref. 8 the logarithmic behaviour is not plausible. The point is that even in the case of $\mu^+\mu^-$ -pair production one has to take into account the atomic form factor for large E_a due to the fact that $-q_{\min}^2$ of eq. (2) decreases. This screening effect implies that the cross section approaches a constant for $E_a \rightarrow \infty$.

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Figure caption

Fig. 1: Bethe-Heitler process of a pseudoscalar particle ϕ off a nucleus A.

Table caption

Table 1: Total cross section of $\mu^+\mu^-$ production for an axion with $x = 1$ according to Fig. 1.

The nucleus is Fe.

$\sigma_{\mu^+\mu^-}$ is in the unit of pb = 10^{-36} cm².

I: our results

II: the results of Ref. 9

III: the results of Ref. 8

Table 2: Total cross section of e^+e^- production for an axion with $X = 1$ off Al.
(our results)

Table 1

E_a /GeV	$\sigma_{\mu^+\mu^-}$ /pb		
	I	II	III
1	9.3	43.3	0.67
2	27.3		
3	42.7	114.9	8.4
4	55.5		
5	66.5	148.7	21.3
6	76		
7	84.5		
8	92		
9	98.8		
10	105.1	196	56.6
20	149.6	243.3	128.8
30	175.3		
40	194.7	297.5	229.6
50	210		
60	222.7		
70	233.1		
80	242.5		
90	250.7		
100	258.2	365.1	392
150	286.6		
200	306.9	412.4	520.8
250	322.7		
300	335.7		
350	346		
400	355.7		

Table 2

E_a/GeV	0.5	0.75	1	3	10	100
$\sigma_{e^+e^-}/\text{pb}$	72.71	74.28	75.08	76.85	77.61	79.94

Fig.1