A.S. AMBARTSUMIAN, G.M. GARIBIAN, C.YANG

THE IONIZATION LOSS OF QUICK CHARGED PARTICLE
IN DETECTORS OF DIFFERENT THICKNESSES

ЕРЕВАНСКИЙ ФИЗИЧЕСКИЙ ИНСТИТУТ

ЕИ-470(12)-81

1981 ЕРЕВАН
A.S. AMBARTSUMIAN, G.M. GARIBIAN, C. YANG

THE IONIZATION LOSS OF QUICK CHARGED PARTICLE IN DETECTORS OF DIFFERENT THICKNESSES

The total energy loss (in the frequency region of order of atomic ones) dependence on both the thickness of detector and the Lorentz factor of the charged particle is discussed. Special attention is given to the conditions under which the Fermi density effect in quick-particle detectors is absent. The obtained results are compared with the recent experiment.

Yerevan Physics Institute
Yerevan 1981
А.С. АМБАРЦУМЯН, Г.М. ГАРИБЯН, ЯН ЩИ

ИОНИЗАЦИОННЫЕ ПОТЕРИ ЭНЕРГИИ БЫСТРОЙ ЗАРЯЖЕННОЙ ЧАСТИЦЫ В ДЕТЕКТОРАХ РАЗЛИЧНЫХ ТОЛЩИН

В работе рассматривается зависимость ионизационных потерь энергии быстрой заряженной частицы при пролете через пластину, от лоренц-фактора заряда и толщины пластины. Особое внимание обращается на условия, при которых будет отсутствовать эффект плотности Ферми. Проводится сравнение с недавно выполненной экспериментальной работой.

Ереванский физический институт
Ереван 1981
YEREVAN PHYSICS INSTITUTE

A.S. AMBARTSUMIAN, G.M. GARIBIAN, C. YANG

THE IONIZATION LOSS OF QUICK CHARGED PARTICLE IN DETECTORS OF DIFFERENT THICKNESSES

Yerevan 1981
The total energy loss of charged particle uniformly passing through a plate of arbitrary thickness in vacuum consists of loss due to the particle's own field in the matter, i.e., ionization loss [1], and additional ones, from the fields arising due to boundaries of the plate [2].

The total energy loss (in the frequency region of order of atomic ones) dependence on the thickness of the plate, $\alpha$, and the Lorentz factor of the charged particle, $\gamma$, is discussed in the present paper.

Let us start with a plate of infinite thickness ($\alpha \to \infty$). As it is known [1], the ionization loss in infinite media (the Cerenkov loss is also accounted) as a function of $\gamma$ after a minimum increases logarithmically and then approaches an asymptotic value (the Fermi plateau). That is, when the velocity of the particle $V$ is not close to the light velocity in vacuum $C$ (fig. 1, region A), the loss is defined by
\[ W_o = - \frac{\omega_p^2 e^2 a}{v^2} \left( \ln \frac{v \varepsilon_o \gamma}{\omega} - \frac{\beta^2}{2} \right) \]  

where \( \omega_p = (4\pi n e^2 / m)^{1/2} \) is plasma frequency of the matter, \( \varepsilon_o \) is minimum distance at which the macroscopic electrodynamics is applicable, \( \beta = v/c \), \( \bar{\omega} \) is mean atomic frequency \([1]\): 

\[ \ln \bar{\omega} = \frac{2}{3 \omega_p^2} \int_0^\infty \omega \left| \text{Im} \left( \frac{1}{\varepsilon(\omega)} \right) \right| \ln \omega d\omega, \]

\( \varepsilon(\omega) \) is permittivity of the matter.

When velocity \( v \) is close enough to \( C \) (more exactly, if \( \gamma = \frac{v}{c} \gg 1 \), fig.1, region B), the loss (in infinite media) is defined by

\[ W_o(v \to \infty) = \frac{\omega_p^2 e^2 a}{c^2} \ln \frac{\varepsilon_o c}{\omega_p} \]  

(Fermi plateau). If the short range collisions are taken into account, too, one must replace in the formulae given above \( \varepsilon_o \) by \( \left( \frac{2 m E_1}{\varepsilon_o} \right)^{1/2} \), where \( E_1 \) is maximum energy in collision, \( m \) is electron mass.

If the plate thickness is finite, an additional loss arises, which can be interpreted as consisting of loss on transition radiation with wide frequency spectrum and of correction to ionization loss concentrated mainly in atomic frequency region. The transition radiation generated at atomic frequencies can be absorbed then in the plate as if increasing in this way the ionisation loss.

The total loss was studied by Garibian et al. \([2-4]\) in plates of finite thicknesses. It was shown that when the plate thickness
\[ \alpha \ll \alpha_{cr} \]  

where \( \alpha_{cr} \sim c \ln \gamma / \omega_p \) (more precise see below), the additional loss completely eliminates the density effect, i.e. the loss will increase with \( \gamma \). This effect was found in [2-4], by expanding the additional loss in powers of the plate thickness, \( \alpha \). It was shown that when \( \gamma \gg 1 \), the linear term has negative sign (i.e. it corresponds exactly to the energy loss) and is determined by

\[ W_{(1)} = - \frac{\omega_p^2 e^2 \alpha}{c^2} \left( \ln \frac{\omega_p}{\omega_1} - \frac{\beta^2}{2} \right) \]  

(4)

where

\[ \ln \omega_1 = \frac{2}{\pi \omega_p^2} \int_0^\infty \omega \ln \mathcal{E}(\omega) \ln \omega d\omega. \]  

(5)

Summed with the formula (2) the total loss logarithmically increases with \( \gamma \) (fig.1, region D):

\[ W = - \frac{\omega_p^2 e^2 \alpha^2}{c^2} \left( \ln \frac{\alpha \omega_c c \gamma}{\omega_1} - \frac{\beta^2}{2} \right). \]  

(6)

It should be noted that this formula differs from (1) only by the definition of mean frequency.

The term proportional to \( \alpha^2 \) is positive, i.e. it decreases the linear one:

\[ W_{(2)} = \frac{\pi \omega_p^4 e^4 \alpha^2}{4 v^3 \bar{\Omega}}, \]  

(7)

\[ \bar{\Omega} = \frac{\pi \omega_p^4}{4} \left[ \int_0^\infty \int \Im(\mathcal{E}(x))\Im(\mathcal{E}(y)) dx dy \right]^{-1} \]

The ratio of (7) to (4) is
The dependence of $C_t$ on $\gamma$ for different matters is plotted in Fig. 2. The meanings of $\omega_0$, $\omega_1$, and $\mathcal{S}$ for these substances as calculated according to [5] are given in Table 1.

The formulae (4) and (7) relate to the case of normal incidence of the particle. If the particle incidences under any $\psi$ angle to the plate, we have formulae similar to (4) and (7) where the role of the plate thickness is played by the path length of the particle in the plate, i.e. $\alpha/\cos\psi$ (for details see [6]).

It is seen from stated above that under condition (3) the second order term can be neglected, compared with the linear one. But the worse this condition is satisfied the greater is the role of the second order term. When $\alpha \sim \alpha_{cr}$, this term compensates the linear one. Strictly speaking, it means that the expansion in powers of $\alpha$ becomes uneven.

When $\alpha \gg \alpha_{cr}$ and $\gamma \gg 1$, the ionization loss does not depend on $\gamma$ (see (2)). As to the energy of transition radiation absorbed in the plate on atomic frequencies, it can be evaluated as [7]:

$$W_{TR} \sim \frac{e^2}{c} \Delta \omega \ln \gamma$$

where $\Delta \omega$ is some effective interval of atomic frequencies,

$$\left| \frac{W_{(2)}}{W_{(1)}} \right| = \frac{\alpha}{\alpha_{cr}}$$

where

$$\alpha_{cr} = \frac{4c \mathcal{S}}{\mathcal{R} \omega_0^2} \left( \ln \frac{\omega_0 \gamma}{\omega_1} - \frac{1}{2} \right).$$

The dependence of $\alpha_{cr}$ on $\gamma$ for different matters is plotted in Fig. 2.
determined mainly by strong absorption in ultraviolet frequency region (e.g. see [8]). The value of \( \Delta \omega \) will have the order of several tens or hundred eV. From (2) and (10) we have

\[
\left| \frac{W_{TR}}{W_0} \right| \sim \frac{c \Delta \omega \ln \chi}{\alpha \omega_p^2} \sim \chi \frac{\alpha_{cr}}{\alpha}
\]

where \( \alpha \sim \Delta \omega / \omega_p \) is some numerical coefficient of order of unity. When \( \alpha_{cr} \) << \( \alpha \), the role of transition radiation absorbed on atomic frequencies is small, and loss localized in the matter practically does not depend on \( \gamma \) (fig.1, region B).

Let us consider now the curve of \( \gamma \)-dependence of the loss, when the plate thickness \( \alpha \) is given. Since \( Q_{cr} \) depends on \( \gamma \) (see (9)), the same plate can be "thick" if \( \gamma \gg \gamma_{cr} \), or "thin" if \( \gamma \ll \gamma_{cr} \), where

\[
\gamma_{cr} = \frac{\bar{\omega}_1}{\omega_p} \exp \left( \frac{\pi \omega_p^2 \alpha}{4 \gamma_{cr}} \right) \quad (11)
\]

When \( \gamma_{cr} \gg \gamma \) (fig.1, region A and B), the loss is determined by formula (1) or (2), and when \( \gamma \gg \gamma_{cr} \) (fig.1, region D), by formula (6). And when \( \gamma \sim \gamma_{cr} \) (fig.1, region C), there is evidently smooth transition between these two formulae. The \( \gamma \)-dependence of total loss, normalized to the plateau value, is plotted in fig.3 (the matter is silicon). It is seen that the intermediate area \( \gamma \sim \gamma_{cr} \) the \( \gamma \)-dependence is sharper than the logarithmical one, defined by formula (6).

Formula (6) turns into formula (1) when \( \gamma \) is of order of 10. That's why, when

\[
\alpha \propto \frac{\bar{\omega}_1 \cdot c}{\omega_p^2} \sim \alpha' \kappa_{at}
\]
( $\lambda^\prime$ is a number of order of unity, $k_a$ is wave length corresponding to atomic frequencies, e.g. $10^{-5}$- $10^{-6}$ cm), the $\gamma^\prime$ dependence curve has no constant sector (the absence of plateau).

The effect predicted in [2] was then considered experimentally in [9], where the ionization loss of electrons with energies from 20 to 86 MeV in foils of polystyrene were observed. It was found out that in foils with thicknesses of $10^{-3}$ cm the loss did not increase with $\gamma^\prime$, and in foils with thicknesses of $10^{-6}$- $10^{-5}$ cm the increase was logarithmic.

On the other hand the measurements in [9] were not absolute, but relative. Absolute measurements were carried out recently [10]. Alas, in [10] was considered loss in 100 mcm ($10^{-2}$ cm) silicon foil in which the effect of logarithmic increase with $\gamma^\prime$ (within the electron energies available on accelerators) must not be observed because of the big thickness of the foil. For such thickness we have according to formula (11) $\gamma^\prime_{cr} \geq 10^{5000}$ (nevertheless, see [10,11]).

It should be noted that in [11] as a requirement for the presence of the density effect the following restriction on the foil thickness is given: $\alpha > c \gamma^\prime / \omega_p$. In reality this requirement is the condition of formation of transition quanta in whole region of frequencies up to the boundary one, equal to $\omega_p \gamma^\prime$. As for the ionization loss, the main contribution is made by quanta with frequencies of order of atomic ones.

In conclusion, let us consider the influence of multiple scattering on ionization loss. The ionization loss as well as the loss on Cerenkov and transition radiation are based on the me-
chanism of electrical polarization of the matter. The quickest mechanism of such polarization is the electronical one [1]. Its relaxation time is of order of atomic times \( \sim a/\nu \), where \( a \) is size of the atom, \( \nu \) is velocity of atomic electrons), i.e. \( 10^{-16} \text{sec} \) (for not too heavy atoms). If this time is much less than the interaction time of quick particles with the nuclei of the matter during the multiple scattering, then the influence of the latter on the ionization loss can be neglected. It is known that the interaction time, e.g. for silicon, is of order of \( 10^{-9} \text{sec} \) [12], i.e. such influence does not take place. Nevertheless, one should mind that the multiple scattering brings to bremsstrahlung [13]. If during the experiment the bremsstrahlung is absorbed, this contribution to total loss must be accounted.

<table>
<thead>
<tr>
<th></th>
<th>( \omega_p )</th>
<th>( \bar{\omega}_1 )</th>
<th>( \bar{\omega} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>13,7</td>
<td>30,5</td>
<td>52,6</td>
</tr>
<tr>
<td>Toluene</td>
<td>19,8</td>
<td>52,3</td>
<td>87,4</td>
</tr>
<tr>
<td>( \text{C}_6\text{H}_5\text{CH}_3 )</td>
<td>30,7</td>
<td>66,7</td>
<td>116</td>
</tr>
<tr>
<td>Graphite</td>
<td>31,7</td>
<td>105,3</td>
<td>171</td>
</tr>
</tbody>
</table>

Table 1. Some characteristic values of quantities from the ionization loss formulae (eV).
Fig. 1. The range of values of \((a, \log \gamma)\) for different \(\gamma\)-dependence of ionization loss:

A - a minimum and logarithmical increase (formula (1))

B - Fermi plateau (formula (2))

C - the region of more sharp \(\gamma\)-dependence

D - the logarithmical increase (formula (5)).
Fig. 2. The $\chi$ -dependence of for different matters: 
1-lithium, 2-toluene, 3-silicon, 4-graphite.

Fig. 3. The $\chi$ -dependence of total loss $W_o$, normalized on 
Fermi plateau: $a_1 = 10^{-5}$ cm, $\gamma_{cr}(a_1) = 55$; $a_2 = 5 \times 10^{-5}$ cm, $\gamma_{cr}(a_2) = 5.5 \times 10^2$; $a_3 = 3 \times 10^{-5}$ cm, $\gamma_{cr}(a_3) = 5.5 \times 10^2$. 

REFERENCES


[8] A.N.Zaidel, E.J.Shreider, Vakuumnaya spectroscopy i ee pri-


The manuscript was received 23 January 1981.
А.С.АМБАРЦУМБ, Г.М.ГАРИБЯН, ЯН ШИ
ИОНИЗАЦИОННЫЕ ПОТЕРИ ЭНЕРГИИ БЫСТРОЙ ЗАРЯЖЕННОЙ
ЧАСТИЦЫ В ДЕТЕКТОРАХ РАЗЛИЧНЫХ ТОЩИХ
(на английском языке)
Ереванский физический институт
Тех.редактор А.С.Абрамян
индекс 3624