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OPTIMIZATION OF CLUSTER-COUNTING TRANSITION RADIATION DETECTORS

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ABSTRACT

The optimal parameters for cluster-counting transition radiation detectors have been calculated. The results for electron/pion separation at energies ~ 10 GeV and for kaon/pion separation at energies ~ 100 GeV are given.

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1. INTRODUCTION

The identification of particles by transition radiation (TR) is of practical interest in two cases:

- i) Separation of electrons from large hadron background at momenta more than 1 GeV/c [1,2];
- ii) Separation of kaons and pions at momenta above about 100 GeV/c [3].

Usually the experimental TR arrangement consists of a few identical radiator-detector modules. The radiator is often fibres or foils of polyethylene, mylar or lithium and the detector is usually proportional chambers filled with xenon gas with a small addition of molecular gas for gain stabilization.

The conventional method of TR detection is the measurement of the sum of the ionization from charged particles and from photoelectrons created by TR quanta. The main disadvantage of this method is due to the large fluctuations of ionization loss in thin gas layers. Its optimization was considered elsewhere [4,5].

Attempts have been made [6,7] to reduce the background from ionization loss in detector material. We think that the method of cluster-counting along the particle track is the most effective one [8,9]. The idea of this method is the registration of those ionization clusters only for which the energy exceeds a fixed threshold value. In this case the background is formed by knock-on or delta electrons. These δ electrons have a Poisson distribution in contrast to a very wide distribution of the integrated ionization loss in thin layers.

The number of TR quanta and its energy depends on the radiator material and its structure. In this paper we describe the results of calculations for the cluster-counting method, for which we find different optimization parameters compared to the conventional TR detection [4,5]. The optimization is made for two cases of electron/pion separation at a few GeV/c and kaon/pion separation at ~ 100 GeV/c.

2. THE CONSTRAINTS IMPOSED FOR THE OPTIMIZATION OF TRANSITION RADIATION DETECTOR PARAMETERS

2.1. The total length L_{tot}

We fixed the total length of the TR detector along the particle beam for electron/pion separation, at $L_{\text{tot}} \leq 40$ cm. This condition may be of interest for storage ring experiments and other compact detectors. For the kaon/pion separation at ~ 100 GeV/c in the experiments at fixed-target accelerators L_{tot} was not fixed.

2.2. The total quantity of material M_{tot}

The total quantity of material along the particle trajectory in a TR detector must be limited in order to reduce the interaction of particles with the material of the detector.

For kaon/pion separation, the optimization calculations were made with a fixed value of M , $M_{\text{tot}} = 8 \text{ g.cm}^{-2} \approx 0.1$ of a nuclear interaction length. For electron/pion rejection M_{tot} was required to be less than 0.1 of a radiation length.

2.3. The number of modules n_s

The number of radiator-chamber modules in the TR detectors was varied from 6 to 24. For electron/pion separation, because of the fixed value of $L_{\text{tot}} \leq 40$ cm, the number of modules was varied from 4 to 10.

2.4. The particle Lorentz factor γ

Since for a limited L_{tot} the electron-pion separation in the region $2 < E < 50$ GeV/c practically does not depend on the momentum value, the optimization for this case was made for a fixed value $p = 5.1$ GeV/c ($\gamma_e = 10^4$). In the case of kaon/pion rejection most calculations were made for $p = 140$ GeV/c ($\gamma_\pi = 10^3$).

2.5. The material and structure of TR radiators

We considered materials of low atomic number for radiators: lithium, beryllium, boron, carbon and mylar. As the structure, we considered thin foils for Li and mylar, powder for Be and B, and fibres for C. Here we do not consider the practical realisation of such structures. The characteristic parameters for periodic structures of radiators are a , the

thickness of the foil and b , the gap between the foils. In case of non-periodic radiators we used a , which is defined as the mean size of powder particle or fibre diameter, and b , the mean distance between the powder particles or fibres.

To calculate the number of TR γ quanta N_γ generated in radiators we used the formulae from Refs. [10,11] for regular and irregular media. We assumed that the gaps of radiators were filled with helium at normal pressure.

2.6. The length of xenon L_{xe}

The usual detector for γ quanta in the energy region 5 to 30 keV is a proportional chamber filled with xenon. To stabilize the gas gain in a proportional chamber as well as to reduce the diffusion of drifting electrons and to diminish the spatial size of the clusters, it is necessary to add a polyatomic admixture to the main gas. We chose for this purpose methane (CH_4) because of its low density and small average atomic number in comparison with the xenon. We took into consideration the presence of methane for the calculation of background clusters for δ electrons. We used the value L_{xe} corresponding to the thickness of gaseous xenon at normal pressure along the particle trajectory in each chamber as the optimization parameter.

2.7. The energy threshold for cluster detector E_0

We considered the following sources of clusters in the proportional chamber:

- i) TR γ -quanta;
- ii) single δ electrons with the energy above the threshold;
- iii) two or more merged δ electrons (each with an energy less than the threshold, but with the total energy above the threshold).

In this case the distance for merging was taken as 1.2 mm. This value was chosen from the following considerations: calculations show that the diffusion width of a cluster after a drift of 1 cm in a 50% Xe + 50% CH_4 mixture is 0.6 mm [12]. If we use a conventional proportional chamber [7] where the particle track is drifting simultaneously from two sides to the anode plane then the part of the track on which the clusters can be superimposed will be equal to twice the diffusion cluster width, i.e. 1.2 mm.

The number of superimposed δ electrons was calculated using the formulae of Ref. [13] for the energy spectra of δ electrons. The distribution of ionization energy loss in gas was calculated by taking into account the atomic levels. The contribution of superimposed electrons in the total number of ionization clusters is 20%.

2.8. The rejection coefficient R

The distribution of the number of clusters detected by a TR detector in the beam consisting of two types of particles (K/π or e/π) is the sum of two Poissonian distributions with the mean values $N_{K(e)}$ and N_{π} .

The rejection coefficient R , corresponding to a threshold value of cluster number N_o , is the ratio of efficiencies ϵ of two types of particles at the fixed value of cluster number N_o .

$$R(N_o) = \frac{\epsilon_{\pi}(N_o)}{\epsilon_{K(e)}(N_o)}$$

In our simulations we used only the value of N_o corresponding to the efficiency of registration of kaons (or electrons) $\epsilon_{K(e)} = 90\%$. In this case the rejection coefficient has the significance of probability for a false identification of kaons (or electrons). In our calculations we do not take into account the energy resolution of the chambers and the parameters of the associated electronics. Also we do not consider the influence of such effects as miscounting of clusters or random coincidences.

3. THE RESULTS

The main results are presented in Figs. 1 to 7 and in Tables 1 and 2.

3.1. Kaon/pion separation

The results show that the number of registered γ quanta at $\gamma = 10^3$ practically does not depend on the gap between the foils b for $b \geq 80 \mu\text{m}$. Therefore we fixed the $b = 100 \mu\text{m}$ (although in some cases we show results with $b = 50$ and $200 \mu\text{m}$ for comparison). At a fixed value of Lorentz factor γ the foil thickness a has an optimum which gives the maximum

number of γ quanta and the best rejection coefficient R (Fig. 1 a,b). The largest number of γ quanta and the best K/π separation at 140 GeV/c is obtained for a Be powder radiator for $a = 5 \mu\text{m}$ or for a Li foil radiator for $a = 15 \mu\text{m}$. The number of TR quanta and the rejection coefficient R for these radiators are given in Fig. 2 for different γ 's. The deterioration of R for $\gamma > 1600$ is connected with the increase of N_γ from kaons.

The dependence of R on L_{xe} has a broad minimum in the interval $L_{xe} = 6-12 \text{ mm}$. Fig. 3 shows the dependence of $R_{K-\pi}$ on the threshold energy for cluster registration E_0 with the radiator and chamber parameters optimum for 140 GeV/c (see Table 1). The rejection coefficient depends very strongly on the total quantity of material M and the number of radiator-chamber modules n_s , as illustrated in Figs. 4a and 4b. Note that the fixed $M = 8 \text{ g}\cdot\text{cm}^{-2}$ and $n_s = 12$ effectively give rise to a limitation on the performance. The calculated rejection coefficient can be very high at the optimum values of the parameters but the interactions of particles with the radiator material will limit the real rejection factor. Figs. 5a and 5b show the dependence on a at a fixed value of the rejection coefficient $R = 1\%$. Fig. 5d represents the curves for different fixed values of $R = 0.03, 0.1, 0.3, 1.0$.

One can see that the upper boundary of the γ region increases with increasing a and b and the lower boundary depends strongly only on a . For the best separation in the region of low γ the optimum radiators are Be with $a = 4 \mu\text{m}$ and Li with $a = 10 \mu\text{m}$.

3.2. Electron pion separation

The dependence of the number of absorbed TR quanta on the radiator parameters a and b for $\gamma = 10^4$ are shown in Figs. 6a and 6b. At a fixed total length of TR detector the gap size has an optimum at $b = 100 \mu\text{m}$. The optimum parameters of a TR detector for electron/pion rejection are shown in Table 2. The dependence of $R_{e-\pi}$ on the total length of the detector and on the number of radiator-chamber modules is shown in Figs. 7c and 7d. The best electron/pion separation is for the Be powder radiator.

CONCLUSIONS

The results for the optimization of the parameters of cluster-counting TR detectors show that the identification efficiency increases rapidly with the increasing average number of TR quanta above $N_{\gamma} \geq 12$. This is connected with the Poisson distribution of the number of quanta in a cluster. The best results are obtained with radiators of Be, Li and B with $a = 5-20 \mu\text{m}$. The technical problems of producing such radiators are not yet solved. Their development will aid the problem of electron/pion and kaon/pion identification with a high rejection factor $R \leq 10^{-3}$, using relatively simple electronics [7]. With such radiators the quantity of material along the beam for the TR detector will be 5 to 10% of a nuclear interaction length for kaon/pion identification and 2 to 5% of a radiation length for electron/pion identification. For example, an electron/pion detector with a total length of 15 cm (Fig. 7c) and $R = 10^{-3}$ could be a very important part of the experimental installations for colliding beam detectors such as LEP [14]. Unfortunately for the moment only the carbon fibres [7,14] are available for TR detectors for kaon/pion identification with $R \approx 10^{-2}$.

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TABLE 1

The optimal parameters of a TR detector for kaon/pion separation at a momentum of 140 GeV. (The number of radiator-chamber modules is 12, the total quantity of material $M_{\text{tot}} = 8 \text{ g} \cdot \text{cm}^{-2}$ and the distance between the foils $b = 100 \mu\text{m}$).

Material	a (μm)	L_{xe} (mm)	E_0 (keV)	$R_{\text{K}-\pi}$ (%)
Li foils	11-15	7-9	2.5	0.0005
Be powder	3-6	10-12	3.5	0.0025
B powder	3-5	13-16	4.5	0.2
C fibres	3-5	14-17	5.0	1.6

TABLE 2

The optimal parameters of a TR detector for electron/pion separation at the momentum of 5-10 GeV/c. (The number of radiator-chamber modules is 6, and the length of the detector $L_{\text{tot}} = 22 \text{ cm}$.)

Material	a (μm)	b (μm)	L_{xe} (mm)	E_0 (keV)	$R_{\text{e}-\pi}$ (%)	M_{tot} rad length
Li foils	20-30	100	5.7	3.0	0.07	0.015
Be powder	6-9	50	11.13	3.5	0.0008	0.055
B powder	4-7	75	13-16	4.5	0.3	0.050
C fibres	6-10	100	15-17	5.0	0.7	0.055

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FIGURE CAPTIONS

Fig. 1 The dependence on a , the thickness of the radiator foil (or powder particle) for the radiators of beryllium or boron powder, carbon fibres, and lithium or mylar foils with the gap between the foils (or the mean distance between powder particles or fibres) $b = 100 \mu\text{m}$. The TR detector consists of 12 radiator proportional chamber modules with a total quantity of material $M_{\text{tot}} = 8 \text{ g}\cdot\text{cm}^{-2}$ and with optimized threshold energy for cluster registration, E_0 .
 (a) the number of absorbed TR quanta N_γ for 140 GeV/c pions;
 (b) the pion-kaon rejection coefficient $R_{\pi\text{-K}}$ at an energy of 140 GeV/c.

Fig. 2 The dependence on the Lorentz factor of pions γ_π for a TR detector consisting of 12 modules, $M_{\text{tot}} = 8 \text{ g}\cdot\text{cm}^{-2}$, $b = 100 \mu\text{m}$ with optimized L_{xe} and E_0 .
 (a) the number of absorbed TR quanta n_γ with $L_{\text{xe}} = 13 \text{ mm}$, $E_0 = 3.5 \text{ keV}$;
 (b) the kaon-pion rejection coefficient $R_{\text{K-}\pi}$.

Fig. 3 The dependence of $R_{\text{K-}\pi}$ on the threshold energy for cluster registration E_0 for a TR detector of 12 modules, $M_{\text{tot}} = 8 \text{ g}\cdot\text{cm}^{-2}$, and $\gamma_\pi = 10^3$. For the Be powder radiator: $a = 15 \mu\text{m}$, $b = 100 \mu\text{m}$, $L_{\text{xe}} = 11 \text{ mm}$. For the Li foil radiator: $a = 15 \mu\text{m}$, $b = 100 \mu\text{m}$, $L_{\text{xe}} = 7 \text{ mm}$.

Fig. 4 The dependence on total quantity of material M for different radiators with L_{xe} and E_0 optimized, $\gamma_\pi = 10^3$, kaon registration efficiency $\epsilon_K = 0.9$, (a) the kaon/pion separation coefficient $R_{\text{K-}\pi}$ for a TR detector with 12 radiator-chamber modules. For a B powder radiator $a = 4 \mu\text{m}$, $b = 100 \mu\text{m}$. For a Be powder radiator $a = 5 \mu\text{m}$, $b = 100 \mu\text{m}$. For a Li foil radiator $a = 15 \mu\text{m}$, $b = 100 \mu\text{m}$. (b) the coefficient $R_{\text{K-}\pi}$ for a beryllium powder radiator ($a = 5 \mu\text{m}$, $b = 100 \mu\text{m}$) with different numbers of radiator-chamber modules.

- Fig. 5 The regions of kaon/pion separation coefficient $R_{K\pi}$ in the $(\gamma_{\pi}-a)$ plane for different radiators with $M_{tot} = 8 \text{ g}\cdot\text{cm}^{-2}$, $\epsilon_K = 0.9$ and L_{xe} , E_0 optimized.
- (a) $R_{K-\pi} \leq 1.0\%$ inside the region.
12 radiator-chamber modules, $b = 100 \mu$.
 - (b) $R_{K-\pi} \leq 1.0\%$ for Be powder radiator with $b = 100 \mu$ and different numbers of radiator-chamber modules (6, 12, 18).
 - (c) $R_{K-\pi} \leq 1.0\%$ for different b values (50, 100, 200 μ) and 12 radiator-chamber modules. Dashed lines for Be powder radiators, solid lines for Li foil radiators.
 - (d) different values of $R_{K-\pi} = 0.03 - 1.0\%$ for Li foil radiator with $b = 100 \mu$ and 12 radiator chamber modules.

- Fig. 6: The dependence of the number of absorbed TR quanta N_{γ} for 5.1 GeV electrons ($\gamma_e = 10^4$). Total length of the TR detector $L_{tot} = 30 \text{ cm}$ with 10 radiator-chamber modules, $L_{xe} = 7 \text{ mm}$, $E_0 = 3 \text{ keV}$.
- (a) Dependence on radiator foil (or powder particle) thickness a for different radiators with $b = 100 \mu$;
 - (b) Dependence on radiator gap b for different radiators with optimized a .

- Fig. 7 The dependence of the electron/pion separation coefficient $R_{e-\pi}$ for various parameters for 5.1 GeV/c electrons and the efficiency of electron registration $\epsilon_e = 0.9$.
- (a) the dependence on a , the foil thickness: solid lines for Be powder radiator with $L_{tot} = 17.5 \text{ cm}$ and 5 radiator-chamber modules, dashed lines for Li foil radiator with $L_{tot} = 18 \text{ cm}$ and 8 modules.
 - (b) the dependence of xenon in each chamber L_{xe} . Solid line for Be powder with $a = 8 \mu$, $b = 78 \mu$, $L_{tot} = 17.5 \text{ cm}$, $E_0 = 3.5 \text{ keV}$, 5 modules; dashed line for Li foil radiator with $a = 30 \mu$, $b = 100 \mu$, $L_{tot} = 28 \text{ cm}$, $E_0 = 3 \text{ keV}$, 8 modules.
 - (c) the dependence on total TR detector length L_{tot} with different radiator-chamber module numbers. Solid lines for Be powder radiators, $a = 8 \mu$. Dashed lines for Li foil radiators, $a = 30 \mu$.
 - (d) the dependence of total TR detector length L_{tot} with 6 radiator-chamber modules and optimized values of b , L_{xe} , E_0 .

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7