Characteristics of semiconductor pion stop tagging system

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Abstract. A determination of the coordinates of charged particle stops is one of the tasks that have to be solved in a wide class of experiments. A method based on the use of semiconductor detectors (SCD) to determine the stops of particles (muons and pions) was proposed and experimentally tested. The dependence that allows calculating the stopping point of the pions in the tagging system was obtained experimentally. This dependence can be used to optimize the thickness values of monitor detectors.

1. Introduction

Measurements of the spectra of secondary charged particles has a prominent place in studies of the interaction of stopped \( \pi^- \)-mesons with nuclei. In such experiments special attention is paid to the registration of particles with relatively large losses in the thickness of the target, as well as the rejection of background associated with particles stopping outside the target.

In [1, 2], a method for monitoring the beam using silicon semiconductor detectors (SCD) was proposed and experimentally tested. The method is based on the analysis of the values of pion energy losses in monitor detectors for selecting events associated with stops in the target. It was shown that this method provides a high efficiency of selecting of useful events \( \sim 90\% \) at a low background.

The purpose of this work is to determine the optimal values of the thickness of the silicon detectors used in tagging systems.

2. Residual particle range in the target

The tagging system consists of two Si detectors (D1 and D2) located in front of the target (T) [1]. The proposed method is based on the dependence of ionization losses in the detector on the particle energy. The dependence of the average energy loss in the D1 detector on the particle range is shown in figure 1. It can be seen that the measurement of energy loss in D1 makes it possible to determine the residual path of the particle. However, as can be seen from figure 1, two values of the residual range (branches \( a \) and \( b \)) correspond to the same energy loss. In this case, the branch \( a \) refers to the particles that stop in the detector D1, and the branch \( b \) refers to the particles that stop in the detector D2 and the target, or fly through this system.

The detector D2 of the tagging system is used to exclude events with a stop in D1. A signal from D2 proves that the event belongs to the \( b \) branch. Then the stops in the target (T) with thickness \( \Delta R \) correspond to the energy loss in the detector D1, which lie in the range \( \Delta E_{\text{min}} < \Delta E_1 < \Delta E_{\text{max}} \). When determining the stop point only a measurement of first detector, the second detector is selected to be thinner in thickness.
Figure 1. The dependence of the average energy losses in the detector D1 of the residual range of the particle.

Figure 2. Dependence of the energy loss of pions in D1 on the value of the residual path.

The presented method has a finite spatial resolution, which consists of the following factors: fluctuations of ionization losses in monitor detectors, the intrinsic energy resolution of SCD, and range straggling in the target.

For a monoenergetic particle beam with energy $E_0$, the dispersion of energy losses $\sigma_i(E_0)$ in the detector D1 is described by the Peyne formulas [3]. Then the accuracy of determining the range is equal to:

$$\sigma_R \approx \frac{1}{d(\Delta E)/dR}_{E=E_0} \cdot \sigma_i(E_0),$$

where $\Delta E(R)$ corresponds to the branch $b$ in figure 1.

The energy resolution of the detector $\sigma_i$ can be taken into account by replacing $\sigma_i(E_0)$ with $\left(\sigma_i^2(E_0) + \sigma_d^2\right)^{1/2}$. Residual ranges straggling $\sigma_f$ should also be taken into account. As a result, we get the following expression:

$$\sigma_R \approx \left[ \frac{1}{d(\Delta E)/dR}_{E=E_0} \cdot \left(\sigma_i^2(E_0) + \sigma_d^2 + \sigma_f^2\right) \right]^{1/2}.$$

Note that usually the residual ranges straggling gives only a small contribution to the value of $\sigma_R$ and can be omitted.

The method for determining $\sigma_R$ is shown in figure 2. For a particle with an initial energy $E_0$ the solid curve shows the dependence of the energy loss $\Delta E$ on the value of the residual path $R$. The dashed curves present the a curve shifted vertically by $\Delta E(E_0) \pm \sigma(E_0)$ respectively.

The energy losses $\Delta E(E_0) \pm \sigma(E_0)$ correspond to the ranges $R_1$ and $R_2$. Then according to the proposed method, the spatial resolution for particles with residual range in the target $R_f$ is defined as $\sigma_R \approx (R_2 - R_1)/2$.

Figure 3 shows the results of calculations of the relative spatial resolution for $\pi$-mesons as a function of the $W/R_f$ for two values of the residual range in silicon $R_f = 0.25$ and $2$ mm ($W$ is the thickness of D1). The calculations assumed that the detector has a high intrinsic energy resolution ($\sigma_d \ll \sigma_i(E)$) It is seen that the obtained functions differ by no more than 5%. Therefore, we can assume that the relative spatial resolution depends only on the $W/R_f$ ratio:

$$\frac{\sigma_R}{R_f} \approx f_\pi(W / R_f).$$
Figure 3. The calculated value of the relative spatial resolution as a function of the ratio $W/R_f$: 1 – $R_f$ = 0.25 mm; 2 – $R_f$ = 2 mm.

Figure 4. The calculated dependence of the relative spatial resolution as a function of the ratio $W/R_f$ for various particles: muons (μ), pions (π), protons (p) and deuterons (d).

Similar calculations were performed for other types of particles. Figure 4 shows the results for muons (μ), pions (π), protons (p), and deuterons (d) ($R_f$ = 1 mm). It can be seen that the curves have a similar form and the approximate relation exists:

\[
\frac{f_j(W/R_f)}{f_j(W/R_f)} \approx \sqrt{\frac{m_j}{m_i}},
\]

where $m_i, m_j$ are the particle masses.

Thus, the relative spatial resolution is determined by the universal function (F):

\[
\frac{\sigma(R_f)}{R_f} \approx \sqrt{\frac{m}{m_\pi} \cdot f_\pi(W/R_f)} = \sqrt{m \cdot F(W/R_f)},
\]

where $m$ is the mass of the incoming particle and $m_\pi$ is the mass of the pion.

The dependence has a wide minimum in the range of values $W/R_f$ ~ 2, which corresponds to the equality of energy losses in the detector and the residual energy.

For some values of the $W/R_f$ ratio, ionization loss fluctuations have a non-Gaussian distribution and, in addition, ionization losses are non-linearly related to residual ranges. Therefore, the results obtained were verified using Monte Carlo simulation. Fluctuations in ionization losses in the detector were modeled for a particle beam evenly distributed over the ranges. The calculated values of the $W/R_f$ ratio have a similar shape to the curves in figures 3 and 4 and quantitatively exceeded them by no more than 10% in the minimum area.

3. Optimal thicknesses of monitor detector

Determining the optimal thickness of the detector $W_{opt}$ is an important task for detecting stops at the edge of the target (for example, when rejecting particles passing through the target). As shown in figure 3, the best resolution is achieved when the detector thickness is approximately twice the distance to the stop point. It follows that $W_{opt} \approx 2G$, where $G$ is the distance from the detector D1 to the edge of the target, i.e. the sum of the thicknesses of the second detector and the target.

From the linear increase of the absolute resolution from the value of $G$ (at the optimal thickness of D1), it is necessary to use the thinnest possible detector D2. However, there are certain limitations
associated with both the manufacturing technology and the difficulty of setting a sufficiently low threshold on a thin detector. Depending on the ratio of the thickness of the target and the detector D2, it may be more appropriate to distinguish stops at the leading edge of the target based on the readings of the second detector. The choice is made by comparing the absolute spatial resolutions of each detector at a given target point.

The correctness of the calculations was verified using data on secondary protons obtained in an experiment on the absorption of negative pions by nuclei \([1, 2]\). For this purpose, the readings of several silicon detectors were used, which were used to complete SCD telescopes of the spectrometer [1]. The spatial resolution of the first detector D1 was studied, and the following SCD readings were used to determine the stopping point.

A two-dimensional distribution of the energy loss \(\Delta E\) in D1 and the residual range of \(R_f\) particles was obtained. Proton identification was performed using the corresponding branch of the \((\Delta E - R_f)\) matrix, which corresponds to the \(\Delta E-E\) method. The distributions of residual ranges for various fixed energy losses in D1 obtained from the \((\Delta E - R_f)\) matrix were approximated by a Gaussian distribution. The maximum of this distribution was assumed to be equal to the mean residual range, and standard deviations were interpreted as spatial resolutions.

The experimental data allowed us [1] to determine the dependence of the relative spatial resolution for various residual ranges at a fixed detector thickness (figure 5). Comparison with the results of the calculations using the method described above (taking into account the energy resolution of the detector 90 keV) shows good agreement.

![Figure 5](image)

**Figure 5.** Experimental (1) and calculated (2) dependences of the relative spatial resolution for protons at the detector thickness \(W = 2.62\) mm.

4. Conclusion
A universal dependence is obtained that allows calculating the spatial resolutions of monitor systems based on silicon detectors. This dependence can be used to optimize the thickness of the SCD. It is shown that the best spatial resolution is achieved when the detector thickness is equal to twice the residual range.

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