Position Sensitivity by Light Splitting in Scintillator Arrays[1]

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Abstract

A novel detector design of overlapping plastic scintillator elements in cylindrical geometry has been developed for detection of low multiplicity events of fast protons and other light charged particles: Each particle traversing the detector from the axis outwards will produce light in several elements. The relative amounts of energy deposited in those elements allow to interpolate on the particle trajectory beyond the resolution given by the granularity. The detector covers the angular range $10° \leq \Theta_{lab} \leq 72°$ and $0° \leq \varphi \leq 360°$ with an inner layer of scintillator bars of triangular cross section and an outer one of

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rings. The material is BC408. Tests with minimum ionizing electron beams show that spatial resolutions of $\Delta\Theta_{lab} \approx 1.5°$ and $\Delta\varphi_{12} \approx 1.5°$ (FWHM) can be obtained for electrons or proton pairs with energies in the GeV range. In the EDDA experiment the ultimate spatial resolution is then determined by the size of the interaction area rather than by the intrinsic pulse height resolution of the detector.

1. Introduction

With the advent of proton synchrotrons providing cooled beams in the momentum range up to 3.3 GeV/c [1] and with lifetimes allowing the use of internal targets [2], experiments with high resolution and luminosity are within range. In this situation, the particle physics of nucleon-nucleon interactions can address the study of rare events with mesonic degrees of freedom, or, alternatively, of (quasi)elastic binary events taken during the smooth energy variation of projectile acceleration.

The design of dedicated detectors then has to meet requirements resulting from the high count rates of low multiplicity events, a large solid angle coverage and the need for fast triggering with good selectivity. Detector designs therefore frequently include plastic scintillator barrels and front end caps for time-of-flight measurements with a granularity dictated by the geometry and kinematics of the experiment [3, 4, 5, 6].

In this paper, we describe a cylindrical structure of plastic scintillators that combines a moderate granularity with the option for an off-line improvement of the spatial resolution by a factor of 5-10 in two dimensions. The improvement is obtained by determining the point of incidence from the energies deposited in adjacent, overlapping scintillator elements, and will be referred to as "light splitting". The scheme, although applicable to multihit detection with multi layer structures of the kind realized e.g. in [4, 5], shall be demonstrated here for detection of binary events. In particular we have in mind the EDDA experiment [7] at COSY [8] that intends to study the excitation functions of elastic pp-scattering and possible intermediate (dibaryonic) excitation modes.

Triggering on binary events will rest on their coplanarity, yielding an azimuthal trigger condition

$$\varphi_2 - \varphi_1 = 180^\circ \tag{1}$$

and on their kinematics, imposing a constraint $\Theta_{2,lab} = f(\Theta_{1,lab}, T_p)$ on the scattering angles, which, in the case of pp-scattering of projectiles with energies T_p at an internal hydrogen target, is

$$\tan\Theta_{1,lab}\tan\Theta_{2,lab} = \frac{2m_p}{2m_p + T_p} \tag{2}$$

The EDDA detector is shown in Fig. 1 in a schematical fashion. It consits of two double layers, an inner double layer composed of helically wound scintillating fibers, and an outer double layer consisting of scintillator bars and rings. The trigger is provided by the outer layer. The experiment will trigger on condition eq. 1 with a granularity defined by the scintillator bars and on eq. 2 with the granularity of the semi-rings determining Θ_{lab}. The bars and rings will also be used, however, to determine particle trajectories for a more stringent off-line analysis. This requires a spatial resolution better than afforded by the granularity of the outer detector layer, and it is made possible by the light splitting scheme. The latter is the main focus of the present paper, as it can easily be generalized to more complex detector geometries.

The paper is organized as follows: In Sect. 2 we present the geometrical design of scintillator elements intended for light splitting. Sect. 3 is devoted to experimental details of prototype studies in an electron test beam. The results of these measurements are used in Sect. 4 to deduce the improvement in spatial resolution that can be obtained with electrons and expected for proton pairs, and the theoretical and practical limitations of the light splitting concept. Our main conclusions are summarized in Sect. 5.

2. Scintillator Design Algorithms

In order to enhance the spatial resolution in φ beyond the granularity given by the number of scintillator bars comprising the cylindrical array, the elements are not given a pointing geometry but on the contrary overlapping cross sections. The requirement that every proton track originating from the target position should traverse two scintillator bars leads to the irregular cross section $ABCD$ shown in Fig. 2a. It can be constructed for *any* ratio of inner to outer diameter and *any* number N of bars. If PH_1 and PH_2 denote the pulse heights read out at the same end from the neighbouring bars 1 and 2, respectively, the ratio

$$Q_{12} = \left(\frac{PH_2 - PH_1}{PH_2 + PH_1}\right) \tag{3}$$

varies between -1 and +1 with the point of incidence on the base line AB of the "elementary cell" $ABDE$. For a particle with constant specific energy loss along its way through the cell, the dependence is in first order linear, otherwise the stopping powers must be explicitely taken into account.

The manufacturing of such irregular trapezoids is costly and time consuming; the lack of symmetry also causes problems for quality control and for support construction. It is therefore desireable to have simpler, more symmetric and equally effective geometries, such as the triangles shown in Fig. 2b. This is achieved by making ABC a straight line. The condition for $\angle ABC = \pi$ is:

$$\angle OBC = 0.5(\pi + \varphi_0) \tag{4}$$

Because of this constraint, the radii R_i and R_o and the number N of scintillator elements are no longer mutually independent, as the sine law requires for the triangle OBC:

$$R_i \sin(\frac{\pi + \varphi_0}{2}) = R_o \sin(\pi - \frac{\pi + \varphi_0}{2} - \varphi_0) \tag{5}$$

or, with $\varphi_0 = 2\pi/N$:

$$\frac{R_o - R_i}{R_i} = \frac{\sin(\frac{\pi}{2}(1 + \frac{2}{N}))}{\sin(\frac{\pi}{2}(1 - \frac{6}{N}))} - 1 \tag{6}$$

It follows from eq. 6, that a minimum of $N = 7$ triangular bars is required to form a cylinder-like configuration. With increasing number N, the thickness of the cylinder wall for a given R_i decreases. It can be shown easily that the triangle ACD is an isosceles one; its height is given by

$$h = \cos(\frac{\pi}{N})(R_o - R_i) \tag{7}$$

and approaches $(R_o - R_i)$ rapidly with increasing N. The resulting ratio $(R_o - R_i)/R_i$ is shown in Fig. 3.

The trigger concept of the EDDA detector is based on a number $N = 32$ of elements. In order to test the proposed light splitting scheme we have studied a pair of both trapezoidal and triangular types of scintillator bars.

Their dimensions are given in Table 1. The material is $BC408$ in both cases, a PVT based plastic scintillator [9].

The light splitting scheme can equally well be implemented for the outer half of the outer layer of the EDDA detector which consists of semi-rings. They cover the angular range $10° \leq \Theta_{lab} \leq 72°$ or $25° \leq \Theta_{cm} \leq 155°$. The geometrical granularity desired is equidistant in the center-of-mass system with $\Delta\Theta_{cm} \approx 5°$; the semi-rings will therefore have widths $L_i(\Theta_{lab})$ decreasing with increasing Θ_{lab} and ring number i according to $L_i = L_{i+1}(1 + D_R/R_R)$, whereas the thickness D_R can be kept constant, cf. Fig. 2c. We have tested a set of four prototypes with thicknesses $D_R = 1\,\mathrm{cm}$ and $L = 2\,\mathrm{cm}$ corresponding to a forward position $\Theta_{lab} \approx 25°$, again made of BC408 (Table 1).

In detail, the thickness of the wrapping material has to be taken into account, and the overlap of the adjacent elements has to be increased to guarantee a minimum value for the energy deposited. These modifications, however, are not fundamental to the light splitting scheme and will be omitted here.

The prototypes mentioned - two pairs of bars and the four semi-rings - were machined with different techniques to transmit the light by total reflection; the surfaces involved are indicated in Table 1, and the influence of the surface quality achieved will be discussed in terms of the attenuation lengths in Sect. 5.4. The complete scintillator elements were equipped with different types of light guides, cf. Sect. 3.2, and they were wrapped with thin aluminum foil and a light tight layer of TEDLAR, a black foil made of polyvinylfluoride. For the irregular bars, the aluminum foil was replaced by TYVEK, a paperwhite, diffuse reflecting foil made of polyethylene [10].

3. Experimental Set Up and Measurements

3.1 Particle Beam

Prototype tests have been performed with a 3 GeV electron test beam provided by the DESY II synchrotron facility. The beam profile was defined by two pairs of crossed scintillator bars with the tested object being either behind the two crosses (cf. Fig. 5) or between them. In addition, a vetoing aperture made of scintillator material could be inserted to further reduce the beam dimension to a spot of 1.5 mm diameter. The prototype under study was placed right behind this aperture and could be moved under remote control in the plane perpendicular to the electron beam. An astronomical support allowed for rotations around orthogonal axes going through the (virtual) target point T of the EDDA configuration (cf. Fig. 1) such that the beam of minimum ionizing electrons simulated the azimuthal (φ) and polar (Θ_{lab}) angle of the trajectories of reaction protons. Alignment was achieved by maximizing the normalized coincidence yield and with an optical telescope to within ± 0.5 mm.

3.2 Photomultipliers and Electronics

The scintillator bars were read out with photomultipliers of the type Valvo XP2011B that have an active cathode diameter of 32 mm. The geometrical concept of the EDDA detector requires them to be positioned pointing radially outward. The bars with the trapezoidal cross sections were therefore equipped with light guides made of lucite that are bending by 90° with a radius $R = 20\,\mathrm{cm}$; a gentle transition of the cross section from the circular to the trapezoidal shape yields the maximum possible light transfer.

The more practical bars with triangular cross sections were tested with five different twistedlight guides (cf. Fig. 4a) adapting the whole read out area of $65\,\mathrm{mm} \cdot 7\,\mathrm{mm}$ to the photocathode; this type of coupling was reported the most efficient one [11]. A comparison of the light transmission for identical multipliers and optical contacts yielded the following results with respect to a straight light guide: Insertion of a light guide with matching triangular cross section between the twisted guide and the scintillator bar that bends, with a radius of 4 cm, the read out by 90°, reduces the transmission to $(70 \pm 3)\%$. The same result is obtained with a light guide that is glued at an angle of $\Theta_{Sc} = 90°$ or even 105° to the front of the scintillator bar. These results were obtained with the front side M of the light guide being carefully polished, and declined, as shown, by $\Theta_M = \Theta_{Sc}/2$ (which is larger than the limit of 42° for total reflection), and both scintillator and light guide wrapped in thin aluminum foil. If the declined surface M is, however, coated with an evaporated layer of aluminum, the light yield reduces to 48%; a similar reduction by a metallic mirror surface has been reported in [12]. From these results it was decided to concentrate on the geometrically acceptable solutions of Fig. 4a.

The scintillator rings must be subdivided into semi-rings to allow for read out and kinematical triggering. Two variants have been taken into consideration and tested with semirings of inner diameter $R_i = 17\,\mathrm{cm}$. Versions 1 and 2 have an (almost) tangential read out as shown in the inset of Fig. 4b. The staggering of adjacent semirings takes care of the size of the photomultiplier bodies (Hamamatsu R1450, (active) cathode diameter 19 mm (15 mm)) and bases. However, when mounted, opposite semirings must be shifted by the thickness of the scintillator material.

This disadvantage is avoided with the modified read out geometries 3 and 4 (Fig. 4b). The semi-rings are cut at angles of 50° and 40° with respect to the radial direction, and the ends M are highly polished such that the light is reflected into the (almost) radial light guides. This way semirings can be combined to rings with a minimum of dead zones. The light yield of these bent read outs was determined with the Compton edges of a ^{22}Na source; it is reduced to about 75% as compared to the straight light guides, cf. Fig. 4b. The enhanced intensity on either end is due to the reflections from the inclined front and rear end as could be confirmed with a Monte Carlo calculation [13]. Read outs 3 and 4 will be used in the EDDA detector.

The block diagram for the electronics and data acquisition applied in detector tests with the electron beam is shown in Fig. 5 in reduced form. The trigger section (left) allows to distinguish between two types of events. A fivefold coincidence between the front paddle and two times two small crossing scintillator fingers defines the raw trigger with a cross section of the electron beam on the tested set up of 0.5 cm · 1 cm. For a few percent of these events the vetoing aperture indicates the projectiles impinging on the center spot of 1.5 mm diameter (central trigger); they were separated by software.

The signals from typically four detector elements (two bars or four semi-rings) are fanned into TDCs (LeCroy 2228A) and QDCs (LeCroy 2249A), respectively. The common TDC start signal is generated from the trailing edge of the trigger signal which is defined by the slightly delayed signal of the best performing finger. The gate signal for the charge sensitive digitizers QDC was given a length of 40 - 60 ns. Event rates were generally less than 700 Hz that dead time and pile up effects were negligibly small. The eventwise data acquisition and subsequent replay occurred on a VAX computer.

3.3 Experimental Procedure

The options to position the scintillator elements with an accuracy of ± 0.5 mm with respect to the point of electron beam incidence, and to vary the angle of incidence as well, have been used to perform sequences of measurements across pairs of scintillator bars that allowed to study the light splitting scheme quantitatively and that are referred to as φ scans. Similarly, Θ scans were performed across sets of semi-rings. Both types of scans were done near either end of the objects as well as midway in between. In addition, we have scanned all types of scintillators in their respective longitudinal dimension in order to determine attenuation lengths. Count rates varied between 10^{-1} and 10^{2} Hz due to the intermittent and parasitical availability of the beam. Reproducibility and consistency of these measurements were repeatedly checked.

4 Results and Discussion

4.1 Light Splitting Scheme and Spatial Resolution

As an example of how a particle's point of incidence upon a scintillator array is determined from light splitting, consider the example of the bars with trapezoidal cross section (Fig. 2). The base line AB of length 14.7 mm was scanned with vertical incidence of the electron beam in 10 equidistant steps. The thickness of the scintillator material thus varies from 1 mm to 10 mm corresponding to mean deposited energies ΔE_e ranging from 0.25 MeV to 2.5 MeV, respectively. The pulse height spectra read out with the nearby photomultiplier are shown in Fig. 6a. They exhibit Landau shapes, broadened by the finite beam spot size and the experimental resolution, and, for the highest values ΔE_e, a tail that indicates the onset of showering. Eventwise application of eq. 3 yields ratios Q_{12} which are, to a good approximation, a linear measure of φ, see Fig. 6b. It can be estimated that the spatial resolution is in the order of $\Delta Q_{12} \approx 0.3(FWHM)$ which converts into $\Delta\varphi \approx 1.5°(FWHM)$, cf. Sect. 4.2. The systematic variation from the linearity is essentially due to the variationin scintillator thickness with the angle of incidence.

In order to disentangle the influence of the finite beam spot size from the principial limitations due to variations of the deposited energy and the detector resolution, a fit procedure was applied to the whole set of spectra within one scan. The variation of the *deposited* energy Δ at a point with thickness x of traversed scintillator material is supposed to originate from a Landau [14, 15]distribution $F_x(\Delta)$. Under the assumption that the intrinsic detector resolution is totally due to the statistics in the number of photoelectrons, its influence can be described by a broadening Gaussian $G_{\sigma_0}(\sigma(\Delta), \nu)$ with a standard deviation

$$sigma(\Delta) = \sigma_0 \sqrt{\Delta}, \tag{8}$$

where σ_0 is an energy independent parameter. The spectrum of the *measured* energy is obtained from the folded distribution

$$G_{\sigma_0} \bigotimes F_x(\Delta) = \int_{-\infty}^{\Delta} G_{\sigma_0}(\sigma(\Delta - \nu), \nu) F_x(\Delta - \nu) d\nu \tag{9}$$

We assume further that the electron beam is of constant intensity within a circular spot of radius R_b such that

$$f_{\sigma_0}^{(i)}(\Delta) = \int_{-R_b}^{+R_b} G_{\sigma_0} \bigotimes F_{x_i(R')}(\Delta) \sqrt{R_b^2 - R'^2} dR' \tag{10}$$

denotes the anticipated distribution for the i^{th} spectrum. The parameter σ_0 is searched for by fitting eq. 10 simultaneously to all spectra of the scan. A factor $\exp -z/\lambda$ is taken into account in calculating $f_{\sigma_0}^{(i)}$ in cases where photon losses on the way of length z to the photomultiplier occur due to the effective attenuation length λ (cf. Sect. 4.4) of the scintillator element.

4.2 The Scintillator Bars

4.2.1 Spatial Resolution with Electrons

For a quantitative determination of the azimuthal resolution $\Delta\varphi$ and its dependence on the point of incidence of the electron beam, the normalized ratio $Q_{12}(\varphi)$ defined in eq. 3 must be considered in more detail. This will be exemplified for the trapezoidal scintillator bars. For minimum ionizing particles, PH_i is related to the path length x_i in the i^{th} scintillator bar (cf. Fig. 2a) via

$$PH_i = x_i \frac{\overline{\Delta E_{max}}}{(R_o - R_i)} g_i \tag{11}$$

where g_i notes the overall gain factor of the photomultiplier read out, and $\overline{\Delta E_{max}}$ the average energy deposited on a path of length $(R_o - R_i)$, i.e. on $\overline{AE}$ and $\overline{BD}$. Geometrical considerations yield

$$\frac{x_1}{x_2} = \frac{R_0}{R_i} \frac{\sin(\varphi_0 - \varphi)}{\sin\varphi} \tag{12}$$

Insertion of eqs. 11 and 12 into eq. 3 leads to

$$Q_{12}(\varphi) = \frac{\sin(\varphi_0 - \varphi) - c\sin\varphi}{\sin(\varphi_0 - \varphi) + c\sin\varphi} \tag{13}$$

with $c = R_i g_2 / R_o g_1$. This expression can be converted into

$$\varphi = \arctan\left[\frac{(1 - Q_{12})\sin\varphi_0}{(1 - Q_{12})\cos\varphi_0 + (1 + Q_{12})c}\right] \tag{14}$$

and allows to calculate eventwise the coordinate φ of incidence from the experimental value Q_{12}. To the extent that c and $\cos\varphi_0$ can be approximated by unity, eq. 14 represents a linear dependence of φ on Q_{12}, and the widths of the corresponding distributions are related via $\Delta\varphi \approx 0.5\Delta Q_{12}\sin\varphi_0$. This is the basis for the estimate given in Sect. 4.1.

The exact solution is obtained from application of eq. 14 to the measurements presented in Fig. 6a. The results shown in Fig. 7 reveal an interesting trend of $\Delta\varphi(FWHM)$ with the nominal coordinate φ of incidence. The resolution is best for $\varphi \approx 0°$ or φ_0, i.e. for $x_1 \approx 0$ or $x_2 \approx 0$, because the influence of the Landau distributions and photoelectron statistics on Q_{12} cancels if one term dominates in numerator and denominator of eq. 3. An additional contribution comes from the finite size of the electron test beam.

In order to explore the relative contributions of the effects mentioned to the resolution $\Delta\varphi$, a Monte Carlo simulation has been performed that allows to switch these contributions on and off. In a first step the experimental detector resolution was extracted. The parameter values found for σ_0 are fairly constant in the whole range of deposited energies Δ and thus confirm the scaling $\sigma \propto \Delta^{1/2}$. The absolute value for energy deposition at the read out ends of both the trapezoidal and the triangular scintillator bars is $\sigma_0 = 2.5 \pm 0.1\,\mathrm{keV}^{1/2}$. This corresponds to a resolution of 185 keV (FWHM) for $\Delta = 1\,\mathrm{MeV}$. The detector resolution deteriorates like $exp(z/2\lambda)$ as the distance z between particle trajectory and photomultiplier increases, thereby attenuating the light collection and degrading the photoelectron statistics accordingly.

In a Monte Carlo simulation, energy losses of 3 GeV electrons have been used to generate the pulse height spectra to occur in the photomultipliers at either end of the scintillator bar. Optionally, the spectra could be folded with the detector resolution and with a homogeneous electron beam profile of radius $r_0 = 0.75\,\mathrm{mm}$. The results are shown in Fig. 7. The full simulation reproduces the experimental results $\Delta\varphi(\varphi)$ very well. Switching off both beam profile and detector contribution yields the ultimate spatial resolution. These values are not achievable in reality, because already the inclusion of a small ($r_0 = 0.75\,\mathrm{mm}$) beam width makes the calculation approach the experimental result. We conclude that in our case with deposited energies varying between 0 and 2.5 MeV the beam radii in the order of 1 mm and larger will dominate the detector resolution. Therefore the resolution will greatly benefit from a beam cooling.

4.2.2 Spatial Resolution for Proton Pairs

So far, only the response of the EDDA detector components to *one* traversing *electron* has been considered. For the detector operation, the resolution with respect to a *pair* of associated *protons* is more essential, because these events constitute the trigger on coplanarity.

Based on the results obtained for electrons we have extrapolated the proton pair resolution by means of a Monte Carlo simulation. Representative results are presented – again for the scintillator bars with trapezoidal cross sections – in Fig. 8.

For a given projectile energy T_p, a scattering event was fixed by selecting the polar ($\Theta_{lab,1}$) angle for the first proton, an azimuthal angle φ_1 equally distributed between 0° and φ_0, and the kinematically corresponding angles for the second proton. The proton energies ΔE_p deposited in the traversed scintillator bars were given Vavilov distributions and a subsequent folding with a Gaussian to simulate the finite resolution due to the photoelectron statistics. The standard deviation $\sigma(\Delta) = \sigma_0\sqrt{\Delta E_p}$ was taken to be that of the electron experiment (cf. Sect. 4.1), however, with a correction of ΔE_p to account for the light attenuation losses between the position of proton incidence on the bars and the photomultiplier read out (cf. Sect. 4.4). The resulting pulse heights for the two opposite pairs of adjacent bars were converted with eq. 14 into a pair of angles, φ_1, φ_2. This reconstruction was based on the assumption that the protons originate from a point like, centered target.

The resulting differences have their centroids at 180°, the widths $\delta(\varphi_2 - \varphi_1)$ are shown in Fig. 8a for two values of T_p. On the average, the resolution is for $T_p = 500\,\mathrm{MeV}$ in the order of $1.0^\circ FWHM$; it deteriorates slightly with increasing T_p due to the reduced energy ΔE_p deposited and the associated higher statistical uncertainties. The values $\delta(\varphi_2 - \varphi_1) \leq 1.5^\circ$ obtained for $T_p = 1.5$ GeV and their dependence on $\Theta_{lab,1}$ remain unchanged within the uncertainties stated if T_p is further increased.

The effect limiting the resolution $\delta(\varphi_2 - \varphi_1)$ is largely the Vavilov distribution of ΔE_p rather than the experimental resolution. Switching off the Gaussian folding ($\sigma(\Delta) = 0$) yields only a minor improvement as is shown in Fig. 8b for $T_p = 1.5\,\mathrm{MeV}$. From this observation we conclude that the photomultiplier read out is an uncritical part of the light splitting concept for the geometry discussed here.

So far we have ignored the finite size of the beam spot on the target. Proton pairs emerging from a realistic size of interaction area will, however, broaden the reconstructed distribution of the coplanarity parameter $\varphi_2 - \varphi_1$. For sake of simplicity, we assume a Gaussian beam profile of standard deviation σ_{pp}. Fig. 9a shows, for $T_p = 1500\,\mathrm{MeV}$, that a beam spot width of only $\sigma_{pp} = 0.5\,\mathrm{mm}$ leads to a substantial broadening $\delta(\varphi_2 - \varphi_1) \approx 2.2°$. The width of the coplanarity distribution will therefore in all practical cases be dominated by the finite interaction area. For example, a value $\sigma_{pp} = 2\,\mathrm{mm}$ leads to a width of $\approx 6.4°$, see Fig. 9b; in this case the light splitting scheme would only lead to a moderate improvement over the hardware granularity with $N = 32$, if only the outer detector layer (cf. Fig. 1) is considered. In conjunction with the inner (ScF) layer, however, the spatial resolution obtained with light splitting may be used to full advantage in reconstructing the tracks of proton pairs.

4.3 The Scintillator Semi-Rings

The semi-rings in the EDDA detector are to provide the polar angle Θ_{lab}. For a test of the angular resolution $\Delta\Theta_{lab}$ attainable, the set of four semi-rings was aligned to the electron test beam as shown in Fig. 5, corresponding to a full coverage of the angular interval $22.6° \leq \Theta_{lab} \leq 25.8°$ in the azimuthally centered position $\varphi = 90°$. The test beam was restricted with the veto aperture to a diameter of 1.5 mm. The interval was scanned with 14 points of incidence, $0.25°$ apart from one another.

The spectra resulting from an eventwise analysis with eq. 3 for the most forward one of the three pairs of subsequent semi-rings are compared in Fig. 10a for 6 points of incidence as indicated in the inset. The widths of the position peaks are comparable with their spacings, i. e. $\Delta\Theta_{lab}(FWHM) \approx 0.25°$. The resolution is therefore improved by a factor 5 over the mere geometrical granularity of the ring structure. The resolution is dominated by the contribution $\Delta\Theta_{lab} \approx 0.22°$ coming from the finite size of the beam spot; therefore, the consequences for the detection of high energy protons with the scintillator bars mentioned at the end of Sect. 4.2.2 apply to the semi-rings as well.

The centroids of the position peaks from the three subsequent pairs of semi-rings are plotted in Fig. 10b as a function of Θ_{lab}. Obviously the ratio $Q_{i,i+1}$ is in each elementary cell an almost linear measure of Θ_{lab} and the sequence of cells lines up smoothly and without gap.

For eventwise calculation of Θ_{lab} from the measured ratio Q of pulse heights, a relation corresponding to eq. 12 for the scintillator bars is needed. For the ring geometry sketched in Fig. 2c we find

$$\frac{x_i}{x_{i+1}} = \left(\frac{L_i \sin(\Theta_i + \theta)}{H_i \sin\theta} - 1\right)\left(1 + \frac{D_R}{R_R}\right). \tag{15}$$

With the abbrevations $c_i = (1 + D_R/R_R)g_i/g_{i+1}$ and $d_i = L_i/H_i$ the pulse height ratio (eq. 3) can be expressed as

$$Q(\Theta_i + \theta) = \frac{c_i d_i \sin(\Theta_i + \theta) - (c_i + 1)\sin\theta}{c_i d_i \sin(\Theta_i + \theta) - (c_i - 1)\sin\theta}. \tag{16}$$

Therefore, $\Theta_{lab} = \Theta_i + \theta$ may be obtained eventwise from Q as

$$\Theta_{lab} = \Theta_i + \arctan\left[\frac{\frac{1}{d_i} + \frac{1+Q}{c_i d_i (1-Q)} - \cos\Theta_i}{\sin\Theta_i}\right]. \tag{17}$$

For rings with $D_R \ll R_R$ and photomultipliers adjusted in their gains g_i, i.e. $c_i \approx 1$, and with the approximations $\theta \ll \Theta_i$ and $\sin\theta \approx \theta$, eq. 17 reduces indeed to a linear relation $\theta \propto (1-Q)$ as was qualitatively stated before.

4.4 Light Attenuation

The $1/e$ light attenuation length of BC408 bulk material is quoted as $\lambda =$ 380 cm [9]. For long scintillation detectors with small cross sections, however, the losses are mostly due to imperfect reflection at the surfaces. Slabs cut from cast sheets with dimensions 2000 mm · 120 mm · 20 mm (10 mm, 5 mm) show values for λ of 275 cm (210 cm, 190 cm) [9] that go down further to $\lambda = 30$ cm for dimensions 200 mm · 20 mm · 1 mm [16]. Machining of surfaces usually gives rise to additional light losses.

We have determined the attenuation lengths for the scintillator bars and rings under study with both, the Compton edges of a ^{22}Na source and with the 3 GeV electron test beam. The results listed in Table 1 differ considerably with geometry as well as with surface quality. The trapezoidal slab has four machined surfaces that were prepared using standard tools and polishing afterwards. In contrast, the triangular slabs and the semi-rings keep some surfaces with cast quality, cf. Table 1; for the machined ones, diamond tools were used. This resulted in a marked improvement of λ, as will be shown.

In order to obtain a more quantitative measure for the surface contribution, a simplifying model has been applied. Light losses were assumed to occur (i) due to absorption in the bulk material (λ_{bulk}) and (ii) at each total reflection. If λ_{exp} denotes the experimentally determined attenuation length, we obtain for the light losses $dI(z)$ along the fraction dz of the scintillator axis in z-direction

$$dI(z) = -I(z)\left[\frac{\overline{\cos\beta}}{\lambda_{bulk}} + \sum \frac{N_R^i}{L} V^i\right] dz = -I(z)\frac{dz}{\lambda_{exp}} \tag{18}$$

where $z\overline{\cos\beta}$ is the average distance the light has travelled in z direction by total reflection after isotropic emission. The sum extends over all types i of scintillator surfaces; each term is composed of the number of reflections per unit length, N_R^i/L, and the fractional intensity loss per reflection, V^i. For application of eq. 18, $\overline{\cos\beta}$ and N_R^i have been calculated for a coefficient of refraction $n(BC408) = 1.59$ with the light transport code GUIDE7 [17]. The loss factors V^i were then treated as fit parameters to reproduce the data λ_{exp} for the different geometries and surface qualities under study. We find average values $V = 2.79\%$ for the trapezoidal bars, and 1.56% (1.43%) for the triangular bars (semi-rings). The latter ones consist to roughly 50% of machined surfaces. For a sample of $8\,\mathrm{mm} \cdot 65\,\mathrm{mm} \cdot 970\,\mathrm{mm}$ with cast major surfaces we obtained $\lambda_{exp} = 141\,\mathrm{cm}$ or $V = 0.37\%$. It was therefore concluded that light losses can be substantially reduced by driving the diamond tools with extremely smooth running motors at optimized speed and careful attention to the maximum surface temperatures. This was confirmed during the process of full scale production of EDDA scintillator elements. The attenuation length for the triangular bars could be improved to $\lambda_{exp} = 124$ cm or $V = 0.41\%$, indicating that the machined surfaces reached the quality of the cast ones.

4.5 Timing Properties

The study of pairs of scintillator elements traversed by an electron beam gives twofold timing information, namely (i) the time signals from the read out photomultipliers PM1 - PM4 with respect to the trigger, cf. Fig. 5, and (ii) the time differences between two of these PMs.

From scans in the longitudinal direction of scintillator elements, data of type (i) provides the effective velocity of light as slope of time vs. distance. The result for the triangular scintillator bar is $c_{eff} = 16.0 \pm 0.3$ cm/ns; this value agrees well with 15.9 cm/ns reported [12] for the DELPHI time-of-flight (TOF) counters made of NE110, dimensions 350 cm $\cdot$ 19 cm $\cdot$ 2 cm, and with 16.3 ± 0.2 cm/ns for a TOF counter [18] made of SCSN38 (150 cm $\cdot$ 20 cm $\cdot$ 2 cm). The refractive index is the same for all three materials within 0.01. For the semi-rings we observe a reduced value 13.3 ± 0.3 cm/ns with reference to the average radius. Simulations with GUIDE7 indicate, that this difference results mostly from the modifications of the pulse shape by the light reflected at the far end of the semi-rings. It gives rise to a delayed maximum when the point of incidence of the probing electrons approaches that end. A similar observation has been reported elsewhere [19].

When scanning the electron beam across a pair 1,2 of scintillator elements, the widths $\delta(\Delta t_{12})$ of the time differences Δt_{12} from type (ii) data represent the folded contributions of start and stop signal. Each one is assumed to consist of two contributions: A constant term for the intrinsic resolution of the photomultiplier e.g. due to noise and spread of transit time, and a term reflecting the statistics in the number N_e of photoelectrons. For identical photomultipliers and read out geometries we expect therefore

$$\delta(\Delta t_{12}) = \sqrt{2\gamma^2 + \frac{\beta^2}{N_{e1}} + \frac{\beta^2}{N_{e2}}} \tag{19}$$

The numbers N_e can be determined by calibrating the pulse height in units of the single electron response [20]. We have performed a scan midway (i.e. 45 cm away from either read out) across a pair of triangular scintillators, that were arranged back-to-back such that $N_{e1} = N_{e2}$. The results are shown in Fig. 11 together with a best fit of eq. 19. The parameter values $\gamma = 0.22\,\mathrm{ns}$ and $\beta = 5.8\,\mathrm{ns}$ indicate a time resolution $\delta(\Delta t_{12}) = 1.26\,\mathrm{ns}$ (FWHM) for a deposited energy $\Delta = 1\,\mathrm{MeV}$ per scintillator bar, that is dominated by the photoelectron statistics. This value can be reduced by improving the attenuation length λ_{exp} and a careful setting of the constant fraction discriminators by a factor up to 1.5 [20]. Determination of the parameters γ and β from a scan of a pair of semi-rings with the intended read out geometry under variation of N_e by light attenuation yielded $\beta = 8.2 \pm 0.1\,\mathrm{ns}$, corresponding to a resolution $\delta(\Delta t_{12}) = 0.92\,\mathrm{ns}$ for $\Delta = 1\,\mathrm{MeV}$ deposited halfway, i.e. at the position $\varphi = 90^0$. These resolutions are compatible with the requirements for fast triggering.

5. Summary and Conclusions

A scintillator configuration designed to provide position information in excess of that afforded by detector granularity was explored both experimentally and by Monte Carlo simulations. The cross sections of the scintillator elements were shaped such that the light produced by a traversing particle is split among at least two adjacent scintillators; by this, the normalized difference of their light outputs is an almost linear measure of the particle's coordinate of incidence. Experimental tests with a collimated beam of 3 GeV electrons show that the scheme – called position sensitive light splitting – works for both polar and azimuthal coordinates of a cylindrical scintillator geometry as expected from Monte Carlo simulations. The spatial resolution obtained is typically five times better than the detector granularity yielding $\Delta\varphi \approx 1.5°$ and $\Delta\Theta_{lab} \approx 1.5°$ (FWHM).

The spatial resolution can be understood as essentially resulting, for particle trajectories originating from a nuclear interaction in a target, from the finite size of the beam spot and from the statistical variation in the number of photoelectrons produced. This being the limiting factor, efficient light collection is important, requiring high quality scintillator surfaces. Good results were obtained with diamond pointed machine tools, smoothly running driving motors and attention to maximum surface temperature, and with cast scintillator surfaces.

Both the experimental tests and the Monte Carlo simulations were done for a specific scintillator configuration – suitable for an internal target experiment (EDDA) to be done at the cooler synchrotron COSY – but the concept of position sensitive light splitting is quite general, and application to other detector geometries is straight forward.

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Figure Captions

Fig.1 Schematic diagram of the layers comprising the EDDA detector: Scintillator semi-rings (ScSr) and bars (ScB), scintillating fibers (ScF), beam line (BL). The projectile hits the target (T) and generates two outgoing protons (p_1, p_2).

Fig.2 Cross sectional view of a layer of a) trapezoidal scintillator bars with the elementary cell ABDE; b) triangular scintillator bars; c) a sequence of semi-rings with the hatched area defining the elementary cell.

Fig.3 Relative thickness of a cylinder composed of N triangular scintillator bars. The arrows indicate the choice $N = 32$.

Fig.4 Read out geometries of a) the triangular scintillator bars connected to twisted light guides with $\Theta_{Sc} = 90^0$ and $\Theta_M = \Theta_{Sc}/2$ and reflecting surface M; b) variants 1-4 for the semi-rings and their light transmission vs. φ normalized to that of the straight read out 1.

Fig.5 Schematic set up of prototypes, beam defining scintillators, electronics and data acquisition at the 3 GeV electron test beam.

Fig.6 a) Energy ΔE_e deposited by 3 GeV electrons in scintillator material BC408 of thickness d. The crosses give the experimental pulse height distributions, the solid lines a simultaneous fit. b) Mean pulse height ratios $Q_{12}(\varphi)$ and standard deviations $\pm\sigma$ of their distributions; the solid line denotes the linear approximation, the dashed one the exact result of eq. 14.

Fig. 7 Azimutal resolution $\Delta\varphi(FWHM)$ vs. coordinate φ of incidence of 3 GeV electrons: Experimental results (solid dots) compared to Monte Carlo calculations for real beam size ($r_0 = 0.75$ mm) and detector resolution ($\sigma(\Delta) = \sigma_{exp}$) (solid line), ideal beam ($r_0 = 0$) but σ_{exp} (dashed), and ideal beam and detector ($\sigma(\Delta) = 0$) (dash-dotted).

Fig.8 Azimutal resolution $\delta(\varphi_2 - \varphi_1)$ of simulated elastic pp-events for a) T_p = 500 MeV and 1500 MeV for a detector resolution $\sigma(\Delta) = \sigma_{exp}$; b)$T_p$ = 1500 MeV with the Gaussian folding being switched on ($\sigma(\Delta) = \sigma_{exp}$) and off ($\sigma(\Delta) = 0$).

Fig.9 Resolution $\delta(\varphi_2 - \varphi_1)$ for T_p = 1500 MeV: a) for ideal beam and detector ($\sigma(\Delta) = \sigma_{pp} = 0$, crosses), for experimental detector resolution σ_{exp} combined with an ideal ($\sigma_{pp} = 0$, diamonds) or with an extended ($\sigma_{pp} = 0.5$ mm, circles) beam; b) influence of the beam spot size σ_{pp} on the resolution $\delta(\varphi_2 - \varphi_1)$.

Fig.10 Light splitting scheme applied to semi-rings: a) Spectra of pulse height ratios (eq. 3) from adjacent semi-rings; b) centroids of the ratios $Q_{i,i+1}$ measured for a scan extending over 4 semi-rings from $\Theta_{lab} = 22.5^o$ to 25.8^o.

Fig.11 Time resolution of a triangular scintillator bar with an energy ΔE_e deposited 45 cm away from the read out.