OPERATION OF CYLINDRICAL WIRE SPARK-CHAMBERS IN LOW-PRESSURE HELIUM

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ABSTRACT

A pair of cylindrical wire spark-chambers is used for detecting alpha particles emitted in high-energy $\pi^4\text{He}$ interactions. A particular feature of the system is the low gas pressure employed, corresponding to a thickness of 0.7 mg/cm^2 . The angular error for 5.48-MeV alpha particles is 1.2° FWHM. The chambers are insensitive to minimum-ionizing particles.

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1. INTRODUCTION

In an experiment where high-energy pions interact with ${}^4\text{He}$ nuclei¹⁾, it is necessary to measure the momentum vectors of the recoiling α particles. The angles are typically between 60° and 90° and the momenta are between 0 and 700 MeV/c.

In order to obtain a good angular precision spark chambers are preferred. Due to the low event rate from the gas target in the experiment the chambers have to cover a large solid angle. Furthermore, the high rate of energy loss of the α 's makes it necessary to keep the amount of matter traversed very low.

The set of two coaxial wire chambers which have been constructed for the purpose are equipped with wires parallel to the axis on all the four cylindrical surfaces. The useful azimuthal angle is 315° . The transparency of the system is high, 88%, and alpha particles that hit the wires are in general absorbed. The chambers are operated in low-pressure helium gas²⁾. There are no intermediate walls so that the gas is present also in the drift space between the two chambers. The whole assembly is enclosed in a vacuum vessel with feed-throughs for the high-voltage and read-out cables.

The coordinates are measured by means of the current-distribution method³⁾. The longitudinal coordinates are obtained in the usual way in which the currents to each side of the wire surfaces are measured by means of transformers. In order to get a good accuracy in this measurement wires of high resistance are used. The surfaces which are facing each other, are made of low-resistance wires connected at their ends by high-resistance collectors. By measuring the current-distribution around the collectors information about the azimuthal coordinate is obtained.

The pressure employed corresponds to a thickness of 0.7 mg/cm^2 for a distance equal to the radius of the big chamber. The angular error is 1.2° FWHM as can be seen in Section 6. A large part of this uncertainty is attributed to multiple Coulomb scattering in the gas. The insensitivity to minimum-ionizing particles (Section 4) is an advantage because it prevents spurious sparks caused by background radiation.

2. MECHANICAL AND ELECTRICAL DESIGN

A photo of the chambers is shown in Fig. 1. The external dimensions are $\varnothing 760 \times 800 \text{ mm}^2$ for the big and $\varnothing 340 \times 600 \text{ mm}^2$ for the small chamber. Each chamber consists of four rings equipped with printed circuits and wires with a spacing of 2 mm. The distance between the two surfaces is 4 cm. The chambers are held by a frame made of two circular end-pieces, connected by a beam at the bottom. The mechanical parts are made of fibre glass and epoxy resin. Adjustment screws between the frame and the chambers are used to obtain the desired wire tension, which is about 40 grammes. There are stainless-steel wires ($\varnothing 70 \mu$) on the outer surface of the large chamber and on the inner surface of the small one. The remaining two surfaces are made of gold-plated molybdenum wires ($\varnothing 50 \mu$). The overall transparency of the system is thus 88%.

There is a 45° wire-free region at the bottom, used to bring in the connections to the wire cylinders. Fig. 2 shows the high-voltage conductors, coated by insulating layers of silastene which is a silicon elastomer.

A circuit diagram of the high-voltage electronics is shown in Fig. 3. The high-voltage pulser and the spark gaps are commercial units (EG & G).

As the position information is derived directly from the charges flowing to the chambers, it is important for the storage capacitors to be discharged completely every time the chambers are pulsed. This is ensured by shunting the spark gaps with resistances and capacitances with sufficiently high time-constants.

The delay of the high-voltage pulses with respect to the trigger pulse is typically 150 ns. The high-voltage pulse has a rise-time of 30 ns and a height of 8 kV. The pulse width determined by the RC time constant is about 100 ns. This short pulse width favours the formation of inclined sparks and gives a small charge-to-pulse-height ratio, which is necessary in order to avoid unwanted break-downs in the chambers.

The ringing frequencies of the spark currents are approximately 4 and 2.5 MHz for the small and big chambers respectively. In order to avoid capacitive coupling of energy between the two chambers the outer surfaces are grounded. In this way the grounded wires of the small chamber act as a screen between the two high-voltage surfaces.

3. READ-OUT SYSTEM

The longitudinal position x is obtained from the surfaces made of stainless-steel wires (1 Ω/cm). These wires are connected together at each end by low-impedance printed-circuit collectors. The high-voltage pulses are fed to two opposite points of each collector, via the conductors shown in Fig. 2. The conductors are threaded through ferrite cores and signals proportional to the currents are obtained from secondary windings on them. From the transformed signals U_1 to U_4 for each surface (Fig. 4) a position-sensitive parameter y is obtained:

$$y = \frac{U_L - U_R}{U_L + U_R} = \frac{U_1 + U_2 - U_3 - U_4}{U_1 + U_2 + U_3 + U_4} \quad (1)$$

In the case of the two surfaces made of low-resistance molybdenum wires, the interconnections at their ends are made by means of constantan wires (1 Ω/cm). The transformer signals are here summed and subtracted such that y gives information about the azimuthal position, that is the position along the constantan wires.

In order to see how the parameter y depends on the position x it is necessary to carry out a circuit analysis which is very complex with a complete chamber. We may treat each wire surface separately, however, as the chamber dimensions are considerably smaller than the electrical wave length and as the capacitance between the two cylinders is small enough to be neglected.

Before proceeding to a circuit analysis for one surface, we give the reason for feeding each collector in two points. According to Fig. 4, neglecting connections and shunting wires, y can be written:

$$y = \frac{1 - 2x}{1 + 4nZ (1 - n/n_0)/r} \quad (2)$$

where r = wire resistance, $2Z$ = collector impedance between two wires.

The second term in the denominator gives the dependence of y on the position from one end defined by the number of wires n . This unwanted variation is increased by a factor 4 if the collectors are fed at one end only.

In the Appendix the influence of the shunting wires is accounted for. Eq. A8, which is the result of this analysis, may in a straight-forward way be extended to the case with two feed-points per collector. The result is:

$$y = \frac{1 - 2x}{1 + \frac{2Zn^2(n_0-n)^2}{r[n^2+(n_0-n)^2]}} \quad (3)$$

In the big chamber there are $n_0 = 500$ wires between two feedpoints, each wire has a resistance $r = 70\Omega$, and the impedance Z at spark frequencies is around $0.1 \text{ m}\Omega$. The variation of the denominator in eq. (3) due to this is 9%. However, the spark current which can be approximated by a damped sine-wave, $i = i_0 e^{-t/T} \sin(\omega t)$, has a frequency-spectrum composed of components around the fundamental frequency ω , and low-frequency components typical of the time constant T , which is of the order of several microseconds. As Z , which is almost purely inductive, is an order of magnitude smaller for these low-frequency components it is preferable to use them as read-out signals.

In Fig. 4 is shown the circuit which we use to convert the spark current to pulse-height. The inductance L of the two transformers seen from the secondary side is $400 \text{ }\mu\text{H}$. The high-frequency components are reduced to negligible values in filters. The voltage u across R and C due to the current $i_0 e^{-t/T}$ is

$$u = \frac{M i_0 T}{LC[1-T/RC + T^2/LC]} [e^{-t/T} - e^{-t/2RC} \cos \omega_e t] \quad (4)$$

where

$$\omega_e = [1/LC - 1/4R^2 C]^{\frac{1}{2}},$$

and M is the mutual inductance between transformer and conductor. As T will vary with spark position along a wire by about a factor 2, the amplitude in eq. (4) will be affected. In order to reduce the influence of these variations, the values of R and C , 50Ω and 330 nF respectively, have been chosen so that $T \ll RC$ and $T^2 \ll LC$. The pulse height is then proportional to $i_0 T$, which is a measure of the charge in the primary circuit.

The signals U_L and U_R from the four planes are integrated, amplified and digitized according to Fig. 6. The signals are sensed $3.2 \text{ }\mu\text{s}$ after the

chamber is triggered. This time is long enough to ensure that the maximum value of the amplitude in eq. (4) is reached.

4. OPERATION AND PERFORMANCE

Good spark conditions are obtained at a pressure of 40 mm Hg with 10% C_2H_5OH . A slightly higher pressure is used, when the experimental conditions permit. A 10-MeV alpha particle liberates around 1000 electrons, whilst a minimum-ionizing particle in this gas gives only one or two electrons on the average.

The break-down process starts with Townsend multiplication which stops at around 10^8 electrons when faster mechanisms take over. The coefficient α is 30 in our case (Fig. 7a); this means that a multiplication path of 6 mm is needed before 10^8 electrons are produced.

The time for clearing the chambers from the electrons at a field of 40 V/cm is 4 μs as can be seen from Fig. 7b, ⁵⁾, where drift velocities in He are shown.

A serious problem connected with the low pressure is the long life-time of the meta-stable states, which gives rise to delayed electrons; these electrons may limit the rate with which the chambers can be pulsed. In Fig. 7c ⁶⁾ is shown how the life time of the 3s state in helium, which is the most abundant meta-stable state, depends on pressure. At 40 mm Hg the life time is 2.5 ms. This figure is only indicative as the life time of the meta-stable atoms depends critically on the size of the vacuum vessel as well as on gas impurities.

At low gas pressure it is difficult to avoid unwanted discharges with or without the spark from an ionizing track. Precautions have therefore been taken in the mechanical design of the chambers so that electrical field concentrations are minimized. Examples of this are the insulating rings at the ends of the wire cylinders (Fig. 8). In spite of this we have had discharges between these rings, which we have stopped by means of thin sheets of black paper midway between the two planes. We think that the paper helps in two ways. Firstly it absorbs very strongly photons, which will reduce the second Townsend coefficient. Secondly it prevents avalanches trying to develop in the frame.

Another weak point has been the conductor arrangement (Fig. 2) where initially strong discharges occurred between the electrodes. Because of this, most of the system of conductors inside the low-pressure chamber was potted in Silastene producing a solid block of insulating material in which the conductors are embedded.

After these and other minor improvements we are able to develop sparks without any accompanying break-downs that would destroy the read-out information. The sparks are well-defined at the ground planes. The track-following properties cease at about 30° angle with respect to the normal.

5. CALIBRATION

The calibration device in Fig. 9 simulates experimental conditions when α 's are emitted from the centre of the chambers. This device consists of a metal rod with 7 collimated alpha-sources (^{241}Am , 5.48 MeV) for longitudinal calibration and 2 other sources for azimuthal calibration. The collimator channels have dimensions $50 \times 5 \times 0.5 \text{ mm}^3$. For the longitudinal calibration we have 6 channels perpendicular to the cylinder axis and 3 channels at 66° , 75° and 83° with the axis. These channels permit us to make detailed studies of inclined tracks. The total intensity from the 9 channels after collimation is $50 \alpha/\text{sec}$. The calibration device is placed on the cylinder axis and can be rotated to different azimuthal positions from the outside of the low-pressure vessel.

The read-out parameter y , according to eq. (1), is calculated by means of the digitized signals U_L and U_R from each plane. In this calculation we correct for the biases of the encoders and the small difference in gain between the amplifiers. The six 90° channels are used to obtain the relation between the read-out parameter and the longitudinal coordinate in millimetres. A least-squares fit with polynomials of degree 1, 2 and 3 is used. Table 1 shows the differences between measured and fitted coordinates when polynomials of degree 1 and 2 are fitted. The second-order fit is sufficient for the experiment. There is a small dependence of the longitudinal read-out parameter on the azimuthal angle as is expected from eq. (3). It is, however, satisfactory for the precision to choose intervals of 45° in which the same coefficients are used.

The azimuthal read-out parameter is fitted to the azimuthal angle in a similar way. Table 2 shows the differences in degrees for the small sparkchamber.

6. RESOLUTION

Fig. 10 shows the distributions for four of the longitudinal channels. The contributions to the measured widths of these peaks are the multiple Coulomb scattering, the channel width of the collimator and the intrinsic error of the spark-chamber.

The calculated standard errors due to multiple Coulomb scattering are 0.9 mm at the small spark chamber and 4.7 mm at the large spark-chamber. The contributions due to the channel widths are 1.1 mm and 3.4 mm. The average errors from the calibrations are 2.4 mm and 6.2 mm. Using these figures we deduce the intrinsic errors, which are 1.9 mm FWHM and 2.2 mm FWHM for the small and large chambers respectively. The error in the azimuthal coordinate is of the order of 5 mm FWHM.

The dip angle is obtained from the two longitudinal coordinates. The width of the angular distribution is 1.5° independent of channel inclination. After having corrected for the channel width the residual error is 1.2° FWHM. The correction which has to be applied for inclined tracks is critically depending on the applied clearing field and high-voltage pulse. For the case of 8-kV positive pulses and 160-V negative clearing voltages on the inner planes, the measured angle has to be reduced by 2.5° at 66° ; this correction is linear up to 90° , where it is 0° .

7. MEMORY AND DEAD TIME

When the chambers are pulsed in the absence of any strong ionization there may under certain conditions, be faint read-out currents. This happens, for instance, when the high-voltage pulse is delayed with respect to a preceding track or when a relativistic particle has traversed the chamber. In both cases a small number of electrons are liberated. In the presence of a strong ionizing track this is harmless. The faint currents are rejected by the condition that the sum of the currents should exceed half its nominal value, if the

coordinate is to be calculated. This condition was used to obtain the plots in Fig. 11. The measured memory times are in good agreement with what is calculated by means of the drift velocities.

As the trigger rate in the experiment does not exceed 0.5 sec^{-1} no real attempt has been made to optimize the repetition rate. The maximum rate is of the order of $2-3 \text{ sec}^{-1}$.

8. ACKNOWLEDGEMENTS

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APPENDIX

DERIVATION OF A RELATION BETWEEN THE RATIO $(I_L - I_R)/(I_L + I_R)$ AND THE RELATIVE POSITION x ALONG A WIRE

The current $I = I_L + I_R$ can be decomposed as follows:

$$\begin{aligned} I_L &\equiv \frac{I_L + I_R}{2} + \frac{I_L - I_R}{2} \\ I_R &\equiv \frac{I_L + I_R}{2} - \frac{I_L - I_R}{2} \end{aligned} \quad (A1)$$

From symmetry it follows that the part $(I_L + I_R)/2$ of the current will pass the collectors without redistribution via the wires. This can be seen by means of the circuit diagram for one plane in Fig. 5. The part $(I_L - I_R)/2$ flows in the loop to the left in Fig. 5, as if there was no external connection. The circuit problem consists of finding the potential V_x and the current I_x at the spark wire which gives a current $(I_L - I_R)/2$ in the leftmost loop. The currents I_a and I_b through the spark wire are obtained by adding to I_x the directly transmitted part $(I_L + I_R)/2$ of the current.

$$\begin{aligned} I_a &= \frac{I_L + I_R}{2} + I_x \\ I_b &= \frac{I_L + I_R}{2} - I_x \end{aligned} \quad (A2)$$

The voltage V_x across the last wire can be expressed by means of eq. A2 as function of x and currents:

$$V_x = (I_L + I_R)(rx - r/2) + rI_x \quad (A3)$$

where r is the wire resistance.

By means of filter theory it is possible to express I_x and V_x as function of the current $(I_L - I_R)/2$. From Fig. 5 one sees that the points between the resistances may be interconnected as they are at equal potential. Hence the network consists of two parallel branches of cascade-coupled T sections. The

characteristic impedance Z_M and the attenuation function Γ for each branch are

$$Z_M = [(r+Z)Z]^{\frac{1}{2}} \quad (A4)$$

$$\Gamma = 2n \operatorname{arsinh}[Z/r]^{\frac{1}{2}}$$

The characteristic equations are

$$-V_x/2 = I_x Z_m \coth \Gamma - (I_L - I_R) Z_m / (2 \sinh \Gamma) \quad (A5)$$

$$0 = I_x Z_m / \sinh \Gamma - (I_L - I_R) Z_m (\coth \Gamma) / 2$$

The desired relations are then:

$$I_x = (I_L - I_R) (\cosh \Gamma) / 2 \quad (A6)$$

$$V_x = -(I_L - I_R) Z_m \sinh \Gamma$$

By means of equations A3 and A6 the relation between position-dependent parameter y and position x is derived:

$$y = \frac{I_L - I_R}{I_L + I_R} = \frac{1 - 2x}{\cosh \Gamma + (Z_m/r) \sinh \Gamma} \quad (A7)$$

For $Z \ll r$ series expansion of hyperbolic functions and use of eq. A4 gives:

$$y = \frac{1 - 2x}{1 + 2n(n+2)Z/r} \quad (A8)$$

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FIGURE CAPTIONS

- Fig. 1 Cylindrical wire chambers.
- Fig. 2 High-voltage conductors and read-out transformers.
- Fig. 3 High-voltage electronics.
- Fig. 4 Current flow in one plane, n_0 = number of wires, $2Z$ = collector impedance between two wires, r = wire resistance, L = inductance of the two transformers.
- Fig. 5 Equivalent net-work for one plane.
- Fig. 6 Block diagram of read-out electronics.
- Fig. 7 Characteristic gas parameters (from refs 4, 5 and 6).
a) First Townsend coefficient α .
b) Electron drift velocities in He.
d) Life time of the 3S_1 meta-stable state in He.
- Fig. 8 Section showing end piece of one chamber.
- Fig. 9 Calibration device.

Fig. 10 Measured longitudinal distributions of α 's from four channels for the big chamber, top, and the small chamber, bottom.
 $a = 9^\circ$ channel, $b = 83^\circ$ channel, $c = 75^\circ$ channel, $d = 90^\circ$ channel.
 The channels a, b and c have a common origin on the axis and the channel d is displaced 94 mm from channel a.

Fig. 11 Efficiency vs delay for two clearing voltages, 45 mm Hg total pressure, 14% C_2H_5OH .

TABLE CAPTIONS

Table 1 Differences between the measured and fitted axial coordinates for the big chamber.

Table 2 Differences between the measured and fitted azimuthal angles for the small chamber.

Fig 1

Fig 2

Fig 3

Fig 4

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Fig 5

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Fig 7A

Fig 7B

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Fig 8

Fig 9

Fig 10

Fig 11