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THE OMEGA SPECTROMETER RING IMAGING CERENKOV DETECTOR
Recent Detector Modifications and Event Analysis

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Abstract

A Ring Imaging Cerenkov (RICH) detector has now been successfully operated throughout a high-energy (70-200 GeV/c) photoproduction experiment at the CERN Omega Spectrometer. Recently complementary data using a hadron beam was taken with the same equipment. In each case about 20 million interactions were recorded. We discuss here features of the RICH device not yet described in previous publications and indicate by means of examples the way in which the RICH information is being used in the context of the overall experimental data analysis.

Introduction

At previous IEEE Nuclear Science Symposia [1,2] and elsewhere [3,4] we have discussed the design and development of a large angular acceptance RICH. In this device, UV Cerenkov photons produced by charged particles traversing a 5 m path in a gas radiator are focused by a mirror system to form ring images which fall inside a set of Time Projection Chambers (TPCs). Here they photoionize molecules of tetrakisdimethyl-aminoethylene (TMAE) vapour added to the gas filling. One coordinate of each photoelectron on the ring is obtained from the time required for it to drift under a constant electric field to a central wire chamber structure (MWPC). The resulting left-right ambiguity can be resolved by the track position information from the spectrometer. The other coordinate is given by the position of the MWPC wire at which the photoelectron arrives. Figures 1 and 2 are reproduced here from [2] for reference purposes.

As indicated in [2], a preliminary run was made in 1984 during which experience was gained concerning the background levels present in our experimental environment. On the basis of this run, we were also able to decide on a set of operating conditions suitable for the data-taking runs of 1985 (tagged photon beam) and 1986 (hadron beam), during which stability and reliability of RICH operation were extremely important. The results of a careful study of the 1984 data can be summarized as follows:

1) A high level of random background associated with the electron beam used to generate the tagged photon beam was encountered. An increase of the TPC drift velocity was therefore necessary to reduce the memory time to a value at which this background was acceptable.

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Fig. 1 General view of the Omega RICH.

2) A reduction in gas gain (MWPC HT) was desirable for two reasons. Firstly, we observed that an important component of the event associated (i.e. non-random) background came from charged track photon feedback. This phenomenon, in which secondary photoelectrons are produced by UV photons created in MWPC avalanches, can be reduced by reducing the gas gain. Secondly, interruptions to deal with MWPC overcurrent trips and occasional wire breakages could be reduced by operating at lower MWPC HT.

3) A beam independent calibration method for measuring the drift velocity and the drift time coordinate at zero drift distance was clearly needed to avoid time consuming calibration runs.

4) About 10 photoelectrons were observed for high momentum ($\beta = 1$) rings with the N_2 radiator gas used (thresholds 5.7 GeV/c for pions, 20.4 GeV/c for kaons). In spite of this relatively high signal, the background conditions mentioned above degraded the π/K separation efficiency, particularly at momenta close to pion threshold. Raising the refractive index of the radiator gas, to solve this problem by increasing the detectable signal, has several advantages compared to the alternative of increasing N_0 . A factor of two increase in the refractivity would increase by a factor four the detected signal from a pion at 7 GeV/c. Although a substantial increase in N_0 is possible (but not by a factor of four) this would mean operating the TPCs in such a way that the event-associated background would be much higher and their stability less reliable. Finally, increasing

Fig. 2 Time projection chamber.

the refractive index extends the momentum range over which π/K separation is possible by decreasing the pion threshold.

5) A loss of photoelectrons was observed which increased with increasing drift distance [2]. We attribute this to electron attachment to the various components of the TPC gas. Some impurities in the TMAE contribute to this effect. We therefore decided to adopt a more sophisticated method of TMAE preparation which would remove electronegative impurities more efficiently.

We have carried out a series of improvements in the light of the considerations mentioned above. These are described in Section A) below and were in place for the larger part of the data taking periods of 1985 and 1986. During each of these runs some 20 million event triggers were written on magnetic tape. At the same time, off-line analysis methods have been developed to handle the RICH information in the context of the data analysis of the experiment as a whole. Section B describes these methods and illustrates them by means of event examples.

Section A: Recent Modifications and Improvements

A1. Focusing Structure

In order to reduce the overall memory time, an increase in the TPC drift velocity was necessary, implying an increase in drift field and/or a change of gas mixture. The isobutane component in the TPC gas mixture could be reduced from 20% to 10% without significantly increasing the background from photon feed-back. However, laboratory measurements [2] showed that an increase in drift field would be accompanied by an increased loss of photoelectrons to the cathode separators and (to a lesser extent) to the cathode wires which distribute the HT.

A simple focusing system has therefore been added to the central four TPCs (those most susceptible to random backgrounds), which steers photoelectrons to

the anode wires more effectively at the drift fields used. At the same time most of the cathode wires have been removed from all TPCs.

The focus structure consists of an array of 500 micron stainless steel rods positioned parallel to the centre line of each separator edge and spaced 1 mm from it. To support this array, insulating bars of 3 mm x 6 mm section are fixed across all separators close to the glass windows. Each bar is fitted with suitable sockets to locate the rods and distribute the focus voltage. The other end of the rod is electropolished to produce a rounded profile and is located by an industrial sapphire annulus which is accurately glued to the separator edge. The cathode voltage is supplied to the separators by two 100 micron beryllium copper wires, one outside the active volume of the TPC and the other equidistant from the quartz and glass windows. Where this second wire crosses the focus rods, a 2 mm long PTFE sleeve is fitted over the rod to prevent electrical breakdown.

Figure 3 shows the field lines computed by a two dimensional finite element electrostatics program, PE2D [5] for MWPCs with and without a focus structure. In both cases the effect of cathode wires has been ignored. For the sake of clarity, field lines from the cathodes to the anodes have been omitted. The figure refers to -2 kV cathode voltage and 418 V/cm drift field. The PE2D model predicts 55% efficiency without focus rods and 100% for an idealized focusing system operating at -2.5 kV. This is in reasonable agreement with the figures of 58% and 93% measured in laboratory tests.

Fig. 3 Computed MWPC field maps.

A2. TPC Operation

In 1985-1986 TPCs were operated at drift fields of 418 V/cm (as in 1984). The reduction in the isobutane concentration to ~ 10% increased the drift velocity (v_d) from 3.7 to 5.0 cm/ μ s. In 1985 the central four TPCs, with focusing added, ran at 600 V/cm (v_d = 6.4 cm/ μ s).

The MWPCs were operated in 1985-1986 at reduced gas gain. This was achieved without loss of single photoelectron detection efficiency by increasing the sensitivity of the readout electronics. Modifications were made to the RF screening of the TPCs and the earthing of the analogue electronics. The consequent reduction in noise level permitted a lowering of readout threshold by a factor of four. A similar reduction in the gas gain was then possible, corresponding to a reduction of 150 V in the MWPC operating HT. Following these changes, we at first observed an increase in sensitivity to cross-talk initiated by charged track ionization avalanches and propagated by the cathode structure. This cross-talk was suppressed by adding suitable RC terminators to

these structures. The residual effect appears as a vertical line of simultaneous digitisings centred on the wire collecting ionisation from the charged track (see Fig. 10a).

A3. Fibre Optic Calibration Device

Accurate and frequent measurement of the drift parameters referred to in the introduction is essential to both the on-line and the off-line analyses. These measurements could be obtained by measuring the curve of drift distance versus drift time for charged track TPC impacts, using impact positions predicted from the Omega Spectrometer data by the track identification program TRIDENT [6]. However, special MWPC settings were necessary for this method and frequent calibration runs of this type slowed up the rate of data taking.

For the runs in 1985 and 1986 a more straightforward approach was therefore implemented, the details of which are shown in Fig. 4. Ultraviolet photons are produced within a low-pressure (200 torr) hydrogen discharge lamp [7] operating as a 'free-running oscillator' at 6 to 15 Hz. The light passes through the fused silica body of the lamp and into plastic clad, fused silica fibres [8] which enter the detector in two bundles. Two fibres, of equal length, are fixed by commercially available bulkhead connectors to a glass-fibre bar from which two 600 micron i.d. ceramic collimators direct the light through the quartz window of each TPC. The collimators are accurately positioned 120 mm apart and normal to the electron drift direction. The emergent photons then photoionize the TMAE vapour in the TPC gas and the resultant photoelectrons drift to the MWPC structure where they are detected in the normal manner. Each time the lamp 'fires', an induced pulse is used to generate a trigger to the experimental readout and also to gate an ADC which measures the pulse height of the signal from a photomultiplier tube viewing the discharge via a 2 m fibre. This ADC signal is used to check the stability of the lamp operation.

Fig. 4 Fibre optic system.

Prototype tests showed that noise was induced in the detector readout by the firing of the discharge lamp. The circuit is therefore contained within a doubly-screened enclosure consisting of two hermetically-sealed boxes. The inner box is of copper and the outer one of steel to eliminate both electrostatic and electromagnetic pickup. The lamp is decoupled from the copper box by a 1 Ω resistor. The inner box is only earthed to the outer box at one point, as is the outer box to the RICH detector. All signals and HTs enter and leave the enclosure via capacitive feedthroughs (low-pass RFI 'π' filters). All fibres pass between the two boxes within copper

pipes. The result of these precautions was that no correlated noise signals could be seen from the detector at the lowest possible TPC readout thresholds.

During data-taking, the trigger from the lamp is ORed into the main experimental trigger. The lamp pulsing rate can be altered by changing the RC time constant of the components. The number of observed photoelectrons per pulse is normally set at around 0.5. This value is tuned by moving the individual fibres with respect to the lamp body and so altering the solid angle.

The same lamp has been used throughout the setting-up and running in 1985-1986 and no observable deterioration has been seen after a total of five months operation. The calibrations obtained by this method are in excellent agreement with those obtained by the charged track impact extrapolations discussed above.

A4. Radiator Gas Recirculation System

A mixture of hexafluoroethane (C_2F_6) and nitrogen was chosen as the radiator gas for the 1985 and 1986 runs. Such mixtures have excellent UV transmission above 1500 Å, low chromatic dispersion and a refractive index (n) which can easily be brought to a required value by adjusting the relative proportions of the component gases. A mixture of 62% C_2F_6 and 38% N_2 (with refractivity, $n-1 \approx 600 \times 10^{-6}$ as used in 1986) gives pion and kaon thresholds of 4.0 GeV/c and 14.3 GeV/c, respectively. A gas recirculation system was used to conserve C_2F_6 (which is expensive) and to provide the high purity required for good VUV transmission. The system holds the radiator pressure to a constant differential ($+0.3 \pm 0.1$ mb at the top of the radiator vessel) relative to atmospheric pressure by adjusting the flow of gas to and from the radiator according to ambient temperature and pressure variations. It is also able to separate C_2F_6 from N_2 by liquefaction and then store C_2F_6 in liquid form when the RICH is not in use.

Figure 5 shows the main components of the gas recirculation system. The recirculation capacity is two volume changes (2×120 m³) per day and activated copper and molecular sieve filters in the recirculation loop continuously remove oxygen and water vapour. The pressure control function is achieved by two proportional valves, one controlling the flow into the vessel and the other acting on the pumps at the outlet. The pneumatic control system is backed up, for safety reasons, by an electronic pressure sensor and electromagnetic valves.

During RICH operation a 600 l dewar serves as a gas reservoir. Two stages of pumping can together reach a pressure of up to 15 bar which in conjunction with a purpose built refrigeration system allows efficient separation of the C_2F_6 from the mixture. The oxygen and water vapour filters are situated between the two pumping stages where the pressure is about 3 bar.

Prior to filling, the system was purged with nitrogen to reduce oxygen and water vapour levels to less than 10 ppm. C_2F_6 was then introduced into the bottom of the radiator vessel at a rate of 5 m³/h until the required refractive index was reached. Up to 70% C_2F_6 concentration could be achieved by direct nitrogen displacement in this manner.

Fig. 5 Radiator gas recirculation system.

After the filling procedure, measurement of the refractive index of gas from the top and bottom of the radiator showed complete mixing in less than 24 hours. No gas layering was observed during subsequent operation.

Fig. 6 UV transmission of radiator gas.

Monitoring of O_2 , H_2O and N_2 (% in C_2F_6) was provided at various points in the system. In equilibrium conditions we measured about 2 ppm of H_2O and 4 ppm of O_2 at the RICH outlet. These were reduced to < 0.5 ppm by the filters. It was also possible to measure the VUV transmission of the gas in a 4 m test cell and the absorption spectrum so obtained was consistent with these values. Figure 6 shows a typical measured transmission spectrum for the 1985 conditions (about 55%

$C_2F_6/45\% N_2$) extrapolated to the average Cerenkov photon path length of 750 cm in the radiator. The effect of 3 ppm O_2 and 3 ppm H_2O has been superimposed on the curve.

A5. Preparation of the TMAE

Industrially produced TMAE normally contains oxidation products and other impurities, both from the manufacturing process and from its accumulated storage time. Together, these impurities absorb UV photons strongly and possess marked electronegativity [9,10]. If not removed they would compete with the photoionization process and reduce the drift efficiency of the photoelectrons.

Since the maximum drift time of photoelectrons in our TPCs is only 3-4 μs the electronegativity problem, though noticeable, is not serious. We have measured [2] an electron drift efficiency of 80%, over an average drift path of 11 cm, using samples of TMAE for which a simple purge with nitrogen was used to remove impurities of higher volatility than TMAE itself. The 20% losses include electronegative effects of other components of the gas mixture (80% methane, 20% isobutane and water and oxygen at about 3 ppm and 10 ppm, respectively). For our recent experimental runs we have therefore reduced the isobutane component to $\sim 10\%$ and chosen a simple 'washing' procedure in TMAE preparation which makes use of the polar nature of the water molecule to remove electronegative impurities not eliminated by purging [9,11].

Small samples of TMAE (80 cm^3) are transferred to a conical flask in a glove box containing an atmosphere of N_2 (measured $O_2 < 3$ ppm). Recently distilled, de-ionised water (18.3 $M\Omega cm$) is first bubbled with nitrogen to remove dissolved oxygen. The water is then added in equal volume to the TMAE and the mixture is shaken vigorously. An opaque, orange-coloured mixture is formed but the fractions quickly separate when shaking is ceased, allowing the impurity laden water to be removed with a separating funnel. The procedure is repeated several times, the TMAE becoming clearer at each step and assuming a seawater-green colour.

In a second stage, surplus water is removed by shaking with silica gel, supplied by the makers in vacuum-tight sachets in ready to use form. The liquid is then filtered, the entire operation being repeated four or more times with fresh silica gel.

At this point the TMAE is placed in a stainless steel bubbler as used in the RICH operation. The vessel is immersed in water at about $17^\circ C$ and $1 m^3$ of nitrogen, for each mole of TMAE, is bubbled through at 40-50 l/h. The bubbler is then placed in a copper cooling coil through which water is passed from a refrigerated water bath set at a temperature chosen to give a suitable TMAE vapour pressure. When the temperature has stabilized, nitrogen is bubbled through the TMAE and into a 10 cm long absorption cell. The VUV properties of the mixture of N_2 and TMAE vapour are measured with a monochromator beam scanned over the region 1460-2340 $\text{\AA}$. The systematic errors on our measurements of absorption coefficients obtained in this way are estimated to be about 5%.

Figure 7 shows typical absorption curves at molecular concentrations corresponding to the TMAE vapour pressure at $10^\circ C$ [curves a) and b)] and $15^\circ C$ [curve c)]. Curve a) was obtained immediately after the washing procedure and shows traces of residual impurities. Curve b) was obtained after the purging stage described above. Purging is normally continued with N_2 until no further change can be detected.

Fig. 7 Absorption coefficient of TMAE vapour.

The absorption curve of untreated TMAE is normally several times higher than curve b). Our procedure prior to 1986 (purging alone without washing) produced curves similar to b) after about 1 m³ of N₂ had been bubbled through the liquid per mole of TMAE [3].

Section B: Off-line Analysis of RICH Data

The techniques used in analysing RICH data to produce particle identification can best be illustrated by reference to a specific example. Figure 8 shows the tracks produced in the Omega Spectrometer by the interaction of a 140 GeV π^+ in the 60 cm liquid hydrogen target. This event is of interest because the three tracks entering the RICH, to produce the ring images seen in Fig. 9, span the momentum range over which the RICH is designed to have good π/K separation. The vector momentum and position of each track entering the RICH is known with high precision from the spectrometer [6]. This information is used to predict the expected coordinates of the centre of the associated ring image ('+' in Figs. 9 and 10). Knowing the refractive index of the radiator gas, the ring radii expected for each possible particle type (e, μ , π , K, p) are calculated and 'search bands' in radius constructed (the concentric annuli in Fig. 10). The widths of these bands are determined by the known resolution of the RICH and the known uncertainties of the fitted track momentum and direction from Omega.

Fig. 8 Omega event display.

For each hypothesis on the particle type, the populations of these bands are predicted. This population is made up from the expected Cerenkov signal and background. The background is estimated for each track by measuring the density of hits between the search bands. If there are sufficient hits in the band corresponding to the hypothesis being made, a fit to a circle is performed, yielding a fitted radius and its estimated error [1]. A probability for each hypothesis is then constructed by comparison of the expected populations and radius, with those observed.

Fig. 9 Event digitisings in the RICH.

Fig. 10 a) Track 1 (+29.56 GeV/c)

Track 1 (Fig. 10a): This is a 29.56 GeV positively charged track. At this momentum we do not expect to distinguish between the e, μ and π hypotheses and only the π , K and p search bands are shown in Fig. 10a. The hits associated with the search bands are denoted by 'X' in the figure, the predicted centre by '+' and the track impact point by '*'. The background for this track has contributions from several sources, all of which are understood, but only some of which are recognized and removed by the present analysis procedure. Techniques are under development

to improve the treatment of this background, but for the moment we rely on the estimation outlined above which is sufficient to allow a clear identification of the particle type.

The K and p hypotheses are ruled out by the large number of hits in the π band (19 compared to 4.0 expected from background only), the π hypothesis being three orders of magnitude more probable (Poisson) than K or p.

Fig 10 b) Track 2 (-61.36 GeV/c)

Track 2 (Fig. 10b): This is a 61.36 GeV negatively charged track. Only the proton and pion bands are shown in the figure; at this momentum (close to the upper limit at which π/K separation is possible) the e, μ, π and K bands overlap significantly.

The proton hypothesis is ruled out by the absence of signal in the p band AND the presence of signal in the π band which cannot be explained by the observed background level; the p hypothesis is 7 orders of magnitude less probable than e, μ, π or K. The decision between π and K is made on the basis of the fitted radius (both π and K could explain the population of the bands with high probability). For the π band, the fitted radius is 17.54 ± 0.08 cm to be compared with the predicted radius of 17.56 cm. For the K band, the fitted radius (of the points in the band) is 17.41 ± 0.08 cm to be compared with a prediction of 17.13 cm. This information is combined with that from comparison of populations to form a ' χ^2 probability' [1] (which is 100% when the predictions match the observations exactly). For this track, the π hypothesis gives 85.5% probability and the K hypothesis 3.9% probability.

Note that a threshold Cerenkov counter, operating at the same refractive index, would have been unable to exclude the K and p hypotheses for either of the above tracks.

Track 3 (Fig. 10c): This is a 7.54 GeV positively charged track. At this momentum both K and p are below threshold. The track is clearly not p or K (probability 7 orders of magnitude less than π) -- the e and μ hypotheses are also ruled out by the radius at which the observed signal appears (15.07 ± 0.11 cm) compared to the expected 17.60 for e , 16.14 for μ and 14.96 for π . Although a

Fig. 10 c) Track 3 (+7.54 GeV/c)

threshold Cerenkov would have excluded p or K, it could not have ruled out μ and e .

Conclusions

Modifications to the TPCs and readout have provided the flexibility to control the level of background without loss of signal detection efficiency (N_0) and with a gain in the stability and reliability of the detector. The introduction of a radiator gas recirculation system provides the capability to tune the refractive index to match the physics requirements of experiments using the spectrometer and in particular has allowed an improvement in performance at lower momenta. A UV fibre calibration system provides the accurate and continuous monitoring of TPC drift parameters which is essential to subsequent off-line analysis.

The present analysis techniques provide particle identification over the design momentum range and some improvement is expected from the development of methods for recognizing and removing the remaining event related backgrounds. The RICH now operates as a standard facility with the Omega Spectrometer. It has been used by three experiments (WA69, WA71, WA82) and is planned to be used by experiments running in 1987.

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