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**DEVELOPMENT OF LARGE-AREA FAST RICH PROTOTYPES
WITH PAD READOUT AND SOLID PHOTOCATHODES**

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Abstract

In the frame of the RD26 Collaboration at CERN we have built and tested several prototypes of fast RICH detectors suitable for the construction of large systems. The detectors used a solid photocathode consisting of a 500 nm CsI layer evaporated on a conventional pad readout board of a multiwire proportional chamber (MWPC) operated with a methane/isobutane mixture at atmospheric pressure. The results indicate that such a detector may be used for long periods of time in stable operating conditions provided the gas mixture is continuously flushed through the detector. Evidence is shown for a significant loss of transmission of Cherenkov photons in the NaF radiator due to internal anisotropy of the crystal. We present the results of the performance of the photocathodes, the quantum efficiency of the CsI we have extracted from the measured Cherenkov photons, and the identification achievable in a high-density environment such as the detector ALICE planned for the heavy-ion Large Hadron Collider (LHC). The results of a study of primary and secondary electron photoemission of CsI layers indicate that the surface structure and electron yield depend on the source material and on the heat treatment of the layer.

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1 INTRODUCTION

Since the publication of Seguinot et al. [1] reporting evidence for a significant quantum efficiency (QE) of thin CsI layers operating in gas counters, a large amount of activity has developed on the subject [2]. The efforts developed were in two main directions: the first is the measurement of the maximum QE, trying to optimize the electron yield in controlled conditions (evaporation condition, substrate, exposure to air, origin of CsI, etc.), the second is the testing of the feasibility and performance of large systems—several hundreds of cm^2 —where the technological problems of building a reflective photocathode and the conditions of exploitation considerably limit the available choices of the substrate, the state of the substrate surface, the minimum time of exposure to air, the amount of treatment that can be applied (mainly in regard to thermal treatments), and finally the conditions of operation of the gas detectors. To a certain degree the interests of the two groups are only partially converging: namely, while the groups aiming for a detector have to work for an optimal solution regarding performance and price, the other groups are aiming for a maximum QE in the ideal conditions. In the present work we present the results obtained on prototypes of RICH detectors using solid photocathodes incorporated on the pad cathode of a multiwire proportional chamber (MWPC) of sizes up to $30 \times 30 \text{ cm}^2$. The results were analysed in terms of the technological feasibility, the achieved Cherenkov angle resolution, and the particle identification power. The data obtained in the beam were also analysed to extract the QE achieved in the range of wavelengths covered by the transparency of the overall detector. To elucidate the physical parameters influencing the QE of the photocathodes (PCs), studies of the CsI layer surface were undertaken using ESCA and X-ray techniques.

2 STRUCTURE OF THE RICH PROTOTYPES

The RICH prototypes used in the present work were of the proximity-focusing type with a solid radiator NaF of 10 mm thickness. The gap length between the radiator and the UV photon detector has been chosen such as to give ring locii of a mean radius of 35 and 100 mm respectively, for the two sizes of photocathodes studied ($10 \times 30 \text{ cm}^2$, and $30 \times 30 \text{ cm}^2$).

The photon detector was a MWPC with a pad readout photocathode.

The design of the detector aims at a detection capability in a wide dynamical range allowing to detect simultaneously the large amplitude signal originated by the charged particles that have emitted the Cherenkov photons in the radiator and the low exponential distribution of the signal created by the single electrons emitted from the photocathode surface. The distances between anode and cathode and between sense wires were chosen as 2 and 4 mm, respectively, with anode wires of $20 \mu\text{m}$ diameter. Such a geometry allows for readily achievable mechanical tolerances on large surfaces of detectors.

For the entrance cathode plane two types of geometries were tested—a standard $500/50 \mu\text{m}$ mesh and a plane of wires 2 mm apart. The tests made on the small prototype have shown that an increase in photon transparency is obtained, with no negative consequences on the other aspects of operation. The large prototype has so far been operated only with a mesh cathode.

The pad plane is manufactured as a sandwich of thin G10 foils and foam, allowing for a very rigid, and yet light structure. The pad size was in all cases $8 \times 8 \text{ mm}^2$.

The detector was operated with either pure methane or a mixture of methane/isobutane, 95/5 in volume, at atmospheric pressure.

The main difference between the current fast RICH and those using a photosensitive vapour lies in the fact that the gap volume for the development of the ring pattern is not, any longer, physically separated from the UV detector. This means that the electrons created in the gap by the charged particles have to be prevented from reaching the active volume of the MWPC. This has been achieved in the present prototypes by incorporating an additional wire plane close to the radiator, thus creating a collecting electrode for the electrons in the gap. The performance of this electrode has given full satisfaction.

3 PHOTOCATHODES

All the photocathodes used in the tests were of 500 nm thickness except for one of 1000 nm. The pad plane was produced using standard printed-board technology, which implies etching the pads on a copper layer covered by gold chemically deposited, all on a G10 substrate layer. Owing to the treatments during production the surface is rather rough, with frequent scratches several μm deep and wide.

The evaporation of the small PCs ($10 \times 30 \text{ cm}^2$) was done in a standard way in an evaporation station with a crucible centrally positioned with respect to the pad plane. The pad cathode was mounted in the evaporator together with the connections to the pad electronics on its back. To prevent excessive outgasing, the back side of the pad plane was protected by a tight box, pumped separately. The distance crucible-plane was approximately 36 cm. The rate of evaporation was 3–7 nm/s. The CsI layer was evaporated continuously on the pad plane, without having to recur to masking the pads. For the large PCs a dedicated evaporation station was built. To keep the station reasonably compact even for large areas, a multiboat evaporation mode was adopted. Four crucibles were simultaneously operated to achieve a uniform layer over the pad plane. The conditions of evaporation were the same as for the small PCs. The vacuum before the evaporation was typically $5 \times 10^{-8} - 10^{-7}$, and during evaporation $10^{-6} - 5 \times 10^{-6}$ Torr. Two quartz balances monitored the evaporation rate and the layer thickness. The temperature of the substrate during evaporation was 22–25°C. After evaporation, nitrogen was released into the station, the pad plane dismounted and transferred through air to the MWPC, mounted into the detector structure, flushed with argon, and then transferred to the beam where the detector was flushed with the operating mixture. The total exposure to air was 5–10 minutes.

4 BEAM TESTS

The prototypes were tested at the CERN PS accelerator using a proton beam of 3 GeV/c ($\beta = 0.9544$). The event trigger was given by the time coincidence of four small scintillators defining a beam spot of about $5 \times 5 \text{ mm}^2$ at the chamber. However, since the beam size is much larger than the spot, the chamber was submitted to a flux of 1–3 kHz per sense wire.

The distance radiator-photocathode was chosen such as to give rings of a mean radius of 40 mm and 100 mm in the case of the small and the large PC, respectively.

In total 7 PCs have been tested, 4 of the smaller size and 3 of the larger size. The pad substrates were always the same; only evaporation parameters and exploitation conditions were varied.

5 PERFORMANCE OF THE PROTOTYPES

The first observation is that the coverage of the pad cathode by a thin layer of CsI has not hindered, in any way, the stable operation of the chamber. All the 7 PCs reached

operating voltages in less than an hour without exhibiting a ‘formation’ period. Most of the photocathodes were irradiated over periods of weeks without showing deterioration, stray current, or discharges. However, for the PC of 1000 nm thickness a few microdischarges were observed during the first voltage application, after which it behaved as the chambers with a thinner layer.

The collection electrode has performed satisfactorily, keeping the cluster size of the minimum ionizing particles at 4 ± 2.5 pads, providing the localization of the particle with an accuracy of 400 μm along the wire, by calculating the centre of gravity of the induced charges.

In the large RICH prototype the typical single-electron efficiency was 80–90% with a mean of 1.6 ± 0.6 pads per photoelectron cluster. In the tests a typical mean number of 13 ± 4 pads hit were recorded in the ring fiducial area, corresponding to 7–8 detected photoelectrons per event. The single-photon clusters were identified by applying an algorithm to resolve merged clusters using the topological information (given cluster pattern cannot be produced by a single electron), and the amplitude information on the individual pads in the cluster (e.g. if a cluster is represented by three aligned pads, the maximum amplitude has to be in the middle pad if it was produced by a single electron). The distribution of the number of pads and photoelectrons per event is given in Fig. 1.

The Cherenkov angle dispersion per photon is 21 mrad. The dispersion of the Cherenkov angle calculated per event is 8.5 mrad (Fig. 2).

In the following, we enumerate the different parameters that have been changed in the preparation of the PCs and/or in the exploitation, and their effect on the performance of the RICH.

No visible differences were observed for the following variation of parameters:

- Evaporation rate: from 2 to 10 nm/s.
- Vacuum during evaporation: from 10^6 to 10^5 Torr.
- Treatment of the photocathode by a flow of methane in the evaporation station immediately following the evaporation.

For the following modifications, some effects were observed:

- Exposure of the PC to a humid gas flow for several hours. Reduction of 10–15% in the number of detected photoelectrons during the flow. When dry gas circulation was re-established the detector performance recovered after several hours.
- Exposure of the PC to dry air circulated in the MWPC for one hour. After recirculation of the gas mixture, no decrease in performance was observed.
- Heating of the detector in the beam to 50°C, under normal gas flow. A degradation in performance is registered, possibly due to an outgassing of vapours, either from the pad substrate, or the stesalit walls of the detector frames.

At the level of the performance described here, the photocathodes tested exhibit a rather robust behaviour and reproducibility in the production procedure, and the conditions of exploitation.

6 EXTRACTION OF THE QUANTUM EFFICIENCY OF CsI

The extraction of the quantum efficiency was possible due to the high chromaticity of the NaF radiator [3], [4]. The chromatic dispersion being much larger than the geometric effect, owing to the thickness of the radiator, it is possible to define fiducial zones in the ring images corresponding to defined photon energy ranges. Especially, this approach was possible in the case of the RICH with 100 mm radii, but a variant of the same technique was possible also in the case of the small RICH detector. To correlate the radii with the

photon energy we used the detector geometry and the refractive index from Ref. [5]. To calculate the QE, the photon transparency given as the product of all the UV photon absorbers on the way from the point of emission to the photocathode was used as well as the single-electron efficiency extracted from the amplitude distribution of single-electron clusters identified as such in the recorded events. The overall transparency of the RICH detector using a NaF radiator is given in Fig. 3 for two cases: the case when a mesh entrance cathode is used, and the case of a wire plane cathode. It is obvious from Fig. 3 that a 20% larger transparency is achieved in the case of a wire cathode.

In Fig. 4 we show the QE extracted from the present measurements with both types of photocathodes. Both detectors give a remarkably similar result for the QE, indicating that, starting from the same base material and a similar treatment, fairly uniform responses may be expected.

Although our result is about half that of the values obtained by Seguinot [1] and Anderson [6], it is in general agreement with all the other reported measurements ‘on the low side’. This is in itself a successful result if it is borne in mind that all the other results were obtained under almost optimal conditions—well polished substrate surfaces, small areas, well-controlled environment, etc. It should be stressed that none of the recipes recently suggested by Anderson et al. [7] have been tested in the present work on RICH detectors, leaving space for further improvements of the photon yield of PCs.

It should be pointed out that the QE quoted here should be taken as a minimum value from our tests. We have observed during the runs the existence of ‘dead zones’ in the fiducial area of the ring, which could be eliminated by moving the radiator with respect to the beam. However, examining the events off line for uniformity we find in fact a non-uniformity in the photon density over the ring fiducial volume, both in the azimuthal and the radial direction. We illustrate in Fig. 5 the non-uniformity of the photon density in the ring fiducial showing the azimuthal distribution of photoelectrons, integrating the superimposed events in the whole radial width of the ring for 4° bins in the azimuthal angle. These non-uniformities have been substantiated by observation, only in visible polarized light, of patches of low transmission across the NaF surface. Additionally, the manufacturer has confirmed that such inhomogenities can appear owing to internal strains during crystal growth. From Fig. 5 we can evaluate that the losses cannot be smaller than 30%, comparing the average value over the ring that was used in the calculation of the QE quoted here, increasing by the same amount the quantum efficiency shown in Fig. 4 and the number of photons per event mentioned earlier.

7 MEASUREMENT OF THE PHOTON YIELD OF CsI PCs WITH ESCA

Photoemission spectromicroscopy studies were performed on small samples, using the SCIENTA ESCA 300 system, equipped with a rotating anode (Al K α radiation source), an X-ray monochromator, and a concentric hemispherical analyser [8] at the École Polytechnique fédérale, Lausanne. The measurements were performed in ultra-high-vacuum (UHV) conditions. For the present we limit ourselves to the preliminary results obtained with several photocathodes where the effects of the surface structure were studied to correlate the effect of different source materials (crystal versus powder CsI), and the effect of heating treatment in vacuum conditions, during and after evaporation.

The secondary electron spectrum and yield have been measured, as well as the primary electrons corresponding to the 3d levels of CsI.

In Fig. 6 we show the secondary electron spectrum obtained for three different samples produced in the following way:

- Sample 1 was evaporated using CsI powder, heated to 50°C; after evaporation the sample was continuously heated for 36 hours in the evaporating station, under vacuum, at the same temperature.
- Sample 2 was prepared from CsI in crystalline form taking care to premelt the crystals in the crucible. The temperature of the substrate was kept the same as for sample 1. The heating period after the evaporation was 20 h.
- Sample 3 was prepared from crystal without heating the substrate either during the evaporation or afterwards.
- Sample 3a is physically the same sample as 3 except for the fact that the sample was heated in the ESCA environment for 6 h at 50°C.

All the samples were evaporated on copper substrates. All the spectra were taken at identical conditions of X-ray flux, and spectrometer parameters.

The spectra of secondary electrons exhibit several features worth mentioning here—the yield depends rather strongly on the type and/or treatment imposed on the samples, the position of the maximum of the secondary electron yield shifts towards smaller energies for the crystal samples, and finally the width also depends on the source material and/or treatment.

The spectra of primary electrons from the 3d core level of iodine for samples 3 and 3a are shown in Fig. 7. A marked difference is observed depending on the sample. We show only the results obtained for iodine (the result for the caesium core level is identical). Before treatment a dominant peak is observed with an admixture of another contribution 0.8 eV higher in binding energy. After the thermic treatment the picture is completely changed—there is no longer any dominant peak; two peaks 0.5 eV apart appear with about the same amplitude. An energy shift is also apparent and may be due to slightly different charging effects of the surfaces of CsI or to a genuine energy shift in the core-level energy.

The modifications observed, both in the primary and the secondary electron spectrum, indicate a structural change on the surface of the CsI layer. This observation may be significant with respect to the controversy existing with respect to the QE values obtained in different laboratories. Indeed, slight variation in the production procedure may provoke small changes in the structure of the layer. Actually, the best results on QE were reported by Anderson et al. [7] who used a thermal treatment.

More information we have gained from these measurements is that the surface charging was very small (about 1 eV in most cases) with 500 nm thick layers. On the contrary, when powder pellets or crystals of CsI were measured, much larger charging effects were observed; this is typical of insulators. This confirms our findings on the smooth operation of the MWPC using the CsI PC.

8 A SOLID PHOTOCATHODE RICH IN THE HIGH-PARTICLE-DENSITY ENVIRONMENT OF ALICE/LHC

ALICE (A Large Collider Experiment) [9] is a dedicated heavy ion experiment planned for the LHC (Large Hadron Collider) operating in heavy-ion mode (lead on lead) collisions. The possibility of using a RICH wall for particle identification in the momentum range 0.8–2.5 GeV/c is being considered for this experiment.

The detector would be a proximity-focusing fast RICH using a liquid C₆F₁₄ radiator, and a solid PC of the type presented here. The general layout presented in Fig. 8 is

governed by the need to optimize the performance in the azimuthal as well as in the polar angle. The main constraints are the following: the best localization accuracy is achieved along the sense wires so that the wires have to be positioned parallel to the magnetic field. Also the best Cherenkov angle resolution is achieved for track incidence normal to the radiator or at a small angle around it. This requirement necessitates the tilting of the Cherenkov modules. In the present design the single module will have a surface of the order of $1.5\text{--}2\text{ m}^2$.

Owing to the very high density of particles expected ($50/\text{m}^2$) it is important to investigate the possibility of particle identification and pattern recognition in the proposed detector. With that goal, a simulation [10] was made, using the measured response of the detector presented here, and two values for the QE (20% lower than the results of Ref. [1] and the QE measured in the present tests). The simulated events were then analysed for the Cherenkov angle resolution achievable in the simulated events that were produced with the particle density, and the momentum/particle mix as obtained from event generators. The analysis of the pictures described in Ref. [10] shows that the proposed fast RICH, with a gap corresponding to maximal Cherenkov ring radii of 100 mm, could distinguish within 3σ pions and kaons at the following momenta:

- i) 3.7 GeV/c for single particles in the detector, using the high QE value,
- ii) 2.4 GeV/c for densities of $50/\text{m}^2$, using the high QE value,
- iii) 2.1 GeV/c for densities of $50/\text{m}^2$, using the low QE value, and the other parameters as in the present prototypes.

9 CONCLUSION

The present tests of the operation of RICH prototypes with different sizes and 7 different PCs allow the following conclusions to be drawn:

- i) Stable operation of the MWPC was achieved over a period of months with a QE equal to the values obtained by most groups using the same evaporation procedure and the same source material, demonstrating that the manufacture of technologically simple and robust PCs is possible without recurring to masking procedures for the evaporation of the CsJ;
- ii) No ageing effects were observed over the duration of the tests, providing the PC was kept in the detector under a constant gas flow.

The NaF radiator was found to have important internal defects causing opacity for the polarized UV photons.

The measurements of the photoelectron emission obtained with ESCA has demonstrated that heat treatment and source material do have a bearing on the structure of the surface CsI, meaning that optimization of the present PCs is both possible and necessary.

The analysis of the simulated events, using realistic detector parameters and response in high-density environments, has shown that the use of a fast RICH detector in the ALICE experiment is feasible.

Figure 1: Distribution of the number of pads and photoelectrons measured with the $30 \times 30 \text{ cm}^2$ RICH. The black and white dots on the photon cluster distribution correspond to the raw clusters (black dots), and to the clusters resolved using the analogue information on the amplitudes of individual pads (circles), as explained in the text.

Figure 2: Distribution of the Cherenkov angle per photon and per event.

Figure 3: Overall photon transmission in a RICH using a 10 mm NaF radiator for different operating gases, and two types of entrance cathode—mesh and wire plane.

Figure 4: QE extracted from the present measurements with the two sizes of photo-cathodes. The shaded area in the case of the small PC represents the spread of the results obtained with different evaporations and gas mixtures, and anode voltages ranging from 2000 to 2100 V. The observed spread reflects the fluctuation of the results without clear patterns favouring a particular experimental situation. Owing to reasons explained in the text, the values may be underestimated by about 30%. For the large PC the analyses of three runs are shown.

Figure 5: Plot of the azimuthal distribution of detected photoelectrons in 4° bins on the superimposed events of one run.

Figure 6: Secondary electron spectrum for the samples 1, 2, 3, and 3a, described in the text.

Figure 7: Primary electron spectrum of the 3d core level of iodine for the sample 3 (a), and the sample 3a (b), described in the text.

RICH PID WALL

Figure 8: Design of the RICH barrel for ALICE. The perspective view (a), and a side view (b) of a single row of modules along the beam axis showing the tilting of elements.