A PHOTON DETECTOR FOR RELATIVISTIC HEAVY ION COLLISIONS (*)

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A Photon Detector for Relativistic Heavy Ion Collisions

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The detection of direct photons produced in relativistic heavy ion collisions is discussed. Physics motivations and experimental difficulties are presented. After a description of the PHOS electromagnetic calorimeter of ALICE, I will present, how its identification capabilities can be substantially improved by adding a pre-shower detector (PPSD). The PPSD consists of a passive converter sandwiched between two large active area MICROMEGAS chambers. Preliminary results of the beam tests for the PPSD prototype will be also described.

1 Introduction

Relativistic heavy ion collisions offer a unique tool to produce, in the laboratory, the primordial matter of the universe essentially consisting of a plasma of deconfined quarks and gluons (QGP). During the last decades, a great experimental effort has been devoted to the search of such a state of matter in fixed target experiments at bombarding energies from 10A to 200A GeV (equivalent to available energies in the nucleon-nucleon center of mass of $\sqrt{s} \sim \sqrt{2E_{lab}m_N} = 5A-20A$ GeV) [1]. However, the QGP discovery has not been firmly established yet. Nevertheless, it has been recently claimed that the partonic phase has been already reached, as indicated by the enhanced strangeness production and J/Psi suppression [2, 3, 4, 5].

New heavy-ion experiments programmed at RHIC (Brookhaven) and LHC (CERN) colliders with higher available energy in the center of mass frame ($\sqrt{s}=200A$ and 5000A GeV, respectively) will certainly allow to reach an energy density high enough to form a baryon free quark-gluon plasma. Some of the programmed experiments: STAR [6] and PHENIX [7] at RHIC, and ALICE [8] at LHC, will look at most of the probes sensitive to the different phases of the heavy-ion reaction, including a possible QGP phase. A coherent explanation of the full set of probes, from peripheral to central reactions, will probably be the only way to claim the QGP discovery. Among the different possible probes and related observables (hadrons, strangeness, heavy mesons, di-electrons, etc), direct photons will contribute to explore the partonic phase, studying its equilibration and QGP thermal properties [9]. As direct photons I mean those photons produced in the high energy density zone of the reaction, and not coming from the subsequent electromagnetic decay of the produced neutral mesons (neutral pions, eta-, phi- or omega-mesons). These direct photons will emerge from the heart of the reaction as free non-interacting particles, probing specific phases of the heavy ion reaction.

First in this talk I will summarize the main aspects of direct photon production in relativistic heavy ion collisions. The next three following sections will be devoted

to the various aspects and difficulties encountered in the measurement of these direct photons. Afterwards in Sections 4-6 I will describe the main existing or under-development experimental set-ups. In the next following section, I will, then, present one of the main activities of the *Groupe Photon de Subatech*, namely the improvement of the photon identification capabilities of the photon spectrometer for ALICE (PHOS) [10, 11]. The main idea behind is based on adding a pre-shower detector in front of PHOS. This pre-shower detector (PPSD) consists of a sandwich of two gas chambers, based on MICROMEGAS technology, with a passive inner lead converter. In details I will describe the PPSD prototype and some preliminary results of the tests done at PS(CERN) facility. The final section will serve to draw some conclusions and oversee perspectives.

2 Direct photons in relativistic heavy-ion collisions

During a heavy-ion reaction, different ephemeral states of the many-body system will be dynamically created. It starts with a phase of strongly interacting partons from the colliding hadrons, and finishes with the freeze-out phase of a thermalized hadron gas. Each phase of the reaction will contribute to the total direct photon yield (see [9] for more details).

According to the Bjorken picture [12] of relativistic heavy-ion collisions, the system will evolve in the following way:

- **Formation phase.** During a few tenth of fm/c valence and sea partons will strongly interact. At this stage Compton and annihilation processes (Fig.1) are the most important leading order processes which contribute to the direct photon production. These "hard processes" will mainly populate the high energy tail of the direct photon spectrum, for transverse energies larger than 5 - 15 GeV.
- **Equilibration phase.** After ions have traversed each other, a longitudinal expanding system of non-equilibrated partons is formed. Partons will start to interact until they likely, reach thermal and chemical equilibrium (after 0.5 to 2 fm/c). Still Compton and annihilation processes in this thermalizing parton system will mainly contribute to the production of intermediate transverse energy photons, from 2 to 10 GeV.
- **Equilibrated gas of deconfined partons.** The equilibrated plasma of deconfined quarks and gluons quickly cools from $T \sim 0.5 - 2.0$ GeV down to the phase transition temperature $T \sim 170$ MeV. QGP thermal radiation will contribute to the production of the low and intermediate transverse energy photons, from 1 to 4-5 GeV.
- **Hot hadron gas.** The expanding system will further cool down and the partons *hadronize* or *fragment*, creating a hot hadron gas. Thermal radiation of this gas (π annihilation and ρ capture) will, a priori, contribute to the low photon transverse energies, from 1 to 3 GeV.

Fig. 1. Selection of leading order Feynman diagrams for direct photon production in parton-parton interactions.

- **Neutral meson decay.** Finally, 10^7 fm/c later, neutral mesons issuing from the freeze-out of the hot hadron gas, will decay electromagnetically. These decays, like π^0 electromagnetic decay, will occur close to the interaction point (hundreds of nanometers in the energy range of interest here, $E_\pi \sim 1$ GeV), so the direct component cannot be separated from the meson-decay one, on an event-by-event basis. Decay photons will therefore constitute the main contribution to the photon spectrum in the low and intermediate energy domain: up to to 5-10 GeV. Indeed, about 80 to 95% of the total photon yield is produced during the ultra-late (in the heavy-ion reaction time scale) decay of neutral mesons. Nevertheless, the neutral meson production can be identified experimentally by, e.g. the invariant mass analysis of the photon pairs, and therefore, the contribution from meson decay can be experimentally subtracted.

3 Electromagnetic decay of neutral mesons

3.1 Calculating the meson-decay photon spectrum from the measured neutral meson spectrum

The measurement of neutral mesons (pion and eta-mesons) through invariant mass analysis opens up the possibility to experimentally determine the contribution of the meson decay photons to the total photon spectrum [13]. In this section, I will show a simple case where the photon spectrum from neutral pion decay is

straightforward to calculate.

Fig. 2. Kinematic variables of the electromagnetic decay of a neutral pion in two photons

First, let us consider a pion which decays and emits two photons in flight. In the pion rest frame, both photons are emitted with a relative angle of 180° and with an energy equal to $m_\pi/2$, where m_π is the meson mass. The energy of each photon in the laboratory frame is obtained from the Lorentz boost:

$$E_i = \frac{\gamma m_\pi}{2} [1 + (-1)^i \beta \cos \theta] \quad (1)$$

and the energy asymmetry of the photon pair is, then, given by:

$$x = \frac{|E_1 - E_2|}{|E_1 + E_2|} = \beta \cos \theta \quad (2)$$

Since photons are isotropically emitted in the π rest frame, $\cos \theta$ is an uniform distribution between -1 and 1. In the laboratory frame, the photon energy is, thus, uniformly distributed between $E_1 = \gamma m_\pi/2(1 - \beta)$ and $E_2 = \gamma m_\pi/2(1 + \beta)$. The density probability to detect a photon with an energy E_γ coming from the π^0 decay is:

$$\frac{dP}{dE_\gamma} \sim \frac{1}{E_\pi} \quad (3)$$

for $E_1 < E_\gamma < E_2$ and assuming that $|E_2 - E_1| \sim E_\pi$. Let us consider that the neutral pion distribution has been measured (e.g. by invariant mass analysis of photon pairs [14, 15]) and can be described by the following phenomenological expression:

$$\frac{d\sigma_\pi}{dE_\pi} = K \times E_\pi^{-n} \quad (4)$$

the photon spectrum from the pion decay is then calculated as:

$$\left[\frac{d\sigma_\gamma}{dE_\gamma}\right]_\pi = 2 \int_0^{E_\gamma} dE_\pi \times \frac{d\sigma_\pi}{dE_\pi} \times \frac{dP}{dE_\gamma} = K \times \frac{2}{n} E_\gamma^{-n} \quad (5)$$

where the 2 factor is included to take in account the decay into two photons, and where we have integrated from zero up to the photon energy (i.e. $E_1 \sim 0$ and $E_2 \sim E_\pi$). We find that the photon spectrum from neutral pions has the same shape as the parent neutral pion spectrum, multiplied by a factor $2/n$. The direct photon spectrum is then obtained from:

$$\left[\frac{d\sigma_\gamma}{dE_\gamma}\right]_{\text{direct } \gamma} = \left[\frac{d\sigma_\gamma}{dE_\gamma}\right]_{\text{total}} - \left[\frac{d\sigma_\gamma}{dE_\gamma}\right]_{\pi^0} \quad (6)$$

This simple case shows how to proceed to obtain the direct photon spectrum. However, other experimental complications, like the fact that photons and neutral pions are measured in a limited rapidity window, as well as the misidentification of photons, or the contribution from heavier neutral mesons, are ignored here.

3.2 Identification of photons from the neutral meson decay on an event-by-event basis

For photon energies much larger than the meson mass, the relative angle of the decay photons is, on the average, very small and both decay photons can be detected with high efficiency within the geometrical acceptance of the electromagnetic calorimeter. In this particular case, the rejection of decay photons can be done on an event-by-event basis. The relative angle between the decay photons is given by the following expression:

$$\cos \theta_{12} = \frac{\gamma^2 \beta^2 (1 - \cos^2 \theta) - 1}{\gamma^2 (1 - \beta^2 \cos^2 \theta)} \quad (7)$$

θ is the photon polar angle in the meson rest frame (see Fig.2). It is defined with respect to the axis defined by the meson momentum in the laboratory. Thus, $\theta = 0$ or $\theta = \pi$ implies that the photon direction is co-linear with the pion direction in the laboratory frame. Assuming $\gamma \gg 1$:

$$\cos \theta_{12} \sim 2\beta^2 - 1 \quad (8)$$

and,

$$\cos(\theta_{12}/2) \sim \beta \quad (9)$$

or, easier to handle,

$$\theta_{12} \sim \frac{2}{\gamma} \quad (10)$$

In Fig.3, the relative angle of the photon pair θ_{12} is calculated as a function of the decay photon polar angle θ in the meson rest frame for $\gamma = 5, 25$ and 125 (i.e. for

Fig. 3. Relative angle of the photon pair θ_{12} calculated as a function of the photon polar angle θ in the meson rest frame for $\gamma = 5$ (solid-line), 25 (dashed-line) and 125 (dotted-line).

$E_\pi = 0.7, 3.5$ and 17.5 GeV and $E_\eta = 2.7, 13.7$ and 68.6 GeV). We observe that the plotted θ_{12} distribution from eq.(7) is close to the uniform distribution given by eq.(10).

The efficiency of the decay photon rejection thus increases with the meson energy and depends on the calorimeter geometry (rapidity, transverse momentum and azimuthal angle acceptances). Let us consider a photon detector placed at a distance of ~ 5 m away from the interaction point in a collider and covering the mid-rapidity range. One can estimate the meson energies for which a rejection of the decay photons can be applied with high efficiency. For relative angles θ_{12} below 4 or 2 degrees (i.e. for neutral-pion energies above 4 or 8 GeV or eta-meson energies larger than 15 or 30 GeV, respectively), both decay photons will be detected with a high probability and the meson-decay photon rejection method can be efficiently applied.

In general, both photons will be detected as a "single" very energetic electromagnetic shower for very large meson energies. This occurs when the relative angle is lower than 0.5 degrees, considering the mentioned detector geometry and an intrinsic Molière radius of 2 cm for the crystals. Such an overlapping of the showers from decay photons will occur for pion energies larger than 30 GeV (or eta meson energies larger than 125 GeV). In this energy regime, the rejection of decay photons can still be done, by shape analysis of the electromagnetic shower developed in the

calorimeter. Indeed, the lateral size of the shower will be larger when induced by a photon pair than when induced by a single photon.

In the extreme case of neutral-pion energies larger than 100 GeV (eta meson energies larger than 390 GeV) direct photons and decay photons cannot be distinguished anymore. In this energy regime the direct photons cannot be measured, except if one changes considerably the geometry of the photon detector.

4 Learning from WA80/93/98 experiments

Direct photons have been measured for 30 years in hadron + hadron collisions [16]. However, the first attempt to measure direct photons in relativistic heavy ion reactions was done in the WA80, WA93 and WA98 experiments at CERN during the nineties. The main goal of these experiments was to measure at SPS energies the transverse energy distribution of direct photons in the mid-rapidity region. The photon transverse energy ranges from 1 to 4 GeV. These measurements aimed at determining whether the partonic phase was reached at these heavy-ion energies and whether an equilibrated plasma was formed. The studied systems were p+C, p+Au, O+C and O+Au at 60A and 200A GeV [2, 17, 19] (WA80 experiment), S+Au at 200A GeV [20] (WA93 experiment) and p+C, p+Pb and Pb+Pb at 158A GeV (WA98 experiment, preliminary results were shown in the last Quark Matter conference [1] by D.Bucher). The experimental set-up [13] used for the photon calorimetry was essentially the same in all these experiments. Basically, photons were detected by an electromagnetic calorimeter (SAPHIR lead-glass calorimeter and a lead-glass array for WA80, lead-glass calorimeter and a BGO array with longitudinal segmentation in WA93, and LEDA lead-glass calorimeter for WA98 experiment). Photons were discriminated against hadrons by means of the lateral development of the electromagnetic shower. In WA80 and WA98 experiments, a charged particle veto detector (CPV) was placed in front of the electromagnetic calorimeter to improve the photon discrimination power against charged hadrons [18].

At the actual stage of the analysis the results published on the direct photon production [2] indicate that such a measurement was beyond the experimental reach due to systematic errors introduced by the subtraction of the existing background (mainly π^0 and η photon decay contributions) and in the photon identification procedure. Nevertheless, these measurements were able to provide an upper limit for the direct photon differential cross-section, at the level of $\sim 7\%$ of the total photon yield (Fig.4) in S+Au collisions at 200A GeV. The measured upper limit for central reactions was found to be in contradiction with a scenario in which the number of degrees of freedom of the system is limited to that of a hadron gas.

The following encountered experimental difficulties are at the origin of most of the systematic errors:

1. Photon conversion. The proper consideration of the e^+e^- conversion probability of photons before reaching the calorimeter is crucial to determine the production yield of photons, neutral pions, and eta mesons.

Fig. 4. Adapted from [2]. Upper limits at the 90% confidence level on the invariant excess photon yield per event for the 7.4% minimum bias cross-section of the most central S+Au collisions at 200A GeV.

2. Non-target background contribution. Neutral pions, eta mesons and photons are also produced in interactions outside the target material, inducing a systematic error in the extraction of their yields.
3. Detector efficiency in high multiplicity reactions. Due to the high particle multiplicity in central heavy ion reactions, detector efficiency strongly changes with the detector occupancy. Moreover artifacts like overlapping of showers contribute to enlarge the systematic error.
4. Scaling of m_t for eta meson production. The ratio eta/pion is deduced from the m_t -scaling [21], since η meson production is measured with low statistics.

5. Other neutral meson and baryon decays, like ω - and ϕ -mesons or Σ^0 baryons, also contribute to the photon decay background.
6. Neutral hadron background. Neutron and anti-neutron developing hadronic showers in the calorimeter can be misidentified as photons. This contribution can only be estimated using the results of event generators, since neutral hadrons are not directly measured.
7. Charged hadron background. Due to the limited efficiency of the charged particle veto detector, some charged hadron induced showers could be misidentified as photons.
8. Energy non-linearity. Neutral pion energy, E_π is determined by the sum of the decay photon energies: $E_\pi^{measured} = E_1 + E_2$. Non-linearity effects in the photon calorimeter would imply that $E_\pi \neq E_\pi^{measured}$, introducing a systematic error in the measurement of the neutral pion spectrum.

5 PHOS: a photon detector for ALICE

In this section, I will briefly described the PHOTon Spectrometer for ALICE. More detailed information can be found elsewhere [10, 11]. PHOS is an electromagnetic spectrometer of high granularity consisting of 17280 lead-tungstate crystals, PbWO_4 (see Tab.1). Each crystal ($2.2 \times 2.2 \times 18 \text{ cm}^3$, 20 radiation lengths) is coupled to a PIN-diode with low noise preamplifiers. The fast scintillator PbWO_4 emits two light components: a blue one at 420 nm and a green one at 500 nm. Nevertheless the light yield at room temperature is low compared to other heavy mass scintillators. Therefore the working temperature will be lowered to -25°C where the light yield is increased by a factor 3 with respect the one measured at room temperature. Furthermore the electronic noise is also reduced. The PHOS spectrometer will be positioned at the bottom of the ALICE set-up, 4.6 meter away from the interaction point, and will cover the pseudorapidity range from -0.12 to 0.12 and an azimuthal angle domain from 45° to 135° (see Fig.5).

Table 1. *PWO properties.*

Density	8.28 g/cm ³
Radiation length	0.89 cm
Interaction length	19.5 cm
Molière radius	2.0 cm
Refractive index	2.16

A charged particle veto detector (CPV) will be placed in front of PHOS for additional rejection of charged hadrons. Two options have been considered, sofar, for the design of this CPV [11]:

- A detector based on known techniques of multiwire proportional chambers (MWPC).
- A detector based on MICROMEGAS gas chambers [23]. More details concerning the MICROMEGAS option, currently developed by our group, are given in next section.

PHOS has been optimized for the detection of photons with energies between 0.5 and 10 GeV/c. Neutral pions and eta mesons will be measured by invariant mass analysis of the photon pairs. Due to the limited solid angle covered by PHOS, π^0 (η) transverse momentum distribution will be measured for values larger than 1 GeV/c (2 GeV/c).

Photon induced showers will be identified by the characteristic width of electromagnetic showers together with an anti-coincidence with the CPV. Rejection of neutral hadrons like antineutrons will be more problematic because, although the width analysis will reject part of the neutral hadron contribution, the time of flight will not be measured by PHOS spectrometer.

6 Hints to improve photon detection in relativistic heavy ion reactions

The improvement of the photon identification capabilities of the PHOS detector has been one of our main goals pursued during this year. Since direct photons only represent about 5 to 20 % of the total photon yield, the measurement of the photon excess will be limited by the systematic errors on the total photon, π^0 and η meson yield extraction, which is expected to be around 5.6% [11]. We have studied the improvement of the photon identification power to eliminate, what we consider, the Achilles' heel of PHOS:

1. Rejection of anti-neutrons. The contribution of anti-neutrons to the measured photon spectrum will be of the order of $\sim 10\%$. Nevertheless, anti-neutrons will not be concomitantly measured, and their contribution can only be estimated from simulations of the ALICE detector either with proper theoretical event generators, or using distributions inferred from the antiproton production.
2. The Molière radius of a crystal limits the maximum particle density of the ALICE environment in which photons and neutral mesons can be efficiently measured. The Molière Radius of the PWO is quite small ($R_M = 2.0$ cm), allowing for the measurement of photons in the most central Pb+Pb collisions at LHC energies (where the particle density could be as much as 8000 per pseudorapidity unit). However the detector occupancy will be close to 20% and the overlapping of showers could introduce an additional source of systematic errors in the extraction of the photon and neutral mesons yields.

In this respect, two different axes of investigation have been developed within our group:

Fig. 5. Geometry of the PHOS spectrometer in the ALICE detector obtained from the ALIROOT package [22]. PHOS is placed 4.6 m away from the interaction point, on the bottom of the ALICE setup. This version of PHOS geometry consists of 5 modules, with 64×64 PW0 crystals each.

1. Study of the topology of the photon induced shower. As we have already mentioned, the shape of the induced shower can be exploited to discriminate hadronic showers from electromagnetic ones. We have studied the width of hadronic and electromagnetic showers along the eigen directions of the lateral shower development, in order to improve the quality of the hadron rejection power. This study is described in detail elsewhere [26].
2. The addition of a Pre-shower detector in front of PHOS, which, as we will show in the next section, considerably improves its identification capabilities.

7 PPSD detector

The PHOS Pre-Shower Detector (PPSD, see schematic view on Fig.6) consists of a sandwich of charged particle detectors (Charged Particle Veto detector, CPV and Charged Particle Conversion detector, CPC) with a passive converter in between. Such a detector is placed in front of the PHOS crystals denoted as EMCA in the rest of this talk. The charged particle detectors are two gaseous detectors, with pad read-out, based on MICROMEAS technology [23]. The MICROMEAS gaseous detector is described in the next section.

Particle identification in PHOS with the PPSD option

Fig. 6. Schematic view of the PHOS Pre-shower detector.

Complementary information provided by the PPSD considerably improves the identification power of PHOS:

1. Muons will be identified as minimum ionizing particles (MIPs) in Veto, Conversion and EMCA detectors.

2. About 40% of charged hadrons, like π^+ , π^- , K^+ , K^- , etc. can also be detected as MIPs, while the remaining 60% will be detected as MIPs in the veto and conversion detectors and will develop a hadronic shower in EMCA.
3. Photons will be unambiguously detected by the conversion detector (CPC) and an electromagnetic shower in EMCA. The detection efficiency will depend on the thickness of the passive converter. Considering a thickness equal to n radiation lengths (X_0), the pair radiation length (or attenuation length for photons energies larger than 20 MeV) is $\lambda_{pair} = 9/7 \times X_0$ (for a lead converter, $\lambda_{pair} = 8.2 \text{ g/cm}^2$). The probability for e^+e^- conversion in the passive converter is then:

$$P_{e^+e^-}(n) = 1 - e^{-7n/9} \quad (11)$$

obtaining that $P_{e^+e^-}(1) = 0.54$ and $P_{e^+e^-}(2) = 0.79$.

In addition, PPSD detector can be used as a shower vertex detector, or, as a standard charged particle veto detector:

- The conversion detector can be used to determine the electromagnetic shower vertex with a resolution better than the Molière radius of the EMCA crystal. In particular, the shower vertex provided by the conversion detector can be exploited to identify overlapping electromagnetic showers in the calorimeter, and consequently, to decrease the systematic error induced by this non-desired effect.
 - Photons can also be identified as electromagnetic showers in EMCA, using the PPSD as a standard CPV. This photon identification method is suitable for the identification of neutral mesons by invariant mass reconstruction of photon pair since i) the invariant mass peak of the meson resonance is strong enough to neglect photon misidentification and ii) photon+photon efficiency will be larger.
4. Neutrons, antineutrons and other neutral hadrons will not be misidentified as photons, since the conversion detector will not be sensitive to these particles. Only neutral hadrons interacting in the passive converter could be misidentified as photons. The interaction probability of hadrons in the passive converter of a thickness $n \times X_0$ can be estimated as:

$$P_I(n) = 1 - e^{(-nX_0/\lambda_I)} \quad (12)$$

where λ_I is the nuclear interaction length. For lead, λ_I is 194 g/cm^2 . We obtain $P_I(1) \sim 3\%$ and $P_I(2) \sim 6\%$. We roughly estimate that the neutral hadron rejection power is increased by one order of magnitude with the PPSD option as compared to the CPV-only option.

5. Electrons and positrons could be identified as an electromagnetic shower in EMCA and MIPs in the Veto and Conversion detectors.

In April 1999, we developed a prototype of the PPSD detector. It was tested at CERN in August 1999 under a hadron and electron beam. In the following sub-sections, we describe the PPSD prototype and present the preliminary results obtained from the test.

7.1 MICROMEGAS Detector

The basic element of the PPSD consists of a large MICROMEGAS [23, 24, 25] chamber, $432 \times 392 \text{ mm}^2$, with an active area of $415 \times 375 \text{ cm}^2$. The detector is an asymmetric two-stage parallel plate detector. The first stage, the 3 mm thick conversion gap is separated from the $100 \mu\text{m}$ thick amplification gap, by a micromesh frame resting on insulating spacers. By applying suitable voltages to the three electrodes a very high electric field in the amplification region (100 kV/cm) and a quite low electric field in the drift region can be achieved. The passage of a charged particle through the conversion gap generates primary electrons which are amplified in the small amplification gap. The ion cloud is quickly collected on the micromesh providing the possibility of a fast trigger signal. The electrons are collected on an anode and the two-dimensional localization is provided by a pad layout. The detector elements are shown in Fig.7 and Fig.8.

- the anode electrode is made of an 1.0 mm thick electronic board (GI180). On one side rectangular $22 \times 22 \text{ mm}^2$ copper pads are printed, whereas the signal collecting strips are printed on the other side. Each pad is pierced by a conductive pine hole to allow readout through the board; the rigidity of the board is provided by an additional 3 mm thick board made of low X_0 (composite material EPOXY glass and ROHACELL); $100 \mu\text{m}$ high micro spacers are deposited on the pads with a pitch of 2 mm in the z and y directions;
- the electro-formed mesh, made of pure Ni, forms a $3 \mu\text{m}$ thick grid matrix; the grid consists of $39 \mu\text{m}$ squared holes outlined by $11 \mu\text{m}$ of Ni in steps of $50 \mu\text{m}$, providing a maximum transparency of 59%; it is stretched on a Plexiglas frame and rests on the micro-spacers.
- the cathode electrode is glued on a 3 mm thick plate made of composite material sandwiched between two $300 \mu\text{m}$ thick GI180 boards covered with a $9 \mu\text{m}$ layer of copper.

The gas, an Ar+10% isobutane mixture, (other gas mixtures are being tested: Ar+ 30% CO_2 , Ne+ 30% isobutane and Ne+ 30% CO_2) flows through the detector with a pressure slightly above atmospheric pressure. The gas tightness of the detector is ensured by a 2 mm thick composite material box with the lid pierced for the gas inlet. The total thickness of the detector is 13 mm, corresponding to 1.76% of X_0 throughout the active area and at most 2.8% on the edge of the detector. When overlapping, the maximum X_0 stays below 5%. The measured efficiency for a detector of this kind is greater than 95%.

Fig. 7. Principle design of a MICROMEAS detector for the PHOS CPV: side view of an assembled detector.

The signals of the individual pads are collected at the backplane of the amplification electrode by individual strips and transported to the front-end electronics located on the two opposite sides of the detector. The electronics adds 1% of X_0 to the 1.76% in the active area.

Such a module with its 256 pads covers four PHOS modules of 64 crystals with a one-to-one correspondence between the pad and the crystal.

7.2 Test at PS (CERN)

The prototype of the PPSD detector was tested in the T10 hall at CERN. The main goals of this experiment were to test the prototype as well as the validity of the pre-shower concept for PHOS. More precisely, the test aimed at studying:

1. The uniformity of the response function.
2. The gain of the MICROMEAS detector in the amplification zone as a function of the micromesh voltage (HV_{mesh}).
3. The efficiency of the MICROMEAS detector to minimum ionizing particles as a function of HV_{mesh} .

Fig. 8. Principle design of a MICROMEAS detector for the PHOS CPV: enlarged view showing the various components.

4. The probability of electrical discharges per ionizing particle crossing the detector.
5. The background induced by the passive converter in the gaseous detectors.

The choice of the gas mixture during the experiment was Ar + 10% isobutane. The voltage of the drift zone was fixed to $HV_{drift} = -1000$ V, although this parameter had a minor impact on the results.

7.3 Experimental set-up.

Fig. 9. *Experimental set-up of the test done by the PHOS collaboration in August 1999*

Beam. The PS accelerator at CERN delivered a secondary beam of 2 GeV/c momentum. This beam consisted of hadrons ($\sim 60\%$, mainly charged pions) and leptons ($\sim 40\%$, electrons and muons). The size of the beam "spot" was about $10 \times 10 \text{ cm}^2$ and the spill duration was 1 s with an inter-spill of 9 s. The beam intensity was in the range 10^3 to 10^5 particles per spill.

Trigger. Two plastic scintillators (Pl₁ and Pl₂ in Fig.9) with a square shape of $10 \times 10 \text{ cm}^2$ were placed along the beam line to define the main trigger of the experiment (Pl₁ and Pl₂ coincidences defined the *wide beam trigger*). A small plastic scintillator Pl₃ ($1 \times 1 \text{ cm}^2$) was also included in the trigger electronics during some runs to define a *narrow beam trigger*, allowing for a direct measurement of the MICROMEGAS detector efficiency since only one pad of the MICROMEGAS detector was hit.

Beam identification. Two Cherenkov detectors C_i were placed upstream of the detector to identify the impinging particles. However, only C_2 (filled with CO_2 at atmospheric pressure) was working well. It allowed a discrimination between hadrons (protons and charged pions) and leptons (electrons and muons).

Passive Converter. During some runs, a square passive lead converter of $10 \times 10 \text{ cm}^2$ was placed between the MICROMEGAS detectors. The thickness of the converter was 1-3 radiation lengths (0.5-1.5 cm).

MICROMEGAS detectors. Two MICROMEGAS detector prototypes (described in section 6.2) were placed upstream and downstream with respect to the

passive converter. Amplification of the pad signal was performed by GASSIPLEX based electronics. The electronic set-up consisted of 3 GASSIPLEX chips of 16 channels each. They were directly connected to the detector board. GASSIPLEX sequential signal was digitalized by the V550 VME ADC (up to 1024 channels). Operations on the GASSIPLEX and the V550 module were synchronized via a V551A VME sequencer.

PHOS array. An array of 8×8 PHOS type crystals was placed at the end of the beam line.

7.4 Gain and efficiency of the gas detectors

Fig. 10. Amplitude distribution for a typical hit pad for $HV_{mesh} = -420$ V.

With the wide beam trigger, the amplitude distribution for a typical hit pad (see Fig.10) reveals two components:

- For low amplitude (for channel 50) the intrinsic electronic noise of the pad exhibits a Gaussian distribution. This corresponds to events in which beam particles fire the wide beam trigger and hit one of the neighboring pads. The mean of the Gaussian distribution is related to the V550 pedestals and the width to the pad electronics noise, which depends on the environment and on the capacitance of the pad anode.
- At higher amplitude the detector response to ionizing particles displays the usual Landau distribution due to fluctuations of the number of primary electrons created in the drift region. For a 3 mm gap of Ar+ 10% isobutane at

atmospheric pressure, on average, $N_e^{Pri} = 30$ primary electrons per MIPs, are created. The mean of the Landau distribution is related to the gain of the detector in the amplification zone and its width is mainly related to the average number of primary electrons (smaller average number of primary electrons leading to larger fluctuations).

The relative weight of both components (noise versus response) depends on the beam characteristics. In the present case (wide beam trigger, Fig.10) the beam is larger than the size of the pad ($2.2 \times 2.2 \text{ cm}^2$), which explain the fact that the noise peak on Fig.10 represents about 18% of the full statistics. For narrow beam trigger (not presented here) the beam is smaller than the pad size, and the noise contribution almost disappears. For a pad anode positioned out of the beam trajectory, the amplitude distribution is dominated by the noise component.

Fig. 11. Gain of our MICROMEGAS prototype. The gas mixture was Ar+ 10% isobutane and $HV_{drift} = -1000 \text{ V}$.

To dig more in the understanding of the MICROMEGAS working conditions it is of interest to study the pad amplitude properties as a function of the micromesh voltage $HV_{mesh} = -380$ to -450 V . Assuming that the GASSIPLEX amplification is 10 mV/fC and the dynamic range of the ADC is 1.5 V (10 bits conversion), we can estimate the number of electrons collected by the pad as:

$$N_e^{Pad} = (L_m - G_m) \times 1.465 [mV/ch] \times \frac{1}{10 [mV/fC]} \times \frac{1}{e [fC]} \quad (13)$$

where L_m and G_m are the maximum of the Landau and Gauss distributions respectively and e is the electron charge in fC. The gain in the amplification zone is

obtained as:

$$Gain = \frac{N_e^{Pad}}{N_e^{Pri}} \quad (14)$$

where N_e^{Pri} is the average number of primary electrons in the drift zone. In Fig.11, the evolution of the detector gain with the micromesh voltage is shown. In the measured HV_{mesh} range, the gain changes by one order of magnitude, from $3 \cdot 10^2$ to $3 \cdot 10^3$. Approximately, an increase of 20 V of the HV_{mesh} doubles the gain of the MICROMEGAS detector.

Fig. 12. Efficiency of our MICROMEGAS prototype for PPSD detector. The gas mixture was Ar+ 10% isobutane.

The detector efficiency to MIPs has been studied as a function of HV_{mesh} (see Fig.12). We observe that for HV_{mesh} larger than 410 V (leading to detector gains larger than $8 \cdot 10^2$), the detector efficiency is above 95%. The steep decrease of the detector efficiency for HV_{mesh} lower than 410 V is caused by the fact that the gain is too low to induce a signal on the pad larger than the nominal noise dispersion.

7.5 Discharges in the amplification zone

Micro-pattern detectors as MICROMEGAS, exhibit a transition to streamer regime followed by a electrical discharge, induced by ionizing particles. This transition occurs when the avalanche size reaches a critical value of a few 10^7 electrons [27]. Since heavy ionizing particles, like alpha particles, loose around 500 KeV of their kinetic energy in the drift gap (whereas a MIP loses around 1 KeV, generating around 30 primary electrons), the gain of a MICROMEGAS counter will be limited

Fig. 13. Discharge probability per ionizing particle as a function of the HV_{mesh} .

to a few 10^3 . The same effect is observed when the gaseous detector is irradiated with MIPs. In this case, nuclear processes in the drift gap could be at the origin of the induced discharges [28].

Although MICROMEGAS detectors are very resistant to micromesh sparks, a discharge will induce a non-negligible dead time over the whole detector active area, leading to a fall in the overall detector efficiency. As a consequence, a compromise between the gain of the detector and the discharge probability per MIP has to be established. In the case of the ALICE experiment, considering that the most central Pb+Pb collisions would generate around 5000 charged particles per rapidity unit, on average less than 3 particles will hit each MICROMEGAS chamber (active area $40 \times 40 \text{ cm}^2$ placed at 4.6 m away from the vertex point). The counting rate will be of the order of $2 \cdot 10^4$ particle per second. This implies that MICROMEGAS detectors placed in front of PHOS should exhibit a discharge probability per ionizing particle lower than 10^{-6} .

We have measured (see Fig.13) the discharge probability per ionizing particle as a function of the HV_{mesh} . We obtain discharge probabilities between 10^{-6} to 10^{-5} . However, for a discharge probability equal to 10^{-6} ($HV_{mesh} = -380 \text{ V}$), the intrinsic detector efficiency is too low (see Fig.11 and Fig.12). Similar results are obtained for different prototypes and the discharge probability does not depend on the beam intensity, as it was expected. We should note that the beam intensity was measured by Pl_1/Pl_2 coincidences, therefore, impinging particle trajectories out of the plastic active area, and hitting the MICROMEGAS detector were not counted. This induces an asymmetric systematic error which would tend to slightly decrease the measured discharge probability.

8 Conclusions and perspectives

Measurements of transverse momentum distribution of direct photons in relativistic heavy-ion collisions at RHIC (PHENIX) and LHC (ALICE) represent an experimental challenge. Direct photon production at high transverse momentum ($p_T > 4$ GeV/c) will certainly probe the partonic and equilibration phase of the interaction system, revealing the initial conditions of the searched primordial plasma. Complementarity, direct photon production at lower transverse momentum ($p_T < 4$ GeV/c) will be sensitive to the thermal radiation of the equilibrated system of partons and/or hadrons. Decay photon contributions to the total photon spectrum will be measured by invariant mass analysis of the photons pairs. A direct identification of π^0 decay photons for the higher photon energies ($E > 5$ GeV) has been described.

In the ALICE experiment at LHC (CERN), direct photon production in the energy range 0.5 to 10 GeV will be studied with the PHOS electromagnetic calorimeter.

We have proposed to equip PHOS with a pre-shower detector (PPSD) placed in front of the PbWO_4 crystals. The PPSD will considerably improve the identification capabilities of PHOS. In particular, the possibility of a better rejection of neutral hadrons and the identification of overlapping showers, will reduce the systematic errors on the extraction of the direct photon yield.

Large active area MICROMEGAS gaseous chambers have been chosen as charged particle detector, due to their small radiation length, small avalanche size and low cost. A PPSD prototype has been built and tested at PS (CERN) in a proton, pion and electron beam of 2 GeV/c momentum. Efficiencies larger than 95% and detector gains larger than 10^3 have been measured. We found that, with the selected gas mixture (argon plus 10% isobutane), the discharge probability per ionizing particle was too high, for the ALICE environment conditions.

At present, we are testing a gas mixture with a lighter noble gas, neon plus 30% of isobutane. The probability of discharge per ionizing particle should decrease about two orders of magnitude [28] since cross-sections of nuclear processes is considerably reduced. Recently, we have also developed a new prototype with a 200 μm amplification gap and using a large area 100 μm step micromesh. First tests with cosmic rays are encouraging since gains larger than 10^3 are reached. The main goal of this R&D is to decrease the cost of the PPSD by almost a factor two, due to the lower cost of the micromesh of 100 μm steps. PPSD option for PHOS could, then, be selected with a minor impact on the PHOS budget, but with a noticeable improvement on the single photon identification power.

A more ambitious simulation project has been recently undertaken by the PHOS collaboration. The main goal is the evaluation of the quality of the direct photon measurement in relativistic Pb+Pb collisions with the PPSD option for PHOS.

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