STUDY OF BaF₂ CALORIMETERS IN FUTURE HADRON COLLIDERS

G. Charpak, V. Peskov and D. Scigocki

CERN, Geneva, Switzerland

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ABSTRACT

In this contribution we discuss prospective BaF$_2$ calorimeters for experiments with the future large hadron colliders (LHC, SSC, or ELOISATRON). We propose electromagnetic calorimeters made of BaF$_2$ crystals preceded by a BaF$_2$ preshower counter with a high granularity. The readout of the preshower counter is done with parallel-plate avalanche chambers combined with photocathodes. For the BaF$_2$ calorimeter, we propose new readouts using either photosensitive gaseous or liquid ionization chambers. We describe our latest results on new, stable photocathodes, which are solid at room temperature and have an efficiency comparable to that of TMAE vapour, and discuss the future possibilities of new organometallic photocathodes. New measurements on the BaF$_2$ radiation hardness are presented. A possible passive compensation ($e/h = 1$) for homogeneous electromagnetic BaF$_2$ calorimeters, using independent readout for the scintillation and the Cherenkov light, is discussed. We also present a family of inorganic scintillators, which could replace BaF$_2$ advantageously in the future.

1. INTRODUCTION

It is commonly acknowledged that the main requirements for the electromagnetic calorimetry to be used at future colliders such as the Large Hadron Collider (LHC), the Superconducting Super Collider (SSC), or the ELOISATRON, are a high speed (15 ns bunch crossing), a high radiation resistance (up to 0.1 MGy), a good energy resolution, and the best possible hermeticity. Different calorimeters, which it was claimed would be equal to these problems, were discussed at recent conferences dedicated to instrumentation for the high-luminosity colliders.$^1$ Calorimeters made of dense inorganic scintillators were considered to be one of the best options. A promising candidate is BaF$_2$. The properties of BaF$_2$ are: a high density (4.9 g/cm$^3$), a short radiation length (2.05 cm), a very fast ultraviolet scintillation component with a decay time of 600 ps,$^2$ a photon yield that is independent of the temperature,$^{3,4}$ and a resistance to radiation damage up to 0.1 MGy.$^5,6$ The question concerning BaF$_2$
calorimeters, which is still under intense discussion, is the best choice for the readout. Three types of readout have been investigated. The first readout used in BaF$_2$ calorimetry consisted of low-pressure multiwire proportional chambers (MWPCs) filled with a photosensitive vapour [e.g. tetrakis(dimethylamine)ethylene (TMAE)] or using a liquid-TMAE photocathode;\textsuperscript{7–9} the device was called a solid-scintillator proportional counter (SSPC). It was based on the overlap, in the spectral region between 170 and 230 nm, of the BaF$_2$ fast emission and the TMAE quantum efficiency, shown in Fig. 1. The sensitivity of the readout by low-pressure MWPCs and TMAE vapour, for the BaF$_2$ fast emission, peaks at 193 nm. The TMAE vapour pressure is rather low (about 0.5 Torr at room temperature), and it is necessary to work at high temperatures, up to 40 °C, in order to increase the efficiency. Under these conditions, about 10 photoelectrons are produced in the detector per MeV deposited in the BaF$_2$. This determines the limit in energy resolution that can be achieved by a device such as an SSPC with gain, i.e. about 2%/\sqrt{E}(GeV).\textsuperscript{10} The SSPC is compact, and because of the low pressure it is insensitive to direct ionization. It allows the detector to be sampled while keeping the properties of an homogeneous calorimeter. It can cover large surfaces, with a high granularity. A prototype SSPC calorimeter (Fig. 2) was tested between 1 and 9 GeV.\textsuperscript{10} An energy resolution of about 3.9%/\sqrt{E} (GeV) was measured with a good linearity, a position resolution close to 1 mm, and an e/\pi rejection factor of 10$^{-3}$ at 5 GeV.\textsuperscript{10} A time resolution of better than 1 ns was also obtained.\textsuperscript{10} This readout for BaF$_2$ calorimeters is not attractive because of the rapid ageing effect caused by polymerization of the TMAE in MWPCs.\textsuperscript{11} Furthermore, to obtain fast timing and insensitivity to the direct ionization it is necessary to work at low pressure.

Another solution, developed by Lorentz et al.,\textsuperscript{12} is to use solid (Si) photodiodes to read out BaF$_2$ crystals. They are simple and very compact. An energy resolution of about 2%/\sqrt{E}(GeV) was measured between 2 and 40 GeV with the prototype shown in Fig. 3,\textsuperscript{12} by recording the fast and the slow components of the BaF$_2$ emission. Such
Fig. 2. Schematics of the CERN prototype SSPC calorimeter and details of one layer.

CRYSTAL SIZE: 1 CRYSTAL Ø10 cm, L=10 cm, 4 CRYSTALS Ø13.5 cm, L=7.5 cm

Fig. 3. Set-up of the BaF₂ calorimeter readout by solid photodiodes¹².
photodiodes have no gain, which greatly simplifies the long-term stability problem, but their use is limited because of the high capacitance of the large devices needed in calorimetry. In addition, these standard photodiodes are sensitive to the BaF₂ slow component (600 ns decay time), which may induce an important pile-up in the high rates expected at the future high-luminosity hadron colliders.

The last readout candidate for BaF₂ calorimetry is photomultipliers (PMs). A PM is a fast device, but it occupies a lot of space. This does not permit a high granularity, and PMs are very sensitive to magnetic fields.

We suggest a new approach to the readout of BaF₂ crystals, either by parallel-plate avalanche chambers (PPACs) combined with photocathodes that are sensitive to the BaF₂ fast emission, or by photosensitive gaseous (or liquid) ionization chambers.

2. GASEOUS DETECTORS WITH PHOTOCATHODES

The main disadvantage of the BaF₂ readout by MWPCs is the bad ageing properties of TMAE vapour at atmospheric pressure and at low pressure. The upper limit of the collected charge is about $10^{-3}$ C per centimetre of wire. After this limit, the polymerization of TMAE on the wires results in unstable operation and a continuous decrease of the gain. On the other hand, BaF₂ is extremely radiation-resistant. But until now, all the measurements with respect to BaF₂ radiation hardness were made at very high dose rates during a short time, and generally with small crystals. We have tested a BaF₂ crystal, of dimensions $2 \times 2 \times 5$ cm$^3$, submitting it to the γ-rays of a $^{60}$Co source at a dose rate of 100 Gy/h, up to a total dose of 0.5 MGy. No effect on the scintillation was seen. The transmission before and after irradiation, measured between 190 and 350 nm, is presented in Fig. 4. The effect on the transmission is negligible below 230 nm, where the fast component is emitted. After these measurements, we placed the same crystal close to a CERN SPS beam for a short test, in order to obtain the upper limit of the BaF₂ radiation hardness. The additional dose received by the crystal in three weeks was 1.7 MGy. The crystal became blue and lost half of its transmission below 230 nm (see Fig. 4). The gain of an SSPC used in a BaF₂ calorimeter is about $10^3$–$10^4$, and the efficiency with TMAE vapour is about 10

![Graph](image)

Fig. 4. Transmission of a BaF₂ crystal as a function of wavelengths: 1) Before irradiation; 2) after 0.5 MGy; 3) after 1.7 MGy; 4) after three weeks recovery.
photoelectrons per MeV deposited in the BaF₂.¹⁰ For a total charge of $10^5$ per MeV, we estimate that 1 C represents $2 \times 10^3$ Gy deposited in the BaF₂. For a wire chamber of 10 cm², with 2 mm wire spacing, the limit on the current is about $5 \times 10^{-2}$ C, which represents about 100 Gy deposited in the BaF₂. It is clear that the radiation hardness of BaF₂ and that of the MWPCs filled with TMAE vapour do not match. But until recently, TMAE was the only photosensitive compound that could be used with MWPCs to detect the fast component of the BaF₂ emission. We have therefore developed a new type of SSPC made of gaseous detectors, i.e. wire and parallel-plate avalanche chambers combined with new photocathodes as the photosensitive element, working at room temperature.¹⁴,¹⁵ In such detectors the photoelectrons are extracted from the photocathode only, and the gas does not play any role in the photoionization process. Therefore the detector can be filled with gases such as dimethyl ether, which have good ageing properties.¹⁶ In this section we describe the latest measurements on photocathodes, as well as the results obtained with an SSPC made of a PPAC combined with photocathodes.

2.1 New Photocathodes for Gaseous Detectors

The possibility of using organic photocathodes, in the liquid or solid phase, for gaseous detectors that are efficient in the VUV region, has recently been investigated.¹⁷ Some photocathodes permitted us to achieve a high efficiency for the BaF₂ fast emission; for instance, in a mixture of a few per cent of TMAE + solid neopentane (NP), an efficiency of more than 10% was achieved below 210 nm. However, since these photocathodes are generally made of a mixture containing TMAE, they are very sensitive to impurities, especially oxygen; their deposition, by cooling of the support, has therefore to be done under very clean conditions.¹⁷

We chose an organometallic liquid at room temperature—ethyl ferrocene (EF)—as being the most advantageous for the photocathodes used in the SSPCs. Although its quantum efficiency is lower than that of TMAE + solid NP, the EF does not interact with air and has a low vapour pressure.¹⁵ It can thus be used as a liquid photocathode with good stability at room temperature. Figure 5 shows the quantum efficiency of a thin layer of EF deposited on a copper cathode, and that of a thick liquid-EF layer. A thin layer is made of a few molecular layers. It can be obtained simply by the adsorption of EF molecules when the cathode is brought into contact with the vapour at room temperature. A similar effect was observed by Anderson et al.¹⁸ with TMAE vapour. These effects can be explained by the π-electrons penetrating the surface of the metal and forming an electric dipole layer; this decreases the work function of the metal and increases the quantum efficiency.¹⁸ With a thick layer, the ionization of the liquid is the dominant feature—not the nature of the photocathode. The photoelectrons created in the liquid get some kinetic energy from the applied electric field. If this energy is superior to the conduction-band energy $V₀$, then the photoelectrons can be extracted from the liquid into the gas, where they are detected.¹⁸ Figure 5 shows that at 193 nm, i.e. the peak wavelength of the BaF₂ fast component, a thick liquid-EF layer is about seven times more efficient than an adsorbed layer. However, it is much easier and more attractive to work with adsorbed layers. We tried to increase the efficiency of these layers by using different metals as a substrate for the photocathode, which changes the work function of the support. We observed that the quantum efficiency of the EF adsorbed layers depends on the metal and on the quality of the cathode surface.¹⁹ Photocathodes that are solid at room temperature were studied also.²⁰ Such photocathodes are attractive because of their simplicity: they can be deposited under vacuum with the optimum thickness, and when placed
Fig. 5. Quantum efficiencies measured with a single-wire counter: 1) EF at $T = 40^\circ C$ and a gap $l = 15$ mm; 2) thin layer of EF condensed on a copper cathode in an electric field $E = 1$ kV/cm; 3) thick condensed layer with $E = 7.5$ kV/cm; 4) clean copper cathode.

in the detector they will operate with a good stability. The best result was obtained with pure reflective CsI photocathodes, with a measured quantum efficiency of about 10% below 190 nm; this result was verified by Breskin et al.

In 1979, CsI photocathodes in gaseous detectors were investigated for UV and VUV imaging. A study that is being made at present by the group of J. Séguinot and T. Ypsilantis shows that CsI covered with adsorbed TMAE reveals remarkable properties. The study was made in an ionization chamber mode only. We have repeated it partly with high multiplication gaps, which are necessary for BaF$_2$ preshower counters and calorimeters. The results, presented here, are encouraging.

**Experiment.** The set-up is similar to the one described in Ref. [17]. The same single-wire counter was used in the proportional mode, with high gain (up to $10^5$), but the metallic cathode was not cooled. The CsI layer (500 nm thick) was evaporated onto the metallic cathode, which was then placed in the detector. A gas mixture of argon (91%) + methane (9%) was flushed into the detector through a bubbler of liquid

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* T. Ypsilantis, Progress in Cherenkov Ring Imaging, March 1979, unpublished report, private communication.
EF or TMAE, so as to form the adsorbed layer on the CsI photocathode. The bubbler and the detector were kept at room temperature. In some measurements the gas mixture was flushed through the detector after the deposition of the adsorbed layer, without passing through the bubbler; this was done in order to remove the vapour.

**Results.** Figure 6 shows the relative quantum efficiency versus the emission wavelengths for photocathodes of clean stainless steel; of stainless-steel covered with a condensed layer of EF; of pure CsI; and of CsI covered with a TMAE adsorbed layer. With EF + CsI, the quantum efficiency is about 15% at 193 nm; with TMAE + CsI, it is 20%. The main disadvantage of a pure CsI photocathode is that it cannot be in contact with air for more than 10 minutes without losing its sensitivity. We have observed that when the CsI is coated with an EF adsorbed layer, it can stay at least one hour in contact with the air without any modification of the quantum efficiency. This effect was also seen with TMAE and was explained by the strong attachment of these molecules to the surface, which changes the chemical properties of the molecule when it is adsorbed. Because of this property, it is probably not necessary to keep the CsI photocathode permanently in contact with the EF or TMAE vapours. Therefore CsI + EF or TMAE photocathodes can be used in the atmosphere of gases chosen for their excellent ageing properties, such as dimethyl ether. These photocathodes are simple and easy to manipulate: they do not suffer from a brief contact with air;

![Quantum yield as a function of wavelengths](image)

Fig. 6. Quantum yield as a function of wavelengths: 1) clean stainless-steel cathode; 2) EF layer condensed on the stainless-steel cathode; 3) pure CsI; 4) CsI + TMAE adsorbed layer.
they are easy to deposit (vacuum deposition + adsorbed layers); they can achieve an efficiency that is comparable to or better than that of TMAE vapour, with a good uniformity on large surfaces. For the readout of the BaF$_2$ fast scintillation, they can be combined with detectors such as PPACs, working at high gain (up to $10^5$) without noticeable photon feedback and filled with gases having good ageing properties.

2.2 Investigation of VUV Emission from the Avalanches in Parallel-Plate Avalanche Chambers

In order to understand why we have little or no photon feedback even at a relatively high gain of $\sim 10^5$ (whilst the sensitivity of the photocathode is $> 10\%$), we have investigated the VUV emission from the avalanches. For these measurements, we used a PPAC coupled to a photosensitive wire chamber through a CaF$_2$ window (Fig. 7). The PPAC was flushed with pure argon or with a mixture of Ar + TEA vapour. The wire chamber was flushed with pure argon or with a mixture of Ar + 17 Torr of TEA. The avalanches in the PPAC were initiated by $^{55}$Fe or $^{241}$Am sources. The measurements were done in the PPAC at a gas gain of between 1 and $10^4$. The VUV photons produced during the development of the avalanche in the PPAC were detected by the wire chamber with a probability of about 10% to 25%.

Some results of our measurements are presented in Fig. 8. One can see that the VUV emission from the PPAC is detected only for high charges collected on the

![Fig. 7. Set-up for the investigation of the VUV emission from the avalanches in a PPAC.](image)

![Fig. 8. Probability of detection of photoelectrons in the photosensitive wire chamber versus the collected charge in the PPAC, for $\alpha$-particles and 5.9 keV photons from a $^{55}$Fe source.](image)
anode: about 0.25 pC for the $^{55}$Fe source, which corresponds to a gain of about $6 \times 10^3$. Taking into account the efficiency of the wire chamber and the solid angle, the number of the VUV photons emitted in the avalanche is estimated to be about 10. With TEA, the number of inelastic collisions, which we estimate from the intensity of the emission at 280 nm, is about $10^6$. Therefore, during $10^6$ inelastic collisions, only about 10 VUV photons are created. The reason is explained in Ref. 24. According to our measurements, this probability decreases sharply when the TEA concentration is increased. The same results are obtained with TMAE. Our experiments show that solid photocathodes, which are highly efficient in the VUV region, can be combined with the gaseous detectors that are being designed by us for the multiplication of the photoelectrons extracted from the photocathodes, even with large gains. These results are part of a systematic study, which is being pursued together with P. Fonte and F. Sauli, on the accurate characterization of photon emission in avalanches in the gas mixtures commonly used in various gaseous detectors.

2.3 Solid-Scintillator Proportional Counters with Parallel-Plate Avalanche Chambers

Photocathodes were first used in an SSPC with wire chambers. We worked with EF semitransparent photocathodes deposited on the BaF$_2$ crystal of the SSPC. The gap between the crystal and the MWPC, where the VUV photon converted in the photosensitive vapour, was no longer necessary and was transformed into a parallel-plate amplification gap. The detector worked in a multistep mode. If enough gain is achieved in the first amplification gap of the SSPC, then the MWPC becomes redundant. It was thus possible to build less complicated SSPCs by using a simple PPAC with organic photocathodes working at room temperature, instead of the MWPC and the conversion gap with vapours at high temperature. At low pressure, it is not possible to apply a high electric field, because the gain is proportional to the electric field per unit of pressure. On the other hand, we have observed that the quantum efficiency of EF photocathodes increases with the applied field. Therefore it is better to work at high pressure in the PPAC in order to increase the electric field and thus optimize the sensitivity of the photocathode. With a PPAC at atmospheric pressure, only the electrons close to the photocathode receive the full amplification; the electrons created by direct ionization in the other part of the gap receive less gain. For a gain of $10^4$ to $10^5$ in a 3–4 mm thick PPAC, only 1/10 of the gap close to the photocathode can produce a detectable noise signal that is due to direct ionization. This contribution is negligible compared with the signal coming from the photocathode, even at atmospheric pressure and especially with helium as the main gas carrier in the mixture. A PPAC is a compact (3–4 mm thick) and fast device; pulse widths of less than 10 ns at the base were obtained with fast current amplifiers. It has a low sensitivity to magnetic fields and a very high rate capability compared with MWPCs. The ageing properties of PPACs are estimated to be better than those of MWPCs. At equivalent gain, the same charge is collected on a wider surface, because the avalanche is larger with a PPAC than around a wire. An SSPC made with an MWPC filled with TMAE vapour was tested for ageing measurements. When the gain in the MWPC dropped to zero because of the polymerization on the wires, the conversion gap of the SSPC used as a PPAC still continued to work without any change in the gain. With EF vapour, the result of an ageing test was better, by a factor of 10, than with TMAE vapour.
We have built a prototype SSPC, made with a PPAC combined with EF photocathodes. The construction is shown in Fig. 9. It contains a $2.5 \times 2.5 \times 7$ cm$^3$ BaF$_2$ crystal covered by a mesh, coupled to the PPAC, with 4 mm between the electrodes. The detector was filled with EF vapour at room temperature, and with tetramethysilane (TMS) under 100 Torr, mixed with helium at 1 atm. The detector worked successfully, and could reach a high gain ($10^5-10^6$) under stable conditions. We have observed that the detector can work with an adsorbed layer, using either a semitransparent photocathode formed on the BaF$_2$ surface, or a reflective photocathode that is deposited on the metal plate facing the crystal simply by reversing the voltage polarity. With an adsorbed layer of EF, the efficiency was identical in the two modes, but the reflective one is more stable at high rates because the surface of the crystal was covered by a mesh instead of being metallized. In the semitransparent mode the positive ions can charge the BaF$_2$ surface and disturb the gain uniformity. The two modes can be made symmetric by metallizing the crystal’s surface with a layer that is transparent to the UV photons, for instance a 2 nm thick layer of tungsten.

We have made a preliminary test in a 7 GeV beam at CERN. The stainless-steel container of the BaF$_2$ PPAC was sealed by a CaF$_2$ window on which the PM (C31000M) was mounted directly (see Fig. 9) and used to trigger on the energy deposited in the crystal. The BaF$_2$ crystal was mounted without a reflector. Calculations and measurements show that this reduces the intensity of the BaF$_2$ light entering in the PPAC by about 30%. We estimated that the energy deposited by the muons in our BaF$_2$ crystal was approximatively 49 MeV, and the maximum energy deposited by the electrons was about 0.6 GeV. When we worked with the muon beam, the efficiency of the PPAC in coincidence with the PM was about 100%. The energy resolution for electrons was about 20%. The transparency of this crystal was only 50% for the BaF$_2$ fast scintillation. This means that in the case of a crystal with 90% transparency, and using an Al foil as reflector, we can expect the energy resolution at 1 GeV to be about 10%. With a PPAC using a thicker layer of EF, we may expect the efficiency and the energy resolution to be better. The quantum efficiency of a CsI photocathode with a TMAE adsorbed layer was measured to be similar to or higher than that of TMAE vapour. The number of photoelectrons is estimated to be about 10 per MeV of energy deposited in the BaF$_2$ crystal. Therefore, the energy resolution of a SSPC calorimeter using these photocathodes and PPACs would be equivalent to or better than that measured with low-pressure MWPCs and TMAE vapour, i.e. 4%/√E(GeV).
3. ONE POSSIBILITY FOR FUTURE BaF$_2$ CALORIMETERS

The final design of the experiments destined for the future large hadron colliders (LHC, SSC, or ELOISATRON) is not yet decided. But it is evident that the experiments need high-performance calorimeters. They have to be fast, be very resistant to radiation, and have a very good energy resolution and hermeticity and a good granularity.$^1$ Two families of detectors are being investigated. The traditional approach uses separate detectors to measure electromagnetic and hadronic showers. It allows the technique to be optimized in each case. Homogeneous calorimeters, which give the best energy resolution, can be used for the electromagnetic calorimeter and compensating sampling devices for the hadronic one. In the second concept, the same detector measures both the electromagnetic and hadronic showers. The electromagnetic energy resolution is degraded because it is necessary to use sampling techniques in order to obtain the compensation (e/h = 1) for the hadronic measurements. The electromagnetic energy resolution measured with such detectors is about 15%/√E (GeV), compared with 2% to 4%/√E (GeV) with homogeneous devices.$^{27}$ This geometry is popular because it is more simple, and it avoids eventual perturbations in the hadronic measurements—and especially in the compensation process—coming from a non-compensating electromagnetic calorimeter placed in front of the hadronic device. One of the main problems for detectors placed in the environment of future high-luminosity colliders is the high level of radiation. The radiation doses decrease when the distance between the detector and the beam increases, except in the electromagnetic part of the calorimeter where the π$^0$s produce a strong increase in the level of radiation (about a factor of 10)$^{28}$ (Fig. 10). This

![Diagram of radiation dose in the calorimeter as a function of the distance from the beam.](image)

Fig. 10. Radiation dose in the calorimeter as a function of the distance from the beam.
dose determines the radiation resistance needed by a detector that is used as the electromagnetic and the hadronic part of the calorimeter if the same technique is employed. If different detectors are chosen, the electromagnetic device will shield the hadronic one. If the same detection technique is used but for the hadronic measurements only, and with another electromagnetic calorimeter in front of the hadronic device, then the radiation resistance will be 10 times greater than if the same detector were used for both the electromagnetic and the hadronic measurements.

We suggest an homogeneous electromagnetic BaF$_2$ calorimeter composed of a BaF$_2$ preshower counter with a high granularity followed by a few layers of BaF$_2$ crystals, the total thickness being 25 radiation lengths. The geometry is presented in Fig. 11. The granularity for the BaF$_2$ calorimeter is determined only by the energy measurements and by a longitudinal sampling that is good enough for the e/$\pi$ separation. The BaF$_2$ preshower counter placed in front of the calorimeter is about 2.5 radiation lengths thick, with a high-granularity readout (about 5 mm) to measure the position of the showers. Such a detector would be very fast. It would have the energy resolution of an homogeneous device, a high position resolution, and a good e/$\pi$ rejection factor, and there would be a possibility of passive compensation ($e/h = 1$) (see subsection 3.3). In addition, the potential radiation resistance and the possibility of high granularity with this type of BaF$_2$ calorimeter would allow the detector to be placed very close to the beam, if this were required. Thus the total volume could be reduced, and likewise the cost of the whole experiment. Figure 12 shows a possible minimum-volume configuration using a BaF$_2$ calorimeter. The minimum distance from the beam is about 50 cm. The volume of BaF$_2$ needed for such a geometry is about 15 m$^3$. Crystals of high enough quality are now being produced in China and in the Soviet Union at a lower price than in the West. The price of BaF$_2$ in the USSR is between $1 and $5 per cubic centimetre, depending on the size and the quality of the crystals and on the amount produced. The production capacity is now only a few tonnes per year.
Fig. 12. A possible minimum volume configuration with a BaF$_2$ calorimeter for an experiment for the LHC, SSC, or ELOISATRON.

A BaF$_2$ preshower counter and the best candidates for the readout of the BaF$_2$ calorimeter are described in the following subsections, together with the possibility of passive compensation with such an homogeneous calorimeter.

3.1 BaF$_2$ Preshower Counter

A preshower counter in front of a calorimeter is needed for high-precision position measurements of the showers, and to increase the e/π rejection capability. Such a device could be necessary not only for the BaF$_2$ calorimeter described in this paper, but also for many of the detector candidates for the calorimetry to be used in experiments at the future high-luminosity colliders. We propose a preshower counter made with BaF$_2$ crystals read out by PPACs combined with photocathodes. The design of the detector is presented in Fig. 13. Crystals of 2.5 radiation lengths

![Diagram of BaF$_2$ preshower counter]

Fig. 13. Construction of the BaF$_2$ preshower counter.
(5 cm) are used, with the granularity of the calorimeter module following that of the preshower counter. Each crystal is coupled to a 3–4 mm thick PPAC having independent metallic pads, $5 \times 5 \text{ mm}^2$, for reading out the signal produced in the chamber. Semitransparent or reflective photocathodes can be used, and the detector can work in either of two polarities simply by reversing the direction of the applied field. The best candidate known at present is the reflective photocathode of CsI + adsorbed layer of TMAE, deposited on the pads (see subsection 2.1 and Ref. 23). Minimum-ionizing particles (MIPs) will deposit 32 MeV in the detector; an electromagnetic shower will deposit a few hundred MeV. For the photocathode efficiency estimated at about 10 photoelectrons per MeV deposited in the BaF$_2$, the gain needed in the PPAC is about $10^3$–$10^4$. The position of the shower, or of the MIPs, will be measured on the pads by the centre-of-gravity method, and the difference in the energy deposited will make it possible to measure a good $e/\pi$ separation in the preshower counter.

3.2 Readout of BaF$_2$ Calorimeters

The relatively poor efficiency of SSPCs—about 10 photoelectrons per MeV deposited in BaF$_2$—cannot really degrade the energy resolution of a calorimeter designed for experiments at the future large hadron colliders. The main limitation on the energy resolution of all the calorimeter candidates in such experiments comes from the constant term, which depends essentially on the calibration and the stability of these detectors. This term should be less than 1%, and readout systems with gain—such as SSPCs and PMs—involve complex technologies for controlling the stability of huge detectors at this level. The average thickness of the BaF$_2$ crystals in the calorimeter proposed in this paper is about 10–15 cm for a few layers. In this case, the energy deposited per crystal by an electromagnetic shower is high. At the energies that will be investigated in experiments where such a detector can be used, there will probably be no need for a high gain in the SSPCs of the BaF$_2$ calorimeter. We propose to transform PPACs combined with photocathodes into photosensitive gaseous ionization chambers working with a very small gain or without gain, or to use photosensitive liquid ionization chambers, in order to simplify the readout of the BaF$_2$ calorimeter.

3.2.1 Gaseous ionization chambers combined with photocathodes. The readout with PPACs and photocathodes seems simpler than with MWPCs and TMAE vapour. But the high fields applied with a PPAC, about 1 kV/cm, create some constraints on the planarity and the parallelism of the two faces of the detector. Mechanical tolerances of about 10 $\mu$m are needed in order to obtain a good gain homogeneity. With 30 $\mu$m tolerances, the gain uniformity in a PPAC was measured to be $\pm 15\%$.30 Furthermore, the gain in PPACs is sensitive to temperature and pressure changes. The stability of the gain at the 1% level requires either a control of these parameters or an individual gain-monitoring per PPAC with an electronic adjustment of the high voltage. All these requirements can be achieved with prototypes, but for several thousand detectors this is a technical challenge.

A simple way of avoiding these problems is to amplify only a little or not to amplify at all, and to make the SSPC work in a collection mode. In the last case, the PPAC is then transformed into a gaseous ionization chamber without gain. Some prototypes of low-pressure photodiodes with standard bi-alkali photocathodes have been studied by Sauli.31 A prototype designed for calorimetry, filled with 0.5 atm of methane, worked successfully without amplification.32 A quantum yield close to that of a vacuum photodiode was obtained, as well as a good long-term stability.32
Such gaseous photodiodes, as well as vacuum photodiodes, require complex technology (sealed detectors and window), equivalent to that for PMs. It is difficult to have large surfaces and at the same time a good uniformity of the photocathode, and therefore their price is high. The photosensitive gaseous ionization chambers proposed by us are technically simple, and they work at room temperature and at atmospheric pressure. Photocathode candidates (CsI + EF or TMAE adsorbed layers) are not destroyed by brief contact with air, and they are uniform. The demonstration of the high quantum efficiency of such photocathodes, obtained in collaboration with the group of J. Séguinot and T. Ypsilantis\textsuperscript{23}, makes the ionization chamber mode attractive for calorimetry with BaF\textsubscript{2}. Therefore, large surfaces can be obtained at a low price because no window is needed between the BaF\textsubscript{2} crystal and the ionization chamber. These detectors can be flushed, and even if the photocathode is damaged, full recovery is possible after flushing with a gas mixture containing the same photosensitive vapour (TMAE or EF) as the one initially deposited on the CsI photocathode. Under such conditions, photosensitive ionization chambers have good long-term stability. The transformation of the PPAC in a gaseous ionization chamber without amplification would allow a reduction of the gap and thus a decrease in the drift-time of the photoelectrons. For a typical drift velocity of 5 cm/\(\mu\)s, the electron collection time will be only 10 ns in a gap 500 \(\mu\)m thick. The capacitance of such a detector will be about 2 pF/cm\textsuperscript{2}. If the typical size of a BaF\textsubscript{2} calorimeter module will be about 10 cm\textsuperscript{2}, the total capacitance of such a fast and large-size ionization chamber will be only 20 pF, which is compatible with fast electronics. Without any gain in the chamber, the mechanical tolerances needed for a PPAC are reduced, and a gain monitoring is no longer necessary. Note that as the photocathode cannot be damaged by feedback from the positive ions, the long-term stability of the chamber, which depends on the behaviour of the photocathode only, would be good. In addition, the ageing caused by polymerization due to the charge density in the avalanche does not exist since there is no gain. The influence of direct ionization is still negligible with respect to the gap thickness needed (about 0.5–1 mm), particularly with a gas mixture based on helium. The capacitance of these gaseous ionization chambers is much lower than that of solid photodiodes. Furthermore, the photocathodes that can be used in such detectors are sensitive to the BaF\textsubscript{2} fast component only. The main limitation of these detectors, compared with that of the solid-state photodiodes, comes from their lower efficiency. The highest efficiency measured with TMAE vapour in an SSPC is about 10 photoelectrons per MeV deposited in the BaF\textsubscript{2} crystal, whilst it is a few hundred photoelectrons in a Si photodiode\textsuperscript{12} where both the fast and slow components of the BaF\textsubscript{2} scintillation are used. As was mentioned before, the recent measurements of the new reflective photocathodes (CsI + TMAE or EF) presented in subsection 2.1 and in Ref. 23 showed an efficiency for the BaF\textsubscript{2} fast emission that is at least equivalent to that with TMAE vapour. Ten photoelectrons per MeV deposited in BaF\textsubscript{2} represent only 1%/\(\sqrt{E(\text{GeV})}\) at energies up to 1 GeV, for the statistical contribution in the energy resolution of an ionization chamber. If the typical noise of the required amplifiers is about 1500 electrons, up to 1 GeV, the signal-to-noise ratio seems to be comfortable, but it might not be possible to detect MIPs with full efficiency. This could constitute a limitation for calorimeters where MIPs can be used to monitor the calibration. The yield needed for detecting MIPs adequately should be equivalent to the one obtained with a PM, i.e. between 100 and 400 photoelectrons per MeV (depending on the size and the quality of the crystal). The average efficiency of TMAE calculated for the BaF\textsubscript{2} fast scintillation is about 10%. The same calculation made with a standard PM—an XP2020Q—gives an efficiency of 20%. The difference in the number of primary photoelectrons detected with gaseous detectors or with PMs comes essentially from
the difference in optical coupling with the crystal. The refractive index of BaF$_2$ is about 1.56 around 200 nm. A good optical contact is obtained between a PM window and the BaF$_2$ crystal by using optical grease. For gaseous detectors with vapours or reflective photocathodes, the difference in index between the crystal and the gas is large, and a better optical contact is not possible. Most of the photons produced in the crystal are trapped by internal reflection. This effect could explain the difference in photoelectron yield between SSPCs filled with TMAE vapour, and PMs. We hope that semitransparent photocathodes directly deposited on the BaF$_2$ crystal will make the light collection in an ionization chamber equivalent to that of a PM. Measurements of new photocathodes in a semitransparent mode, using the components that achieved high quantum efficiencies in the reflective mode, are under way.

3.2.2 Photosensitive liquid ionization chambers. Bottcher$^{33}$ and Holroyd et al.$^{34}$ have measured high quantum efficiencies in organic liquids with a photosensitive liquid ionization chamber. They obtained a quantum efficiency of 4.6% at 235 nm with a mixture of tetramethylpentane (TMP) + 1% TMAE, 16% with a mixture of TMS + 1% TMAE, and 17% with tetramethyl-p-phenylenediamine (TMPD) + NP. The efficiency increases at shorter wavelengths. The measurements made by Peskov et al.$^{17}$ using these organic liquids as photocathodes in gaseous detectors, showed a loss in efficiency, compared with that obtained with the liquid ionization chamber, after the transition of the photoelectrons from the liquid to the gaseous phases. The quantum efficiency of organic-liquid photocathodes is strongly dependent on the thickness of the layer, on the nature of the gas used in the detector, on the applied electric field, on the level of impurities and so on. These parameters control the transition efficiency of the photoelectrons between the liquid and the gaseous phases, which is generally relatively poor. Even with gaseous ionization chambers, the primary photoelectron statistics are probably not a problem for energies above 1 GeV. But the difficulty could be to detect MIPs. An ionization chamber filled with organic liquids, e.g. TMS or TMP + TMAE, working as a liquid photodiode to read out the BaF$_2$ fast scintillation, is an attractive solution for increasing the quantum efficiency of such a device. Based on our estimate, the efficiency for the BaF$_2$ fast component would be equivalent to that for a PM, i.e. about 100–200 photoelectrons per MeV deposited in the BaF$_2$ crystal. As we know, TMS and TMP are liquids with high electron mobility: 100 cm$^2$/V·s for TMS and 30 cm$^2$/V·s for TMP.$^{35}$ The mean free path of the UV photons in the organic-liquid mixtures is less than 10 µm. Using these liquids, it is possible to imagine very fast and compact photosensitive liquid ionization chambers. The electron collection time of a liquid ionization chamber with TMS + 1% TMAE and a gap of 0.1 mm, in an electric field of 10 kV/cm, will be about 10 ns. The capacitance of such a device will be about 30 pF/cm$^2$. The properties and qualities of this detector are equivalent to those discussed for the gaseous ionization chambers. But liquid chambers can work only in the semitransparent mode. The photoelectrons are produced close to the surface of the crystal and drift along the gap before being collected by the metallic electrode parallel to the crystal’s surface. A metal coating, e.g. 2 nm of tungsten or NiCr, is needed on the crystal’s surface to define the electric field between the crystal’s face and the metallic pad. For these liquid ionization chambers, the BaF$_2$ surface can be used as the window of the detector, or a quartz window can be chosen for separating the readout from the scintillator. Our calculations showed that the direct ionization contribution produced by the shower development in a BaF$_2$ calorimeter sampled by this readout would be less than 1% of the total signal coming from the scintillation. The main limitation for liquid photodiodes using TMS + TMAE would come from the purification problems. In experiments using warm liquid calorimeters,$^{36}$ large
volumes of liquid are needed, because this is the active part of the calorimeter, i.e. the place where the detected energy is deposited. Complex technologies are necessary in order to produce such large quantities of pure liquid for sealed ionization chambers. Furthermore, these detectors are a few millimetres thick, and the electron drift time is a few hundred nanoseconds for the longer distance. Therefore, to avoid electron attachment, a very high level of purification is needed. In the case of a photosensitive liquid ionization chamber, the thickness is one order of magnitude lower, and the electron drift time should be much lower. This should permit a decrease in the purification requirements so as to obtain satisfactory working conditions and long-term stability. In addition, with a BaF₂ calorimeter all the energy is deposited in the scintillator, not in the liquid sampling chambers. The latter collect only the photoelectron signal produced by the scintillation. Then the volume needed for such liquid ionization chambers is only about 10 l for 100 m² of detector. The total volume necessary in an experiment at the future large hadron colliders would probably not exceed 100 l. The small circulation system that is necessary to purify the liquid continuously could be included in the mechanical support for the BaF₂ crystals. This type of readout for the BaF₂ calorimeter is attractive. Therefore, not only its quantum efficiency, but also the technological difficulties encountered in building such a device, will have to be investigated.

3.3 Possibility of a Homogeneous Compensating BaF₂ Calorimeters.

The classical active compensation with hydrogen is possible only in sampling calorimeters and not in homogeneous devices, where the best electromagnetic energy resolutions are measured. Compensation is needed for the hadronic measurements so as to obtain an increase in energy resolution with increasing energy. The ideal detector should meet the best energy resolution of an homogeneous electromagnetic calorimeter and of a compensating hadronic device. It could be an homogeneous electromagnetic calorimeter with passive compensation (e/h = 1)—in order not to disturb the hadronic measurements—placed in front of a classical active compensating hadronic calorimeter. Passive compensation means that it is necessary to measure only that part of the energy deposited by the π₀'s of an hadronic shower, which interact in the electromagnetic calorimeter to obtain e/h = 1. This passive compensation does not improve the hadronic energy resolution. However, this is not important because the electromagnetic calorimeter represents only about one nuclear interaction length, and just a small part of the energy is deposited by an hadronic shower in this part of the detector. This type of compensating electromagnetic calorimeter should not really disturb the hadronic energy measurement by changing the active compensating properties of the hadronic calorimeter.

Only about 10–15% of the energy deposited by the purely hadronic component of a shower comes from MIPs, and the bulk of the ionization is produced by particles (neutrons, protons, nuclear fragments, and soft gammas) that emit relatively little or not Cherenkov light in transparent media. On the other hand, the electromagnetic (π₀) fraction of the shower produces both ionization and Cherenkov light in transparent media. Winn and Worstell have investigated the possibility of achieving compensating calorimetry in homogeneous transparent materials by measuring the ionization energy (with scintillating or drifted ions) and the Cherenkov light independently. Since the electromagnetic fluctuations in the shower could be known in this way, the calorimeter response could be corrected. Using a Monte Carlo simulation, they found that this type of detector—made, for example, of liquid argon—could achieve the same energy resolution as that of an homogeneous calorimeter for electromagnetic showers; for hadronic showers, the calculated energy resolution is
Fig. 14. One module of a BaF₂ homogeneous calorimeter with passive compensation by the independent readout of the scintillation and Cherenkov light.

\[ \frac{\sigma_E}{E} = 81\% / \sqrt{E(\text{GeV})} + 0.4\% \text{ for energies between 20 and 1000 GeV.} \]  

Note that the constant term is essentially zero, which proves that \( e/h = 1 \). The necessary condition for achieving these values is that the ionization signal must be clearly separated from the Cherenkov signal.

As a candidate for such an homogeneous compensating calorimeter, we propose to use BaF₂ scintillators. The idea is based on the independent readout of the Cherenkov and the scintillation light by two photosensitive detectors placed on the faces of the crystal perpendicular to the beam direction (see Fig. 14). One readout has to be sensitive to the BaF₂ fast scintillation in order to measure either the total energy deposited by an electromagnetic shower or the part lost by an hadronic one. The other readout should not be sensitive in the wavelength window containing the BaF₂ scintillation, but be sensitive to the Cherenkov light. It will be used only to measure the energy deposited by the \( \pi^0 \)'s of the hadronic showers. This contribution can be subtracted from the total energy deposited in the calorimeter and measured by the first detector, which is sensitive to the scintillation. The passive compensation would be effective for the part of the energy deposited by an hadronic shower that interacts in the BaF₂ calorimeter.

The candidates for the scintillation readout are the devices described above (PPACs with photocathodes, and photosensitive gaseous or liquid ionization chambers). Two wavelength regions are useful for the Cherenkov readout: below and above the BaF₂ scintillation region. Below 170 nm, the same type of readout as that used for the scintillation can also be used with photosensitive elements, with no efficiency above 170 nm and high efficiency below it. The quantum efficiency at these wavelengths is not known for many of the photosensitive compounds and has to be investigated. A good candidate for gaseous ionization chambers or PPACs is TEA vapour, with an efficiency of up to 20% at short wavelengths and a cut-off at 165 nm. If the theoretical cut-off in the transmission is about 130 nm in BaF₂, then a good transmission for long crystals at wavelengths below 170 nm could be a technical problem owing to some contamination. The purification requirements are difficult to meet in long crystals. The other possibility is to read out the Cherenkov light above the BaF₂ slow component of the scintillation, i.e. above 400 nm, where the transmission, even in very long crystals, is better than 90%. Organic vapours or photocathodes have no efficiency at these wavelengths. A candidate could be a standard solid-state photodiode, which achieves about 70% quantum efficiency in the visible region.
4. PERSPECTIVES

4.1 New Photocathodes

The aim of our collaboration with the Laboratory of Organometallic Compounds of the Moscow State University is to study systematically the chemical and physical properties of new compounds to be used as efficient photocathodes in the VUV spectral region for gaseous detectors, and particularly to read out BaF$_2$ scintillation. This laboratory has already supplied us with very good quality ethyl ferrocene. They are now going to synthesize for us new organometallic compounds that are estimated to be good candidates for photocathodes: 1,1'-trimethyleneferrocenophene, biferrocenyl, (dimethylamino)methylferrocene, ferrocenyl phosphine, and ferrocenyl methyl alcohol and such derivatives. They are also planning to carry out a systematic study of bentsandwich complexes and square-planar complexes. It is expected that such molecules can combine small chemical activity with low ionization potential.

Photocathodes made with other organometallic compounds, for example biferrocene, are being investigated at the Brunel University (UK). They have obtained encouraging results, with an increase in the sensitivity of metallic cathodes covered with thin layers of these organometallic substances, in a spectral region extending up to 350 nm. Other products with molecules close to those of TMAE, and with calculated very low ionization potential, are being synthesized by the Katrinsky group at the Florida University. They will be tested by the Séguinot–Ypsilantis group at CERN.

There is also a lot of interest in finding new simple and stable photocathodes, with a high sensitivity in the VUV spectral region, that will work in gaseous detectors. Several groups are now working along these lines. We can expect that in the near future this family of photocathodes will increase.

4.2 New Scintillators

The efficiency of all the photocathodes we have studied increases greatly in the wavelength region below 200 nm. This means that SSPCs using these photocathodes will be much more efficient with scintillators that emit in this region and thus achieve better energy resolution. However, BaF$_2$ was until recently the only known scintillator to possess adequate properties for SSPCs.

The discovery that in lanthanum fluoride (LaF$_3$) crystals doped with Nd$^{3+}$, the scintillation peaks at 173 nm and has a decay time of 6.3 ns, allows the use of this scintillator in an SSPC filled with TMAE vapour. The main advantages of LaF$_3$ over BaF$_2$ are its higher density (5.94 g/cm$^3$) and its shorter radiation length ($X_0 = 1.7$ cm), but the light yield is small (because it is difficult to obtain crystals with good transparency in the wavelength emission region) and the detection efficiency is no higher than that obtained with the BaF$_2$ device. On the other hand, the mechanism by which BaF$_2$ emits light with a fast component was not understood until the studies made by Valbis and his group enabled them to explain it and to understand why BaF$_2$ has such a unique ensemble of properties as a scintillator. Based on this research, a new family of inorganic scintillators was discovered. Their properties are similar to those of BaF$_2$, but their maximum light emission is in a wavelength region between 140 nm and 200 nm, where the known photosensitive vapours and photocathodes achieve high efficiencies. In these crystals the energy separation between the valence band—involving mainly the halogen electronic states—and the upper caution core band is smaller than the band gap. After excitation, which causes holes to appear

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in the core band, radiative electronic transitions from the valence band to the core band take place, giving rise to a specific emission called cross-luminescence (CRL). This mechanism explains the fast component of the BaF$_2$ scintillation. The CRL was measured in CsCl, CsBr, RbF, and RbCl, as well as in KF. It is possible to add a third component to these simple crystal bistructures in order to obtain crystals of higher densities, with the same light emission. The first crystals of this type that were produced, were KCaF$_3$ and KMgF$_3$. The emission spectra of these scintillators is shown in Fig. 15. An SSPC with a KMgF$_3$ crystal coupled to a wire chamber filled with TEA vapour achieved half the efficiency obtained with BaF$_2$ and TMAE vapour, i.e. four photoelectrons per MeV deposited in the crystal. Then a prototype KMgF$_3$ crystal combined with a PPAC filled with TEA vapour was tested at Serpukhov, and achieved the same efficiency. But if the new scintillators, such as KMgF$_3$, have scintillation properties equivalent to those of BaF$_2$ and a similar high resistance to radiation, they have the handicap of a lower density, 3.1 g/cm$^3$, and longer radiation lengths, $X_0 = 7$–8 cm. Valbis and his group are now working on new crystals based on lutetium, KLuF$_4$, or yttrium, $K_2YF_5$, which have higher density and shorter radiation length, e.g. $\sim 4.8$ g/cm$^3$ and $X_0 \sim 2$ cm for KLuF$_4$. The emission spectrum of KLuF$_4$ is presented in Fig. 16. The maximum emission is peaked at 165 nm. But

Fig. 15. Luminescence spectra of a) KMgF$_3$ and b) KCaF$_3$, both at 80 K (o) and 300 K (•), as a function of photon energy.

Fig. 16. Luminescence spectrum of KLuF$_4$ as a function of photon energy.
the main limitation comes from the fact that these new dense crystals probably cannot be obtained in large sizes, because their thermochemical properties do not allow the use of large autoclaves, similar to those used in producing large SiO\textsubscript{2} crystals for example, and they cannot be obtained from the melt by other methods.

However, different techniques are now being used to develop new crystals that are optically perfect, of a reasonable size, and have good properties as scintillators.

5. CONCLUSIONS

In studying the coupling of BaF\textsubscript{2} scintillator crystals to gaseous detectors, we have taken several steps towards showing the feasibility of BaF\textsubscript{2} high-granularity preshower detectors and electromagnetic calorimeters with properties matching the requirements of future colliders: fast timing, radiation hardness, and good granularity and energy resolution.

Our study reveals that simple amplifying structures made of solid photocathodes between parallel electrodes, in gases at atmospheric pressure, permit adequate amplification.

Steady progress is being made in the study of photocathodes that can be simply composed of adsorbed layers of photosensitive vapours or thin layers of photosensitive liquid mixtures, as well as solid photocathodes with adsorbed layers of photosensitive vapours, with efficiencies of the same order of magnitude as that of photomultipliers in the VUV region.

We have discussed the coupling of BaF\textsubscript{2} preshower counters to other systems, with the possibility of compensating the variation in response for electrons and hadrons by the independent readout of the scintillation and the Cherenkov light.

Research is being carried out to replace BaF\textsubscript{2} with heavier scintillators emitting at a wavelength region that permits higher efficiencies to be achieved with gaseous detectors. But among the scintillators that will be available in the near future, it would seem that BaF\textsubscript{2} is the best candidate for the construction of calorimeters. Therefore, a vigorous investigation should be undertaken to find a means of reducing the cost of the crystals for large-volume detectors to be used in future hadron colliders.

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