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**RECENT DEVELOPMENTS IN BaF_2 SCINTILLATOR
COUPLED TO A LOW-PRESSURE WIRE CHAMBER**

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ABSTRACT

A mode of operation is discussed for a detector using BaF_2 as the scintillator, and tetrakis(dimethylamine)ethylene (TMAE) as the photosensitive agent adsorbed on a NiCr layer to form a photocathode. The position resolution of the detector with a crystal 25 mm thick and 120 mm in diameter is measured to be about 3 mm FWHM. The physics of TMAE as a liquid is also discussed.

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1. INTRODUCTION

In earlier works [1–3] it has been shown that the short-wavelength component of the scintillator BaF_2 can be detected by a wire chamber using tetrakis(dimethylamine)ethylene (TMAE) as the photosensitive material. This has given rise to a new class of instrument, consisting of a solid scintillator plus a proportional counter (SSPC). The SSPC combines the high stopping power of a high-density solid with the versatility of a proportional counter.

As a scintillator, BaF_2 has many desirable features, as can be seen in Table 1 which summarizes some properties of BaF_2 , BGO, and NaI(Tl) [4–7]. The density of BaF_2 is 4.8 g/cm^3 and it has a radiation length of only 2.1 mm. The short-wavelength component, peaking at 225 nm, has a decay constant of only 0.6 ns. This material is also rugged and non-hygroscopic, and is readily available in sizes up to 150 mm in diameter. We believe, from contacts with the manufacturers, that the price of BaF_2 could soon be comparable with that of NaI(Tl) .

The best results for the SSPC have been achieved with low-pressure wire chambers (see Breskin [8,9] on the subject). These detectors allow for high photoelectron collection efficiency and good timing properties that permit one to take advantage of the fast response of the BaF_2 . Low-pressure wire chambers also have the advantage of being themselves insensitive to radiation, ensuring that only the light from the scintillator is detected in a high-energy physics environment. Finally, because of the fast ion drift in low-pressure wire chambers, an SSPC can be operated at very high rates with far less space-charge problems than at one atmosphere.

In an earlier work [3] we reported on an SSPC with a BaF_2 crystal 25 mm thick and 120 mm in diameter. The TMAE was condensed on a cooled surface. With this detector we achieved a timing resolution of 540 ps FWHM with 350 MeV α -particles. An energy resolution of 28.5% FWHM was measured for protons losing about 18 MeV in the crystal.

In this work we carry the study of the SSPC further. We will discuss a new, simpler mode of operation that does not require cooling, as well as the imaging capability of the SSPC. The physics of TMAE as a liquid photocathode will also be discussed.

2. GAS VERSUS SURFACE

In the first work with the SSPC, the TMAE was condensed as a very thin liquid on a surface, which is not difficult owing to its low vapour pressure. The cathode surface was typically kept at 2°C . This gave good results, with an estimated quantum efficiency of about 4%. But, for the field of high-energy calorimetry, one would gladly sacrifice some of this efficiency for easier construction and operation. As was reported earlier, when TMAE is introduced in to an evacuated chamber all surfaces become photosensitive. We thus made a study of the operation of the SSPC without cooling.

The counter was rebuilt in the configuration shown in Fig. 1. The surface of the BaF_2 crystal (25 mm $\times$ 120 mm diameter) was coated with a 15 Å layer of NiCr, which serves as a UV transparent conductive coating. A wire grid was placed 5 mm from the BaF_2 crystal and a copper-clad printed-circuit board was placed 5 mm from the grid. The NiCr surface and the printed circuit were kept at ground potential, while the grid was connected through a picoammeter to a power supply.

In operation the evacuated chamber was first filled with TMAE at various pressures. After a short time, left to allow the TMAE to reach an equilibrium, methane was introduced to bring the pressure to 9 Torr. This was to ensure that there was no charge gain under the applied voltage. The

BaF₂ was then excited by a strong ⁹⁰Sr source. The current was measured with a collection voltage of +30 V and then of -30 V. At +30 V the electrons from the gas and from the surface were measured. At -30 V only the positive ions from the gas were collected. Thus the contribution from the surface and the gas could be determined. One motivation for these measurements is that since there is some overlap between the BaF₂ emission spectrum and the TMAE gas photoionization spectrum (Fig. 2) [10,11], we wanted to verify that there was a contribution from the surface without cooling.

The results of these measurements are shown in Fig. 3, where the contribution of the gas and TMAE on the surface are plotted as a function of TMAE pressure. The temperature corresponding to this pressure is also shown. As can be seen from the data, the contribution from the gas starts to saturate at about 15 °C, while the surface contribution continues linearly over the region examined. For the above measurements the gas contributed about 75% of the signal at a pressure of 0.44 Torr (23 °C) [1].

These measurements were made with the SSPC at 23 °C. A question yet to be studied is the effect of surface temperature on the gas-to-surface ratio. From earlier tests [3] we have determined that most of the efficiency that we measure from the surface is from the NiCr surface of the BaF₂, with a small contribution from the surface of the printed-circuit board. This may be due to less light being available to this second surface.

It should be noted that in actual operation of an SSPC the charge released in the gas makes a much smaller contribution to the signal than implied above. This is because low-pressure wire chambers operate very close to a parallel-plate mode. Thus the charge from the surface undergoes a full gain of

$$G(\text{surface}) = e^{\alpha d},$$

where α^{-1} is the mean free path for charge amplification and d is the gap width. The average gain on the charge uniformly distributed in a parallel-plate counter is

$$G(\text{parallel plate}) = (1/\alpha d) e^{\alpha d}.$$

This is because charges liberated closer to the anode will receive substantially less gain. So for a gain of 10^4 for the counter, the average gain of the charges liberated in the gas is reduced by almost an order of magnitude.

3. IMAGING CAPABILITY

One of the characteristics of the SSPC that makes it unique, as compared to other scintillation detectors, is its potential for high spatial resolution. To demonstrate this aspect, we rebuilt our test detector as shown in Fig. 4. The BaF₂ crystal was separated from the amplification region by a 4 mm drift region to reduce ion feedback and thus allow higher gain. The cathode-to-cathode spacing was 6 mm. The second cathode was a printed circuit with a row of $5 \times 5 \text{ mm}^2$ pads to allow a one-dimensional determination of the event location. Two additional $5 \times 10 \text{ mm}^2$ pads were also included to allow a check that the event was at least roughly centred on the row of smaller pads. In operation, we filled the SSPC with TMAE at 25 °C and 18 Torr of isobutane to increase the gain for the cathode amplifiers. The voltages were $V_c = +40 \text{ V}$ and $V_a = +1020 \text{ V}$. It should be noted that we have measured gains as high as 10^4 in pure TMAE.

A calculation of the light distribution on the surface of the BaF₂ crystal was made for one and two particles traversing the crystal. Figure 5 shows the intensity as a function of radius for BaF₂ thicknesses of 2.54 cm and 10 cm. Figures 5a and 5b are for single particles passing normally ($\theta = 0^\circ$) through the crystal, and at $\theta = 30^\circ$, respectively. At first the narrow distribution seems surprising. It is due to the fact that the solid angle subtended by a spot on the surface goes as ρ^{-2} , where ρ is the distance between a point of scintillating crystal and the spot on the surface. Thus the surface nearest to the point of exit (or entry) receives a large amount of light. This gives the narrow distribution, with the additional light from the thicker crystal going mostly into the wings of the distribution. Figures 5c and 5d show the simulation with two particles, 1.5 cm apart, passing at $\theta = 0^\circ$ and $\theta = 30^\circ$, respectively.

In our first test with cosmic rays, we found the signals on our pads had a distribution consistent with our simulations. Figure 6 shows typical pulse-height distributions on the $5 \times 5 \text{ mm}^2$ cathode pads for two cosmic-ray events. The two channels on the right are pads 17 and 18 in Fig. 4. This we feel is further evidence that most of the electrons come from the BaF₂ surface, with little contribution from the TMAE on the surface of the printed circuits.

A test of the position resolution of the detector was made with a beam of π^- , μ^- , and e^- at the Synchro-cyclotron at CERN. The momentum of the particles was 200 MeV/c. The particles entered the crystal with a beam size of about 3 mm. A centroid was calculated for 220 events; then the detector was displaced by 9 mm and an additional 220 events were recorded. The resulting position spectra are shown in Fig. 7. The width of the peaks is about 4.5 mm FWHM. Thus the position resolution of this detector for high-energy particles is about 3 mm FWHM.

It should be noted that, although the simulations and the measurements indicate that a good position resolution is possible for one particle, and a reasonably good two-particle separation is possible from a large crystal, the energy loss of each of two close particles cannot be accurately determined. For this, an array of BaF₂ rods with smaller cross-section would be better.

4. THE LIQUID PHOTOCATHODE

Although the experimental material reported on in this paper involves TMAE that is either in the gas phase or adhering to a surface, we would like to discuss here the physics of TMAE as a liquid photocathode (LPC).

The photoionization threshold, E_{TH} , of a photosensitive material dissolved in a non-polar liquid is expected to be lower than the ionization potential, IP, in the gas phase. This threshold is for electrons collected in the solvent, which in our case is TMAE itself. The relation between E_{TH} and IP is given by [12,13]

$$E_{\text{TH}} = \text{IP} + V_0 + P_+, \quad (1)$$

where V_0 is the ground-state energy, with respect to the vacuum, of a free electron in the liquid, and P_+ is the polarization energy of the positive ion.

In the case where V_0 is positive or zero the photoelectric threshold for the LPC, E_{LPC} , will be given by Eq. (1), i.e.

$$E_{\text{LPC}} = \text{IP} + V_0 + P_+, \quad \text{for } V_0 \geq 0. \quad (2)$$

In the common case where V_0 is negative, the photoelectron must overcome V_0 at the surface, and thus it expresses itself as a work function, cancelling its effect on the threshold in the liquid. Thus we expect

$$E_{LPC} = IP + P_+, \quad \text{for } V_0 < 0. \quad (3)$$

The value of V_0 for TMAE is in fact negative [14] and thus Eq. (3) is applicable.

To evaluate P_+ for liquid TMAE, the Born equation can be used [15,16] to give

$$P_+ = (-e^2/2R)[1 - (1/\epsilon_{op})], \quad (4)$$

where ϵ_{op} is the optical dielectric constant and R is the radius of the sphere for the positive ion.

We have measured the index of refraction of TMAE, for the shortest wavelength that will traverse it, to be $n = 1.51$. Since $\epsilon_{op} = n^2$, and using the value of $R = 3.21 \text{ \AA}$ [15], we calculate $P_+ = -1.26 \text{ eV}$. Taking the value of $IP = 5.36$ [15] we arrive at $E_{LPC} = 4.10 \text{ eV}$ from Eq. (3). This is in good agreement with the earlier experimental estimate of Anderson [2] of $E_{TH} = 4.3 \text{ eV}$.

Although we believe that when V_0 is negative it does not express itself in the lowering of the threshold of the LPC, its value is not without physical effects. Firstly, within the liquid the threshold is lowered by V_0 and thus there are electrons liberated within the liquid that do not escape. Secondly, the value of V_0 will probably express itself in the quantum efficiency of the LPC. There is a thermalization range, r , for a photoelectron, which in general increases as V_0 becomes more negative [16]. Thus the electron must be liberated in a distance r' , less than r , from the surface in order to still have enough energy to escape. If one assumes that the photoelectrons leave the atoms in all directions, a simple calculation shows that only about 25% of the electrons liberated within a distance r' of the surface will escape. Thus as V_0 becomes more negative, r' increases and therefore one would expect the quantum efficiency to increase.

From the earlier measurements of Anderson et al. [3], the quantum efficiency of the TMAE LPC was estimated at 4%. This means that the electrons are coming from a depth great enough to stop at least 16% of the light. This implies a large r' and therefore a very negative V_0 .

There are some interesting implications if r' , and therefore the electron mobility μ , is large for liquid TMAE [17]. The mobility of electrons in a non-polar liquid increases rapidly with r , as does the probability that the electron escapes from the Coulomb field of the positive ion. Thus there may be an application for TMAE in liquid ionization chambers. This is certainly a subject for further study.

The above arguments also imply that with an LPC we are only seeing a small fraction of the electrons available. It is possible that, with strong electric fields, these electrons can be removed from the TMAE, giving a much higher quantum efficiency and a threshold lowered by V_0 .

5. CONCLUSIONS

It has now been shown that the SSPC has good spatial resolution as well as good energy and timing resolution. However, it would be desirable to improve the efficiency of the photocathode for application in medium-high-energy physics and in nuclear medicine. For this, work should continue on improving the light collection from the BaF_2 and on improving the electron extraction from the LPC.

The prospects of using TMAE for liquid ionization detectors also look promising. The most obvious application would be for uranium calorimeters, where its low vapour pressure, and thus low fire hazard, would be advantageous.

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Table 1

Properties of three scintillators^{*)}

	BaF ₂	BGO	NaI(Tl)
Density (g/cm ³)	4.9	7.1	3.7
Radiation length (cm)	2.1	1.1	2.6
dE/dx (min.) (MeV/cm)	~ 6	8	4.8
Linear attenuation coefficient at 511 keV (cm ⁻¹)	0.47	0.92	0.34
Peak emission (nm)	225 310	480	410
Decay constant (ns)	0.6 620	300	250
Index of refraction	1.56	2.15	1.85
Light yield (photons/MeV)	2×10^3 6.5×10^3	2.8×10^3	4×10^4
Hygroscopic	No	No	Yes

*) See Refs. [4–7]

Figure captions

- Fig. 1 : Counter configuration used to measure the effect of TMAE in the gas and on the surface.
- Fig. 2 : Part of the emission spectrum of BaF_2 and the absorption of TMAE as a function of wavelength.
- Fig. 3 : Contribution of the TMAE on the counter surface and in the gas as a function of TMAE pressure. The corresponding TMAE temperature is also given.
- Fig. 4 : Counter configuration, with details of the cathode pads, used to measure the one-dimensional position resolution of the SSPC.
- Fig. 5 : Simulation of the light intensity on the surface of BaF_2 crystals 2.54 cm thick and 10 cm thick, for one particle a) normal to the surface ($\theta = 0^\circ$), b) $\theta = 30^\circ$; and for two particles 1.5 cm apart c) $\theta = 0^\circ$ and d) $\theta = 30^\circ$.
- Fig. 6 : Cathode signals for two cosmic-ray events. The two channels on the right are pads 17 and 18 in Fig. 4.
- Fig. 7 : Two superimposed position spectra for the SSPC, displaced by 9 mm. The beam diameter was about 3 mm and the peak widths are about 4.5 mm FWHM, implying a position resolution of about 3 mm FWHM.

CONFIGURATION I

Fig. 1

Fig. 2

Fig. 3

CONFIGURATION II

CATHODE CKT DESIGN

Fig. 4

Fig. 5

[illegible]

Fig. 7