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NEW SCINTILLATORS FOR PHOTSENSITIVE GASEOUS DETECTORS

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ABSTRACT

A new family of scintillators are presented. Their properties are similar to those of barium fluoride, and the spectrum of the scintillation emission is between 140 and 300 nm. Our latest efficiency measurements of ethyl ferrocene and triethylamine liquid or caesium iodide solid photocathodes, in parallel-plate avalanche chambers (PPACs) at high electric field, are also presented. We discuss the revolutionary consequences of the combination of the new scintillators with PPACs with semitransparent photocathodes deposited on the crystals, such as high speed, high resistance to radiation damage, compacity, high gamma efficiency, and applications to tracking devices with scintillation optical fibres.

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1. INTRODUCTION

The proposal to couple a dense inorganic scintillator, barium fluoride (BaF_2), with a low-pressure multiwire proportional chamber (MWPC) filled with a photosensitive vapour such as tetrakis-(dimethylamino)ethylene (TMAE) or liquid TMAE photocathode, in order to detect its light emission, came from Anderson et al. [1–3]; they named the device the solid scintillation proportional counter (SSPC). 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 [4]; a photon yield that is independent of temperature [5, 6]; and a resistance to radiation damage up to 10^5 Gy [7, 8]. Adding these advantages to those of a low-pressure chamber—resulting in a very fast collection time and good time resolution [9], a high rate capability, and a very low sensitivity to direct ionization—made the SSPC working with TMAE vapour a very attractive device for many applications, such as nuclear medicine [10, 11] and electromagnetic calorimetry [12]. But nobody succeeded in using liquid TMAE photocathodes in an SSPC, because of its low efficiency [13].

Until recently BaF_2 was the only known scintillator to possess adequate properties; on the other hand, the only photosensitive compound that had been used with MWPCs to detect the fast component emitted by BaF_2 was TMAE.

The discovery of a new vapour, ethyl ferrocene (EF), photosensitive to the BaF_2 fast emission, broke the monopole of TMAE vapour in SSPCs [14]. Also a new type of organic photocathodes, much more efficient in the VUV region than liquid TMAE, was investigated by Peskov et al. [13]; some of these could be used to detect the BaF_2 fast scintillation in an SSPC [13, 15]. A new concept of SSPC was then developed successfully: it consists of BaF_2 crystals coupled with a parallel-plate avalanche chamber (PPAC) working at room temperature and with a gas mixture at atmospheric pressure [16]. This type of detectors permits us to keep most properties of the traditional SSPC, with high-temperature, low-pressure wire chambers filled with TMAE vapour, eliminating its main disadvantages (see Section 3).

The other way to improve the SSPC would be to find new scintillators that would have properties similar to those of BaF_2 , but a shorter emission wavelength, in the range where the known photosensitive vapours and photocathodes achieve higher efficiencies. The discovery of a scintillation peaked at 173 nm , with a decay time of $\sim 6.3 \text{ ns}$, in lanthanum fluoride (LaF_3) crystals doped with Nd^{3+} allows its use in an SSPC filled with TMAE vapour [17]. The light yield is very small and the detection efficiency was not higher than that obtained with the BaF_2 device. The main advantages of LaF_3 over BaF_2 are its higher density (5.94 g/cm^3) and its shorter radiation length ($X_0 \approx 1.7 \text{ cm}$).

On the other hand, the mechanism by which BaF_2 emits light with a fast component (which gave it its unique properties) was not understood. Studies made by Jansons et al. [18] have now allowed them to explain this fast scintillation process. Based on this research, a new family of inorganic scintillators was discovered [18, 19]. Their properties are similar to those of BaF_2 , but they emit light in a wavelength region between 140 nm and 300 nm .

In this paper we detail the characteristics of these scintillators, and discuss the implications of their use in SSPCs for a wide range of applications. In particular, we show the revolutionary consequences of the association of this new type of scintillators with a PPAC at room temperature and at atmospheric pressure, using semitransparent photocathodes as readout.

2. THE NEW SCINTILLATORS

Recently Valbis and his group investigated the luminescent properties of heavy alkali and alkaline-earth metals such as BaF_2 , CsCl (caesium chloride), RbF (rubidium fluoride), etc. [18], of KF (potassium fluoride), KMgF_3 (potassium magnesium fluoride), KCaF_3 (potassium calcium fluoride), and solid solutions of $\text{KF} + \text{RbF}$ [19]. In these crystals the energy separation between the valence band, involving mainly the halogen electronic states, and the upper cation core band is smaller than the band gap. After excitation generating holes in the core band, radiative electronic transitions from the valence

band to the core band take place, giving rise to a specific emission which these authors proposed to call cross-luminescence (CRL).

The spectra and decay kinetics of CRL were studied under excitation by a 7 keV electron beam, with current density $\approx 100 \mu\text{A}/\text{cm}^2$ in the pulsed regime. The experimental set-up, based on a Seya-Namioka-type vacuum monochromator with a concave diffraction grating (1200 grooves/mm) was used as described in Ref. [20]. The spectra were measured in a photon-counting regime, using a FEU-106-type photomultiplier tube with a magnesium fluoride (MgF_2) entrance window. The decay kinetics were studied using the correlated photon-counting method under excitation by 100 ns long electron pulses having a decay time of 2 ns, which was also the limit of the minimum measurable CRL decay times.

The fluoride crystals were grown by the Bridgman method, in graphite crucibles, in fluorizing or inert atmosphere. The chlorides and bromides were grown in fused silica crucibles, in air. For CRL measurements, small samples (about $1 \times 1 \times 0.5 \text{ mm}^3$) were fixed to the cryostat's cold-finger using indium metal.

In these studies, the fast emission spectrum of BaF_2 (see Fig. 1 [18]) was explained as coming from the radiative electronic transitions between the F-2p valence band and the Ba^{2+} -5p core band. Since the ionization threshold of the Cs^+ -5p core bands of caesium halides is lower than that of other alkali halides' core bands, the CRL was anticipated in the region of relatively low photon energy. Figure 2 (from Ref. [18]) presents the spectra of the fast component of the emission of two Cs halides, CsCl and CsBr (caesium bromide). It was expected [18] that, with RbF, the whole CRL spectrum would also correspond to the transparency region of the crystal; consequently, the CRL intensity would be comparable to that in CsCl and CsF (caesium fluoride). The results confirmed these expectations (see Fig. 3 from Ref. [18]).

In order to illustrate the fact that the emission wavelength of these scintillators can be controlled, we show in Fig. 4 (from Ref. [19]) the different emission spectra of KF when the Rb^+ concentration is changed. Such wavelength shifts could be used, for instance, to obtain a better overlap of the emission spectrum with the transparency region. The CRL spectra of KMgF_3 and KCaF_3 (see Fig. 5, from Ref. [19]) exhibit two main maxima, of nearly equal intensity. The total CRL intensity is comparable to that of BaF_2 ; it remains constant (within 10%) in the temperature range between 80 K and 400 K. The CRL spectrum lies entirely within the transparency region. As all the scintillators described in this paper, KMgF_3 and KCaF_3 have an emission decay time ($< 2 \text{ ns}$) comparable to that of the BaF_2 fast emission. In addition, their resistance to radiation damage [21] was also estimated to be comparable to that of BaF_2 .

All these properties, combined with an emission wavelength between 140 and 300 nm, made these two scintillators an interesting alternative to BaF_2 , their main disadvantages being their lower density ($\sim 3 \text{ g}/\text{cm}^3$) and long radiation length ($X_0 \approx 7\text{--}8 \text{ cm}$). However, these scintillators are not unique, and others are being developed by the same group; belonging to the same family, they have the same general characteristics, but their atomic number and density are higher.

Recently, Valbis and his group studied BaF_2 crystals doped with a large proportion of hydrogen (up to one atom of H for one atom of Ba). Their preliminary measurements showed that these crystals kept the other properties the same as those of the pure BaF_2 .

3. APPLICATION TO SSPCs

3.1 Wire chambers filled with photosensitive vapours

All the scintillators quoted in the first section emit light in the wavelength region below 300 nm. Some of them, such as KMgF_3 and KCaF_3 , have properties similar to those of BaF_2 and, in addition, have a maximum light emission between 150 and 180 nm. In this region the common photosensitive vapours used in SSPCs, such as TMAE, have achieved very high efficiencies (between 35 and 60% for TMAE, see Fig. 6); other photosensitive vapours, such as triethylamine (TEA), nitrogen monoxide

(NO), toluene, ..., are sensitive to this scintillation (see Fig. 6). Some of them, e.g. TEA, have a rather high vapour pressure at room temperature and do not interact with air, simplifying their manipulation. It was thus attractive to use TEA to detect the emission of these new scintillators in SSPCs. This was done by Buzulutzkov et al. [21], who coupled a KMgF_3 crystal with a wire chamber filled with a gas mixture of methane (CH_4) + 7.5% TEA at one atmosphere. They measured an efficiency of ~ 4 –5 photoelectrons per MeV of energy deposited in the crystal. The sensitivity is half that obtained with TMAE and BaF_2 , but a major improvement is the possibility to work at room temperature, whereas the temperature needed to achieve a high enough pressure, and thus efficiency, is 40 °C with TMAE and 80 °C with EF. However, even with TEA vapour, it is still necessary to work at low pressure in order to exploit the good timing properties and insensitivity to direct ionization of traditional SSPCs. Furthermore, the BaF_2 fast emission was recently detected also with a layer of TEA adsorbed on a BaF_2 crystal in an SSPC [22], making it less interesting to use the new scintillators with TEA. It seems more attractive to use them with TMAE vapour: the efficiency would then be higher, by factors of at least 5 to 10, than with TEA (see Fig. 6). This high sensitivity would not only greatly improve the results obtained with BaF_2 in electromagnetic calorimetry [12] and in positron emission tomography (PET) [10, 11], but it would also open a new range of applications in astrophysics, industrial imaging, nuclear medicine imaging, and so on.

3.2 Parallel-plate amplification counters (PPACs)

with liquid or solid semitransparent photocathodes

The main physical limitations of the traditional SSPC, made with BaF_2 and a low-pressure wire chamber filled with TMAE, are set, on the one hand by the fast ageing effect due to polymerization observed with TMAE in a wire chamber [23], and on the other hand by the small spectral overlap between the BaF_2 fast scintillation and the TMAE quantum efficiency (see Fig. 7), which had allowed only a small part of the BaF_2 fast emission to be detected. The practical disadvantages of this detector are that it has to be operated at low pressure in order to keep the properties of this traditional type of SSPCs, and also that TMAE vapour is very reactive to air and corrosive for many materials. Besides, in order to increase the vapour pressure of TMAE in the chamber, and hence the efficiency, it is necessary to work at high temperature. The discovery of the new photosensitive vapour, ethyl ferrocene (EF) [14], interesting since it does not interact with air, did not allow us to increase the efficiency with respect to TMAE vapour, and did not solve the problem of high temperature. The solution may come from the work of Peskov et al. [13], who observed that there is an increase of up to 3 orders of magnitude of the quantum efficiency of metallic photocathodes when they are covered by liquid or solid layers of organic compounds (see Fig. 8). The shift in ionization potential, which is smaller when these organic compounds are in the liquid or solid phase than in the gaseous one [13], allows some of these compounds to be used, in an SSPC, to detect the BaF_2 fast scintillation. Semitransparent photocathodes of liquid EF, adsorbed or condensed on a BaF_2 crystal, were tested in an SSPC containing a mixture of $\text{He} + \text{CH}_4$ at atmospheric pressure and room temperature with good results [15]. Semitransparent photocathodes deposited directly on the surface of the scintillator crystal serve as the photosensitive element in the SSPC; this makes it possible to eliminate the gap that is needed to convert the VUV light emission in the photosensitive vapour. The low-pressure chamber can then be replaced by a PPAC working at atmospheric pressure and room temperature, directly coupled with the crystal, and keeping similar properties.

A prototype, made of a BaF_2 crystal covered by an EF (condensed or adsorbed) layer as the photocathode, coupled to a PPAC of 4 mm thickness and filled, at atmospheric pressure, with a gas mixture of helium and 100 Torr of tetramethyl silane (TMS), worked successfully at room temperature [16]. The properties of this new type of readout for SSPCs are: compacity (3–4 mm thickness), very fast

collection time (≤ 10 ns) and very good time resolution (≤ 1 ns), negligible sensitivity to direct ionization at atmospheric pressure (with helium) and to a magnetic field [24], high gain (single-photoelectron detection), high rate capability [24] (no space-charge effect), and we did not observe any ageing effect due to polymerization. Nevertheless, the efficiency obtained with this new device is no higher than the traditional one, with a low-pressure wire chamber and TMAE vapour.

In order to improve this new SSPC, it would be attractive to find photocathodes that detect the BaF₂ fast scintillation more efficiently. A promising result was obtained with a solid photocathode, made with a new compound [16] called CPIHMB (for cyclopentadienyl-iron-hexamethyl-benzene) (see Fig. 9). It belongs to a large new family of organometallic compounds, discovered by Astruc [25]. They have good chemical stability, associated with very low ionization potential (some of them between 4.2 and 4.8 eV in the gaseous phase). A programme of measurements of the quantum efficiencies of these new promising compounds, in the gaseous and in the liquid or solid phases, is being developed.

The most revolutionary improvement for the SSPC concept is the coupling of the new scintillators, covered with semitransparent photocathodes, in the liquid or the solid phases, with PPACs working at room temperature and atmospheric pressure. The advantage of this type of counter, developed originally with BaF₂, was explained above. Moreover, our calculations show that it is very inefficient, for photon collection, to detect the scintillation light with photosensitive vapours in SSPCs, because all these crystals have a high index of refraction ($n = 1.56$ for BaF₂ and $n \approx 1.5$ for KMgF₃): by internal reflection, only a small part of all the photons produced by the scintillation escape out of one face of the crystal. This phenomenon is also well known when the BaF₂ is coupled to a photomultiplier (PM)—the light yield then increases by a factor of at least 2, if a good optical contact is obtained by applying an optical grease between the surface of the crystal and the PM window. In the case of liquid or solid semitransparent photocathodes, which are of course in direct contact with the surface of the crystal, the light yield increases significantly, since the difference of refraction index is smaller: typically $n \approx 1.3$ for liquid photocathodes. We estimate that the light yield would increase by a factor of 2.5 to 5 (depending on the transparency of the crystal).

These organic photocathodes achieve rather good efficiencies already in regions of relatively high wavelengths, e.g. $\sim 2\text{--}7\%$ at 235 nm (see Fig. 8). This efficiency can increase strongly in regions of shorter wavelengths; see, for example, Fig. 10, where the increase of the efficiency of an EF liquid photocathode is of at least one order of magnitude when the wavelength drops from 235 to 200 nm. In the wavelength region of maximum emission of the new scintillators (for KMgF₃ and KCaF₃ between 150 and 180 nm), the quantum efficiencies of our photocathodes would be much higher, and could probably achieve values equivalent to what can be obtained with a photomultiplier. Moreover, it was observed by Holroyd et al. [26] that the number of photoelectrons extracted from the liquid photocathode into the gaseous phase increases with the intensity of the applied electric fields. This effect was verified by our measurements in SSPCs. For example the increase of efficiency measured between 1 kV/cm and 5 kV/cm is shown in Fig. 8 for a photocathode made of methane + neopentane (NP) + TMAE, cooled at $T < -20$ °C; Fig. 10 shows this increase between 1 kV/cm and 7.5 kV/cm for an EF-liquid photocathode. As a consequence, in a PPAC, in which the applied electric fields are higher than ~ 10 kV/cm, the use of the liquid photocathodes optimizes the quantum efficiency of the SSPC. Even if the sensitivity is generally rather lower, it is more attractive, from the point of view of practicability (e.g. manipulation) and of stability, in SSPCs, to use solid photocathodes at room temperature than liquid ones. A good candidate would be pure tetramethyl-p-phenylenediamine (TMPD), in which a relatively high efficiency was achieved at 200 nm [13]; another could be caesium iodide (CsI), with a quantum efficiency of $\sim 10\%$ in the wavelength emission region of the new scintillators (see Fig. 6). We estimate that a CsI photocathode should achieve an efficiency equivalent to or higher than that obtained with TEA in an SSPC with KMgF₃.

In addition, it is estimated that PPACs are much less sensitive to the ageing effect due to polymerization observed in the majority of proportional wire counters; this is because the local charge density is much lower in a PPAC than around wires. Moreover, in order to avoid photon feedback on the photocathode and to reach a high gain in the PPAC, it is necessary to use a good quencher in the gas mixture, tetramethyl silane (TMS) for example. Next, the quenchers we introduce should have very good ageing properties; the best known so far candidate is dimethyl ether (DME). No ageing effect was observed in proportional wire chambers filled with pure DME up to 1.2 C per centimetre of wire [27].

We expect that the association of the new scintillators, covered with CsI semitransparent photocathodes, with a PPAC filled with helium and DME, could achieve properties and results equivalent to those obtained with BaF₂ associated with a low-pressure wire chamber filled with TMAE. In addition, there would be no ageing effect in the counter, the radiation resistance would be equivalent to that of BaF₂, and the compacity would be better: ~ 3 mm as against 1 cm.

4. DISCUSSION

An electromagnetic calorimeter made with PPACs as described above, estimated to be very resistant to radiation damage, to have a time resolution of < 1 ns and a signal collection time of < 10 ns, with an energy resolution of $\sim 4\%/\sqrt{E}(\text{GeV})$ or better, would be very well adapted to the needs of experiments in high-luminosity accelerators, such as the SSC and the LHC. In many other applications, positron emission tomography (PET) for instance, this type of SSPC would be a great improvement, since it could cover large surfaces at a low price, with a good position resolution. If electromagnetic calorimetry is important in high-energy-physics experiments, another aspect, as essential, of the experiments planned for the high-luminosity accelerators is hadronic calorimetry. In fact, homogeneity would make it necessary to use the same technique in electromagnetic and hadronic calorimetry.

Ideally, these new detectors should possess all the following qualities:

- high speed,
- high resistance to radiation damage,
- ability to realize compensation phenomena, in order to achieve a good energy resolution,
- technical ease of building,
- compacity.

Classical sampling calorimeters made of uranium or lead and organic scintillators [28, 29], or those based on the new approach developed by Wigmans [30], with lead and scintillating fibres, are fast enough and can achieve compensation, but their radiation resistance is not high enough in the hot region of the SSC or LHC, whereas those made of uranium with a warm liquid such as TMP [30] are good on radiation resistance but not fast enough. Also, they are technically difficult to realize. To make a hadronic sampling calorimeter, it would be of advantage to use SSPCs made of a PPAC and photocathodes with inorganic scintillators, such as BaF₂ or the other ones presented in this paper, sampled with uranium or lead. Such a calorimeter would have all the qualities required above, except for the compensation, since the inorganic scintillators do not contain the hydrogen which is necessary to achieve it.

The BaF₂ crystals doped with a large proportion of hydrogen may be of interest for the purpose. Then a fine-sampling hadronic calorimeter, using uranium or lead and this 'new' crystal coupled to PPACs with semitransparent photocathodes as readout, should combine the speed and technical practicability of the uranium (or lead)/organic scintillator detectors with the good resistance to radiation damage of the uranium/warm liquid detectors. In addition, this compact calorimeter would also probably achieve compensation.

A recent step forward in the manufacturing of BaF₂ optical fibres^{*)} opens considerable prospects for the solution of an important problem in detector physics. While scintillating fibres present attractive features for many problems in particle physics, they suffer from a major defect when they are compared to gaseous detectors, namely the difficulty to delay the information for a time long enough for the selection and gating of the events of interest to be made.

The solution that has been found for the manufacturing of BaF₂ fibres can be extended to a vast variety of scintillators. It consists in depositing the substance on a quartz fibre, by chemical vapour deposition (CVD). The author^{*)} advocates that BaF₂ films of 1 to 100 μm can be deposited on quartz fibres of diameter 10 μm to 500 μm . This opens the way for devices where the light coming from a bundle of such fibres is converted into electrons in a gaseous photosensitive device; there the photoelectrons are amplified, delayed, gated and multiplied again in a multistep device, with the emission of light induced by the adequate addition of a vapour such as TEA or TMAE and the detection of the image pattern in a CCD. With some of the new scintillators, the photosensitive device could consist of the thin transparent photocathodes discussed previously, with efficiencies of the order of 10%. Since a single photoelectron can easily be imaged with the multistep chamber, this may lead to the efficient detection of the energy deposited in the fibres, although the yield of light is smaller for these scintillators than in the plastic scintillation fibres investigated up to now for particle tracking or calorimetry. It is an alternative approach to a solution imagined by Sauli^{**)} , where visible light is transformed into VUV by accelerating electrons, in vacuum, between a photocathode sensitive to visible light and a thin layer of BaF₂.

5. CONCLUSION

The perfect overlap between the emission spectra of the new scintillators and the quantum efficiencies of the photosensitive elements used in gaseous detectors would strongly improve the SSPC concept. In particular, an SSPC made of these scintillators covered with solid or liquid photocathodes, coupled with a PPAC working at room temperature and at one atmosphere, would reach a sensitivity that would be practically equivalent to that of a PM ($\geq 10\%$), keeping the properties of proportional gaseous detectors, i.e. compacity, possibility to cover large surfaces, negligible sensitivity to magnetic fields, low noise, ... In addition, this detector would be very fast (time resolution ≤ 1 ns and collection time of the signal ≤ 10 ns), with a high rate capability and a very high resistance to radiation damage.

All these characteristics should allow substantial improvements in many fields of application, at low energies (PET, for example) as well as high energies (electromagnetic and hadronic calorimetry, for instance).

We expect that a new field of applications would also be opened with the scintillating fibres made of BaF₂ and probably of the new scintillators, coupled with photosensitive gaseous detectors as readout.

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*) D. Winn (Fairfield University), private communication.

**) F. Sauli, Proposal for the development of an optic-electronic image delay tube, Proposal for LAA project, CERN, 6 June 1988.

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Figure captions

- Fig. 1 Luminescence emission spectra normalized to equal maximum intensity of BaF_2 at $T = 80 \text{ K}$ ($\circ$) and 300 K ($\bullet$).
- Fig. 2 Luminescence emission spectra normalized to equal maximum intensity of CsCl at 300 K ($+$) and CsBr at 300 K ($\circ$) and 80 K ($\bullet$).
- Fig. 3 Luminescence emission spectra normalized to equal maximum intensity of RbF at 80 K ($\circ$) and 300 K ($\bullet$) and RbCl at 300 K ($+$).
- Fig. 4 Luminescence emission spectra of $\text{K}_{1-x}\text{Rb}_x\text{F}$ solid solutions, with varying $x = 0$ (a); 0.001 (b); 0.01 (c); 0.1 (d); 1 (e).
- Fig. 5 Luminescence emission spectra of KMgF_3 (a) and KCaF_3 (b) at 80 K ($\circ$) and 300 K ($\bullet$).
- Fig. 6 Emission spectrum of KMgF_3 and quantum efficiencies of TEA and TMAE vapours and of CsI solid photocathodes as a function of photon wavelength λ . (1) KMgF_3 emission spectrum; (2) TEA vapour quantum efficiency; (3) TMAE vapour quantum efficiency; (4) CsI solid photocathode quantum efficiency.
- Fig. 7 BaF_2 emission spectrum and TMAE vapour quantum efficiency as a function of wavelength
- Fig. 8 The experimental quantum efficiency as a function of the photon wavelength λ for various liquid and solid photocathodes at a pressure of 1 bar , unless otherwise noted, and electric field $E = 1 \text{ kV/cm}$; (1) methane + TMAE, $T_{\text{cath}} = 0 \text{ }^\circ\text{C}$; (2) methane + TMP + TMAE, $T_{\text{cath}} = -15 \text{ }^\circ\text{C}$; (3) methane + neopentane (NP) + TMAE, $T_{\text{cath}} = 0 \text{ }^\circ\text{C}$; (4) methane + TMS + TMAE, $p = 1.5 \text{ bar}$, $T_{\text{cath}} = -5 \text{ }^\circ\text{C}$; (5) methane + NP + TMAE, $T_{\text{cath}} < -20 \text{ }^\circ\text{C}$; (6) same as (4) with electric field $E = 5 \text{ kV/cm}$.
- Fig. 9 Quantum efficiency as a function of wavelength for different photocathodes. (1) Clean Cu; (2) Cu + condensed CPIHMB; (3) Cu + condensed CPIHMB + TMS; (4) Cu + condensed EF.
- Fig. 10 Quantum efficiencies measured with a single-wire counter: (1) EF at $T = 40 \text{ }^\circ\text{C}$ and a gap $L = 15 \text{ mm}$; (2) thin layer of EF condensed on a copper cathode in an electric field $E = 1 \text{ kV/cm}$; (3) same as (2), with $E = 7.5 \text{ kV/cm}$; (4) clean copper cathode.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

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Fig. 10