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# Position-Sensitive Gaseous Photomultipliers:

Research and Applications



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# **Preface**

# EXPLORATION OF PHOTOELECTRIC AND PHOTOIONIZATION EFFECTS IN GASEOUS PHOTODETECTORS

The photoelectric emission was discovered a long time ago. In1887 Hertz observed that sparks can be produced between two electrodes if the gap is irradiated by ultraviolet (UV) radiation. His discovery attracted a great attention and was continued by several investigators, e.g. Hallwach, Righi et al. It was proven that a clean surface of zinc, if charged negatively, loses its charge when exposed to the UV light, whereas if this electrode is charged positively, it retains its charge. Later detailed studies were performed by Stoletov (in the period between 1888 and 1891) who observed the direct proportionality between the intensity of the incident light and the induced photocurrents.

It is remarkable that these early works were made before the discovery of the electron. Only after many other investigations, including the one performed by Thomson, it was realized that the observed photoelectric effects can be explained in terms of electron emission induced by light. In the framework of classical physics, the photoeffect was interpreted as transfer of light energy to the metal, which lead to the increase of the kinetic energy of its electrons and subsequent thermal emission. According to this explanation the photoeffect should depend on the light intensity. However, Lenard discovered experimentally that below a certain light frequency there is no electron emission regardless how intense the light is. Only above the threshold frequency the photocurrent was proportional to the light intensity.

A quantum theory of this effect was developed in 1905 by Albert Einstein, who found a mathematical relationship between the energy of photon  $E_v$ =hv (where v is the light frequency and h is the Plank constant), the photocathode work function  $\phi$  and the maximum energy of the released photoelectrons  $E_v$ ,

$$E_{\nu} = E_{\nu} - \varphi$$
.

For this ground breaking theory, which well explained the experimental data, Albert Einstein was awarded by a Noble prize in physics in 1921.

Although the importance of this theory is difficult to overestimate, until 1929 the practical role of the photoeffect was very limited (mainly it was exploited in photometry) since the quantum efficiencies of the known materials were quite low. In 1929 an Ag-O-Cs photocathode was introduced, which had much higher quantum efficiency and was sensitive not only to UV, but also to visible and infrared light (Koller, 1930; Campbell, 1931). Cs-based photocathodes immediately found many applications, one of the most impressive at this old time was the reproduction of sound from film. The most important, however, was the development of some photoemissive devices: vacuum photomultiplier tubes, iconoscopes

etc. This lead to a technical revolution, for example appearance of electronic television cameras capable of operating at low light fluxes.

Later some other highly efficient photocathodes were introduced including cesium, antimony, and multialkali. This opened the way for developing various vacuum photodetectors, e.g. photodiodes and photomultipliers having quantum efficiencies for UV, visible or infrared photons close to 30%. Photomultiplier tubes combined photocathodes with a dynode amplification structure exploiting secondary electron emission. The multiplication factor of such dynode system may reach values above 10<sup>5</sup> enabling detection of single photoelectrons. Unfortunately, the position resolution of these detectors was determined by the size of photocathodes which varied from 1 to several cm.

For a long time vacuum photomultipliers were really unique. There were practically no other devices capable to compete with them. The situation changed dramatically at the end of 1970 when for the first time position-sensitive gaseous photodetectors were introduced (Séguinot, 1977; Bogomolov, 1978). In these detectors three new principles were combined:

- 1. Gas photoionization,
- 2. Avalanche multiplication, and
- 3. Segmented electrodes allowing to measure a 2-dimensional position of the absorbed UV photons.

The gas photoionization is based on the fact that photons with energy higher than the ionization potential of the gas ionizes the atoms or molecules so that free photoelectrons and positive ions are created (see Chapter 1 for more details). Since the ionization energy of atoms and molecules is larger than their work function,  $E_i > \varphi$ , the first designs of gaseous photomultipliers had high sensitivity only for far ultraviolet light (VUV), i.e. photons with energy between 5 and 25 eV.

In most gaseous detectors, the primary (photo)electrons experience a avalanche multiplication process. This happens in a high enough electric filed so that the electron can gain sufficient kinetic energy for impact ionization (see Chapter 2). As a result of the avalanche multiplication the collected charge on the segmented anode can reach value as high as 10<sup>6</sup> electrons (in some cases even more) making it is easy to detect photoelectrons electronically.

Avalanche electrons approaching segmented anodes induce signals on them as well as on segmented cathode. From the measured profile of these signals the avalanche position can be determined with high accuracy, often below 0.1 mm. The typical example of such a design is the multiwire proportional chamber (MWPC), considered in Chapter 3. Photosensitive MWPCs immediate found applications in high-energy physics and astrophysics, mainly in detection of Cherenkov light, and in plasma diagnostics (see Chapter 15).

The next breakthrough happened when the MWPC was combined with solid photocathodes, e.g. CuI (Peskov, 1980; Francke, 2004) allowing to extend the sensitivity of such detectors to longer wavelength, up to 350 nm. For a decade the photosensitive MWPCs were the only position-sensitive detectors of UV and VUV radiation.

Later, gaseous detectors were combined with photocathodes sensitive to visible light (Ag-O-Cs, cesium, antimony and multialkali) (see Chapter 7). These detectors had quantum efficiencies comparable to vacuum photomultipliers making them attractive also for measurements in the visible range of the spectrum.

By the end of 1980-ies the first vacuum position-sensitive detectors appeared on the market. They were microchannel plates and multianode photomultipliers (see Introduction and Chapter 8 for details).

In the 1990-ies, solid state photodetectors operating in avalanche mode started to be used in some experiments. Although only relatively small size matrix (3x3mm<sup>2</sup>) of these detectors are commercially available (see Chapter 8) they are considered as very promising.

So, what is the role of gaseous photomultipliers among other detectors?

The main advantages of gaseous detectors are:

- 1. They can be built with very large sensitive areas,
- 2. They have low cost and relatively simple designs,
- 3. They are practically insensitive to magnetic fields,
- 4. Some of their designs are capable of performing measurements in narrow spectral intervals without the use of monochromator or filter.

### THE CHALLENGES

It was not an easy task to develop gaseous photodetectors capable of competing with commercial devices. The main challenges were:

- To find photosensitive liquids/gases having at the same time the lowest possible ionization potentials
  and high enough vapor pressure, and select among them those which are not extremely chemically
  aggressive so that they can be used in practice.
- 2. To find ways of handling them, which includes storage, transfer technique, cleaning etc.
- 3. To find detector materials compatible with the photosensitive vapors.
- 4. Develop large area gaseous photomultipliers and associated electronics.
- Developing solid photocathodes sensitive from UV to visible light and withstanding contact with gases.
- 6. Develop a technology of installing these photocathodes inside the gaseous detectors.
- 7. To find an optima gas amplification structure capable of operating at high gas gains, and being combined with solid photocathodes.
- 8. Develop not only gas-flushed detectors, but also sealed ones.

Let us briefly comment on these challenges. It is clear that various compounds having low ionization potentials can be found through the search in the literature or through personal contacts with chemists specialized on the subject. Unfortunately, most of these substances are chemically aggressive which is directly related to their low ionization potential. The outer electrons are weakly bound to the molecule. This is one of the difficulties. Another one is to select from them those which have high enough vapor pressures. Note that as a rule these substances are either liquid or solid. To use them in practice is not a trivial task since their vapor pressure is usually rather low, which leads to low light absorption and as a consequence to low practical quantum efficiency. The next difficulties were how to clean these substances from impurities capable of absorbing free electrons, which also reduce the quantum efficiency, and how to transfer them into the gaseous detectors. This required development of a special technology. More over one have to select proper materials for the detectors and to perform long-term tests to be sure they will not be damaged due to contact with the chemically active vapors.

Another great task was to construct and assemble large area gaseous photodetectors, flushed with mixtures containing low ionization potential vapors. One of the problems was to find the way to suppress the photon feedback caused by the avalanche light emission. The feedback reduces the maximum achievable gains. One also had to develop special low noise electronics.

The next challenge was to combine gaseous detectors with solid photocathodes which allowed to extend their sensitivity to longer wavelengths. This required studying known photocathodes, used in vacuum devise, in gas atmosphere. The problem was (and still is) that most of these photocathodes degrade fast if tiny impurities of oxygen or water are present in the gas mixture. They are also easily damaged under ion bombardment.

Traditional gaseous detectors, for example MWPCs combined with highly efficient photocathodes sensitive to long wavelength, suffer from photon and ion feedback problems which becomes much stronger than in the case of photosensitive vapors. The challenge was to develop appropriate amplification structures capable efficiently suppressing both photon and ion feedback.

Finally, the most difficult challenge with regard to the gaseous detectors sensitive to visible light was the development of sealed detectors. It requires finding appropriate materials which does not outgas anything during long times. For commercial applications only sealed gaseous photomultipliers may represent any interest as a continuous gas flow is troublesome.

### SEARCHING FOR SOLUTIONS

The search for gases with low ionization potential started immediately after position sensitive photodetectors were discovered (Séguinot, 1977; Bogomolov, 1978). It resulted in that several promising liquids with low ionization potentials were identified and tested, e.g., trimethylamine, triethylamine, ethylferrocene tetrakis (dimethylamino) ethylene (TMAE), see Chapter 3.

Much more difficult was to find ways to handle these liquids. For example, TMAE, which was the most attractive due to its low ionization potential, is chemically aggressive, it has low vapor pressure at room temperature and requires cleaning prior the use in detectors. These serious technological problems were overcome through the hard works of a quite large community of specialists: physicists, engineers, chemists etc. The problem TMAE's chemical aggressiveness was solved by a careful selection of detector materials. The problem of low efficiency to VUV photons was solved by heating the entire detector, including the TMAE injection system, to temperature up to 50-60°C. To clean the TMAE, a special setup was built at CERN serving various experiments at CERN and elsewhere.

Of course, during the development of the TMAE-flushed MWPC some unexpected small and big problems were revealed. One of them was the accumulation of polymer depositions on the anode and cathode wires leading to a slow degradation of the detector performance (a so called aging effect). A special research program was launched to attack this problem. Another problem was the photon feedback. This effect was diminished by a special geometry of detectors, by optimization of the gas mixture and by developing low noise electronics.

As a result of all these measures, large detectors were built and successfully used in various experiments at CERN and elsewhere (see Chapters 10-13). Some of them operated in time projection mode allowing to obtain 2D and 3D images of Cherenkov photons (see Chapter 10). Gaseous detectors filled with photosensitive vapors allowed obtaining important results in high energy physics, astrophysics and plasma diagnostics experiments.

The next important step in the evolution of gaseous photomultipliers was the development of gaseous amplification structures combined with solid photocathodes which allowed to extend their sensitivity beyond the ionization threshold of TMAE.

Note that solid photocathodes can be divided in two main categories:

- 1. Sensitive only to VUV and UV light, for example CuI, CsI.
- 2. Sensitive to UV and visible light e.g., SbCs, bialkali.

As a rule, photocathodes belonging to the first category are more robust. They even withstand a short contact with air. This is why UV sensitive photocathodes were the first to be used in practice.

One important problem to overcome was the photon feedback, another one the photoelectron back diffusion. The first is caused by secondary photons produced in the avalanche process in the detector illuminating the photocathode and producing secondary pulses. The second is due to photoelectrons extracted from the solid photocathodes due to diffusion, which return back to the cathode reducing its quantum efficiency. Both of these problems were solved by the gas optimization. It turned out that one of the best gases for this purpose is methane, CH<sub>4</sub>.

More complications arose and were overcome when constructing gaseous photomultipliers sensitive to visible light.

These photocathodes degrade fast if the gas contains even small traces of oxygen, water or some other chemicals. For this reason, photocathodes sensitive to visible light is unpractical to use in gas-flushed mode. They are acting as getters for impurities continuously coming with the gas and are eventually irreversibly damaged. Therefore, the best approach is to use them in sealed mode. The development required finding means for photocathode manufacturing, development of sealed gas chambers filled with ultraclean gases made of materials with very low outgassing properties, development of gas amplification structures capable suppressing photon and ion feedbacks etc.

Although the technology of manufacturing of solid photocathodes is described in some publications and books (see for example Sommer, 1968) there are many important details which physicist dealing with gaseous photomultipliers discovered and solved via their own experience.

To make visible photocathodes more robust for contact with gases it was tested to cover them with a thin protective layer, having some transparency for photoelectrons created from the photocathode, but strongly reducing the gas diffusion through the film (see Chapter 7). This approach, indeed, provide remarkable protection, but the price to pay was the loss of some photoelectrons in the layer and thus decrease of detection efficiency especially in long wavelengths.

The success of the gaseous photomultipliers sensitive to visible light was impossible without developing gas amplification structures capable suppressing photon and ion feedbacks. In first prototypes glass capillary tubes operating in avalanche mode were used. Later they were replaced by a more sophisticated structure consisting of several hybrid hole-type structures allowing to reach higher gas gains than with capillary plates, close to 10<sup>6</sup> (see Chapter 7).

Above only a few examples of challenges that has been overcome are presented. One can imagine that in reality many more problems arose and were solve before gaseous photomultiplier became mature devices capable competing with other types of photodetectors.

## ORGANIZATION OF THE BOOK

The book describes the development of these detectors, as well as practical tips how to make them work in the best possible way.

In Chapter 1 two main principles of conversion photons to photoelectrons used in gaseous photodetectors are considered: gas photoionzation and a photoelectric effect from solid photocathodes. There are also descriptions of liquid photocathodes which offer lower ionization thresholds compared to the corresponding vapors. The great success of solid photocathodes covered with an adsorbed layer of some photosensitive vapors is described in detail. The thin layer of an absorbed photosensitive vapour reduces the cathode work function and as a result it extends the photosensitivity threshold towards long wavelengths and also enhance their quantum efficiencies, sometime by a factor of two.

Chapter 2 describes the process of electron avalanche multiplication of photoelectrons allowing to reach electrical signals sufficient for detection single primary electrons. Electron avalanche multiplication can advantageously be used in position sensitive photomultipliers to with high efficiency detect single photons with respect to position, time, direction and energy.

In Chapter 3 position-sensitive gaseous photomultipliers filled with photosensitive vapors are described. The ultimate goal is not only to detect photons with a high efficiency, but also to determine their position with an accuracy often down to a few micrometers. In many measurements it is important to know when the photon was detected with a precision of less than a nanosecond. The detectors should have excellent stability. Their performance should not degrade with time.

Chapter 4 is dedicated to an exotic photosensitive compound, liquid photocathodes which were studied intensely for a number of years around 1988. The motivation was driven by the fact that the threshold energy for photoionization in liquids is generally lower than in gases owing to the polarization energy of the positive ion and the lowering of the electron conduction band energy. Moreover, it was observed that the gaseous compounds used as photocathodes while absorbed on surfaces, makes them photosensitive even if the thickness of this layer was extremely thin, just a few monolayers. This opened up the dream of a well-defined photosensitive layer. In a photosensitive detector with a gaseous photoelectric converter it is difficult to know where each individual photoelectron is actually emitted. The conversion volume has to be made thick enough to allow efficient conversion of the incoming photons and this smears the position resolution, and reduces the time resolution. A thin layer photocathode would eliminate this smearing in space and time. Furthermore, the gas system might be simplified, or even removed with such a liquid cathode. Chapter 4 summarize the results of these studies, which led to the important development related to solid photocathodes in gaseous detectors.

Chapter 5 describes the early work on UV sensitive solid photocathodes for gaseous detectors. A solid photocathode is advantageous over gaseous and liquid photocathodes due to its well defined emission point of the photoelectrons. Gaseous detectors with solid photocathodes are simpler to manufacture, are sensitive to longer wavelength and have better time resolution than detectors filled with photosensitive gases. They should be able to operate at high gas gains and detect single photoelectrons. Finally, compared to vacuum photomultipliers they have little sensitivity to magnetic fields and can measure the coordinate of photon conversion and can be made with large areas and arbitrary shapes. All this leads to that gaseous photomultipliers with solid photocathodes open a new page in photosensitive detection technique. Chapter 5 reviews the early development of solid photocathodes and the road towards the modern photocathodes which have revolutionized the photosensitive detector technology.

In Chapter 6 UV-sensitive CsI and Cs<sub>2</sub>Te photocathodes are described. The development of CsI and Cs<sub>2</sub>Te solid photocathodes present the breakthrough in photosensitive gaseous photodetectors we all had been waiting for, and put so much effort in finding. It was actually going back to basic. CsI had for a long time been used in vacuum photomultipliers. Recent studies proved to also work well in gas flows, and can even be exposed to air for shorter times. Hence, it is rather easy to handle compared to other photocathodes. For example, it can easily be mounted inside avalanche gaseous detectors in a glove box, and even in air. Due to these advantages, the CsI-based photon detectors represent the most effective solution concerning cost and performance for large detector area applications in relatively low rate (or low occupancy) experiments. The main application of CsI-based photodetectors is as Cherenkov ring imaging detectors. For example, large area CsI-MWPCs are used in the ALICE (~11 m²) and COMPASS (5.8 m²) experiments at CERN.

In Chapter 7 the latest generation of gaseous photomultipliers, sensitive up to visible region of spectra are described. They represent the most exciting and promising developments which may open the possibility of building large-area positon sensitive gaseous photomultipliers. Laboratory and commercial prototypes of such detectors were developed and extensively tested. Typically they consist from a sealed envelope housing a cascaded hole-type structure combined with reflective or semitransparent photocathodes: SbCs or bialakali. Sealed gaseous photomultipliers sensitive to visible light now have high quantum efficiency comparable to commercial vacuum photodetectors and are stable in time. In contrast to vacuum devices, they have little sensitivity to magnetic fields, which is an important advantage allowing them to be used in many applications.

In Chapter 8 a review of alternative position-sensitive vacuum and solid state detectors is presented. This includes microchannel plates, multi-anode photomultipliers, solid–state avalanche detectors and hybrid detectors combining in one design two or more detection principles or sensors.

These types of detector appeared after the development of gaseous photomultipliers filled with photosensitive gases, they start to conquer the market of photo-sensors and applications, and represent now a serious alternative to gaseous detectors.

Chapter 9 describes the history and physics of Cherenkov light, the light emitted in a medium as a charged particle traverses it with a speed greater than the phase velocity of the light. The most important feature of this light is that it is emitted in a cone at a specific angle to the track, depending of the velocity of the incoming particle. This means that by measuring this angle one can determine the velocity of relativistic particles with good accuracy. Combining this information with information about the particle's momentum, the mass of the particle is known and, since the mass of each particle is unique, the particle is identified.

The Cherenkov effect has been used to identify particles ever since its discovery, and is becoming an even more important part of particle physics experiments of today, since new technology has provided better and better equipment to detect the faint light. These detectors are known as Cherenkov detectors.

Chapter 10 describes the history of development of practical devices exploiting the Cherenkov effect and used for particle identification. Slowly, starting from the first small prototypes, bigger and more sophisticated devices were built and used in many experiments. A real breakthrough happened after introduction of Ring Imaging Cherenkov detectors (RICH). However, a full scale implementation of these new detectors would be impossible without a complimentary work, the search for vapors having low ionization potential and compatible with gaseous detectors such as a multiwire proportional counter. As a result of these efforts two useful vapors were identified: Triethylamine and Tetrakis(dimethylamino)ethylene.

After solving the technical problems associated with the chemical aggressivety of tetrakis (dimethylamino) ethylene the latter was successfully used in such a giant detector as DELPHI (Detector with Lepton, Photon and Hadron Identification) RICH as well as in many other detectors.

Note that most of RICH detectors are quite complicated to construct and operate. Chapters 11-14 describe in more detail examples of such detectors and their performance.

Chapter 11 is dedicated to the NaF RICH detectors used in CP LEAR (charge parity violation studies at Low Energy Antiproton Ring) experiment at CERN. In this particular RICH design the NaF radiator is used together with a quartz window separating the drift volume from the photosensitive MWPC flushed with a gas mixture containing tetrakis (dimethylamino) ethylene vapors. The use of these vapors as photo converter allowed to achieve at the same time good separation power and high detector efficiency. To avoid having a large conversion region the detector has to be heated to 40° - 50°C. In the MWPC the pad readout was used to give a non-ambiguous two-dimensional reconstruction of the hit pattern.

The separation power of the NaF RICH counter is superior to conventional methods like time of flight, dE/dx, and threshold Cherenkov counters, etc. It is fast and compact and represents only about 20% of a radiation length, and can therefore be used as an efficient particle identifier in the medium energy range ( $p_{proton}$  < 5 GeV/c).

In Chapters 12 and 13 examples of RICH detectors used in astrophysics balloon born experiments are given.

In Chapter 12 the Cosmic AntiParticle Ring Imaging Cherenkov Experiment (CAPRICE) is described. It used for the first time a RICH detector combined with magnet spectrometer that is sensitive to unit charged particles (previously, the Chicago University group had flown a gas-RICH detector sensitive to helium and higher charges).

The aim of the experiment was to measure the flux of antimatter, mainly antiprotons and positrons, and light isotopes in the cosmic radiation. This RICH detector used a NaF solid radiator, tetrakis (dimethylamino) ethylene vapor as photo-converter and cathode pad readout in the photosensitive MWPC operated at low gain. Besides particle identification on an event-by-event basis it efficiently rejects multi-particle events and albedo particles.

In Chapter 13 the next generation of the CAPRICE experiment is described. The science objectives were to measure the antimatter component in the cosmic rays in the energy range 2–50 GeV and to study the cosmic ray composition in the atmosphere in the energy region between a few hundred MeV and 330 GeV. The main goal of the gas-RICH detector was to identify antiprotons in a large background of electrons, atmospheric and locally produced negative pions and muons. Because of the large number of detected photoelectrons and the low noise level in the MWPC, a good velocity identification was possible by the induced signal on the pad plane originating from the Cherenkov light. By combining the RICH detector information on Cherenkov angle with the rigidity information in the magnetic spectrometer and the identification capability of the imaging calorimeter, particles were fully identified over large energy ranges.

Chapter 14 deals with the latest generation of RICH detectors based on a CsI photocathode coupled to a gaseous detectors. Large area CsI-MWPC were/are successfully used in several experiments at CERN and elsewhere. For example, an active area of the CsI RICH operating in ALICE (A Large Ion Collider Experiment) experiment is about 11 m<sup>2</sup>. All these detectors have shown to be efficient and stable over long periods of time.

After the invention of micropattern gaseous detectors CsI- based photo-sensors gained new momentum and large area CsI-gas electron multipliers made of Kapton were implemented in the PHENIX hadron blind detector. A so-called CsI-thick gas electron multipliers manufactured from the standard printed circuit will be installed in 2017 at the COMPASS upgrade RICH.

In Chapter 15 the main applications of gaseous photomultipliers beyond RICH detectors are described. They include applications in spectroscopy, plasma diagnostic, astrophysics, flame detection, readout gaseous and solid scintillators, and cryogenic detectors. Their advantages are described and compared with alternative techniques.

Some photosensitive substances (e.g. tetrakis (dimethylamino) ethylene vapors, CsI, etc.) were/are used also in other type of gaseous detectors, e.g. light imaging chambers and in gaseous multipliers exploiting a secondary electron emission effects. As follow from this chapter gaseous photomultipliers are unique for some applications.

# THE PLACE OF GASEOUS PHOTOMULTIPLIERS IN APPLICATIONS AND AMONG ALTERNATIVE DETECTORS

Introduction of gaseous photomultiplier was an important step in evolution of photosensors. They were the only position-sensitive detectors capable detecting single UV photons. At this time the only other devices were small non-position sensitive vacuum photomultipliers. Moreover, since they were mainly operated at pressure of 1 atm, there was no special mechanical constrains on the window size and the chamber wall strength. This enabled large area detectors. None of the existing detectors at this time could compete with UV sensitive gaseous photomultipliers.

With time appeared commercial position-sensitive vacuum and solid state detectors, but they had / have relatively small sensitive areas. Hence, the UV gaseous photomultipliers remained to be leaders in cost-effectiveness for large area coverage applications. They have also other important features: insensitivity to magnetic fields (up to 4 T), low cost, the possibility to choose construction materials with low radioactive background etc. For these reasons they were employed in the largest RICH detectors ever built, the DELPHI RICH and the SLD CRID, successfully operated between 1987 and 2000.

Later, the development of large-area CsI photocathodes made another breakthrough in Cherenkov photodetection allowing the transition from the photoionization in gas to photoelectron extraction from solid photocathodes in respectively faster MWPCs. Nowadays the majority of large RICH systems presently in operation in high energy physics are still based on such a technology. The necessity to increase the counting rate capability for future applications (for example for the COMPASS RICH) has produced a further evolution of gaseous photomultiplier and all new developments are based on micro-pattern gaseous counters, combining fast detector operation with low cost per unit of surface.

Promising results have also been obtained from R&D on micro-pattern photomultipliers using photocathodes sensitive to visible light. Commercial prototypes were build and their preliminary tests demonstrated good performance, so these detectors also may have a great feature. We hope that this book will be useful for students, engineers, researches, professors and technicians.

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