

The Next Generation of Photo-Detectors for Particle Astrophysics

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ABSTRACT

We advocate support of research aimed at developing alternatives to the photomultiplier tube for photon detection in large astroparticle experiments such as gamma-ray and neutrino astronomy, and direct dark matter detectors. Specifically, we discuss the development of large area photocathode microchannel plate photomultipliers and silicon photomultipliers. Both technologies have the potential to exhibit improved photon detection efficiency compared to existing glass vacuum photomultiplier tubes.

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1. Introduction

High energy physics and astroparticle physics experiments require large area photon counting detectors with high efficiency and low cost per channel cost. Currently, vacuum technology is the only way to achieve the large areas while maintaining high gains and photon-counting operation. Even as the requirements of future experiments grow, the available vendors of vacuum-based photon detectors are shrinking. Companies that manufacture vacuum tube based photon counting detectors are reducing their capabilities in favor of more profitable semiconductor based technologies. This threatens to raise the costs, extend the planning required, and even compromise large scientific projects based on the detection of coherent light phenomena, especially scintillation and Cherenkov light.

The most common photon detection device in use for high energy and astroparticle physics is the photomultiplier tube (PMT); first developed in the 1930s (Lubsandorzhiev 2006). In addition to particle, nuclear and astrophysics experiments, the technology is used today in a wide range of research fields such as space, medicine, biology, and chemistry. While the basic structure of PMTs remains unchanged from its inception, much development has taken place with regard to improved photocathode efficiency, precision timing characteristics, and multi-anode readout capability. Depending on the details of the dynode structure, amplifications of 10^7 can be achieved while still retaining single photoelectron sensitivity. Photocathode efficiencies presently are typically on the order of 20%, although new photocathode technologies can achieve twice that value. The transit time for the generation of a signal is typically $< 100\text{ns}$, with the transit time spread, and thus, timing resolution for single photoelectrons, on the order of a nanosecond. The cost of a phototube can be as low as $\$10/\text{cm}^2$ of photocathode coverage, with optimized detectors costing up to 10 times that. Alternative technologies to PMTs have arisen, but the superb performance and economics of phototubes is such that major innovation for vacuum photomultipliers has proceeded slowly.

A promising new approach being pursued by several research groups is to combine modern semiconductor technology with vacuum devices. For example, new cathode structures (in some cases semiconductor heterostructures engineered to promote efficient electron transport and other features such as intrinsic high gain or fast timing) are being combined with new kinds of electron multipliers that lend themselves to very large areas, and mass fabrication. Designs for these electron multipliers range from silicon and ceramic microchannel plates and semiconductor nanostructures to gas electron multipliers (GEMs) aimed at dramatically reducing the cost per unit area. New techniques for direct deposition of cathode surfaces on silicon microchannels could result in dramatic improvements. The funding for all of these developments falls short of what is required to maintain credible efforts at universities and national laboratories. Development work at U.S. research institutions is lagging compared

to similar efforts based mainly in Europe. A substantial change in the status quo is needed for new technical approaches to be developed before further shrinkage of commercial technology occurs and for the U.S. to remain competitive in the development of photon detection technology.

In this white paper we address two such technologies that hold the potential for replacing the PMT in many astrophysical applications: large area microchannel plate photomultipliers (MCP) and Geiger-mode avalanche photodiodes or silicon photomultipliers (SiPM).

2. Physics Motivations

2.1. Gamma-ray Astronomy

TeV Gamma-ray astronomy is one of the youngest sciences, having established its first firm detection, the Crab Nebula, (Weekes *et al.* 1989) in 1988. In the past 3 years, the number of TeV-band sources has increased by an order of magnitude, including the remnants of supernova explosions, neutron stars, supermassive black holes, and possibly associations of massive stars. TeV gamma-ray astronomy has a broad science program which includes cosmology and fundamental physics through studying of the nature of dark matter, searching for a TeV component in Gamma-ray Bursts, determining the origin of cosmic rays, and studying jet phenomena in supermassive black holes (Buckley *et al.* 2008).

High-energy gamma rays can be observed from the ground by detecting secondary particles of the atmospheric cascades initiated by the interaction of the gamma-ray with the atmosphere. Imaging atmospheric Cherenkov telescopes (IACTs) (Hinton 2004; Lorenz 2004; Acciari *et al.* 2008) detect Cherenkov photons ($\lambda > 300\text{nm}$), which are produced by electrons and positrons from the cascade. The technique focuses Cherenkov photons onto a finely pixelated camera typically composed of a few hundred phototubes and operating with an exposure of a few nanoseconds. The technique provides energy threshold triggering with energy resolution of $\sim 15 - 20\%$. The next generation of telescopes are attempting to reach sensitivities an order of magnitude greater than today's instruments. A major challenge is to scale observatories to this sensitivity while reducing the cost per detector channel significantly from what would be the case by simply cloning present day instrumentation to achieve an IACT coverage of $\sim 1\text{km}^2$.

The Cherenkov light pool from an atmospheric cascade consists of a large region (radius $\sim 120\text{m}$) in which the photon density is roughly constant and outside of which the photon density declines as a power law. The Cherenkov spectrum is shown in figure 1 for particles of a 50 GeV gamma ray shower. Cherenkov light arriving at the camera is detected by

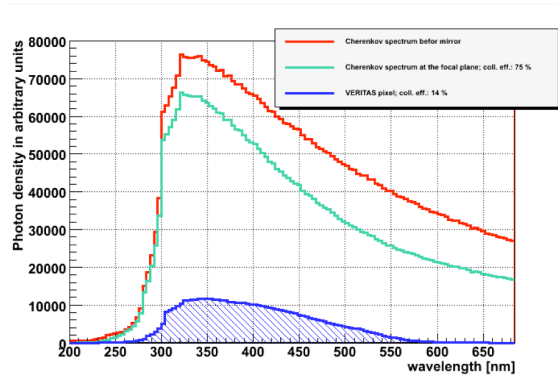


Fig. 1.— The Cherenkov spectrum emitted by particles of a 50 GeV gamma ray shower (red line). The sharp attenuation of the spectrum below 300nm is due to atmospheric absorption. The cyan line shows the Cherenkov spectrum after two reflections on mirror surfaces and the blue hatched area shows the $\sim 10\%$ of the total Cherenkov light arriving on the ground (here $\sim 1200\text{m}$) that is detected by standard bi-alkali photomultipliers typical of those used in IACTs.

standard bi-alkali photomultipliers with UV glass entrance windows. Typically only $\sim 10\%$ of the light is detected allowing for considerable improvement in sensitivity via enhanced overall photon detection efficiency. In addition to better photon detection efficiency, future IACT arrays seek to have finer angular resolution by factors of 2-3 over present instruments. The feasibility of incorporation of multi-anode phototubes into IACT cameras has been demonstrated (Byrum *et al.* 2007). These would allow angular resolution on an event-by-event basis of perhaps 0.05° . Cameras based on silicon photomultipliers may offer similar resolution with improved photon detection efficiency and detector robustness.

2.2. Cosmic-ray Astrophysics

Over the past century, the study of cosmic radiation has had a significant impact on our understanding of nature. The discovery of new fundamental particles in cosmic radiation, e.g. the positron and the muon, fundamentally changed our knowledge of matter and led to the emergence of modern particle physics. The continued study of the cosmic radiation may yield significant information on supernova remnants, supermassive black holes, and the nature of dark matter. Additionally, cosmic ray outreach projects play an accessible role in the education of young people on the methods of physical science. Atmospheric fluorescence detectors, which are critical in the highest energy cosmic-ray detectors such as HIRES and the Pierre Auger Observatory, need large area photodetectors.

2.3. Neutrinos

The confirmation and study of neutrino oscillation over the past two decades was a breakthrough in our fundamental understanding of the nature of matter. The observation of neutrinos from supernova 1987a has improved our understanding of the supernova process while placing independent limits on neutrino mass. Neutrino detectors hold the promise of answering some of our most fundamental questions about nature, but inexpensive, large area photodetectors are needed to advance this key area of science over the next decade.

Two technologies stand out for the future of neutrino science: water Cherenkov detectors and liquid argon time projection chambers (Barger *et al.* 2007). Progress in water Cherenkov neutrino detection is aiming toward a million ton detector. The surface area surrounding the water volume is covered with photon counting detectors, and at the megaton scale, such experiments face significant costs from covering millions of square meters with photodetectors.

Liquid argon time projection chambers detect the neutrino produced lepton by drifting electrons liberated from large argon volumes to wire grids. Large area photodetectors enhance this technology by detecting the scintillation light created during this process (Eraditato 2006). The scintillation light is a much more accurate timing process for the neutrino interaction. Since most neutrino sources, e.g. accelerators and supernovae, have low duty-cycles, accurate timing will enable significant reduction of backgrounds, increasing the speed and quality of scientific results from liquid argon neutrino detectors.

2.4. Direct Dark Matter Detection

A model for dark matter motivated by theoretical extension of the Standard Model of Particle Physics is the presence of Weakly Interacting Massive Particles (WIMPs) produced in the early universe and forming large extragalactic structures. Direct detection of these very weakly interacting particles may be accomplished using very large, radiopure detectors that can detect nuclear recoils from elastic scattering of WIMPs. These scatters would give only a few keV of recoil energy and interaction rates could be as low as a few events per ton per year.

Detectors based on liquified noble elements have made promising breakthroughs during the past decade and may rapidly increase the sensitivity to WIMP-nucleus recoils. However, these technologies already require specialized photon-counting devices. Not only must the photo-detectors work at temperatures appropriate for liquified xenon (165 K) or argon (87 K), but these devices must use less radioactive materials in their composition; modern PMTs

are already the most troublesome source of background for noble liquid dark matter detectors that are in the construction and commissioning phase. The next generation of liquid noble dark matter detectors are expected to need many square meters of photosensitive area.

If the WIMP-nucleus scattering is not detectable by current experiments, a new large area photo-detector is necessary for future noble liquid detectors. As discussed in section 3.1, a possible solution to large area photodetection is the Microchannel Plate photomultiplier. These structures have a simple flat panel construction and, if they are made of low Z materials, could be adequately radiopure. The fast timing characteristics of these devices can contribute to event localization. Other solutions include hybrid photo-diodes, but both solutions are in the research and development phase. Future dark matter detectors based on liquid noble elements will be significantly delayed during the next decade if the pace of research in large area photodetectors continues at its current rate.

3. Photodetection Technology in Astrophysics: Advantages and Limitations

The advantages of PMTs in astronomy and astrophysics are high gain, fast signal formation, blue sensitivity, single photon response, potential large sensitive area arrays, and the fact that it is a proven technology with reasonable cost per channel or per photocathode coverage. The limitations are the generally low quantum efficiency, the difficulties in installation and support, e.g. the photocathode size is limited and each tube is relatively bulky and delicate. Moreover, high voltage needs to be supplied to each device often requiring a massive overall cable burden. Furthermore, PMTs under bias are damaged if accidentally exposed to day light and are sensitive to magnetic fields.

3.1. Large Area Photo-detectors Using Microchannel Plate Technology

Progress in modern micro-electronics, materials science, and nano-technology provide an opportunity to apply advanced microchannel plate technology to develop large-area economical photodetectors. A Microchannel Plate (MCP) is an array of miniaturized electron multipliers oriented parallel to each other. An MCP typically consists of lead silicate glass processed to enhance secondary emission and to improve detection efficiency for specific radiation: UV, soft x-ray, etc. Commercial devices are fabricated with channel diameters $\leq 25\mu\text{m}$ with the most advanced MCP having $2\mu\text{m}$ channels for high image detail and fast response time. The fabrication of traditional glass MCPs is a costly multi-step process and large area MCPs are difficult to produce.

Anodization of aluminum can produce pores with diameters between 20 and 500nm, the use of anodized aluminum oxide (AAO) membrane coated with conductive metal oxide as an MCP has been proposed (Drobychev *et al.* 2006). This could be an industrially economical process based on self assembly. AAO feasibility studies have proceeded and initial tests have shown promising results (Routkevitch 2009).

The use of Atomic Layer Deposition (ALD) for MCP's has been developed over the last several years, and a great deal of work has been done understanding the basic issues and exploring the multi-dimensional parameter space ¹. ALD provides the ability to deposit one molecular layer at a time and create a layer of material with a specific work function. By using modern micro-electronics, materials science, and nano-technology, one could create a complete photomultiplier inside of each microchannel pore.

Futhermore, new photocathode materials based on nano-technology also have the potential for comparable (or higher) quantum efficiencies by optimizing the cathode surface morphology and dielectric constant, and thus, tailoring the near-surface electric field such that it could significantly enhance photoelectron emission. This approach could offer an alternative to lowering the surface work-function of a conventional photocathode by fine (and expensive) tuning of its already complex chemical composition. Additional gains in overall detector efficiency could be obtained by using nano-engineered photon-trapping surface geometries with reduced reflection losses, thus benefiting from technologies now standard in the solar cell industry.

3.2. Silicon Photomultipliers

Many of the disadvantages in everyday handling of PMTs do not apply to semiconductor photon detectors, for example, vulnerability to mechanical stress or damage when exposed to strong light sources when biased. However, the use of semiconductor photo-detectors in astroparticle physics has been limited mainly because devices are too small and too costly.

During the last decade, the possibility to use silicon photo-detectors has attracted increasing attention, mainly due to the development of a novel detector concept: the Silicon Photomultiplier (SiPM) or the Geiger-mode APD. The sensor, originally developed by several groups in Russia (Bondarenko *et al.* 2000), is comprised of an array of avalanche photo-diodes, typically 10^{2-4} per square millimeter ². Each photo-diode (or cell) is biased above

¹see <http://www.arradance.com/>

²see <http://cerncourier.com/cws/article/cern/28805>

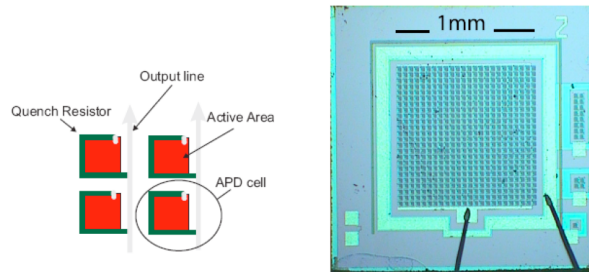


Fig. 2.— Schematic layout of a SiPM; the figure shows four cells of a SiPM. Each cell is biased above breakdown and connected via a quenching resistor to a common readout. Right: photograph of a SiPM produced by MEPhI Pulsar.

breakdown and operates in Geiger-mode, i.e. a photon is detected by a breakdown of a cell which generates a large output pulse (typically several 10^{4-6} electrons). The breakdown is quenched by a polysilicon resistor attached to each cell, which limits the current in the substrate below. The quenching resistor of each cell is connected to a common network so that the output signal of the SiPM is the summed signals of all cells (see figure 2). The SiPM offers many advantages such as low power, low voltage, compactness, excellent timing resolution, good linearity, robustness, and insensitivity to magnetic fields. These characteristics make the SiPM an interesting candidate for astrophysics experiments both on the ground and in space.

SiPM applications to astroparticle physics experiments have been successfully demonstrated. Most tests focused on its use in Cherenkov telescopes (Biland *et al.* 2008; Wagner 2009) which is currently one of the most demanding applications in terms of photon detection efficiency (PDE). One of these tests showed that the performance of at least one type of SiPM is superior to the performance of a PMT with respect to PDE. The potential of a $\text{PDE} > 40\%$ is one of the biggest attractions of SiPMs albeit a challenging goal. Already, the PDE of some SiPMs outperforms that of the classical PMT with peak efficiencies of about 30% at 450nm. In the future it seems feasible that peak PDEs of 60% and maybe higher can be achieved. The focus of future activities will be the development of specially engineered entrance windows and avalanche structures which will enhance the sensitivity in the blue to UV wavelength range. The design of new, blue sensitive structures depends on the ability to develop processes which produce thin implantation layers at the surface to minimize the absorption of short wavelength photons in insensitive areas just below the entrance window while avoiding a concomitant increase in noise rate from the implantation layers.

The noise rate of SiPMs ranges between a few 100kHz and a few MHz per mm^2 sensor area at room temperature. Although a noise rate at the lower end, i.e. a few 100 kHz is sufficient for many applications in astroparticle physics experiments, moderate cooling and

temperature stabilization is required to compensate the temperature dependent changes of SiPMs. For example, the gain changes by about $1\%/^{\circ}\text{C}$. With improved processing, for example, the replacement of the polysilicon resistor by a less temperature dependent material, the temperature dependence can also be reduced. Recent work at the Max Planck Institute/Munich, Germany has demonstrated the feasibility of using a thermistor to automatically adjust the bias voltage to reduce gain variation (Miyamoto 2009). A separate group at the same institution is experimenting with replacing the polysilicon quench resistor with a bulk integrated structure (Ninkovic 2009). This would allow a much improved geometric detection efficiency, i.e. eliminate the dead area the polysilicon produces.

Available SiPMs have sizes between 1mm^2 and 25mm^2 . In astroparticle experiments photo-detector size requirements typically range between 2cm to 40cm sized PMTs. Whereas, for example, in Cherenkov telescopes SiPM have about the right size, the application of SiPM in neutrino telescopes is limited.

One avenue of research for SiPMs is the possibility of incorporating them into an application specific integrated circuit (ASIC). SiPMs are inherently a digital device: each pixel is sensitive to interaction of a single photon to which it produces a “standard” pulse with a rather small Gaussian variance about the mean. The ability to distinguish many incident photons is limited by the accumulation of noise, afterpulsing, and statistical variance. Even treating the output pulse as an analog sum of “fired” pixels and digitizing the signal, tens of individual photons can be distinguished (c.f. figure 3). Integration of the device into an ASIC capable of actually sensing the number of pixels that absorbed a photon would take advantage of the digital nature of the signal. This would allow, for example, image reconstruction on IACTs by counting photons with a spatial resolution on the camera plane of a few square millimeters.

4. Conclusion

Traditional vacuum photomultiplier tubes are the “workhorses” of high energy gamma-ray, cosmic-ray, and neutrino astrophysics. While recent technical advances have improved the photon detection efficiency of phototubes by as much as a factor of two, the number of suppliers of research quality PMTs is shrinking and viable new alternatives have recently been developed. We have briefly discussed two of these alternatives: microchannel plate photomultipliers and silicon photomultipliers. MCPs have the potential to be developed into less costly large area photo-detectors for direct dark matter searches and neutrino astronomy. SiPMs with their higher photon detection efficiency, robustness (mechanical and upon exposure to high light levels), and few square millimeter unit size appear to be a possible

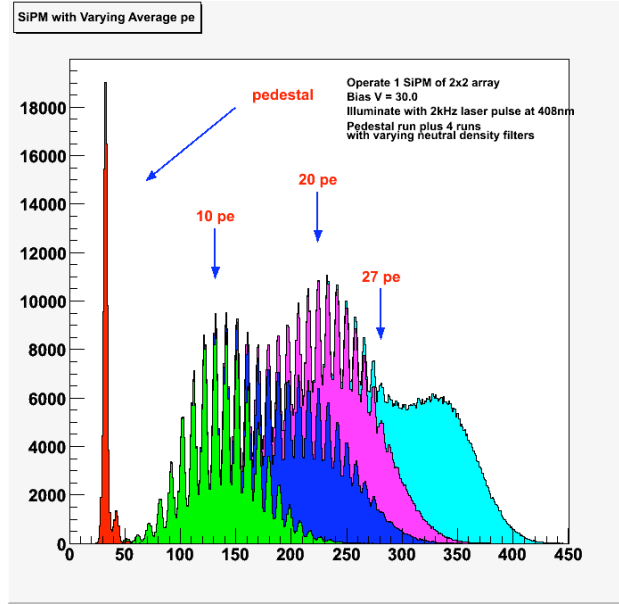


Fig. 3.— Pulse height distribution for a $5 \times 5\text{mm}^2$ SiPM exposed to a 2kHz laser pulse of wavelength 408nm. The distribution is the sum of a pedestal run plus 4 data runs with the average number of incident photons varied using neutral density filters. At least 27 individual photons per pulse firing pixels in the photo-diode array are distinguished. The limit on counting photons in this analog-to-digital manner comes from noise and variance of the pulse height along with resolution limitation of the readout electronics.

alternative for ground-based IACT camera photo-detectors. Both technologies are in need of significant further development to reach their potential. Much work has been done by commercial manufacturers and research groups based mainly in Europe. U.S. universities and national laboratories could play a significant role in developing these technologies to useful next generation photo-detectors for high energy astrophysics. We advocate support for funding this research and development and for supporting groups in the U.S. that are pursuing applied research with MCPs and SiPMs.

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