Photo-Detectors in Astroparticle Physics Experiments

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Outline

- Astroparticle physics
  - Cosmic rays, VHE gamma-rays, neutrinos
- Detection of cosmic rays
- Detection of gamma rays from ground
- G-APDs for Cherenkov telescopes
- Two slides about large hemispherical PMTs
Particle Astrophysics

What are the cosmic accelerators?

Use:

- Cosmic Rays
- Gamma Rays
- Neutrinos

Often one deals with very low fluxes

Need large detector areas/volumes

-> Atmosphere / ice / water

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Air Showers

Use measured air shower characteristics for:
- calorimetry
- particle ID
- tracking

Readout:
- Fluorescence light
- Cherenkov light
- Particles
- Radio

- Not like in a laboratory
- Remote places
- Weather
- Inhomogenous detector medium
- Background (light from the sky)
Light from Air Showers

Cherenkov Light

- Emitted by shower particles
- Continuum emission
- Typically $10^{-3}$ of the energy of the primary
- Directed forward in narrow cone
  * ~1deg opening angle
  * Illuminates 100,000 m$^2$ area on ground
- Used to detect cosmic rays and gamma rays with energies above $E > 10^{10}$ eV

Fluorescence Emission

- Deexcitation of atmospheric nitrogen molecules
- Line spectrum
- Typically $10^{-5}$ of the energy of the primary
- Isotropic emission
  → can be viewed from large distances
- Used to detect particles with energies above $E > 10^{16}$ eV

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Pierre Auger Observatory

Detection of cosmic rays above $10^{16}$ eV

Surface array:
1600 stations
1.5 km spacing

Detects shower particles coming to ground

Fluorescence detectors:
4 telescope enclosures
6 telescopes per enclosure
24 telescopes in total
One 4-fold Event

$E \sim 10^{19} \text{ eV}$
Fluorescence Detectors

- Shower observed from 20-30 km distance
- Shower development takes several 100 μs

Reconstruct:
- Energy from the light yield
- Particle ID from shower maximum
- Arrival direction with stereoscopy and information from surface array

One AUGER fluorescence telescope
Observation of Cosmic Rays from Space

shower parameter:

angular size:
a few degree up to several ten degree
(≈5° for $1^{20}_{20}$eV zenith angle < 75°)

photons arriving at EUSO:
≈550 ph/m² (10$^{20}$eV zenith angle 45° in half of FOV of EUSO optics)

shower duration: ≈100μs…≥300μs

wavelength range: 330nm…400nm

Cherenkov light:
opening angle: ≈1° -> 1km diam. for shower in 10km at 60° zenith angle
photons arriving at EUSO: ≈ 500 ph for albedo of 5%
Gamma-Ray Instruments

- satellites
- Cherenkov telescopes
- water Cherenkov detectors and particle detectors

Gamma-ray energy:
- 1 GeV
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV
Imaging Air Cherenkov Technique

Cherenkov light from an air shower illuminates \( \sim 100,000 \text{ m}^2 \) area

faint and fast bluish flash of light
- 2 photons per m\(^2\) for a 50 GeV gamma ray
- 2-3 ns spread in photon arrival time

Energy threshold limited by:
1. The number of collected Cherenkov photons
   - large mirror surfaces (\( \sim 200 \text{ m}^2 \))
   - high efficiency photon detectors
2. Separation of shower signals from fluctuations in the night sky background
Imaging Technique

Background:
- Charged cosmic rays (hadrons)
- $10^3 \ldots 10^4$ times more abundant

Background rejection:
- Based on shower shape
- Orientation of the image
Observation of Gamma-Rays from Ground

Energy Range: ~100 GeV - ~10 TeV
Energy Resolution: ~15%
Angular Resolution: 0.05° - 0.1°
Sensitivity: 1 Crab in < 30 sec
Field of View: ~4°

80+ sources detected in the last 20 years
VERITAS in Arizona

Now in planning: arrays of ~50 telescopes

MAGIC in the Canaries
H.E.S.S. In Namibia
Use of Photomultiplier in IACTs

Cherenkov telescopes f/D $\geq 1$
  -> large plate scale
  -> large photon sensors 1” diameter

PMT advantages/disadvantages

- Large areas
- Large gain
- Single photoelectron resolution
- Well established technology

- Sensitive to magnetic fields
- Damaged in daylight/sunlight
- Afterpulsing
- Use of high voltage
- Bulky and fragile
- Aging
- Costly
- Average QE $< 20\%$
Cherenkov Light Detection Efficiency

Cherenkov telescopes have an optical throughput of about 10%. The detection efficiency of the photomultipliers is the bottleneck.

Higher throughput means:
- lower threshold
- better energy resolution
- better angular resolution
- better background suppression

With immediate impact on the science:
- deeper into the universe
- many sources have intrinsic cutoffs below 100 GeV
- morphology studies:
  - pulsar wind nebula
  - shell type supernova remnants
  - pair halos around AGN

High efficiency sensors → better physics
The G-APD

a promising photon detector concept invented in Russia in the 80’s available now in large quantities and from many producers

Major advantages:
- High intrinsic QE of a semiconductor
- Geiger mode operation → sensitive to single photons
- Bias voltage < 100 V
- High intrinsic gain
- Is not damaged in daylight
- Mechanical and electrical robust

P. Buzhan et al.
http://www.slac-stanford.edu/pubs/icfa/fall01.html

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Factors limiting the Photon Detection Efficiency

- Geometrical occupancy of the Geiger diodes (aimed at 70%)
- Reflection losses on the SiPM surface (<10% possible)
  - Can be tuned by coating
- $\lambda_{\text{min}}$ determined by thickness of surface implantation
- $\lambda_{\text{max}}$ determined by thickness of active volume
- Classical Quantum efficiency (~100%)
- Breakdown Initiation Probability (~90%)
  - Function of the electric field in the avalanche region

Currently achieved 20-40%
The short List of Requirements

- **Price:** G-APD are presently 5-10 times more expensive than PMTs. We want to be cheaper than PMTs. (not a matter of production costs)

- **PDE 300nm-600nm:** 100% is the limit but we would even be happy with 60% in the blue. It seems possible in the future. **Biggest challenges**

- **Size:** 5x5 mm$^2$ to 10x10 mm$^2$

- **Dark count rate:** < 100 kHz/mm$^2$ needed
  - Thermal generated Charge carriers, afterpulsing, optical crosstalk achieved by some devices at room temperature otherwise moderate cooling necessary

- **Temperature Dependence of Gain:** varies between ~5%/K and 0.3%/K; 0.3%/K is ok
  - Requires large breakdown voltages, small cell capacitances, high overvoltages

- **Optical Crosstalk:** can be several 10% needed are less than a few %
  - Trenches between cells → now pursued by most producers

**Suitable G-APD become available now**

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Test on La Palma with MAGIC

MPPC-33-050C from Hamamatsu:
- Sensor size: 3x3mm²
- Single APD size: 50x50µm²
- Nominal bias: 70.4V
- Dark rate at nominal bias: ~2MHz
- Gain at nominal bias: $7.5 \times 10^5$
- Crosstalk at nominal bias: 10%

Array of 4 MPPCs:
- Light catchers with factor 4 concentration; 6x6mm² to 3x3mm²

One bias for all MPPCs

A big promise
Array mounted next to the MAGIC camera for 3 nights for fine tuning and tests

G-APDs signals recorded by the MAGIC DAQ for each trigger

- Array not removed or protected during day
- It was raining for one day; no problem!

Dark rate at night ~ 20 MHz
10 times higher than intrinsic dark rate of MPPC
Recording Photons from Air Showers with G-APD

4 G-APDs in the focal plane of MAGIC

One recorded event:

G-APD signals

Signals of surrounding PMTs
Shower Signals: MPPC vs PMT

event selection:
- two PMTs next to MPPCs with more than 15 photoelectrons in each tube

~300 events from ~30 min data

On average the MPPC records 1.6 times more photons
A Prototype G-APD Camera

Tests planned with one of the former HEGRA telescopes (CT3) this summer

A test module of a G-APD camera built at ETH

Thanks to I. Braun (ETH) for providing picture and info about DWARF/FACT
More Camera Developments

For EUSO and Cherenkov telescopes

Hiroko Miyamoto
MPI for Physics, Munich
Neutrino Detectors

TeV telescopes:
ICECube/Antares/Nestor,Baikal,Dumond ...

MeV detectors
Frejus, Macro, IMB,Kamioka,SuperK/SNO ....

Use all large surface PMTs
Large Spherical PMT

Used in:
- Surface Cherenkov detectors:
  Auger SD, ICE top
- Neutrino detectors:
  ICEcube, ANTARES, Baikal, ...
Hemispherical Light Amplifier

- Bombard fast scintillation crystal with photoelectron
- Readout scintillation light with G-APD

Vacuum Silicon Photomultiplier

Direct detection of 10kV photoelectron
With MPPC

See http://tipp09.kek.jp/
Summary

- There is big need for high efficiency photo-detectors in astroparticle experiments
- All diameters between a few mm to several 10 cm
- All application have in common
  - Low photon intensities in mostly large backgrounds
  - Blue sensitivity 300-400 (600) nm
  - Single pe resolution
- Currently used by all experiments: the classical PMT
- The G-APD is a promising photo detector
  - Some applicable G-APDs exist
  - We want more
    - Lower prices
    - Higher photon detection efficiencies
Backup
Schwarzschild-Couder Telescope

Present AGIS base line

Advantage:
- Small plate scale
  0.05 deg → 5mm
- No need for large photon detectors

Primary mirror: 76 ~ 1m² panels
Secondary mirror: 35 ~ 1m² panels
Total: 111 segments

Primary diameter: 11.5 m
Central hole: 5.63 m
Secondary diameter: 6.6 m
Focal plane distance: 25 m (from SM)
Field of View: 8 degrees
Camera diameter: 90 cm

Replication technology (electroforming, glass slumping, Carbon/Graphite Fiber Reinforced Plastic) can be used to reduce costs of manufacturing of aspheric mirrors

Effective light collecting area: ~70 m²
Total mirror area: ~100 m²
PSF less than: 3 arcmin (within FoV)
Future Plans

Large arrays of Cherenkov telescopes (~50)
Extending energy range to lower and higher energies

Two ongoing initiatives:
AGIS in the US
CTA in Europe

AGIS:
• $120 million project
• Array of ~ 50 telescopes
• Schwarzschild Couder telescopes
  • 8° FoV
  • Camera with 15 000 pixel
  • Pixel size: 3x3 – 5x5 mm²

Cherenkov photon density on ground for a 50 GeV gamma ray
Blue and Green sensitive Devices

Astroparticle experiments need Blue sensitive devices

Blue light is absorbed within the first few 100 nm

→ thin entrance windows

Electrons have a higher probability of starting an avalanche

→ Need p-on-n structure for blue sensitivity

Or new concepts e.g. back side illumination

Pursued by the HLL/MPI for Physics

D. Renker, E. Lorenz, JINST 4 )2009)
Temperature Dependence

Temperature dependence of parameters increases systematic uncertainties
- energy estimation
- flux measurements

Solutions:
- Compensate with external thermistor
- Thermal control (~1 degree)
- Do a good job producing devices
  * Low breakdown voltages
  * Low cell capacitances
  * High overvoltage

\[ DG = \text{Tempcoef} \times \text{BrkdwVoltage} / \text{DOvervoltage} \]

A good device
Dark Counts

Needs to be below the photon background from the night sky

G-APD are noisy devices:
- 100 kHz – 1 MHz per mm²

Rate depends on many parameters

Mostly thermal generated e/h-pairs
Additional effects:
- Afterpulsing
- Tunneling

In astroparticle physics: needs to be lower than photon background rate

Rates of 100 kHz/mm² should do

Affects lower energies
- Trigger: increase in accidental triggers
- Analysis: noise in shower images
Optical Crosstalk

Avalanches emit photons
~1 photon per $10^5$ e/h-pairs

Causes additional cells to fire -> pile up

Non-negligible probability that 5 or more cells fire
Increase of accidental triggers in IACT
-> higher energy threshold

Probability needs to be ~1% not to be dominating the rate of accidental triggers

Most promising solution: trenches between cells

Example from ST Microelectronics

IEEE PTL, VOL. 18, NO. 15, 2006
Future Plans in VHE Astrophysics

Goals:
- 10x improved sensitivity
- Extended energy range

Require:
- Large arrays of Cherenkov Tel.
- Telescopes with larger FoV
- Novel trigger concepts
- Higher detection efficiency for Cherenkov light

European initiative:
CTA

US initiative:
AGIS

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SiPM requirements (Dynamic Range)

γ – Characteristics

arrival time window: 1ns...3ns

angular size: 0.1°...~1°

photon yield: ≈100 ph/m² (1TeV γ)

wavelength range: 300nm...600nm

effective dynamic range per camera pixel <10⁴ phe

SiPM cell sizes of 100µm x 100µm are just at the limit

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SiPM requirements (dark rate)

Night Sky Background (photons) per MAGIC Camera Pixel:
10^9 Hz

2 \times 10^6 Hz NSB per mm² in the camera pixel

10^5 Hz/mm² intrinsic dark rate is the baseline

50% PDE
and
Intrinsic Dark rate = 10% NSB

10^5 Hz dark rate is possible at room temperature with available prototype SiPMs
SiPM requirements (optical crosstalk)

In avalanche produced photons cause inter SiPM pixel crosstalk
→ Overestimation of the signal
→ Influences signal shape studies for g/h separation

Crosstalk is proportional to charge generated in breakdown

Solutions:
• Trenches between SiPM pixels
• lower Gain
  → lower electric field → lower breakdown probability → lower PDE
• Modelling
  → simulations can fit crosstalk measurements over a wide range of parameters (Temperature of hot electrons; photon emission efficiency)
A crosstalk probability of a few percent can be corrected for by simulations
Trenches to suppress crosstalk

without trenches (Gain $3 \times 10^6$)

with trenches (Gain $3 \times 10^7$)

done by MEPhI
Fast and slow Crosstalk Component

1: picoseconds (conversion and immediate breakdown)
2: ~1nsec (conversion, phe drift and breakdown)
3: ~10-100nsec (conversion; diffusion; drift and breakdown)

Component three contributes to afterpulsing (dark rate) in addition to trapped electrons in the avalanche region
Application of SiPMs in IACTs

SiPM sizes of 5x5 mm² require interconnection of several SiPM to one camera pixel with one common signal readout

R&D necessary on:

Photon concentrators:
  to overcome dead space between SiPMs

Electronic readout:
  low power consumption
  ultra high bandwidth
  summing amplifier

Cooling:
  thermal isolation
Signal Readout

- 1 GHz broadband buffer/preamplifier after each SiPM
- all SiPMs (4) of one camera pixel connected to summing amplifier
- good HF layout mandatory
- ASIC is not fast enough

Fast transimpedance amplifier → currently developed at MPI
Photon Concentrators

1. Lightguide made out of Plexiglas

2. Winston Cones

+ Additional µ-lens array on top of each SiPM

Light concentrators needed to reduce dead area between SiPMs
Cooling

- Moderate Cooling (-20 °C) needed to reduce dark noise rate below NSB
- Might not be necessary with new SiPMs
- Double glazed Camera entrance window
  - Gas with low thermal conductivity SF₆ or Ar
## Comparison G-APD / PMT

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<td>Average QE &lt;20%, possible &gt; 50%</td>
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PDE dependence on the Bias Voltage

![Graph: Photon Detection Efficiency SensL PSS080218 470 nm]

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