Development of New Photosensors for Huge Detectors

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Work supported by National Nuclear Security Administration (NNSA), Office of Nonproliferation Research and Engineering, DOE
Very rare and/or weak phenomena

- Proton Decay
- Neutrino Physics
- Geo-neutrino Physics
- Neutrino Astrophysics
- Gamma-ray Astronomy
  (low detection threshold + wide acceptance angle)
- Ultra-high energy cosmic rays (>10^{19} eV)
- Neutrinoless Double Beta Decay
- WIMP Searches
Sensitivity for the detection of very rare phenomena

Very Large Volumes/Areas

“Natural” Transparent Media (Water, Atmosphere, Ice, +GdCl, scint.)

PHOTOSENSORS

No other choice than
Cherenkov angle in water
\(~40\) degrees

Full angular coverage

→ “Camera” surrounds the detector volume
Irreducibly Large Illuminated Area

strong internal signal concentration from the photocathode to the dynode column

Vacuum

( photon $\rightarrow$ photoelectron )
A Water Cherenkov Detector optimized for:
- Light attenuation length limit
- PMT pressure limit
- Cost (built-in staging)

UNO Collaboration
99 Physicists
40 Institutions
7 Countries

UNO Detector Conceptual Design

Only optical separation

60x60x60 m^3 x 3
Total Vol: 650 kton
Fid. Vol: 440 kton (20xSuperK)
# of 20" PMTs: 56,000
# of 8" PMTs: 14,900

NNN05-Aussola, April 2005
“From a very strong field, the
• Homestake Mine (SD), and the
• Henderson Mine (CO)
stood out as by far the most promising prospects for further consideration.

The conceptual designs the teams associated with these sites will develop will lead to more detailed plans associated with a down-select to a single site in the third stage of the community-based planning process.”
Large water projects in Colorado ~75 million years ago

The Stalker
Slinking up to a school of Apsopellic, Thalassomedon uses its 20-foot neck—half its body length—to hide its bulk in the dim waters behind. This is the classic Loch Ness monster form. Within a group called plesiosaurs, Thalassomedon was built for stealth rather than speed. It carried stones in its stomach for ballast and to aid with digestion. Four flippers, each the size of a human, let Thalassomedon glide through the water.
CERN ~250 million years ago

Swimmers
Hatchling nothosaurs head for the safety of water as a hungry but terrestrial Ticinosuchus shows up near a lagoon in ancient Switzerland. Nothosaurs were among the earliest reptiles to take to the sea and were closely related to plesiosaurs. Because nothosaurs may have had to come ashore to lay eggs, the eggs and hatchlings would have been vulnerable to Ticinosuchus. Yet once the hatchlings reached deeper water, they were safe—for the moment.

MONSTER FACTS:
WHAT NOTHOSAURS CIRCUMNAVIGATE: WHEN 250 MILLION YEARS AGO WHERE EUROPE

Art by Jerry Auer
Frejus (near CERN) - MEMPHIS

Present Tunnel

Future Safety Tunnel

Present Laboratory

Future Laboratory with Water Cerenkov Detectors
Hyper-Kamiokande
OUR GOAL

To introduce a new Technology for

Industrial Mass-Production

of large photosensor areas

based on modified existing technologies

(e.g. the assembly of modern, plasma and field-emission flat-panel TV screens; low production cost ~$1000 per sq. meter)

+ ‘REAL’ (non-physics) MARKETS
SEARCHING FOR RARE AND/OR WEAK RADIATION SOURCES

PARTICLE ASTROPHYSICS
(new generation of experiments)

NUCLEAR SECURITY
(nonproliferation)

MEDICAL IMAGING
WIDELY ACCESSIBLE
MEDICAL DIAGNOSTICS
Industrial Mass-Production of Very-large-area cameras
GOOD MARKETS for MASS PRODUCTION?

- PARTICLE ASTROPHYSICS (new generation of experiments)
- NUCLEAR SECURITY (nonproliferation)
- MEDICAL IMAGING
  - WIDELY ACCESSIBLE
  - MEDICAL DIAGNOSTICS
  - Industrial Mass-Production of Very-large-area cameras

REAL MARKETS (STEADY and LARGE)
“If you have a good idea today, you are likely to require many committees, many years and many people to get the project from concept to observation. The situation was very different in 1964…

*Neither of us remember a formal proposal ever being written to a funding agency.*”

Ray Davis Jr. and John Bahcall, CERN Courier July/August 2000
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OUR REALITY:

1. Invent a new technology
2. Patent protect
3. Get a grant
4. Find a real MARKET
5. Find venture capital
6. Form a startup company
Several Unconventional Photosensors

UC Davis (D.F. and Eckart Lorenz)
• Flat-Panel ReFerence Camera Concept (Patented)
• Light Amplifier - general concept
  – ReFerence panels → scintillator (fiber) readout
  – Hemispherical - QUASAR or SMART PMT in a modified configuration
    + Geiger-mode APDs
• “SIMPLE” Space Imaging Camera Concept for EUSO, OWL, but also ground-based applications (Patented)

Weizmann Institute, Israel (Amos Breksin, Rachel Chechik)
• Gaseous panels

CERN (Braem, Joram)
• ‘More-classical’ HPDs
Semiconductor Photosensors

→ developed very successfully
(but pixel sizes and areas - too small)

Vacuum Photosensors

(suitable for large-area applications, strong area reduction) did not develop significantly since mid-1960s

Why?

Because of the Vacuum?
Development of Other Vacuum Devices

~1960

~2000

Production Cost ‘05 < $1,000/m²
ENCLOSURE: FLAT-PANEL TV

3 existing mass-production technologies

PHOTON $\rightarrow$ ELECTRON
CONVERSION:
CLASSICAL PHOTOCATHODE

ELECTRON DETECTION:
SEMICONDUCTOR
Geiger-MODE
AVALANCHE DIODE
Ideal Light Concentrator
(takes the maximum of Liouville!)

Photoelectrons

Photon

PIN, APD, or SCINTILLATOR

Optimal Electron Lens

Photocathode
Very Important: Hexagonal Packing

Entrance Aperture

Photocathode
Flat-Panel Honeycomb Sandwich Camera Construction

Industrial Production (no glass blowing etc.)
Intrinsic Mechanical Stability, Low Buoyancy,..
PROTOTYPE DEVELOPMENT

UNSEALED 1-PIXEL
- CYLINDRIC 2001-2002
- HEXAGONAL 2003

SEALED PANELS (7 pixels, 5 inch)
- SEALED with In/Au/Cr
- SEALED with SOLDER GLASS

Equipment (Candescent, Litton Night Vision) ~$2M
Strong signal concentration, factor $\sim 1500$

(one of our goals)

Replaces the entire Dynode Column!
Provides $\sim 100\%$ Collection Efficiency!

- APD
- Scintillator + Fiber (both of small and comparable diameter $\Rightarrow$ good coupling efficiency)
Reference Panel Prototype (under construction)
UHV Transfer System:

• Photocathode deposition
• Indium/Au/Cr deposition
• Vacuum sealing
The vacuum sealing process
Light Amplifier Concept

Scintillators + fiber optics

NO electronics in the vacuum

Resolution determined outside!!

READOUT ➔

APD array
Light Amplifier Concept

- Scintillators + fiber optics
- Resolution determined outside!!
- No electronics in the vacuum

LIGHT IN – LIGHT OUT

APD array

Resolution determined outside!!
SMART PMT, QUASAR

photocathode

Benthos sphere
16" i.d.

R = 170 mm

phosphor
scintillating layer

power supply
photomultiplier
Hemispherical LIGHT AMPLIFIER

Fiber Plate

Scintillator Y2SiO5(Ce)

Al (100 nm)

Geiger-mode APD array

SMART PMT, QUASAR

1 photoelectron $\rightarrow$ >15 photons in APD
SMART PMT, QUASAR

CURRENT SETUP

SINGLE Geiger-mode APD, 1x1 mm²

No face-plate → low light Collection Efficiency ~1:150

Pulsed LED+fiber

SMART PMT, QUASAR
Geiger-mode APD
ZS-2 from Sadygov, MICRON

57.4 V power

Pulsed LED+fiber

Coax signal

EXTREMELY SIMPLE!
A Typical Single-Photon Signal in the Geiger-mode APD

1 photo-electron → 200 mV
Superposition of many light pulses in the Geiger-mode APD (full bandwidth)

Note the individual photon structure and decay spectrum of the scintillator
Rotating Light Source (LED)

Image @ Scintillator

IMAGING (even without fiber coupling)
Gaseuos Photomultipliers – GPM

A. Breskin et al.
Weizmann Institute

GEM- and THGEM-based gaseous photomultipliers
Multi-GEM GPM

**Semitransparent Photocathode**

- high 2D precision [0.1-0.2 mm]
- high gain [>10^5] → single photon sensitivity!
- fast signals [ns] → good timing

**Reflective Photocathode**

A. Buzulutskov et al. NIM A 443 (2000)164  
D. Mörmann et al. NIM A 478 (2002) 230
GPM for visible light

Sealed detector package with semitransparent K-Cs-Sb PC

Sealing in gas: In/Sn; 130-150°C

13% = best QE measured after sealing. 2 weeks stability

Best sealed GPMT: stable for 1 month

Wavelength [nm]

300 400 500 600

Q E %

5 10 15

under development:
Silicon (with Glasgow Univ.), ceramic
Expected higher stability

D. Mörmann et al. NIM A504 (2003) 93
M. Balcerzyk et al. IEEE TNS 50 (2003) 847
A VERY FLAT GASEOUS IMAGING PM

~10mm

readout
photocathode

THGEM

100x100mm2 THGEM With 2D delay-line readout

φ 0.3mm holes
CONCLUSIONS

• Photosensors are key element for many future projects

• New low-cost photosensors produced in large quantities may revolutionize the field

• Industrial mass-production \(\rightarrow\) MARKET

• New concepts:
  • Flat-Panel: vacuum or gas
  • Hemispherical (still requires too much handwork)
  • Light Amplifier based on Geiger-APDs (in general)
Silicon photomultiplier (SiPM)

SiPM main features:
- Sensitive size 1x1mm² on chip 1.5x1.5 mm²
- Gain $2 \times 10^6$
- $U_{bias}$ ~ 50V
- Recovery time ~ 100 ns/pixel
- Number of pixels: 576
- Nuclear counter effect: negligible (due to Geiger mode)
- Insensitive to magnetic field
- Dynamic range ~ $10^3$/mm²

For further details see:
“Advanced study of SiPM”
http://www.slac.stanford.edu/pubs/icfa/fall01.html

B. Dolgoshein  “SiPM possible applications”

Single photoelectron (single pixel) spectra

SiPM:
• excellent single photoelectron resolution
• low ENF expected

More about pixel signal resolution: tens of photoelectrons

• SiPM consists of a large number of pixel photoelectron counters with binary readout for each pixel, working as analogue device
• signal uniformity from pixel to pixel is quite good
ZS-2 from Sadygov, MICRON

1 photo-electron $\rightarrow$ 200 mV
Superposition of many light pulses in the Geiger-mode APD

(signal integrated)

~5 photo-electrons $\rightarrow$ 1 V
“Light Amplifier” Concept

Scintillators + fiber optics

NO electronics inside!!

Resolution determined outside!!

READOUT ➔ APD array
Spherical LIGHT AMPLIFIER

Fiber Plate

scintillator

Al (100 nm)

Geiger-mode APD array

1 photoelectron → >15 photons in APD

SMART PMT, QUASAR
Base pressure ~6x10^{-11} Torr

Evaporation Chamber
Sealing Chamber
Load-lock Chamber
TRANSFER SYSTEM
For 5” prototypes
Cs, Na, K dispensers
Probability for an Electron to Reach the Vacuum Surface (Random Walk)

Therefore: 

QE ~ 10-20%
Photon Absorption (Electron Creation)

Probability for an Electron to Reach the Vacuum Surface (Random Walk)

(e.g. Substrate, Reflector, ...)

LOW PRODUCTION COST!
UV Photon Absorption (Electron Creation) Mostly @ Surface

Probability for an Electron to Reach the Vacuum Surface (Random Walk)

Thin Photocathode on a Reflector, Interference Multi-layer Systems

Vacuum

UV Photon

Photo-Electron

Photocathode

Westinghouse, RCA, ITT ~1963-1975
Reflection Mode vs. Transmission Mode

Extension into “blue & UV”

~30-43 % QE bialkali
~190-450 nm
(Hamamatsu side-on PMT R7517)
HAMAMATSU
PRELIMINARY DATA
NOV. 1998

PHOTOMULTIPLIER TUBE
R7517

High Q.E., Bialkali Photocathode
28mm (1-1/8 Inch) Diameter, 9-Stage, Side-On Type

FEATURES
● Spectral Response.......................................................... 185 to 760 nm
● High Cathode Sensitivity
  Luminous ................................................................. 160 µA/Im Typ.
  Radiant at 420nm ...................................................... 105 mA/W Typ.
  Quantum Efficiency at 220nm ....................................... 40% Typ.
● High Anode Sensitivity (at 1000V)
  Luminous ................................................................. 1600A/Im Typ.
  Radiant at 420nm ...................................................... $10.5 \times 10^5$ A/W Typ.

APPLICATIONS
● Fluorescence Spectrophotometers
● Fluorescence Immuno Assay
● SO$_2$ Monitor (UV Fluorescence)
TransReference

Single-Photon Color Sensitivity

[Diagram showing photons and PC 1, PC 2, PC 3 with spectral coverage and wavelength axes]
TransReFerence

Single-Photon Color Sensitivity

Transmission-Reflection
(and also light trap)
Single-Photon Resolution

Number of Detected Photons

- APD
- PMT
- HPD

TransReference

Reference
Photocathode Cooling - Diminished Dark Current

Thermionic emission [e/sec/cm²]

-20°  0°  20°  40°

Carlsbad NM

Cooling (Peltier)

InGaAs

S20

WATER
VERY EFFICIENT MAGNETIC SHIELDING

Slow electrons

e.g. UNO with Magnetic Field (???)