Peculiarities of the Hamamatsu R11410-20 photomultiplier tubes

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Outline

• R11410-20 use in the RED100 detector;
• Systematic characteristics of 34 samples;
• Photon emission problem;
• Particle detection with the PMT’s window medium.
1. RED100: search for coherent elastic neutrino scattering off Xe nuclei

- A two-phase emission detector;
- \(\sim 250\) kg of Xe, \(\sim 100\) kg in fiducial volume (“wall-less”);
- Sensitivity to \(\sim 1\) keV recoil energies;
- \(38\) (32) Hamamatsu R11410-20 low-background PMTs;
- To be exposed at Spallation Neutron (Neutrino) Source, Oak Ridge National Laboratory, USA;
- On its final stage of assembling at MEPhl.

For more details: D. Akimov et al 2013 JINST 8 P10023
R11410-20 in RED100

- Two arrays (top and bottom) 19 PMTs each;
- All PMTs positively biased;
- Individual signal and HV cables (combined) for each PMT;
- Cirlex® based PMT voltage dividers, total resistance - 18.5 MΩ
Why R11410-20?

- Low background (~10 mBq/PMT);
- Operational temperature: -110..50 °C;
- Excellent single photoelectron resolution;
- Large window (64 mm photocathode diameter);
- High QE (around 30%) at 178 nm (Xe scintillation wavelength).
Titanium cryostat: designed and manufactured in Russia

Recent photos

Copper/PTFE internal structure in the middle of assembling process at MEPhI

Titanium cryostat: designed and manufactured in Russia
2. R11410-20 systematic characterization procedure and results

- All PMTs tested at room temperature:
  - gain;
  - single photoelectron response;
  - dark count rate as a function of bias voltage;
  - afterpulses time spectra, etc;

- Selective test of dark count vs temperature dependencies (down to -60 °C).
Gain matching: single photoelectron amplitude dependencies on bias voltage
Dark count rate vs bias voltage (room temperature)
3. Light emission assumption check

Measuring dark count rate of KB0019 and KB0054 PMTs vs KB0054 bias voltage (yes, seems strange).

Decoupled windows - constant dependence for #019 and strong increase for #054 (as it should be).

When PMTs viewed by each other, “dark” rate of both of them highly depends on #054 rate.

No reverse influence observed => could be explained by photoemission nature of the KB0054 PMT dark pulses.
Converting it to a single plot: 2d dependence of #054 dark count rate on #19 rate

Important to note: both PMTs show purely single photoelectron dark pulses spectrum => if light emission happens, it will be undetectable with a coincidence detection scheme.
Dark count temperature dependence

Dark rate drops exponentially with temperature (down to -60°C) for one out of four separately measured PMTs.

No stable dark count decrease for three other PMTs – dark count at -60°C could be even higher, than at room t°.
The PandaX experiment data on the same type of PMTs (Hamamatsu R11410-...) operated in cryogenic Xenon conditions shows high and unstable dark (or nearly dark) count rates.

![Diagram showing dark rate of bottom PMTs]

taken from:

arXiv:1405.2882
Indication of light emission happening after cool down

Dark rate for #019 PMT increases abruptly at low temperatures - could be detected by an adjacent PMT placed “face to face”.

Here both PMTs are noisy when switched on simultaneously, but only one (#019) is noisy while the adjacent PMT is off.

The adjacent #021 PMT hasn’t shown any distinguishable signs of light emission down to -60°C (thermal chamber limit).

Possible light emission nature

Hamamatsu already announced some information on faint light emission from the ceramic stem of a similar PMT occurring at low temperatures (around -180°C).\(^1\)

Possible reasons for light emission in warm conditions:

- **Bremsstrahlung from the dynodes**
  Predictable and even directly shown [arXiv:1307.5463]. In a conventional PMT such light could be blocked by internal ceramic insulation - in R11410-20 the insulation is made from transparent quartz (radiopurity reasons).

- **Excess admixture metals at the insulators or the support structure**
  The structure could consist of corundum (Al\(_2\)O\(_3\)) with Si and Cr admixtures. Al\(_2\)O\(_3\) + Cr could become ruby with strong **fluorescence of ~700 nm lines** (learned from internal communication with the manufacturer; observed for other type of PMT).

4. Cherenkov light detection in the volume of R11410-20 window

The PMT is equipped with a 3.5 mm thick synthetic silica (quartz) window, which is an excellent Cherenkov radiator.

Moreover, the PMT has ~30% Q.E. in VUV..blue regions, where Cherenkov light intensity behaves as $1/\lambda$ => huge benefit in UV region, where R11410-20 has ~30% Q.E typ.

(plot from the Hamamatsu photomultiplier handbook)
Atmospheric muons’ light yield in R11410-20 window

Fewer photoelectron signals should be detected while facing downwards in case of atmospheric muon nature:

Schematic view of the experimental setup: a plastic scintillator “cup” viewed by an additional XP2020 PMT
R11410-20 faced upwards:

85 ph.e. typ. muon light yield (~250 ph.e./cm)

R11410-20 faced downwards:

35 ph.e. typ. muon light yield
511 keV gammas detection in R11410-20 window

![Graph of photoelectrons vs. amplitude with data points for different detector configurations: R11410 (3.5 mm quartz) with 1.0% efficiency, R11410 (3.5 mm quartz) with 2 cm extra quartz and 1.6% efficiency, and R11410 (3.5 mm quartz) with lead shielding.]
Summary

• Hamamatsu R11410-20 is a noteworthy PMT with extraordinary good radio purity characteristics and single photon detection capabilities;

• Evidences of single photon emission by R11410-20 internal structure occurring at room and reduced temperatures are observed in several pieces;

• Light emission nature is not clearly understood, but certain hints (connected with R11410-20 specific construction features) are presented – the study would be continued;

• The effect should be (and is being) taken into account while planning tremendous dark matter experiments (e.g. LZ¹) utilizing hundreds of R11410-.. PMTs;

• R11410-20 could be used as a standalone Cherenkov detector due to its thick quartz window and high Q.E. at VUV region;

• We hope that the described above unusual PMT features would not be an insurmountable obstacle for the RED100 detector effective operation.

For more details: arXiv:1110.0103
Thank you for your attention!
Back up
Detected Cherenkov vs Full spectrum in Fused Quartz

Quartz


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Additional PMT

Nal(Tl)

\[ \gamma, 0.511 \text{ keV} \]

Hamamatsu R11410-20

\[ \gamma, 1.3 \text{ MeV} \]

\[ ^{44}\text{Ti} \]

\[ \sim 0.5 \text{ mm Cu envelope} \]

Additional PMT

\[ \gamma, 0.511 \text{ keV} \]

\[ ^{44}\text{Ti} \text{ spectrum} \]

Counts

\[ 0.511 \text{ keV} \]

\[ 1.2 \text{ MeV} \]

\[ 1.5 \text{ MeV} \]

ADC channels
Light insulation with factory-supplied black plastic PMT window coverings

x3 increase

Robust light insulation

no increase

thr=1/3 A(sphe), both for KB0019 and KB0054 (individual for each voltage value), room temperature.
Signs of ruby luminescence in Hamamatsu R11920-100 shown in MPI Tech Report “Afterpulses in the R11920-100”,

Max Ludwig Knötig

April 2012

The dark count rate values were measured under the threshold of \( \sim \frac{1}{3} \) \( A_{\text{sphe}} \)

Internal noises spectrum for KB0051, \( U_b=1750 \) V
The afterpulses time spectrum

\[ \tau = l \sqrt{\frac{2m}{qU}} \]

time an ion drifts to the photocathode

On the next slide – a set of afterpulses time spectra measured during five subsequent minutes each, with the same PMT →
~200 pC of charge was taken from the photocathode after an hour of the PMT’s operation (the last shot)
KB0580, $U_b=1600$ V, 90-100 min.

Apparently, other type of afterpulses in the different time frames (but extremely low rate)
KB0019, $U_b = 1750$ V, x4 ampl
To prevent the atmospheric helium penetration into the PMT’s volume, all devices are stored in a sealed metallic box, which is purged by gaseous nitrogen, which comes from the vapor above liquid nitrogen, stored in a Dewar vessel.
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Dark rate values distribution over 34 PMTs (special bias voltages for equal gain)