B.K. Lubsandorzhiev, R.V. Vasiliev, Y.E. Vyatchin.

Photoelectron backscattering in vacuum phototubes
• 2005 - 75th Anniversary of Photomultiplier invention.

• L.A. Kubetsky 1930.
Kubetsky’s tube

L.A. Kubetsky (1906-1959)
First photomultiplier - Kubetsky’s tube

- Multistage
- $10^3$-$10^4$ Gain
• With history of 75 years Photomultiplier is still: “Photomultiplier is “a thing in itself””

A.Y.Chudakov
• Vacuum phototubes deal with an amplitude and time spectroscopy of photoelectrons.

• Spectroscopy of slow electrons is a very complicated issue still.

• Phototube response is smeared by photoelectron backscattering
Electron backscattering

- Left - dependence of electron backscattering on electron energy
- Right - energy distribution of inelastically backscattered electrons
- Stehberger 1928, McKay 1948, Sternglass 1954, Shulman et al 1958
- Bronshtein and Fraiman 1969, Shulman and Fridrikhov 1977
- $\eta \sim 40-50\%$!
Energy spectrum of secondary electrons

- I - Genuine secondary electrons,
- II - intermediate - inelastically backscattered electrons
- III - elastically backscattered electrons
Late events in vacuum photodetectors

- Bezrukov, Lubsandorzhiev 1983. We called them «задержанные импульсы» (delayed pulses)
- Taplin 1993 («Late events»)
- There are very rich data on backscattering in HPD (D’Ambrosio and Leutz 2003 for all references)
Backscattering in classical PMTs

- EMI9350
- 20 cm hemispherical PMT

Lubsandorzhiev et al. Proc. of 2nd Beaune Conf.
Peak in late events time distribution are not due to photoelectron backscattering?

Due to «anode afterglow»?

So in this case the peak should coincide with doubled electron transit time of PMT
Transit time distributions of ET9116B and 9117B

- ET9116B, ET9117B - fast, 6 stages PMTs with hemispherical photocathodes, 3 and 5 cm in diameter
Transit time distributions of EMI9083 and XP2982

EMI9083 is 1.5 cm fast PMT with SbCs$_3$ first dynode
XP2982 is 3 cm fast PMT with CuBe first dynode

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Transit time distributions of FEU-130 and FEU-143

FEU-130 and FEU-143 - PMTs with high gain GaP first dynode

FEU-130 - slow 3 cm PMT, FEU-143 - fast 5 cm PMT

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Transit time distributions of FEU-Baikal-1 and XP2020

- FEU-«Baikal-1» - no prepulses, AlMg alloy first dynode.
- Left - XP2020, CuBe first dynode.

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### $K_{\text{late}}$ - probability of late events

**Too low?**

**SbCs emitters have $\eta \sim 40\text{-}50\%$.**

**Where are backscattered electrons?**

<table>
<thead>
<tr>
<th>PMT</th>
<th>$1^{\text{st}}$ dynode material</th>
<th>$\sigma$</th>
<th>$Z_{\text{eff}}$</th>
<th>$K_{\text{late, %}}$</th>
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</thead>
<tbody>
<tr>
<td>EMI9083B</td>
<td>SbCs$_3$</td>
<td>6-10</td>
<td>54</td>
<td>2</td>
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<tr>
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<td>SbCs$_3$</td>
<td>6-10</td>
<td>54</td>
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<tr>
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<tr>
<td>EMI9350</td>
<td>SbCs$_3$</td>
<td>6-10</td>
<td>54</td>
<td>4-5</td>
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<tr>
<td>R1463</td>
<td>NaKCsSb</td>
<td>4-6</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>XP2020</td>
<td>CuBe</td>
<td>5</td>
<td>28</td>
<td>2</td>
</tr>
<tr>
<td>XP2982</td>
<td>CuBe</td>
<td>5</td>
<td>28</td>
<td>1</td>
</tr>
<tr>
<td>FEU-143-1</td>
<td>GaP</td>
<td>20</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>FEU-130</td>
<td>GaP</td>
<td>20</td>
<td>29</td>
<td>1</td>
</tr>
<tr>
<td>FEU-“Baikal-1”</td>
<td>AlMg</td>
<td>3</td>
<td>12.5</td>
<td>1</td>
</tr>
</tbody>
</table>

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Anode afterglow

• Spectrum of anode afterglow - predominantly in visible region
• (Vetokhin et al.)

EMI9350 anode afterglow kinetics
Late pulses dependence on PMT’s HV power supply

- Two independent HV power supplies are used to fix $U_{c-1d}$
$U_{c-1d}$ is fixed, $U_{c-a}$ is adjusted

- FEU-143-1
- black points - time interval between prepulses and main peaks
- white points - time interval between main and late pulses peaks
- peak of late pulses is not due to anode afterglow.
Transit time distributions of EMI9350 under different thresholds

- a) - h)
- 0.05 - 0.5 p.e.
Transit time distributions for other types of vacuum photodetectors

- R5900
- $K_{\text{late}} \sim 1-2\%$
- R3809U, $K_{\text{late}} < 1\%$
- courtesy of Becker-Hickl (www.becker-hickl.com)
Backscattered photoelectrons in HPD

- Multiphotoelectron charge spectrum with and without backscattering (simulated) (C.D’Ambrosio and H.Leutz, 2000)
QUASAR-370

- Hybrid phototube with luminescent screen.
- Best tubes have 1 ns (FWHM!) time resolution and 40% single electron resolution
QUASAR-370 SER

• M3 - single photoelectron peak of QUASAR-370
• M2 - single photoelectron peak of small PMT - FEU «Baikal-1»
Time response of QUASAR-370

- Left - transit time distribution, no prepulses and late pulses!
- Right - anode signal waveform

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Dependence of elastic scattering on energy

- $r$ - probability of elastic backscattering

(Shulman A.R., S.A.Fridrikhov)
Studies of R1463 with low threshold

- Threshold - \( \sim 0.005 \) p.e.!
- Green - spectra measured with cathode camera switched off, i.e. cathode and 1 dynode are short circuited
R1463

- Single photoelectron charge spectrum after subtraction of prepulses spectrum
- effect of backscattering is low
Where are backscattered photoelectrons?
Mechanism of secondary electron emission

- The most part of secondary electrons are produced not by forward electron flux but by backward electron flux, i.e. by backscattered electrons. (Bronshtein I.M, Fraiman B.C.)
δ-η plot

- δ - secondary emission coefficient (genuine)
- η - electron inelastic backscattering coefficient
Conclusions

• Photoelectron backscattering is general phenomenon for practically all kinds of vacuum photodetectors.

• Very likely there are no contradictions between experimental data concerning $\eta$ and $K_{late}$

• It seems photoelectron backscattering does not deteriorate dramatically amplitude and time resolution of vacuum photodetectors
• Combined thorough experimental and simulational efforts are necessary to solve photoelectron backscattering problem completely