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Physics 4796 - Experimental Physics
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Physics 4796 Lab Writeup
Performance Characterization and Single Photon Counting with a Photomultiplier Tube

1 Introduction

In this lab you will will familiarize yourself with the photomultiplier tube (PMT). Since its invention more than 80 years ago this device has been the workhorse detector for low level visible light. It is capable of room-temperature operation reaching the quantum limit of detecting single photons with acceptable efficiency and excellent signal-to-noise. Its importance has if anything increased in recent years as quantum secure communication methods including those involving entanglement have been discussed and begun to be realized. You will measure three basic PMT performance parameters; the photocathode quantum efficiency, the quantum counting efficiency, and the gain.

The recommended textbook Building Scientific Apparatus pp 261 ff has a good brief discussion of PMT's. Much more detailed information about PMT's (including applications) is in the Hamamatsu Photomultiplier handbook, which is available chapter-by-chapter at:

`http://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE-Chapter1.pdf`

The classic RCA Photomultiplier Handbook is also posted on BlackBoard, along with manufacturer's information for the PMTs used in the lab.

This writeup is very brief and does not cover every detail needed to understand and perform this lab. A scientific paper describing the exact measurements to be made in this lab is posted on Blackboard under "Lakes and Poultney article on QE/QCE measurement". That article is your main how-to reference for this lab. (Ignore the fact that Lakes and Poultney used a HeNe laser as a light source- it is immaterial for this lab.)

The photomultiplier tube (PMT) is a vacuum tube device in which the first step of light detection is to convert incident light into electron(s) by the photoelectric effect. A diagram of how the PMT works is shown on page 263 of Building Scientific Apparatus and on page 29 of the RCA Photomultiplier Handbook.

After emission from the photocathode, the photoelectron(s) is(are) then accelerated by a high voltage of up to several hundred volts, at which point they strike the first of a series of metal electrodes ("dynodes"). Dynodes are made of materials selected for a high "secondary emission coefficient". Secondary emission is a process in which an accelerated electron strikes a dynode and part of its energy goes into knocking out several more "secondary" electrons from the dynode surface. Electric fields in the PMT collect the secondary electrons and accelerate them onto the next dynode, where each of them again undergoes secondary emission, and so forth. The PMT is constructed with 10-20 dynodes one after another, each collecting and amplifying the charge from the preceding one.

With typical secondary emission coefficients of ~ 5 and with 10 stages, the charge gain is then $\sim (5)^{10}$, which is about 10^7. After the last dynode, all the produced electrons are collected on a final (non-multiplying) electrode called the anode. The PMT output signal is usually a current pulse from the collected charge, read out from the anode.

With gain of 3×10^7, a single photoelectron (from a single photon of light) would be amplified by a PMT into 3×10^7electrons, all packed into a pulse lasting only a few nanoseconds. The average current in such an amplified output pulse is about 3×10^7 $e^-/3{\times}10^{-9}$ sec or about 10 mA, easily measurable with a fast oscilloscope. (10 mA flowing to ground through the 50 Ω input impedance of a fast 'scope gives a voltage drop of .010 A $\times$ 50 Ω = .05 Volt). Efficient detection of single photons is important in most but not all applications of PMT's. The short pulses and very tight (sub-nanosecond) time correlation between arrival of a photon and the anode pulse are also essential for many applications.

Of course there is always a background or "dark count rate" (sometimes called "dark current") due to thermal emission of electrons from the photocathode. High quality 50 mm diameter PMTs have dark count rates of 1000 counts/sec or less at room temperature, and may be cooled for critical applications.

The parameters we will measure in this lab are:

- The photocathode quantum efficiency (QE): this is **the probability that a photon striking the photocathode window will knock out a photoelectron**. The QE is not equal to 1.00 since not every photon that hits the photocathode is absorbed (typical PMTs have semitransparent thin-film photocathodes) and not every photon that is absorbed succeeds in knocking out a photoelectron. For a given photocathode material, the QE varies considerably with the wavelength of the light used. Typical peak QE values are only 20-40%, though higher values are achieved with specialized PMT types.

  To measure the QE, we direct photons at a known rate onto the photocathode and measure the photocurrent emitted from the photocathode with a sensitive ammeter. The ratio of the photocurrent (expressed in electrons per second) divided by the incident photon rate (expressed in photons per second) is the QE.

- The quantum counting efficiency (QCE): this is **the probability that a photon striking the photocathode will produce a fully amplified, countable pulse from the PMT**. The QCE is not equal to the QE mainly because not every photoelectron emitted from the photocathode is successfully collected and passed into dynode chain. Typical QCE values are 70-90% of the QE.

  To measure the QCE, we direct photons onto the photocathode at a known, reasonably low rate, and use suitable pulse counting gear to measure the rate of output pulses produced by the PMT. The QCE is then calculated by dividing the output pulse rate (expressed in pulses per second) by the incident photon rate (expressed in photons per second).

- The gain: this is **the number of electrons in an output pulse produced by a single photoelectron**. which is approximately the same (why approximately?) as **the ratio of the amplified output current (the anode current) to the photocathode current under steady illumination**.

  To measure the gain using the second definition, we direct photons onto the photocathode at a known, reasonably low rate and measure the photocurrent produced. Then we measure the amplified output current at the anode for the same flux of photons, and take the ratio. To use the first definition, we direct photons onto the photocathode at a known, reasonably low rate, and use suitable pulse counting gear to measure the sizes of the amplified pulses.

To do the above measurements we need a source of photons with a known rate. Instead of using an expensive NIST-traceable light source or some other method, we use an ordinary LED and calibrate it with a Thorlabs photodiode and amplifier. We convert the photodiode current to photon flux by relying on the photodiode data sheet for its "responsivity" (basically the photodiode QE) as a function of wavelength.

2 Prelab Questions:

1. Lakes & Poultney recommend a photocathode current of about 100 nA for the QE measurement. How many electrons per second is this? For a typical value of the QE, roughly how many photons per second striking the photocathode would produce this photocurrent?

2. For light of 500 nm wavelength, how much optical power does the photon rate from the preceding question represent?

3. What are the units of responsivity given for the SM1PD1A photodiode? Explain what this specification means. Suppose we expose the SM1PD1A to a light source of wavelength 500 nm which produces a photodiode output current of 1 μA. What is the power in Watts striking the diode? What is the rate of 500 nm photons striking the diode?

4. Explain why the resistor value in the constant current LED circuit shown in Figure 1 below is reasonable given the optical power desired on the photocathode. (Hint- assume that the LED converts the IV power dissipated in it into light with 100% efficiency. You may assume that the voltage drop across the LED itself is 2.5 V and that the current in the circuit adjusts itself to drop the remaining 2.5V across the resistor.)

5. What does a discriminator do? (Hint-look this up in <u>Building Scientific Apparatus</u>).

6. Estimate the factor by which the photon rate striking the photocathode is reduced in the setup for the QCE measurement (photocathode masked, LED filtered) compared to that of the QE measurement.

3 The Experiment

You must study the article by Lakes and Poultney to understand the measurement methods used in this lab. <u>All</u> the measurements are made inside a "dark box" which is necessary since PMT's *are instantly destroyed* by room light if the high voltage is on.

3.1 QE Measurement

Equipment needed: LED light source(s), Daedalon E-085 spectrophotometer, Neutral Density (ND) filters, Thorlabs SM1PD1A photodiode and PDA200C amplifier, PMT high voltage bias circuit ("K-mode base"), Fluke high voltage power supply, 9813B PMT.

As stated above, this measurement is accomplished by exposing the PMT to a known rate of photons and measuring the photocurrent produced.

3.1.1 Light Source Characterization

Do not use the PMT for this part of the measurement. To measure QE we require a light source that produces photons at a known rate and directs them onto the PMT photocathode. For a light source, we use an LED driven by a DC current. The LED must be wired in forward bias, with a series resistor to limit the current, as shown in Figure 1:

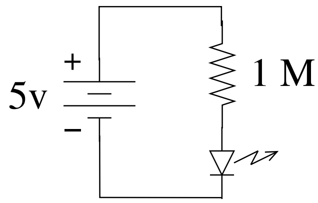

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Figure 1: LED steady current drive circuit.

To find out the photon flux from this light source, we calibrate it by measuring the light output using a photodiode with a known responsivity (Amperes/Watt). The measured current output of the photodiode when it is exposed to the LED is converted into Watts of LED light output, using the known responsivity. You will need to study the Thorlabs manuals (posted on BlackBoard and available in print) to operate the SM1PD1A photodiode and PDA200C amplifier and to get the active area of the photodiode. You need the photodiode active area in order to scale up the rate of photons on the little photodiode to that on the bigger PMT face. LED's do not emit light isotropically so it is important to separate the LED and the detectors by at least 15 cm during the calibration and the measurements, and to insure that the LED is accurately pointed at the detectors.

Before trying the calibration, measure the output spectrum of the LED using the s Daedalon E-085 spectrophotometer.

For the calibration, first follow the instructions in the PDA200C manual to connect the photodiode to the amplifier. Measure the photocurrent produced by the LED at a distance of 15 cm inside the dark box. Introduce ND filters or adjust the LED power supply until you get a photocurrent of about 4 nA. This will be a good light intensity to use with the PMT. Calculate the rate of photons on the photodiode in this configuration. Now don't change anything.

3.1.2 QE Measurement with PMT

Make sure the high voltage power supply is off. Carefully plug the PMT into the K mode base, aligning it with the missing pin. The K mode base applies negative high voltage (use about 300 V) to the photocathode and connects all the other dynodes together to an output where the photocurrent can be measured, again using the PDA200C amplifier. Mount the PMT inside the dark box with its photocathode 15 cm from the LED, and connect the high voltage cable to the high voltage supply and the signal cable to the PDA200C, but keep the high voltage power supply turned off. Close the dark box and insure that it is light tight.

Turn on the LED exactly as it was when you calibrated it. Turn on the PMT high voltage supply to -300 V. Measure the photocurrent produced by the PMT. Compute the QE from the ratio of the photocurrent (converted to electrons/sec) to the photon rate (photons/sec) striking the photocathode. Note: it is sufficiently accurate to assume that the photon rate on the photocathode is equal to the photon rate on the photodiode measured in the previous subsection, multiplied by the ratio of the photocathode area to the sensitive area of the photodiode (from the anufacturer's data sheet). Show your results to the instructor before proceeding.

You may wish to repeat this with several different colored LED's (red, yellow, green) and compare your results to the S20 photocathode sensitivity curve in the Hamamatsu PMT Handbook.

Make sure to turn the high voltage power supply off before opening the dark box.

3.2 Gain Measurement using Steady Illumination

As stated above, this measurement is accomplished by exposing the PMT to a known rate of photons and measuring the anode photocurrent produced.

Equipment needed: LED light source, Neutral Density (ND) filters, Thorlabs PDA200C amplifier, a different PMT high voltage bias circuit ("Q-mode base"), Fluke high voltage power supply, 9813B PMT.

Make sure the high voltage is off. Exchange the K mode base for the Q mode base. The Q mode base is the circuit shown in the PMT data sheet. It uses a voltage divider to apply graded negative high voltages to the photocathode and each of the dynodes, as recommended by the manufacturer for normal high-gain operation of the PMT. With this circuit, the full amplified current from the last dynode is collected on the anode. We measure the anode current.

If we were now to expose the PMT to the same light intensity as in the QE measurement, the output current would now be higher by a factor of the gain, which is of the order of 10^7. This would exceed the maximum allowed output current of the PMT and most likely damage it irreversibly. So we first introduce additional ND filters in front of the LED adding up to an optical density of 3. This reduces the light intensity by a factor of 1000. The attenuation of the ND filters should be checked by a simple procedure described in the Lakes & Poultney article.

After placing the additional ND filters, put the PMT with Q mode base back in the dark box at 15 cm from the LED and connect the cables. Close the dark box and insure that it is light tight. Turn the PMT high voltage up to negative 2000 V. Measure the output current with the PDA200C. Repeat this for a few different values of the high voltage between -1500 and -2300 V. Compute and plot the gain vs. high voltage on a semilog plot.

Turn off the PMT high voltage and leave it off for now.

3.3 QCE Measurement

Equipment needed: LED, ND filters, Thorlabs PDA200C amplifier, photocathode mask, fast amplifier, discriminator, scaler, 9813B PMT, K mode and Q mode bases, PMT, high voltage supply. You will need the instructor's help to set up the pulse counting equipment.

As stated above, this measurement is accomplished by directing photons at a known rate onto the photocathode and measuring the rate of output pulses produced by the PMT.

A non-ideal property of PMT's mentioned above makes this measurement a little more complicated. This property is called the "dark count rate". Even when absolutely no light is striking the photocathode, PMT's produce fully amplified output pulses at a certain rate (typically a few tens of pulses per second for each cm^2 of photocathode area at room temperature) This happens because a material that acts as a good photocathode binds its electrons so loosely that the thermal energy is enough to eject electrons from the photocathode at a low rate even when there is no light. So we must measure the pulse rate with and without the known rate of incident photons and subtract to find the pulse rate associated with the photons. We must also insure that our pulse counting gear is set sensitively enough to count the relatively small single photoelectron pulses.

3.3.1 Obtaining a Suitable, Known Rate of Incident Photons

Be sure the PMT high voltage is off. Set up the LED as it was used for the QE measurement. It turns out that even the reduced rate of photons used for the gain measurement is too high for the pulse counting electronics to handle. So, we need to reduce the rate by "masking" (covering all but a small, measured fraction of) the PMT photocathode, while still using the ND filters.

Tape the "mask" (opaque disk with 2.5 mm diameter hole) over the photocathode so that only the un-masked portion will see the light from the LED. Mount the K mode base on the PMT. Place an ND=3 and an ND=0.5 filter over the LED. From the photocurrent you obtained in the QE measurement, compute the rate of photons you expect to be striking the photocathode in this arrangement. Apply -300 V to the K-mode base and try to measure the net photocurrent with the PDS-200C. If the current is below the noise floor of the instrument, remove some ND filters and try again. Show your calculations and results to the instructor before proceeding.

3.3.2 Adjusting the Pulse Counting Gear

Replace the K mode base with the Q mode base. Connect the PMT signal line to the discriminator and the discriminator output to a scaler. Set the discriminator level to 50 mV and the output pulse width to 50 ns. Place the PMT at 15 cm from the LED as before. Close the dark box and insure that it is light tight.

Following the procedure of Lanes & Ppultney, we will now find a setting for the PMT high voltage which allows it to count single photoelectrons efficiently. This is done by "taking a plateau curve"- measuring the pulse counting rate as a function of high voltage and locating the flat "plateau region" where single photoelectrons are being counted and at higher voltages the sharply increasing "noise knee" where partially-amplified pulses and electronic noise are being counted.

Turn on the PMT HV to 1500 V and count the number of pulses in 1 minute with LED on and LED off. Repeat these counts for HV settings increasing by 100 V up to 2300 V. Do not exceed 2300 V. Plot the LED-on and LED-off curves and the difference. Show your results to the instructor before proceeding. If everything has been done correctly, the QCE can be calculated from the ratio of the (LED on minus LED off) counting rate in the plateau region, divided by the computed rate of photons striking the photocathode.

3.3.3 Checking the Gain From the Plateau Curve

The plateau curve allows you to estimate the HV at which the single photoelectron pulses become bigger than the 50 mV discriminator threshold. Estimate the gain at this HV and compare it to the value you got earlier in the DC measurement. (Hint- see the discussion in the Introduction to this writeup in which pulse currents and charges are discussed). Show the instructor your results before proceeding.

Be sure the PMT high voltage is turned off.

3.4 Optional (But Highly Recommended!)– Seeing the Quantum Limit on the Oscilloscope

To do this we will drive the LED with pulses instead of a steady current. We will watch on the oscilloscope and see what happens to the PMT output as the LED pulses get smaller and smaller. We will see that when each LED driver pulse is large enough to make many photoelectrons all at once, within a single pulse, each and every LED light pulse produces a PMT output pulse. In this many-photoelectron regime, reducing the size of the LED drive pulse is seen to reduce the PMT output pulse height proportionally.

However when the LED driver pulses get small enough so that each pulse produces on average one or fewer photoelectrons, *the PMT output pulses stop getting smaller* as the LED drive pulse is further reduced. Their pulse height stops decreasing but the pulses come less often- each LED pulse no longer produces a PMT output pulse. When the LED pulses are this small, we will either see a PMT pulse with a constant height corresponding to a single photoelectron amplified by the PMT gain, or no pulse at all. This is the quantum limit. You are seeing single visible light photons.

See the instructor for help setting up the LED pulser and the oscilloscope triggering.

Be sure the PMT high voltage is off. Open the dark box and remove the photocathode mask. Replace the DC-driven LED with the one appropriately terminated for pulsed operation (this will prevent electronic noise from ruining your view of the single photoelectron pulses). Connect the LED pulser to the LED.

Close the dark box and insure that it is light tight. Show your setup to the instructor before proceeding. Turn on the PMT high voltage to the middle of the plateau region. Trigger the oscilloscope with the trigger output of the LED pulser and observe the PMT output after the fast amplifier. If everything is set up correctly you should see quite large pulses ($\sim$.1-1 Volt) occurring every time the oscilloscope is triggered. Show your setup to the instructor before proceeding. Now reduce the pulse amplitude using the adjustment on the pulser and additional attenuators if necessary (Note: on one of the types of LED pulsers in use, the output pulses are made smaller by turning the amplitude adjustment screw *clockwise*). You should see the progression described in the first paragraph of this section. Save some representative oscilloscope traces for inclusion in your lab report.