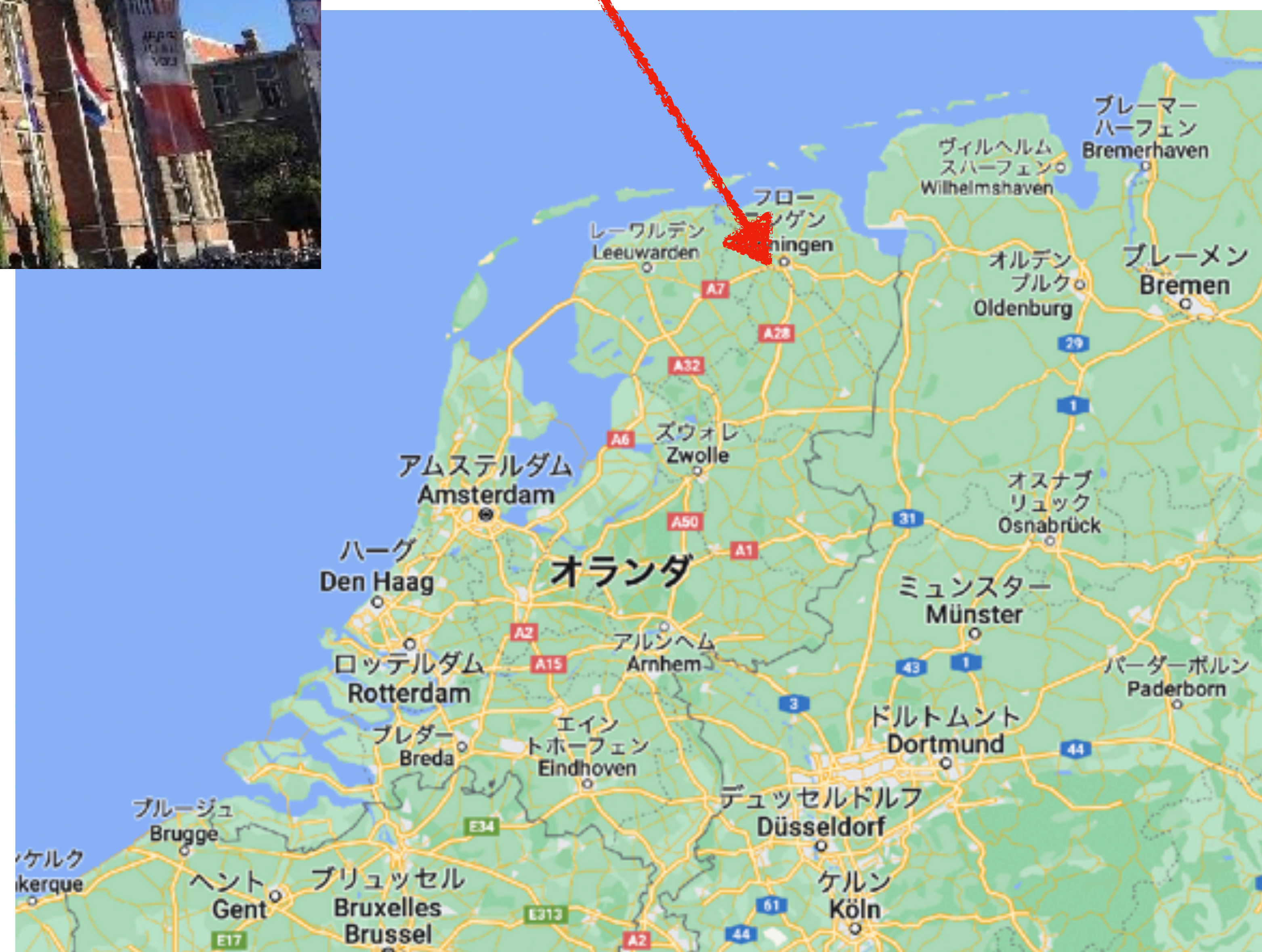
Photo detectors

August/2023
NOMACHI, Masaharu

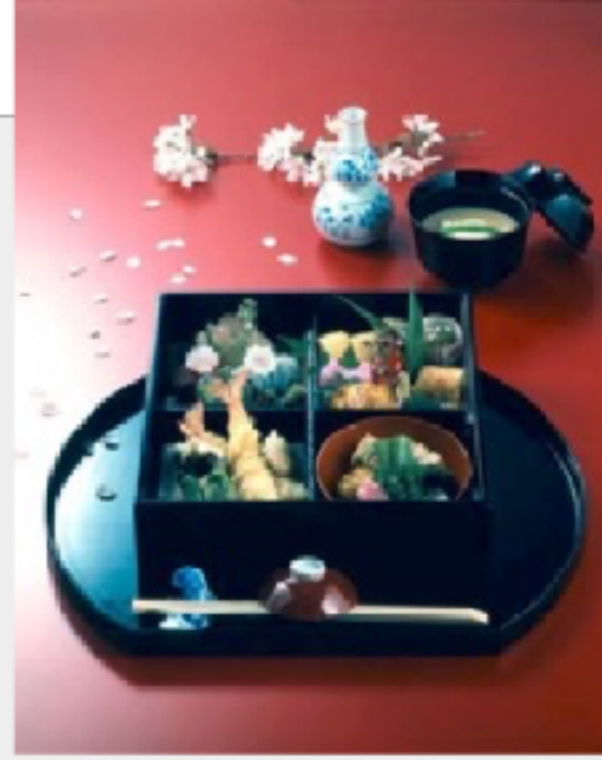
European Center Osaka University @ Groningen



Osaka University

Contact us at: info.groningen@overseas.osaka-u.ac.jp

大阪大学
OSAKA UNIVERSITY



Wondershare
PDFelement

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Quantum sciences in OU

The 1st president, Hantaro Nagaoka, is a physicist in Quantum physics

Hideki Yukawa

The Nobel Prize in Physics 1949

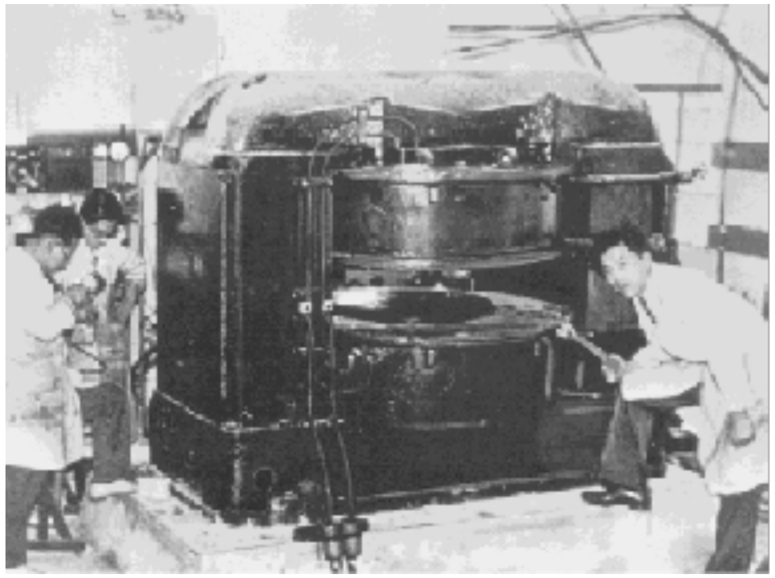
Prize motivation: "for his prediction of the existence of mesons on the basis of theoretical work on nuclear forces"
Born: 23 January 1907, Tokyo, Japan

Died: 8 September 1981, Kyoto, Japan

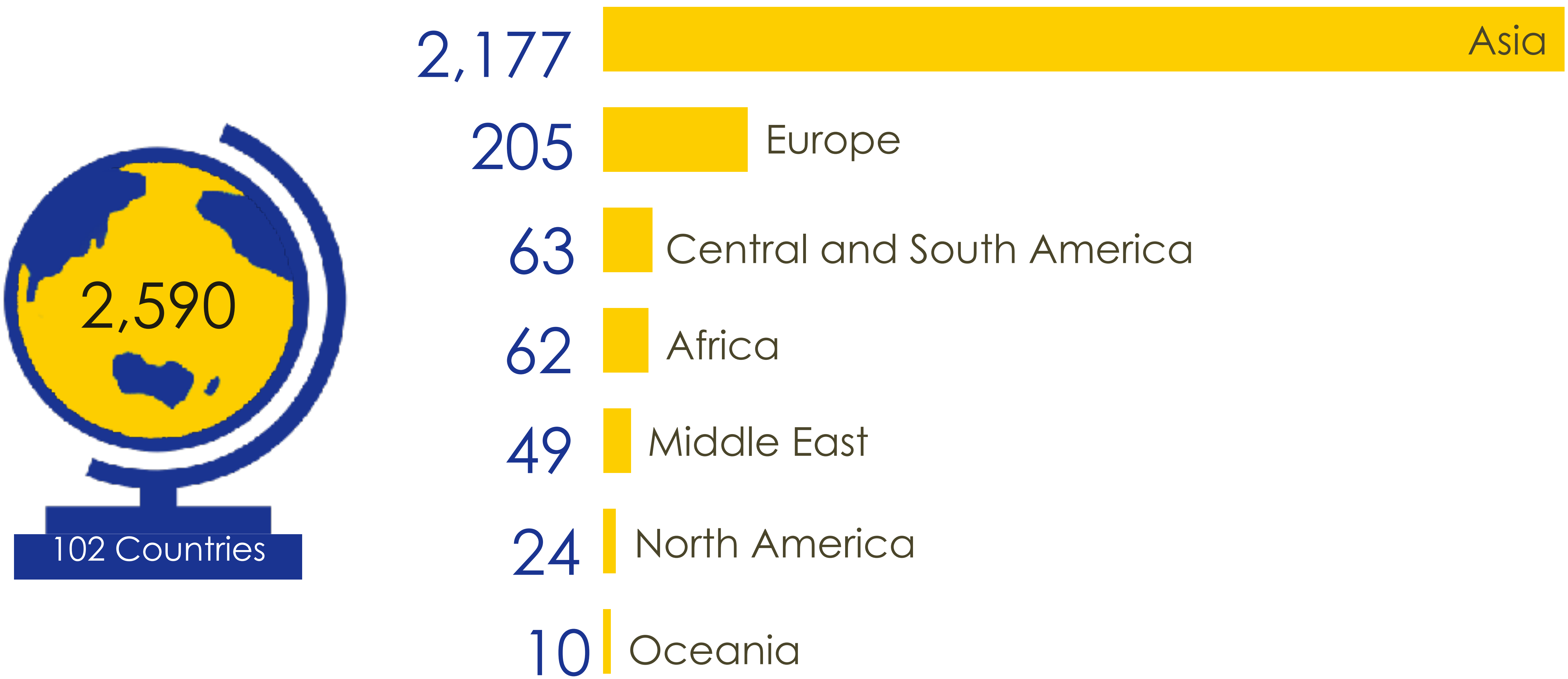
https://www-yukawa.phys.sci.osaka-u.ac.jp/en/memorial

Prof. Seishi KIKUCHI

1932, cyclotron was invented in US.
1935-1937 cyclotron was developed in Osaka University.



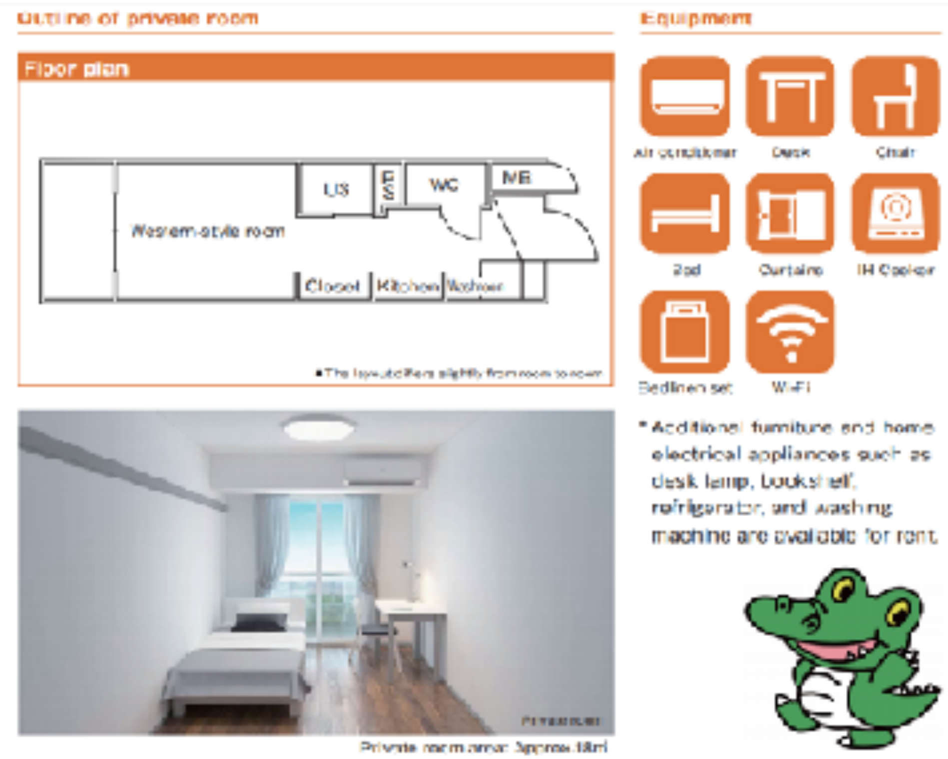
International Students (as of May 1, 2022)

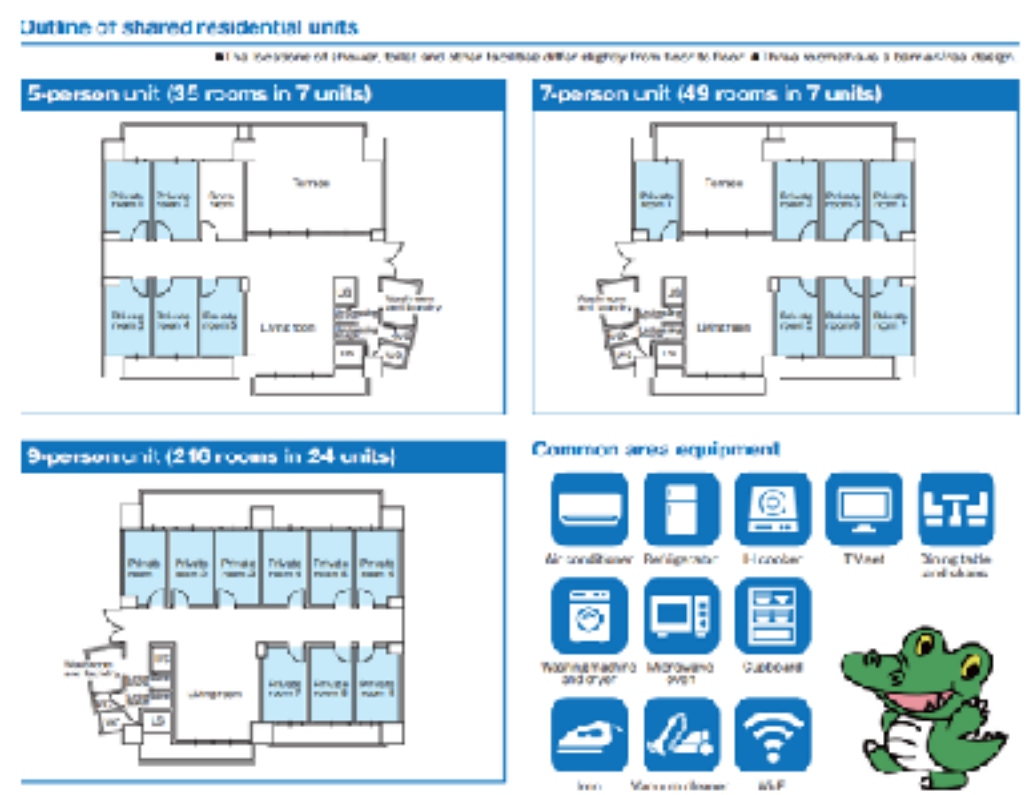


Opportunities to Study in English

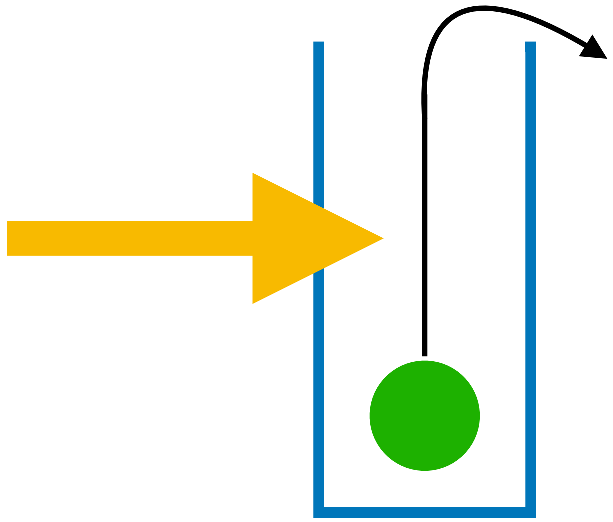
	Study in Japanese	Programs in English
Undergraduate degree program	All programs	• **Human Sciences International Undergraduate Degree Program** • **International Undergraduate Program in Science** (the first 1.5 years in English, later years in Japanese)
Graduate degree programs	All graduate programs	• **Science** (2) • **Engineering** (8) • **Engineering Science** (1) • **Information Science and Technology** (1) • **Economics** (1)
Non-degree	- Exchange programs iExPO Exchange Program - Japanese Language & Culture program, Maple	• **Frontier-Lab Program**: To join leading research labs • **OUSSEP**: Exchange program for undergraduate students • Many other opportunities for graduate students to come as non-regular students

Osaka University's Global Villages





Light detection



How can we detect light

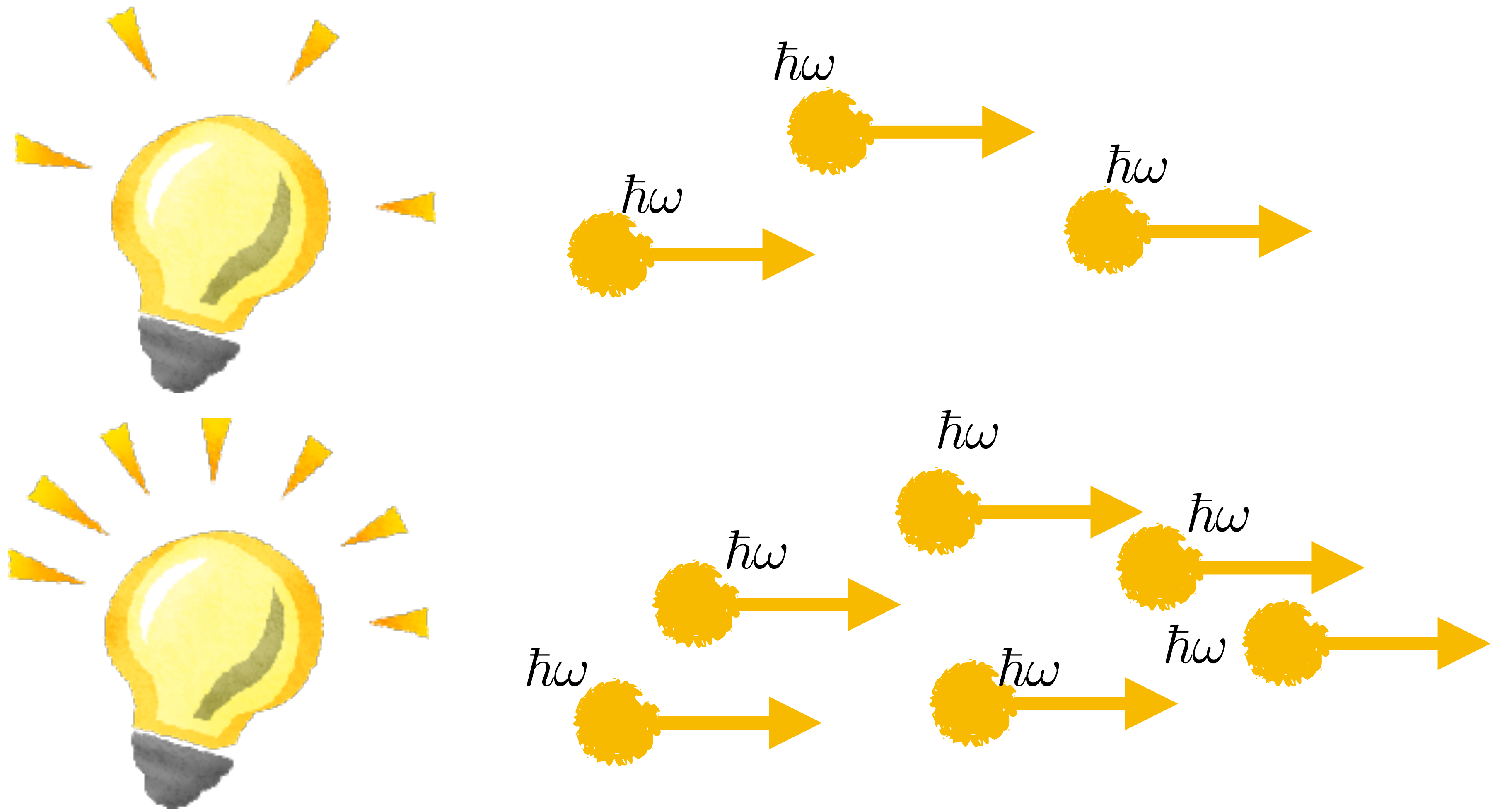
We need ENERGY to excite the micro system

How can we detect weak light
Do we need accumulate the energy enough to excite?

No.
Energy is quantize as photon.
Intensity = the number of photon
Count the photon.

Quantized Energy flow

Energy flow is quantized. **Intensity is the number of photon**



Photon energy = wave length = color

Photo from the Nobel Foundation archive.

Max Planck

The Nobel Prize in Physics 1918

Prize motivation: "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta"

photoelectric effect

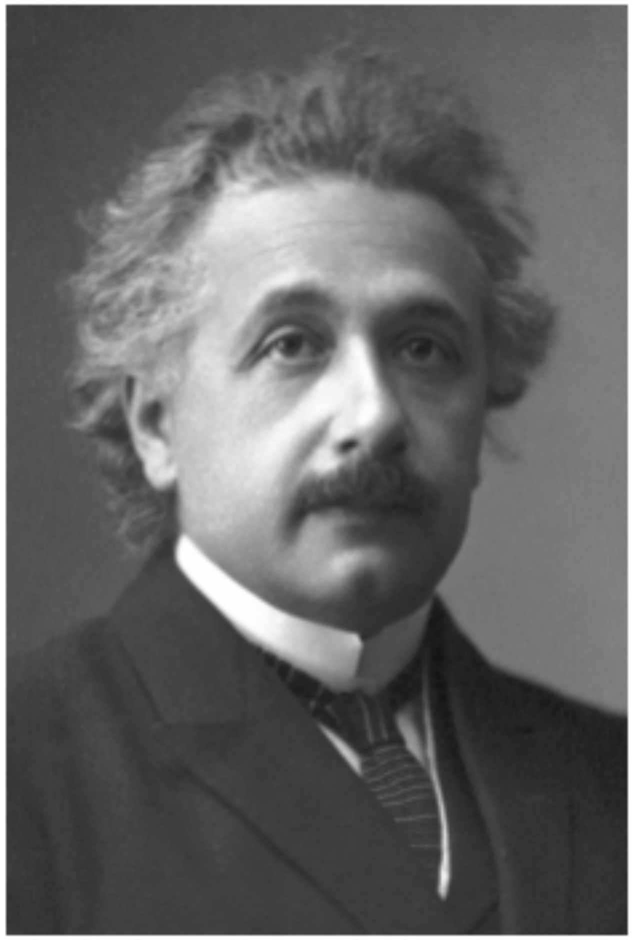
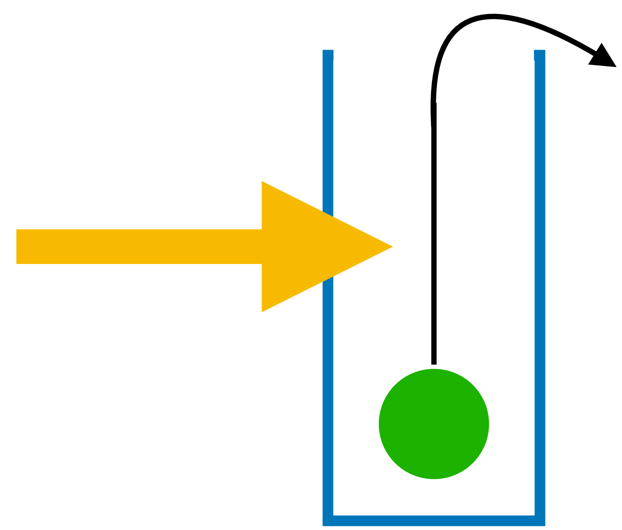


Photo from the Nobel Foundation archive.

Albert Einstein

The Nobel Prize in Physics 1921

Prize motivation: "for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"



Photon energy must be larger than Binding energy

The uncertainty principle

The Feynman Lectures on Physics, Volume I

Chapter 38.The Relation of Wave and Particle Viewpoints **38–4The size of an atom**

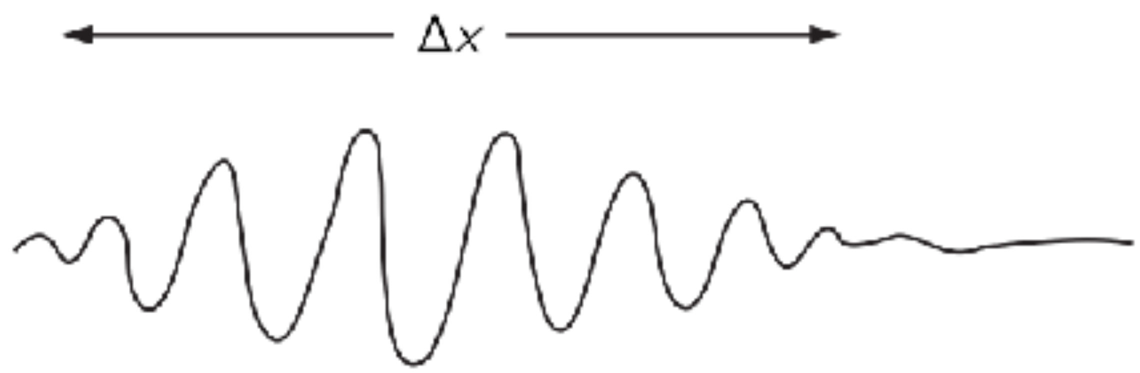


Fig. 38–1. A wave packet of length Δx.

we cannot define a unique wavelength for a short wave train.

The uncertainty principle

$$\Delta x \Delta p \geq \frac{1}{2}\hbar$$

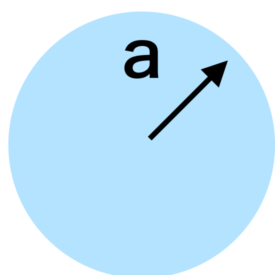
binding energy

Confining small volume ~ The uncertainty principle

$$\Delta x \Delta p \geq \frac{1}{2}\hbar$$

$$\Delta x \sim a$$

$$\Delta p \sim p$$



$$ap \sim \hbar$$

The Kinetic Energy $\frac{p^2}{2m}$ is of the order $\frac{\hbar^2}{2ma^2}$

The Potential Energy is $-\frac{1}{4\pi\epsilon_0}\frac{e^2}{a}$

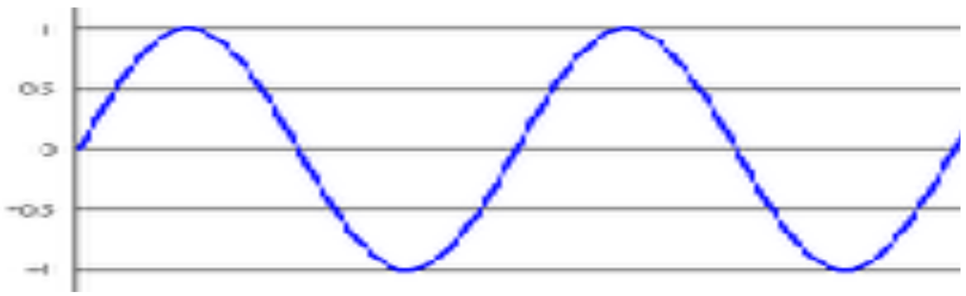
The Total Energy is $\frac{\hbar^2}{2ma^2} - \frac{1}{4\pi\epsilon_0}\frac{e^2}{a}$ $\quad T \sim -U/2 \quad a = \frac{4\pi\epsilon_0\hbar^2}{me^2}$

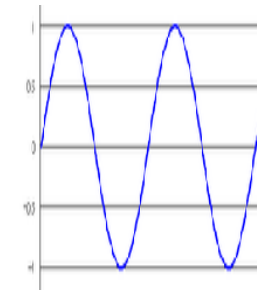
Fine structure constant $\alpha = \frac{1}{4\pi\epsilon_0}\frac{e^2}{\hbar c} = \frac{1}{137}$

The Total Energy is $-\frac{1}{2}mc^2\alpha^2 =$ -13.6 eV

Binding energy of hydrogen

$\hbar c$ = 197 eV nm $\qquad$ $\hbar c$ = 197 MeV fm





$$\text{Energy} = \frac{2\pi\hbar c}{\text{Wave length}}$$

2 eV = 600 nm (Visible light)
1 keV = 1.2 nm (～size of atom)
20MeV = 60 fm (～size of atomic nuclei)

chemical energy

Battery voltage is related to the chemical interactions.

Alkaline manganese battery (1.5V)

$$MnO_2 + H_2O + Zn \rightarrow Mn(OH)_2 + ZnO$$

Ni-Cd battery (1.2V)

$$2NiOOH + Cd + 2H_2O \rightleftharpoons 2Ni(OH)_2 + Cd(OH)_2$$

Thermal Energy

Energy of gas molecular is proportional to the temperature.

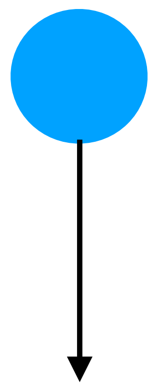
$$E = kT$$

k is Boltzmann constant $8.6171E^{-5}$ eV/K

at room temperature, it is about 26 meV = 0.03 eV

It is much lower than the ionization energy

Gravitation



Free fall of 1 kg from 1m high

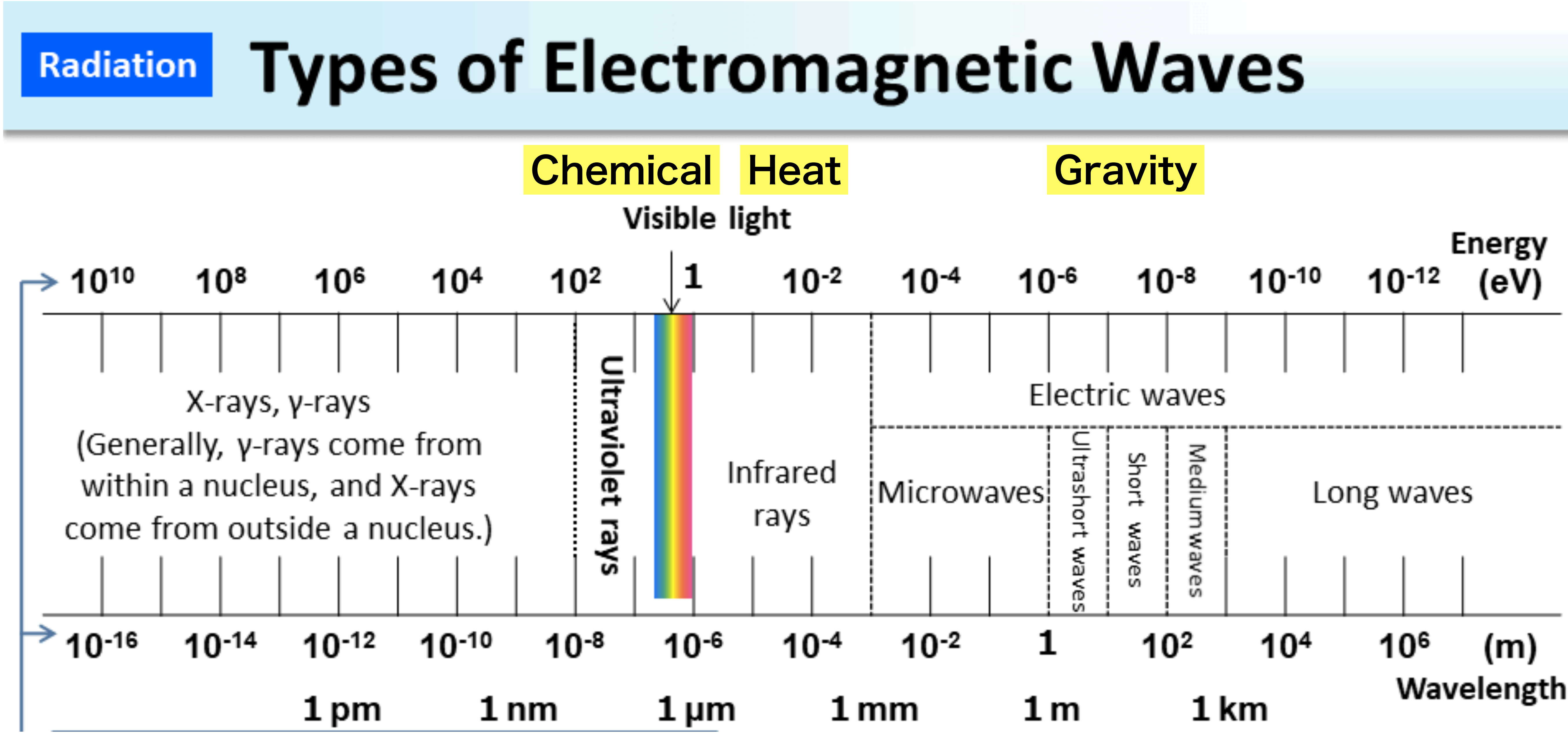
$mgh = \sim 10\ J = 6 \times 10^{19}\ eV$

It is large energy but each nucleon may get …

$6 \times 10^{19}\ eV / (1000 \times 6 \times 10^{23}) = 1 \times 10^{-7}\ eV = 100\ neV$

Compare to other Energy, it is several order smaller.

Energy Scaleionizing radiation

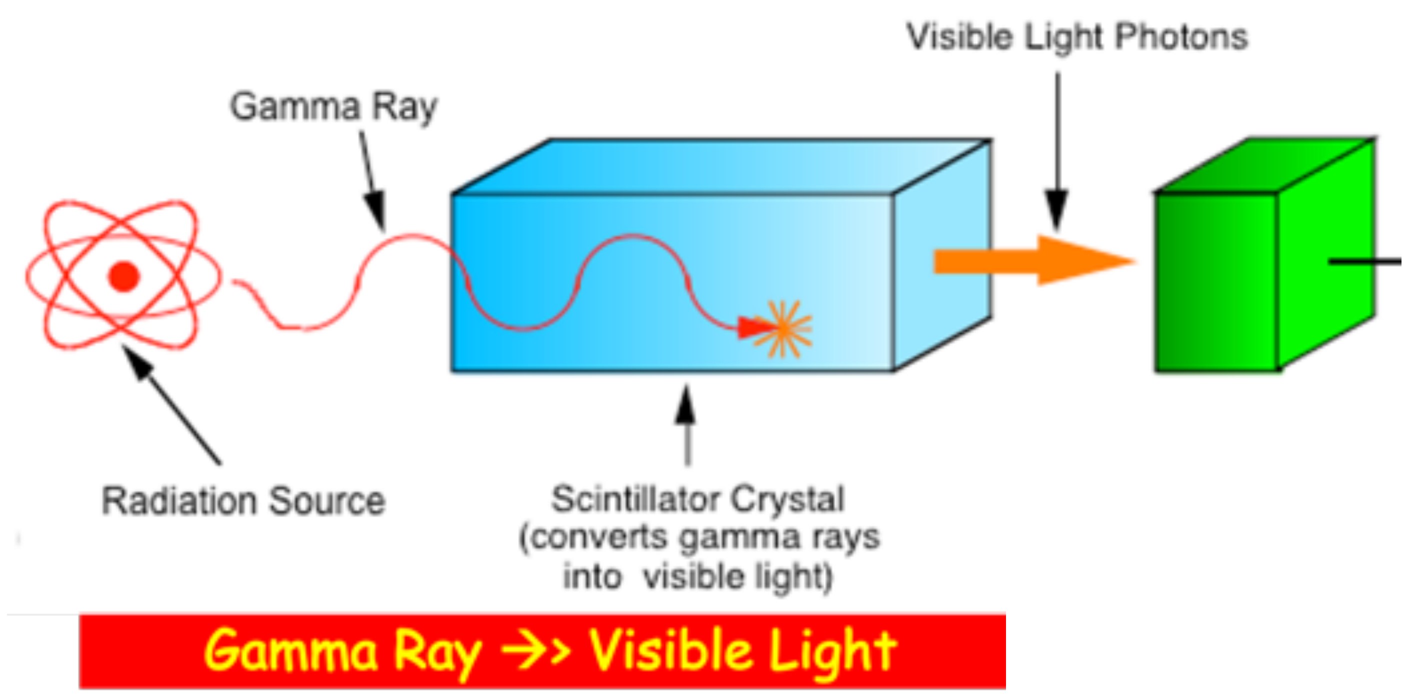


ionizing radiation

https://www.env.go.jp/en/chemi/rhm/basic-info/1st/index.html

Photon Counting

How many photon from scintillator?



LYSO scintillating crystal causes 16,000 photon for 511keV gamma rays.
We see ~one direction out of 6 (L-R,U-D,F-B) direction.
So ~2,670 photon will come out.
LYSO is 2mm x 2mm but Sensor is 1mm x 1mm. It is 1/4
Consequently, only 670 photon will hits the sensor.

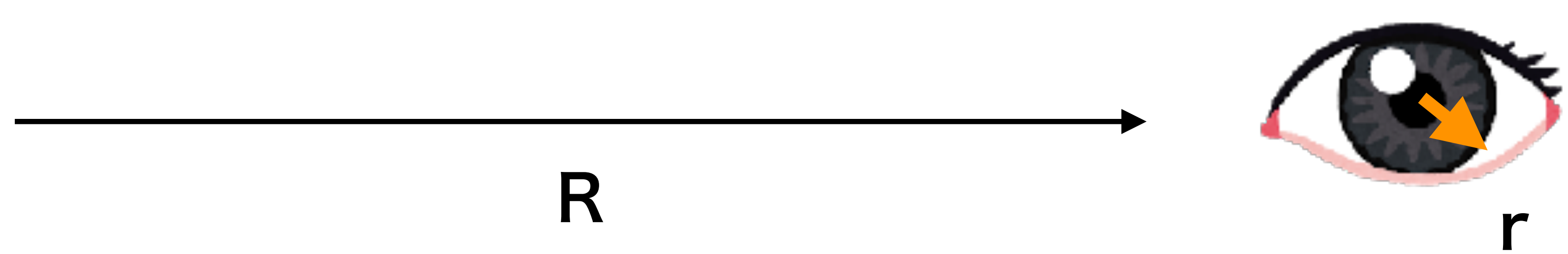
The number of photon

How many photon are we seeing?

Visible light is ~2eV $\quad 1\mathrm{eV} = 1.6 \times 10^{-19}\mathrm{J}$

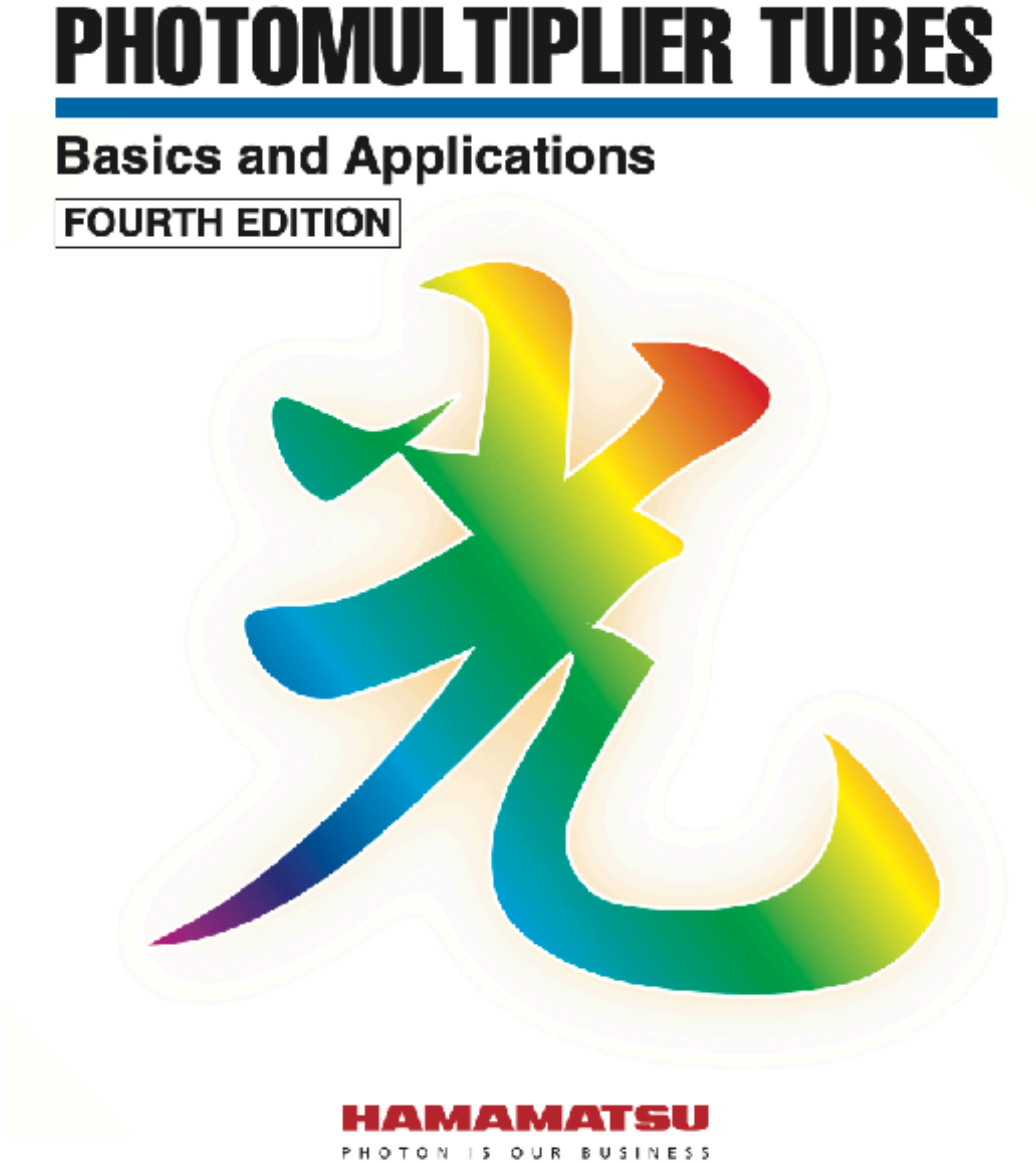
$$1\mathrm{W} = 1\mathrm{J/s} = \frac{1}{1.6\times10^{-19}\mathrm{eV/s}} = \frac{10^{19}}{1.6} \times \frac{1}{2\mathrm{eV/electron}} = 3 \times 10^{18}\mathrm{electron/s}$$

0.1s flush ~ 3×10^{17} photon

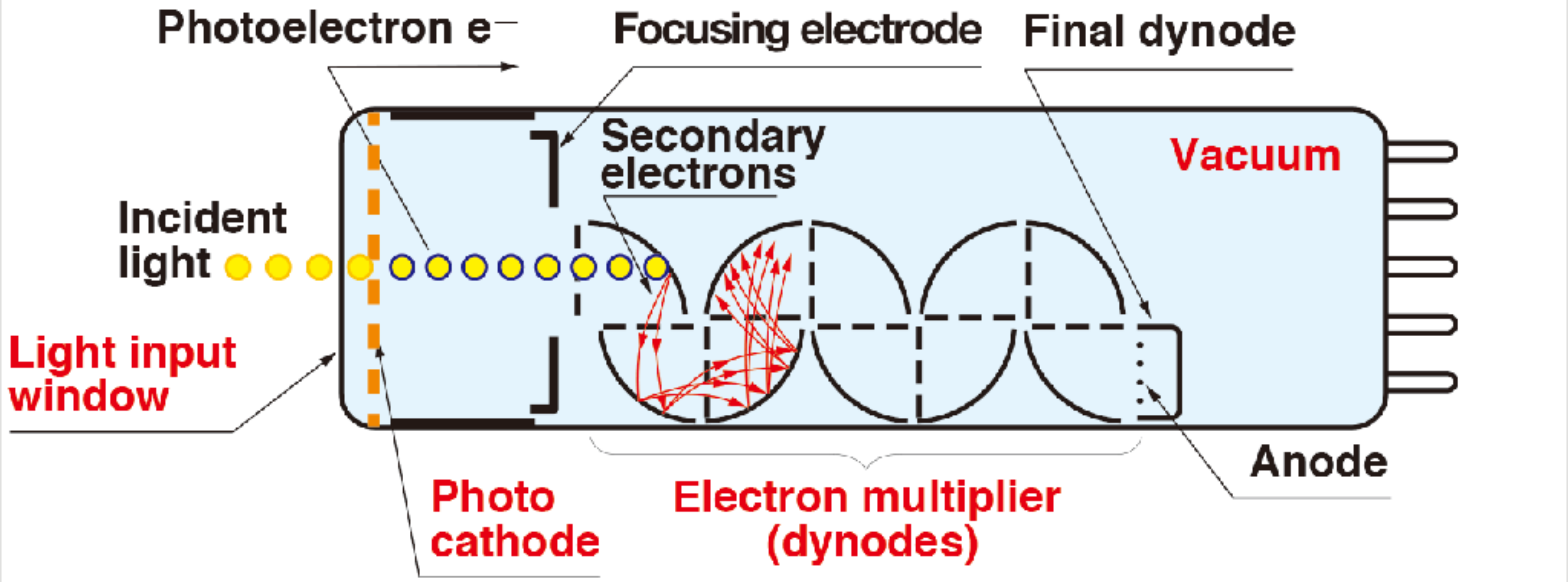


Int eye $\displaystyle \frac{\pi r^2}{4\pi R^2} = \left(\frac{r}{2R}\right)^2$ of probability

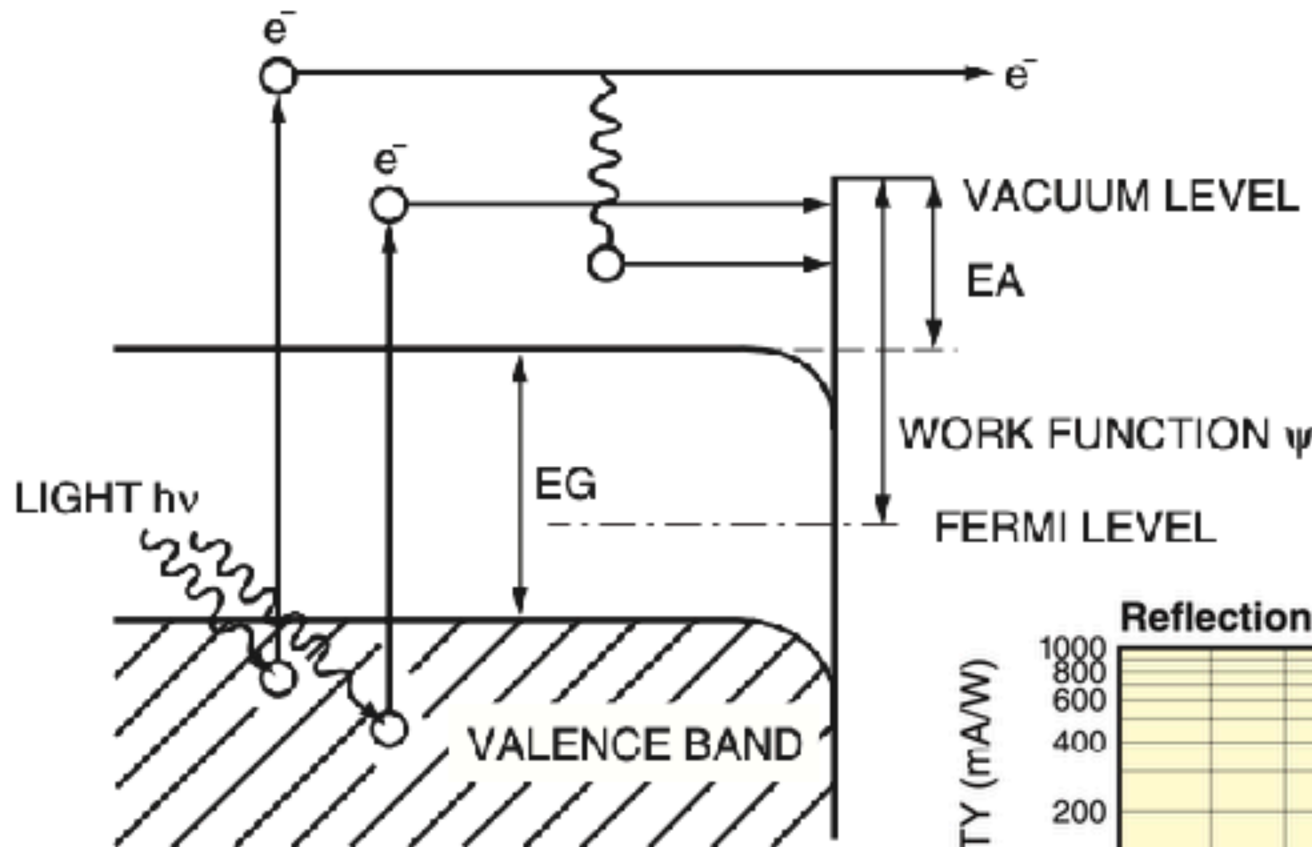
600 photon = 1 W flush 0.1s is seen in 22 km distance



https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/etd/PMT_handbook_v4E.pdf


Photoelectron e⁻
Focusing electrode
Final dynode
Secondary electrons
Vacuum
Incident light
Light input window
Photo cathode
Electron multiplier (dynodes)
Anode

(1) ALKALI PHOTOCATHODE



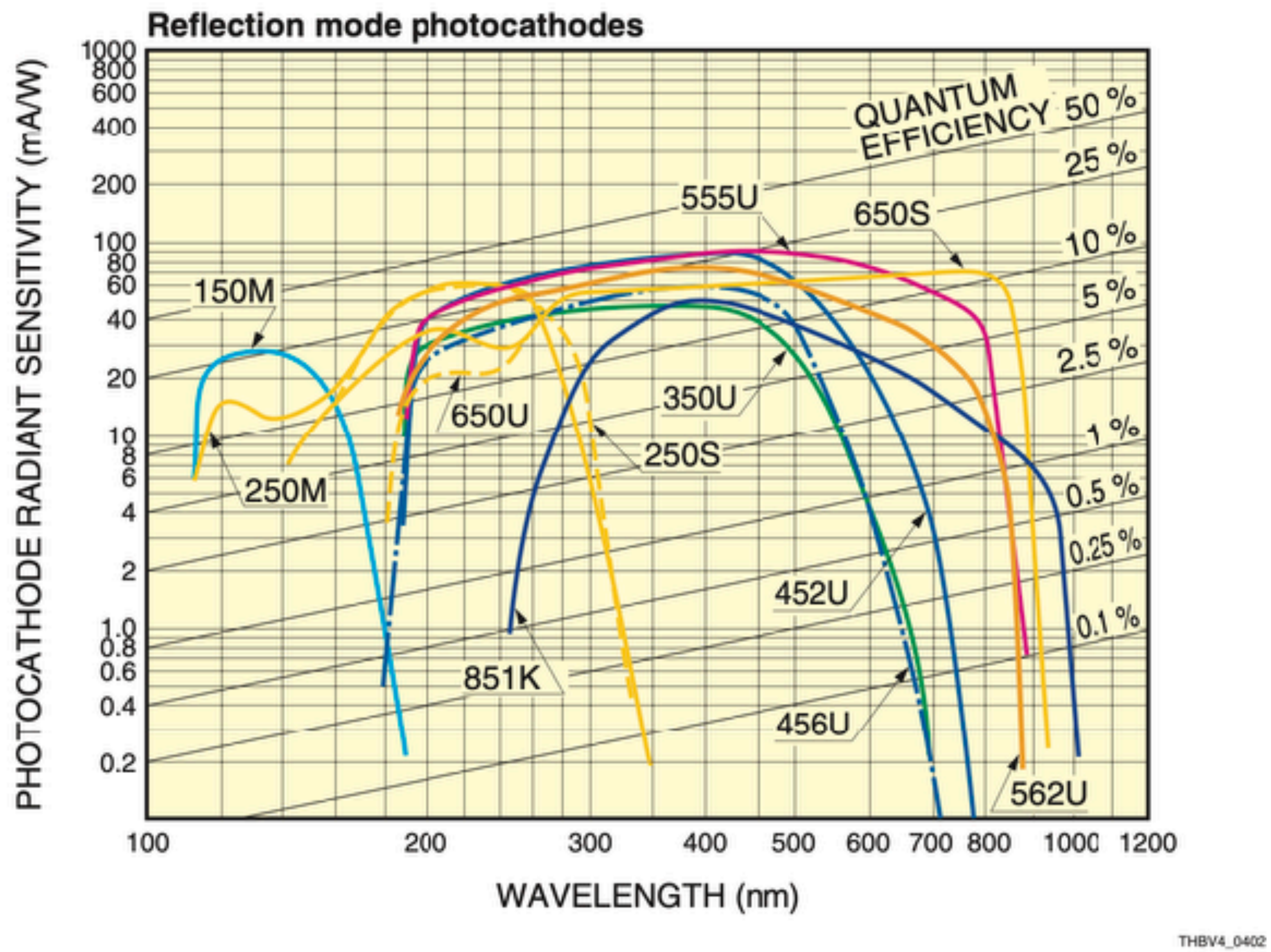


Figure 4-2 (a): Typical spectral response characteristics of reflection type photocathodes

2.4 Electron multiplier (dynode)

As stated above, the potential distribution and electrode structure of a photomultiplier tube is designed to provide optimum performance. Photoelectrons emitted from the photocathode are multiplied by the first stage through the last stage (up to 19 stages) in the electron multiplier, with current amplification ranging from 10 to as much as 10^8 times, and are finally sent to the anode.

Major secondary emissive materials[17)-21)] generally used are alkali antimonide (Sb), beryllium oxide (BeO), and magnesium oxide (MgO). These materials are coated onto a substrate electrode made of nickel, stainless steel, or copper-beryllium alloy. Figure 2-6 shows a model of the secondary emission multiplication of an electron multiplier.

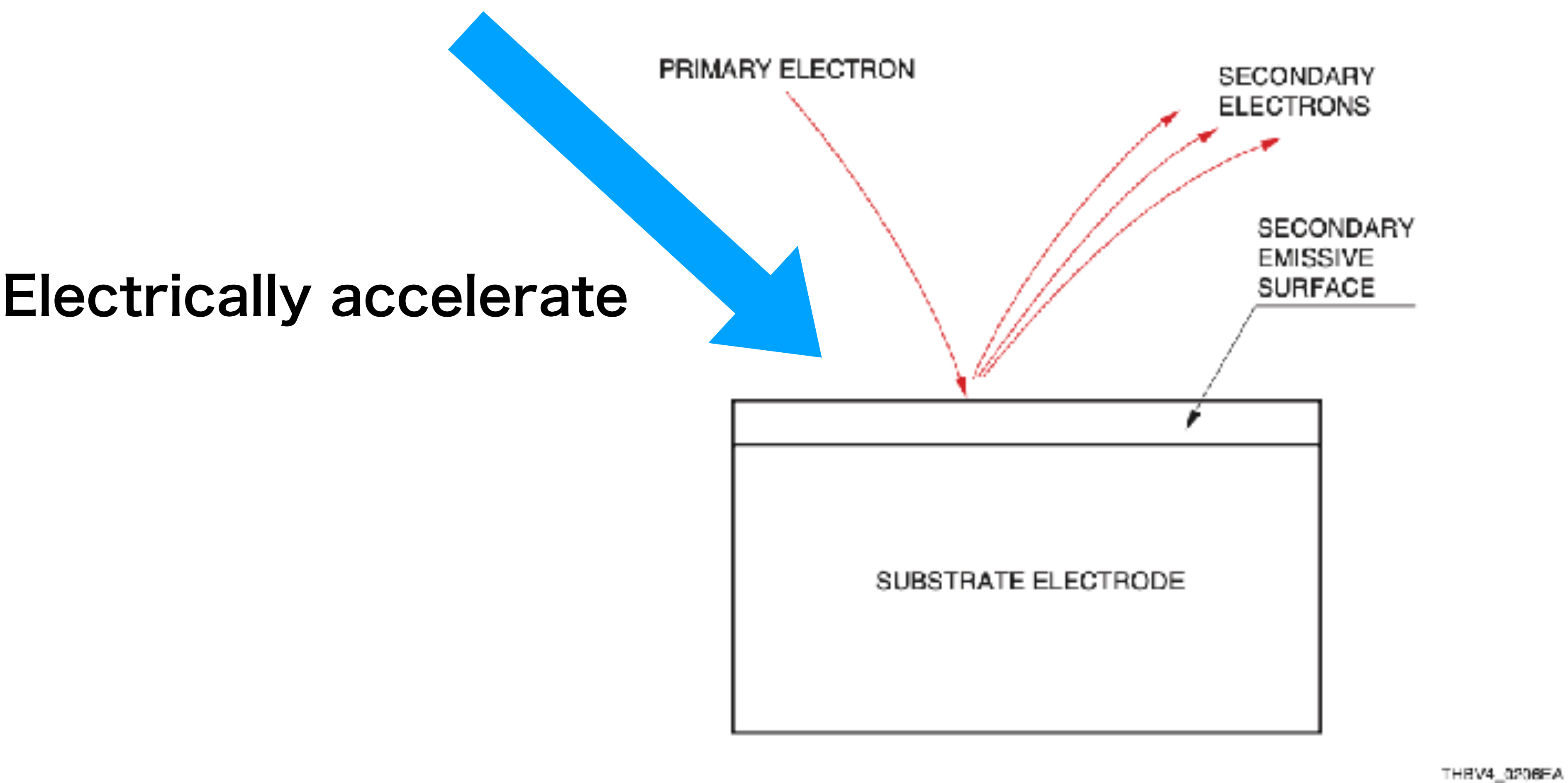


Figure 2-6: Secondary emission model of electron multiplier

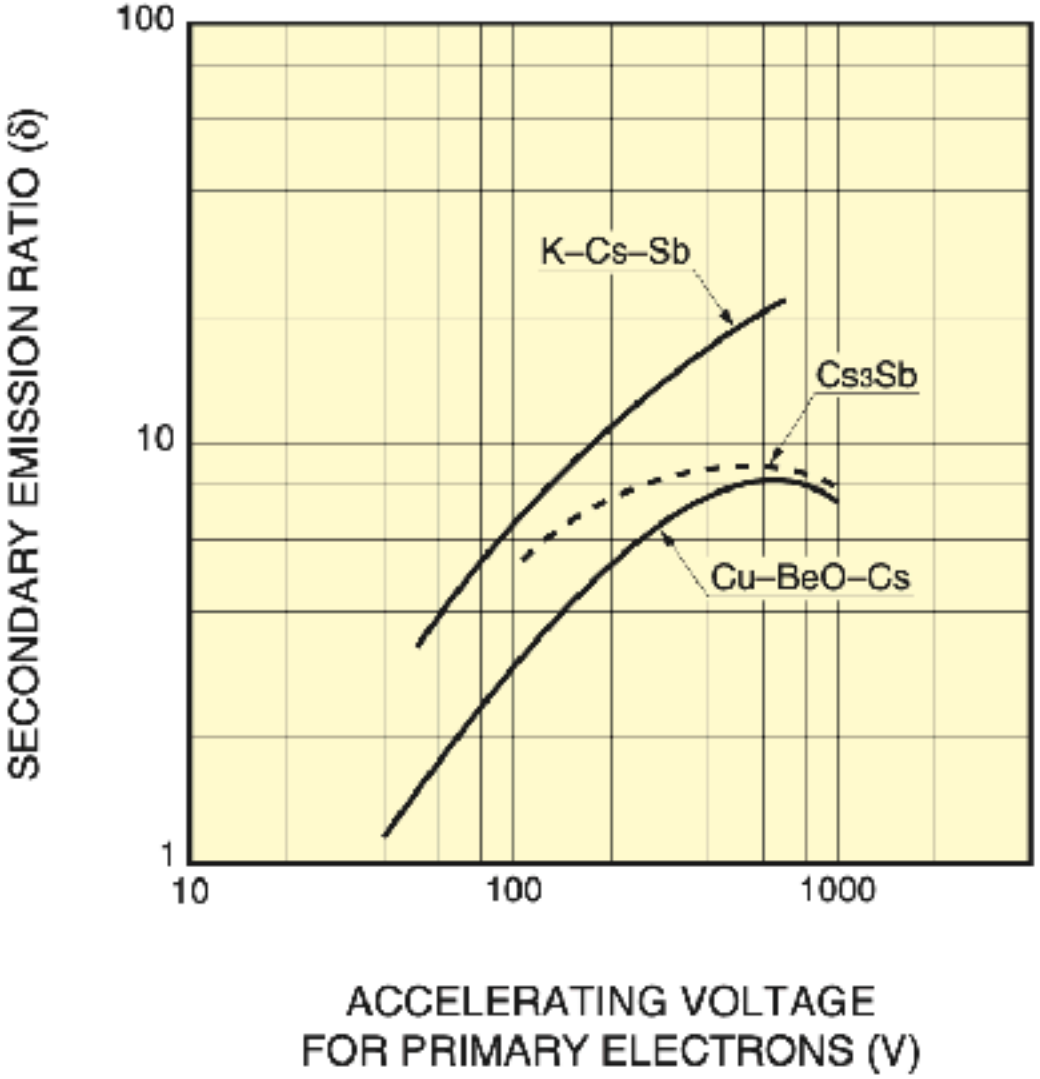
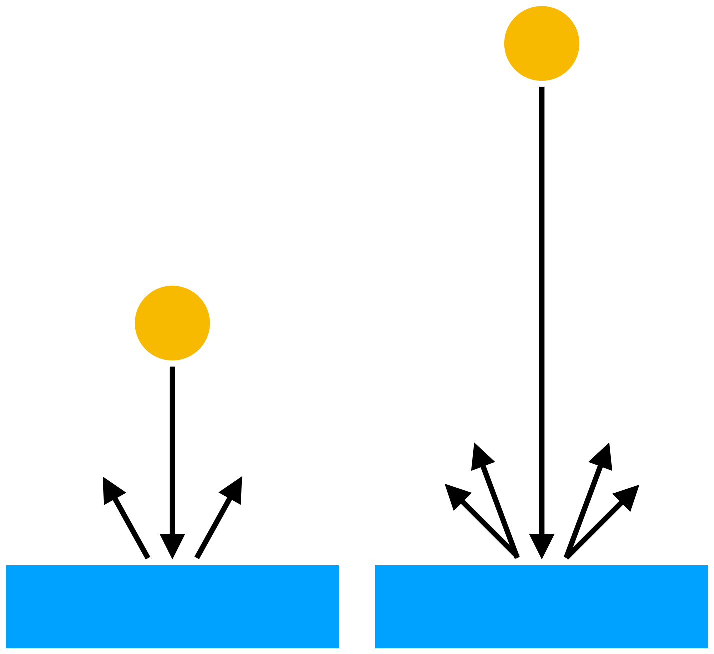
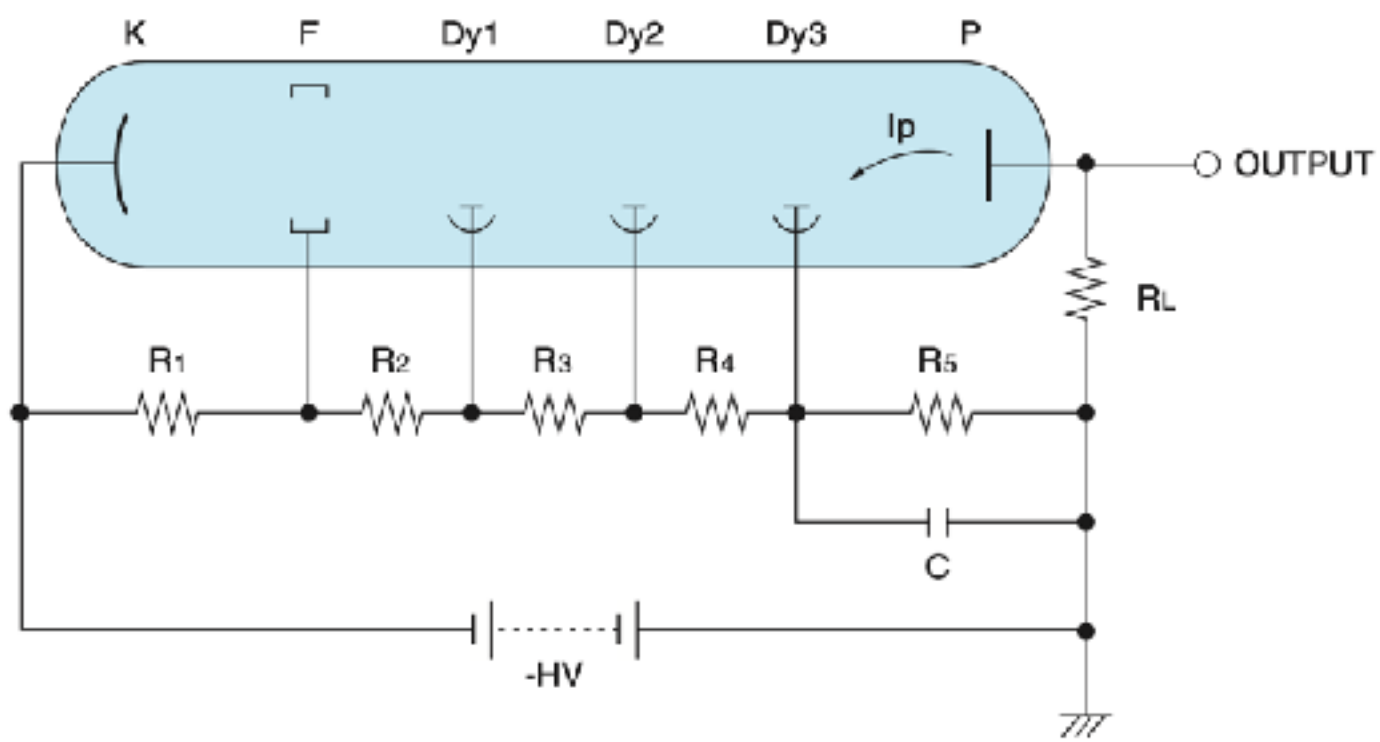


Figure 2-7: Secondary emission ratio





THE

Figure 3-3: Basic photomultiplier tube operation using a voltage-divider circuit

- The number of photoelectron ~ 1000
- Multiplication ~ 10^5 -> 10^8 electron
- Can we measure?

Electron Counting

How many electron do we need?

Ammeter can measure about 1μA. How many electron?

$$1\mu\mathrm{A} = \frac{10^{-6}}{1.6 \times 10^{-19}}\ \mathrm{e/s} = 6 \times 10^{12}\ \mathrm{e/s}$$

We can see→ 0.1s

6×10^{11}electron is needed to “See”

10^8 is not enough to “See”

10^8 electron pass in 10ns.

Current = Charge/ Time

$1.6\times10^{-19} \times 10^8 / (10 \times 10^{-9}) = 1.6$ mA

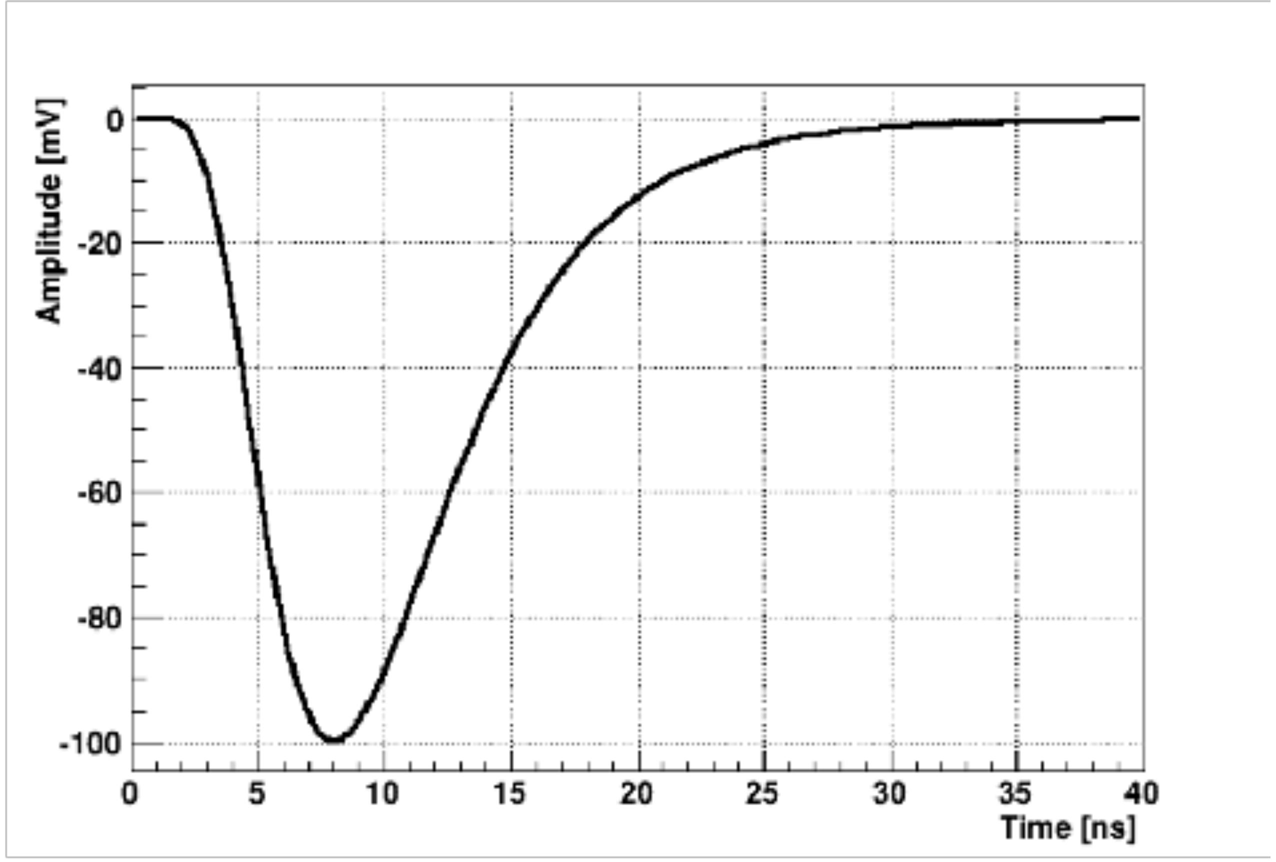
Cannot see in Ammeter but can be detected by electronics.

Electronics can measure voltage.

Current to Voltage

1.6mA x 50Ω = 80mV

Why 50Ω？



- Scintillation -> Acceptance -> Quantum efficiency
- The number of photoelectron ~ 1000

expected to be Poissonian, namely:

$$P_{n,\mathrm{ph}} = \frac{\lambda^n e^{-\lambda}}{n!},$$

where λ is the mean number of emitted photons.

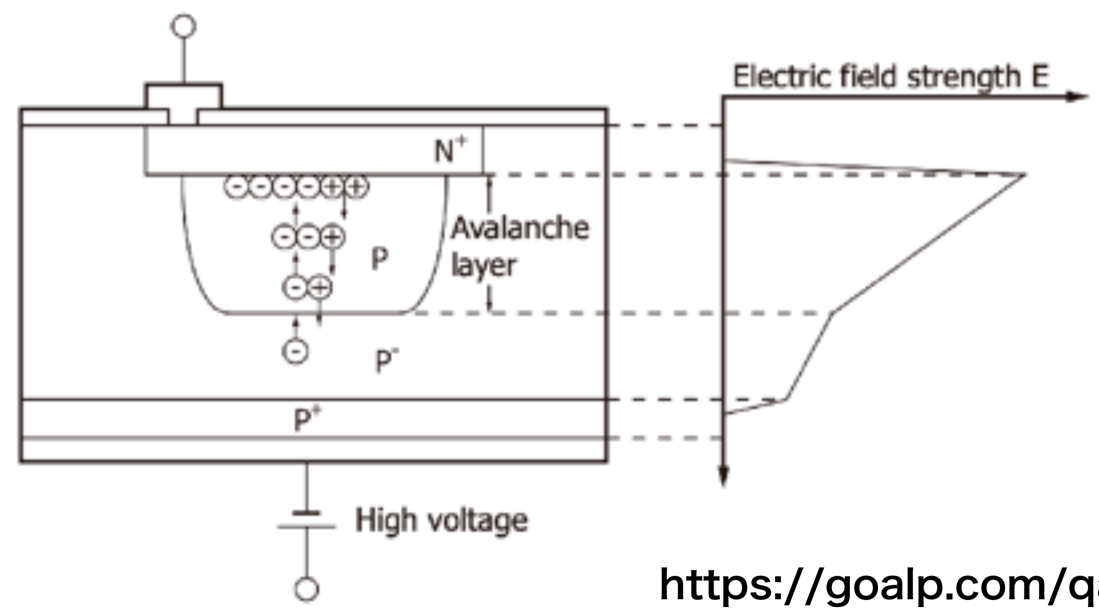
- Each process is Poisson distribution = convolution of Poisson is Poisson

MPPC (SiPM)

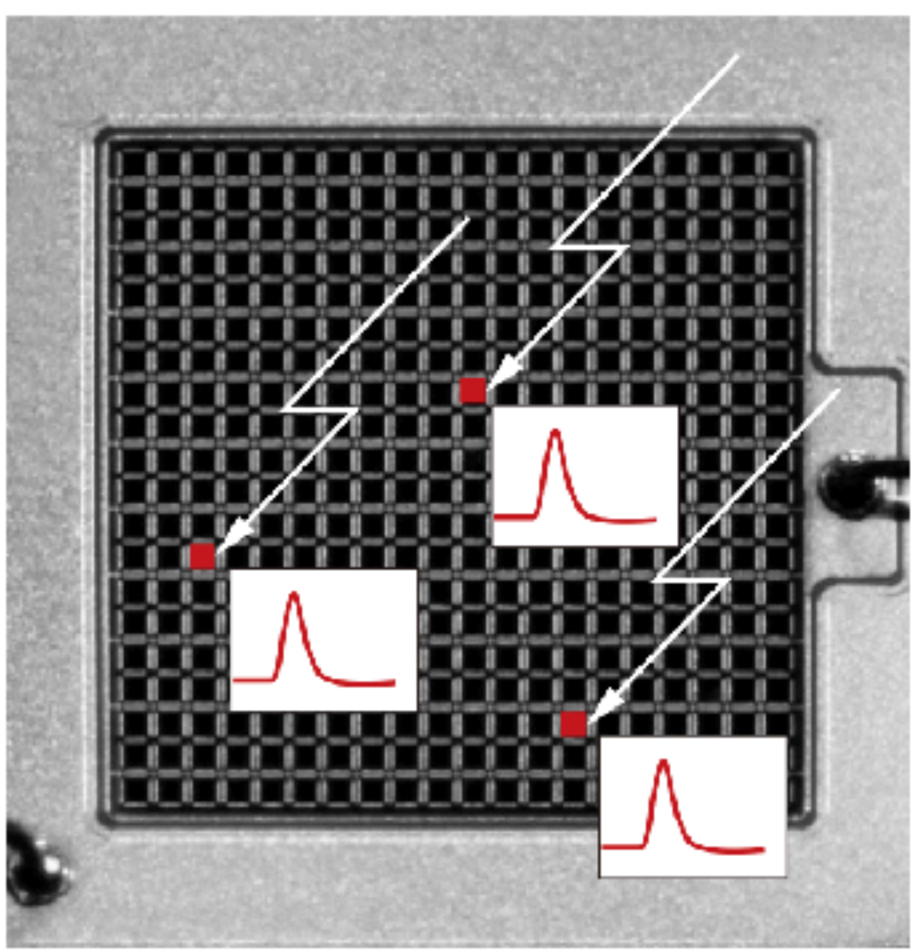
Multi-Pixel Photon Counter (MPPC), also known as silicon photomultiplier (SiPM)

https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/si-apd_kapd9007e.pdf
https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/mppc_kapd9008e.pdf

[Figure 1-1] Schematic diagram of avalanche multiplication (near infrared type)



[Figure 1-2] Image of MPPC's photon counting

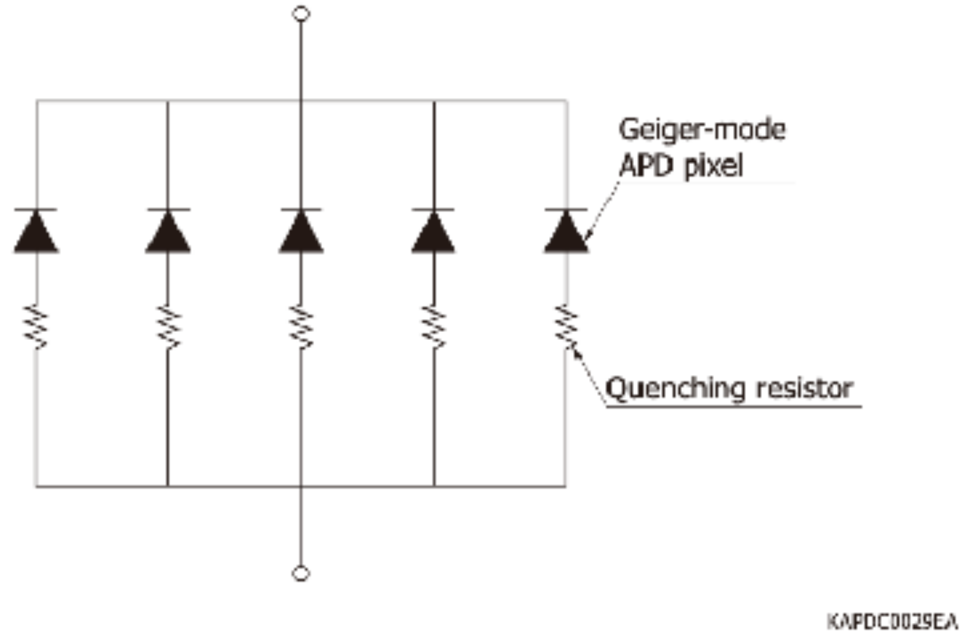


KAPDC0049EA

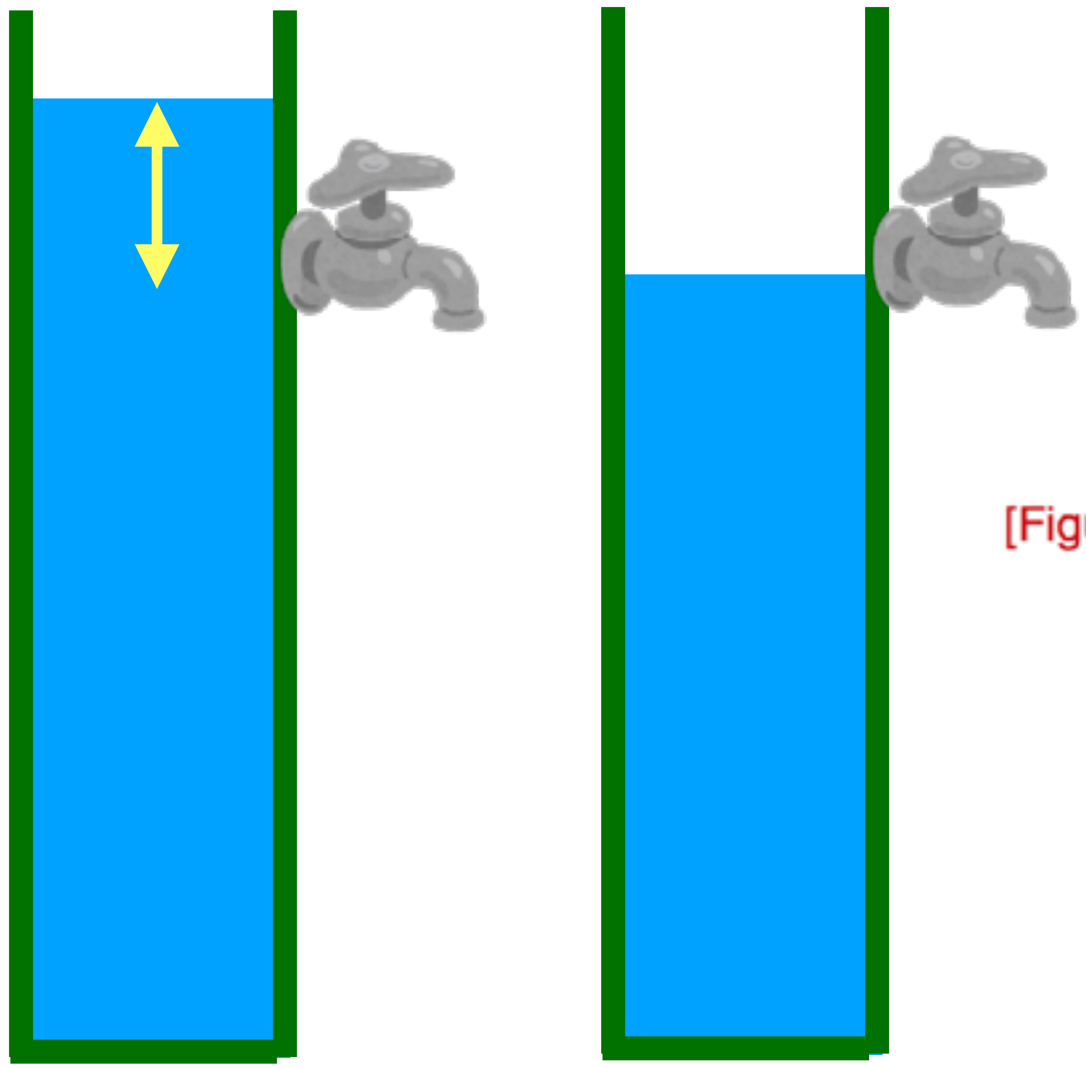
https://goalp.com/qa-139

Figure 1-1 shows a structure of an MPPC. The basic element (one pixel) of an MPPC is a combination of the Geiger mode APD and quenching resistor, and a large number of these pixels are electrically connected and arranged in two dimensions.

[Figure 1-1] Structure

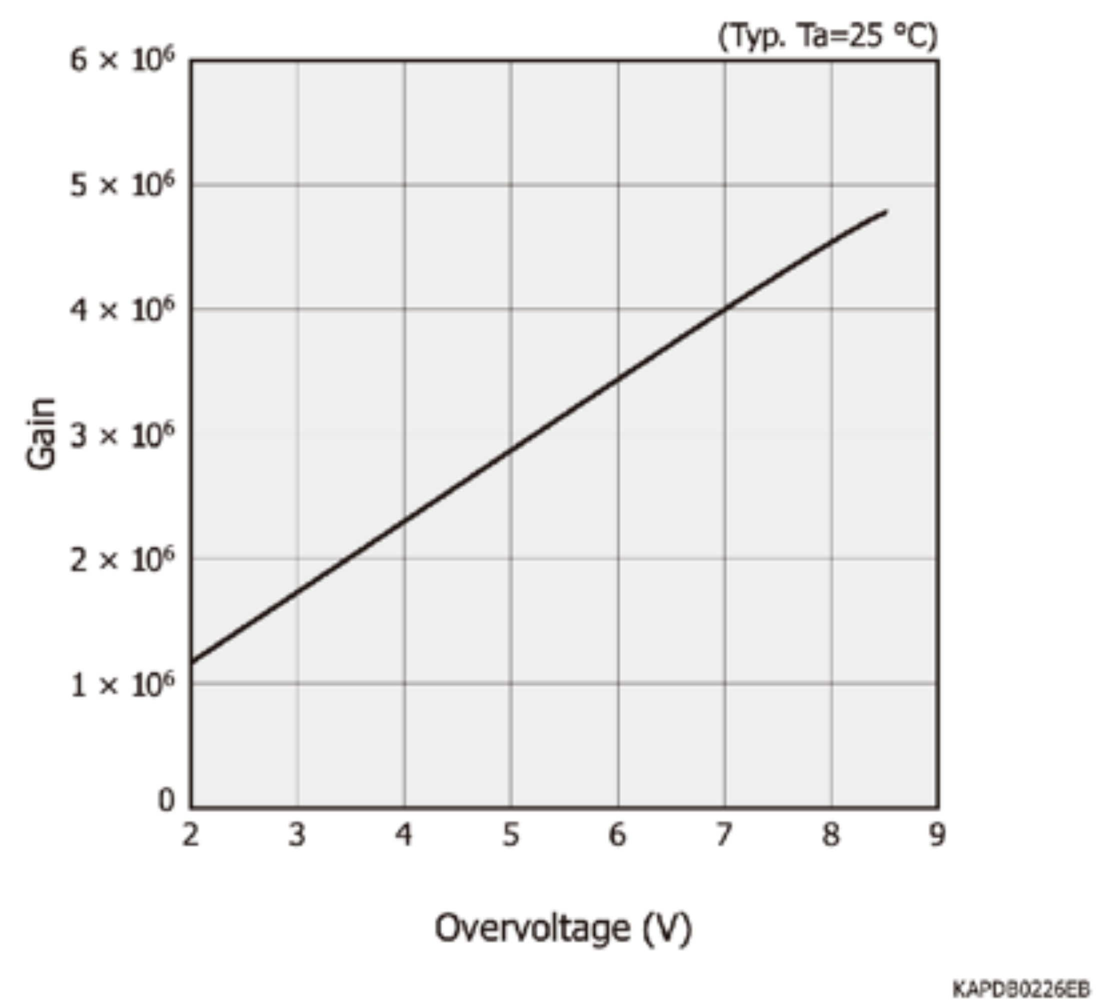


overvoltage



$$Gain = \frac{C\ \Delta V}{q_e},$$

[Figure 3-1] Gain vs. overvoltage (pixel pitch: 50 μm)



Too high gain (huge avalanche)
destroy the device

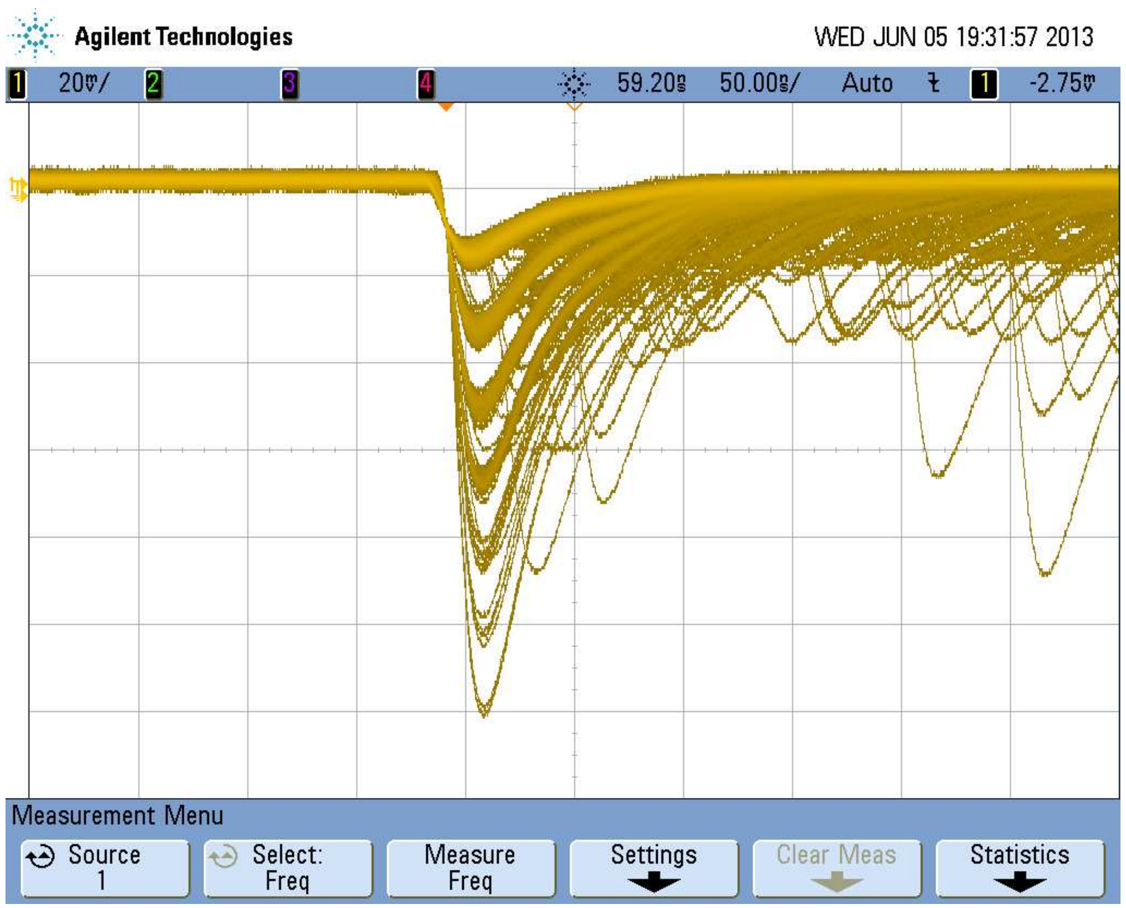


Fig. 1: Response of a SiPM Hamamatsu MPPC S10362-11-100C illuminated by a light pulse.

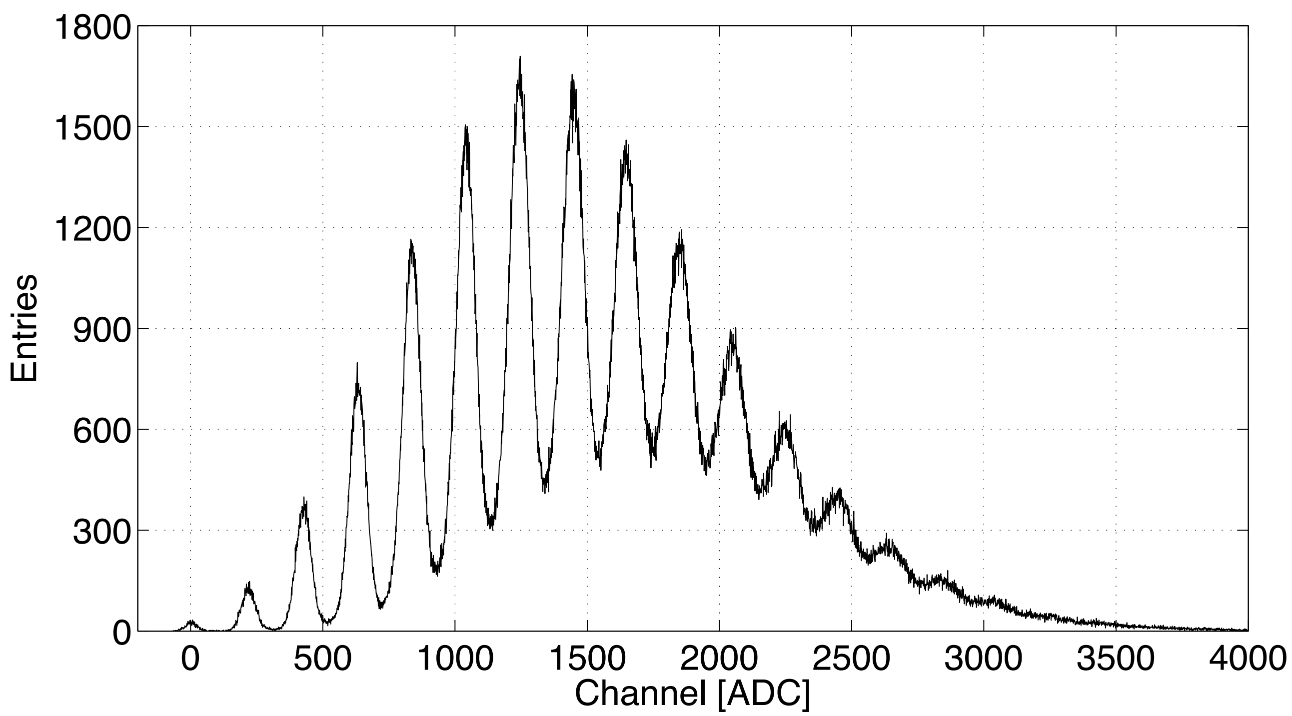


Fig. 2: Photoelectron spectrum probing a LED source measured with a Hamamatsu MPPC S10362-11-100C at a bias voltage of $70.3V$ and temperature of 25^oC.

CAEN EducationalNoteED3127

The number of pixel is finite.
The number of photon is large, the number of pixel is not proportional.

When some pixels are already occupied, a photon has chance to hit occupied pixel. The probability of adding one more hit is the same as the probability of vacancy. Here, we discuss about a MPPC which has M pixels.

1 Occupancy

When m pixels are vacant, the probability of hitting vacant pixel is $\gamma = m/M$. When one more photon hits, the number of vacancy decreases to $m - \gamma$. Since $m = M\gamma$, the vacancy decreases to $(M-1)\gamma$.

n hit causes $M - m_n$ occupied pixels, and γ_n. Them,

$$m_{n+1} = m_n - \gamma_n \quad (1)$$

$$M\gamma_{n+1} = (M-1)\gamma_n \quad (2)$$

$$\gamma_{n+1} = \frac{M-1}{M}\gamma_n \quad (3)$$

Since $\gamma_0 = 1$,

$$\gamma_n = \left(\frac{M-1}{M}\right)^n = e^{-\alpha n} \quad (4)$$

Here

$$\alpha = -\log\left(\frac{M-1}{M}\right) \sim \frac{1}{M} \quad (5)$$

Then, the number of occupied pixels is

$$M - m_n = M - M\gamma_n = \left(1 - \left(\frac{M-1}{M}\right)^n\right) M = \left(1 - e^{-\alpha n}\right) M \quad (6)$$

SiPM in eazyPET has 400 pixel.