CHAPTER 1

INTRODUCTION

1.1 Overview of This Manual

The following provides a brief description of each chapter in this technical manual.

Chapter 1 Introduction

Before starting to describe the main subjects, this chapter explains basic photometric units used to measure or express properties of light such as wavelength and intensity. This chapter also describes the history of the development of photocathodes and photomultiplier tubes.

Chapter 2 Basic Principles of Photomultiplier Tubes

This chapter describes the basic operating principles and elements of photomultiplier tubes, including photoelectron emission, electron trajectories, electron multiplication by use of electron multipliers (dynodes), and anodes.

Chapter 3 Basic Operating Methods of Photomultiplier Tubes

This chapter is aimed at first-time photomultiplier tube users. It describes how to select and operate photomultiplier tubes and how to process their signals.

Chapter 4 Characteristics of Photomultiplier Tubes

Chapter 4 explains in detail the basic performance and various characteristics of photomultiplier tubes.

Chapter 5 How to Use Photomultiplier Tubes and Peripheral Circuits

This chapter describes how to use the basic circuits and accessories needed for correct operation of photomultiplier tubes.

Chapter 6 Photon Counting

Chapter 6 describes the principle, method of use, characteristics and advantages of photon counting used for optical measurement at very low light levels where the absolute amount of light is extremely small.

Chapter 7 Scintillation Counting

Chapter 7 explains scintillation counting with photomultiplier tubes for radiation measurement. It includes descriptions of characteristics, measurement methods, and typical examples of data.

Chapter 8 Photomultiplier Tube Modules

This chapter describes photomultiplier tube modules (PMT modules) developed to make photomultiplier tubes easier to use and also to expand their applications.

Chapter 9 Position Sensitive Photomultiplier Tubes

Chapter 9 describes multianode position-sensitive photomultiplier tubes and center-of-gravity detection type photomultiplier tubes, showing their structure, characteristics and application examples.

Chapter 10 MCP-PMT

This chapter explains MCP-PMTs (photomultiplier tubes incorporating microchannel plates) that are high-sensitivity and ultra-fast photodetectors.

Chapter 11 HPD (Hybrid Photo-Detectors)

This chapter describes new hybrid photo-detectors (HPD) that incorporate a semiconductor detector in an electron tube.

Chapter 12 Electron Multiplier Tubes and Ion Detectors

Chapter 12 describes electron multiplier tubes (sometimes called EMT) and ion detectors ideal for mass spectroscopy, showing the basic structure and various characteristics.

Chapter 13 Environmental Resistance and Reliability

In this chapter, photomultiplier tube performance and usage are discussed in terms of environmental durability and operating reliability. In particular, this chapter describes ambient temperature, humidity, magnetic field effects, mechanical strength, etc. and the countermeasures against these factors.

Chapter 14 Applications

Chapter 14 introduces major applications of photomultiplier tubes, and explains how photomultiplier tubes are used in a variety of fields and applications.

1.2 Photometric Units

Before starting to describe photomultiplier tubes and their characteristics, this section briefly discusses photometric units commonly used to measure the quantity of light. This section also explains the wavelength regions of light (spectral range) and the units to denote them, as well as the unit systems used to express light intensity. Since information included here is just an overview of major photometric units, please refer to specialty books for more details.[1) 2)]

1.2.1 Spectral regions and units

Electromagnetic waves cover a very wide range from gamma rays up to millimeter waves. So-called "light" is a very narrow range of these electromagnetic waves.

Table 1-1 shows how spectral regions are designated when light is classified by wavelength, along with the conversion diagram for light units. In general, what we usually refer to as light covers a range from 10^2 to 10^6 nanometers (nm) in wavelength. The spectral region between 350 and 750nm shown in the table is usually known as the visible region. The region with wavelengths shorter than the visible region is divided into near UV (shorter than 350nm), vacuum UV (shorter than 200nm) where air is absorbed, and extreme UV (shorter than 100nm). Even shorter wavelengths span into the region called soft X-rays (shorter than 10nm) and X-rays. In contrast, longer wavelengths beyond the visible region extend from near IR (750nm or up) to the infrared (several micrometers or up) and far IR (several tens of micrometers or up) regions.

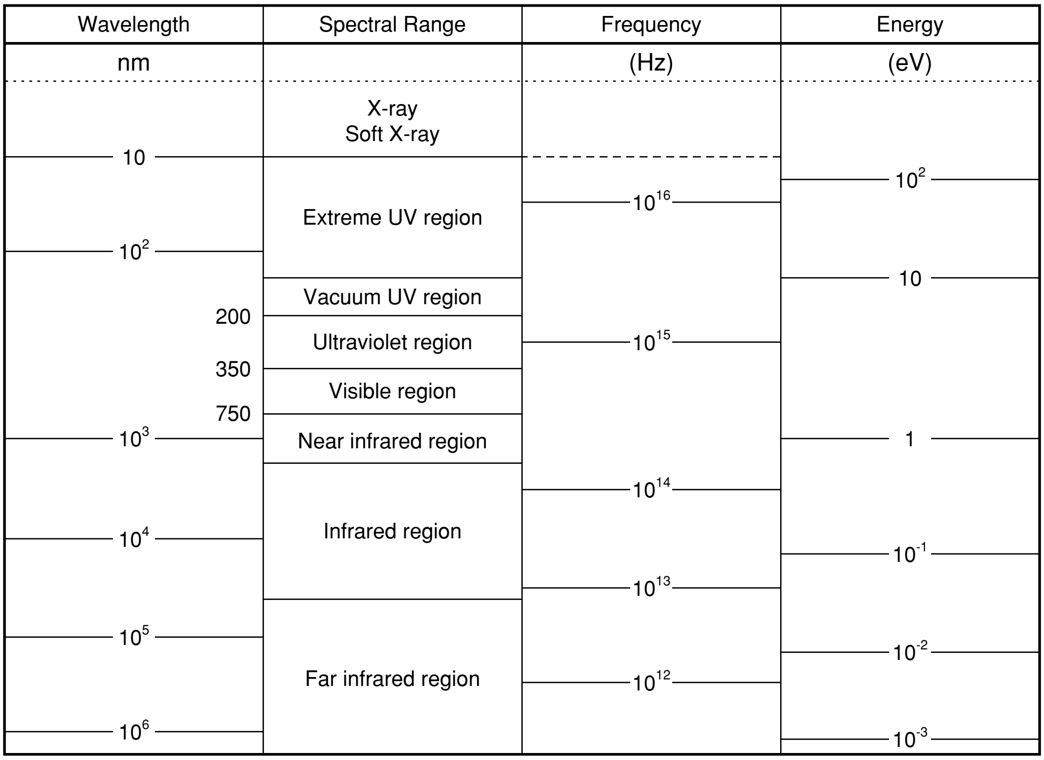

Table 1-1: Spectral regions and unit conversions

Light energy E (J) is given by the following equation (Eq. 1-1).

$$E = h\upsilon = h\cdot\frac{c}{\lambda} \quad \text{(Eq. 1-1)}$$

h : Planck's constant 6.626×10^{-34}(J·s)
υ : Frequency of light (Hz)
c : Velocity of light 3×10^{8}m/s
λ : Wavelength (nm)

Eq. 1-1 can be rewritten as Eq. 1-2, by substituting E in eV, wavelength in nanometers (nm) and constants h and c in Eq. 1-1. Here, 1 eV equals 1.6×10^{-19} J.

$$E(eV) = \frac{1240}{\lambda} \quad \text{(Eq. 1-2)}$$

From Eq. 1-2, it can be seen that light energy increases in proportion to the reciprocal of wavelength.

1.2.2 Units of light intensity

This section explains the units used to represent light intensity and their definitions.

The radiant quantity of light or radiant flux is a pure physical quantity expressed in units of watts (J/s). In contrast, the photometric quantity of light or luminous flux is represented in lumens which correlate to the visual sensation of light.

If the number of photons per second is n and the wavelength is λ, then Eq. 1-1 can be rewritten as Eq. 1-3 from the relation of W=J/S.

$$W = NE = \frac{Nhc}{\lambda} \quad \text{(Eq. 1-3)}$$

Here, the following equation can be obtained by substituting specific values for the above equation.

$$W = \frac{N \times 2 \times 10^{-16}}{\lambda}$$

The above equation shows the relation between the radiant power (W) of light and the number of photons (N), and will be helpful if you remember it.

Table 1-2 shows comparisons of radiant units with photometric units (in brackets [ ]). Each unit is described in subsequent sections.

Quantity	Unit Name	Symbol
Radiant flux [Luminous flux]	watts [lumens]	W [lm]
Radiant energy [Quantity of light]	joules [lumen･sec.]	J [lm·s]
Irradiance [Illuminance]	watts per square meter [lux]	W/m^2 [lx]
Radiant emittance [Luminous emittance]	watts per square meter [lumens per square meter]	W/m^2 [lm/m^2]
Radiant intensity [Luminous intensity]	watts per steradian [candelas]	W/sr [cd]
Radiance [Luminance]	watts per steradian･square meter [candelas per square meter]	$W/sr/m^2$ [cd/m^2]

Table 1-2: Comparisons of radiant units with photometric units (shown in brackets [ ])

1. Radiant flux [Luminous flux]

Radiant flux is a unit to express radiant quantity, while luminous flux shown in brackets [ ] in Table 1-2 and the subhead just above is a unit to represent luminous quantity. (Units are shown this way in the rest of this chapter.) Radiant flux (Φe) is the flow of radiant energy (Qe) past a given point in a unit time period, and is defined as follows:

$$\Phi e = dQe/dt \text{ (J/s)} \quad \text{(Eq. 1-4)}$$

On the other hand, luminous flux (Φ) is measured in lumens and defined as follows:

$$\Phi = km \int \Phi e(\lambda) v(\lambda) d\lambda \quad \text{(Eq. 1-5)}$$

where $\Phi e(\lambda)$: Spectral radiant density of a radiant flux, or spectral radiant flux
km : Maximum sensitivity of the human eye (638 lm/W)
$v(\lambda)$: Typical sensitivity of the human eye

The maximum sensitivity of the eye (km) is a conversion coefficient used to link the radiant quantity and luminous quantity. Here, $v(\lambda)$ indicates the typical spectral response of the human eye, internationally established as spectral luminous efficiency. A typical plot of spectral luminous efficiency versus wavelength (also called the luminosity curve) and relative spectral luminous efficiency at each wavelength are shown in Figure 1-1 and Table 1-3, respectively.

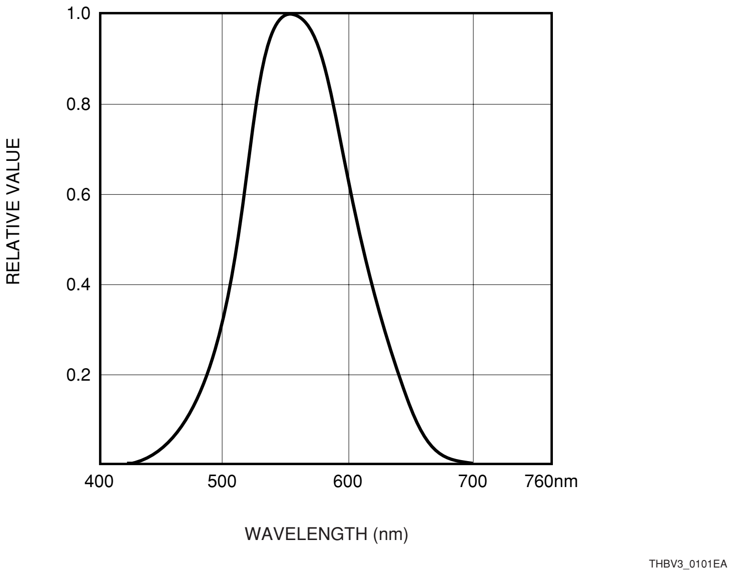

Figure 1-1: Spectral luminous efficiency distribution

Wavelength (nm)	Luminous Efficiency	Wavelength (nm)	Luminous Efficiency
400	0.0004	600	0.631
10	0.0012	10	0.503
20	0.0040	20	0.381
30	0.0116	30	0.265
40	0.023	40	0.175
450	0.038	650	0.107
60	0.060	60	0.061
70	0.091	70	0.032
80	0.139	80	0.017
90	0.208	90	0.0082
500	0.323	700	0.0041
10	0.503	10	0.0021
20	0.710	20	0.00105
30	0.862	30	0.00052
40	0.954	40	0.00025
550	0.995	750	0.00012
555	1.0	60	0.00006
60	0.995		
70	0.952		
80	0.870		
90	0.757		

Table 1-3: Relative spectral luminous efficiency at each wavelength

2. Radiant energy [Quantity of light]

Radiant energy (Qe) is the integral of radiant flux over a duration of time. Similarly, the quantity of light (Q) is defined as the integral of luminous flux over a duration of time. Each term is respectively given by Eq. 1-6 and Eq. 1-7.

$$Qe = \int \Phi e dt \ (W{\cdot}s) \quad \text{(Eq. 1-6)}$$

$$Q = \int \Phi dt \ (lm{\cdot}s) \quad \text{(Eq. 1-7)}$$

3. Irradiance [Illuminance]

Irradiance (Ee) is the radiant flux incident per unit area of a surface, and is also called radiant flux density. (See Figure 1-2.) Likewise, illuminance (E) is the luminous flux incident per unit area of a surface. Each term is respectively given by Eq. 1-8 and Eq. 1-9.

$$\text{Irradiance } Ee = d\Phi e/ds \ (W/m^2) \quad \text{(Eq. 1-8)}$$

$$\text{Illuminance } E = d\Phi/ds \ (lx) \quad \text{(Eq. 1-9)}$$

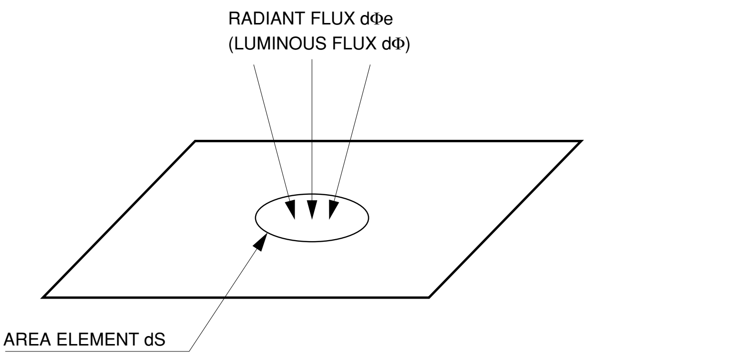

Figure 1-2: Irradiance (Illuminance)

4. Radiant emittance [Luminous emittance]

Radiant emittance (Me) is the radiant flux emitted per unit area of a surface. (See Figure 1-3.) Likewise, luminous emittance (M) is the luminous flux emitted per unit area of a surface. Each term is respectively expressed by Eq. 1-10 and Eq. 1-11.

Radiant emittance $Me = d\Phi e/ds$ (W/m^2) .... (Eq. 1-10)

Luminous emittance $M = d\Phi/ds$ (lm/m^2) .... (Eq. 1-11)

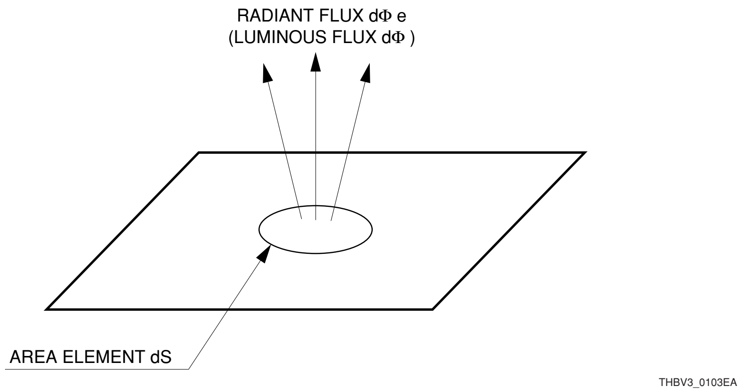

Figure 1-3: Radiant emittance (Luminous emittance)

5. Radiant intensity [Luminous intensity]

Radiant intensity (Ie) is the radiant flux emerging from a point source, divided by the unit solid angle. (See Figure 1-4.) Likewise, luminous intensity (I) is the luminous flux emerging from a point source, divided by the unit solid angle. These terms are respectively expressed by Eq. 1-12 and Eq. 1-13.

Radiant intensity $Ie = d\Phi e/dw$ (W/sr) .... (Eq. 1-12)

Where

Φe : radiant flux (W)
w : solid angle (sr)

Luminous intensity $I = d\Phi/dw$ (cd) .... (Eq. 1-13)

Where

Φ : luminous flux (lm)
w : solid angle (sr)

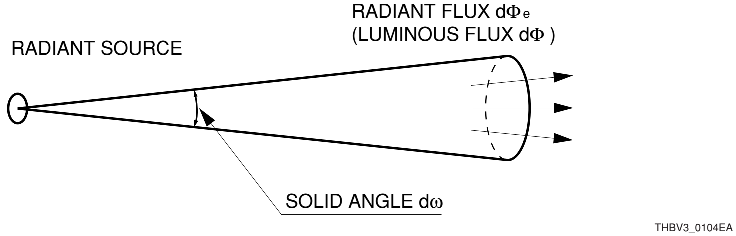

Figure 1-4: Radiant intensity (Luminous intensity)

6. Radiance [Luminance]

Radiance (Le) is the radiant intensity emitted in a certain direction from a radiant source, divided by unit area of an orthographically projected surface. (See Figure 1-5.) Likewise, luminance (L) is the luminous flux emitted from a light source, divided by the unit area of an orthographically projected surface. Each term is respectively given by Eq. 1-14 and Eq. 1-15.

$$\text{Radiance } Le = dIe/ds \cdot \cos\theta \ (W/sr/m^2) \quad \text{(Eq. 1-14)}$$

Where

Ie: radiant intensity
s : area
θ : angle between viewing direction and small area surface

$$\text{Luminance } L = dI/ds \cdot \cos\theta \ (cd/m^2) \quad \text{(Eq. 1-15)}$$

Where

I: luminous intensity (cd)

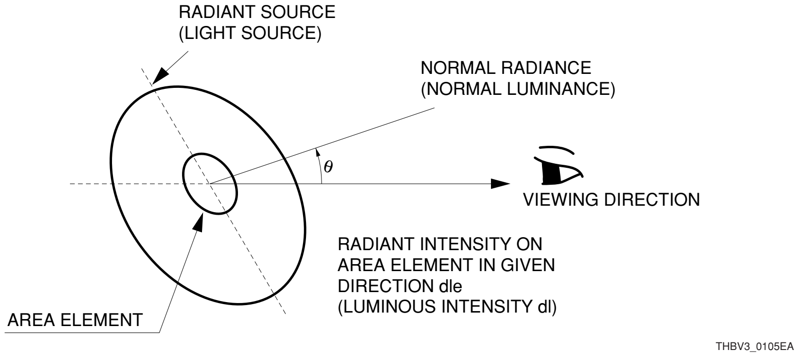

Figure 1-5: Radiant intensity (Luminous intensity)

In the above sections, we discussed basic photometric units which are internationally specified as SI units for quantitative measurements of light. However in some cases, units other than SI units are used.

Tables 1-4 and 1-5 show conversion tables for SI units and non-SI units, with respect to luminance and illuminance. Refer to these conversion tables as necessary.

	Unit Name	Symbol	Conversion Formula
SI Unit	nit stilb apostilb lambert	nt sb asb L	$1nt = 1cd/m^2$ $1sb = 1cd/cm^2 = 10^4 cd/m^2$ $1asb = 1/\pi\ cd/m^2$ $1L = 1/\pi\ cd/cm^2 = 10^4/\pi\ cd/m^2$
Non SI Unit	foot lambert	fL	$1fL = 1/\pi\ cd/ft^2 = 3.426\ cd/m^2$

Table 1-4: Luminance units

	Unit Name	Symbol	Conversion Formula
SI Unit	photo	ph	$1ph = 1\ lm/cm^2 = 10^4\ lx$
Non SI Unit	food candle	fc	$1fc = 1\ lm/ft^2 = 10.764\ lx$

Table 1-5: Illuminance units

1.3 History

1.3.1 History of photocathodes[3]

The photoelectric effect was discovered in 1887 by Hertz[4] through experiments exposing a negative electrode to ultraviolet radiation. In the next year 1888, the photoelectric effect was conclusively confirmed by Hallwachs.[5] In 1889, Elster and Geitel[6] reported the photoelectric effect which was induced by visible light striking an alkali metal (sodium-potassium). Since then, a variety of experiments and discussions on photoemission have been made by many scientists. As a result, the concept proposed by Einstein (in the quantum theory in 1905),[7] "On a Heuristic Viewpoint Concerning the production and Transformation of Light", has been proven and accepted.

During this historic period of achievement, Elster and Geitel produced a photoelectric tube in 1913. Then, a compound photocathode made of Ag-O-Cs (silver oxygen cesium, also called S-1) was discovered in 1929 by Koller[8] and Campbell.[9] This photocathode showed photoelectric sensitivity about two orders of magnitude higher than previously used photocathode materials, achieving high sensitivity in the visible to near infrared region. In 1930, they succeeded in producing a phototube using this S-1 photocathode. In the same year, a Japanese scientist, Asao reported a method for enhancing the sensitivity of silver in the S-1 photocathode. Since then, various photocathodes have been developed one after another, including bialkali photocathodes for the visible region, multialkali photocathodes with high sensitivity extending to the infrared region and alkali halide photocathodes intended for ultraviolet detection.[10-13]

In addition, photocathodes using III-V compound semiconductors such as GaAs[14-19] and InGaAs[20,21] have been developed and put into practical use. These semiconductor photocathodes have an NEA (negative electron affinity) structure and offer high sensitivity from the ultraviolet through near infrared region. Currently, a wide variety of photomultiplier tubes utilizing the above photocathodes are available. They are selected and used according to the application required.

1.3.2 History of photomultiplier tubes

Photomultiplier tubes have been making rapid progress since the development of photocathodes and secondary emission multipliers (dynodes).

The first report on a secondary emissive surface was made by Austin et al.[22] in 1902. Since that time, research into secondary emissive surfaces (secondary electron emission) has been carried out to achieve higher electron multiplication. In 1935, Iams et al.[23] succeeded in producing a triode photomultiplier tube with a photocathode combined with a single-stage dynode (secondary emissive surface), which was used for movie sound pickup. In the next year 1936, Zworykin et al.[24] developed a photomultiplier tube having multiple dynode stages. This tube enabled electrons to travel in the tube by using an electric field and a magnetic field. Then, in 1939, Zworykin and Rajchman[25] developed an electrostatic-focusing type photomultiplier tube (this is the basic structure of photomultiplier tubes currently used). In this photomultiplier tube, an Ag-O-Cs photocathode was first used and later an Sb-Cs photocathode was employed.

An improved photomultiplier tube structure was developed and announced by Morton in 1949[26] and in 1956.[27] Since then the dynode structure has been intensively studied, leading to the development of a variety of dynode structures including circular-cage, linear-focused and box-and-grid types. In addition, photomultiplier tubes using magnetic-focusing type multipliers,[28] transmission-mode secondary-emissive surfaces[29-31] and channel type multipliers[32] have been developed.

At Hamamatsu Photonics, the manufacture of various phototubes such as types with an Sb-Cs photocathode was established in 1953. (The company was then called Hamamatsu TV Co., Ltd. until 1983.) In 1959, Hamamatsu Photonics marketed side-on photomultiplier tubes (931A, 1P21 and R106 having an Sb-Cs photocathode) which have been widely used in spectroscopy. Hamamatsu Photonics also developed and marketed side-on photomultiplier tubes (R132 and R136) having an Ag-Bi-O-Cs photocathode in 1962. This photocathode had higher sensitivity in the red region of spectrum than that of the Sb-Cs photocathode, making them best suited for spectroscopy in those days. In addition, Hamamatsu Photonics put head-on photomultiplier tubes (6199 with an Sb-Cs photocathode) on the market in 1965.

In 1967, Hamamatsu Photonics introduced a 1/2-inch diameter side-on photomultiplier tube (R300 with an Sb-Cs photocathode) which was the smallest tube at that time. In 1969, Hamamatsu Photonics developed and marketed photomultiplier tubes having a multialkali (Na-K-Cs-Sb) photocathode, R446 (side-on) and R375 (head-on). Then, in 1974 a new side-on photomultiplier tube (R928) was developed by Hamamatsu Photonics, which achieved much higher sensitivity in the red to near infrared region. This was an epoch-making event in terms of enhancing photomultiplier tube sensitivity. Since that time, Hamamatsu Photonics has continued to develop and produce a wide variety of state-of-the-art photomultiplier tubes. The current product line ranges in size from the world's smallest 3/8-inch tubes (R1635) to the world's largest 20-inch hemispherical tubes (R1449 and R3600). Hamamatsu Photonics also offers ultra-fast photomultiplier tubes using a microchannel plate for the dynodes (R3809 with a time resolution of 30 picoseconds) and mesh-dynode type photomultiplier tubes (R5924) that maintain an adequate gain of 10^5 even in high magnetic fields of up to one Tesla. More recently, Hamamatsu Photonics has developed TO-8 metal package type photomultiplier tubes (R7400) using metal channel dynodes, various types of position-sensitive photomultiplier tubes capable of position detection, and flat panel photomultiplier tubes. Hamamatsu Photonics is constantly engaged in research and development for manufacturing a wide variety of photomultiplier tubes to meet a wide range of application needs.

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