2. Identification of nuclides by radiation measurement and radioactivity

[Purpose]

Recently, interest in basic knowledge of radiation and its handling methods has been significantly increasing in our everyday life. In particular, the effect of radiation on living organisms has become an important research topic. The purpose of this laboratory session is to understand and obtain basic knowledge of radiation, radioactivity, how to measure them, and how to protect against damage by radiation using counting technique the radiation (β- and γ-rays) emitted from weak radioactive materials. Here, radiation refers to particles and electromagnetic waves emitted by cosmic rays and radioactive materials. Naturally existing heavy nuclides, such as ^{238}U, ^{232}Th, and ^{226}Ra, emit radiation from their nuclei to diminish the excessive number of nucleons and to lower the energy of nuclei. Unstable atoms stabilized by emitting radiation are generally called radioactive materials. The property to emit radiation from unstable nuclei is called radioactivity, and the process of emission is called radioactive disintegration (or decay). In other words, radiation emission is associated with energy flow, and radioactivity refers to the ability to emit radiation as well as to the quantity of radioactive materials present. Radiation is mainly classified into electromagnetic radiation (X- and γ-rays), charged particle beams (*e.g.*, β^--electron, β^+-positron, and proton beams), and uncharged neutron beams. Alpha (α) decay is the process of emitting helium nuclei $^4_2$He (alpha particles); beta (β) decay is the process of emitting electron beams; and gamma (γ) decay is the process of emitting electromagnetic waves.

[Principle]

《Half-life》

The decay of radioactive materials occurs with a certain probability. The number of atoms that decay per unit time is proportional to the number of total atoms of radioactive materials existing at the time of decay. Assuming that the number of atoms at time t is N and the constant of proportionality is λ, the number of atoms decreases by dN between t and $t+dt$, which is expressed by

$$-dN = \lambda N dt \tag{1}$$

Solving this differential equation by assuming that the numbers of atoms are N_0 and $N(t)$ at times 0 and t, respectively,

$$N(t) = N_0 \exp(-\lambda t) \tag{2}$$

where λ means the decay constant unique to each nuclide. In actual measurement, N is determined after subtracting the natural count measured in the absence of a target sample to eliminate background radiation.

The half-life ($T_{1/2}$) is the amount of time required for the number of atoms to fall to half its original value through the decay of a radioactive material. From Eq. (2), the half-life is given by

$$N = \frac{N_0}{2} = N_0 \exp\left(-\lambda T_{1/2}\right) \tag{3}$$

$$T_{1/2} = \frac{\ln(2)}{\lambda} \tag{4}$$

《Absorption coefficient》

Assuming that dN atoms are absorbed by a microsubstance with a thickness of dx per second and the constant of proportionality is μ, similar to that in the equation for half-life, we obtain

$$-dN = \mu N dx \tag{5}$$

Solving this differential equation for N, we obtain

$$N(x) = N_0 \exp(-\mu x) \tag{6}$$

which represents the number of atoms obtained after subtracting the effect of background radiation. Here, μ [m^{-1}] is the absorption coefficient unique to each material. By modifying Eq. (6) and taking the natural logarithm of both sides, we obtain

$$\ln \frac{N(x)}{N_0} = -\mu x \qquad \therefore N(x) = -\mu x + \ln N_0 \tag{7}$$

which describes a linear relationship. The slope of the plot of the natural logarithm of counting rate is the absorption coefficient, which corresponds to the shielding efficiency, μ, and the y-intercept ($\ln N_0$) is the radiological dosage emitted

by the radiation source.

《Derivation of radioactivity by fixed geometry counting method》

The relationship between the measured counting rate per second n_0 (obtained after correction of background radiation and the effects of absorption by a shielding material and air) and the radioactivity of the radiation source (disintegration rate, D) is given by

$$D = \frac{n_0}{G \cdot (1 - A_s) \cdot (1 + s_b) \cdot (1 + s_h)} \tag{8}$$

where G is the geometric efficiency given by the ratio of the solid angle (between the radiation source and the detector) to the all solid angle (4π). When the size of the radiation source is negligible, G is given by

$$G = \frac{1}{2}\left(1 - \frac{d}{\sqrt{d^2 + R^2}}\right) \tag{9}$$

where R is the radius of the incident window of the detector and d is the distance between the radiation source and the detector. A_s is the self-absorption coefficient used to correct the absorption of radiation by the radiation source itself. Note that the estimation of the level of self-absorption is extremely difficult, and the use of a radiation source for which one can assume $A_s \rightarrow 0$ is preferable. The term S_b represents the effect of backscattering. β^--rays experience some backscattering from the bench on which the radiation source is fixed and then enter the detector. By this mechanism, the count of the detector exceeds the original count, which should be corrected. The term S_h represents the contribution of scattering by the surrounding materials including walls and air.

The fixed geometry counting method has been widely used for the measurement of radioactivity because the equipment and the calculation are simple. However, the estimation of correction terms is difficult as explained above and the measurement accuracy is not high.

[Laboratory apparatus, instruments, and reagents]

《On laboratory bench (Experiments A and B》				
Radiation measurement apparatus KCR-200 (main body)	1	,	Radiation source（β^--ray source）	1
Laboratory bench KE-300	1	,	Absorver（Al, Cu, and W plates）	1 each
β-ray detector (semiconductor detector) CSB-02	1	,	PC used for analysis（Excel）	1

《On laboratory bench （Experiment C）》				
Radiation measurement apparatus KCR-200 (main body)	1	,	Radiation source（γray source）	1
Laboratory bench KE-300	1	,	PC used for analysis（Excel）	1
γ-ray detector （CsI-scintillator）CSX-10	1	,		

《On laboratory bench（Experiment D）》				
Petri dish (with lid)	1	,	Ethanol	1
Sponge	1	,	Cooling fin	1
Black drawing paper	1	,	Flashlight	1
Radiation source（β^--ray source）	1		Liquid nitrogen	A/R

[Preparation before experiments]

1. Summarize the experimental procedures of assignments A, B-1, B-2, C, and D (for example, in the form of flowchart) in the experimental notebook.
2. Summarize some information on the radiation, for example the type, nature, or characteristics in the experimental notebook.

3. Examine the radiation detectors, especially a semiconductor detector, a GM counter, a scintillation counter, and a cloud chamber, and their principle of measurements, and summarize the difference between beta ray and gamma ray measurements in the notebook.

[Experimental procedures]

You will work in pairs and carry out Experiments A and B on Day 1 and Experiments C and D on Day 2. For Experiments A, B, and C, the same radiation measurement apparatus KRC-200 (main body) will be used; only the detection unit is different for β^-- and γ-rays. Read "Appendix 1. Manual for radiation measurement apparatus (KRC-201)" carefully to carry out the experiment efficiently. Record the data on your notebook as described in the Report Form, store the data on a USB memory stick to take home, and use the data to write your report. In principle, a staff member places and changes the radiation sources. You must not touch the radiation source without permission. First, turn on the main body of the KRC-200 and the PC used for analysis. Wait for 5 min for the KRC-200 to stabilize before starting the measurement.

A. Dependence of β^--ray intensity on distance

In this section, the dependence of radiation intensity on distance is determined by changing the distance between the radiation source and the detector. This measurement is very important from the viewpoint of radiation protection in the case of radiation leakage. Fully understand the significance of the measurement and carry out the measurement efficiently according to the following procedure.

1. Arrange the experimental system as shown in Fig. 1
2. Without a radiation source present, measure the background counting rate three times (1 min. each) and calculate the average counting rate. (Place the radiation source far from the detector and your body and touch the radiation source for the shortest possible time.) The counting rate obtained is also used in the assignment B.

1st	2nd	3rd	Average

3. Change the distance between the radiation source and the detector (L) from 1.0 mm to 15 mm along the grid on the section paper according to the sheet below. Measure the counting rate three times (1 min each) and obtain the average counting rate[*1] for each distance.
4. Plot the relationship between the distance L' and the true counting rate[*2] on a scatter diagram using the MS Excel. Note that the true distance between the radiation source and the detector is $L' = L + 6.0$ (mm) because there is a 6.0 mm gap between the entrance and the detection unit of the semiconductor detector (see Fig. 1).

L (mm)	***L'*** (mm)	1st	2nd	3rd	Average	True count rate
1.0						
2.0						
3.0						
4.0						
5.0						

7.0						
10.0						
15.0						

5. Obtain an approximate curve from the experiment data using the power function $y = x^n$ and Excel to determine the relationship between L' and true counting rate.

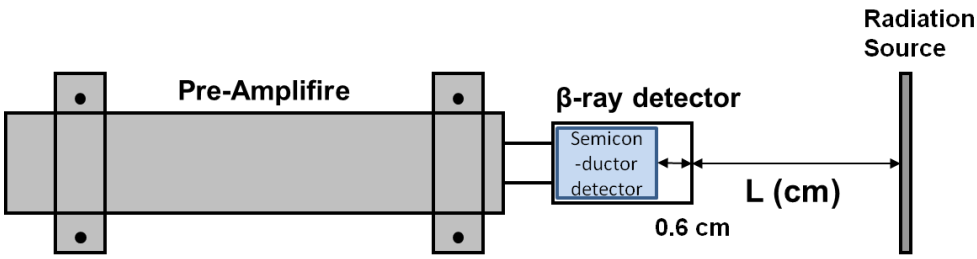


Fig. 1. Schematic of experimental system for Experiment A

*1 《Measurement method》 The control panel of the KRC-200 (main body) is shown in Fig. 7.

1) Confirm that switch ⑩ is on "DISC" and set the DISCRI dial ⑧ to 1.0.

2) Press the start button ③ to start measurement. The measurement stops when the lamp above the button turns off after the lapse of preset measurement time (1 min in this experiment). The measurement time can be set using the timer preset dial ⑦. Confirm that dial ⑦ is set to "1 min (or 60 sec)"; if not, set this value using the precision screwdriver provided. Ask a staff member if you have any questions.

*2 The true counting rate means the counts per second (cps) obtained by subtracting the mean background counting rate from the mean counting rate in the presence of the radiation source and dividing the counting rate by measurement time (60 s).

B-1. β^--ray and shielding effect

In this section, the attenuation of a radiation dose is measured by placing metal shielding plates of varying thickness between the radiation source and the detector. This measurement is important from the viewpoint of selecting appropriate materials for use to shield against radiation. In addition, the radioactivity of a radiation source is obtained from the results of this measurement. Carry out the measurement as described below. Through the experiment in this section, you will learn how to select an appropriate material to prevent radiation leakage and understand the difference between radiation and radioactivity. You will carry out two exercises described in Experiments B-1 and B-2.

6. Arrange the experimental system as shown in Fig. 2. The distance between the radiation source and the detector should be fixed value of L = 1.0 – 2.0 mm: the distance allows for the placement of a shielding plate between the detector and the radiation source. Insert the shielding metals in the space between the radiation source and the detector
7. Place shielding plates (aluminum, copper, or tungsten plate) of varying thickness between the detector and the radiation source. Measure the intensity of β^-ray three times (1 min each) and obtain the true counting rate from the average intensity of the β^--ray. Carry out the measurement starting with the thinnest shielding plate. For example, use shielding plates with thicknesses of 0.1, 0.2, 0.3, 0.4, 0.5, 0.7, 1.0 mm … in this order according to the sheet below, and continue taking measurements until the change in intensity becomes almost constant. In particular, measurements using aluminum plates with a thickness interval as small as possible are preferred considering

Experiment B-2.

8. Using the MS Excel, plot the relationship between the thickness of the shielding plate (aluminum, copper, or tungsten plate) and the natural logarithm of the true counting rate on a scatter diagram. The relationship can be approximated by a linear function expressed by Eq. (7) in [Principle]. Calculate the absorption coefficients of aluminum (μ_{Al}), copper (μ_{Cu}), and lead (μ_{Pb}) from the slope of each approximate curve. When two slopes are obtained (i.e., a curve is obtained), carry out a linear approximation only using several counting rates obtained for thin shielding plates (the portion with a large slope). The background counting rate obtained in Experiment A-2 can be used in this experiment.

Thickness (mm)	1st	2nd	3rd	Average	Count rate n	Natural Log LN(n)
0.1						
0.2						
0.3						
0.4						
0.5						
0.7						
1.0						

9. Suggest the most appropriate material for use as a shield by comparing the absorption coefficients of the three materials examined in this study and discuss the reason for your choice.

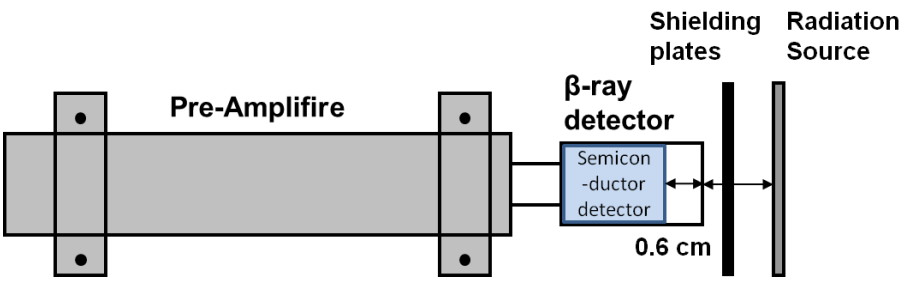


Fig. 2. Schematic of experimental system for Experiment B

B-2. Calculation of radioactivity

In this section, the radioactivity of a radiation source is derived from the relationship between the thickness of an aluminum plate and the true counting rate obtained in Experiment B-1. Radioactivity is the ability to emit radiation and is defined by the number of total radiation events per second or by the disintegration rate [unit, Becquerel (Bq)]. There are several methods of estimating radioactivity. Here, you will learn the fixed geometry counting method. Although, the accuracy of this method is not high, radioactivity can be obtained by a relatively easy correction.

10. Convert the thickness of the aluminum plate (mm) used in Experiment B-1 to surface density [g cm^{-2}]. Here, (surface density) = (true thickness) × (density). The density of aluminum is 2.69 g cm^{-3}. This conversion is carried out because the absorption coefficient with respect to the mass of a material that shields against β^--rays is independent of the identity of the material, and the absorption of β^--rays by various materials can be handled

uniformly.

11. The β^--rays observed in Experiment B-1 are absorbed not only by the aluminum plate but also by the surrounding air molecules and attenuate. Assuming that the density of air is 1.29 mg cm^{-3} that the distance between the radiation source and the entrance of the detector is L (= 0.3) [cm], the surface density of air is 1.29 × (L + 0.6) [mg cm^{-2}]. (The distance between the entrance and the detection unit of the semiconductor detector is 0.6 cm.) The surface density of all materials that shield against β^--rays is obtained by adding the surface density of air to that of aluminum obtained in step 1. Plot the relationship between the surface density of all shielding materials (aluminum and air) (x-axis) and the natural logarithm of counting rate on a scatter diagram using the MS Excel.

Fig. 4. DISCRI dial ⑧ (The number in the upper window is the digit in the ones place and the number on the dial is the digit in the tenths place.)

12. The y-intercept obtained by approximating the plots using the linear function given by Eq. (7) in [Principle] is the true counting rate n_0 of the emission from the radiation source that is not shielded by the aluminum plate or air. Obtain the true counting rate n_0 by this method.
13. You can obtain the disintegration rate D using the true counting rate n_0 per second and Eq. (8) in [Principle]. Calculate D of the radiation source used in this experiment. Radioactivity (Bq) = disintegration/s = the number of atoms whose nucleus decays per second. For Eq. (8) in [Principle], we assume $S_b = 0.5$ and $A_s = S_h \approx 0$. Calculate the geometric efficiency G using Eq. (9). The radius of the incident window of the detector R is 0.5 cm and the distance between the radiation source and the detector d is given by d = (measured value, L) + 0.6 cm.

C. γ-ray energy spectra and identification of radiation source

In this section, you will understand the mechanism of γ-ray emission and the principle of the detector by analyzing the γ-ray energy emitted by ^{137}Cs and ^{22}Na; you will also learn the method of identifying γ-ray nuclides.

14. γ-ray sources ^{137}Cs and ^{22}Na are fixed on each bench as shown in Fig. 3. Each group should move from bench to bench to measure the γ-ray energy spectra of ^{137}C and ^{22}Na according to the conditions summarized in Table 1.[*1, 2]
15. Plot the relationship between the reading values on the DISCRI dial ⑧ (CH, channel) and the counting rate (counts per second) on a scatter diagram using Excel. Do not need to include a table of the numerical data.
16. Observe the shape of the γ-ray energy spectra and discuss their characteristics using the scatter graph, referring to the information in [Appendix].
17. Attach the two γ-ray energy spectra obtained to your report.

CH	Count rate for ^{137}Cs	CH	Count rate for ^{22}Na
1.20		1.1	
1.25		1.2	
1.30		1.3	
1.35		1.4	
・		・	
・		・	
4.15		7.0	
4.20		7.1	

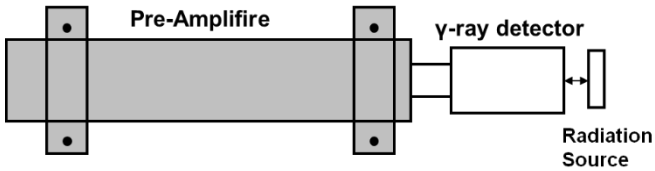


Fig. 3. Schematic of experimental system for Experiment C

*1 《Measurement method》 The central panel of the radiation measurement apparatus KRC-200 (main body) is shown in Fig. 7.

1) Confirm that the switch ⑩ is on "SCA".

2) Press the start button ③ to start measurement. The measurement stops when the lamp above the button turns off after the lapse of the preset measurement time. The measurement time can be set using the timer preset dial ⑦. Confirm that dial ⑦ is set to "40 s".

3) Set the initial value of the DISCRI dial ⑧ (see Fig. 4) and increase the value with an incremental memory step [this memory is called the channel (CH) and corresponds to the γ-ray energy], as summarized in Table 1. Count the γ-rays for every 40 s for each CH.

Table 1 Conditions for obtaining γ-ray energy spectra

Nuclides	Initial value of DISCRI⑧	Memory step	CH numbers
^{137}Cs	1.2 – 4.2	0.05	60
^{22}Na	1.1 - 7.1	0.10	60

*2 To measure ^{137}Cs, start by setting the DISCRI dial ⑧ to 1.2. Increase the value by approximately 0.05 and carry out the measurement for 40 s at 60 CHs (namely, until DISCRI dial ⑧ reaches 4.2). After measuring the first sample, move to another sample.

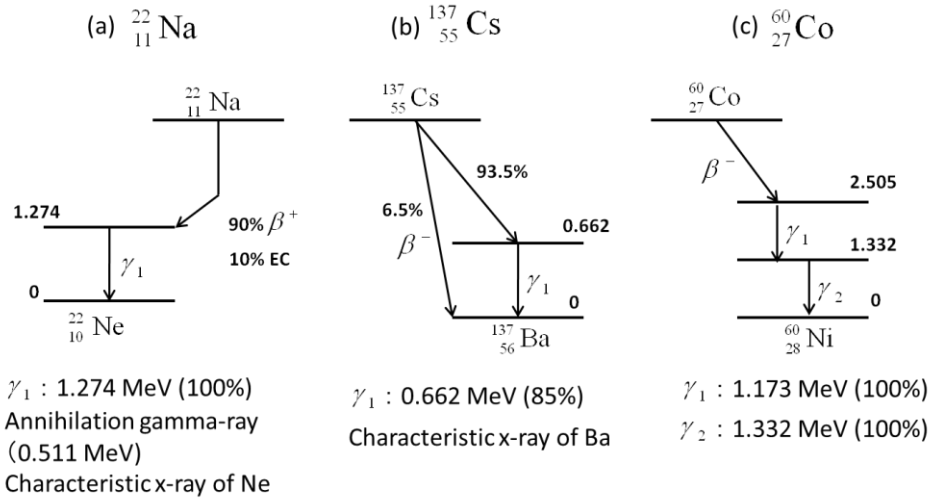


Fig. 5. Radioactive decay diagram of ^{60}Co, ^{22}Na, and ^{137}Cs

*3 《Data analysis》 As described in [Appendix], the CH on the abscissa at which a bell-shaped (Gaussian) peak structure is observed is proportional to the energy of the γ-rays emitted from the radiation source. As the energy of the γ-rays detected increases, a Gaussian peak structure is observed at a higher CH. For example, for the ^{60}Co radiation source, two peaks are observed because two γ-rays, 1.173 and 1.332 MeV, are emitted as shown in Fig. 5. The CH values at which two peak structures are observed correspond to the energies of γ-rays. Discuss the characteristics of the energy spectra of the γ-ray sources, ^{137}Cs and ^{22}Na, on the basis of the CH values at which the two peak structures are observed and Fig. 5. ^{22}Na emits positrons, the antiparticles of electrons, which are collectively called the annihilation radiation [Fig. 5(a)], and therefore emits γ-rays of 0.511 MeV by the annihilation of electrons and positrons.

D. Observation of radiation using cloud chamber

In this section, you will construct a cloud chamber that enables the observation of invisible radiation and therefore observe that radiation. Using the cloud chamber, you can observe the path (trajectory) of radiation that is generally invisible. Each group will construct a cloud chamber following the diagram shown in Fig. 6. You will confirm the presence and type of radiation by observing the trajectory of radiation.

18. Place a circular piece of black drawing paper at the bottom of a Petri dish. Place a sponge of appropriate length inside the Petri dish so that part of its side is open (the inside of the Petri dish is irradiated with a flashlight through this gap).
19. Moisten the sponge and the black drawing paper with an appropriate amount of ethanol to fix the black drawing paper at the bottom of the Petri dish. (Be careful not to put too much ethanol.)
20. A staff member places a radiation source at the center of the Petri dish. Put a lid on the Petri dish and place it at the center of a cooling fin.
21. Cool the bottom of the cooling fin with liquid nitrogen (handled by the staff member).
22. Irradiate the inside of the Petri dish with the flashlight from the gap of the sponge. After 3–5 min, you will observe the trails of radiation around the radiation source.
23. If you cannot observe the trails and mist or water drops are generated in the Petri dish, the Petri dish has been cooled too much. Dry the inside the Petri dish with a dryer and repeat from step 1.
24. Sketch the trails of radiation on your notebook. You will observe trails that are thick and short and others that are thin and long. Discuss the reason for the different trails.
25. If you have enough time, place a filter paper instead of a radiation source in the Petri dish and observe the trails. The provided filter paper has absorbed air molecules in a closed room in a concrete building for approximately 1 hour. Discuss the source of the radiation from the filter paper.

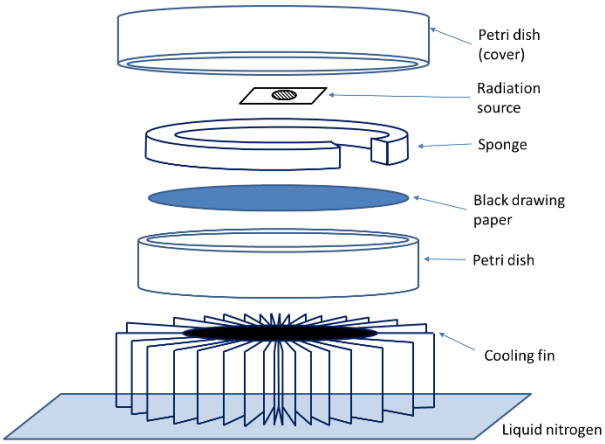


Fig. 6. Preparation of cloud chamber (a staff member handles liquid nitrogen and places a radiation source)

[Notes]

26. The detector is a precision apparatus and reliable results will not be obtained if the detection unit or the main body is damaged. Be careful not to drop or poke the detector.
27. The radiation source used in this experiment is called a sealed source; it is safe because it emits a low-intensity radiation. However, avoid physical contact with the source or handling the radiation source for long periods to prevent external exposure. Do not drink, eat, or do makeup during the experiment to prevent internal exposure. Wash your hands thoroughly after the experiment without fail.
28. Turn off communication devices such as smartphones and mobile phones because they may cause noise. If you must really use these devices, consult with a staff member. Use the MS Excel on a PC or a scientific calculator for calculation.

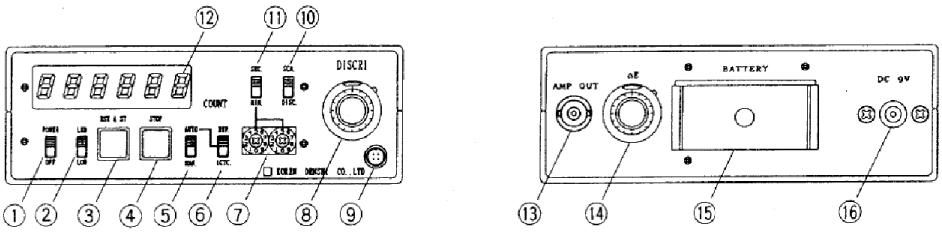
[Appendix]

1. Manual for radiation measurement apparatus (KRC-201)

《Front panel》

29. Power switch ON/OFF

    ON is the measurement state. The battery automatically turns off when an AC adaptor is used. Press the power



1	Power switch	9	Terminal for connection to the detector
2	LED brightness switch	10	SCA / DISCRI selecting switch
3	Reset and start push button	11	Time (MIN / SEC) selecting switch
4	Stop button	12	Counter
5	AUTO/MAN selecting switch	13	Amplifire output
6	REPEAT/ICYC selecting switch	14	Single channel ΔE dial
7	Timer setting	15	Battery case for 9 V
8	Discriminator dial	16	Terminal for DC 9 V IN adapter

Fig. 7. KRC-201

switch and wait **approximately 3 s** before starting the measurement, because the system counts the charge noise of the preamplifier during this time.

30. Turn the LED brightness switch to “bright” for the general experiment when an AC adaptor is used.
31. Reset and start push button. Press the start button to start the measurement.
32. Button for stopping measurement. Use this button to stop the measurement in the manual mode.
33. Switch for selecting “AUT” (active timer set) or “MAN” (manual timer set). For “MAN”, only the reset and start push button is active.
34. Switch for selecting “1CYC” (one measurement by the timer) or “REP” (automatically repeated measurement).
35. Dials for setting the duration of measurement (1 s – 99 min).
36. This dial is active in the “COUNT” mode. Up to 1/500 of a full scale is set as the minimum memory. A 500CH division is used for the SCA measurement for each minimum memory.
37. Terminal for connection to the detector.
38. This switch is active in the “COUNT” mode. DISCRI mode (discriminator mode): Noise counting is carried out at a dial memory of 0.00. The energy at which noise counting stops by turning the dial corresponds to approximately 120 keV. SCA mode (single channel mode): The width of a single channel (ΔE) is set using dial ⑭ on the rear panel. ΔE is preset to 1/10 of the range of the discriminator. Here, the DISCRI dial serves as a lower level discriminator (LLD).
39. Switch for selecting the duration of measurement (“MIN” or “SEC”).
40. Panel for numeric display (six digits, green, and LED display). It lights continuously in the “COUNT” mode.

《Rear panel》

41. BNC connector for amplifier output. This connector is not used in this experiment.
42. Dial for setting the single channel ΔE. This dial has been preset to 0.05-0.10 for this experiment. Do not change the setting unless instructed to do so.
43. Battery case for 9 V dry cells. This case is not used in this experiment.
44. Terminal for DC 9 V IN adaptor. Connect the terminal to an outlet via an AC adaptor.

2. Principle of detector

The radiation detectors used in this experiment are a semiconductor detector (for β-ray measurement) and a scintillation counter (for γ-ray measurement). The operating principles of these detectors are outlined below. Students who wish to study more details may refer to related references.

≪Semiconductor detector (Experiments A and B: β-ray measurement≫

As

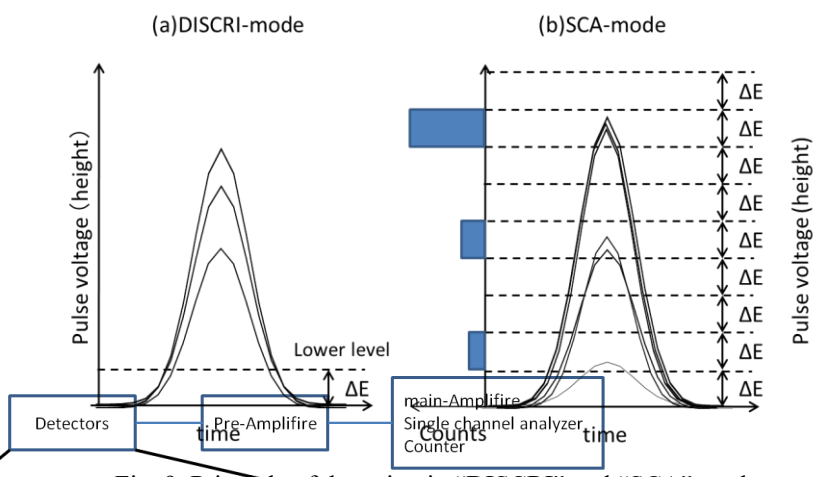


Fig. 9. Principle of detection in "DISCRI" and "SCA" modes

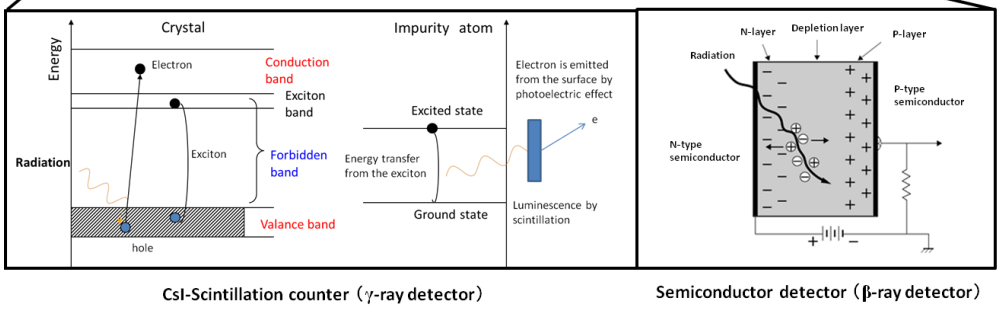


Fig. 8. Principle of detectors and block diagram of detection

shown in Fig. 8 (right), the semiconductor detector detects particles or radiation using semiconductors. Electrons that are ionized by the passage of radiation in the semiconductor detector form electron–hole pairs, which are collected on an electrode by applying a reverse bias electric field. By amplifying and measuring the collected electric charges, the energy lost in the cavity is determined.

≪Scintillation counter (Experiment C: γ-ray measurement≫

As shown in Fig. 8 (left), when an optically transparent crystal [CsI(Tl), cesium iodine containing thallium, in this experiment] is irradiated with charged particles or electromagnetic waves, an excited state of dopant atoms arises as a relaxation phenomenon after excitation and light of a specific wavelength is emitted in some cases. This light can be detected by a radiation detector that converts it into electrical signals by amplifying electrons emitted owing to the photoelectric effect. This type of detector is called a scintillation counter and generally consists of a detection unit (scintillator), a photomultiplier, and a preamplifier. For the detection of γ-rays by the scintillation counter, almost all the energy of the γ-rays entering the scintillator should be transferred to the scintillator through the photoelectric effect described in next section of Appendix. An element of higher atomic number as the scintillator is preferred because the probability of the photoelectric effect increases proportionally to the fifth power of the atomic number.

≪Amplification of signals and counting≫

The electrical signals converted from photoelectrons emitted from the scintillation counter or electric charges emitted from the semiconductor detector are amplified by the preamplifier and detected as voltage signals. The signals called the pulse voltage are identified by the magnitude of voltage (wave height).

"DISCRI" mode in Fig. 9(a): This mode is used to measure the counting rate of all radiations measured in Experiments A and B. In this mode, all voltage pulses with a wave height exceeding a specified value are counted. This mode is used to measure the counting rate of radiation (proportional to radioactivity).

"SCA" mode in Fig. 9(b): This mode is used to determine the energy distribution of radiation as observed in Experiment C. SCA stands for single-channel analyzer. In this mode, the amount of radiation with a wave height equivalent to the pulse voltage within a single channel ΔE can be counted. As the energy of input radiation increases, the wave height of the output voltage from the radiation detector also increases. When the radiation for each CH value is counted by turning the "DISCRI" dial while maintaining ΔE constant in the SCA mode, the energy of radiation that is detected most and therefore the energy distribution of radiation can be determined.

3. Structure of γ-ray energy spectra

In Experiment C, γ-rays with a certain energy are emitted from radioisotopes, ^{137}C and ^{22}Na. The measured γ-ray energy spectra have a common Gaussian peak structure. This finding indicates that the energy of γ-rays emitted from a certain radiation source is converted into voltage signals in a scintillation counter owing to the photoelectric effect described later, and the energy is detected as a voltage with a wave height proportional to the energy as shown in Sec. 2 of Appendix. However, not only the photoelectric effect but also the Compton effect is observed in the detector. The energy of scattered light due to the Compton effect changes continuously with scattering angle. Therefore, the energy spectrum due to the Compton effect continuously distributes in a lower energy region than the peak of a bell-shaped (Gaussian) spectrum due to the photoelectric effect as shown in Fig. 10. The spectrum due to the Compton effect is structured as a result of the scattering of γ-rays with a unique energy emitted from a sample in the detector. Note that the energy specific to the γ-ray is shown as the peak in the spectrum due to the photoelectric effect. From the peak in the spectrum due to the photoelectric effect, the γ-ray energy is determined to identify the radiation source.

≪Photoelectric effect≫

As shown in Fig. 11(a), when a material is irradiated with electromagnetic waves, photons transfer energy to the electrons in the material and ionize it; this is called the photoelectric effect. Part of the energy of the photons is consumed to remove bound electrons from atoms. The consumed energy is called the ionization energy or the work function when the target is an individual atom or the metal surface, respectively. When electromagnetic waves, such as γ-rays and X-rays, are of high energy (in the MeV range), the binding energy (work function) in the eV range is ignored and the kinetic energy of the emitted electrons is considered approximately equal to the energy of the photons.

≪Compton effect≫

The Compton effect as shown in Fig. 11(b) mainly results from the interaction between loosely bound electrons in the outermost

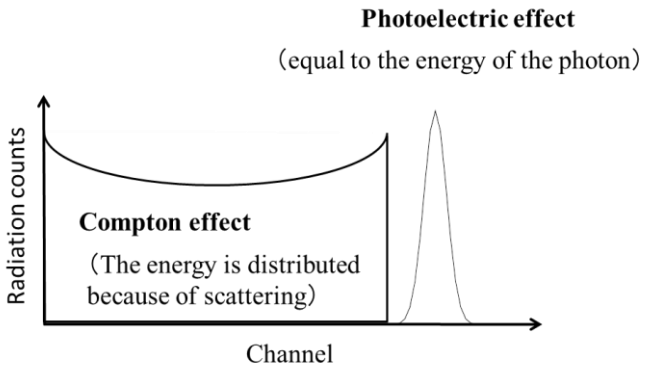


Fig. 10. Energy spectra of γ-rays

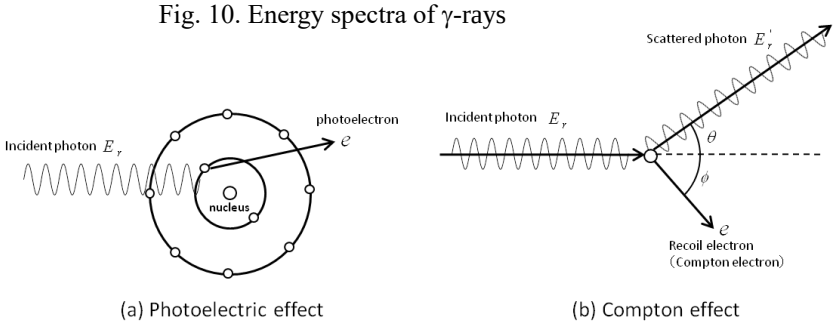


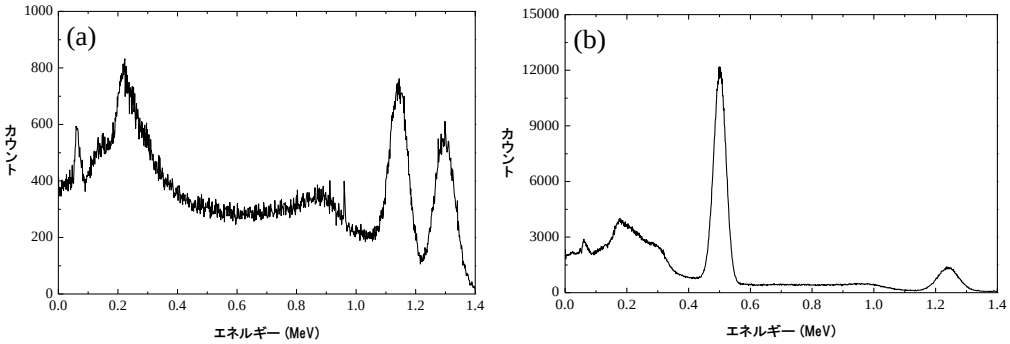
Fig. 11. Interaction between material and γ-rays (electromagnetic waves)

orbital and electromagnetic waves. As a result of the collision between photons and electrons, part of photon energy is given to the electrons. As a result of inelastic collisions, electromagnetic waves are scattered and their energy decreases. In general, photon energy is converted to the kinetic energy of electrons in the photoelectric effect, whereas the kinetic energy of electrons is decreased by an amount corresponding to the energy of scattered waves in the Compton effect; thus, it is possible to distinguish between the two.

[Report assignments]

Summarize not only the experimental results of each tasks but also the objects, experimental principle, procedures, and discussion including the preparations before experiments as the full report. Figures will be made using MS Excel (or similar type of graphical software). Note that in the assignment C, do not need to include the numerical data.

45. Discuss the reason for the measurement of background radiation in Experiments A and B.
46. In the assignment A, what is the relationship between the intensity of radiation (β^--rays) emitted from a radiation source and the distance between the radiation source and the detector?
47. In the assignment B-1, which material is the most appropriate as a shield against radiation (β^--rays)? Discuss the reasons behind your experimental results.
48. Explain the procedure for estimating the radioactivity from the amount of radiation emitted per second (counting rate).
49. Explain the characteristics and shape of the energy spectra of γ-rays emitted from the radioisotopes, ^{137}C and ^{22}Na.
50. When measuring the γ-ray energy spectra emitted from two kinds of radioisotopes, the graphs were obtained as following. Estimate the two kinds of radioisotopes referring Fig. 5. Note that horizontal axis in the figures were already calibrated from CH to "γ-ray energy".



51. Explain the operating principle of cloud chambers.
52. In the assignment D, discuss the difference between thick short and thin long trails from the results of the experiment using the cloud chamber.
53. Discuss protection methods against radiation in case of leakage or accidents on the basis of the results of this experiment.

[References]

[1] G. F. Knoll, Translated by I. Kimura and E. Sakai, Handbook of radiation measurement 4th ed., Nikkan Kogyo Shimbun, Ltd. (2006) (in Japanese).

[2] Y. Kawada, Physical Engineering Experiment 9, Radiation Measurement Technology, University of Tokyo Press (1991) (in Japanese).

Also, consult other references by yourself to study the outlines of radiation measurement.