A β-γ Coincidence Measurement System for Precise Determination of γ-ray Emission Probabilities of Short-Lived FP Nuclides

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For the precise determination of γ-ray emission probabilities of short-lived FP nuclides, a β-γ coincidence measurement system has been developed, which utilizes a thin plastic scintillation detector as a β-ray detector. To demonstrate the performance of the developed system, it was applied to the measurement of absolute γ-ray emission probability I_γ of short-lived nuclide, ^{28}Al ($T_{1/2} = 2.24$ (min)), whose I_γ is well known.

1 Introduction

For the nuclear transmutation study of radioactive waste, it is of fundamental importance to obtain precise nuclear data, such as thermal neutron capture cross sections, σ_0. However, some of the available nuclear data are poor in accuracy. In recent years, many works have been extensively done to improve accuracy of such nuclear data using modern radiation detectors and electronics, usually with the activation method[1].

In a conventional activation method, a sample is irradiated with reactor neutrons and γ rays emitted are measured, and the cross sections are deduced from the γ-ray yields. In the calculation, absolute γ-ray emission probabilities I_γ are used. Therefore, precision of I_γ is one of the major factors which determine the precision of the final result, and it is essential that I_γ is precisely determined.

For nuclides with their half lives longer than several minutes, a $4\pi\,\beta$-γ coincidence method has been successfully applied. However, in this method, a radioactive sample has to be set inside a $4\pi\,\beta$-ray gas flow proportional counter so as to attain β-ray detection efficiency to be close to unity, and it takes a couple of minutes to prepare a sample and to set up a β-ray counting system. It is, therefore, difficult with the method to determine absolute γ-ray emission probabilities of short-lived nuclides, whose half lives are considerably shorter than few minutes.

For precise determination of γ-ray emission probabilities of short-lived nuclides, a β-γ coincidence measurement system has been developed, which utilizes a plastic scintillation counter as a β detector and a fast data acquisition system. In this system, energy and timing information are accumulated in event-by-event mode. By using a plastic scintillator for β-ray detection instead of a $4\pi\,\beta$-ray gas flow proportional counter, the time required for the preparation of the radiation detection equipments is greatly reduced, because there is no need of putting a sample inside a detector and setting up a gas-flow β-ray counting system. It is also essential for efficient measurement of radiation from short-lived nuclei to use a fast data processing system which operates at high counting rates. In addition to these, it is inevitable in such high counting condition to determine dead times precisely to extract true coincidence events unambiguously.

2 The β-γ coincidence System

A schematic diagram of the β-γ coincidence system is shown in Figure 1. The system consists of a Ge γ-ray detector, a plastic scintillation β-ray detector and a fast data acquisition system.

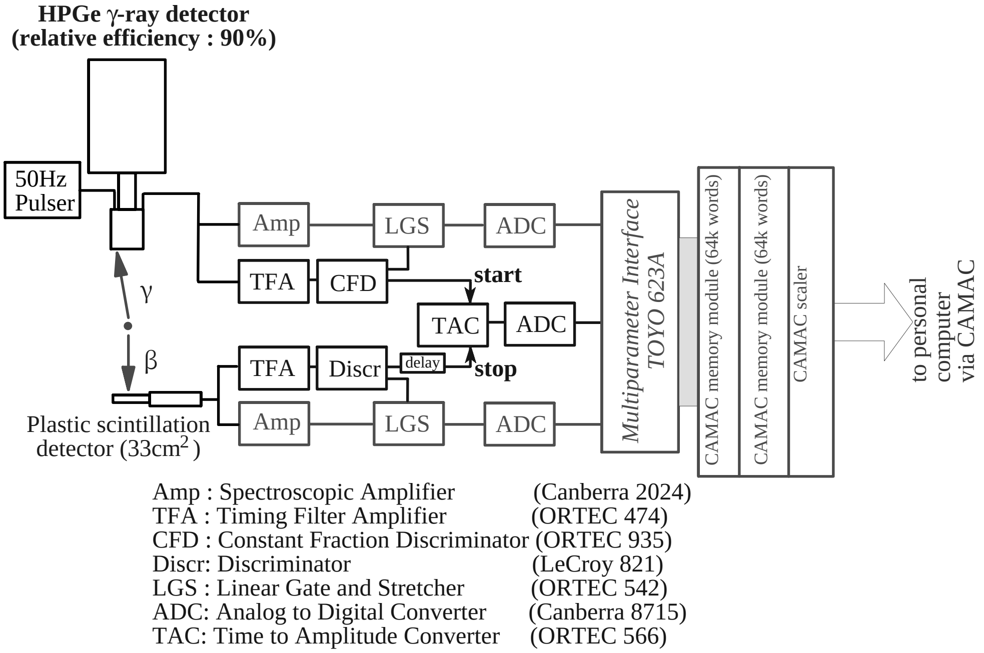

Figure 1: A schematic diagram of the β-γ coincidence system.

A large volume Ge detector whose relative detection efficiency is 90% of that of 7.6 cm×7.6 cm NaI is employed to measure γ rays from short-lived nuclei efficiently. For β-ray detection, a thin and small plastic scintillation detector is used, which is 4 mm in thickness and has an area of 33 cm^2. By using a plastic scintillator as a β-ray detector, the time required for preparation of the irradiated sample and the detection equipments is greatly reduced, and one can efficiently measure radiations from short-lived nuclei. In principle, it is applicable to the measurement of I_γ of a nuclide whose half life is the order of a second.

The energy signal of each detector is fed into an amplifier and then converted by a fast analog-to-digital converter (ADC, Canberra 8715). The timing signal is fed into a discriminator circuit and timing information is extracted. Time difference between the two signals are recorded using a time-to-amplitude converter (TAC) and an ADC. For an efficient measurement of radiations from short-lived nuclei, one should perform a measurement at a high counting rate so as to improve a statistical accuracy. In such a measurement, the TAC information is inevitable to eliminate accidental coincidence events and to extract true number of coincidences.

The data converted by ADCs are processed by a multi-parameter interface module (TOYO 623A) to compose a list of event data. The data are recorded in event-by-event mode to distinguish true coincidence events and to eliminate spurious events such as that caused by accidental coincidence. To reduce dead times in the course of the data acquisition, the data are temporarily accumulated in one of the two memory modules with large capacity (LeCroy MM8206A), which are cyclically connected to operate as a ring buffer, and are transferred to a personal computer for storage when the other memory module is active.

The system is operated in singles trigger condition: when at least one of the two detectors detects a radiation, data of both detectors are stored. The coincidence events are extracted in later off-line analysis.

3 An application to the determination of I_γ in ^{28}Al

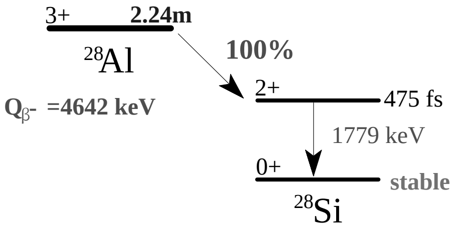

Figure 2: Decay scheme of ^{28}Al.

To demonstrate the system for an actual I_γ determination of a short-lived nuclide, an experiment was done for 1779 keV γ ray of ^{28}Al. Decay scheme of ^{28}Al is shown in Figure 2. The ^{28}Al decays into ^{28}Si with a half life of 2.24 minutes. In the decay, only one γ ray (1779 keV) is emitted, and the I_γ is known to be unity[2]. In this case, I_γ is expressed as

$$I_\gamma = \frac{1}{\epsilon_\gamma}\frac{n_c}{n_\beta}, \tag{1}$$

where ϵ_γ is detection efficiency of the γ ray, n_β is counting rate of β detector, and n_c is counting rate of β-γ coincidence event.

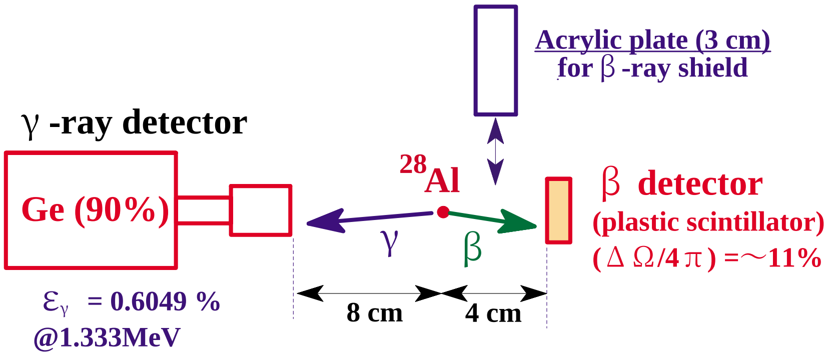

Figure 3: Experimental setup of the I_γ measurement for 1779 keV γ ray in ^{28}Al.

The setup of the experiment is shown in Figure 3. Natural Al foils of 6.76 mg/cm^2 in thickness and 99.0% in chemical purity were irradiated in Rotating Specimen Rack of the research reactor in Rikkyo University. Activity of about 1 MBq was produced by one minute of irradiation, and after cooling of about six minutes, β- and γ-rays were measured for ten minutes. The data were saved every 20 seconds. Measurements were also done with a β-ray shield placed between the irradiated sample and the β detector in order to estimate contribution of γ rays to the β detector. An acrylic plate of 3 cm thickness was used as the β-ray shield.

Shown in upper half of Figure 4 is a typical γ-ray spectrum. As can be seen in the figure, no remarkable γ ray is observed other than 1779 keV γ ray in ^{28}Al. Depicted in lower half of the figure is a decay curve of the 1779 keV γ ray after a correction for dead times. Drawn in the figure in a solid line is a result of fitting the data by a function of the time, t,

$$A\,e^{-\frac{ln(2)}{\tau}\,t} + C, \qquad (2)$$

where A, τ and C are fitting parameters. The τ means a half life. By averaging the values of τ obtained in all runs, a half life was obtained as $T_{1/2} = 2.248 \pm 0.018$ (min), which agrees with that reported in ref.[2] within the errors, and therefore the γ ray was assigned to be originated from ^{28}Al.

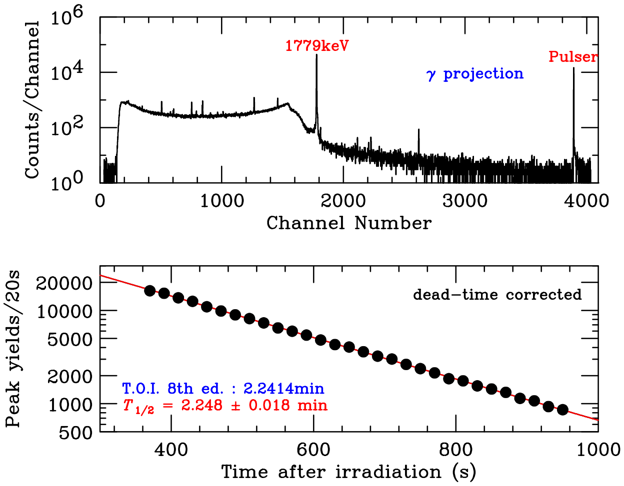

Figure 4: (Upper) : A γ-ray singles spectrum observed in a run. (Lower) : A decay curve of the 1779 keV γ ray in ^{28}Al in the same run, after dead-time correction.

The histogram shown in Figure 5 is a singles β-ray spectrum in a run without the β-ray shield, after subtraction of data in runs with the β shield. A β-ray spectrum obtained by imposing a gate on the 1779 keV γ-ray peak region is also plotted in the figure, which is normalized to the singles one. The singles data deviates from the one gated by 1779 keV γ ray only below about 30 channel, which suggests that there are some events which were not caused by β rays emitted from ^{28}Al. Therefore, lower boundary of summing was varied and the influence to the result was examined when extracting the number of β rays.

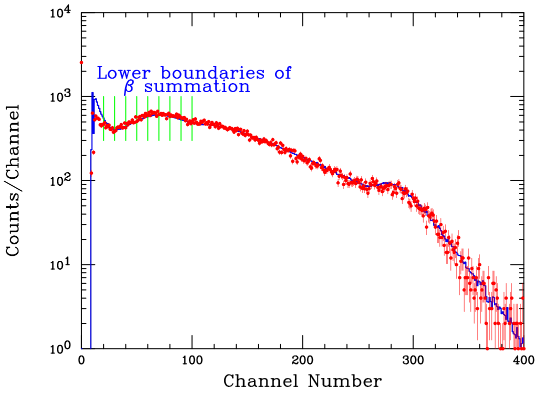

Figure 5: A singles (histogram) and a 1779 keV γ-ray gated (dots) β-ray spectrum in a run.

The number of β rays coincident with the 1779 keV γ ray was deduced by imposing several gates; Γ_P, Γ_H and Γ_L were applied on the γ ray data, while gates T_P and T_O on the TAC data, as shown in Figure 6. Let $n(\Gamma_i, T_j)$ be the number of β counting rate obtained by applying the gates Γ_i and $T_j (i = P, H, L, j = P, O)$ on the γ-ray and the TAC data, respectively. The true β coincidence counting rate n_c is obtained using the following relation,

$$\begin{aligned} n_c = n(\Gamma_P, T_P) \quad &- \quad R \times n(\Gamma_P, T_O) \\ &- \quad R' \left(\frac{n(\Gamma_L, T_P) + n(\Gamma_H, T_P)}{2} - R\,\frac{n(\Gamma_L, T_O) + n(\Gamma_H, T_O)}{2} \right) \end{aligned} \quad (3)$$

where R represents the ratio of width of T_P to that of T_O, and R' the ratio of width of Γ_P to that of Γ_L.

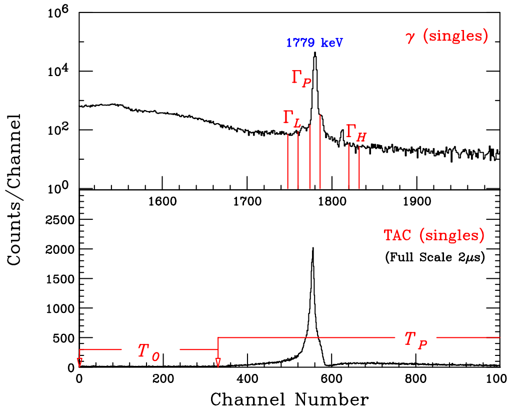

Figure 6: Gates imposed on the γ-ray and TAC data to extract the true number of coincidences.

Shown in Figure 7 are decay curves of β singles (n_β) and coincidence (n_c) counting rates above the 20 channel of β-summing threshold, after the subtraction of data with β-ray shield and the dead-time correction. Dashed lines in the figure represent the result of fitting the data by a function of the same form as in (2), with C and τ fixed at 0 and 2.24 minutes, respectively. A slight deviation is observed in the singles data after about 800 seconds, which seems to be caused by the remaining long life backgrounds. Therefore, the data were fitted with the function (2) and component with half life of 2.24 (min) was extracted. In the fit, τ was fixed at 2.24 minutes and both A and C were varied as free parameters.

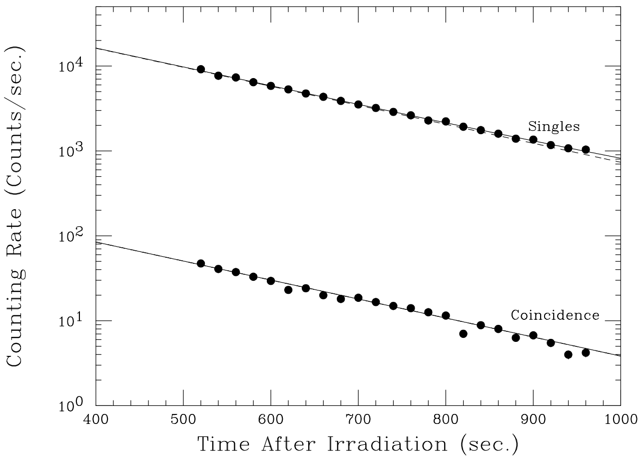

Figure 7: (Points) : Decay curves for β and coincidence channels. (Lines) : Results of the fit with (solid) and without (dashed) a constant term.

From the n_β and n_c obtained as above, I_γ of the 1779 keV γ ray was calculated using the relation (1) for each lower limit of β summation. The γ-ray detection efficiency at 1779 keV was determined using ^{60}Co, ^{137}Cs and ^{152}Eu standard sources. Precision of the efficiency was about 2%. The preliminary values of the obtained I_γ are plotted in Figure 8 against the lower limits of β summation. Errors shown in the figure include all the errors except the one of the γ-ray detection efficiency. Above the 30 channel of β summation limit, the results agree with one another within the errors. The results with errors less than one percent is obtained except an error originated from the determination of ϵ_γ. The obtained results are about two percents smaller than that reported previously [2]. Including the error of the γ-ray detection efficiency, the result agrees with the previous data within the limits of errors.

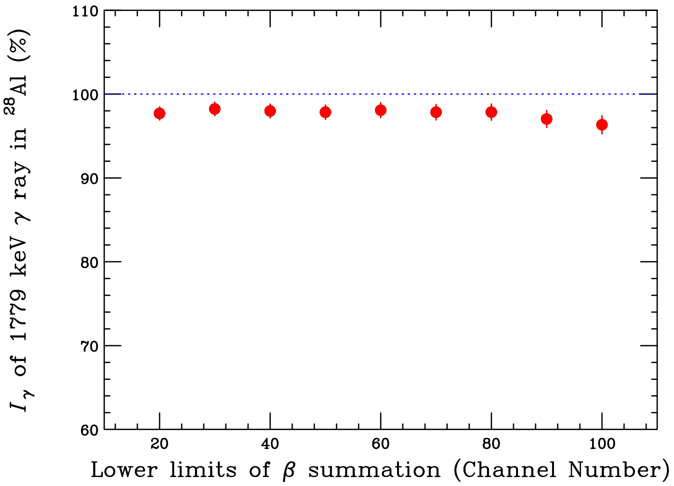

Figure 8: Results obtained in the present experiment for I_γ of 1779 keV γ ray in ^{28}Al.

4 Conclusion

For the precise determination of absolute γ-ray emission probabilities I_γ of short-lived nuclides, a β-γ coincidence measurement system has been developed, which utilizes a thin plastic scintillation detector as a β-ray detector.

The system was applied to the measurement of the absolute γ-ray emission probability of a short-lived nuclide ^{28}Al. The system was demonstrated to have the ability to measure the absolute γ-ray emission probabilities of short-lived nuclides with the precision of $\lesssim 2\%$. By improving accuracy of γ-ray detection efficiency, an absolute γ-ray emission probability will be determined with the total error less than 1%.

References

[1] Nakamura, S.: Talk given in this conference.

[2] Firestone, R. B.: “Table of Isotopes”, 8th ed., John Wiley & Sons, Inc., New York (1996)