Design of a prompt gamma neutron activation analysis system at HANARO

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Abstract

The design feature is described for a prompt gamma neutron activation analysis (PGAA) system at HANARO, the 30 MW research reactor in Korea Atomic Energy Research Institute (KAERI). The primary purpose of this system is to analyze boron concentration in biological samples for research of neutron capture therapy. By considering the performance, available space and cost of setup, the PGAA system will use a thermal neutron beam diffracted by pyrolytic graphite (PG) in the existing ST1 horizontal beam line. The energy of monochromatic neutrons is 12.4 meV by setting the Bragg angle of 22.5°. The backgrounds will be low due to the use of diffracted beam and be further reduced through a Bi filter and a couple of LiF collimators. A neutron flux of 10^7 n/cm^{2}sec is expected at sample position. The feature of low backgrounds will permit a closer detector position less than 10 cm from sample while the actual location will be decided upon test measurements. Capture γ-rays of 478 keV from $^{10}B(n,\alpha)^7Li^*$ reaction will be detected by a 30% n-type HPGe detector and processed by a fast ADC. The goal of detection sensitivity for natural boron is 2,500 cps/mg. By completing the facility, efforts to improve the system performance will be further implemented in parallel with widening application of PGAA to other elements.

1. Introduction

Boron Neutron Capture Therapy (BNCT) is a radiation therapy for curing tumors by $^{10}B(n,\alpha)^7Li$ reaction which is induced by neutron irradiation on the injected ^{10}B compounds. The treatment for patients and improvement of facility are being continued at several places in the world. In KAERI, a BNCT facility using thermal neutron beam is being set up. From the standpoint of radiation

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protection, it is mostly important to minimize radiation damage on normal cells. Hence the measurement of ^{10}B concentration in tumor cells must be reliable in order to give an accurate dose of neutron irradiation. The ^{10}B concentration is commonly determined by measurement of prompt γ-rays emitted from $^{10}B(n,\alpha)^{7}Li^{*}$ reaction, the technique of which is well established now in PGAA[1,2]. Also those elements such as Cd, Sm, Gd can be analyzed by PGAA to the level lower than μg/g hence the application is wide in biology, geology etc[3,4]. In the early days direct white beam from reactor was used[5], but it soon was improved to use a beam of thermal neutron by reducing fast neutrons and γ-rays sufficiently. The performance is continuously upgraded by utilizing cold neutrons[6,7,8]. In this paper, the design feature of a PGAA system to be set up at HANARO is discussed.

2. Extraction of thermal neutron beam

The beam line to be used for extracting thermal neutron is ST1 of HANARO. The upper area of $7^{w}\times 2^{h}$ cm^2 in ST1's beam cross section will be used for PGAA and the central beam of area $7^{w}\times 10^{h}$ cm^2 is led to the Polarized Neutron Spectrometer (PNS). For low background of fast neutrons and γ -rays one option is that the system's location be away from the hall end of beam tube by neutron mirror guide. At HANARO, a thermal neutron beam diffracted by PG crystals will be used as an alternative option upon considering the space and cost of setup. The PG crystal is widely used in neutron spectroscopy[9] and has a higher reflectivity for the basal plane (002) than those of other planes[10]. The diffracted neutron flux ϕ_D is given by

$$\phi_D = \phi(E)\, R_E \frac{A_0}{A_1}$$

$$= \phi_{th} \frac{E}{(kT)^2} \exp(-\frac{E}{kT}) R_E \frac{A_0}{A_1}, \quad (1)$$

where $\phi(E)$ is the neutron spectrum of incident flux, R_E is the integrated reflectivity, and A_0/A_1 is the ratio of the cross section of the incident beam on PG to that of the diffracted beam[11]. The total thermal neutron flux ϕ_{th} is 10^{10} n/cm^2sec at the exit of ST1 tube. The diffracted flux and neutron absorption rates for several Bragg angles from a typical PG of 1/8″ thickness and 30′ mosaic width are shown in Table 1. Due to the severe restriction of the available space, the Bragg angle of 22.5° is chosen. The estimated neutron flux at sample position is 10^7 n/cm^2sec by considering the beam divergence.

Table 1. The neutron flux and absorption rate of boron for diffracted neutrons at several Bragg angles.

Bragg angle	E [meV]	R_E [meV]	ϕ_D [n/cm²sec]	$N\sigma(E)\phi_D$ [absorptions /mg sec]
15°	27.2	3.03	4.18×10^8	1.7×10^7
22.5°	12.4	1.11	1.22×10^8	7.4×10^6
30°	7.28	0.55	4.32×10^7	3.4×10^6
40°	4.40	0.28	1.46×10^7	1.5×10^6

A schematic diagram of the beam line is shown in Fig. 1. Due to the existing devices in PNS line, diffracting neutrons on the horizontal plane is not fitted. Hence a solution was found to use inclined diffraction and setup on the

upper plate of PNS front shield. Sample will be positioned at 20 cm higher above the upper plate. To achieve low background a Bi filter and a couple of LiF collimators will be positioned between PG and sample. By reducing the background level HPGe detector can be positioned at short distance less than 10 cm from the sample. The actual position of the detector will be decided upon test measurements.

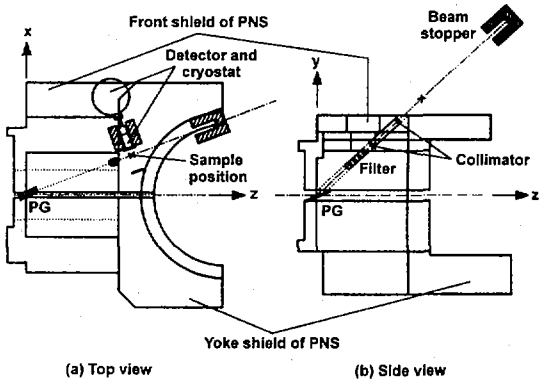

Fig. 1. Schematic diagram of the PGAA system at HANARO. Shielding design is not drawn in the figure.

3. Prompt γ-ray spectroscopy system

The γ-ray detection will be performed by using a single HPGe detector. The Compton suppression technique has the merit of reduced background counting rate, but simplicity of the system and space limitation were considered. The relative efficiency of the detector is chosen as 30% so that the absolute efficiency for 478 keV γ-ray from $^{10}B(n,\alpha)^{7}Li^{*}$ reaction is expected to be more than 0.5%. To enhance the maximum tolerable count rate of the system, a fast ADC with the conversion time of 800 nsec and an amplifier with the gated integration technique are selected. The saturation limit of input count rate will be about 200 kcps. A schematic block diagram of the γ-ray spectroscopy system is shown in Fig. 2.

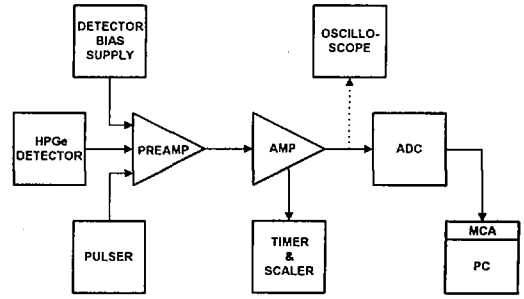

Fig. 2. Block diagram of the detection system for PGAA.

4. Design performance of the system

The performance of a PGAA system is partially considered in terms of detection sensitivity and detection limit. Detection sensitivity is given as the count rate of capture γ-rays per unit mass of an element in sample target. Hence the detection sensitivity, S is given by

$$S = \varepsilon p_\gamma N \int_0^\infty \phi(E)\sigma(E)dE = c\varepsilon\phi\sigma(E_m), \quad (2)$$

where ε is the absolute detection efficiency for capture γ-ray, p_γ is the γ -ray yield per neutron absorption, N is the number of isotopic element per unit mass of the target element, c is a constant, ϕ is the total thermal neutron flux, and $\sigma(E_m)$ is the cross section for the most probable energy E_m of the neutron spectrum. In eq. (2) neutron scattering effect in the target is neglected. The absorption cross section $\sigma(E)$ shows 1/v dependency on the

velocity of thermal neutrons. Therefore, eq. (2) gives a figure of merit for detection sensitivity of the PGAA system. A comparison of sensitivities for boron calculated by eq. (2) and the real measured values from several facilities using thermal neutrons is shown in Fig. 3. Apart from the data of Massachusetts Institute of Technology (MIT), the calculated values agree with measurements. For HANARO, the detection sensitivity for boron is expected to reach 2,500 cps/mg. This performance, if achieved, will be excellent among most of the thermal PGAA systems.

The detection limit, L_D is given by[14]

$$L_D = k\frac{\sqrt{B}}{t_c S}, \qquad (3)$$

where k is a constant related to the confidence level, B is the background counts, and t_c is the counting time. To lower the detection limit, background γ -rays should be reduced. This can be achieved by considering the following conditions : i) a beam line construction for reduced fast neutrons and γ-rays, ii) suppression of secondary γ-rays generated from the structural and shield materials, and iii) a good surrounding shield for γ-ray detector. An excessive detector shield however limits the sample-to-detector distance, hence results in a degradation of the detection sensitivity. Simple comparison of the relative contributions of the detection sensitivity and the background counting rate on the detection limit, indicates that a closer position of detector is preferred to while the actual position needs to be determined by experiment. The ^{10}B concentration in samples to be analyzed for BNCT is around a few μg/g[1]. Hence a design aim of the detection limit is set to 100 ng of natural boron by an hour's collection.

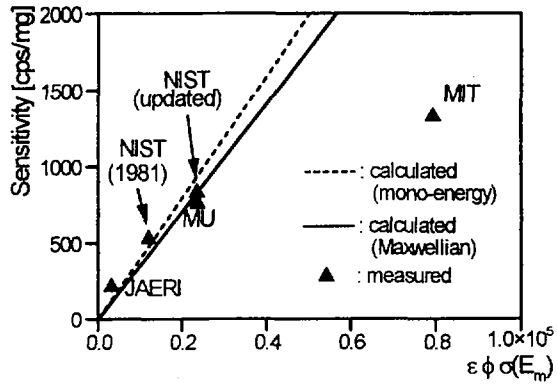

Fig. 3. Measured sensitivities for boron versus a figure of merit at several thermal PGAA facilities (JAERI : Japan Atomic Energy Research Institute[7], NIST : National Institute of Standards and Technology[5,12], MU : Missouri University[13], MIT : Massachusetts Institute of Technology[2]).

5. Conclusion

The design feature of the PGAA system to be installed at HANARO is discussed and described. Using the monochromatic neutrons of 12.4 meV diffracted by PG crystals, the neutron flux at sample position is expected of the order of 10^7 n/cm^{2}sec. Hence the detection sensitivity for boron will be around 2,500 cps/mg. The detection limit for boron is aimed to be 100 ng by an hour's collection. The detailed design is on the way. On completing the facility by 1999, efforts to improve the system performance will be further implemented in parallel with widening application of PGAA to other elements.

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