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Current research activities on nuclear data measurements at ANNRI

Atsushi Kimura*, Shunsuke Endo, Gerard Rovira and Shoji Nakamura
Nuclear Science and Engineering Center, Japan Atomic Energy Agency
2-4 Shirakata, Tokai, Naka, Ibaraki 319-1195, Japan
**Corresponding author: kimura.atsushi04@jaea.go.jp*

1. Introduction

Accurate cross-sections are required for detailed technical designs and safety evaluations of innovative nuclear reactor systems. Especially, to estimate isotopic production and the transmutation rates in the field of nuclear systems such as transmutation systems of radioactive wastes and various innovative reactor systems, neutron capture cross-sections of minor actinides (MAs) and long-lived fission products (LLFPs) are particularly important [1-3]. However, due to the high radioactivity of these products, precise measurements are quite challenging.

The Accurate Neutron-Nucleus Reaction measurement Instrument (ANNRI) was constructed to overcome this problem through a partnership between Hokkaido University, Tokyo Institute of Technology, and JAEA. ANNRI is located on Beam Line No. 04 of the Materials and Life science experimental Facility (MLF) at the Japan Proton Accelerator Research Complex (J-PARC). Since 2008, measurements of neutron-induced cross-sections of MAs and LLFPs have been performed using high-intensity pulsed neutrons. Neutron capture and/or total cross sections of ^{244}Cm, ^{246}Cm, ^{241}Am, ^{243}Am, ^{237}Np, and many stable isotopes have been reported. These results are expected to contribute significantly to the development of innovative nuclear systems. ANNRI has been used not only for nuclear data measurements but also for nuclear astrophysics and microanalysis.

This paper presents a brief overview of ANNRI and its current research activities on cross-section measurements.

2. A brief overview of ANNRI

2.1 Beam Line

By injecting 3-GeV pulsed protons from the J-PARC rapid cycle synchrotron to the mercury target in MLF, pulsed neutrons are produced through spallation reactions in the mercury target of MLF. Three different types of supercritical hydrogen moderators are used to slow down the pulsed neutrons. The Coupled Moderator, which produces the most intense neutron beam, supplies neutrons to the ANNRI.

Figure 1 shows the vertical cross-sectional view of ANNRI. Neutron collimators, neutron resonance filters, and disk choppers were installed to provide a high-quality neutron beam to the detector systems.

2.2 Characteristics of Pulsed Neutron Beam

In Fig. 2, the neutron intensity at the sample position of the Ge spectrometer (21.5 m) under the current proton beam power of 800 kW as of 2023 is compared to that of DANCE at LANSCE and n TOF at CERN [4]. Figure 2 also shows the expected neutron intensity under the future 1-MW operation; the present and future neutron intensities of ANNRI are higher than those of the other facilities.

Proton beams are normally supplied to MLF at a repetition rate of 25Hz and in the "double-bunch mode", where the pulsed protons consist of two bunches, each bunch with a width of 0.1 μs and separated by 0.6 μs. In the "double-bunch mode", at the low neutron energy region, the time structures of the single and double

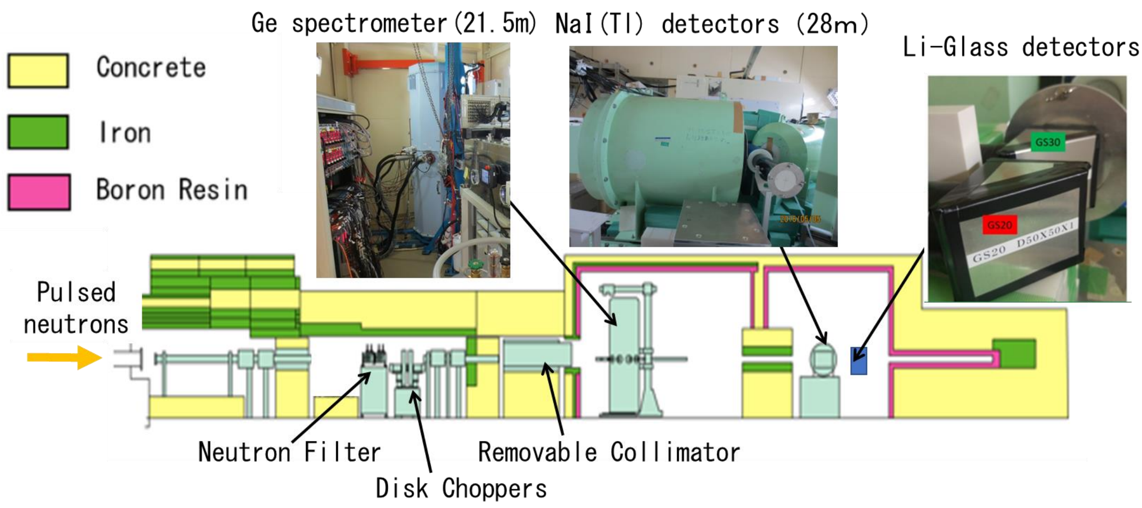

Fig. 1. Vertical cross-sectional view of ANNRI.

bunches are almost the same. However, in the neutron energy range above 100 eV, the time structure splits into two peaks in the TOF spectra.

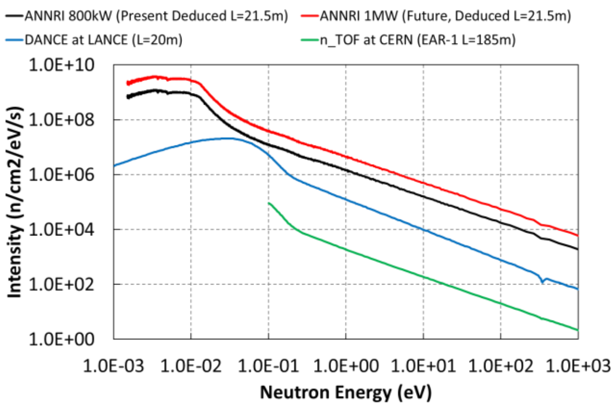

Fig. 2. Neutron intensities per second at the 21.5-m sample position of ANNRI under 800-kW operation compared to that of DANCE at LANSCE and n TOF at CERN [4]. The expected neutron intensity under the future 1-MW operation is also shown.

2.3 Detector systems in ANNRI

The ANNRI is equipped with three detector systems. To determine the neutron capture cross-section, an array of Ge detectors and a NaI(Tl) spectrometer are installed at flight lengths of 21.5 and 27.9 meters, respectively. Moreover, for total cross-section measurements, Li-glass detectors are placed at a flight length of 28.5 m.

The array of Ge detectors consists of two cluster-type Ge detectors, eight coaxial-type Ge detectors, and anticoincidence BGO shields around each Ge detector. Each cluster-type Ge detector contains seven Ge crystals. As a result, the array of Ge detectors consists of 22 Ge crystals. For 1.33 MeV photons, the photo-peak efficiency of the array of Ge detectors is 2.28 ±0.11% [5]. The Ge detector signals are fed into a CAEN V1724 (14 bit, 100 MHz). The TOF and pulse height (PH) are measured event by event.

The NaI(Tl) spectrometer consists of two cylindrical NaI(Tl) detectors, 330 mm in diameter and 203 mm in length and 203 mm in diameter and 203 mm in length located at 90 degrees and 125 degrees to the neutron-beam line, respectively [6]. Each NaI(Tl) detector is covered with neutron and gamma-ray shields. With a CAEN 1720 (12bit, 250MHz), signals from the NaI(Tl) detectors are analyzed, and then the resulting TOF and PH data are recorded in the same manner as for the array of Ge detectors.

In 2017, for neutron total cross-section measurements, two different types of Li-glass detectors were installed in ANNRI [7]. To obtain neutron transmission spectra, a ^{6}Li-glass detector (Saint-Gobain GS-20), which uses enriched ^{6}Li (> 95%) and has dimensions of 50 mm x 50 mm×1 mm, is used, for neutron detection by means of the ^{6}Li(n,γ)^{3}H reaction. To estimate the gamma-ray background a ^{7}Li-glass detector is employed. The scintillator for the ^{7}Li-glass detector is a GS-30 scintillator supplied by Saint-Gobain, which has a high ^{7}Li enrichment of over 99.99% and has the same size and chemical composition as the GS-20 scintillator. Signals from the detectors are analyzed with a CAEN 1720, and the TOF and PH are recorded in the same way.

2.4 Neutron beam filter system

Proton beams are normally supplied to MLF at the repetition rate of 25Hz and in the "double-bunch mode". As the result of the "double-bunch mode", neutrons with two different energies are observed at the same time-of-flight channel. For example, at a flight length of 28-m and flight time of 7.4 μs, 300-keV and 75-keV neutrons are observed.

In 2020, to extend the range of neutron energy measurements to the keV region, a neutron beam filter system using Fe, Cr, and Si has been incorporated at the removable collimator of ANNRI. [8]. These filter materials have ‘‘resonance windows’’ in their neutron cross-sections so that neutrons with energies corresponding to these windows are transmitted, while neutrons with other energies are attenuated. The installed neutron filters can cut out pulsed neutron beams with discrete energies: 24 keV for Fe and 54 and 145 keV for Si.

3. Current research activities at ANNRI

The current status of the neutron cross-section measurements for the main nuclides is listed in Table 1. The neutron capture cross-sections of many MAs and stable isotopes have been reported. In recent years, using the Li-glass detectors, the total cross sections of $^{241,\ 243}$Am, ^{93}Nb and ^{155,157}Gd have also been reported. Furthermore, using the neutron filtering system, the neutron capture cross-sections of ^{241,243}Am in the keV region were reported. These results will make significant contributions to the development of innovative nuclear systems.

Table 1: Current status of the neutron cross-section measurements for the main nuclides.

Nuclide	Capture	Total	Reference
$^{244,\ 246}$Cm	F	-	[9, 10]
^{237}Np	F	-	[11]
^{241,243}Am	F*	F	[12-15]
^{105,107,108}Pd	P	-	[16, 17]
^{99}Tc	P	-	[18]
^{142}Nd	F	-	[19]
^{93}Nb	F	F	[20]
$^{155,\ 157}$Gd	F	F	[21]
^{91,96}Zr	P	-	[22]
^{112,116,118,120,122,124}Sn	P	-	[23, 24]
^{74,77}Se	P	-	[25]

F: Final results were reported.
P: Preliminary results were reported.
*Capture cross-section measurements with the neutron filter system were reported.

4. Summary

In ANNRI, measurements of neutron-induced cross-sections of the MAs and LLFPs using high-intensity pulsed neutrons have been performed since 2008. Neutron capture and/or total cross sections of ^{244}Cm, ^{246}Cm, ^{241}Am, ^{243}Am, ^{237}Np, and many stable isotopes have been reported. These results will make significant contributions to the development of innovative nuclear systems.

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