Precision neutron flux measurement with a neutron beam monitor

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Abstract. Neutron beam monitors are regularly used in various neutron beam experiments to compare two or more sets of data taken in different experimental conditions. A neutron lifetime experiment at BL05, the NOP beamline, in J-PARC requires to monitor the initial neutron intensity with an precision of 0.1% to measure the neutron lifetime with the same accuracy. The performance of a thin ³He gas neutron beam monitor used for the experiment was studied to estimate the systematic uncertainties in the neutron lifetime measurement.

1. Introduction
A precision neutron lifetime measurement is underway at BL05, the NOP beamline, in J-PARC [1]. It is aimed to measure the neutron lifetime with an accuracy of 0.1% by detecting the neutron decays in flight. In such a precise measurement, it is crucial to monitor the neutron intensity with high precision.

At a spallation neutron source, the neutron intensity fluctuates with time depending on the characteristics of the proton beam to the neutron target, the current, the position, and the profile. The moderator temperature should also affect the neutron intensity as well as the energy spectrum. Figure 1 shows such time variation of the neutron intensity measured at the NOP beamline in J-PARC. Short-term and long-term fluctuations of the neutron flux that exceed far beyond 0.1% are clearly observed. A rough correlation between the proton current and the neutron intensity can be seen in the first half period, but later the discrepancy increased more than 1%. This fact tells that it is definitely necessary to continuously keep track of the incident neutron flux for the neutron lifetime experiment.

2. Systematic uncertainties in neutron beam monitoring
Beam monitoring with a gas proportional counter is affected by the change of the gas gain that depends on the high voltage, the temperature, the atmospheric pressure, and the beam flux (space charge effect). However, in a sealed gas detector such as a ³He neutron detector, the gas pressure or the gas density remains the same with atmospheric pressure changes, and therefore no gas gain change. The gas gain should also vary with the incident beam position because of the electric field distribution inside the detector. The data acquisition electronics such as amplifiers and ADC may be responsible
for the instability. All these characteristics regarding the systematic uncertainties in the neutron flux measurement are to be examined.

![Figure 1](image1)

**Figure 1.** Time variation of the incident neutron flux was measured at the NOP beamline in J-PARC (crosses). Each measurement point corresponds to the average over one hour. The proton beam current to the neutron target is also plotted in circles (right axis). The left and right axes are properly scaled.

3. Neutron beam monitor and data acquisition system

The neutron beam monitor MNH10/4.2F used in the neutron lifetime experiment was purchased from CANBERRA (Figure 2). It is a thin $^3$He gas detector with a neutron detection efficiency of $\sim 4 \times 10^{-5}$ at the thermal energy. The specifications of the beam monitor are listed in Table 1.

The data acquisition (DAQ) electronics are schematically shown in Figure 3. The detector output is connected to a charge amplifier CANBERRA 2006E followed by a shaping amplifier ORTEC 570 with a decay time constant of $\sim 5 \mu$s. The pulse heights are digitally recorded in the list mode with their trigger times by a peak detect ADC module IWATSU A3100. The nominal high voltage (HV) of 1000 V for the beam monitor is provided by a HV power supply ORTEC 556. The specifications of each module are summarized in Table 2.

![Figure 2](image2)

**Figure 2.** Neutron beam monitor used for the neutron lifetime measurement at the NOP beamline in J-PARC.
### Table 1. Specifications of the neutron beam monitor.

| Mechanical structure | material | A5 aluminum |
|----------------------|----------|-------------|
| active length        | 100 mm   |
| active width         | 42 mm    |
| active thickness     | 40 mm    |
| window thickness     | 2 mm (each side) |

**Gas**
1.3 bar of Ar + 10% of CH₄ + little ³He

**Mean high-voltage**
1000 V

**Neutron detection efficiency**
~ 4 × 10⁻⁵ (thermal neutrons)

### Figure 3. The data acquisition electronics for the neutron beam monitor.

### Table 2. Selected specifications regarding the stability for the DAQ electronic modules.

| High voltage power supply | Temperature coefficient | < ±50 ppm/°C |
|---------------------------|-------------------------|---------------|
| ORTEC 556                 | Long-term drift         | < 0.01%/hour   |
|                           |                         | < 0.03%/24hour |

| Preamplifier              | Integral nonlinearity   | < ±0.02% |
|---------------------------|-------------------------|----------|
| CANBERRA 2006E            | Temperature coefficient | < ±0.01%/°C |

| Shaping amplifier         | Integral nonlinearity   | < ±0.05% |
|---------------------------|-------------------------|----------|
| ORTEC 570                 | Temperature coefficient | ≤ ±0.0075%/°C |
|                           | DC Level                | ≤ ±50 µV/°C |

| Peak detect ADC           | Integral nonlinearity   | ≤ ±0.025% |
|---------------------------|-------------------------|----------|
| IWATSU A3100              | ADC resolution          | 13 bits for 10 V full scale |

### 4. Neutron beam measurements

Neutron beam tests were performed at the NOP beamline in J-PARC. The experimental setup was essentially the same as the neutron lifetime measurement [1] except for the HV and the position dependence tests where the neutron beam was tightly collimated. The cross sectional profile of the neutron beam was a square of 20 mm × 20 mm, and incident at the center of the beam monitor. The neutron flight path from the neutron source to the beam monitor was 18.4 m.

The pulse height distribution of the beam monitor signal is shown in Figure 4. The spectrum looks quite strange for a ³He neutron detector. It turned out that the detector somehow contains boron or boron compound that makes several peaks and a shoulder in addition to the one by the ³He(n,p) reactions:

\[
³\text{He} + n \rightarrow p (573 \text{ keV}) + ³\text{H} (191 \text{ keV}).
\]

The highest peak denoted as I in Figure 2 corresponds to the total energy of p (573 keV) + ³H (191 keV).
Peaks II, III, and IV are from the neutron absorption reactions of \(^{10}\text{B}^\):  
\[ ^{10}\text{B} + \text{n} \rightarrow ^{7}\text{Li (1015 keV)} + \alpha (1777 \text{ keV}) \quad 6\% \quad \text{and} \quad ^{7}\text{Li (840 keV)} + \alpha (1470 \text{ keV}) + \gamma (482 \text{ keV}) \quad 94\% , \]
and they correspond to \(^{7}\text{Li (1015 keV)}, \alpha (1470 \text{ keV}), \) and \(^{7}\text{Li (1777 keV)}, \) respectively. The 482 keV \(\gamma\) rays are not detected. The \(^{7}\text{Li (840 keV)}\) energy depositions are contained in peak I and do not make a separate peak due to the limited energy resolution. There is a shoulder denoted as V in the spectrum, and it is most likely made up by \(^{7}\text{Li (840 keV)} + \alpha (1470 \text{ keV})\) where the total deposition energy becomes 2310 keV. It is obvious that boron or boron compound is not in the gas state but adheres to the inner walls of the beam monitor because each reaction product, \(^{7}\text{Li}\) or \(\alpha\), forms a peak individually, and the accompanying produced nuclei are absorbed in the detector walls. If boron compound were in the gas state, there would appear two peak at 2310 keV and 2792 keV by the \(^{7}\text{Li}\) and \(\alpha\) pairs. The peaks/shoulder and the corresponding particle(s) energy are summarized in Table 3.

![Figure 4](image.png)  
**Figure 4.** Pulse height distribution by the neutron beam monitor. Four peaks I, II, III, and IV are observed together with a shoulder (V). The neutron events are identified as the pulse heights over the nominal threshold of 150.

**Table 3.** The peaks and the shoulder in Figure 4 and the corresponding particle(s) energy.

| Peak / shoulder | Reaction and particle(s) energy |
|-----------------|--------------------------------|
| I               | \( p (573 \text{ keV}) + ^{4}\text{He (191 keV)} \) from \(^{4}\text{He(n,p)}\) |
|                 | \(^{7}\text{Li (840 keV)}\) from \(^{10}\text{B(n,}\alpha)\) |
| II              | \(^{7}\text{Li (1015 keV)}\) from \(^{10}\text{B(n,}\alpha)\) |
| III             | \(\alpha (1470 \text{ keV})\) from \(^{10}\text{B(n,}\alpha)\) |
| IV              | \(\alpha (1777 \text{ keV})\) from \(^{10}\text{B(n,}\alpha)\) |
| V               | \(^{7}\text{Li (840 keV)} + \alpha (1470 \text{ keV})\) from \(^{10}\text{B(n,}\alpha)\) |

The instability of the neutron detection efficiency should not be affected by the presence of \(^{10}\text{B}\) since the energy deposition by the \(^{10}\text{B(n,}\alpha)\) reactions are much higher than the nominal threshold of 150 for the neutron identification. However, it has position dependence as detailed in the next chapter.
The time-of-flight (TOF) spectrum of the incident neutron beam in the neutron lifetime experiment apparatus is shown in Figure 5. The peak counting rate was observed to be ~ 22000 cps around a tof of 21 ms, which corresponds to a neutron wavelength of ~ 0.45 nm, when the proton accelerator was operated at ~ 300 kW with a repetition rate of 25 Hz. It is noted that Figure 5 shows the neutron counting rate in which the neutron detection efficiency of the beam monitor is convoluted.

**Figure 5.** TOF spectrum of the incident neutrons in the neutron lifetime experiment. Only cold neutrons are delivered to the apparatus by the use of neutron supermirror benders (see Ref. 2 for details). The highest intensity appears around TOF of 21 ms. Frame-overlap neutrons are seen in TOF less then ~ 10 ms.

### 5. Results and discussions

#### 5.1. Gain fluctuation and neutron detection efficiency

The change of the neutron detection efficiency due to the fluctuations of the gas gain and the amplifier gains was estimated with the pulse height spectrum in Figure 4 by changing the energy threshold around the nominal value of 150. Figure 6 shows such dependency to be \( \Delta \varepsilon /\Delta G = -0.104 \), where \( \Delta \varepsilon \) and \( \Delta G \) are the normalized values of the efficiency and the gain changes, respectively. This leads the tolerance of the gain variation to be 1% to keep the efficiency change within 0.1%. The temperature stabilities of the electronic modules are much less than 1% in normal room temperature as shown in Table 2; the amplifiers and the ADC have good enough linearities as well.

#### 5.2. High voltage

The high voltage (HV) dependence of the detector gas gain was measured by actually changing the HV to the beam monitor and turned out to be \( \Delta G /\Delta V = 3.7 \times 10^{-3} /V \) around the nominal HV of 1000 V (Figure 7). The corresponding tolerance is \( \pm 2.7 \text{ V} \) or \( \pm 0.27\% \) to keep \( \Delta G < 1\% \). HV power supplies commonly used in physics measurements, including ORTEC 556, have better stabilities and smaller temperature coefficients compare to this tolerance (Table 2).
Figure 6. The relation between the neutron detection efficiency and the gas/amplifier gain was estimated by changing the ADC threshold level.

Figure 7. The dependence of the gas gain on the input high voltage.

5.3. Neutron flux effect
The detector gas gain may drop with increasing counting rate because of the space charge effect where a huge amount of gas ions is created near the anode wire by the electron avalanche and disturbs the electrostatic field. Such nonlinearity of the gas gain was studied by changing the neutron intensity with attenuators. Aluminum plates were placed ~ 2 m upstream the beam monitor as neutron attenuators. Figure 8 shows the attenuation in the neutron intensity by ~10% with 12 mm thick aluminum, corresponding to an attenuation factor of 0.84% for an aluminum thickness of 1 mm. The gas gains for the different neutron intensities were measured as the peak pulse height of $I$ in the pulse height spectrum. The gas gains measured with different aluminum thicknesses are plotted in Figure 9. No clear dependence on the neutron intensity is observed. The gas gain variation is less than 0.1% for a change of the neutron intensity of 10% in the neutron lifetime experiment apparatus.
5.4. The temperature dependence of the gas gain
The temperature dependence of the gas gain in sealed proportional counters was studied by Vanha-Honko [3], and it was found to be \( \sim 100 \text{ppm}^\circ\text{C} \), which is small enough compared to the requirement of 1%.

5.5. Position dependence
The position dependence of the neutron detection efficiency was measured by scanning the beam monitor position to the fixed neutron beam of \( \phi 10 \text{ mm} \). The position was moved with 8 mm steps in the longitudinal (12 positions) and transverse (5 positions) directions. The signal pulse heights were measured at each detector position to see the position dependent gas gain. Figure 10(a) shows the peak attenuation by aluminum plates.

Figure 8. The neutron beam attenuation by aluminum plates.

Figure 9. The gas gains were measured as the peak pulse heights in the pulse height spectra with different neutron attenuations.

Figure 10(a) shows the peak
pulse heights of I in the pulse height spectra as the gas gains, normalized with that at the detector center. A systematic change of the detector gas gain is clearly seen due to the electrostatic field distribution inside the beam monitor. Sharp drop and increase near the edges are visible in the longitudinal direction. For the transverse direction, the gas gain change is rather limited, and the minimum appears at the center. The position dependence of the gas gain around the detector center is ~0.3%/cm and ~1.5%/cm for the longitudinal and transverse directions, respectively.

The neutron detection efficiency map, normalized at the center, is shown in Figure 10(b). Apparently, there is no systematic change in the efficiency, and the variation is more than 10% and randomly distributed. The $^{10}$B adhesion should be responsible for it, but the reason of the randomness in the $^{10}$B thickness is not known. This position dependence is not acceptable for the neutron lifetime experiment, and therefore the beam monitor has to be fixed at a definite position.

![Figure 10](image)

**Figure 10.**
Left: (a) the position dependence of the peak I pulse height (~ch240) in Figure 4 is shown as the gas gain variation, normalized at the detector center.
Right: (b) the neutron counting efficiency is plotted for each incident neutron position. The efficiency is normalized at the detector center. The beam monitor sketched at the right bottom corner shows the positional relation between the plots and the beam monitor.

Finally, we note that background events including gamma rays, neutrons coming from other than the beamline, the electronics noise, and other sources were measured by placing a $^{10}$B$_4$C plate or a $^6$LiF plate in front of the beam monitor for every beam test, and each number of the background events was confirmed to be negligible small.

6. Conclusions
We have studied the performance of a neutron beam monitor MNH10/4.2F manufactured by CANBERRA. The neutron counting efficiency of the detector with the data acquisition electronics was measured its stability to the high voltage drift, the temperature variation, and the neutron intensity fluctuation, and it was found to satisfy the requirement in the neutron lifetime experiment. The position dependence of the detector gas gain was also studied and turned to have a systematic trend with a limited change. It was discovered, however, that the neutron detection efficiency varies randomly with the incident neutron position probably due to the adhesion of boron or boron compound.
on the inner walls of the beam monitor. The variation is more than 10%, which far exceeds the tolerable level, and the beam monitor has to be used with a fixed position to the incident neutron beam.

References
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