Measurement of neutron total cross sections of Sn-Pb alloys in solid and liquid states

Takuya Uemura[1], Jun-ichi Hori[1], Kazushi Terada[1],

Tadafumi Sano[2], Jun Nishiyama[3], Rei Kimura[4], Ken Nakajima[1]

1. Kyoto University, 2. Kindai University, 3. Tokyo Institute of Technology,
4. Toshiba Energy Systems＆Solutions Corporation

Abstract

A very small modular reactor, namely, **MoveluX^{TM}** (Mobile-Very-Small reactor for Local Utility in X-mark) has been developing by Toshiba Energy Systems ＆ Solutions Corporation. MoveluX^{TM} is a thermal reactor that uses a calcium hydride as a neutron moderator. The use of a **Sn-Pb alloy** as the in-core heat transport medium is being considered. The Sn-Pb alloy is a **solid** state when the reactor is started, and becomes a **liquid** state since the core temperature reaches 660℃ during operation. However, there are no reports on experimental data for **total cross sections** of Sn-Pb alloys in both solid and liquid states. In the present study, the total cross sections was obtained from **neutron transmission measurements** by the **time-of-flight (TOF)** method using the Kyoto University Institute for Institute for Integrated Radiation and Nuclear Science – Linear Accelerator (KURNS-LINAC). The sample temperature was changed from room temperature (solid) up to 300℃ (liquid). The detail of the total cross section measurement experiments and the result obtained so far is discussed.

I. Introduction

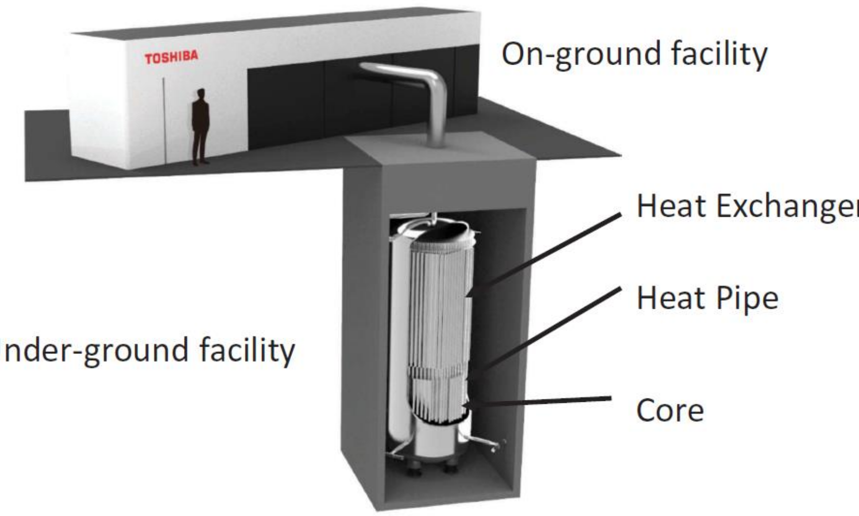


Fig.1. A schematic view of the MoveluX™ reactor system[1] by Toshiba Energy Systems＆Solutions Corporation.

Background

- A Small Modular Reactor (SMR) has been receiving attention all over the world.

In Japan,
MoveluX™ has been developing.

- **Sn-Pb alloy** is considered as an in-core heat transport medium in MoveluX™.
  For…
  - Reduction of thermal contact resistance
  - Decay heat removal system without electric power

- Nuclear data is important for assessing the impact on the core.

✓ **No reports on experimental data for neutron total cross sections of Sn-Pb alloy**

Purpose

- Measurement of the total cross sections of Sn-Pb alloys in solid and liquid states

- Comparison with the total cross sections of the solid and the liquid states

II. Materials and Methods

- **The total cross sections** of Sn-Pb alloys have been measured using KURNS-LINAC.

Table1. Sn-Pb alloys and Al case data

	Sn–Pb alloy (Sn:60%, Pb:40%)			Al
Sample	liquid (in Al case)	solid [1] (in Al case)	solid (rod)	Al case
Weight (g)	413.52	413.52	200.51	193.42
Size (mm^2)	2750	2625	3835	4200
Thickness (mm)	10	10	6	1 (beam line)

Table2. Measurement time

	Sample	Measurement time (h)
Sn–Pb alloy	liquid (300℃)	12.0
	liquid (250℃)	12.0
	liquid (210℃)	12.0
	solid [1] (re–solid)	12.0
	solid (rod)	9.0
	Al case	12.0
	Blank	9.0
	Al case+ res. filter[2]	3.0

Table3. Measurement Condition

LINAC Condition	Reptation rate[3]	50 Hz
	Pulse width	1 μs
	Average current	28.4 μA
Flight length	Distance	12.09 m

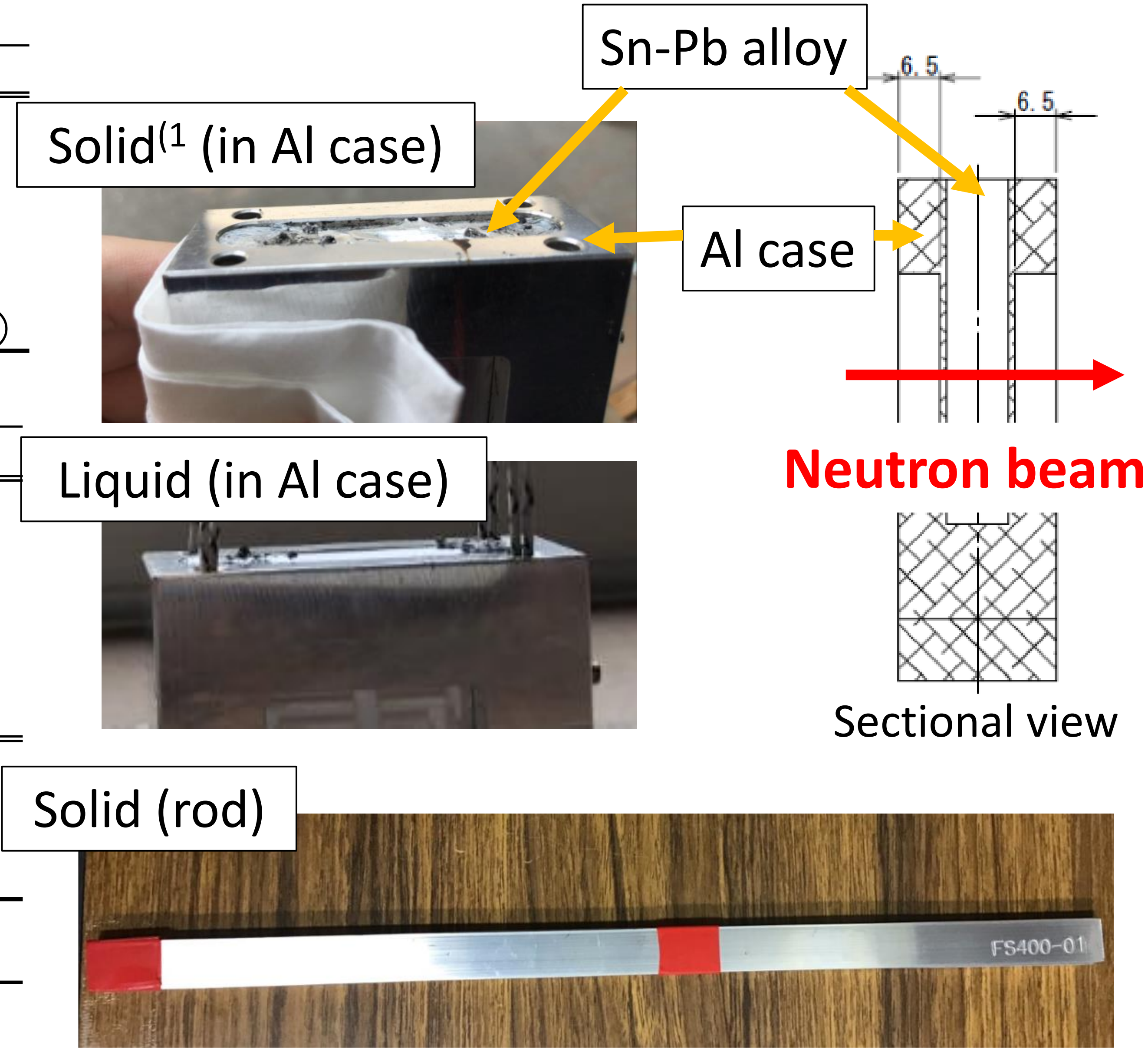


Fig.2. Each sample of Sn-Pb alloys and Al case

※ 1) It is resolidificated after melting in Al case.
2) Contain of Mn, Co, Ag, In, and Cd.
3) 30 Hz in only liquid (210℃) measurement.

☐ Derivation of total cross section $\sigma_{tot}(E)$ by following equation

$$\sigma_{tot}(E) = -\frac{1}{n}\ln\frac{(C_s(E) - C_{s,b}(E))/M_s}{(C_o(E) - C_{o,b}(E))/M_o}$$

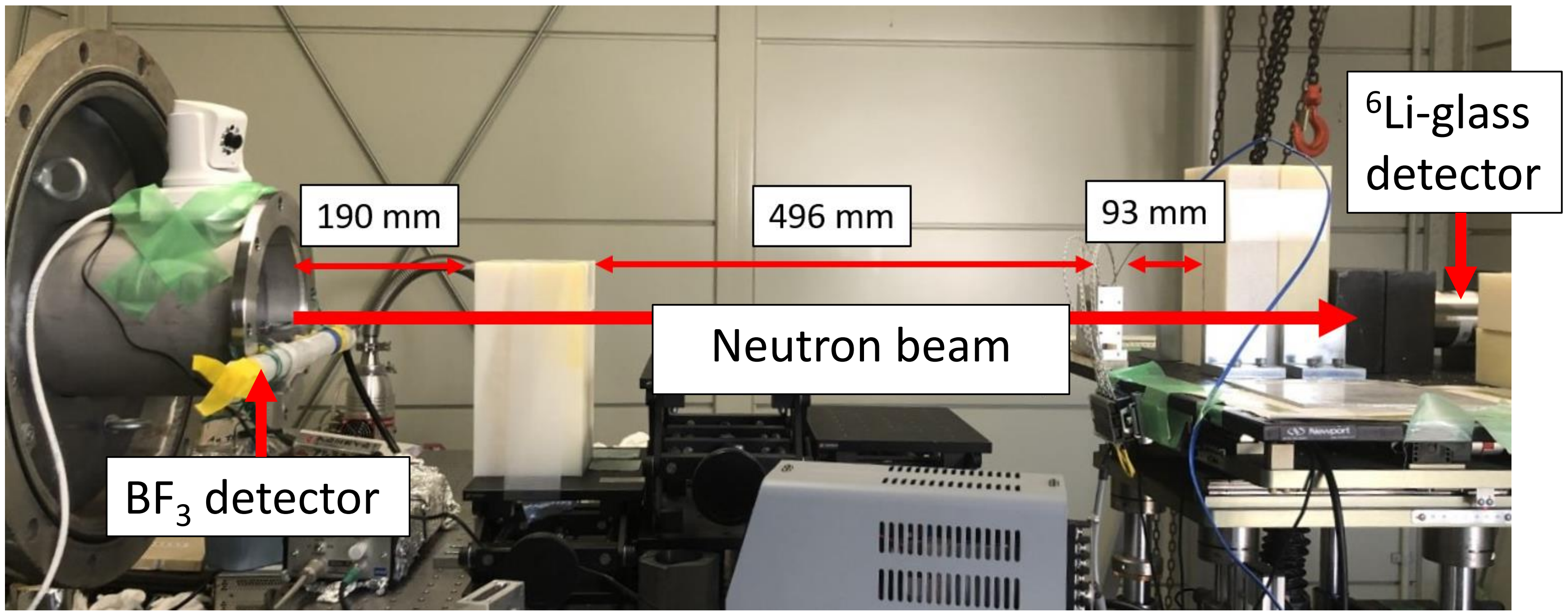
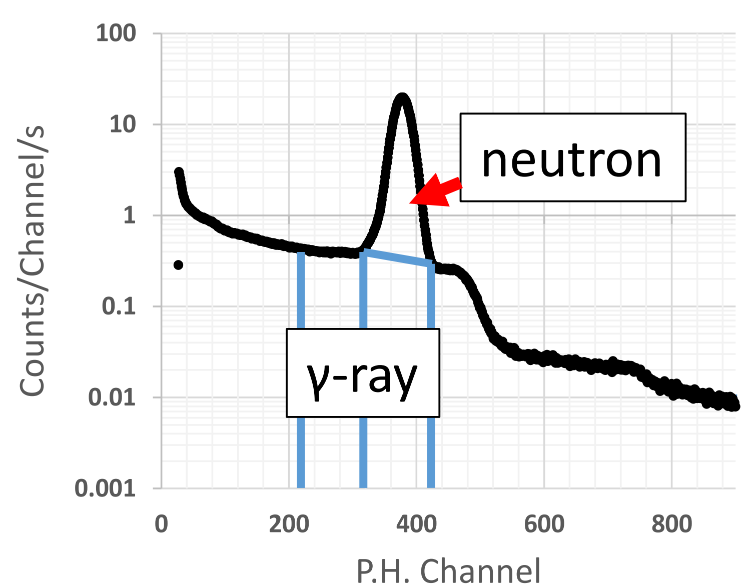


Fig.3. Measurement System of 12 m measurement room

Where, $C_s(E)$ and $C_o(E)$ are the neutron count rates for the sample-in and sample-out by ^{6}Li-glass detector. $C_{s,b}(E)$ and $C_{o,b}(E)$ are the background for the sample-in and sample-out. M_s and M_o are the neutron counts rates by BF_3 detector to fix neutron fluctuation between measurements. n is the atomic number density [atom/barn] of Sn-Pb alloy sample.

☐ Background level

The background level was estimated by Pulse Height of each measurement. For 320-420 ch in P.H. channel, neutron and γ-ray are included. For 220-320 ch, γ-ray is included. Therefor, the background level was evaluated from TOF spectra correspo-nding to each P.H. channel normalized by area. It is confirmed that the gamma rays background showed in good agreement with the dip of the res.filter in Fig.4.



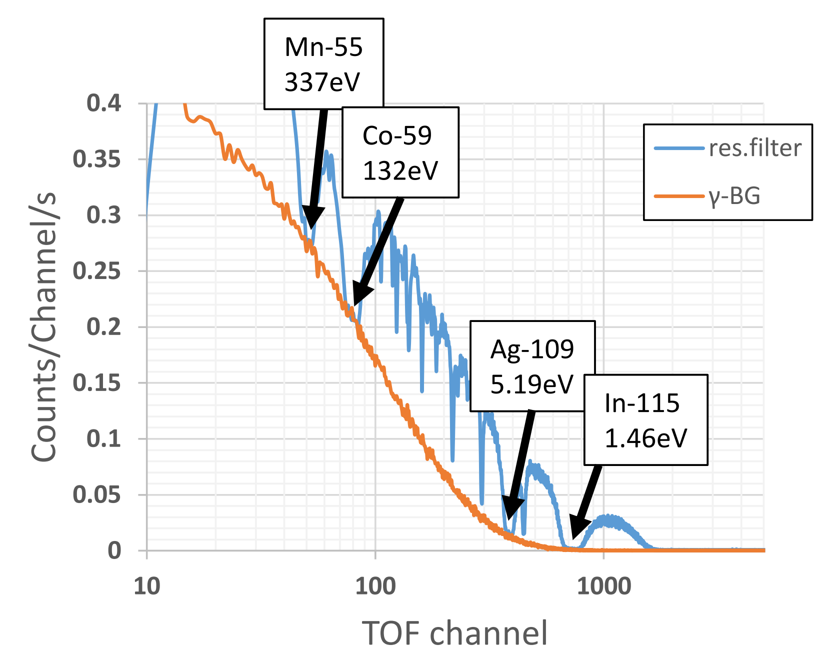


Fig.4. Pulse Height and TOF spectra of res.filter and γ-ray back ground level.

III. Results and Discussion

□ Comparison of the total cross sections of the liquid state of Sn-Pb alloys between sample temperature.

Fig.5 shows the total cross sections of the liquid Sn-Pb alloys between sample temperature (210℃,250℃ and 300℃). The detail view from 0.002 eV to 0.003 eV shows the below.

Most of the total cross sections match within the margin of error. However, it was found that there was a difference of total cross sections between that of 210℃ and 250℃, 300℃ at 2.16 meV and 2.52 meV. It is considered that this is because the crystal structure of the solid state is left in 210℃. This means that the liquid Sn-Pb alloy at 210℃ was not completely melted. On the other hand, the total cross sections at 250℃ and 300℃ have a small difference, and both can be regarded as completely melted. However, in the present study, it is difficult to say clearly that there is a difference due to sample temperature.

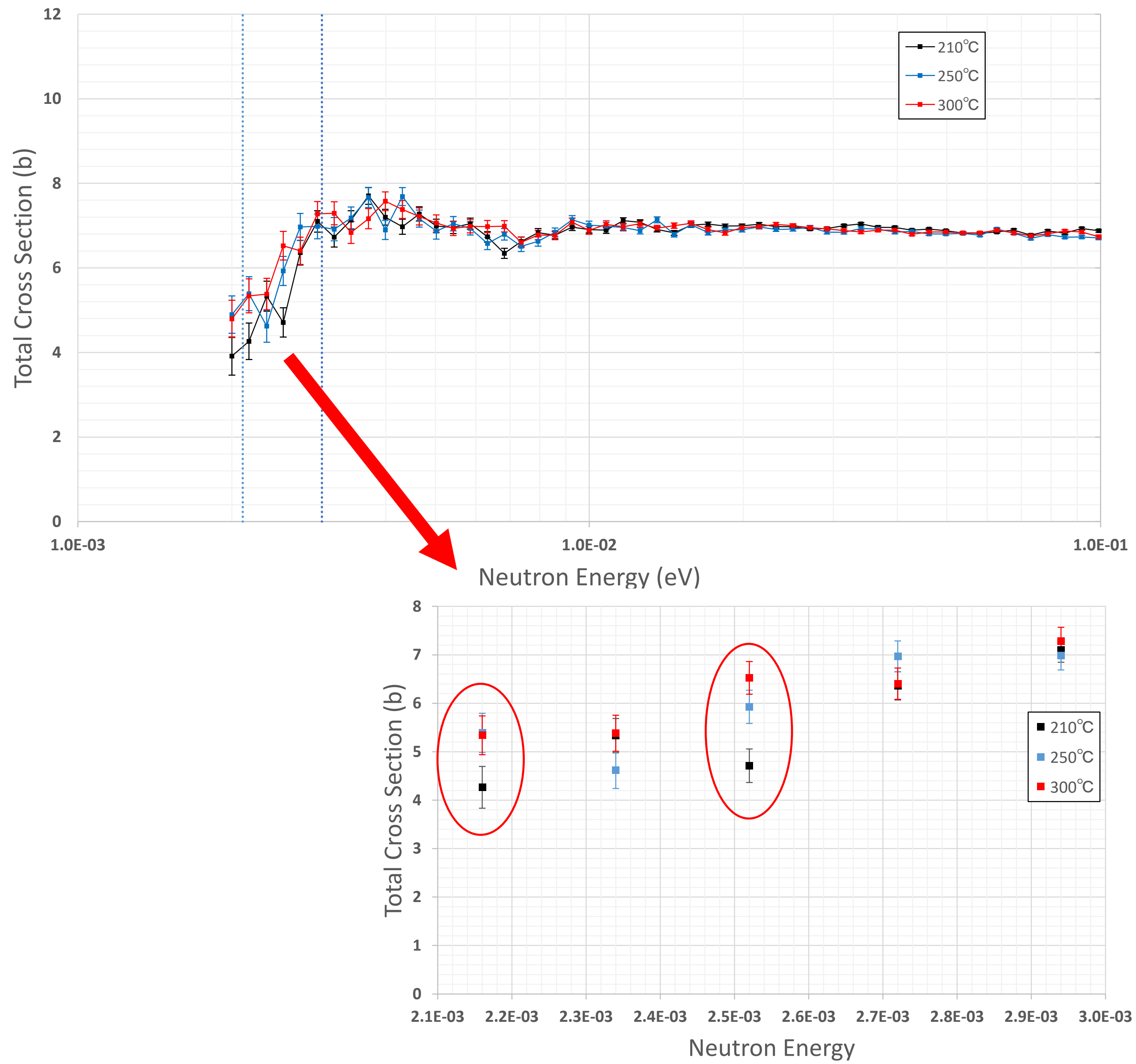


Fig.5. Comparison of the total cross sections of liquid Sn-Pb alloys between temperature. (210℃,250℃ and 300℃).

☐ Comparison of the total cross sections of solid and liquid states of Sn-Pb alloys.

The total cross sections of the Sn-Pb alloys in solid and liquid states were compared in Fig. 6. In the solid state, Bragg edges due to the crystal structure were observed in the below 0.01eV. However, it turns out that some of Bragg edges in the liquid state has decreased in the total cross section and widened in the energy region. This means that the crystal structure of the solid has changed due to melting, and the interference between neutrons and nuclei has expanded.

The comparison between JENDL-4.0 (free-gas model) and the measured data of total cross sections showed in good agreement above 0.1eV (JENDL-4.0[2] shows the total cross sections of Sn and Pb weighted by the atom number density of each composition). It is considered that this is because the influence of coherent scattering due to the crystal structure is little above 0.1eV.

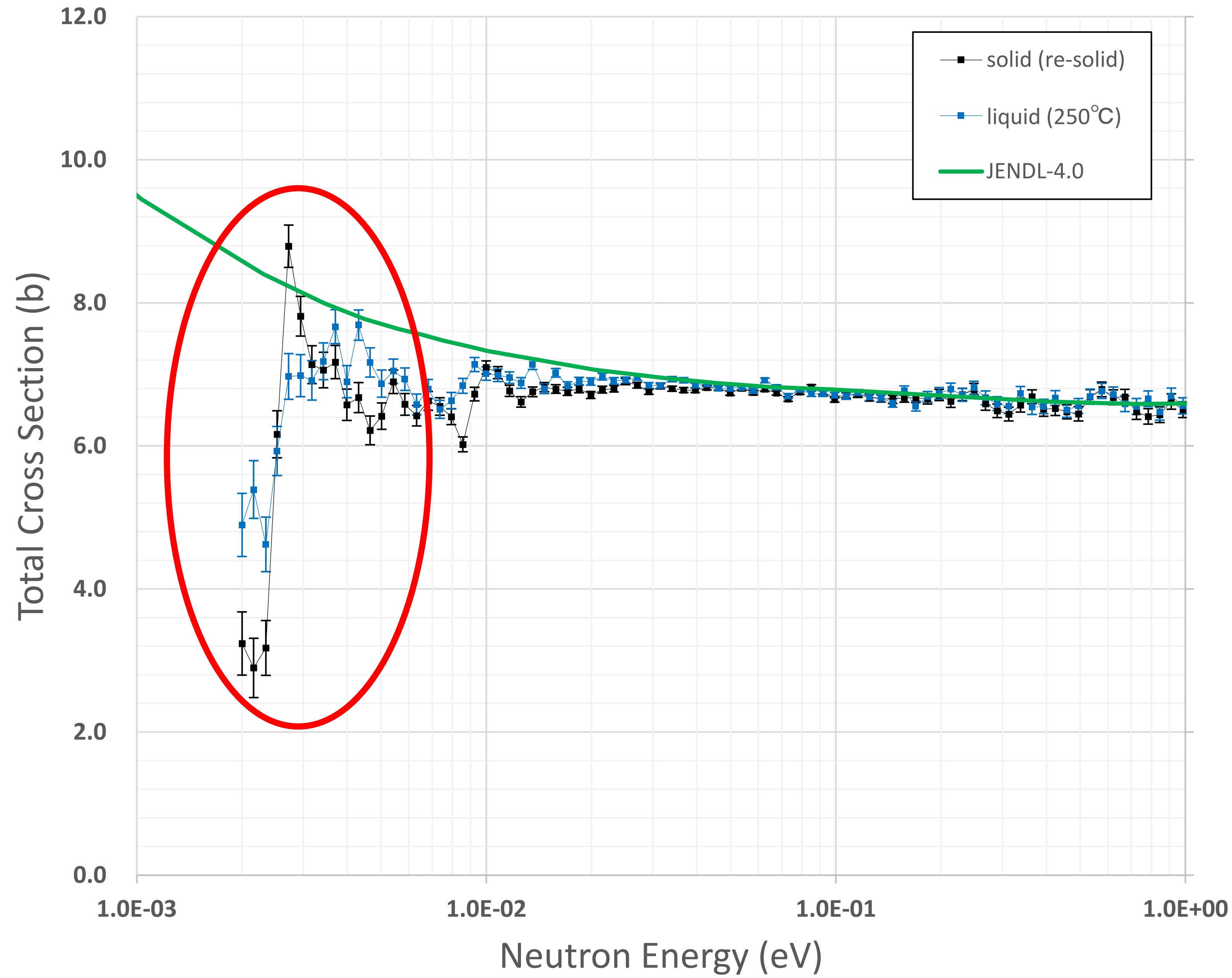


Fig.6. Comparison of the total cross sections of Sn-Pb alloys in the solid, the liquid (250℃) and JENDL-4.0[2].

☐ Comparison of the Bragg edges of the solid and the solid resolidificated after melting of Sn-Pb alloys.

Fig.7 showed the comparison of the measured total cross sections of Sn-Pb alloys and Pb. The Sn-Pb alloys are the solid state (rod) and the solid resolidificated after melting (re-solid). The Pb data was measured by G. Muhrer[3]. Some energies of the Bragg edges matched between the solid and the re-solid of Sn-Pb alloys. The energies of these Bragg edges were in those caused by d_{hkl} spacing between Sn and Pb. It was confirmed that these were the effect of coherent scattering. However, Bragg edges of 3.42 meV, 6.82 meV and 17.1 meV, which is due to the crystal structure of Pb, couldn't be seen by resolidification.

Due to influence of Bragg edge, the difference in total cross sections between neutron energies is large below 20 meV. However, no noticeable Bragg edge could be seen above 20 meV.

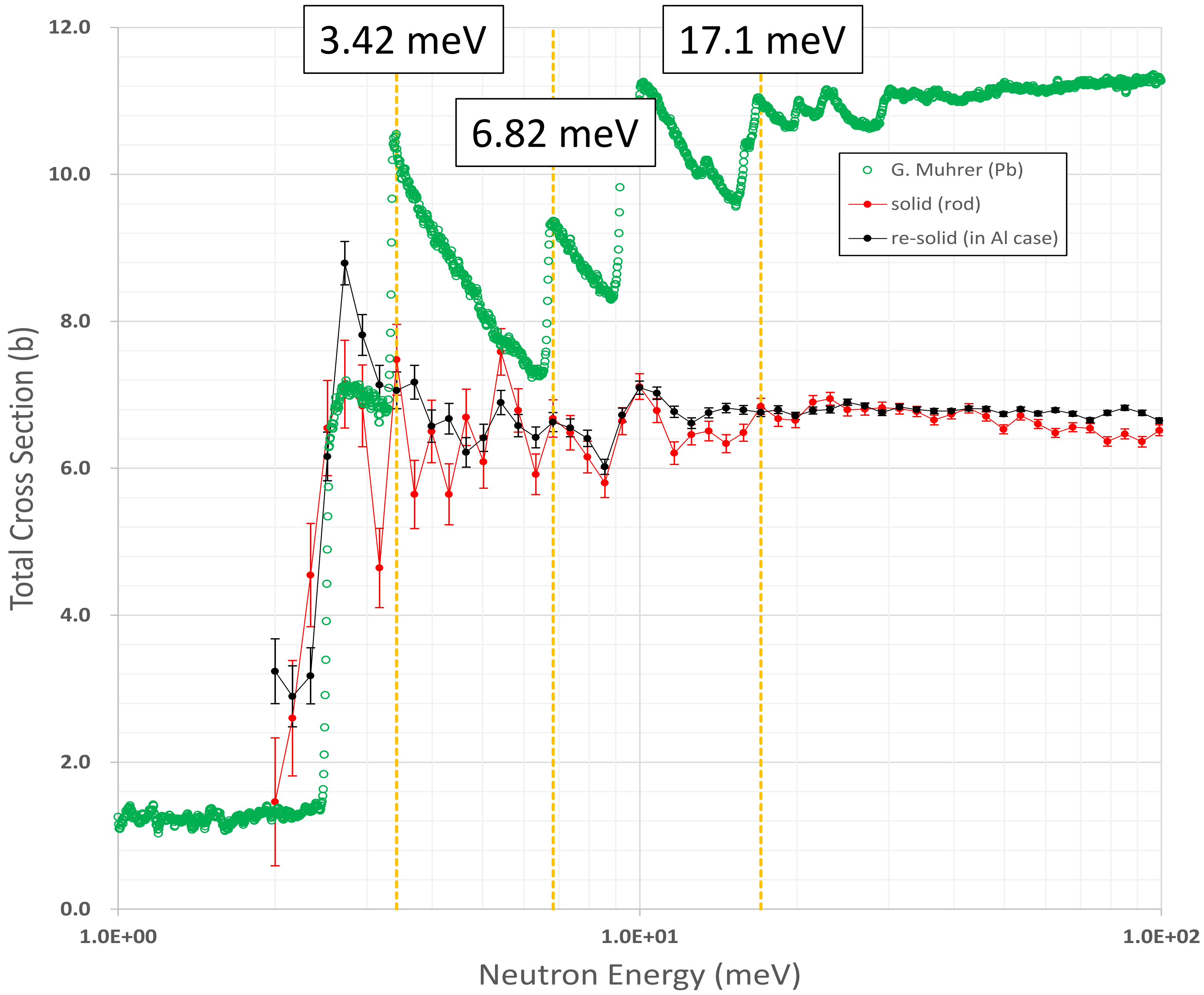


Fig.7. Comparison of the total cross sections of the solid, the solid resolidificated after melting (re-solid) of Sn-Pb alloys and measured data of Pb by G. Muher [3].

IV. Conclusion and Future Work

We have performed the neutron total cross section measurements of Sn-Pb alloys in solid and liquid state using TOF method at the KURNS-LINAC. The sample temperature was changed from room temperature (solid) up to 300℃ (liquid). The measurement results were compared with the previous experimental data of Pb and the evaluated data in JENDL-4.0.

The total cross sections of solid and liquid states were compared and **the change in Bragg edge** due to the difference of crystal structure **was observed** in the energy range below 0.01eV. From the result, it was confirmed that **the effect of coherent scattering decreased by melting** from the solid to the liquid. Comparing the total cross sections of the solid and the solid resolidificated after melting, it was confirmed that **Bragg edges**, which is thought to be due to the crystal structure of Pb, **couldn't be seen by the resolidification**.

This study shows important data for using solid and liquid alloys as the heat transport medium in the core of thermal reactors. As a future work, from the data of the solid and the liquid obtained in this experiment, we will evaluate the impact of Sn-Pb alloys on the core.

Reference

[1] Rei Kimura et al., "Ensuring Criticality Safety of vSMR Core During Transport Based on Its Temperature Reactivity.", Nucl. Sci. Eng., 2020; 194: 213-220

[2] K. Shibata et al., "JENDL-4.0: A New Library for Nuclear Science and Engineering.", J. Nucl. Sci. Technol., 2011; 48(1): 1-30

[3] G. Muhrer et al., "Comparison of the measured and the calculated total thermal neutron cross-section of Pb", Nucl. Instrum. Methods Phys. Res. Sec. A, 2007; 572: 866-873