Overview of Research and Applications of Neutron Beams: Present Status and Future Activities in Japan

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There are four neutron sources available for beam experiments in Japan as shown in Table 1. The continuous beam with medium flux from JRR-3 and the intense pulse neutron source of J-PARC/MLF are used for structural and dynamical studies on materials and in life science. Both facilities are at the Tokai site of JAEA, a center of excellence in neutron science. The large pulse height and the time-of-flight (TOF) technique significantly increase the efficiency of the spectrometers at J-PARC/MLF, which now operate at ~200 kW. The proton beam power will be increased to ~300 kW this summer and to 1 MW in the future. JRR-3 remains useful because the time-averaged flux is comparable to that of J-PARC/MLF. The TOF technique is highly efficient for measurements in a wide momentum-energy (q,w) space, while time-averaged flux is crucial for pinpoint measurements in a narrow (q,w) space. The upgrade and reallocation of instruments at JRR-3 are under consideration for the purpose of complementary use with J-PARC/MLF.

TABLE 1. NEUTRON SOURCES FOR BEAM EXPERIMENTS IN JAPAN.

Neutron source	Type	Beam character	Power, Time-averaged flux	Instruments	Location
JRR-3	Swimming pool + heavy-water reflector	Continuous	20 MW, $3x10^{14}$ $cm^{-2}s^{-1}$ for thermal	37 instruments	Tokai-Ibaraki
J-PARC /MLF	Spallation, Liquid hydrogen moderator	Short pulse 25 Hz,	1 MW, ~$3x10^{14}$ $cm\text{-}^{2}s^{-1}eV^{-1}srad^{-1}$ (thermal, CM)	23 instruments	Tokai-Ibaraki
KUR	Swimming pool, Tank type	Continuous	5 MW, $3x10^{13}$ $cm^{-2}s^{-1}$ for thermal	8 instruments	Kumatori-Osaka
Hokudai Linac	Electron linac	Short pulse	45 MeV, 1 mA	3 beam lines	Sapporo-Hokkaido

The neutron fluxes of the Kyoto University Reactor (KUR) and the Hokkaido university linac (Hokudai Linac) are rather weak. One of the most important applications of KUR is boron neutron capture therapy (BNCT). Furthermore, KUR also concentrates on very cold neutron (VCN) radiography and prompt gamma analysis (PGA). Development studies on new techniques and/or neutron optical devices such as detectors, mirrors, and monochromators should be performed for KUR and the Hokudai Linac, because test experiments can be carried out with a well controlled weak flux, and sufficient beam time to conduct many trial-and-error experiments. Education is also an important role of these neutron sources operated by universities.

A summary of the instruments at JRR-3 and J-PARC/MLF is given in TABLE 2. Inelastic machines such as triple-axis spectrometers (TAS), TOF spectrometers, and spin echo spectrometers are widely used for condensed matter physics and chemistry. The number of neutron crystallographical studies is increasing very rapidly, such as to develop high-performance batteries and to study biomaterials such as proteins and DNA, for which J-PARC is most powerful. The lack of beam time for small angle neutron scattering (SANS) experiments is the most serious problem in JRR-3. New SANS instruments should be constructed particularly at JRR-3. The demand for neutrons in engineering (such as for residual stress analysis) is constantly increasing. The complementary use of JRR-3 and J-PARC/MLF is also essential to meet this demand. New types of neutron imaging techniques are being developed

that apply pulse neutron sources. Generally speaking, however, research reactors are advantageous for neutron radiography owing to the strong and continuous neutron beam. A continuous beam is favorable for taking dynamic images with various time resolutions. There is no plan to carry out irradiation studies such as activation analysis and the production of neutron transmutation doping (NTD) silicon and radioisotopes at J-PARC, for the simple reason that the irradiation requires a high total neutron flux. These studies remain very important applications of research reactors.

TABLE 2. LIST OF THE INSTRUMENTS AT JRR-3 AND J-PARC/MLF.

	JRR-3		**J-PARC/MLF**	
Inelastic	Thermal TAS	7	Chopper	3
	Cold TAS	2	Inverse geometry	1
	Chopper	1		
	Spin echo	2	Spin echo	(1)
Elastic	Powder	3	Powder	2
	Diffraction	4	Diffraction	2
	SANS	3	SANS	1
	Double-crystal SANS	1	High pressure	1
	Reflectivity	2	Reflectivity	2
	Engineering	2	Engineering	1
Imaging	Thermal	1		
	Cold	1		
	Interferometer	1		
PGA	Thermal	1		
Others	Nuclear data+MPGA	1	Nuclear data	1
	Neutron beta decay	1	Optics & fundamental	1
	Test beam port	4	Test beam port	1
Irradiation	Reactor core	9		
	Heavy-water tank	8		
Total	(Beam instruments)	37		17

In addition to the application of neutrons for fundamental science, the rapid increase in proprietary use by industry is remarkable in Japan, and this is a key issue in the peaceful use of nuclear energy. Here, the running cost is also an important factor that should be considered.

The complementary use of continuous and pulse neutron sources is expected to be a new trend in neutron science in the next generation. SNS and HFIR are located at the same site in Oak Ridge, USA. The European spallation source (ESS) is planned in Europe. In the last ten years several medium class reactors (HANARO, ANSTO, FRM-II, etc.) have been built. Collaborations between institutions with different types of neutron sources will be very important to maximize the quality and quantity of scientific output.