The RIKEN-RAL Muon Facility at the ISIS Neutron and Muon Source

P. King,[*1,*2] M. Iwasaki,[*3] K. Ishida,[*3] and I. Watanabe[*3]

The RIKEN-RAL Muon Facility is one of RIKEN's significant overseas outposts and a major collaboration between RIKEN and the UK. The Facility is part of the ISIS Neutron and Muon Source, located at the Rutherford Appleton Laboratory (RAL) in the UK. ISIS is the UK's national neutron and muon source, but it has many international partnership arrangements, and one of the largest and longest standing is the collaboration with RIKEN. The Facility performs a very wide variety of pure and applied studies using muons.

The collaboration began in the late 1980's under the leadership of Prof Kanetada Nagamine. The first agreement between RIKEN and RAL to build the Facility and collaborate in muon science was signed in 1990 for 10 years. First muons were produced in 1994 and the Facility was officially inaugurated by the then RIKEN President Prof Arima in 1995. The Facility has been performing muon science studies since then, with further agreements between RIKEN and RAL in 2000 (10 years) and 2010 (7.5 years).

In 2015 the Facility celebrated 20 years of muon production and 25 years of formal agreements between RIKEN and RAL. Over its lifetime, the Facility has been recognized in a number of ways. This includes regular presentation at meetings of the UK-Japan Joint Committee on Co-operation in Science and Technology chaired by the UK Chief Scientist, where it is used as a good example of UK-Japan science collaboration. In 2003 Prof Nagamine received the Toray Science and Engineering Prize from the Toray Science Foundation of Japan, and in 2002 Dr Paul Williams (CLRC Chief Executive) received the Minister's Commendation for Meritorious Service in the Field of International Exchange from the Japanese Minister of Education, Culture, Sports, Science and Technology.

Muons for use in the Facility are produced by the decay of pions generated by the interaction of the ISIS 800-MeV proton beam with a 1-cm thick carbon target. The Facility is able to accept "surface" muons, produced from pion decays within the carbon production target. These are positive muons with high flux and with momentum of around 30 MeV/c which are then directly transported to the experiment areas. The Facility also incorporates a decay channel, within which pions from the carbon production target are allowed to decay in-flight. This enables higher momentum (up to around 110 MeV/c) positive muons to be produced, as well as allowing negative muons to be generated. This means that the facility is very flexible, enabling both positive and negative muons with variable momenta to be generated for muon science experiments.[1)]

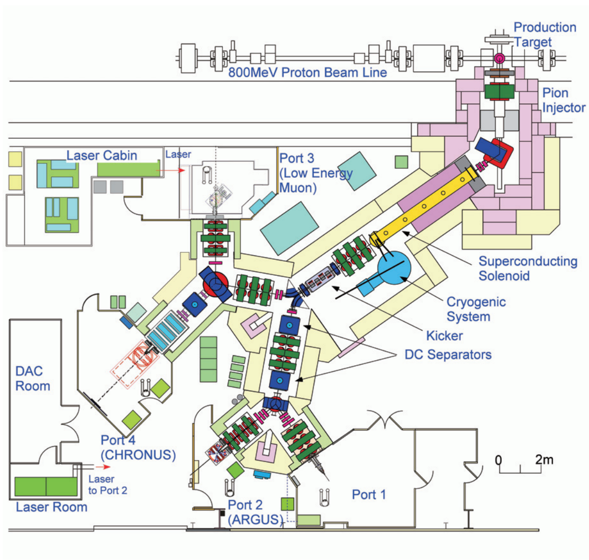

Fig. 1. The RIKEN-RAL Muon Facility at the ISIS Neutron and Muon Source, UK. Muons or pions are generated at the production target, and muons are transported to one of four experiment areas. The superconducting solenoid allows decay of pions in-flight, enabling variable momenta positive or negative muons to be produced.

The ISIS primary proton beam is pulsed at 50 Hz, meaning that the RIKEN-RAL Muon Facility is a pulsed muon source. The science that can be done at the Facility is, in many ways, complementary to that which can be done at continuous muon sources at PSI in Switzerland or TRIUMF in Canada. The RIKEN-RAL Muon Facility is the only pulsed source of decay-channel muons in Europe, and so is a unique resource for muon studies.

The science of the facility is very varied, and broadly falls into two categories: fundamental physics studies using muons, and condensed matter and molecular science employing muons as probe particles.

A key science driver for the facility when it was first established was investigation of the process of muon catalyzed fusion (μCF). μCF is a cold fusion process occurring between deuterium and tritium nuclei. A d$t\mu$ molecule is formed within a liquid or solid deuterium-tritium mixture, which enables the d and t nuclei to approach closely enough to fuse, releas-

*1 Director of RIKEN Facility Office at RAL, RIKEN Nishina Centre (2012–present)
*2 STFC ISIS Neutron and Muon Source
*3 RIKEN Nishina Centre

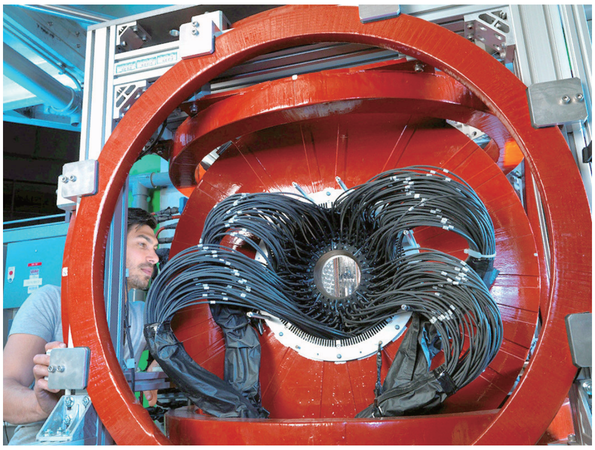

Fig. 2. Adam Berlie, joint RIKEN-RAL / ISIS appointment, with the CHRONUS spectrometer.

ing energy and characteristic reaction products. The RIKEN-RAL Muon Facility provided an ideal source of negative muons to enable this process to be studied in detail, including revealing new effects in its temperature dependence.[2] Other fundamental physics studies at the facility have included precise measurement of the muon lifetime[3] and muonic atom spectroscopy for studies of nuclei.[4]

A key application of muons is the study of atomic- and molecular-level properties of materials in condensed matter physics and chemistry. Muons produced at RIKEN-RAL are spin polarized, an effect occurring naturally from the pion decay. Positive muons maintain their polarization when implanted into materials, and observation of the time-dependence of the polarization of the muon ensemble within a sample provides information on local magnetic fields. In turn this informs on the magnetic properties of the material as well as enabling processes such as diffusion to be studied. The polarization of the implanted muons is observed by detection of the positrons emitted when the muons decay after their average lifetime of 2.2 μs. These positrons are preferentially emitted in the direction of the muon spin at time of decay, enabling the behavior of the muons with a material to be followed. The Port 2 area of the Facility has been home to the ARGUS muons spectrometer since the early days of the facility, and this was supplemented with the CHRONUS spectrometer on Port 4 which began a μSR programme in 2014.

Studies of a wide variety of magnetic and superconducting materials have been a feature of the RIKEN-RAL Muon Facility. This includes, for example, studies of critical behavior around magnetic transitions,[5] model organic systems,[6] non-Fermi liquid spin dynamics,[7] the interplay between magnetism and superconductivity,[8] spin liquid systems[9] and other frustrated systems.[10] Diffusion and charge dynamics also feature, for example in organic[11] and inorganic (battery)[12] materials.

The Facility has seen development of key techniques for condensed matter and molecular studies using muons. These include laser-stimulation of samples, allowing excited state spectroscopy,[13] and studies of materials under pressure which are enabled by the higher momentum beams available from the decay channel.

The traditional muon technique for condensed matter studies allows the bulk of the material to be probed, as muons penetrate a large fraction of a mm into a sample. In order to allow studies at much smaller depths closer to the surface, and interface studies, work has been ongoing to develop a source of low energy muons on Port 3 of the RIKEN-RAL Muon Facility. The method being used is particularly suitable to a pulsed muon facility, and involves laser ionization of muonium atoms (positive muons which have picked up an electron to form a light hydrogen atom with the muon as nucleus) to produce keV muons as opposed to the MeV muons normally used. The method has been extensively developed at RIKEN-RAL, and the characteristics of the low energy muon beam that is produced have been detailed.[14] This method is now in operation at the J-PARC muon facility following its development at RIKEN-RAL. It offers the potential for fundamental muon studies, such as muon $g-2$ measurement, as well as condensed matter investigations.

Recently, new applications of muons have been developed at the facility. This includes studies of single-event upsets in microelectronic circuits[15] and elemental analysis of materials with negative muons.[16] Novel methods are also being developed for fundamental studies of the proton radius[17] in order to resolve discrepancies between different measurements on this subject. Overall, the Facility has produced more than 400 publications since its beginning in 1994, across a very broad range of pure and applied subject areas using muons.

A particular strength of the facility has been the development of collaborations and the attraction of researchers from around the world. Over 80 separate Japanese groups have used the facility over its lifetime, and around 40 groups worldwide have collaborated on science at the facility. Particularly of note is the development of links between RIKEN and Asian universities, resulting in MoUs with five Indonesian universities (first signed in 2008 and renewed in 2011 and 2015), and an MoU with Universiti Sains Malaysia, first signed in 2012 and renewed in 2015. These Asian links have resulted in multiple workshops and meetings, a variety of publications, in, in particular, the involvement of around 10 masters and PhD students from Indonesia and Malaysia whose theses have been based on work performed at RIKEN-RAL.

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