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Dr Yasushige Yano
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Dear Dr Yano,

RIKEN-RAL Muon Facility – International Advisory Committee Review Report

I am writing to enclose the report from the recent review of the RIKEN-RAL Muon Facility.

The RIKEN-RAL Muon Facility is a world-class facility, with unique capabilities that enable measurements which cannot be performed elsewhere. The Committee were very impressed by the strength and diversity of the scientific and technical achievements that have been made. The facility's accomplishments, and the strength of the collaboration that has developed between RIKEN and RAL, should be a source of pride for both institutes. The facility staff are enthusiastic and very able, and their strengths are one of the key reasons behind the facility's strong technical achievements.

The Committee noted exciting opportunities for further developments at the RIKEN-RAL facility, building on the existing strong infrastructure investment. These include development of a very high rate μSR spectrometer, enhancement and exploitation of the low-energy muon source, pressure capabilities for μSR and further exploration of fundamental physical processes in muon catalysed fusion. Some areas where there are strong technical achievements would value further advice from relevant RIKEN programme panels to consider their future scientific direction. Continued development at RIKEN-RAL will provide the technology, expertise and scientific community needed for the future exploitation of the new J-PARC muon source presently being constructed.

It was a pleasure to chair the RIKEN-RAL International Advisory Committee. Very many thanks for your hospitality during the review, and to the members of the RIKEN-RAL Muon Group for organising the review and for providing background material and talks for the review process. I look forward to the second review meeting in Japan later this year.

Yours sincerely

Andrew Taylor

RIKEN-RAL MUON FACILITY

INTERNATIONAL ADVISORY COMMITTEE REVIEW REPORT

NOVEMBER 2007

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1. Executive Summary

The RIKEN-RAL International Advisory Committee met for two days in November 2007 to consider the scientific and technical activities of the RIKEN-RAL Muon Facility. The Committee consisted of both International and Japanese experts appointed by Professor Yasushige Yano, the Director of the RIKEN Nishina Centre - listed in Appendix 1.

The Committee heard a variety of reports on the activities of the Facility, together with documentary evidence relating to Facility work, including publications and annual reports. The Committee's agenda is given in Appendix 2. The following sections of this report give more detailed findings and recommendations for each of the various science areas covered by Facility activities. The broad findings and recommendations are summarised here.

Findings and Recommendations

1. The RIKEN-RAL Muon Facility is world-class. It has unique capabilities, including, for example, the world's highest rate μSR spectrometer and unrivalled μCF facilities, enabling investigations in a variety of areas which cannot be performed elsewhere. It has an impressive diversity of science programmes within the one Facility.

2. The technical developments achieved by the Facility are particularly notable. Across the entire range of science areas covered by the Facility's activities, the Committee were impressed by the depth and diversity of experimental infrastructure and technical accomplishments.

3. The uniqueness of the Facility and what has been achieved scientifically and technically, together with the strong partnership that has been generated between RIKEN and RAL, should be a source of pride for both organisations.

4. The RIKEN-RAL Facility staff are dedicated, enthusiastic, motivated and extremely competent. They are one of the reasons for the strong scientific and technical achievements of the Facility, and they enable a wider community of scientists in Japan and further afield to benefit from the Facility.

5. The publication output from the Facility represents good value for money in terms of cost per paper when compared with similar facilities world-wide.

6. There are opportunities to look for further synergies between RIKEN-RAL activities and wider STFC activities – for example, through greater collaboration with the European Muon Group at ISIS; through liaison on laser developments with the STFC Photon Science Department (and the Laser Group in RIKEN); and through collaboration on development of pressure capabilities for μSR with the European partnership involving ISIS and PSI. RIKEN may wish to explore with ISIS the possibility of further muon flux improvements through use of thicker muon production targets.

7. Some programme areas, for example the muonic X-ray studies and μCF, would benefit from advice and guidance from the appropriate RIKEN advisory committees, or from other external collaborations with relevant experimental or theoretical groups.

8. The significant infrastructure investment in the RIKEN-RAL facility should be capitalised upon to ensure maximum benefit is gained through the unique facilities available. The Committee noted the significant future potential in areas such as the development of a very high rate μSR spectrometer on Port 4; the strong potential of the low-energy muon source; the addition of pressure capabilities to μSR studies on Port 2; and the further opportunities for unique exploration of fundamental physical processes in muon catalysed fusion.

9. It is clear that the unique facilities developed at the RIKEN-RAL facility are in demand by non-Japanese users, and that the collaborative agreement allowing 50% of the use of beam time by non-Japanese researchers works well for the benefit of both parties. In particular the current state of art spectrometer ARGUS is very attractive to condensed matter users and it is anticipated that the unique slow muon beams that could be delivered at port 3 would similarly attract foreign users.

10. The continued running of the RIKEN-RAL Facility is not only compatible with the build-up of muon activities at J-PARC, but is essential for muon studies at J-PARC to reach their full potential. The RIKEN-RAL Facility will continue to enable development and proofing of key technologies for J-PARC, such as low-energy muon beam development and μSR spectrometer construction. In addition, the RIKEN-RAL Facility will enable the continued training and development of community expertise in muon techniques, essential for J-PARC's success, together with stimulation of the Japanese and Asian communities who will in the future exploit the J-PARC muon source.

Specifically

11. ***Muon Catalysed Fusion:*** The RIKEN-RAL facility has unique capabilities worldwide which have led over recent years to key discoveries regarding the molecular processes involved in μCF. Further studies can continue to build upon this work, exploiting the expertise of the group to explore the effects of density and temperature in the solid phase aiming towards scientific break-even.

12. ***Muonic X-ray Measurement:*** A unique facility has been developed and demonstrated to allow study of nuclear structure parameters and μ^- nuclear capture rates using pulsed muon beams. There are further opportunities to improve the sensitivity of the apparatus. There is a need for more consideration of the physics aims of the experiment, including identification of key nuclei that the technique can be realistically applied to together with the role of the method alongside other nuclear structure and atomic techniques.

13. ***Condensed Matter Science:*** There is a highly successful, diverse and productive condensed matter physics programme with excellent publication record presently focused on the ARGUS spectrometer. There are good opportunities for further development of the programme through provision of extreme environments together with a new, very high data rate spectrometer on Port 4. There is the potential to attract further Japanese and Asian users of the μSR technique.

14. ***Muon Lifetime Measurement:*** The group have developed novel instrumentation for precision measurement of the muon lifetime. Systematic errors presently limit their precision to some 50 ppm. They are likely with the present set-up to be able in due course to confirm measurements by other groups that are expected to reach the few ppm level, and to

demonstrate technologies relevant to J-PARC. The project needs evaluation with respect to the competing use of time on Port 2 for μSR measurements.

15. ***Ultraslow Muon Development:*** A low-energy muon source has been developed and demonstrated based on laser ionisation of muonium. The source has excellent energy resolution, time width and spot size. This is an area with high potential for wide applications. Further investment is to be encouraged, to improve the low-energy muon flux and enable strong demonstration experiments.

16. ***Laser Developments:*** Developments are ongoing to provide pulsed laser stimuli for μSR experiments, a technique ideally suited to an intense pulsed muon source. There is considerable potential for excellent science, and strong demonstration experiments need to be chosen.

Overall Conclusions

The international advisory committee is of the opinion that the RIKEN-RAL Facility provides unique instruments which serve a dynamic user community and produce excellent science at a competitive cost. The superb technical skills used to develop state of art equipment are matched by the competence and dedication of a strong physics team. RIKEN should be proud of such an achievement. The committee noted two areas that need further scientific guidance from the RIKEN PAC to optimise the use of the very precious beam time at RAL.

2. RIKEN-RAL Muon Facility

Overview of the Facility

The first agreement between RIKEN and RAL on muon science was signed in September 1990. This initial ten year contract was renewed for a further decade in September 2000. These agreements have seen the construction, operation and utilisation of the world's most powerful pulsed muon facility at ISIS, the UK's pulsed spallation neutron and muon source. Known as the RIKEN-RAL Muon Facility, this project is the largest research collaboration project between the UK and Japan. It is set in the context of over twenty years of successful partnership between ISIS and Japanese institutes on neutron science and muon spectroscopy, including collaboration to build several ISIS neutron instruments. The RIKEN-RAL Muon Facility is described in detail in [1].

Within the agreements, RIKEN is responsible for the construction, operation and maintenance of the RIKEN-RAL Muon Facility, and ISIS is responsible for provision of the intense proton beam for muon generation. Increasingly there is partnership between the two institutes not only for technical work carried out on the Facility, but, for example, for the development of new techniques such as high-pressure facilities for condensed matter studies. UK and European scientists have access to 50% of the time on the ARGUS μSR spectrometer at Port 2 of the Facility.

Significance of the Facility

The RIKEN-RAL Muon Facility has at its centre a pion decay channel which allows production of both positive and negative muons with variable momentum. These can be fed at any one time to up to two of the four experimental areas: ***Port 1*** is used for muon catalysed fusion investigations; ***Port 2*** primarily for condensed matter and molecular studies, together with muon lifetime measurements; ***Port 3*** for development of a low-energy muon beam; and ***Port 4*** is presently equipped for development of muonic X-ray studies from unstable nuclei. Each of these areas is dealt with separately in this report. The Facility is the most intense pulsed muon facility in the world; for example, the ARGUS μSR spectrometer at Port 2 has the highest time-differential muon data rates. The muon intensity, together with the significant technology investment that has been made in the experimental infrastructure, mean that many of the studies performed are unique and that the RIKEN-RAL muon source is a world-class facility.

Since 1997, 217 publications have resulted from work at the Facility. In terms of cost per paper, this compares very favourably with similar facilities and represents good value for money. Over this period the facility has received almost 350 experimental proposals, attracted over 430 visiting researchers, and has experimental collaborations with 41 Japanese and 12 world-wide institutions. The committee identified 19 papers in prestigious journals (see Section 9) which had high scientific impact. The committee noted that 21 master degrees and 12 Ph.D's. were awarded to Japanese students from work performed at the RIKEN-RAL facility. Also 8 UK doctoral degrees were conferred to non-Japanese students who used the RIKEN–RAL facility.

Future Developments and Recommendations

The first-class technology developments across all areas of activity were clearly evident and one of the factors in making the RIKEN-RAL Muon Facility unique. Continued technology development at the Facility will enable the assessment of future requirements at J-PARC together with sustaining expertise in muon methods essential for the future J-PARC programme. It was therefore recognised that not only is the RIKEN-RAL Muon Facility at present compatible with the build-up of activity at J-PARC, it is essential to enable the full realisation of the potential of the J-PARC muon source in terms of technology developments and the stimulation of the Japanese and Asian muon communities. In addition, there continue to be significant opportunities to capitalise on the very significant investment made in the RIKEN-RAL Muon Facility infrastructure to ensure full benefit is reaped from this investment. The Review noted that the RIKEN-RAL staff are very dedicated, hard-working, enthusiastic and extremely able, and have contributed significantly to the success of the RIKEN-RAL programme.

The Review noted the proposed future developments across the RIKEN-RAL activities – specific comments on these are found in relevant sections. The Review noted that there exist significant opportunities for further collaboration between RIKEN-RAL and other STFC facilities, including the European Muon Facility at ISIS and the STFC Photon Science Department for laser developments.

3. Muon Catalyzed Fusion

μCF Science

This programme is aimed at studying the dynamics of few-body molecules incorporating a negative muon, namely D-μ-D,D-μ-T,T-μ-T molecules. These molecules are rich in processes which are challenging our understanding of the underpinning atomic and molecular structure. Molecular formation, transfer from one atom to another, sticking probability to one of the fusion products, and reactivation are a few of the specific problems studied in these molecules. Muon catalyzed fusion has been investigated for about thirty years to understand the parameters which control the number of fusions generated by a single muon during its life time. The RIKEN-RAL group has been pioneering the most detailed comprehensive study and has contributed to identifying conditions that could lead to a break-even energy balance between the energy necessary to generate the muon and the energy given by the induced multiple fusions.

μCF at RIKEN-RAL Muon Facility

These studies, which were very pre-eminent at PSI, TRIUMF, DUBNA until very recently, are now led worldwide by the RIKEN-RAL group at RAL with pulsed muon beams with tritium and deuterium gas and at TRIUMF with DC beams and deuterium gas only. This is in part due to the unique facilities developed by the group at RIKEN-RAL which combine high intensity negative pulsed muon beams at high momentum and a state of the art Tritium gas handling facility. They have developed a method to generate controlled initial molecular states and to determine the ratio of ortho to para molecules. The work with Tritium molecules can only be done at RAL.

Key achievements

The group has established the importance of resonant formation in DD mixtures [2]; it has determined the probability for the muon to be removed from the fusion cycle by sticking to the Helium produced in the fusion – a key parameter limiting the cycling rate for the muon; and has established the reactivation probability (release of the muon) via an innovative X-ray detection method. This has challenged current atomic models. In the last few years, a key discovery was made by the RIKEN-RAL group when they established that the rate of fusions was also dependant upon the initial molecular state and that its dependence upon density and temperature was contradicting theoretical models [3]. This was measured in DD mixtures and is now studied at RIKEN-RAL in D-T molecules. These studies were conducted in the gas phase and in a solid target at normal density.

Future work and Recommendations
Having established the key parameters controlling the cycling rate, and developed unique tools to do so, the group is preparing to explore the role of density and temperature in the solid phase. This requires the development of new targetry and handling of a larger tritium volume for which the RIKEN-RAL group has the most expertise. The goal would be to establish a good understanding of these effects to assess the likelihood of reaching an energy balance for this process.

In conclusion, the group has contributed key experimental elements to the understanding of this process by clever instrumental development and by exploring a rather wide parameter space. At the moment a theoretical framework for a comprehensive scientific evaluation of future prospects for energy generation is lacking and this will be needed to zoom in on the most effective parameters. At the level of current understanding, major engineering efforts will be needed to reach economic self-sufficiency. The group should focus the next phase on the understanding of density/temperature in the solid phase and try to engage a theoretical effort to digest the information gathered so far.

4. Muonic X-ray Measurement

Science Overview
This experimental project aims to study the muonic *X*-ray spectroscopy of unstable nuclei using a very unique technique in which a thin solid hydrogen film is used to stop both a μ^- beam and a radioactive A* beam. The *X*-rays as the muons transfer from the hydrogen muonic atom to the heavier μA* atom are then observed. This *X*-ray spectroscopy is intended to study nuclear structural parameters, absolute charge radii and quadrupole moments of unstable nuclei and also μ^- capture in very neutron rich nuclei, which would be difficult to determine by other methods. Such scientific goals motivated this experimental group to this very innovative and challenging solid hydrogen film method.

Muonic X-ray measurement at RIKEN-RAL Muon Facility
A pulsed μ^- beam has the advantage that the *X*-rays can be detected under suppressed background conditions. RIKEN-RAL with its highest-intensity pulsed beam is well suited to develop this experiment. A dedicated apparatus was installed at Port 4 to use the low momentum 27 MeV/*c* μ^- beam. As the first stage of this project, the injection of stable isotopes has been investigated. An ion source and an optics system with a maximum energy of 33 keV was installed in the area to implant ions from the opposite side of the muon stopping target. The experimental system has been carefully designed, constructed and tuned for the maximum μ^- transfer rate. The committee was very much impressed by the technology developed by the group.

Key achievements
First, an Ar ion implantation was performed to test the two target conditions in detail. One was the two-layer arrangement which took advantage of the Ramsauer-Townsend effect in the diffusion of μd and the other was the method of non-uniform implantation into a solid D_2 layer. Under optimum conditions the 2p→1s transition with 644 keV could be successfully

observed in both cases [4]. This result can be considered as the first muonic X-ray observation using the solid hydrogen film method. Recently a new surface ionization ion source has been installed which provides both alkali and alkaline-earth metal beams. Preliminary results have been obtained for the $2p_{3/2} \rightarrow 1s_{1/2}$ and $2p_{1/2} \rightarrow 1s_{1/2}$ transitions in ^{86}Sr and ^{88}Sr; these results are consistent with previous data. For further studies of the nuclear parameters of stable nuclei using this technique, however, it will be necessary to show that this method can compete with and hopefully complement other experimental techniques such as laser spectroscopy.

Future work and Recommendations
As presented by the group, it is possible to proceed to long-lived unstable nuclei using this ion source by realizing a much smaller target and a higher cloud μ^- flux. The *X*-ray detection efficiency (currently two detectors) will certainly need to be improved. The inevitable requirement will be to construct a reliable RI handling system in the ion source. Several candidates for alkali-, alkaline-earth and rare-earth metals were mentioned. However, considering the increased experimental difficulties, and the necessary manpower and capital investment required, it is strongly recommended that the experimental group works out what unique interesting physics can be extracted from which unstable nuclei, and obtain advice from the Nuclear and Particle Physics Program Advisory Committee (PAC). The IAC would like to hear such a concrete proposal in its next meeting.

5. Condensed Matter Physics

Overview of Condensed Matter Science at RIKEN-RAL
The RIKEN-RAL group has a diverse and highly productive programme in condensed matter physics that is very successful. It underpins a large body of research which has been performed by researchers based at RIKEN-RAL, in Japan and also in Europe. This area has had a very strong link with theory (a number of theoretical papers have arisen from RIKEN-RAL work on organic magnets).

RIKEN-RAL Condensed Matter Facilities
The ARGUS spectrometer has been key to the success of the programme so far. This is because of (1) the *high data rate*, which allows users to attempt problems that they would not do elsewhere, (2) the ability to use *small samples* (running in 'flypast' mode), which allows problems to be tackled on the most cutting-edge samples (which because of their novelty are only available in tiny quantities) and (3) the possibility of using *decay muons,* which allows the use of high pressure techniques. Success has been demonstrated in the first two of these, while the third (high pressure) is currently under active development and we expect that this is an area in which high profile science is likely to be achieved. We note that there is a high demand for μSR beamtime on ARGUS from both Japanese users and ISIS users and the provision of the Port 4 spectrometer will help to meet this need and provide enhanced μSR capabilities.

Selected science highlights
The condensed matter programme in μSR provides more than 60% of the publication output of the facility, including a number of high-profile papers. Highlights include work on filled skutterudites, molecular magnets, conducting polymers, high-temperature superconductors, low-dimensional magnets, spin crossover systems, spin gapped systems and non-collinear magnets. Some examples of publications are given below [5-12].

Future developments and recommendations
This is a key area for investment by RIKEN since the μSR programme is an excellent way to widen the science base in Japan and Asia and provide necessary underpinning of a future programme at J-PARC. There are a number of new opportunities arising at the moment: (1) *remote access* can enable a wider science base in Japan and Asia to participate in the RIKEN-RAL programme and help to reach out to potential users for whom μSR would not be their main technique; (2) the development of techniques to provide *extreme sample conditions* will enable a deeper science base for more experienced users; (3) the new Port 4 μSR spectrometer, with more detectors, can build on the established advantages of the ARGUS spectrometer. We recommend that this area is strongly invested in by RIKEN.

It would also be useful for the RIKEN-RAL group to further exploit the synergies which exist (1) with the ISIS muon group, who share similar interests in μSR techniques, science and development, (2) the STFC laser group, for technical assistance with pump probe experiments and (3) with the PSI muon group (via the European joint project between ISIS and PSI) who are also investing in high pressure technique development.

6. Muon Lifetime Measurement

Science Overview
The predictive power of the standard model is based on very precise knowledge of a few fundamental constants. The Fermi constant G_F is one of these constants, which using second order QCD calculations can be calculated with a precision of less than 0.3 ppm. The most precise experimental determination is based on a measurement of the mean lifetime of the positive muon τ_μ. To obtain the required precision on G_F, τ_μ must be measured with a precision slightly better than 1 ppm. Several groups worldwide are performing muon lifetime experiments. The latest published result has reached a precision of 11 ppm[1]. The group behind this experiment is planning to collect data with 100 fold improved statistics which may lead to τ_μ with the 1 ppm precision.

Muon Lifetime measurement at RIKEN-RAL Muon Facility
The muon lifetime experiment at the RIKEN-RAL Muon facility shares Port 2 with the μSR instrument for condensed matter. The instrument has a highly segmented detector; it can take full advantage of the very intense double pulse and the very low background between pulses. The muons are stopped in a target consisting of paramagnetic Ho, which has a very short relaxation time. The system is furthermore equipped with a very accurate clock and a new fast data acquisition system. The instrumentation is novel – the other muon lifetime experiments are based on CW sources – and technically absolutely world class.

Key achievements
By the end of 2005 the group had collected $1.15\ 10^{10}$ events and determined τ_μ with a precision of 51 ppm [13]. The systematic errors for the measurement with this setup, is however about an order of magnitude too high to arrive at 1 ppm precision. The group has made concerted efforts to understand and reduce the systematic errors. From the presentation it was not clear whether these systematic errors were fully understood and unambiguously called for the development of a new detector system.

[1] [1] Chitwood et. al. Phys. Rev. Lett. 99 (2007) 032001

Future work and Recommendations

The muon life time experiments elsewhere are advanced to a level that the RIKEN-RAL group probably will not be able to be the first experiment reaching the 1 ppm level, but will be able to confirm measurements performed elsewhere. While this is important in itself, we propose to re-evaluate the project in view of the possible alternative use of the beam port for μSR experiments, where the RIKEN-RAL facility is unique and very successful. The highly segmented scintillator detector development initiated for the new muon lifetime experiment is however technically of a very high standard, and a key development for future μSR instruments at new higher intensity pulsed muon sources such as J-PARC. It would also allow the RIKEN-RAL facilities to utilise a possible intensity increase at RAL (higher current and thicker muon production target), and thereby further enhance the uniqueness of the RIKEN-RAL μSR facility – the highest rate μSR facility world wide.

7. Ultraslow Muon Development

Technique Overview

The RIKEN-RAL group has developed the pulsed ultraslow muon beamline with excellent quality by using the unique method of the resonant ionization of thermal muonium in vacuum in a strong collaboration with the KEK muon science group, and constructed a complete setup for μSR experiments. The low-energy muon source had been the long-standing desire of the muon community to explore the dynamic properties of thin films and multilayers, at surfaces and interfaces, and of nanomaterials. Requests for a high quality low-energy beam have been increasing after the stimulating work on the depth profile analysis near surfaces achieved by using the DC low-energy muons produced by the cold moderation method at PSI.

Ultra Slow Muon Generation at RIKEN-RAL Muon Facility

The pulsed ultraslow muon beam line at RIKEN-RAL consists of the production target for thermal muonium in vacuum, the laser system for resonant ionization and reacceleration, the U-shaped transport beamline with low background and the μSR setup for low energy muon experiments. It has the advantages of low momentum bite, small beam spot size, low background, and short time width, as well as the capability for external trigger – a nice match to a low-duty extreme experimental condition such as laser excitation. The resonant ionization of thermal muonium in vacuum is a quite a unique technique in pulsed ultraslow muon generation in combination with intense pulsed lasers. This method was initiated by the work at KEK following the discoveries of both thermal muomium production in vacuum and the resonant ionization of thermal Mu. At RIKEN-RAL, the successful development was achieved by using the intense pulsed surface muon beam in Port 3 with 10 years' effort of technical improvements and optimisation of the entire system. Although the available flux is much lower than that at PSI and still far from the practical level, the excellent properties of the beam have been confirmed by the muon decay spectrum, spot size measurements, time-of-flight measurements on muon implantation with external trigger, frequency response and energy dependence of initial asymmetry in test samples. The future potential of the facility was demonstrated by observation of successive magnetic transitions in a thin film of 100 nm in thickness which is a promising candidate for spintronics.

Key achievements

Major achievements are (1) the establishment of the method for pulsed ultraslow muon generation by the resonant ionization of thermal Mu in vacuum [14, 15], (2) generation of ultraslow muons with yields of 15-20 events/sec demonstrating the advantages of the pulsed low energy muon compared to the DC low energy beam at PSI; small spot size of 4 mm beam diameter at the sample; tunable energy range between 0.1 and 18keV; high energy resolution of 14 eV at 9 keV; high time resolution of 7.5 ns in single pulse structure; and extremely low background resulting in a high S/N ratio above 10^4 [16-18], (3) development of intense laser system for VUV (122nm) and optimisation for stable operation for extended periods, typically continuous 7 days enabling practical application, (4) a successful construction of the delicate μSR setup with extremely low background, (5) demonstration of the potential of the facility[16, 18].

These achievements provide strong potential for a useful user facility at RIKEN-RAL and will attract new users in surface science and nanotechnology. Normalized by the intensity of incoming MeV muons, the ultraslow muon source at RIKEN-RAL attains almost the same production efficiency as the DC slow muon source at PSI [17]. Synergies with the STFC Photon Science Department and the Laser Group in RIKEN could lead to further enhancement of the ultraslow muon rate. Further opportunities to increase the efficiency at RIKEN-RAL were clearly shown by evidence-based data [19]. With improvements at RIKEN-RAL, this technique will bring an innovation in muon science and would be the ideal tool for the intense pulsed muon source in J-PARC.

Future work and Recommendations

This is one of the most promising areas with a high potential for wider applications, and it is therefore highly recommended to extend further the investigations at RIKEN-RAL with enhanced opportunities for flux improvements as well as strong demonstration experiments.

Further improvements are expected through (1) increase of the luminosity at the thermal muonium production target by optimisation of incoming MeV muons from superconducting solenoid transport, (2) upgrading the laser system in either 122 nm and 355 nm, or investigation of different ionization scheme such as two 244 nm photons or three 366 nm photons, (3) increase of thermal muonium production efficiency including the investigation of alternative target materials. To provide further potential of the pulsed ultraslow muon beam, study of acceleration to higher energy is encouraged, towards the sub-mm sized beam.

In the short-term, the panel recommends that a high priority be given to the support of this project and the provision of sufficient staff effort. This is necessary to enhance and extend the development work and build on the initial success of this project. The panel sees the ultraslow muon project at RIKEN-RAL as an important innovation which underpins future world-class nanoscience research at J-PARC.

8. Laser Developments

Technique Overview and work to date

The pulsed laser is a natural match for a pulsed muon beam. The RIKEN-RAL group are proposing further development of laser techniques to be used in conjunction with μSR, and have designed a new laser lab as part of this.

Future work and Recommendations

Laser techniques are technically challenging to integrate with μSR experiments, but the RIKEN-RAL group has the technical capability in this area to proceed with success. One can foresee several applications using lasers to probe states, excite the system or even to prepare radicals. This proposal builds on the proven expertise of the group in using lasers and exploiting the subtleties of atomic physics to achieve novel science. A pulsed source is exactly the right place to invest in these developments. This development has the potential to produce some world-leading science if the technical obstacles can be overcome and if the right science topics are chosen to study with this technique. The advisory committee were strongly supportive of this avenue of research.

9. Key Papers

[1] *The RIKEN-RAL Muon Facility*, T Matsuzaki et al., Nucl Inst Meth A 465 (2001) 365

[2] *New insights in muon catalyzed dd fusion by using ortho-para controlled solid deuterium*, A Toyoda et al., Phys. Rev. Lett. 90 (2003) 243401.

[3] *Dependence of muon catalyzed dd fusion on the ortho-para ratio in solid and liquid deuterium*, H Imao et al., Phys. Lett. B 632 (2006) 192.

[4] *Muonic Atoms of Unstable Nuclei*, P.Strasser et al., *Proceedings of the International Workshop on Physics with Ultra Slow Antiproton Beams* (RIKEN, Wako, Japan, 2005), AIP Conference Proceedings 793 (2005) 242.

[5] *Chiral-like critical behavior in the antiferromagnet cobalt glycerolate*, FL Pratt et al., Phys. Rev. Lett. 99 (2007) 017202

[6] *Evidence for magnetic ordering associated with the metal-insulator transition in $SmRu_4P_{12}$ studied by muon spin relaxation*, K Hachitani et al., Phys. Rev. B 73 (2006) 052408

[7] *Low-temperature spin diffusion in a highly ideal S=1/2 Heisenberg antiferromagnetic chain studied by Muon spin relaxation*, FL Pratt et al, Phys. Rev. Lett. 24 (2006) 247203

[8] *Muon spin relaxation and rotation study on the solid solution of the two spin gap systems* $(CH_3)_2CHNH_3.CuBr_3$, T Saito et al., Phys. Rev. B 74 (2006) 134423

[9] *μSR study of the anomalous magnetic behaviour in the excess oxygen doped $La_{1.6}Nd_{0.4}CuO_{4+\delta}$ around the hole concentration of 1/8 per Cu*, I Watanabe et al., Phys. Rev. B 73 (2006) 134506

[10] *Muon-spin-relaxation and magnetic-susceptibility studies of the effects of the magnetic impurity Ni on the Cu-spin dynamics and superconductivity in La2-xSrxCu1-yNiyO4 with x=0.13*, T Adachi et al., Phys. Rev. B 70 (2004) 060504

[11] *Magnetic ordering and spin dynamics in the quasi-one-dimensional spin-1/2 chains of $CuNb_2O_6$ observed by muon spin rotation and relaxation*, VV Krishnamurthy et al., Phys. Rev. B 68 (2003) 014401

[12] *Non-Fermi liquid spin dynamics in $CeCoGe_{3-x}Si_x$ (x=1.2 and x=1.5)*, VV Krishnamurthy et al., Phys. Rev. Lett. 88 (2002) 046402

[13] *Precision measurement of the positive muon lifetime at the RIKEN-RAL muon facility*, D Tomono et al., AIP Conference Proceedings 842 (2006) 906

[14] *First Observation of slow muon beam at RIKEN-RAL*, Y. Matsuda et al., , Physica B 326 (2003) 217

[15] *Slow muon experiment by laser resonant ionization method at RIKEN-RAL muon facility,* P. Bakule et al., Spectrochimica Acta B 58 (2003) 1019

[16] *Pulsed source of ultra lo-energy muons at RIKEN-RAL,* P Bakule et al., Physica B 374-375 (2006) 456

[17] *Generation and applications of slow polarized muons,* P Bakule and E Morenzoni, Contemporary Physics 65 (2004) 203

[18] *Generation of low-energy muons with laser resonant ionisation*, Y. Matsuda et al., Nuclear Physics B 155 (2006) 346-348.

[19] *The new world of μSR by ultra slow muon beam*, Y. Matsuda and Y. Miyake, Solid State Physics 39 (2004) 330

Appendix 1: List of International Advisory Committee Members

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Appendix 2: Committee Agenda

Monday 26 November 2007

1. Welcome and Overview of the Review process	Y. Yano
2. Introduction to the RIKEN-RAL Muon Facility	T. Matsuzaki
3. Muon Catalyzed Fusion	K. Ishida, T. Matsuzaki
4. Muonic X-ray Measurements	P. Strasser
5. Visit to the RIKEN-RAL Muon Facility	
Introduction to RAL	A. Taylor
Introduction to ISIS	P. King
Tour of the Facility	RIKEN-RAL Group members

Tuesday 27 November 2007

6. μSR studies (Condensed matter physics)	T. Matsuzaki
7. Muon Lifetime Measurement	D. Tomono
8. Ultra-slow Muon Generation and Applications	Y. Matsuda, P. Bakule
9. UK and European use of Port 2	F. Pratt
10. Closed discussion	
11. Concluding remarks	