Report of the KEK-IMSS Muon Science Advisory Committee (MuSAC)

MuSAC-2019

May 2020

The MuSAC-2019 meeting was held at J-PARC, Tokai (KEK Tokai Campus), between February 25th and February 26th 2020.

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I MUSE Overview

Professor Y. Miyake, Head of KEK-MSL, welcomed the panel and introduced the KEK-MSL activities at J-PARC. KEK-MSL is responsible for the operation and development of the J-PARC/MUSE facility, including the safe delivery of the proton beam onto the muon target and its safe operation. He introduced the tasks of MuSAC, which is to evaluate the scientific program of MUSE, the facility operation and future developments of the facility, and to give comments and suggestions to the KEK-IMSS Director, to efficiently operate and develop the MUSE facility with the current limitations on budget and manpower.

The committee received then the presentations of the ongoing S-type proposals, and three talks about future plans in intermediate terms. The research reports of S-type proposals demonstrate the rich field of muon applications, from fundamental particle physics to condensed matter physics, material science, elemental analysis, and ideas to use the muons as novel microscopy/tomography probe. This broad field of topical applications is a unique strength of the MUSE facility. No other experimental probe can compete with the versatility of the muon as a means to study the origin of matter and universe, and to explore the diversity of matter and life – being in line with the research mission of J-PARC, as defined by J-PARC Director Prof. N. Saito in his opening talk of the MAC-2019 meeting.

MUSE has currently three beam lines in operation for the international users' community: D1 and D2 for the μSR and negative muon programs, and S1 with the Artemis spectrometer for μSR. The U-line for the generation of ultra-slow muons (USM) for use in thin-film μSR (U1A) and muon microscopy (U1B) is currently being commissioned, with continuous improvements in the laser system for the efficient generation of USM. Construction of the H-line is ongoing, where 55 M JPY are still missing for completion of H-line and the H1 area, where H1 will host the MuSEUM and DeeMe particle physics experiments. Planning for the H-line extension with H2 area and extension hall is progressing, which will host the g_{μ}-2/EDM experiment and the Muon Transmission Microscope TμM. Funding for building the S2 beam line with experimental area could be secured within the new S-type proposal for a precision measurement of the muon mass by 1*s*-2*s* laser spectroscopy of muonium. The S2 area can be used for the μSR program or other experiments afterwards. The completion of the MUSE facility requires the S3 and S4 beam branches with experimental areas. These are future plans, that are yet to be funded, where S3 will host a μSR spectrometer for hydrogen related studies (in cooperation with JAEA), and S4 a high field spectrometer using RF pulsed μSR and μ-SR.

While user facility operation of D1, D2, S1, and U1A, U1B, and H1 is possible with present resources by a re-organization of staff in the operation of the proton beam around the muon production target, see section IV, the extension of S2 and the realization and operation of the future S3/S4 will need additional budget and manpower. MuSAC notes that this full suite of experimental facilities will further strengthen the role of MUSE as a world-leading facility in muon science.

II Research Projects (S-type Proposals)

Precision Measurement of Muonium Hyperfine Structure and Muon Magnetic Moment

The MuSEUM collaboration aims at a new precision measurement of the ground state hyperfine splitting (HFS) in muonium, both, at very low magnetic field and at a high magnetic field. This is a very important and timely experiment. It aims at delivering improved values for the muon magnetic moment and the muon mass. Both are fundamental constants and important targets as such, but also required input to an improved measurement of the muon anomalous magnetic moment g_μ-2, as presently ongoing at FNAL and later at J-PARC in the future H2 area. Together with the experimental effort by MuSEUM, theorists are working internationally on improved QED calculations, including higher order and weak corrections. With robust theory prediction and improved muon mass, the HFS measurement will allow crucial tests of the Standard Model and searches for exotic physics. Because of the great impact the precision result will have, every effort should be taken to guarantee a very solid result.

The MuSEUM collaboration has made impressive progress and brought the experiment to the point that the data accumulated in beam times at the D-line at low magnetic field already supersedes the previous best experimental result from LAMPF in its statistical precision. Impressive technical developments include monitor detectors, segmented scintillators with MPPC readout, development of a silicon strip detector using synergies with the g_μ-2/EDM experiment, development of a new cavity at high field, and several more. Great progress has also been made in measuring at various Kr gas pressures, allowing to better extrapolate to zero pressure, and in an exploratory study with Kr/He gas mixture to cancel the pressure shift by a large degree. The collaboration appears to be on a very good trajectory to control the pressure related systematics. Another source of systematic uncertainty requiring attention is the RF power drift.

The collaboration has proven that it is capable of efficiently using beam time and that the hardware appears to be up to the task. Further significant progress, including, in particular, all work at high field, requires the H1 area and the full H-line to be operational, including separator and slit system. If the Wien-filter separator is not available, MuSAC encourages beam studies at the H-line to use other positron separation techniques, e.g. using degraders in front of the last dipole magnet. Completion of the H-line must be of top priority in order to not delay the timely production of important high-visibility scientific results. To guarantee the acceptance of the future results of this precision experiment, MuSAC additionally urges the MuSEUM collaboration to establish upfront a robust scheme for an unbiased, blind analysis.

Search for Muon-Electron Conversion utilizing Pulsed Proton Beam from RCS (Rapid-Cycle Synchrotron)

The DeeMe project received a 5-year extension of the stage-2 approval from the muon-PAC at KEK/IMSS, and the detector system has been completed and is ready to use, including a spectrometer magnet borrowed from TRIUMF, and novel HV-switching MWPCs. Completion of the H-line should have highest priority in order to run the experiment in a timely manner, to provide a result before COMET phase-I, and in order to maximize the potential of a major discovery at J-PARC. MuSAC applauds the willingness of the DeeMe team to contribute to the building and commissioning of the beam line to ensure the timely start of the physics run with the high intensity beam.

Development of General-Purpose μSR Spectrometer with Semiconductor-based Optical Detectors and Measurement of New Element Strategy Samples with New Functions

Good progress has been reported in the application of μSR to the characterization of hydrogen states in the technologically relevant semiconductors ZnO and InGaZnO4 (IGZO). This is reflected in several publications of the results which appeared in 2019, while other studies of the MUSE team on magnetism in heavily carrier-doped iron-oxy-pnictides are under review, and a paper on the electronic structure and role of interstitial hydrogen in β-MnO_2 is in preparation. MuSAC is pleased to see the production of these interesting results within the MEXT "Element Strategy Initiative to Form Core Research Center for Electron Materials", led by H. Hosono from Tokyo Tech. MuSAC welcomes the continuation of the program in the next S-type proposal "Microscopic mechanism of hydrogen-sensitive properties in inorganic materials", started in FY2019, and is looking forward to see new results in upcoming experiments on new functional materials.

Application of Muon Radiography for the "Photon and Quantum Basic Research Coordinated Development Program"

The current status of the development and application of "negative muon radiography" was presented. Negative muon radiography is a non-destructive elemental depth-profiling analysis in materials using muonic X-rays emitted during the formation of negative muon atoms. Thus far, this method has been applied to the development of lithium batteries by Toyota CRDL. and to archaeological research. As an example of the latter, the results of the analysis of gold and silver coins used in the Edo period in Japan were shown. MuSAC was impressed by learning that the measurement accuracy was significantly improved by optimizing the beam tuning to decrease the momentum and beam spread, and the acquisition efficiency was also improved by moving the Ge detectors closer to the sample to allow measurements at larger solid angles. These advances in technology, while still in the testing stage, have proven their effectiveness by allowing the depth profile of gold and silver content in gold and silver coins to be significantly evaluated. In addition, specific plans for further improving the beam intensity in the low energy region and adding Ge detectors are presented, which are expected to make a significant contribution to archaeological research in the near future.

Development of D1 Spectrometer Instruments and μSR experiment in Strongly Correlated Electron Systems

The upgrade of instrumentation for the spectrometer in the D1 area has improved the accuracy of experiments on strongly correlated electron systems. Ongoing efforts over the past five years have resulted in the installation of a large aperture superconducting magnet, the development of a beam profile monitor and the development of a fly-past chamber for background reduction, which have greatly improved the experimental accuracy for small samples. In addition, a sample holder has been developed for small samples and a sample-rotation mechanism that operates in the mK temperature region. This enabled high-precision measurements of spatial anisotropy of the electronic properties of small sample materials. In further evaluating these improvements, studies on several unconventional superconductors have revealed interesting new properties, such as isotropy of spontaneous magnetization in Sr_2RuO_4, magnetic field dependence of the superconducting properties of BiS_2-type compounds, and coexistence of magnetism and superconductivity in the $CeCo(In,Zn)_5$ system. MuSAC appreciates that the development of the D1 spectrometer has been steadily and successfully carried out, and it is expected to significantly contribute to the progress in the field of strongly correlated electron systems.

Transmission Muon Microscopy

The Transmission Muon Microscope TμM at the H2-line is in a R&D phase where several prototype components are being prepared for tests. MuSAC is pleased to see that a collaboration involving nine institutions from Japanese universities, research centers (KEK/J-PARC and RIKEN) and industry (Sumitomo Heavy Industries) has been set up. If successful, this facility will offer unique capabilities to visualize nanoscale structures and functions of >~10-μm-thick biological specimen. As in the case of the USM microscope, the feasibility of the TμM will crucially depend on the generation of ultra-slow muons, which is currently limited by the intensity of ionizing Lyman-α laser pulses. First test experiments are planned at 5 MeV energy at the U1B line in FY2021, while the final stage with energy of 100 MeV depends on the completion of the H2 line.

Precision Measurement of Anomalous Muon Magnetic Moment

The measurement of the muon g-2/EDM represents a key experiment for testing the standard model. Since there is the competing experiment FNAL E989 at Fermilab, it is necessary to start the J-PARC experiment in a timely manner. For the VUV laser to ionize muonium, an output of 10 μJ has been achieved and the prospect of reaching the target 100 μJ has emerged. Other technical goals – such as the acceleration of thermal muons, the spiral beam injection into the storage magnet, and the development of detector components – seem to be on a good track and reachable. In order to secure a large amount of competitive funds, which is the biggest challenge, J-PARC/KEK-IMSS must provide timely support in infrastructure development in order to carry out the experiment.

Precision measurement of the Muon Mass by 1*s*-2*s* Laser Spectroscopy of Muonium

The proposed ten times improved precision measurement of the muon mass is another key experiment for testing the Standard Model, and complementing the MuSEUM and the g_μ-2 effort in an ideal way. Doppler shift is the largest source of the systematic error in the proposed experiment. The use of slow muonium from aerogel targets at room temperature, and its ionization by the combination of a CW laser at 244 nm and a pulse laser at 355 nm not only yields a signal for the 1*s*-2*s* measurement, but also provides another route to generate a high intensity slow muon beam, as required by the muon g-2/EDM experiment. The greatest technical problem in the muon g-2/EDM experiment is the efficient ionization of muonium by a pulse laser at Lyman-α (122 nm) to drive the 1*s*-2*p* transition. Ionization is then again accomplished by the resonant 2*p*-vacuum excitation with a pulse laser at 355 nm. The 244 nm UV laser method employed in this experiment may provide another option to circumvent the problem of efficient Lyman-α generation. Ensuring manpower in preparing and executing the experiments is a common issue for both project groups, and MuSAC recommends encouraging good cooperation between the two groups in the future.

III Future Plan in Intermediate Term

Muon Microscopy

Plans were shown to develop, in addition to the transmission muon microscope TμM at the H-line, new experimental setups which may establish unique new muon applications in scanning μ^+ and μ^- microscopy. These plans are very challenging, and the feasibility of the planned applications is still to be demonstrated. Although MuSAC welcomes the initiative for future challenging projects, it is not clear, how these developments can be carried out with the current manpower constraints (see also the future plan for “Muon Materials Science”). MuSAC considers it essential to focus MUSE activities at the current stage on completion of H-line and the commissioning of USM to produce scientific results in important scientific fields of topical research.

Muon Materials Science

A 3-point future plan was presented: a station at S3 for hydrogen related studies, and a station at S4 for high magnetic fields using RF-pulsed μSR, and μ^-SR. While the prospects of having additional new μSR capabilities available are very promising, it is hard to imagine how these developments might be undertaken with the current manpower constraints. Under these circumstances, it might be more appropriate to focus the present efforts on the USM program, particularly to develop expertise of μSR in nanometer-thin materials. It is very urgent that the USM source is completed and starts to produce science as soon as possible.

Muon Fundamental Physics

The presented 8-10 years perspective for the fundamental muon physics program has a clear vision and is strongly endorsed by MuSAC. Its overarching goal is to use the unique capabilities of J-PARC/MUSE to perform crucial tests of the established Standard Model of particle physics and to search for, and eventually discover, new physics that goes beyond the Standard Model. The strategy builds on the approved projects g_μ-2/EDM, MuSEUM, Mu1*s*-2*s*, and DeeMe, and has plans for new projects, such as a search for Mu-Mubar oscillations and a measurement of the HFS of muonic He atoms. All these have strong physics motivations addressing open issues in fundamental nuclear and particle physics. The projects have strong collaborations leading or co-leading the experiments' construction and the science program.

It is a top priority to finish construction and commissioning of the H-line to the H1 area at MUSE in order to allow the DeeMe and the MuSEUM to proceed with their respective data taking campaigns. The Mu1*s*-2*s* experiment will contribute the funding to open up the S2 beamline, which is also a very welcome development but should not delay the MUSE effort to finish the H-line. MuSAC also explicitly welcomes the idea to study an alternative Mu ionization scheme using the 1*s*-2*s* two-photon transition and synergies with the S2-collaboration. This might provide a back-up plan for the future ultraslow muon production needed for the g_μ-2/EDM and microscopy activities.

For g_μ-2/EDM and for the transmission muon microscopy TμM, activities are being pursued to establish the concrete planning for the future H2 area in an extension building. Resources for these infrastructure initiatives still need to be found and the realistic pathway to achieve this needs further design work. The committee recommends, as the best path forward, the priority completion of the H-line in FY2020 with its commissioning involving collaborators from DeeMe and MuSEUM. This should be followed by science data taking of DeeMe and of MuSEUM, before requesting and reviewing strategies for early scientific results. Such success with visible results from H1, will likely boost all future activities.

IV General Comments and Recommendations

MuSAC acknowledges the outstanding work of the MUSE team and the achievement of another year of stable operation at 500 kW beam power. MuSAC is very pleased to see the continuing interest from broad scientific communities in muon science at J-PARC, and that the user program is running smoothly. MuSAC appreciates the continuous efforts on providing safe operation of the facility. The presentation of a plan to reach the design 1 MW operation of MLF in 2023 by MLF Director Professor T. Kanaya is appreciated, and MuSAC is looking forward to the operation of MUSE at the design proton beam power.

A concern is a potential delay of the H1 line completion due to the missing funding of 55 M JPY. This causes delay in the timely production of important scientific output of the DeeMe collaboration, and MuSAC strongly recommends that KEK-IMSS and J-PARC find a quick solution to complete the H1 line.

MuSAC greatly appreciates that the number of approved proposals has shown a steady increase in the last two years: from 76 proposals in 2018 to 108 proposals in 2019, where the number of proposals from overseas researchers increased from 7 to 20, and the number of S-type proposals from 3 to 7. We assign this positive development to the establishment of stable proton beam operation, and also to the stable operation of S1 beamline and its increasing permeation into the community. MuSAC evaluates that the continual efforts of MUSE staff to expand the users' community paid off as an increase in the number of international users and P-type proposals. MuSAC recommends continuing a careful survey on the degree of satisfaction of users and various levels of outreach activities.

Although MuSAC positively evaluates the personnel actions (promotions, hires and changes) in the past years for the ongoing renewal of generations, there is still a strong concern that the shortage of manpower may cause significant difficulties in keeping and developing the activities of MUSE in view of the planned expansion of the facility to the S2, H1, and H2 areas. MuSAC is also concerned about the situation that a large part of scientific and developing activities of the MUSE facility have been carried out relying on non-permanent scientists and engineers. MuSAC strongly recommends increasing efforts to make tighter collaborations with universities and private companies, not only in Japan but also overseas. This will allow establishing a shared human resource system, such as introducing cross-appointment positions, and organizing and providing attractive career-paths. MuSAC also encourages cultivating talent to take over leadership for the overall management of MUSE facility, and recommends KEK-IMSS to support this important activity. To provide more manpower for running the muon science program, MuSAC recommends the transfer of the MUSE responsibility for M1/M2 proton beam and muon production target to a single dedicated J-PARC-wide group, concentrating the expertise and capabilities to deal with beam transport and safety in a uniform site-wide manner, thus ensuring a J-PARC-wide safety concept. This would be in line with international standards. MuSAC considers this as essential to the further success of MLF. Additionally, MuSAC encourages J-PARC/KEK-IMSS and MUSE management to establish joint appointments with universities and companies, to take up some of the tasks of user support. It will also be helpful to increase efforts to make tighter collaborations with universities, thus attracting more users to MUSE.

V Charges given to MuSAC

In the following we address the charges given to MuSAC point by point:

1) **How does the MuSAC evaluate the present status of the MUSE?**

   MUSE is still in the transition from the construction phase to an international user facility. This means additional load on MUSE staff, to develop and build new beamlines and instrumentation, in addition to the operational load of organization and support for the increasing number of domestic and international user groups. MuSAC acknowledges the outstanding work of the MUSE team in their effort to combine these challenging tasks. MuSAC is pleased to see the increasing interest of external research groups in using MUSE.

2) **How does the MuSAC evaluate research projects in MUSE? Are these research outputs adequate?**

   The research projects presented to MuSAC demonstrate the rich field of muon science at MUSE in a broad range of applications from fundamental studies to material and soft matter science, and applied studies such as characterization of battery materials and non-destructive elemental depth analysis of archeological samples. The two latter fields are in collaboration with companies and archeological institutions and museums, which represents a unique extension to user groups/research fields which are not typical for muon facilities in general. This wide range of applications, attracting new user groups and opening new fields of muon applications is clearly a strength of MUSE, which makes it unique among all the muon facilities around the world.

   Scientific results from the Inter-University Research Program maintain a high standard of productivity. MuSAC was impressed to see that a variety of significant studies have recently been completed by the members of the program, which is reflected in the list of publications of MUSE in 2019. The research output of MUSE in terms of publications is adequate compared to other international large scale facilities.

3) **How does the MuSAC evaluate the recent developments of facilities in MUSE?**

   The recent developments at MUSE – for example, the continuous improvements on the sample environment of the μSR instruments, the muonic Xrays applications, and the ultra-slow muon project – are very important for the future success of the facility and they will further facilitate MUSE’s transition to a world-leading muon center.

4) **How does the MuSAC evaluate the funding situation of MUSE?**

The present funding situation is a matter of concern. The significant reduction of about 25% of the budget in FY2020 makes it very difficult to continue the successful transition from construction phase to user facility operation that includes the completion of H-line and the S3 and S4 ports of the S-line. As a first step, MuSAC recommends to generate a detailed financial plan for the completion and operation of all the MUSE beam lines (including personnel). In a second step MUSE management may seek additional sources of external funding by collaborations in joint projects, as MUSE succeeded to do for the S2 port which will host a new high precision muonium 1*s*-2*s* laser spectroscopy experiment.

5) **How does MuSAC evaluate the relationship with industries?**

MuSAC is very pleased to see the continuation of cooperation with industrial partners, such as Toyota CRDL for battery research and SOCIONEXT for investigating soft-errors in SRAM modules caused by cosmic muons, and the establishment of a new collaboration with Sumitomo Heavy Industries in the Transmission Muon Microscope project. These kinds of activities are in line with J-PARC's mission to develop the society of the future. At present, this strong cooperation with industrial partners is unique among the muon facilities in the world.

6) **Is MUSE moving in the right direction? Are the future development items adequate?**

MuSAC acknowledges the attained status of stable user operation in the D1/D2 and S1 lines, and fully supports the current high priority activities: to finish commissioning of the U-line and the construction of the H-line. The further planned extension of the facility in S2, H2 and later S3/S4 are necessary to fully exploit the capabilities of MUSE, and to make MUSE into a unique muon facility. The present resources are insufficient to carry out all of these future developments. For better planning and resource utilization, MuSAC strongly recommends providing project and risk management plans for the U-line commissioning/H-line construction, and for the subsequent completion of the S2-S4 areas. Together with possible future collaborations with external groups, the required additional budget and manpower should be provided to run MUSE in its full expansion stage.

7) **How does MuSAC evaluate the leadership of MUSE in the field of muon science? Has MUSE been a core academic research hub?**

The combination of material science (μSR), applied research in depth-resolved non-destructive elemental analysis, and new high-precision particle physics experiments is unique at MUSE, and demonstrates the potential for leadership of the facility in muon science. Being still in the transition phase from construction to user facility, MuSAC is convinced that MUSE will become a core academic research hub with its full suite of instrumentation.

8) **Have MUSE users in addition to in-house scientists been making outstanding contributions to related scientific fields?**

As is normal for a facility in transition from the construction phase to a user facility, the user groups perform their experiments in close collaboration with in-house scientists. It is therefore expected, that outstanding results of MUSE experiments are based on such collaborations. In the medium-term, when users will be trained and become familiar with the MUSE instrumentation, they will become more independent from in-house scientists. The muon g-2, DeeMe, and muonium 1*s*-2*s* collaborations are led by external groups. The results of these experiments will be very important for the search for physics beyond the Standard Model of particle physics. These projects already provided outstanding developments in detector, data acquisition and beam line technologies.

9) **Does MUSE play a role of an international academic research center?**

MUSE is on a good path to become one of the leading international academic research centers after completion of the construction phase. Currently, there are mainly Japanese groups – except the international muon g-2, DeeMe, and MuSEUM collaborations – using the facility. However, MuSAC is convinced that MUSE will increasingly attract user groups from abroad, once the full suite of instrumentation is available. This is already reflected by the factor of three increase (from 7 to 20) of the number of proposals from overseas researchers submitted to MUSE. MuSAC is very pleased to see this trend.

10) **Does MUSE provide appropriate support for national researchers and research communities?**

As far as MuSAC can judge from the talks presented at the meeting, MUSE is providing a good level of support for the research community. This is manifested, for example, by surveys on the degree of satisfaction of users and various levels of outreach activities. MuSAC recommends continuing these activities to provide the best support possible.

11) **Does MUSE provide appropriate support for researchers/visitors from abroad?**

MuSAC cannot see any difference in the support for national and international users. MUSE is aiming to provide appropriate support for both groups of researchers.

12) **How does MuSAC evaluate the effort of expanding the research fields by MUSE? Does MUSE create networks for scientific collaboration?**

MUSE is excellent in expanding the research fields at the facility. This can be seen, for example, in the extension of negative muon applications in μSR and non-destructive elemental analysis, where a new collaboration with renowned research groups has been formed within the project “Toward new frontiers: Encounter and Synergy of state-of-the-art astronomical detectors and exotic quantum beams” for the Grant-in-Aid for

Scientific Research on Innovative Areas. Another excellent example are the collaborations and activities within the MEXT “Element Strategy Initiative to Form Core Research Center for Electron Materials”. With the ultra-slow muon microscope and Transmission Muon Microscope (TμM), MUSE is pursuing a unique new way for muon applications. For the TμM project, a collaboration has been founded including research institutions (J-PARC/KEK, RIKEN), a company (Sumitomo Heavy Industries), and several universities.

It is obvious, that these efforts can be only achieved by the creation of new networks for scientific collaborations.

13) How does MuSAC evaluate contributions to education in Academia?

At MUSE, PhD students and Postdocs are part of the research and development projects. MuSAC encourages MUSE management to establish a joint appointment scheme with universities, as outlined in section IV, to facilitate the recruiting of graduate students. This is essential for the training of the next generation of researchers and potential future expert users of MUSE. In line with this important task, MuSAC is very pleased to see the ongoing organization of the annual J-PARC Joint Neutron and Muon School for graduate students, Postdocs, and early career researchers.

APPENDIX I

Members of MuSAC:

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Andrew MacFarlane (University of British Columbia)

Klaus Kirch (ETH Zurich and Paul Scherrer Institute)

Kenya Kubo (International Christian University)

Martin Mansson (Royal Institute of Technology)

Takashi Nakano (Research Center for Nuclear Physics)

Thomas Prokscha (Paul Scherrer Institute) Chair

Tadayuki Takahashi (Institute for the Physics and Mathematics of the Universe)

Unable to attend: Martin Mansson (Royal Institute of Technology)