

Japan Academy Prize to:

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 Organization
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for “Explorations of Muon-Beam Science and Non-Destructive Muon Radiography
 of Large-Scale Objects”

Outline of the work:

Dr. Kanetada Nagamine has contributed greatly to the development of interdisciplinary science by pioneering new research fields involving the production and use of muon beams and by initiating radiography that makes use of very-high-energy cosmic-ray muons.

1) Pioneering the development of radiography with high-energy muons

Dr. Nagamine initiated radiography using GeV muons that arrive nearly horizontally to explore the inner structures of large-scale geophysical formations such as volcanoes, thus opening a new approach to the prevention of natural disasters. Before his work, Alvarez *et al.* in 1970 had used vertically incoming cosmic-ray muons to investigate the interior of an Egyptian pyramid, placing a detector in the middle of a tunnel through the pyramid. This approach obviously cannot be applied to an active volcano. Dr. Nagamine and his colleagues made the first successful non-destructive radiography measurements using near-horizontal cosmic-ray muons [1,9,10]. They introduced new experimental techniques a) to make reliable and precise measurements of the intensities and tracks of weak muon signals and b) to remove huge background signals. By detecting the reduction in intensity of the near-horizontal muons at each track through an object, they were able to obtain the density-length of each track, thus providing a radiographic image of the object. By continuing such measurements over months and years, Dr. Nagamine and his group were also able to identify time-dependent changes in the volcanic activity. This method is now recognized to be capable of providing new and unique information about the geophysical phenomena related to earthquakes and volcanic eruptions, and it is now used world-wide [for recent work, see N. Lesparre *et al.*, *Geophys. J. Int.* **190**, 1008–1019 (2012); T. Kusagaya and H. K. M. Tanaka, *Proc. Jpn. Acad., Ser. B* **91**, 501–510 (2015)].

2) Applications of cosmic-ray-muon radiography to examine the inner structures of large-scale and dangerous industrial machinery

In general, cosmic-ray-muon radiography is a very effective non-destructive method for observing the interiors of large artificial structures that are inaccessible for human beings, similar to detecting the internal activity of a volcano. For example, Dr. Nagamine’s group has applied near-horizontal cosmic-ray-muon radiography to investigate the inner structure of an operating blast furnace, which is typically run without stopping, and they have successfully measured the erosion of the outer brick wall caused by heat radiation [4,9,10]. In addition, they have determined the time-sequential behavior of the melting iron, a result that may

enable the optimization of the operating conditions of the blast furnace.

3) Application of cosmic-ray-muon radiography to the inner structures of nuclear reactors

As a natural extension of this work, when serious damage occurred to the Fukushima-Daiichi nuclear reactors, Dr. Nagamine initiated a project [1] to use horizontal cosmic-ray radiography in the presence of the severe radiation background to determine non-destructively the extent of the damage to the inner parts of the destroyed nuclear reactors. He and his colleagues showed that this method can determine the locations and status of the reactor fuel rods from outside the damaged nuclear reactors. This method thus contributed to the elucidation of the actual conditions in the Fukushima-Daiichi disaster by detecting the status and localization of the melted reactor fuel rods. This is the most powerful application to date of the non-destructive method of cosmic-ray-muon radiography.

4) Production of intense, ultra-slow (below keV) muon beams and their use in developing new approaches to particle physics and the materials/life sciences

In parallel with the development of cosmic-ray-muon radiography of large-scale objects, Dr. Nagamine has also developed new experimental methods using accelerator-generated muons. He and his colleagues have made substantial progress in applying muon-spin-rotation/relaxation/resonance methods to materials science and other fields [6]. For example, after the completion of the Booster Synchrotron in 1975, Dr. Nagamine developed facilities and methods to use pulsed-muon experiments to explore the extreme phenomena created by the pulsed-muon beams [2,15,16]. He and his colleagues obtained measurements of long-lived phenomena such as the quantum diffusion of muonium in matter, delayed decay phenomena, and electron-transport phenomena in materials and in the life sciences [5,8,14]. In particular, Dr. Nagamine's group discovered the thermal emission of muonium after the stopping of MeV positive muons in hot tungsten [13]. Moreover, they conducted pulsed-laser resonant ionization of thermal muonium to evaluate aspects of quantum electrodynamics [12], a project that included Nobel laureate Dr. Steven Chu. In addition, Dr. Nagamine's group has established a method for producing beams of ultra-slow (below keV) positive muons (by laser ionization of thermal muonium) [2,11]. Such ultra-slow muon beams have opened a new experimental method for studying condensed matter at surfaces and interfaces. At the same time, such beams have opened a pathway to advanced particle-physics studies, such as precise measurements of the anomalous magnetic moment and electric-quadrupole moment of the muon.

5) Fundamental and industrial nuclear-energy-related sciences using muons

Dr. Nagamine has pioneered new experimental approaches and has proposed new atomic-energy sources utilizing nuclear fusion that employ catalytic reactions involving negative muons [3,7]. He has also developed concepts for element transmutation caused by the nuclear capture of negative muons. These methods can be applied to the effective production of medical isotopes and to the removal of long-lived radioactive isotopes from nuclear reactors.

6) The construction of various experimental research facilities for muon science, the creation of a muon-science community, and leadership in experimental muon-science research

Since his first association with the University of Tokyo in 1971, Dr. Nagamine has led substantial achievements at accelerator facilities in Japan and around the world. 1) He has developed pulsed-muon facilities at KEK (Tsukuba, Japan), at RAL (Didcot, UK), and at J-PARC (Tokai, Japan), and he has participated in the development of the continuous-beam muon facility at TRIUMF (Vancouver, Canada). 2) Dr. Nagamine has led the growth of scientific-research groups that use pulsed accelerator muons as well as

research groups involved in cosmic-ray-muon radiography.

Dr. Nagamine has thus contributed to the development of unique and interdisciplinary muon science. His outstanding accomplishments have been due to his originality and pioneering entrepreneurship.

List of Main Publications (Extracted from about 600 publications)

1. K. Nagamine, Radiography with Cosmic-Ray and Compact Accelerator Muons; Exploring Inner-Structure of Large-Scale Objects and Landforms, *Proc. Jpn. Acad., Ser. B* **92**, 265–289 (2016).
2. K. Nagamine, Past, Present and Future of Ultra-Slow Muons, *JPS Conf. Proc.* **2**, 010001 (2014).
3. K. Nagamine, Muon-Catalyzed Fusion (μ CF) (Chapter 11). In: K. Heinloth (ed.) Nuclear Energy. Landolt-Börnstein: Group VIII Advanced Materials and Technologies (Numerical Data and Functional Relationships in Science and Technology), Vol. 3B. Springer, Berlin, Heidelberg, 2005, pp. 555–602.
4. K. Nagamine, H. K. M. Tanaka, S. N. Nakamura, K. Ishida, M. Hashimoto, A. Shinotake, M. Naito and A. Hatanaka, Probing the Inner Structure of Blast Furnaces by Cosmic-Ray Muon Radiography, *Proc. Jpn. Acad., Ser. B* **81**, 257–260 (2005).
5. K. Nagamine and E. Torikai, Electron Transfer in Proteins and DNA Probed by Muon Spin Relaxation, *J. Phys.: Condens. Matter* **16**, S4797–S4806 (2004).
6. K. Nagamine, Introductory Muon Science. Cambridge University Press, Cambridge, 2003.
7. N. Kawamura, K. Nagamine, T. Matsuzaki, K. Ishida, S. N. Nakamura, Y. Matsuda, M. Tanase, M. Kato, H. Sugai, K. Kudo, N. Takeda and G. H. Eaton, Discovery of Temperature-Dependent Phenomena of Muon-Catalyzed Fusion in Solid Deuterium and Tritium Mixtures, *Phys. Rev. Lett.* **90**, 043401 (2003).
8. K. Nagamine, F. L. Pratt, S. Ohira, I. Watanabe, K. Ishida, S. N. Nakamura and T. Matsuzaki, Intra- and Inter-Molecular Electron Transfer in Cytochrome c and Myoglobin Observed by the Muon Spin Relaxation Method, *Phys. B (Amsterdam, Neth.)* **289–290**, 631–635 (2000).
9. K. Nagamine, M. Iwasaki, K. Shimomura and K. Ishida, Method of Probing Inner-Structure of Geophysical Substance with the Horizontal Cosmic-Ray Muons and Possible Application to Volcanic Eruption Prediction, *Nucl. Instrum. Methods Phys. Res., Sect. A* **356**, 585–595 (1995)
10. K. Nagamine, Geo-Tomographic Observation of Inner-Structure of Volcano with Cosmic-Ray Muons, *J. Geography* **104**, 998–1007 (1995) [in Japanese].
11. K. Nagamine, Y. Miyake, K. Shimomura, P. Birrer, J. P. Marangos, M. Iwasaki, P. Strasser and T. Kuga, Ultraslow Positive-Muon Generation by Laser Ionization of Thermal Muonium from Hot Tungsten at Primary Proton Beam, *Phys. Rev. Lett.* **74**, 4811–4814 (1995).
12. S. Chu, A. P. Mills, Jr., A. G. Yodh, K. Nagamine, Y. Miyake and T. Kuga, Laser Excitation of the Muonium $1S$ – $2S$ Transition, *Phys. Rev. Lett.* **60**, 101–104 (1988).
13. A. P. Mills, Jr., J. Imazato, S. Saitoh, A. Uedono, Y. Kawashima and K. Nagamine, Generation of Thermal Muonium in Vacuum, *Phys. Rev. Lett.* **56**, 1463–1466 (1986).
14. K. Nagamine, K. Ishida, T. Matsuzaki, K. Nishiyama, Y. Kuno, T. Yamazaki and H. Shirakawa, Solitons in Polyacetylene Produced and Probed by Positive Muons, *Phys. Rev. Lett.* **53**, 1763–1766 (1984).
15. K. Nagamine, H. Nakayama, J. Imazato, Y. Kuno, M. Fujiwara, A. Yamamoto and T. Yamazaki, Superconducting Solenoid and its Cooling System for Pulsed Muon Channel, *IEEE Trans. Magn.* **17**, 1882–1885 (1981).
16. K. Nagamine, Pulsed μ SR Facility at the KEK Booster, *Hyperfine Interact.* **8**, 787–795 (1981).