Birth and Achievements of Muon Science Laboratory

December 23, 2020

40 Years Birthday Symposium of Pulsed Neutron and Muon at KEK

K. NAGAMINE

Professor Emeritus of KEK and University of Tokyo, Researcher Emeritus of RIKEN

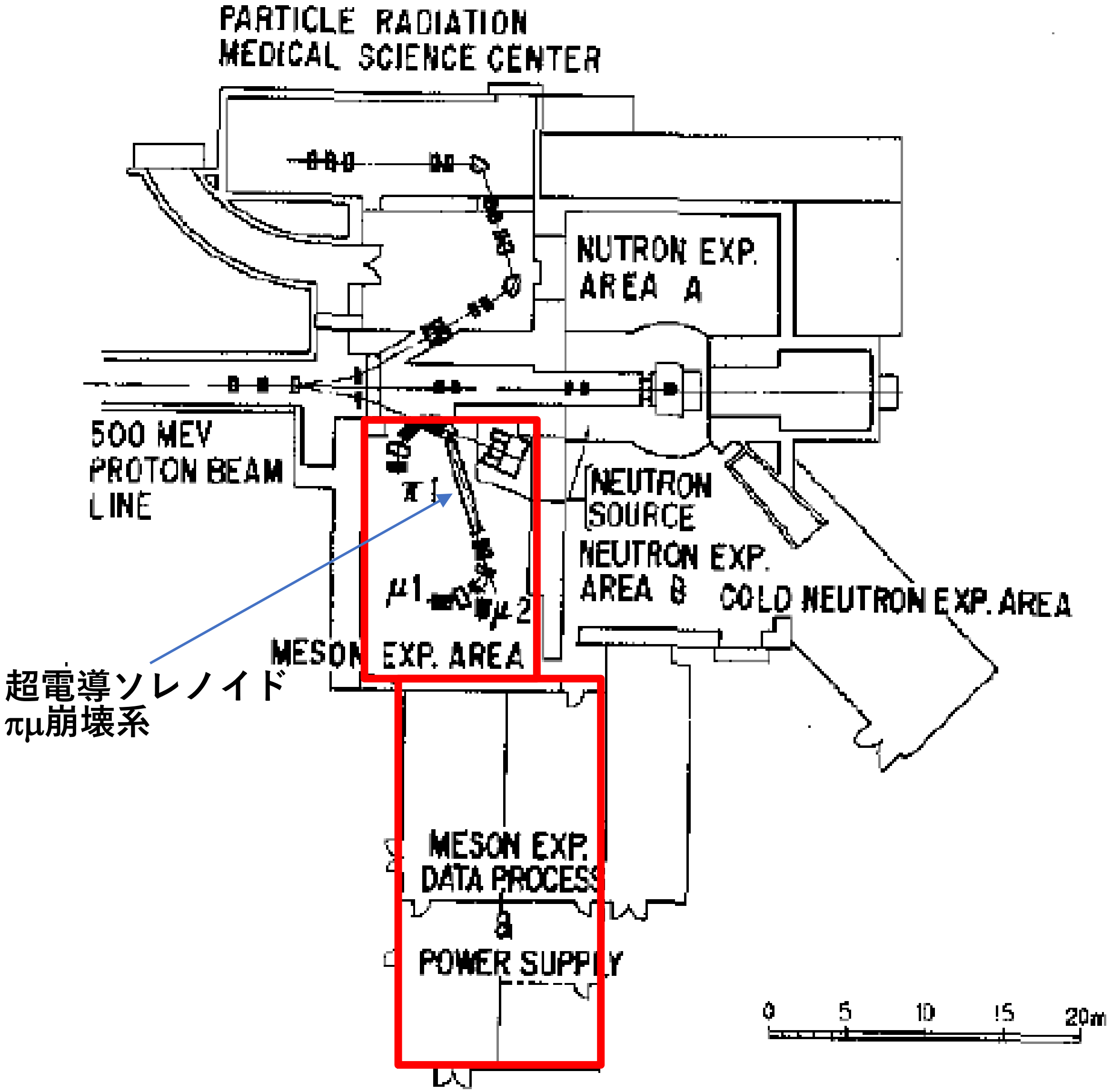
Birth and Achievements of Muon Science Laboratory

- Construction of Muon Science Laboratory
- Achievements of Muon Science Laboratory
- Succession to RIKEN-RAL and J-PARC MUSE
- Some Thoughts for Further Developments

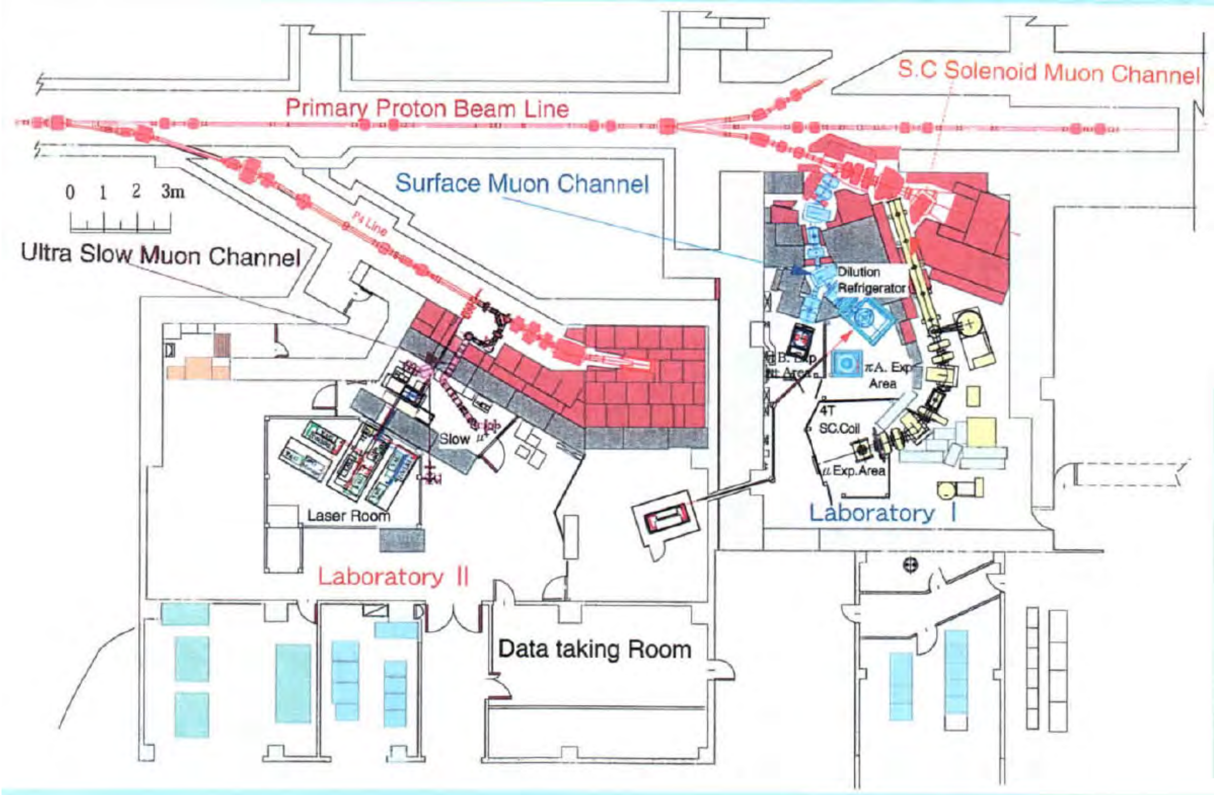
Construction of Muon Science Laboratory

1978, April Japanese government has approved the establishment of Meson Science Laboratory in Science Faculty of the University of Tokyo to construct experimental facility at KEK-BSF and conduct scientific research by using pulsed muon/pion produced by 500 MeV proton synchrotron.

1980, June Completion of the superconducting muon channel and initiation of the world-first pulsed muon production followed by initiation of the puled muon experiments.

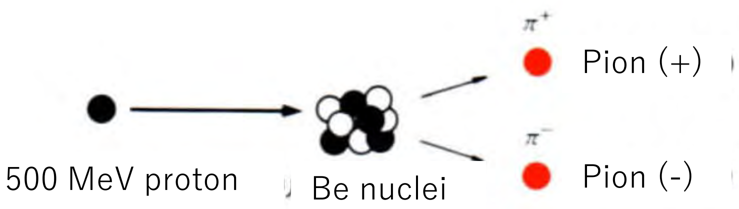


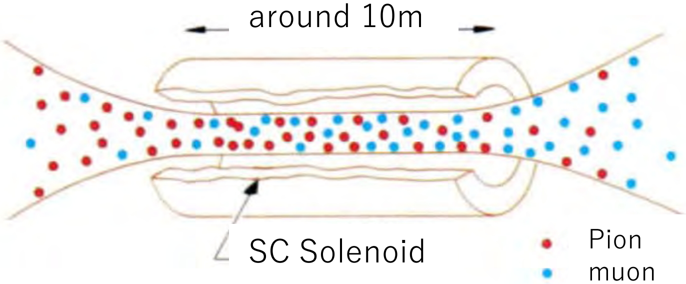
Booster Utilization Facility in June, 1980 where MSL of University of Tokyo enclosed by red line.



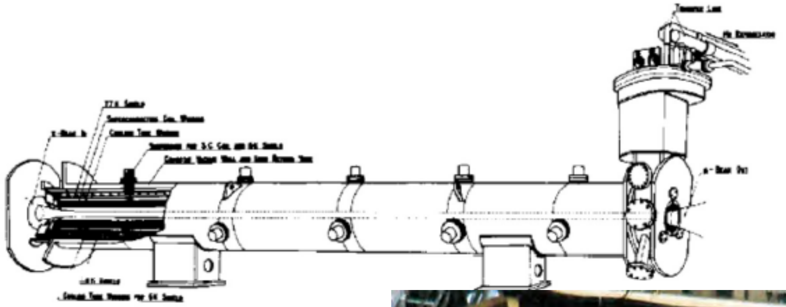
UT-MSL in March, 1997. UT-MSL joined to the reorganized KEK in this form in April.

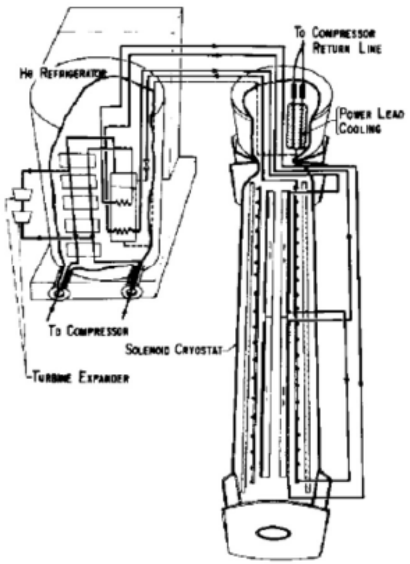
A Large-Scale (6m long, 12cm bore, 5T) Superconducting Solenoid and He Cooling System developed for Efficient Pion-to-Muon Decay Section

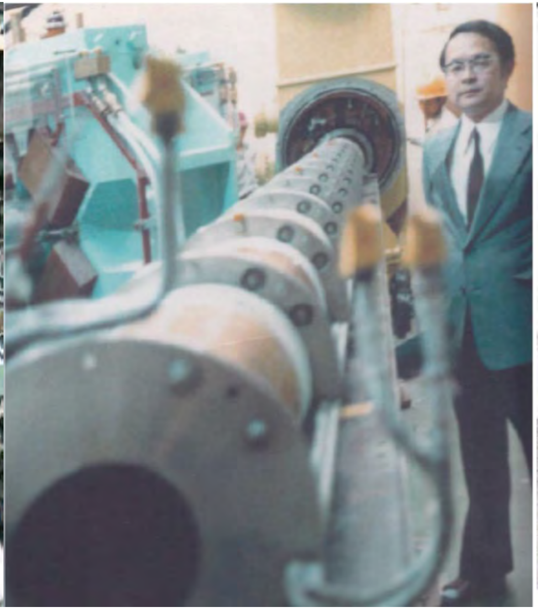


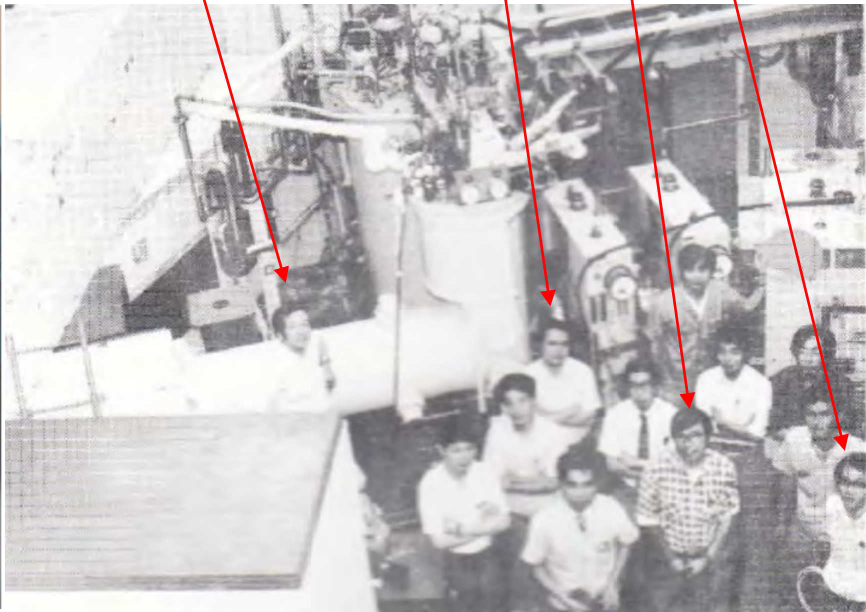


Completed in the morning of the scheduled First-Beam day of June 12, 1980!

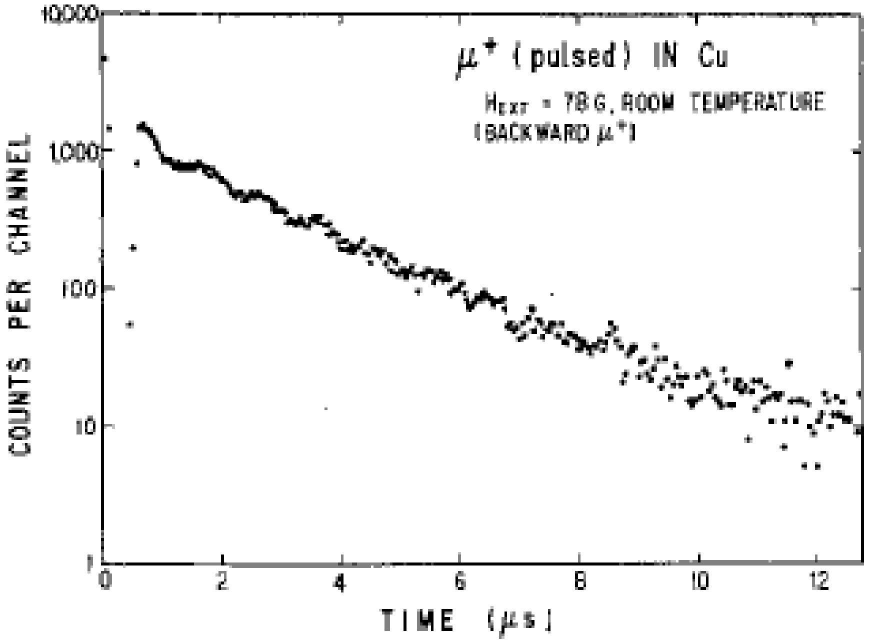


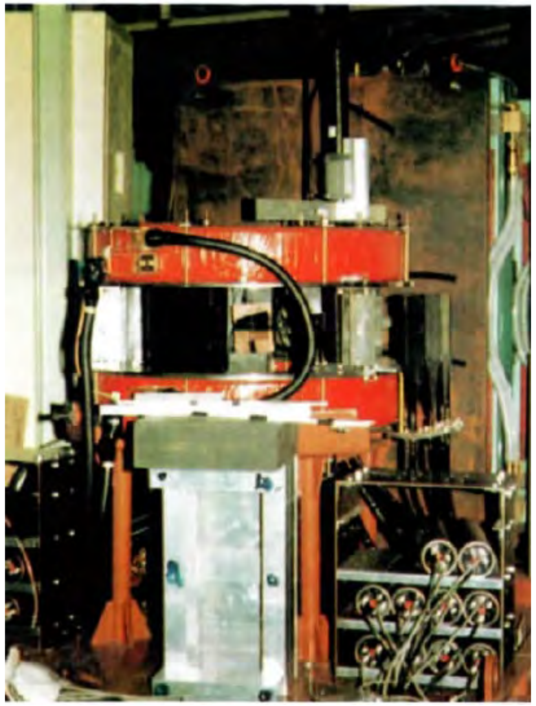




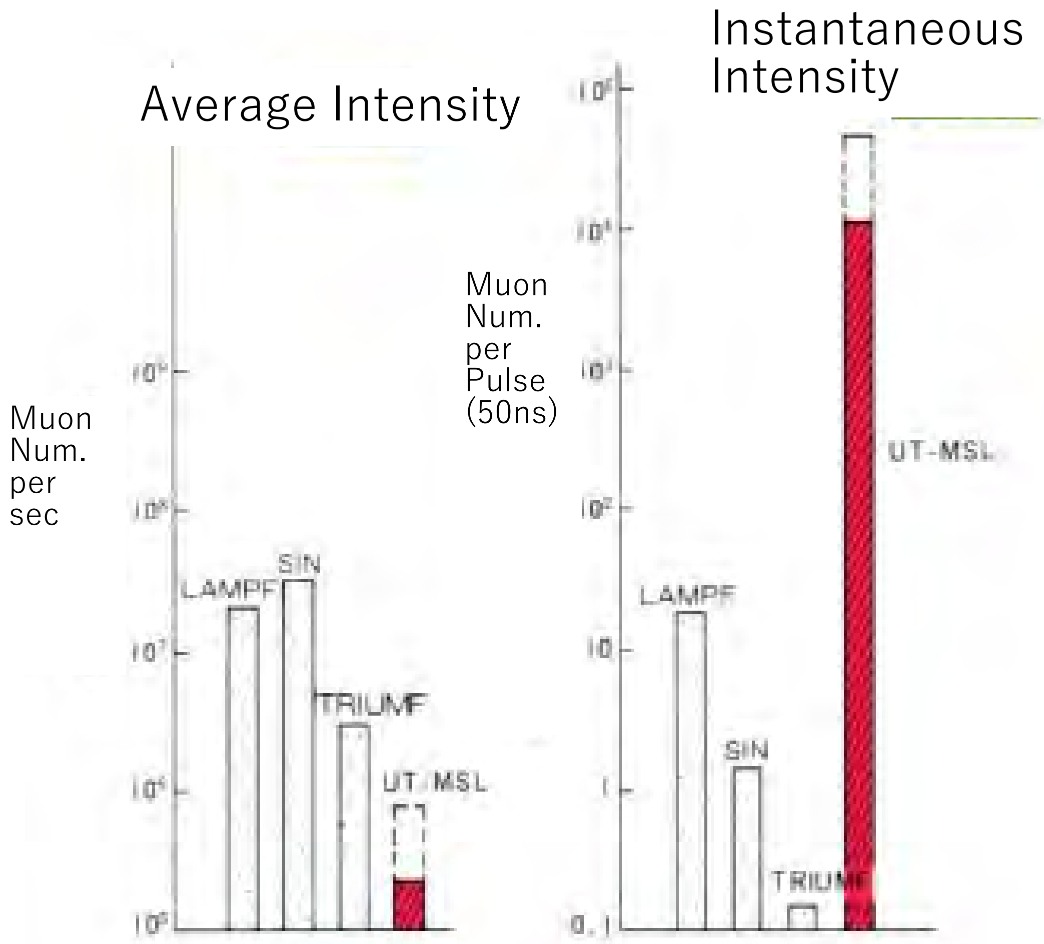


The first observation of pulsed μSR June, 1980.





Time spectrum(left) and spectrometer (right)



Comparison of muon intensity

Achievement of Muon Science Laboratory (1980-2010)

Hyperfine Interactions 8 (1981) 787-796

KN report (1980)

PULSED μSR FACILITY AT THE KEK BOOSTER

K. Nagamine

Meson Science Laboratory, Faculty of Science
University of Tokyo, Bunkyo-ku, Tokyo, Japan

The construction of a new superconducting muon channel has just been completed in our laboratory at the Booster Facility of KEK (National Laboratory for High Energy Physics). The channel takes a sharply pulsed proton beam, and it has been confirmed that an intense pulsed, focussed beam is produced. The instantaneous intensity is at least 10^3 times higher than any other muon channel in a major meson factory. The first μSR spectrum was observed in a time range beyond 10 μS. The beam will be valuable not only for μSR studies of long relaxation, but also for muon spin magnetic resonance experiments.

1. Slow depolarization phenomena - Pulsed μSR will pin down values of depolarization rates for which conventional μSR gives only upper limits. Typical examples are: (a) μ^+ slow relaxation in paramagnetic Fe, Co, Ni, spin glass, Kondo system etc; (b) μ^- relaxation in weak ferromagnets etc; (c) weak muonium reaction in H_2O, H_2 etc; (d) μ^+ fast diffusion in metals such as Al, Nb, V etc.

2. Magnetic resonance induced by a high rotating field - Pulsed μSR can only realize the direct observation of muon spin resonance if the required r.f field is applied only at a low duty cycle. The new r.f. source now under preparation [3] can provide H_1 of 50 kW peak power and 100 G, which is switched on for 10 μs and off for 50 ms. The frequency range will cover, for the first step, up to 100 MHz. Local field measurements will be done in a longitudinal decoupling field, in particular, for magnetic insulators.

3. Transient phenomena after pulsed disturbance, excitation etc. - The recovery of host materials after irradiation, stress, heating, laser excitation etc., can be monitored by the pulsed μSR method.

Significance of pulsed muons (Now, 2020)

1) Long time-range measurement of μe and μSR
2) Observation of muon phenomena under huge white noise
3) Observation of muon phenomena with extreme experimental conditions like RF, Lasers, etc.

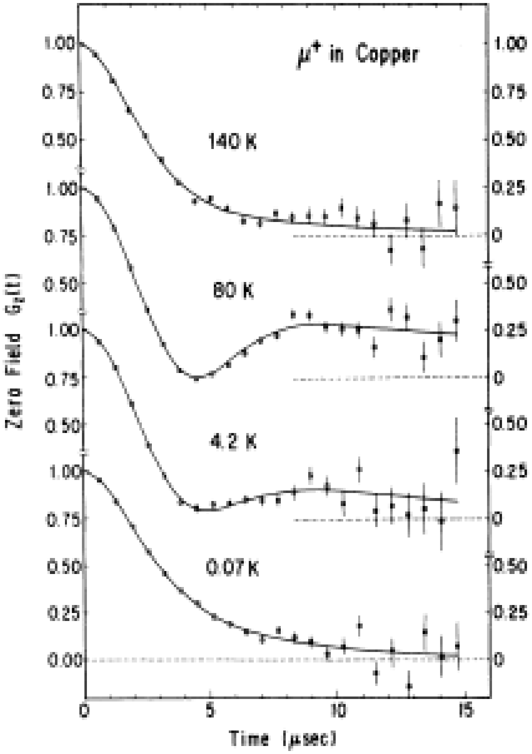
Long time-range measurement of μSR

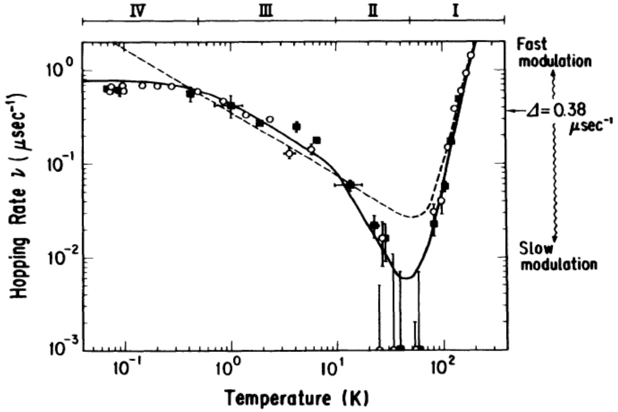
Coupling with extreme experimental conditions

Long-time observation of μe Decay and μSR (1)

Quantum diffusion of μ^+

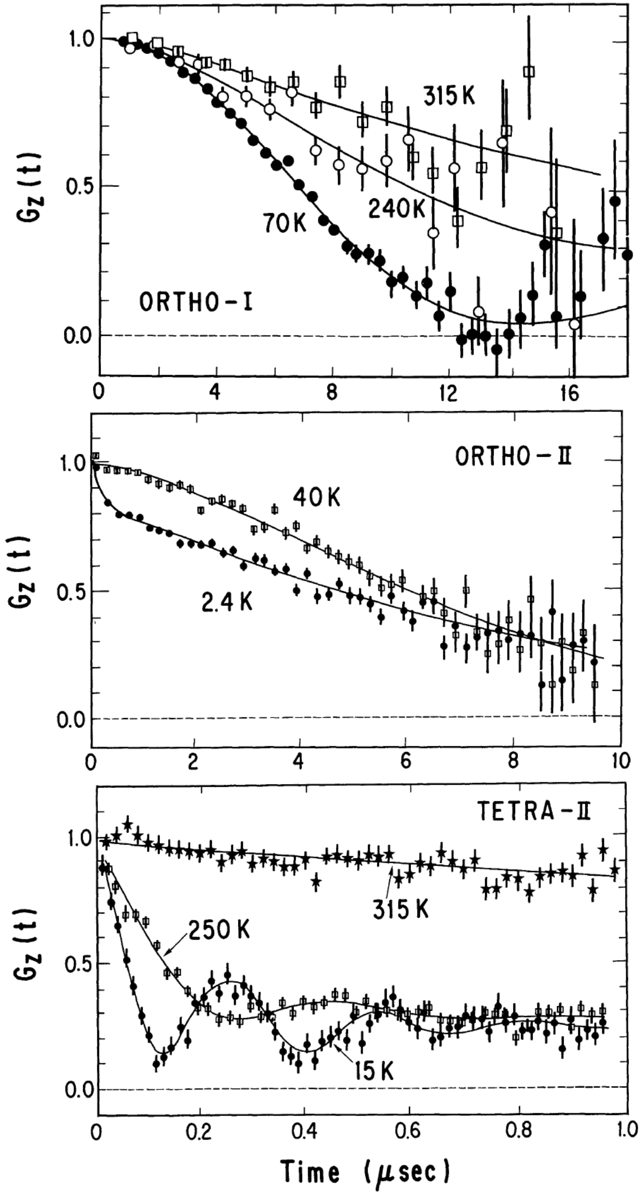
R.Kadono et al. Phys. Rev. B39 (1989) 23.





Magnetic Order of Oxide Superconductors

N. Nishida et al. J. Phys. Soc. Jpn. 57 (1988) 597.



μSR with pulsed muons is established as a powerful tool for characterization of new materials and extensive studies are going on in RIKEN-RAL and J-PARC.

Long-time observation of μe Decay and μSR (2)

Observation of Soliton-motion of electrons produced by μ^+

Prof H. Shirakawa (Nobel prize 2000); μSR sample of Polyacetylene was prepared by him.

VOLUME 53, NUMBER 18 PHYSICAL REVIEW LETTERS 29 OCTOBER 1984

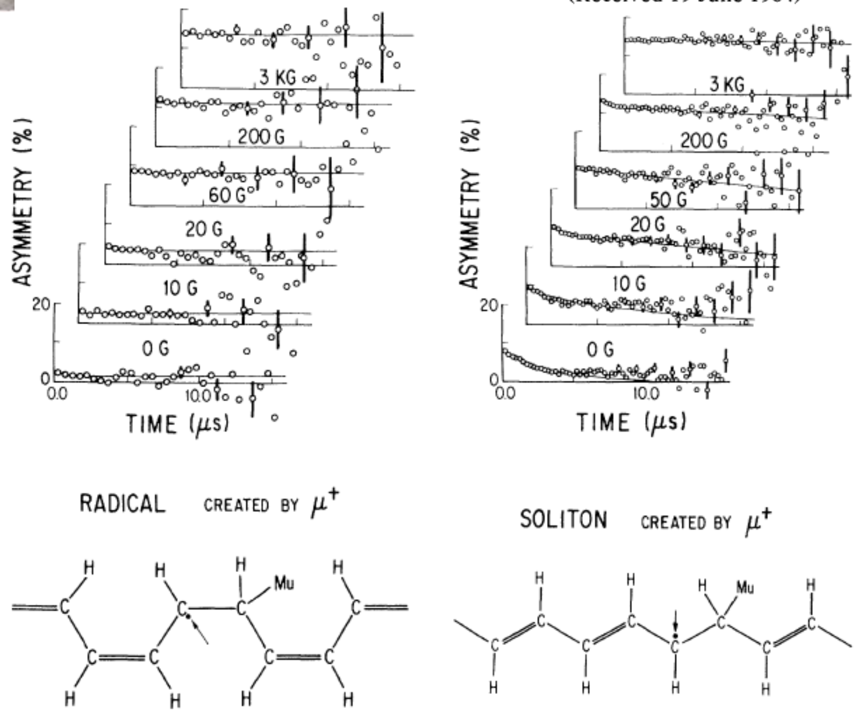
Solitons in Polyacetylene Produced and Probed by Positive Muons

K. Nagamine, K. Ishida, T. Matsuzaki, K. Nishiyama, Y. Kuno, and T. Yamazaki
Meson Science Laboratory, University of Tokyo, Bunkyo-ku, Tokyo, Japan

and

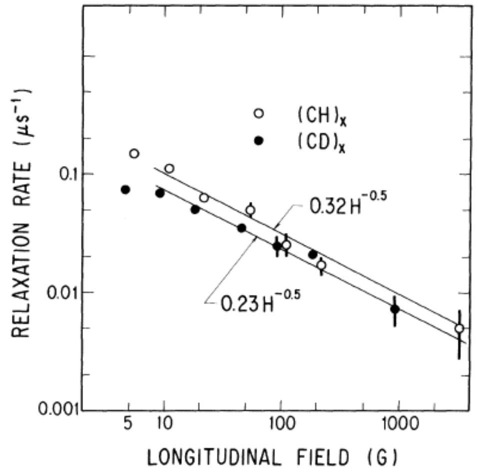
H. Shirakawa
Institute of Materials Science, University of Tsukuba, Sakura-mura, Ibaraki, Japan

(Received 19 June 1984)



Field decoupling of muon radical state in cis-Polyacetylene

Field suppression of spin dynamics in trans-Polyacetylene



Observed characteristic field dependence in trans-PA

This research was extended from conducting polymer to DNA and protein. KN & E. Torikai, J. Phys. Cond. Matt. 16 (2004) S4797.

Long-time observation of μe Decay and μSR (3)
Production of Thermal Muonium in Vacuum

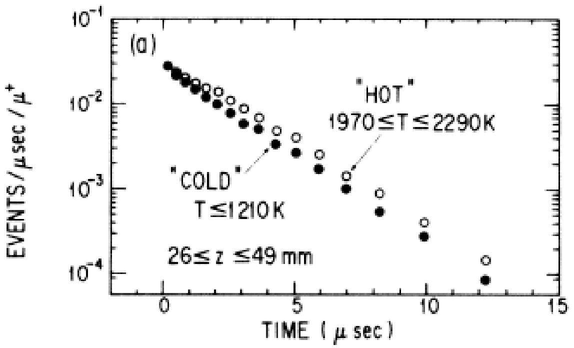
VOLUME 56, NUMBER 14 PHYSICAL REVIEW LETTERS 7 APRIL 1986

Alan and Vicky Mills

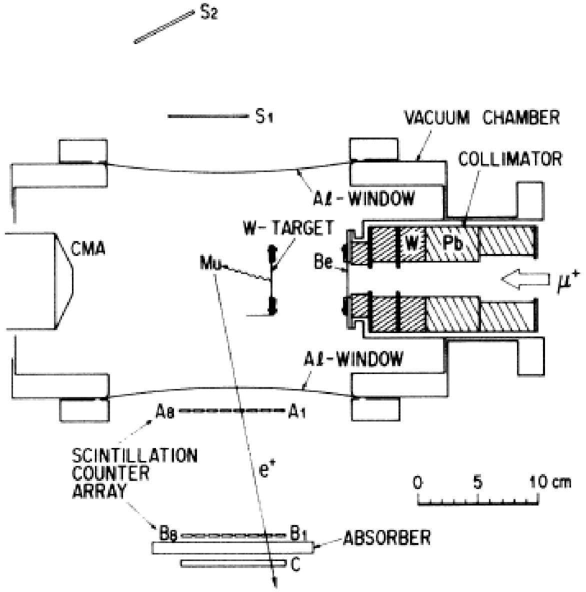
Generation of Thermal Muonium in Vacuum

A. P. Mills, Jr.,[1] J. Imazato,[2] S. Saitoh,[3] A. Uedono,[4] Y. Kawashima,[2] and K. Nagamine[2]
[1] *AT & T Bell Laboratories, Murray Hill, New Jersey 07974*
[2] *Meson Science Laboratory, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[3] *Department of Industrial Chemistry, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[4] *Institute of Materials Science, University of Tsukuba, Sakura-mura, Ibaraki, Japan*
(Received 30 December 1985)

We find that thermal-energy muonium atoms are emitted from a clean hot tungsten foil in which positive muons are stopping near the surface. The temperature dependence of the thermal-muonium signal yields a surprisingly low activation energy of 0.66(4) eV, suggesting that we are observing the thermionic emission of muonium from the solid. The total muonium yield at 2300 K is about 0.04 per stopped muon of 23 MeV/c initial muon momentum. A number of new experiments should be possible using this unique source of thermal muonium in vacuum.



Behavior of thermal muonium production from surface of hot tungsten



Layout of experiment

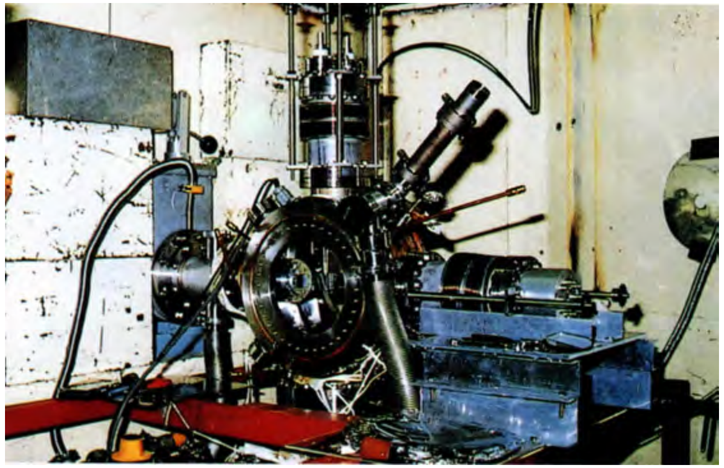
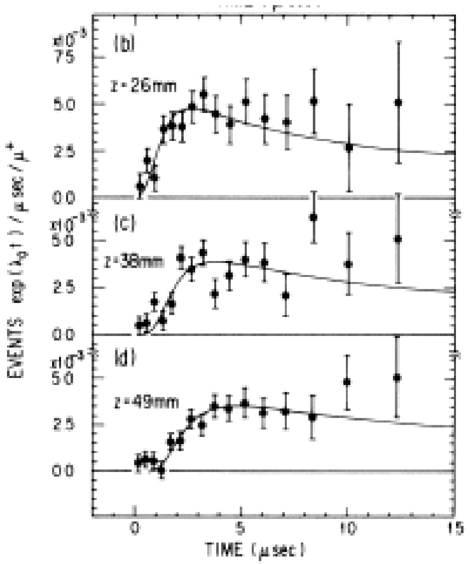


Photo of apparatus



Muons under extreme experimental conditions (1)
Laser Resonant Ionization of Muonium

VOLUME 60, NUMBER 2 PHYSICAL REVIEW LETTERS 11 JANUARY 1988

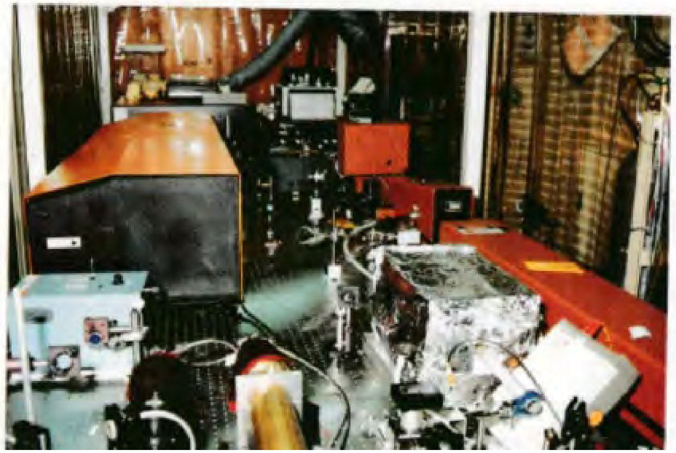
Laser Excitation of the Muonium 1S-2S Transition

Steven Chu,[(1),(a)] A. P. Mills, Jr.,[(2)] A. G. Yodh,[(1)] K. Nagamine,[(3)] Y. Miyake,[(3)] and T. Kuga[(3),(b)]
[(1)]*AT&T Bell Laboratories, Holmdel, New Jersey 07733*
[(2)]*AT&T Bell Laboratories, Murray Hill, New Jersey 07974*
[(3)]*Meson Science Laboratory, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
(Received 4 September 1987)

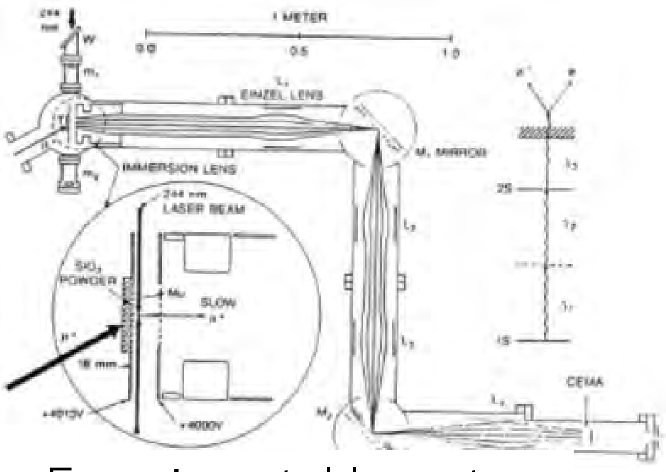
We present evidence for the excitation of the two-photon Doppler-free 1S-2S transition in muonium. Thermal muonium atoms were produced in vacuum by a 27.5-MeV/c pulsed positive-muon beam incident on a powdered SiO_2 target. Transitions were induced by the light from a frequency-doubled pulsed dye laser and were detected by photoionization of the 2S state. The $1S(F=1) \rightarrow 2S(F=1)$ transition frequency is within 300 MHz of the QED prediction.

Pecision QED experiment as well as initiation of new and powerful method of muon cooling

Allen Mills, Steve Chu (1997 Nobel prize), Nagamine

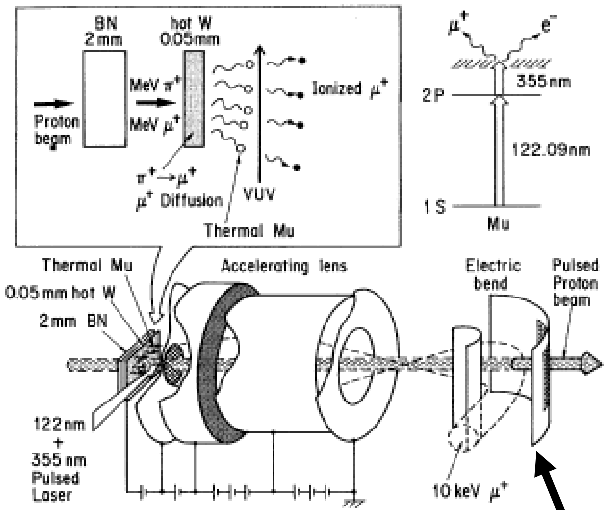


Pulsed lasers from Bell Lab.



Experimental layout

Muons under extreme experimental conditions (2)
Production of Ultra-slow Positive Muons



Experimental Arrangement

VOLUME 74, NUMBER 24 PHYSICAL REVIEW LETTERS 12 JUNE 1995

Ultraslow Positive-Muon Generation by Laser Ionization of Thermal Muonium from Hot Tungsten at Primary Proton Beam

K. Nagamine,[1,2] Y. Miyake,[1] K. Shimomura,[1] P. Birrer,[1] J. P. Marangos,[1,3] M. Iwasaki,[1] P. Strasser,[2,4] and T. Kuga[5]
[1]*Meson Science Laboratory, Faculty of Science, University of Tokyo (UT-MSL), Hongo, Bunkyo-ku, Tokyo 113, Japan*
[2]*Muon Science Laboratory, The Institute of Physical and Chemical Research (RIKEN), Wako, Saitama 351-01, Japan*
[3]*Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW72BZ, United Kingdom*
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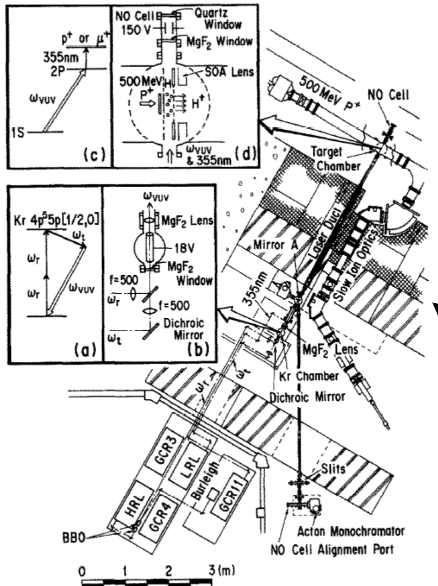
(Received 27 September 1994; revised manuscript received 17 April 1995)

N·H ELSEVIER
Nuclear Instruments and Methods in Physics Research B 95 (1995) 265–275
NIM B Beam Interactions with Materials & Atoms

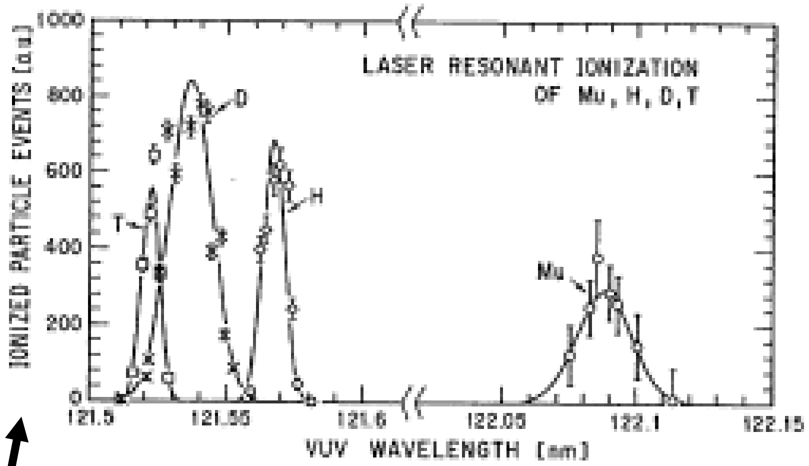
Laser system for the resonant ionization of hydrogen-like atoms produced by nuclear reactions

Y. Miyake [a,*], J.P. Marangos [a,b], K. Shimomura [a], P. Birrer [a], T. Kuga [c], K. Nagamine [a]
[a] *Meson Science Laboratory, Faculty of Science, University of Tokyo (UT-MSL), Hongo, Bunkyo-ku, Tokyo 113, Japan*
[b] *Blackett Laboratory, Imperial College of Science, Technology and Medicine, Prince Consort Road, London SW7 2BZ, UK*
[c] *Institute of Physics, College of Arts and Sciences, University of Tokyo, Komaba, Meguro-ku, Tokyo 153, Japan*
Received 18 July 1994; revised form received 28 September 1994



Laser system

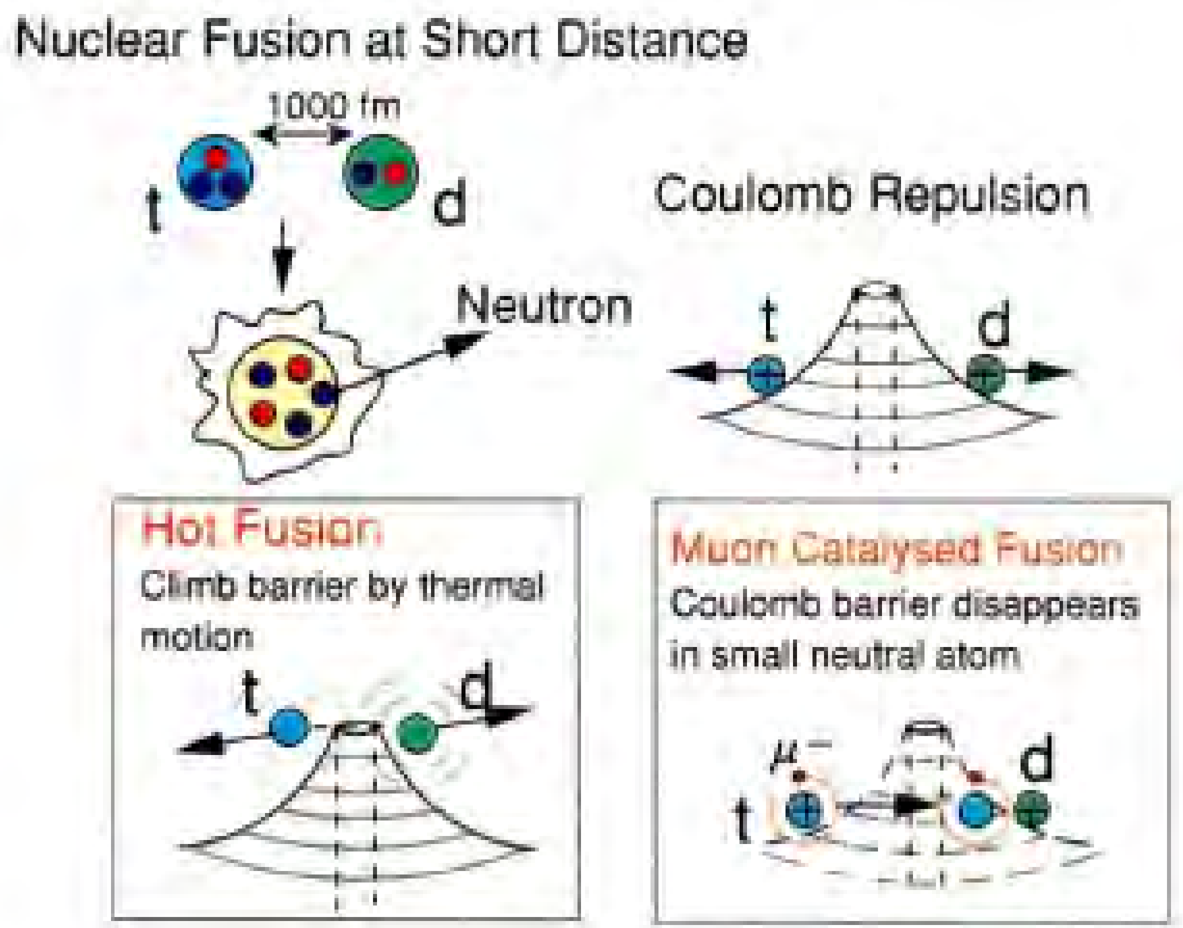
Observed ultra-slow μ^+

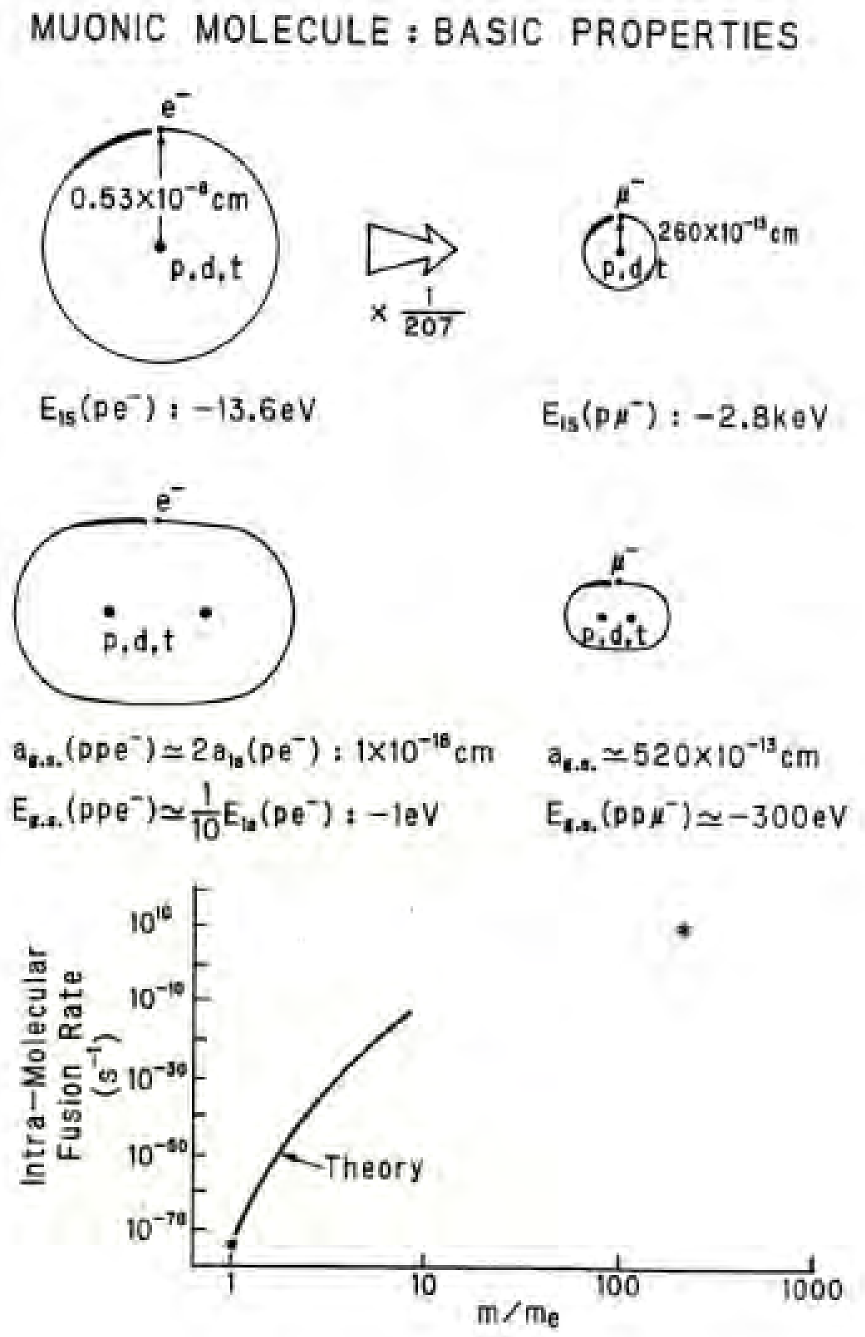


Nagamine Miyake Shimomura Birrer

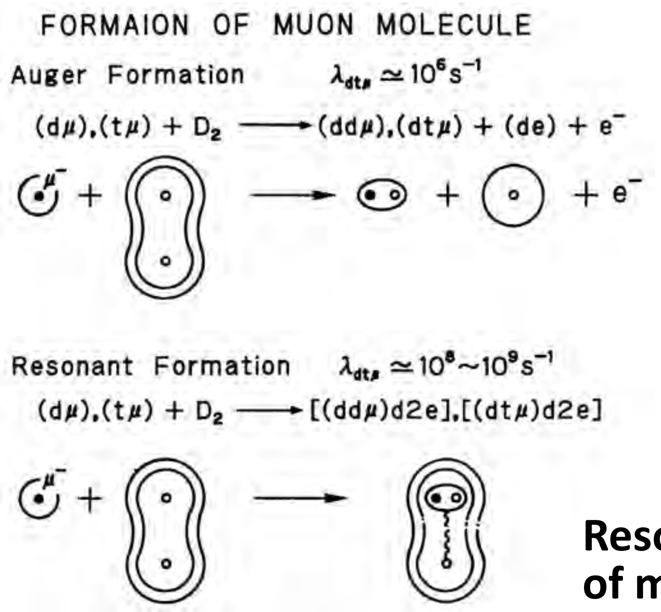
→Under development at J-PARC via RIKEN-RAL

Observation of rare muon phenomena under white-nose
Alpha sticking X-ray in DT-μCF (a)

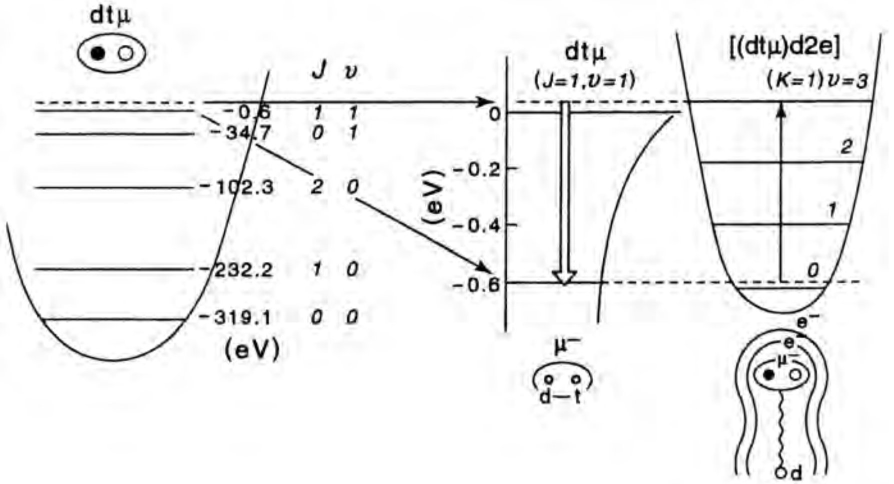


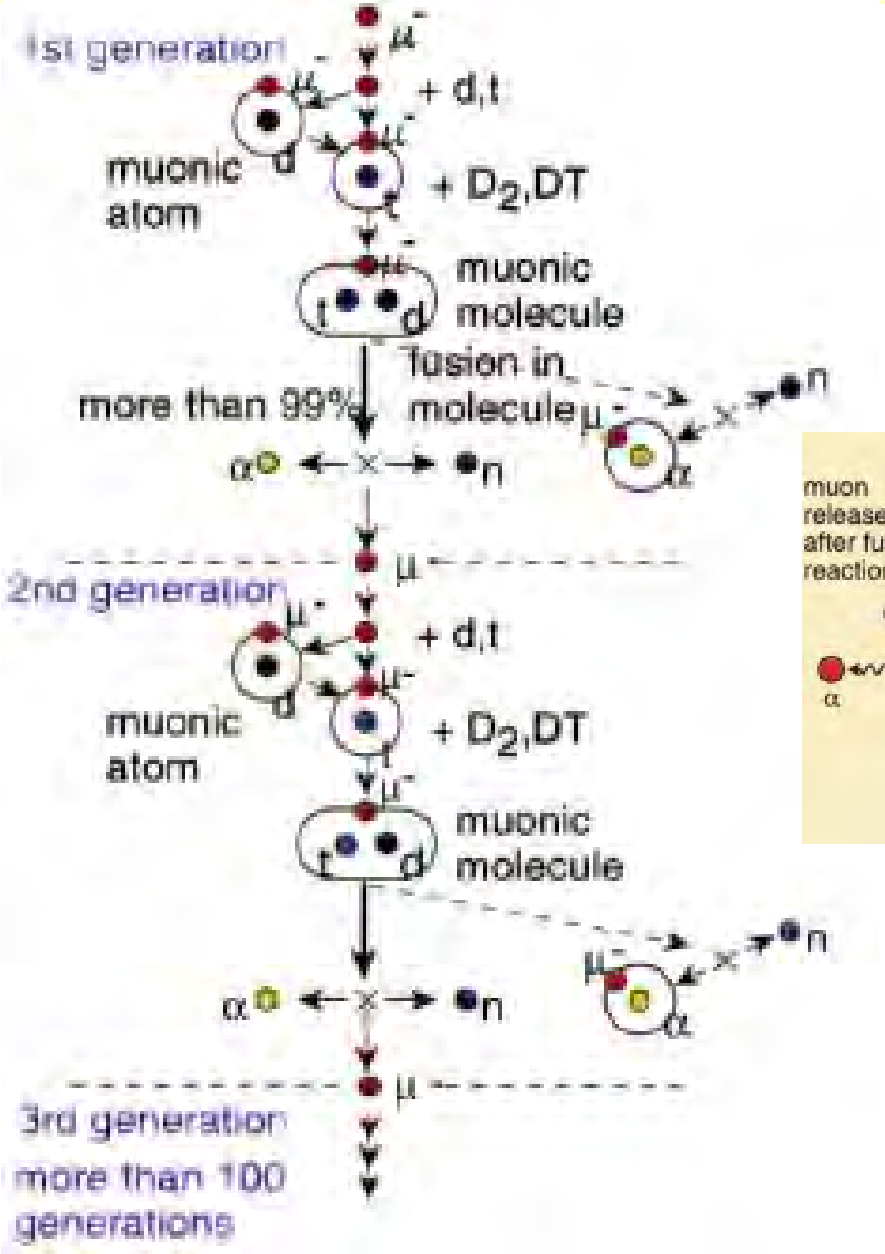


Observation of rare muon phenomena under white-nose
Alpha sticking X-ray in DT-μCF (b)

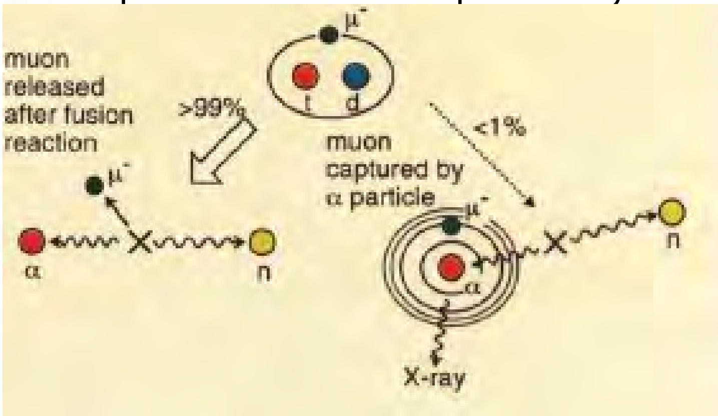


Resonant formation of muon molecular ion within 20 ps.





μCF reaction occurs successively and terminates by muon to alpha sticking. Direct observation of sticking by X-ray is the most important for energy production capability.



Under huge radiation from t-decay, 10 keV weak X-ray of sticking can be realized by pulsed muon.

Observation of rare muon phenomena under white-nose
Alpha sticking X-ray in DT-μCF (c)

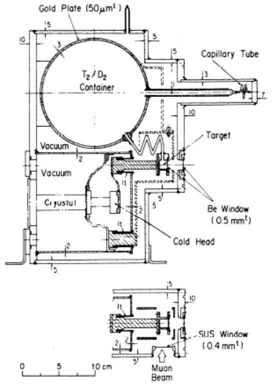
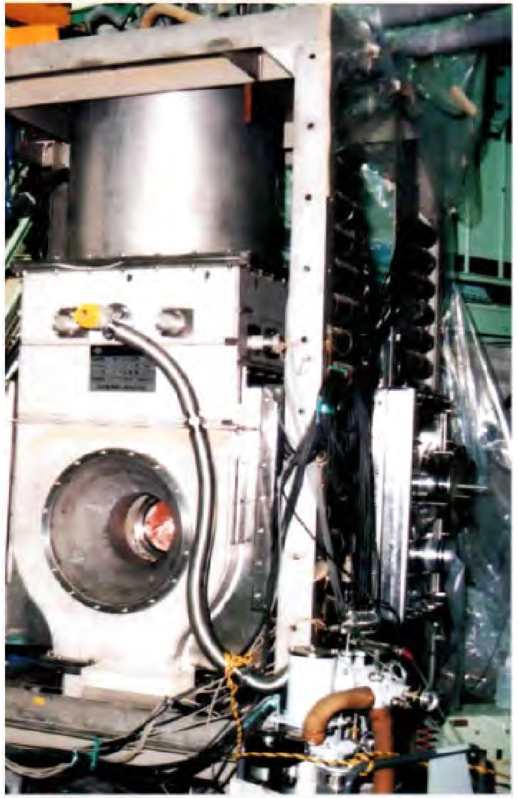
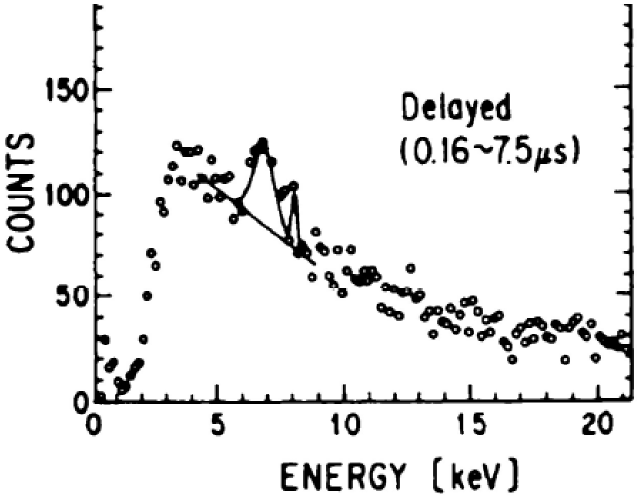
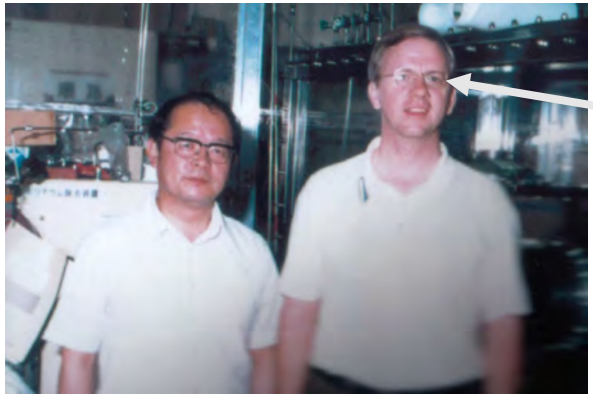


Fig. 2. Schematic view of the doubly sealed tritium-deuterium target chamber used in the present experiment; vertical view (above) horizontal cut-view along the muon beam plane (below).



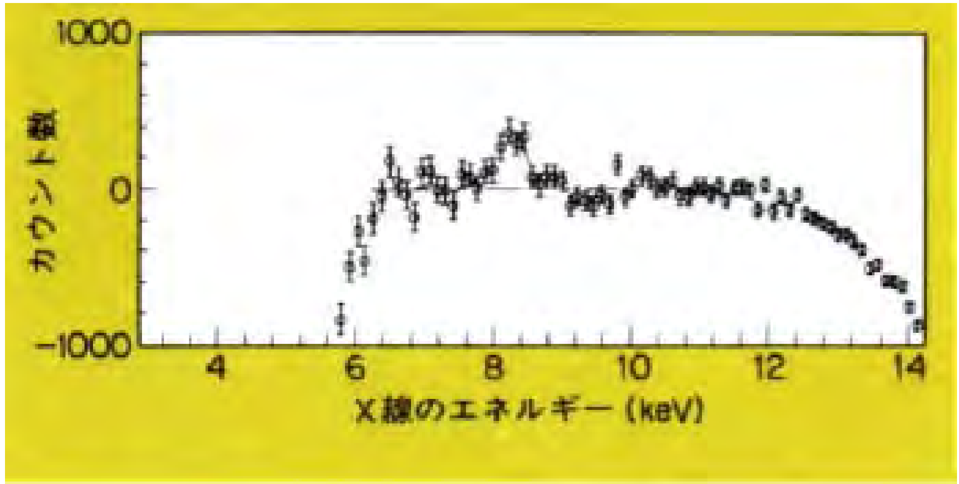
1985 Exp. ;
Realized by using D-T gas from LANL with the help of S.E.Jones (BYU).





S.E.Jones(BYU, later proposer of condensed matter Fusion)

1988 Exp. ; Realized by collaboration with Tritium group of JAEA



Request for improvement of this experiment became a trigger of creation of RIKEN-RAL.

Succession to RIKEN-RAL and J-PARC MUSE

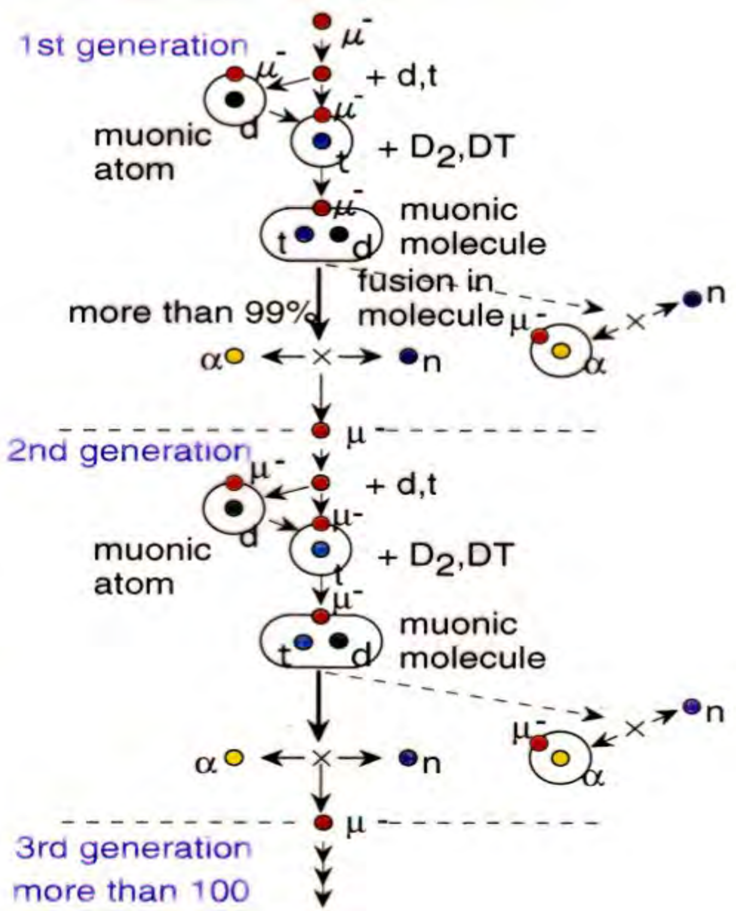
→ Talk by Dr K.Ishida

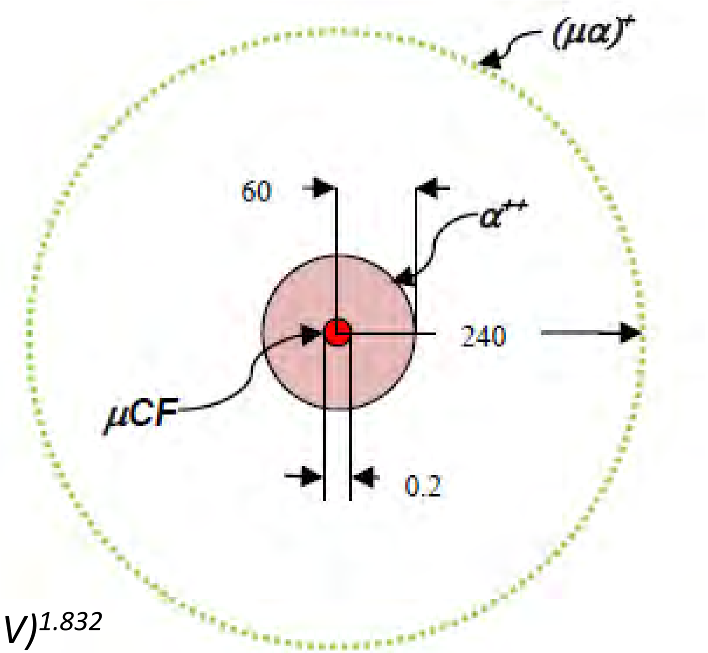
→ Talk by Dr Y.Miyake

Some Thoughts for Further Developments;

Towards non-linear Muon Phenomena

Expectations for non-lenear muon phenomena
Strongly Correlated μ CF (1)





$R_{\mu}(D_2)(g/cm^2) = 0.01E(MeV)^{1.832}$
$R_{\alpha}(D_2)(g/cm^2) = 0{,}00010\ E(MeV)^{1.825}$
$R_{\mu\alpha}(D_2)(g/cm^2) = 0.00041\ E(MeV)^{1.825}$

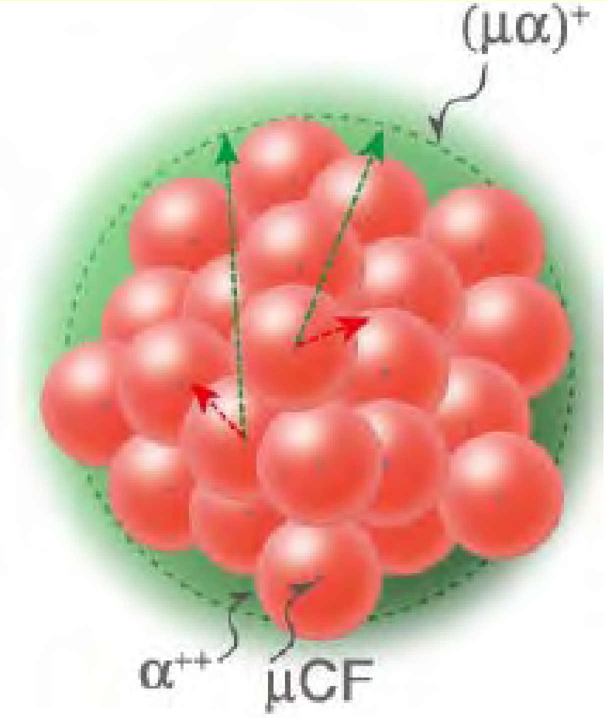
Spatial structure of μCF
Successive fusion occurs within 0.2μm.
More than 100 alphas propagate to 60μm.
Once sticking happens, $(\mu\alpha)^+$goes to 240μm.

Expectations for non-lenear muon phenomena *Strongly Correlated μ CF (2)*

By intense accelerator, intense pulsed muons can be stopped within mm region of D-T mixture, producing a high density μCF phenomena where produced α can ionize the (μα) of the neighboring μCF reaction.

Possible realizable muon density in D-T mixture.
2×10(13) μ^-/cm^3
there, density of high temperature plasma due to α^{++} from the high density μCF,
1.5×10(7) $/\mu^-$ → 3×10(20) $/cm^3$
the ω_s expected from such plasma,
$\omega_s \sim 0.001$

There, more than 1200 μCF can take place per one muon producing more than 20GeV energy, which exceeds cost of one muon, realizing a break-even.



Assume

$\lambda_{dt\mu} = 800\ \mu s^{-1}$ & $W = 0$ at $\phi = 1.5$
($\lambda_0 = 0.45\ \mu s^{-1}$, $C_D = 0.5$)

$$Y_n = \frac{\phi\lambda_c}{\lambda_0} \rightarrow 1300$$

Producing 23 GeV/muon !

versus muon/5 GeV

By stopping intense pulsed negative muons in mm space of D-T, high density μCF is produced with a high density of alpha. This alpha makes high T and high density plasma to dissociate (μα) once sticking happens.
More than $10^{12}/(500\mu m)^3$ muons is enough to realize a break-even.

Conclution
Birth and achievements of Muon Science Laboratory

- In 40 years ago, pulsed muon science had been initiated at UT-MSL of KEK-BSF and various scientific achievements have been obtained.
  Acknowledgements to Professors T. Yamazaki and T. Nishikawa.

- Further developments are in progress at the world-strongest pulsed muon facility J-PARC MUSE.
  Acknowledgements to Drs K. Nishiyama, R. Kadono, Y. Miyake and K. Shimomura

- Developments are supported by the activities of users.
  Acknowledgements to Drs N. Nishida, E. Torikai, J. Sugiyama and Y. Koike

- Next further developments are expected.
  e.g.) realization of non-linear muon phenomena