Non-particle physics with intense muon beams

K. Ishida (RIKEN)

at the NuFact03 Workshop, 6 June 2003, New York

(non-particle physics with muons)

Muon's interaction with materials.

as a unique probe, tool

change their properties, new phenomena

A few examples of muon's applications

based mainly on the works by muon groups at RIKEN and KEK-MSL

M. Iwasaki, T. Matsuzaki, I. Watanabe, Y. Matsuda, P. Strasser, S. Ohira

K. Nagamie, K. Nishiyama, R. Kadono, Y. Miyake, K. Shimomura, W. Higemoto, N. Kawamura

Non-particle Physics

Non-particle physicist's view of muon

μ^- = heavy electron (~200 m_e)

μ^+ = light proton (~1/9 m_p), radioactive hydrogen isotope

A negative muon in materials, as heavy electron, makes muonic atoms

- muonic atom cascade
- nuclear and atomic spectroscopy
  - muon mass, nuclear charge radii, QED test
- muon nuclear capture
- muon catalyzed fusion

muon catalyzed fusion (principle)

After injection of muons into D/T mixture (or other hydrogen isotopes)

Formation of muonic atoms and molecules

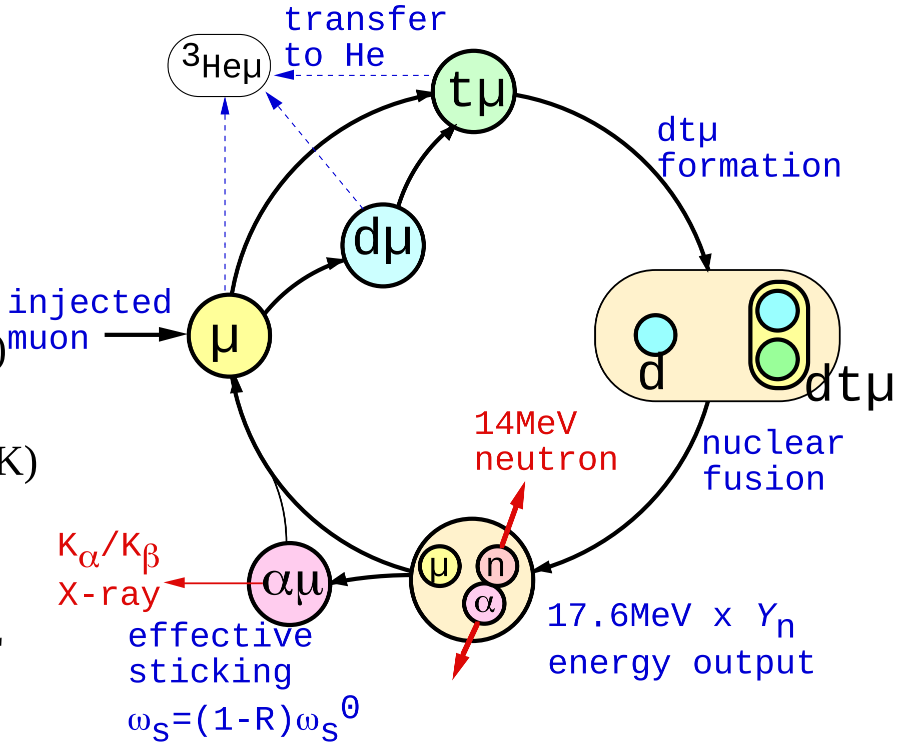
In small dtμ molecule Coulomb barrier shrinks and d-t fusion

Muon released after d-t fusion

- muon works as catalyst -

History

1947 Hypothesis of μCF (Frank)
1957 observation of pdμ fusion (Alvarez)
1966 observation of resonant ddμ formation
1967 hypothesis of resonant formation(Vesman)
1979-82 observation of large dtμ formation rate
1987 observation of x-rays from $(\alpha\mu)^+$ (PSI,KEK)
1993 large ddμ formation rate in solid
1995 study with eV beam of (tμ)
1997 systematic study of x-rays at RIKEN-RAL
^{3}He accumulation, tHeμ, ...



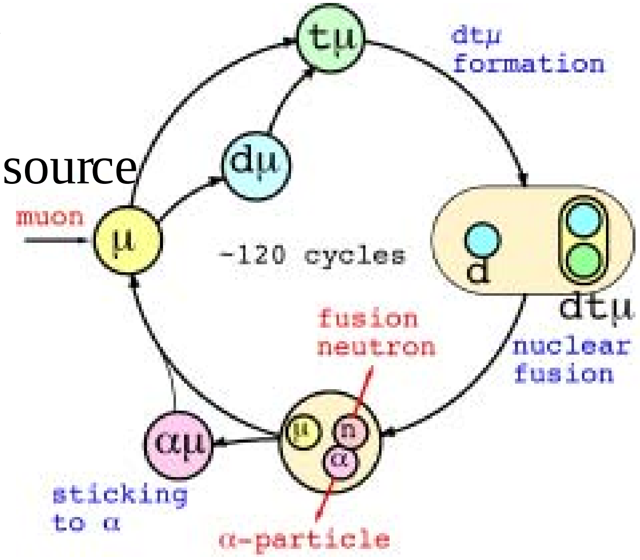
simplified μCF cycle

μCF (motivation)

1. Wonder world of exotic atoms
   - physics in small scale, rich in few body physics
     - versatile reactions of muonic atoms and molecules
     - impact to theories of few-body problems
   - amplification of energy scale by resonance (from meV to MeV)

Fusion energy (17.6MeV)	resonance
dt resonance (10keV)	tunneling
dtμ ground state (250eV)	
dtμ shallow bound state (1eV)	cascade
thermal energy (10meV)	resonant formation

2. Possible applications for fusion energy, neutron source
   - Fusion per μ^- : $Y_n = \phi\lambda_c/\lambda_n = 1/(\lambda_\mu/\phi\lambda_c + W)$
   - W ↘ and $\phi\lambda_c$ ↗ for more Y_n
   - 140 fusions = 2.5 GeV
   - muon production cost = 5 GeV



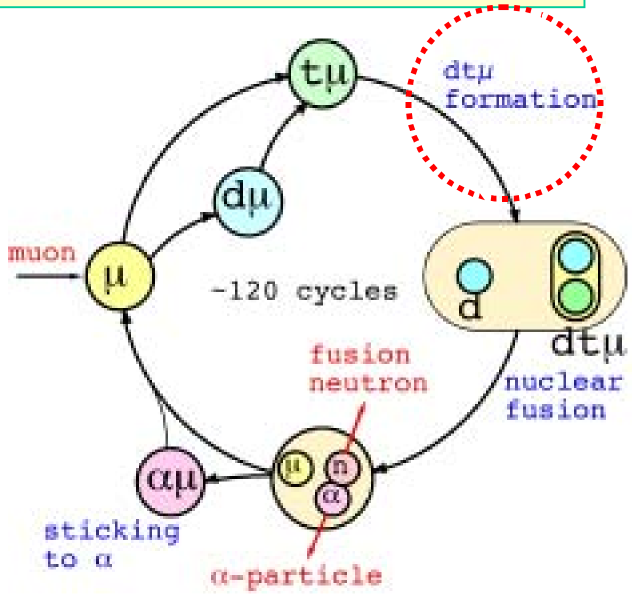
Key process of μCF (dtμ formation)

Key to improving μCF efficiency (1)

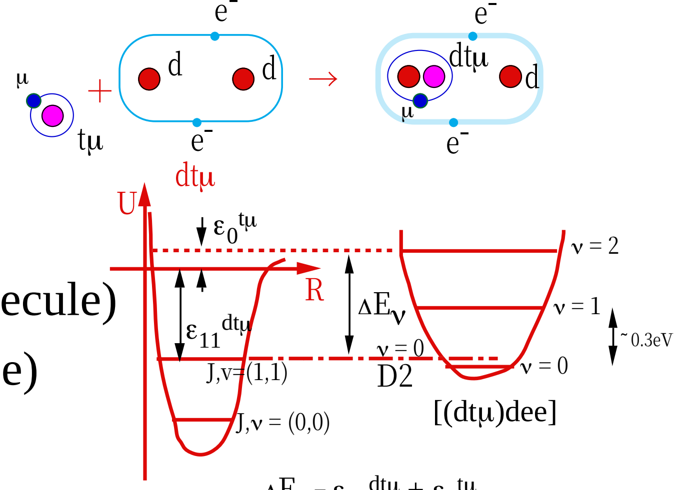
- reaction rates >> muon decay rate (0.45 x 10^6 /s)
  - slowing down and capture
  - muonic atom cascade
  - muon transfer
  - dtμ molecular formation
  - cascade in molecule, fusion

Present understanding of dtμ molecular formation

- Auger formation : 10^6 /s
  - $t\mu + D_2 \to (dt\mu) + D + e^-$
- resonant molecular formation : 10^9 /s
  - $t\mu + D_2 \to ((dt\mu)\ dee)$
  - (dtμ binding energy ~ excitation of comp. molecule)
  - (tμ energy to match the small energy difference)
- temperature dependence of ddμ formation (Dubna)
- high rate of dtμ formation ~4 x 10^8 /s (LAMPF)



$t\mu + (D_2)_{\nu iKi} \rightarrow [(dt\mu)_{11}dee]^*_{\nu fKf}$



$\Delta E_\nu = \varepsilon_{11}^{dt\mu} + \varepsilon_0^{t\mu}$

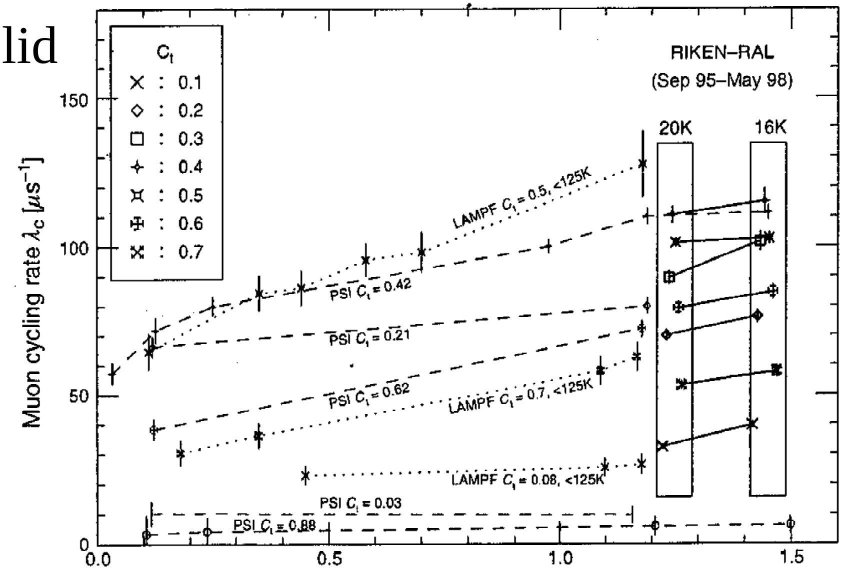
Present understanding of dtμ formation

dtμ molecule formation

- unexpectedly high dtμ formation rate (4×10^8 /s) was understood by Vesman mechanism of resonant dtμ molecular formation
- still many surprises
  - non-trivial density dependence even after normalization
    - three-body effect : $t\mu + D_2 + D_2' \rightarrow ((dt\mu)dee) + D_2''$
  - low temperature & solid state effect
  - φ dependence applies even to solid

Towards higher cycling rate

- high-energy resonance (~eV)
- high temperature, high density
- ro-vibrational molecule state



(*b*)

density φ

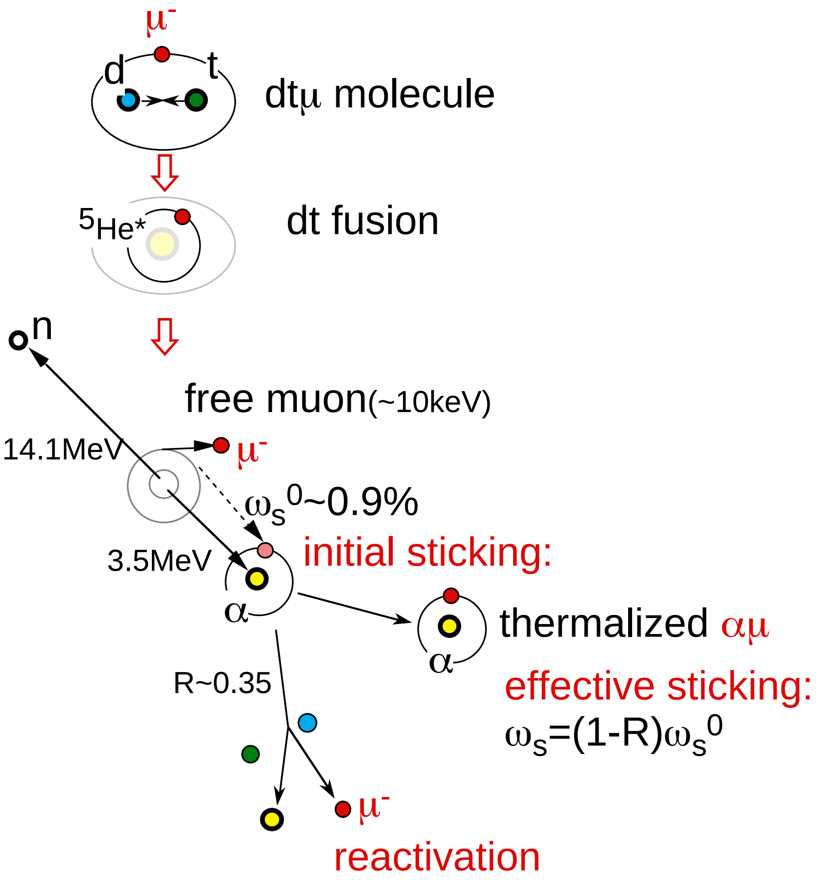
Key process of μCF (μ-to-α sticking)

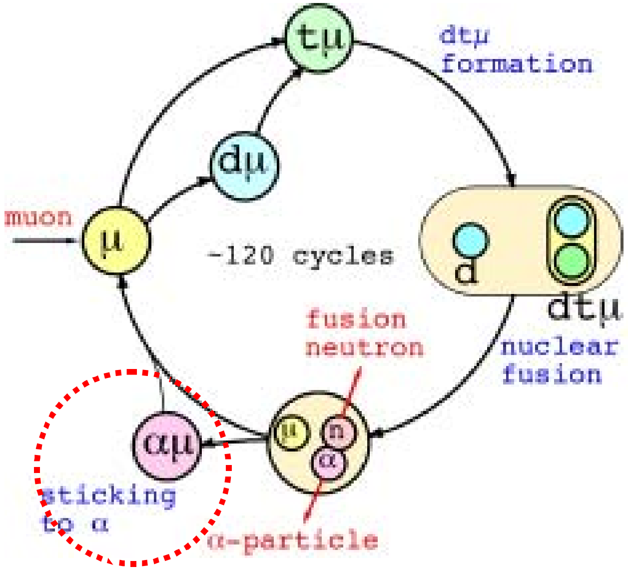
Key to improving μCF efficiency (2)

Muon loss processes

- Muon-to-alpha sticking : ω_s
- Muon transfer to helium etc

μ-to-α sticking is the most serious obstacle to high fusion yield ($Y_n < 1/\omega_s$)





Present understanding of μ-to-α sticking

Discrepancy between theory and experiment

$\omega_s = \omega_s^0 (1-R)$

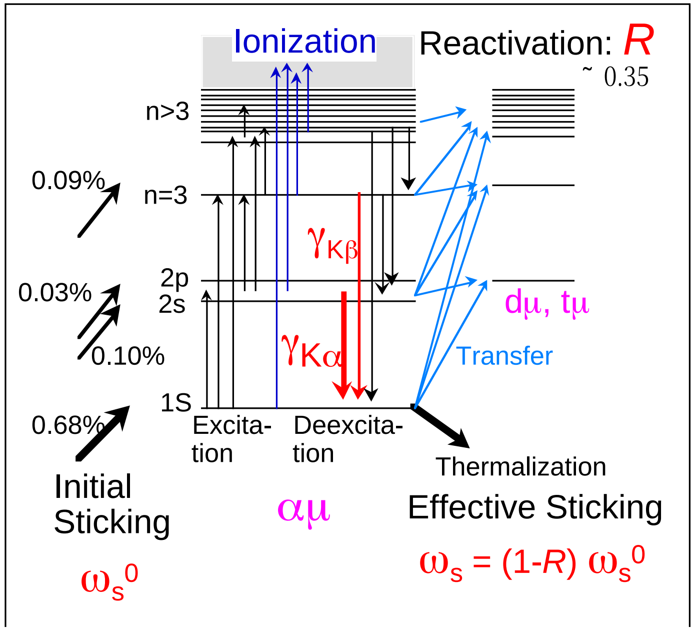
more significant at high density => enhanced reactivation?

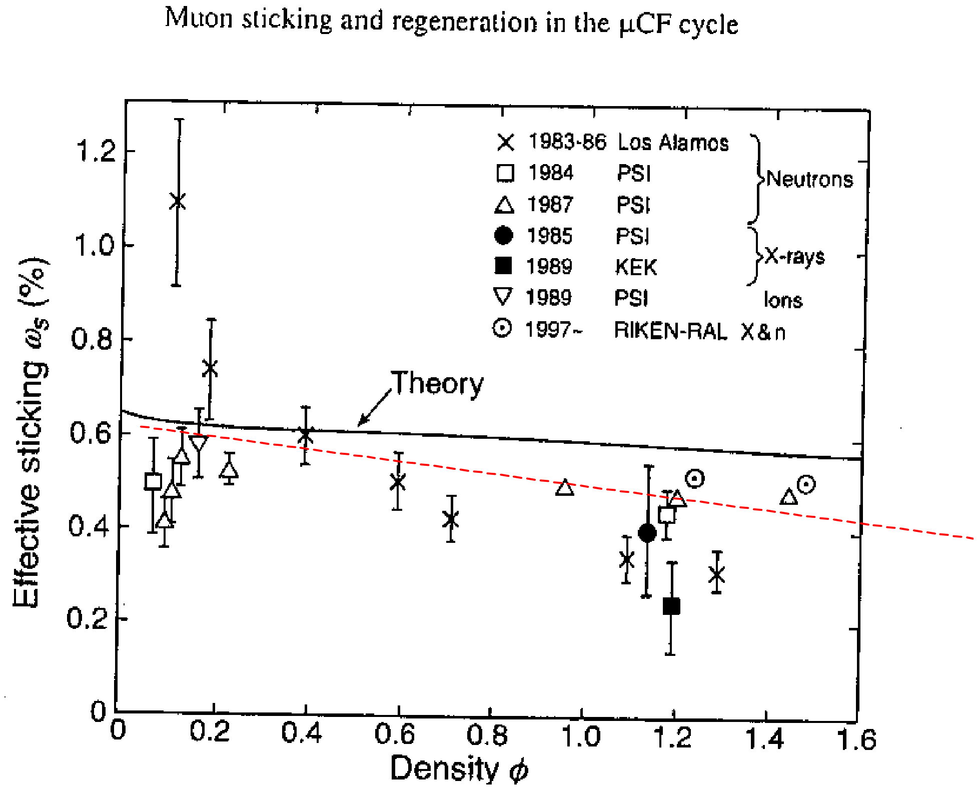
competition of excitation/ionization and radiative de-excitation

direct observation of sticking

$(\alpha\mu)^+ / \alpha^{++}$ ion

x-rays

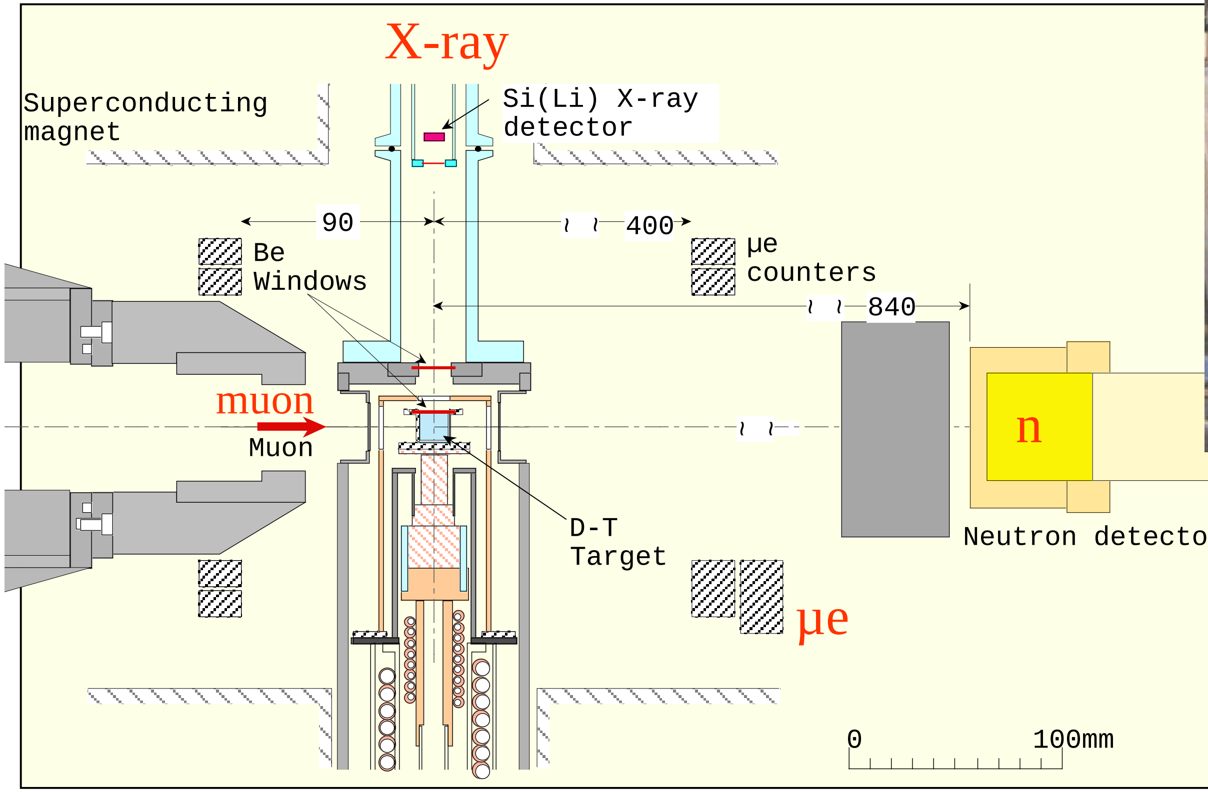




μCF at RIKEN-RAL

RIKEN-RAL experiment

- 1 c.c. liquid/solid D_2-T_2 (1500Ci=GBq)
- 120 muon stops /pulse
- 10^6 fusions /s (long term & controlled)




μCF setup
(RIKEN-RAL Port1)

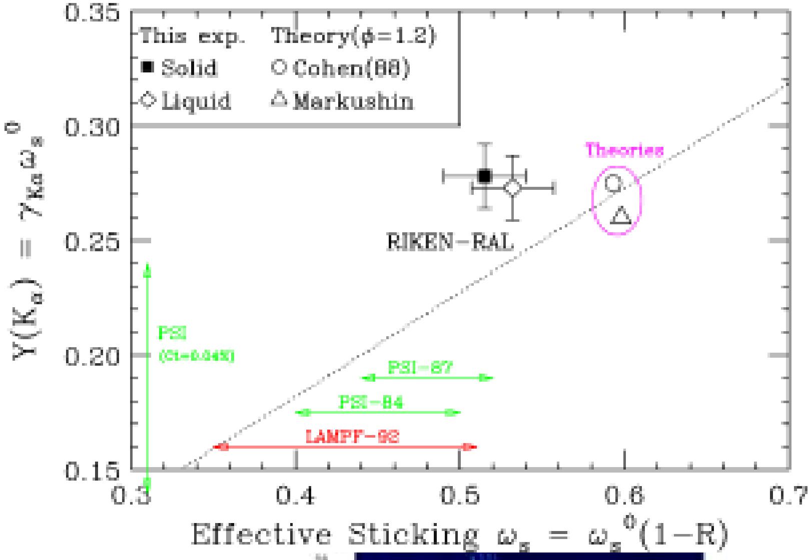
μ-to-α sticking (RIKEN-RAL result)

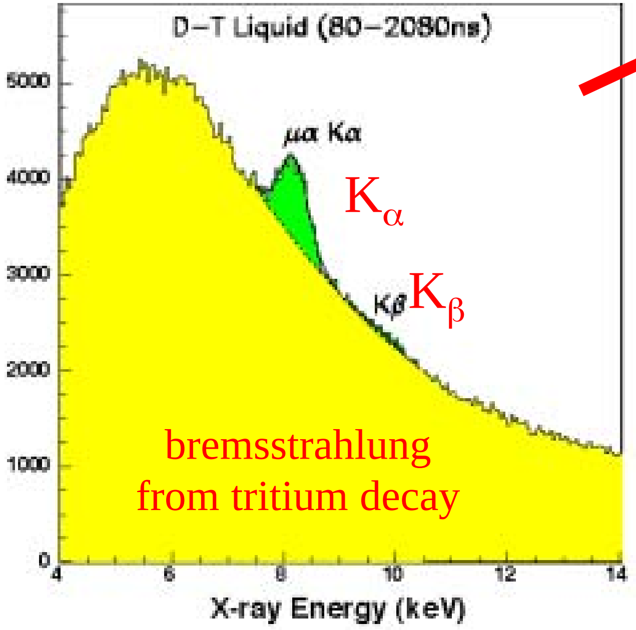
Progress at RIKEN-RAL

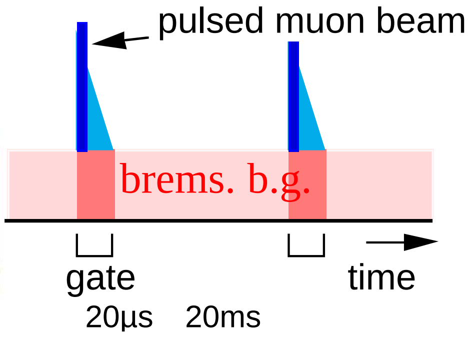
- observation of Kα and Kβ x-rays from $(\alpha\mu)^+$ above huge brems. b.g.
- Y(Kα)~ theory, Y(Kβ) << theory, final sticking ω_s< theory
- enhanced reactivation from n>=3
  - also, PSI $(\alpha\mu)^+ / \alpha^{++}$ ion measurement

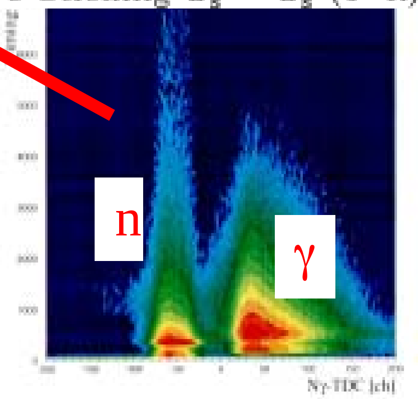
Enhance reactivation by further understanding

- high density, plasma, r.f.









Muon Catalyzed Fusion (Other topics)

Energetic muonic atoms

- acceleration in cascade process
  - Auger, radiative + Coulomb, intermediate molecule formation
- acceleration in muon transfer
- slow thermalization
  - scattering cross-section minimum (Ramsauer-Townsend, phonon)

(μxHe) (x=p,d,t) muonic molecules

- formation, decay, ^{3}He accumulation in solid

μCF in solid hydrogen film

- TRIUMF
  - energetic(~1eV) dμ, tμ beam (Ramsauer-Townsend)
  - and μCF (eV resonance)
  - non-thermalization effect in solid
- RIKEN-RAL
  - towards efficient formation of radioactive muonic atoms

μCF (energy balance issue)

Achieved 130 fusions catalyzed per muon.

still smaller than scientific breakeven (~300)

There have been surprises waiting such as,

Enhanced reactivation of $(\alpha\mu)^+$

Three-body effect in $dt\mu$ formation

Non-thermalization effect

=> need exotic atom/molecule theory of highly-correlated condensed matter

These suggest advantage of high-density target

ϕ	R	$\omega_s^0(1-R)$	$\phi\lambda_c$	N
1.25	0.5	0.45%	300 x $\lambda\mu$	130
2.2	0.65	0.30%	600 x $\lambda\mu$	220
10	0.95?	0.04%	6000 x $\lambda\mu$	2000

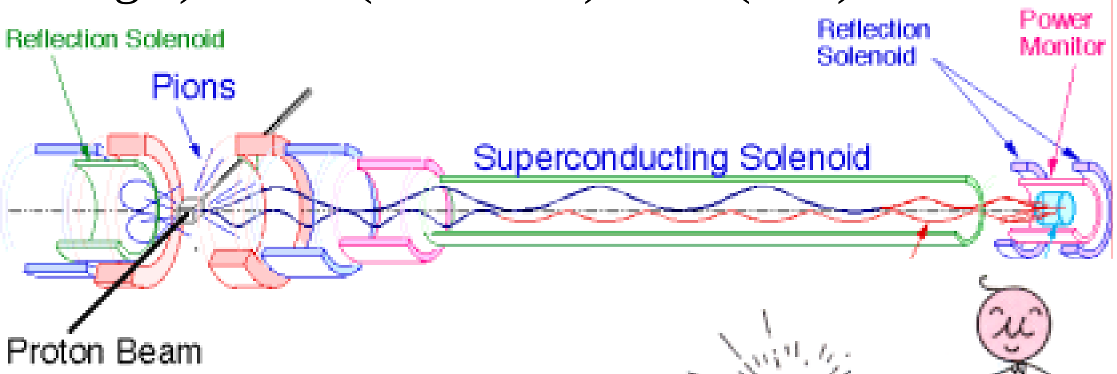
ϕ ~ 2.2 (practical limit with static high pressure ~100MPa)

ϕ ~ 10 (inertial confinement)

Muon catalyzed fusion (future)

High-intensity, high-quality muon beam and µCF

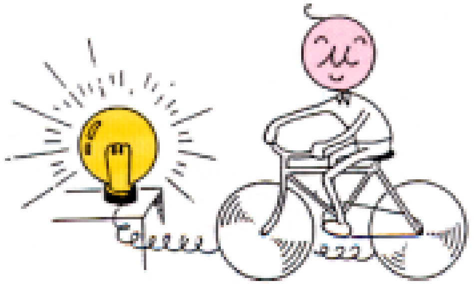
- High-density, high-temperature - needs well tailored beam
- Short-lived extreme conditions (plasma, laser, r.f.)
- Intense fusion neutron source (design, ADS)
- sub kW µCF reactor at high-intensity MW proton accelerator
  - J-PARC, neutrino-factories, dedicated FFAG
  - 3µW x 100(beam+target) x 3000(collection) x 100(D/T)=0.1kW



Exotic beams

- slow µ-, pµ,dµ,tµ beam, $(\alpha\mu)^+$ beam

Muonic atom spectroscopy (µA* project)



muon cycling
(from KEK-MSL pamphlet)

Radioactive Muonic Atoms

K. Nagamine, P. Strasser

PHYSICS MOTIVATION

- Nuclear charge distribution ⇨ **Muonic X-ray spectroscopy of unstable nuclei**
- Deformation properties of nuclei ⇨ **Quadrupole HF splittings of muonic X-rays**
- Muon capture in n-rich nuclei ⇨ **Important astrophysics implications (r-process)**
- Novel nuclear structure effects may exist far off the valley of stability ?

WHY NOW ?

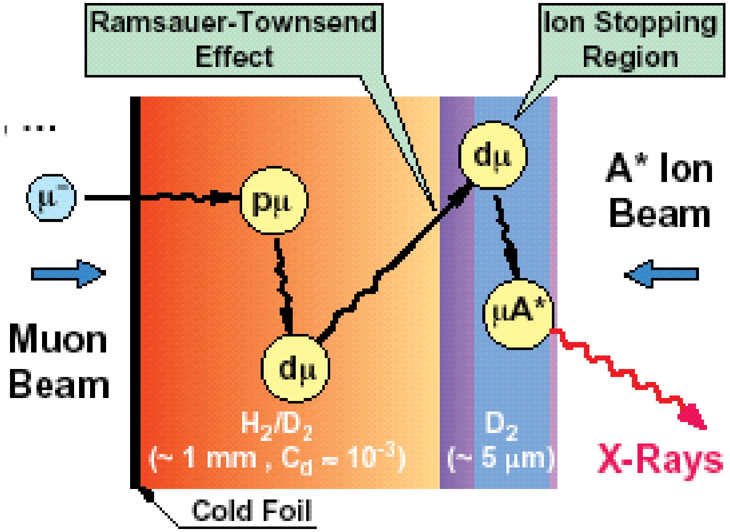
- Soon more intense proton accelerators
- Higher flux muon beams, next generation RNB, , ...

TECHNICAL FEASIBILITY

- **Solid Hydrogen Film** to stop both μ□ & A^*
- **Muon Transfer Reaction** to form μA^*

$\boxed{\mu H + A_z^* \rightarrow \mu A_z^* + H}$ with $\boxed{\lambda_z \approx C_z Z\, 10^{10}\ s^{-1}}$

HIGH TRANSFER RATE & HIGH EFFICIENCY



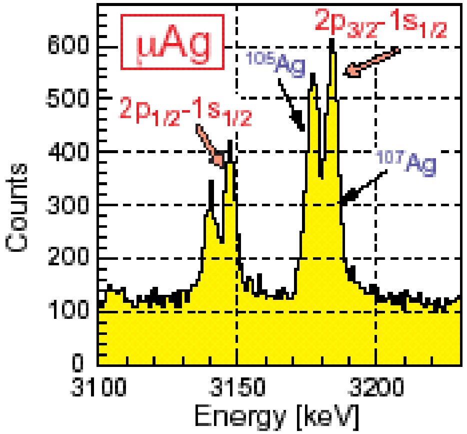
Radioactive Muonic Atoms (2)

Test Experiment to Implant Stable Ions in Solid Hydrogen Films

Germanium γ-Ray Detector

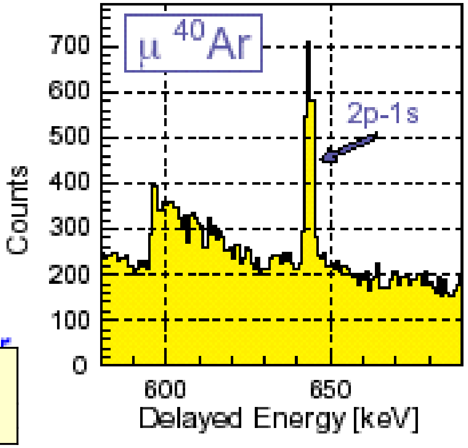
μA* Setup (RIKEN-RAL Port4)

μA* Target System



PRELIMINARY RESULTS

Delayed Muonic Argon X-rays from Muon Transfer to Implanted Argon Ions



Talk by P. Strasser (WG2, today)

using muon spin (μSR)

Non-particle physicist's view of muon

μ^- = heavy electron (~200 m_e)

μ^+ = light proton (~1/9 m_p), radioactive hydrogen isotope

μSR (muon spin rotation/relaxation/resonance)

- The most successful application of muon -

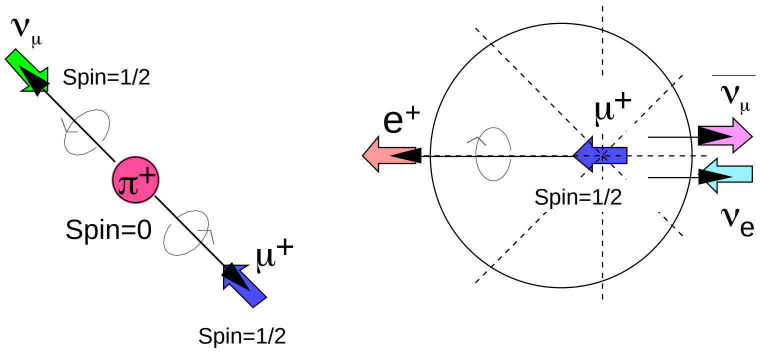
injection of spin polarized muon beam from π decay into materials

characteristic motion of muon spin by external and internal field

observation of muon spin direction by asymmetric emission of e^+/e^-

extract spin relaxation function from time modulation

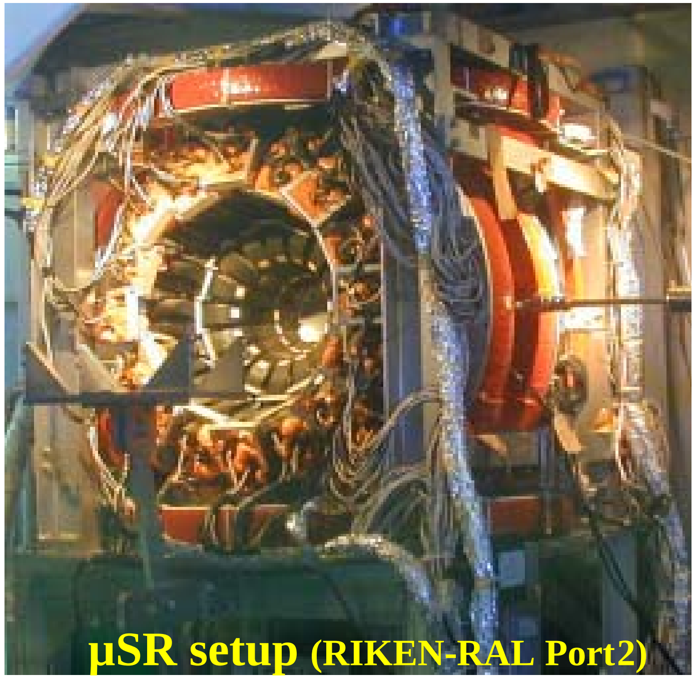
of the positron emission in exponential decay

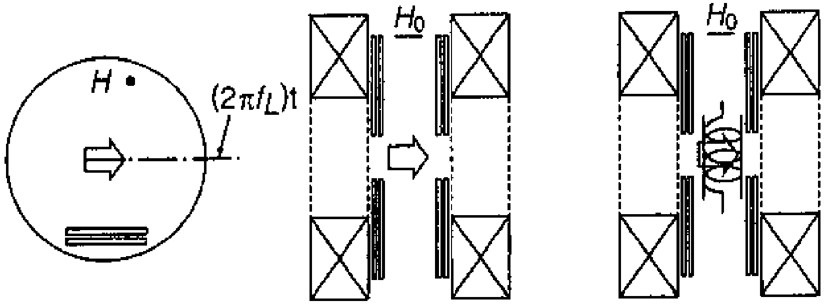


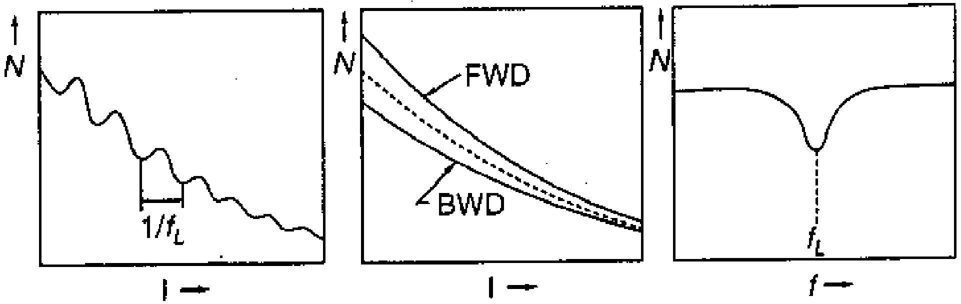
μSR principle

Extract muon spin relaxation function
from time dependent modulation in muon decay
like NMR but
unique status as probe

- does not need strong magnetic field
- does not need specific nuclei
- sensitivity to shorter time than NMR


μSR setup **(RIKEN-RAL Port2)**





μSR examples

Traditionally, μSR is a good probe of magnetism
and had strong applications in metals, magnetic materials, semiconductors
of rather simple crystal structure.

detection of weak anti-ferromagnetism etc

spin fluctuation in ns~μs range

also,

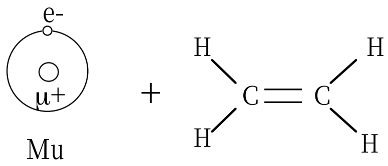
muon's active behavior as light hydrogen was developing

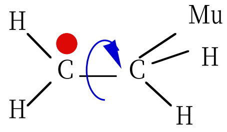
hydrogen diffusion

in semiconductor

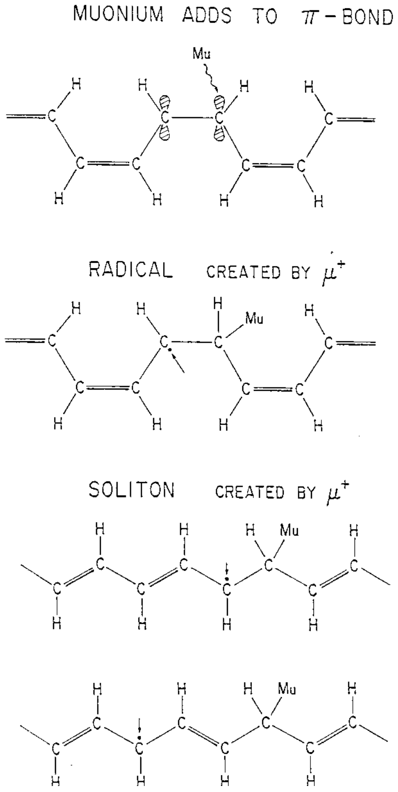
chemistry

μSR examples (chemistry, polymers)



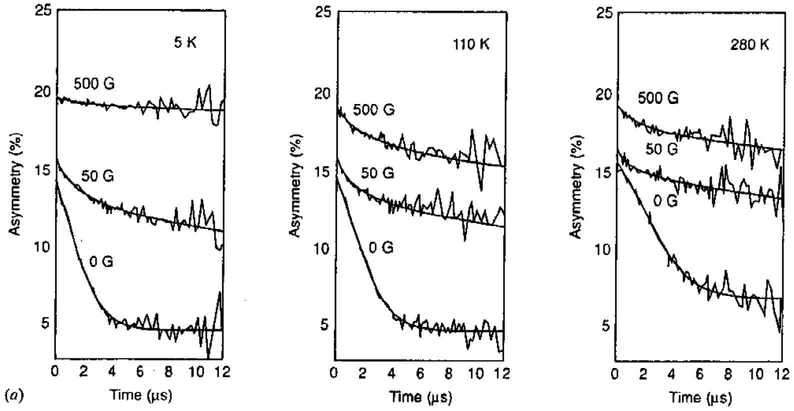


- Muon as hydrogen isotope in chemistry
  - muonium, radicals
  - bond rotation frequency vs temp. etc
  - electron spin density distribution
    - high field TF-μSR, resonance, LCR
- Muon as active introducer of electron spin and probe
  - polyacethylene
  - conducting polymers (polyaniline etc)
  - theory for relaxation by 1-D moving excitations
    - Risch-Kehr relaxation function
    - $G(t) = \exp(\Gamma t)\,\mathrm{erfc}((\Gamma t)^{1/2})$

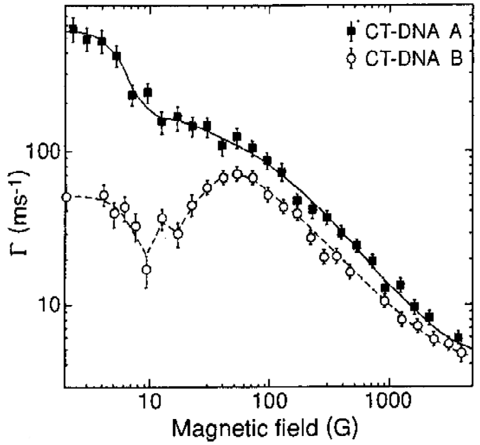


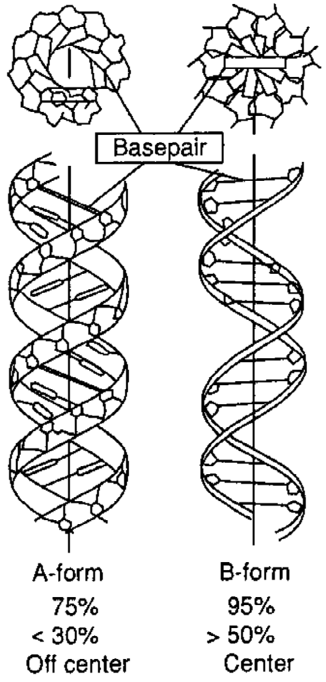
μSR examples (macromolecules & beyond)

The picture (1-dimensionally moving electron spin)
was applied to wide range of polymers
as well as cytochrome and DNA
- once considered dirty materials for μSR (many different muon sites)
with clean relaxation function and field dependence
the picture works to quite extents



cytochrome





μSR future

Unlimited range of μSR applications

- metals, magnets, chemicals, high T_c s.c., polymers, biology, ...

Present limitations of μSR

- limited number of facilities (PSI, TRIUMF, KEK, RAL, ..)
- muon site ? disturbance ?

Use of high-intensity muon beam in μSR

- techniques to cover μSR site ambiguity
  - high resolution muon spin resonance, hyperfine field
  - μ^-SR (site=atom, lower efficiency to μ^+SR)
  - μ^-SR with muonic x-ray tagging (even lower efficiency)
- beam
  - new precious samples (usually small and thin) ->
    - phase space tailored beam, ultra slow muon beam

Ultra slow muon beam

Low energy muon beam

- Precision spectroscopy - low velocity, low density
- surface
- thin, small samples

History:

1976 “Surface” muon beam (~4MeV) Pfifer et al

  stopping range struggling ~0.1mm

1986 Thermal Muonium hot W (KEK), SiO_2 (PSI)

1988 1s-2s-unbound: spectroscopy   Chu et al

Slow μ+ by

1995- laser ionization 1s-2p-unbound (KEK & RAL)

1995- Rare gas solid moderator (PSI, Morenzoni et al) 15eV muons

Applications of ultra slow muon beam

Rare gas solid moderator (PSI, Morenzoni et al) 15eV muons

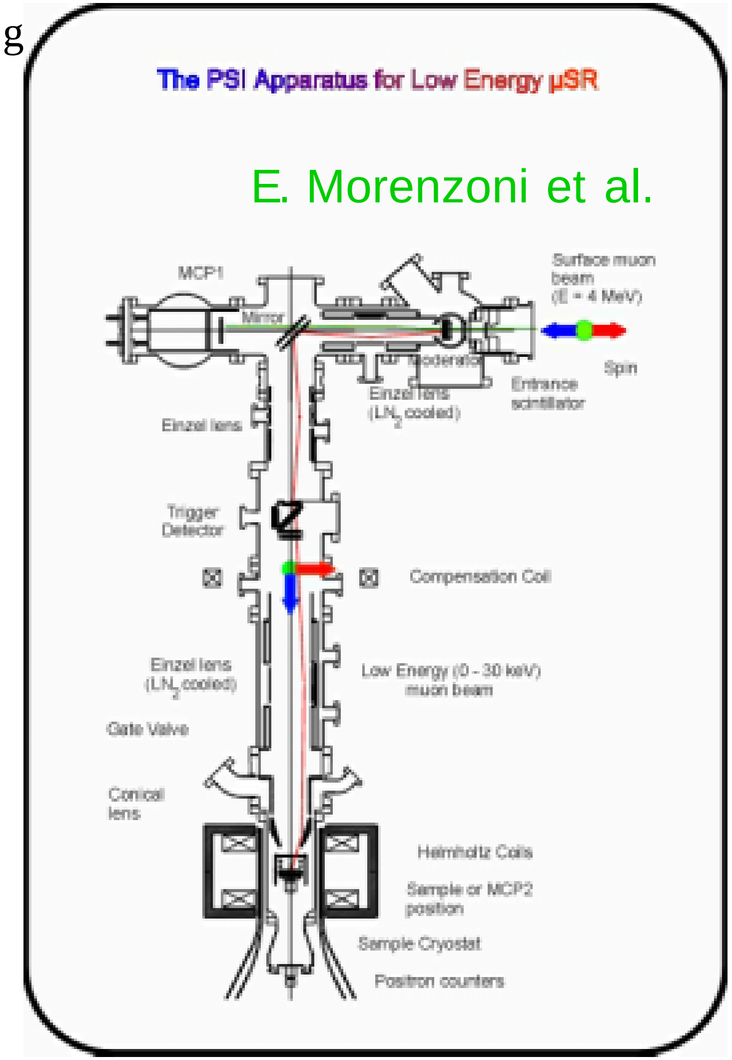
- energy loss process terminates below energy g
- in cryo-crystal
- $10^{-5} \sim 10^{-4}$ moderation probability

thin films, multi layers, interface

- nm ~ μm

applications

- field distribution vs depth
- magnetization of nanoclusters
- micro beam
- source for acceleration



The PSI Apparatus for Low Energy μSR

E. Morenzoni et al.

Ultra slow muon beam

Laser ionization (KEK, RIKEN-RAL)

Thermal muonium + laser ionization

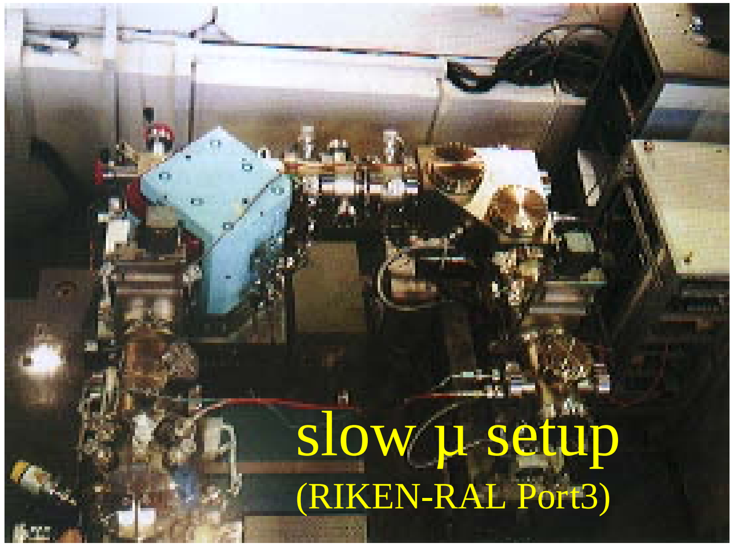
1s->2p(122nm) ->unbound

thermal muonium ~ 4%

ionization <= laser power

thermal energy

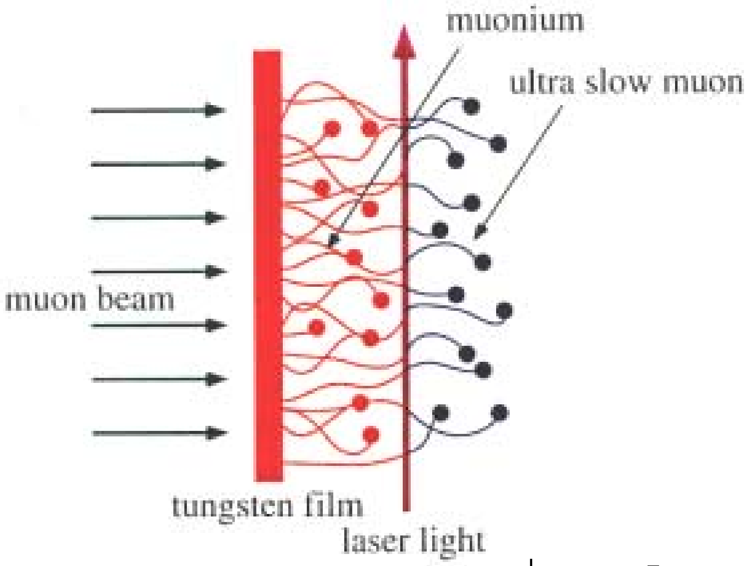
muon timing by laser

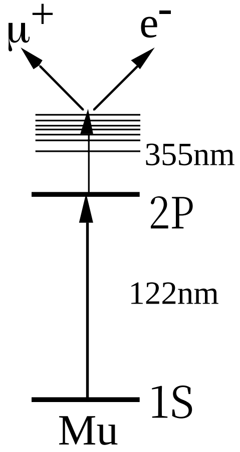


slow μ setup

(RIKEN-RAL Port3)

Talk by Y. Matsuda (WG2, tomorrow)





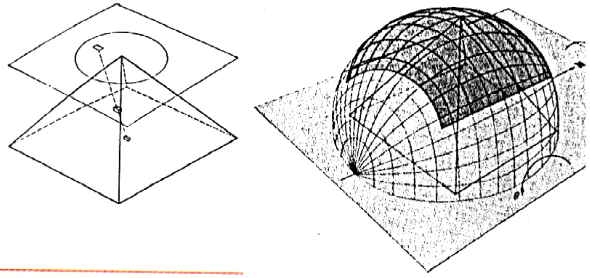
Muon radiography

Using high penetration power of muons (in water)

μ : ~5m@1GeV, increase almost linearly

p, n : strong interaction (~50cm)

e, γ : shower (Lrad = 58cm)



Pyramids of Giza

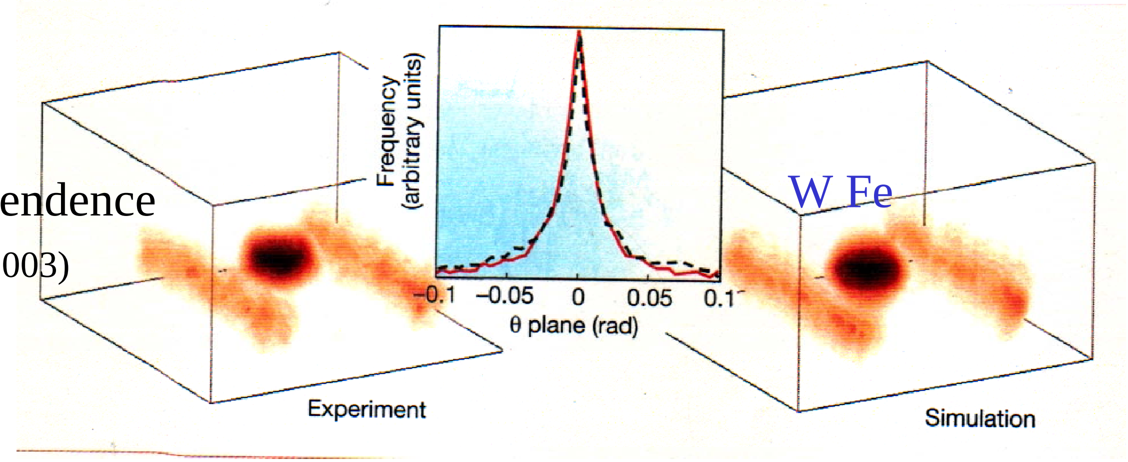
non-existence of hidden chamber (40 - 70 GeV cosmic muons)

- L. Alvarez et al, Science 167, 832 (1970)

Muon Scattering (LosAlamos)

~70GeV cosmic ray, Z dependence

- Borozdin et al, Nature 422, 277(2003)



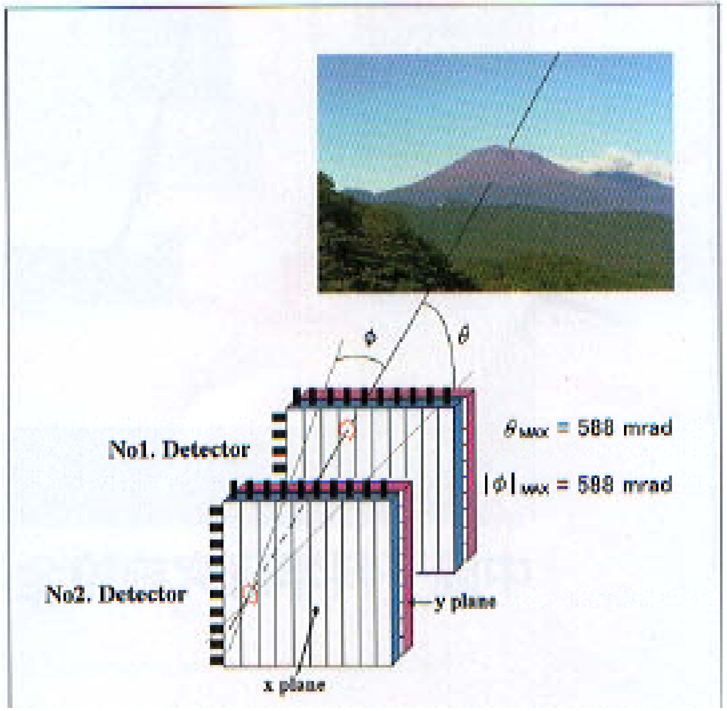
Muon Radiography (2)

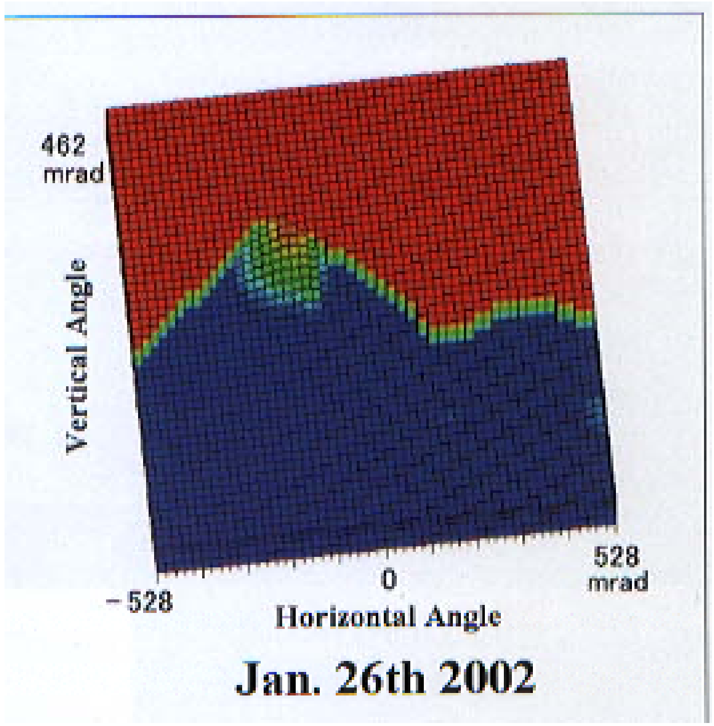
Mountains : K. Nagamine (KEK), H. Tanaka (Nagoya) et al

TeV cosmic ray transmission (~km)

Mt. Tsukuba, N.I.M. A356 (1995) 585

Volcano Mt. Asama



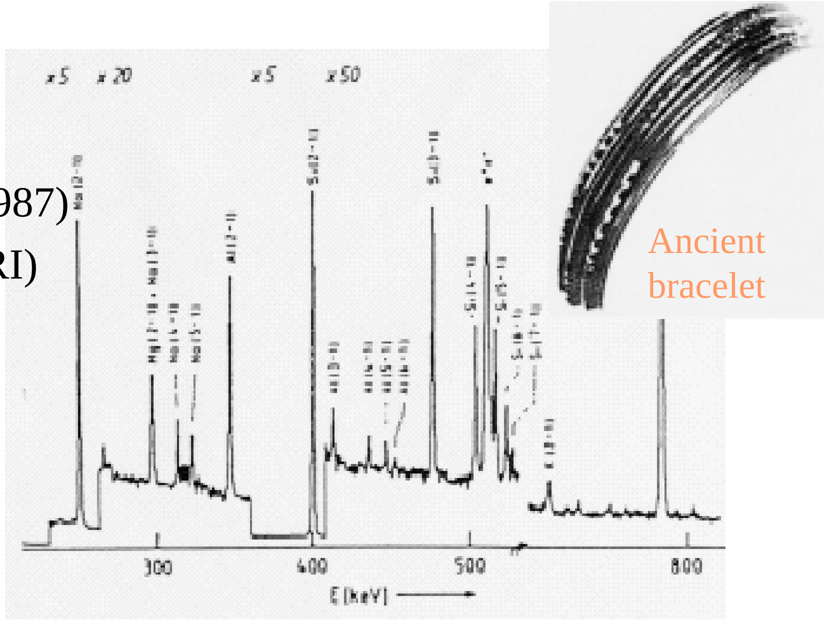


Jan. 26th 2002

Muon Radiography (3)

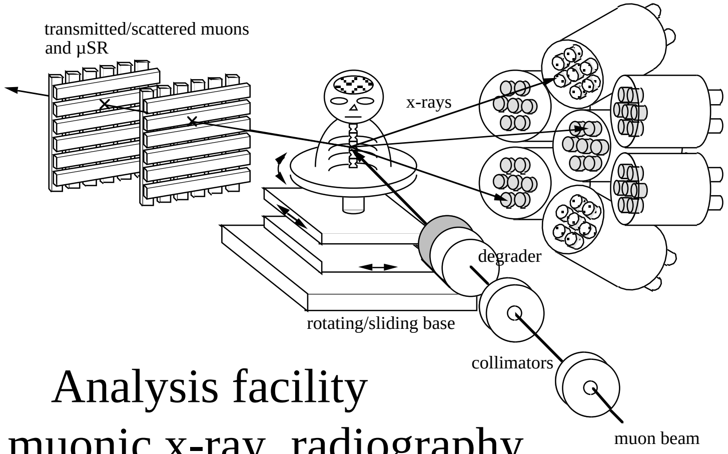
Elements analysis (PSI, LAMPF, KEK)

- muonic x-rays
  - bracelet: H. Bossy et al, SIN Newsletter 19 (1987)
  - old coins, ceramics: S. Sakamoto (KEK, JAERI)
- multi-element
- nondestructive
- 3D sensitive



Design of a new muon source for radiography

Talk by Shimomura (WG2, tomorrow)



Analysis facility

μSR, muonic x-ray, radiography

Summary

(personal view)

µSR => well established, new materials,
technical development, theoretical descriptions

µCF => relatively mature, but large unexplored region and many surprises

ultra slow muon beam => developing, higher intensity

radiography => proof of principle, development of detectors, beams

µA* => proof of principle starting

All these needs high-intensity muon sources of variety,
with more efficient muon production.

- Muon beam energy
  - eV, keV, MeV, GeV, TeV (from nano-structure to volcano)
- Muon beam structure
  - 1MHz (cyclotron, slow extraction) particle physics event-by-event
  - 1kHz (rapid synchrotron, FFAG) µSR, pulsed measurement
  - <1Hz (fast extraction) g-2 etc