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5/11/05

Muon Science in the 21st Century

Intense Muon Sources $10^{11} \rightarrow 10^{17} \rightarrow ?$ μ/sec

A Road Map Starting With MECO: 5×10^{11} $\mu^{\pm}$/sec (2009)

Future Potential

Condensed Matter
Materials Science (Nanoscience)

Chemistry
Biology
Medicine
Archeology
⋮
Home Security
* Neutrino Factory
⋮

Technological Revolution?
You Decide

See Books By: Hughes + Wu
*Nagamine
Kuno + Yokoi

Outline

1. Basic Muon Properties
   μSR muon spin rotation, relaxation, resonance
   Muonium (μ^+e^-)
   Muonic Atoms μ^-N

2. Present vs Future Muon Sources
   > Factor 1000 Intensity Increase!

3. MECO at BNL (Muon-Electron Conversion)
   $\mu^-Al \rightarrow e^-Al$ 2×10^{-17} sensitivity!
   NSF Funding FY2005 Construction → 2009 Physics

4. Conceptual Intense Muon Facility (IMF)
   Solenoidal Trap, FFAG → Clean, Intense $\mu^\pm$

5. Some Applications
   * i) Ultra Slow μ^+SR (0-10eV) $\gtrsim 10^5\mu^+$/sec
   Surface Science, Nanoscience ...
   ii) Muonium (μ^+e^-) Biology, Chemistry...
   iii) μ^- Elemental Analysis (Medical Diagnostics)
   iv) μ^- Catalyzed Fusion → slow μ^- + 14MeV neutrons

6. Outlook

1. Basic Muon Properties $\mu^{\pm}$ (spin = 1/2)

$m_\mu = 105.658389(34)$ MeV $\sim \underbrace{207\, m_e}_{\mu^- \text{ Heavy Electron}} \sim \underbrace{1/9\, m_p}_{\mu^+ \text{ light proton}}$

$\tau_\mu = 2.19703(4) \times 10^{-6}$ sec $\quad \mu^+ \to e^+ \nu_e \bar{\nu}_\mu + \gamma, e^+e^-, \gamma\gamma \ldots$

e^+ spectrum $\quad x = \frac{2E_e}{m_\mu} \quad 0 \le x \le 1$

$$\frac{dN(x,\theta)}{dx\, d\cos\theta} \sim x^2(3-2x)\left[1 \mp \underbrace{P\frac{(1-2x)}{3-2x}\cos\theta}_{\text{Parity Violating Asy.}}\right] \qquad \left\langle \frac{1-2x}{3-2x} \right\rangle = 1/3$$

e^+ angular distribution tracks polarization $P(t)$

polarization P measures magnetic fields

sin μBt precession $\quad \vec{\mu} \simeq \frac{e}{m_\mu}\vec{S} \quad \simeq 3\vec{\mu}_p$

Muon Spin Rotation (μSR) or Relaxation, Resonance

Use muons to study magnetic properties:

* Superconductivity (High T_c)
  Semiconductors
  etc.
  Chemical Kinetics
  Diffusion
  ⋮

Muonium μ^+e^- light hydrogen

μ^+ polarization tracks electron dynamics

$\vec{S} = 0, 1$ Resonance Effects (Crossing)

Muonic Atoms $\mu^- N$ spectrum ~ 207 x electron X-rays

radius ~ 1/207 r_{Bohr} ($\mu^- N \to 2p_\mu N'$)

Polarization usually lost

Copious Muon Production:

$$p \to \text{target Nucleus} \to X + \pi^\pm$$
$$\xrightarrow[99.99\%]{} \mu^\pm \overset{(-)}{\nu}_\mu \quad \text{100\% Polarized!}$$

If Optimized 1 proton (~8GeV) → 1 $\mu^\pm$!!

Pion Factories: PSI, TRIUMF, RAL $E_p < 1$GeV $I_p \sim 10^{15}$-10^{16} p/sec!

Efficiency (current) 10^{-8} μ/proton → $\underbrace{10^7 \sim 10^8 \ \mu^\pm/\text{sec}}_{\mu SR \text{ facilities}}$ $N_{\mu^+} > N_{\mu^-}$

Muon Collider Concept (Neutrino Factory) High Luminosity $\mu^+\mu^-$

Requires $\gtrsim 10^{13}$ $\mu^\pm$/sec!

AGS $E_p \sim 8$-28 GeV, $\sim 4 \times 10^{13}$ p/sec → 10^{12} $\mu^\pm$/sec practical

Can the AGS produce 10^{12} $\mu^\pm$/sec? (Yes!)

What would you do with them?

2. Present + Future Muon Sources (× 1000 Intensity!)

Present: PSI $\sim 10^8$ μ/sec $E_p \simeq 0.59$ GeV } continuous
TRIUMF $\sim 10^7$ μ/sec $E_p \simeq 0.5$ GeV } continuous
ISIS $\sim 10^6$ μ/sec $E_p \simeq 0.8$ GeV } pulsed

Current AGS $E_p \simeq 24$ GeV, 7×10^{13} p/1.6 sec → 0.14 MW } less power
but high $\mu^\pm$ efficiency (Solenoidal Trap)

* Straightforward → 5×10^{11} $\mu^\pm$/sec (Now!)
Future Upgrade → 5×10^{12} $\mu^\pm$/sec

BNL will produce + use 5×10^{11} $\mu^\pm$/sec in 2009!
As part of RSUP NSF project

3. MECO (Muon-Electron Conversion)

$\mu^- Al \to e^- Al$ $E_e = 106$ MeV (Clean + Distinctive)

Current PSI Bound $< 6 \times 10^{-13}$!
MECO → $< 5 \times 10^{-17}$! Discovery?

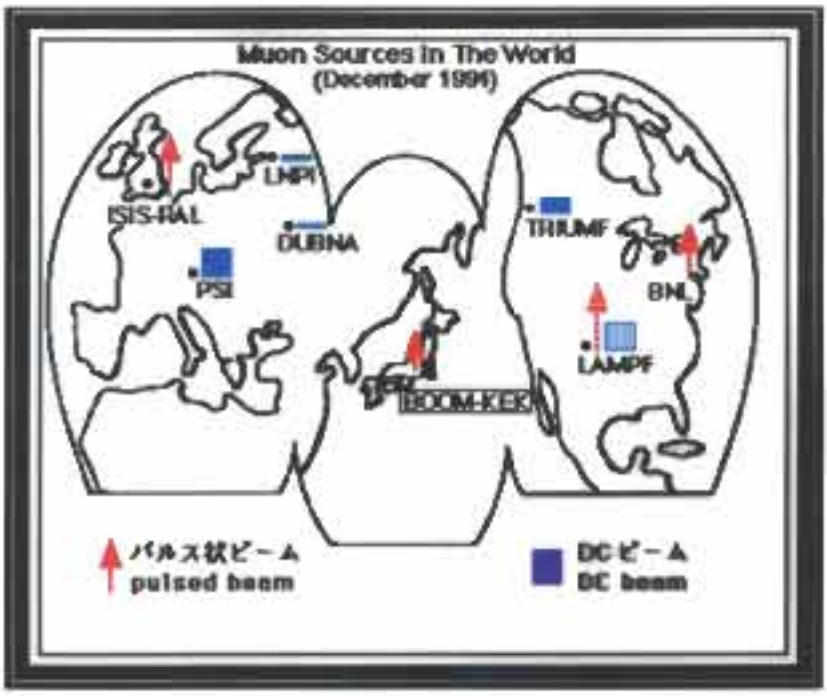
Solenoidal Capture $\sim 5 \times 10^{11}$ μ^-/sec
Stop $\sim 10^{11}$ μ^-/sec

MIT Conceptual Design
NSF Funded!
} Reality in 2008-2009!

BNL will have the world's most intense muon source!

From K. Nagamine

Muon Facilities



- **TRIUMF survey of muon beams**
- **Comparison of muon rates in various beamlines**
- **Mega beam line at LAMPF (now called LANCE)**

  This beamline has been decommissioned and may be available. Contactperson: Martin Cooper, 505-667-2929, mcooper@lanl.gov

  Three pages from the LAMPF Users Handbook.

  This beam was designed by Pat Thompson, now at BNL/RHIC, 516-344-7635.

  See, P.A. Thompson et al, 'The Stopped Muon Channel at LAMPF', NIM 161 (1979) 391-411.

- **BNL D Line**

  The "Gif image" includes the D2 muon channel

- **Muon beam lines at the Paul Scherrer Institute**

  1. μE1 beam line

  2. μE4 beam line

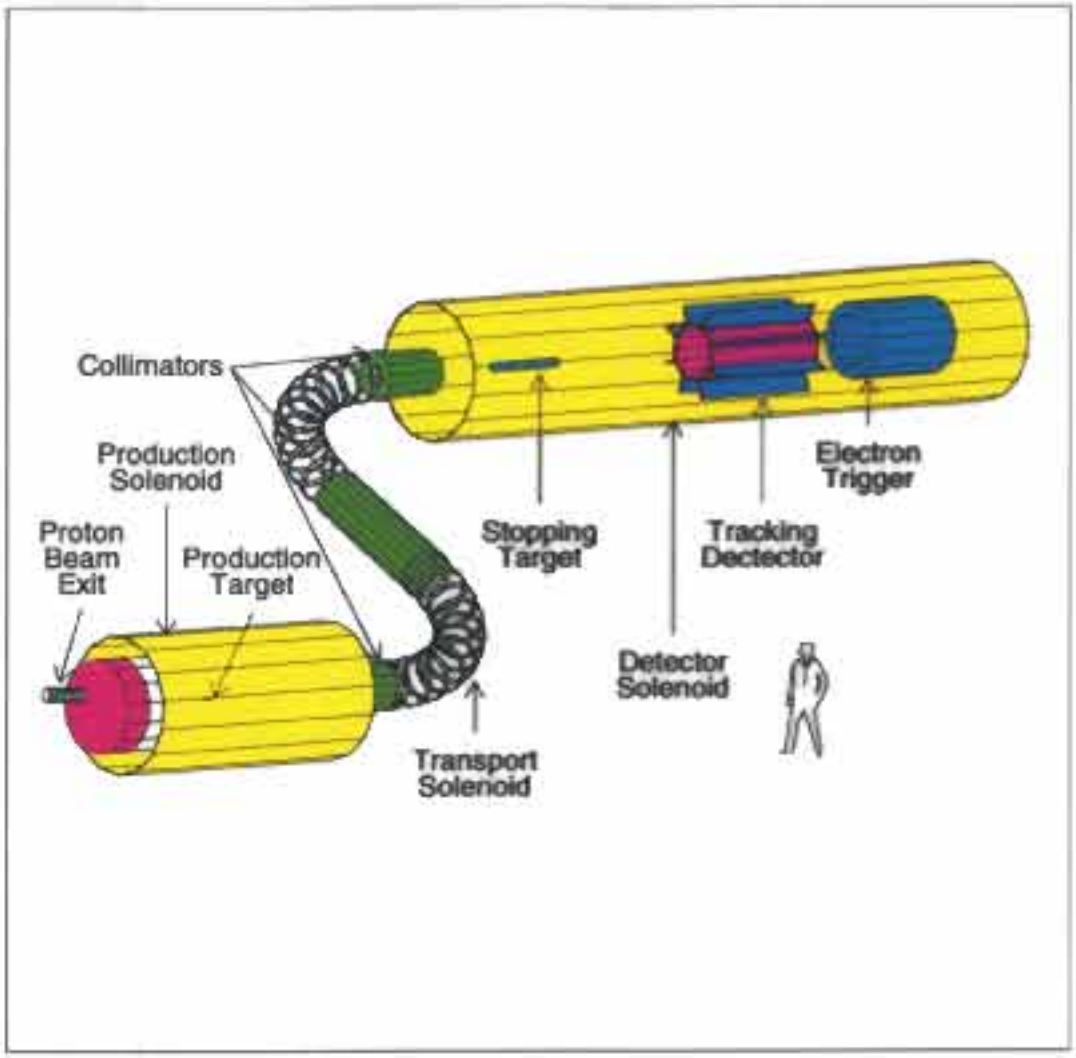


FIG. 31. Schematic layout of the MECO detector (provided by W.R. Molzon).

Features of the MECO Experiment

- **1000–fold increase in μ beam intensity over existing facilities**
  - High Z target for improved pion production
  - Axially-graded 5 T solenoidal field to maximize pion capture

- **Curved transport selects low momentum μ^-**
- **Muon stopping target in a 2 T axially-graded field to improve conversion e^- acceptance**
- **High rate capability electron detectors in a constant 1 T field**

4. Conceptual Intense Muon "Facility" (IMF)

Condensed Matter, Chemistry, Biology ....

Current μSR programs $10^5 \sim 10^6 \mu^+/sec$

Can they use $5 \times 10^{11} \mu^\pm/sec$?
Do they need $5 \times 10^{11} \mu^\pm/sec$?

Continuous Facilities $1/\tau_\mu = 1/2\times10^{-6} sec \simeq 500000 \mu/sec$
study $1 \mu^+$ at a time $\rightarrow 10^5/sec$

Don't need more in traditional uses
Biologists: "We don't use muons!"

* New Research Approaches + Opportunities
→ Fast Diagnostics

Make Ultra Slow Muons (0-10eV)
implant precisely, surface studies, nanoscience ...

i) Cold Moderator (eg solid Ar) → 2eV μ^+
efficiency $\lesssim 10^{-5}$
PSI ~ 200 slow μ^+/sec (Surface Studies)
eg Meissner Effect

ii) Mu (μ^+e^-) Formation → Slow, laser ionization → 0.2eV μ^+
ISIS → $O(1) \mu^+/sec$ using Tungsten K. Nagamine

Higher Efficiency ?

At BNL, we can make $> 10^5$ μ^+/sec ultra slow (easy ?)

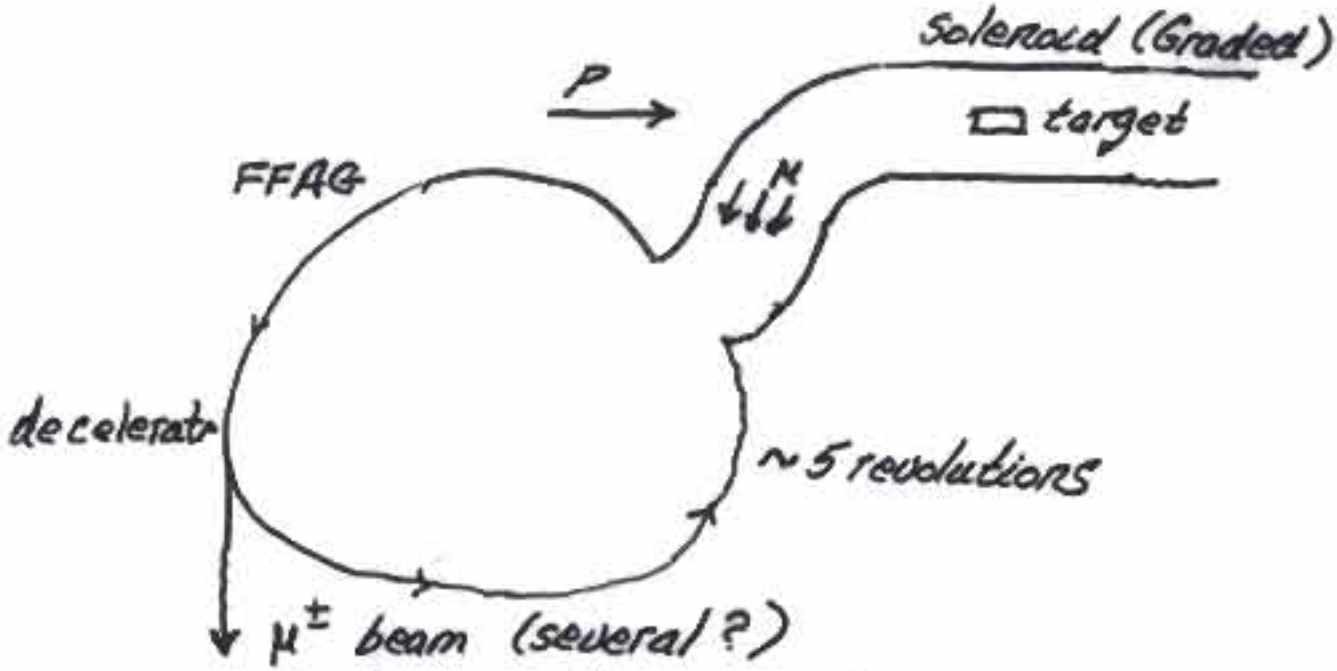
Many Research Opportunities

(Revolutionize Muon Physics)

Some Technical Issues:

Polarization (~20%) → 60% Momentum Selection

Momentum Spread
Beam Structure
Contamination
} FFAG (Fixed Field Alternating Gradient)
(KEK idea for JPARC)



small momentum spread
$> 10^{11}$ $\mu^\pm$/sec, 60% pol ~20MeV momentum, clean

Use MECO design + expertise + FFAG

What can you do with $10^{11}\ \mu^{\pm}$/sec ?
$10^{5} \sim 10^{6}$ ultra slow μ^{+}/sec ?

5. Some Applications (My Favorites)

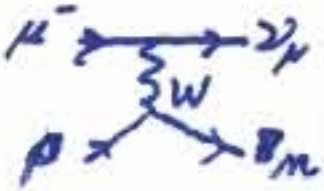
** i) 10^{5} ultra slow μ^{+}/sec : Surface Physics
(study mag. fields as a function of depth)
Nanoscience ~ probe nm scale at micro level
Small Samples (

ii) Muonium Implantation $\mu^{+}e^{-}$ replaces hydrogen $p^{+}e^{-}$

Use μSR to study e^{-} dynamics in biology
e^{-} transfer (K. Nagamine)
Chemical Reactions
(muon spin Resonance or Relaxation)

iii) μ^{-} Elemental Analysis

μ^{-} capture by heavy nucleus cascade → X rays (High E)
2p → 1s distinctive



reduces lifetime
$\sim Z^4$

Use X rays + μ^{-} lifetime (via e^{-} detection)
measure elements in samples (or Human Organ)

eg $2p \to 1s$ X-ray

Hydrogen 1.9 KeV
Aluminum 347 KeV
Lead 5782 KeV
etc.

} Identify relative abundances

Elements in Human Body (From K. Nagamine)

	(%)	μ^- Lifetime (μs)	$2p \to 1s$ X-ray (KeV)
C	23	2.026	755
N	2.6	1.907	102
O	61	1.795	133
P	1.1	0.611	458
Ca	1.4	0.333	786

eg Anomalous Al → "Problem" (Diagnostic Tool)

Archeology, Materials...

iv) μ^- Catalyzed Fusion

→ ^4He + n (14 MeV) + low energy μ^- + energy (17.6 MeV)

1 muon can do ~ 200 fusions!

Use 14 MeV neutrons ~ 10-100 × μ^- for fusion studies
Cold Muons!
Tritium Production
Other?

400 fusions → Scientific Break Even. 1000 fusions → Energy Source

Non Linear Enhancements?

Use low energy (slow) μ^- for biology (other?) Elemental Analysis
~10 keV

Use energy to heat the physics building!

Many Other Applications Possible
see
"Introductory Muon Science" by K. Nagamine
(Cambridge Press)

6. Outlook

Before the end of this decade, AGS will be producing
~5×10^{11} μ^+/sec for MECO $\mu^- Al \rightarrow e^- Al$
Major Discovery Possible!

10000x previous sensitivity!

MECO Brings Technical Expertise
* Solenoidal Design + Construction
Targetry
etc.

Already g-2 expertise at BNL

With > 1000 x muon flux, revolutionize μSR science
other applications
(life sciences?)

Build it and they will come (No Brainer!)

Road Map: ~2012 MECO Discovers $\mu^- Al \to e^- Al$ Detailed Study
or sets $< 5\times10^{-17}$ bound
proposal 10^{-19} sensitivity (upgrade 10^{13} μ/sec.

Proof: Very Intense Muon Sources Possible!

Several Intense Muon Sources (IMS) Proposals
$> 10^{12}\ \mu^\pm$/sec
BNL, FNAL (8GeV Linac 2MW)?, Darmstadt, *JPARC...

Complement: Light Sources, Neutrons (SNS), MRI
Nanoscience Centers

Other Fundamental Muon Physics: $\mu^+ \to e^+\gamma$, $\mu^+ \to e^+e^-e^+$
$\mu^+e^- \to \mu^-e^+$
μ edm

Neutrino Factory $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$
$E_\nu \simeq 20\text{-}50$GeV $\mu^- \to e^- \underbrace{\bar{\nu}_e \nu_\mu}$

Oscillations
Scattering
Map Earth's Interior
⋮
$\mu^+\mu^-$ Collider?

↓

A World of Muons μCF? Energy?

How Will We Know Muon Techology Rules?