Making Muons

Peter Baker
ISIS Pulsed Neutron and Muon Source

With thanks to James Lord for diagrams
Everyone’s local muon source
Everyone’s local muon source

- Muons made 15km above Earth’s surface
- Flux ~ 1 cm\(^{-1}\)min\(^{-1}\)
- Energy ~ 4 GeV
- Stopping range ~ 20 m
- Distribution of directions
- No polarization
Everyone’s local muon source

- Muons made 15km above Earth’s surface
- Flux $\sim 1 \text{ cm}^{-1}\text{min}^{-1}$
- Energy $\sim 4 \text{ GeV}$
- Stopping range $\sim 20 \text{ m}$
- Distribution of directions
- No polarization
- Useful for a limited number of samples!
Making Muons
(in a useful manner)

Peter Baker
ISIS Pulsed Neutron and Muon Source
What do we want?

1. Positive or negative muons
2. Low contamination with other particles
3. Muons hitting the sample
4. Muons stopping in our sample (well-defined and suitable energy)
5. Few muons missing the sample
6. High spin polarization (if needed)
7. Useful time structure for experiment
8. Lots of muons!
How do we get it? (Plan of talk)

- Particle accelerators
- Muon production targets
- Getting the muons to the sample
  - Focussing
  - Bending
  - Selecting the right particles
  - Manipulating the beam
- Planning and designing
- Monitoring to check it works
- Future possibilities
PARTICLE PHYSICS AND PARTICLE ACCELERATORS
Pion production – physics

**Lower energy**
- Single pion production
  - \( p^+ + p^+ \rightarrow p^+ + n + \pi^+ \)
  - \( p^+ + n \rightarrow p^+ + p^+ + \pi^- \)
- Needs \( E_p > 280\text{MeV} \)
- Maximum production \( 500\text{MeV} < E_p < 1\text{GeV} \)
  - MuSIC: 392MeV
  - TRIUMF: 520MeV
  - PSI: 590MeV
  - ISIS: 800MeV

**Higher energy**
- Double pion production
  - \( p^+ + p^+ \rightarrow p + p + \pi^+ + \pi^- \)
- Needs \( E_p > 600\text{MeV} \)
- Production increases up to \( E_p \sim 1.5\text{GeV} \)
  - J-PARC: 3GeV
Particle accelerators

Cyclotrons (quasi-continuous)

Synchrotrons (pulsed)
Muon sources of the world

ISIS, Oxfordshire, UK

MuSIC, Osaka, Japan

TRIUMF, Vancouver, Canada

Paul Scherrer Institute, Zurich, Switzerland

J-PARC, Ibaraki, Japan
## Continuous and pulsed beams

<table>
<thead>
<tr>
<th></th>
<th><strong>Continuous</strong> (e.g. PSI)</th>
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</thead>
<tbody>
<tr>
<td><strong>Beam structure</strong></td>
<td>Effectively DC (structure $\ll \tau_\mu$)</td>
</tr>
<tr>
<td><strong>Counting system</strong></td>
<td>Each muon counted in, each positron counted out</td>
</tr>
<tr>
<td><strong>Rate limit (time-differential)</strong></td>
<td>When two muons in sample ($\sim 20$ million/hour)</td>
</tr>
<tr>
<td><strong>Integral counts</strong></td>
<td>Just count positrons with 100% duty factor</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>If second muon not detected ($\text{Measure to } \sim 5\tau_\mu$ without tricks)</td>
</tr>
<tr>
<td><strong>Small samples</strong></td>
<td>Can use veto counters to exclude muons missing sample</td>
</tr>
<tr>
<td><strong>Frequency range</strong></td>
<td>Limited by detectors and electronics (500MHz $\rightarrow &gt; 10$GHz)</td>
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<table>
<thead>
<tr>
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<th><strong>Pulsed</strong> (e.g. ISIS)</th>
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<tbody>
<tr>
<td><strong>Beam structure</strong></td>
<td>Pulse $\ll \tau_\mu$, spacing $\gg \tau_\mu$</td>
</tr>
<tr>
<td><strong>Counting system</strong></td>
<td>Average start time from accelerator, count positrons</td>
</tr>
<tr>
<td><strong>Rate limit (time-differential)</strong></td>
<td>A few counts per detector per pulse ($\sim 150$ million/hour)</td>
</tr>
<tr>
<td><strong>Integral counts</strong></td>
<td>Always gives time-differential signal with 0.01% duty factor</td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>Mostly cosmic rays ($\text{Measure to } &gt; 12\tau_\mu$ routinely)</td>
</tr>
<tr>
<td><strong>Small samples</strong></td>
<td>Either collimate or use ‘fly-past’</td>
</tr>
<tr>
<td><strong>Frequency range</strong></td>
<td>Limited by pulse width ($\sim 10$MHz)</td>
</tr>
</tbody>
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MUON PRODUCTION TARGETS
Muon Production Targets – I

- Material: Low atomic number and high melting point
  - High atomic number gives more neutrons by spallation and more scattering of the beam
- Usually Graphite, sometimes Beryllium
- Beams and therefore targets are in vacuum
- ISIS target heated to ~600°C, cooling by conduction to the edge and radiation
- Rotating targets necessary for effective cooling at higher power sources (see next slide)
- Most protons (> 95%) pass through with little energy loss, so can be used to make neutrons
Muon Production Targets – II

PSI rotating wheel

J-PARC rotating wheel
Different pion decays – I

- “Surface” muons from pions at rest (in the production target)
  \[ p_\mu = 27 \text{MeV/c} \quad E_\mu = 4 \text{MeV} \]

- “Forward” muons from pions in flight
  \[ p_\mu > p_\pi \quad \text{High energy} \]

- “Backward” muons from pions in flight
  \[ p_\mu < p_\pi \quad \text{High energy} \]
Different pion decays – II

• “Surface” muons from pions at rest (in the target)
  - Muons decay into the beamline
  - Muons collected in one direction are 100% polarized
  - Allows for simple beamline design but limits thickness of windows (and other material) before the sample
  - Final spin polarization >95%

• “Forward” and “Backward” muons from pions in flight
  - Needs a more complicated and lengthy beamline (£/CHF/$/¥)
  - Choice of momentum can be made for experiments allowing pressure cells etc. to be used
  - Negative muons available
  - Final spin polarization ~ 80%
BEAMLINE COMPONENTS
Simplest possible beamline

- Main problem – low muon flux
- Other problems – other particles transmitted and high radiation level at the sample

Production target
Evacuated beam pipe (muons would scatter and stop in air)
Slits to define spot
Sample
Add focussing

- Really needs more than one lens
  - First lens close to the source to capture large solid angle
  - Last lens close to the sample to give a small beam spot
- Still transmits many other particles – poorly focussed if they have the wrong momentum
- Neutrons still go through
  - Unless blocked on axis
Electromagnetic lenses

Quadrupoles (£)
- No deflection on axis
- Focussing (x) and defocussing (y)
- Therefore need doublets or triplets

Solenoids (£££)
- Able to focus both axes simultaneously
- Can also be built with bends for steering
Focussing with quadrupoles

- Doublets give different x and y magnification
- Triplets preserve image shape
Adding corners

- Use dipole magnets to bend the beam
- Removes wrongly/uncharged particles
- Momentum slit used to pick range of momenta transmitted to the sample
- Combining two dipoles and quadrupoles can give an achromatic beam
- Still lets other particles through if they have the same momentum and charge
Cleaning the beam – Separator

- Magnetic parts of the beamline only select momentum
- Need to separate surface muons (p=27 MeV/c, v=0.24c) from positrons with p=27 MeV/c (but v ≈ c)
- Use perpendicular E and B fields chosen to balance forces for particles with correct velocity

\[ F_{\text{mag}} = B \, q \, v \]
\[ F_{\text{elec}} = E \, q \]

\[ m^+ \rightarrow \gamma \rightarrow e^+ + \bar{\nu}_e \]

\[ \text{Beam} \]
Spin rotation – I

- Muons going round a magnetic bend:
  - Deflected by: $\theta = dB\gamma e / p$
  - Spin precession of: $\phi = B\gamma t = dBge / 2p$
  - Exact match for $g = 2.0$, but muon $g = 2.00233$
  - Spin follows momentum unless there are many turns (like muon storage rings used to measure $g-2$)

- Electrostatic deflection leaves the spin unchanged but rotates the momentum
  - ISIS kicker gives $4^\circ$ horizontal spin rotation for EMU and HiFi
Spin rotation – II

- A separator with crossed electric and magnetic fields rotates the spin without changing the momentum
  - ISIS separator gives 6° rotation (vertical)
- Using higher fields and/or longer path length gives bigger rotation
  - Ideal case is 90°, but diminishing returns beyond 70°
  - Useful for higher transverse fields because muons enter the sample along the field direction
  - Rotation of ~45° allows simultaneous measurement of longitudinal and transverse relaxation rates
Controlling spot size

**Local collimation**
- Lead near instrument
- Need to stop muons and their decay positrons from hitting detectors

**Remote collimation**
- Metal slits at a focal point earlier in beamline
- Positrons can’t reach detectors
Dealing with pulsed beams

- Synchrotrons like ISIS normally output pairs of proton pulses
  - ISIS separation 330ns @ 50Hz (with 1 pulse in 5 missing)
- Separation normally less than muon lifetime so the spectra overlap, complicating data
- Need to separate pulses
Historical interlude

- Simplest way to separate pulses is to discard one
- This is how ISIS first did it (30 years ago)
- Device was called UPPSET (Uppsala, Pulse Eliminator and Trimmer)
- Removed the second pulse before it reached the MuSR instrument (then the only one)

A. I. Borden et al., Nucl. Inst. and Methods A 292, 21-29 (1990)
A modern kicker

- Why not throw away the pulse into instruments that can use it?

- ISIS south-side kicker is electrostatic
- RIKEN kicker is electromagnetic, better for high momentum muons
Other uses for kickers

Continuous source: Background reduction
- PSI have the MORE (muons on request) system to reduce background counts

Pulsed source: Increased frequency resolution
- ISIS and later J-PARC have demonstrated pulse slicing to narrow the muon pulses
Shutters for muons

- Being able to stop the muon beam is quite important
  - Safe sample changes
  - Not switching off the accelerator frequently
- Surface muons stopped by 5cm lead plates
  - Neutrons need ~1m of steel
- Also have interlock systems to prevent people meeting muons
Dai-Omega beamlines

Good:
Large solid angle capture (20x normal designs)
Very high beam intensity

Bad:
Complex and expensive
Lower polarization
Needs radiation-hard SC

e.g. H. Miyadera et al.,
PUTTING IT ALL TOGETHER
Beamlines for decay and surface muons

Figure from Jess Brewer
Examples from ISIS

South side (Surface muons only) North side (Surface/decay muons)
PLANNING AND DESIGNING BEAMLINES
Designing a beamline – I

- Use a program such as TRANSPORT to calculate focusing effect of elements – fairly quick calculation
- Plots beam envelope along beamline
Designing a beamline – II

- Use a ray-tracing program such as TURTLE to work out paths of individual muons
- Slower calculation but more realistic and able to provide flux at sample and where other muons stop
Designing a beamline – III

- Monte-Carlo simulation programs such as GEANT4 can calculate beam transport too
- Most computationally intensive
- Best suited to modelling individual components or special cases

* e.g. Modelling of PSI LEM beamline and implementing a spin rotator
BEAMLNE MONITORING
How to monitor your beamline

In the beamline itself

• Ideal case (£££) is measuring beam profile at several points
• Normally have some intermediate counters on slits or other apertures
• Tuning the beamline magnet currents and E-fields to see what comes out is most common way to work out how optimal the set-up is

At the instrument

• How many muons come out?
  – On big plate/small sample
• What shape is the beam?
  – Camera or reference samples
• How far do the muons penetrate?
  – Stopping in metal foils in front of haematite or quartz
• How big is the signal as a function of frequency?

These are routine activities at muon facilities
FUTURE POSSIBILITIES
How to do things better?

Pulsed sources
- Higher pulse frequency (~20kHz ideal vs ~50Hz)
- Pulse slicing to increase frequency resolution
- Higher solid angle beam capture for higher flux

Continuous sources
- Higher fluxes could give very small beam sizes for tiny samples (< mm)
- Tracking muons and positrons could beat the ‘1 muon at a time’ limit

Accelerators
- FFAGs and LINACs may provide better sources for muon production in future
Conclusions

• There are plenty of muons in the sky but you need a huge sample to use them

• Different sorts of particle accelerator are best suited to different sorts of muon experiment

• Transporting muons is well-understood and computer simulation can aid beamline design

• Plenty of scope for future improvements!