Muon facilities beyond particle physics

Rhea Stewart, ISIS Muon Group

Muon Collider Synergies Workshop, Orsay

23rd June 2023

Outline

1. Muon user facilities map – present and future
2. Core muon beam characteristics for condensed matter experiments
3. Different types of muon source: continuous and pulsed sources
4. The ISIS pulsed muon source
5. The muon spectroscopy technique
6. A selection of science highlights
7. Future development opportunities!

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OUP 2022

Muon Spin Spectroscopy, Nature Reviews Methods Primers
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Muons at ISIS, Phil. Trans. R. Soc. A, 377:20180064, Hillier et al

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1 Muon facility map – present and future

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2 Core muon beam characteristics for condensed matter studies

Typical energy ranges	low energy: (0.5 - 30)keV, surface: ~4MeV, and decay: (15 – 60)MeV
Charge	μ^+ and μ^- beams
Flux	10^6-10^8 $\mu^+ s^{-1}$
Spin polarisation	~ 100% for μ^+ and μ^- beams! (exceptions: elemental analysis and imaging)
Beam spot size	Typically, around (10 – 30)mm^{2*}

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ISIS Neutron and Muon Source

* can do better with collimation at the cost of flux. This is a major limitation for us.

Different types of muon source – continuous and pulsed

Continuous Sources
(e.g. PSI & Triumf)

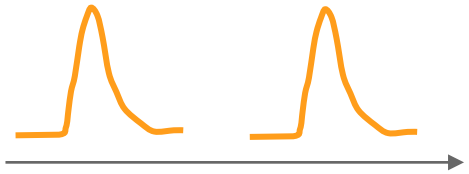
- Single muon at a time, rate limited
- Fast relaxations, rapid precession
- Higher intrinsic background
- Compact detector arrays

Existing low energy muon facility for surface and interface studies

Pulsed Sources
(e.g. ISIS & J-PARC)

- Bursts of muons (10s Hz, 50μs spacing)
- Weak relaxations, slow precession
- Lower intrinsic background
- No fundamental rate limit in time differential measurements
- Big detector arrays

Pulsed environments



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ISIS Neutron and Muon Source

Good complementarity, with many experiments making use of both.

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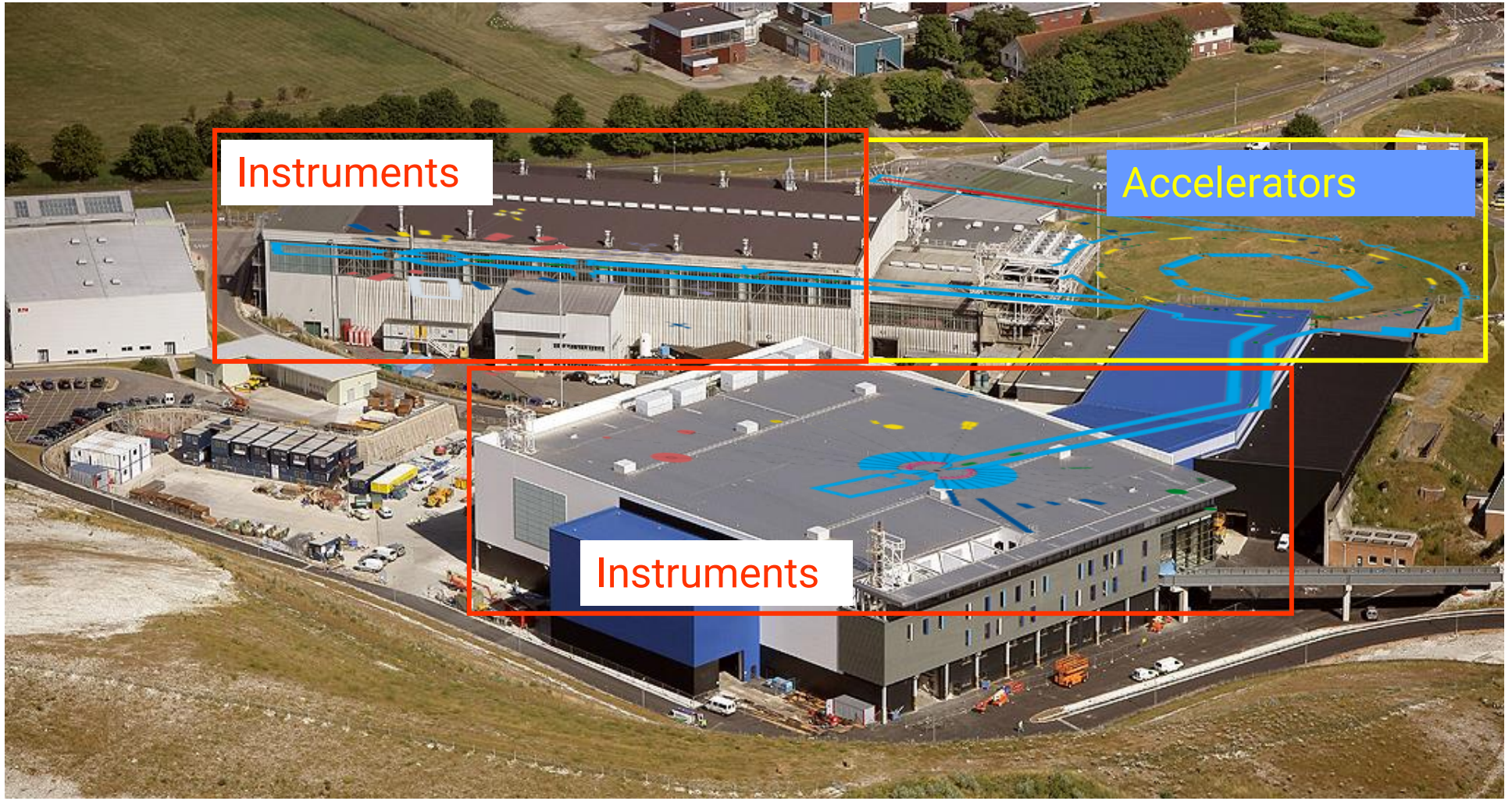

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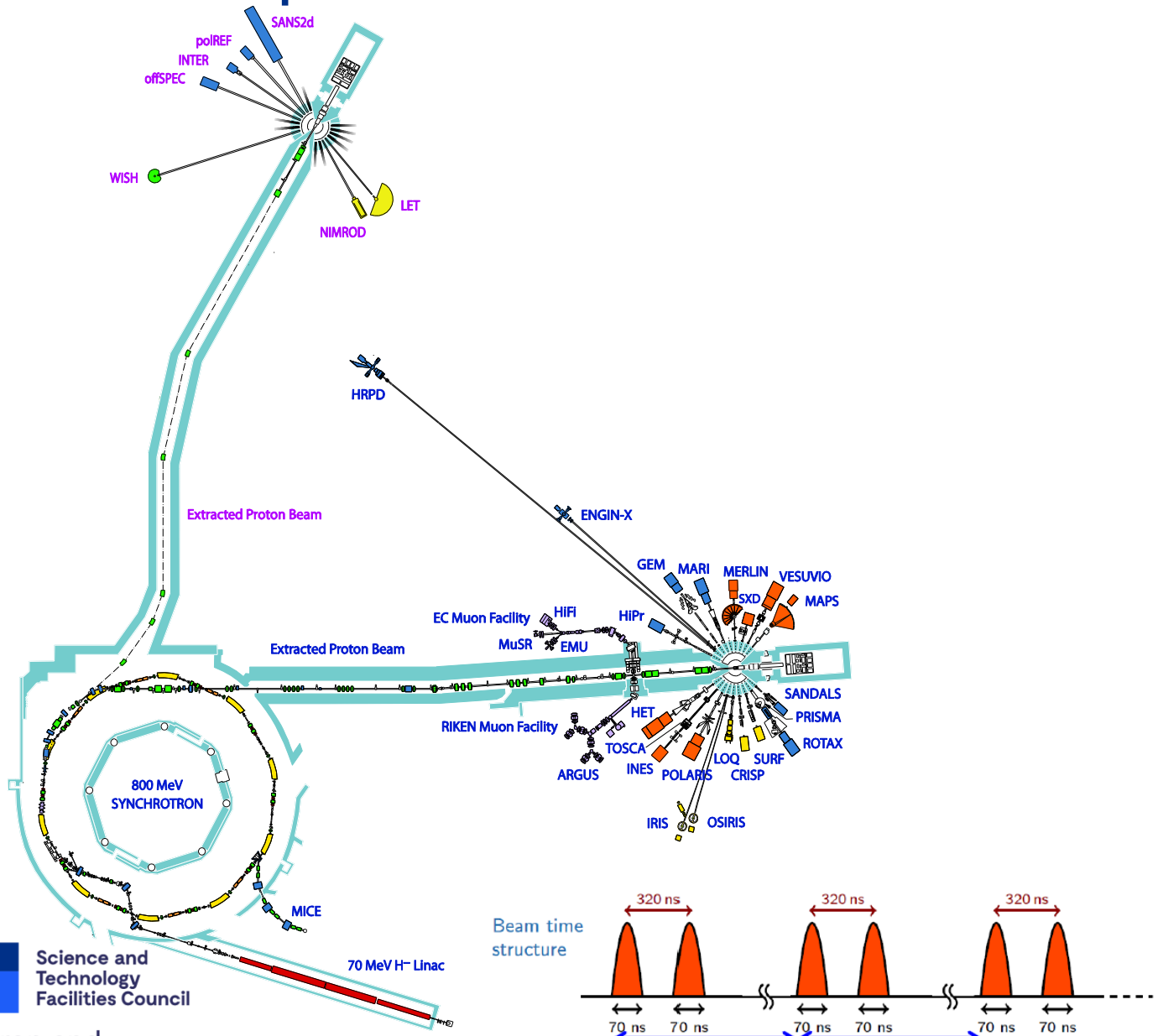
ISIS Neutron and Muon Source

A World Centre for Condensed Matter Science with Neutrons and Muons
Typical year: 1200 experiments, 3000 visitors, 30 countries, 600 publications

The ISIS pulsed neutron and muon source



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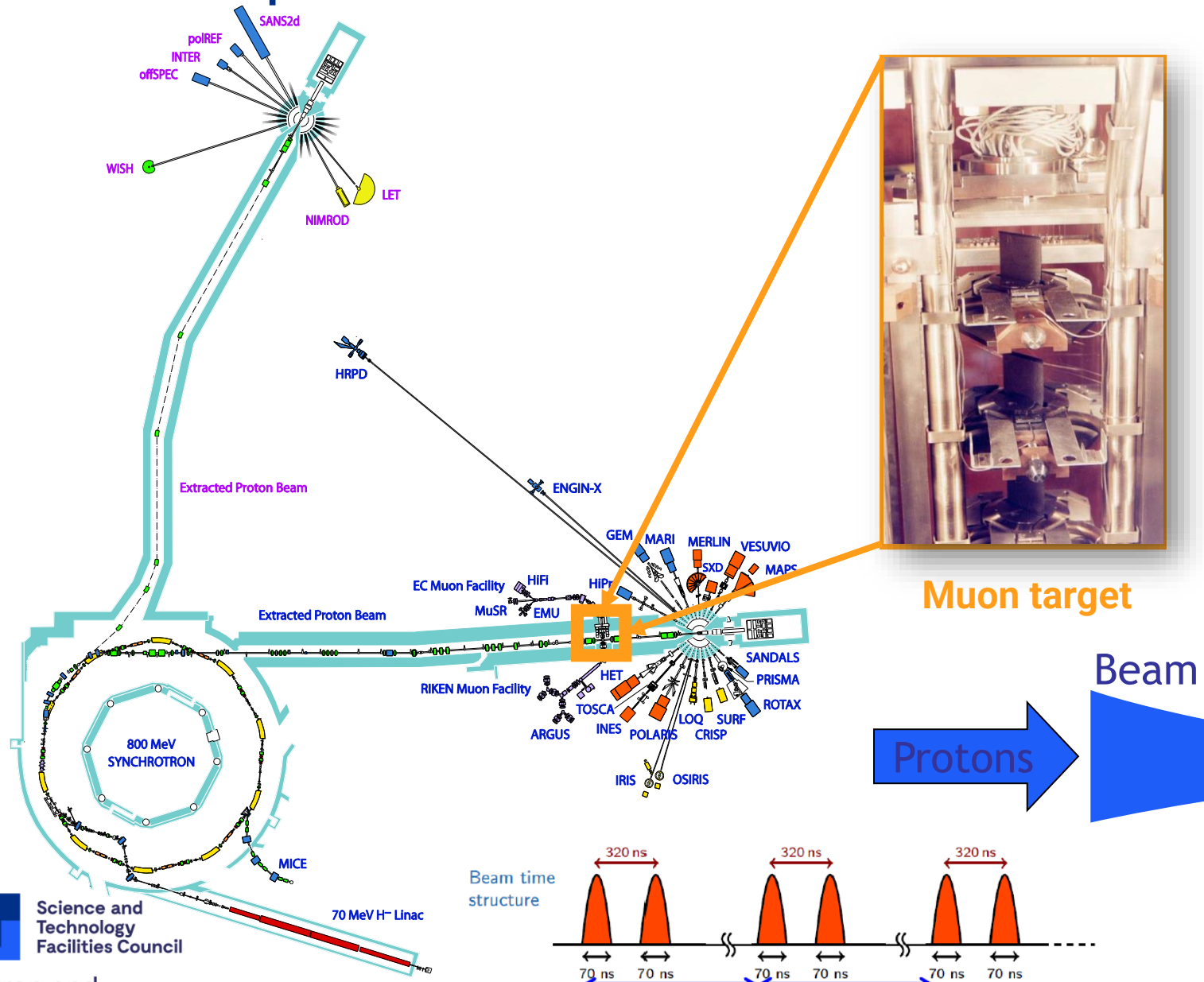
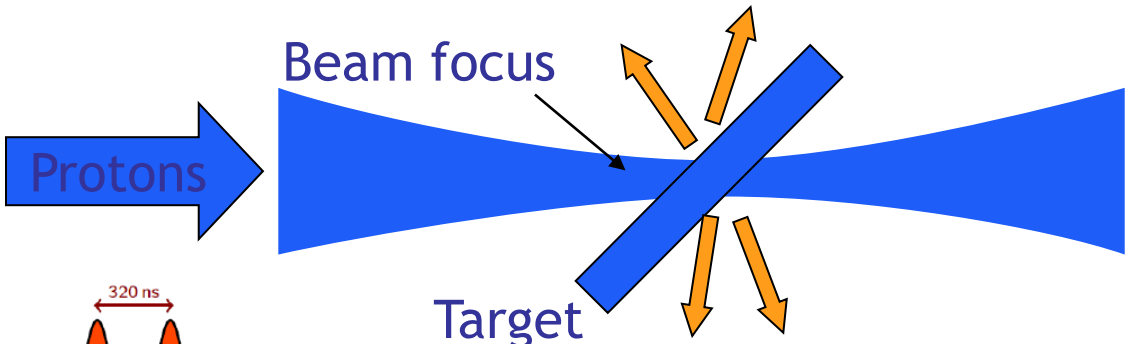
ISIS Neutron and Muon Source

The ISIS pulsed neutron and muon source



Muon target

- Graphite target
- Takes ~5% of the proton beam



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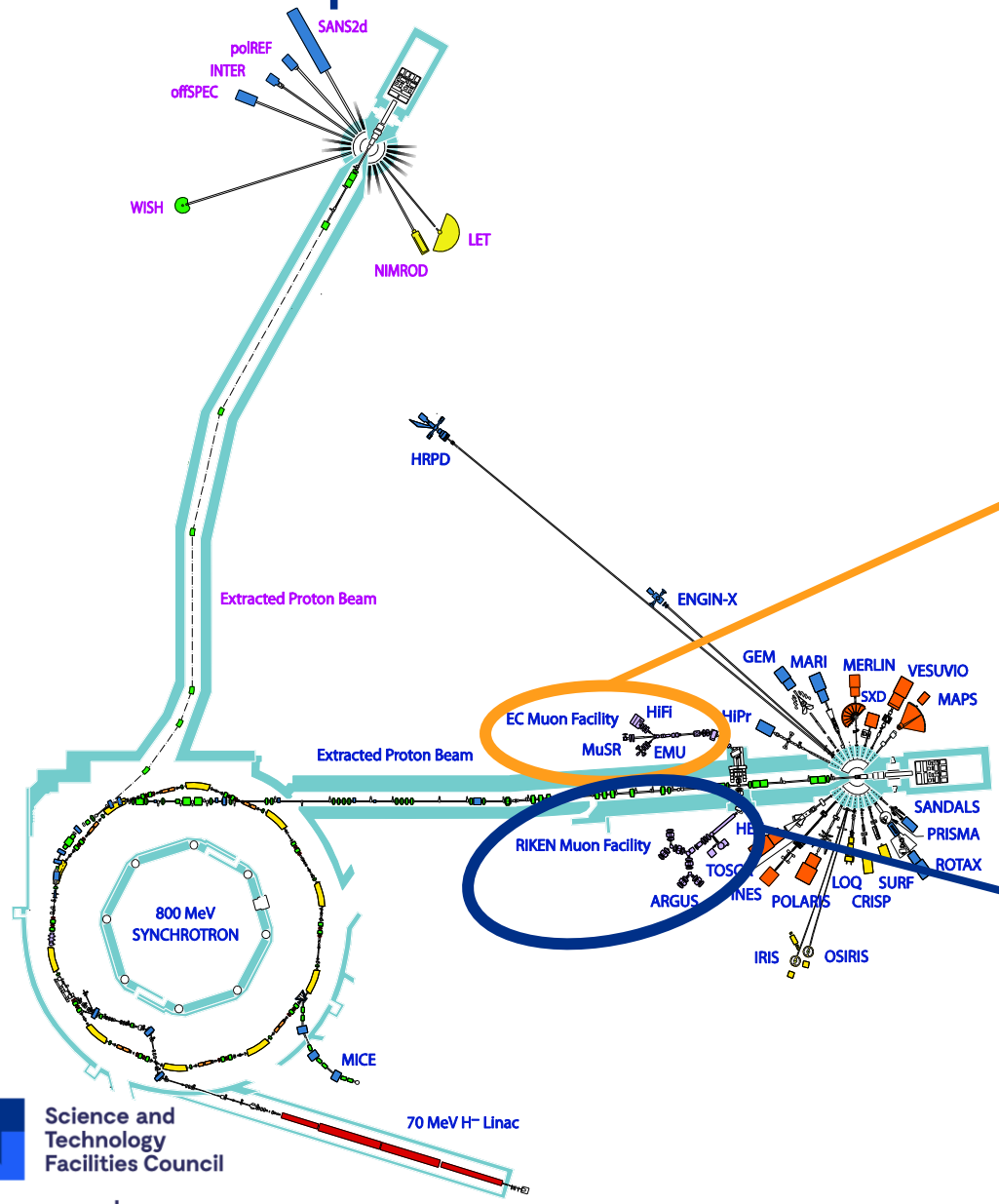
ISIS Neutron and Muon Source

The ISIS pulsed muon source – our instruments



EC muons (EMU, MUSR & HIFI)

Surface Muon beam
100% spin polarised
Fixed momentum ~27 MeV/c
Pulses split between beamlines

RIKEN-RAL(CHRONUS, ARGUS & MuX)

Decay Muon beam
Positive or negative muons
Spin polarised
Variable momentum ~15- 120 MeV/c
Pulses can be split between beamlines

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5 The muon spectroscopy technique – the muon lifecycle

1 Pion production: high energy protons collide with C nuclei in graphite target.

2 $\pi^+ \rightarrow \mu^+ + \nu_\mu$
muons are 100% spin polarised

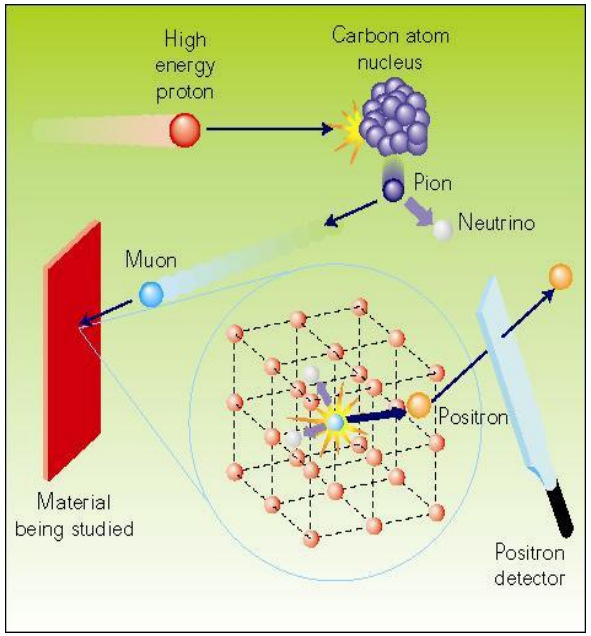
3 Implantation,
surface muons -> 0.1-1mm
and LE ->10-100nm.

4 Muons interact with local magnetic environment

5 Decay, lifetime 2.2μs
$\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$
we detect the decay positrons

6 **The positrons are preferentially emitted in muon spin direction**

7 Measure the positron distribution to determine the muons' polarisation in time. Learn about the muons' local environment or the muon behaviour itself.



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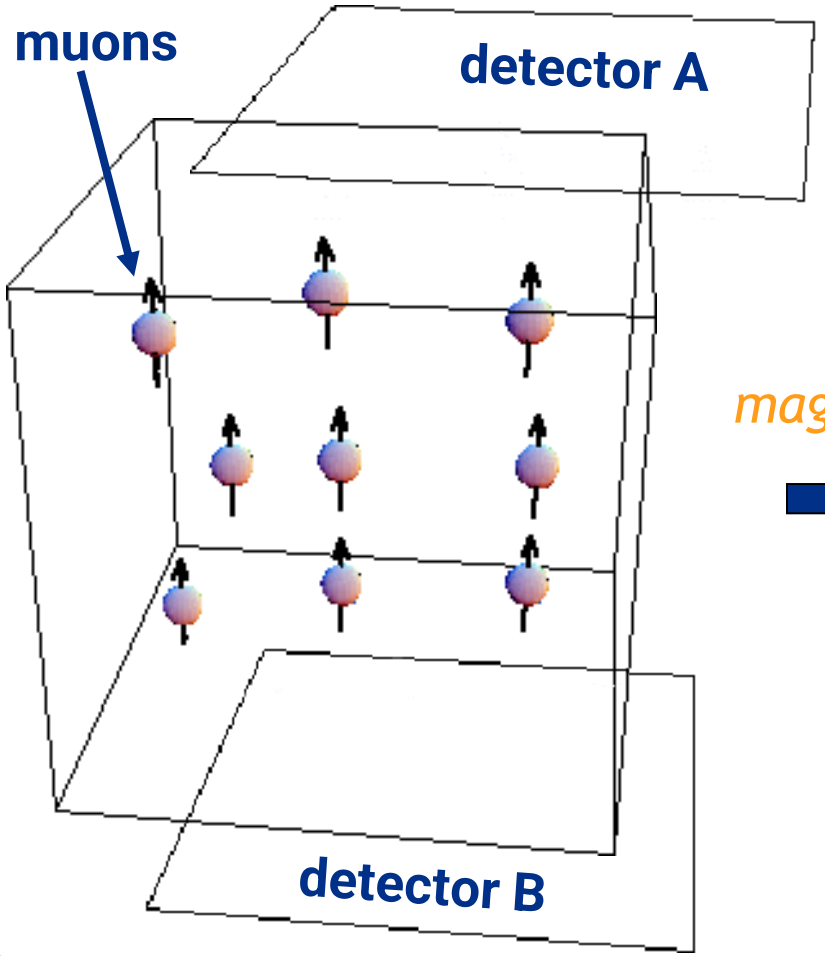
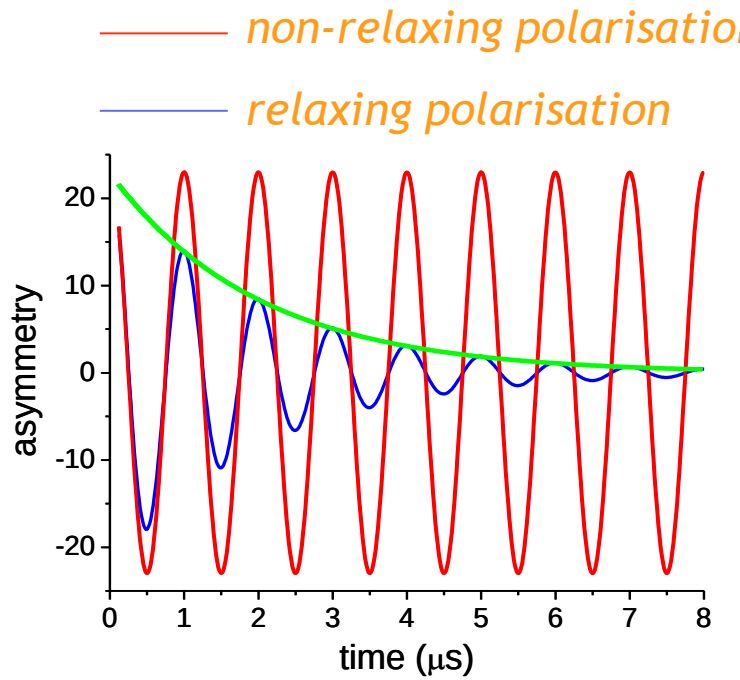
The muon spectroscopy technique



magnetic field

‘asymmetry’ (t)

$$= \frac{N_A(t) - N_B(t)}{N_A(t) + N_B(t)} = a_0 G_x(t) \cos(\omega t)$$



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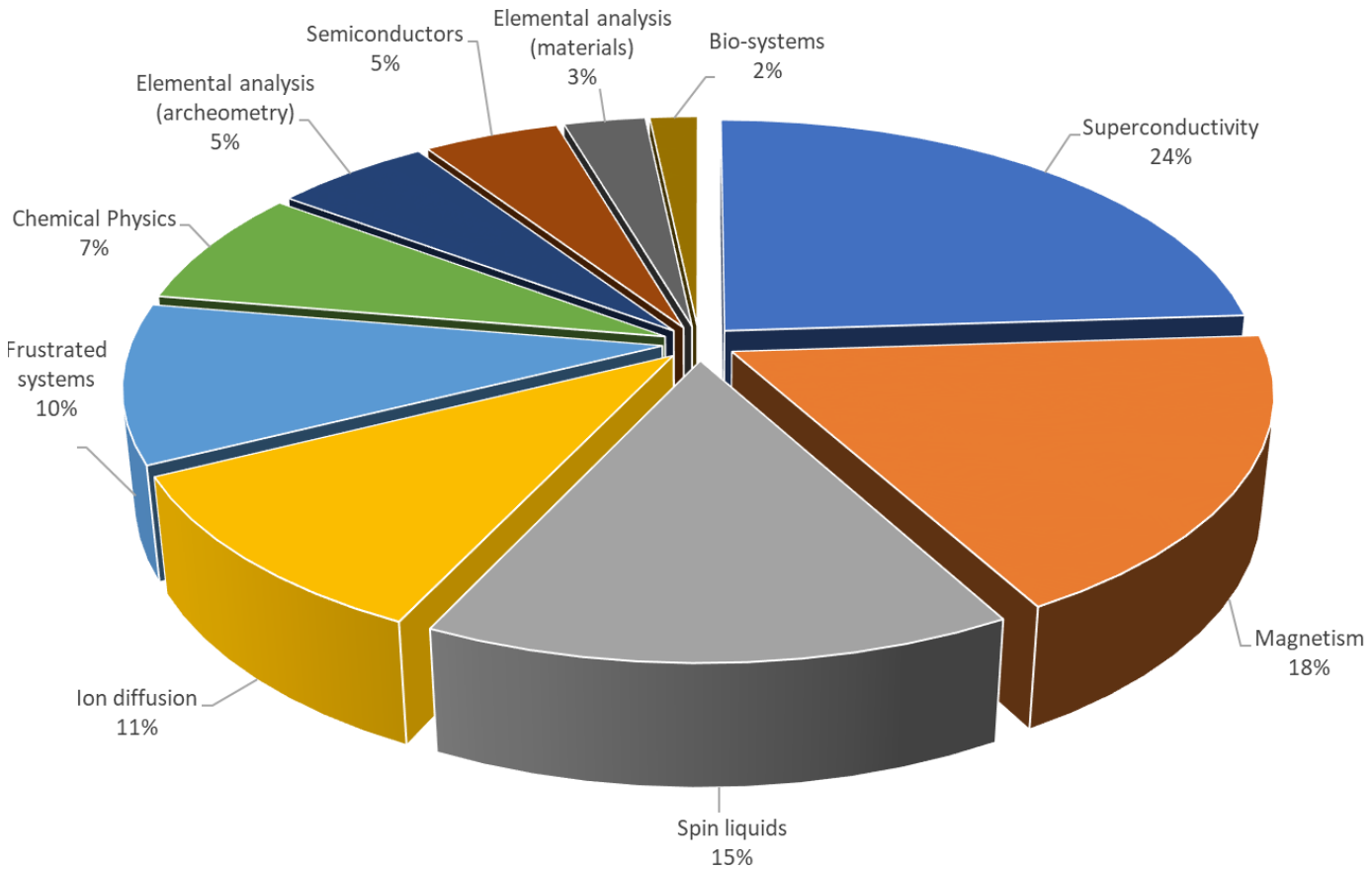
Science highlights – science supported



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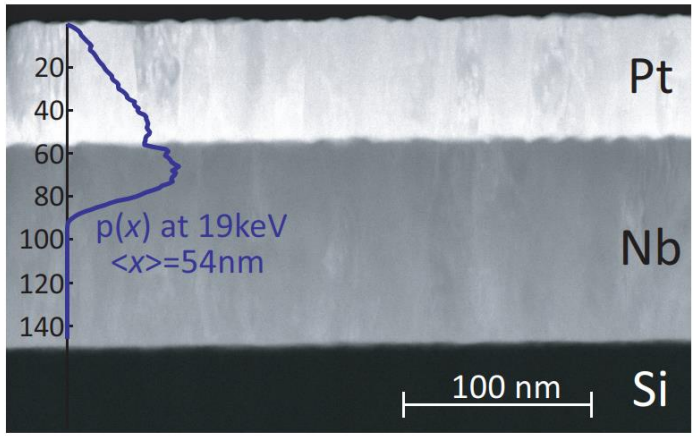
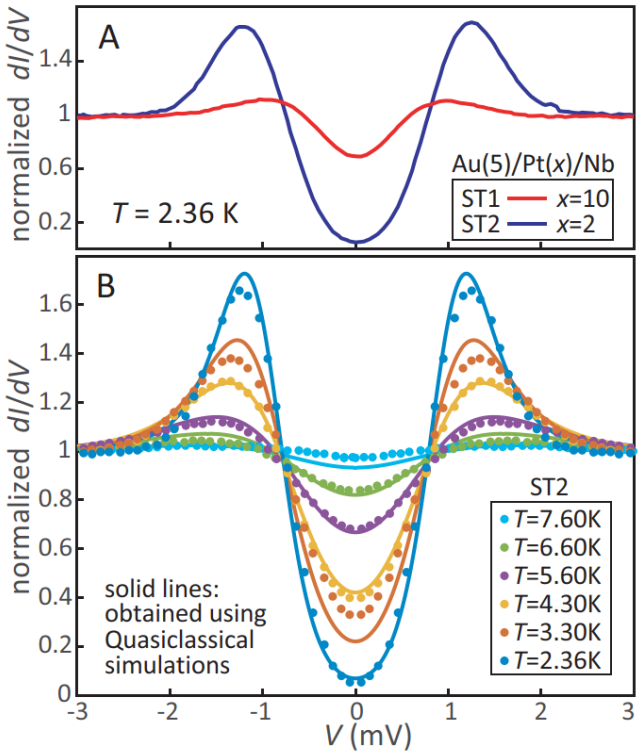
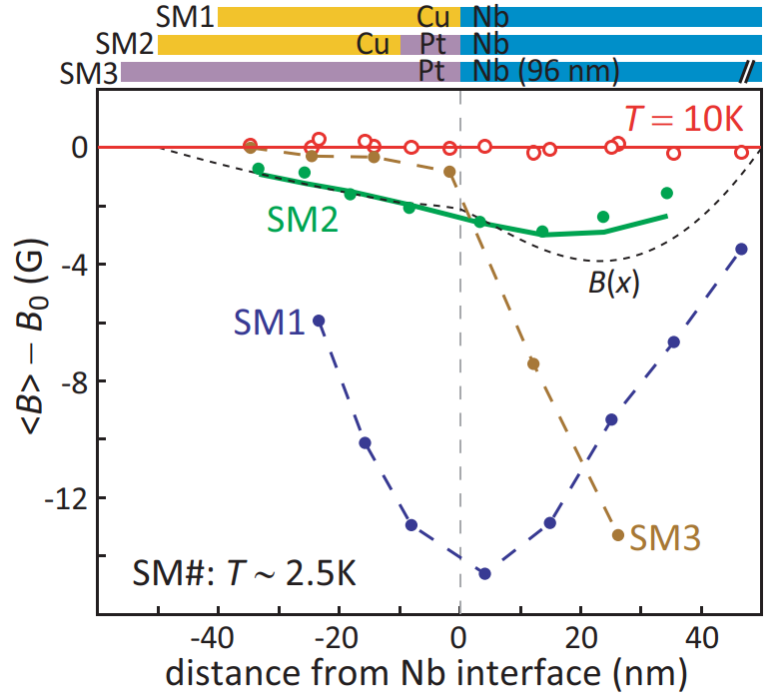
ISIS Neutron and Muon Source

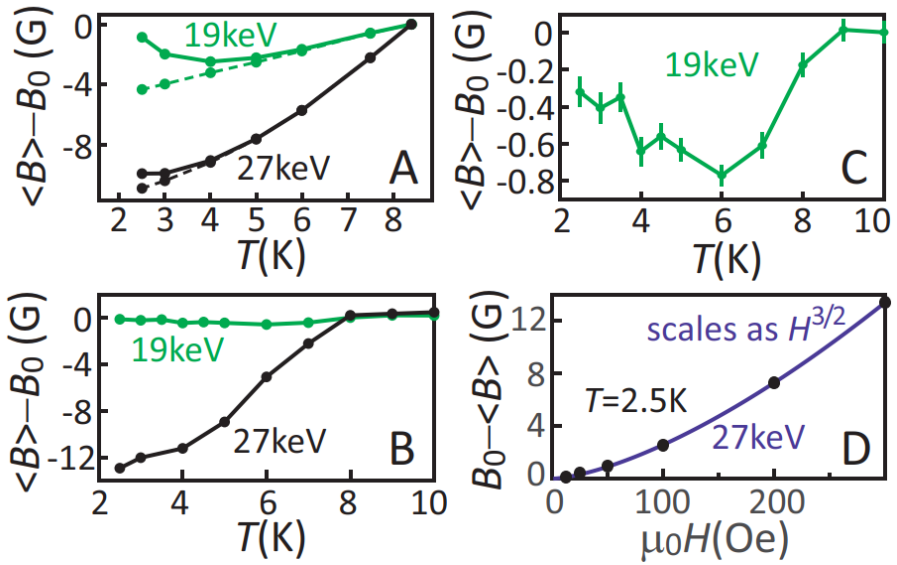
Breakdown of proposals for muon beamtime as a total for Rounds 19/2, 20/1, 22/2, 23/1

6 Science highlights I – thin film superconductors







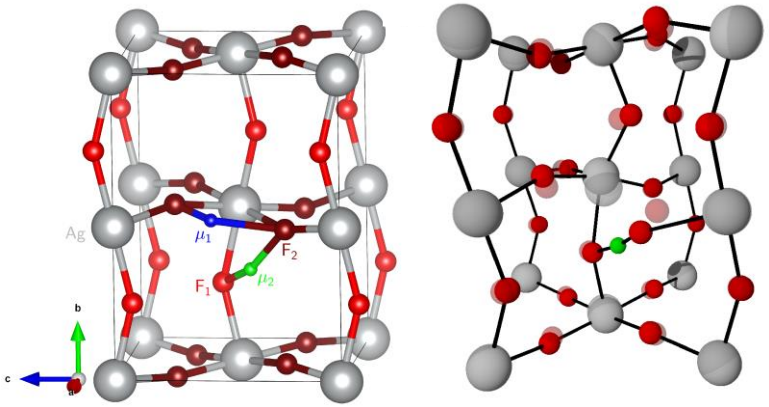


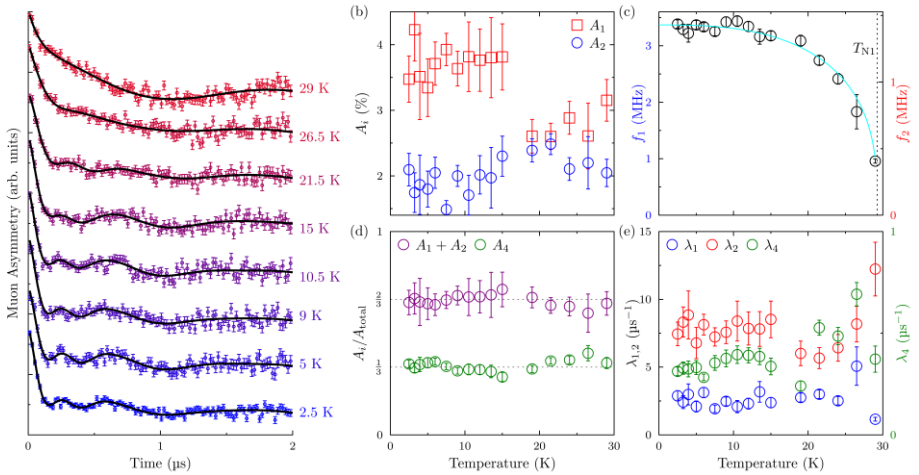
Unconventional superconducting states induced by spin-orbit interaction at the Pt/Nb interface.

Only possible to uncover this physics using low energy muons!

Submitted to Nature Communs. (2023)

6 Science highlights II – $KAgF_3$: Using F--μ--F states to measure magnetic materials

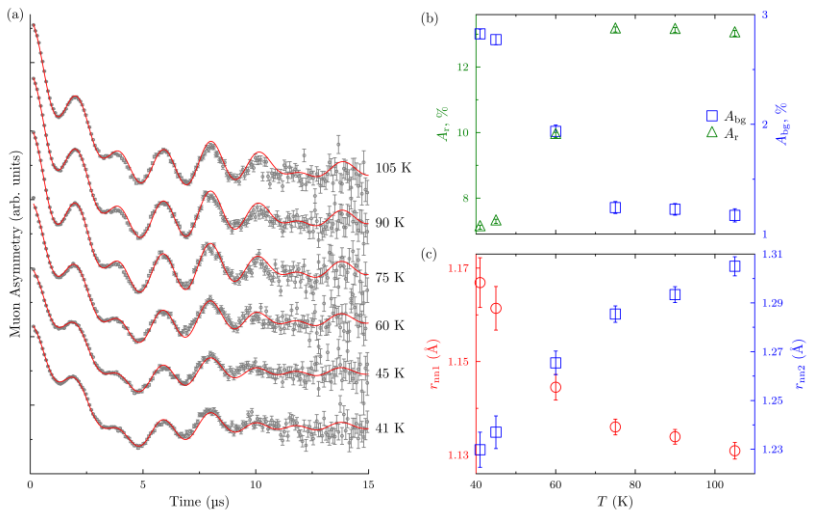


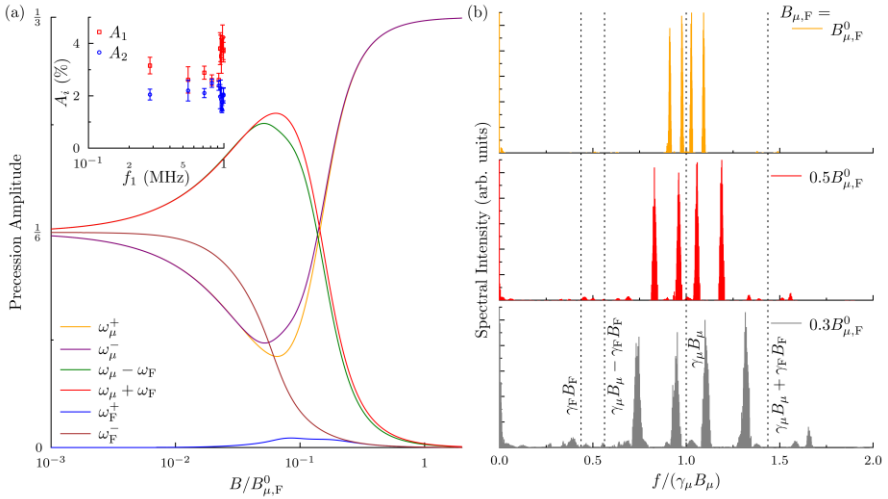


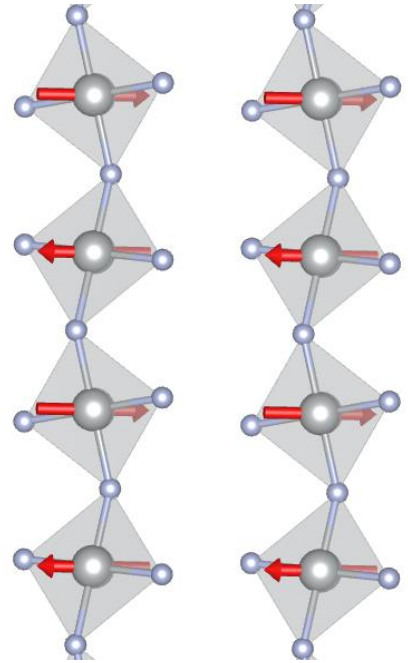
Discover an A-type AFM structure with $\mu_{Ag} = 0.47\mu_B$

Use F--μ--F states above T_c and DFT to find the muon site

Use magnetic oscillations to find the magnetic structure below T_c

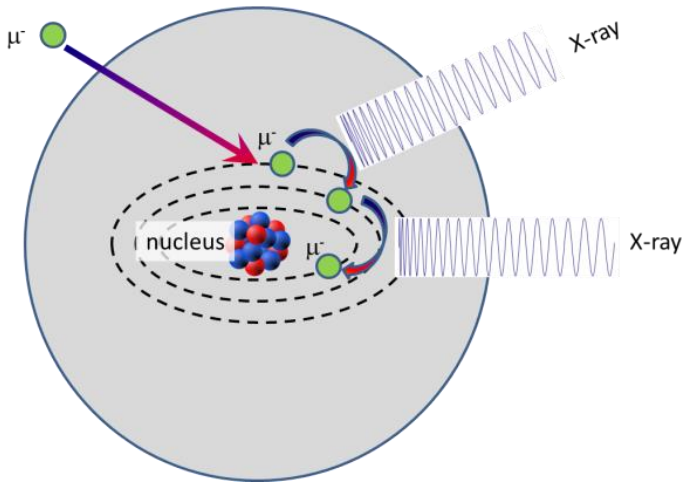






J. M. Wilkinson et al., PRB **107** 144422 (2023)

Science highlights III – elemental analysis in cultural heritage

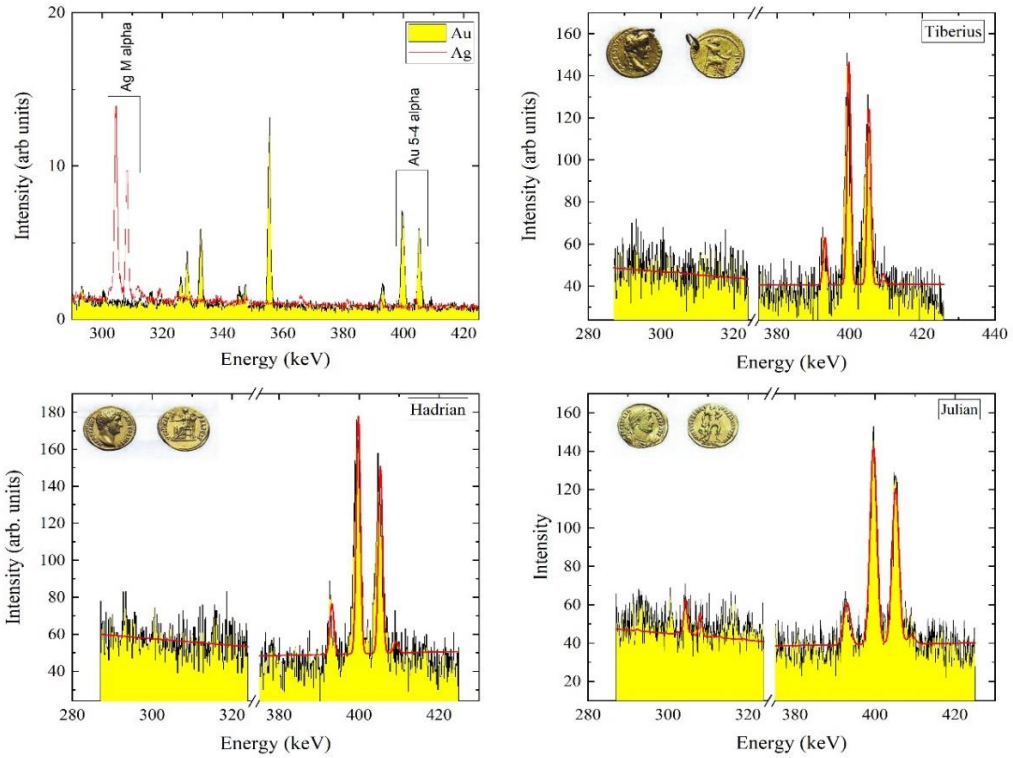


μ- captured by nuclei

transition energies atom dependent

can be compared to known spectra to find composition

non destructive,
penetrating,
variable
implantation depth



Green et al, J. Arch Sci (2021)

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7 Future development opportunities

Source and beam developments

- More intense beams
- High repetition rate pulsed sources
- Improved target design to increase muon/ pion yield
- Improved muon extraction (polarised and unpolarised)
- Higher energy beams for muon (and pion) imaging
- Highly collimated beams for imaging and to measure smaller samples
- More low energy muon facilities

Instrument developments

- Si pixel detectors, tracking detectors (muons in, positrons out)
- Bigger detector arrays
- Pulse slicing to increase/ cheat time resolution
- Digital signal processing of the raw event traces from detectors

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Super-MuSR as part of the Endeavour project at ISIS

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Probably many more. Any ideas?

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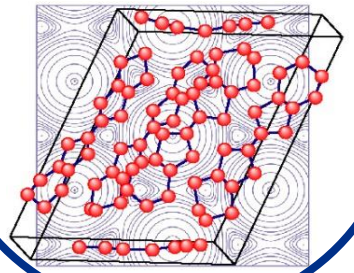
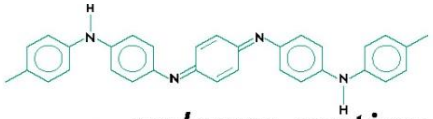
(Spin polarised) muons tell us a lot about a variety of condensed matter systems…

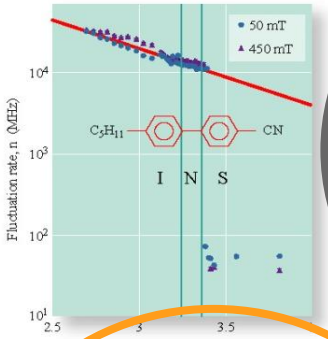
superconductors





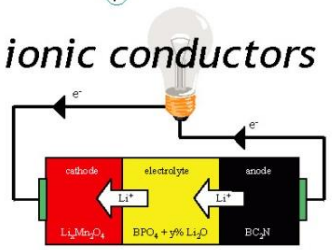
polaron motion

molecular dynamics

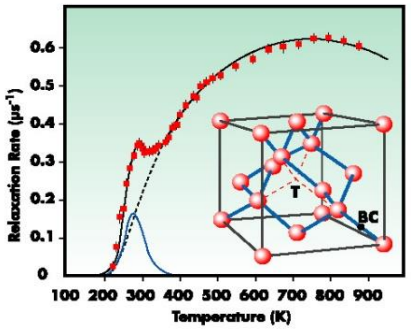


Elemental Analysis

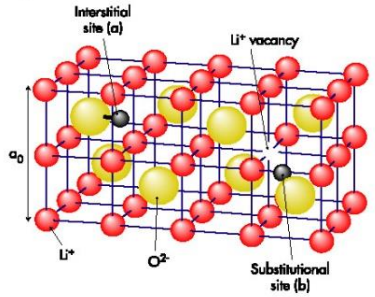
ionic conductors



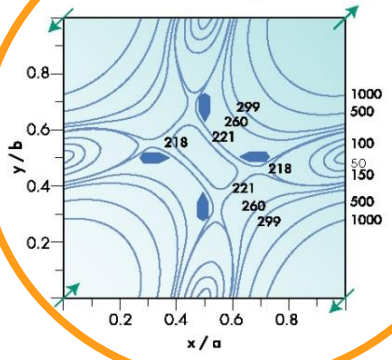
semiconductors



proton conductors



magnetism



Electronics Irradiation

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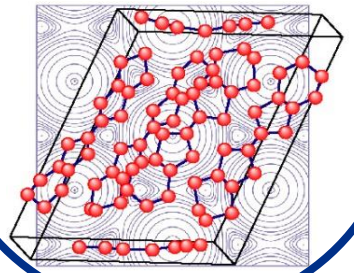

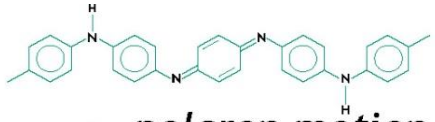

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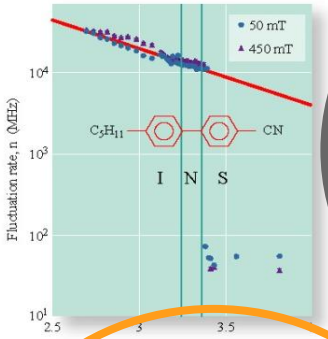
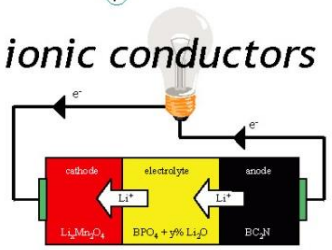
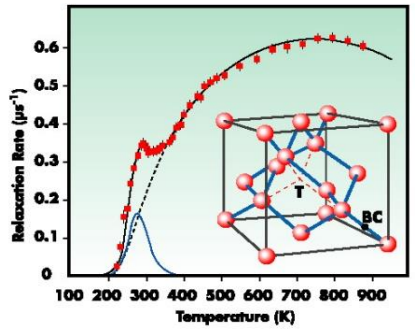


Elemental Analysis

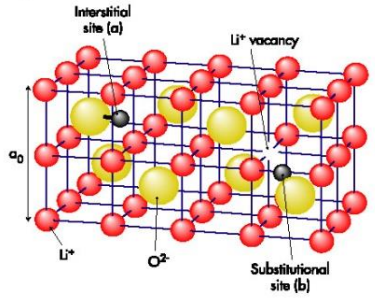
ionic conductors



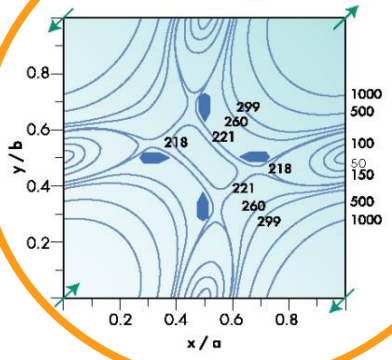
semiconductors



proton conductors



magnetism



Electronics Irradiation

…but they could tell us a lot more!

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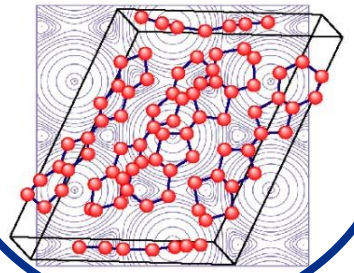
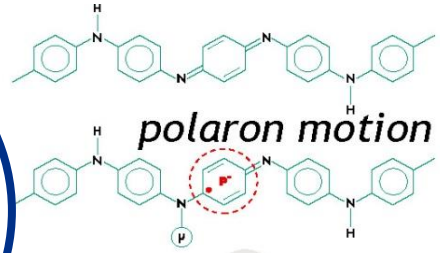
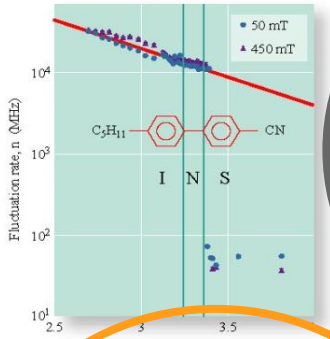




molecular dynamics



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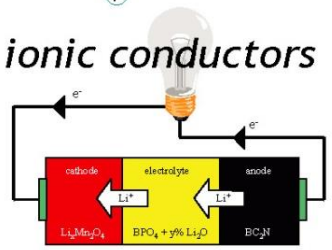
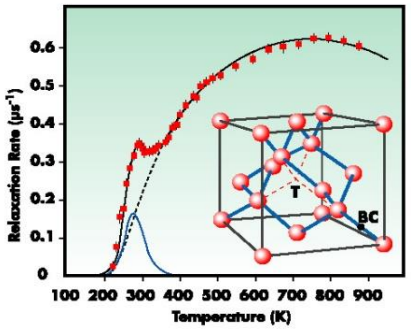
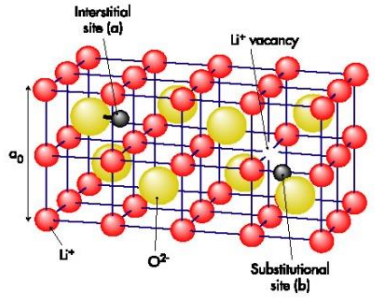


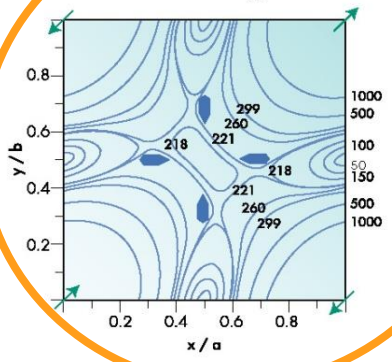
semiconductors



proton conductors



magnetism



Electronics Irradiation

…but they could tell us a lot more!

Science and Technology Facilities Council

ISIS Neutron and Muon Source

Thank you!