Muons are unstable elementary particles that are found in space, and which can also be produced with a billion times that intensity by particle accelerators. This book describes the various applications of muons across the spectrum of the sciences and engineering.

Scientific research using muons relies both on the basic properties of the particle and also the microscopic (at the atomic level) interaction between muons and surrounding particles such as nuclei, electrons, atoms, and molecules. Examples of research that can be carried out using muons include muon catalysis for nuclear fusion, the application of muon spin probes to study microscopic magnetic properties of advanced materials, electron labeling to help in the understanding at the microscopic level of electron transfer in proteins, and nondestructive elemental analysis of the human body. Cosmic-ray muons can even be used to study the inner structure of volcanoes.

This fascinating summary of muon science will be of interest to physicists, materials scientists, chemists, biologists, and geophysicists who want to know how what has come to be known as the particle of the twenty-first century can be used in their areas of research.
Introductory Muon Science

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# Contents

Preface  
List of abbreviations  

## What are muons? What is muon science?  
1. Basic properties of the muon  
   1.1 Mass of the muon  
   1.2 Lifetime of the muon  
2. Muons in the current picture of particle physics  
3. Fundamental interactions of the muon  
   3.1 Electromagnetic (EM) interaction  
   3.2 Weak interaction  
4. Production and decay of polarized muons  
   4.1 Muon polarization in $\pi \mu$ decay  
   4.2 Asymmetry of electron/positron emission in muon decay  
5. Other fundamental muon physics  
6. Muons and muon sciences  

## Muon sources  
1. MeV accelerator muons  
   1.1 Continuous and pulsed muons  
   1.2 Muons from pion decay in flight  
   1.3 Surface positive muons  
   1.4 Cloud muons  
   1.5 Beam optics components for MeV muons  
2. eV–keV slow muons  
   2.1 Thermal Mu and the laser resonant ionization method for slow $\mu^+$ generation  
   2.2 Cold moderator method for slow $\mu^+$  
   2.3 Frictional cooling  
   2.4 $\mu$CF method for slow $\mu^-$  
3. Large acceptance advanced muon channel  

---

Preface  
List of abbreviations  

1 What are muons? What is muon science?  
   1.1 Basic properties of the muon  
      1.1.1 Mass of the muon  
      1.1.2 Lifetime of the muon  
   1.2 Muons in the current picture of particle physics  
   1.3 Fundamental interactions of the muon  
      1.3.1 Electromagnetic (EM) interaction  
      1.3.2 Weak interaction  
   1.4 Production and decay of polarized muons  
      1.4.1 Muon polarization in $\pi \mu$ decay  
      1.4.2 Asymmetry of electron/positron emission in muon decay  
   1.5 Other fundamental muon physics  
   1.6 Muons and muon sciences  

2 Muon sources  
   2.1 MeV accelerator muons  
      2.1.1 Continuous and pulsed muons  
      2.1.2 Muons from pion decay in flight  
   2.2 eV–keV slow muons  
      2.2.1 Thermal Mu and the laser resonant ionization method for slow $\mu^+$ generation  
      2.2.2 Cold moderator method for slow $\mu^+$  
      2.2.3 Frictional cooling  
      2.2.4 $\mu$CF method for slow $\mu^-$  
   2.3 Large acceptance advanced muon channel
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4</td>
<td>100 MeV–GeV decay muons and some advanced generation</td>
<td>36</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Monochromatic 230 MeV $\mu^+$ by $K^+$ decay at production target</td>
<td>36</td>
</tr>
<tr>
<td>2.4.2</td>
<td>100 GeV muon beam for the EMC experiment</td>
<td>36</td>
</tr>
<tr>
<td>2.5</td>
<td>GeV–TeV cosmic-ray muons</td>
<td>37</td>
</tr>
<tr>
<td>3</td>
<td>Muons inside condensed matter</td>
<td>40</td>
</tr>
<tr>
<td>3.1</td>
<td>Stopping muons in matter and polarization change</td>
<td>40</td>
</tr>
<tr>
<td>3.2</td>
<td>Behavior of muons in matter</td>
<td>48</td>
</tr>
<tr>
<td>3.2.1</td>
<td>Diamagnetic $\mu^+$</td>
<td>48</td>
</tr>
<tr>
<td>3.2.2</td>
<td>Paramagnetic muonium</td>
<td>49</td>
</tr>
<tr>
<td>3.2.3</td>
<td>$\mu^–$ Muonic atom</td>
<td>50</td>
</tr>
<tr>
<td>4</td>
<td>The muonic atom and its formation in matter</td>
<td>51</td>
</tr>
<tr>
<td>4.1</td>
<td>Basic properties of the ground state of muonic atoms</td>
<td>51</td>
</tr>
<tr>
<td>4.2</td>
<td>Muonic atom formation mechanism</td>
<td>55</td>
</tr>
<tr>
<td>4.3</td>
<td>Cascade transitions in muonic atoms</td>
<td>57</td>
</tr>
<tr>
<td>4.4</td>
<td>Nondestructive elemental analysis with muonic X-rays and decay electrons</td>
<td>60</td>
</tr>
<tr>
<td>4.5</td>
<td>Future directions of muonic atom spectroscopy</td>
<td>64</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Improving X-ray detection methods</td>
<td>64</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Bent crystal spectrometer</td>
<td>66</td>
</tr>
<tr>
<td>4.5.3</td>
<td>CCD method</td>
<td>66</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Cryogenic calorimeter</td>
<td>67</td>
</tr>
<tr>
<td>4.6</td>
<td>Exotic muonic atom systems</td>
<td>67</td>
</tr>
<tr>
<td>4.6.1</td>
<td>Muonic atom X-ray spectroscopy of unstable nuclei</td>
<td>67</td>
</tr>
<tr>
<td>5</td>
<td>Muon catalyzed fusion</td>
<td>69</td>
</tr>
<tr>
<td>5.1</td>
<td>Concept of muon catalysis of nuclear fusion</td>
<td>69</td>
</tr>
<tr>
<td>5.2</td>
<td>The experimental arrangements for muon catalyzed fusion</td>
<td>74</td>
</tr>
<tr>
<td>5.3</td>
<td>Fusion reaction in a small muonic molecule</td>
<td>74</td>
</tr>
<tr>
<td>5.4</td>
<td>Neutral muonic atom thermalization</td>
<td>79</td>
</tr>
<tr>
<td>5.5</td>
<td>Muon transfer among hydrogen isotopes</td>
<td>81</td>
</tr>
<tr>
<td>5.6</td>
<td>Formation of muonic molecules</td>
<td>82</td>
</tr>
<tr>
<td>5.7</td>
<td>Muon sticking and regeneration in the $\mu$CF cycle</td>
<td>89</td>
</tr>
<tr>
<td>5.7.1</td>
<td>Neutron method</td>
<td>90</td>
</tr>
<tr>
<td>5.7.2</td>
<td>X-ray method</td>
<td>90</td>
</tr>
<tr>
<td>5.8</td>
<td>Application to energy sources and neutron sources</td>
<td>93</td>
</tr>
<tr>
<td>5.8.1</td>
<td>A practical energy source using $\mu$CF</td>
<td>93</td>
</tr>
<tr>
<td>5.8.2</td>
<td>14 MeV neutron source using $\mu$CF</td>
<td>96</td>
</tr>
<tr>
<td>5.9</td>
<td>Present understandings and future perspectives</td>
<td>97</td>
</tr>
<tr>
<td>6</td>
<td>Muon spin rotation/relaxation/resonance: basic principles</td>
<td>100</td>
</tr>
<tr>
<td>6.1</td>
<td>Muon spin rotation</td>
<td>101</td>
</tr>
</tbody>
</table>
6.2 Muon spin relaxation
   6.2.1 Some details of zero-field relaxation functions
   6.2.2 Spin relaxation under longitudinal field: LF-µSR
   6.2.3 Longitudinal field decoupling of muonium (Mu)
   6.2.4 Level-crossing resonance (LCR)
6.3 Muon spin resonance
6.4 µ⁺SR, MuSR and µ⁻SR
   6.4.1 µSR of diamagnetic µ⁺: µ⁺SR
   6.4.2 µSR of paramagnetic Mu: MuSR
   6.4.3 µSR of bound µ⁻: µ⁻SR
6.5 Experimental methods of µSR: continuous vs pulsed
   6.5.1 Continuous µSR
   6.5.2 Pulsed µSR
6.6 Some details of µSR experimental methods
   6.6.1 Advanced muon spin rotation measurements
   6.6.2 Advanced longitudinal relaxation measurements
   6.6.3 Advanced muon spin resonance measurements
   6.6.4 Advanced LCR with continuous beam
7 Muon spin rotation/relaxation/resonance: probing microscopic magnetic properties
   7.1 Application of µSR to studies of the intrinsic properties of condensed matter
      7.1.1 Determination of the µ⁺ site in solids
   7.2 Hyperfine structure at interstitial µ⁺ and at bound µ⁻ close to the nucleus in ferromagnetic metals
      7.2.1 Hyperfine fields at interstitial µ⁺ in ferromagnets
   7.3 Probing critical phenomena and magnetic ordering in metal ferromagnets and heavy fermions
   7.4 Probing spin dynamics in random and/or frustrated spin systems
   7.5 Probing magnetism, penetration depth, and vortex states in high-$T_c$ superconductors
      7.5.1 Magnetism in high-$T_c$ superconductors
      7.5.2 Penetration depth and vortex states in high-$T_c$ superconductors
   7.6 Probing magnetic ordering in exotic magnetic materials
8 Muon spin rotation/relaxation/resonance: probing induced microscopic systems in condensed matter
   8.1 µ⁺ localization and diffusion in condensed matter
      8.1.1 µ⁺ diffusion in Cu (fcc) and other pure metals
      8.1.2 Mu diffusion in KCl and other ionic crystals
   8.2 Probing Mu/µ⁺ center in semiconductors and insulators
      8.2.1 Methods so far applied
# Contents

8.2.2 Muonium-like states in semiconductors 151  
8.2.3 Muonium in alkali halides 152  
8.3 Muonium radicals in chemical compounds 155  
8.4 Probing electron transfer in polymers and macromolecules: labeled-electron method 155  
8.4.1 Formation and decay of muonic radicals in conducting polymers 157  
8.4.2 Probing electron transfer in biological macromolecules: µSR life science 160  
8.5 Muonium chemical reaction 165  
8.5.1 Mu chemical reactions in gases 165  
8.5.2 Mu chemical reactions in aqueous solutions 165  
8.5.3 Mu chemical reactions in solids 165  
8.5.4 Mu chemical reactions on solid surfaces 166  
8.6 Paramagnetic µ⁻O probe 166  

9 Cosmic-ray muon probe for internal structure of geophysical-scale materials 170  
9.1 Penetration of cosmic-ray muons through large-scale matter 170  
9.2 How to obtain imaging of inner structure 174  
9.2.1 Determination of cosmic-ray muon path through the mountain 174  
9.2.2 Correction due to multiple scattering and range straggling 174  
9.2.3 Identification of the relevant cosmic-ray muons against backgrounds 176  
9.2.4 Some practical remarks 176  
9.2.5 Tomographic imaging 176  
9.3 Example of counter system and data analysis 177  
9.3.1 Analog three-counter system 177  
9.3.2 Segmented two-counter system 177  
9.3.3 Data-taking and analysis 178  
9.4 Results of feasibility studies 178  
9.4.1 Mt Tsukuba experiment 179  
9.4.2 Mt Asama experiment 179  
9.5 Prospects for volcanic eruption prediction 179  
9.6 Application to probing the interior of the earth and earthquake prediction 184  
9.7 Application to probing defects in large-scale industrial machinery 184  
9.8 Multiple scattering radiography with cosmic-ray muon 184  

10 Future trends in muon science 185  
10.1 Nonlinear muon effects 185  
10.2 Production of muonic antihydrogen and CPT theorem 187  
10.3 The $\mu^+\mu^-$ atom 188
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.4 Muonium free drop and lepton gravitational constant</td>
<td>189</td>
</tr>
<tr>
<td>10.5 Advanced neutrino sources with slow $\mu^+$</td>
<td>190</td>
</tr>
<tr>
<td>10.6 The $\mu^+\mu^-$ colliders with slow $\mu^+$ and $\mu^-$</td>
<td>193</td>
</tr>
<tr>
<td>10.7 Mobile TeV muon generator and disaster prevention</td>
<td>194</td>
</tr>
</tbody>
</table>

**Further reading**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>197</td>
</tr>
</tbody>
</table>

Index

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Index</td>
<td>199</td>
</tr>
</tbody>
</table>
Preface

Since the discovery of cosmic rays in 1940, elementary particle muons have become fascinating and exotic particles which can be objectives and/or tools for fundamental physics and applied science. In particular, after intense muons became available by using particle accelerators in 1960, the field of scientific research using muons has been growing year by year.

From the author’s viewpoint, three major unique features of muons have formed the basis of all muon-related scientific research: (1) unique mass, such as heavy electrons and light protons; (2) radioactivity with polarization phenomena; and (3) the electromagnetic interaction nature with matter without a strong interaction. These features have promoted the application of muons to: (1) muon catalyzed fusion for future atomic energy; (2) sensitive probes of the microscopic magnetic properties of new materials and biomolecules; and (3) radiography of a large-scale substance for preventing natural disasters, respectively.

The author made special efforts for this book to include a self-contained description of all physics principles required for muon applications. In these applications, we note that muons may be the key particles to provide answers to the basic problems associated with possible crises in human life in the twenty-first century, namely, a shortage of energy resources, the need for more information on the biological functioning of the human body, and the need to prevent natural disasters, such as volcanic eruptions and earthquakes. Complete descriptions are given of ways to apply elementary particle muons to these three major human problems. Instructions are also given to young scientists and/or students about how a basic understanding of fundamental physics can contribute to the growth of human life.

Thus, the academic disciplines of this book can be listed as follows:

1. atomic energy studies, particularly of fusion energy
2. condensed-matter studies of advanced materials
3. life science studies, particularly of the biological functioning of macromolecules
4. geophysical studies related to the prevention of natural disasters, such as volcanic eruptions and earthquakes

The most fundamental properties of muons $\mu^+$, $\mu^-$, and muonium (Mu) are described in Chapter 1 and the sources of muons from both accelerators and cosmic rays are given in Chapter 2, followed by the states of the muon in matter and the thermalization/formation process in Chapter 3. Then, in Chapters 4 and 5, the fundamental properties of muonic atoms and full descriptions of muon catalyzed fusion phenomena and their applications are given, respectively. Then, the subject changes to $\mu$SR (muon spin rotational/relaxation/resonance) spectroscopy, describing the principle in Chapter 6 and its probe nature of host materials as
Preface

an unperturbed probe in Chapter 7, where, because of the wide variety of activities, existing worldwide selected topics are limited to the author’s related field. The µSR studies concerning the active-probe nature for creating new microscopic systems follow in Chapter 8, including biological applications. The relatively young subject of cosmic-ray muon radiography is discussed in Chapter 9, followed by future directions from the author’s point of view in Chapter 10.

The author would like to express sincere thanks to the following people who contributed to the content of each chapter of this book including supply of beautiful figures before publication:

A. P. Mills, Jr, S. Chu, S. N. Nakamura, Y. Miyake, J. M. Poutissou, and K. Jüngmann (Chapter 1)
V. E. Storchak, H. Tanaka, and J. H. Brewer (Chapter 3)
L. I. Ponomarev, T. Koike, S. N. Nakamura, W. Kutschera, K. Sakamoto, M. Oda, and P. Strasser (Chapter 4)
T. Yamazaki, K. Nishiyama, N. Nishida, E. Torikai, J. H. Brewer, R. H. Kiefl, and A. Schenck (Chapter 6)
P. Bakule, Y. Miyake, K. Shimomura, and Y. Mori (Chapter 10)

Careful proof-reading by Drs J. M. Poutissou (Chapter 1), K. Ishida (Chapters 2 and 3), L. I. Ponomarev (Chapters 4 and 5), A. Schenck and T. P. Das (Chapters 6–8) and P. Bakule (Chapter 10) is acknowledged. Careful reading of the whole content with valuable comments and revision of English by Dr R. Macrae is also acknowledged. This work could only be completed with the help of the wonderful keyboard skills of Mrs H. Shiosaka, J. Ogata, S. Satoh, and J. Nakai, to whom the author would like to express his sincere thanks.

The author’s involvement in muon science research began in 1971. A special acknowledgment is given to Professor T. Yamazaki, who introduced me to the field of muon physics with his long-term collaboration and encouragement. The author’s research activities have been supported and encouraged by leading members of the institutions with which the author was associated, to whom sincere thanks are given: Professors T. Yamazaki, A. Arima, T. Nishikawa, H. Sugawara, Y. Kimura, the late M. Oda, S. Kobayashi, E. W. Vogt, and P. W. Williams.

Finally, the author thanks his late parents, Tadao and Masako Nagamine, to whom this book is dedicated.
Abbreviations

µCF  muon catalyzed fusion
µSR  muon spin rotation/relaxation/resonance
AF   antiferromagnetic phase
ALC  avoided-level crossing
bcc  body-centered cubic
BCS  Bardeen–Cooper–Schrieffer
BSCCO Bi$_2$Sr$_2$CaCuO$_{8+\delta}$
BNL AGS Brookhaven National Laboratory, Alternating Gradient Synchrotron
BNL  Brookhaven National Laboratory
CCD  charge-coupled devices
CCS-11 microprogrammed CAMAC processor
CERN European Organization for Nuclear Research
CERN SPS European Organization for Nuclear Research Super Proton Synchrotron
CFD  constant fraction discriminator
CPT  charge transformation, parity inversion, and time reversal
DMAC direct memory access
DSC  discriminator
EM   electromagnetic
EMC  European Muon Collaboration
ESR  electron spin resonance
ESS  European Spallation Neutron Source
fcc  face-centered cubic
FFAG fixed-field alternating-gradient synchrotron
FNAL-MI Fermi National Accelerator Laboratory–Main Injector
FTM  Fourier transformation
hcp  hexagonal close-packed
Hot W hot tungsten
HTCSC high-T$_c$ superconductors
HTF-µSR high transverse field–muon spin rotation
HV   high-voltage power supply
IPNS Intense Pulsed Neutron Source
List of abbreviations

IR interrupt register
ISIS-RAL ISIS–Rutherford Appleton Laboratory
JAERI-KEK Japan Atomic Energy Research Institute–High Energy Accelerator Research Organization
JINR Joint Institute for Nuclear Research
J-PARC Japan Proton Accelerator Research Complex
KEK-PS High Energy Accelerator Research Organization–12 GeV Proton Synchrotron
KEK High Energy Accelerator Research Organization
KEK-MSL High Energy Accelerator Research Organization–Meson Science Laboratory
LAMPF PSR Los Alamos Meson Physics Facility Proton Storage Ring
LAMPF Los Alamos Meson Physics Facility
LBL Lawrence Berkeley Laboratory
LCR level-crossing resonance
LF-\(\mu\)SR longitudinal field \(\mu\)SR
LFNC Lepton Flavor Non-conservation
LHD liquid hydrogen density unit
LHe liquid helium
LN\(_2\) liquid nitrogen
LSCO \(\text{La}_{1-x}\text{Sr}_x\text{CuO}_4\)
LTO low-temperature orthorhombic
LTT low-temperature tetragonal
MCP multichannel plate
MS TDC multistop time-to-digital converter
MuSR muonium spin rotation
NEQ nuclear electric quadrupole moment
NMR nuclear magnetic resonance
PIXE proton-induced X-ray element analysis
PM photomultiplier
PMT photomultiplier tube
PRISM Phase Rotated Intense Slow Muon Source
PSI Paul Scherrer Institute
QED quantum electrodynamics
r.f. radiofrequency
RAL Rutherford Appleton Laboratory
RIKEN-RAL Institute of Physical and Chemical Research–Rutherford Appleton Laboratory branch
SEC Secondary Enclosure Clean-up System
SIMS secondary ion mass spectrometry
SNS Spallation Neutron Source
TDC time-to-digital converter
TF-\(\mu\)SR transverse field muon spin rotation
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGHS</td>
<td>tritium gas-handling system</td>
</tr>
<tr>
<td>TRIUMF</td>
<td>Tri-University Meson Facility</td>
</tr>
<tr>
<td>TRIUMF-UBC</td>
<td>Tri-University Meson Facility–University of British Columbia</td>
</tr>
<tr>
<td>UHV</td>
<td>ultrahigh vacuum</td>
</tr>
<tr>
<td>UT-TRIUMF</td>
<td>University of Tokyo Group at TRIUMF</td>
</tr>
<tr>
<td>V-A theory</td>
<td>vector–axial vector interaction theory</td>
</tr>
<tr>
<td>VUV</td>
<td>vacuum ultraviolet</td>
</tr>
<tr>
<td>YBCO</td>
<td>YBa$_2$Cu$<em>3$O$</em>{7-\delta}$</td>
</tr>
<tr>
<td>ZF-(\mu)SR</td>
<td>zero external field-(\mu)SR</td>
</tr>
</tbody>
</table>