

CONTENTS

PREFACE.....	xv
ACKNOWLEDGMENTS.....	xxi

PART I. PRINCIPLES OF TRACK ETCHING

Chapter 1. Formation of Particle Tracks.....	3
1.1. Introduction.....	3
1.2. Procedures for Revelation of Tracks.....	4
1.2.1. Chemical Etching.....	5
1.2.2. Transmission Microscope Observation.....	5
1.2.3. Decoration Techniques.....	7
Development of Silver Chloride.....	7
Silver Precipitation in Glass.....	8
Iron Precipitation in Mica.....	8
Polymerization.....	9
1.2.4. Detection by Color Change.....	9
1.2.5. Detection with X-Rays.....	10
1.3. Nature of the Damage.....	10
1.3.1. Diameter of the Damaged Region.....	10
Electrical Measurements of Track Diameter.....	11
Stored Energy.....	16
1.3.2. Relative Thresholds for Detection.....	16
1.3.3. Activation Processes in Track Annealing.....	21
Significance of a Spectrum of Activation Energies.....	21

Significance of the Magnitude of Activation Energies	21
1.3.4. Range Deficits	22
1.4. Formation Mechanisms	23
1.4.1. General Description of Heavy Ion Energy Deposit in Solids . . .	24
Crystals and Glasses	26
Polymers	26
1.4.2. Unrealistic Mechanisms	27
Direct Atomic Displacements	27
Thermal Spike	27
Total Energy Loss	29
1.4.3. Possible Track Production Mechanisms	31
Ion Explosion Spike	31
Criterion for Atomic Displacements	33
Restrictions on Track Formation	35
Quantitative Etching Rate Relations	36
Other Ionization-Based Models	37
Secondary Energy Loss	37
Restricted Energy Loss	38
Primary Plus Secondary Damage	39
1.5. Problems and Future Work	39
References	42
 Chapter 2. Basics of Track Etching	 50
2.1. Track Geometry	50
2.1.1. Track Geometry for Constant v_T	50
2.1.2. Track Geometry for Varying v_T	52
2.1.3. Track Geometry for Anisotropic v_G	56
2.2. Etching Efficiency	57
2.2.1. Etching Efficiency vs. Registration Efficiency	60
2.2.2. Etching Efficiency for Anisotropic v_G	60
2.2.3. Etching Efficiency When v_T Varies	61
2.2.4. Prolonged Etching Effects	63
2.2.5. Counting Conventions	64
2.2.6. Effect of Heating	64
2.3. Etching Techniques and Recipes	73
2.3.1. Etches to Be Used for Particle Identification	75
2.4. Environmental Effects	77
2.4.1. Thermal Effects	77
2.4.2. Mechanical Effects	79
2.4.3. Chemical Effects	85
2.4.4. Electrical Effects	86
2.4.5. Photochemical and Irradiation Effects	87

2.4.6. Temporal Effects.....	90
2.5. Scanning Techniques.....	90
2.5.1. Enhancing Track Contrast.....	91
2.5.2. Track Location and Enlargement.....	93
2.5.3. Integrating or Automated Scanning Methods.....	95
2.6. Miscellaneous Special Techniques and Information.....	98
2.6.1. Measurements of Track Dimensions.....	98
2.6.2. Preparation of Replicas for Scanning Electron Microscopy (SEM).....	101
2.6.3. Sample Preparation for 4π Solid Angle Observations.....	103
2.6.4. Commercially Available Detectors.....	104
References.....	105
Chapter 3. Methods of Nuclear Particle Identification.....	119
3.1. Introduction.....	119
3.2. Experimental Problems.....	119
3.2.1. Plastic Detectors.....	120
3.2.2. Glass and Mineral Detectors.....	122
3.3. Particle Identification by Measurements of Etch Rate vs. Residual Range.....	123
3.3.1. Calibration with Beams of Known Ions.....	124
3.3.2. Range-Energy Relations.....	126
3.3.3. Response Curves v_T vs. J for Various Solids.....	127
3.3.4. Generation of Curves of v_T vs. R for All Ions.....	129
3.4. Relativistic Energies, $E \geq 1$ GeV/nucleon.....	131
3.5. Intermediate Energies, $10 \leq E \leq 1000$ MeV/nucleon.....	134
3.6. Low Energies, $0.1 \leq E \leq 10$ MeV/nucleon.....	136
3.7. Very Low Energies, $E \leq 0.1$ MeV/nucleon.....	139
3.8. Particle Identification by the Track Profile Method.....	144
3.9. Particle Identification by Measurements of Etch Pit Diameter....	146
3.10. Particle Identification by Measurement of Maximum Etchable Track Length.....	148
References.....	150

PART II. EARTH AND SPACE SCIENCES

Chapter 4. Fission Track Dating (with Applications to Geochronology, Geophysics and Archaeology).....	159
4.1. Introduction.....	159
4.2. Origin of Natural Tracks: Internal Sources.....	160
4.3. ^{238}U Spontaneous Fission: Fission Track Dating.....	162

4.3.1. Age Calculation and Assumptions.....	163
4.3.2. Experimental Procedures.....	167
Selection of Surfaces to Be Counted.....	167
Track Identification.....	171
Sample Handling.....	171
Selection.....	171
Preparation.....	172
Scanning Procedure for Glass.....	173
Scanning Procedure for Crystals.....	176
Irradiation.....	177
Repreparation and Counting.....	183
4.3.3. Environmental Effects.....	184
Etching Efficiency: Effects of Annealing.....	184
Track Fading.....	185
Correction for Thermally Affected Tracks by Etch Pit Size Measurements.....	189
Correction for Thermally Affected Tracks by the Age Plateau Method.....	192
Erasure of Tracks by Plastic Deformation: Dating Mechanical Events.....	194
Possibility of Uranium Exchange.....	195
4.3.4. Examples of Fission Track Dating.....	196
Ocean Bottom Spreading.....	196
Ancient Man.....	199
East Africa.....	199
The Western Hemisphere.....	202
Thermal Dating in Archaeology.....	203
Thermal Dating in Geological and Space Sciences.....	204
4.3.5. Future Applications of Fission Track Dating.....	208
4.4. Alpha-Recoil Tracks.....	209
Appendix.....	211
References.....	215
 Chapter 5. Modern Energetic Particles in Space.....	 232
5.1. Introduction.....	232
5.2. Galactic Cosmic Rays.....	237
5.2.1. Chemical and Isotopic Composition of Cosmic Ray Nuclei up to Iron.....	239
5.2.2. Energy Dependence of Cosmic Ray Composition.....	245
The Changing Composition at Energies Below 100 MeV/nucleon..	246
The Changing Composition at Energies Above 3 GeV/nucleon...	250
5.2.3. Trans-iron Cosmic Rays ($Z \geq 30$).....	252

Data for Trans-iron Nuclei at High Energy ($\beta \geq 0.9$).....	257
Data for Trans-iron Nuclei at Low Energy.....	258
5.2.4. Search for Superheavy Elements in the Cosmic Rays.....	262
5.2.5. Origin of Cosmic Rays.....	264
Abundances of Elements in the Solar System.....	265
Nucleosynthesis of the Elements.....	265
Abundances at Cosmic Ray Sources.....	269
Do Cosmic Rays Come from Ordinary Galactic Gas?.....	270
Are Cosmic Rays Synthesized in Explosive Events?.....	273
Are There Several Sources of Cosmic Rays?.....	274
5.3. Solar Flare Particles.....	275
5.3.1. Solar Flare Fe Tracks in Glass from the Surveyor Camera....	278
5.3.2. Energy Dependence of Heavy Ion Enhancements in Flares....	282
5.3.3. Charge Composition at High Energies in Flares.....	287
5.4. The Solar Wind.....	289
5.5. Energy Distribution of Heavy Particles in Interplanetary Space...	292
5.5.1. Galactic Cosmic Rays.....	292
5.5.2. Solar Flares.....	293
5.5.3. The Solar Wind.....	293
5.5.4. Suprathermal Ions.....	293
5.5.5. Choice of Spectrum at Inaccessible Energies.....	294
References.....	294
 Chapter 6. Ancient Energetic Particles in Space.....	307
6.1. Introduction to Track Studies in Extraterrestrial Materials.....	307
6.2. External Sources of Tracks in Extraterrestrial Materials.....	311
6.2.1. General Considerations.....	311
6.2.2. Profile of the VH Track Density vs. Depth at High Energies..	313
6.2.3. Profile of the VH Track Density vs. Depth at Low Energies...	320
6.2.4. Absolute Values of VH Track Production Rates at the Orbit of Earth.....	320
6.2.5. Production of Tracks in High-Energy Spallation Reactions....	328
6.2.6. Cosmic Ray Induced Fission.....	329
6.3. Constancy of Heavy Cosmic Rays in Time.....	332
6.4. The Elemental Abundances of Heavy Particles in Space.....	335
6.5. Study of Nucleosynthesis and the Early History of the Solar System by Extinct Isotopes.....	339
6.5.1. Extinct Isotopes in Meteorites.....	339
6.5.2. Extinct Isotopes in Lunar Samples.....	346
The Question of Element X.....	347
6.6. Lunar Surface Dynamics.....	351
6.6.1. Introduction.....	351

6.6.2. Heavy Particle Track Determinations of the Exposure History of Lunar Rocks.....	353
6.6.3. Track Spallation Ages.....	365
6.6.4. Measurement of Mass-Wastage Erosion from Comparison of Spallation and Heavy Particle Exposure Ages.....	368
6.6.5. Solar Flare Studies of Microerosion in Lunar Rocks.....	370
6.6.6. General Aspects of Track Studies in Lunar Soils.....	376
6.6.7. The Unique Radiation Record of the Micron-Sized Fraction of the Lunar Soil.....	385
6.6.8. Calculation of Model Ages for Soil Samples.....	388
6.6.9. Track Results in Some Lunar Soil Samples of Special Interest..	390
6.6.10. The Layering Chronology of Lunar Cores.....	393
6.6.11. Absolute Rates of Microcratering on Lunar Rocks.....	396
6.6.12. Meteoroid Impacts as the Major Driving Mechanism for Dynamic Lunar Processes.....	403
6.7. Solar Wind and Solar Flare Paleontology: Studies of Ancient Solar Radiations in Lunar Soils, Lunar Breccias, and Gas-Rich Meteorites.....	405
6.7.1. Introduction.....	405
6.7.2. Lunar Soils.....	406
6.7.3. Lunar Breccias.....	407
6.7.4. Gas-Rich Meteorites.....	409
References.....	412

PART III. NUCLEAR SCIENCE AND TECHNOLOGY

Chapter 7. Nuclear Physics at High and Low Energies.....	435
7.1. Introduction.....	435
7.2. Half-Lives for Spontaneous Fission and Alpha Decay.....	440
7.3. Lifetimes of Compound Nuclei by the Blocking Effect.....	444
7.4. Fission Barriers.....	447
7.5. Spontaneously Fissioning Isomers.....	448
7.6. The Search for Superheavy Nuclei.....	452
7.7. Low-Energy Charged Particle Reactions Relevant to Astrophysics..	457
7.8. Energetic Fragments from Relativistic Heavy-Ion Reactions.....	459
7.9. Additional Examples.....	464
7.9.1. Ternary Fission.....	464
7.9.2. Complete Fusion Reactions.....	464
7.9.3. The Search for Magnetic Monopoles.....	466
7.9.4. Photofission.....	466
7.9.5. Decay of High-Spin Nuclei.....	469

Appendix. Experiments with Dielectric Track Detectors.....	469
References.....	471
 Chapter 8. Element Mapping and Isotopic Analysis.....	489
8.1. Introduction.....	489
8.2. Bulk Determinations of Uranium.....	490
8.2.1. External Detector Method.....	490
8.2.2. Internal Detector Method.....	495
8.3. Micromapping of Fissionable Materials with Thermal Neutrons...	496
8.3.1. Techniques for Uranium Mapping.....	496
8.3.2. Applications of Uranium Mapping.....	500
Terrestrial Materials.....	500
Extraterrestrial Materials.....	502
8.3.3. Neutron Detection of Other Elements.....	505
8.4. Fast Particle Fission Mapping of Heavy Elements.....	505
8.4.1. Thorium Mapping.....	505
8.4.2. Mapping Other Elements.....	508
8.5. Mapping of Alpha-Particle and Proton Emitters.....	509
8.5.1. Induced Alpha Emission.....	510
8.5.2. Alpha Autoradiography.....	512
8.5.3. Induced Proton Emission.....	513
References.....	514
 Chapter 9. Radiation Dosimetry.....	527
9.1. Introduction.....	527
9.2. Neutron Detection by Tracks from (n , fission) Reactions.....	528
9.2.1. Thermal Neutron Fluences.....	530
9.2.2. Fast Neutron Fluences.....	531
9.2.3. Determination of Biological Dose.....	535
9.2.4. Applications to Reactors and Neutron Generators.....	538
9.2.5. High-Energy Radiation Near Accelerators.....	539
9.3. Neutron Detection by Tracks from Nonfission Reactions.....	541
9.3.1. Alpha Tracks from (n , α) Reactions.....	541
9.3.2. Detection of Fast Neutrons by Means of Recoil Tracks.....	543
9.3.3. Detection of Neutrons with $E \geq 10$ MeV by Multiprong Tracks.....	545
9.3.4. Proton Tracks from (n , p) Reactions.....	545
9.4. Alpha Particle Dosimetry.....	545
9.5. Dosimetry of High- Z Nuclei.....	547
9.5.1. Heavy-Ion Fluences in Accelerators.....	548
9.5.2. Biological Effects of Heavy Ions.....	548
References.....	553

Chapter 10. Diverse Applications in Science and Technology.....	562
10.1. Holes and Controlled Geometry.....	564
10.1.1. Porous Membranes and Filters.....	564
10.1.2. Virus and Bacteria Counter.....	569
10.1.3. Special Devices.....	572
10.1.4. Superfluidity.....	573
10.1.5. Superconductivity.....	573
10.2. Chemical Technology.....	573
10.2.1. Metallurgy.....	574
10.2.2. Gemology.....	574
10.2.3. Fluid Tracers.....	574
10.3. Nuclear Technology.....	577
10.3.1. Radiobiology.....	577
10.3.2. Biological Microchemistry.....	577
10.3.3. Nuclear Fuel Development and Safeguards.....	578
10.3.4. Reactor Applications.....	579
10.3.5. Uranium Exploration.....	580
10.4. Imaging.....	582
10.4.1. Internal Structure of Crystalline Solids.....	582
10.4.2. Neutron Radiography.....	584
10.4.3. Proton and Heavy Ion Radiography.....	586
10.5. Miscellaneous.....	587
References.....	588
Index.....	597