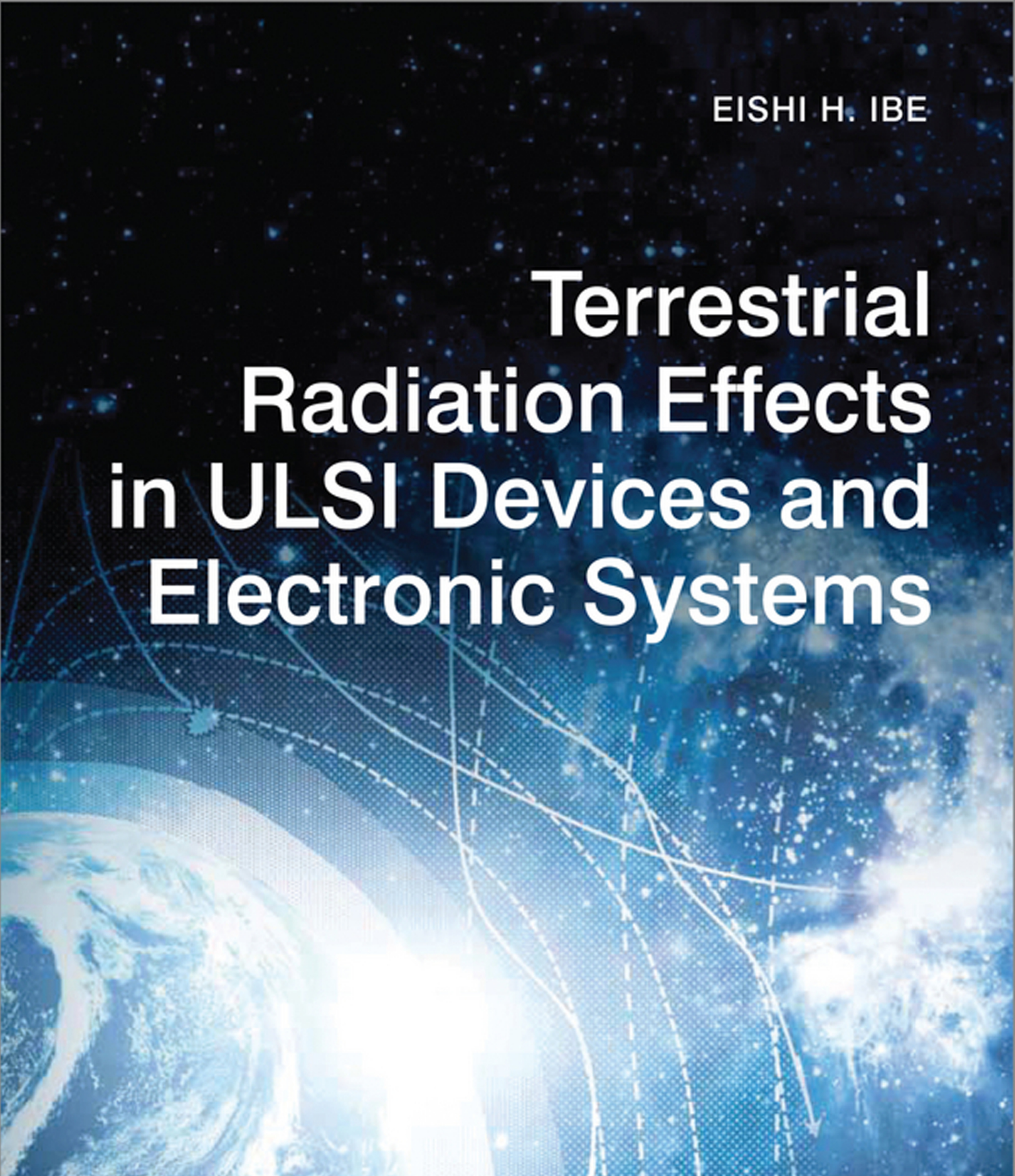

EISHI H. IBE

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To my daughters, Akane and Hikari

Contents

About the Author

Dr. Eishi Hidefumi IBE received his BS degree in Physics from Kyoto University, Japan in 1975, and his PhD degree in Nuclear Engineering from Osaka University, Japan in 1985.

He has joined the Atomic Energy Research Laboratory, Hitachi Ltd in 1975. He was promoted to chief researcher in the Yokohama Research Laboratory (formerly Production Engineering Research Laboratory), Hitachi Ltd. in 2006.

He has made outstanding accomplishments in nuclear engineering during the first 20 years of his career, in particular radiation effects on water (radiolysis) and component materials, and in single event effects on semiconductor devices during the last 18 years. His expertise covers very wide areas of sciences, such as elementary particle/cosmic ray physics, nuclear/neutron physics, semiconductor physics, mathematics and computing technologies, ion-implantation/mixing and accelerator technologies, electro-chemistry, database handling, RBS (Rutherford Backscattering Spectrometry)/Auger/SEM (Scanning Electron Microscopy)/Laser-beam micro analysis, and so on.

He has carried out pioneering work on simulation techniques of water radiolysis in the coolant of nuclear power plants to reveal that water coolant in the core decomposes into H_2 and H_2O_2. He has also established a theoretical basis for the hydrogen water chemistry techniques used to suppress oxidising H_2O_2, which is now widely applied to Japanese boiling water reactors to mitigate inter-granular stress corrosion cracking of the component materials. He has received awards from the Japanese Atomic Energy Society in 1986 and 1990, and from the American Nuclear Society in 1996.

During the last 18 years, he has dedicated himself to the development of quantification and mitigation techniques for terrestrial neutron-induced soft error in electronic devices and components. He developed the novel soft-error models for CMOS (Complementary Metal Oxide Semiconductor) devices. The models have been utilised to design more reliable semiconductor memory devices and logic gates, bringing in the breakthrough knowledge on the nature of terrestrial neutron soft error. Under his leadership, novel experimental techniques to quantify soft-error susceptibility of the devices and components have been developed and accepted as international standards.

He has contributed to IEEE journals such as *EDS* and *TNS*, conferences such as IRPS, IOLTS, ICICDT, WDSN, NSREC, RADECS, RASEDA, ICITA and SELSE as a program committee member, or a reviewer in the field of neutron-induced faults/errors/failures. He has authored more than 90 international technical papers and presentations including 25 invited contributions in the field of radiation effects. He has reviewed more than 200 technical papers responding to requests from the Chairs of the journals and conferences. This accumulation has given him wide and deep scope in the field of single event effects.

Dr. Ibe was promoted to IEEE Fellow for contributions to analysis of soft errors in memory devices in 2008. Some of his achievements are now accessible worldwide through his recent publications with World Scientific Inc. (2008) and Springer (2010, 2011).

Preface

In everyday life, we do not recognise the presence of terrestrial radiation – secondary particles are produced from cosmic ray and radiation from radioisotopes at ground level. Terrestrial radiation is so weak (low flux) that they do not have any visible or recognisable influence on human tissues, but it does have an impact on LSI (Large Scale Integration), VLSI (Very large scale integration) and ULSI (Ultra large scale integration) devices in electronic systems at ground level.

When I was a fourth grade student of the Kyoto University in 1974, my major subject matter was the measurement of lifetime of terrestrial muon. At that time, no one, including me, knew about or even imagined such impacts from terrestrial neutrons.

Rapid progress in semiconductor industries has forced us to be aware of the impacts of terrestrial radiation on semiconductor devices. First, alpha-ray soft error from contaminated radioisotopes on/in the DRAM (Direct Random Access Memory) and SRAM (Static Random Access Memory) devices. As the readers will see in this book, terrestrial neutron-induced soft error has been unacknowledged up until the late 1990s for many reasons. As device scaling has nosedived into below 100 nm, the impacts of terrestrial radiation has spread very widely and deeply. Not only terrestrial neutrons but also other terrestrial radiative particles such as protons and muons are recently among the focus of scientific investigations. Beyond memories, sequential and combinational logic devices and circuits are also being scrutinised. Concerns over failures have broadened from servers/routers to the automobile industry.

It is commonly recognised now that failures in electronic systems due to faults or errors introduced in devices/circuits by terrestrial radiation can only be mitigated by the combination or cooperation of mitigation techniques in two or more stack layers such as substrate, cell, circuit, CPU (Central Processing Unit), middleware, OS (Operating System) and application. This is a very challenging task that requires a wide variety of scientific fields like astronomy, cosmic ray physics, nuclear physics, accelerator physics, semiconductor physics, circuit theory, computer theory, numerical simulation, EDA (Electric Design Automation) tools, coding theory, reliability physics, database handling, and so on.

Meanwhile, this task is fascinating. During my research in this field, I have learned a number of exciting facts about the Earth.

We cannot live without air that is only a 50 km thick layer above the Earth – 1/250 of the diameter of the Earth. An astronaut has a limit to how long he can stay in the inner/outer space due to the limit of radiation exposure by cosmic rays. We, humankind, cannot live on a planet without air and have been protected from harsh cosmic radiation in outer space by only this very thin layer of air in the Earth.

Beautiful aurora australis and borealis are the outcome of interactions between cosmic rays and the atmosphere.

Carbon-14 that is used for radiocarbon dating is produced by nuclear reaction of nitrogen-14 and cosmic ray proton in the atmosphere. Even clouds in the sky have recently been revealed to be mostly triggered by cosmic rays according to CERN's team report.

The author hopes that this book will trigger the readers' interest in the impact of cosmic rays on the Earth and our everyday lives.

16 April 2014
Eishi H. Ibe
Enjoying scuba diving in Saipan, USA

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I gratefully acknowledge Professors Emeritus T. Nakamura, M. Baba and Professor Y. Sakemi for helpful discussions and support for the database on nuclear reactions and high-energy neutron experiments at CYRIC, Tohoku University. We also acknowledge Dr Alexander Prokofiev for cordial support in high-energy neutron experiments at TSL, Uppsala University. Communicative discussions with Drs. C. Slayman, S.-J. Wen of Cisco Systems Inc., N. Seifert of Intel, R. Baumann of TI, M. Nicolaidis of TIMA Laboratory, D. Alexandrescu and A. Evans of iRoc, T. Uemura of Fujitsu Laboratory and H. Kobayashi of SONY are deeply acknowledged. I am also grateful to Professors K. Kobayashi of Kyoto Institute of Technology, H. Onodera of Kyoto University, Drs. M. Yoshimura and Y. Matsunaga of Kyushu University for giving valuable information on SEU tolerant flip-flops and EDA tools. Invaluable discussions and information are given by Drs. Kuboyama, and D. Kobayashi of JAXA, Professor Y. Takahashi of Nippon University, and Ms. A. Makihara of HIREC.

Acronyms

ACE	Architectural Correct Execution
ALLS	Aligned Laboratory System
ALPEN	ALpha Particle source/drain PENtration
ALS	Absolute Laboratory System
ALU	Arithmetic-Logic Unit
AMUSE	Autonomous MUltilevel emulation system for Soft Error evaluation
ANITA	Atmospheric-like Neutrons from thIck TArget
AOI	Area Of Interest
ASIC	Application Specific Integrated Circuit
ASIL	Automotive Safety Integrity Level
ASTEP	Altitude Single event effects Test European Platform
AVF	Architectural Vulnerability Factor
AVP	Architectural Verification Program
BAN	Body Area Network
BCDMR	Bistable Cross-coupled Dual Modular Redundancy
BICS	Built-In Current Sensor
BISER	Built-In Soft Error Resilience
BIPS	Built-in Pulse Sensor
BIST	Built-In Self Test
BL	Bit Line
BNL	Brookhaven National Laboratory
BOX	Buried Oxide
BPSG	Boron Phosphor Silicate Glass
BUT	Board Under Test
CAM	Content Addressable Memory
CAN	Controller Area Network
CCD	Charge Coupled Device
CHB	CHecker Board
CHBc	CHecker Board complement
CL	Confidence Level

CLR	Cross-Layer Reliability
CM	Center of Mass
CMOS	Complementary Metal Oxide Semiconductor
CMP	Chemical Mechanical Polishing
CNL	UC Davis Crocker Nuclear Laboratory
CNRF	Cold Neutron Research Facility
CORIMS	COsmic Radiation IMpact Simulator
CPU	Central Processing Unit
CRAM	Configuration Random Access Memory
CRC	Cyclic Redundancy Code
CYCLON	Cyclotron of Louvain la Neuve
CYRIC	CYclotron and RadioIsotope Center
DCC	Duplication + Comparison + Checkpointing
DF	Derating Factor
DICE	Dual Interlocked storage CEll
DLL	Delay Locked Loop
DMR_1	Dual Modular Redundancy
DMR_2	Dynamic Memory Reconfiguration
DOA	Design On Average
DOAV	Design On Average and Variation
DOUB	Design On Upper Bound
DPM	Defects Per Million
DRAM	Dynamic Random Access Memory
DSP	Digital Signal Processor
DUE	Detected Unrecoverable Error
DUT	Device Under Test
ECC	Error Correction Code/Error Checking and Correction
EDA	Electric Design Automation
EDAC	Error Detection And Correction
EMI	Electro-Magnetic Interference
EX	Execution
FBE	Floating Body Effect
FDSOI	Fully Depleted SOI
FF	Flip-Flop
FFDA	Field Failure Data Analysis
FIT	Failure In Time
FPGA	Field Programmable Gate Array
FRAM	Ferroelectric Random Access Memory
GDS	Graphic Data System
GEM	Generalized Evaporation Model
GPS	Global Positioning System
GPU	Graphic Processing Unit

GPGPU	General Purpose GPU
GPU	Graphic Processing Unit
GTO	Gate Turn-Off Thyristor
HA	High Altitude
HHC	Hierarchical Hardware Checkpointing
HHFL	Heavy Halt Failure
ICICDT	International Conference on IC Design and Technology
ICITA	International Conference on Information Technology and Applications
ID	Instruction Decode
IF	Instruction Fetch
IGBT	Insulated Gate Bipolar Transistor
IOLTS	International On-Line Testing Symposium
INC	Intra-Nuclear Cascade
IRPS	International Reliability Physics Symposium
IUCF	Indiana University Cyclotron Facility
JAXA	Japan Aerospace Exploration Agency
JESD	JEDEC StanDard
J-PARC	Japan Proton Accelerator Research Complex
LABIR	inter LAyer Built-In Reliability
LAMPF	Los Alamos Meson Physics Facility
LANSCE	Los Alamos NationalScience Center
LBNL	Lawrence Berkeley National Laboratory
LEAP	Layout design through Error Aware Placement
LENS	Low-Energy Neutron Source
LET	Linear Energy Transfer
LFSR	Linear Feedback Shift Register
LHFL	Light Halt Failure
LIN	Local Interconnect Network
LINAC	LINear particle ACcelerator
LNL	Laboratori Nazionali di Legnaro
LSI	Large Scale Integration
LTFL	Latency Failure
LUT	Lookup Table
MA	Memory Access
MBU	Multi-Bit Upset
MCBI	Multi-Coupled Bipolar Interaction
MCU^1	Multi-Cell Upset
MCU^2	Micro Control Unit
MF	Masking Factor
MFTF	Mean Fluence To Failure
MNFL	Marginal Failure

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MPR	Memory Page Retire
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NBTI	Negative Bias Temperature Instability
NCAP	European New Car Assessment Programme
NIST	National Institute of Standards and Technology
NMIJ	National Metrology Institute Japan
NoC	Network on Chip
NSAA	Nonstop Advanced Architecture
NSREC	Nuclear and Space Radiation Effects Conference
NYC	New York City
OS	Operating System
PC[1]	Program Counter
PC[2]	Power Cycle
PC[3]	Personal Computer
PCB	Printed Circuit Board
PCSE	Power Cycle Soft-Error
PDSOI	Partially Depleted SOI
PHITS	Particle and Heavy Ion Transport Code System
PIPB	Propagation Induced Pulse Broadening
PLL	Phase Locked Loop
PVF	Program Vulnerability Factor
QMN	Quasi-Monoenergetic Neutron
RADECS	RAdiation Effects on Components and Systems
RAM	Radom Access Memory
RAP	Resilience Articulation Point
RAS	Reliability, Availability and Serviceability
RASEDA	RAdiation effects on SEmiconductor Devices for space Application
RCNP	Research Center for Nuclear Physics
RHBD	Radiation Hardened-By-Design
RIIF	Reliability Information Interchange Format
RILC	Radiation Induced Leakage Current
RMA	Return Material Authorisation
ROM	Read Only Memory
RTL	Register Transfer Level
RTOS	Real Time Operating System
SAW	Surface Acoustic Wave
SBRM	Symptom Based Redundant Multithreading
SBST	Software-Based Self-Test
SBU	Single Bit Upset

SDC	Silent Data Corruption
SEALER	Single Event Adverse and Local Effects Reliever
SEB	Single Event Burnout
SECDED	Single Error Correction and Double Error Detection
SEE	Single Event Effect
SEFI	Single Event Functional Interrupt
SEFR	Single Event Fault Rate
SEGR	Single Event Gate Rupture
SEILA	Soft Error Immune LAtch
SEL	Single Event Latchup
SELSE	Silicon Errors in Logic – System Effects
SEM	Soft Error Mitigation
SER	Soft-Error Rate
SES	Single Event Snapback
SESB	Single Event SnapBack
SET	Single Event Transient
SEU	Single Event Upset
SEUT	Single Event Upset Tolerant
SHE	Software Hardening Environment
SIL	Safety Integrity Level
SILC	Stress Induced Leak Current
SIMS	Secondary Ion Mass Spectrometry
SITR	Self-Imposed Temporal Redundancy
SLC	Single Level Cell
SLFL	Silent Failure
SOI	Silicon On Insulator
SPFD	Sets of Pairs of Functions to be Distinguished
SPICE	SimulationProgram with Integrated Circuit Emphasis
SRAM	Static Random Access Memory
SRIM	Stopping and Range of Ions in Matter
STEM	Soft and Timing Error Mitigation
STI	Shallow Trench Isolation
TAMU	Texas A&M University
TID	Total Ionizing Dose effect
TCAD	Technology Computer-Aided Design
TID	Total Ionisation Dose
TISS	Trusted Interface Subsystem
TMR	Triple Module Redundancy
TRIUMF	Tri-University Meson Facility
TSL	The Svedberg Laboratory
TTA	Time Triggered Architecture
TTNoC	Time-Triggered Network-on-Chip

TVF	Timing Vulnerability Factor
UG	Under Ground
ULSI	Ultra Large Scale Integration
VLA	Very Low Alpha
VLSI	Very Large Scale Integration
WB	Write Back
WL	Word Line

1

Introduction

1.1 Basic Knowledge on Terrestrial Secondary Particles

Cosmic rays, which have extremely high energies, come from the galactic core and the sun to the atmosphere of the Earth. Primary cosmic rays in outer space consist mainly of protons (about 90%). Since cosmic rays are charged particles they twine around lines of geomagnetic or heliomagnetic forces as illustrated in Figure 1.1. Some of them are trapped by geomagnetic force to form the Van Allen radiation belts. Cosmic rays with energies less than the *geomagnetic rigidity cutoff* are deflected before entering the geomagnetic field. On the other hand, some are attracted into geomagnetic poles along with lines of geomagnetic force sometimes accompanied by the aurora borealis or australis. Cosmic rays are deflected more strongly near the equator since the lines of geomagnetic force are parallel to the surface of the Earth. Therefore, the strength of cosmic rays that reach the atmosphere differs depending on the geomagnetic latitude of the Earth.

When the energetic protons enter the atmosphere (troposphere and stratosphere) of the Earth, some protons undergo *nuclear spallation reaction* with nuclei (mainly nitrogen and oxygen nuclei) in the atmosphere to produce a number of light particles including neutrinos, photons, electrons, muons, pions, protons and neutrons as illustrated in Figure 1.2. Since secondary neutrons have longer ranges in the atmosphere compared to protons, they release cascades of spallation reactions in the atmosphere to make *air showers* that reach the surface of the Earth. Figure 1.3 shows an estimated differential neutron spectrum at NYC (New York City) sea level based on measurements in different locations in the USA [1]. The neutron energy at the ground ranges over 1 GeV and its flux beyond 1 MeV is around 20 n/cm^2/h in average. As the air can shield neutrons, strength (flux and energy) of neutrons depends upon altitude and to a slight extent atmospheric pressure [2]. Compared to the neutron flux at ground level, the neutron flux at avionics altitude is much higher by a factor of 100.

Furthermore, as cosmic rays are also deflected by the heliomagnetic field or the sun's activity which has about an 11-year cycle, the strength of the neutron flux at ground level also has about an 11-year cycle as shown in Figure 1.4 [3]. At the *solar maximum*, the neutron flux at ground level is almost at its weakest, while it is at its

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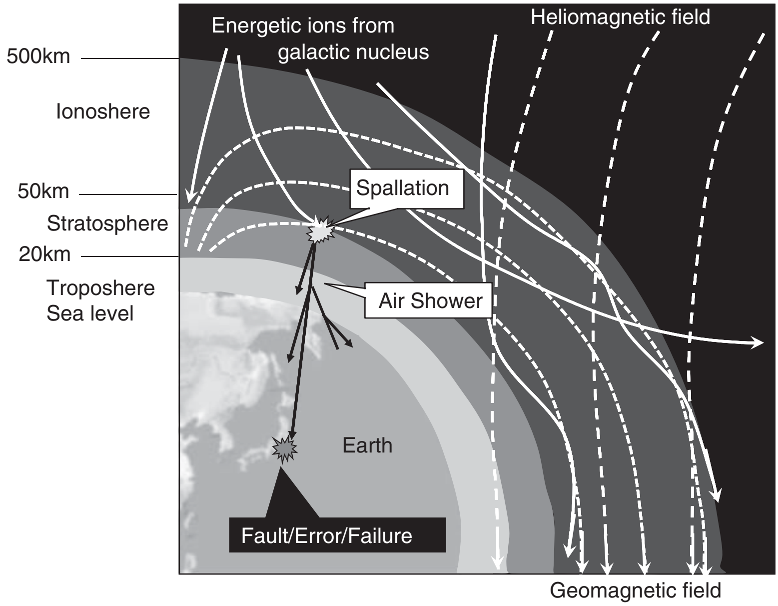

Figure 1.1 Overall scheme of terrestrial radiation-induced single event effects

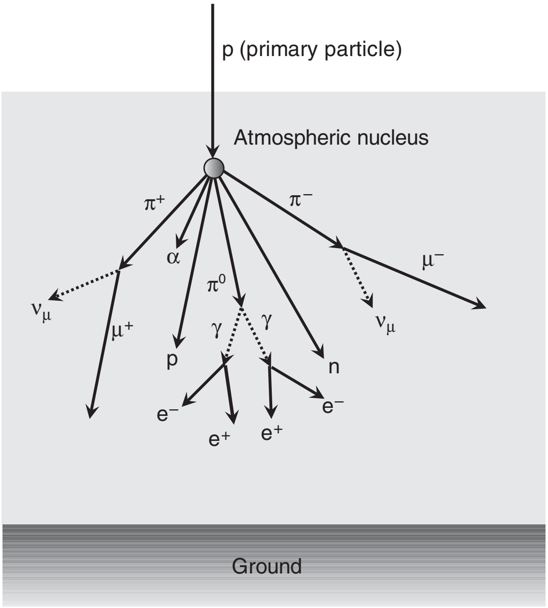

Figure 1.2 Initial stage of secondary particle production

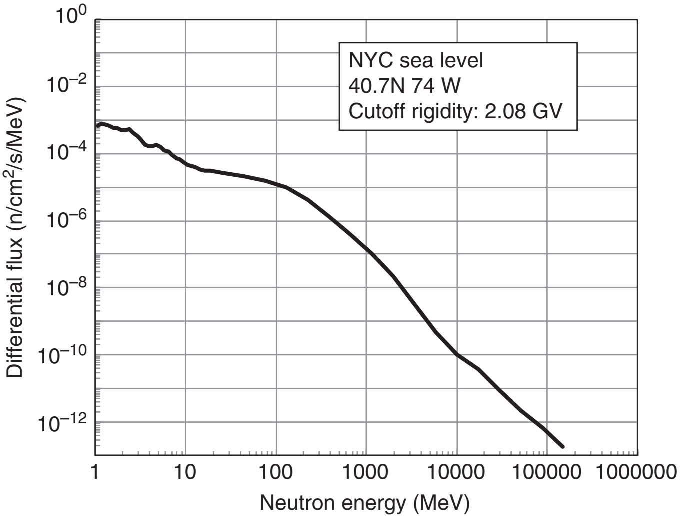

Figure 1.3 Differential high-energy neutron spectrum at NYC sea level based on JESD89A

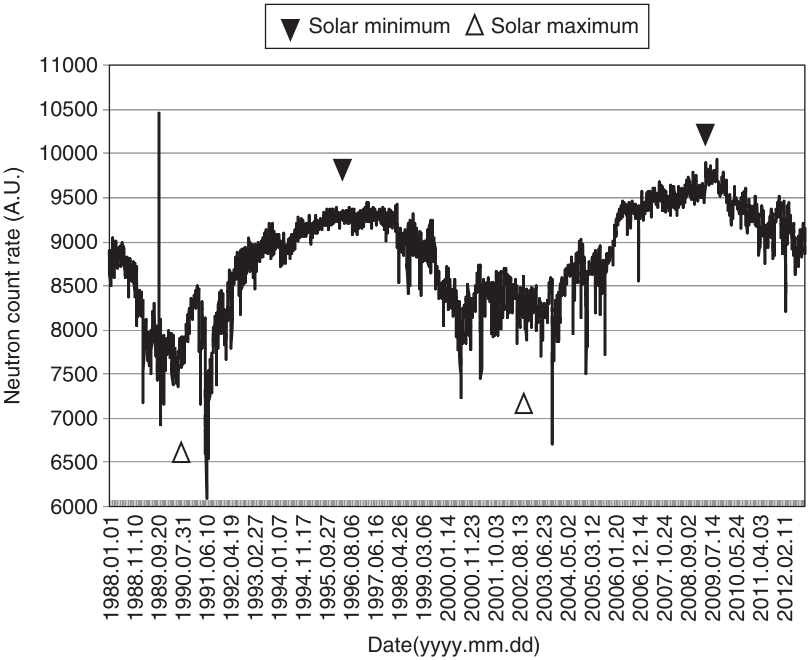

Figure 1.4 Long-term cyclic variation in neutron flux measured at Moscow Neutron Monitor Centre (http://cr0.izmiran.rssi.ru/mosc/main.htm)

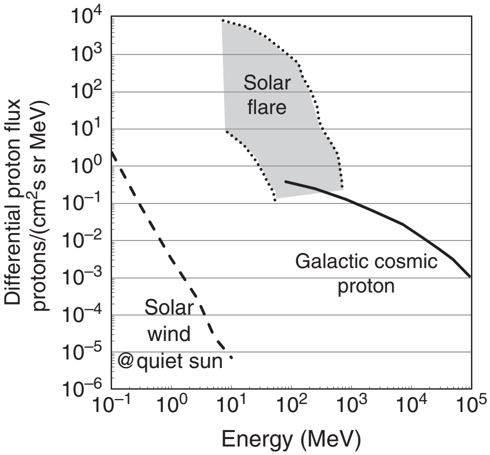

Figure 1.5 Differential proton spectra originated from solar-minimum sun, big flares on the sun and the galactic core

strongest at the *solar minimum*. Under normal activity, the sun emits a large quantity of protons, but their energy level is relatively low as shown in Figure 1.5 for the solar maximum period [4] since protons from the sun do not cause air showers directly at ground level. However, when big flares take place on the sun's surface, a much larger quantity of protons is emitted with energy comparative to the galactic protons as shown in Figure 1.5 [5] and this can cause air showers.

1.2 CMOS Semiconductor Devices and Systems

CMOS (Complementary Metal Oxide Semiconductor) devices like Static Random Access Memory (SRAM) or Flip Flops (FFs) are basically made on the stripe structure of p and n-dual wells. For example, Figure 1.6 shows typical layouts of diffusion layers (nodes) in SRAM one bit and an OR gate cell on the stripe structure. All nodes in memories and logic circuits are basically made on the same stripe structure in a chip. Unlike dual well structure, triple well structure has a deep n-well. As for Silicon On Insulator (SOI), Buried OXides (BOXs) are made under the dual wells as shown in Figure 1.7. Isolation oxides, usually Shallow Trench Isolation (STI) oxides are also made to isolate each node in a lateral direction. When the thickness of the SOI layer is thinner than the depth of the depletion layer in the SD (Source-Drain) channel, the structure is known as FD (Fully-Depleted) SOI. Meanwhile, when the thickness of the SOI layer is thicker than the depletion layer, the structure is known as PD (Partially-Depleted) SOI. Since the upper surface of BOX is completely covered by the depletion layer, parasitic capacitance can be largely reduced compared to Bulk/PDSOI, resulting in steep sub-threshold characteristics, reduction in latency and power consumption.