

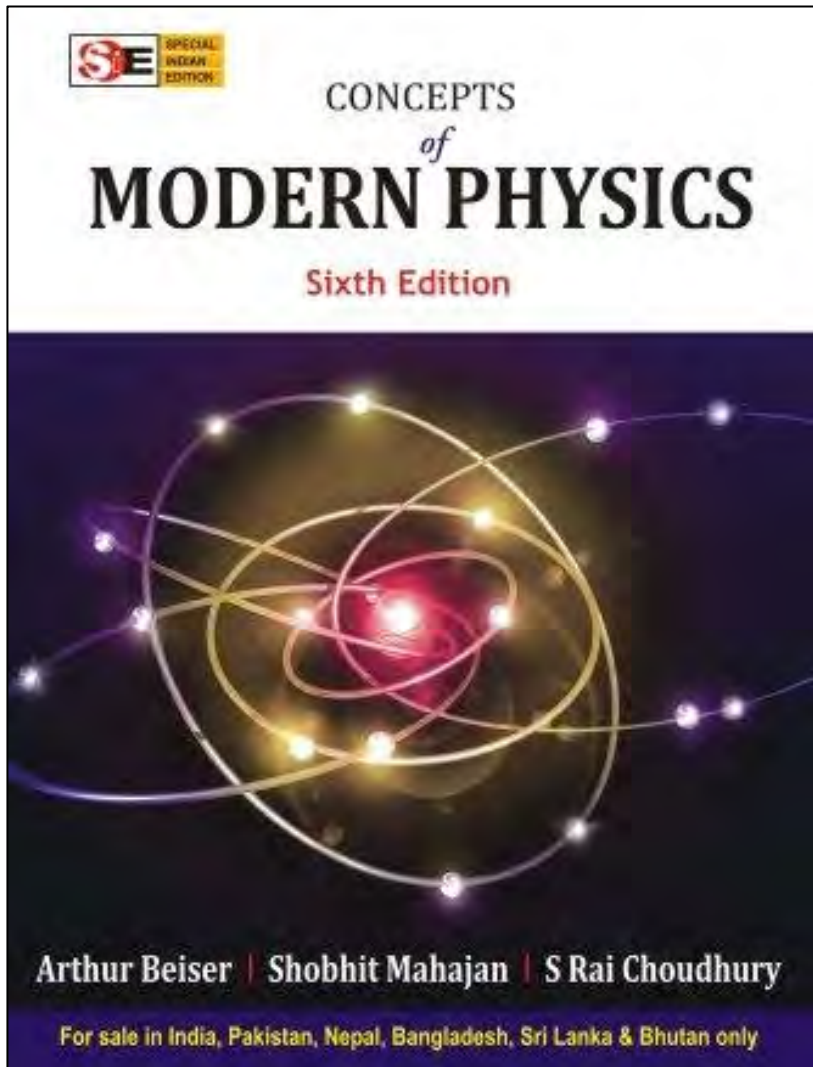


Higher Education

Concepts *of* MODERN PHYSICS

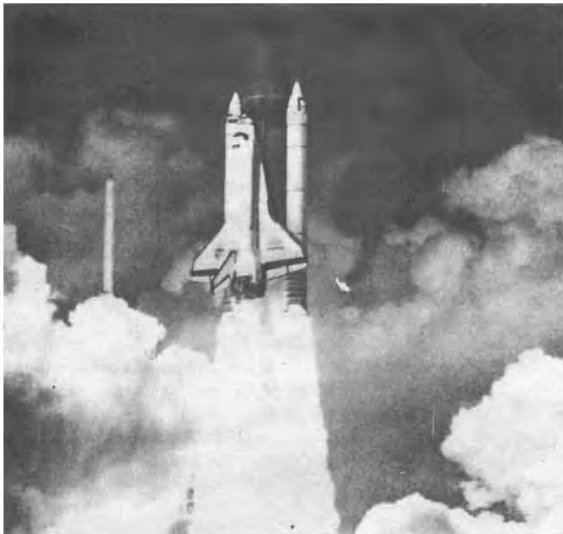
Sixth Edition

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CHAPTER 1

Relativity



According to the theory of relativity, nothing can travel faster than light. Although today's spacecraft can exceed 10 km/s, they are far from this ultimate speed limit.

1.1 SPECIAL RELATIVITY

All motion is relative; the speed of light in free space is the same for all observers

1.2 TIME DILATION

A moving clock ticks more slowly than a clock at rest

1.3 DOPPLER EFFECT

Why the universe is believed to be expanding

1.4 LENGTH CONTRACTION

Faster means shorter

1.5 TWIN PARADOX

A longer life, but it will not seem longer

1.6 ELECTRICITY AND MAGNETISM

Relativity is the bridge

1.7 RELATIVISTIC MOMENTUM

Redefining an important quantity

1.8 MASS AND ENERGY

Where $E_0 = mc^2$ comes from

1.9 ENERGY AND MOMENTUM

How they fit together in relativity

1.10 GENERAL RELATIVITY

Gravity is a warping of spacetime

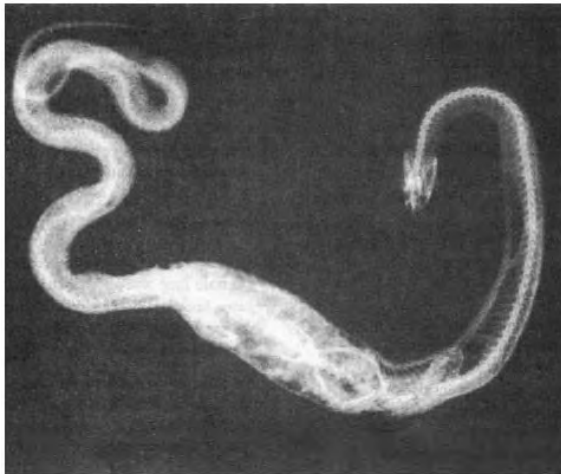
1.11 EINSTEIN'S THEORY OF GRAVITATION

APPENDIX I: THE LORENTZ TRANSFORMATION

APPENDIX II: SPACETIME

CHAPTER 2

Particle Properties of Waves



The penetrating ability of x-ray enabled them to reveal the frog which this snake had swallowed. The snake's jaws are very loosely joined and so can open widely.

2.1 ELECTROMAGNETIC WAVES

Coupled electric and magnetic oscillations that move with the speed of light and exhibit typical wave behavior

2.2 BLACKBODY RADIATION

Only the quantum theory of light can explain its origin

2.3 PHOTOELECTRIC EFFECT

The energies of electrons liberated by light depend on the frequency of the light

2.4 WHAT IS LIGHT?

Both wave and particle

2.5 X-RAYS

They consist of high-energy photons

2.6 X-RAY DIFFRACTION

How x-ray wavelengths can be determined

2.7 COMPTON EFFECT

Further confirmation of the photon model

2.8 PAIR PRODUCTION

Energy into matter

2.9 PHOTONS AND GRAVITY

Although they lack rest mass, photons behave as though they have gravitational mass

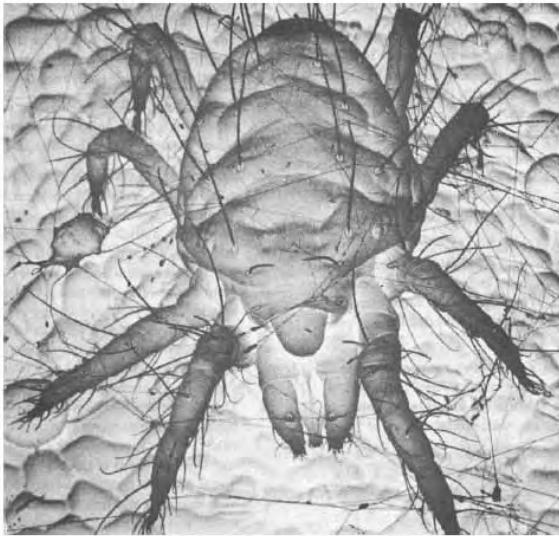
2.10 INTERFERENCE OF LIGHT AT ULTRA-LOW INTENSITIES

2.11 QUANTUM NATURE OF ELASTIC WAVES

2.12 LABORATORY EXPERIMENT OF TWO-SLIT INTERFERENCE WITH ONE PHOTON AT A TIME

CHAPTER 3

Wave Properties of Particles



In a scanning electron microscope, an electron beam that scans a specimen causes secondary electrons to be ejected in numbers that vary with the angle of the surface. A suitable data display suggests the three-dimensional form of the specimen. The high resolution of this image of a red spider mite on a leaf is a consequence of the wave nature of moving electrons.

3.1 DE BROGLIE WAVES

A moving body behaves in certain ways as though it has a wave nature

3.2 WAVES OF WHAT?

Waves of probability

3.3 DESCRIBING A WAVE

A general formula for waves

3.4 PHASE AND GROUP VELOCITIES

A group of waves need not have the same velocity as the waves themselves

3.5 PARTICLE DIFFRACTION

An experiment that confirms the existence of de Broglie waves

3.6 PARTICLE IN A BOX

Why the energy of a trapped particle is quantized

3.7 UNCERTAINTY PRINCIPLE I

We cannot know the future because we cannot know the present

3.8 UNCERTAINTY PRINCIPLE II

A particle approach gives the same result

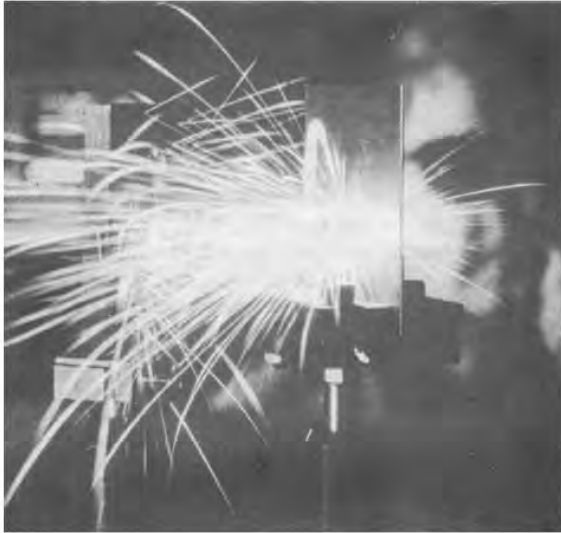
3.9 APPLYING THE UNCERTAINTY PRINCIPLE

A useful tool, not just a negative statement

3.10 INTERFEROMETRY WITH ELECTRONS AND ATOMS

CHAPTER 4

Atomic Structure



Solid-state infrared laser cutting 1.6-mm steel sheet. This laser uses an yttrium-aluminum-garnet crystal doped with neodymium. The neodymium is pumped with radiation from small semiconductor lasers, a highly efficient method.

4.1 THE NUCLEAR ATOM

An atom is largely empty space

4.2 ELECTRON ORBITS

The planetary model of the atom and why it fails

4.3 ATOMIC SPECTRA

Each element has a characteristic line spectrum

4.4 RITZ COMBINATION PRINCIPLE

4.5 THE BOHR ATOM

Electron waves in the atom

4.6 ENERGY LEVELS AND SPECTRA

A photon is emitted when an electron jumps from one energy level to a lower level

4.7 CORRESPONDENCE PRINCIPLE

The greater the quantum number, the closer quantum physics approaches classical physics

4.8 NUCLEAR MOTION

The nuclear mass affects the wavelengths of spectral lines

4.9 ATOMIC EXCITATION

How atoms absorb and emit energy

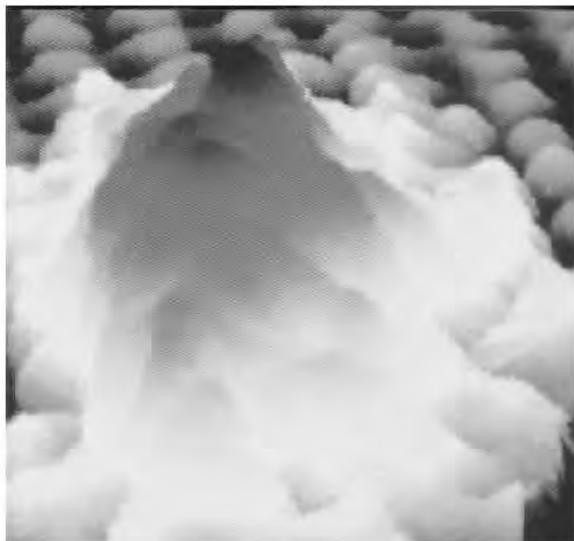
4.10 THE LASER

How to produce light waves all in step

APPENDIX: RUTHERFORD SCATTERING

CHAPTER 5

Quantum Mechanics



Scanning tunneling micrograph of gold atoms on a carbon (graphite) substrate. The cluster of gold atoms is about 1.5 nm across and three atoms high.

5.1 QUANTUM MECHANICS

Classical mechanics is an approximation of quantum mechanics

5.2 THE WAVE EQUATION

It can have a variety of solutions, including complex ones

5.3 SCHRÖDINGER'S EQUATION: TIME-DEPENDENT FORM

A basic physical principle that cannot be derived from anything else

5.4 LINEARITY AND SUPERPOSITION

Wave functions add, not probabilities

5.5 EXPECTATION VALUES

How to extract information from a wave function

5.6 OPERATORS

Another way to find expectation values

5.7 SCHRÖDINGER'S EQUATION: STEADY-STATE FORM

Eigenvalues and eigenfunctions

5.8 PARTICLE IN A BOX

How boundary conditions and normalization determine wave functions

5.9 FINITE POTENTIAL WELL

The wave function penetrates the walls, which lowers the energy levels

5.10 TUNNEL EFFECT

A particle without the energy to pass over a potential barrier may still tunnel through it

5.11 HARMONIC OSCILLATOR

Its energy levels are evenly spaced

APPENDIX: THE TUNNEL EFFECT

5.12 MEASUREMENT IN QUANTUM THEORY

5.13 MEASUREMENT AND DECOHERENCE

5.14 RELATIVISTIC QUANTUM MECHANICS

CHAPTER 6

Quantum Theory of the Hydrogen Atom



The strong magnetic fields associated with sunspots were detected by means of the Zeeman effect. Sunspots appear dark because they are cooler than the rest of the solar surface, although quite hot themselves. The number of spots varies in an 11-year cycle, and a number of terrestrial phenomena follow this cycle.

6.1 SCHRÖDINGER'S EQUATION FOR THE HYDROGEN ATOM

Symmetry suggests spherical polar coordinates

6.2 SEPARATION OF VARIABLES

A differential equation for each variable

6.3 QUANTUM NUMBERS

Three dimensions, three quantum numbers

6.4 PRINCIPAL QUANTUM NUMBER

Quantization of energy

6.5 ORBITAL QUANTUM NUMBER

Quantization of angular-momentum magnitude

6.6 MAGNETIC QUANTUM NUMBER

Quantization of angular-momentum direction

6.7 ELECTRON PROBABILITY DENSITY

No definite orbits

6.8 RADIATIVE TRANSITIONS

What happens when an electron goes from one state to another

6.9 SELECTION RULES

Some transitions are more likely to occur than others

6.10 ZEEMAN EFFECT

How atoms interact with a magnetic field

6.11 ZEEMAN EFFECT EXPERIMENT

6.12 DEGENERACY OF H-ATOM ENERGY LEVELS: FINE STRUCTURE

6.13 SPIN-ORBIT COUPLING

6.14 THE ACCIDENTAL DEGENERACY

CHAPTER 7

Many-Electron Atoms



Helium, whose atoms have only closed electrons shells, is inert chemically and cannot burn or explode. Because it is also less dense than air, it is used in airships.

7.1 ELECTRON SPIN

Round and round it goes forever

7.2 EXCLUSION PRINCIPLE

A different set of quantum numbers for each electron in an atom

7.3 SYMMETRIC AND ANTISYMMETRIC WAVE FUNCTIONS

Fermions and bosons

7.4 MANY ELECTRONS ATOMS

7.5 PERIODIC TABLE

Organizing the elements

7.6 ATOMIC STRUCTURES

Shells and subshells of electrons

7.7 EXPLAINING THE PERIODIC TABLE

How an atom's electron structure determines its chemical behavior

7.8 SPIN-ORBIT COUPLING

Angular momenta linked magnetically

7.9 TOTAL ANGULAR MOMENTUM

Both magnitude and direction are quantized

7.10 X-RAY SPECTRA

They arise from transitions to inner shells

APPENDIX: ATOMIC SPECTRA

7.11 ORBITALS AND QUANTUM CHEMISTRY

7.12 THE APPROXIMATION METHODS

7.13 PASCHEN-BACK EFFECT

7.14 THE STARK EFFECT

CHAPTER 8

Molecules



The infrared spectrometer measures the absorption of infrared radiation by a sample as a function of wavelength, which provides information about the structure of the molecules in the sample.

8.1 THE MOLECULAR BOND

Electric forces hold atoms together to form molecules

8.2 ELECTRON SHARING

The mechanism of the covalent bond

8.3 THE H_2^+ MOLECULAR ION

Bonding requires a symmetric wave function

8.4 THE HYDROGEN MOLECULE

The spins of the electrons must be antiparallel

8.5 COMPLEX MOLECULES

Their geometry depends on the wave functions of the outer electrons of their atoms

8.6 ROTATIONAL ENERGY LEVELS

Molecular rotational spectra are in the microwave region

8.7 VIBRATIONAL ENERGY LEVELS

A molecule may have many different modes of vibration

8.8 ELECTRONIC SPECTRA OF MOLECULES

How fluorescence and phosphorescence occur

8.9 RAMAN EFFECT

CHAPTER 9

Statistical Mechanics



The Crab Nebula is the result of a supernova explosion that was observed in A.D. 1054. The explosion left behind a star believed to consist entirely of neutrons. Statistical mechanics is needed to understand the properties of neutron stars.

9.1 STATISTICAL DISTRIBUTIONS

Three different kinds

9.2 MAXWELL-BOLTZMANN STATISTICS

Classical particles such as gas molecules obey them

9.3 MOLECULAR ENERGIES IN AN IDEAL GAS

They vary about an average of $\frac{3}{2}kT$

9.4 QUANTUM STATISTICS

Bosons and fermions have different distribution functions

9.5 RAYLEIGH-JEANS FORMULA

The classical approach to blackbody radiation

9.6 PLANCK RADIATION LAW

How a photon gas behaves

9.7 EINSTEIN'S APPROACH

Introducing stimulated emission

9.8 SPECIFIC HEATS OF SOLIDS

Classical physics fails again

9.9 FREE ELECTRONS IN A METAL

No more than one electron per quantum state

9.10 ELECTRON-ENERGY DISTRIBUTION

Why the electrons in a metal do not contribute to its specific heat except at very high and very low temperatures

9.11 DYING STARS

What happens when a star runs out of fuel

9.12 STATISTICAL MECHANICS AND THERMODYNAMICS

9.13 ENSEMBLES IN STATISTICAL MECHANICS

CHAPTER 10

The Solid State



Wood ant carrying a microchip that contains several million circuit elements.

10.1 CRYSTALLINE AND AMORPHOUS SOLIDS

Long-range and short-range order

10.2 IONIC CRYSTALS

The attraction of opposites can produce a stable union

10.3 COVALENT CRYSTALS

Shared electrons lead to the strongest bonds

10.4 VAN DER WAALS BOND

Weak but everywhere

10.5 METALLIC BOND

A gas of free electrons is responsible for the characteristic properties of a metal

10.6 BAND THEORY OF SOLIDS

The energy band structure of a solid determines whether it is a conductor, an insulator, or a semiconductor

10.7 SEMICONDUCTOR DEVICES

The properties of the p-n junction are responsible for the microelectronics industry

10.8 ENERGY BANDS: ALTERNATIVE ANALYSIS

How the periodicity of a crystal lattice leads to allowed and forbidden bands

10.9 SUPERCONDUCTIVITY

No resistance at all, but only at very low temperatures (so far)

10.10 BOUND ELECTRON PAIRS

The key to superconductivity

10.11 QUANTUM HALL EFFECT

10.12 LANDAU LEVELS

10.13 EXPERIMENTAL RESULTS

10.14 HALL EFFECT

CHAPTER 11

Nuclear Structure



Nuclear magnetic resonance is the basis of a high-resolution method of imaging body tissues. The screen shows a computer-constructed cross section of the head of the person lying inside the powerful magnet at the rear.

11.1 NUCLEAR COMPOSITION

Atomic nuclei of the same element have the same numbers of protons but can have different numbers of neutrons

11.2 SOME NUCLEAR PROPERTIES

Small in size, a nucleus may have angular momentum and a magnetic moment

11.3 STABLE NUCLEI

Why some combinations of neutrons and protons are more stable than others

11.4 BINDING ENERGY

The missing energy that keeps a nucleus together

11.5 LIQUID-DROP MODEL

A simple explanation for the binding-energy curve

11.6 SHELL MODEL

Magic numbers in the nucleus

11.7 MESON THEORY OF NUCLEAR FORCES

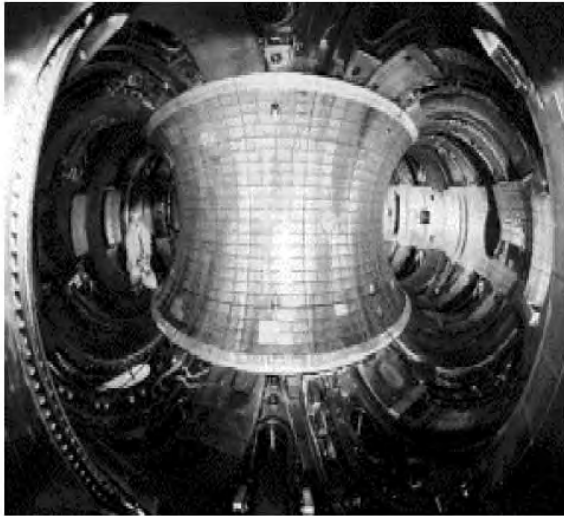
Particle exchange can produce either attraction or repulsion

11.8 NUCLEAR MATTER

11.9 TWO-NUCLEON POTENTIAL

CHAPTER 12

Nuclear Transformations



Interior of the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory. In December 1993 this reactor produced 6.2 MW of fusion power for 4 s from a deuterium-tritium plasma confined by strong magnetic fields.

12.1 RADIOACTIVE DECAY

Five kinds

12.2 HALF-LIFE

Less and less, but always some left

12.3 RADIOACTIVE SERIES

Four decay sequences that each end in a stable daughter

12.4 ALPHA DECAY

Impossible in classical physics, it nevertheless occurs

12.5 BETA DECAY

Why the neutrino should exist and how it was discovered

12.6 GAMMA DECAY

Like an excited atom, an excited nucleus can emit a photon

12.7 CROSS SECTION

A measure of the likelihood of a particular interaction

12.8 NUCLEAR REACTIONS

In many cases, a compound nucleus is formed first

12.9 NUCLEAR FISSION

Divide and conquer

12.10 NUCLEAR REACTORS

$E_0 = mc^2 + \text{$$$}$

12.11 NUCLEAR FUSION IN STARS

How the sun and stars get their energy

12.12 FUSION REACTORS

The energy source of the future?

APPENDIX: THEORY OF ALPHA DECAY

CHAPTER 13

Elementary Particles



Aerial view of CERN, the European particle physics laboratory near Geneva, Switzerland, where many important discoveries were made. A tunnel 27 km in circumference under the large circle will contain the new Large Hadron Collider in which protons and antiprotons will move in opposite directions as they are accelerated to the highest energies yet achieved in the laboratory. It is hoped that their interactions will shed light on the process that gives particles mass. The smaller circle marks an earlier proton-antiproton collider.

13.1 INTERACTIONS AND PARTICLES

Which affects which

13.2 LEPTONS

Three pairs of truly elementary particles

13.3 HADRONS

Particles subject to the strong interaction

13.4 ELEMENTARY PARTICLE QUANTUM NUMBERS

Finding order in apparent chaos

13.5 QUARKS

The ultimate constituents of hadrons

13.6 FIELD BOSONS

Carriers of the interactions

13.7 THE STANDARD MODEL AND BEYOND

Putting it all together

13.8 HISTORY OF THE UNIVERSE

It began with a bang

13.9 THE FUTURE

"In my beginning is my end." (T. S. Eliot, Four Quartets)

13.10 COSMIC RAYS

CHAPTER 14

Cosmology



Horse head nebula: The horse head nebula, about 1500 light years away in the constellation of Orion. Nebulae are interstellar clouds of dust, gas and plasma which are often star forming regions. Study of the emission from nebulae gives us vital information about the early stages of star formation.

14.1 THE BIG BANG

The universe started with a Big Bang and has been expanding since

14.2 DARK MATTER AND DARK ENERGY

The Universe is predominantly made of invisible matter and energy

14.3 THE ELEMENTARY PARTICLES AND THEIR INTERACTIONS

The ultimate constituents of nature and their interactions with each other

14.4 VAN ALLEN BELT

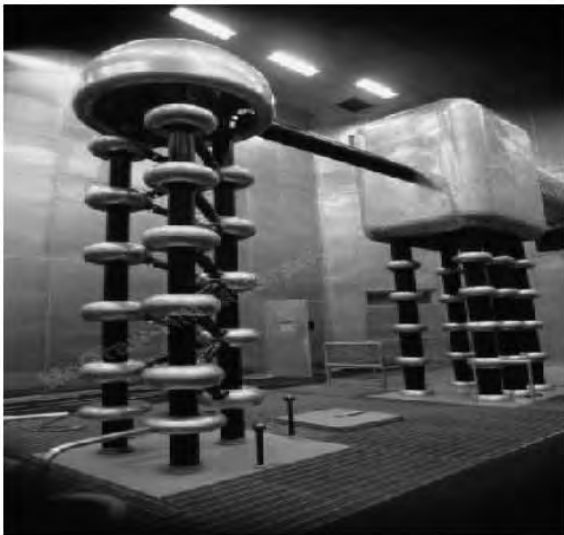
Charged particles arranged in regions around the earth

14.5 EVOLUTION OF STARS

The lifecycle of stars- from their birth to death

CHAPTER 15

Nuclear Reactions and Artificial Radioactivity



Radioisotopes and Radiophysics: Particle Accelerator: Particle accelerators are essential tools for understanding the nature of matter at the smallest levels. From early van de Graff accelerators to the massive Large Hadron Collider, they have proved to be invaluable in expanding our knowledge of the nature of matter.

15.1 NUCLEAR FISSION AND NUCLEAR REACTORS

The power of a thousand suns and its use for humankind

15.2 NUCLEAR FUSION

Criteria for a successful fusion reactor

15.3 CARBON DATING

Use of radioactive phenomenon in archaeology

15.4 PARTICLE DETECTORS

Machines for detecting the sub-microscopic constituents of nature

15.5 PARTICLE ACCELERATORS

The behemoths which allow us to explore nature at the smallest level

15.6 ITER PROJECT

The most powerful machine on earth?

15.7 LARGE HADRON COLLIDER

An engineering feat rivaling the building of the pyramids?