❖ Commuting Operators and Uncertainty Principle (*x* & *p*; *E* & *t*)

One of the most important properties of operator multiplication is the commutation relation or the commutation rule. Two operators, A and B, are said to be commutating or non-commutating depending upon the magnitude of their commutator.

$$[\hat{A},\hat{B}] = \hat{A}\hat{B} - \hat{B}\hat{A} = 0 \ \rightarrow Commutating \tag{399}$$

and

$$[\hat{A},\hat{B}] = \hat{A}\hat{B} - \hat{B}\hat{A} \neq 0 \ \rightarrow Non\text{-}commutating \tag{400}$$

The physical significance of the commutation relations implies in the fact that when two operators commute, they possess simultaneous set of eigenfunctions; and their respective physical properties can be evaluated simultaneously and accurately. However, if the commutator is non-zero, the respective physical properties cannot be obtained simultaneously and accurately; which is actually the popular uncertainty principal. Two of the most common uncertainty systems; position-momentum and energy-time; can also be proved from commutation relations.

➢ *Position-Momentum Uncertainty (x & p)*

The position-momentum uncertainty can be justified only if the commutation of their operators is non-zero. Therefore, we need to find the following.

$$[\hat{x},\hat{p}_x] \tag{401}$$

Let it be operated over a function ψ. We have

$$[\hat{x},\hat{p}_x\,]\psi = \hat{x}\,\hat{p}_x\,\psi - \hat{p}_x\,\hat{x}\ \psi \tag{402}$$

or

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$$[\hat{x}, \hat{p}_x]\psi = x\frac{h}{2\pi i}\frac{\partial}{\partial x}\psi - \frac{h}{2\pi i}\frac{\partial}{\partial x}x\,\psi \tag{403}$$

$$[\hat{x}, \hat{p}_x]\psi = \frac{h}{2\pi i}x\frac{\partial\psi}{\partial x} - \frac{h}{2\pi i}x\frac{\partial\psi}{\partial x} - \frac{h}{2\pi i}\psi\frac{\partial x}{\partial x} \tag{404}$$

$$[\hat{x}, \hat{p}_x]\psi = -\frac{h}{2\pi i}\psi \tag{405}$$

$$[\hat{x}, \hat{p}_x] = -\frac{h}{2\pi i} = \frac{hi}{2\pi} = i\hbar \tag{406}$$

Equation (406) proves that we cannot determine the position and momentum of a particle along one axis simultaneously and accurately.

- ***Energy-Time Uncertainty (E & t)***

The energy-time uncertainty can be justified only if the commutation of their operators is non-zero. Therefore, we need to find the following.

$$[\hat{t}, \hat{E}] \tag{407}$$

Let it be operated over a function ψ(*t*). We have

$$[\hat{t}, \hat{E}]\psi = \hat{t}\,\hat{E}\,\psi - \hat{E}\hat{t}\,\psi \tag{408}$$

or

$$[\hat{t}, \hat{E}]\psi = t\frac{h}{2\pi i}\frac{\partial}{\partial t}\psi - \frac{h}{2\pi i}\frac{\partial}{\partial t}t\,\psi \tag{409}$$

$$[\hat{t}, \hat{E}]\psi = \frac{h}{2\pi i}t\frac{\partial\psi}{\partial t} - \frac{h}{2\pi i}t\frac{\partial\psi}{\partial t} - \frac{h}{2\pi i}\psi\frac{\partial t}{\partial t} \tag{410}$$

$$[\hat{t}, \hat{E}]\psi = -\frac{h}{2\pi i}\psi \tag{411}$$

$$[\hat{t}, \hat{E}] = -\frac{h}{2\pi i} \tag{412}$$

$$[\hat{t}, \hat{E}] = \frac{hi}{2\pi} \tag{413}$$

$$[\hat{t}, \hat{E}] = i\hbar \tag{414}$$

The equation (412) proves that higher the lifetime of the state lower will be energy fluctuation i.e. uncertainty ΔE, and the vice-versa is also true.

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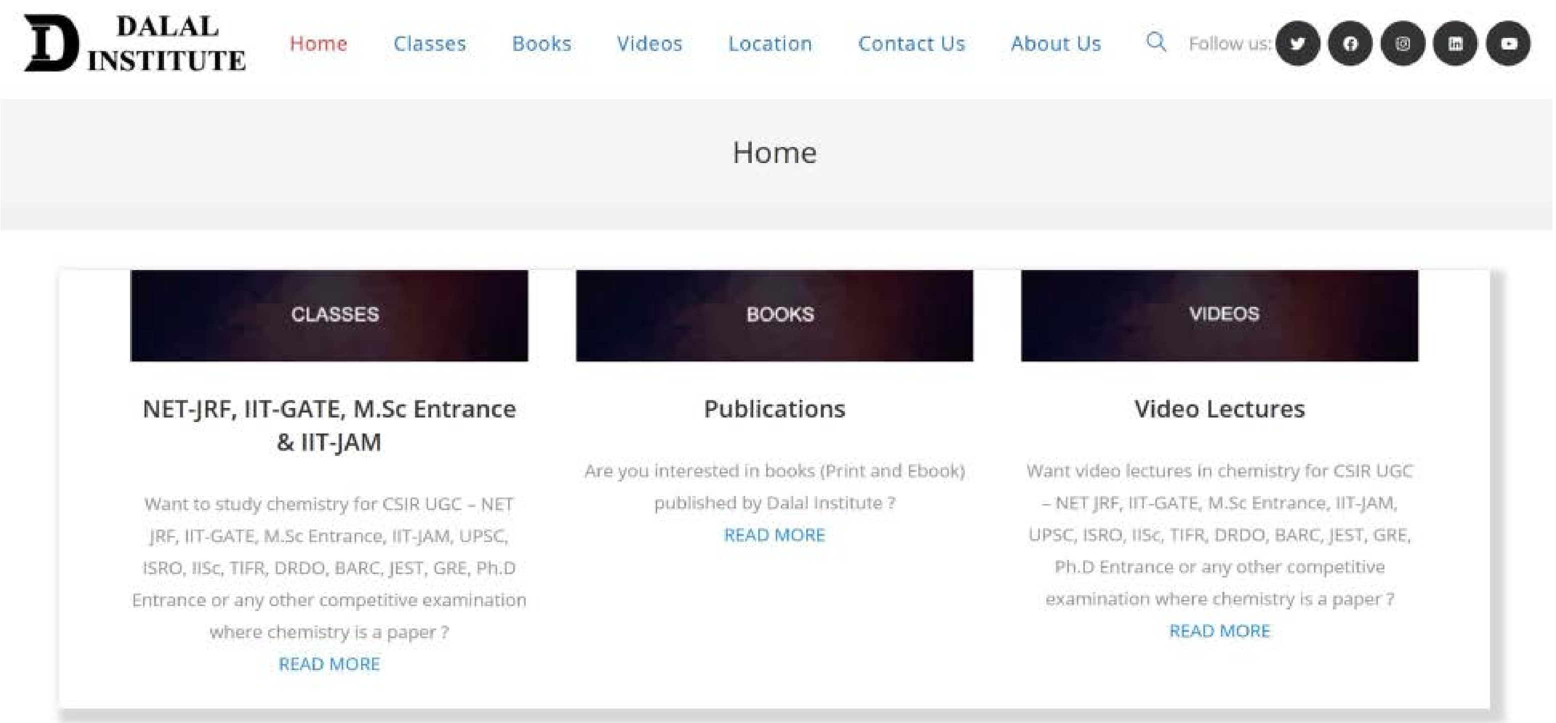

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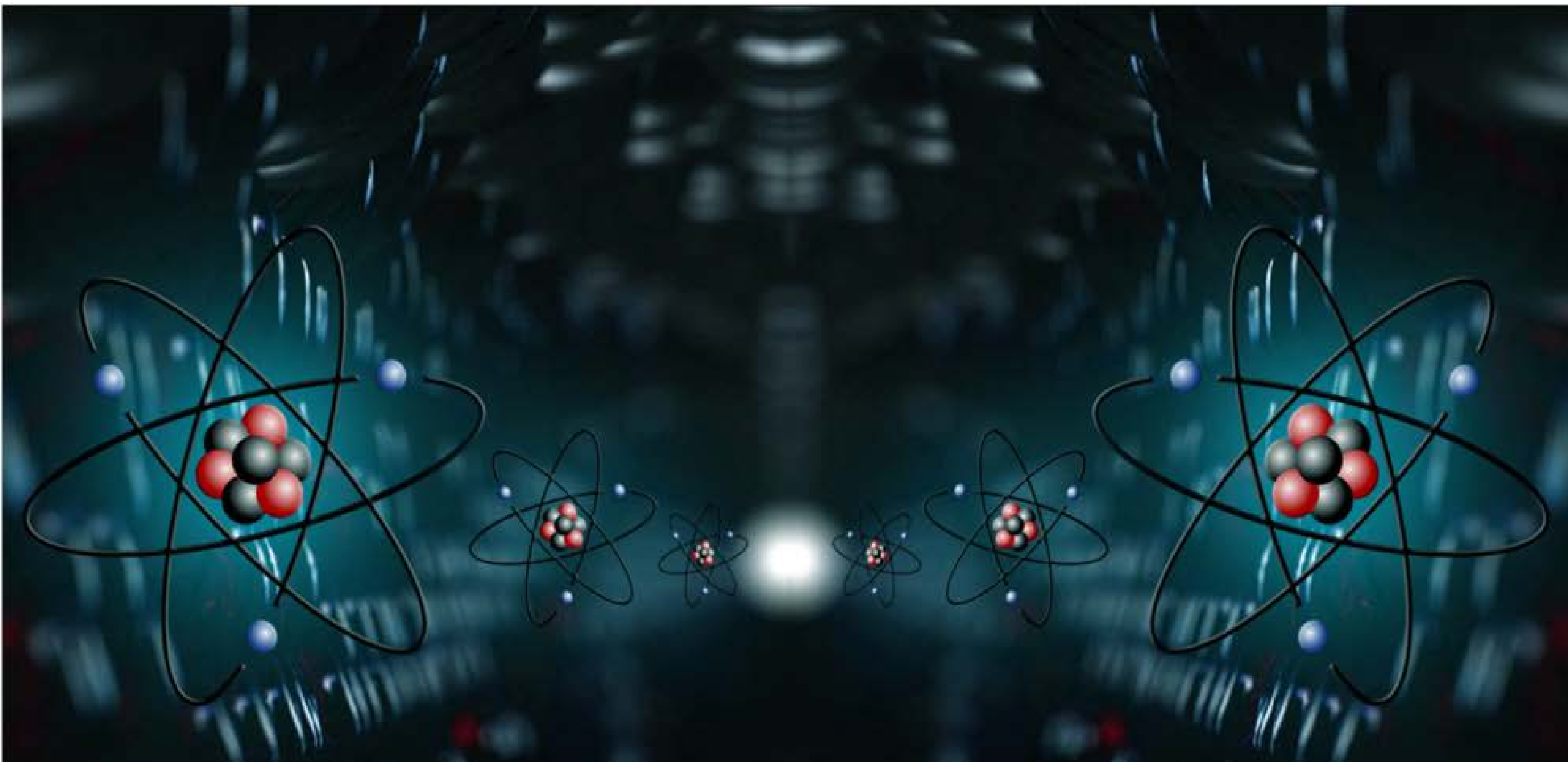

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Table of Contents

CHAPTER 1 .... **11**

Quantum Mechanics – I 11

- Postulates of Quantum Mechanics 11
- Derivation of Schrodinger Wave Equation 16
- Max-Born Interpretation of Wave Functions 21
- The Heisenberg's Uncertainty Principle 24
- Quantum Mechanical Operators and Their Commutation Relations 29
- Hermitian Operators – Elementary Ideas, Quantum Mechanical Operator for Linear Momentum, Angular Momentum and Energy as Hermitian Operator 52
- The Average Value of the Square of Hermitian Operators 62
- Commuting Operators and Uncertainty Principle (x & p; E & t) 63
- Schrodinger Wave Equation for a Particle in One Dimensional Box 65
- Evaluation of Average Position, Average Momentum and Determination of Uncertainty in Position and Momentum and Hence Heisenberg's Uncertainty Principle 70
- Pictorial Representation of the Wave Equation of a Particle in One Dimensional Box and Its Influence on the Kinetic Energy of the Particle in Each Successive Quantum Level 75
- Lowest Energy of the Particle 80
- Problems 82
- Bibliography 83

CHAPTER 2 .... **84**

Thermodynamics – I 84

- Brief Resume of First and Second Law of Thermodynamics 84
- Entropy Changes in Reversible and Irreversible Processes 87
- Variation of Entropy with Temperature, Pressure and Volume 92
- Entropy Concept as a Measure of Unavailable Energy and Criteria for the Spontaneity of Reaction 94
- Free Energy, Enthalpy Functions and Their Significance, Criteria for Spontaneity of a Process ... 98
- Partial Molar Quantities (Free Energy, Volume, Heat Concept) 104
- Gibb's-Duhem Equation 108
- Problems 111
- Bibliography 112

CHAPTER 3 113

Chemical Dynamics – I 113

- Effect of Temperature on Reaction Rates 113
- Rate Law for Opposing Reactions of Ist Order and IInd Order 119
- Rate Law for Consecutive & Parallel Reactions of Ist Order Reactions 127
- Collision Theory of Reaction Rates and Its Limitations 135
- Steric Factor 141
- Activated Complex Theory 143
- Ionic Reactions: Single and Double Sphere Models 147
- Influence of Solvent and Ionic Strength 152
- The Comparison of Collision and Activated Complex Theory 157
- Problems 158
- Bibliography 159

CHAPTER 4 160

Electrochemistry – I: Ion-Ion Interactions 160

- The Debye-Huckel Theory of Ion-Ion Interactions 160
- Potential and Excess Charge Density as a Function of Distance from the Central Ion 168
- Debye-Huckel Reciprocal Length 173
- Ionic Cloud and Its Contribution to the Total Potential 176
- Debye-Huckel Limiting Law of Activity Coefficients and Its Limitations 178
- Ion-Size Effect on Potential 185
- Ion-Size Parameter and the Theoretical Mean - Activity Coefficient in the Case of Ionic Clouds with Finite-Sized Ions 187
- Debye-Huckel-Onsager Treatment for Aqueous Solutions and Its Limitations 190
- Debye-Huckel-Onsager Theory for Non-Aqueous Solutions 195
- The Solvent Effect on the Mobility at Infinite Dilution 196
- Equivalent Conductivity (Λ) vs Concentration $C^{1/2}$ as a Function of the Solvent 198
- Effect of Ion Association Upon Conductivity (Debye-Huckel-Bjerrum Equation) 200
- Problems 209
- Bibliography 210

CHAPTER 5 211

Quantum Mechanics – II 211

- Schrodinger Wave Equation for a Particle in a Three Dimensional Box 211

- The Concept of Degeneracy Among Energy Levels for a Particle in Three Dimensional Box 215
- Schrodinger Wave Equation for a Linear Harmonic Oscillator & Its Solution by Polynomial Method 217
- Zero Point Energy of a Particle Possessing Harmonic Motion and Its Consequence 229
- Schrodinger Wave Equation for Three Dimensional Rigid Rotator 231
- Energy of Rigid Rotator 241
- Space Quantization 243
- Schrodinger Wave Equation for Hydrogen Atom: Separation of Variable in Polar Spherical Coordinates and Its Solution 247
- Principal, Azimuthal and Magnetic Quantum Numbers and the Magnitude of Their Values 268
- Probability Distribution Function 276
- Radial Distribution Function 278
- Shape of Atomic Orbitals (*s*, *p* & *d*) 281
- Problems 287
- Bibliography 288

CHAPTER 6 .... **289**

Thermodynamics – II 289

- Clausius-Clapeyron Equation 289
- Law of Mass Action and Its Thermodynamic Derivation 293
- Third Law of Thermodynamics (Nernst Heat Theorem, Determination of Absolute Entropy, Unattainability of Absolute Zero) And Its Limitation 296
- Phase Diagram for Two Completely Miscible Components Systems 304
- Eutectic Systems (Calculation of Eutectic Point) 311
- Systems Forming Solid Compounds A_xB_y with Congruent and Incongruent Melting Points 321
- Phase Diagram and Thermodynamic Treatment of Solid Solutions 332
- Problems 342
- Bibliography 343

CHAPTER 7 .... **344**

Chemical Dynamics – II 344

- Chain Reactions: Hydrogen-Bromine Reaction, Pyrolysis of Acetaldehyde, Decomposition of Ethane 344
- Photochemical Reactions (Hydrogen-Bromine & Hydrogen-Chlorine Reactions) 352
- General Treatment of Chain Reactions (Ortho-Para Hydrogen Conversion and Hydrogen-Bromine Reactions) 358

- Apparent Activation Energy of Chain Reactions 362
- Chain Length 364
- Rice-Herzfeld Mechanism of Organic Molecules Decomposition (Acetaldehyde) 366
- Branching Chain Reactions and Explosions (H_2-O_2 Reaction) 368
- Kinetics of (One Intermediate) Enzymatic Reaction: Michaelis-Menten Treatment 371
- Evaluation of Michaelis's Constant for Enzyme-Substrate Binding by Lineweaver-Burk Plot and Eadie-Hofstee Methods 375
- Competitive and Non-Competitive Inhibition 378
- Problems 388
- Bibliography 389

CHAPTER 8 .... **390**

Electrochemistry – II: Ion Transport in Solutions 390

- Ionic Movement Under the Influence of an Electric Field 390
- Mobility of Ions 393
- Ionic Drift Velocity and Its Relation with Current Density 394
- Einstein Relation Between the Absolute Mobility and Diffusion Coefficient 398
- The Stokes-Einstein Relation 401
- The Nernst-Einstein Equation 403
- Walden's Rule 404
- The Rate-Process Approach to Ionic Migration 406
- The Rate-Process Equation for Equivalent Conductivity 410
- Total Driving Force for Ionic Transport: Nernst-Planck Flux Equation 412
- Ionic Drift and Diffusion Potential 416
- The Onsager Phenomenological Equations 418
- The Basic Equation for the Diffusion 419
- Planck-Henderson Equation for the Diffusion Potential 422
- Problems 425
- Bibliography 426

INDEX **427**

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