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A Review of UV-Visible Spectroscopy Analytical Technique

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Abstract:
UV-Visible spectroscopy is a widely used analytical technique that helps in understanding how molecules absorb light in the ultraviolet (UV) and visible regions of the electromagnetic spectrum. This method provides valuable information about molecular structure, electronic transitions, and concentration of analytes in a sample. It is known for its high sensitivity, accuracy, and rapid performance, making it applicable in diverse scientific fields such as chemistry, biology, pharmaceuticals, and environmental studies. This study presents an overview of the basic principles, instrumentation components, and significant applications of UV-Visible spectroscopy, emphasizing its importance in molecular analysis and research (Skoog et al., 2017; Hollas, 2004; Pavia et al., 2015).

Keywords: UV-Visible spectroscopy, instrumentation, Beer–Lambert law,
molecular analysis, electronic transitions, molecular structure, absorbance.

Introduction:

Spectroscopy is the branch of science that studies the interaction between matter and electromagnetic radiation. It helps in understanding the physical and chemical properties of substances by observing how they absorb, emit, or scatter light at various wavelengths of the electromagnetic spectrum (Skoog et al., 2018). Spectrometric techniques represent a broad class of analytical methods that rely on the principles of atomic and molecular spectroscopy. These techniques involve the quantitative measurement of radiation intensity, typically using a photoelectric transducer or other electronic detection systems to convert light energy into measurable electrical signals (Holler et al., 2019).
UV–Visible (UV–Vis) spectroscopy is one of the most widely used spectroscopic techniques in analytical chemistry. It measures the absorption or transmission of ultraviolet and visible light by a sample in comparison to a reference or blank solution. The amount of light absorbed at specific wavelengths is directly related to the sample's composition and concentration, providing valuable information about molecular structure and electronic transitions (Pavia et al., 2015; Willard et al., 2021).
Ultraviolet and visible absorption spectroscopy generally involves the measurement of monochromatic light absorption within the wavelength ranges of 185–380 nm for the ultraviolet (UV) region and 380–780 nm for the visible (Vis) region of the electromagnetic spectrum. This technique is extensively applied for qualitative and quantitative analysis of organic and inorganic compounds (Kemp, 2019; USP <857>, 2023).

Figure : 1 Uv-Visible spectophotomaters

Principle :

The principle of UV–Visible spectroscopy is based on the absorption of ultraviolet (UV) or visible light by chemical compounds, resulting in the production of characteristic spectra. This technique relies on the interaction between light and matter, where the absorption of electromagnetic radiation leads to electronic excitation within a molecule (Skoog et al., 2018).

When a molecule absorbs ultraviolet or visible radiation, its electrons become excited — moving from a ground state (lower energy level) to an excited state (higher energy level). The energy difference between these two states corresponds to the wavelength of light absorbed (Kumar & Sharma, 2022).

Three types of ground-state orbitals are usually involved in such transitions:

1. σ (sigma) bonding molecular orbital
2. π (pi) bonding molecular orbital
3. n (non-bonding atomic orbital)

Two types of antibonding orbitals can also participate:

1. σ* (sigma star) antibonding orbital
2. π* (pi star) antibonding orbital

The following electronic transitions are possible in UV–Vis spectroscopy: σ → σ* n → σ* n → π* π → π*

Transitions such as σ → σ* and n → σ* generally occur in the far UV region (180–240 nm) because they require higher energy. Therefore, saturated compounds (containing only single bonds) show weak absorption in the normal UV region. In contrast, unsaturated compounds with π or non-bonding electrons undergo π → π* and n → π* transitions, which occur at longer wavelengths and require less energy (Pavia et al., 2015).

The structure of a molecule greatly influences both the wavelength of maximum absorption (λmax) and the intensity of absorption. Even small structural changes can shift the absorption band into the visible region, particularly in conjugated systems. Many inorganic compounds, especially those of transition metals, absorb in the visible region due to charge-transfer transitions, in which electrons move between metal ions and surrounding ligands (Kumar & Sharma, 2022).

Absorbance Laws

Two important laws explain the quantitative aspect of UV–Visible absorption:

Beer's Law and Lambert's Law :

Beer–Lambert Law states that the absorbance of a solution is directly proportional to the concentration of the absorbing species and the path length through which the light passes (Skoog et al., 2018). Mathematically, it is expressed as:

A = abc Where: A = Absorbance

a = Molar absorptivity ($L \cdot mol^{-1} \cdot cm^{-1}$) b = Path length (cm)

c = Concentration of the absorbing species ($mol \cdot L^{-1}$)

According to this law, as the number of absorbing molecules increases, the degree of absorption also increases proportionally, making it the foundation of absorption spectroscopy (Kumar & Sharma, 2022).

Applications in UV-Visible Spectroscopy :

In UV-Visible spectroscopy, the Beer–Lambert Law is extensively used for quantitative analysis, such as determining the concentration of organic molecules, transition metal ions, or biological macromolecules. Calibration curves are prepared by plotting absorbance against concentration, which ideally yields a straight line within the law's valid range (Sharma, 2019).

Limitations of Beer–Lambert Law :

Although Beer's Law is reliable under ideal conditions, deviations may occur due to physical, chemical, or instrumental factors. These deviations cause nonlinearity between absorbance and concentration (Raman & Singh, 2020).

1. Non-Linearity at High Concentrations :

At higher concentrations, solute molecules may interact or form aggregates, altering the refractive index and changing their ability to absorb light (Hollas, 2004).

2. Instrumental Errors :

Stray light, wavelength mismatch, or detector sensitivity issues can cause errors in absorbance readings, leading to inaccurate concentration determinations (Skoog et al., 2018).

3. Chemical Interference :

Association or dissociation reactions can modify the number of absorbing species, causing deviations from linearity (Pavia et al., 2015).

4. Light Scattering :

The presence of suspended particles or turbidity in the sample scatters incident light, reducing transmitted intensity and distorting the absorbance measurement (Kumar & Sharma, 2021).

5. Interfering Substances :

Coexisting compounds that absorb at or near the same wavelength as the analyte can lead to overlapping spectra, making quantitative analysis less accurate (Bathaie & Farajzadeh, 2019).

Instrumentation of UV-Vis Spectroscopy :

The essential components of a UV-Visible spectrophotometer are

1. Source(uv and visible)
2. Monochromator

3.Sample container(cuvette)

4. Detector
5. Amplifier and recorder

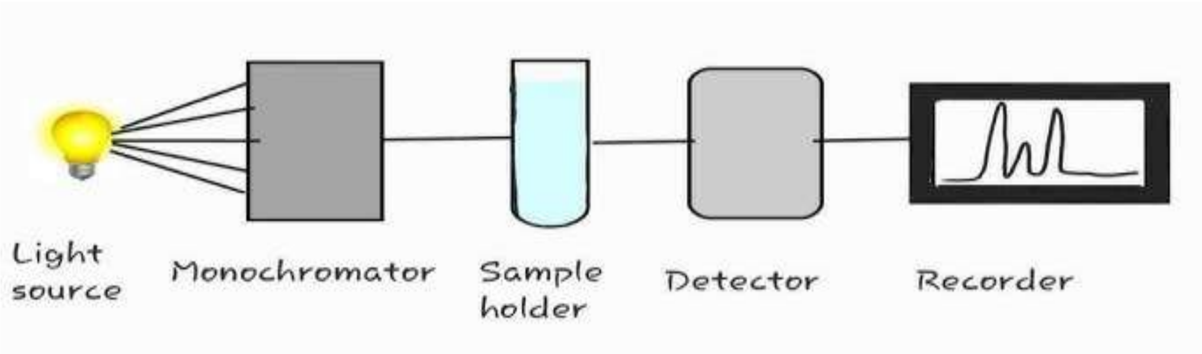

Figure : 2 Uv-Visible Spectroscopy

Light Sources in UV–Visible Spectroscopy :

To carry out UV–Visible spectroscopy, a stable and broad-spectrum light source is required to provide radiation across the ultraviolet (UV) and visible regions of the electromagnetic spectrum. The choice of lamp depends on the wavelength range of interest and the intensity stability required for accurate absorbance measurements (Skoog et al., 2018; Holler et al., 2014).

(i) Hydrogen Lamp :

A hydrogen discharge lamp emits continuous ultraviolet radiation in the range of approximately 160–380 nm. It operates by passing an electric current through hydrogen gas under low pressure, which excites the gas molecules and results in the emission of UV light. Although reliable and cost-effective, hydrogen lamps are gradually being replaced by deuterium lamps due to their superior stability (Sharma, 2019).

(ii) Deuterium Lamp :

The deuterium lamp is the most widely used UV source in modern spectrophotometers. It produces a continuous emission spectrum in the 160– 450 nm range and offers higher intensity and long-term stability compared to the hydrogen lamp. The light is generated when a high voltage excites deuterium gas, causing it to emit UV radiation as it returns to the ground state (Pavia et al., 2015; Kumar & Sharma, 2021).

(iii) Tungsten Lamp :

The tungsten filament lamp, also known as a tungsten-halogen lamp, is the standard light source for the visible region (approximately 330–900 nm). It operates similarly to an incandescent bulb, where an electric current heats a tungsten filament, causing it to emit visible and near-infrared light. Tungsten lamps are often used in combination with deuterium lamps to cover both UV and visible ranges in a dual-lamp spectrophotometer (Raman & Singh, 2020).

(iv) Xenon Discharge Lamp :

The xenon discharge lamp contains xenon gas that emits a strong, continuous spectrum from 250 to 600 nm. It provides intense radiation suitable for both UV and visible analysis. Due to its high brightness and fast response, it is frequently used in instruments that require pulsed or flash illumination, such as highperformance spectrophotometers (Hollas, 2004; Bathaie & Farajzadeh, 2019). (v) **Combined Light Source :**

Most modern UV–Visible spectrophotometers employ a combination of deuterium (UV region) and tungsten (visible region) lamps. The instrument automatically switches between the two depending on the wavelength range being measured, ensuring continuous coverage from 190 to 900 nm (Skoog et al., 2018).

Types of UV Spectroscopic Analytical Techniques :

Several UV spectroscopic analytical methods have been developed to enhance the accuracy, selectivity, and sensitivity of quantitative and qualitative analyses. The most commonly used techniques include the Simultaneous Equation Method, Difference Spectrophotometry, Derivative Spectrophotometry, Absorbance Ratio Method, Dual Wavelength Method, Isosbestic Point Method, Absorbance Factor Method, and Chemometric Multivariate Methods (Kumar & Sharma, 2022; Skoog et al., 2018).

1. Simultaneous Equation Method :

The simultaneous equation method is widely employed for the analysis of multicomponent mixtures, particularly binary or ternary drug combinations that exhibit overlapping absorbance spectra. In this method, the absorbance of each component at two selected wavelengths is measured, and two simultaneous linear equations are formed based on Beer–Lambert's law.

If the absorptivity values of component X at wavelengths λ_1 and λ_2 are ax_1 and ax_2, and those of component Y are ay_1 and ay_2, the total absorbance at each wavelength can be expressed as:

A_1 = a_{x1} b c_x + a_{y1} b c_y
A_2 = a_{x2} b c_x + a_{y2} b c_y

Assuming a path length (b) of 1 cm, the concentrations of X and Y can be calculated by solving these equations. The Glenn criterion for maximum precision suggests that the ratio of the absorbance values of both components should lie outside the range of 0.1–2 to ensure accurate quantification (Patel et al., 2021).

For reliable results, the λmax of both components should be sufficiently different, and the mixture should not undergo chemical interactions that violate the additivity of absorbance principle (Pavia et al., 2015).

2. Difference Spectrophotometry :

Difference spectrophotometry is a selective technique that measures the difference in absorbance (ΔA) between two equimolar solutions of the same analyte under different physicochemical conditions, such as variations in pH, temperature, or solvent polarity.

This method enhances selectivity and precision when analyzing complex formulations, as it isolates the analyte from other absorbing substances. The measured parameter is the amplitude difference between maxima and minima in the difference spectrum, which is plotted against analyte concentration (Kumar & Sharma, 2022).

The technique is especially valuable for :

Studying binary mixtures where one component's absorbance is nullified at the selected wavelength.

Determining analytes that exist in multiple chemical forms with different extinction coefficients.

Reducing interference from excipients in pharmaceutical dosage forms (Patel et al., 2021).

Furthermore, difference spectroscopy has applications in protein characterization and biopharmaceutical formulations, where changes in the difference spectra reflect variations in protein conformation and stability (Gupta & Singh, 2020).

3. Derivative Spectrophotometry :

Derivative spectrophotometry involves the mathematical transformation of a normal (zero-order) absorption spectrum into its first, second, or higher derivatives. This technique is highly effective for resolving overlapping spectral bands, eliminating baseline shifts, and enhancing spectral resolution (Skoog et al., 2018).

Historically, derivative spectra were obtained using optical modulation or electrical signal processing, but modern instruments now apply mathematical algorithms like the Savitzky–Golay smoothing method to generate derivative spectra digitally (Pavia et al., 2015).

4. Ratio-Derivative Spectroscopy :

Ratio-derivative spectroscopy is used for the quantitative estimation of two or more components in a single sample without preliminary separation. Developed from the work of Salinas et al., this method mathematically divides the absorption spectrum of a mixture by that of a standard component, producing ratio spectra.

By differentiating these ratio spectra, the analyst can identify wavelengths corresponding to peaks and troughs, which represent maximum analytical signals for each compound (Gupta & Singh, 2020).

This approach is especially valuable when component spectra overlap, as it allows measurement of one analyte in the presence of others and reduces interference from excipients or co-formulated drugs.

5. Successive Ratio-Derivative Spectra Method :

The successive ratio-derivative method is an extension of the ratio-derivative technique. It enables the estimation of drugs in ternary mixtures even when the concentration ratio among the components is unknown. Through successive mathematical treatment of ratio spectra, individual compound contributions are isolated and quantified (Patel et al., 2021).

6. Q-Absorbance Ratio Method :

The Q-absorbance ratio method, also called the Hufner ratio method, applies to systems obeying Beer–Lambert's law. It is based on the principle that the ratio of absorbances at any two selected wavelengths remains constant for a given substance, independent of concentration and path length (Skoog et al., 2018). Typically, one wavelength corresponds to the λmax of one component, while the other represents an iso-absorptive point where both components exhibit equal absorbance. The concentration of each drug can then be determined using simple ratio equations (Kumar & Sharma, 2022).

7. Absorptivity Factor Method :

This technique is a modification of the classical absorption method and is suitable for binary mixtures with markedly different absorptivities. It requires that no iso-absorptive point exist between the two components. The absorption factor (F) is calculated from the ratio of absorbances at chosen wavelengths where both components show measurable but unequal absorbance.

Linear regression of absorbance versus concentration for one drug, while nullifying the interference of the other, allows the determination of both analytes in the same mixture (Patel et al., 2021).

8. Absorption Factor Method :

The absorption factor method is applied when one component exhibits interference at the λmax of another. In such cases, the average absorbance factor is computed to correct for overlapping spectra.

For components X and Y, the absorbance factor is determined using the average ratio of their absorbance values at specific wavelengths. Once the concentration of Y is found, the concentration of X can be derived using the modified Beer–Lambert relationship. This approach is particularly effective in the 200–400 nm range for resolving binary mixtures without prior separation (Gupta & Singh, 2020).

9. Multivariate Chemometric Methods :

Multivariate analysis, often called chemometric UV analysis, uses advanced statistical and mathematical modeling to interpret spectral data. Instead of relying on single-wavelength measurements, multiple non-selective signals are combined to build a multivariate calibration model, enhancing accuracy and reducing interference (Skoog et al., 2018).

These methods consider several spectral variables simultaneously, making them ideal for analyzing complex or overlapping spectra. Techniques such as Principal Component Regression (PCR) and Partial Least Squares (PLS) are frequently applied in pharmaceutical assays to quantify multicomponent formulations (Patel et al., 2021).

10. Isosbestic Point Method :

The isosbestic point method is used when two compounds possess equal molar absorptivities at a specific wavelength, termed the isosbestic point. At this wavelength, the total absorbance is directly proportional to the sum of the concentrations of both components.

Mathematically,

$A = a_x C_x + a_y C_y = a_x (C_x + C_y)$

Thus, the total absorbance directly gives . If one species' concentration is known by another method, the other can be obtained by subtraction.

This approach is useful especially in stability or purity studies, and has been applied, for example, to the analysis of ternary mixtures of chloramphenicol, dexamethasone sodium phosphate, and tetrazoline hydrochloride in eye drops (Kumar & Sharma, 2022; Patel et al., 2021).

Calibration / Validation of UV–Vis Spectrophotometers :

To ensure accurate, reliable measurements, a UV–Vis instrument must be validated and periodically calibrated. Key performance parameters include:

1. Stray Light (Limit of stray light) :

Stray light refers to unintended light reaching the detector (e.g. via scattering or stray paths) that is outside the nominal wavelength. This can distort absorbance readings, particularly at high absorbance levels. It is commonly tested using cut-off filters or concentrated solutions. For example, a 1.2% (w/v) potassium chloride solution may be used at ~200 nm, and the instrument should show absorbance > 2.0 to meet acceptance criteria.

2. Resolution / Resolving Power :

This ensures the instrument can distinguish closely spaced spectral features. A standard test is the spectrum of toluene in hexane (0.02% v/v): the ratio of absorbance maxima and minima near ~269 nm (versus ~266 nm) must exceed a certain threshold (often ≥ 1.5).

3. Wavelength Accuracy / Wavelength Control :

The instrument's assigned wavelengths must be verified against known reference standards (such as holmium oxide, mercury vapor lines). The tolerance is often ±1 nm in the UV region (200–400 nm) and ±3 nm in higher ranges.

Typical Reference Lines :

Wavelength (nm) Source Element
241.15nm Ho
253.70nm Hg
287.15nm Ho
313.16nm Hg
334.15nm Hg
361.50nm Ho
365.48nm Hg
404.66nm Hg
435.83nm Hg
486.00nm Hβ
536.30nm Ho
546.07nm Hg
576.96nm Hg
579.07nm Hg

4. Control of Absorbance and Wavelength Accuracy : To ensure proper functioning and reliability of a UV–Visible spectrophotometer, the wavelength and absorbance scales must be routinely verified using standard reference materials.

4.1 Wavelength Accuracy : Wavelength accuracy is confirmed by comparing the instrument readings with the known absorption maxima of holmium oxide, mercury vapor, or hydrogen–deuterium discharge lamps. The tolerance limits are generally ±1 nm for the range 200–400 nm and ±3 nm for 400–600 nm (USP <857>, 2023; Pharmaguideline, 2021).

The following table shows the acceptable absorbance range at specific wavelengths (Holmium oxide filter standard):

Wavelength (nm)	Specific Absorbance	Acceptance Range
235	124.5	122.9 – 126.2
257	144.5	142.8 – 146.2
313	48.6	47.0 – 50.3

350	107.3	105.6 – 109.0
430	15.9	15.7 – 16.1

Table : 1 Wavelength against absorption maxima

5. Spectral Slit Width :

The spectral bandwidth (slit width) determines how narrowly the spectrophotometer isolates the selected wavelength. When measuring absorbance at a wavelength maximum, the slit width must be small relative to the half-width of the absorption band. A wide slit allows additional wavelengths to pass through, which may cause erroneously low absorbance values. Once the width is sufficiently small, further reduction should not significantly change the absorbance (Skoog et al., 2018; Pharmaguideline, 2021).

6. Cuvette (Cell) Requirements :

Cuvettes used for UV–Vis analysis must be optically transparent, clean, and matched.

When a reference cuvette is filled with solvent, its absorbance (against air) should not exceed 0.4, and ideally be below 0.2.

The solvent must be identical to that used in sample preparation and should not fluoresce at the measurement wavelength. For example, ethanol, methanol, or cyclohexane are often used, but their absorbance at 254 nm (1 cm pathlength) must not exceed 0.10 (USP <857>, 2023).

7. Solvent Cut-Off Wavelengths :

Each solvent exhibits strong UV absorption below a characteristic wavelength, called the cut-off wavelength. Measurements below this wavelength are unreliable because the solvent absorbs strongly, causing false absorbance readings from the analyte.

When selecting a solvent, the compound's expected absorbance range should be well above the solvent's cut-off limit.

Solvent	Cut-Off (nm)
Water	180
Cyclohexane	200
Iso-octane	202
Ethanol	205
Carbon tetrachloride	265
Benzene	280
Tetrachloroethylene	290
Acetone	325

Table : 2 Common Solvents and Their Cut-Off Wavelengths

Key advantages of derivative spectrophotometry include:

1. Separation of overlapping peaks in multicomponent systems.
2. Reduction of background interference and light scattering.
3. Direct analysis of complex samples (e.g., biological fluids, dosage forms).
4. Improved detection of minor impurities.

Common measurement techniques include the zero-crossing method and peakthrough method, which rely on wavelength points where one component shows zero absorbance, allowing quantification of the other.
Derivative spectroscopy is extensively used in pharmaceutical, clinical, and environmental studies, such as for the quantification of diazepam in human plasma without prior sample extraction (Gupta & Singh, 2020).

Monochromator :
A monochromator is an optical device used to isolate light of a single wavelength (monochromatic light) from a mixture of wavelengths
(polychromatic light). It is essential for precise wavelength selection during absorbance measurements (Holler et al., 2014).

The process involves several key components:

1. Entrance Slit – Allows a narrow beam of light to enter the monochromator.
2. Collimating Lens – Converts divergent light into parallel rays.
3. Dispersing Element (Prism or Diffraction Grating) – Separates the polychromatic light into its component wavelengths, similar to the dispersion of sunlight into a rainbow.
4. Focusing Lens – Directs a specific wavelength toward the exit slit.
5. Exit Slit – Selects the desired monochromatic light to pass through the sample cell for analysis.

The position of the prism or grating determines the wavelength that exits the monochromator, allowing accurate wavelength scanning across the UV–Visible spectrum (Raman & Singh, 2020; Pavia et al., 2015).

➢ **Types of Monochromators:**

(i) Prism monochromator
(ii) Grating monochromator

(i) **Prism Monochromator -** Uses a glass prism to separate light.

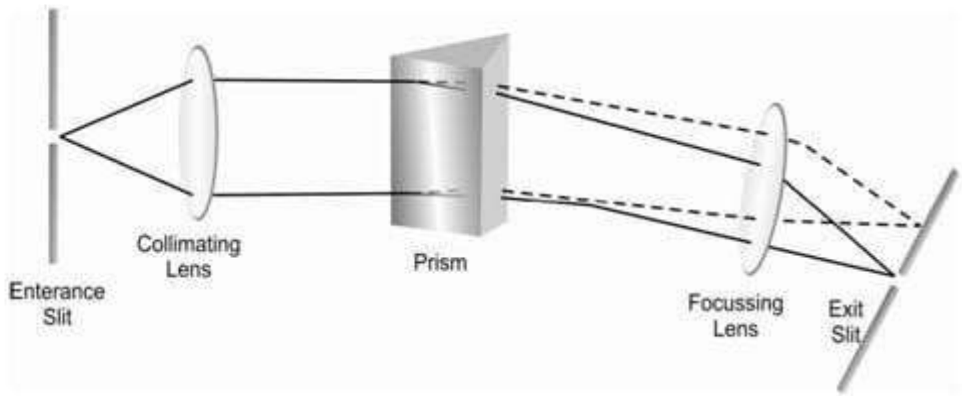

Figure : 3 Prism Monochromator

(ii) **Grating Monochromator -** Uses a diffraction grating for more precise separation. Main Components of a Monochromator.
Entrance slit
Collimating lens

Dispersing device (prism or grating)
Focusing lens
Exit slit

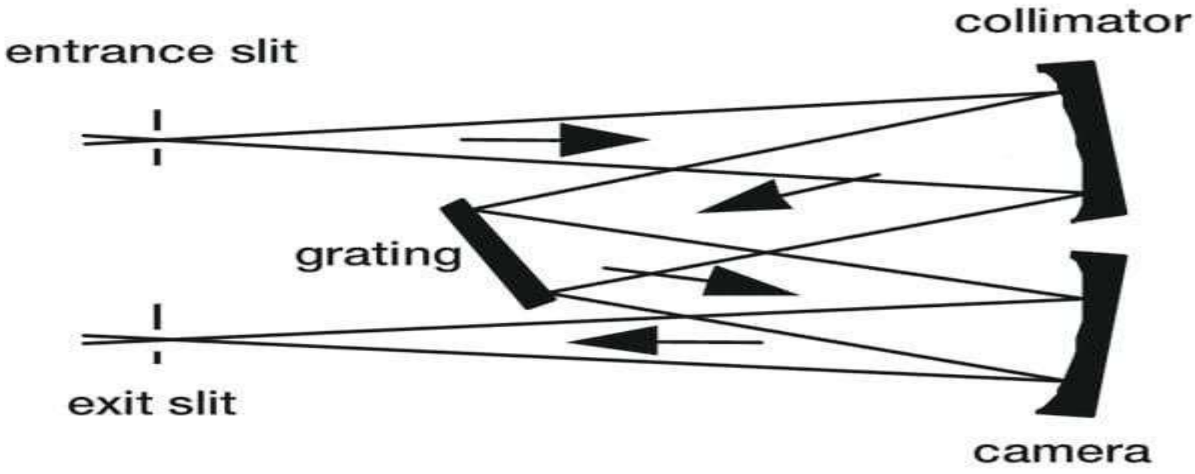

Figure : 4 Grating Monochromator

Advantages of UV-Vis Spectroscopy:

1. **High Sensitivity :** UV-Vis spectroscopy can detect even minimal changes in absorbance, allowing for the identification of trace quantities of compounds in a sample (Ghosh & Nandi, 2024).

2. **Rapid Analysis :** The technique provides quick results, which makes it suitable for routine and high-throughput analytical applications (Technology Networks, 2024).
3. **Simplicity and Cost-Effectiveness :** Instruments used for UV-Vis analysis are relatively inexpensive, easy to maintain, and simple to operate compared to other advanced spectroscopic methods (Cook, 2023).
4. **Versatility of Samples :** It can be applied to liquids, solids, and gases, providing flexibility in different analytical fields (Mettler-Toledo, 2017). **5. Quantitative Accuracy :** This method offers reliable quantification of analytes by applying Beer-Lambert's law (Reule, 2017).
6. **Substance Identification :** The spectral patterns help identify compounds based on their absorbance characteristics, which are often unique to specific chromophores (Ghosh & Nandi, 2024).
7. **Non-Destructive Nature :** Samples remain chemically unchanged after testing, making the method suitable for repeated measurements (Technology Networks, 2024).
8. **Broad Applicability :** UV-Vis spectroscopy is widely used in chemistry, biology, environmental analysis, pharmaceuticals, and materials science (Cook, 2023).

Disadvantages of UV-Visible Spectroscopy :

1. **Limited Structural Information :** UV-Vis spectroscopy primarily identifies conjugated systems and chromophores but cannot provide detailed molecular structural data (Mettler-Toledo, 2017).
2. **Interference from Impurities :** The presence of impurities that absorb at similar wavelengths may distort the absorbance spectrum, reducing accuracy (Reule, 2017).
3. **Sample Limitations :** Turbid, fluorescent, or poorly soluble samples may scatter light, leading to errors in measurement (Technology Networks, 2024). **4. Instrumental Constraints :** Instrument-related issues like stray light, wavelength drift, or detector instability can introduce measurement errors (Reule, 2017).
5. **Low Sensitivity for Certain Analytes :** Some molecules exhibit weak absorbance, limiting the method's ability to detect them in very low concentrations (Ghosh & Nandi, 2024).

6. **Need for Careful Sample Preparation :** Samples must be free of dust, bubbles, and absorbing solvents to ensure reliable readings (Cook, 2023).

Applications of UV-Vis Spectroscopy :

UV-Visible spectroscopy is a versatile method with numerous applications across different scientific fields. Below are some of its major uses: **1. Quantitative Analysis :** By applying the Beer–Lambert law, UV-Vis spectroscopy enables accurate determination of the concentration of analytes in solution (De Caro et al., 2025).

2. **Qualitative Analysis :** It helps in identifying compounds by comparing their absorption spectra to reference spectra of known substances (Ghosh & Nandi, 2024; De Caro et al., 2025).

3. **Pharmaceutical Industry :** UV-Vis is widely used in pharmaceutical laboratories for drug identification, purity assessment, and detection of impurities in drug formulations (The Application of Ultraviolet-Visible Spectrophotometry in Pharmaceutical Analysis, 2024).

4. **Materials Science :** It aids in characterizing nanomaterials, polymers, thin films, and other materials by studying their optical absorption, band gaps, and electronic transitions (Ghosh & Nandi, 2024; IJPRA Journal, UV-Visible Review, 2024).

5. **Environmental Testing :** UV-Vis spectroscopy is applied in monitoring pollutants and contaminants in water, air, and soil. For example, online UV-Vis spectrophotometers are used in drinking water quality monitoring and process control (Applications of Online UV-Vis Spectrophotometer for Drinking Water, 2022).

Conclusion :

UV-Visible spectroscopy is a powerful and widely used analytical technique that enables scientists to understand how molecules absorb light and thus infer structural and electronic properties. Thanks to its high sensitivity, rapid analysis, non-destructive nature, and broad versatility, it finds applications across chemistry, biology, pharmacy, environmental science, and materials research. Using this method, researchers can deepen their understanding of molecular behavior, validate compound identity, and drive innovations in science and technology.

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