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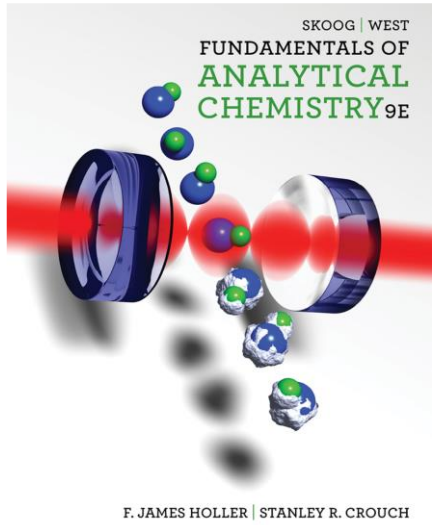
1.



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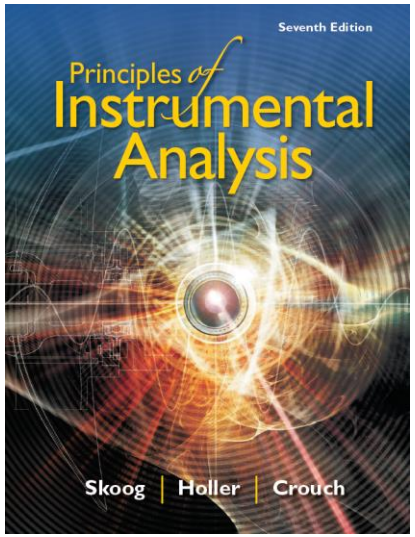

3. ATAKOL's lecture notes

1. Skoog, D.A., West, D.M., Holler, J.F., Crouch, S.R. 2013. Fundamentals of Analytical Chemistry (9E). Cengage Learning, Belmont, USA.
2. Skoog, D.A., Holler, J.F., Crouch, S.R. 2016. Principles of Instrumental Analysis (7E). Cengage Learning, Boston, USA.
3. Prof. Dr. Orhan ATAKOL's lecture notes.

Nuclear Magnetic Resonance Spectroscopy (Basics and Principles)

- Nuclear magnetic resonance (NMR) spectroscopy is based on the measurement of absorption of electromagnetic radiation in the radio frequency region of roughly 4 to 900 MHz.

- In contrast to UV, visible, and lR absorption, nuclei of atoms rather than outer electrons are involved in the absorption process. Furthermore, to cause nuclei to develop the energy states required for absorption to occur, it is necessary to place the analyte in an intense magnetic field.

- NMR spectroscopy is one of the most powerful tools available to chemists and biochemists for elucidating the structure of chemical species. The technique is also useful for the quantitative determination of absorbing species.

- Two general types of NMR spectrometers are currently in use, continuous-wave (CW) and pulsed, or Fourier transform (FT-NMR), spectrometers.
- In both types of instruments, the sample is positioned in a powerful magnetic field that has a strength of several tesla.
- CW spectrometers are similar in principle to optical absorption instruments in that an absorption signal is monitored as the frequency of the source is slowly scanned.
- In pulsed instruments, the sample is irradiated with periodic pulses of RF energy that are directed through the sample at right angles to the magnetic field. These excitation pulses elicit a time-domain signal that decays in the interval between pulses.
- This signal is then converted to a frequency-domain signal by using a Fourier transformation to give a spectrum similar to that obtained by using a CW instrument. Nearly all NMR instruments produced today are of the FT type.

Theory of NMR

- To account for the properties of certain nuclei, we must assume that they rotate about an axis and thus have the property of spin Nuclei with spin have angular momentum p. Furthermore, the maximum observable component of this angular momentum is quantized and must be an integral or a half-integral multiple of $h/2\pi$, where h is Planck's constant.
- The maximum number of spin components or values for p for a particular nucleus is its spin quantum number.
- The nucleus will then have $2I + 1$ discrete states.
- The component of angular momentum for these states in any chosen direction will have values of $I, I - 1, I - 2 \ldots\ldots -I$.
- In the absence of an external field, the various states have identical energies
- The four nuclei that have heen of greatest use to organic chemists and biochemists are ^{1}H, ^{13}C, ^{19}F, and ^{31}P. The spin quantum number for these nuclei is ½.

- The difference in energy ΔE between the two states is given by

$$\Delta E = \frac{\gamma h}{4\pi} B_0 - \left(-\frac{\gamma h}{4\pi} B_0\right) = \frac{\gamma h}{2\pi} B_0$$

- As in other types of spectroscopy, transitions between energy states can be brought about by absorption or emission of electromagnetic radiation of a frequency ν_0 that corresponds in energy to ΔE. Thus, by substituting the Planck relationship $\Delta E = h\nu_0$, we obtain the frequency of the radiation required to bring about the transition.

$$\nu_0 = \frac{\gamma B_0}{2\pi}$$

- The frequency of a magnetic transition is proportional to the applied field strength B_0 with a proportionality constant of $\gamma/2\pi$

- In the absence of a magnetic field, the energies of the magnetic quantum states of a nucleus are identical. Consequently, a large collection of protons contains an identical number of nuclei with magnetic quantum numbers $m = +1/2$ and $m = -1/2$.
- When placed in a magnetic field, the nuclei tend to orient themselves so that the lower energy state ($m = +1/2$) predominates. It is instructive to calculate the extent of this predominance in a typical NMR experiment.

- For this purpose, the Boltzmann equation can be written in the forms:

$$\frac{N_j}{N_0} = \exp\left(\frac{-\Delta E}{kT}\right) \qquad \frac{N_j}{N_0} = \exp\left(\frac{-\gamma h B_0}{2\pi kT}\right)$$

N_j = The number of protons in the higher energy state (m = -1/2)
N_0 = The number in the lower state (m = + 1/2)
k = Boltzmann's constant (1.38×10^{-23} $J.K^{-1}$)
T = The absolute temperature.

- If the numbers of nuclei in the two states were identical, however, we would observe no net absorption because the number of particles excited by the radiation would exactly equal the number producing induced emission.
- Equations demonstrates that the relative number of excess low-energy nuclei is linearly related to the magnetic field strength. Thus, the intensity of an NMR signal increases linearly as the field strength increases. This dependence of signal sensitivity on magnetic field strength has led manufacturers to produce magnets with field strengths as large as 14 T.

- In NMR studies, then, nonradiative relaxation processes are of prime importance
- To reduce saturation and produce a readily detectable absorption signal, relaxation should occur as rapidly as possible; that is, the lifetime of the excited state should be small
- A second factor (the inverse relationship between the lifetime of an excited state and the width of its absorption line) negates the advantage of very short lifetimes
- Thus, when relaxation rates are high, or the lifetimes low, line broadening prevents high-resolution measurements
- These two opposing factors cause the optimal half-life for an excited species to range from about 0.1 to 10 s.

In NMR studies, then, nonradiative relaxation processes are of prime importance. Two types of relaxation processes are important in NMR spectroscopy:

(1) spin-lactice, or longitudinal relaxation

(2) spin-spin, or transverse relaxation

Types of NMR Spectra

There are several types of NMR spectra, depending on the kind of instrument used, the type of nucleus involved, the physical state of the sample, the environment of the analyte nucleus, and the purpose of the data collection. Most NMR spectra canbe categorized as

Wide-Line Spectra

- Wide-line spectra are those in which the bandwidth of the source of the lines is large enough that the fine structure due to chemical environment is obscured.

High-Resolution Spectra

- Most NMR spectra are high resolution and are collected by instruments capable of differentiating between very small frequency differences of 0.01ppm or less. For a given isotope such spectra usually exhibit several resonances that result from differences in their chemical environment.

- Small differences occur in the absorption frequency of the proton; such differences depend on the group to which the hydrogen atom is bonded. This effect is called the **chemical shift.**
- Both the chemical shift and spin-spin splitting are important in structural analysis.
- Experimentally, the two are easily distinguished, because the peak separations resulting from a chemical shift are directly proportional to the field strength or to the oscillator frequency.
- The use of an internal standard is also advantageous in that chemical shifts can be reported in terms that are independent of the oscillator frequency. The internal standard used depends on the nucleus being studied and the solvent system. The compound most generally used for proton studies is tetramethylsilane (TMS), $(CH_3)_4Si$.

Rules Governing the Interpretation of First-Order Spectra

1. Equivalent nuclei do not interact with one another to give multiple absorption peaks
   The three protons in the methyl groups in ethanol give rise to splitting of only the adjacent methylene protons and not to splitting among themselves.
2. Coupling constants decrease significantly with separation of groups, and coupling is seldom observed at distances greater than four bond lengths.
3. The multiplicity of a band is determined by the number n of magnetically equivalent protons on the neighboring atoms and is given by the quantity n+1. Thus, the multiplicity for the methylene band in ethanol is determined by the number of protons in the adjacent methyl groups and is equal 3+1=4.
4. If the protons on atom B are affected by protons on atoms A and C that are nonequivalent, the multiplicity of B is equal to $(n_A+1)(n_C+1)$, where n_A and n_C are the number of equivalent protons on A and C respectively.
5. The approximate relative areas of a multiplet are symmetric around the midpoint of the band and are proportional to the coefficients of the terms in the expansion $(x+1)^{n.}$
   The application of this rule is demonstrated in Table 19-3 and in the examples that follow
6. The coupling constant is independent of the applied field; thus, multiplets are readily distinguished from closely spaced chemical-shift peaks by running spectra at two different field strengths.

NMR Spectrometers

Instrument manufacturers market two general types of NMR spectrometers:

- Wide-line spectrometers
- High-resolution spectrometers

Wide-line instruments have magnets with strengths of a few tenths of a tesla and are considerable simpler and less expensive than are high-resolution instruments. High-resolution instruments are equipped with magnets with strengths that range from 1,4 to 23 T, which correspond to proton frequencies of 60 to 1000 MHz (1 GHZ).

Application of Proton NMR

- The most important chemical applications of proton NMR spectroscopy have been to the identification and structural elucidation of organic, metal-organic, and biochemical molecules.

- In addition, however, the method is often useful for quantitative determination of absorbing species.