uc3m | Universidad Carlos III de Madrid

OpenCourseWare (2023)

CHEMISTRY II

Verónica San Miguel Arnanz

Teresa Pérez Prior

Berna Serrano Prieto

Department of Materials Science and Engineering and Chemical Engineering

STRUCTURAL DETERMINATION

1. INTRODUCTION

Spectroscopy, a method for scrutinizing molecular structures, hinges on disparities in how molecules absorb electromagnetic radiation. Electromagnetic radiation, conveyed through waves characterized by wavelength (λ) or frequency (ν), is scrutinized using this technique. Spectroscopy capitalizes on the principle that molecules absorb electromagnetic radiation in distinct "packets" of energy, or quanta. This absorption occurs when the compound under examination encounters radiation supplying the requisite packet. The absorbed energy induces electronic or mechanical motion within the molecule, known as excitation, culminating in an absorption peak in a graph.

While numerous spectroscopic methods exist, four are particularly prevalent in organic chemistry: (1) nuclear magnetic resonance (NMR) spectroscopy; (2) infrared (IR) spectroscopy; (3) ultraviolet (UV) spectroscopy; and, based on a different principle, (4) mass spectrometry (MS). Spectroscopy encompasses the study of the physical interaction of matter with electromagnetic waves of different wavelengths.

Electromagnetic radiation manifests itself in the form of waves, with a wave being characterized either by its wavelength (λ) or its frequency (ν) Specific mathematical expressions express the relationship between these two properties:

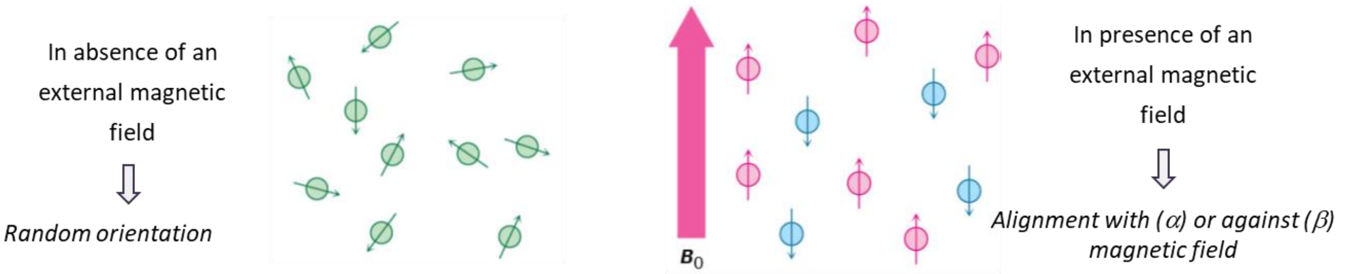
$$\nu = \frac{c}{\lambda}$$

Spectroscopy, as a technique, operates on the fundamental principle that molecules selectively absorb electromagnetic radiation. This absorption phenomenon occurs exclusively when the incident radiation precisely delivers the required quantum to the scrutinized compound. If the frequency of the incoming radiation is ν, the corresponding quantum possesses energy defined as $\Delta E = h\nu$.

The energy absorption initiates electronic or mechanical motion within the molecule, a phenomenon termed excitation. This motion is also quantized, and given that a molecule can undergo various types of excitation, each distinct motion necessitates its specific energy. For instance, infrared radiation induces vibrational excitation of a compound's chemical bonds, while radio waves can induce changes in the alignment of nuclear magnetism within a magnetic field. In essence, spectroscopy exploits the quantized nature of molecular motions in response to electromagnetic radiation to acquire valuable insights into molecules' structural and dynamic characteristics.

2. NUCLEAR MAGNETIC RESONANCE

Nuclear Magnetic Resonance (NMR) spectroscopy utilizes low-energy radiation within the radio-frequency (RF) range. Various nuclei, behaving like spinning magnets due to their positive charge, interact with an external magnetic field (B_0). Both proton (^1H) and ^{13}C nuclei exhibit this behavior, acting as tiny magnets in a strong external magnetic field. Without an external magnetic field, magnetic nuclei spins are randomly oriented; when placed within the poles of a strong magnet, these nuclei align in specific orientations (Figure 1).



Source: Organic Chemistry. A tenth Edition. John McMurry, Cornell University (Emeritus), CC BY-SA 4.0, https://openstax.org/details/books/organic-chemistry.

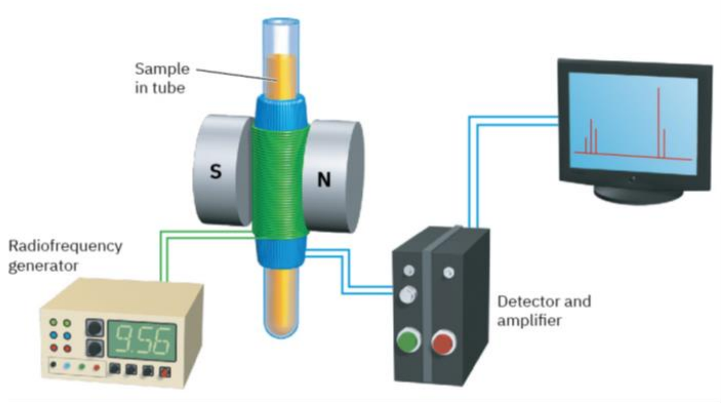
Figure 1. Nuclear spins oriented randomly in the absence of an external magnetic field and with a specific orientation in the presence of an external field, B_0.

A spinning nucleus can align parallel or antiparallel to the external field, with the parallel orientation slightly lower in energy. Irradiating the oriented nuclei with proper-frequency electromagnetic radiation causes energy absorption, resulting in a "spin-flip" to the higher-energy state, leading to nuclear magnetic resonance.

During NMR spectroscopy, a sample containing an organic compound is irradiated with a pulse of RF radiation, promoting nuclei from the α to the β spin state. The emitted signals, detected by the NMR spectrometer, create a graph of frequencies versus intensity, forming the NMR spectrum. The resonance frequency depends on the external magnetic field's strength and the nuclei's identity. Nuclei with an odd number of protons or neutrons exhibit magnetic properties. Surrounding electrons shield nuclei from the whole external magnetic field, creating slight differences in effective magnetic fields for each nucleus, resulting in distinct NMR signals. An NMR spectrum effectively maps the carbon-hydrogen framework of an organic molecule.

2.1. NMR Absorptions

To acquire an NMR spectrum, the sample is dissolved in a deuterated solvent to eliminate solvent peaks. The NMR tube is rapidly spun to average molecular positions in the magnetic field. The resulting spectrum is recorded by varying the magnetic field strength, allowing each nucleus to come into resonance at different field strengths. The performance of a basic NMR spectrometer is shown in Figure 2.



Source: Organic Chemistry. A tenth Edition. John McMurry, Cornell University (Emeritus), CC BY-SA 4.0, https://openstax.org/details/books/organic-chemistry.

Figure 2. Schematic performance of an NMR spectrometer.

2.2. Chemical Shifts

NMR spectra are displayed on charts, with downfield and upfield sides indicating lower and higher shielding, respectively (Figure 3). The chemical shift, denoted as δ, is the position where a nucleus absorbs, influenced by the electron density and structural environment. Tetramethylsilane (TMS) is often used as a reference standard. Calibration is done using the delta (δ) scale, and reported literature spectra often standardize the measured frequency to yield a field-independent chemical shift (δ).

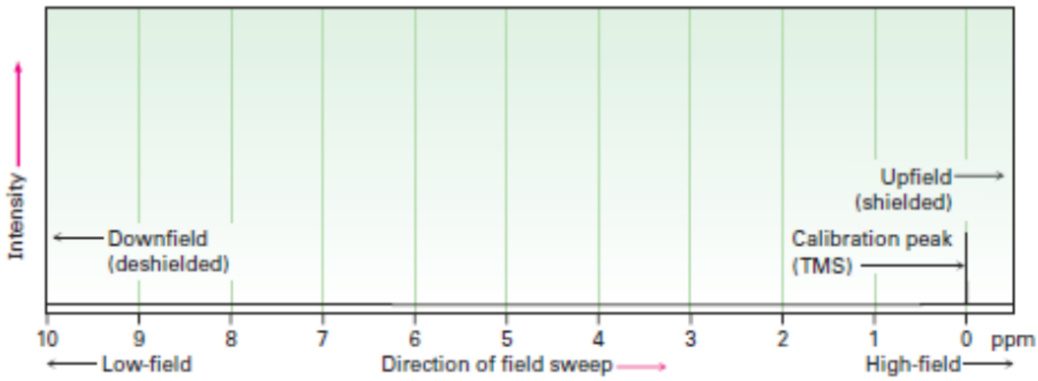
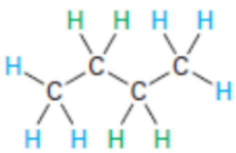


Figure 3. The NMR chart. The downfield, on the left, represents the lower field strength for resonance and in the upfield, on the right, represents the higher field strength and nuclei are more shielding.

2.3. ^{1}H NMR

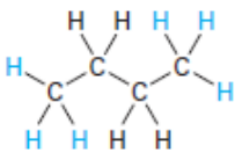
Each electronically distinct hydrogen in a molecule exhibits a unique absorption in ^{1}H NMR, aiding in identifying nonequivalent hydrogens. For smaller molecules, a visual inspection of the structure often reveals the number of proton types and potential NMR absorptions. When uncertainty arises, the equivalence of two protons can be determined by considering the structural consequences of substituting each hydrogen with an X group. Two possibilities emerge:

Chemically Unrelated Protons (*Nonequivalent*): Protons are distinct, leading to different constitutional isomers upon substitution with X.



The $-CH_2-$ and $-CH_3$ hydrogens are unrelated and have different NMR absorptions

Chemically Identical Protons (*Homotopic*): Protons are identical and electronically equivalent, yielding the same product regardless of the substituted hydrogen.



The six $-CH_3$ hydrogens are homotopic and have the same NMR absorption

Chemical shifts in ^{1}H NMR result from local magnetic fields created by surrounding electrons. More shielded nuclei, requiring a higher applied field, absorb on the right side of the NMR chart, while less shielded nuclei absorb on the left (Figure 4). The chemical shift regions (0 to 10 d) provide clues about the proton types in a molecule. Protons bonded to saturated, sp^3-hybridized carbons generally absorb at higher fields, while those bonded to sp^2-hybridized carbons absorb at lower fields. Protons near electronegative atoms (N, O, or halogen) also absorb at lower fields. Deshielding occurs when a hydrogen is close to an electron-withdrawing group, shifting its absorption to lower field.

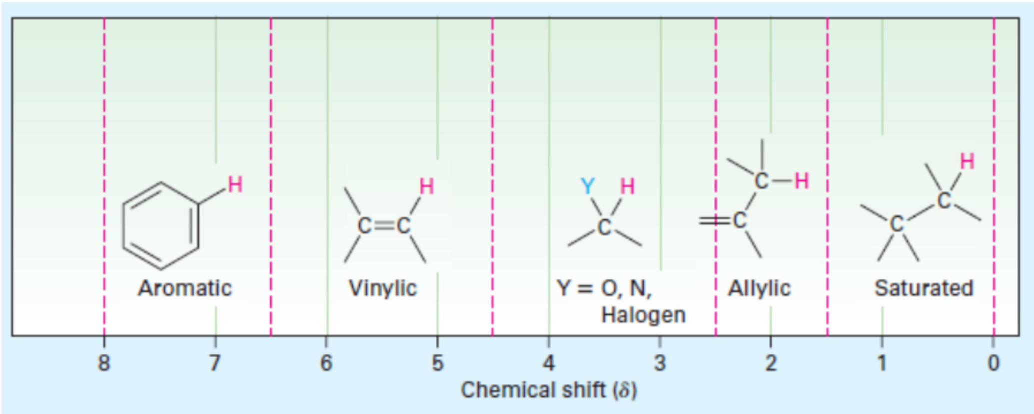


Figure 4. Chemical shifts in ^{1}H NMR.

Spin–spin splitting, caused by interactions between nearby nuclei, results in multiple absorptions. According to the n + 1 rule, protons with n equivalent neighboring protons exhibit n + 1 peaks in their NMR spectrum. The coupling constant (J) represents the distance between peaks in a multiplet. Spin-spin splitting in ^{1}H NMR can be summarized by several rules:

- Chemically equivalent protons don't show spin–spin splitting.
- A proton with n equivalent neighboring protons splits into an n + 1 multiplet with coupling constant J.
- The distance between peaks in a multiplet is the coupling constant J.

As an example, the spectrum of *para*-methoxypropiophenone illustrates these rules (Figure 5). Aromatic ring protons display a split doublet, $-OCH_3$ exhibits an unsplit singlet, and $-CH_2-$ protons adjacent to the carbonyl group form a quartet due to coupling with neighboring methyl protons. The methyl protons appear as a triplet.

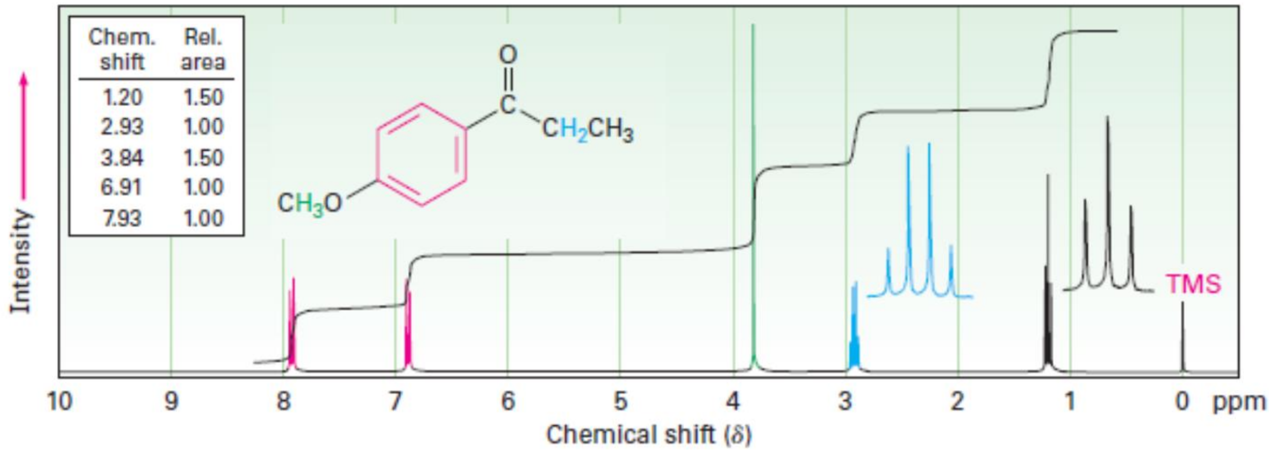


Figure 5. ^{1}H NMR spectrum of *para*-methoxypropiophenone.

2.4. ^{13}C NMR

The inherently low natural abundance of ^{13}C introduces significant noise into individual NMR spectra, as depicted in Figure 6. The signals are weak, resulting in a cluttered appearance due to random background electronic noise. A substantial improvement in the spectrum is achieved by computer-aided addition and averaging of hundreds or thousands of individual runs. In ^{13}C NMR, the low natural abundance of ^{13}C nuclei diminishes the likelihood of adjacency, leading to the absence of coupling with nearby carbons or hydrogens. Broadband decoupling is commonly employed in ^{13}C spectra, achieved by simultaneously irradiating the sample with radiofrequency energy covering both carbon and hydrogen resonance frequencies. This ensures rapid spin-flipping of hydrogens, nullifying their local magnetic fields and preventing coupling with carbon spins.

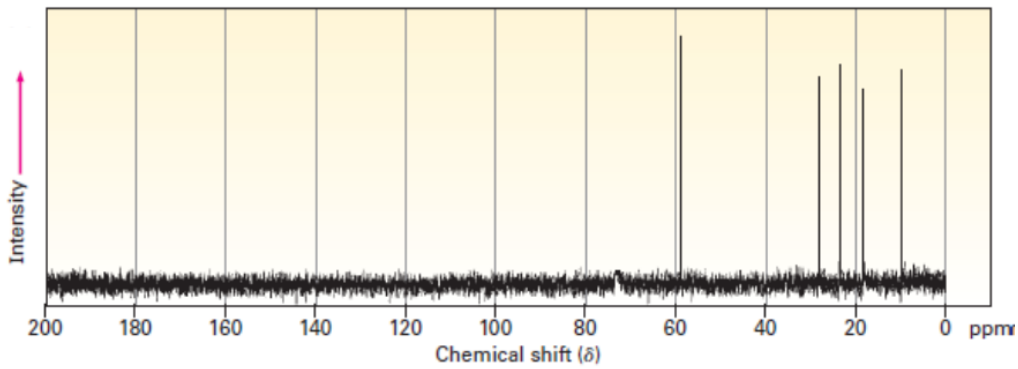
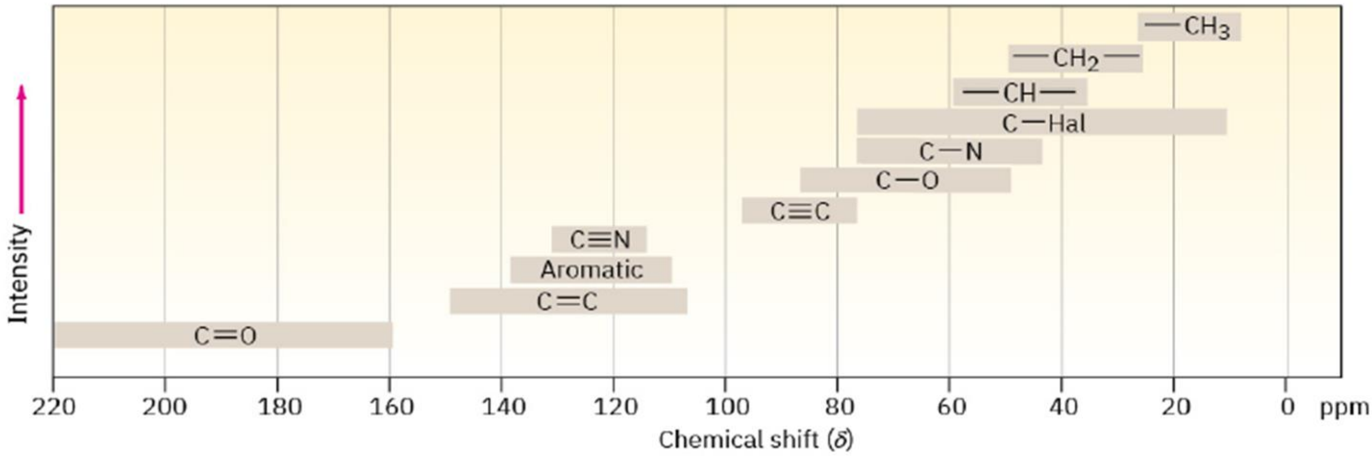


Figure 6. ^{13}C NMR spectrum of 1-pentanol.

Fundamentally, ^{13}C NMR allows for the enumeration of distinct carbon atoms within a molecule. Most ^{13}C resonances fall within the range of 0 to 220 ppm downfield from the tetramethylsilane (TMS) reference line (Figure 7). The precise chemical shift of each ^{13}C resonance is contingent upon the carbon's electronic environment within the molecule. Electronegativity of nearby atoms affects a carbon's chemical shift, with electron-withdrawing groups inducing deshielding. The order of deshielding follows primary <

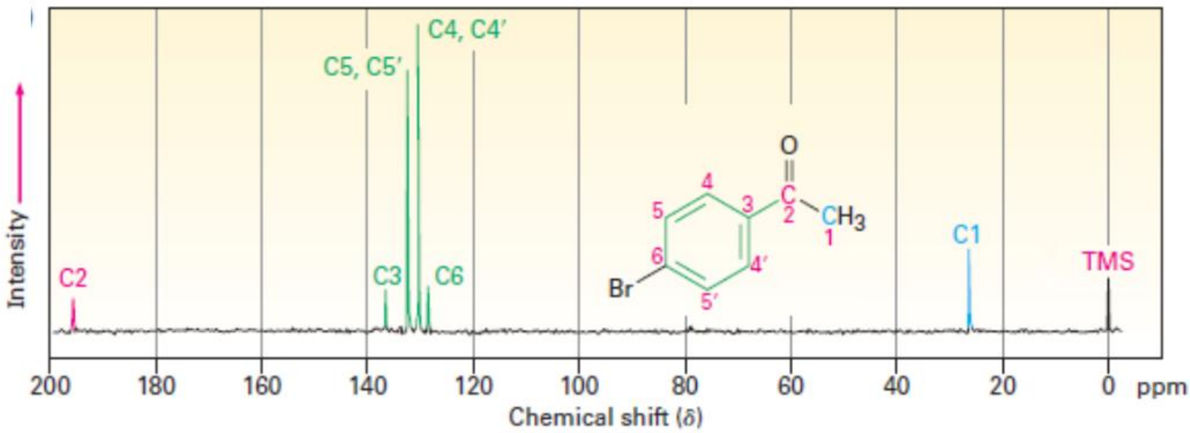
secondary < tertiary carbon, and knowledge of the number of different carbon atoms aids in structural identification. Carbons bonded to oxygen, nitrogen, or halogen absorb downfield (left) of typical alkane carbons. Electronegative atoms pull electrons away from neighboring carbons, causing deshielding and resonance at a lower field. Furthermore, sp^3-hybridized carbons generally absorb within the range of 0 to 90 ppm, while sp^2 carbons absorb from 110 to 220 ppm. Carbonyl carbons (C=O) exhibit distinctive positions in ^{13}C NMR, consistently found at the low-field end of the spectrum, ranging from 160 to 220 ppm.



Source: Organic Chemistry. A tenth Edition. John McMurry, Cornell University (Emeritus), CC BY-SA 4.0, https://openstax.org/details/books/organic-chemistry.

Figure 7. Chemical shift correlations for ^{13}C NMR.

The ^{13}C NMR spectrum of *para*-bromoacetophenone provides insights (Figure 8). Notably, only six carbon absorptions are observed, despite the molecule comprising eight carbons. Symmetry in *para*-bromoacetophenone renders certain ring carbons equivalent, resulting in four absorptions in the range of 128 to 137 ppm.



Source: Organic Chemistry. A tenth Edition. John McMurry, Cornell University (Emeritus), CC BY-SA 4.0, https://openstax.org/details/books/organic-chemistry.

Figure 8. ^{13}C NMR spectrum of *para*-bromoacetophenone.

3. INFRARED SPECTROSCOPY

Infrared spectroscopy proves highly valuable technique due to its ability to identify characteristic bonds of numerous functional groups by absorbing infrared light. This technique measures the vibrational excitation of atoms around the bonds connecting them. The absorption lines in the resulting IR spectrum positionally indicate specific functional groups, forming a distinctive pattern unique to each substance. The infrared region spans from just above the visible (7.8×10^{-7} m) to approximately 10^{-4} m, with organic chemists primarily utilizing the midportion, ranging from 2.5×10^{-6} m to 2.5×10^{-5} m. Consequently, the relevant IR region extends from 4000 to 400 cm^{-1}.

The absorption of IR radiation by organic molecules occurs due to their constant motion and energy distribution. Bonds stretch, atoms move, and molecular vibrations take place. Light-induced vibrational excitation of bonds is observed when the frequency of electromagnetic radiation matches that of the vibration. The resulting increased amplitude of the vibration provides insight into the molecule's specific motions, aiding in identifying functional groups.

Infrared spectroscopy allows the ascertainment of specific functional groups. Strong bonds and light atoms exhibit high stretching frequencies, while weak bonds and heavy atoms absorb at lower frequencies. Highly polar bonds tend to produce more intense absorption bands. Although the complete interpretation of an IR spectrum is challenging due to the multitude of bond stretching and bending motions in organic molecules, the complexity serves as a unique compound fingerprint. The fingerprint region, spanning from 1500 cm^{-1} to around 400 cm^{-1}, is particularly distinctive. Identical IR spectra strongly suggest identical compounds.

Fortunately, comprehensive interpretation is not always necessary for obtaining useful structural information. Most functional groups possess characteristic IR absorption bands that remain consistent across compounds. Recognizing the characteristic absorptions of functional groups, such as the C=O absorption of a ketone or the O-H absorption of an alcohol, facilitates structural analysis.

The Figure 9 illustrates characteristic IR bands of common functional groups. Bonds with different strengths and lengths vibrate at distinct frequencies, enabling the discrimination of functional groups.

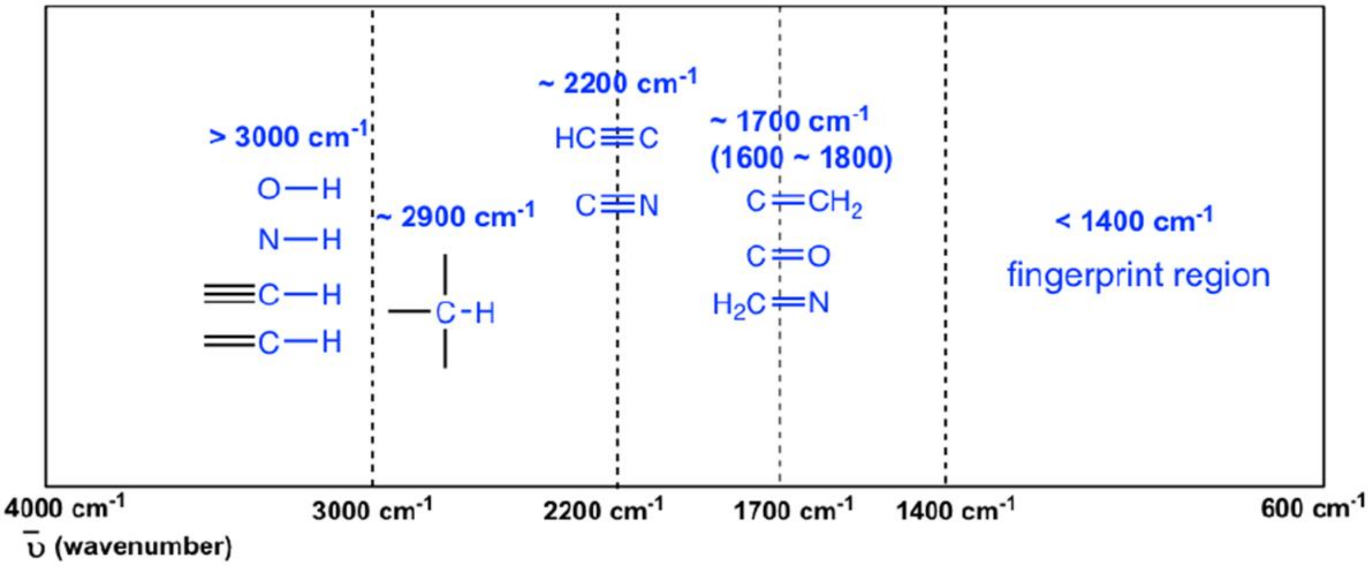


Figure 9. Characteristic IR bands of some common functional groups.