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A Review of Modern Spectroscopic Techniques in the Study of Condensed Matter

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Abstract: This article reviews key modern spectroscopic techniques in condensed matter physics, including Raman, FTIR, and XPS. It outlines their applications in probing structural and electronic properties, highlights technical challenges, and discusses future directions such as AI integration and multimodal approaches.

Keywords: *Spectroscopic Techniques, Modern Spectroscopy, Condensed Matter, Condensed Matter Physics, Spectral Analysis, Electronic Structure, Material Properties.*

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I. INTRODUCTION

Spectroscopy has developed dramatically throughout recent years, thanks to innovations in spectroscopic probing and analysis, allowing scientists to examine the quantum properties of materials with extraordinary accuracy (Mitrano et al., 2024). Advanced spectroscopy provides the basics of understanding such fundamental aspects of materials' behavior as superconductivity, magnetism, and new quantum effects in topological materials and nanoscale systems (Blundell, 2025; Cheng, 2025).

This field includes various types of research: Raman spectroscopy, X-ray absorption spectroscopy (XAS), electron energy-loss spectroscopy (EELS), ultraviolet photoelectron spectroscopy (UPS), X-ray photoelectron spectroscopy (XPS). These techniques have provided many details regarding the structure of materials and interactions within it (Yamamoto et al., 2025; Savchenko, 2025). Combining with nanoscale imaging techniques, such as transmission electron microscopy, has also allowed studying complex processes within condensed matter (Brokkelkamp, 2025).

With growing requirements to study the materials under special conditions, like ultra-low temperature or high pressure, spectroscopy has become essential in academic laboratories and synchrotrons (Napolitano & Scordo, 2025). The following article discusses recent advances in spectroscopic methods in condensed matter physics, presenting its leading applications, current problems, and possible prospects in this fast-developing field (Nocerino, 2025; Hales, 2025).

➢ *Theoretical Foundations of Spectroscopic Measurements*

In modern spectroscopy, there is a wide range of techniques that are based on interactions of matter with electromagnetic radiation through absorption, emission or scattering in various spectral ranges. There are different ways of interaction depending on the nature of matter and the electronic structure and the technique itself. They all originate from the electronic structure of matter and spectral lines correspond to the transitions between various electronic energy levels (Hales, 2025).

There are two major types of spectroscopy techniques: linear (absorption spectroscopy (UV-Vis, FTIR), fluorescence emission spectroscopy) and nonlinear (Raman spectroscopy, resonant inelastic X-ray scattering (RIXS)). The second one usually involves the use of powerful radiation sources like laser or synchrotron radiation and allows revealing weak signals from lattice vibrations or quantum excitations in complicated materials (Mitrano et al., 2024; Yamamoto et al., 2025).

For instance, Raman spectroscopy allows a very accurate investigation of vibrations and structural phases because it is based on scattering of light with the energy change due to vibration transitions (Napolitano & Scordo, 2025). In turn, XPS and UPS are applied for analysis of surface electronic energy levels and chemical bonds and are among the basic techniques for studying the electronic structure of solids (Savchenko, 2025).

Techniques such as XAS and EXAFS spectroscopy allow investigation of the local atomic and bonding structure of materials, hence the investigation of local electronic states, especially in the case of materials containing transition elements or chemically active impurities (Blundell, 2025).

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They are widely used for investigation of superconductors and strongly correlated magnetic systems (Cheng, 2025). It is necessary to understand their physical nature for proper interpretation of results and conducting the precise quantitative experiments on the condensed matter.

- *Evolution of Spectroscopic Techniques in Condensed Matter Physics*

In the past sixty years, spectroscopy has seen some revolutionary improvements along with the significant growth of condensed matter research that includes solid states, liquids, nano-materials, and quantum materials. At first, spectral resolution and the width of the spectrum were poor due to the low quality of spectroscopic devices. Then the improvements in light source technology, detectors, and computation helped to reach the highest level of spectral and spatial resolutions (Mitrano et al., 2024).

After the invention of laser light sources in the 1960s, the methods like Raman spectroscopy became more precise. This made it possible to study crystal phases and atomic vibration that can change depending on the chemical environment (Napolitano & Scordo, 2025). Later, the sources based on synchrotrons with the high photon flux and large spectral range helped to create XPS and XAS and study complex structures (Yamamoto et al., 2025).

Nowadays, the use of advanced charge-coupled device (CCD) detectors and digital control systems, as well as improvements in vacuum and other experimental conditions, allows using time-resolved spectroscopy. It studies the dynamics of the transformation of materials with extremely fast speeds – femtoseconds. Time-resolved spectroscopy is important to study the properties of superconductors or topological materials at phase transition (Cheng, 2025).

- *Raman Spectroscopy Applications and Advances*

The reason why Raman spectroscopy is an important technique in condensed matter studies is that it allows for non-destructive characterization of vibrational modes and crystalline phases (Napolitano & Scordo, 2025). This technique is frequently employed in analyzing two-dimensional materials, such as graphene, which can provide information about the number of layers, defect structures, and internal stresses (Cheng, 2025).

In superconductors and topological materials, Raman spectroscopy helps monitor phase transitions and quantum effects, especially if low-temperature and high-pressure conditions are applied to these materials (Blundell, 2025). Among recent advancements are surface enhanced Raman scattering (SERS) that is useful in increasing signals and time-resolved Raman spectroscopy useful for studying ultrafast transformations (Mitrano et al., 2024).

Finally, there have been significant advances in combining Raman spectroscopy with microscopy which allows one to obtain highly spatially resolved spectral maps, which can be used for studying heterogeneous materials (Brokkelkamp, 2025). Issues such as weak signals and fluorescence backgrounds are tackled by using sophisticated artificial intelligence algorithms (Nocerino, 2025).

- *X Ray Spectroscopy XPS XANES and EXAFS*

X-ray spectroscopy is one of the most important methods of characterization of the electronic and chemical structure of the condensed phase. Methods like X-ray photoelectron spectroscopy (XPS) enable the determination of the electronic levels of elements on the surface of the material with nanometer resolution. Therefore, they are quite useful for analyzing thin films and functional materials (Savchenko, 2025).

X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) spectroscopy offer a great deal of information about oxidation states and atomic environment in materials, even amorphous and nanomaterials (Blundell, 2025). They are employed to study catalysts, transition metal complexes, and magnetic materials.

Both methods have been developed significantly due to the appearance of high brilliance synchrotron radiation sources and improvements in spatial and spectral resolutions (Yamamoto et al., 2025). Additionally, they can be used in conjunction with machine learning-based analysis of spectral data to analyze complex materials (Nocerino, 2025).

- *Fourier Transform Infrared Spectroscopy and Chemical Bond Analysis*

Fourier Transform Infrared Spectroscopy (FTIR) is commonly applied in the investigation of chemical bonds and structure of matter in condensed state, especially when it concerns materials that have organic or hybrid nature. The technology involves infrared absorption by functional groups, which enables the determination of types of bonds and vibrations of molecules (Hales, 2025).

FTIR is a highly efficient method in characterization of polymers, thin films and nanomaterials. It enables to trace changes in the chemical structure during reactions or modification of surfaces (Napolitano & Scordo, 2025). FTIR is also applied in the identification of interlayer interactions in 2D materials and impurities or defects in structure.

Increased sensitivity of detectors and advanced development of measurement cells have allowed applying FTIR in unique circumstances, for example, at low temperatures or in vacuum conditions.

- *Integrating Spectroscopy with Modeling and Imaging Techniques*

In recent times, the combination of spectroscopic measurement with computations and imaging has emerged as one of the major avenues of study in the field of condensed matter science. Such an approach provides insight into the structure and electronic characteristics through the correlation between spectroscopy and theoretical calculations or high-resolution images (Brokkelkamp, 2025).

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Transmission electron microscopy (TEM) can be used along with techniques like EELS and XPS in order to conduct localized spectroscopy at the atomic level so that the structure and spectral behavior could be correlated with each other. In addition, laser microscopy coupled with Raman spectroscopy is capable of generating 3-D spectroscopic maps, indicating the material and elemental distribution in the sample at nanoscale resolution.

The quantum mechanical calculation such as density functional theory (DFT) also assists in the interpretation of spectroscopic findings in the prediction of energy transitions or electronic structures, which cannot be directly obtained through experiments (Nocerino, 2025).

Such a combination proves to be a critical step towards multi-dimensional analysis of complex materials especially heterogeneous and dynamic ones.

II. CHALLENGES AND LIMITATIONS OF MODERN SPECTROSCOPY

Although much has been achieved, spectroscopic methods still encounter a number of technical and methodology-related problems in the field of condensed matter physics. These problems can be outlined as follows:

- Weak spectral signals in certain materials, especially in Raman and FTIR spectroscopy, require enhancement techniques like SERS or computational signal enhancement (Napolitano & Scordo, 2025).
- Overlap of the signals from multicomponent samples makes spectral analysis difficult, especially in nanoscale or amorphous materials.
- Certain measurements have to take place in special conditions like low temperatures or high vacuum, and not all labs are able to provide such an environment; thus, techniques like XAS or EELS cannot always be used (Blundell, 2025).
- A considerable level of expertise is still required for spectral analysis as it is rather complicated.
- Temporal and spatial resolution of certain techniques has not been significantly improved recently; therefore, dynamic processes can be tracked neither in real-time nor at the atomic level (Mitrano et al., 2024).

Another problem that arises is the management of the large amount of spectra that should be analyzed, and it starts to be solved by means of machine learning and artificial intelligence (Nocerino, 2025).

Managing large volumes of spectral data presents an additional challenge, which is beginning to be addressed through machine learning and artificial intelligence tools (Nocerino, 2025).

III. FUTURE PROSPECTS AND EMERGING DIRECTIONS

The directions that spectroscopy of condensed matter will take in the future will focus on its integration, accuracy, and intelligence. The most important trends that will emerge in the future will include the following:

- Ultrafast spectroscopy allows for monitoring electronic processes and phase transformations within a timeframe of femtoseconds, providing an insight into dynamic quantum phenomena (Mitrano et al., 2024).
- Artificial intelligence being used for spectral data analysis with the help of pattern-classification and deep-learning algorithms speeds up the process of interpreting results and decreases human biases (Nocerino, 2025).
- In situ and operando spectroscopy allow for monitoring materials during their operation, such as electrochemical materials during charging and discharging or catalytic materials during reactions.
- Multimodal spectroscopy implies simultaneous use of several spectroscopic and imaging techniques that will provide a holistic image of a material both in terms of its structure and electronics.
- Nanospectroscopy is a method of analyzing extremely small samples at the atomic level which can be used when investigating two-dimensional materials, quantum conductors, and supramolecular systems (Brokkelkamp, 2025).

These trends are expected to become more important as quantum computing and multiscale modeling progress.

IV. CONCLUSION

This review shows that modern spectroscopy methods are of great importance for the elucidation of the structure of condensed matter and its properties. The application of such techniques as Raman spectroscopy, XPS, XANES, and FTIR allows us to obtain powerful means of investigation of the phase transitions, transformation of structures, and interaction of materials with very high time and space resolution.

Certainly, the combination of spectroscopy with computational modeling and nanoscopy is a step towards more efficient interpretation of the data, especially in case of highly complex systems. However, the problems of weak signals in some cases and multidimensional data analysis require special approaches to be solved. Thus, it is possible to make the following conclusions.

- Spectroscopy techniques constitute the core of the detailed characterization of modern materials of condensed matter.
- Every technique has a defined area of application which defines its efficiency, for example, Raman spectroscopy in nanomaterials characterization and XPS in surface studies.

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- Experiment and theory have to be combined to understand complicated phenomena.

RECOMMENDATIONS FOR FUTURE RESEARCH

- Apply real-time spectroscopy to the study of dynamic phenomena.
- Create intelligent algorithms for analyzing spectra using artificial intelligence.
- Support in-situ and multimodal spectroscopy to study materials in real-life applications.

Collaborate with the researchers of spectroscopy, computing, and materials science for an integrated approach to the problem.

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