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Performance Evaluation of Laser Spectroscopy Techniques for Isotope Identification and Separation Based on Isotope Shifts

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ABSTRACT: Laser spectroscopy has become one of the most important technologies for isotope identification and separation because of its high spectral resolution and its ability to accurately measure isotope shifts. Despite significant advances in this field, a comprehensive comparative evaluation of different laser spectroscopy methods in terms of their physical principles, measurement accuracy, and isotope separation capabilities is still required. The aim of this study was to systematically evaluate the performance of laser spectroscopy methods for isotope identification and separation based on their underlying physical principles, spectral resolution, sensitivity, and applications. This study was conducted as a systematic review, in which publications retrieved from major scientific databases were identified, screened, and analyzed. The findings demonstrated that the mass shift and the field shift constitute the fundamental physical basis for isotope discrimination. Collinear Laser Spectroscopy (CLS), owing to its very high spectral resolution, is the most suitable technique for the precise measurement of isotope shifts and the investigation of nuclear structure, whereas Atomic Vapor Laser Isotope Separation (AVLIS) and Molecular Laser Isotope Separation (MLIS) exhibit high efficiency in the selective separation of isotopes. Furthermore, the development of narrow-linewidth lasers, frequency stabilization systems, and advanced data-processing techniques has significantly improved the accuracy and sensitivity of these technologies. Overall, the selection of an appropriate method depends on the intended application, the type of isotope, and the required measurement accuracy. This study provides a comparative framework for understanding the capabilities and limitations of laser spectroscopy methods and can contribute to the future development of isotope identification and separation technologies

KEYWORDS: collinear laser spectroscopy, laser spectroscopy, isotope shift, AVLIS, MLIS, isotope separation.

1. INTRODUCTION

Laser spectroscopy has become one of the most accurate techniques for investigating atomic and nuclear structure, as well as for isotope identification and separation, over the past decades. Advances in narrow-linewidth lasers, frequency stabilization systems, and high-resolution detectors have enabled the measurement of extremely small shifts in atomic transition frequencies, thereby expanding the application of this technology in nuclear physics, materials science, nuclear medicine, and nuclear technology. Furthermore, the growing global demand for High-Assay Low-Enriched Uranium (HALEU) fuel for Small Modular Reactors (SMRs) has made the reassessment of laser-based enrichment technologies a strategic necessity (Platov 2025).

The physical basis of many laser spectroscopy applications is the phenomenon of the isotope shift. Differences in the number of neutrons among isotopes of the same element led to variations in nuclear mass and charge distribution, resulting in very small shifts in the energies of electronic levels and corresponding spectral lines. Precise measurement of these shifts enables isotope identification, investigation of nuclear properties, and the development of selective isotope separation techniques (Campbell and Moore 2023)In addition to high-precision atomic laser spectroscopy, laser–matter interaction techniques have also been developed for rapid and non-contact isotope identification. In these methods, information on isotopic composition can be obtained through the analysis of emission, absorption, or fluorescence radiation generated by laser irradiation of a sample. Although these techniques offer rapid analysis and require minimal sample preparation, spectral line broadening and limited spectral resolution restrict their capability for precise isotope discrimination. Consequently, they are primarily employed as complementary techniques alongside high-resolution spectroscopic methods (Harilal et al. 2018)

In recent years, techniques such as Collinear Laser Spectroscopy (CLS), Atomic Vapor Laser Isotope Separation (AVLIS), and Molecular Laser Isotope Separation (MLIS) have attracted considerable attention because of their high accuracy and excellent

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selectivity. CLS enables highly precise measurements of isotope shifts and nuclear hyperfine structure, whereas AVLIS and MLIS have demonstrated high efficiency in the selective separation of isotopes, particularly for industrial applications (Raggio and others 2024)Despite these significant advances, most published studies have focused on a single technique or a specific application. Comprehensive comparative reviews evaluating different laser spectroscopy methods with respect to their physical principles, measurement accuracy, spectral resolution, and isotope identification and separation capabilities remain limited. This gap makes it difficult to identify the most appropriate technique for specific scientific and technological applications.

Therefore, the aim of the present study is to provide a systematic review of the performance of laser spectroscopy methods for isotope identification and separation. The fundamental principles of isotope shifts, together with the major laser spectroscopy and laser isotope separation techniques, are comparatively evaluated in terms of their operating principles, advantages, limitations, and application fields, with the objective of presenting a comprehensive overview of the current status and future prospects of these technologies.

2. MATERIALS AND METHODS

Study Design and Setting

This study was conducted as a systematic review to evaluate and compare the performance of laser spectroscopy methods for isotope identification and separation. The study was designed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) guidelines to ensure that the processes of literature searching, screening, study selection, and data extraction were transparent, systematic, and reproducible. The review focused on the physical principles of isotope shifts and the performance of Collinear Laser Spectroscopy (CLS), Atomic Vapor Laser Isotope Separation (AVLIS), and Molecular Laser Isotope Separation (MLIS) in isotope identification and enrichment.

2.1 Data Sources and Search Strategy

The literature search was performed using major scientific databases and repositories, including ScienceDirect, SpringerLink, American Physical Society (APS) publications, Nature, arXiv, the International Atomic Energy Agency (IAEA) database, the Organisation for Economic Co-operation and Development Nuclear Energy Agency (OECD-NEA) publications, and other relevant scientific repositories. Studies were identified using combinations of predefined keywords.

The search primarily included publications published between 2015 and 2026. However, earlier classical references were also included when necessary to describe the theoretical foundations of laser spectroscopy and isotope shifts.

2.2 Eligibility Criteria

The inclusion criteria comprised peer-reviewed research articles, review papers, and authoritative scientific books published in English that reported experimental or computational data on isotope shifts, laser spectroscopy, or isotope separation, particularly involving Collinear Laser Spectroscopy (CLS), Atomic Vapor Laser Isotope Separation (AVLIS), and Molecular Laser Isotope Separation (MLIS). Studies providing information on measurement accuracy, spectral resolution, separation efficiency, or practical applications were included. Publications without full text, non-peer-reviewed sources, duplicate records, and studies unrelated to laser spectroscopy or isotope separation were excluded.

2.3 Data Collection and Measurement Procedures

Following duplicate removal and eligibility screening, relevant data were extracted and organized into comparative tables. The extracted information included the spectroscopy or separation method, physical principle, laser–matter interaction, isotope-shift measurement accuracy, spectral resolution, separation efficiency, applications, and the main advantages and limitations of each technique. The study selection process followed the PRISMA flow diagram (Figure 1).

2.4 Data Analysis

The selected studies were evaluated using qualitative comparative analysis (QCA). Comparisons focused on physical principles, analytical performance, isotope identification and separation capability, applications, and limitations. Recent technological developments, industrial and medical applications, and economic aspects of isotope enrichment, including the Separative Work Unit (SWU), were also assessed. Reference management and citation formatting were performed using Zotero according to the APA (7th edition) style.

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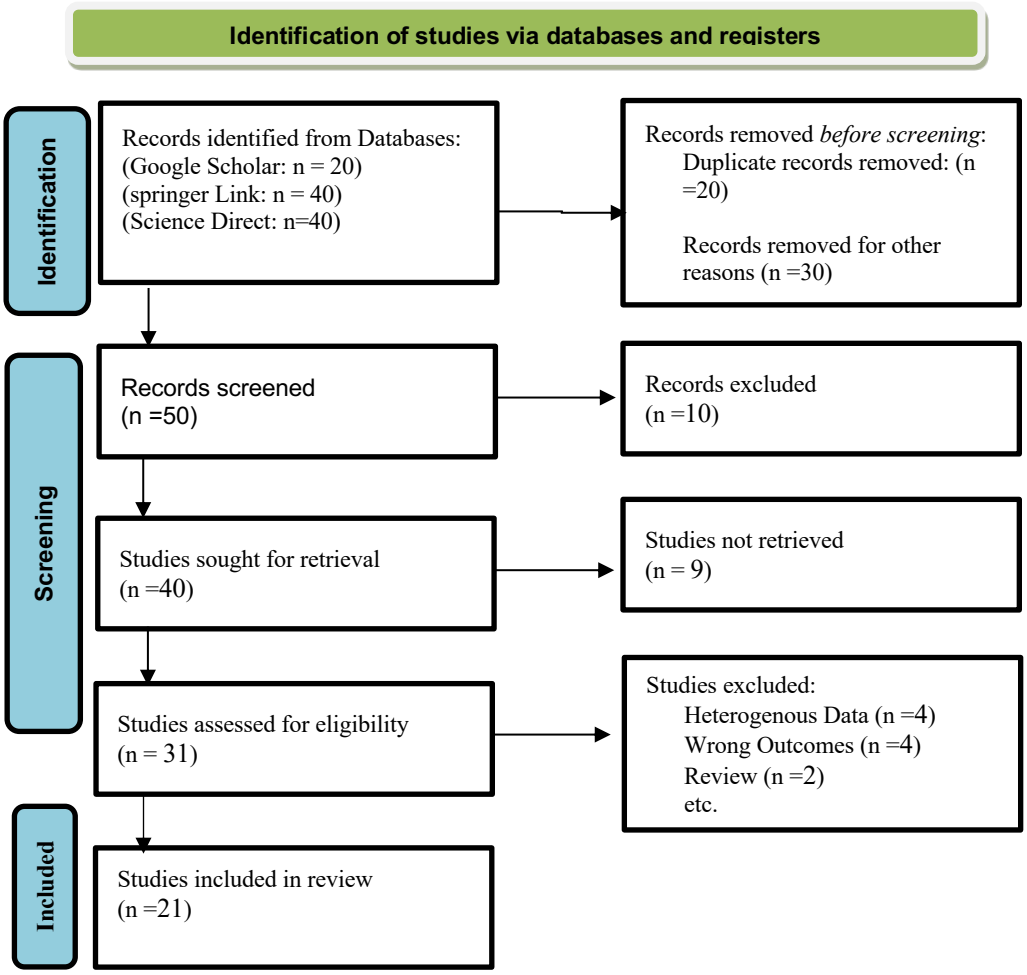

Figure 1. PRISMA flow diagram of the literature search and study selection process

3. RESULTS & DISCUSSION

3.1. Physical Basis of Isotope Shift

The isotope shift is one of the most fundamental phenomena in atomic and nuclear physics and constitutes the physical basis of many modern laser spectroscopy techniques used for isotope identification and separation. Although isotopes of the same element possess the same atomic number and electronic configuration, differences in the number of neutrons result in changes in nuclear mass and nuclear charge distribution. These variations cause slight shifts in the energies of electronic levels and consequently produce small differences in the frequencies or wavelengths of atomic transitions, a phenomenon referred to as the isotope shift.

Recent theoretical calculations have shown that isotope shifts can be investigated not only in individual optical transitions but also in the total electronic binding energy. These shifts, arising from nuclear mass effects, nuclear charge radius variations, and relativistic interactions, become increasingly significant in heavy elements and can be utilized for a more accurate interpretation of isotope spectroscopy data. The results further indicate that, in heavy elements, relativistic interactions and the contributions of inner-shell electrons play a significant role in the isotope shift. Therefore, these effects should be incorporated into theoretical models to achieve accurate atomic energy calculations and reliable interpretation of high-resolution spectroscopic data (Dzuba and Flambaum 2025)From a physical perspective, the isotope shift results from the interaction between atomic electrons and the nucleus. Although the electronic configuration remains essentially unchanged among isotopes of the same element, variations in nuclear mass and size modify the energies of electronic transitions. Since these shifts are typically on the order of a few megahertz

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to several gigahertz, their detection is only possible using high-resolution laser spectroscopy systems. Advances in narrow-linewidth lasers, frequency stabilization techniques, and high-precision optical detectors over the past two decades have enabled the measurement of these extremely small frequency shifts, substantially expanding the application of laser spectroscopy in nuclear structure studies, isotope separation technologies, and fundamental research (Campbell and Moore 2023)

From a theoretical standpoint, the isotope shift consists of two principal components: the Mass Shift (MS), which originates from differences in the masses of isotopes, and the Field Shift (FS), which arises from variations in the nuclear charge distribution and nuclear charge radius. The general expression describing these two contributions is given by:

$$\Delta_{v=}\Delta_{vm} + \Delta_{vf} \quad (1)$$

where Δ_{vm} represents the Mass Shift (MS) and Δ_{vf} denotes the Field Shift (FS). The contribution of each component depends on the atomic number, electronic structure, and nuclear properties of the element. In light elements, the mass shift generally contributes more significantly to spectral line displacements, whereas in heavy elements, particularly the actinides, the field shift becomes the dominant component.

Accurate King plot analysis in simple diatomic molecules provides a reliable approach for separating the mass and field contributions to isotope shifts. Recent investigations on diatomic molecules have further demonstrated that, in addition to the classical mass and field shift components, complex electron–nucleus interactions, particularly those involving inner-shell electrons, play an important role in determining the ultimate precision of spectroscopic measurements. In this context, the King plot has become an important tool for separating the mass and field contributions, while the investigation of deviations from linearity in high-precision measurements provides opportunities to explore novel interactions and even search for signatures of physics beyond the Standard Model (Athanasakis-Kaklamanakis et al. 2023, 2023)

These characteristics make the isotope shift one of the most important measurable quantities in laser spectroscopy. In addition to isotope identification, precise measurements of isotope shifts provide valuable information on the nuclear charge radius, hyperfine structure, nucleus–electron interactions, and the evolution of nuclear structure. Consequently, isotope shifts are now widely applied not only in nuclear physics research but also in nuclear medicine, astrophysics, geochemistry, isotope enrichment technologies, and nuclear safeguards (Makarov 2024)

Figure 1 schematically illustrates the absorption and emission of a photon between two atomic energy levels. When the energy of the incident photon matches the energy difference between the two levels, the electron absorbs the photon and is excited to the upper energy level. After a short lifetime, it returns to the lower level by emitting a photon with the same energy difference. Among different isotopes, slight variations in nuclear mass and nuclear charge radius produce small changes in this energy difference, resulting in shifts in the absorption or emission frequency. These frequency shifts constitute the fundamental operating principle of laser spectroscopy systems for isotope identification and discrimination.

The analysis of the reviewed studies indicates that increasing spectral resolution and reducing spectral line broadening are the two principal factors for improving the accuracy of isotope shift measurements. These advances have enabled the resolution of extremely small frequency differences between isotopes and have facilitated the development of highly accurate isotope identification and separation techniques. Therefore, understanding the physical origin of the isotope shift provides the essential foundation for interpreting the operating principles of the various laser spectroscopy methods discussed in the following sections.

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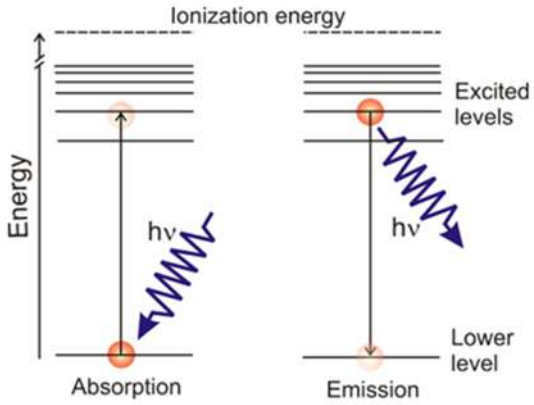

Figure 2. Schematic illustration of photon absorption and emission between the energy levels of an atom (Harilal et al. 2018)

3.2. Mass Shift and Its Components

The mass shift (MS) is one of the two principal components of the isotope shift and originates from the mass difference between isotopes of the same element. In a real atom, the nucleus has a finite mass; therefore, both the electrons and the nucleus revolve around their common center of mass. Consequently, the energies of the electronic levels depend on the nuclear mass, and variations in the number of neutrons produce small differences in atomic transition energies, which are observed as frequency shifts in spectral lines (Ivanov and Kozlov 2025)

From a theoretical perspective, the mass shift consists of two components: the normal mass shift (NMS) and the specific mass shift (SMS). The sum of these two components constitutes the mass contribution to the isotope shift.

The normal mass shift arises from the difference in the reduced mass of the electron–nucleus system and, for many atomic transitions, can be accurately described by the following equation:

$$\Delta_{\nu\, nms} = \nu_0 \frac{(m_2 - m_1)m_e}{m_1 \cdot m_2} \qquad (2)$$

where (m_e) is the electron mass, (υ_0) is the transition frequency, and $m_1$and m_2 are the masses of the two isotopes ((Ivanov and Kozlov 2025)). This relationship indicates that the magnitude of the normal mass shift increases with the mass difference between the two isotopes. In practice, this component is more pronounced in light elements, whereas its relative contribution decreases with increasing atomic number, and the field shift becomes progressively dominant in heavy elements (Dzuba and Flambaum 2025). Theoretical studies further confirm that the significance of the normal mass shift diminishes with increasing atomic number, making it comparatively less important in heavy atoms (Ivanov and Kozlov 2025)

In contrast, the specific mass shift has a different physical origin and arises from the correlated motion of electrons in multi-electron atoms. In this case, the interaction between the momenta of different electrons modifies the total energy of the atomic system, resulting in an additional contribution to the isotope shift. Owing to its dependence on electron correlation and relativistic effects, accurate calculation of this component requires advanced quantum-mechanical computational methods (Ivanov and Kozlov 2025)The physical expression for this component, which originates from the angular and dynamical correlations among electrons in multi-electron atoms, is given by the following equation:

$$\Delta_{\nu_{sms}} = \frac{m_e(m_2 - m_1)}{m_1 \cdot m_2} \cdot \langle \sum_{i \neq j} \vec{p_i} \cdot \vec{p_j} \rangle \qquad (3)$$

where m_e is the electron rest mass, m_1.and m_2 are the masses of the two isotopes, and the term inside the expectation brackets denotes the scalar product of the momentum operators of different electrons, describing their coupling interaction (Ivanov and Kozlov 2025)Recent theoretical studies have shown that the contribution of the mass shift in heavy elements is not limited solely to the mass difference between isotopes; rather, relativistic effects and the contribution of inner-shell electrons also play an important role in determining its final value. Calculations performed using the Relativistic Hartree–Fock method together with the

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Breit interaction indicate that, as the atomic number increases, the sensitivity of the total electronic binding energy to changes in the nuclear charge radius also increases, causing the field shift contribution to become dominant over the mass shift. Furthermore, these studies demonstrate that the difference in isotope shifts between neutral atoms and singly charged ions is generally only a few percent, because the largest contribution to the isotope shift originates from the inner-shell electrons (Dzuba and Flambaum 2025)A review of recent studies indicates that, in light elements, both the Normal Mass Shift (NMS) and the Specific Mass Shift (SMS) make significant contributions to the isotope shift, and in some cases the contribution of the SMS even exceeds that of the NMS. In contrast, with increasing atomic number and nuclear charge radius, the contribution of the field shift gradually increases and becomes the dominant component in heavy elements, particularly in the actinides. This trend indicates that the relative importance of the isotope shift components depends on the atomic and nuclear properties of each element, and therefore no single component can be regarded as dominant for all elements (Campbell and Moore 2023)

From a practical perspective, separating the contributions of the NMS and SMS is of great importance in the analysis of laser spectroscopy data because accurate extraction of nuclear parameters, such as the nuclear charge radius, is only possible when the mass-shift contribution has been calculated with sufficient accuracy and subtracted from the total isotope shift. Therefore, in most laser spectroscopy studies, the mass shift contribution is first determined using theoretical models, after which the field shift contribution is extracted from the experimental data. This approach improves measurement accuracy and reduces the uncertainty associated with determining nuclear properties.

Table 1 summarizes the main characteristics of the two mass shift components alongside the field shift. As can be seen, their physical origins, dependencies, and relative importance differ between light and heavy elements. These differences provide the basis for selecting the most appropriate laser spectroscopy technique for the investigation of different isotopes.

Table 1. Comparison of the Characteristics of the Main Components of the Isotope Shift

Component	Physical Origin	Primary Dependence	Significance in Light Elements
Normal Mass Shift (NMS)	Reduced mass of the electron–nucleus system	Difference in isotope masses	High
Specific Mass Shift (SMS)	Electron–electron correlation	Atomic electronic structure	High
Field Shift (FS)	Changes in nuclear charge distribution and nuclear charge radius	Nuclear structure and nuclear charge radius	Low

3.3 Field Shift and Its Role in Nuclear Structure

The field shift (FS) is the second principal component of the isotope shift and originates from changes in the nuclear charge distribution and the effective nuclear charge radius. Unlike the mass shift, which results from differences in isotope masses, the field shift arises from changes in the interaction between atomic electrons and the nuclear electric field. This effect is particularly significant for electrons in s orbitals, whose probability of penetrating the nuclear volume is relatively high, because variations in the nuclear charge radius directly influence the energies of these electronic states (Campbell and Moore 2023; Demtröder 2015)

Recent studies have shown that the field shift is directly related to the change in the mean-square nuclear charge radius, $\delta\langle r^2\rangle$, and originates from changes in the electromagnetic field experienced by electrons penetrating the nucleus. Consequently, precise (Mohr et al. 2023)evolution of nuclear structure along isotopic chains. As a result, the field shift has become one of the most important tools for investigating the structure of heavy nuclei (Athanasakis-Kaklamanakis et al. 2023)

From a theoretical perspective, the field shift is expressed by the following equation:

$$\Delta_{vf} = f \cdot \delta\langle r^2\rangle \qquad (4)$$

where f is the electronic field-shift factor associated with the atomic transition, and $\delta\langle r^2\rangle$ is the difference in the mean-square nuclear charge radius between two isotopes. This relationship indicates that the larger the change in the nuclear charge radius, the greater the frequency shift produced by the field shift. To the lowest order, the F factor depends on the difference in the electron

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probability density at the center of the nucleus between the initial and final electronic states. Consequently, transitions involving s-orbital electrons exhibit the highest sensitivity to variations in the nuclear charge radius (Mohr et al. 2023)

A review of recent studies indicates that the contribution of the field shift strongly depends on the atomic number. In light elements, variations in the nuclear charge radius are relatively small, and the mass shift constitutes the dominant contribution to the isotope shift. However, with increasing atomic number, particularly in heavy elements and actinides, changes in the nuclear charge distribution become dominant, making the field shift the principal contributor to spectral line shifts. Recent relativistic calculations further confirm this trend, demonstrating that the contribution of the field shift increases rapidly with atomic number, whereas the contribution of the mass shift becomes comparatively negligible (Dzuba and Flambaum 2025)

One of the most important methods for analyzing isotope-shift data is the King plot. In this approach, isotope shifts measured for two independent atomic transitions are plotted against each other. When the experimental data lie on a straight line, the contributions of the mass shift and the field shift can be separated with high precision. Today, the investigation of deviations from King plot linearity is no longer limited to nuclear-structure analysis. High-precision measurements have demonstrated that such deviations may arise from complex electron correlations, higher-order nuclear-structure effects, and even interactions beyond the Standard Model. Therefore, the King plot has become an important tool for testing fundamental theories and searching for hypothetical new particles (Berengut et al. 2020a)).

In addition to its fundamental importance, the field shift has gained increasing significance in practical applications. Recent studies have shown that precise determination of the parameter $\delta\langle r^2\rangle$ plays a crucial role in optimizing laser-based radioisotope separation processes, including those involving Yb-175, thereby improving isotopic purity and enhancing the production of radiopharmaceuticals used in nuclear medicine (Suryanarayana and Sankari 2024)

The reviewed studies indicate that the King plot is not merely a graphical tool but one of the most accurate methods for analyzing laser spectroscopy data to extract nuclear parameters. This method plays a fundamental role in determining the nuclear charge radius, evaluating theoretical models, and improving the precision of isotope-shift measurements. It is now widely employed as a standard analytical technique in many nuclear physics laboratories.

Figure 2 schematically illustrates the principle of King plot analysis. The alignment of isotope-shift data obtained from two independent atomic transitions along a linear relationship indicates that the mass-shift and field-shift components of the isotope shift can be successfully separated. Conversely, deviations from linearity may indicate the presence of higher-order nuclear or electronic effects, or even new fundamental interactions. The investigation of such deviations has recently become an important topic in atomic and nuclear physics (Berengut et al. 2020b)

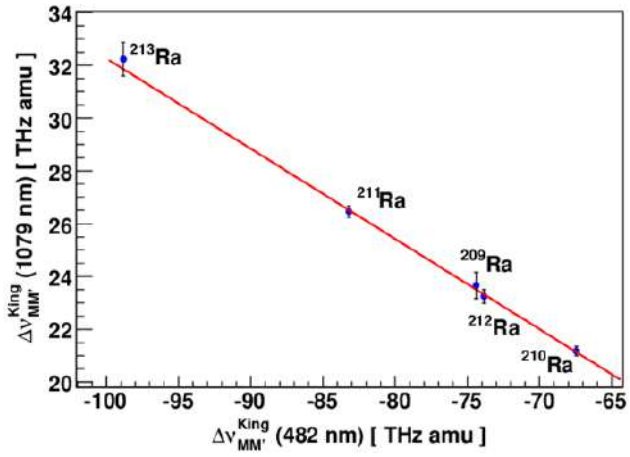

Figure 3. The King plot for modified isotope shifts along a chain of radium isotopes is shown. (Versolato et al., 2011)

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Table 2. Comparison of Mass Shift and Field Shift.

Feature	Field Shift	Mass Shift
Physical origin	Change in nuclear radius and charge distribution	Difference in isotope masses
Main influencing factor	Nuclear size and structure	Nuclear mass
Importance in light elements	Low	High
Importance in heavy elements	Very high	Moderate
Extracted information	Mean-square nuclear charge radius	Mass contribution to atomic transitions

3.4. Analysis of Frequency Shifts in Uranium Isotopes and Their Role in Laser Spectroscopy

Following the theoretical discussion of isotope shifts, the examination of experimental studies demonstrates how this phenomenon is practically applied to isotope identification and separation. Among the various elements, uranium has been one of the most extensively investigated in laser spectroscopy because of its significance in nuclear technology, fuel enrichment, and nuclear safeguard systems. The extremely small differences in the optical transition frequencies of the uranium isotopes U-234, U-235, and U-238 provide a direct means of evaluating the performance of high-resolution laser spectroscopic systems (Campbell and Moore 2023)Experimental investigations of uranium isotopes have shown that the combination of atomic beam production with laser absorption spectroscopy enables highly accurate measurements of isotopic abundances. Bartlett and Castro demonstrated that the production of uranium atomic beams from different uranium compounds, followed by analysis of their absorption spectra, can provide isotopic information with sufficient accuracy for determining uranium enrichment levels. These findings indicate that laser absorption spectroscopy is not only valuable for fundamental studies of nuclear structure but also has practical applications in the analysis of uranium materials and nuclear safeguard systems (Bartlett and Castro 2019)

Analysis of the published data indicates that the spectral line shifts among uranium isotopes are on the order of several gigahertz. These shifts are dominated primarily by the field shift, whereas the contribution of the mass shift is considerably smaller. This observation is consistent with the discussion presented in the previous section and confirms that, in heavy elements, variations in the nuclear charge radius constitute the principal source of isotope shifts (Campbell and Moore 2023)

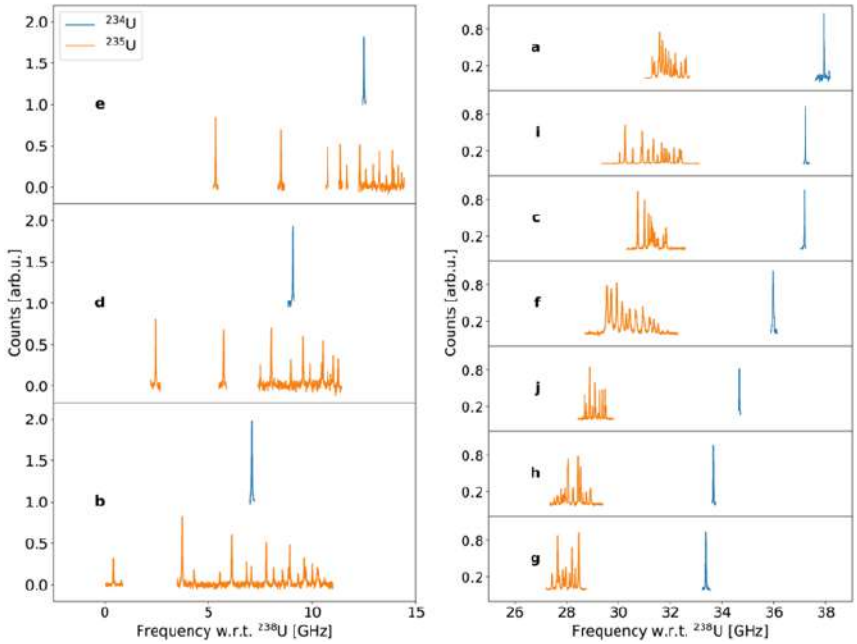

Figure 4. Frequency shifts of optical transitions in the uranium isotopes U-234, U-235, and U-238 (Raggio and others 2024)

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Figure 4 presents a representative optical spectrum of the naturally occurring uranium isotopes. The displacement of the spectral peaks relative to the reference isotope U-238 reflects the differences in electronic transition energies resulting from variations in nuclear mass and nuclear structure. Although these frequency differences are extremely small, the use of narrow-linewidth lasers together with frequency stabilization systems enables their measurement with high precision (Raggio and others 2024)

The reviewed studies indicate that, in heavy-element isotopes, particularly uranium, the field shift is the dominant contributor to the overall isotope shift, whereas the mass shift contributes comparatively little. This finding demonstrates that spectral line shifts in heavy elements primarily reflect variations in nuclear charge radius and nuclear structure. Therefore, the capability to accurately measure these extremely small frequency shifts is a key indicator of the performance of laser spectroscopy systems. Improvements in spectral resolution, narrower laser linewidths, and enhanced frequency stabilization have significantly increased the ability to selectively distinguish isotopes, thereby facilitating the development of laser-based isotope separation technologies, particularly Atomic Vapor Laser Isotope Separation (AVLIS). In AVLIS systems, only the target isotope is selectively excited or ionized at a specific resonant frequency, enabling highly selective and efficient isotope separation. Furthermore, previous studies have shown that precise control of atomic vapor density is essential for minimizing charge-exchange collisions, thereby improving both the separation efficiency and isotopic purity achieved by the AVLIS process.

On the other hand, studies employing CLS have demonstrated that reducing Doppler broadening through the collinear alignment of the ion beam and the laser beam improves the measurement accuracy of isotope shifts to the level of a few megahertz. This level of precision not only enables the extraction of nuclear parameters, such as the nuclear charge radius and hyperfine structure, but also enhances the reliability of measurements in applications related to nuclear technology (Campbell and Moore 2023)

Overall, the analysis of experimental studies on uranium isotopes indicates that isotope shifts are not merely a fundamental phenomenon in atomic physics but also serve as a primary indicator of the performance of modern laser spectroscopy techniques for isotope identification and separation. These findings further demonstrate that high spectral resolution, reduced Doppler broadening, and precise laser frequency control are the three key factors driving the advancement of high-performance laser spectroscopy and isotope separation technologies.

3.5 Comparison of the Performance of Laser Spectroscopy Methods for Isotope Identification and Separation

In this study, the performance of the principal laser spectroscopy and laser isotope separation methods, including CLS, AVLIS, and MLIS, was evaluated based on their physical principles and operational characteristics. Although these methods all rely on the selective interaction of laser radiation with atomic or molecular transitions, they differ significantly in terms of spectral resolution, sensitivity to isotope shifts, the type of information that can be extracted, and their fields of application. In molecular techniques, the selective excitation of vibrational and rovibrational transitions, combined with photochemical processes, forms the basis of isotopic selectivity and plays an important role in improving separation efficiency (Makarov 2022).A review of the published studies indicates that CLS is the most accurate technique for measuring isotope shifts and nuclear hyperfine structure. The reduction of Doppler broadening, together with the use of narrow-linewidth lasers and the collinear alignment of the ion and laser beams, enables the measurement of frequency differences at the level of a few megahertz. Consequently, CLS is regarded as the reference method for determining nuclear charge radii, magnetic moments, and other nuclear parameters in nuclear physics research (Campbell and Moore 2023)

In contrast, AVLIS utilizes the selective absorption of laser photons by atoms in the vapor phase to achieve isotope-specific ionization. Precise tuning of the laser wavelength ensures that only the isotope with the corresponding resonance frequency is excited and subsequently ionized. This feature has made AVLIS one of the most efficient technologies for the enrichment of metallic isotopes, particularly uranium. Recent studies have shown that, in addition to its high isotopic selectivity, this method provides lower energy consumption and higher separation efficiency than conventional isotope separation technologies (Makarov 2025)Studies on MLIS, particularly those involving boron isotopes, have demonstrated that the selective excitation of molecular vibrations and the precise control of photochemical processes enable the separation of isotopes with very small mass differences. The selection of suitable molecular species, the infrared absorption characteristics, and the accurate adjustment of laser parameters are among the most important factors influencing the separation efficiency of this method (Makarov 2025)

On the other hand, comparisons of different isotope separation technologies indicate that, in addition to laser-based methods, emerging technologies such as the Plasma Separation Process (PSP) have attracted attention for the industrial production of certain special isotopes. Feasibility studies on the production of isotopes such as Gd-157 have shown that PSP may serve as a

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complementary or even competing technology in some industrial applications. However, laser-based methods still maintain significant advantages in terms of isotopic selectivity and operational flexibility (Egle and Bigelow 2020)

Overall, the comparison demonstrates that no single method can simultaneously satisfy all requirements for isotope identification and separation. If the objective is the precise extraction of nuclear information and the measurement of atomic parameters, CLS remains the most suitable technique. In contrast, AVLIS and MLIS are more efficient for industrial applications and isotope enrichment. Meanwhile, technologies such as PSP can play a complementary role in certain specialized applications. Therefore, the selection of an appropriate method should be based on the research objective, the isotope of interest, the required level of precision, and the available technical resources.

Table 4. Comparison of the Performance of the Principal Laser Spectroscopy and Laser Isotope Separation Methods.

Comparison Criterion	AVLIS	MLIS	CLS
Operating principle	Selective atomic ionization	Selective molecular excitation	Atomic transition spectroscopy
Primary objective	Atomic isotope separation	Molecular isotope separation	Isotope identification and nuclear structure studies
Spectral resolution	High	High	Very high
Sensitivity to isotope shifts	High	Moderate to high	Very high
Measurement accuracy	High	High	Very high
Major application	Isotope enrichment	Enrichment of molecular compounds	Nuclear physics research
Instrumentation complexity	High	High	Very high
Main advantage	High isotopic selectivity	Suitable for molecular species such as UF_6	Precise measurement of nuclear parameters
Main limitation	Complexity of the laser system	Difficult control of molecular processes	High cost and advanced infrastructure requirements

3.6 Economic Analysis and Evaluation of Laser Isotope Separation Technologies Efficiency

In addition to technical indicators, economic evaluation is one of the important factors in the development of isotope separation technologies. In the enrichment industry, process efficiency is commonly evaluated based on the Separative Work Unit (SWU), energy consumption, and the production cost per SWU. Recent reports indicate that laser-based technologies, due to their higher separation factors, can reduce the number of stages required to achieve the desired enrichment level and consequently decrease operational costs compared with some conventional technologies (Platov 2025)

Economic studies on the SILEX technology have estimated the levelized production cost at approximately 39.7 USD per SWU. A facility with a capacity of one million SWU per year requires an initial investment of about 0.5 billion USD, making it economically competitive with advanced centrifuge-based systems (Baldwin 2016)

On the other hand, the joint report by the OECD Nuclear Energy Agency and IAEA indicates that, under conditions of excess enrichment capacity, reducing the tails assay and applying the underfeeding strategy can improve natural uranium utilization efficiency and enhance the economic performance of the nuclear fuel cycle (OECD Nuclear Energy Agency & IAEA, 2023).

Furthermore, the development of Small Modular Reactors (SMRs) and increasing demand for High-Assay Low-Enriched Uranium (HALEU) fuel (with enrichment levels of (5–20%) have drawn greater attention toward laser isotope separation technologies. Due to their high selectivity and larger separation factors, these technologies can facilitate the production of intermediate-enriched fuels with fewer processing stages and may become important options in future nuclear fuel cycles (Platov 2025).

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3.7 Limitations, Challenges, and Future Perspectives of Laser Spectroscopy Methods

The reviewed studies indicate that, although laser spectroscopy technologies have experienced significant progress over the past two decades, they still face several scientific and technical challenges. The main limitations include the requirement for highly stable lasers with extremely narrow linewidths, precise frequency-control systems, and high-sensitivity detectors. These requirements increase the cost of equipment installation and maintenance and make widespread implementation, particularly in research centers with limited resources, more difficult (Demtröder 2015)

In high-resolution methods such as CLS, advanced optical systems, stable ion sources, vacuum systems, and precise control of ion beam energy are essential. Any fluctuation in these parameters can reduce the accuracy of isotope shift measurements and increase the uncertainty of the results. In contrast, in laser separation technologies such as AVLIS and MLIS, process efficiency depends on factors such as accurate wavelength selection, laser power stability, ionization efficiency, and precise control of laser–atom or laser–molecule interactions. In addition to technical challenges, industrial-scale implementation of these technologies requires compliance with nuclear safety requirements, fault-tolerant system design, and the application of defense-in-depth principles to minimize risks such as radioactive material release, fire, and operational failures (IAEA, 2020)

Recent studies show that advances in ultra-stable laser technology, optical frequency combs, photon detectors, and artificial intelligence algorithms have played an important role in improving measurement accuracy and reducing uncertainty in spectral data. Furthermore, combining experimental approaches with quantum modeling and advanced computational methods has enabled more accurate extraction of nuclear parameters and improved analysis of isotope shifts (Ivanov and Kozlov 2025). In addition, theoretical modeling has demonstrated that laser-based separation of ^{175}Yb isotopes can provide the required isotopic purity for targeted radiopharmaceutical production and contribute to the development of advanced radionuclide-based therapies (Suryanarayana and Sankari 2024)

From an applied perspective, the development of next-generation laser systems with improved frequency stability, miniaturized equipment, and enhanced data-processing techniques is expected to expand the use of laser spectroscopy in areas such as nuclear material monitoring, nuclear medicine, materials science, and the study of unstable isotopes. Among emerging technologies, Multi-Resonance Laser Isotope Separation (MRLIS) offers increased isotope separation efficiency and enables the production of radioisotopes that are difficult or impossible to separate using conventional radiochemical methods. Therefore, this technology may play an important role in the development of radiopharmaceuticals and nuclear medicine applications (Barr and others 2025)

Moreover, the integration of laser technologies with machine learning models, advanced computational methods, and ultrafast lasers has created new opportunities for improving isotope selectivity, processing speed, and identification accuracy. The use of ultrashort pulses and quantum coherence control techniques, including the Ramsey Echo phenomenon, provides the possibility of distinguishing isotopes with extremely small differences and even different nuclear spin states, opening new perspectives for future isotope separation systems (Levitt 2026)

Overall, the results of this review demonstrate that the future development of laser spectroscopy technologies mainly depends on improving spectral resolution, reducing equipment costs, developing more stable systems, and applying intelligent data-analysis approaches. Achieving these goals can significantly expand the applications of these technologies in fundamental research, nuclear technology, nuclear medicine, and related industries.

4. CONCLUSION

This study systematically reviewed and compared the performance of the main laser spectroscopy methods for isotope identification and separation based on isotope shifts. The results demonstrated that mass shift and, particularly, field shift constitute the fundamental physical basis of isotope discrimination. Accurate measurement of these effects enables the extraction of valuable information about nuclear structure, selective isotope identification, and improvement of the accuracy of nuclear analyses.

Comparison of different methods showed that CLS, due to its extremely high spectral resolution, is the most suitable technique for precise measurement of isotope shifts and nuclear hyperfine structures. In contrast, AVLIS and MLIS, through selective laser interactions with atoms or molecules, provide higher efficiency for isotope separation and enrichment. Furthermore, recent studies on uranium and boron isotopes indicate that advances in laser frequency control, reduction of spectral linewidth broadening, and optimization of photochemical processes have significantly improved the accuracy and efficiency of these technologies.

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From an applied perspective, the findings of this review indicate that laser spectroscopy and isotope separation technologies have considerable potential not only in fundamental atomic and nuclear physics research but also in areas such as nuclear fuel enrichment, production of medical radioisotopes, materials science, and nuclear material monitoring. Economic evaluations further suggest that modern laser-based separation technologies, due to their high separation factors and reduced number of processing stages, may become competitive options in the future for producing advanced nuclear fuels, including HALEU.

Nevertheless, the high cost of laser systems, the requirement for precise frequency stabilization, advanced laboratory infrastructure, and the complexity of process control remains among the major challenges in the further development of these technologies. Therefore, continued research in the fields of ultra-stable lasers, multi-resonance techniques, advanced detection systems, quantum modeling, and intelligent spectral data processing can improve measurement accuracy, reduce costs, and facilitate the expansion of scientific and industrial applications of laser spectroscopy in the coming years.

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