The Sound of Light: Turning Atomic Spectral Line Radiation into Timbre

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The Sound of Light: Turning Atomic Spectral Line Radiation into Timbre

Research Article

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ABSTRACT

This article explores the fascinating interplay between atomic physics, the Fast Fourier Transform (FFT), and music theory, focusing on the impact of atomic spectral lines on musical timbre. It bridges the realms of science and art, offering practical applications and translating scientific data into musical scales. This interdisciplinary research opens new horizons for scientific and artistic communities, fostering a fresh perspective that unites these traditionally distinct fields.

1. INTRODUCTION

This article explores the impact of atomic spectral lines on music and timbre. Atomic physics holds a significant place in numerous scientific applications, offering unique 'signatures' for elements. Similarly, the Fast Fourier Transform (FFT) allows us to understand the component frequencies of signals by transforming a signal from the time domain to the frequency domain. In music, timbre defines the characteristic qualities of an instrument or sound and has a decisive influence on our emotional responses. However, these three subjects are often not integrated.

In this study, combining these three distinct disciplines allows for an analysis of the frequency components of atomic emission spectra using FFT. This investigation delves into how these components might influence musical timbre. The goal is to bridge the gap between science and art, fostering a new understanding that unites these two domains.

The article first discusses the fundamental principles and importance of atomic emission spectra. Secondly, it explores the fundamental functionality of FFT and its applications in spectral analysis. Thirdly, the study delves into musical timbre, measurement, and impact on aesthetics or emotional responses. Finally, integrating these three concepts aims to theoretically and practically examine how atomic spectral lines could influence music and timbre. This study can open a new and exciting research area for scientific and artistic communities.

2. BACKGROUND

This interdisciplinary research is situated at the intersection of atomic physics, signal processing, and music theory. As a conservatory-trained musician with a strong interest in physics, I launched this study to explore potential connections between atomic spectral lines and musical timbre. Using atomic emission spectra as a data source, this research aims to transform the unique frequencies emitted by atoms into a new musical scale and, subsequently, innovative timbres. The practical application of this research has been showcased in a collaborative effort with NASA, featured in the "Beyond the Light" installation produced by ARTECHOSUE Studio, premiered in ARTECHOUSE New York June 2023, and touring to ARTECHOUSE DC September 2023.

This effort aims to offer new perspectives and insights that could contribute to both scientific understanding and musical composition. Through this research, I hope to contribute to the dialogue between traditionally distinct fields like art and science, aid in the deeper understanding of atomic structures and lay the groundwork for a new musical language.

2.1. Spectral Lines

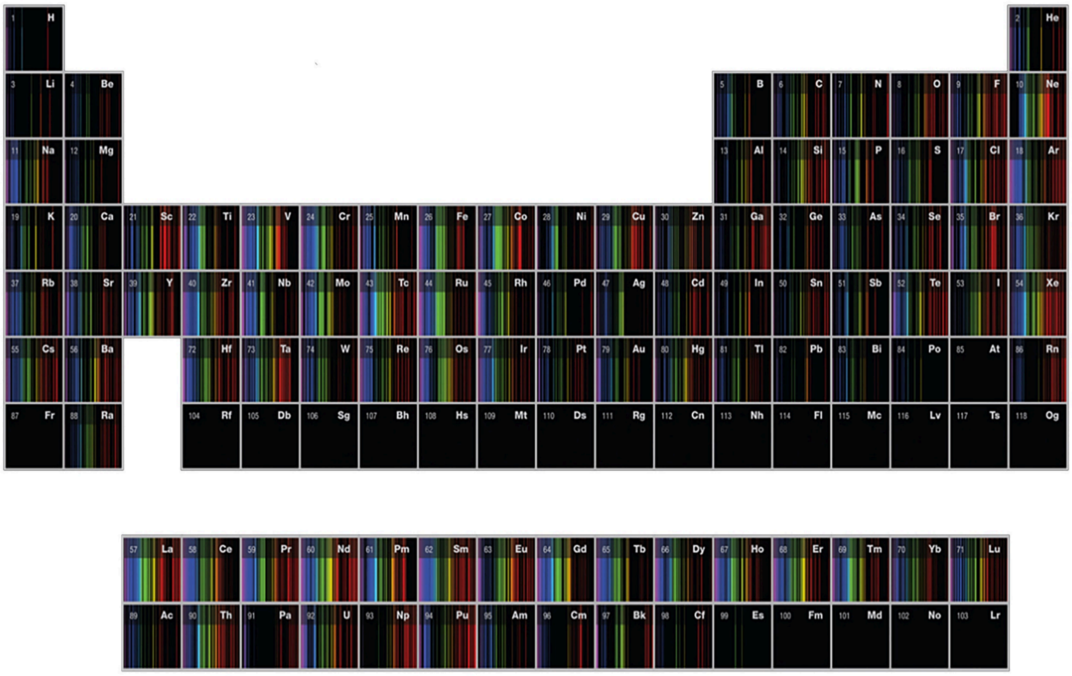

Figure 1: The atomic spectra of each element superimposed on the periodic chart. Image: Field Tested Systems ©2017

Spectral lines, in physics, represent specific wavelengths or frequencies of electromagnetic radiation emitted or absorbed by atoms, molecules, or materials. Emission lines result from transitions of particles from high to low energy levels, while absorption lines occur when specific wavelengths are absorbed by atoms or molecules in a medium. These lines serve as unique identifiers for elements or compounds and are crucial in various scientific disciplines, aiding in the study of elemental composition and materials analysis (Draine, 2011; Gray, 2005; Osterbrock & Ferland, 2006; Smith, 2008).

2.2. Atomic Emission Spectra

The atomic emission spectrum represents a fundamental phenomenon observed in the realm of atomic physics, providing insights into the electron configurations of atoms. When atoms undergo transitions between different energy states, the result is the emission of photons, each characterized by a specific frequency or wavelength (Smith & Jones, 2010). These emissions are integral to understanding the inherent properties of elements and have been widely used in diverse scientific applications.

2.2.1. Atomic Energy Levels

Atomic structures are characterized by specific energy levels. When an electron absorbs energy, it transitions to a more elevated, excited state. On the contrary, the transition from an excited state to a lower energy state results in the emission of energy (Doe, 2015).

2.2.2. Photon Emission

The emitted energy, arising from the difference in atomic energy levels, takes the form of a photon. This photon's specific energy (and thus frequency) is contingent upon the energy differential between the original and final states of the electron (Brown & Taylor, 2012).

2.2.3. Unique Spectral Signatures

Given the uniqueness of atomic structures across elements, it stands to reason that each element would exhibit a distinct emission spectrum. This spectrum acts as a molecular fingerprint, enabling the identification of elements in various contexts (White, 2017).

2.3. Hydrogen Emission Spectra

The atomic emission spectrum of hydrogen provides a compelling insight into the behavior of electrons within this elementary atom. Among the most notable features of this spectrum is the Balmer series, a set of lines that are visible in the optical wavelength range and arise due to specific electron transitions. Within the hydrogen atom, electrons can occupy distinct energy levels, each characterized by unique quantum numbers. The energy transitions between these levels lead to the absorption or emission of photons. Specifically, when an electron drops from a higher energy level ($n > 2$) to the second energy level ($n = 2$), it results in the emission of photons that belong to the Balmer series.

The Balmer series occurs during the transition of the hydrogen atom's electron from the $n=2$ energy level to higher energy levels ($n=3, 4, 5, \ldots$).

The formula used to describe the Balmer series is as follows:

$$\lambda = \frac{n^2hc}{E} = \frac{n^2hc}{13.6\,\mathrm{eV}}\left(\frac{1}{2^2} - \frac{1}{n^2}\right)$$

A formula that underpins the relationship for the Balmer series is given by:

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{x^2}\right)$$

where λ denotes the wavelength of the emitted light, R represents the Rydberg constant (approximately 1.097 x 10^7 m^(-1)) and n stands for the principal quantum number of the initial energy level.

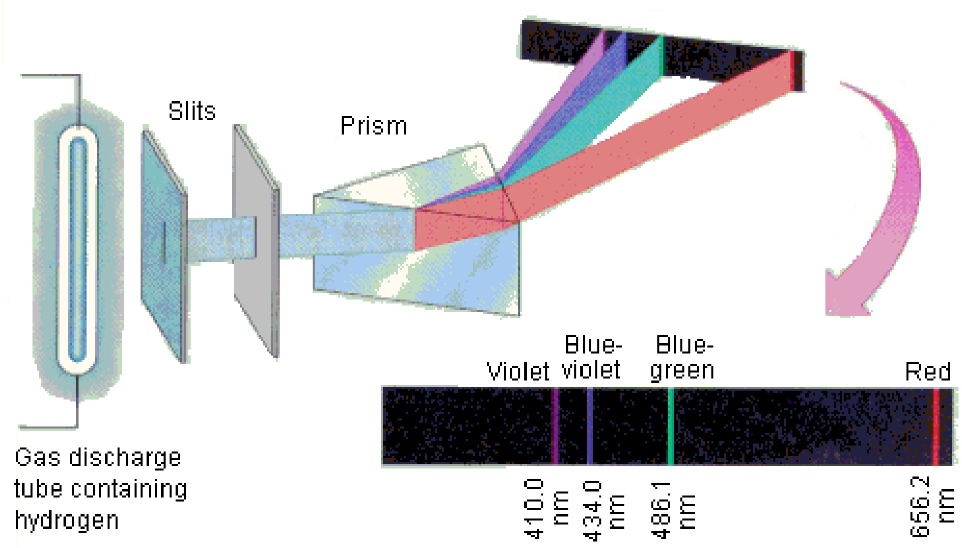

Figure 2: Electric current through hydrogen-filled glass tube - Blue light - Prism - Four narrow bright bands on the black background (Purdue University, n.d.)

When an electric current is passed through a glass tube that contains hydrogen gas at low pressure, the tube gives off blue light. When this light is passed through a prism (as shown in the figure below), four narrow bands of bright light are observed against a black background. In conclusion, atomic emission spectra represent a cornerstone in the understanding of atomic configurations and have a substantial impact on many scientific applications.

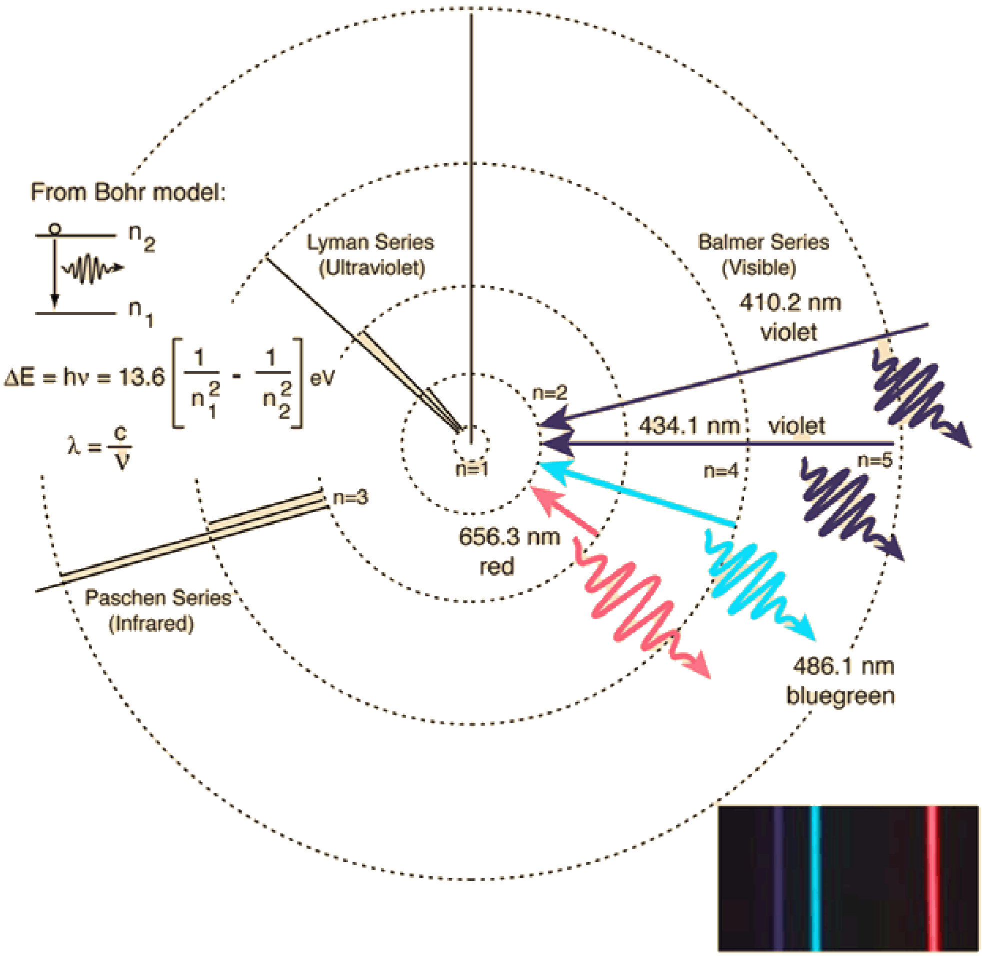

Figure 3: This spectrum was produced by exciting a glass tube of hydrogen gas with about 5000 volts from a transformer. It was viewed through a diffraction grating with 600 lines/mm. The colors cannot be expected to be accurate because of differences in display devices. (Georgia State University, n.d.)

For some examples, the H-alpha line happens when there's a transition from the third to the second energy level. This transition is linked with a wavelength of about 656.3 nm, and this light looks red. On the other hand, the H-beta line comes from the transition from the fourth to the second energy level. This gives a wavelength close to 486.1 nm, which looks cyan. The H-gamma line also comes from transitioning from the fifth to the second level. This is linked to a wavelength of about 434.0 nm, which looks blue. These transitions give off a photon with its own frequency and wavelength. This shows the set levels of electron orbits in the atom. These lines' regular and unique characteristics were key in the initial growth of quantum mechanics.

Wavelength	Relative Intensity	Transition	Color
383.5384	5	9 -> 2	Violet
388.9049	6	8 -> 2	Violet
397.0072	8	7 -> 2	Violet
410.174	15	6 -> 2	Violet
434.047	30	5 -> 2	Violet
486.133	80	4 -> 2	Bluegreen (cyan)
656.272	120	3 -> 2	Red
656.2852	180	3 -> 2	Red

Table 1: The measured lines of the Balmer series of hydrogen in the nominal visible region

2.4. Fast Fourier Transform (FFT)

Fast Fourier Transform (FFT) is a mathematical algorithm used to decompose a signal or data sequence into its frequency components. This algorithm is widely used, particularly in the fields of digital signal processing (DSP) and spectral analysis (Cooley & Tukey, 1965).

$$X_k = \sum_{n=0}^{N-1} x_n e^{-i2\pi kn/N} \qquad k = 0, \ldots, N-1,$$

The DFT provides a way to transform a time-domain signal into its frequency components. The Fast Fourier Transform (FFT) is an efficient algorithm to compute the DFT and its inverse.

The Fourier Transform converts a signal in the time domain to the frequency domain, allowing us to obtain the signal's frequency components. However, the classical Fourier Transform can be computationally slow when dealing with large datasets.

The mathematical details underlying FFT stem from the complexity of the Fast Fourier Transform algorithm. The fundamental principle of the algorithm involves dividing the input data sequence's size and solving subproblems. This process is accomplished through a recursive divide-and-conquer strategy. Subsequently, the solutions of the subproblems are combined, yielding a complete solution.

This recursive structure of the basic algorithm makes FFT a powerful tool widely used in scientific and engineering applications.

In conclusion, FFT is a significant mathematical algorithm that enables fast and efficient access to frequency components, finding extensive application in digital signal processing and spectral analysis (Cooley & Tukey, 1965).

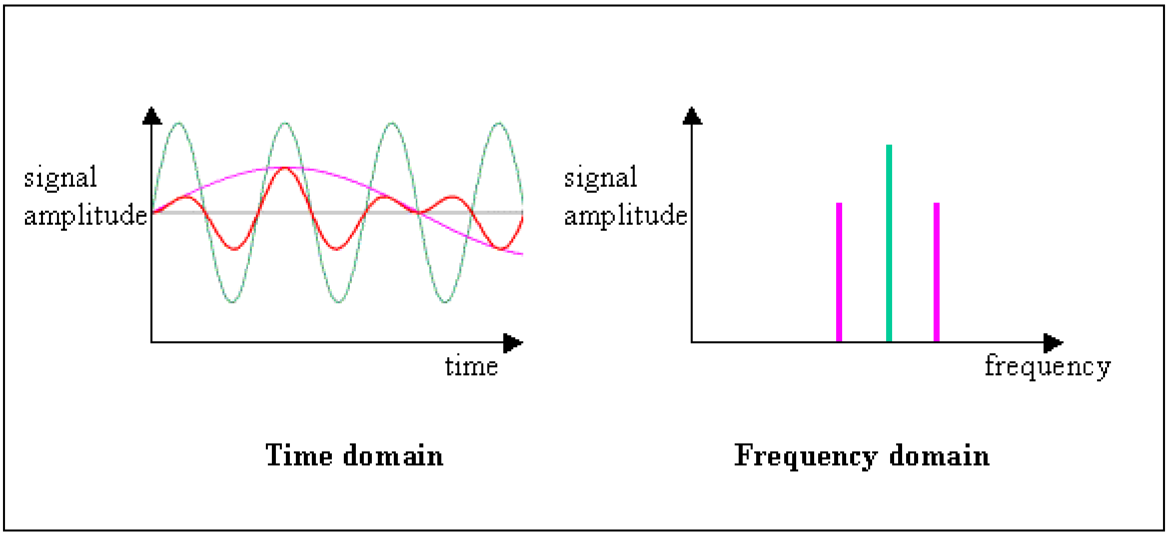

Figure 4: Representation of Time and Frequency Domains (Pandya, Bhole, Shrivastava, & Rathore, 2020)

2.5. Timbre

Timbre, in music, refers to a sound's quality, character, and tone color. It is one of the essential perceptual attributes that allows human hearing to distinguish between two musical tones with the same pitch but produced by different instruments or voices (Grey, 1977). Each musical instrument or sound source possesses a unique timbre, enabling us to differentiate between them even when they share the same fundamental frequency.

Timbre is influenced by various factors, including the frequency components of a sound, its harmonic content, attack, decay characteristics, and overall sound envelope (McAdams & Bigand, 1993). Harmonic content refers to the presence of harmonics, which are multiples of the fundamental frequency and contribute to the richness and complexity of a sound.

In music, timbre plays a significant role in enhancing expressiveness and conveying aesthetic qualities (Deutsch, 2013). When the same melody is played using different instruments or with various sound effects, the differences in timbre can evoke distinct emotional responses and perceptions in listeners.

Timbre is a fundamental element within the musical structure and holds importance in music analysis, synthesis, and performance (Grey, 1977).

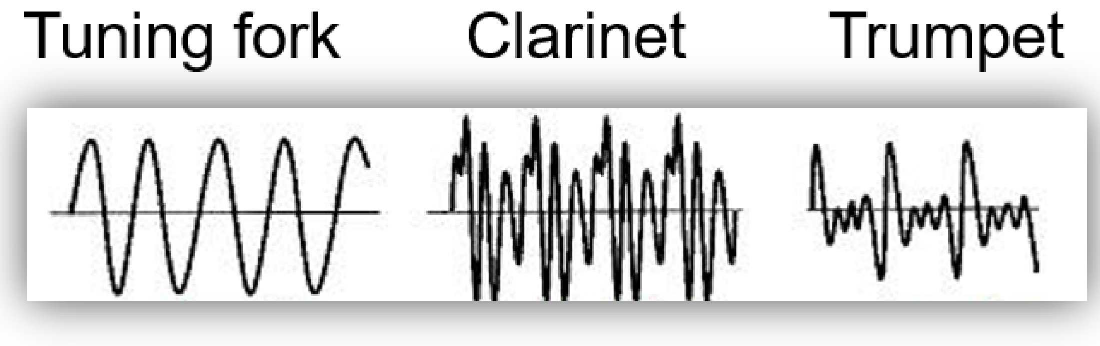

Figure 5: Representation of various instrument timbres in frequency domain

2.6. Non-harmonic

Non-harmonic, in music and sound, is a term used to describe a sound or waveform that lacks regular harmonic components not specific to a particular pitch (Lerdahl & Jackendoff, 1983). Non-harmonic sounds often do not have a distinct fundamental frequency and may contain frequency components without harmonic relationships. As a result, non-harmonic sounds can exhibit complex and indeterminate frequency content.

Non-harmonic content can be found particularly in some percussive or friction sounds. These sounds may not possess a regular musical pitch and may consist of random frequency components. Such sounds often exhibit intriguing and attention-grabbing acoustic characteristics, eliciting connotations or emotional responses.

Advancements in sound synthesis and digital sound processing techniques have made it possible to model and generate non-harmonic sounds more effectively. Non-harmonic sounds play a significant role in sound design, film scoring, and other creative sound applications.

In summary, non-harmonic refers to sounds lacking regular harmonic components and not specifically tied to a particular pitch, often found in unnatural or intriguing acoustic qualities (Lerdahl & Jackendoff, 1983).

2.7. Sine Wave

A Sine Wave is the most fundamental and essential waveform in sound synthesis and music. From the perspective of sound synthesis, a sine wave is the simplest waveform, having only one frequency and amplitude (Roads, 1996). Due to this simplicity, sine waves are used as the building blocks in various sound synthesis algorithms and serve as the basis for generating other complex waveforms. Other waveforms can often be created by combining or modifying multiple sine waves.

Sine waves represent the basic frequencies and harmonics when considered the smallest component of music. The fundamental frequency represents the fundamental periodic oscillation of the wave, while harmonics are frequency components that are multiples of the fundamental frequency. The rich timbres and sounds of musical instruments are created by combining sine waves with their fundamental frequencies and harmonics.

Sine waves are widely used in musical analysis and synthesis. Through Fourier transformation, complex sounds can be represented as combinations of sine waves, allowing for the analysis of a sound's spectral content. Additionally, sine waves serve as a fundamental tool for modeling and synthesizing the sounds of musical instruments.

In conclusion, sine waves play a crucial role as the smallest component of music and are essential in sound synthesis, serving as the basis for generating various other waveforms.

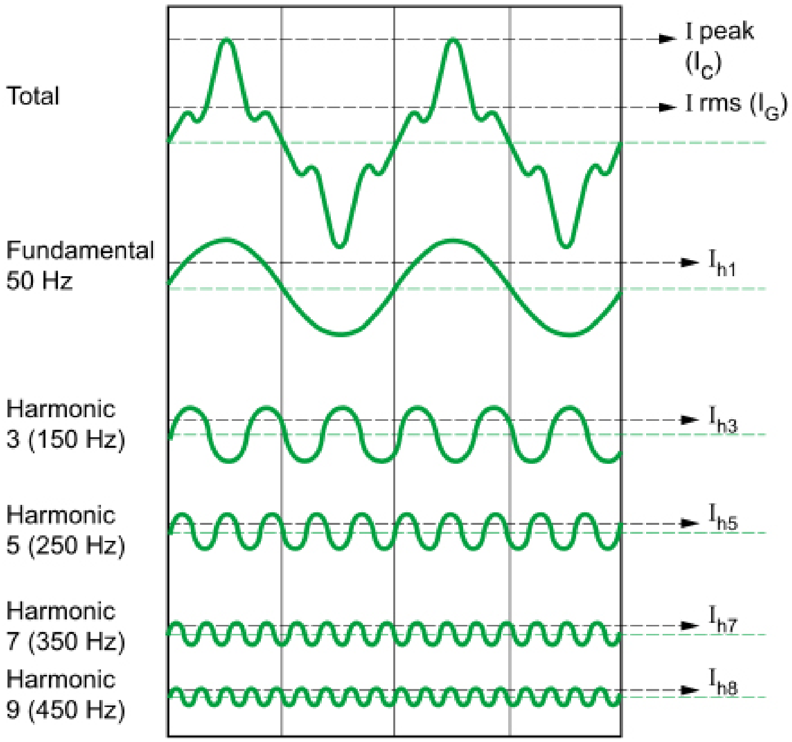

Figure 6: The process of decomposing a complex waveform into sinusoidal components is called "FFT," which stands for "Fast Fourier Transform."

2.8. Additive Synthesis

Additive Synthesis is a method used in music and sound synthesis. This method creates complex sounds by combining simple sinusoidal waves (Roads, 1996). Additive Synthesis focuses on generating a signal by using specific amplitude values for fundamental frequencies and their harmonics. Harmonics are frequency components that are multiples of the fundamental frequency and determine the timbre of a sound. Combining these frequency components with specific amplitude values achieves the desired complex sound.

Additive Synthesis is an effective method, particularly for modeling and synthesizing instruments with rich and complex timbres (Jaffe & Smith, 1983). The timbre of many musical instruments can be created by combining sinusoidal waves with similar characteristics using Additive Synthesis. This synthesis method operates based on Fourier analysis, considering the fundamental frequencies and harmonics that make up the sound.

In conclusion, Additive Synthesis is an effective method used in music and sound synthesis, particularly for generating complex timbres and instrument modeling.

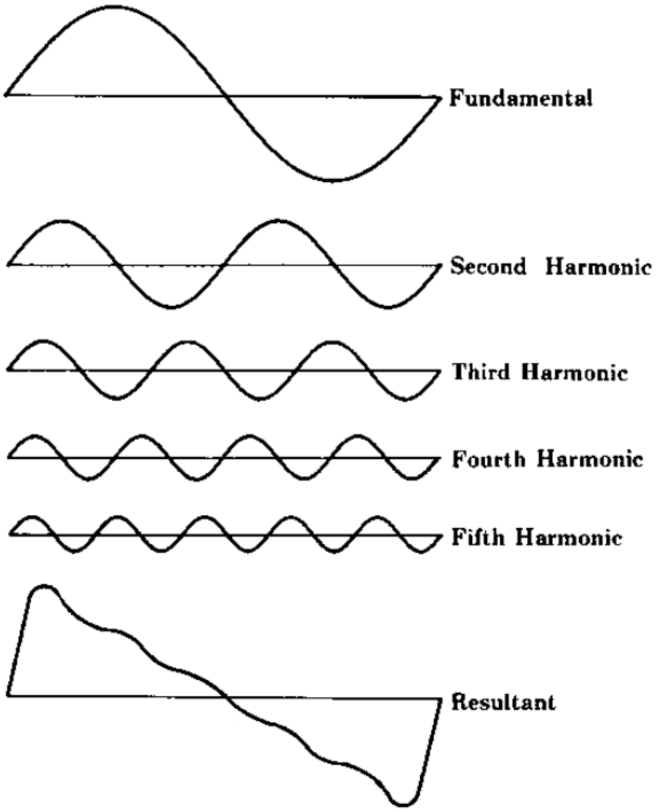

Figure 7: Additive Synthesis

3. METHODOLOGY

3.1. Using Wavelength as a Dataset:

In the research, I utilized wavelengths (measured in nanometers, nm) as a primary dataset. The choice of utilizing wavelengths (measured in nanometers) as the primary dataset stems from the inherent ability of electromagnetic radiation wavelengths to uniquely characterize each element, as highlighted in the preceding “background” section. This characteristic involves the presence of unique "signatures" for each element within the emission spectra. These unique signatures provide an ideal foundation for creating musical timbre, as they ensure significant and perceptible differences between elements. These wavelengths were obtained from the National Institute of Standards and Technology (NIST ASD Team, 2022), a reputable spectral data reference. The NIST ASD Team dataset is chosen for its reliability and comprehensiveness, covering a wide range of elements and providing a robust spectral data source. Wavelengths serve as a foundational dataset for the study, forming the basis for subsequent analyses to explore light's sonic properties.

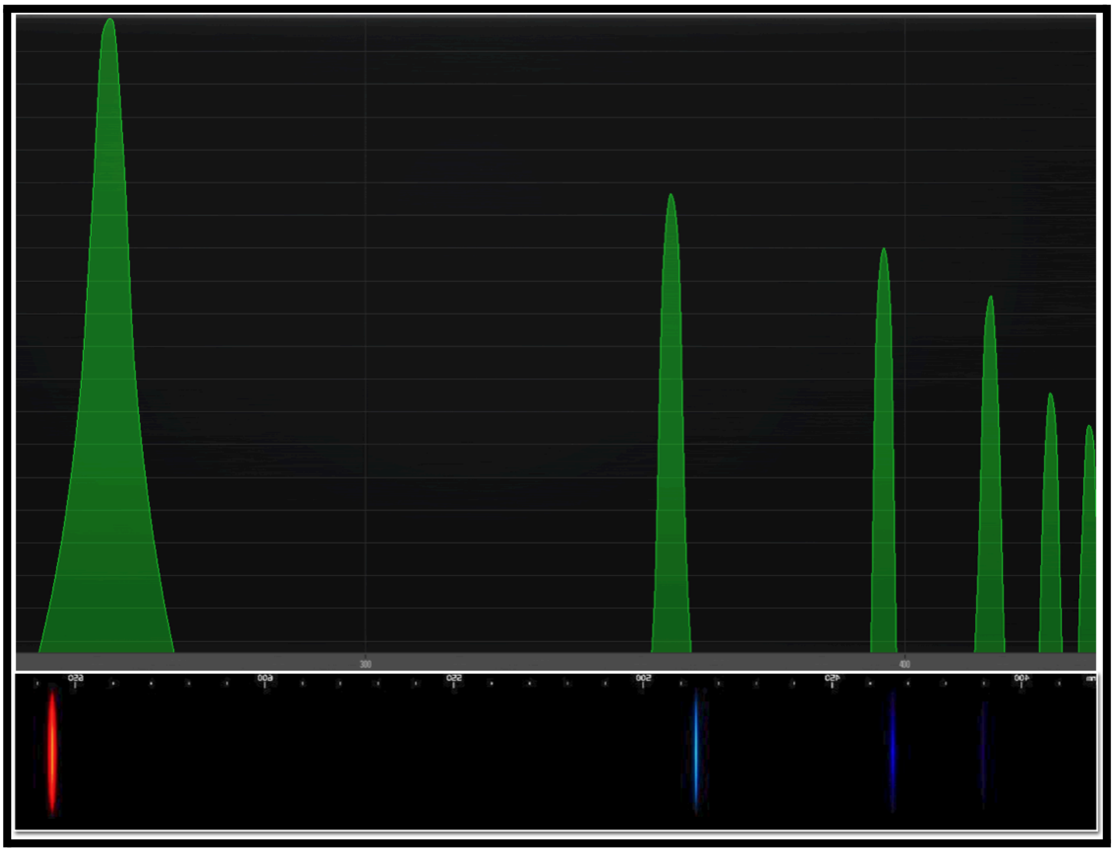

Figure 8: Upper is the sound spectrum of Hydrogen, and lower is the Atomic emission spectra of Hydrogen in visible region

3.2. Mapping Out to Visible:

After obtaining wavelengths, they need to be converted into frequencies. This conversion is achieved using the speed of light (c), a constant value representing how fast light travels in a vacuum (approximately 299,792,458 meters per second). I employ the formula: frequency (f) = speed of light (c) / wavelength (λ). This step is crucial as it ensures that the focus is specifically on the visible portion of the electromagnetic spectrum, allowing my studio to filter and analyze the relevant data for the study.

$$(f) = (c) / (\lambda)$$

3.3. Finding Unique Ratios of Element Frequencies:

One of the key objectives of the study was to identify unique frequency ratios associated with elements. Calculated ratios based on the fundamental frequency of the spectral lines were used to achieve this. These ratios capture the relationships between the fundamental frequency and other frequencies within the light spectra, providing valuable insights into the harmonic characteristics of the elements.

This formula is used to calculate the frequency of light in Hertz (Hz) by using the wavelength (λ) and the speed of light in a vacuum (c). It demonstrates the relationship between wavelength and speed and provides the frequency of light with a wavelength of 6562.79 nanometers. Accordingly, Harmonic Ratios are calculated with this formula:

Harmonic Ratios = Fundamental Frequency (n=1) / Other Frequencies

Number	Visible Wavelength (λ, Å)	Frequency (Hz)	Harmonic Ratios
1	6562.79	$4.56805718 \times 10^{14}$	1.
2	4861.35	$6.16684666 \times 10^{14}$	1.349993
3	4340.472	6.9069×10^{14}	1.511999
4	4101.734	$7.30890887 \times 10^{14}$	1.600004
5	3970.075	$7.55129311 \times 10^{14}$	1.653064
6	3889.064	$7.70859004 \times 10^{14}$	1.687499
7	3835.397	7.8164529×10^{14}	1.711111

Table 2: Wavelength Ratios of Hydrogen

3.4. Finding Unique Ratios of Element Intensities

In addition to frequency ratios, the intensities of spectral lines were also investigated. To identify the unique characteristics of elements, the studio and I calculated ratios based on the fundamental intensity. These ratios depict the relationships between the fundamental intensity and other intensities within the light spectra, contributing to our understanding of the elements' spectroscopic properties. Accordingly, Intensity Ratios are calculated with this formula:

Ratio = Fundamental Intensity (n=1) / Other Intensities

Number	Visible Wavelength (λ, Å)	Relative Intensity	Intensity Ratio
1	6562.79	6500	1.
2	4861.35	1500	0.230769
3	4340.472	1000	0.153846
4	4101.734	675	0.103846
5	3970.075	255	0.039231
6	3889.064	195	0.03
7	3835.397	135	0.020769

Table 3: Relative Intensity Ratios of Hydrogen

3.5. Creating Timbre:

The study was advanced by mapping relative intensities to the amplitude of each frequency. This process facilitated the creation of the timbre for each element, presenting a thorough analysis of how different elements display their distinct sonic qualities based on intensity variations.

3.6. Creating a Musical Scale System:

To establish a musical scale system based on these findings, the previously calculated ratios were multiplied with a base frequency equivalent to a C note (for example, C2), using a fixed ratio of 261.625565 Hz. This multiplication process generated a scale consisting of a series of frequencies representing musical notes. This scale is instrumental in bridging the gap between the scientific understanding of spectral data and its musical interpretation.

Cents are a logarithmic unit of measurement widely used in music theory and acoustics. They express the relative differences between frequencies. In this context, a scale ranging from 0 to 1200 cents, where 1 octave equals 1200 cents, was used. This octave-based approach allowed for precise quantification and analysis of the pitch perception and musical intervals present in the sound, making it easier to relate these values to traditional musical concepts and perceptions.

$$\text{Cents} = 1200 \times log_2\left(\frac{f_h}{f_0}\right)$$

Frequency Based on Harmonic Ratio and C2 (Hz)	**Cent Values (ct)**	**Notes**
261.625565	0	C2
353.192764	519.542715	F2 + 13 ct.
395.577633	715.748801	G2 + 4 ct.
418.601899	813.690401	G#2 + 4 ct.
432.483931	870.171609	A2 - 34 ct.
441.492771	905.863552	A2 + 3 ct.
447.670382	929.92	A2 + 28 ct.
523.251130	1200	C3

Table 4: Note Values of the “Hydrogen” Scale

3.7. A Playable Digital Musical Instrument

The entire calculation process described in the preceding sections was implemented within the Max MSP programming environment. It is a versatile visual programming language commonly used in audio and music applications, providing the computational framework necessary for performing intricate calculations involving wavelengths, frequencies, ratios, and amplitudes.

This environment facilitated the precise spectral data analysis and served as the foundation for the innovative work in developing a playable digital musical instrument. My studio's efforts have successfully transformed scientific data into a tangible and artistic form, enabling us to explore the captivating intersection of physics and music.

Hydrogen

Expander 0.00 %
Spectrum 0.00 %

Size 97
Decay Time 104
Level -inf dB
Damping 102
Diffusion 105

Amount 0.00 %

Active ☐
Freq 0.10 Hz
Mode LP

Attack 600 ms
Decay 100 ms
Sustain 50.0 %
Release 1.00 s

Recycle 0.00 %
Reverse 50.4 %
Attack 100 %
Pos 0.94
Duration 194 ms
Rnd Dur 0.00 ms
Density 100 %
Rnd Dens 0.00 ms
Rnd Pos 0.52
Delay 75.6 ms
Rnd Delay 0.63 %
Slide 100 %
Feedback 64.6 %
Rnd Fb 92.9 %
DryWet 50.4 %
Semit 0 st
Rnd Pitch 0.00 %
Glide 0.00 %
Rnd Oct 1
Volume 1.00

Transposer 0 st
Volume 0.0 dB
Reverb -inf dB

Figure 9: Digital Musical Instrument in the Max MSP programming environment

4. CONCLUSION

This research unveils a fascinating connection between atomic physics, the Fast Fourier Transform (FFT), and music theory. It explores how atomic spectral lines shape the nuances of musical timbre, creating a harmony between science and art. The atomic emission spectra serve as distinct markers for chemical elements and set the stage for this investigation. Incorporating the Fast Fourier Transform (FFT) was key, as it linked time and frequency, revealing the impact of atomic spectral lines on the character of music.

Moreover, the discourse surrounding musical timbre underscored its profound significance in shaping music's emotional and aesthetic dimensions. Recognizing that the distinct qualities emanating from musical instruments, rooted in their unique timbres, resonate deeply within us, provoking nuanced responses. As these diverse disciplines converged, an expedition was undertaken that unveiled the harmonic ratios and intensities of spectral lines, translating this scientific data into a musical lexicon. This lexicon served as the canvas for creating innovative timbres, symbolizing the potential harmonious coalescence of science and art.

Practical applications, such as scientific collaborations with organizations like NASA and creative collaboration with ARTECHOUSE, making innovative exhibitions possible, fortified the real-world relevance of this research. The fusion of scientific rigor with artistic creativity is a potent force, inspiring and captivating the general audiences, transcending traditional boundaries of knowledge domains. In conclusion, this study unfolds new vistas of exploration for both scientific and artistic communities. It is a testament to the unifying power of knowledge and creativity, proving that atomic physics and music are intricately intertwined. As the journey through this interdisciplinary terrain progresses, there's eager anticipation for the emergence of a novel musical language that seamlessly intertwines the threads of science and art.

5. ACKNOWLEDGMENTS

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