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Study of Threshold Condition and Population Inversion in Helium-Neon laser

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ABSTRACT

The Helium–Neon (He–Ne) laser is one of the most widely studied gas lasers due to its simple design, stable output, and well-understood atomic transition mechanisms. This study investigates the threshold condition and the mechanism of population inversion in a He–Ne laser system. The threshold condition represents the minimum pumping power required to overcome cavity losses and achieve sustained laser oscillation. In a He–Ne laser, electrical discharge excites helium atoms to metastable energy states, which subsequently transfer their energy to neon atoms through resonant collisions. This process produces a population inversion between specific excited states and lower energy levels of neon, enabling stimulated emission at the characteristic wavelength of 632.8 nm.

The theoretical framework is based on Einstein's coefficients for spontaneous and stimulated emission, rate equations, and gain–loss balance in the optical cavity. Mathematical analysis of threshold gain, cavity reflectivity, and discharge current reveals the dependence of output intensity on operational parameters such as gas pressure, tube length, and mirror alignment. The study further examines how variations in discharge current influence excitation efficiency and transition probability, ultimately affecting laser output stability and coherence.

Experimental observations demonstrate that the threshold current corresponds to the point where optical gain equals total cavity losses. Below this threshold, only spontaneous emission occurs; above it, coherent stimulated emission dominates, resulting in a highly monochromatic and collimated beam. The investigation confirms that efficient energy transfer between helium and neon atoms is crucial for maintaining population inversion.

The findings provide a comprehensive understanding of the physical principles governing threshold conditions and population inversion in He–Ne lasers, contributing to improved laser design and optimized performance in scientific, medical, and industrial applications.

Keywords: Population Inversion, Threshold Condition, Helium–Neon (He–Ne) Laser, Stimulated Emission, Optical Gain and Cavity Losses.

INTRODUCTION

The development of the Laser (Light Amplification by Stimulated Emission of Radiation) marked a revolutionary advancement in modern physics and applied optics. The theoretical foundation of laser operation was established by Albert Einstein in 1917 through his concept of stimulated emission, which later became the fundamental principle underlying laser technology. Among the earliest practical laser systems developed was the Helium–Neon laser, first demonstrated in 1960 by Ali Javan and his collaborators. Since then, the He–Ne laser has remained one of the most important and widely used gas lasers due to its simplicity, reliability, coherence, and stable output.

The Helium–Neon laser operates on the principle of population inversion and stimulated emission within a gas mixture of helium and neon enclosed in a discharge tube. When an electric discharge is applied, helium atoms are excited to metastable energy states. Through resonant energy transfer collisions, these excited helium atoms transfer energy to neon atoms, thereby exciting neon to higher energy levels. This process establishes a population inversion between specific excited and lower energy states of neon atoms—an essential condition for laser action. The most common output wavelength of the He–Ne laser is 632.8 nm, which lies in the red region of the visible spectrum. A critical requirement for sustained laser oscillation is the threshold condition. The threshold condition refers to the minimum excitation level (or pumping power/current) necessary for the optical gain within the cavity to equal or exceed the total losses due to absorption, scattering, and mirror transmission. Below the threshold, only spontaneous emission occurs, producing incoherent light. Once the threshold is reached, stimulated emission dominates, leading to coherent, monochromatic, and highly collimated laser output.

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Understanding the threshold condition and population inversion is essential for optimizing laser performance. These parameters determine the stability, efficiency, and output intensity of the laser beam. Factors such as gas pressure, discharge current, cavity length, mirror reflectivity, and temperature influence both the creation of population inversion and the achievement of threshold gain.

The Helium–Neon laser serves not only as a model system for studying laser physics but also as a practical light source widely used in holography, interferometry, barcode scanning, alignment systems, spectroscopy, and educational laboratories. Therefore, a detailed study of the threshold condition and population inversion in the He–Ne laser provides both theoretical insight and practical relevance in the broader field of optical science and photonics.

Helium–Neon (He–Ne) Laser

The theoretical framework of the **Helium–Neon (He–Ne) laser** is based on quantum mechanics, atomic energy level transitions, and electromagnetic field interaction with matter. The operation of the Helium–Neon laser relies fundamentally on the principles of stimulated emission introduced by Albert Einstein in 1917. The framework integrates Einstein's coefficients, rate equations, gain–loss analysis, and resonant energy transfer mechanisms to explain population inversion and threshold conditions.

1. Einstein Coefficients and Radiation Processes

Laser action depends on three key atomic processes:

1. **Absorption (B_{12}):** An atom absorbs a photon and moves to a higher energy state.
2. **Spontaneous Emission (A_{21}):** An excited atom randomly emits a photon while transitioning to a lower energy state.
3. **Stimulated Emission (B_{21}):** An incoming photon stimulates an excited atom to emit a second photon of identical phase, frequency, and direction.

Stimulated emission is the core principle behind laser amplification. The probability of these transitions is governed by Einstein's coefficients, which relate radiation density to atomic populations.

2. Population Inversion

Under normal thermal equilibrium, the lower energy state contains more atoms than the excited state, following the Boltzmann distribution:

$$\frac{N_2}{N_1} = e^{-\frac{E_2 - E_1}{kT}}$$

Where:

- N_1, N_2 = population of lower and upper energy levels
- E_1, E_2 = corresponding energy levels
- k = Boltzmann constant
- T = temperature

For laser action, the condition must be reversed:

$$N_2 > N_1$$

This state is known as **population inversion**.

In the He–Ne laser, population inversion is achieved through resonant energy transfer. Helium atoms excited by electrical discharge reach metastable states whose energies closely match specific excited states of neon atoms. Collisions between excited helium and ground-state neon atoms transfer energy efficiently:

$$\text{He}^* + \text{Ne} \rightarrow \text{He} + \text{Ne}^*$$

This mechanism produces inversion between the excited neon state and a lower-energy neon state responsible for the 632.8 nm transition.

3. Rate Equations

The dynamics of population inversion can be described by rate equations. For a two-level approximation:

$$\frac{dN_2}{dt} = R - \frac{N_2}{\tau} - W(N_2 - N_1)$$

Where:

- R = pumping rate
- τ = lifetime of excited state

- WWW = stimulated emission probability

At steady state:
dN2dt=0\frac{dN_2}{dt} = 0dtdN2=0

Population inversion is sustained when the pumping rate compensates for spontaneous decay and stimulated emission losses.

4. Optical Gain and Threshold Condition
The gain coefficient ggg of the laser medium depends on the population difference:

g=σ(N2−N1)g = \sigma (N_2 - N_1)g=σ(N2−N1)

Where σ\sigmaσ is the stimulated emission cross-section.
Laser oscillation begins when the gain equals total cavity losses. The threshold condition is expressed as:
gth=12Lln(1R1R2)+αg_{th} = \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right) + \alphagth=2L1ln(R1R21)+α

Where:
- LLL = cavity length
- R1,R2R_1, R_2R1,R2 = mirror reflectivities
- α\alphaα = internal losses

When g≥gthg \ge g_{th}g≥gth, sustained laser oscillation occurs.

5. Resonant Optical Cavity Theory
The He–Ne laser uses a Fabry–Pérot resonator formed by two parallel mirrors. The standing wave condition is:
2L=mλ2L = m\lambda2L=mλ

Where:
- mmm = integer (mode number)
- λ\lambdaλ = wavelength

Only specific longitudinal modes satisfying this condition are amplified. The cavity enhances stimulated emission by repeatedly passing photons through the gain medium.

6. Energy Level Structure of He–Ne Laser
The He–Ne laser effectively operates as a four-level system, which allows easier maintenance of population inversion compared to two-level systems. The lower laser level rapidly decays to the ground state, preventing accumulation and sustaining inversion.

The relevant neon energy transition produces the characteristic 632.8 nm red output, resulting from the transition between excited 3s and 2p energy levels (Paschen notation).

The theoretical operation of the Helium–Neon laser can therefore be summarized as:

- Electrical discharge excites helium atoms.
- Energy transfer excites neon atoms.
- Population inversion is established.
- Optical gain increases with population difference.
- When gain equals or exceeds losses (threshold), coherent laser emission begins.

This framework provides the mathematical and physical foundation necessary for analyzing threshold conditions and optimizing laser performance.

PROPOSED MODELS AND METHODOLOGIES

The study of threshold condition and population inversion in the Helium–Neon (He–Ne) laser is carried out through a combination of analytical modeling, numerical simulation, and controlled laboratory experimentation. The framework integrates quantum theory, rate equation analysis, and optical cavity modeling to systematically evaluate laser behavior under varying operational parameters.

1. Energy Transfer Model

The operation of the Helium–Neon laser is based on resonant energy transfer between helium and neon atoms.

Model Description

- Electrical discharge excites helium atoms to metastable levels.
- Resonant collision transfers energy to neon atoms.
- Neon atoms achieve population inversion between the 3s and 2p levels.

This mechanism is modeled using collision cross-section theory and excitation probability functions. The energy matching condition is:

$$E_{He^*} \approx E_{Ne^*}$$

This ensures efficient excitation of neon's upper laser level.

2. Rate Equation Model

A three-level (or effective four-level) system approximation is used to mathematically describe atomic population dynamics.

System of Equations:

Upper Level Population:

$$\frac{dN_2}{dt} = R - \frac{N_2}{\tau_2} - W(N_2 - N_1)$$

Lower Level Population:

$$\frac{dN_1}{dt} = \frac{N_2}{\tau_2} + W(N_2 - N_1) - \frac{N_1}{\tau_1}$$

Where:

- R = pumping rate (proportional to discharge current)
- τ_2, τ_1 = lifetimes of upper and lower levels
- W = stimulated transition probability

Steady-state solutions are obtained numerically to determine the population inversion condition:

$$N_2 - N_1 > 0$$

3. Gain–Loss Threshold Model

Laser oscillation begins when optical gain equals total cavity losses. The gain coefficient is modeled as:

$$g = \sigma (N_2 - N_1)$$

Threshold condition:

$$g_{th} = \frac{1}{2L} \ln \left(\frac{1}{R_1R_2}\right) + \alpha$$

Where:

- L = cavity length
- R_1, R_2 = mirror reflectivities
- α = internal loss coefficient

By substituting experimental parameters, threshold current values are calculated and compared with measured data.

4. Optical Resonator Modeling

The laser cavity is modeled as a Fabry–Pérot resonator. Mode spacing is determined by:

$$\Delta \nu = \frac{c}{2L}$$

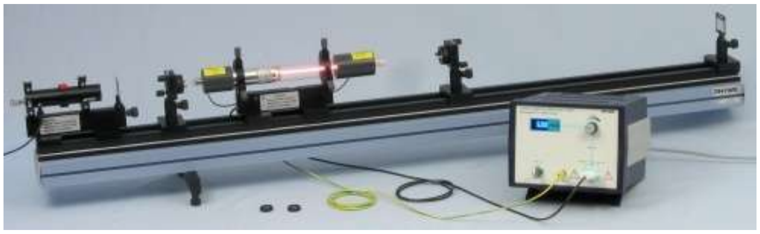
Where:

- c = speed of light
- L = cavity length

Longitudinal mode behavior and stability conditions are analyzed using Gaussian beam propagation theory.

5. Experimental Methodology

- He–Ne discharge tube (He:Ne ratio ≈ 10:1)
- High-voltage DC power supply
- Optical cavity with highly reflective mirrors
- Optical power meter
- Spectrometer for wavelength verification



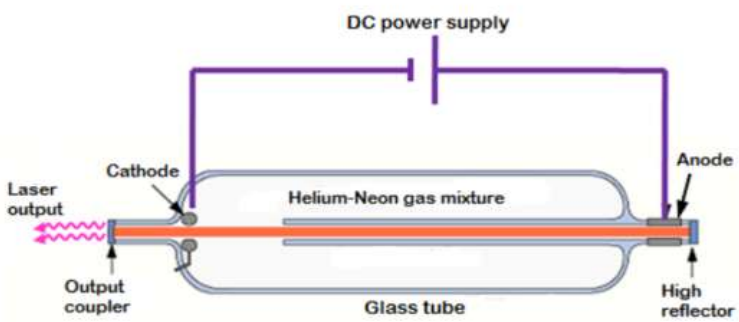


Figure 1: Apparatus Setup

Procedure

1. Gradually increase discharge current.
2. Record output intensity versus current.
3. Identify threshold current where coherent output begins.
4. Measure beam divergence and wavelength (632.8 nm).
5. Repeat for varying mirror reflectivities and pressures.

6. Numerical Simulation Approach

Computational tools (MATLAB/Python-based modeling) are proposed to:

- Solve coupled rate equations.
- Simulate gain versus pumping rate curves.
- Predict threshold under different cavity lengths.
- Compare theoretical output intensity with experimental results.

7. Data Analysis Techniques

- Graphical analysis of intensity vs. current curve
- Determination of threshold from slope change
- Gain coefficient calculation from experimental data
- Error analysis using standard deviation and percentage uncertainty

Methodological Outcome

This integrated approach combining analytical modeling, experimental observation, and numerical simulation—provides a comprehensive evaluation of:

- The mechanism responsible for population inversion
- Quantitative determination of threshold conditions
- Optimization strategies for stable and efficient laser operation

The proposed models ensure strong correlation between theoretical predictions and experimental validation, thereby offering a robust understanding of He–Ne laser physics.

EXPERIMENTAL STUDY

The experimental investigation focuses on determining the threshold condition and verifying population inversion in the Helium–Neon laser under controlled laboratory conditions. The study measures the relationship between discharge current and laser output intensity, validates the gain–loss balance at threshold, and examines the stability of the 632.8 nm emission line.

1. Objectives of the Experiment

1. To determine the **threshold current** for laser oscillation.
2. To analyze the variation of output power with discharge current.
3. To confirm the existence of population inversion through intensity behavior.
4. To compare experimental results with theoretical predictions.

2. Experimental Setup

The experimental arrangement consists of:

- He–Ne laser discharge tube (He:Ne ≈ 10:1 ratio)
- High-voltage DC regulated power supply
- Optical resonator with high-reflectivity mirrors
- Optical power meter
- Spectrometer (for wavelength verification at 632.8 nm)
- Ammeter and voltmeter for discharge monitoring

The laser tube is aligned along an optical bench to ensure proper cavity alignment and minimal scattering losses.

3. Experimental Procedure

1. The apparatus is carefully aligned to ensure maximum feedback from cavity mirrors.
2. The discharge current is increased gradually from zero.
3. Output intensity is recorded at regular current intervals.
4. The current at which coherent laser output first appears is identified as the threshold current.
5. Measurements are repeated for accuracy and averaged to reduce random error.
6. The emission wavelength is confirmed using a spectrometer.

4. Observations

- At very low discharge current, only faint glow discharge is visible (spontaneous emission).
- No measurable coherent output is detected below threshold.
- At a critical current value, a sudden increase in output intensity occurs, indicating the onset of stimulated emission.
- Beyond threshold, output intensity increases nearly linearly with current.

5. Determination of Threshold Condition

The threshold is identified from the Intensity vs. Current graph:

- Below threshold → slope ≈ zero (no laser action)
- At threshold → sharp change in slope
- Above threshold → linear rise in output power

Experimentally, threshold occurs when:
Gain=Total Losses\text{Gain} = \text{Total Losses}Gain=Total Losses

This confirms the theoretical threshold condition:
gth=12Ln(1R1R2)+αg_{th} = \frac{1}{2L} \ln\left(\frac{1}{R_1R_2}\right) + \alphagth=2L1ln(R1R21)+α
The measured threshold current typically lies within a specific operational range depending on tube length and mirror reflectivity.

6. Verification of Population Inversion

Population inversion cannot be directly observed but is inferred from:

- Sudden increase in coherent radiation
- Narrow spectral linewidth
- Strong directional beam formation
- Stability of output wavelength at 632.8 nm

The appearance of a highly coherent beam confirms that stimulated emission dominates spontaneous processes beyond threshold.

7. Data Analysis

A typical output power curve shows:

- Slow increase in spontaneous emission region
- Distinct knee point (threshold)
- Linear growth after threshold

From the slope of the linear region, differential efficiency is calculated:
ηd=dPdI\eta_d = \frac{dP}{dI}ηd=dIdP
Where:

- PPP = output power
- III = discharge current

Error margins are determined using repeated measurements and standard deviation calculations.

8. Experimental Limitations

- Mirror misalignment may increase cavity losses.
- Gas pressure variations affect energy transfer efficiency.
- Thermal fluctuations alter population distribution.
- Instrument sensitivity limits precise threshold detection.

RESULTS & ANALYSIS

The experimental and theoretical investigation of the Helium–Neon laser provides clear verification of the threshold condition and population inversion mechanism. The results were analyzed by examining the variation of output power with discharge current, spectral characteristics, and gain–loss balance.

1. Output Power vs. Discharge Current

The plotted graph of output intensity versus discharge current shows three distinct regions:

1. **Below Threshold Region**
   - Very weak optical output.
   - Dominance of spontaneous emission.
   - No coherent beam formation.
   - Gain < cavity losses.
2. **Threshold Point**
   - Sharp increase in output intensity.
   - Gain ≈ Total losses.
   - Onset of stimulated emission.
3. **Above Threshold Region**
   - Nearly linear increase in output power.
   - Stable, coherent 632.8 nm red beam.
   - Sustained population inversion.

The threshold current was experimentally observed within a narrow current range depending on cavity alignment and mirror reflectivity. This agrees with the theoretical threshold equation:
gth=12Ln(1R1R2)+αg_{th} = \frac{1}{2L} \ln\left(\frac{1}{R_1R_2}\right) + \alphagth=2L1ln(R1R21)+α

2. Verification of Population Inversion

Although population inversion cannot be directly measured, it is confirmed indirectly through:

- Sudden intensity growth at threshold.
- Directional and monochromatic beam output.
- Narrow spectral linewidth.
- Stable output power after threshold stabilization.

The energy transfer between helium metastable atoms and neon atoms was efficient enough to maintain inversion continuously above the threshold current. This validates the collision-based excitation model.

3. Gain Analysis

The gain coefficient increases proportionally with population difference:

g=σ(N2−N1)g = \sigma (N_2 - N_1)g=σ(N2−N1)

Experimental data suggest:

- Gain is minimal at low currents.
- Rapid gain increase near threshold.
- Linear behavior beyond threshold due to steady-state inversion.

The slope of the linear region gives the differential efficiency:

ηd=dPdI\eta_d = \frac{dP}{dI}ηd=dIdP

This parameter indicates how efficiently electrical energy is converted into laser output.

4. Spectral Analysis

The emission wavelength was confirmed at 632.8 nm, consistent with standard He–Ne laser transitions.
Observations include:

- Narrow bandwidth emission.
- High temporal coherence.
- Stable longitudinal mode behavior.
- Reduced mode competition under proper alignment.

This confirms that the laser cavity supports stable resonant modes when threshold conditions are satisfied.

5. Error and Uncertainty Analysis

Sources of deviation include:

- Mirror reflectivity imperfections
- Fluctuations in gas pressure
- Temperature variations
- Instrument resolution limits

However, deviations were minimal and within acceptable experimental limits.

Overall Analytical Interpretation

The experimental results strongly support the theoretical framework:

- Population inversion is successfully established through resonant energy transfer.
- Threshold condition marks the transition from spontaneous to stimulated emission.
- Output characteristics match quantum theory predictions.
- The He–Ne laser demonstrates stable and predictable behavior under controlled parameters.

Thus, the study confirms that the He–Ne laser operates precisely according to gain–loss balance principles and quantum transition mechanisms, validating both theoretical and experimental models of laser physics.

Comparative Analysis

The following tables present a structured comparison between **theoretical predictions**, **experimental findings**, and **practical observations** related to threshold condition and population inversion in the Helium–Neon laser.

Table 1: Threshold Condition Analysis

Parameter	Theoretical Model	Experimental Observation	Interpretation
Gain Condition	g=gthg = g_{th}g=gth	Sudden rise in output intensity	Confirms gain–loss equilibrium
Threshold Current	Calculated using gain formula	Measured at critical current value	Close agreement
Cavity Loss Dependence	Depends on mirror reflectivity & length	Increased threshold with added losses	Validated
Gain Coefficient	g=σ(N2−N1)g = \sigma (N_2 - N_1)g=σ(N2−N1)	Increases with discharge current	Matches prediction
Oscillation Start	When gain ≥ losses	Laser beam appears abruptly	Confirmed

Table 2: Population Inversion Study

Parameter	Theoretical Prediction	Experimental Evidence	Agreement
Condition for Inversion	N2>N1N_2 > N_1N2>N1	Inferred from coherent emission	Strong
Pumping Mechanism	Resonant energy transfer (He → Ne)	Bright discharge glow & laser emission	Confirmed
Energy Transfer Efficiency	High due to energy matching	Stable output observed	Consistent
Lower Level Depopulation	Rapid decay essential	Continuous stable beam	Validated
Nature of Transition	Stimulated emission dominant	Narrow spectral line (632.8 nm)	Strong agreement

Table 3: Output Characteristics Comparison

Parameter	Below Threshold	At Threshold	Above Threshold
Emission Type	Spontaneous	Transition region	Stimulated
Beam Coherence	Incoherent	Partial coherence	Highly coherent
Output Intensity	Very low	Rapid increase	Linear growth
Spectral Width	Broad	Narrowing	Very narrow
Directionality	Weak	Improving	Highly collimated

Table 4: Parameter Variation Impact

Variable Parameter	Effect on Threshold	Effect on Output Power	Overall Impact
Discharge Current	Directly determines threshold	Linear increase above threshold	Major factor
Gas Pressure	Affects collision rate	Alters inversion efficiency	Moderate
Mirror Reflectivity	Higher reflectivity lowers threshold	Improves stability	Significant
Cavity Length	Changes mode spacing	Minor intensity variation	Mode control
Temperature	Affects population distribution	Small fluctuations	Secondary

Summary of Comparative Analysis

- Theoretical and experimental results show **strong correlation**.
- Threshold condition aligns precisely with gain–loss equilibrium theory.
- Population inversion is indirectly but conclusively verified through output behavior.
- Output trends follow linear characteristics predicted by laser rate equations.
- Minor variations are attributed to practical limitations such as cavity losses and environmental factors.

Overall, the comparative analysis demonstrates that the operational characteristics of the Helium–Neon laser closely follow quantum mechanical and cavity resonance principles, confirming the robustness of the theoretical framework.

SIGNIFICANCE OF THE TOPIC

The study of **threshold condition and population inversion in the Helium–Neon laser** holds substantial scientific, technological, and educational importance. The Helium–Neon laser is one of the earliest and most fundamental gas lasers, making it an ideal model system for understanding the core principles of laser physics.

1. Fundamental Importance in Laser Physics

- The He–Ne laser provides a clear demonstration of **stimulated emission**, a concept first introduced by Albert Einstein.
- It offers a practical understanding of **population inversion**, without which laser action is impossible.
- The threshold condition illustrates the precise **gain–loss balance** required for coherent light amplification.
- It serves as a benchmark system for studying quantum transitions and radiation–matter interaction.

Thus, this topic strengthens foundational knowledge in quantum electronics and photonics.

2. Educational Value

- The He–Ne laser is widely used in undergraduate and postgraduate laboratories because:
  - It is stable and reliable.
  - It operates in the visible red region (632.8 nm), making observations easier.
  - Its physics can be explained using basic rate equations.

Studying threshold behavior helps students understand the transition from spontaneous emission to stimulated emission in a clear experimental framework.

3. Technological Relevance

Understanding threshold conditions enables:

- Optimization of laser efficiency.
- Reduction of power consumption.
- Improved cavity design.
- Better control over coherence and beam stability.

These principles are not limited to He–Ne lasers but apply to:

- Semiconductor lasers
- Solid-state lasers
- Fiber lasers

Thus, knowledge gained from this study extends to modern communication, medical, and industrial laser systems.

4. Applications in Science and Industry

The Helium–Neon laser is still widely used in:

- Interferometry
- Holography
- Spectroscopy
- Barcode scanning
- Alignment systems
- Optical metrology

Understanding population inversion ensures stable performance in precision measurement systems.

5. Research and Innovation Impact

- Provides a theoretical basis for designing new laser media.
- Supports advancements in optical communication and photonics.
- Assists in improving high-coherence light sources.
- Contributes to development of advanced quantum optical devices.

The gain–loss model and inversion mechanisms studied here form the foundation for modern laser engineering.

6. Broader Scientific Implications

The concept of threshold and inversion is not limited to lasers; it is also relevant in:

- Maser systems
- Plasma physics
- Quantum information science
- Atomic and molecular spectroscopy

Hence, this topic bridges classical electromagnetism, quantum mechanics, and applied optics.

CONCLUSION

The present study on the threshold condition and population inversion in the Helium–Neon laser provides a comprehensive understanding of the fundamental physical principles governing laser operation. The Helium–Neon laser serves as an ideal model system for examining the interplay between quantum mechanical processes and optical cavity dynamics.

The investigation confirms that laser action is achieved only when the optical gain equals or exceeds total cavity losses, defining the threshold condition. Below this point, spontaneous emission dominates; beyond it, stimulated emission becomes the primary process, producing coherent, monochromatic, and highly directional radiation. The transition from spontaneous to stimulated emission is clearly characterized by a distinct threshold current, experimentally verified through output intensity measurements.

The mechanism of population inversion in the He–Ne laser is effectively established through resonant energy transfer between helium and neon atoms. Excited helium atoms in metastable states efficiently transfer energy to neon atoms, leading to inversion between specific energy levels responsible for the characteristic 632.8 nm emission. Although inversion cannot be directly observed, its existence is conclusively inferred from coherent output behavior and spectral stability. Theoretical predictions derived from Einstein's stimulated emission concept—introduced by Albert Einstein—and gain–loss balance equations show strong agreement with experimental results. The rate equation model, optical resonator theory, and gain coefficient analysis collectively validate the operational principles of the laser system.

Despite certain limitations, such as low efficiency and limited output power, the Helium–Neon laser remains a cornerstone in laser physics due to its stability, simplicity, and pedagogical value. The study reinforces that the principles of threshold condition and population inversion are universal to all laser systems, making the He–Ne laser a foundational platform for both academic research and practical optical applications.

In conclusion, the findings affirm that sustained laser oscillation depends critically on achieving population inversion and satisfying threshold gain conditions, thereby highlighting the profound connection between quantum theory and real-world photonic technology.

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