# 2025-2026 Fall Semester | DEPARTMENT OF PHYSICS

## QuTiP-Based Two-Level System Oscillation Simulation


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### Abstract

In this study, two-level quantum systems were modeled using the QuTiP library. Based on the performed simulations, the sensitivity of the system to pulse area and detuning parameters was determined; vacuum Rabi oscillations were observed within the framework of the Jaynes-Cummings model; and the consistency between theoretical models and numerical methods was demonstrated.


### Introduction & Historical Context

**The Quantum Revolutions:** Quantum optics has evolved from the early wave-particle duality (Newton vs. Huygens) and Planck's quantization of energy to the **Second Quantum Revolution**, where we now directly manipulate and program individual quantum states.

**Two-Level System (TLS) Approximation**: In laser-atom interactions, we simplify complex atomic structures by considering only two resonant energy levels ($|g\rangle$ and $|x\rangle$). This approximation is valid when the driving light is near-resonant with the transition frequency.

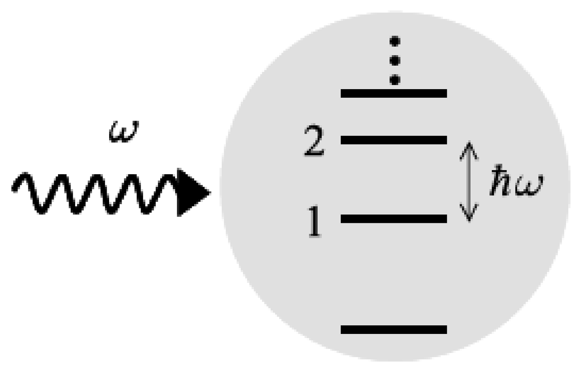


**Figure 1:** Energy Level Scheme of a Two-Level System (TLS)

### Theoretical Framework

**The Hamiltonian:** The dynamics are governed by the system Hamiltonian, which includes the free energy of the states and the interaction term under the **Electric Dipole Approximation**.

**Rotating Wave Approximation (RWA):** To simplify the time-dependent Schrödinger equation, high-frequency oscillating terms are neglected. This yields a simplified Hamiltonian that predicts **Rabi Oscillations**—the periodic exchange of energy between the light field and the atom.

$$H_{int} = \hbar\Omega cos(\omega t)\sigma_x = \frac{\hbar\Omega}{2}\left(e^{iwt} + e^{-iwt}\right)\sigma_x.$$

$$H_{RWA} = \frac{\hbar\Delta}{2}\sigma_z + \frac{\hbar\Omega}{2}\sigma_x.$$

$$\Delta = \omega - \omega_{0.} \text{ Detuning}$$

$$\hat{H} = \frac{\hbar}{2}\begin{pmatrix}\Delta & \Omega \\ \Omega & -\Delta\end{pmatrix}. \textit{ Hamiltonian matrix representation}$$

The eigenvalues of the Hamiltonian operator correspond to the energy levels:

$$\lambda = \pm\frac{\hbar\Omega_R}{2}, \Omega_R = \sqrt{\Omega^2 + \Delta^2}.$$

$\Omega_R$ :Where $\Omega$ denotes the generalized Rabi frequency. The obtained solution is:

$$|\psi(t)\rangle = \begin{pmatrix}\cos\left(\frac{\Omega_R t}{2}\right) - i\frac{\Delta}{\Omega_R}\sin\left(\frac{\Omega_R t}{2}\right) \\ -i\frac{\Omega}{\Omega_R}\sin\left(\frac{\Omega_R t}{2}\right)\end{pmatrix}.$$

The probability of being in the excited state is given by:

$$P_2(t) = |\langle 2 \mid \psi(t)\rangle|^2 = \frac{\Omega^2}{\Omega_R^2}\sin^2\left(\frac{\Omega_R t}{2}\right).$$

$\Delta = 0$ . (The resonance condition)

$$p_2(t) = \sin^2\left(\frac{\Omega t}{2}\right).$$

As the detuning increases, the oscillation amplitude decreases, and the frequency becomes $\Omega_R$.

In conclusion, Rabi oscillations describe the periodic transition between two energy levels in quantum systems. The amplitude and frequency of this transition depend on the coupling strength and detuning of the system. The formula derived using the Rotating Wave Approximation (RWA) effectively characterizes this system.

### Jaynes–Cummings Model

It represents the interaction of a two-level atom with a single-mode quantized electromagnetic field (vacuum mode). In this model, both the atom and the field are treated quantum mechanically. Dressed States refer to the new energy levels formed when the atom and photon become inseparable.

### Vacuum Rabi Oscillations (Simulation Findings)

Quantum Signature: In contrast to classical theory, the Jaynes-Cummings (JC) model predicts that even in the absence of initial photons (n=0), an atom transitioning from the excited state to the ground state emits a photon, and this energy oscillates periodically within the system. This phenomenon is a direct consequence of the zero-point energy inherent in the quantum vacuum.

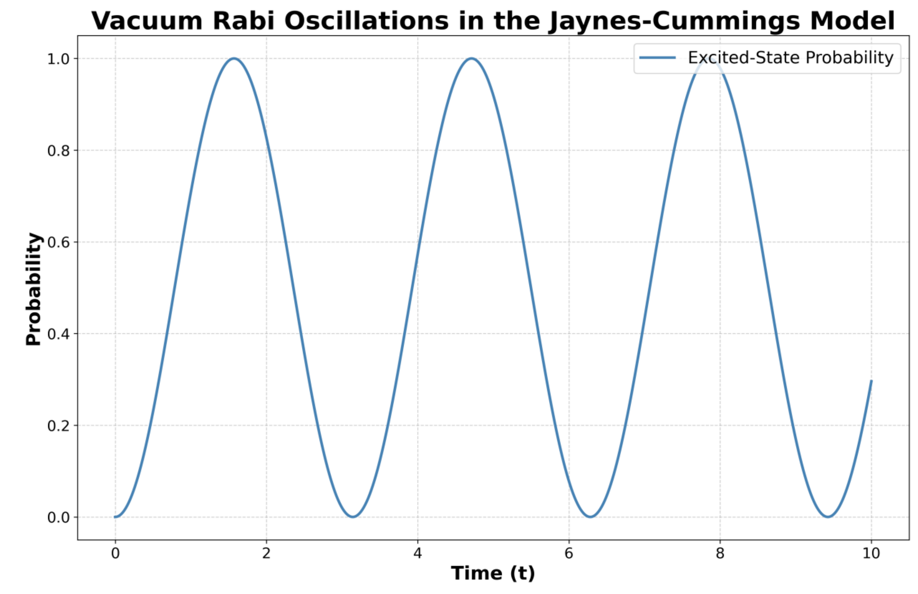


**Figure 2:** Vacuum Rabi Oscillations in the Resonant Jaynes-Cummings Model

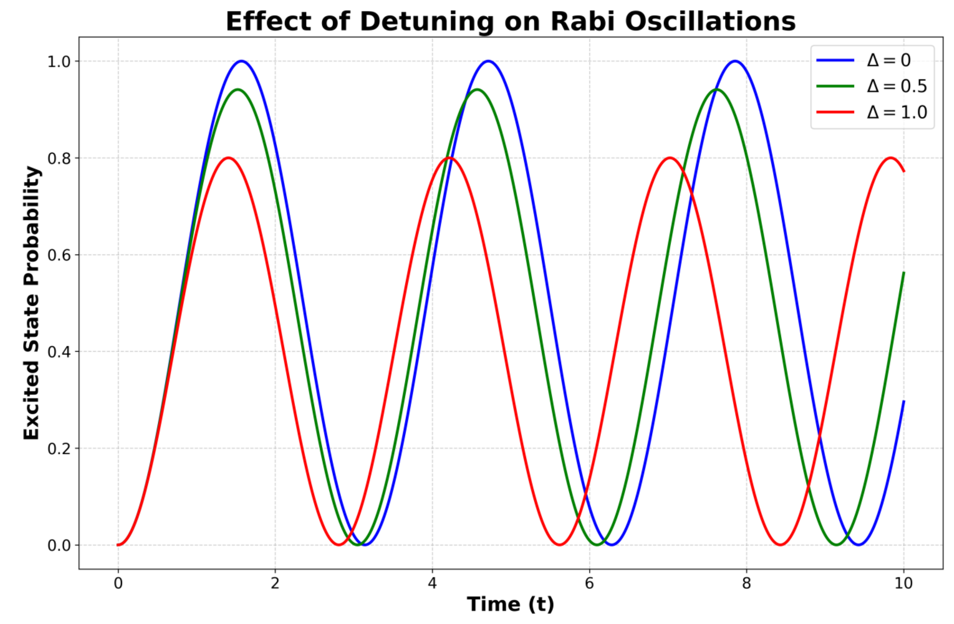


**Figure 3**: Effect of Detuning on Rabi Oscillations

**Table 1:** Comparison of System Dynamics under Different Detuning Values

| Detuning Δ | Probability Oscillation | Colour | Interpretation |
|---|---|---|---|
| 0 | High amplitude, low frequency | Blue | Full resonance→ ΩR=Ω |
| 0.5 | Low amplitude, fast oscillation | Green | ΩR>Ω |
| 1 | Even lower amplitude and faster oscillation. | Red | ΩR>>Ω |

### Why simulation, Why QuTiP?

**Open Systems:** Solves noise and loss effects using Lindblad master equations.
**Dynamic Analysis:** Simulates time-dependent laser fields and system evolution.
**Visualization:** Facilitates easy visualization of quantum states and parameters.

```
#Tensor products for atom-cavity system
a  = tensor(destroy(N), qeye(2))
sm = tensor(qeye(N), destroy(2))

#Hamiltonian with Rotating Wave Approx.
H = wc * a.dag() * a + wa * sm.dag() * sm + \
    g * (a.dag() * sm + a * sm.dag())

#Solving Master Equation (Lindblad)
result = mesolve(H, psi0, tlist, c_ops=[],
e_ops=[a.dag()*a, sm.dag()*sm])
```

### Time-Dependent Laser Interaction (Driven Two-Level System)

In this section, the driving of a two-level quantum system by a realistic Gaussian laser pulse, rather than a constant field, is addressed. To account for the time-dependent interaction, the Hamiltonian is explicitly defined as a function of time, H(t). The system dynamics were analyzed using the time-dependent solver of the QuTiP library, and the influence of the laser pulse envelope on the system was examined in detail.

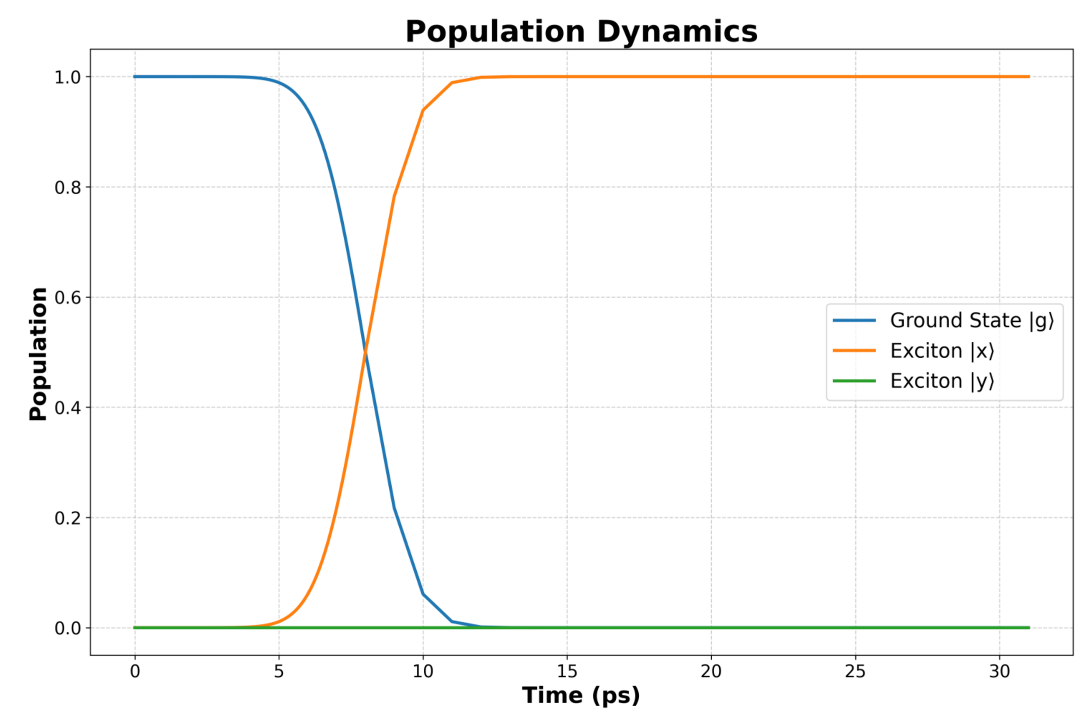


**Figure 4:** Population Dynamics

### Rabi Oscillations and Population Inversion

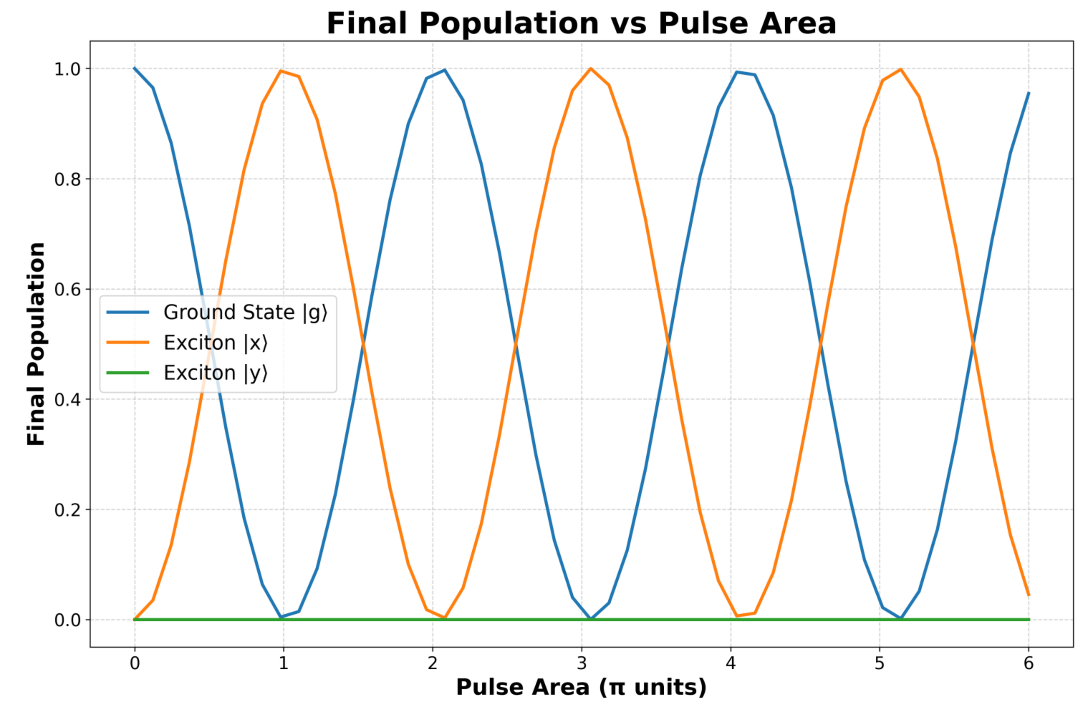


**Figure 5:** Final Population vs. Pulse Area

The obtained results clearly demonstrate the coherent population transfer (Rabi flopping) from the ground state $|g\rangle$ to the excited state $|e\rangle$ during the laser pulse. Under optimal pulse area conditions, complete population inversion was observed, which is in excellent agreement with theoretical expectations.


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# 2025-2026 Güz Yarıyılı

# FİZİK BÖLÜMÜ

## MINKOWSKI VE RINDLER UZAY-ZAMANLARINDA SKALER ALAN:

## UNRUH IŞINIMI

**Cansu Ünal 21022033**

**Danışman: Prof. Dr. Reyhan Kaya**

Bu çalışmada, kuantum alan kuramında parçacık ve vakum kavramlarının mutlak değil, gözlemciye bağlı yapılar olduğu problemi ele alınmıştır. Serbest bir skaler alan, önce Minkowski uzay-zamanında kanonik olarak kuantize edilerek eylemsiz gözlemciler için standart parçacık yorumu kurulmuştur. Ardından, düzgün ivmeli gözlemcilere uyumlu Rindler koordinatları kullanılarak alan denklemleri çözülmüş ve bu gözlemciler için tanımlanan modlar elde edilmiştir. Minkowski ve Rindler modları arasındaki ilişki Bogoliubov dönüşümü aracılığıyla analiz edilmiştir. Bu analiz sonucunda, ivmeli gözlemcilerin eylemsiz vakumu termal bir spektrum olarak algıladığı açıkça gösterilmiştir. Elde edilen bulgular, Unruh etkisinin matematiksel temelini ortaya koymakta ve parçacık kavramının gözlemciye bağlı doğasını vurgulamaktadır.

## KAVRAMSAL PROBLEM

Kuantum alan kuramında parçacık ve vakum kavramları, genellikle eylemsiz gözlemciler için tanımlanan küresel bir zaman koordinatına dayanır. Bu yapı, parçacık kavramını gözlemciden bağımsız ve mutlakmış gibi sunar. Ancak gözlemci ivmeli hareket ettiğinde, uzay-zamanın küresel zaman simetrisi kaybolur ve bu tanım geçerliliğini yitirir. Bu durumda aynı kuantum alan farklı gözlemciler tarafından farklı parçacık içerikleriyle algılanabilir. Unruh etkisi, bu gözlemci bağımlılığının en çarpıcı sonuçlarından birisidir.

## SKALER ALAN VE KLEIN-GORDON DENKLEMİ

Kuantum alan kuramında nesne parçacıklar değil, uzay-zaman üzerine tanımlı alanlardır. Serbest skaler bir alanın dinamiği, Lorentz simetrisini koruyan bir Lagrange yoğunluğu üzerinden tanımlanır. Alan denklemi bu Lagrangian'ın varyasyonundan elde edilir.

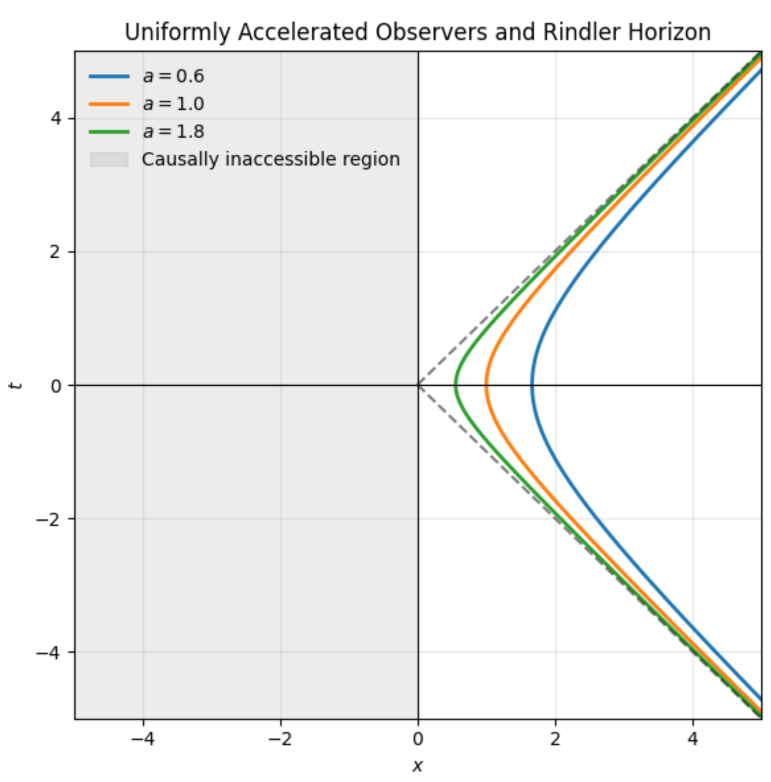
$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2$$

Bu Lagrangian'a Euler-Lagrange denklemi uygulandığında alanın uzay ve zamandaki evrimini belirleyen Klein-Gordon denklemi elde edilir.

$$(\Box + m^2)\phi = 0$$

Alanın mod yapısı bu denklemlerin çözümleri üzerinden tanımlanır ve parçacık kavramı, bu mod ayrımına dayanır. Pozitif frekanslı çözümlerin seçimi, vakum durumunu ve parçacık yorumunu belirler.

## MINKOWSKI VE RINDLER UZAY-ZAMANLARI




**Şekil 1:** Sabit öz ivmeye sahip gözlemcilerin dünya çizgileri.

Minkowski uzay-zamanı eylemsiz gözlemciler için doğal bir referans çerçevesi oluşturur. Bu nedenle zaman çerçevesi küresel olarak tanımlıdır ve uzay zamanın tamamı erişilebilirdir. Nedensel yapı ışık konileri tarafından belirlenir ve parçacık ile vakum kavramları bu küresel zaman koordinatlarına göre tanımlanır.

$$ds^2 = -c^2dt^2 + dx^2$$

Metrik altında tam olaylar tek bir zaman parametresile sıralanabilir ve parçacık kavramı gözlemciden bağımsızdır. Sabit ivmeli gözlemcileri tanımlamak için Minkowski uzay- zamanındaki dünya çizgileriden farklı bir geometrik yapı ortaya çıkar. Sabit ivmeli gözlemci için temel koşul hissedilen öz ivmenin zaman boyunca sabit kalmasıdır. Bu koşul dünya çizgisinin doğrusal değil, sabit Minkowski aralığına karşılık gelen bir eğri olmasını gerektirmektedir. Değişmez aralık koşulu hiperbolik dünya çizgileri üretir.

Bu hiperbolik yapıyı düzgün biçimde parametrize etmek için Rindler koordinatları tanımlanır. Sınırlı bölgede Minkowski koordinatları ivmeli gözlemcilere uyarlanmış şekilde ifade edilir.

$$ct(\tau) = \frac{c^2}{a}\sinh\left(\frac{a}{c}\tau\right), \qquad x(\tau) = \frac{c^2}{a}\cosh\left(\frac{a}{c}\tau\right)$$

Ve böylece hiperbolik dünya çizgilerine karşılık gelir.

$$ds^2 = -a^2\xi^2\,d\tau^2 + d\xi^2$$

Işık doğrularına (x=ct) asimptotik olarak yaklaşan bu hiperbolik yapı ivmeli gözlemciler için erişilmeyen bölgelerin ortaya çıkmasına yol açar ve bu sınırlar Rindler koordinatlarında olay ufku olarak yorumlanır. Böylece Rindler koordinatlarının hiperbolik yapısı, sabit ivmeli gözlemcilerin uzay-zamandaki nedensel erişimini ve zaman tanımını doğrudan geometrik olarak kodlanır. Farklı zaman tanımları içeren bu koordinatlar alan çözümlerinin frekans ayrımını gözlemciye bağlı hale getirir.

## MINKOWSKI VE RINDLER UZAYINDA ALAN ÇÖZÜMLERİ

Kütleli bir skaler alanın dinamiği, koordinat sisteminden bağımsız formda Klein-Gordon denklemi ile ifade edilir.

$$\frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\phi\right) - m^2\phi = 0.$$

Alan operatörü, bu modlar üzerinden yaratma ve yok etme operatörleri cinsinden ifade edilir.:

$$\hat{\phi} = \int dk\left(\hat{a}_k f_k + \hat{a}_k^\dagger f_k^*\right).$$

İvmeli çerçevede Klein-Gordon denklemi aşağıdaki gibidir. kullanılarak denklem, uzaysal kısım için adi diferansiyel denkleme indirgenir:

$$\frac{1}{a^2\xi^2}\partial_\tau^2\phi - \partial_\xi^2\phi - \frac{1}{\xi}\partial_\xi\phi + m^2\phi = 0 \;\rightarrow\; X'' + \frac{1}{\xi}X' + \left(\frac{\Omega^2}{a^2\xi^2} - m^2\right)X = 0.$$

z=am eaξ koordinat dönüşümü ile denklem, sanal dereceli (ν=iΩ/a) **Modifiye Bessel Denklemi** standart formuna dönüşür.

$$X_{pp} + \frac{1}{p}X_p - \left(1 + \frac{\nu^2}{p^2}\right)X = 0$$

Elde edilen denklemin iki matematiksel çözümü vardır. Ancak fiziksel bir alanın uzaysal sonsuzda sınırsız büyümesi mümkün değildir. Bu nedenle, sonsuzda üstel olarak büyüyen çözüm elenir ve fiziksel sınır koşullarına uygun olan, yani sonsuzda sönümlenerek sonlu kalan çözüm seçilir:

$$\phi_\Omega(\tau,\xi) = N_\Omega\, e^{-i\Omega\tau}\, K_{i\Omega/a}(m\xi).$$

Alan ivmeli gözlemcinin kendi referans çerçevesine özgü tanımladığı operatörler cinsinden ifade edilir. Bu çerçevede parçacık içermeyen en düşük enerjili durum olan Rindler vakumu, ivmeli gözlemcinin tanımladığı operatörlerin alanı boşluk olarak algıladığı durumdur:

$$\hat{\phi} = \int d\Omega\left(\hat{b}_\Omega u_\Omega + \hat{b}_\Omega^\dagger u_\Omega^*\right).$$

## BOGOLIUBOV DÖNÜŞÜMLERİ VE PARÇACIK YORUMU

Rindler modları, Minkowski modları cinsinden genel olarak aşağıdaki biçimde açılabilir:

$$u_\Omega = \int dk[\alpha_{\Omega k}u_k + \beta_{\Omega k}u_k{}^*].$$

Katsayılar, Klein-Gordon iç çarpımı ile projeksiyon yapılarak elde edilir.
Hesaplamanın kalbi, Rindler modlarının olay ufku (x=0) civarındaki davranışıdır. İntegrand, modifiye Bessel fonksiyonları içerir ve şu formdadır:

$$\beta_{\Omega k} \sim \int_0^\infty dx\, x^{i\Omega/a}\, e^{ikx}.$$

Minkowski ve Rindler modları arasındaki ilişkiyi belirleyen integral, x=0 noktasındaki logaritmik dallanma noktası nedeniyle standart yöntemlerle sıfırlanmaz. Karmaşık düzlemde, Minkowski vakumunun analitik yapısını korumak için alt yarı düzlemden yapılan dolanım, logaritmik argümanda zorunlu bir değişim yaratır: lnx⟶lnx−iπ⟹Faz Faktörü¨: e−πΩ/a. Bu özellik, Bogoliubov katsayıları arasında evrensel bir ilişki doğurur:

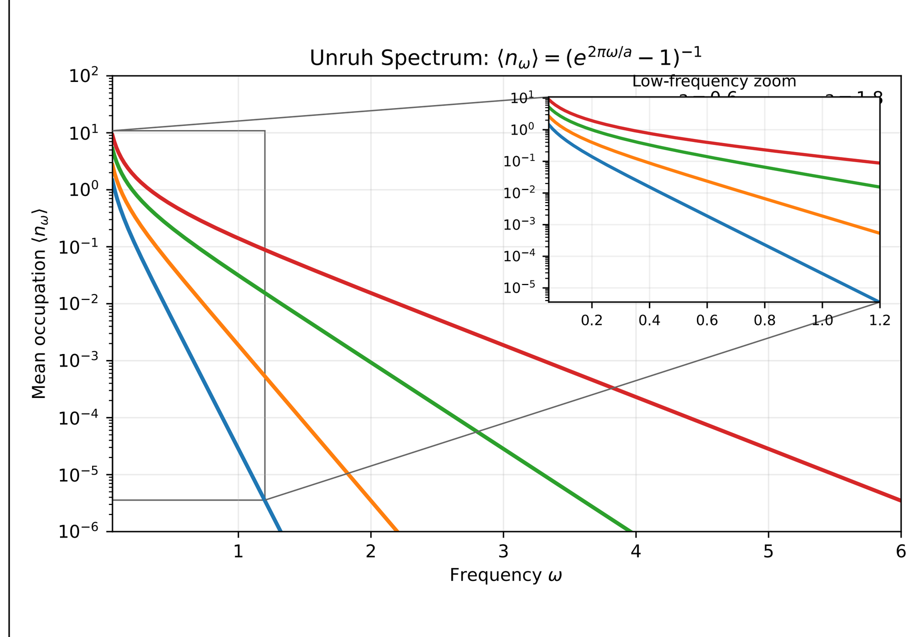
$$\beta_{\Omega k} = -\,e^{-\pi\Omega/a}\alpha_{\Omega k}^*.$$

Kuantum alan teorisinde olasılığın korunumu için Bogoliubov dönüşümünün üniter olması gerekir, bu da katsayılar üzerinde bir normalizasyon koşulu doğurur:

$$\int dk\left(|\alpha_{\Omega k}|^2 - |\beta_{\Omega k}|^2\right) = \delta(0) \implies |\alpha|^2 - |\beta|^2 = 1.$$

Bu üniterlik şartı ile analitik devamdan gelen faz ilişkisi birleştirildiğinde, Rindler gözlemcisinin ölçtüğü ortalama parçacık sayısı doğrudan aşağıdaki formunda elde edilir:

$$\langle N_\Omega\rangle = |\beta_{\Omega k}|^2 = \frac{1}{e^{2\pi\Omega/a} - 1}.$$




**Şekil 2:** Unruh Termal Spektrumu

Sonuç olarak, ivmeli gözlemci için elde edilen parçacık sayısı spektrumu, tam olarak Bose–Einstein dağılımı biçimini alır ve etkin bir sıcaklık tanımı yapılmasına imkân verir. Bu sıcaklık, herhangi bir termodinamik varsayıma değil, Minkowski ve Rindler zaman tanımlarının analitik olarak eşdeğer olmamasına dayanır. Dolayısıyla Unruh etkisi, parçacık kavramının uzay-zamandan bağımsız mutlak bir nicelik olmadığını; gözlemcinin hareketine ve buna karşılık gelen zaman evrimine bağlı olarak tanımlandığını açık biçimde ortaya koyar. Bu durum, vakumun göreliliğinin düz uzay-zamandaki en yalın ve doğrudan örneğini sunar.

## KAYNAKÇA

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[2]N. D. Birrell and P. C. W. Davies, Quantum Fields in Curved Space, Cambridge University Press (1982)
[3]R. M. Wald, Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics, University of Chicago Press (1994).

# YTU FEN EDEBİYAT FAKÜLTESİ

## 2025-2026 Güz Yarıyılı FİZİK BÖLÜMÜ

# APPLICATION OF RARE EARTH ELEMENT DOPED GLASS BASED LUMINESCENT SOLAR CONCENTRATORS for BUILDING-INTEGRATED PHOTOVOLTAICS


**Emre İLTER Ç1805C005**

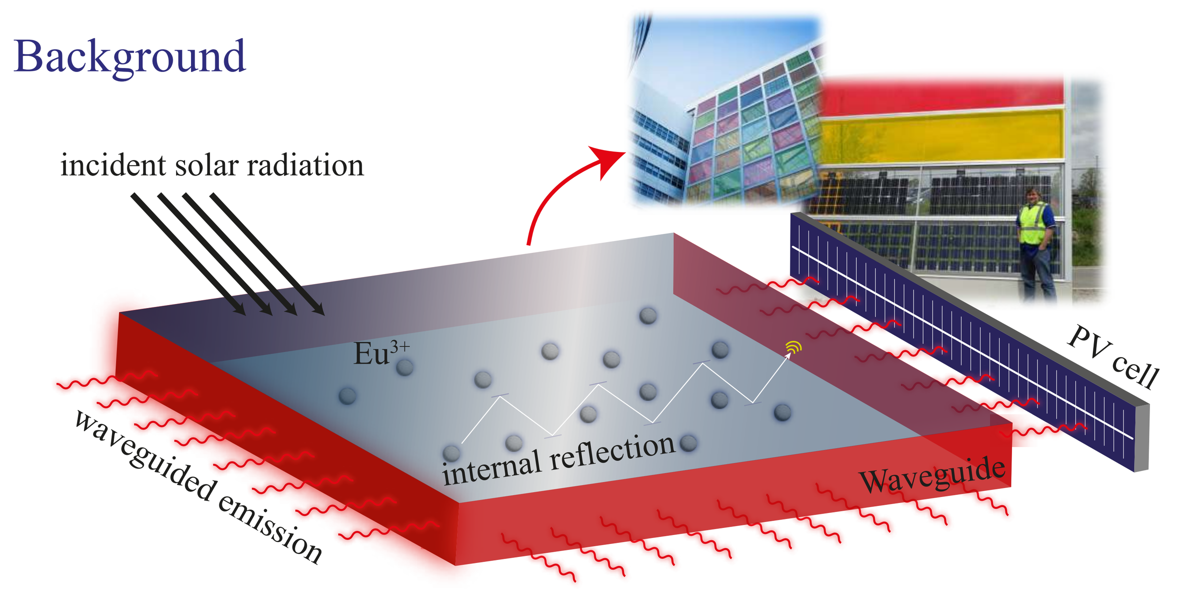
**Danışman: Doç. Dr. Murat ÇALIŞKAN**

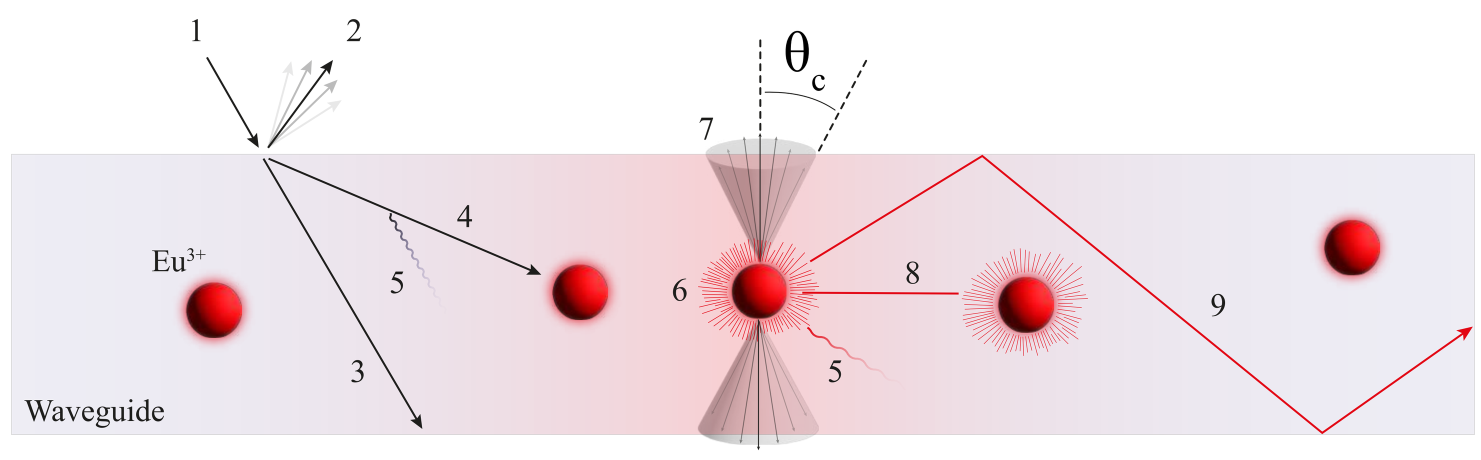


## ABSTRACT

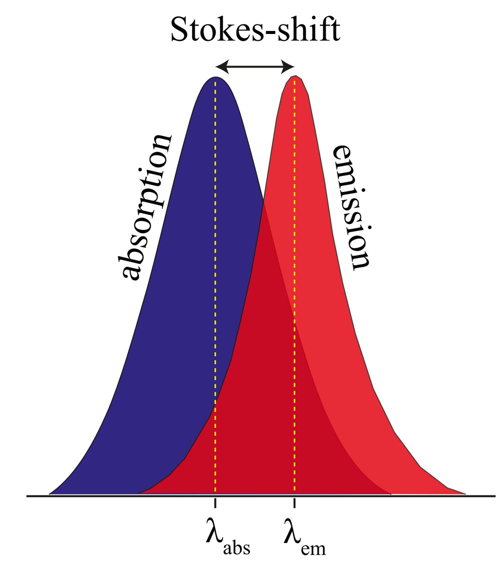
The integration of photovoltaic technology into building structures requires light-collecting surfaces, known as Building Integrated Photovoltaics (BIPVs), that are transparent, mechanically stable, highly durable, and easily manufactured at scale, and that must perform reliably under varying light conditions, including direct, diffuse, and interior illumination. Among various approaches, Luminescent Solar Concentrators (LSCs) offer excellent design flexibility by effectively separating the light collection from PV conversion. An LSC spectrally shifts incoming photons and directs them through a waveguide structure to strategically placed PV cells along the device edges to generate electrical energy. This study demonstrates for the first time a glass-based LSC system standardized to a thickness of 2.5 mm, activated by $Eu^{3+}$ rare-earth ions. To ensure suitability from small-scale testing to large-scale applications, the research employed a combined approach of experimental testing and predictive numerical modeling. First, the optimum doping level for the $Eu^{3+}$-doped planar glass platform was determined. This maximized photon transport efficiency while also characterizing the material's visual behavior. Devices with a surface area of 2x2 $cm^2$ exhibited an average optical transmittance of approximately 90% in the visible range, excellent color fidelity (Color Rendering Index, CRI ~98), and remarkable resistance to thermal, chemical, and physical degradation. The external quantum efficiency for this system remained constant at ~6.4% regardless of device size, while the smallest 2x2 $cm^2$ unit achieved a peak power conversion efficiency of 0.837%, decreasing to 0.164% at 6×6 $cm^2$. The findings demonstrate that $Eu^{3+}$-doped glass LSCs offer the potential for high aesthetic integration and visual transparency while maintaining practical photon-electric conversion. In this context, the system is envisioned as a durable, transparent, and scalable LSC technology for architectural elements such as modern windows and façade systems.

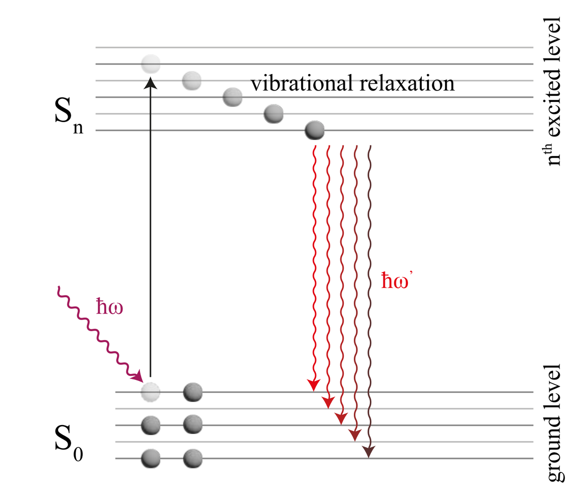

## Background



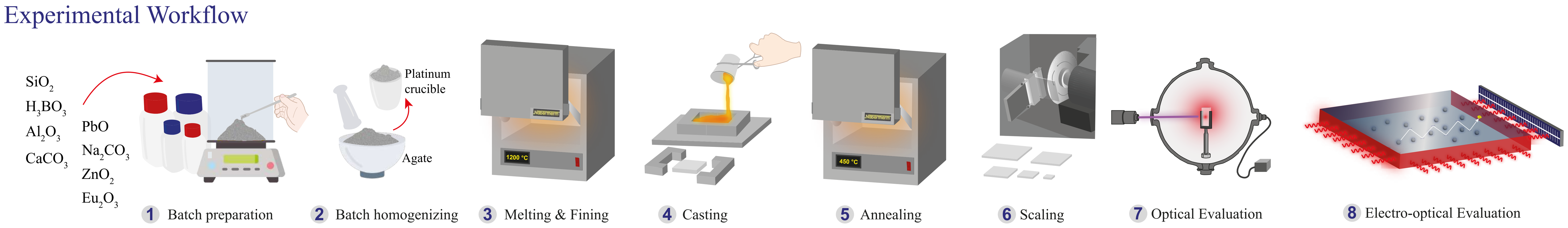




1. incidence 2. reflection 3. transmittion 4. absorption 5. host attenuation 6. PL emission 7. escape-cone loss 8. re-absorption loss 9. total internal reflection



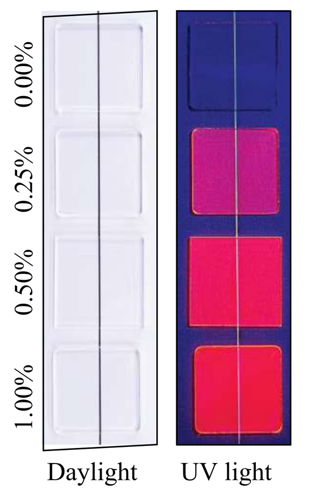

## Experimental Workflow

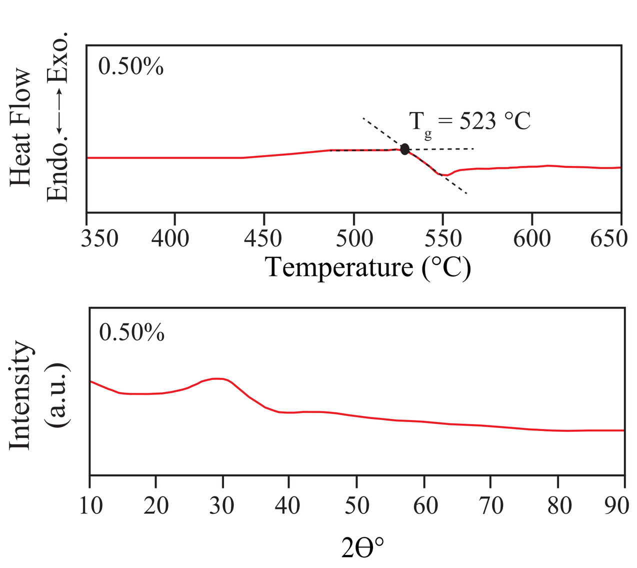


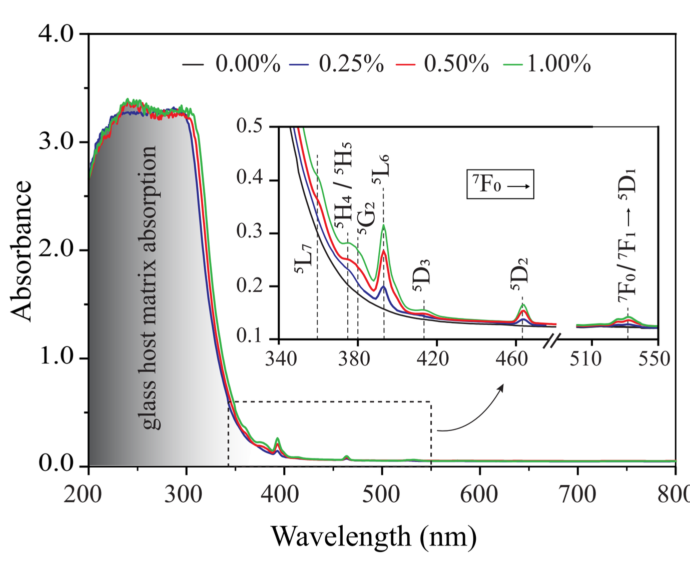

## Terms & Symbols

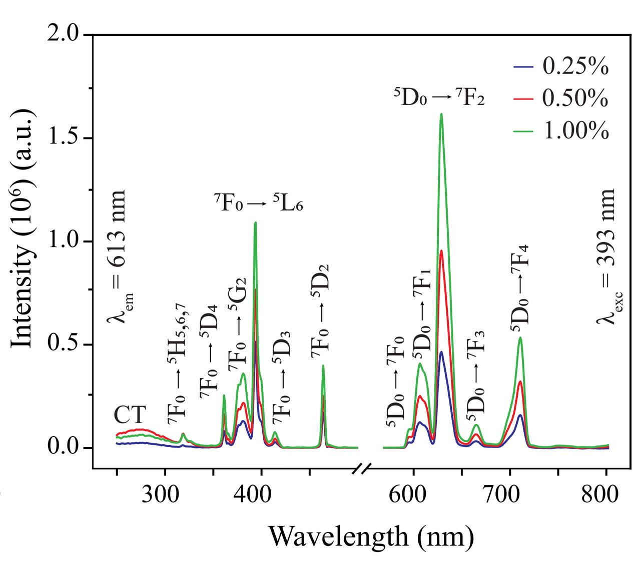
$\eta_{ext}$ = external photon efficiency
$\eta_{abs}$ = absorption efficiency
$\eta_{pl}$ = intrinsic emission efficiency
$\eta_{pl,waveguide}$ = extrinsic emiss. eff.
$\eta_{ra}$ = re-absorption survivol fac.
$\eta_{trap}$ = trapping efficiency
$\eta_{tr}$ = transport efficiency
R = specular reflectance
$n_{wg}/n_s$ = refractive indexes
α = absorption coefficient
$\theta_c$ = critical angle
$\varphi_s$ = AM1.5G standart sunlight
$\eta_{edge}$ = edge photon efficiency
$I_{edge}/I_{surface}/I_{bulk}$ = PL intensities
$\eta_{int}$ = internal photon efficiency

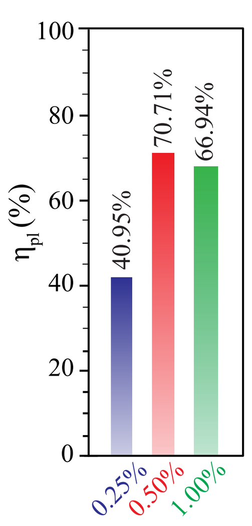
## Results

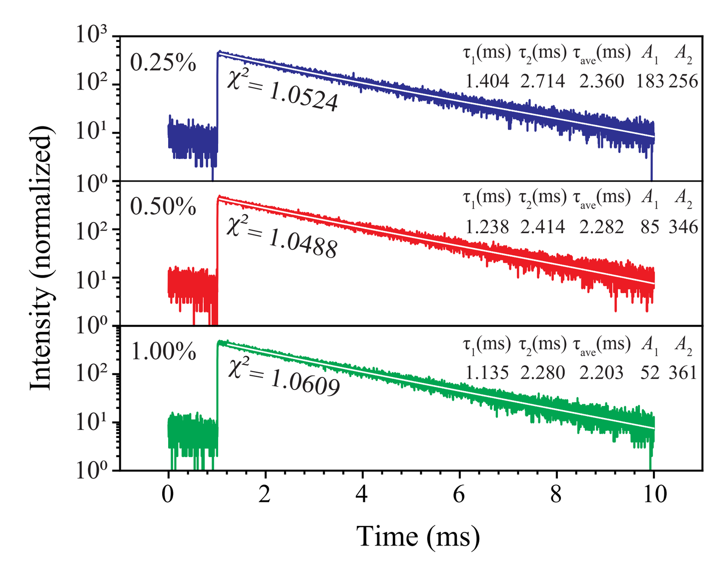


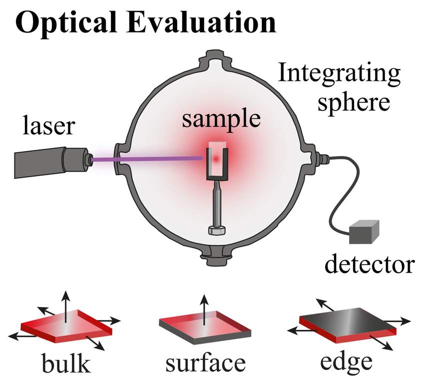




$$\eta_{pl} = \frac{k_r}{k_r + k_{nr}} \qquad k_r = \frac{\eta_{pl}}{\tau_{ave}} \qquad kn_r = \frac{1 - \eta_{pl}}{\tau_{ave}}$$

| | 0.25% | 0.50% | 1.00% |
|---|---|---|---|
| $k_r$ ($s^{-1}$) | 173 | 309 | 303 |
| $k_{nr}$ ($s^{-1}$) | 250 | 128 | 150 |

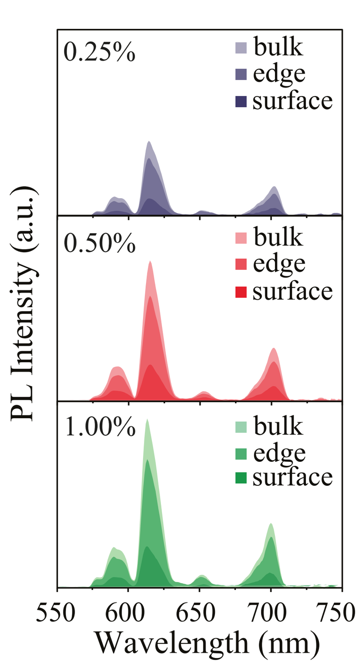
Results indicate that the sample with 0.50 mol% dopant concentration exhibits the highest radiative rate ($k_r$) and the lowest non-radiative decay rate ($k_{nr}$). Consequently, the photoluminescence efficiency ($\eta_{pl}$) is maximized for this concentration, identifying it as the optimal composition for emission performance.

### Optical Evaluation




*black surfaces are blocked, red surfaces emit light.

**schematic shows measurement setup used to determine waveguide properties




### Problem in Optical Evaluation

$$\eta_{ext} = (1\text{-}R)\eta_{abs}\eta_{pl}\eta_{ra}\eta_{trap}\eta_{tr}$$

$$R = \frac{(n_{wg} - n_s)^2}{(n_{wg} + n_s)^2}$$

$$\eta_{abs} = (1 - e^{-\alpha_{393\,nm} d}) \qquad \eta_{trap} = \cos\theta_c$$

$\eta_{ra}\,\eta_{tr}$ → Weber-Lambe Model; Klimov Model

Traditional models are inadequate for glass-host waveguides as they only treat absorption as wavelength-dependent, leading to oversimpli-

$$\eta_{abs} = \frac{\int \varphi_s(\lambda)(1 - e^{-\alpha(\lambda) d})\, d\lambda}{\int \varphi_s(\lambda)\, d\lambda}$$

$$\eta_{ext} = (1\text{-}R)\eta_{abs}\eta_{pl,waveguide}\eta_{edge}$$

$$\eta_{edge} = \frac{\int I_{edge}(\lambda)\, d\lambda}{\int I_{bulk}(\lambda)\, d\lambda}$$

$$I_{edge}(\lambda) = I_{bulk}(\lambda) - I_{surface}(\lambda)$$

$$\eta_{int} = \eta_{pl,waveguide}\eta_{edge}$$

$$\eta_{ext} = (1\text{-}R)\eta_{abs}\eta_{int}$$

While $\eta_{edge}$ intrinsically incorporates $\eta_{ra}$, $\eta_{trap}$, and $\eta_{tr}$ current experimental approaches typically rely on single-wavelength excitation, which fails to reflect the system's performance under broadband sungliht

### Refined Model

$$\eta_{ext}(\lambda) = (1\text{-}R)\, \eta_{abs}(\lambda)\, \eta_{pl,waveguide}(\lambda)\, \eta_{edge}$$

$$\eta_{ext}^{sun} = \int \eta_{ext}(\lambda)\, d\lambda$$

To account for wavelength-dependent variations, the waveguide photoluminescence efficiency is treated as a spectral distribution,$\eta_{pl,waveguide}(\lambda)$, rather than assuming that all emission events occur with an identical yield.

Instead of being calculated separately, the standard $\eta_{abs}$ model is replaced by the spectral absorption efficiency and integrated directly into the main equation.

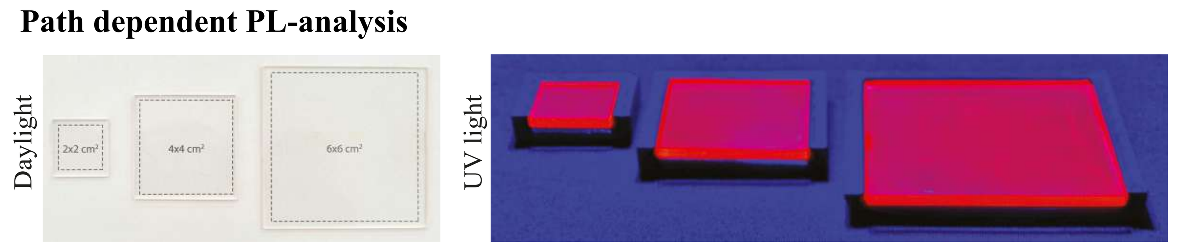
$\eta_{edge}$ is kept constant as an integral multiplier, as each emission event undergoes the same transport process.

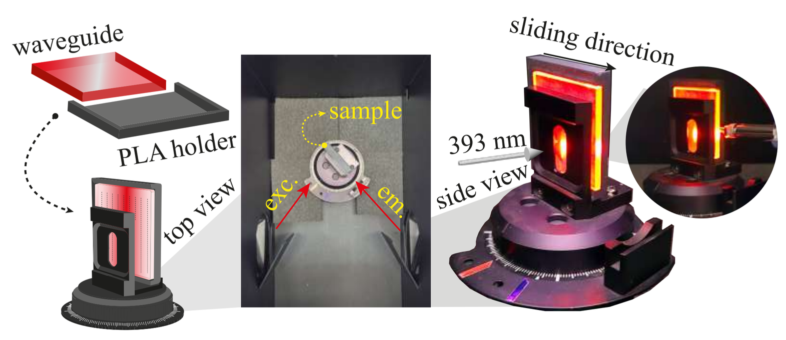
### Results

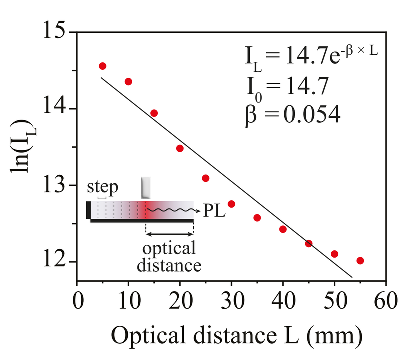
| | 0.25% | 0.50% | 1.00% |
|---|---|---|---|
| $\eta_{edge}$ | 77.60% | 77.49% | 77.30% |
| $\eta_{int}$ | 31.78% | 54.79% | 51.74% |
| $\eta_{ext}$ | 11.18% | 19.89% | 22.30% |
| $\eta_{ext}^{sun}$ | 3.491% | 6.483% | 6.351% |

The findings demonstrate that the 0.50 mol% $Eu_2O_3$-doped glass achieves a solar waveguiding efficiency of 6.483%. While conventional methodologies often yield values as high as 25%, such figures lack physical realism and fail to provide meaningful insights into actual device performance under solar conditions.

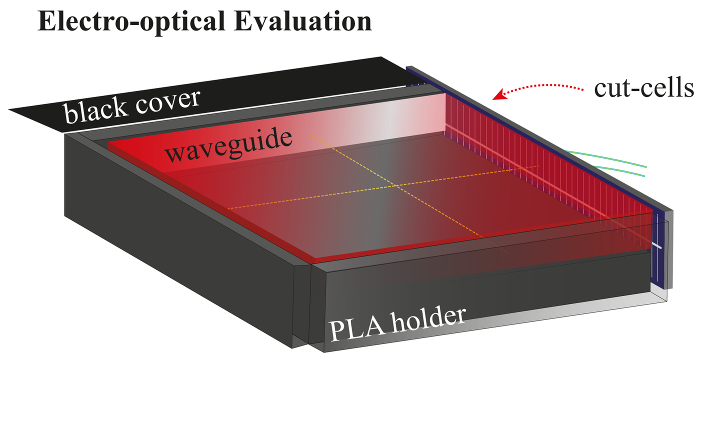
### Path dependent PL-analysis

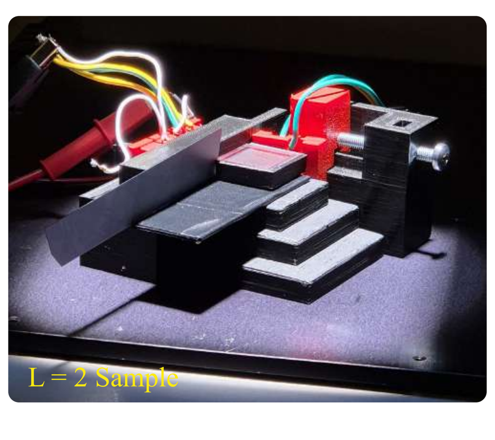


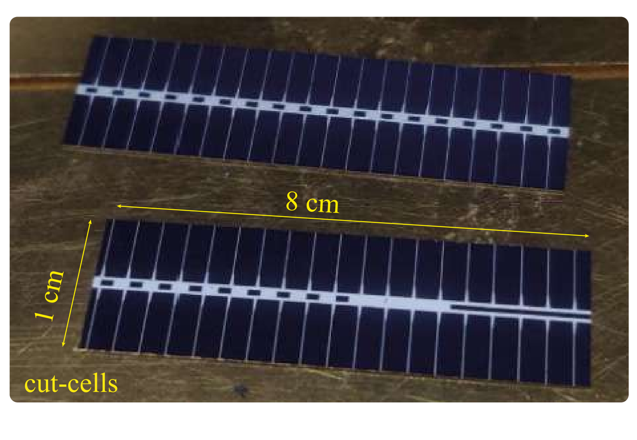



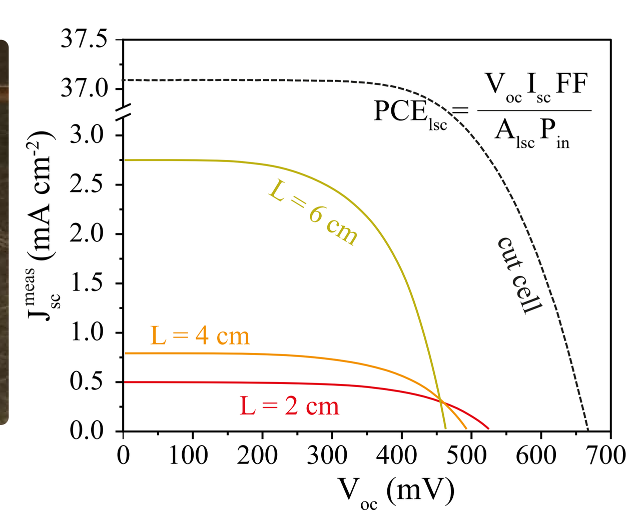



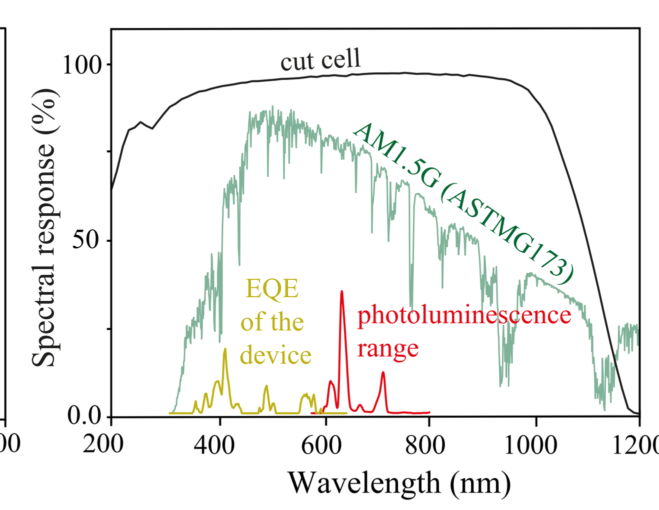

### Electro-optical Evaluation




$$PCE_{lsc} = \frac{V_{oc} I_{sc} FF}{A_{lsc} P_{in}}$$

$$EQE_{lsc} = EQE_{pv} \int \eta_{ext}(\lambda)\, d\lambda \qquad J_{sc} = e \int EQE_{lsc}\, \varphi_s(\lambda)\, d\lambda$$

| L (cm) | $V_{oc}$ (mV) | $I_{sc}$ (mA) | $J_{sc,meas}$ ($mA/cm^2$) | $J_{sc,calc}$ ($mA/cm^2$) | $PCE_{meas}$ (%) | $PCE_{calc}$ (%) |
|---|---|---|---|---|---|---|
| 2 | 463 | 2.75 | 0.69 | 0.60 | 0.85 | 0.74 |
| 4 | 493 | 3.17 | 0.20 | 0.30 | 0.26 | 0.40 |
| 6 | 525 | 4.47 | 0.12 | 0.20 | 0.16 | 0.28 |

By utilizing the $\eta_{ext}(\lambda)$ the $EQE_{lsc}$ and $J_{sc}$ values are accurately estimated. Any observed discrepancies are attributed to the absence of an index-matching media between the waveguide and the PV cell in the current experimental setup.

## Conclusion

This study presented the first systematic evaluation of rare-earth-doped glasses as both the luminescent medium and the optical waveguide for LSC applications. In this work, highly transparent and color-neutral planar $Eu^{3+}$-doped borosilicate glasses (2.5 mm thick; 2×2-6×6 $cm^2$) exhibited an invariant external photon efficiency of approximately 6.4% under AM1.5G illumination for all device dimensions, demonstrating efficient photon harvesting and transport throughout the glass matrix. The resulting devices exhibited PCE values exceeding 0.8% for the smallest geometry, confirm both the scalability and consistent performance at even increased dimensions. When compared with previously reported $Eu^{3+}$-based LSCs employing polymeric or hybrid hosts, the present platform shows remarkably superior UV stability, environmental durability, and compatibility to external stimulus compared to its predecessors. Overall, these results establish rare-earth-doped glasses as a durable and high-performance materials, offering a promising route toward long-lifetime, architecturally integrated BIPV applications.

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E. İlter et al., "Scalable Perovskite Quantum Dot Glass Nanocomposites for High-Efficiency Luminescent Solar Concentrators", Advanced Functional Materials, vol. 35, no. 47, Nov. 2025, doi: 10.1002/adfm.202506829

# FACULTY of ARTS and SCIENCES

# 2025-2026 Fall Semester DEPARTMENT OF PHYSICS

## PROBIOTIC BACTERIA IN MATERIALS PHYSICS: OPTO-ELECTRONIC PROPERTIES

**İrem Nur ADIGÜZEL 21022603**

**Advisor: Prof. Dr. Kutsal BOZKURT**

## ABSTRACT

Probiotics are widely used biological materials in food and pharmaceutical applications. In this study, probiotic samples were analyzed using UV–Visible (UV–Vis) spectrophotometry to investigate their absorbance behavior. Prepared probiotic solutions were measured at selected wavelengths, and absorbance spectra were compared. The results demonstrate that UV–Vis spectroscopy is an effective method for comparative analysis of probiotic samples. These findings highlight the potential of UV–Vis spectroscopy as a rapid and effective tool for the preliminary characterization of probiotic-based materials in materials physics and opto-electronic applications.

## INTRODUCTION

Probiotics are defined as live microorganisms that provide healthbenefits when consumed in adequate amounts. Understanding thephysical and optical properties of probiotic samples is important fortheir characterization and quality assessment. UV–Visspectrophotometry is a commonly used analytical technique that allowsthe investigation of biological samples through absorbancemeasurements based on light–matter interaction. Therefore, theapplication of simple optical techniques such as UV–Visspectrophotometry is of interest for the rapid and comparative analysisof probiotic samples. Although probiotics are mainly studied in biological and medical sciences, their optical and opto-electronic properties remain relatively unexplored in materials physics. Therefore, this study aims to investigate the UV–Vis absorbance behavior of probiotic formulations and to evaluate their potential as functional materials using optical characterization techniques.

Biological systems may exhibit optical and electromagnetic sensitivity at the cellular level. Previous studies have shown that external physical stimuli can influence cellular components such as mitochondria, ion channels, cytoskeleton, and nucleus. These interactions may lead to changes in signaling pathways, gene expression, and cellular behavior, highlighting the relevance of optical characterization techniques in biological and probiotic-based materials.

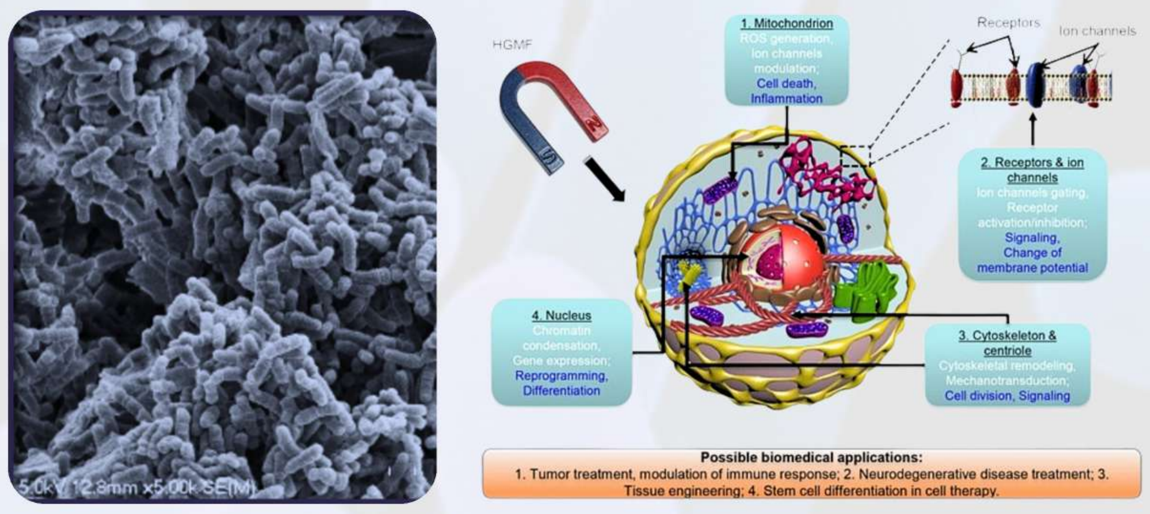


**Figure 1:** (a) SEM image showing the microscopic morphology of probiotic bacteria. (b) Schematic illustration of potential cellular interaction pathways affected by external physical stimuli, including mitochondria, ion channels, cytoskeleton, and nucleus, along with possible biomedical applications.

## THEORETICAL BACKGROUND

UV–Visible (UV–Vis) spectrophotometry is a widely used analytical technique for investigating the optical properties of materials. The method is based on the interaction between electromagnetic radiation in the ultraviolet and visible regions and the sample. When light passes through a sample, part of the incident radiation is absorbed depending on the molecular structure and concentration of the material.

The amount of absorbed light is quantitatively described by the Beer–Lambert law, which establishes a linear relationship between absorbance and concentration for dilute solutions:

$$A = \varepsilon \cdot c \cdot l$$

where A is the absorbance, ε is the molar absorptivity, c is the concentration of the absorbing species, and l is the optical path length of the cuvette.

In biological and probiotic samples, absorbance arises from various organic components such as proteins, nucleic acids, and cellular structures. Differences in absorbance spectra can therefore be associated with variations in sample concentration, composition, and dispersion. UV–Vis spectroscopy provides a rapid, non-destructive, and reliable method for comparative analysis of probiotic solutions. In this context, UV–Vis spectroscopy provides valuable information about the concentration-dependent optical behavior of probiotic solutions, which is directly relevant to the experimental measurements performed in this study.

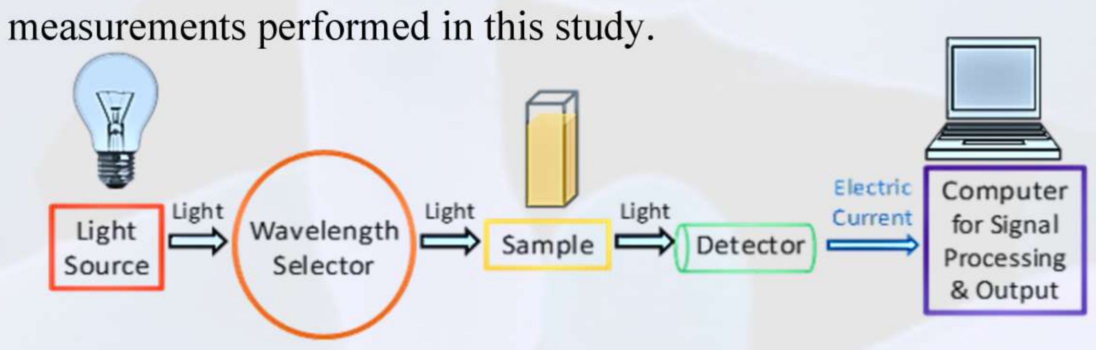



**Figure 2:** Schematic representation of the UV–Vis spectrophotometry principle.

## MATERIALS

The materials used in this study include a UV–Vis spectrophotometer, quartz cuvettes, a magnetic hotplate stirrer, beakers, and probioticcapsule samples. All experiments were carried out under controlledlaboratory conditions.

(a) (b)

**Figure 3:** (a) UV–Vis spectrophotometer used for absorbance measurements of probiotic samples. (b) Quartz cuvettes used for spectrophotometric measurements.

## EXPERIMENTAL PROCEDURE

1. Probiotic capsule contents were dissolved in distilled water.
2. Solutions were homogenized using a magnetic stirrer.
3. Prepared samples were transferred into quartz cuvettes.
4. Absorbance measurements were performed using a UV–Vis spectrophotometer.

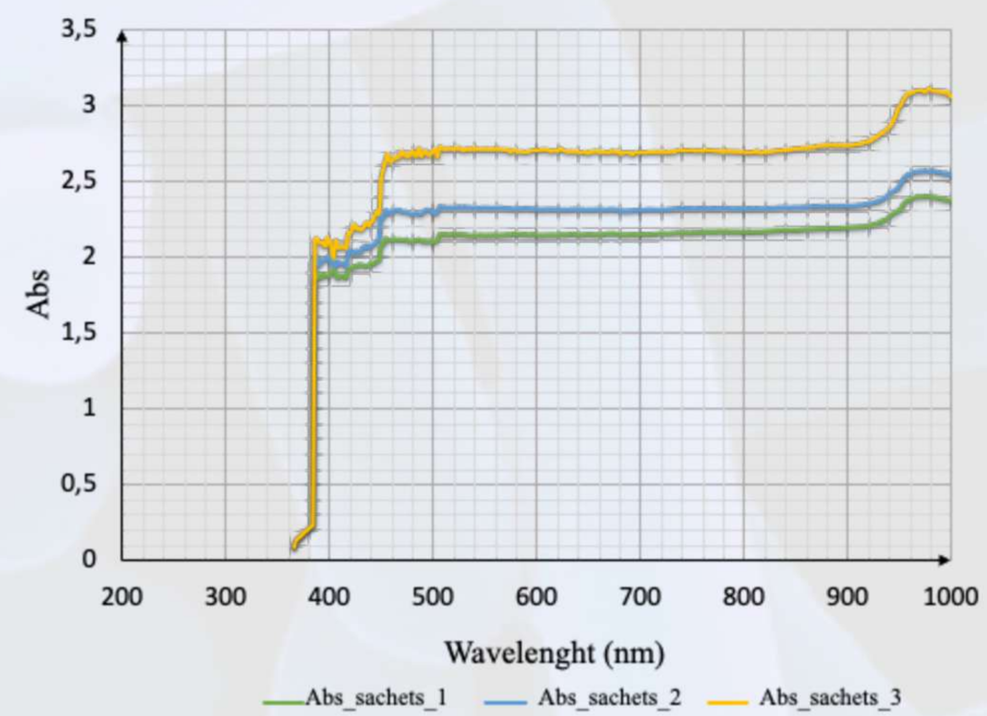
Absorbance measurements were performed in the wavelength range of 300–800 nm using a UV–Vis spectrophotometer. Each measurement was repeated three times to ensure reproducibility and reliability of the results.

(a) (b) (c)

**Figure 4:** (a) magnetic stirring, (b) UV–Vis measurement. (c) probiotic capsule content after preparation.

## RESULTS AND DISCUSSION

The absorbance measurements revealed clear differences among theprobiotic samples, indicating variations in their optical properties. These differences may be associated with concentration-dependentbehavior, particle dispersion, or compositional variations in theprobiotic formulations. The results demonstrate that UV–Visspectrophotometry can be effectively used not only for qualitativecomparison but also as a preliminary analytical tool for probioticcharacterization. The increase in absorbance with the number of probiotic sachets indicates a concentration-dependent optical response. Higher absorbance values suggest a greater presence of light-absorbing biological components, which may influence the opto-electronic behavior of the samples.




**Graph :** Comparative wavelength-dependent absorbance spectra of probioticsolutions containing one, two, and four sachets.

An increase in absorbance intensity was observed with increasing probiotic concentration. This behavior indicates a higher amount of light-absorbing biological components in the solution, which may contribute to enhanced optical interaction in the visible region.

## CONCLUSION

In this study, probiotic samples were successfully analyzed using UV–Vis spectrophotometry. The obtained results indicate that absorbancemeasurements can be used to compare different probiotic formulationsbased on their optical behavior. This approach may be useful forpreliminary screening, quality control, and further experimentalstudies involving biological samples. The present study provides a basis for future investigations combining optical measurements withbiological and physicochemical analyses. Future studies may focus on combining optical measurements with electrical and structural analyses to further explore the functional properties of probiotic-based materials.

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# 2025-2026 Fall Semester DEPARTMANT OF PHYSICS

## INVESTIGATION OF BETAVOLTAIC EFFECTS IN PEROVSKITE-BASED SEMICONDUCTORS

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Prof. Dr. Kutsal BOZKURT

## ABSTRACT

This study investigates the potential of perovskite-based semiconductors for betavoltaic energy conversion. The generation, separation, and collection mechanisms of electron–hole pairs induced by beta radiation in semiconductor materials are examined. Owing to their tunable band gap, long carrier diffusion length, and defect-tolerant electronic structure, perovskite materials offer significant advantages for betavoltaic applications. Literature-based simulation and experimental studies are evaluated to analyze the electrical behavior of perovskite-based betavoltaic cells with p–i–n architecture. The results indicate that perovskite semiconductors represent a promising material platform for low-energy beta radiation harvesting and long-lifetime nuclear energy conversion devices

## INTRODUCTION

Betavoltaic energy conversion is a nuclear-based power generation mechanism that directly converts the kinetic energy of beta particles emitted during radioactive decay into electrical energy using semiconductor junctions. Unlike photovoltaic devices, betavoltaic cells operate independently of light and can provide long-lifetime, maintenance-free power for low-energy applications. However, conventional inorganic betavoltaic devices suffer from limited efficiency under low-energy beta irradiation.

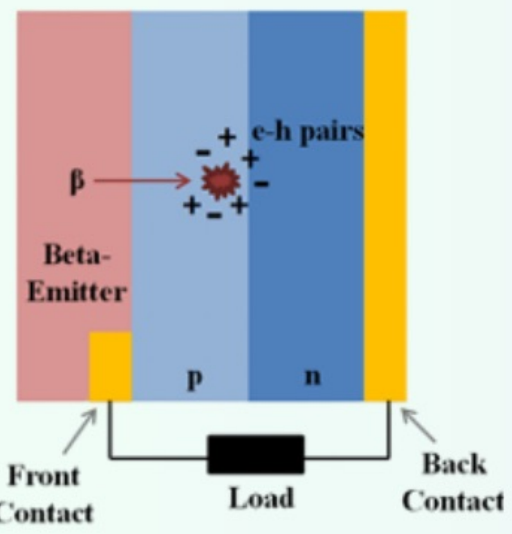



**Figure 3.1:** Basic working principle of a betavoltaic cell illustrating beta particle interaction with a semiconductor junction

## BETAVOLTAIC PRINCIPLE

In betavoltaic devices, energetic beta particles emitted from a radioactive source interact with the semiconductor lattice and lose energy through ionization processes. This interaction generates a large number of electron–hole pairs along the particle trajectory. The built-in electric field within the depletion region of a p–n or p–i–n junction separates these charge carriers before recombination occurs, enabling their collection at the electrodes and resulting in electrical power generation.

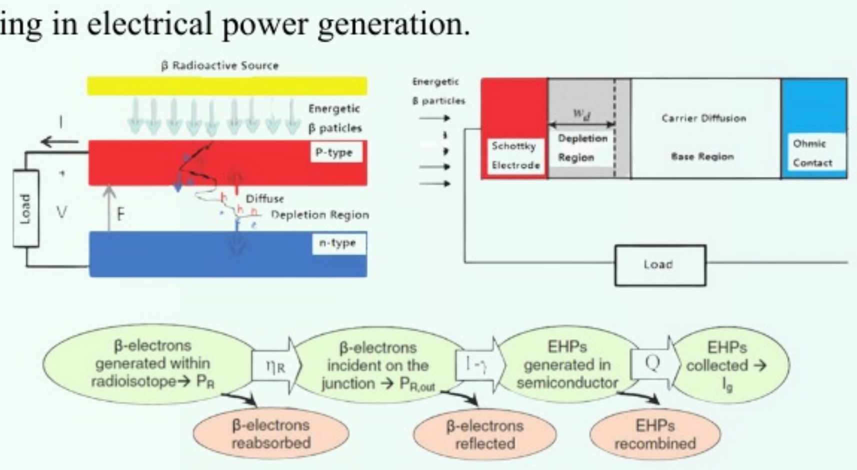


**Figure 3.3:** Schematic overview of the betavoltaic energy conversion process.

## PEROVSKITE MATERIALS

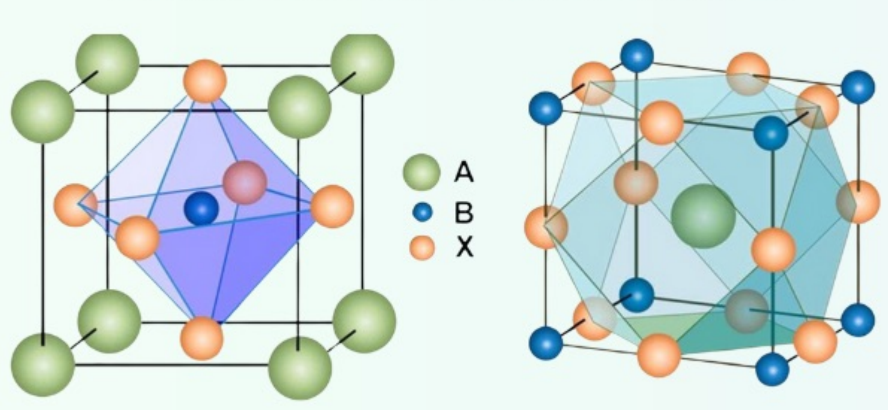



**Figure 4.1:** Representation of the $ABX_3$ perovskite crystal structure, showing the A-site, B-site, and $BX_6$ octahedral framework.

Perovskite materials are semiconductors with a flexible $ABX_3$ crystal structure and tunable electronic properties. Their long carrier diffusion length and defect-tolerant nature enable efficient charge generation and collection, making them suitable for betavoltaic energy conversion applications.

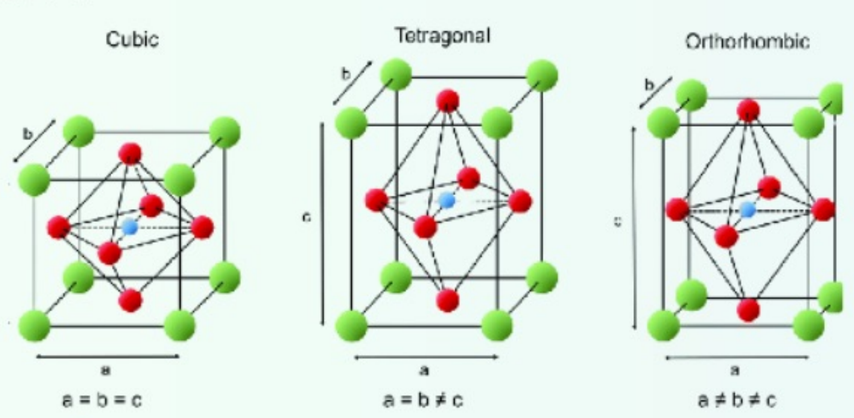



**Figure 4.2:** Schematic representation of cubic, tetragonal, and orthorhombic phases in halide perovskites, showing changes in lattice parameters and octahedral distortions

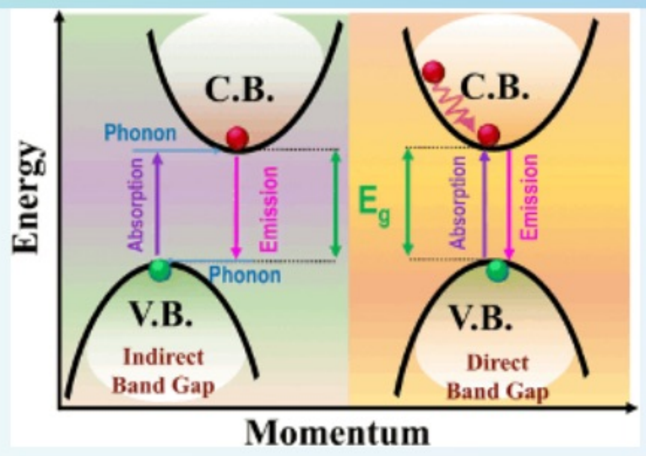



**Figure 4.3:** Illustration of indirect and direct band gap electronic structures, highlighting efficient charge carrier transitions in direct band gap semiconductors such as perovskites.

## DEVICE ARCHITECTURE

A p–i–n multilayer architecture is used to enhance charge separation and carrier collection under beta irradiation. The intrinsic layer increases the effective depletion region, while transport layers facilitate selective extraction of electrons and holes, reducing recombination losses.

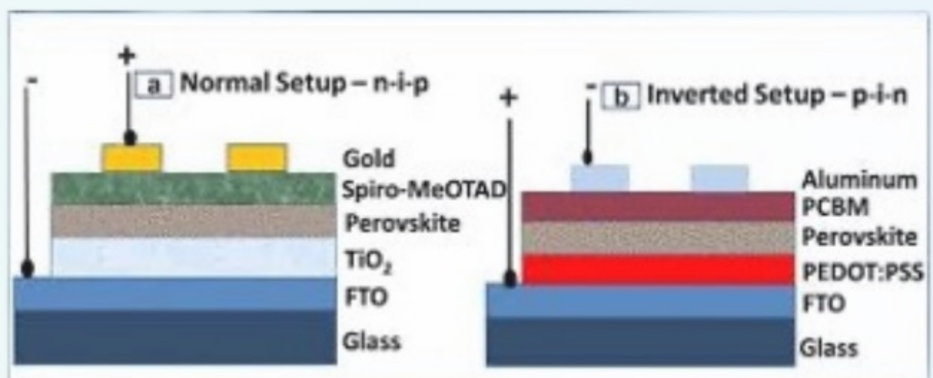



**Figure 6.1:** Schematic illustration of conventional n–i–p and inverted p–i–n multilayer device architectures commonly used in perovskite-based semiconductor devices and adapted for betavoltaic applications.

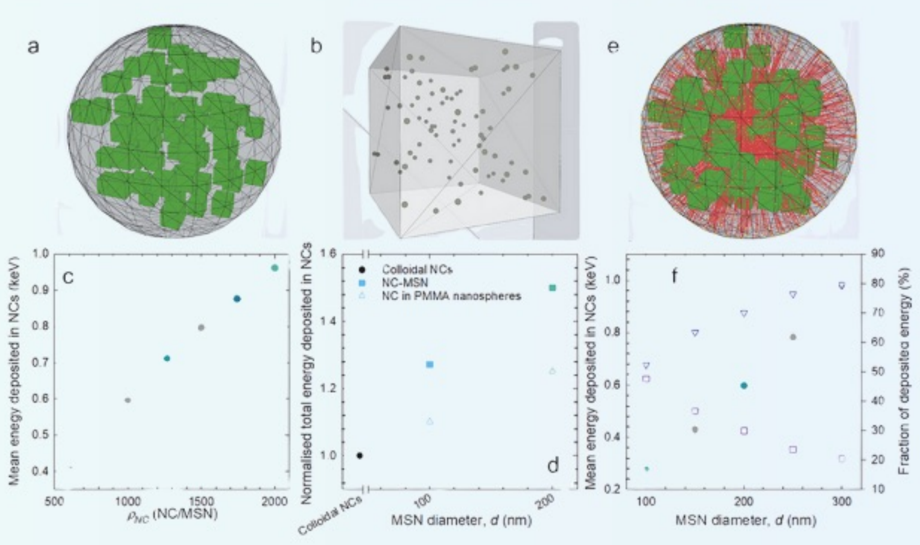


**Figure 5.1:** Monte Carlo–based simulation results illustrating beta particle energy deposition behavior as a function of material geometry and characteristic dimensions, highlighting the influence of structural parameters on energy absorption efficiency.

## EXPERIMENTAL SETUP

Perovskite films were prepared under inert atmosphere conditions using spin-coating techniques. Electrode deposition was carried out via thermal evaporation, and the electrical characteristics of the devices were measured using current–voltage (I–V) characterization.

**Figure 7.1:** Nitrogen-filled glovebox system used for perovskite solution preparation, thin-film deposition, and electrical characterization under inert atmosphere to minimize moisture and oxygen-induced degradation.

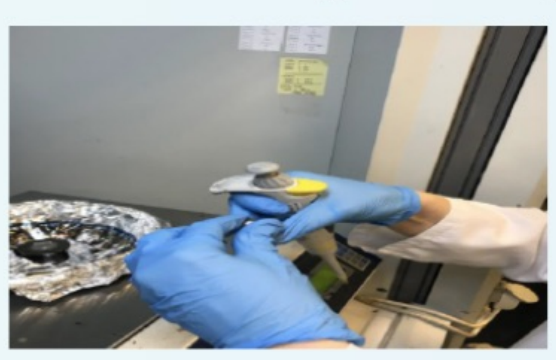


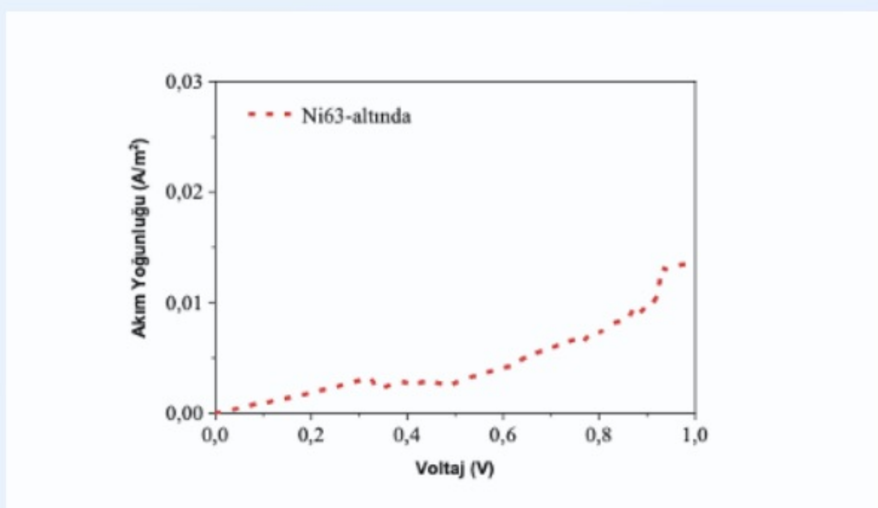
**Figure 7.3:** Spin-coating system used for the deposition of perovskite thin films during the preparation of the active layer in perovskite-based betavoltaic devices.

**Figure 7.4:** Thermal evaporation system used for the deposition of metallic top electrodes under high-vacuum conditions.

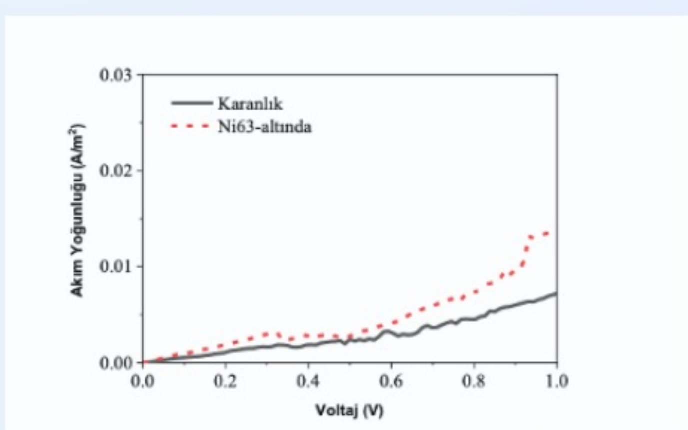
**Figure 7.2:** Experimental setup used for current–voltage (I–V) characterization.

## RESULTS

The electrical characterization results show an increase in current density under beta irradiation compared to dark conditions. This behavior confirms beta-induced charge carrier generation and the presence of a measurable betavoltaic effect in perovskite-based devices.




**Graph 1:** Comparison of reported current–voltage characteristics of a perovskite-based betavoltaic device under dark conditions and Ni-63 beta irradiation.




**Graph 3:** Comparison of reported current–voltage characteristics of a perovskite-based betavoltaic device under dark conditions and Ni-63 beta irradiation, illustrating the influence of beta-induced carrier generation

## CONCLUSION

This study demonstrates that perovskite-based semiconductor devices exhibit a clear betavoltaic response under beta irradiation. The use of a p–i–n multilayer architecture effectively enhances charge carrier separation and collection by extending the depletion region and reducing recombination losses. Overall, the results highlight the strong potential of perovskite semiconductors as promising candidates for low-power, long-lifetime betavoltaic energy harvesting applications.

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YILDIZ TECHNICAL UNIVERSITY
Faculty of Arts and Sciences

2025-2026 AUTUMN SEMESTER × PHYSICS DEPARTMENT

# The Silicon Scout: Feasibility of Autonomous Anomaly Detection via Agentic LLM Orchestration

Fikret Anıl HAKSEVER

Supervisor: Prof. Dr. Bora IŞILDAK


## SUMMARY

The High-Luminosity Large Hadron Collider will significantly increase both the volume and complexity of collision data, placing growing strain on traditional, human-driven exploratory analysis workflows.
As an initial investigation, this study examines whether supervised fine-tuning of Large Language Models (LLMs) can directly support anomaly detection in collider physics. These experiments probe the ability of LLMs to learn from numerical collider observables and generalize to unseen physics scenarios.

The supervised fine-tuning studies reveal fundamental limitations in both representation and generalization, motivating a shift away from end-to-end LLM inference. In response, an agentic framework is developed in which Large Language Models (LLMs), operating on custom implementations of analytic tools such as LaCATHODE and Isolation Forest.
Tests on benchmark and blind datasets show that such systems can efficiently navigate complex analysis spaces, while final statistical interpretation remains human-driven.


## INTRODUCTION

High-energy collider searches have traditionally focused on testing specific theoretical models. While highly successful, this approach is naturally biased toward expected signatures and may overlook unanticipated phenomena. As the High-Luminosity Large Hadron Collider (HL-LHC) increases both data volume and event complexity, this limitation becomes more pronounced.

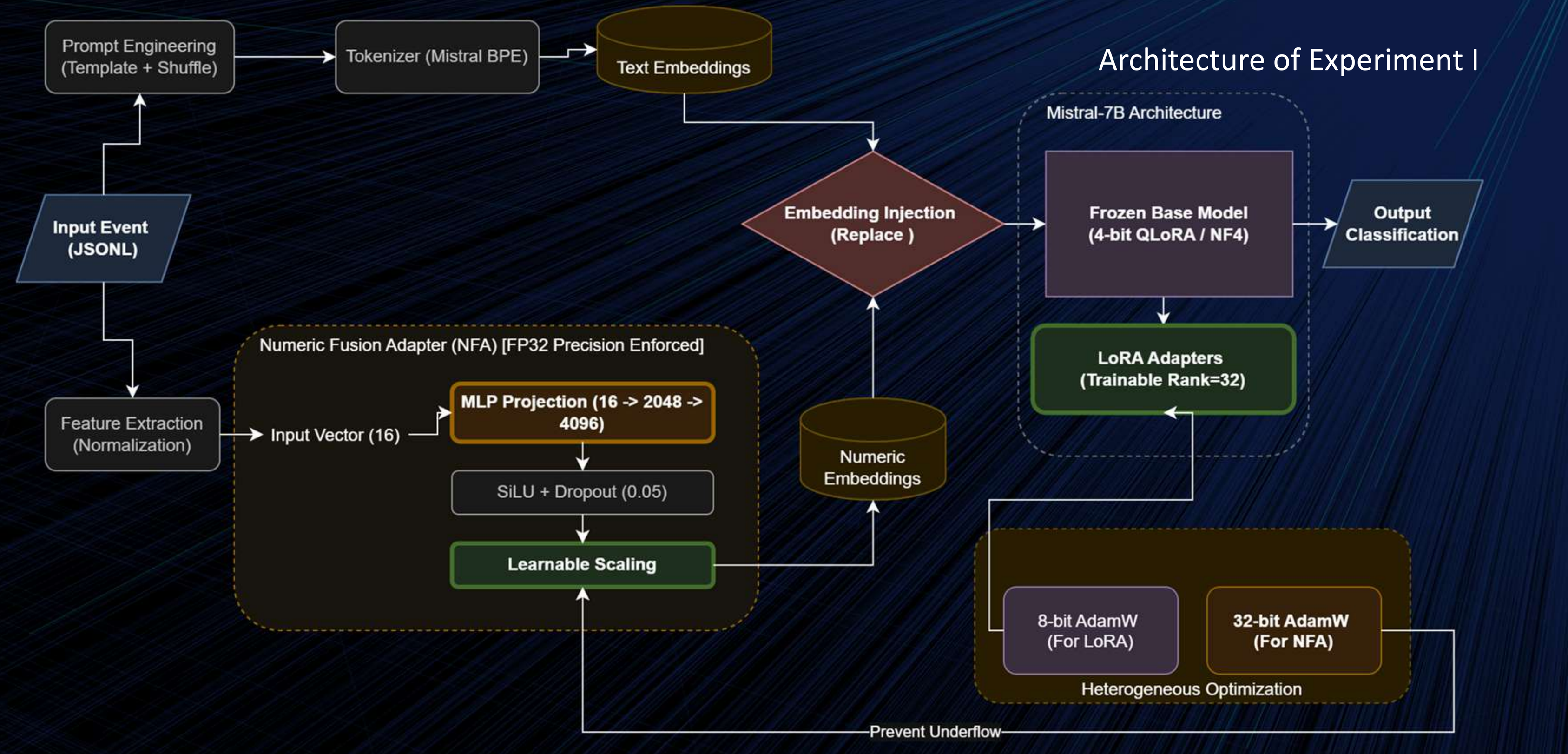
Anomaly detection provides a complementary strategy by searching for deviations from known Standard Model background behavior without assuming a specific signal model. However, such searches rely heavily on expert-driven coordination of multiple analysis techniques. This work explores whether parts of this exploratory process can be automated by Large Language Models (LLMs) while preserving interpretability and statistical control.

## EXPERIMENT I - SUPERVISED CLASSIFICATION VIA LLM

As a baseline study, supervised classification is performed to evaluate whether a high-quality collider classifier can be constructed for a well-defined signal hypothesis. Event-level observables from the LHC Olympics 2020 [1] R&D dataset, are embedded into the model using a Numeric Fusion Adapter (NFA), enabling direct conditioning on continuous physics variables. Training is performed using Low-Rank Adaptation (LoRA), and the task is defined as signal–background discrimination for a specific simulated resonance.

This setup mirrors standard hypothesis-driven searches in high-energy physics. Models (LLMs) while preserving interpretability and statistical control.

Architecture of Experiment I



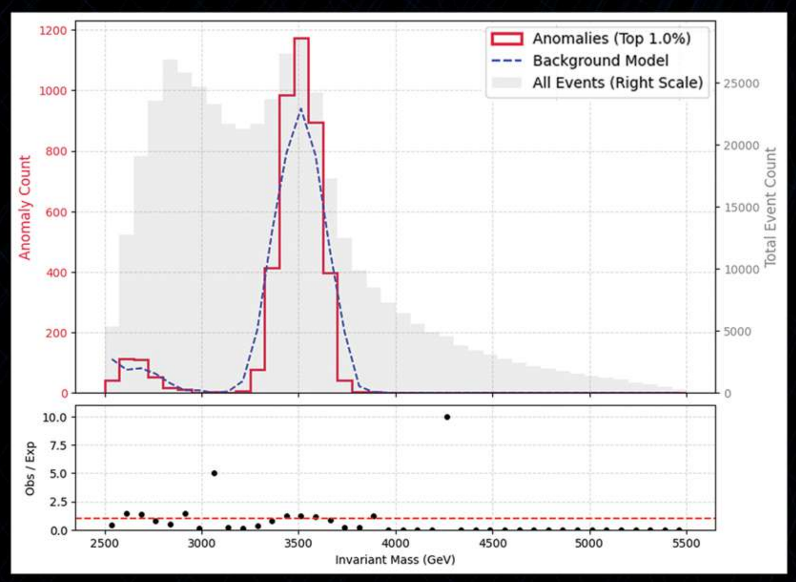

The supervised classifier achieves strong performance on the simulated dataset, reaching a global accuracy of 96.25% and demonstrating effective separation between background and the targeted signal. This confirms that, when a precise theoretical model and corresponding simulations are available, supervised learning provides high sensitivity and can closely approximate optimal decision boundaries.

However, the validity of this approach is inherently limited by the assumed signal model encoded in the simulations. Events that deviate from or fall outside the simulated hypothesis are likely to be rejected, even if they correspond to genuine new physics. This reflects the lamppost problem: searches are most sensitive where simulations exist, creating blind spots for unanticipated phenomena.

| Class | Precision | Recall | F1-Score | Correct / Total |
|---|---|---|---|---|
| **Background** | 0.97 | 0.99 | 0.98 | 7,192 / 7,250 |
| **Signal** | **0.90** | **0.68** | **0.77** | **508 / 750** |
| **Global Accuracy** | | | **96.25%** | 8,000 |
| **Macro Average** | 0.93 | 0.83 | 0.88 | 8,000 |
| **Weighted Average** | 0.96 | 0.96 | 0.96 | 8,000 |

Experiment I - Checkpoint 5600 from 8th of November 2025

## EXPERIMENT II - THE AGENTIC DISCOVERY FRAMEWORK



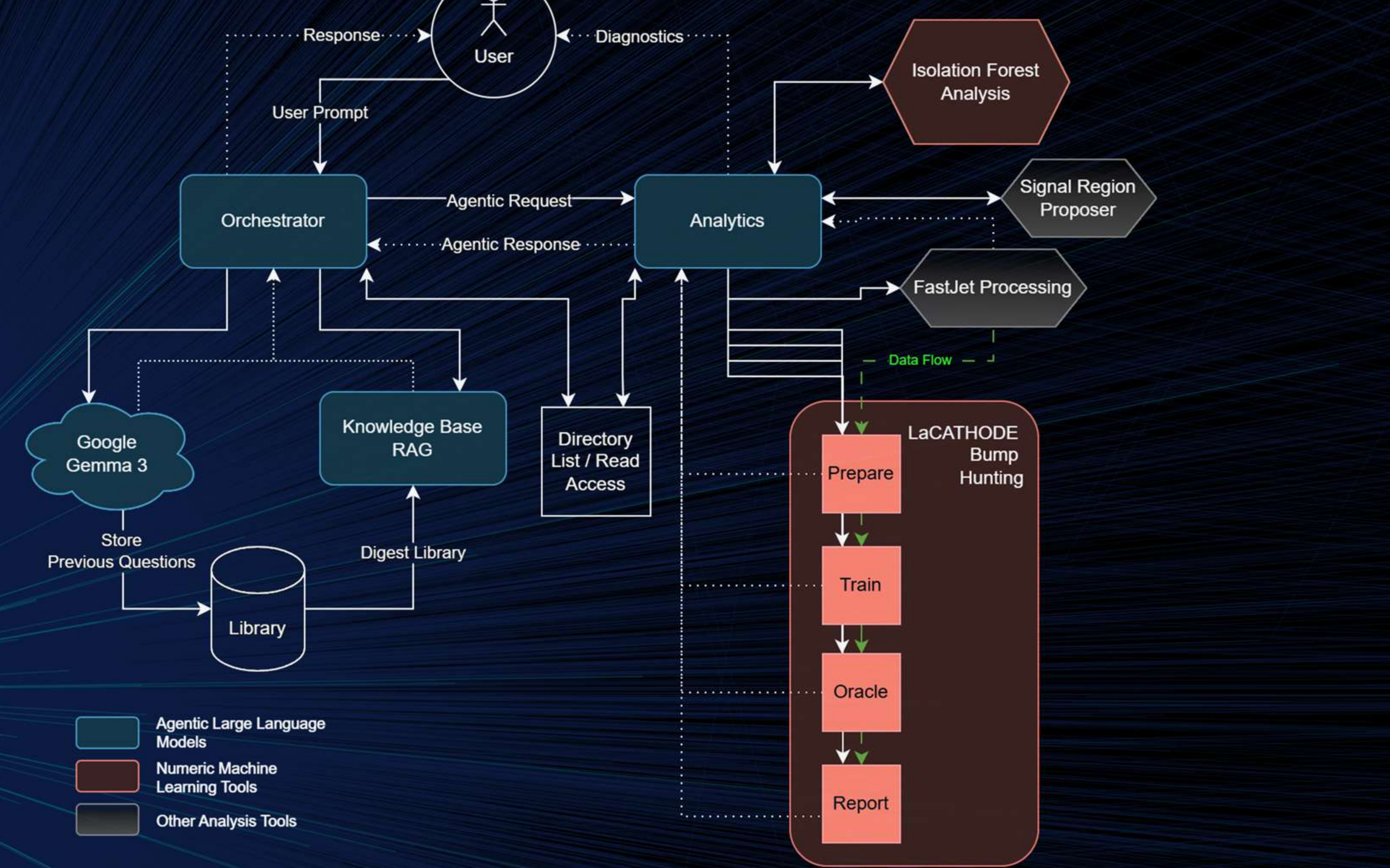

LaCATHODE* Sliding-window results of LHC Olympics 2020 R&D dataset.

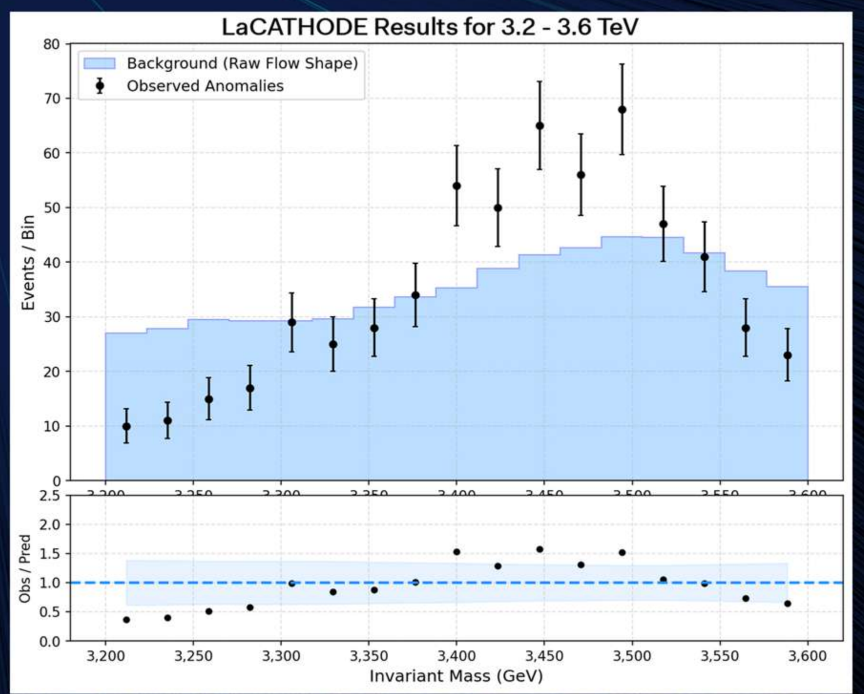
To address the generalization limits of supervised learning, a deterministic tool orchestration framework was developed. This architecture deploys a quantized local LLM strictly as a reasoning engine within a structured ReAct loop. As illustrated in the framework diagram, the model does not generate code dynamically. Instead, it bridges abstract reasoning and numerical analysis by linking data states to pre-verified physics tools. The agent interprets tool outputs to determine subsequent analysis actions, such as refining a scan window or switching algorithms.

As the primary anomaly detection tool a new implementation of the LaCATHODE[2]* density estimation technique has been developed. This custom implementation was independently validated via a sliding-window scan on LHC Olympics 2020 R&D dataset. The tool successfully recovered the known signal structure without agent intervention, establishing a baseline of trust prior to autonomous deployment.

* *LaCATHODE: Latent-Classifying Anomalies THrough Outer Density Estimation*

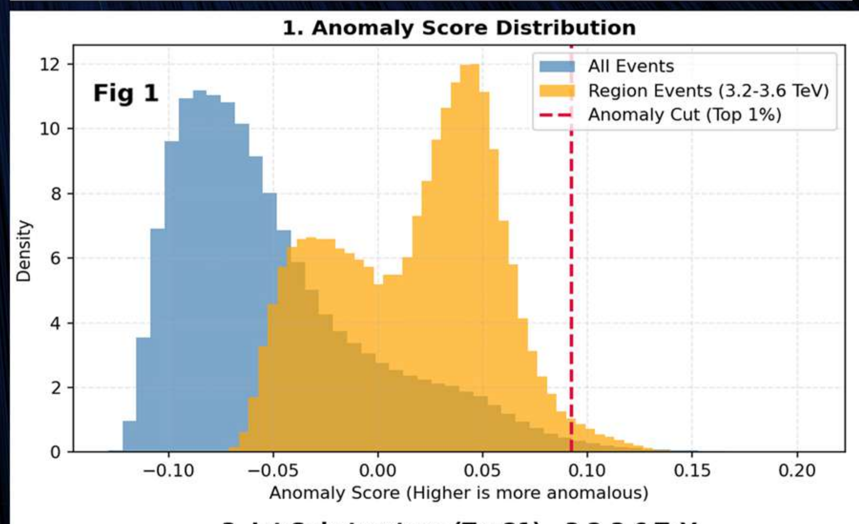
THE AGENTIC DISCOVERY FRAMEWORK

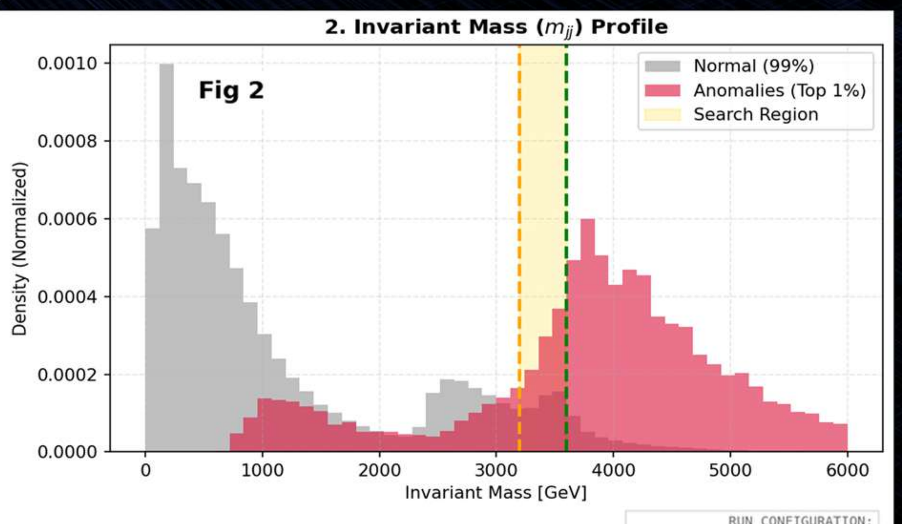


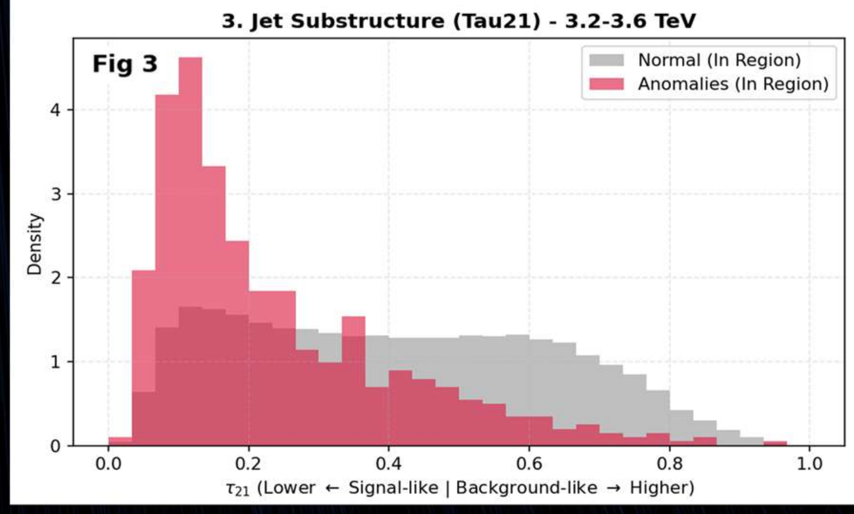




The system's autonomous orchestration capabilities were validated through systematic evaluations on the LHC Olympics R&D dataset. Across multiple runs, the agent consistently employed the Signal Region Proposer to identify potential kinematic windows, followed by LaCATHODE for targeted anomaly detection. This adaptive strategy successfully isolated the signal excess from the background.

To independently verify these candidates, the agent triggered the Isolation Forest[3] tool to inspect the jet substructure morphology within the flagged region. This secondary validation step confirmed the anomalous nature of the events, allowing the system to converge on the correct $W' \rightarrow XY$ topology with a discovery significance of $7.41\,\sigma$.




**INTERPRETATION GUIDE**

**Fig 1 : Score Distribution**
Events to the right of the red line are selected as anomalies.

**Fig 2 : Mass Bump Hunt (Crucial)**
Look for a sharp peak (resonance) in the Red histogram.
If Red just follows Gray (but shifted right), it's likely just the kinematic tail (not new physics).

**Fig 3 : Substructure Check**
Real signals often have 2-prong structure (Low Tau21).
- If Red peaks at low values (<0.4): Strong Signal Evidence.
- If Red peaks at high values (>0.6): Likely QCD Noise.

### THE BLACKBOX STRESS TEST

Testing on the challenging LHC Olympics Black Box 1 dataset exposed the system's primary limitation. When repeatedly confronted with ambiguous tool outputs, the agent risks prioritizing narrative closure over probabilistic accuracy. For instance, when faced with conflicting data; such as a positive morphological signal from Isolation Forest but a null result from LaCATHODE, the framework has risk of hallucinating a confirming statistical fit to resolve the dissonance.

## CONCLUSION

This study validates deterministic tool orchestration for autonomous discovery. By shifting the LLM from direct inference to reasoning-based execution, the framework successfully navigated complex parameter spaces to isolate anomalies. While LLM behavior over conflicting tool outputs confirm the need for human oversight, future iterations incorporating adversarial networks could significantly enhance reliability. Currently the optimal path remains a human-in-the-Loop workflow. The Silicon Scout filters noise to present high-quality candidates, empowering the physicist to focus on strict statistical validation.

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The background art for this poster is a geometric projection of the LHCO 2020 Black Box 1 dataset. The dense dark blue tracks represent the dominant Standard Model background (QCD), while the rare cyan trajectories identify the anomalous signal events.

YTU FEN EDEBİYAT FAKULTESİ

2025-2026 GÜZ YARIYILI

FİZİK BÖLÜMÜ

# PHYSICS-INFORMED NEURAL NETWORKS FORZ-BOSON RESONANCE ANALYSIS IN HIGH ENERGY PHYSICS

Yavuzhan FINDIKGİL 21022006        Prof. Dr. Bora IŞILDAK.

## ABSTRACT

This thesis develops and applies a Physics-Informed NeuralNetwork(PINN) approach for Z boson resonance analysis in high energy physics. Unlike traditional curve fitting methods, the PINN approachintegrates physical knowledge (Breit-Wigner distribution) directly into the neural network architecture and loss function. Using 31,855 dimuon events from the CERN CMS experiment, the mass and natural width of the Z boson were determined. The developed PINN model successfully disentangles detector resolution effects from intrinsic particle properties. Results demonstrate that thenatural width shows excellentagreement with theParticle Data Group (PDG) reference value within 0.11% deviation.

## INTRODUCTION AND OBJECTIVES

Precise determination of Zboson parametersis critical fortesting the Standard Model, but experimentalmeasurementsare affectedby detector resolution uncertainties. The observed mass spectrum is a convolution (Voigt profile) of the particle's intrinsic Breit-Wigner distribution and the detector's Gaussian response function. While traditional methods typically measure the "observed width," the objectives of this study are: To integrate physical constraints into the neural network architecture, To disentangle detector resolution effects f rom intrinsic physical parameters, to perform precise estimation of Zboson mass and width.

## MATERIALS AND METHODS

Open dimuon data from the CMS experiment was used. Selection criteria included muon transverse momentum pT>20 GeV, pseudorapidity $|\eta|<2.4$, and opposite-charge pairs. A total of 31,855 events were analyzed in the mass window of 70-110 GeV.

## PINN ARCHITECTURE

PINN Architecture: The model uses a hybrid architecture combining data-driven learning with physical modeling.

The tot al loss function is defined as:

$$L_{total} = L_{data} + \lambda_1 L_{physics} + \lambda_2 L_{reg}$$

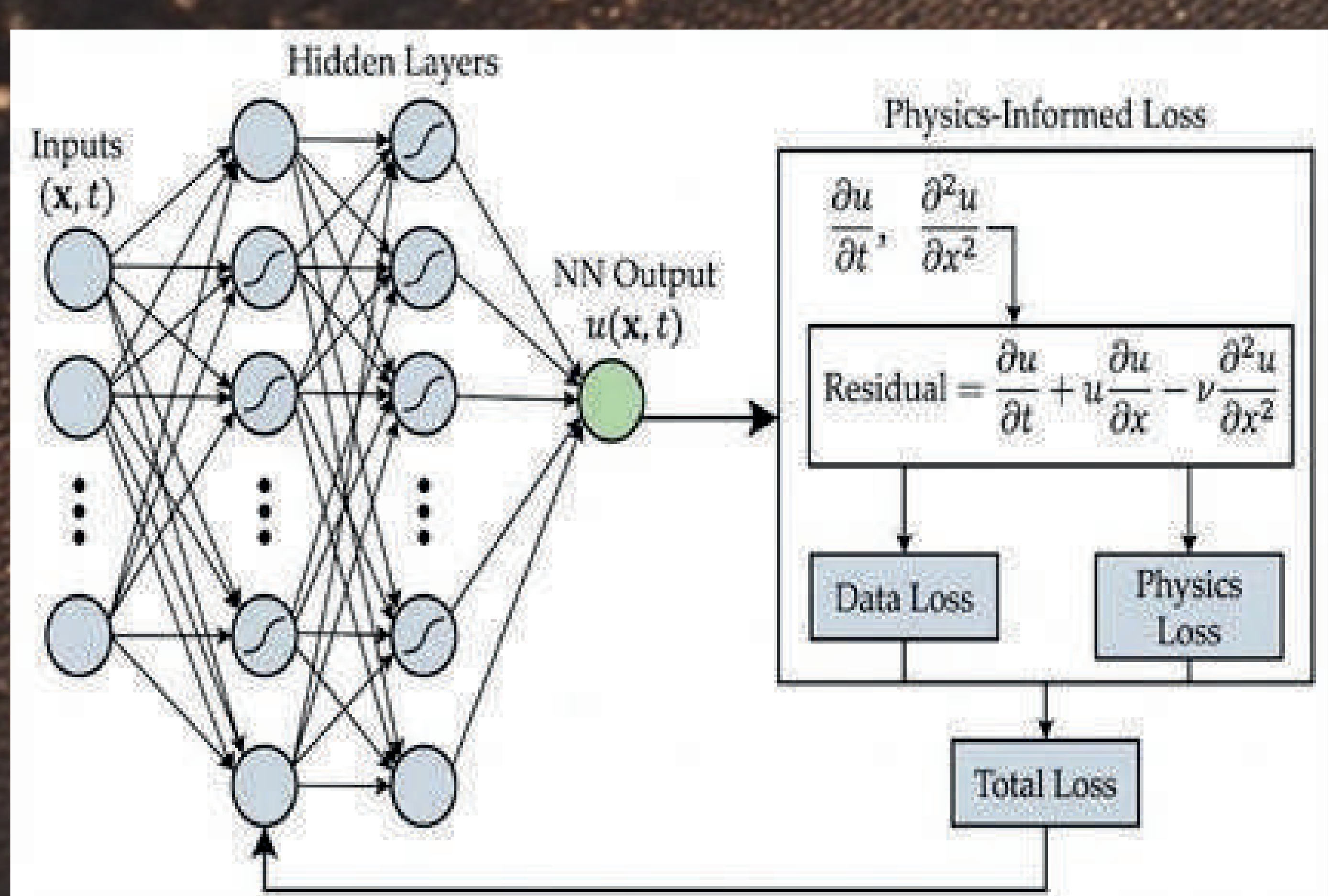
Here, L physics uses the Breit-Wigner resonance form as a constraint. The model was developed using PyTorch and trained using a "Curriculum Learning" strategy.

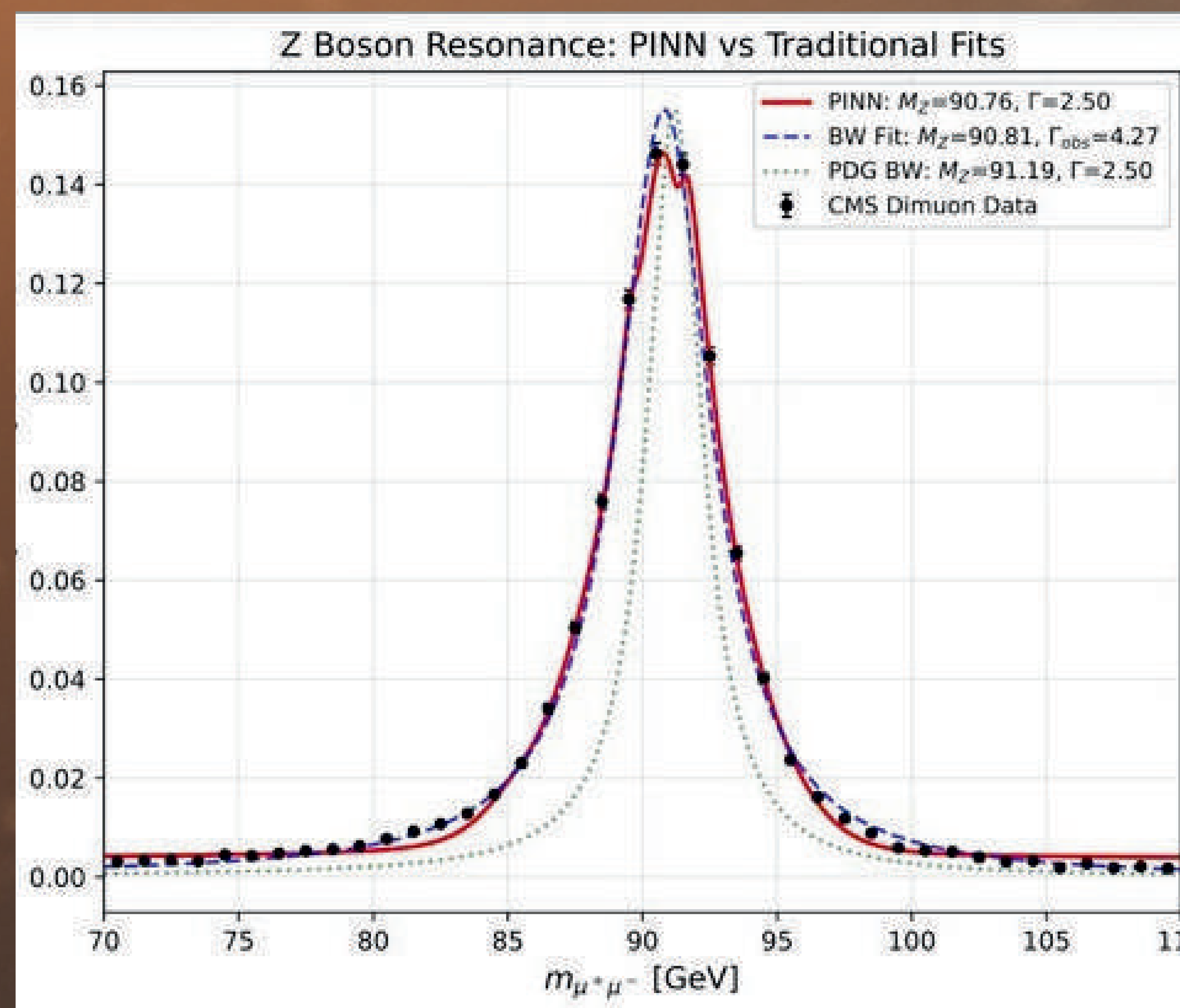
L data: It measures the error between the model's predictions and the actual experimental data using Mean Squared Error (MSE).

L physics: It enforces physical laws by constraining the model to match the Breit-Wigner resonance form and known Z boson properties

L reg: It ensures the model produces a smooth curve and prevents overfitting or unrealistic oscillations

L total: It is the weighted sum of the data, physics, and regularization losses, serving as the final objective function for training




## CONCLUSION AND DISCUSSION

This work demonstrates that Physics-Informed Neural Networks are a powerful tool for separating intrinsic physical parameters from experimental effects in high-energy physics analyses. The high accuracy in natural width estimation (0.11% error) proves the success of the method. Ablation studies revealed that physics priors are critical for the model to converge to the correct solution. This approach offers a potential solution for redu cing systematic uncertainties in future collider experiments.

## RESULTS

While the traditionalBreit-Wignerfitmeasured theobserved width as 4.27 GeV, the PINN method succesfully seperated this into intrinsic width (=2.5 GeV) and detector resolution (=2.69). The natural width is statistically consistent with the PDG referance value.

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# 2025-2026 GÜZ Yarıyılı FİZİK BÖLÜMÜ

## Güneş Enerji Santrallerinin Yer Seçiminin Makine Öğrenimi ile Analizi

**İpek ŞAHİN 20022067**

**Danışman: Doç. Dr. Mehmet KILIÇ**

## ÖZET

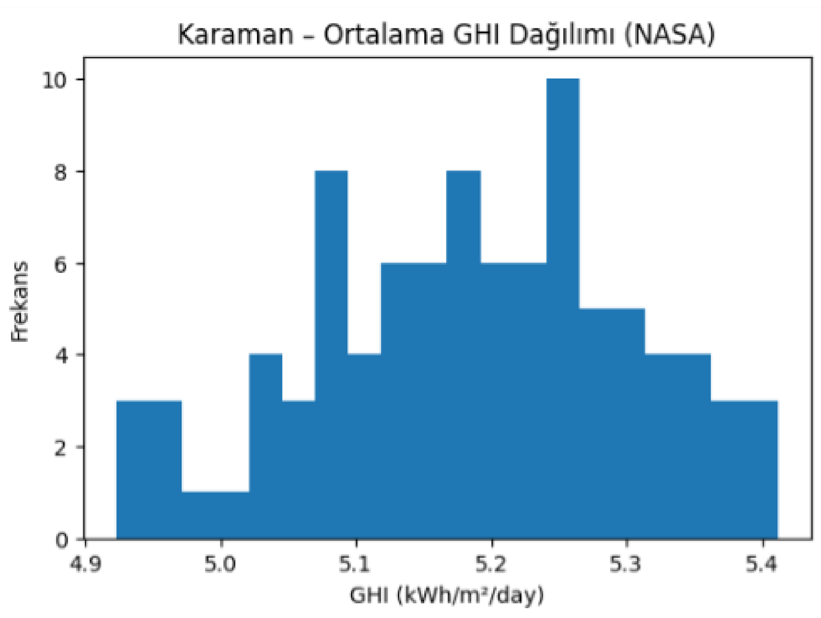
Orta Anadolu Bölgesi’nde güneş enerjisi santrali (GES) kurulumu için uygun alanlar iki aşamalı bir yaklaşımla belirlenmiştir. İlk aşamada NASA POWER verileri kullanılarak uzun dönemli GHI analizi yapılmış ve K-Means kümeleme yöntemiyle yüksek potansiyelli bölgeler tespit edilmiştir. İkinci aşamada bu bölgeler Google Earth Engine ortamında eğim, NDVI ve arazi örtüsü kriterleriyle mikro ölçekte değerlendirilmiştir. Sonuçlar, Konya ve Karaman’ın GES yatırımları için daha avantajlı olduğunu göstermektedir.

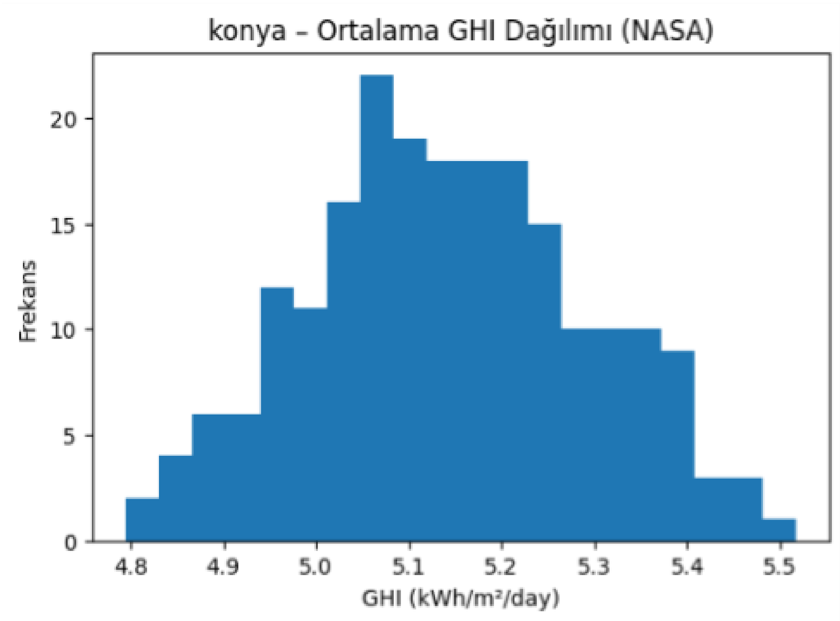
## GES Yer Seçiminin Makine Öğrenimi ile Analizi

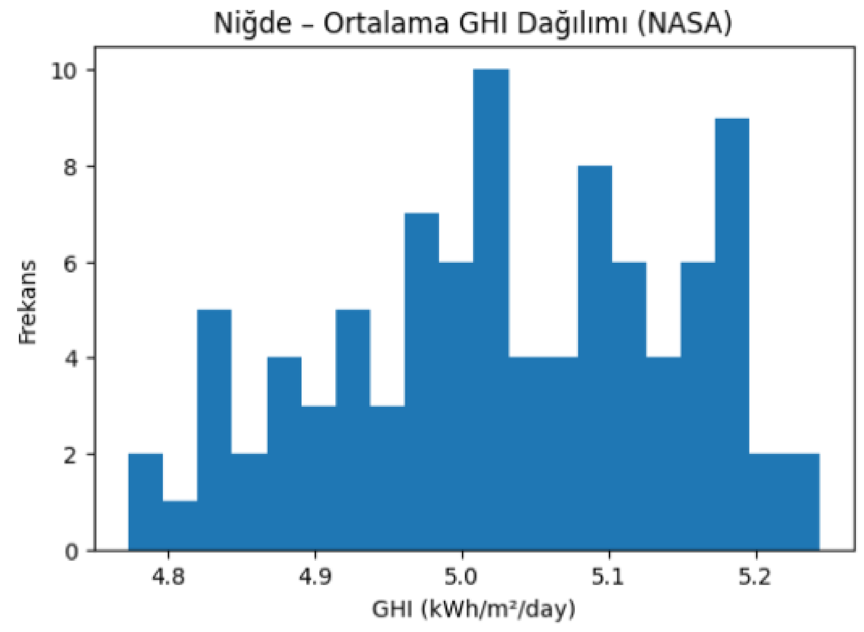
Orta Anadolu Bölgesi’nde GES kurulumu için uygun alanlar, uzun dönemli uydu verileri ve makine öğrenimi yöntemleri kullanılarak iki aşamalı bir yaklaşımla belirlenmiştir.

İlk aşamada güneş ışınımı potansiyeli, ikinci aşamada ise arazi uygunluğu değerlendirilmiştir.

Bu veriler kullanılarak bölgenin güneşlenme karakteristikleri analiz edilmiş, mevsimsel değişimler ve uzun dönemli eğilimler ortaya konmuştur. Aylık ortalama GHI değerleri, yaz aylarında maksimum seviyelere ulaşırken kış aylarında belirgin şekilde düşmektedir. Buna rağmen yıllık ortalamaların düşük standart sapma göstermesi, bölgenin güneş enerjisi açısından iklimsel olarak kararlı bir yapıya sahip olduğunu göstermektedir.

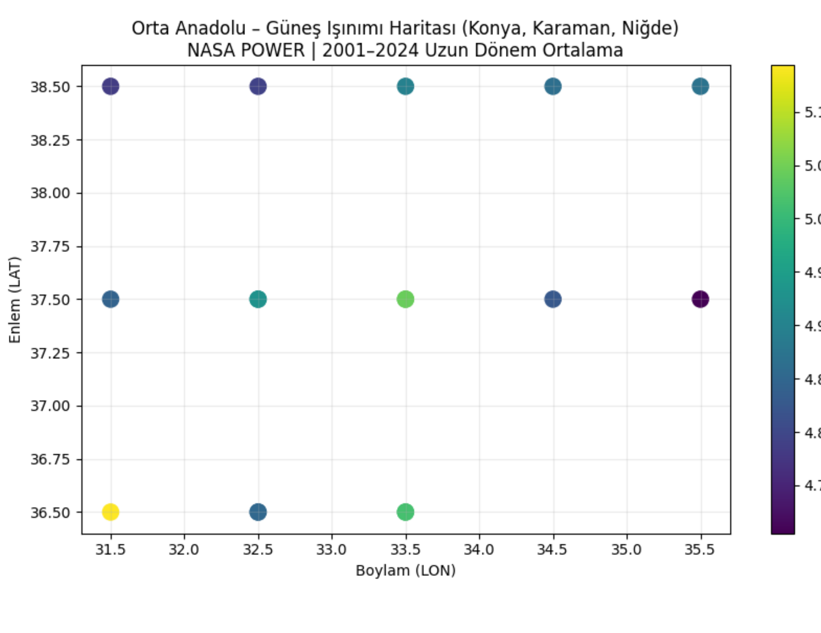


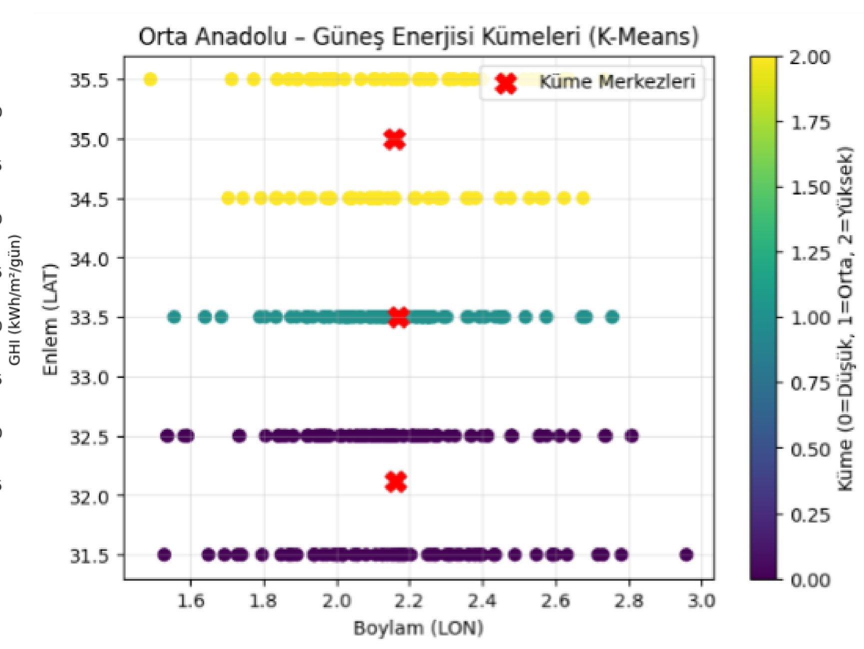




Uzamsal GHI dağılımı, enlem, boylam ve yıllık ortalama GHI değerlerinden oluşan özellik matrisi kullanılarak K-Means kümeleme yöntemi ile sınıflandırılmıştır.

Analiz sonucunda yüksek potansiyelli alanların Konya ve Karaman illerinde yoğunlaştığı görülmüştür.

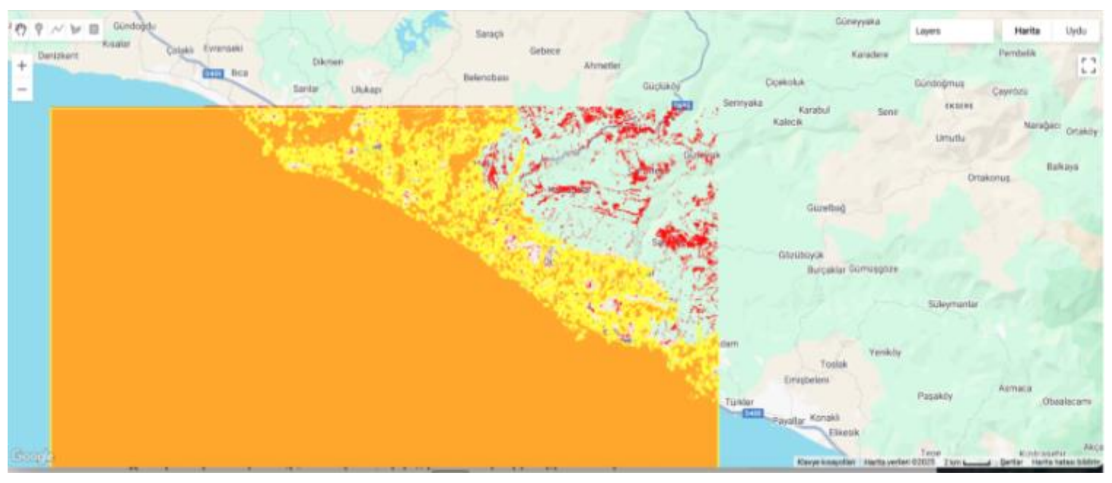


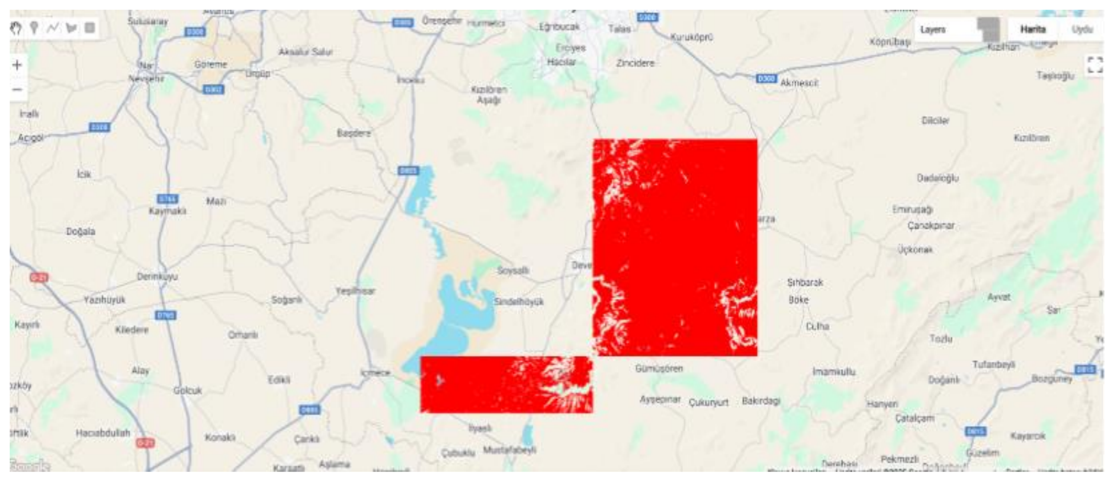

| İl | Enlem (°N) | Boylam (°E) | GHI (kWh/m²/gün) |
|---|---|---|---|
| Karaman | 37.500° | 33.500° | 5.043 |
| Konya | 36.500° | 31.500° | 5.144 |
| Niğde | 38.500° | 35.500° | 4.872 |

*Tablo 2.4 – Her İl İçin Seçilen Optimum GES Noktaları*

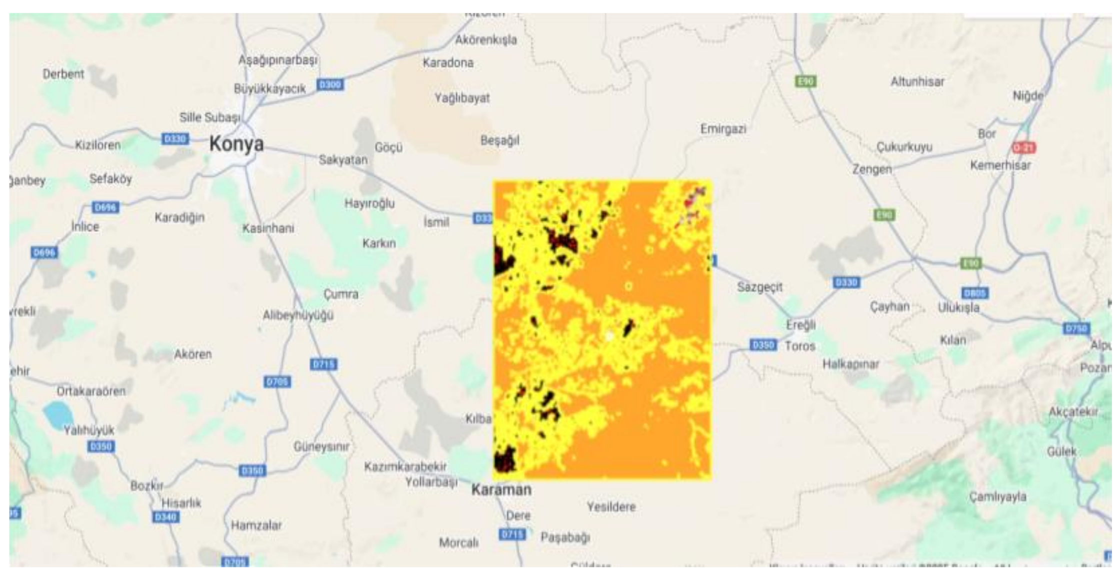
- Makro ölçekte yüksek güneş potansiyeline sahip olarak belirlenen alanlar, çalışmanın ikinci aşamasında mikro ölçekte değerlendirilmiştir. Bu kapsamda **Google Earth Engine** platformu kullanılarak Sentinel-2 uydu görüntülerinden elde edilen NDVI verileri ile bitki örtüsü yoğunluğu, SRTM sayısal yükseklik modeli ile arazi eğimi analiz edilmiştir.
- Ayrıca arazi örtüsü sınıfları dikkate alınarak GES kurulumu için uygun olmayan alanlar analiz dışı bırakılmıştır.
- Belirlenen eşik değerler doğrultusunda yapılan uygunluk filtrelemesi sonucunda, her il için fiziksel olarak elverişli alanlar tespit edilmiş ve bu alanlar arasından **en büyük sürekli bölge** seçilmiştir.
- Seçilen bölgelerin geometrik merkezleri, GES kurulumu için **önerilen optimum noktalar** olarak belirlenmiştir.
- Sonuçlar**, Konya ve Karaman illerinin** hem yüksek güneş ışınımı hem de topografik uygunluk açısından **Niğde’ye kıyasla daha avantajlı olduğunu** göstermektedir.



Konya ili için mikro ölçekli GES uygunluk analizi sonuçları:
**31.48°E – 36.48°N**
Uygun alanın büyüklüğü **3 279.97 km²**



Niğde ili için mikro ölçekli GES uygunluk analizi sonuçları
**35.52°E – 38.51°N**
Uygun alanın büyüklüğü **2 435.07 km²**




Karaman ili için mikro ölçekli GES uygunluk analizi sonuçları
**33.52°E – 37.49°N**
Uygun alanın büyüklüğü **2 792.53 km²**

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# 2025-2026 GÜZ Yarıyılı FİZİK BÖLÜMÜ

### Seramik Malzeme Üretiminde Nano Malzeme Kullanımının Yapısal ve Elektriksel Özellikler Üzerine Etkisi

**Buse KÖK 20022080**

**Danışman: Doç. Dr. Mehmet KILIÇ**

## ÖZET

Bu çalışmada nano ve mikro boyutlu $Bi_2O_3$ katkılarının Bi-2223 esaslı seramiklerin yapısal, morfolojik ve dielektrik özellikleri üzerindeki etkilerini incelenmiştir. Bu kapsamda, katkı boyutunun faz oluşumu, mikro yapı düzeni ve frekansa bağlı elektriksel davranış üzerindeki rolü karşılaştırmalı olarak değerlendirilmiştir. Elde edilen sonuçlarla, nano katkı kullanımının seramiklerin elektriksel performansının iyileştirilmesindeki potansiyeli ortaya konulması hedeflenmiştir.

## NANO MALZEMELERİN SERAMİKLERDE KULLANIMI

Nano malzemeler, 1–100 nm boyut aralığındaki yapıları sayesinde yüksek yüzey alanı/hacim oranına sahip olup fiziksel, kimyasal ve elektriksel özelliklerde önemli iyileşmeler sağlar. Nano boyutlu katkılar, sinterleme davranışını ve mikro yapıyı kontrol ederek tane büyümesini sınırlar, daha homojen tane sınırları oluşturur ve düşük sıcaklıklarda kararlı seramik yapıların elde edilmesine olanak tanır.

## DİELEKTRİK SPEKTROSKOPİSİ

Seramik esaslı dielektrikler; yüksek ısıl kararlılıkları, düşük elektriksel kayıpları ve uzun ömürleri sayesinde enerji depolama ve mikroelektronik uygulamalarda yaygın olarak kullanılır. Dielektrik davranış, kompleks dielektrik geçirgenlik ile tanımlanır;

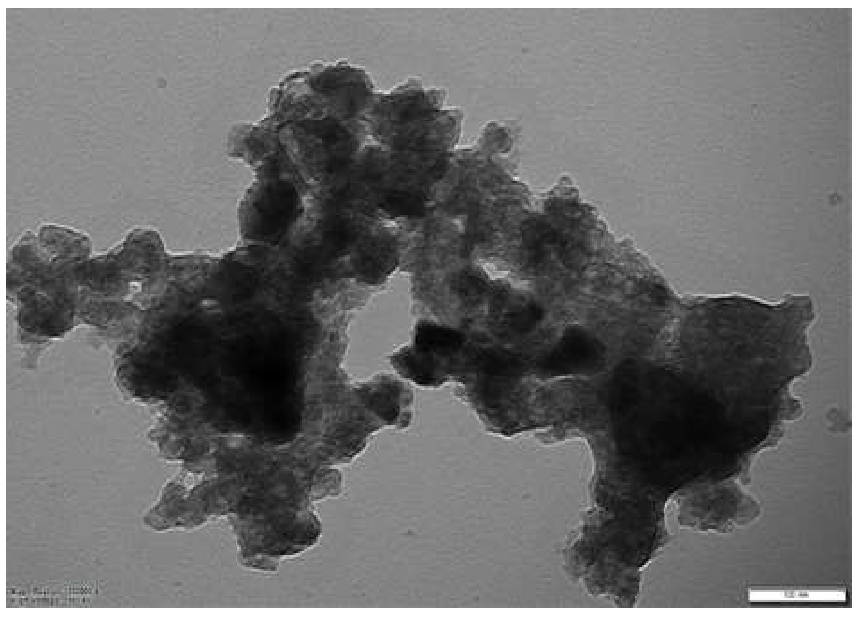
$$\varepsilon * = \varepsilon' - j\varepsilon''$$

Bu ifadenin gerçek kısmı (ε′) enerji depolama kapasitesini, sanal kısmı (ε′′) ise dipol gevşemeleri, ara yüzey etkileri ve iletkenlikten kaynaklanan enerji kayıplarını ifade eder.

## DENEYSEL YÖNTEM

### Yapısal ve Morfolojik Analizler

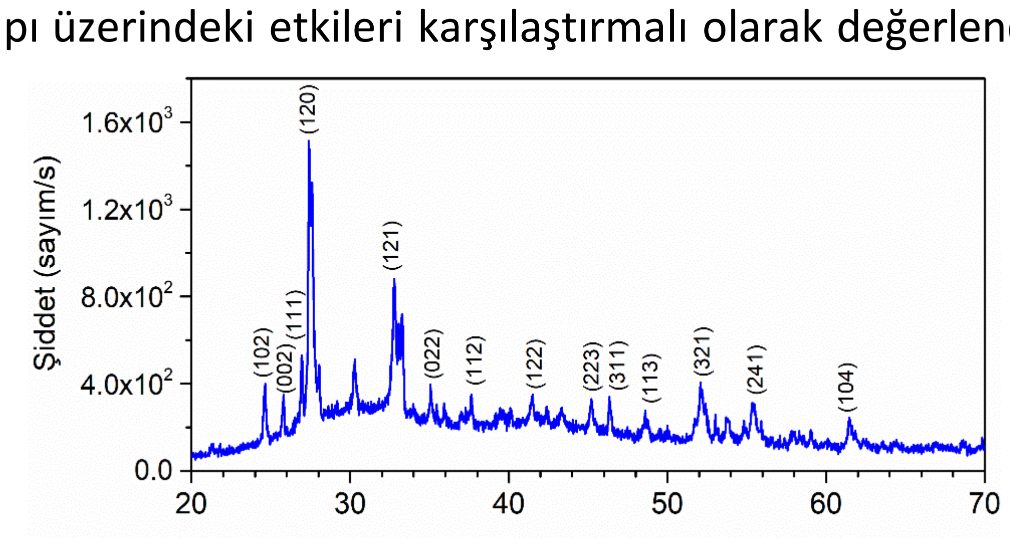
Nano ve mikro $Bi_2O_3$ katkılı Bi-2223 seramiklerinin yapısal ve mikro yapısal özellikleri XRD, SEM ve TEM analizleriyle incelenmiştir.



**Şekil 1:** Sentezlenen $Bi_2O_3$ nano parçacıklarının TEM görüntüsü

### X-Işını Kırınımı (XRD) Analizi

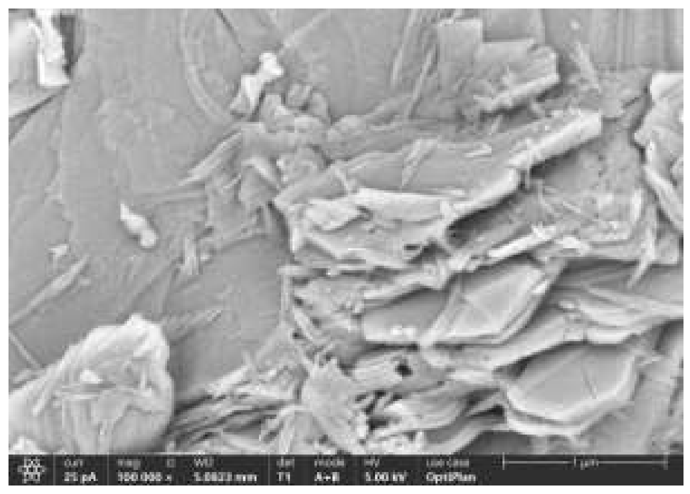
XRD analizleri, faz tanımlaması, kristal düzeni ve kristal boyutuna ilişkin bilgileri ortaya koyarken; nano ve mikro katkıların faz oluşumu, faz saflığı ve kristal yapı üzerindeki etkileri karşılaştırmalı olarak değerlendirilmiştir.



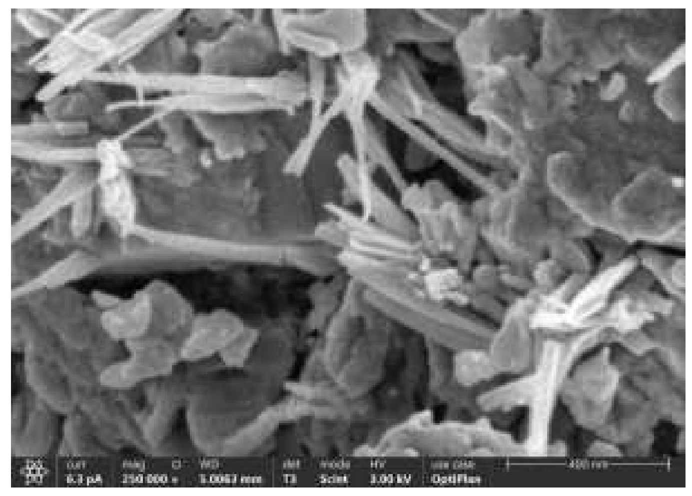

**Şekil 2:** $Bi_2O_3$'nin X-ışını kırınım (XRD) deseni

### Taramalı Elektron Mikroskobu (SEM) ve Mikro Yapı Analizi

Seramik numunelerin mikro yapısı SEM ile incelenmiş; tane morfolojisi, porozite, tane sınırları, katkı dağılımı ve mikro çatlaklar değerlendirilmiştir.



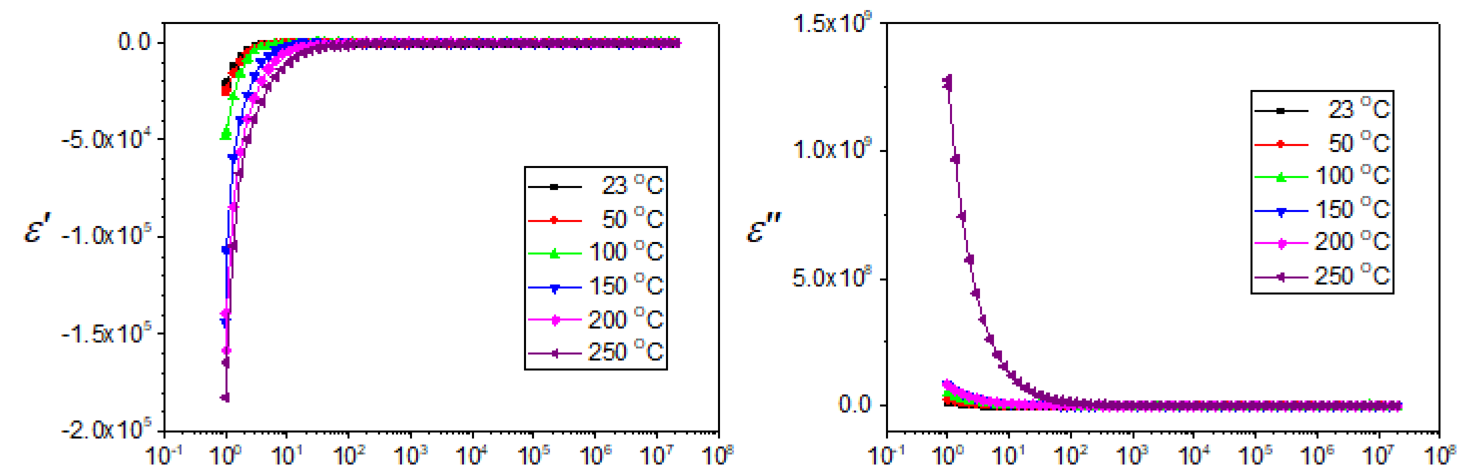
**Şekil 3:** Mikro Bi-2223 seramiğinin SEM görüntüsü



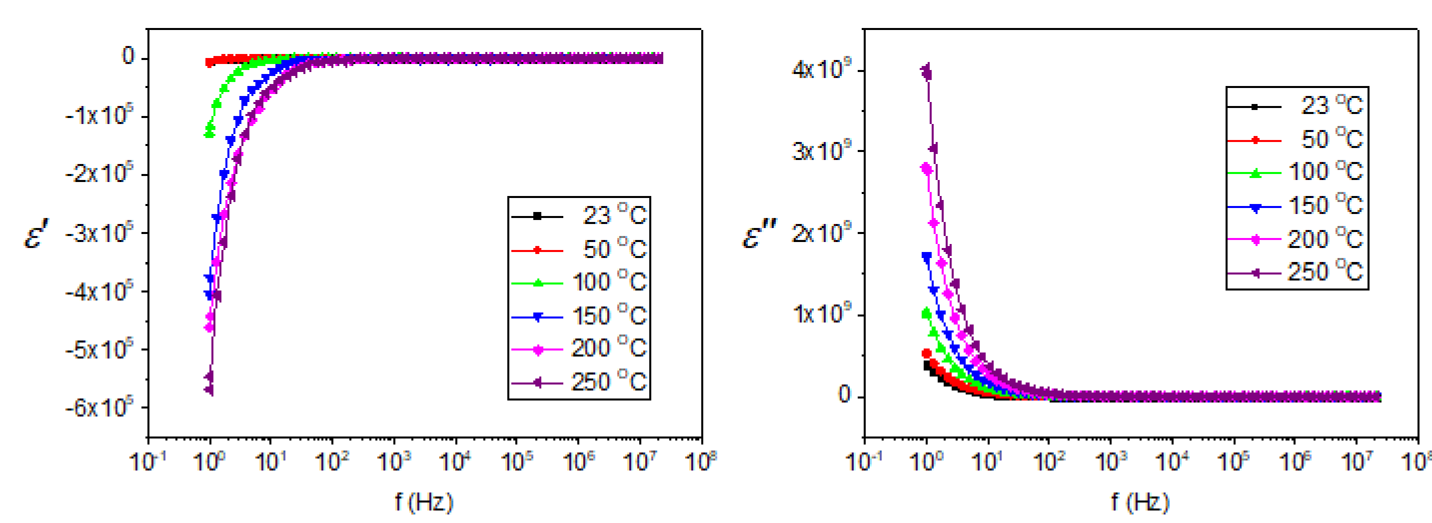
**Şekil 4:** Nano Bi-2223 seramiğinin SEM görüntüsü

## BULGULAR

Nano $Bi_2O_3$ katkılı seramiklerde negatif–pozitif ε′ geçişinin daha yüksek frekanslara kaydığı ve ε′ değerlerinin genel olarak daha yüksek olduğu belirlenmiştir; bu sonuç nano katkının kutuplanma süreçlerini ve tane sınırı etkilerini daha etkin hâle getirdiğini göstermektedir. ε″ değerleri düşük frekansta yüksek olup frekans arttıkça azalmış, yüksek frekanslarda doygunluğa ulaşmıştır. Genel olarak dielektrik analizler, nano $Bi_2O_3$ katkısının Bi-2223 seramiklerinin elektriksel kararlılığını ve dielektrik performansını belirgin biçimde iyileştirdiğini ortaya koymuştur.




**Şekil 5:** 23-250 °C sıcaklık aralığında mikro-$Bi_2O_3$ içerikli Bi-2223 seramiğinin kompleks elektriksel geçirgenliklerinin gerçek (ε′) ve sanal (ε″) bileşenlerinin frekansla değişimleri.




**Şekil 6:** 23-250 °C sıcaklık aralığında nano-$Bi_2O_3$ içerikli Bi-2223 seramiğinin kompleks elektriksel geçirgenliklerinin gerçek (ε′) ve sanal (ε″) bileşenlerinin frekansla değişimleri.

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YTU FACULTY of ARTS and SCIENCES

# 2025-2026 Fall Semester DEPARTMENT OF PHYSICS

## Dielectric and Energy Storage Properties of Epoxy/$Gd_2O_3$ Nanocomposites Prepared with Hydrothermally Synthesized Nanoparticles

Batuhan OTRAKÇI 20022084

Supervisor: Prof. Dr. Zeynep GÜVEN ÖZDEMİR

## ABSTRACT

This study investigates the dielectric performance of epoxy nanocomposites reinforced with hydrothermally synthesized nanoparticles (5, 10, and 20 wt%). The results demonstrate a significant enhancement in the dielectric constant (ε′) due to Maxwell–Wagner polarization, with the 20 wt% loading showing the highest energy storage capacity. Crucially, these improvements were achieved while maintaining low dielectric loss, confirming the material's potential for high-performance capacitor applications.

## INTRODUCTION

Epoxy resins are widely preferred in insulation systems due to their superior mechanical and thermal properties; however, their low dielectric constant limits their use in energy storage applications. To overcome this limitation, this study investigates the dielectric properties of epoxy nanocomposites reinforced with hydrothermally synthesized Gadolinium Oxide (ε′) nanoparticles (5, 10, and 20 wt%). The primary objective is to enhance the dielectric permittivity through the Maxwell–Wagner interfacial polarization mechanism provided by the high surface area of nanoparticles, thereby developing a high-performance material for next-generation capacitors without compromising electrical insulation.

## METHOLODOLOGY

The experimental procedure consists of three main stages: nanoparticle synthesis, composite fabrication, and characterization.

**2.2.Nanoparticle Synthesis:** High-purity Gd2O3 nanoparticles were synthesized via the hydrothermal method by treating Gadolinium Nitrate Hexahydrate solution in an autoclave at 200°C for 12 hours, followed by washing and drying at 80°C as shown in Figure 2.1.

**2.2. Composite Fabrication:** Nanocomposites were prepared by dispersing the synthesized nanoparticles into Bisphenol-A epoxy resin at filler loadings of 5, 10, and 20 wt%. The mixture (2:1 resin/hardener ratio) was cast into Teflon molds and cured in vacuum for 24 hours at room temperature.

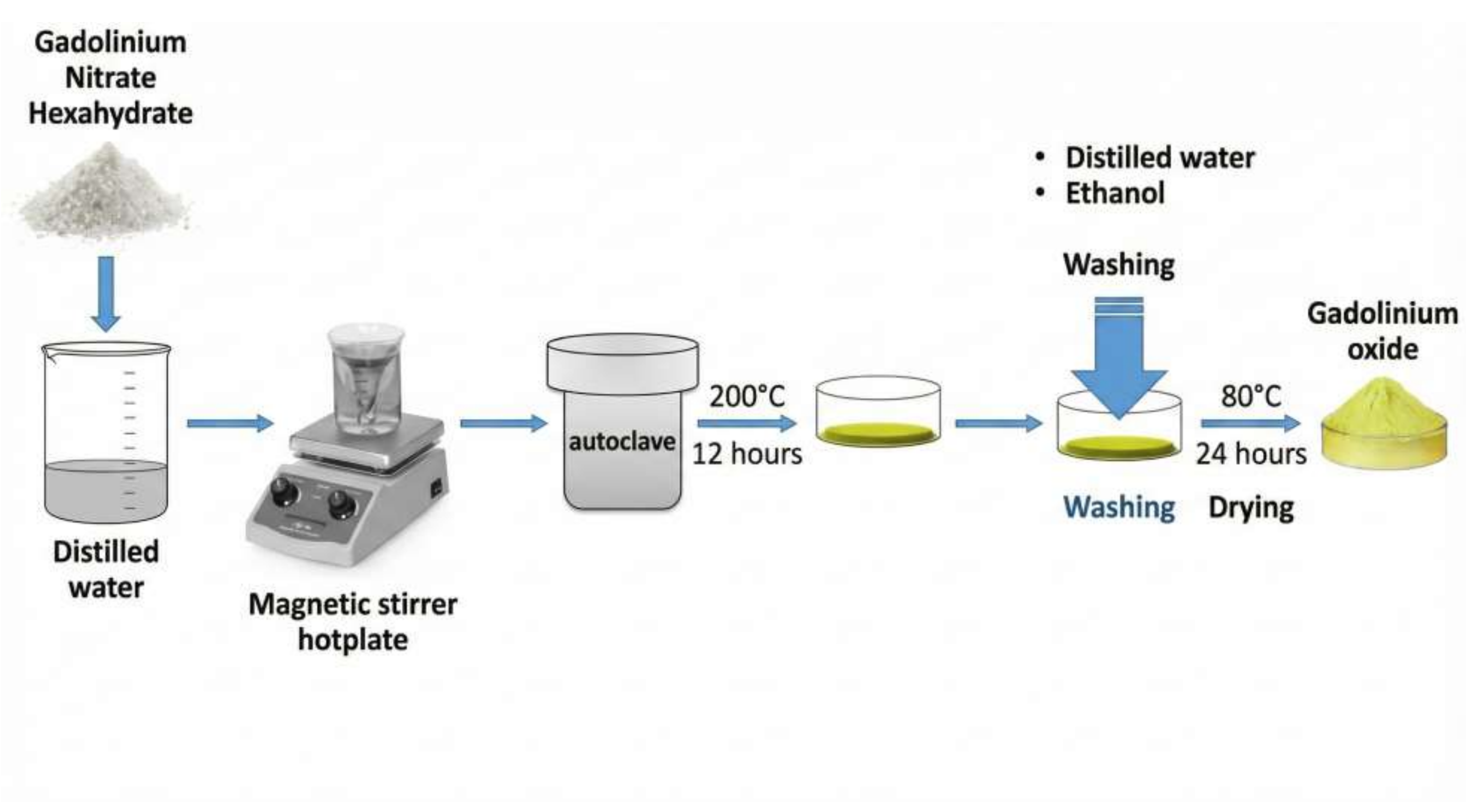


Figure 2.1. Schematic representation of the hydrothermal synthesis of Gd2O3 nanoparticles.

**2.3. Characterization:** Structural characterization via XRD analysis confirmed the formation of high-purity BCC phase crystals (Figure 2.2), while FESEM observations revealed a nearly spherical morphology with an average particle size of 80–100 nm (Figure 2.3). Subsequently, frequency-dependent dielectric measurements were conducted using a Broadband Impedance Analyzer in the range of 1 Hz – 15 MHz.

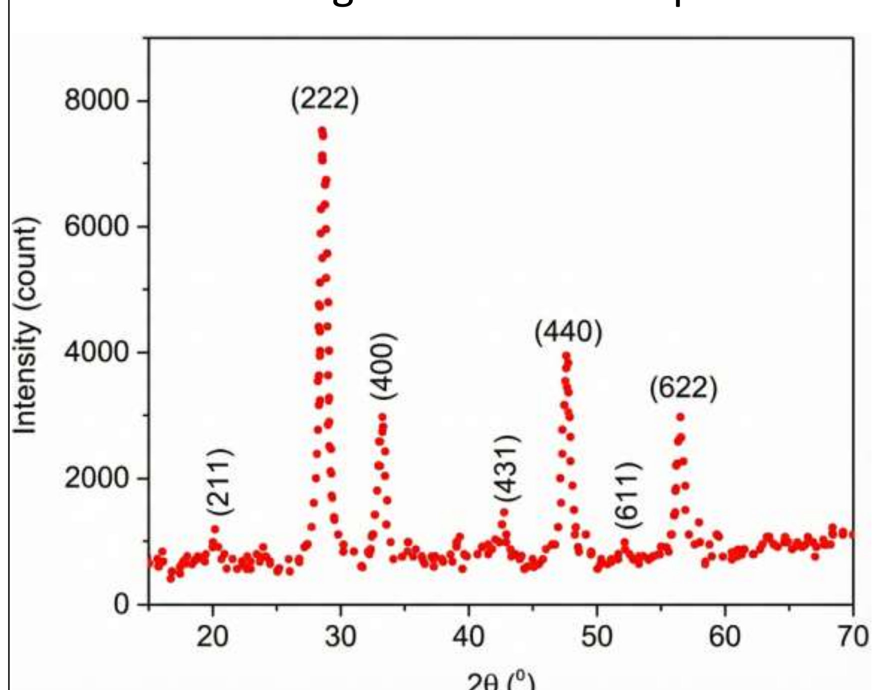


Figure 2.2. XRD patterns of the synthesized $Gd_2O_3$ nanoparticles.

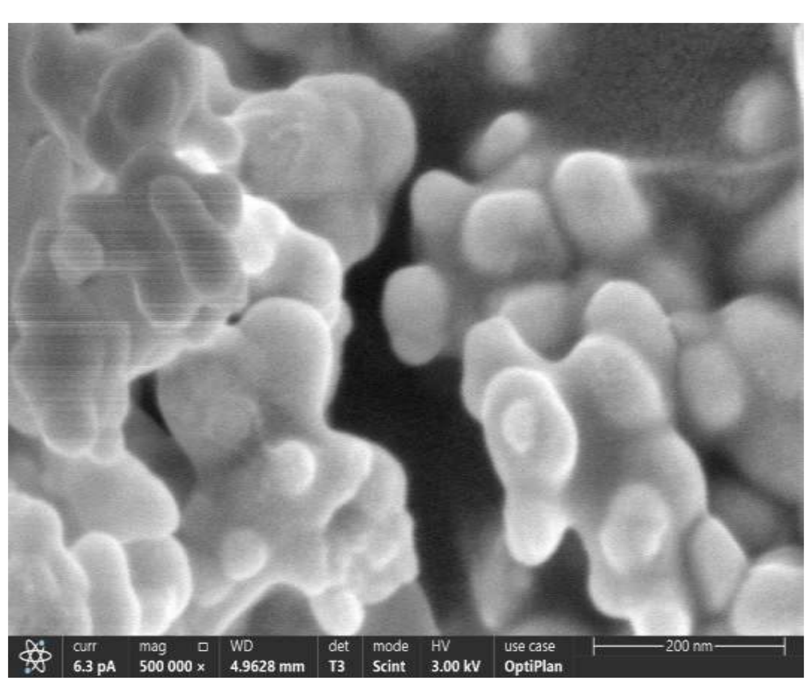

Figure 2.3. FESEM image showing the surface morphology of the synthesized $Gd_2O_3$ nanoparticles.

## RESULTS

**3.1. Analysis of Dielectric Constant (ε′):** The frequency-dependent variation of the dielectric constant was investigated in the range of 1 Hz – 15 MHz. As seen in the results, ε decreases with increasing frequency for all samples. This is a typical behavior where dipoles cannot follow the rapidly alternating electric field at high frequencies.

However, the incorporation $Gd_2O_3$ nanoparticles systematically increased the dielectric constant compared to neat epoxy. This enhancement is primarily attributed to the Maxwell-Wagner interfacial polarization effect, which creates localized charge accumulation at the interfaces between the nanoparticles and the epoxy matrix. Consequently, the 20 wt% nanocomposite exhibited the highest dielectric performance, proving its superior energy storage capacity.

**3.2. Analysis of Dielectric Loss (ε′′):** The dielectric loss factor (ε) represents the energy dissipated as heat. In the low and medium frequency regions ($10^1$ – $10^5$ Hz), the loss values for all nanocomposites remained near zero, similar to neat epoxy. This confirms that the insulating character of the material is preserved despite the high filler loading.

Although a slight increase was observed at high frequencies (>$10^6$ Hz) due to dipole relaxation processes, the energy dissipation remained at acceptable levels. Thus, the study confirms that 20 wt% doping achieves the optimal balance between high energy storage and low dielectric loss.

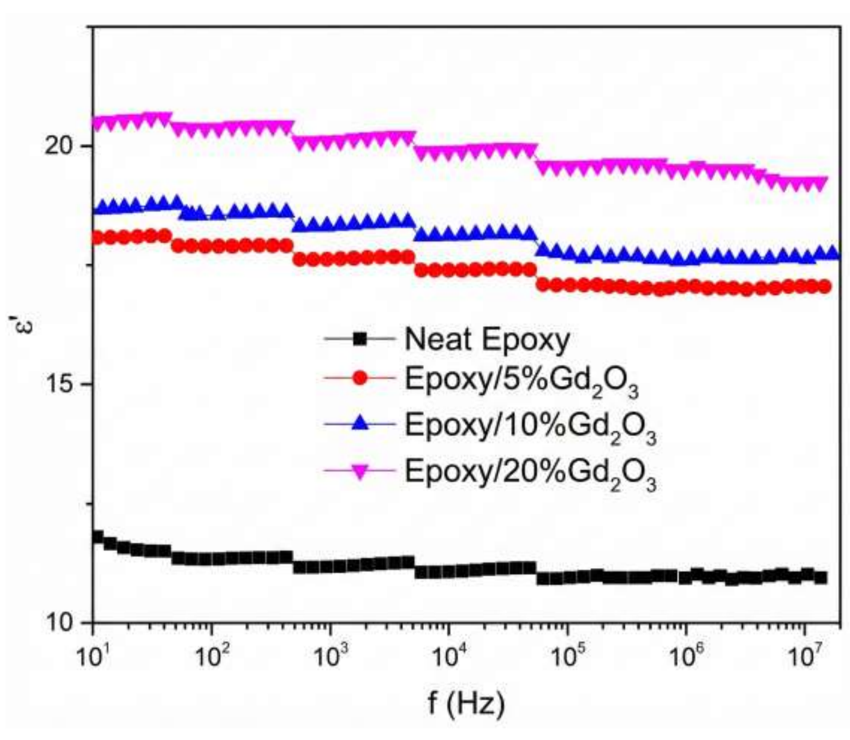


Figure 3.1. ε′ — f graph of Epoxy/ $Gd_2O_3$ nanocomposites

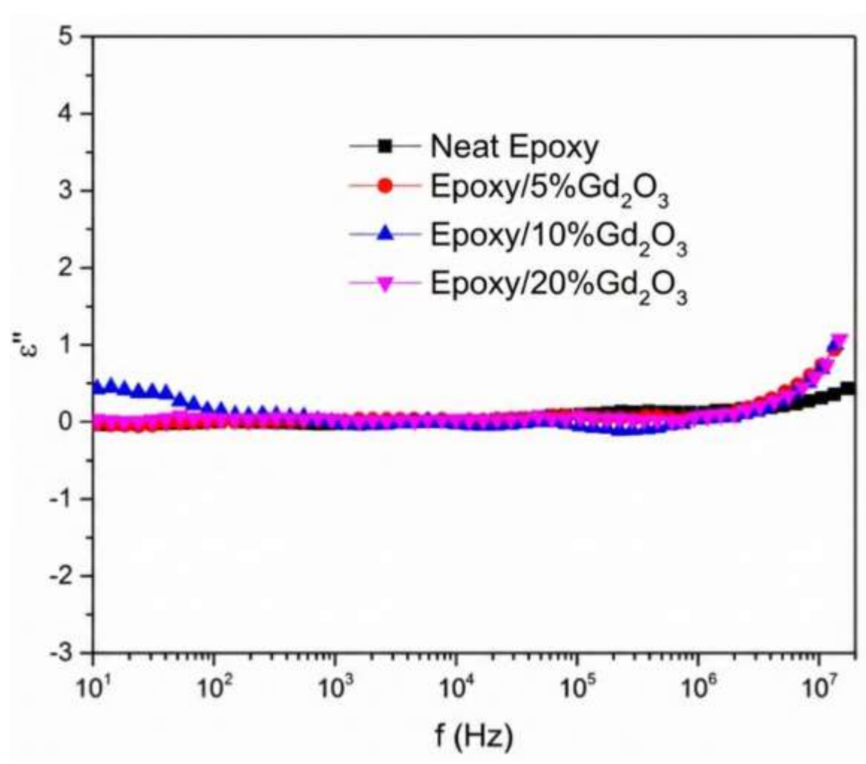


Figure 3.2. ε″ – f graph of Epoxy/$Gd_2O_3$ nanocomposites

## CONCLUSION

High-purity body-centered cubic (BCC) $Gd_2O_3$ nanoparticles with an average size of 80–100 nm were successfully synthesized via the hydrothermal method. The integration of these nanoparticles into the epoxy matrix significantly increased the dielectric constant (ε′), primarily due to the strong Maxwell–Wagner interfacial polarization effect. Among all samples, the nanocomposite with 20 wt% filler loading exhibited the highest energy storage capacity.

Crucially, the dielectric loss (ε′′) remained low across the frequency range, indicating that the improved energy storage performance was achieved without compromising the insulating character of the epoxy resin. These findings suggest that Epoxy/$Gd_2O_3$ nanocomposites are promising candidates for next-generation capacitors and advanced high-voltage insulation systems.

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# 2025-2026 Güz Yarıyılı FİZİK BÖLÜMÜ

## TIBBİ GÖRÜNTÜLEME TEKNİKLERİ

**Zeynep Sude SERENLİ 20022019**

**Danışman: Dr. Öğretim Üyesi Yaşar KARABUL**

## ÖZET

Bu çalışma, modern tıbbi tanı ve tedavi süreçlerinde kritik rol oynayan görüntüleme modalitelerinin fiziksel temellerini, teknolojik altyapılarını ve klinik uygulamalarını karşılaştırmalı olarak analiz etmeyi amaçlamaktadır. Çalışma kapsamında transmisyon tabanlı iyonlaştırıcı teknikler (Radyografi, BT), iyonlaştırıcı olmayan yöntemler (USG, MRG) ve emisyon tabanlı nükleer tıp sistemleri (Sintigrafi, SPECT, PET); görüntü oluşturma mekanizmaları ve radyasyon güvenliği parametreleri açısından incelenmiştir. Yapılan değerlendirmeler sonucunda; Bilgisayarlı Tomografi sistemlerinin anatomik detaylandırmada "altın standart" teşkil ettiği ancak yüksek radyasyon riski taşıdığı, buna karşın MRG ve USG'nin üstün yumuşak doku kontrastı ve radyasyonsuz biyolojik güvenlik avantajı sunduğu saptanmıştır. Nükleer tıp yöntemlerinin doku metabolizmasını haritalama yeteneği, özellikle hibrit sistemlerin (PET/BT, SPECT/BT) gelişimiyle anatomik veriyle entegre edilerek tanısal doğruluğu maksimize etmiştir.

## TARİHÇE

Tıbbi görüntüleme, 1895'te Roentgen'in X-ışınlarını keşfiyle başlayarak modern radyolojinin temellerini atmıştır. Floroskopi; erken dönemdeki radyasyon ve lüminesans sorunlarını, modern görüntü yoğunlaştırıcılar ve dijital dedektörlerle aşarak tanısal doğruluğu optimize etmiştir. Nükleer tıp disiplini ise radyoaktivite çalışmaları ve 1964'te Hal Anger'ın gama kamerasıyla fonksiyonel görüntüleme kapasitesine ulaşmıştır. Tanısal spektrum; 1930'larda ultrasonografi, 1973'te Bilgisayarlı Tomografi (BT) ve takiben Manyetik Rezonans (MRG) ile genişlemiştir. Günümüzde hibrit sistemlere (PET/BT) evrilen teknoloji; yapay zeka ve foton sayımlı dedektörlerle radyasyon dozlarını ALARA prensibince minimize etmektedir. Bu dijital dönüşümün fiziksel temelini kavramak adına, modern tanının yapı taşı olan X-ray radyografi mekanizmasını incelemek kritiktir.

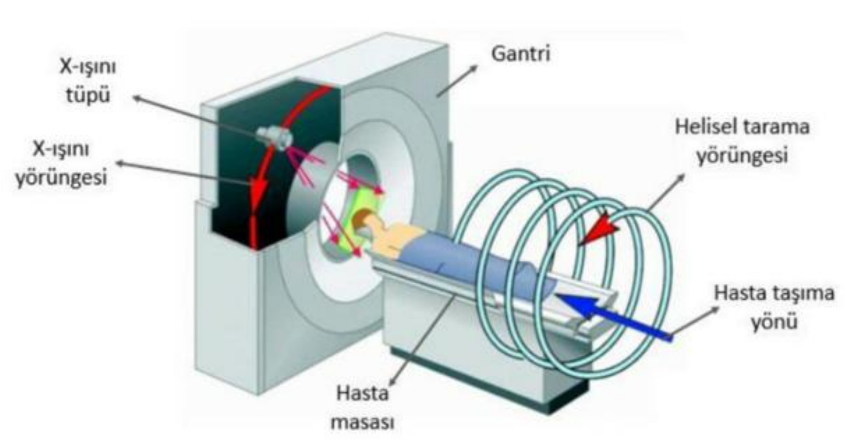
## X-RAY RADYOGRAFİ (RÖNTGEN)

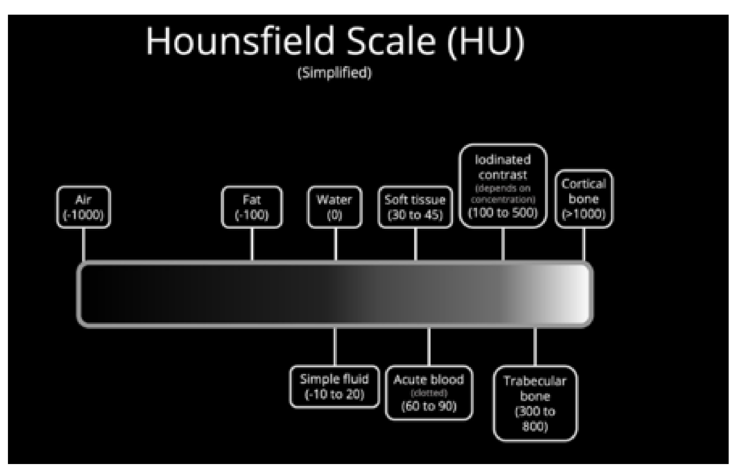
Roentgen, X-ışınlarının farklı doku soğurma kapasitelerini kanıtlayarak canlı görüntülemede dönüm noktası yaratmıştır. Sistem; elektronların anoda çarpmasıyla oluşan Frenleme (Bremsstrahlung) ve Karakteristik Radyasyon mekanizmalarıyla çalışır. Demet kalitesi, düşük enerjili fotonları süzen filtrasyon ve alanı sınırlayan kolimasyon ile optimize edilir. Görüntü oluşumu diferansiyel soğurma (atenuasyon) prensibine dayanır; yoğun yapılar radyopak (beyaz), hava içeren dokular radyolüsent (siyah) izlenir. Yüksek uzaysal çözünürlük, hız ve düşük maliyet ile temel tanı aracı olsa da; süperpozisyon (üst üste binme) ve sınırlı yumuşak doku kontrastı ana limitasyonlarıdır.



## BİLGİSAYARLI TOMOGRAFİ (BT / CT)

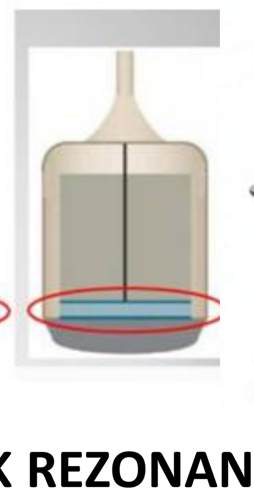
Bilgisayarlı Tomografi (BT), konvansiyonel radyografideki yapıların üst üste binme (süperpozisyon) sorununu, vücudu kesitsel tarayarak ortadan kaldırır. Sistem, dönen "gantry" içindeki tüp ve dedektörlerle binlerce atenuasyon profili toplar. Özellikle Helikal (Spiral) BT, sürekli hacimsel veri toplayarak travma vakalarında saniyeler içinde 3D tüm vücut modellemesi sağlar. Görüntü işlemede, doku yoğunluğunu standardize eden Hounsfield Birimleri (HU) kullanılır (Su: 0, Hava: -1000, Kemik: +1000 HU). BT, milisaniyelik hızı ve üstün kontrast çözünürlüğü ile "altın standart" olsa da; yüksek "Etkin Doz" (mSv) yükü nedeniyle pediatrik ve gebe hastalarda kullanımı sınırlıdır. Ayrıca yoğun materyal kaynaklı metal artefaktları ve fonksiyonel veri eksikliği (sadece anatomik haritalama) temel limitasyonlardır.



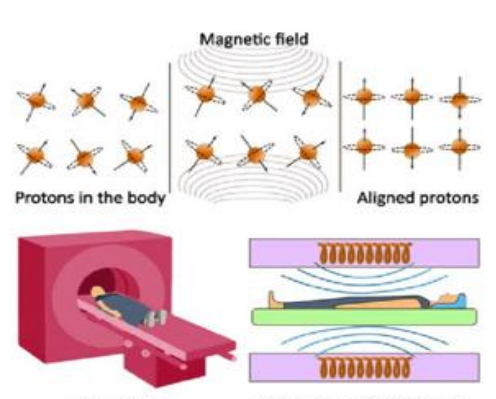

## ULTRASONOGRAFİ (USG)

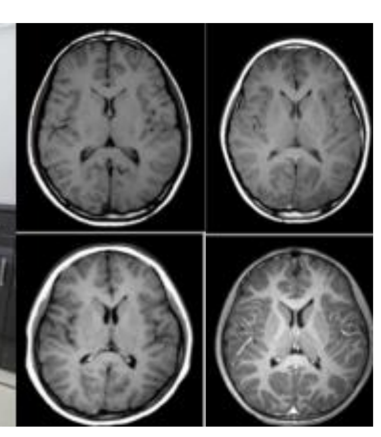
Ultrasonografi (USG), iyonlaştırıcı radyasyon yerine yüksek frekanslı ses dalgalarının doku içindeki yayılım ve yansıma prensiplerine dayanan, biyolojik güvenlik açısından en risksiz görüntüleme modalitesidir. Sistemin çalışma mekanizması Piezoelektrik Etkiye dayanır; prob içerisindeki kristaller elektrik enerjisini mekanik ses dalgasına, dokudan geri dönen yankıları (eko) ise dijital görüntü sinyaline dönüştürür. Görüntü karakterizasyonu "Ekojenite" kavramı ile tanımlanır; ses dalgalarını geçiren sıvılar Anekojenik (Siyah), yansıtan sert dokular ise Hiperekojenik (Beyaz) profil verir. Radyasyon içermemesi ve gerçek zamanlı (real-time) inceleme olanağı, USG'yi obstetrik ve yumuşak doku tanısında birincil tercih haline getirmiştir. Ancak ses dalgalarının hava ve kemik bariyerini aşamaması ve tanısal doğruluğun uygulayıcının tecrübesine (operatör bağımlılığı) dayanması yöntemin temel limitasyonlarıdır.




## MANYETİK REZONANS GÖRÜNTÜLEME (MRG / MRI)

Manyetik Rezonans Görüntüleme (MRG); iyonlaştırıcı radyasyon yerine güçlü manyetik alan ve radyo frekans (RF) dalgaları kullanan ileri bir kesitsel görüntüleme teknolojisidir. Sistemin temeli su moleküllerindeki Hidrojen protonlarına dayanır; manyetik alanda hizalanan protonlar, RF uyarımı sonrası yaydıkları enerji sinyalleriyle yüksek çözünürlüklü anatomik görüntüler oluşturur. Bilgisayar algoritmalarıyla işlenen bu sinyaller, dokuların yoğunluk farklarına göre yüksek çözünürlüklü anatomik görüntülere dönüştürülür.



Donanım mimarisi, sıvı helyum ile soğutulan süper iletken mıknatısları barındıran "tünel" (bore) yapısındadır. Radyasyon riski taşımaması ve hasta pozisyonunu bozmadan yapılan "Multiplanar Görüntüleme", yöntemi pediatrik vakalarda güvenli kılar. Özellikle beyin ve kıkırdak gibi yumuşak dokularda sunduğu üstün kontrast çözünürlüğü ile "altın standart« tır. Ancak; uzun çekim süreleri (20-45 dk), hareket artefaktları ve klostrofobik tünel yapısı temel zorluklardır. Ayrıca güçlü manyetik alan; kalp pili veya ferromanyetik implant taşıyan hastalarda hayati risk oluşturduğundan mutlak kontrendikedir.

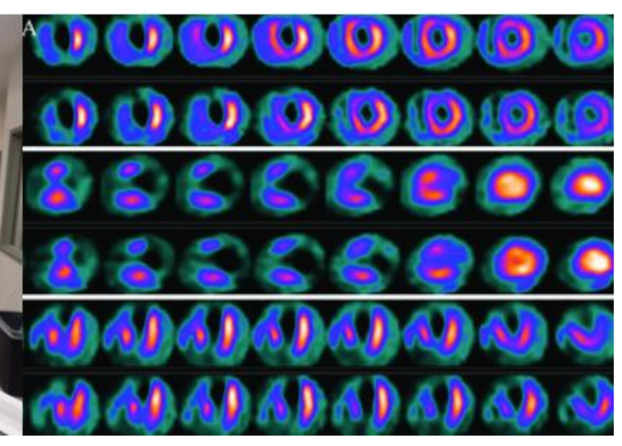
## SİNTİGRAFİ (GAMA KAMERA)

Sintigrafik görüntüleme, anatomik morfolojiden ziyade radyoizotop emisyonlarına dayanarak dokuların metabolik haritasını çıkaran fonksiyonel bir nükleer tıp yöntemidir. Sistemin görüntüleme ünitesi olan Gama Kamera (Anger Kamera);vücuttan yayılan fotonları kolimasyon (yönlendirme), sintilasyon (kristallerle ışığa dönüşüm) ve fotomultiplikasyon (sinyal yükseltme) adımlarıyla dijital veriye dönüştürür. Klinik değerlendirmede doku aktivitesi iki paternde yorumlanır: Radyofarmasötik birikiminin arttığı malignite veya inflamasyon odakları "Hot Spot" (Sıcak Alan); nekroz gibi canlılığını yitirmiş hipoaktif bölgeler ise "Cold Spot" (Soğuk Alan) olarak tanımlanır. Sintigrafinin en büyük avantajı, anatomik bozulma gerçekleşmeden aylar önce hücresel patolojileri saptayabilmesi ve tek dozla Tüm Vücut Tarama yapabilmesidir. Ancak, radyolojik yöntemlere kıyasla düşük uzaysal çözünürlük ve hastanın işlem sonrası radyasyon kaynağına dönüşmesi nedeniyle izolasyon gerektirmesi temel limitasyonlarıdır.



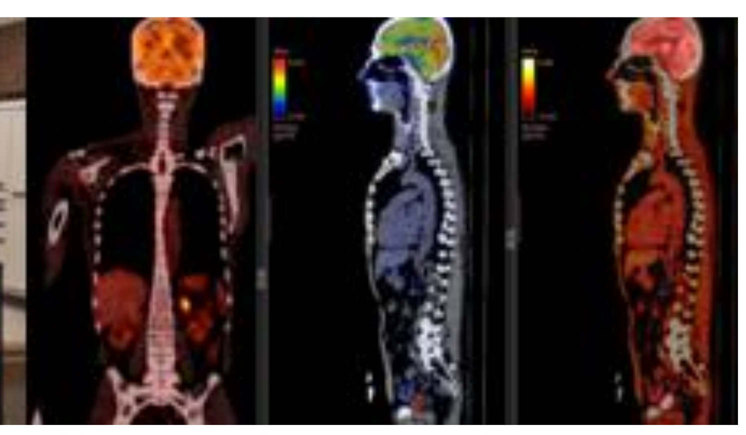
## SPECT (Tek Foton Emisyon Bilgisayarlı Tomografi)

Planar sintigrafinin süperpozisyon ve derinlik algısı kısıtlılığını aşan SPECT teknolojisi; dedektörlerin rotasyonuyla topladığı verileri işleyerek üç boyutlu kesitsel haritalar oluşturur. Bu süreç, derin yerleşimli lezyonların lokalizasyonunu ve kontrast çözümlemesini belirgin şekilde artırır. Anatomik detay eksikliği ve derin dokulardaki sinyal kaybı (atenuasyon), sistemin BT ile entegre edildiği Hibrit SPECT/BT teknolojisiyle giderilmiştir. Fonksiyonel ve yapısal veriyi tek seansta birleştiren bu yöntem; uzun çekim süreleri ve hareket artefaktları riskine rağmen tanısal doğruluğu maksimize eden ileri bir standart sunar.

## PET (Pozitron Emisyon Tomografisi)

PET, pozitron-elektron çarpışmasıyla oluşan Annihilasyon fotonlarının eş zamanlı algılanmasına (Çakışma Sayımı) dayanır. En sık kullanılan F-18 FDG (şeker analoğu) ajanı sayesinde, yüksek glikoz tüketen tümör odakları moleküler düzeyde görüntülenir. Metabolik verinin (PET) anatomik detaydan yoksun olması sorunu, yapısal verinin (BT) tek seansta eklendiği PET/BT hibrit sistemleriyle aşılmıştır. Kanser evrelemesinde "Altın Standart" olan bu füzyon teknolojisi, SUV değeriyle sayısal analiz ve anatomik küçülme öncesi erken tedavi yanıtı takibi sağlar. Ancak; hastanın maruz kaldığı yüksek radyasyon dozu, izotop üretimi için gereken pahalı Siklotron altyapısı ve enfeksiyona bağlı yalancı pozitiflik riski yöntemin temel kısıtlılıklarıdır.

## HİBRİT GÖRÜNTÜLEME SİSTEMLERİ

Anatomik (BT, MRG) ve fonksiyonel (PET, SPECT) yöntemlerin kısıtlılıkları, her iki disiplinin tek bir gantry gövdesinde birleştirildiği Hibrit Görüntüleme teknolojisiyle aşılmıştır. Sistem, hasta hareket etmeden topladığı verileri Görüntü Füzyonu (Co-registration) yazılımlarıyla üst üste bindirerek, yapısal anomali ile metabolik aktiviteyi tek karede eşleştirir. Onkolojide "altın standart" olan PET/BT; BT bileşeni ile anatomik rehberlik ve atenüasyon düzeltmesi sağlayarak SUV (Standart Tutulum Değeri) ölçüm doğruluğunu maksimize eder. SPECT/BT ise, entegre BT sayesinde SPECT'in düşük uzaysal çözünürlüğünü telafi eder; özellikle tiroid ve kemik metastazlarının benign (iyi huylu) oluşumlardan ayrılmasında kritiktir. Teknolojinin son noktası PET/MR; iyonlaştırıcı radyasyon yükünü azalttığı için pediatrik vakalarda güvenlidir ve beyin/pelvis tümörlerinde üstün yumuşak doku kontrastı sunar. Bu hibrit yaklaşım, tanısal doğruluğu %30-40 oranında artırırken hassas radyoterapi planlamasına olanak tanır.

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