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The Variation of the Linewidths and Amplitudes of Sub-Doppler Resonances of ^{87}Rb D_2 Line with Laser Beam Intensity

Ersoy ŞAHİN*[1]

Abstract

The sub-Doppler resonances linewidths and amplitudes depend on the laser beam intensity. The effect of laser beam intensity on the resonance linewidths and amplitudes obtained from different energy transitions of atoms varies from resonance to resonance. The effect of laser beam intensity on resonance linewidths and amplitudes is of great importance for diode laser frequency stability applications. It needs to be determined by measuring. The effect of the laser beam intensity on the linewidths and amplitudes of sub-Doppler resonances were measured by laser heterodyne spectroscopy using the linearly polarized frequency stabilized extended cavity diode lasers. The measurements are compatible with the theory and the uncertainty of the measurements are fewer than 1.6 MHz and 0.3 mV for linewidths and amplitudes, respectively.

Keywords: Sub-Doppler resonance, linewidth, amplitude, saturation absorption spectroscopy, laser frequency stability

1. INTRODUCTION

Sub-Doppler resonances are detected by the saturation spectroscopy method [1, 2]. Derivative signals obtained from saturation resonances by different spectroscopic methods are used to establish the frequency stability of lasers [3-6]. The level of frequency stability that the laser will reach depends on the linewidth and amplitude of the saturation resonance used as a reference, and high-frequency stability levels can only be achieved by using derivative signals obtained from resonances with narrow linewidth and high amplitude [7, 8]. Linewidth and amplitude of saturation resonances depend on the polarization of the laser beam, the laser beam intensity, the diameter of the laser beam, and the ambient temperature parameters where the atoms are located [9-11]. The effect of laser beam intensity on the linewidths and amplitude of the hyperfine resonances of the ^{87}Rb D_2 line have not been measured. The polarization and the diameter of the laser beam on the linewidths and amplitude of the hyperfine resonances of the ^{87}Rb D_2 have been studied [9, 10]. Laser beam intensity increases the linewidth of the saturation resonance (saturation broadening) and causes a light shift of the resonance frequency [12, 13]. It is of great importance for applications that the laser beam intensity should be at a value that will both expand the resonance linewidth at the minimum level and shift the resonance frequency the least [14-18].

In this study, the effect of the laser beam intensity on the linewidths and amplitudes of the

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F=1→F/=0,1,2 and F=2→F/=1,2,3 hyperfine resonances of ^{87}Rb D_2 line were measured. The linearly polarized counter-propagated pumping and probe beams were used for creating and detecting the resonances respectively. During the measurements, the laser beam intensity of the probe beam was constant, and the pumping beam was changed. The saturation resonances were recorded by using the computer-controlled lock-in amplifier, digital multimeter, and frequency counter. The variation of the saturation resonances linewidths and amplitudes with laser beam intensity was investigated by statistical analysis of the measurements.

2. MEASUREMENT METHOD

The variation of the linewidths and amplitudes of the sub-Doppler resonances of ^{87}Rb D_2 energy transitions with laser beam intensity were determined by using two extended cavity diode recording (L_{rec}) and reference (L_{ref}) lasers with a linewidth of less than 150 kHz and operating at a wavelength of 780 nm. The measurement setup is in Figure 1 and it is the experimental setup used in the previous study. [19]. For creating and detecting the resonances, counter-propagated pumping and probe laser beams with diameters of 3 mm obtained from the L_{rec} were used. The two optical paths were obtained by splitting the beam of the L_{rec} laser with a beam splitter (BS_1). To get rid of the back reflection from the optics to the L_{rec} laser, an optical isolator (OI) was placed in front of the laser. By using the beam splitter (BS_3), the first optical path was divided into two parts and some part of it was used for the beat frequency measurements with a reference laser while the other part was sent to the temperature-controlled Fabry-Perot interferometer with the usage of a mirror (M_4) for creating a transmission resonance of the interferometer. The beam expander (BE) was used to enlarge the laser beam of the second optical path and the diaphragm (D) was used for adjusting the beam diameter of the L_{rec} laser to 3 mm. The counter-propagated pumping and probe laser beams were obtained by using the polarizing beam splitter (PBS). The laser beam reflected from the polarizing beam splitter was used for optical pumping (pumping beam), and the transmitted beam (probe beam) was used to detect resonances. By using the beam splitter (BS_2) and mirror (M_3), the reference laser beam constituted for removing background signal coming from the probe laser beam on the differential photodetector (DFD). For generating linear polarized parallel pumping and probe laser beams, the half-wave (λ/2) plate was used for adjusting the angle of the pumping beam polarization that was 90º different linearly polarized to the probe laser beam. The intensity of the pumping laser beam was changed with a neutral density filter (ND_2), whereas the probe laser was kept constant at 0.1 mW/cm^2 usage of the neutral density filter (ND_1).

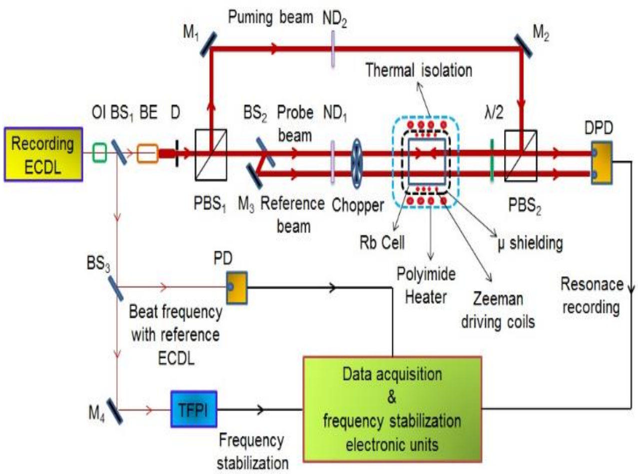

Figure 1 Measurement setup

The pumping and probe laser beams were optically superimposed inside a cylindrical glass cell with a length of 5 cm and a diameter of 3 cm, in which there is enriched Rb atoms. To ensure that the linewidth and amplitude of the resonances are not affected by the external magnetic field and ambient temperature, the Rb glass cell was magnetically shielded by wrapping two layers with Mu-metal, and temperature stability was achieved with polyamide heaters wrapped on the shielding. The magnetic field was measured less than 1 μT inside the shielding, the Rb glass cell temperature was kept stable at 22.5 ºC from peak to peak at 5 mK [20]. To perform precise and repeatable measurements, both lasers were frequency stabilized.

The frequency stability of the L_{rec} laser was done by applying the first derivative of the transmission resonance of the temperature-controlled Fabry-Perot interferometer to both the laser current and the piezoelectric transducer as feedback. Neither the piezoelectric transducer nor the current of the L_{rec} laser was modulated because the frequency modulation [21], which must be applied to obtain the derivative of the transmission resonance, increases the linewidths of the saturation resonances and also causes fluctuations in their amplitudes. The derivation of the transmission resonances were obtained by modulating and demodulating the Fabry-Perot interferometer's piezoelectric transducer by using the locking amplifier sinus signal. The L_{ref} laser frequency was stabilized by using the third derivative of saturation resonances of ^{87}Rb as a feedback signal. The feedback signal was applied both to the current and piezoelectric transducer of the laser. The derivative signal of the saturation resonances were obtained by modulation of the L_{ref} laser current with the sinus signal and demodulation from the lock-in amplifier. The beat frequency between the two lasers (laser heterodyne spectroscopy) was detected via a fast photodetector and recorded over a computer-controlled frequency counter to perform the frequency scale of the measurements [22]. The L_{rec} frequency was scanned with the sawtooth signal applied to the piezoelectric transducer of the Fabry-Perot interferometer from the signal generator, and the $F=1 \rightarrow F^{/}=0,1,2$ and $F=2 \rightarrow F^{/}=1,2,3$ hyperfine resonances of the ^{87}Rb transition line were recorded by using a computer-controlled lock-in amplifier and digital multimeter. The variation of resonance linewidths and amplitudes with laser beam intensity was investigated by statistical analysis of repeated measurements. Each value of laser intensity in the graphs of resonance linewidths and amplitudes is the mean value of the resonances that have been recorded five times in consecutive, and the standard deviation around the mean value is given with uncertainty bars as k=1.

3. LINEWIDTH AND AMPLITUDE MEASUREMENTS OF HYPERFINE RESONANCES OF ^{87}Rb D_2 LINE

The energy level diagram of ^{87}Rb is indicated in Figure 2. The fine structure is a result of the coupling between the orbital angular momentum **L** of the outer electron and its spin angular momentum **S**. The total electron angular momentum is given by **J** = **L** + **S**. For ground state L = 0 and S = 1/2, so J =1/2 and for the first excited state L = 1, so J = 1/2 or J = 3/2. According to the value of J, the transition split into two parts D_1 line ($5^2S_{1/2} \rightarrow 5^2P_{1/2}$, 794 nm) and D_2 line ($5^2S_{1/2} \rightarrow 5^2P_{3/2}$, 780 nm). The hyperfine structure is a result of the coupling of **J** with the total nuclear angular momentum **I**. The total atomic angular momentum F is then given by **F** = **J** + **I**. For the ground state, J = 1/2 and I = 3/2, so F = 1 or F = 2. For the excited state of the D_2 line, F can take the values 0, 1, 2, and 3 [23].

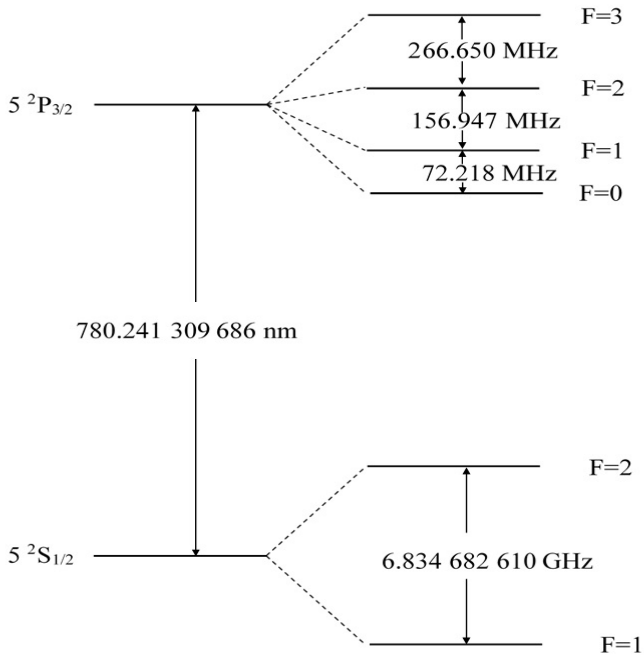

Figure 2 The fine and hyperfine structure energy levels of ^{87}Rb D_2 line

Figure 3 shows the variation of the $F=1 \rightarrow F^{/}=0,1,2$ and $F=2 \rightarrow F^{/}=1,2,3$ hyperfine resonances of the ^{87}Rb D_2 line with pumping laser beam intensity. The left column of the figure is the spectrum of $F=1 \rightarrow F^{/}=0,1,2$, and the recorded crossover (CO) resonances in the case of pumping laser beam intensity (a) 1.19, (b) 2.39 and (c) 3.98 mW/cm^2.

The spectrum of $F=2 \rightarrow F^{/}=1,2,3$, and crossover resonances recorded at (I) 0.4, (II) 1.59, and (III) 3.58 mW/cm^2 values of pumping laser beam intensity is in the right column of Figure 3.

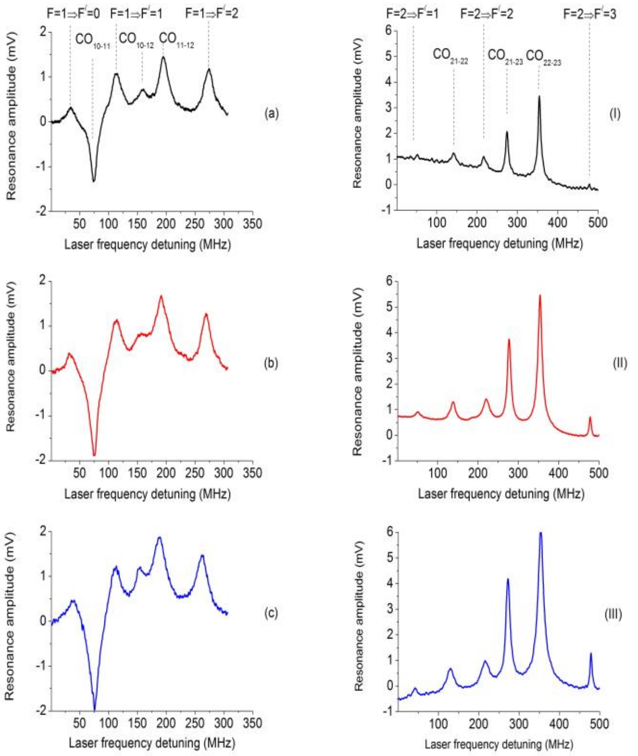

Figure 3 The effect of the laser beam intensity on linewidths and amplitudes of $F=1 \rightarrow F^{/}=0,1,2$, $F=2 \rightarrow F^{/}=1,2,3$, and crossover resonances

3.1. Variation of Linewidths Hyperfine Resonances of ^{87}Rb D_2 Line with Pumping Laser Beam Intensity

The variation of linewidths of $F=1 \rightarrow F^{/}=0,1,2$, and crossover resonances with pumping laser beam intensity is shown in Figure 4. As can be seen from Figure 4, the full half-maximum linewidths (FWHM) of the $CO_{11\text{-}12}$, $CO_{10\text{-}11}$, and $F=1 \rightarrow F^{/}=2$ resonances have expanded with increasing pumping laser beam intensity. The linewidths of the $F=1 \rightarrow F^{/}=0$ and $F=1 \rightarrow F^{/}=1$ resonances have broadened to 2.4 and 3.2 mW/cm^2 laser beam intensity values respectively and then began to narrow. Since the $CO_{10\text{-}12}$ crossover resonance signal could not be detected from sufficient signal amplitude, the variation of the pumping laser beam intensity on the resonance linewidth could not be analyzed.

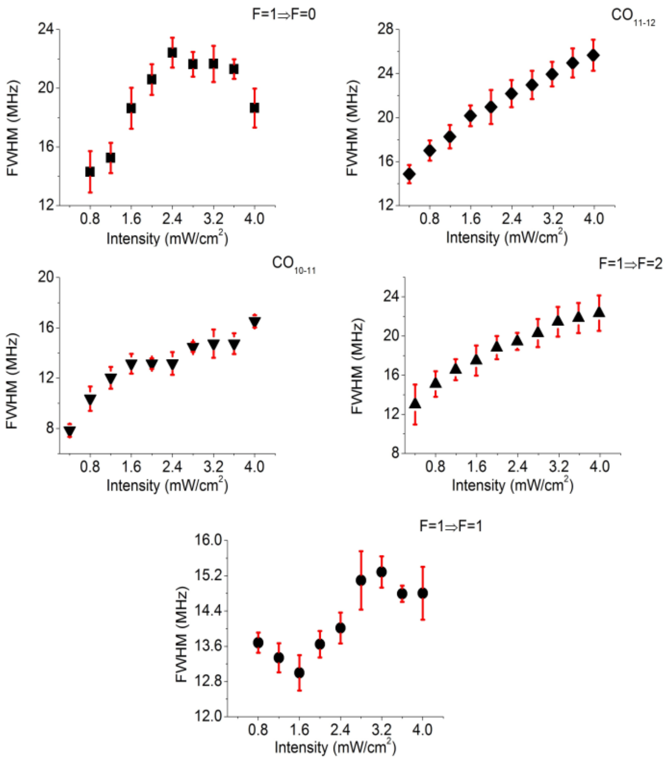

Figure 4 Variation of linewidths of $F=1 \rightarrow F^{/}=0,1,2$, and crossover resonances with laser beam intensity

Figure 5 shows the variation of linewidths of $F=2 \rightarrow F^{/}=1,2,3$, and crossover resonances with pumping laser beam intensity. The linewidths of $CO_{22\text{-}23}$, $CO_{21\text{-}23}$, and $F=2 \rightarrow F^{/}=3$ transition resonances broadened with the increase of pumping laser beam intensity. The linewidth of $CO_{21\text{-}22}$ and $F=2 \rightarrow F^{/}=2$ transition resonances broadened up to the laser beam intensity value of 0.8 mW/cm^2, after this value, despite the increase in the laser beam intensity value, there is no visible broadening in the linewidth. Since $F=2 \rightarrow F^{/}=1$ resonance amplitude could not be detected in the signal amplitude to be analyzed, the analysis of the linewidth could not be performed.

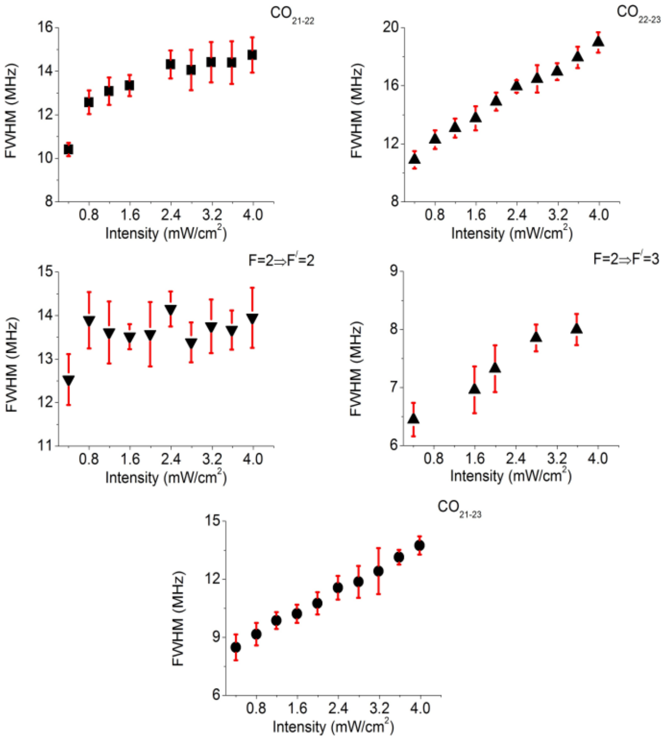

Figure 5 Variation of linewidths of F=2→F$^{/}$=1,2,3, and crossover resonances with laser beam intensity

The linewidth measurements of the saturation resonances are in agreement with the theory. The expansion of the laser beam intensity on the resonance linewidth is expressed

$$\Gamma^{/} = \Gamma.[1+(\frac{I}{I_{sat}})]^{1/2}$$

by the equation where Γ is the natural linewidth of the resonance defined by the lifetime of the atoms at the upper energy level, and I_{Sat} is the saturation intensity value [12]. The lifetime of the ^{87}Rb atoms at the F=2→F$^{/}$=3 transition at the F$^{/}$=3 level is 26.24 ns (6.065 MHz), I_{Sat} =2.5 mW/cm^2 for linearly polarized laser beam [23]. According to the equation, if the laser radiation intensity I=0.4 mW/cm^2, the line broadening of the laser beam intensity on the resonance linewidth Γ$^{/}$=6.5 MHz is calculated. This value is in agreement with the measured value for the line width of the F=2→F$^{/}$=3 saturation resonance and is within the measurement uncertainty (Figure 5).

3.2. Variation of Amplitudes of Hyperfine Resonances of ^{87}Rb D_2 Line with Pumping Laser Beam Intensity

The variation of amplitudes of F=1→F$^{/}$=0,1,2, F=2→F$^{/}$=1,2,3, and crossover resonances with pumping laser beam intensity is given in Figures 6 and 7. Except for the F=2→F$^{/}$=3 resonance, the amplitudes of the resonances increase up to the laser beam intensity value of 1.8 mW/cm^2. After this value, there are no increase in resonance amplitudes and there are saturated. The amplitude of the F=2→F$^{/}$=3 resonance increases as the laser beam intensity increases. CO_{10-12} and F=2→F$^{/}$=1 resonances could not be analyzed because their amplitudes could not be detected in the signal amplitude to be analyzed.

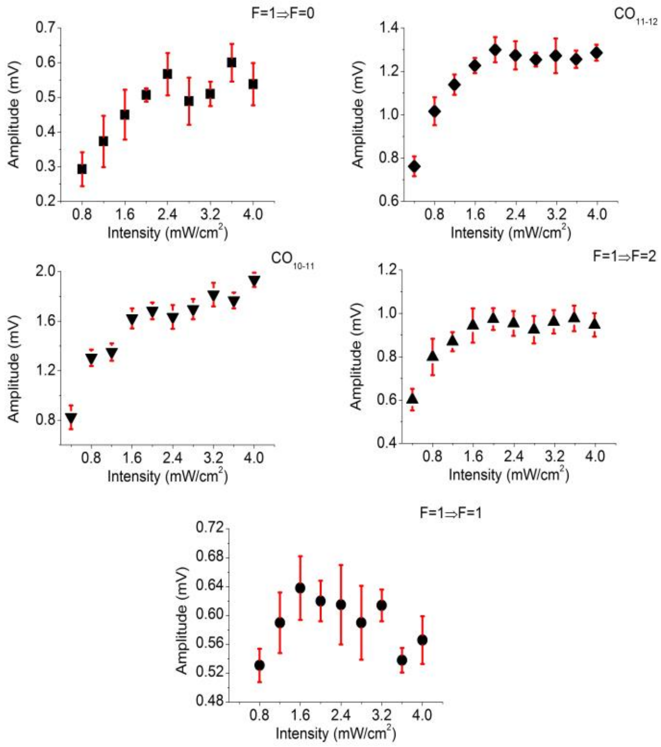

Figure 6 Variation of amplitudes of F=1→F$^{/}$=0,1,2, and crossover resonances with laser beam intensity

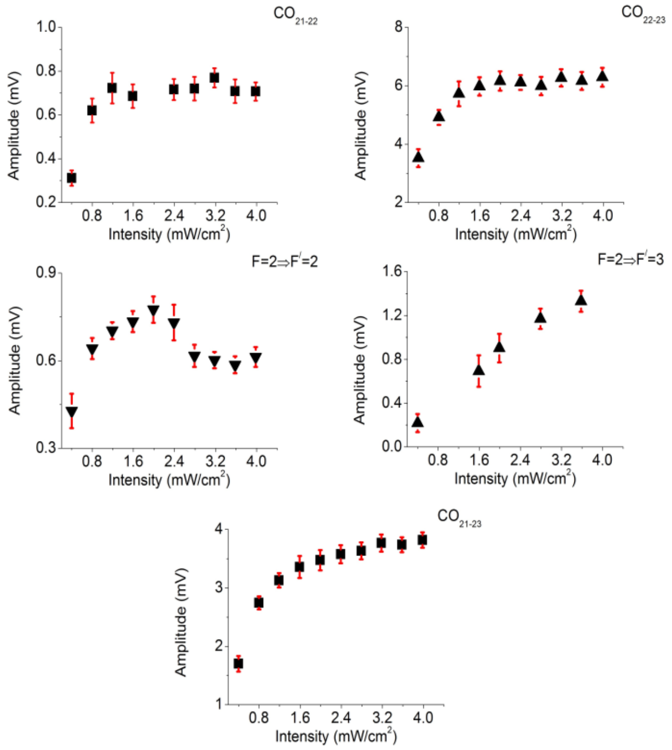

Figure 7 Variation of amplitudes of F=2→F/=1,2,3, and crossover resonances with laser beam intensity

4. CONCLUSION

The variation of the sub-Doppler resonance linewidths and amplitudes of ^{87}Rb D_2 energy transition line with the laser beam intensity was measured with linearly polarized laser beam precisely by using the laser heterodyne spectroscopy method. To perform the measurements sensitively and accurately, frequency stabilized extended cavity diode lasers, temperature-controlled magnetically shielded ^{87}Rb cell, and temperature-controlled Fabry-Perot interferometer were used. For each of the sub-Doppler saturation resonances, it was investigated at which value the pumping laser beam intensity had the narrowest linewidth and the highest resonance amplitude, and values consistent with the theory were measured. The uncertainty of the measurements is fewer than 1.6 MHz and 0.3 mV for linewidths and amplitudes, respectively. The measurements made are important in terms of laser frequency stability studies and laser applications requirements.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the author.

Authors' Contribution

The author contributed 100% to preparing the article.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The author of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that I do not make any falsification on the data collected. In addition, I declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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