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Araştırma Makalesi / Research Article

Measurement of Double Differential Cross Sections for Electron Impact Ionization of Sulfur Hexafluoride Molecule

Murat YAVUZ[1*], Hüseyin Ali YALIM[1]

[1] *Afyon Kocatepe University, Department of Physics, Afyonkarahisar, Türkiye.*

Sorumlu yazar e-posta: muratyavuz@live.com.* *ORCID ID: http://orcid.org/0000-0002-7262-6681*

hayalim@aku.edu.tr. *ORCID ID: http://orcid.org/0000-0002-9452-7844*

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Electron spectrometry; Electron-Molecule Collision; Double Differential Cross Sections; Sulfur Hexafluoride.

Abstract

Sulfur hexafluoride (SF_6) is a widely used insulator in the industry, but it also has a high global warming potential. Studying electron impact ionization of SF_6, particularly measuring the energy and angular distributions of the collision products, can provide valuable information about the underlying physics of the collision process and the nature of SF_6 molecule. In this study, double differential cross sections (DDCSs) for electron impact ionization of SF_6 have measured using a crossed beam experimental setup. The incident electron beam, with an energy range of 50-350 eV, was directed towards a target gas composed of SF_6, and scattered electrons were detected as a function of the energy and scattering angle. The findings of this study offer significant insights into the molecular structure of SF_6 and will contribute to enhancing the understanding of charged particle interactions involving SF_6.

Sülfür Hekzaflorür Molekülünün Elektron Etkisi ile İyonlaşma İkili Diferansiyel Tesir Kesitlerinin Ölçümü

Anahtar kelimeler
Elektron Spektrometri; Elektron-Molekül Çarpışmaları; İkili Diferansiyel Tesir Kesiti; Sülfür Hekzaflorür.

Öz

Sülfür heksaflorür (SF_6), küresel ısınma potansiyeli olmasına rağmen yalıtkanlık özellikleri nedeniyle endüstride sık kullanılan bir gazdır. SF_6'nın elektron etkisi ile iyonlaşma çalışmaları, özellikle çarpışma sonucu açığa çıkan parçacıkların enerji ve açısal dağılımlarının ölçülmesi, iyonlaşma sürecinin temel fiziksel özellikleri ve SF6 molekülünün yapısı hakkında değerli bilgiler sağlamaktadır. Bu çalışmada, SF_6'nın elektron etkisi ile iyonlaşma olayı için ikili diferansiyel tesir kesiti (DDCS) ölçümleri yapılmıştır. SF_6 molekülü 50-350 eV enerjili elektronlar ile çarpıştırılarak ortaya çıkan elektronlar enerji ve saçılma açısının fonksiyonu olarak dedekte edilmiştir. Bu çalışmanın bulguları, SF_6'ın moleküler yapısı hakkında önemli bilgiler sunmakta olup, molekülün yüklü parçacıklar ile olan etkileşimlerinin anlaşılmasına katkı sağlayacaktır.

1. Introduction

Sulfur hexafluoride (SF_6) is widely utilized in various industrial applications and electrical equipment due to its exceptional insulating properties. It is commonly employed in gas-insulated switchgear, circuit breakers, transformers, and other high-voltage electrical components. SF_6 is also utilized in the production of semiconductors, flat panel displays and electronic devices. Despite its usefulness, SF_6 is a potent greenhouse gas with a global warming potential approximately 23500 times higher than carbon dioxide. Moreover, SF_6 has a long atmospheric lifetime of 3200 years, contributing to environmental concerns and the depletion of the ozone layer (Rabie and Franck 2018, Wang *et al.* 2019). In this sense, there is emerging need to explore replacements and investigate the properties of alternative insulation gases.

The exceptional electrical insulation capabilities of SF_6 arise from its molecular structure and the robustness of chemical bonds between its atoms. It consists of a central sulfur atom surrounded by six fluorine atoms, with fluorine atoms exhibiting high electronegativity. Consequently, the sulfur-fluorine bonds possess strong electron-attracting properties, rendering them resilient even under high-voltage conditions. Furthermore, SF_6 remains stable without undergoing significant chemical reactions at typical temperatures and pressures. These factors collectively contribute to SF_6's capacity to endure high voltages without breakdown (Wang *et al.* 2021).

Crossed-beam experiments offer a powerful and direct approach to measure the differential cross sections for electron impact ionization. By colliding an incident electron beam with atoms/molecules and detecting the resulting outcome electrons at different energies and scattering angles, it is possible to obtain detailed information about the ionization processes and the energy and angular distribution of the ejected electrons (Yavuz *et al.* 2016).

The interaction of electrons with SF_6 molecules leads to complex ionization dynamics, involving multiple scattering and energy transfer processes. Measuring cross sections provide valuable insights into the underlying mechanisms governing these interactions, enabling a deeper understanding of the electronic structure and dynamics of SF_6 and its role in various applications.

As the industrial applications became apparent, experiments focusing on electron-SF_6 collisions were conducted, requiring precise cross-sectional data to comprehend these interactions. A comprehensive summary of previous research in this field can be found in the review by Chrisophorou and Olthoff (2000). Investigations on the total cross section (TCS) of sulfur hexafluoride, as well as the exploration of compounds that can potentially replace it while possessing similar electrical properties, have gained increasing importance in the literature (Goswami and Antony 2014, Joshipura *et al.* 2004, Park *et al.* 2022). Experimental and theoretical studies have focused on the interaction of SF_6 in its gaseous form under pressure with charged particles.

SF_6 is also of interest for understanding molecular structures at a fundamental level due to its highly symmetric nature and investigating electron-molecule interactions. The literature on the excitation of SF_6's vibration levels and resonances, particularly with low-energy electrons is relatively extensive (Fabrikant *et al.* 2005, Fedus 2022, Winstead and McKoy 2004).

In recent years, remarkable research has been conducted using electron momentum spectroscopy (EMS) technique to measure electron momentum profiles of SF_6 molecules (Wang *et al.* 2018, Wang *et al.* 2020, Watanabe *et al.* 2016, Watanabe *et al.* 2019, Zhao *et al.* 2015). These studies aim to investigate the interference effects of the molecule's orbital structure on the electron momentum profile. Due to the nature of EMS technique, these investigations have been performed using high-energy electrons (>1 keV).

The literature on differential cross-section measurement studies in this area is rather limited. While Nixon et al. 2016 and Giardini-Guidoni *et al.* (2008) conducted triple-differential cross-section measurements, the DDCS measurements, which are the focus of this study as well, were only performed in a few spectra in specific sections of the studies conducted by Al-Nasir *et al.* (1996) and Pal *et al.* (2004).

In this study, we present the experimental measurement of double differential cross sections (DDCS) for the electron impact ionization of SF_6 molecules that covers a range of incident electron energies from 50 eV to 350 eV. The obtained data provides crucial insights into the ionization dynamics of SF_6 and its applications in various fields. The results contribute to the fundamental understanding of electron-molecule interactions and can facilitate the development of improved models, simulations, and practical implementations involving SF_6.

2. Materials and Methods

The experimental setup used for electron-molecule collision studies is an electron collision spectrometer. This setup consists of an electron gun, a Faraday cup, a target gas, and two rotatable electrostatic hemispherical deflector energy analyzers equipped with a channel electron multiplier (Dogan *et al.* 2013, Yavuz *et al.* 2014). The whole system is housed in the vacuum chamber which has base pressure of 8.10^{-8} mbar and during the experiment it reaches to $5{,}5.10^{-6}$ mbar.

The electron gun is responsible for generating a well-controlled and focused electron beam. It typically employs cylindrical lenses to control the electron beam parameters, such as energy and focus and it is employed a thermal cathode design and a Wehnelt electrode. The energy of electrons is controlled by adjusting the voltage applied to the cathode, allowing for precise variations of 100 eV in the range of 50 eV to 350 eV with in desired increments. The current of the electron beam, typically ranging from 3 to 4 µA, is measured using a Faraday cup positioned downstream of the gun.

The molecular beam, composed of the target molecules, is produced using a nozzle. The molecular beam is directed towards the interaction region where it intersects with the 2 mm afocal electron beam. In the interaction region, the electron beam collides with the molecules, leading to various processes such as ionization, excitation, and dissociation.

The detection system typically includes electron energy analyzers, which can measure the energy and angular distributions of the scattered or ejected electrons. These analyzers are hemispherical deflector analyzers equipped with channel electron multipliers to amplify electron signals. The electron energy analyzer and Faraday cup are positioned on separate concentric tables outside of the vacuum chamber, allowing them to be rotated independently within the horizontal plane. The channel electron multipliers at the exit of the electron analyzers produce measurable signals, which are amplified and processed to distinguish the true signal from noise. The processed signal is then counted using a dual counter or timer.

Overall, the electron collision spectrometer provides a controlled environment to investigate the dynamics and outcomes of electron-molecule collisions. It enables researchers to study various processes and interactions, contributing to our understanding of molecular physics and chemical reactions.

In this study, we measured the Differential Double Differential Cross Sections (DDCSs) of SF_6 molecules at ranges from 50eV to 350eV electron impact energies for detection angles ranging from 25° to 130°. The energy resolution was below 0.8 eV, and the angular resolution was better than ±1°. To gather data, a series of runs were conducted at various incident electron energies (E_0), ranging from 50eV to 350eV with in 100eV increments. In each run, the DDCSs were measured, considering the energy and angle of the scattered or ejected electrons. Different detection energies were chosen at different E_0 values to examine the homogeneous variation in the experimental accessible energy scale. The data were recorded in counts per second and determined as relative cross section.

3. Results and Discussion

This study focuses on observing the variation in the angular distributions of detected electrons at different energies relative to each other in DDCS measurements. Since the structural changes in the cross section are investigated, the measurements have been normalized with respect to their maximum value for each set. In order to observe the variation smoothly, the data points have been connected using B-Spline interpolation.

The only comparable measurements to this study were performed as part of the study conducted by al-Nasir *et al.* (1996). The comparison demonstrates structurally good agreement except for angular displacement, which can be considered insignificant in terms of examining the variation of cross sections with energy (Figure 1). This comparison serves as a validation of our experimental setup and methodology.

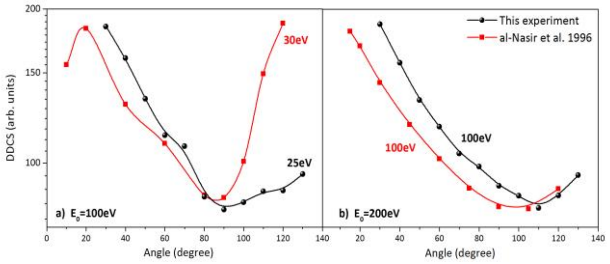

Figure 1. DDCS measurements compared to al-Nasir et al. 1996 for available results.

DDCS measurements for the electron impact ionization of SF_6 molecule for 50eV incident energy are shown in Figure 2.

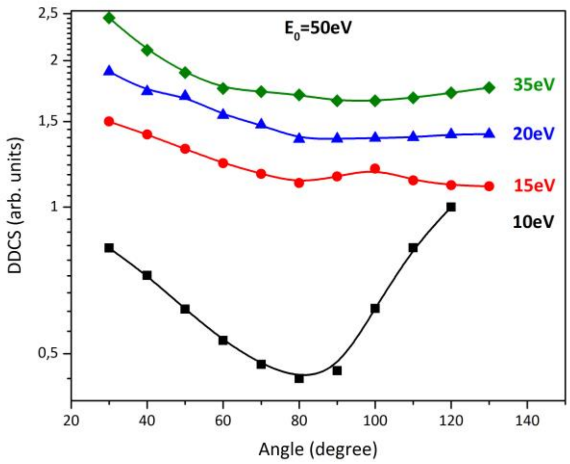

Figure 2. DDCS measurements for 50eV incident energy.

A general decreasing trend is observed in the DDCS values for E_0=50eV as the scattering angle is increased. This trend signifies a decrease in the probability of electron detection at larger angles. This behavior can be explained by the diminished interaction between the incident electrons and the SF_6 molecules, resulting in a lower likelihood of ionization events. It indicates that the scattering process dominates in this region. However, an exception is observed for the detected electrons at 10eV energy, where a minimum is observed at an angle of 80°. This minimum is interpreted as a result of complex ionization events caused by the longer interaction time for slow electrons.

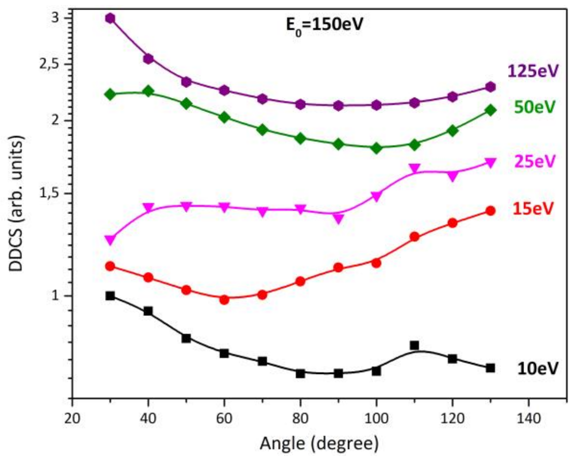

Figure 3. DDCS measurements for 150eV incident energy.

It is worth noting that the electrons detected in the experiment may have undergone scattering or ionization processes. Due to the inherent indistinguishability of these electrons, the measured DDCS values encompass a combined contribution arising from both scattered and ionized electrons. The DDCS results obtained at E_0=150eV exemplify this phenomenon (Figure 3), wherein lower-energy detected electrons exhibit complex variations with increasing scattering angles, while higher-energy electrons demonstrate scattering behavior.

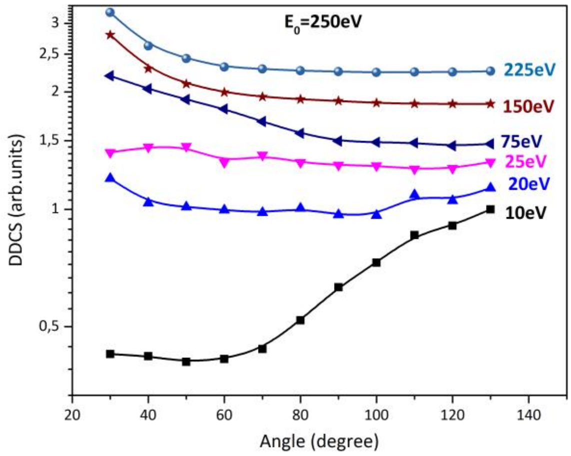

Figure 4. DDCS measurements for 250eV incident energy.

Comparing the DDCS values at E_0=250eV (Figure 4), at higher energies, the cross sections show a smooth decreasing trend, indicating a higher probability of electron scattering. Conversely, as the detection energy decreases, the structure of the DDCS indicates an increasing probability of ionization event.

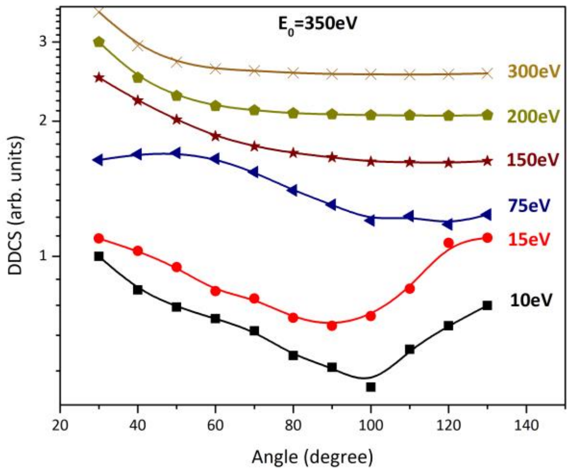

Figure 5. DDCS measurements for 350eV incident energy.

Figure 5 shows the present measurements of DDCS at 350eV incident energy, for various detected electron energies. The dependence of the DDCS values on the detection energy is evident. At lower energies (10eV, 15eV, and 75eV), the cross section values present maxima and minimums, indicating a higher probability of ionization and post collision effects. As the detection energy increases, the DDCS values decrease smoothly with increasing scattering angle, implying probability of scattering process for detected electrons.

4. Conclusion

The DDCS experiments provide crucial insights into the ionization processes occurring in atoms and molecules. These findings are expected to enhance our understanding of the underlying ionization processes and their implications in the broader field of atomic and molecular physics, as well as industries depending on this.

The results of this study contribute to our knowledge of the electron-molecule interaction processes and have implications for various scientific and technological applications. Understanding the ionization behavior of SF_6 is crucial for fields such as plasma physics, gas discharges, and environmental research.

Overall, the DDCS measurements for electron impact ionization of SF6 molecules shed light on the underlying physics and offer valuable information for developing accurate models and simulations. They contribute to the broader understanding of electron-molecule interactions and pave the way for advancements in various research areas.

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