Differential cross sections at 0° and 180° for electron-impact excitation of the $E\ ^3\Sigma_g^+$ state of N_2

G. B. Poparić,* M. D. Vićić, and D. S. Belić
Faculty of Physics, University of Belgrade, Studentski trg 16, P.O. Box 368, 11000 Belgrade, Yugoslavia
(Received 10 April 2002; published 19 August 2002)

Relative differential cross sections at forward and backward angles for excitation of the $E\ ^3\Sigma_g^+$ state of N_2 have been measured in the resonant, near threshold energy region. Measurements are performed by using a double trochoidal electron spectrometer and are calibrated on the absolute scale by simultaneous measurements of this process and vibrational excitation of the ground state of N_2 via $^2\Pi_g$ resonance. The contributions at 0° and 180° are separated by electron beam modulation and time-of-flight detection of scattered electrons. Obtained results confirm directly theoretical predictions of the symmetry of angular distribution of scattered electrons from $^2\Sigma_u^+$ resonance.

DOI: 10.1103/PhysRevA.66.022711 PACS number(s): 34.80.Gs

I. INTRODUCTION

A pronounced resonant contribution to electron-impact excitation of the $E\ ^3\Sigma_g^+$ state of a N_2 molecule, in the near-threshold energy region, was first observed by Heideman *et al.* [1] and confirmed by Ehrhardt and Willmann [2]. Sanche and Schulz [3], in electron transmission measurements, also observed strong resonant threshold excitation. Mazeau *et al.* [4] have determined the energy position of the resonant peak to be 11.90 eV, and attributed it to the core excited shape resonance. Golden *et al.* [5], in a combined transmission and emission experiment, have determined the energy of the peak to be 11.92 eV.

The total cross sections for excitation of the $E\ ^3\Sigma_g^+$ state were estimated by Borst *et al.* [6] in a measurement of the total metastable excitation function. In these measurements the energy position of the peak is located at 12.2 eV, somewhat further from the threshold energy of 11.874 eV, and higher than results from other authors. This discrepancy in energy position is probably due to poor energy resolution, of about 0.6 eV, in Borst *et al.* [6] measurements. The total cross sections have also been determined by Brunger *et al.* [7] in their measurements of metastable nitrogen molecule production. Zubek [8] has performed absolute cross section measurements by using a technique similar to Brunger *et al.* [7].

As can be seen from the review of Brunger and Buckman [9], there is a lack of systematic differential cross section measurements of this process in the region from threshold to 15 eV. This region is very rich with resonances and measurements of differential cross sections would help to understand these resonant mechanisms of excitation. Only a few authors investigated the symmetry of the resonance just above the threshold energy. Sanche and Schulz [3] have proposed the resonant state to have Σ or Π symmetry by considering its electron configuration. They have proposed the *p*-partial wave to be involved in the scattering process. Mazeau *et al.* [4] have measured its relative angular distribution in the range from 15° to 120°. Obtained angular dependence at intermediate angles confirmed particularly its $p\sigma$ symmetry. This symmetry was theoretically proposed by investigations of Read [10] considering resonant electron-molecule scattering angular distributions. Proposed $^2\Sigma_u^+$ symmetry of the resonance is in agreement with the angular dependence obtained by Mazeau *et al.* [4]. Its extrapolation with the theoretically proposed model function of Read [10] is symmetric around its minimum at 90°.

The most recent measurements of this process in the near threshold energy region are performed by Poparić *et al.* [11] using a crossed beams double trochoidal electron spectrometer. A near-threshold resonant contribution to the differential cross section (DCS) is studied with a high efficiency and high energy resolution. The absolute values of the DCSs and the total cross sections in this energy region were obtained by using theoretically predicted angular distribution of inelastically scattered electrons. In the present work we have developed a method to measure separately DCS at critical angles of 0° and 180°, in order to complete and normalize previously measured angular distribution.

II. EXPERIMENTAL SETUP

The present measurements are performed by using a modified crossed beams double trochoidal electron spectrometer, described earlier [12]. Due to the presence of a magnetic field, needed for trochoidal electron selectors operation, in the originally designed apparatus the detected signal consists of the sum of electrons inelastically scattered at 0° and 180°. Electrons scattered at 0° travel straight to the analyzer system and to detector, see Fig. 1. On the other side, inelastic electrons scattered at 180° move backward along the incident electron beam, are reflected on the potential barrier of the monochromator, reach again the collision region and from there follow the same path as the 0° electrons. Thus they travel a longer distance and need a longer time to reach the detector. This fact is used to separate these two groups of electrons by recording their time-of-flight spectra. For this kind of measurements the incident electron beam from the monochromator needs to be pulsed in an appropriate way. A similar technique has been used earlier by Allan [13] and Asmis and Allan [14].

Electron beam chopping is enabled by introduction of a

*Electronic address: gopop@ff.bg.ac.yu

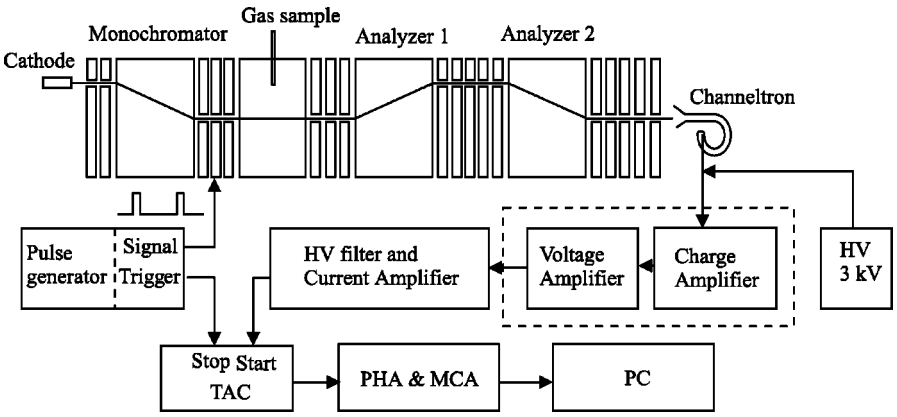

FIG. 1. Schematic diagram of the spectrometer including electronic circuits of the time-of-flight resolved measurements.

square shaped asymmetric pulse signal of 1.96 MHz from a 33 MHz clock. Square pulses of 30 ns, 2 V high, are separated by 480 ns. This signal is superimposed on the voltage of the second electrode after throchoidal electron monohromator (TEM), as shown in Fig. 1. The potential of this electrode keeps the electron beam on during 30 ns of the pulse time and off for the rest of the time. Since the collision can occur only during the ''pulse on'' time, the rising time of the pulses can be used as a trigger of the time-to-amplitude converter (TAC). In fact, this signal is used as a stop trigger of the TAC. For the start of the TAC the signal from the channeltron is used. Therefore each recorded event represents the time difference between electron detection and the next pulse coming from the generator. This configuration has no influence on the results, but increases the detection efficiency. The signal from the channeltron is processed by a fast charge amplifier, voltage amplifier, and high-voltage filter. Obtained pulses are used for the start signal of the TAC. The signal from the TAC is loaded to a pulse-height analyzer (PHA) and multichannel analyzer (MCA). Obtained time-of-flight spectra are analyzed by an on-line computer. The principal scheme of this arrangement is also shown in Fig. 1.

III. RESULTS AND DISCUSSION

Relative differential cross sections at forward and backward angles for electron impact excitation of $v=0$ vibrational level of the $E\ ^3\Sigma_g^+$ state of N_2 have been measured at an incident electron energy of 11.94 eV, at the resonant peak just above threshold. Besides its physical importance, this energy region is chosen because it gives inelastically scattered electrons with small residual energy, below 0.1 eV. Such a low residual energy leads to a significant time difference between forward and backward scattered electrons and thus enables their separation. The relative ratio of electrons scattered at 0° and at 180° has been obtained in the pulsed mode of spectrometer, by measuring time-of-flight spectra of scattered electrons. Typical results of our time resolved measurements at an incident energy of 11.94 eV and residual energy of 0.067 eV, via the $^2\Sigma_u^+$ resonance, are shown in Fig. 2. As it can be seen from the figure, the spectrum consists of two distinct peaks on the time scale. The first narrower one, at 300 ns, belongs to electrons scattered at 0°, directly to the analyzer and detector. The second, broader peak, around 400 ns, corresponds to electrons scattered at 180°, which are reflected by the monochromator potential barrier, and detected somewhat delayed in time. The ratio of differential cross sections at 0° and at 180° is proportional to the ratio of integrals of events of these two peaks. The obtained ratio is equal to 1, within the estimated error of 5%. Similar measurements are performed at several energies in this energy region and obtained results are in very good agreement with each other. For higher electron energies, however, residual energy is also higher, the time difference between forward and backward scattered electrons becomes shorter and two peaks in the spectrum are closer, making their separation imposible. This fact can be overcome by the introduction of a decelerating electrode system for backward scattered electrons in front of the collision region. This has been sucessfully demonstrated by Asmis and Allan [14].

Obtained experimental results are in a very good agreement with the theory and for the first time directly confirm theoretically predicted angular distribution of this resonance to be fully symmetric around 90°. This fact is used to normalize differential cross sections. Absolute value of the differential cross section at 0°, for this particular electron energy, is obtained by simultaneous measurements of this process and vibrational excitation of the ground state of N_2 via $^2\Pi_g$ resonance [11,15]. Angular distribution from the $^2\Pi_g$ resonance is also symmetric around 90°, furthermore two considered angular distributions have a very much similar form. These measurements are performed under the same experimental conditions and for the same scattered electron

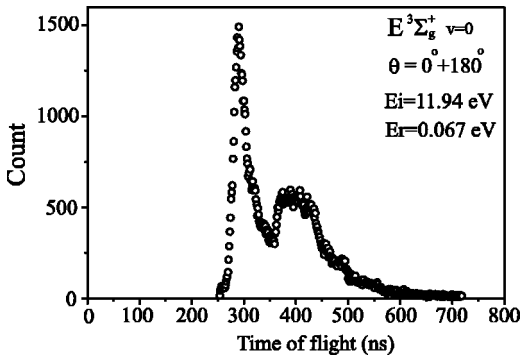

FIG. 2. Relative count rate as a function of the time of flight of scattered electrons.

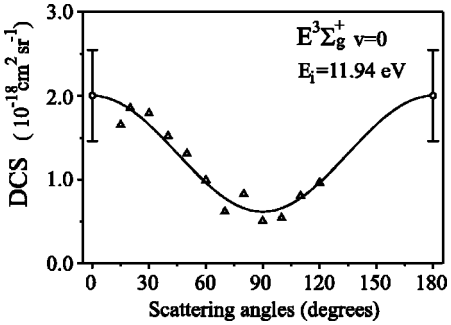

FIG. 3. The absolute differential cross sections for excitation of the $E\ ^3\Sigma_g^+$ state of N_2 at 11.94 eV: ○, present results and Δ, Mazeau *et al.* [4].

residual energy. Obtained absolute differential cross section values for excitation of the $E\ ^3\Sigma_g^+$ state of N_2 at 0° and 180° are shown in Fig. 3.

Relative differential cross sections of the $E\ ^3\Sigma_g^+$ state of N_2, via $^2\Sigma_u^+$ resonance, at 11.90 eV, have been measured earlier by Mazeau *et al.* [4] for scattering angles from 15° to 120°. The form of these measurements is also in a good agreement with the theoretical predictions of Read [10] for the $^2\Sigma_u^+$ resonance. The best fit of the results of Mazeau *et al.* we have obtained in a simple form with the following expression: $A(1+2\cos^2\theta)$, where θ is the scattering angle. The constant A is normalized to our results at 0° and 180°. The obtained fit is also shown (full line) in Fig. 3. In this way the relative measurements of Mazeau *et al.* [4] are also put on the absolute scale. Obtained results are in a very good agreement between each other, up to the form, over a wide range of angles and enable further determination of the integral cross sections.

The estimated errors of the measured differential cross sections are 27%, which includes the uncertainty of a ground state excitation cross section of 20%, relative to which these cross sections are normalized, and statistical error of 2%. A remaining error of 5% belongs to the uncertainty of the separation procedure of the two groups of electrons in the time-of-flight spectra.

IV. CONCLUSIONS

The relative differential cross section at forward and backward angles for excitation of the $E\ ^3\Sigma_g^+$ state of N_2 was measured in the resonant near threshold energy region. The contributions at 0° and 180° are resolved by employing the time-of-flight technique. Theoretically proposed, symmetric angular distribution of scattered electrons via $^2\Sigma_u^+$ resonance has been directly confirmed by this experiment.

ACKNOWLEDGMENT

This work was supported in part by the Ministry of Science and Technologies of the Republic of Serbia.

[1] H.G.M. Heideman, C.E. Kuyatt, and G.E. Chamberlain, J. Chem. Phys. **44**, 355 (1966).
[2] H. Ehrhardt and K. Willmann, Z. Phys. **204**, 462 (1967).
[3] L. Sanche and G.J. Schulz, Phys. Rev. A **6**, 69 (1972).
[4] J. Mazeau, R.I. Hall, G. Joyez, M. Landau, and J. Reinhardt, J. Phys. B **6**, 873 (1973).
[5] D.E. Golden, D.J. Burns, and V.C. Sutcliffe, Phys. Rev. A **10**, 2123 (1974).
[6] W.L. Borst, W.C. Wells, and E.C. Zipt, Phys. Rev. A **5**, 1744 (1972).
[7] M.J. Brunger, P.J.O. Teubner, and S.J. Buckman, Phys. Rev. A **37**, 3570 (1988).
[8] M. Zubek, Chem. Phys. Lett. **146**, 496 (1988).
[9] M.J. Brunger and S.J. Buckman, Phys. Rep. **357**, 215 (2002).
[10] F.H. Read, J. Phys. B **1**, 893 (1968).
[11] G. Poparić, M. Vićić, and D.S. Belić, Phys. Rev. A **60**, 4542 (1999).
[12] M. Vićić, G. Poparić, and D.S. Belić, Rev. Sci. Instrum. **69**, 1996 (1998).
[13] M. Allan, J. Electron Spectrosc. Relat. Phenom. **48**, 219 (1989).
[14] K.R. Asmis and M. Allan, J. Phys. B **30**, L167 (1997).
[15] M. Vićić, G. Poparić, and D.S. Belić, J. Phys. B **29**, 1273 (1996).