ATOMIC COLLISION PROCESSES

and

LASER BEAM INTERACTIONS with SOLIDS

M. Milosavljević and Z. Petrović
(Editors)

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PREFACE

This book contains articles of invited lectures and progress reports from the XVI Summer School and International Symposium on the Physics of Ionized Gases (16th SPIG), held from 25-28 September 1993, in Belgrade, Yugoslavia.

The programme of 16th SPIG covered the following topics: Atomic Collision Processes, Particle and Laser Beam Interaction With Solids, Low Temperature Plasmas and General Plasma. The speakers (invited lectures and progress reports) were proposed to and selected by the Scientific Committee. This volume includes the papers dealing with atomic collision processes and laser beam interactions with solids.

We are indebted to the speakers for participating at the Conference and for preparing their manuscripts for this book. We hope that the book will be a valuable source of information in the considered topics.

On behalf of the Scientific and the Organizing Committees we would like to express our gratitude to all individuals, bodies and institutions who have helped and supported the organization of 16th SPIG and preparation of this book.

Editors

Atomic Collision Processes and
Laser Beam Interactions with Solids

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ELECTRON IMPACT CROSS SECTIONS FOR SODIUM AND CADMIUM ATOMS*

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1. INTRODUCTION

Experimental studies of angular distributions of electrons scattered by atoms date from early 1930's with the work of Arnot [1] and Mohr and Nicoll [2]. In the 1960's and 1970's new experiments with metal vapour targets were performed using monochromatic electron beams. However, since that time, absolute values of differential (in the electron scattering angle) cross sections have been scarce in the literature. Especially, for direct excitation there are very few data.

Differential cross section $\sigma(\theta)$ for electron scattering by atom represents a fundamental observable characterizing collisional process. It is equal to the number of electrons scattered per unit time into an element of solid angle $d\Omega$ in the direction (θ,ϕ) from an unpolarized beam, by unpolarized target atom. By this definition, both elastic scattering and excitation of particular energy level are included. Integrating over solid angle one obtains integral cross section:

$$Q_I=2\pi\int_0^{\pi}\sigma(\theta)\sin\theta d\theta \tag{1}$$

or higher-order energy-dependent integrated cross sections as the momentum transfer or diffusion cross section:

$$Q_M=2\pi\int_0^{\pi}\sigma(\theta)[1-(1-\frac{\Delta E}{E_0})^{1/2}\cos\theta]\sin\theta d \tag{2}$$

where ΔE is the excitation energy, and the viscosity cross section:

$$Q_V=2\pi\int_0^{\pi}\sigma(\theta)[1-(1-\frac{\Delta E}{E_0})\cos^2\theta]\sin\theta d\theta \tag{3}$$

Electron-atom collisional processes have been reviewed in several reports: Bransden and McDowell [3] reviewed theoretical and experimental data for light atoms at intermediate electron energies; Trajmar and Williams [4] and Trajmar [5] reviewed electron - metal atom collision cross sections; Hanne [6] reviewed spin effects in inelastic

* This Progress Report was presented at XV SPIG'90 in Dubrovnik, but was not included in the book of *Physics of Ionized Gases - 1990*. The Report is updated in order to cover present status of the investigation.

collisions; Andersen *et al.* [7] reviewed collisional alignment and orientation parameters; Kessler [8] reviewed electron-polarization phenomena; McCarthy and Weigold [9] reviewed theoretical treatments in electron-atom scattering; Madison [10] reviewed perturbation series method; Bartschat [11] reviewed recent progress in close-coupling theory. Also a whole issue of *Advances in Atomic, Molecular and Optical Physics* [12] is devoted to the cross section measurements.

The motivation for this study of electron - metal atom collisions was to provide a basic set of collisional data which can serve to both experimentalists and theoreticians in this field. Crossed beam technique, used in our experiment, became standard way to provide both high energy and angular resolution data which can serve as a reference or normalization guides to some novel and more refined techniques recently developed in electron - atom collisions. Let us mention just three different approaches: *i)* experiments with polarized electrons and atoms [8 and references therein], *ii)* experiments utilizing atom recoil technique [13] and *iii)* measurements of excitation cross sections as a function of changes in spin and orbital angular momenta [14]. From a theoretical point of view it is a challenge for each particular approach, let us mention close-coupling (CC) and distorted-wave (DW) approximations to resemble the shapes and the magnitudes of all measured quantities.

The report begins with the brief description of the apparatus. This is followed by a few details of the experimental procedure. Finally, results of measurements on sodium and cadmium atoms in the intermediate impact energy range and wide angular range are presented.

2. APPARATUS

Scattering experiment is performed in crossed electron-atom beam arrangement. An electron with the impact energy E_o and wave number $\mathbf{k}_o$ is scattered by an unpolarized atom into the angle θ with the energy E_n and wave vector $\mathbf{k}_n$. Scattering process is characterized by cross section which is time independent probability for specific process to occur. It is energy dependent value. In this experiment scattered electrons are detected as a function of impact energy, scattering angle and energy loss. The apparatus described earlier [15,16] has been modified for the work with metal vapours.

Schematic diagram of the electron spectrometer is shown in figure 1. A monochromator consists of thoriated tungsten hair-pin filament, gold-plated cylinders and lenses and molybdenum hemispherical selector. It produces well collimated (± 1°) and monochromatic electron beam (30 meV, 1-10 nA) which crosses perpendicularly effusive atomic beam produced by Knudsen type oven. Scattered electrons have been analyzed in energy and angle by hemispherical analyzer and detected by electron single channeletron multiplier. The monochromator is fixed in position and the analyzer can rotate from -30° to +150°. what is large angular range which allow us to detect minima in $\sigma(\theta)$ at large scattering angle.

Electron optics is isolated from the main vacuum chamber and differentially pumped to avoid metal deposition on insulators and to establish constant conditions for electron beam. Impact energies range from 3.4 to 85 eV. Spectrometer was ran in energy-loss mode and impact energy mode. Signal is processed by standard multiscalling technique.

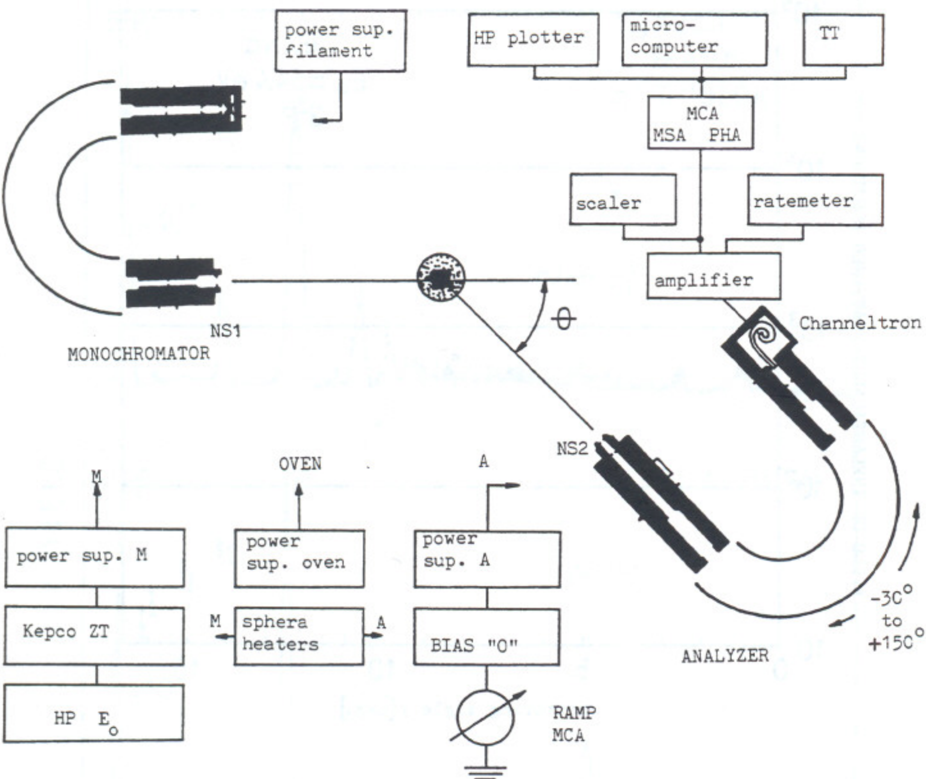

Fig. 1. Schematic diagram of the electron spectrometer

3. EXPERIMENTAL PROCEDURE

The scattering intensity distribution as a function of θ was measured by adjusting the detector to record only those electrons with an energy loss corresponding to a particular transition. The measured scattering intensity distribution was converted to relative differential cross sections by utilizing the proper effective path length correction factor [17].

Electron impact energy was determined from energy dependence of elastically scattered electrons by Cd atoms. Several resonances were observed and the first one was attributed to the first excitation channel 5 ^3P_o in Cd. For the sodium measurements we have been looking for the appearance of the 3 ^2P excitation with the well known threshold at 2.102 eV. Energy scale could be determined within ± 0.2 eV.

Actual zero scattering angle was determined from the symmetry at positive and negative scattering angles. In figure 2 is shown the symmetry of these intensities.

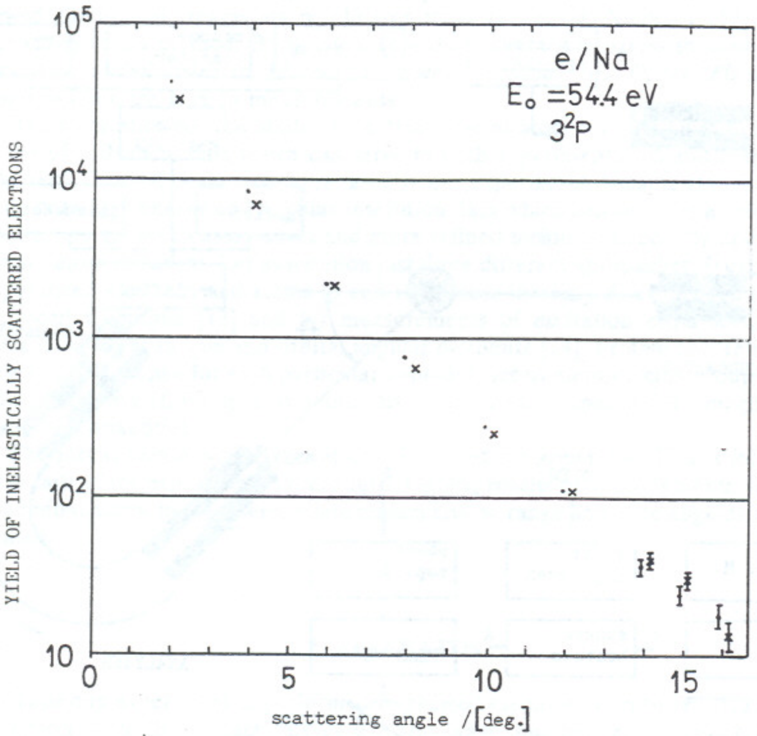

Fig. 2. Yield symmetry for inelastic electron scattering at positive (•) and negative (x) scattering angles

Energy resolution of 45 meV was obtained in the experiment. That allow us to distinguish $3\ ^2D$ and $4\ ^2P$ states in sodium or many separate transitions in cadmium.

Atomic beam pressure was kept low enough to avoid any double scattering which can lead to erroneous determination of angular distribution. In figure 3 an example of the energy loss spectra obtained at two different oven temperatures (T = 520 K and 610 K) is shown. At high temperature double scattering process is significantly pronounced at the position of twice the resonant transition energy.

Experimental angular resolution also effects $\sigma(\theta)$ measurements. We measured spatial electron distribution and we differ the distances of nozzle from the interaction region (1.5, 2 and 3 mm). From these measurements and from the acceptance angle of the analyzer we estimate the angular resolution to be 1.5°.

To determine relative intensity ratios between different transitions it was necessary to obtain energy transmission of the analyzer. Rather than a single curve it is an area determined by tuning conditions. In figure 4, an example at 20 eV impact energy is shown.

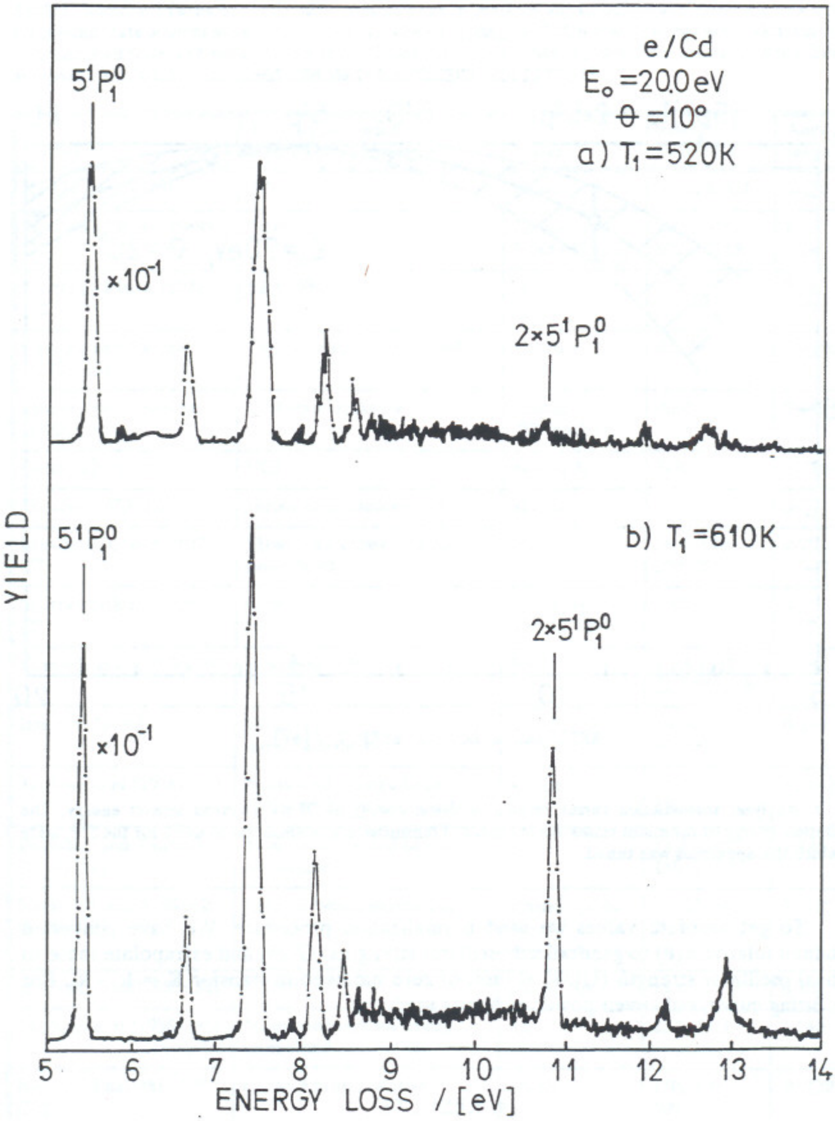

Fig. 3. Electron energy loss spectra for Cd atom at *a)* low, and *b)* high oven temperature. At *b)* a double scattering process is significantly pronounced at the position of twice the resonant transition energy.

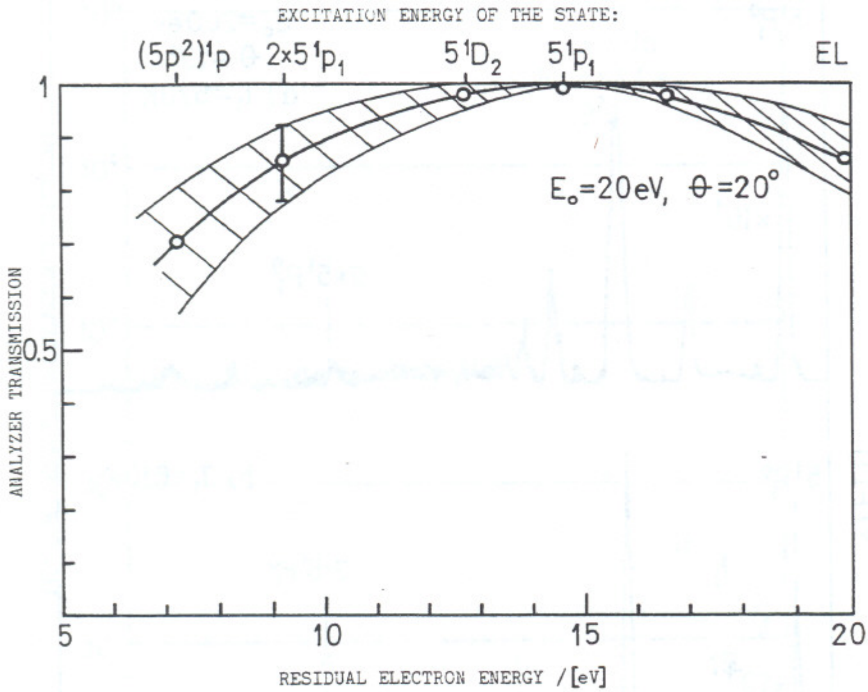

Fig. 4. Analyzer transmission versus residual electron energy at 20 eV electron impact energy. The excitation energy of cadmium states are indicated. Transmission is normalized to unity for the 5^1P_1 state at which the apparatus was tuned.

To get absolute values we used normalization procedure. We have converted obtained relative $\sigma(\theta)$ to generalized oscillator strengths (GOS) and extrapolate these to optical oscillator strength (OOS) at limit of zero momentum transfer $\mathbf{K} = \mathbf{k}_n - \mathbf{k}_o$. For the fitting curve, only even power of **K** was used.

4. RESULTS

A. ELECTRON-SODIUM SCATTERING

Differential cross sections for elastic scattering and the excitation of the 3^2P, 4^2S 3^2D and 4^2P states were determined. Electron impact energies were 54.4, 20, 10 and 5 eV. The results have been previously partially presented [18,19]. A summary of related experimental and theoretical work on electron impact differential cross sections, $\sigma(\theta)$, for the sodium atom reported by several other authors is detailed in table 1.

Table 1. Summary of experimental and theoretical work on electron impact differential cross sections, $\sigma(\theta)$, for ground state sodium atom. *CCn*, *n* channel close coupling; *nCCO*, *n* coupled-channel optical theory; *DW*, distorted-wave; *PO*, polarized orbitals; *CI*, configuration interaction; *SBA*, *FBA*, second and first Born approximation; *GOS*, generalized oscillator strength.

Author	Type of experiment / theoretical approach	States	Energy range [eV]	Angular range [°]
Karule (1965) [20]	PO	elastic	0.1, 0.6, 1.4	0-180
Hertel and Ross (1969) [21]	GOS	3p, 4s, 3d, 4p, 5s,4d+4f,5p,6s	40.5, 50.5, 67.5, 100.5	0
Hertel and Rost (1971) [22]	SBA, FBA	4s	25-500	0-20
Gehenn und Reichert (1972) [23]	Crossed beam, normalized	elastic	0.5-20	25-150
Moores and Norcross (1972) [24]	CC4 state exchange	elastic, 3^2P $m_l=0,\pm1$	0.1-5	0-180
Carse (1972) [25] .	CC2	elastic, 3p	5-30	20-180
Walters (1973) [26]	frozen core Glouber, FBA	elastic, 3p	54.4	0-50
Shuttleworth *et al* (1977) [27]	Modulated crossed beam, normalized	3p	54.4, 100, 150, 250	0-20
Shuttleworth *et al* (1977) [28]	GOS	4s, 3d, 4p, 5s, 4d+4f, 5p	7-500	0
Kennedy *et al* (1977) [29]	unitarized DWPO	3p	5.1,8.1, 12.1, 22.1,54.4,100	0-180
Issa (1977) [30]	CC2; impact parameter	elastic, 3p	10-50; 50-200	0-180
Teubner *et al* (1978) [31]	Modulated crossed beam, normalized; optical model	elastic	54.4, 75, 100, 150	12-140
Buckman and Teubner (1979) [32]	Modulated crossed beam, normalized	3p	54.4, 100, 150, 217.7	2-145
Srivastava and Vušković (1980) [33]	Crossed beam, normalized	elastic, 3p, 4s, 3d+4p, 4d+4f+5p+5s	10, 20, 40, 54.4	10-120
McCarthy *et al*(1985)[34]	CCO	elastic, 3p	54.42	0-180
Teubner *et al* (1986) [35]	Modulated crossed beam, normalized	3p	22.1, 54.4	2-140
Rao and Bharathi (1987) [36]	Crossed beam, relative	elastic	150, 300, 400	30-120
Mitroy *et al* (1987) [37]	FBA, static-exchange, CC2, CC4, FBA-CI, CC4-CI, CC5-XC (core excitation)	elastic, 3p, 4s, 3d	5,10,20, 22.1, 54.4, 100, 150, 217	0-180
Allen *et al* (1987) [38]	Modulated crossed beam, norm.; complex phaseshift	elastic	54.4	9.5-142.5

Oza (1988) [39]	CC4	elastic	10	0-180
Gien (1988) [40]	modified Glouber	elastic	100-500	5-160
Msezane *et al* (1988) [41]	CC2 - CC6	elastic, 4s	5-100	0-140
Лендьел *et al* (1988) [42]	CC	elastic	1.92, 2.0, 2.092	0-180
Marinković (1989) [18]	Crossed beam, normalized	elastic, 3p, 4s, 3d, 4p	5, 10, 20, 54.4	2-150
Balashov *et al* (1989) [43]	DW optical potential	elastic, 3p	20, 22.1, 54.4, 75, 100	10-160
Han *et al* (1990) [14]	deconvolution from recoil shifted fluorescence spectrum	$3S(M_S=1/2)\rightarrow 3P_{3/2}(M_J)$	2.6, 3.1, 3.6	0-180
Jiang *et al* (1990) [13]	atom recoil	3p	10	1-20
McCarthy *et al*(1991)[44]	CC4, CC8, 8CCO	elastic, 3p	20	0-180
Bray *et al* (1991) [45]	3CCO, CC3	elastic, 3p	10, 20, 22.1, 40, 54.4, 100	0-180
Bray *et al* (1991) [46]	1CCO	elastic	20, 22.1, 54.4, 100	0-180
Marinković *et al* (1992) [19]	Crossed beam, normalized	elastic, 3p, 4s, 3d, 4p	10, 20, 54.4	2-150
Madison *et al* (1992) [47]	second order DW	elastic,3p,4s,4p	10-150	0-180
Lorentz and Miller (1992) [48]	Crossed beam, normalized	elastic, 3p	20, 22.1, 54.4, 100,150	1-130
Ying *et al* (1993) [49]	atom recoil	3p	2.3, 2.4, 2.5, 2.6, 3.0, 3.3	1-60
Trail *et al* (1994) [50]	CC4-CC11, R-matrix	elastic, 3p, 4s, 3d, 4p	1.0 - 8.6	0-180
Msezane *et al* (1994) [51]	GOS	3p	10, 20, 54.4	0-20

The resonant excitation and the elastic scattering at the largest measured energy of 54.4 eV (2 Hartree units) have been extensively studied by many authors experimentally and theoretically. Recent measurements of Lorentz and Miller [48] agree well with the 3CCO calculations by Bray *et al* [45], except that second observed minimum in $\sigma(\theta)$ is deeper then the calculations predict. In figure 5 is shown the review of the 3^2P excitation $\sigma(\theta)$.

All shown experiments are the relative measurements which utilized different normalization procedure to get absolute scale. Teubner's and our measurements are normalized by extrapolation to the experimentally observed OOS. Srivastava and Vušković normalized their data on the Enemark and Gallagher's [52] measurements of integral cross sections which are also normalized to the Born cross sections at high energies. Measurements by Lorentz and Miller [48] are normalized on integral cross section obtained by Mitroy *et al* [37] CC4 calculations. Here are presented three other theories, covering the whole angular range - Balashov *et al* [43], DW approximation with a phenomenological optical potential with the inclusion of the imaginary part of the potential, Bray *et al* [45], 3CCO calculations and Madison *et al* [47], second order DW theory.

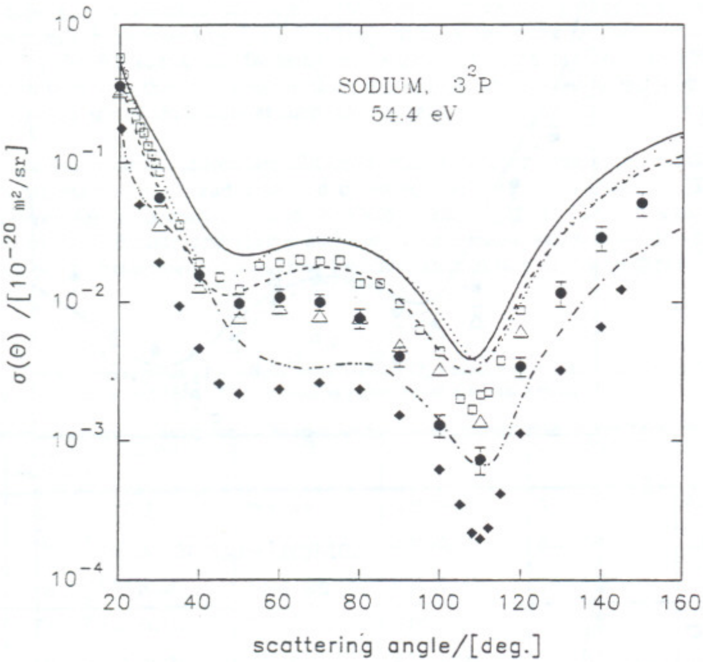

Figure 5. Differential cross sections for the 3^2P at 54.4 eV: ●, present (absolute error indicated): Δ, Srivastava and Vušković [33]; □, Lorentz and Miller [48]; ♦, Buckman and Teubner [32]; ...., Mitroy *et al* [37]; —••, Balashov *et al* [43]; --, Bray *et al* [45]; —, Madison *et al* [47].

Although the general shapes of all the presented curves are similar, there is significant difference in the magnitude at large scattering angles. The discrepancy among experiments could arise due to: *i)* different normalization procedure, *ii)* different angular resolution, *iii)* presence of double scattering process.

For the elastic scattering at the same energy agreement between measurements by Lorentz and Miller [48] and 3CCO calculations by Bray *et al* [45] is even better than for the 3^2P excitation.

At 20 eV impact energy, agreement between experiment and theory is excellent for the 3^2P excitation and very good for elastic scattering, except that the second minimum is shifted toward larger angles in both CC4 and CCO [37,45] and DW [47] calculations. It would be useful to determine more precisely the position of the first minimum about 40° as it is very sensitive test for different calculations. Comparison among different experimental and theoretical values is shown in figure 6.

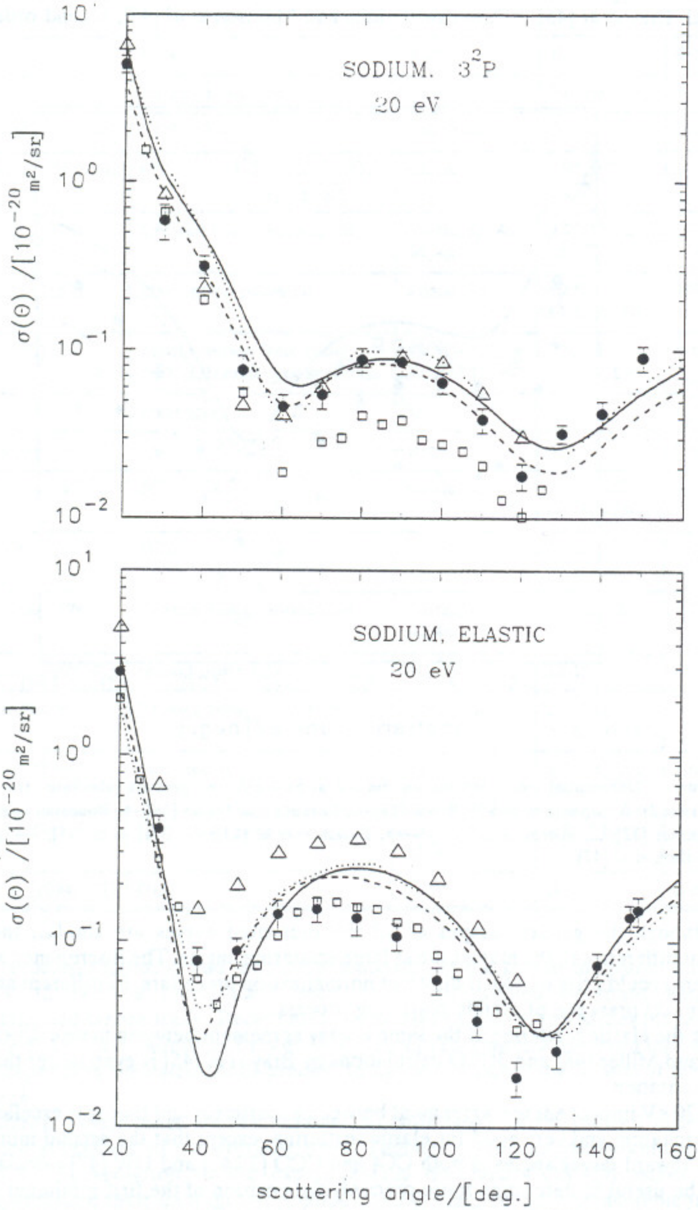

Figure 6. Same as fig.5. except for 20 eV. *a)* The 3^2P excitation, *b)* elastic $\sigma(\theta)$.

At 10 eV our experimental results for the 3^2P excitation are lower at intermediate angular range then the predictions of CC and CCO [37,45] and DW [47] theories, as well as experiment [33]. Also there are indices of shallow minimum at 130° which theories do not recognize, except CC4 [37] calculations with the minimum placed around 160°.

Low energy electron collisions with sodium from the ground state has been comprehensively reviewed by Trail *et al* [50]. At 5 eV there are no other experimental results for the 3^2P excitation. By using our normalization on the OOS procedure, we obtain $\sigma(\theta)$ values that are smaller than theoretical ones, what might indicate that normalization is not applicable at such low energies.

Integrated cross sections are obtained from measured differential cross sections after extrapolation to 0° and 180° and by using formulae 1-3. In table 2 results are summarized for the normalization to the OOS of the 3^2P state, The ratios of the cross section of the 3^2P state and elastic and the other excited states were determined in separate set of experiments accounting for the transmmition of the analyzer.

Table 2. Integrated cross sections: Q_I - integral cross section, Q_M - momentum transfer cross section, Q_V - viscosity cross section, in units of 10^{-20} m^2. Values in parentheses are total errors.

Energy / [eV]	Cross section	Elastic	3^2P	4^2S	3^2D	4^2P
	Q_I	13.5 (3.3)	29.4 (4.8)	0.72 (0.14)	3.17 (0.88)	0.47 (0.14)
10	Q_M	0.67 (0.16)	4.11 (0.69)	0.20 (0.05)	0.84 (0.23)	0.16 (0.05)
	Q_V	0.89 (0.23)	7.24 (1.20)	0.30 (0.06)	1.38 (0.38)	0.24 (0.07)
	Q_I	9.20 (1.34)	35.6 (7.0)	1.10 (0.23)		
20	Q_M	1.32 (0.22)	3.07 (0.56)	0.20 (0.04)		
	Q_V	1.02 (0.17)	4.95 (0.87)	0.27 (0.06)		
	Q_I	4.18 (0.65)	19.8 (3.0)	0.63 (0.12)	1.24 (0.22)	0.68 (0.14)
54.4	Q_M	0.74 (0.12)	0.69 (0.11)	0.079 (0.016)	0.074 (0.014)	0.048 (0.010)
	Q_V	0.45 (0.07)	0.98 (0.15)	0.078 (0.015)	0.11 (0.02)	0.069 (0.014)

B. ELECTRON-CADMIUM SCATTERING

Differential cross sections for elastic scattering and excitation of the 5^3P_o, 5^3P_1, 5^3P_2, 5^1P_1, 6^3S_1, 6^1S_o, $6^3P_{o,1,2}$, 5^1D_2, 6^1P_1, 7^1S_o, $6^1D_2+7^1P_1$, 8^1S_o and $7^1D_2+8^1P_1$ states were measured. Impact energies were 85, 60 , 40, 20, 15, 10, 6.4 and 3.4 eV. To our knowledge these are the first measurements of the $\sigma(\theta)$ of the exited states. The results have been previously partially presented [18,17]. A summary of related experimental and theoretical work on electron impact differential cross sections, $\sigma(\theta)$, for the cadmium atom reported by several other authors is detailed in table 3.

Table 3. Summary of experimental and theoretical work on electron impact differential cross sections, $\sigma(\theta)$, for ground state cadmium atom. *CCn, n* channel close coupling; *nCCO, n* coupled-channel optical theory; *DW,* distorted-wave; *PO,* polarized orbitals; *SBA, FBA,* second and first Born approximation; *GOS,* generalized oscillator strength.

Author	Type of experiment / theoretical approach	States	Energy range [eV]	Angular range [°]
Childs and Massey (1933) [53]	Crossed beams, relative	elastic	4, 8, 13, 18, 23, 28, 38, 48	25-130
Newell *et al* (1971) [54]	GOS	5^3P, 5^1P, 6^1S, 5^1D, 6^1P, 7^1S, 6^1D, 7^1P, 8^1P	60, 75, 85, 100, 150	0
Gregory and Fink (1974) [55]	Dirac equ. with static potential			
Nogueira *et al* (1987) [56]	Crossed beams, normalized	elastic	60, 75, 85, 100, 150	10-70
Pangatiwar and Srivastava (1989) [57]	optical potential			
Nahar (1991) [58]	Dirac equ. with model potential	elastic	6.4 - 300	0-180
Marinković *et al* (1991) [17]	Crossed beams, relative	elastic, 5^3P_0, 5^3P_1, 5^3P_2, 5^1P_1, 6^3S_1, 6^1S_0, $6^3P_{0,1,2}$, 5^1D_2, 6^1P_1, 7^1S_0, $6^1D_2+7^1P_1$, 8^1S_0, $7^1D_2+8^1P_1$	3.4 - 85	2-150
Madison *et al* (1991) [59]	first order DW	elastic, 5^3P_1, 5^3P_2, 5^1P_1, 5^1D_2, 6^1S_0, 6^1P_1	20 - 85	0-180
Srivastava *et al* (1992) [60]	RDW	5^3P_0, 5^3P_1, 5^3P_2, 5^1P_1	20 - 85	0-180
McEachran and Stauffer (1992) [61]	RDW	elastic	3.4, 6.4, 10	0-180
Srivastava *et al* (1992) [62]	RDW	5^1D_2, 5^3D_1, 5^3D_2, 5^3D_3	20 - 100	0-180
Ozimba *et al* (1994) [63]	GOS	5^1P_1	6.4, 10, 20, 40, 60, 85	0-20

The curves for relative elastic $\sigma(\theta)$ at these energies show good agreement in shape when compared with other theories and experiments. In order to obtain absolute values of differential cross sections one should utilize normalization. The choice of best normalization procedure will be the subject of further investigation.

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