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DIFFERENTIAL CROSS SECTIONS FOR ELASTIC SCATTERING OF ELECTRONS ON ATOMS

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1. INTRODUCTION

Differential cross section determination is a way to obtain informations on values possessing anisotropy relative to the scattering angle. Results of the relative differential cross section measurements give only qualitative insight into the process of atomic particles interaction. The determination of absolute cross section is much more difficult, since it requires additional conditions to be satisfied by the measuring device. Nevertheless, the results obtained in this way yield quantitative measure of the investigated physical process.

The usual final product of the scattering experiment is a differential spectrum of the number of scattered electrons which have lost a certain amount of energy during the collision. If the absolute cross section of one of these scattering processes,appearing as a separate peak in the spectrum, is known, then it is possible to obtain data on absolute cross sections of every separate resolved transition by comparing it with the value of the known cross section. Therefore it is not necessary to determine experimentally the absolute value of the cross section for each process occuring during the electron-atom collision. The most convenient peak of the spectrum for calibration purposes is the peak due to elastic scattering. In inert gases it is separated from the first inelastic transition peak for several electronvolts. Namely, the measured absolute values of the elastic scattering cross sections is usually used as a calibration standard in determining inelastic cross sections which are, as a rule, measured relatively.

The recently published review paper by Kieffer(1) includes all the so far determined values of total and differential cross sections on atoms and molecules which are taken to be considerably credible. From this paper one can see that there is a rather small number of absolutely determined cross sections for elastic differential scattering. Measurements on helium atom have been performed by a number of authors(2),(3),(4),(5),(6). Beside on helium, the absolute cross sections for elastic scattering were measured on nitrogen and carbon monoxyde(5), as well as on mercury(7).

2. EXPERIMENTAL PROCEDURE

The scheme of the scattering experiment is given in Fig.1. Electrons coming out of the source are scattered, elastically and

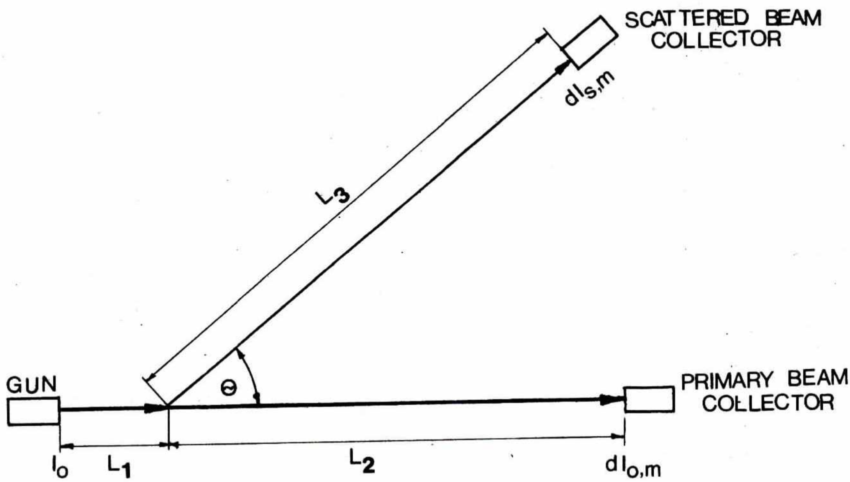


Fig. 1.

inelastically, on gas particles along the beam path. The distance from the source chamber exit slit to the center of effective interaction volume (coinciding with the center of the source chamber rotation axis) is denoted by L_1, and that from this center to the collector of the primary and scattered beam by L_2 and L_3, respectively. Angle θ is the angle at which the measurement of scattered electrons is performed. All the electrons reaching the collectors are not always detected due to the reflection on surfaces or to the secondary electron emission. Also, electrons entering the analyzer chamber may happen not to reach the collector electrode. Primary and scattered beam collection efficienties, and analyzer transmision efficiency are designad by $F_{o,col}$, $F_{s,col}$ and F_{an}, respectively.

Determination of cross section for elastic scattering of electrons on atoms is the objective of the present survey. Taking into account the simplification due to the fact mentioned, as well as the conditions under which the electron beam is passing through the gaseous target, the following relation connects all the values appearing in the present experiment

$$\frac{I_{s,m}(\theta)}{I_{o,m}} = \exp\left[-\sigma_t \cdot \frac{p}{kT} \cdot (L_2 - L_3)\right] \cdot \frac{pV}{kT \cdot S} \cdot \frac{F_{an} \cdot F_{s,col}}{F_{o,col}} \cdot \sigma(\theta) \cdot \Delta\Omega \qquad /1/$$

The right-hand side of the equation containes the cross section for total scattering σ_t as well as the differential cross section for elastic scattering $\sigma(\theta)$. Introducing

$$\sigma_t \cdot (L_2 - L_3)/kT = 1/p_o \qquad /2/$$

the first relation may be transformed into the form which represents the equation of the straight line:

$$\ell n\left[\frac{I_{s,m}(\theta)}{I_{o,m} \cdot p}\right] = \ell n\left[\frac{V \cdot \Delta\Omega}{kT \cdot S} \cdot \frac{F_{an} \cdot F_{s,col}}{F_{o,col}} \cdot \sigma(\theta)\right] - \frac{p}{p_o} \qquad /3/$$

If for certain value of electron energy and a defined scattering angle at constant gas temperature, values of the primary and scattered beam are measured for different pressures, points are obtained which make the experimental straight line, what is seen on Fig.2. The inclination of the line is denoted by A, and the intersection with the ordinate by B. The value of B is proportional to the differential cross section for elastic scattering:

$$B = \ell n\left[\frac{V \cdot \Delta\Omega}{kT \cdot S} \cdot \frac{F_{an} \cdot F_{s,col}}{F_{o,col}} \cdot \sigma(\theta)\right] \qquad /4/$$

This part of the method, pertaining to the relation between the cross section for differential scattering and the measured values of pressure, and currents of the primary and scattered electron beam in the course of the experiment, is the same as that used by Bromberg(5).

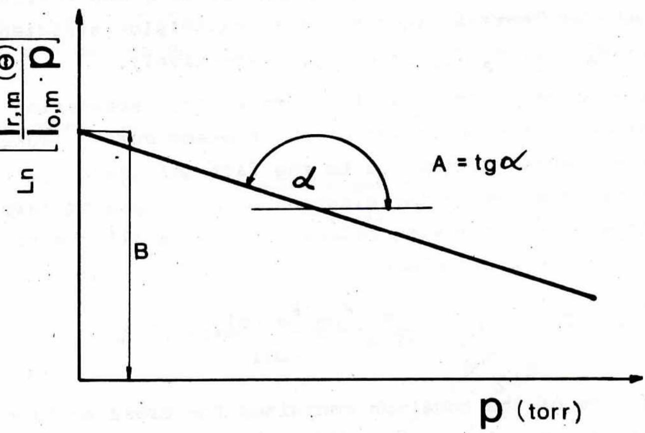


Fig. 2.

Finally, in determining the absolute value of the cross section for elastic scattering, using equation

$$\sigma(\theta) = \frac{kT\cdot S}{V\cdot\Delta\Omega}\cdot\frac{F_{o,col}}{F_{an}\cdot F_{s,col}}\cdot\exp(B) \qquad /5/$$

beside the value of intersection B for a given value of angle θ, the temperature on which the process occured, as well as the geometric conditions of the experiment and collection efficiency factors of the primary and scattered electron beam are to be known.

The temperature was determined by inserting a thermocouple into the interaction volume and it was controlled in the course of the experiment.

The knowledge of geometric conditions of the experiment includes the determination of the beam cross section in the center of the interaction volume, S; the effective solid angle of the detector , ΔΩ; and the interaction volume, V. Values S and ΔΩ are independent of the angle θ at which the measurement of scattered electrons is performed. The third term of the so called geometric factor, represents the value of the effective interaction volume. This is the part of the volume which is at the same time covered by the electron beam and by the space viewing angle of the analyzer. In other words, the effective interaction volume is that part of the volume in which the investigated event can occur and the electron scattered can be energy analized and detected. Great attention was paid to the determination of it's value since it is considerably complicated as compared to the determination of the first two parts of the geometric factor. Analytical formulae have been obtained and used in calculating the interaction volume as function of the scattering angle θ (8). For this purpose it was necessary to know the parameters of the experimental device which are represented in Fig.3. They are: r - distance from the electron source chamber exit slit to the center of the effective interaction volume; R - distance from this center to the analyser chamber entrance slit; α - angle of the electron beam divergency in the horizontal plane; β - viewing angle of the analyzer in the horizontal plane. When the apertures

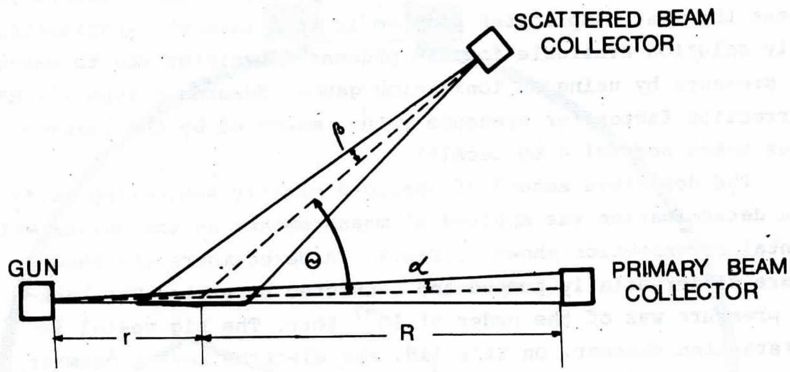


Fig. 3.

of source and analyser electrodes are circular, the electron beam and the analyzer viewing angle are conical in shape. If apertures on electrodes are rectangular, the interaction volume is obtained by the intersection of two pyramids. In determining it's value it is necessary also to know the angle of the electron beam divergency in the vertical plane, γ. All the parameters necessary for the determination of the geometric factor depend on the construction of the experimental device, except the angle of the electron beam divergency which is influenced by potentials of the electron gun electrodes, too, so that value of the angle α must be experimentally checked by measuring the angular width of the electron beam.

The electron beam collection factors, $F_{o,col}$ and $F_{s,col}$, were assumed to be equal to unit. This is justified by the fact that the collector electrodes have positive potential by which the secondary electrons are prevented from leaving them. In the same manner the reflection of electrons is reduced almast to zero. The construction of the analyser provides its transmission coefficient to be equal to unity, too.

The determination of the cross section is reduced to the measurement of primary and scattered electron beam currents and to the measurement of the absolute value of pressure. The smaller the signals are, the more difficult becomes to measure acurately the electron current. That was the reason that data of the scattered electron beam signal were obtained sometimes by averaging with a recorder.

The determination of the absolute value of the pressure is of course the most complicated problem in this kind of experiments. The only solution available for the present experiment was to measure the pressure by using an ionization gauge, Edwards - type IG-2MA. The correction factor for pressure values measured by the instrument was taken according to Leck(9).

The described method of absolute elastic scattering cross section determination was applied at measurements at the device with horizontal cross section shown on Fig.4. Three chambers are shown which are differentially pumped and connected by slits. The background pressure was of the order of 10^{-7} torr. The big vessel is the interaction chamber. On it's lid, the electron source chamber and opposite to it's exit slit the collector of the primary beam are mounted. The other small chamber containes the energy analyser and detector. By rotating the lid of the interaction chamber the change of the angle θ is acheaved. The horizontal plane in which the axes of the source, primary and scattered beam collectors are situated, must remain unchanged during the rotation. A tungsten filament is used as the source of electrons. The beam of electrons is formed by a very simple five-electron gun. The energy width of the used beam was 1 electron volt, which is satisfactory for the measurement of cross sections of elastic scattering in inert gases. For the detection of elastically scattered electrons a retarding field analyser was used(23). All electrons which have lost a part of their energy in the course of interaction were separated, while only those were measured which have detained their energy in the course of interaction, independent of the kind of elastic process they went through.

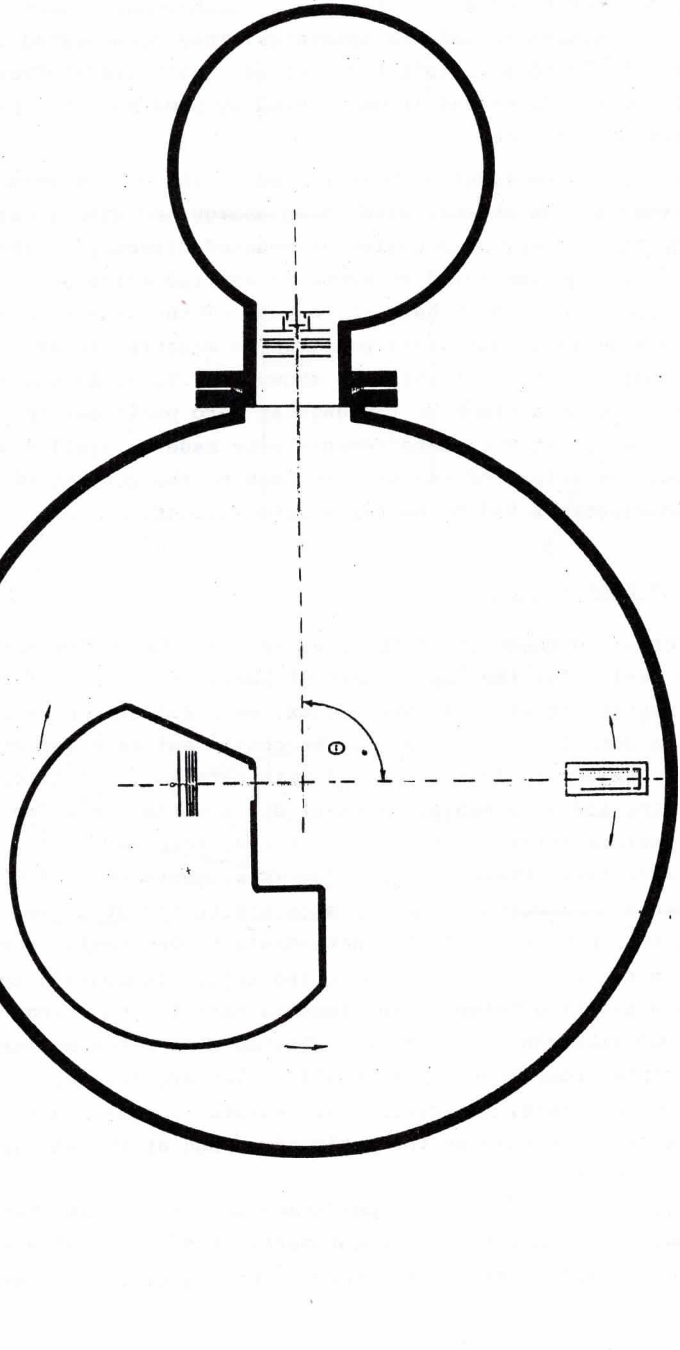


Fig. 4.

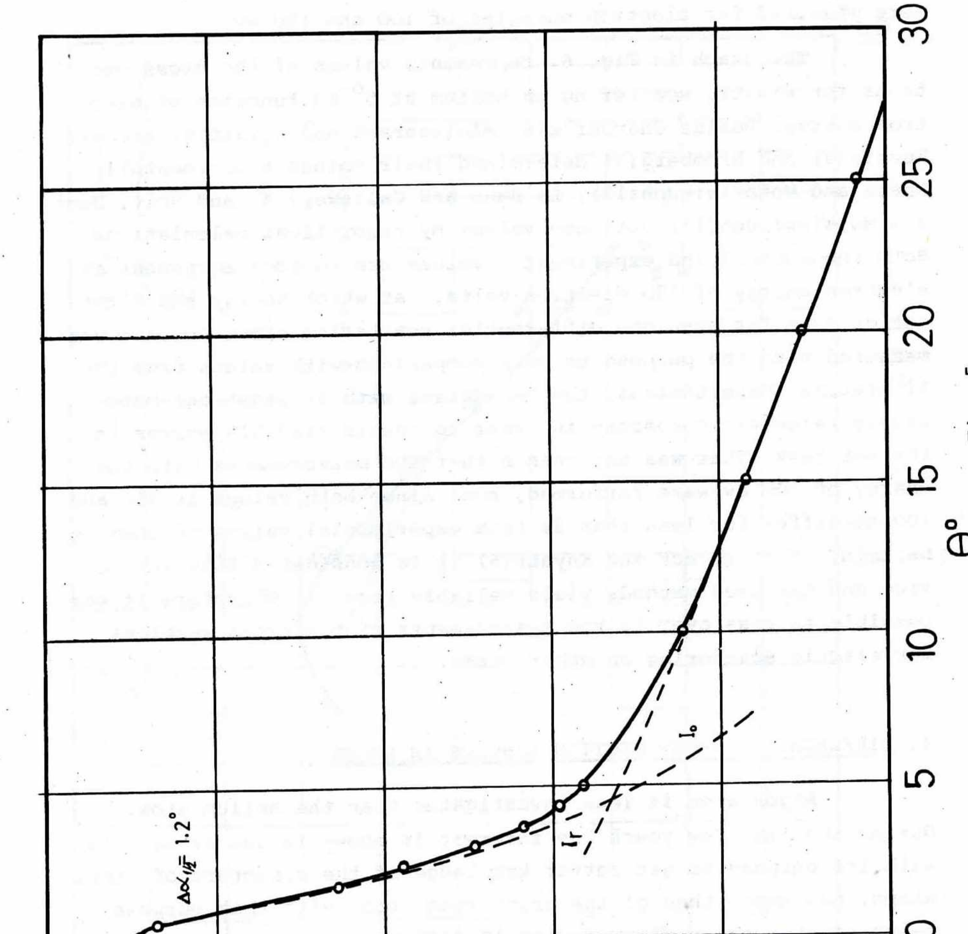
In order to secure the undisturbed motion of electrons, it was necessary to exclude all magnetic and electric fields from the interaction volume. The effect of the Earth magnetic field was predominant, so that three pairs of mutually orthogonal square coils(1o) were arranged around the apparatus. They compensated the Earth magnetic field to a satisfactory degree. The residual field was of about 5 milli Gauss and it was caused by some magnetic parts of the experimental device.

The collimated electron beam formed in the source chamber, entered the interaction chamber with known energy and with a certain energy width. The primary beam collector mounted directly in the front of the electron gun could be somewhat shifted aside at small scattering angle ($\pm 10^{o}$), so, that only a part of the primary beam can reach the analyser. That maked possible to measure the angular width of the beam a result of which is shown in Fig. 5. At the same time this was used as a check of the angular zero position. In figure 5 one can see that when measurements were made at small scattering angles, the effect of the primary beam on the current of the scattered electrons had to be taken into account.

3. CALIBRATION MEASUREMENTS

In order to check the method, as well as the performance of the whole device for the measurement of absolute cross sections for elastic scattering at different angles, measurements on helium atom have been done first (11). Helium is convinient as a target since measured values could be compared with data from the literature on existing absolute measurements of differential cross sections for elastic scattering in the wide energy interval(2),(3),(4),(5),(6). Nevertheless, there are only few experiments dealind with the measurements on electron - helium atom scattering at angles smaller than 15^{o}. Lawson et al.(12) determined theoretically the cross sections on helium at zero scattering angle, indicating to contradictions existing between experimental data in the energy interval 1-1000 electron volts. They suggested that exact measurements of absolute cross sections at small angles are necessary. For this purpose Chamberlain, Mielczareck and Kuyatt(6) measured the elastic cross sections only at the angle of 5^{o} and at the energy of 50-400 electron volts.

Since even in experiments performed on our experimental device there was a possibility for measurements at 5^{o}, special attention has been paid to values obtained at this angle. Cross sections



I_r (A)
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
0
5
10
15
20
25
30
Θ°
$\Delta\alpha_{1/2} = 1.2^\circ$
I_r
I_o

Fig. 5.

were measured for electron energies of 100 and 150 eV.

The graph in Fig. 6. represents values of the cross sections for elastic scattering on helium at 5° in function of electron energy. Beside Chamberlain, Mielczerack and Kuyatt(6) authors Westin(3) and Bromberg(5) determined their values experimentally. Khare and Moiseiwitsch(13), La Bahn and Callawey(14) and Holt, Hunt and Moisiewitsch(15) obtained values by theoretical calculations. Both theoretical and experimental values are in good agreement at electron energy of 150 electron volts, at which energy the first set of data for absolute differential scattering cross section was measured with the purpose to make comparison with values from the literature. Nevertheless, the comparison with at least one more energy value was necessary in order to obtain credible answer to the set task. That was the reason that the measurements with the energy of 100 eV were performed, too. Since both values at 150 and 100 eV differ for less than 2% from experimental values of Chamberlain, Mielczerack and Kuyatt(6) it is considered that the device and the used methods yield veliable results. Therefore it was possible to pass over to the measurements of the cross sections for elastic scattering on other atoms.

4. DIFFERENTIAL CROSS SECTION RESULTS IN ARGON

Argon atom is less investigated than the helium atom. During the last few years the interest is shown in gathering data with the purpose to get better knowledge of the structure of other atoms, and among them of the argon atom, too. With this purpose measurements were performed with 10 different electron energies in the range from 60-150 eV(16). The scattering angle was changed between $5\text{-}15o^{\circ}$. Results of measured cross sections were obtained as the mean values of several completely plotted curves for the same electron energy. The obtained values were determined with an error up to $\pm$2o%.

There are no published data on the absolutely determined values of cross sections for elastic scattering of slow electrons on argon atom obtained experimentally.

All ten curves are represented together in Fig.7. in the angular interval $40\text{-}140^{\circ}$. It is obvious that the maximum at 90° shows tendency of decrease and that it shifts towards smaller angles with the increase of energy, what is predicted theoretically also. Faxen-Holzmark's theory(17) gives the relation between the

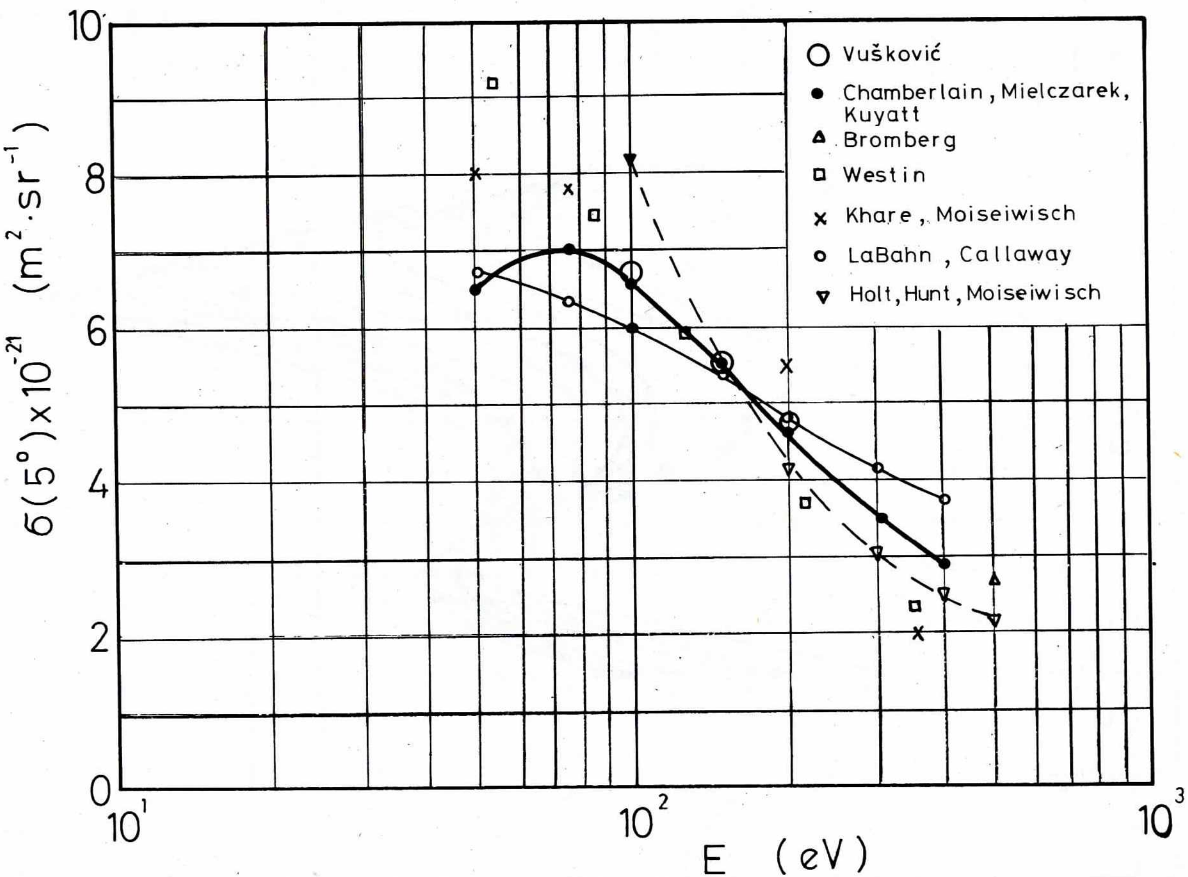

σ(5°) x 10^-21 (m^2.sr^-1)
E (eV)
10
8
6
4
2
0
10^1
10^2
10^3
Vušković
Chamberlain, Mielczarek, Kuyatt
Bromberg
Westin
Khare, Moiseiwisch
LaBahn, Callaway
Holt, Hunt, Moiseiwisch

Fig. 6.

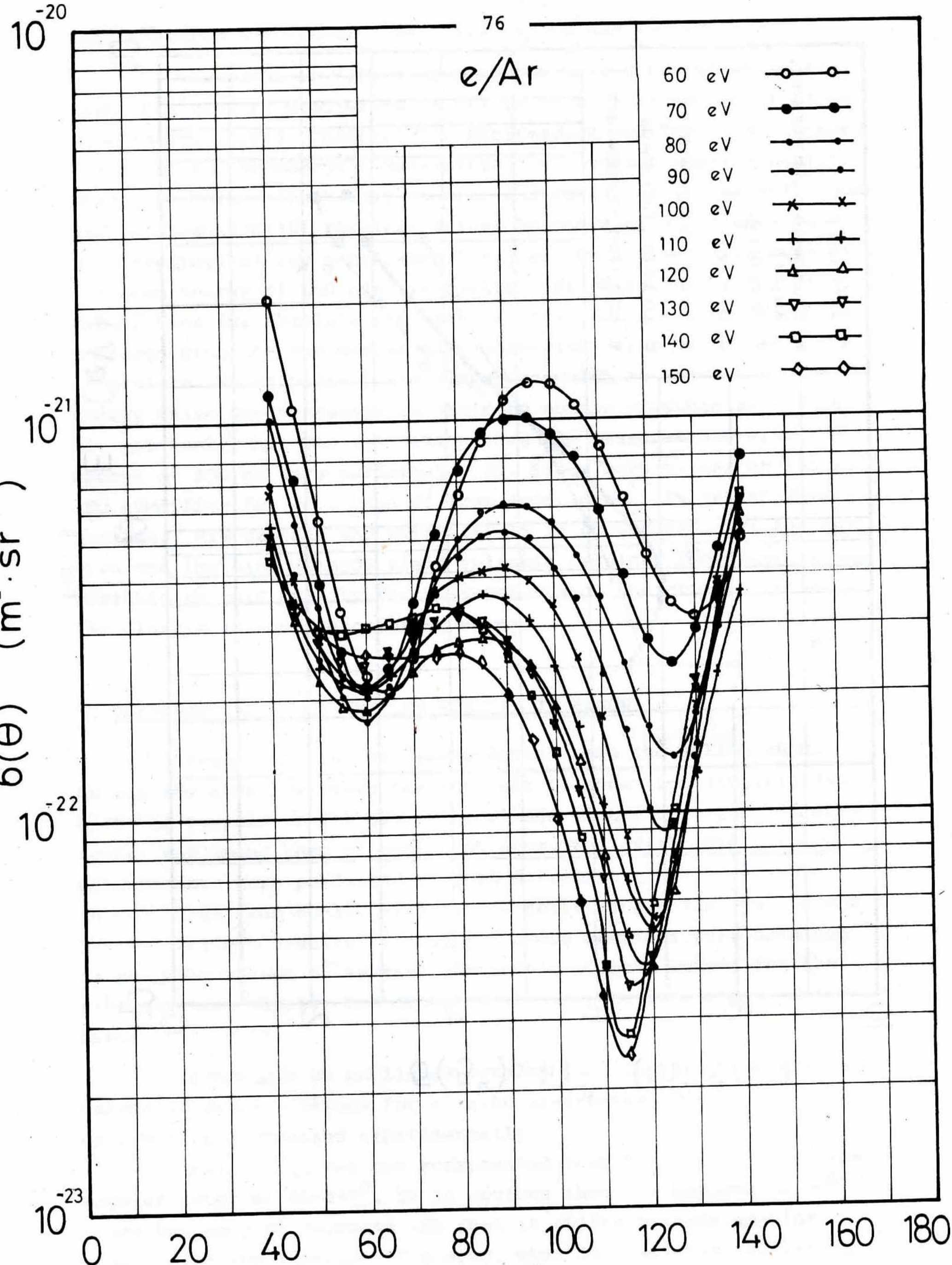

e/Ar
60 eV
70 eV
80 eV
90 eV
100 eV
110 eV
120 eV
130 eV
140 eV
150 eV
10^-20
10^-21
10^-22
10^-23
6(Θ) (m²·sr⁻¹)
0
20
40
60
80
100
120
140
160
180
Θ°

Fig. 7.

phase shifts and the values of cross sections for differential scattering. In the energy range within which our measurements were made, the greatest contribution to the cross section is obtained by partial waves with small quantum number ℓ. According to Walker (18) who used relativistic approximation, the phase shift of the zeroth partial wave is nearly two times greater than the phase shift of the first wave, and that it is an order of magnitude larger than the phase shift of the second partial wave. Beside that, the dependence of the first two phase shifts in function of energy within the energy region mentioned, are smooth decreasing functions. The phase of the third partial wave is approximately constant. Hence, according to the theory, the decrease of the cross section values is expected with the increase of electron energy in the vicinity of the scattering angle of 90°. This decrease is the consequence of the fact that in the angular range of about 90° the contribution to the cross section for differential scattering are obtained only by partial waves with even quantum number ℓ, i.e. phase η_0, η_2 etc. Since η_0 decreases with the energy increase (η_2 is nearly an order smaller than η_0 and approximately constant), the decrease of the cross section for the differential scattering with energy may be taken to be direct consequence of the behavior of the phase shift η_0.

It is seen in Fig. 7. that in the given energy interval the second minimum becomes deeper with the energy increase. This is the consequence of the very important role of the terms of Legendre polynomial with greater index in the angular range of about 120°.

Since there are no experimental results known to the author on absolute cross sections for elastic scattering of electrons on argon, we have compared our results with those of the relative measurements obtained by other authors, by normalizing them to our values at the scattering angle of 90°. An example of such a comparison can be seen in Fig.8. at the electron energy of 150 eV. The relative measurements performed by Webb(19) were made some 40 years ago, while measurements by Schackert(20) are of a more recent date. The greatest difference exists in the case of the values of the second minimum. This is quite easy to understand having in mind that the currents of the scattered beam are small, so that their determination represents a serious experimental difficulty.

Elastic scattering of electrons on argon atom was theoretically studied by Thompson(21) and Walker(18). Thompson made use of the polarized orbitals, while Walker made calculations of the process

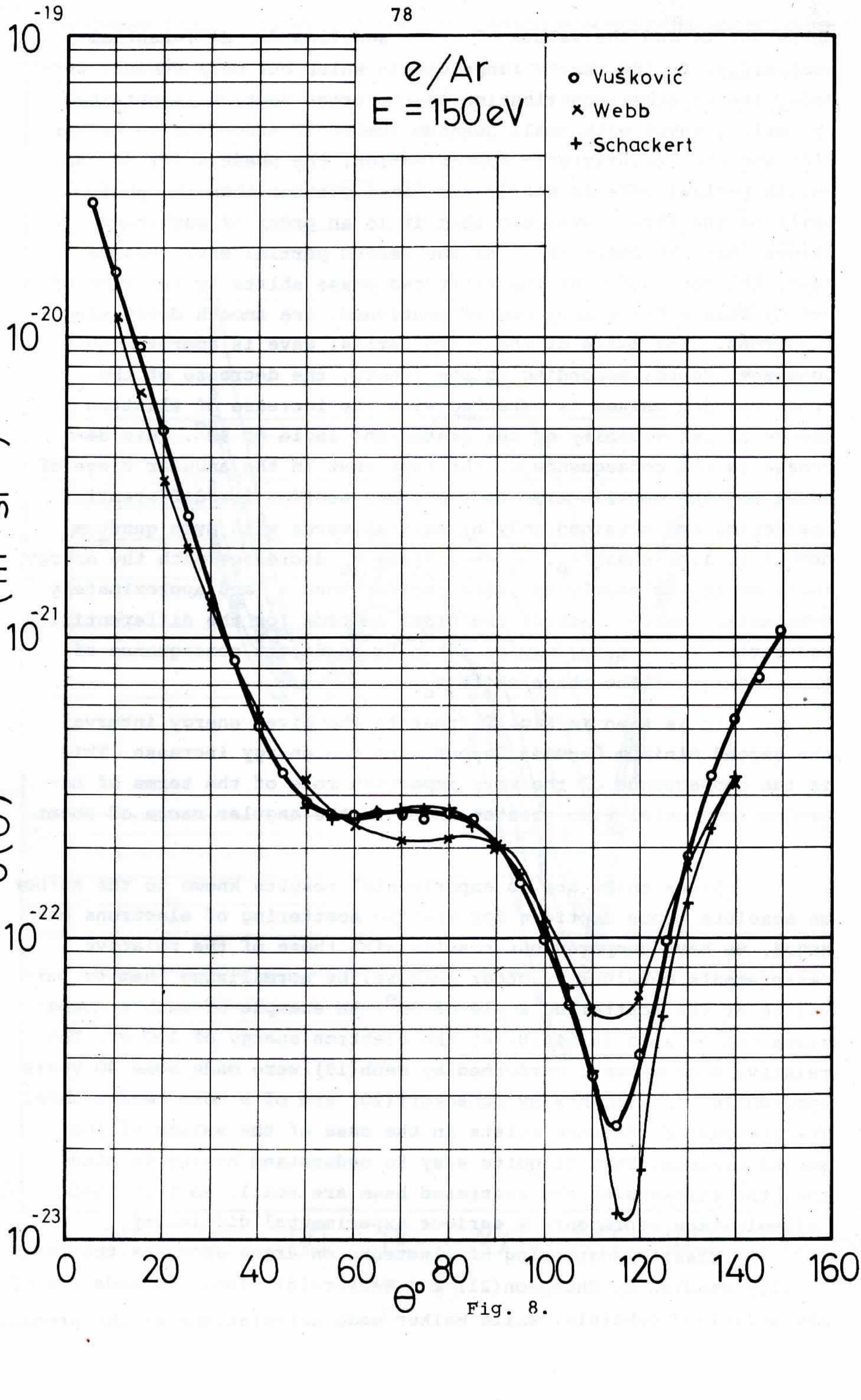

e/Ar
E = 150eV
o Vušković
× Webb
+ Schackert
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
$\sigma(\Theta)$ $(m^2 \cdot sr^{-1})$
0
20
40
60
80
100
120
140
160
Θ^o

Fig. 8.

by relativistic effects. Thompson's investigations are concerned with energies lower than those at which our measurements were performed. Nevertheless, for electron energies of 80, 90 and 100 eV, Thompson and McDonough(22) used the same method for the calculation of differential cross sections for elastic scattering. In Fig. 9. their values are to be seen at electron energies of 80 eV, together with our curve. The theoretical curve is in good agreement with the experimental one in shape, but values are 2-4 time greater. This discrepancy may be explained by inadequacy of the method of polarized orbitals at these electron energies where the influence of dynamic factors on scattering is more pronounced than exchange and polarization effects.

5. CONCLUSION

The described method for differential elastic cross section determination can be succesfully applied to all atomic particles if the elements of the experimental apparatus used for measurements are of apropriate quality. Firstly, the electron energy width must be much lower that the energy difference between the ground and first excited state of the target particle. Secondly, the scattered electron collector must incorporate an electron energy analyser able to give a differential energy spectrum of the scattered electrons, some of them having lost part of their energy in the collision. The energy resolution of the analyser must be large enought to separate the elastically scattered electrons from all inelastically scattered ones.

The way we used the described method gives good results only for electron scattering on atoms (mainly on inert gas atoms), where the first excited state is far enough from the groung state, i.e. at least a few electron volts. Reasons for that are, first, that we used a very simple five electrode electron gun as the electron beam source, having an energy distribution of 1 eV; and second, that the detection of scattered electrons has been done using a retarding field energy analyser, giving an integral spectrum where the elastically scattered electrons are separated from all inelastically scattered electrons in a rather rough way.

It should be stressed here that the present experimental model does not take into account the possibility for the scattered electrons outside the beam to be returned to the beam. Electrons may be double scattered at angles which are different from the angle at which the measurements are performed, and to be able to enter the

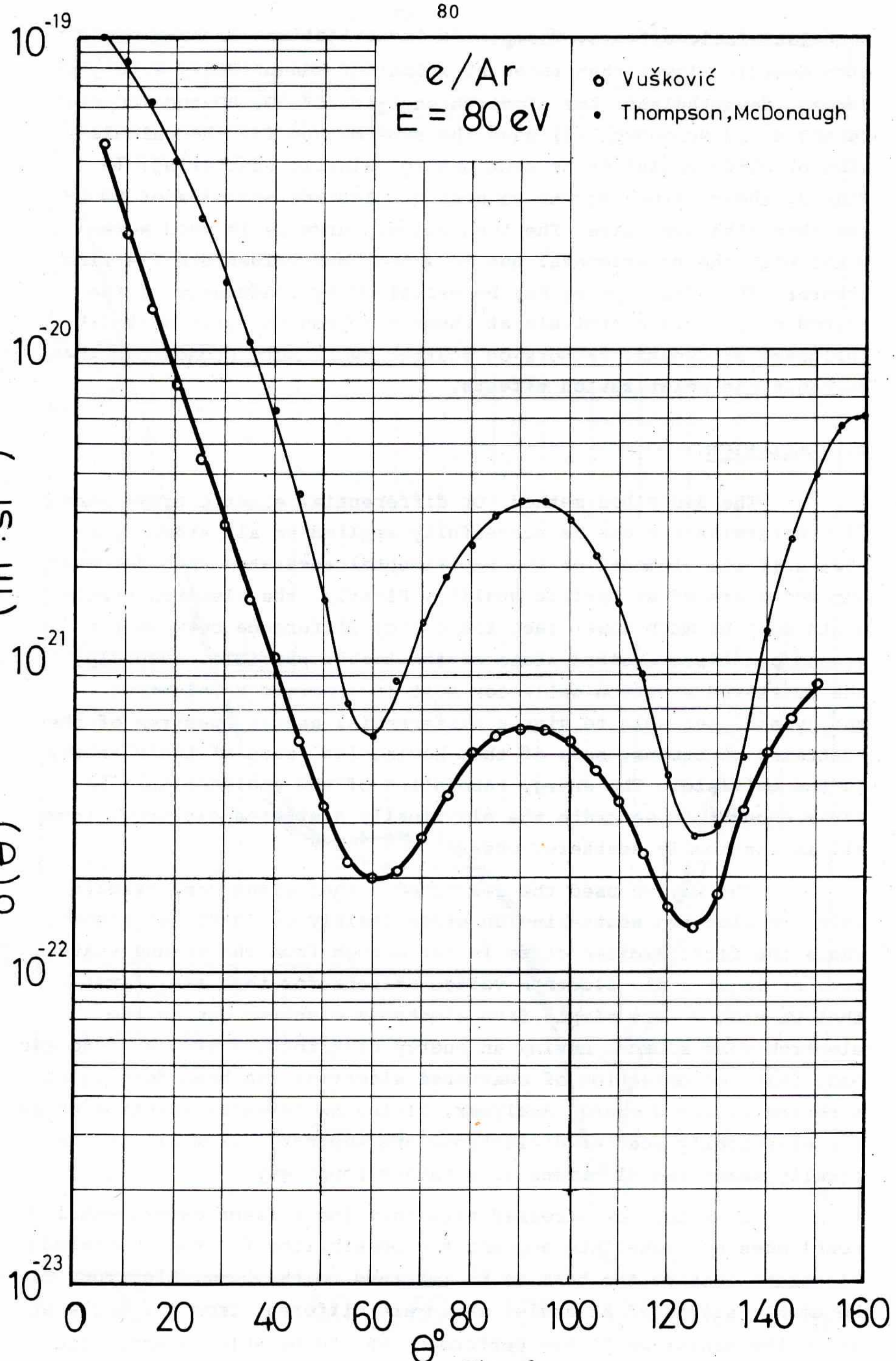

e/Ar
E = 80 eV
o Vušković
• Thompson, McDonaugh
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
σ(Θ) (m².sr⁻¹)
0
20
40
60
80
100
120
140
160
Θ°

Fig. 9.

analyser. This process makes to a large extend difficult the calculation of the total cross section from the inclination of the experimental curve. The consequence is a drastic change of that inclination with the change of the scattered electron current. This change of the inclination can even impair the relative cross section measurement if it is not done at an extremely low target gas pressure. The effect does not influence the results when the measurements are extrapolated to the zero gas pressure, which makes the basis of the described method for determination of absolute values for differential cross sections.

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