Electron impact differential and integral cross sections for excitation of the $n = 2$ states of helium at 29.2 eV, 39.2 eV and 48.2 eV

R.I. Hall, G. Joyez, J. Mazeau, J. Reinhardt, C. Schermann

To cite this version:
ELECTRON IMPACT DIFFERENTIAL AND INTEGRAL CROSS SECTIONS FOR EXCITATION OF THE \( n = 2 \) STATES OF HELIUM AT 29.2 eV, 39.2 eV and 48.2 eV

R. I. HALL, G. JOYEZ, J. MAZEAU, J. REINHARDT and C. SCHERMANN

Laboratoire de Physique et Optique Corpusculaires
Université de Paris VI, T. 12, E5
11, quai Saint-Bernard, Paris 5e, France

(Reçu le 11 mai 1973)

Résumé. — Nous décrivons ici un dispositif de spectrométrie électronique de haute résolution utilisant des monochromateurs électrostatiques et la technique des faisceaux croisés. Les problèmes liés à sa construction et à son emploi pour des mesures de sections efficaces sont analysés. Nous avons déterminé les valeurs absolues des sections efficaces différentielles et totales d'excitation des états \( n = 2 \) de l'hélium à des énergies de 29,2 eV, 39,2 eV et 48,2 eV. Les résultats sont présentés et comparés aux calculs théoriques disponibles à l'heure actuelle.

Abstract. — A high resolution electron impact spectrometer using electrostatic monochromators and the cross-beam technique is described. Considerations related to its construction and use in measuring cross-sections are discussed. This instrument has been used to obtain absolute values for differential and integral excitation cross-sections of the \( n = 2 \) manifold states of helium at 29.2 eV, 39.2 eV and 48.2 eV. The observations are presented and compared with currently available theoretical calculations.

1. Introduction. — When an electron collides with an atom or molecule, many processes can take place (excitation, ionization, dissociation, etc.), and the probability of a particular process taking place is characterized by its cross section. Knowledge of these cross sections is of great importance in many branches of physics (astro, laser, plasma, upper atmosphere, etc.) and much effort has been concentrated on this goal in recent years.

Excitation cross sections have been obtained by optical techniques from the observation of spectral line intensities. Such techniques have been very fruitful but while possessing excellent resolution, are hampered by cascading, technical difficulties in the ultraviolet region and are limited, essentially, to the study of optically allowed transitions. Information on cross sections can also be obtained by analyzing the energy and intensity of the electrons after collision. This technique is known as electron impact spectroscopy, a technique which is developing very rapidly as the technology for producing and handling electron beams with high resolution is being mastered. After a period of phenomenological description of electron collisions, this method is now beginning to be used to produce absolute values for collision cross sections. It is, as yet, lacking in resolution compared to optical techniques, but nevertheless has many assets. Firstly, electrons corresponding to ultra-violet or infrared energies can be detected with equal ease. At low impact energies optical selection rules do not apply and forbidden transitions can be excited with a high probability. Also cross sections can be measured which are differential in angle of the scattered electron. This is of considerable use as a stringent test of theories. Differential cross sections often reveal failings in a theory which by a comparison to integral cross sections can hide. These advantages all add up to the fact that high resolution electron impact spectroscopy is a valuable probe into atomic physics and is rapidly becoming a serious rival to classical spectroscopy.

Electron collisions with helium atoms are most important and are the subject of much study. Experimentally, helium is inert and easy to work with. From a theoretical standpoint, it is the simplest atom for which there are no exact wave functions or atomic potentials. Consequently, this collision system is a testing ground for theoretical and experimental methods before subsequent application to more complex systems.

Excitation of helium by electron impact can be roughly divided into fast and slow collision categories.
depending on the incident electron velocity with respect to the orbital velocity of the helium valence electrons. In the fast category (> 100 eV) the collision can be regarded as a sudden, small perturbation. The process strongly resembles photoabsorption and is concerned only with the properties of the helium atom, as in spectroscopy. First order plane wave theories give a good account of experimental observation in this energy region (see the review articles by Moiseiwitsch and Smith [1], Inokuti [2] and Lassettre [3]) but there is still conjecture as to how good, that is, whether these theories are to within 10% or not of experiment [4], [5].

In the slow collision category (< 100 eV) the electron looses its mechanical individuality and the collision is concerned with the dynamics of the negative ion He. Here the theoretical problem is more complex as approximations of simplicity comparable to those made for fast collisions are less reliable. The close coupling approximation gives good results to 2 eV above threshold [6] but there are no calculations at present which give a good agreement with experiment in the region 2-100 eV above threshold. Recently, calculations by Madison and Shelton [7] using the distorted wave approximation have given encouraging results for the excitation of the 2 1P state and it will be interesting to see if the results are as good for the other three n = 2 states. In order to test the elaborate theoretical techniques which are beginning to be applied to calculating excitation cross section in this difficult energy region, accurate differential cross sections to large angles are needed.

At present, while several measurements of integral cross sections for exciting the 2 1P state have been reported [8]-[11], very few measurements of the differential cross sections for excitation of the n = 2 states below 60 eV have been made. Ehrhardt and coworkers [12]-[13] obtained relative differential cross sections near the threshold of these states which gave insight into the resonant processes which dominate these cross sections in this region. In pioneering work, Trajmar and coworkers [14]-[16] measured differential cross sections for these states between 26 eV and 55 eV up to a 70° scattering angle and placed them on an absolute scale by normalization to the optically measured 2 1P integral cross sections of Jobe and St. John [8]. Very recently this group has performed new and more accurate measurements at 29 eV and 40 eV [17]-[18] up to 140° but this time normalized their results to the recent optical 2 1P integral cross sections of Donaldson et al. [11]. Crooks and coworkers [19], [20] have also very recently determined differential cross sections in the 50 eV energy region. In this case absolute measurements were made and no normalization procedure was utilized.

In this paper we report the construction of an electron impact spectrometer using electrostatic monochromators which is particularly adapted to performing measurements at energies down to threshold, to scattering angles of 127 degrees and with high resolution (~ 30 meV). The physical considerations which go into building such an instrument are discussed, as well as the precautions which must be taken when measuring differential cross sections. This instrument has been employed to obtain differential and integral cross sections for excitation of the n = 2 manifold states of helium at 29.2 eV, 39.2 eV, and 48.2 eV. These observations have been placed on an absolute scale by a new normalization method which uses the accurate differential elastic cross sections of Andrick and Bitsch [21] for the 29.2 eV and 39.2 eV measurements, and those of La Bahn and Callaway [22] for the 48.2 eV results.

2. Experimental. — 2.1 Experimental set-up. — Basically the experiment consists of a beam of electrons which impinges on a beam of atoms. The atomic beam scatters the electrons, and the scattered electrons are then analyzed in energy and scattering angle. In order to resolve electrons which have undergone neighbouring energetic processes, the uncertainty on the energy of the incident beam and the post-collision analysis must be adequate. In this apparatus the resolution is defined by two electrostatic energy filters as schematized in figure 1.

![Schematic of the experimental setup](image)

2.1.1 Incident electron beam. — Electrons emitted by an indirectly heated cathode are focussed onto the entrance slit of a 127° cylindrical electrostatic energy filter. The energy and energy dispersion of the electrons selected by the filter depends on its geometry (0.3 mm by 3 mm slits on a 125 mm radius) and the radial electric field applied between the grids G1 and G2 (radius 15 mm and 10 mm). Grids are employed to define the electric field in order to prevent space charge build-up; stray electrons cross the grids and are collected on the biased plates P1 and P2. The grids are 90% transparent and are made up of a single row of parallel 0.05 mm diameter wires. The mechanical construction of the monochromator is similar to the one described by Kerwin et al. [23].

After energy selection the electron beam is accele-
rated to the required energy and focussed by three electrodes of the Read [24] type (6 mm apertures and 3 mm apart) to which are added two steering electrodes, one cut in half horizontally, and the other vertically.

2.1.2 Scattering center. — A dense gas target and a good vacuum throughout the chamber is obtained by allowing the electron beam to intercept the gas beam at the outlet of a 1 mm diameter tube whose position can be adjusted during the experiment. The unscattered electrons are collected in a Faraday cup which allows focusing and monitoring of the incident beam and also plays an important role in reducing background noise in the post-collision analyzer system by reducing the number of stray electrons in the vacuum chamber.

2.1.3 Analysis and detection of scattered electrons. — The scattered electrons are decelerated and focussed onto the entrance slit of a second electrostatic filter by a three electrode Read type [24] lens. This filter is identical to the first and generally operates under the same conditions; i.e., the same potential difference is applied between the grids for both filters. The entire analyzer system can rotate around the collision center for angles \( \theta \) from \(-30^\circ\) to \(+127^\circ\). Electrons with a particular residual energy \( E_R \) selected by the analyzer are accelerated after the exit slit onto a tubular electron multiplier where they are counted and then stored in an 800 channel scaler.

Background from electrons which are not scattered from the collision center are particularly troublesome at low energies and small angles. This is taken into account by scanning the multichannel scaler successively in add and subtract modes. In the add mode the gas flows normally through the capillary tube and the signal and background is recorded. In the subtract mode the gas flow is injected into the chamber through a separate inlet thus maintaining the same background pressure. In this case the background alone is obtained.

2.2 Operational modes. — 2.2.1 Energy-loss spectrum. — An electron with an incident energy \( E_i \) excites a target particle to the energy level \( E_{ex} \) and leaves the collision center with an energy \( E_i - E_{ex} \) in a direction \( \theta \). This electron is detected when the tuned energy \( E_i \) of the analyzer is equal to \( E_i - E_{ex} \) and when it is at the scattering angle \( \theta \).

If the incident energy and scattering angle are kept constant and the analysis energy \( E_s \) is scanned, then a recording of the scattered electrons shows a series of peaks corresponding to the different energy levels of the target particle. The peak heights represent the relative probability of exciting the levels at that incident energy and scattering angle.

2.2.2 Constant residual energy spectrum. — If \( E_s \) and \( \theta \) are kept constant and \( E_i \) is scanned then a recording of the scattered current again shows a series of peaks corresponding to excitation of levels of the target particle. Here the peak heights represent the relative probability of exciting the levels at an energy \( E_i \) above their threshold at that scattering angle. A recording obtained for zero residual energy is known as a threshold excitation spectrum.

2.2.3 Excitation function. — An excitation function is obtained by plotting the scattered current while varying \( E_i \) and \( E_s \) so that their difference \( E_i - E_s = E_{ex} \) remain constant. Such a plot represents the relative probability of exciting the level of energy \( E_{ex} \) as a function of the incident energy \( E_i \) and at that scattering angle.

2.2.4 Angular dependence. — If the energies \( E_i \) and \( E_s \) are kept constant and the scattering angle \( \theta \) varies, then a recording of the scattered signal represents the angular behaviour of the scattered electrons which have undergone the process \( E_{ex} = E_i - E_s \) and is also the angular dependence of the differential cross section.

2.3 Performance of the experimental set-up. — To a first approximation the dispersion or full width at half height of the electron energy distribution \( \gamma_F \) in the incident beam is given by the relationship [25]:

\[
\gamma_F = \frac{d}{R} E_F
\]

where \( d \) is the width of the slits (0.3 mm), \( R \) is the mean radius of the filter (12.5 mm) and \( E_F \) is the energy of the electrons selected by the filter.

2.3.1 Measurement of the energy dispersion. — In the case of energy loss and constant residual energy spectra, it is shown (see Appendix I) that \( \gamma_F \), the width at half height of an observed peak, assuming a Gaussian distribution for the electrons and identical dispersion (width at half height of transmission function, for the selector \( \gamma_s \) and analyzer \( \gamma_A \), is such that:

\[
\gamma_F = \sqrt{2} \gamma \quad \text{where} \quad \gamma = \gamma_s = \gamma_A.
\]

Thus, the peaks observed in these spectra are broader than the dispersion of the incident electrons. This is reasonable because the energy dispersion is measured by the analyzer which is an imperfect instrument.

In the case of an excitation function it is shown that \( \gamma_E \), the observed width at half height of an infinitely fine structure, is such that:

\[
\gamma_E = \frac{\gamma}{\sqrt{2}}.
\]

Consequently, the width \( \gamma_E \) is half that of \( \gamma_F \). This phenomenon is observed experimentally. For instance, the elastic peak (energy loss spectrum) in helium is observed to be twice as broad as the window resonance at 19.35 eV in the elastic cross section (excitation function).
2.3.2 Broadening due to the thermal motion of the target atoms. — As the electron mass is small compared to the target particle mass, a first approximation considers the centre of mass stationary throughout the collision. In this case the energy of the scattered electron is the same in both the laboratory and center-of-mass coordinates systems. However, as the resolution of electron scattering experiments steadily improves, the finite mass and motion of the target particles must be considered.

The energy variation of the electron $\Delta E$ in the laboratory system, when it produces a change in the internal energy $E_n$ of the target atom, is given by the relationship (Appendix II),

$$\Delta E = -E_n - \frac{m_1}{m_2} \left( \frac{1}{2} m_1 |\Delta v|^2 \right) + m_1 \Delta v \cdot v_2$$

where $\Delta v$ is the electron velocity change, $v_2$ the target velocity, and $m_1$ and $m_2$ the electron and target mass, respectively.

The second term essentially represents a shift of the observed energy loss peak from the excitation energy and depends on the angle of observation. This effect is small, and in the unfavorable case of excitation of the $n = 2$ states of He ($E_n \sim 20$ eV) is of the order of 2.5 meV at 90°.

The last term introduces an energy change which depends on the velocity of the target particles, and as they have a thermal distribution a broadening of observed structure in an energy loss spectrum or excitation function results. Moreover, this broadening increases with scattering angle because of $\Delta v$. Such an effect was thought to have been observed by us in elastic scattering from He using a resolution of 38 meV (width of elastic peak at 10° scattering angle) but a repeated experiment did not produce confirmation. Calculations are being undertaken to estimate the magnitude of the expected broadening.

2.3.3 Operational conditions. — As electric fields are used in the energy filters, good working conditions, particularly at low energy (< 1 eV), require that the residual magnetic fields be less than $10^{-3}$ G. For this reason the system is built of a non-magnetic alloy (Arcap AP 4, composition Ni 45 %, Cu 53.5 % and others 1.5 % but no Zn) and the residual field is reduced to $\sim 10^{-3}$ G by the use of Helmholtz coils and an in-vacuum Mumetal shield. Cleanliness of all metal surfaces in contact with the electrons is also essential for good energy selection and stable working conditions. This is obtained by a regular bake-out at 250°C.

When the resolution of the selector and analyzer increases, the intensity of the electrons detected after the analyzer decreases. Thus, the potentials applied to the grids in the filters depend on the particular choice of resolution-intensity compromise. If 0.40 V is applied between the grids, the energy of the electrons selected by the filters is 0.5 eV, the resolution as measured by $\gamma_p$ is 30 meV and the incident beam intensity is 3 nA. For 1.5 V between the grids the filtered energy is 1.87 eV, the resolution $\gamma_p$ is 90 meV and the incident beam intensity is 45 nA.

The scattered electron signal can be increased by increasing the target beam density but this also increases the background pressure in the instrument which limited to a maximum of $5 \times 10^{-4}$ torr. Above this pressure the scattering of electrons on the background gas within the filters becomes appreciable.

2.4 Observation of the angular dependence of differential scattering cross sections. — The electron scattering cross section for a particular process is the number of these processes taking place per unit time per target particle, divided by the number of incident electrons per unit time per unit area. The differential cross section is then the cross section per unit solid angle when an electron is scattered in a given direction. The measurement of the angular dependence of a differential cross section requires several precautions which are described in this section.

2.4.1 Angular resolution of the analyzer. — In general the angular behaviour of the scattered electrons varies smoothly, consequently the angular resolution of the analyzer is unimportant. In the present instrument the half-angle subtended by the aperture of the analyzer optics at the scattering centre is 6° but as the electron optics are weak the resolution is probably much smaller.

2.4.2 Collision volume. — The intensity of scattered electrons detected depends on the collision volume «seen» by the analyzer and the way it varies with angle. In this crossed beam experiment this volume is made small by adjusting the target gas injection tube so that the incident beam just grazes the outlet. Under these conditions the effect on the angular behaviour is small and in practice the correction required for normalization to very accurate angular dependencies is never more than 10 % (see 2.5).

2.4.3 Residual electric and magnetic fields. — The residual magnetic field is low throughout the instrument ($\sim 10^{-3}$ G) and the electric field in the collision centre is reduced by shielding and by baking-out to remove insulating layers which would otherwise charge up. The efficiency of these precautions is observed by checking that the angular dependencies are symmetric with respect to the incident beam direction.

2.4.4 Energy distribution of the scattered electrons. — As better resolution is used in light gases, the effects described in section 2.3.2 will introduce two further errors. Firstly, the shift of the observed energy loss will produce an under-estimation of the dependence with increasing angle. This is because the analyzer will no longer be on the signal maximum for the process as it moves towards higher angles.
Secondly, since the analyzer has a small bandwidth, only a fraction of the electrons scattered from a process are transmitted, and as the distribution of these electrons is broadened at large angles, the measured signal will again underestimate the angular dependence as the scattering angle increases. Thus it will be more accurate when obtaining angular dependencies to record energy loss spectra at different angles and measure the peak heights. This height can be corrected for the broadening effect. It can be shown (Appendix III) that in the case of a Gaussian distribution, the weakening of the signal is proportional to the increase in width at half height of the energy-loss peak. Consequently, the necessary correction factor is easily obtained.

2.5 Measurement of the Differential Cross Section of the \( n = 2 \) States of Helium. — The angular variation of the relative intensities of the electrons having excited the four \( n = 2 \) states of He have already been determined by this group (26) up to a scattering angle of \( 80^\circ \) at incident energies of 29.2, 39.2 and 48.2 eV (calibrated against the resonance at 19.3 eV). This was accomplished by plotting energy loss spectra (Fig. 2) at different angles and comparing peak heights. These observations have now been extended to a \( 127^\circ \) scattering angle and the absolute differential cross section for excitation of the four levels obtained by the following normalization procedure.

Firstly, the analyzer is set to detect electrons with an energy loss corresponding to excitation of the \( 2\,^1P \) level (21.21 eV) i.e. for a 39.2 eV incident energy the analyzer detects electrons with an energy of \( 39.2 - 21.2 = 18.0 \) eV. The \( 2\,^1P \) level is chosen as it is generally the most intense. The angular dependence of the scattered electrons is then obtained by sweeping the analyzer angle and noting the count rates with and without the gas beam (Section 2.1.3) and subtracting. Now the analyzer is made to detect elastically scattered electrons by keeping all of its parameters fixed and changing the incident energy i.e., in this case from 39.2 eV to 18 eV, and the angular dependence measured in the same way as above. Hence, the differential cross section for exciting the \( 2\,^1P \) level at 39.2 eV is known relative to the elastic differential cross section at 18 eV after taking into account the change in incident intensity when the incident energy changes from the elastic to inelastic case. The elastic angular dependence is then normalized to the absolute differential cross section at that energy and the differential cross section for the \( 2\,^1P \) level obtained.

The absolute measurements of Andrik and Bitsch [21] at 8 and 18 eV are used for the 29.2 and 39.2 eV, \( 2\,^1P \) results and the theoretical values of La Bahn and Callaway [22] at 27 eV for the \( 2\,^3P \) cross section at 48.2 eV. The absolute differential cross section for the \( 2\,^3P, \, 2\,^1S \) and \( 2\,^3S \) levels are obtained from the \( 2\,^1P \) cross section by means of the previously measured relative intensities.

This method assumes that the collision volume remains the same when the analyzer measures elastic and inelastic electrons. This is reasonable as, firstly, the incident current changes only slightly and is well focused into the small collector behind the gas beam. Secondly, the correction to the observed elastic angular dependencies is never more than 10 % with respect to the absolute values and does not change with incident energy, which implies that the collision volume is small and does not change with energy.

3. Results and discussion. — 3.1 Differential Cross Sections. — The angular variation of the scattered intensity ratios of the \( 2\,^3P, \, 2\,^1S \) and \( 2\,^3S \) states with respect to the \( 2\,^1P \) state from \( 10^\circ \) to \( 127^\circ \) at 29.2 eV, 39.2 eV and 48.2 eV are presented in table I. The \( 2\,^1P \) differential cross section was put on an absolute scale by the normalization procedure described in the previous section. The absolute differential cross sections for the other three transitions were then obtained from the above intensity ratios and yielded the values shown in tables II, III and IV at 29.2 eV, 39.2 eV and 48.2 eV respectively. An estimation of the error in the measurements is also shown in these tables. The value assigned to the error...
### Table I

Scattered intensity ratios of the $2\,^3P$, $2\,^1S$ and $2\,^3S$ states with respect to the $2\,^1P$ state at 29.2 eV, 39.2 eV and 48.2 eV.

<table>
<thead>
<tr>
<th>$\theta$ deg.</th>
<th>$E_i = 29.2$ eV</th>
<th>$E_i = 39.2$ eV</th>
<th>$E_i = 48.2$ eV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2,^3P$</td>
<td>$2,^1S$</td>
<td>$2,^3S$</td>
<td>$2,^3P$</td>
</tr>
<tr>
<td>10</td>
<td>.044</td>
<td>.48</td>
<td>.094</td>
</tr>
<tr>
<td>15</td>
<td>.058</td>
<td>.40</td>
<td>.110</td>
</tr>
<tr>
<td>20</td>
<td>.080</td>
<td>.32</td>
<td>.124</td>
</tr>
<tr>
<td>30</td>
<td>.19</td>
<td>.16</td>
<td>.17</td>
</tr>
<tr>
<td>40</td>
<td>.50</td>
<td>.05</td>
<td>.30</td>
</tr>
<tr>
<td>50</td>
<td>1.12</td>
<td>.08</td>
<td>.74</td>
</tr>
<tr>
<td>60</td>
<td>1.56</td>
<td>.20</td>
<td>1.24</td>
</tr>
<tr>
<td>70</td>
<td>1.85</td>
<td>.40</td>
<td>1.60</td>
</tr>
<tr>
<td>80</td>
<td>2.2</td>
<td>.63</td>
<td>1.90</td>
</tr>
<tr>
<td>90</td>
<td>2.45</td>
<td>1.05</td>
<td>1.90</td>
</tr>
<tr>
<td>100</td>
<td>2.7</td>
<td>1.5</td>
<td>1.50</td>
</tr>
<tr>
<td>110</td>
<td>3.0</td>
<td>2.1</td>
<td>1.15</td>
</tr>
<tr>
<td>120</td>
<td>3.2</td>
<td>2.7</td>
<td>.97</td>
</tr>
<tr>
<td>125</td>
<td>3.3</td>
<td>3.2</td>
<td>1.0</td>
</tr>
<tr>
<td>127</td>
<td>3.4</td>
<td>3.4</td>
<td>1.0</td>
</tr>
</tbody>
</table>

### Table II

Experimental differential cross sections for excitation of the $n = 2$ states of helium at an impact energy of 29.2 eV. The estimated errors are indicated. These results were obtained by normalizing the $2\,^1P$ differential cross section to the 8 eV elastic differential cross section of Andrick and Bitsch as described in the text.

<table>
<thead>
<tr>
<th>$\theta$ deg.</th>
<th>$2,^1P$ $10^{10}$cm$^2$/sr</th>
<th>$2,^3P$ $10^{10}$cm$^2$/sr</th>
<th>$2,^3S$ $10^{10}$cm$^2$/sr</th>
<th>$2,^3S$ $10^{10}$cm$^2$/sr</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>48 ± 8</td>
<td>2.07 ± 0.55</td>
<td>22.6 ± 6.0</td>
<td>4.42 ± 1.15</td>
</tr>
<tr>
<td>20</td>
<td>26.1 ± 2.6</td>
<td>2.13 ± 0.42</td>
<td>8.37 ± 1.70</td>
<td>3.24 ± 0.65</td>
</tr>
<tr>
<td>30</td>
<td>12.3 ± 1.3</td>
<td>2.33 ± 0.47</td>
<td>1.97 ± 0.40</td>
<td>2.09 ± 0.42</td>
</tr>
<tr>
<td>40</td>
<td>5.2 ± 0.6</td>
<td>2.17 ± 0.45</td>
<td>0.26 ± 0.05</td>
<td>1.61 ± 0.33</td>
</tr>
<tr>
<td>50</td>
<td>2.3 ± 0.2</td>
<td>2.24 ± 0.43</td>
<td>0.19 ± 0.03</td>
<td>1.70 ± 0.32</td>
</tr>
<tr>
<td>60</td>
<td>1.32 ± 0.08</td>
<td>2.13 ± 0.36</td>
<td>0.26 ± 0.04</td>
<td>1.64 ± 0.28</td>
</tr>
<tr>
<td>70</td>
<td>0.96 ± 0.10</td>
<td>1.98 ± 0.36</td>
<td>0.38 ± 0.07</td>
<td>1.53 ± 0.28</td>
</tr>
<tr>
<td>80</td>
<td>0.89 ± 0.10</td>
<td>2.02 ± 0.36</td>
<td>0.61 ± 0.10</td>
<td>1.70 ± 0.31</td>
</tr>
<tr>
<td>90</td>
<td>0.91 ± 0.10</td>
<td>2.40 ± 0.48</td>
<td>0.95 ± 0.19</td>
<td>1.72 ± 0.34</td>
</tr>
<tr>
<td>100</td>
<td>0.83 ± 0.08</td>
<td>2.51 ± 0.50</td>
<td>1.24 ± 0.25</td>
<td>1.24 ± 0.25</td>
</tr>
<tr>
<td>110</td>
<td>0.75 ± 0.07</td>
<td>2.73 ± 0.55</td>
<td>1.56 ± 0.31</td>
<td>0.86 ± 0.17</td>
</tr>
<tr>
<td>120</td>
<td>0.73 ± 0.07</td>
<td>2.65 ± 0.53</td>
<td>1.97 ± 0.40</td>
<td>0.71 ± 0.14</td>
</tr>
<tr>
<td>125</td>
<td>0.71 ± 0.07</td>
<td>2.72 ± 0.55</td>
<td>2.26 ± 0.45</td>
<td>0.71 ± 0.14</td>
</tr>
</tbody>
</table>
Experimental differential cross sections for excitation of the n = 2 states of helium at an impact energy of 39.2 eV. The estimated errors are indicated. These results were obtained by normalizing the $2^{1}P$ differential cross section to the 18 eV elastic differential cross section of Andrick and Bitsch as described in the text.

<table>
<thead>
<tr>
<th>$\theta$ deg.</th>
<th>$2^{1}P$</th>
<th>$2^{3}P$</th>
<th>$2^{1}S$</th>
<th>$2^{3}S$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{-19}$ cm$^2$/sr</td>
<td>$10^{-19}$ cm$^2$/sr</td>
<td>$10^{-19}$ cm$^2$/sr</td>
<td>$10^{-19}$ cm$^2$/sr</td>
</tr>
<tr>
<td>10</td>
<td>107 ± 30</td>
<td>1.82 ± 0.72</td>
<td>26.7 ± 10</td>
<td>6.0 ± 2.3</td>
</tr>
<tr>
<td>20</td>
<td>48.8 ± 8</td>
<td>3.12 ± 1.00</td>
<td>7.32 ± 2.3</td>
<td>4.6 ± 1.5</td>
</tr>
<tr>
<td>30</td>
<td>17.10 ± 1.7</td>
<td>3.76 ± 0.75</td>
<td>1.23 ± 0.24</td>
<td>2.5 ± 0.5</td>
</tr>
<tr>
<td>40</td>
<td>6.27 ± 0.7</td>
<td>3.76 ± 0.75</td>
<td>0.22 ± 0.04</td>
<td>1.13 ± 0.22</td>
</tr>
<tr>
<td>50</td>
<td>2.98 ± 0.3</td>
<td>3.13 ± 0.65</td>
<td>0.024 ± 0.012</td>
<td>0.60 ± 0.12</td>
</tr>
<tr>
<td>60</td>
<td>1.86 ± 0.2</td>
<td>2.23 ± 0.45</td>
<td>0.108 ± 0.022</td>
<td>0.372 ± 0.075</td>
</tr>
<tr>
<td>70</td>
<td>1.50 ± 0.13</td>
<td>1.88 ± 0.36</td>
<td>0.31 ± 0.06</td>
<td>0.301 ± 0.058</td>
</tr>
<tr>
<td>80</td>
<td>1.24 ± 0.07</td>
<td>1.62 ± 0.26</td>
<td>0.58 ± 0.09</td>
<td>0.248 ± 0.040</td>
</tr>
<tr>
<td>90</td>
<td>1.02 ± 0.06</td>
<td>1.35 ± 0.22</td>
<td>0.82 ± 0.13</td>
<td>0.205 ± 0.033</td>
</tr>
<tr>
<td>100</td>
<td>0.98 ± 0.06</td>
<td>1.32 ± 0.21</td>
<td>1.23 ± 0.20</td>
<td>0.196 ± 0.031</td>
</tr>
<tr>
<td>110</td>
<td>0.80 ± 0.05</td>
<td>1.10 ± 0.18</td>
<td>1.36 ± 0.22</td>
<td>0.287 ± 0.047</td>
</tr>
<tr>
<td>120</td>
<td>0.70 ± 0.07</td>
<td>0.98 ± 0.20</td>
<td>1.55 ± 0.31</td>
<td>0.420 ± 0.085</td>
</tr>
<tr>
<td>125</td>
<td>0.72 ± 0.1</td>
<td>1.03 ± 0.25</td>
<td>1.81 ± 0.45</td>
<td>0.653 ± 0.165</td>
</tr>
</tbody>
</table>

Experimental differential cross sections for excitation of the n = 2 states of helium at an impact energy of 48.2 eV. The estimated error is indicated. These results were obtained by normalizing the $2^{1}P$ differential cross section to the 27 eV theoretical elastic differential cross section of La Bahn and Callaway as described in the text.

Erratum: in the column 4, line 6, read 0.28 ± 0.06 instead of 0.28 ± 0.6

<table>
<thead>
<tr>
<th>$\theta$ deg.</th>
<th>$2^{1}P$</th>
<th>$2^{3}P$</th>
<th>$2^{1}S$</th>
<th>$2^{3}S$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{-19}$ cm$^2$/sr</td>
<td>$10^{-19}$ cm$^2$/sr</td>
<td>$10^{-19}$ cm$^2$/sr</td>
<td>$10^{-19}$ cm$^2$/sr</td>
</tr>
<tr>
<td>10</td>
<td>180 ± 80</td>
<td>2.1 ± 1.0</td>
<td>24 ± 13</td>
<td>5.1 ± 2.8</td>
</tr>
<tr>
<td>20</td>
<td>58 ± 10</td>
<td>2.9 ± 0.8</td>
<td>6.4 ± 1.7</td>
<td>2.9 ± 0.8</td>
</tr>
<tr>
<td>30</td>
<td>16.6 ± 2.0</td>
<td>3.0 ± 0.6</td>
<td>1.39 ± 0.28</td>
<td>1.36 ± 0.28</td>
</tr>
<tr>
<td>40</td>
<td>5.4 ± 0.7</td>
<td>2.7 ± 0.6</td>
<td>0.30 ± 0.06</td>
<td>0.45 ± 0.10</td>
</tr>
<tr>
<td>50</td>
<td>2.65 ± 0.30</td>
<td>2.1 ± 0.4</td>
<td>0.087 ± 0.017</td>
<td>0.132 ± 0.026</td>
</tr>
<tr>
<td>60</td>
<td>1.80 ± 0.20</td>
<td>1.69 ± 0.35</td>
<td>0.28 ± 0.6</td>
<td>0.043 ± 0.008</td>
</tr>
<tr>
<td>70</td>
<td>1.41 ± 0.12</td>
<td>1.30 ± 0.25</td>
<td>0.45 ± 0.09</td>
<td>0.020 ± 0.003</td>
</tr>
<tr>
<td>80</td>
<td>1.14 ± 0.07</td>
<td>1.03 ± 0.20</td>
<td>0.74 ± 0.15</td>
<td>0.016 ± 0.003</td>
</tr>
<tr>
<td>90</td>
<td>0.96 ± 0.06</td>
<td>0.86 ± 0.17</td>
<td>0.96 ± 0.19</td>
<td>0.017 ± 0.003</td>
</tr>
<tr>
<td>100</td>
<td>0.76 ± 0.05</td>
<td>0.70 ± 0.14</td>
<td>1.13 ± 0.22</td>
<td>0.043 ± 0.008</td>
</tr>
<tr>
<td>110</td>
<td>0.65 ± 0.06</td>
<td>0.60 ± 0.12</td>
<td>1.23 ± 0.25</td>
<td>0.26 ± 0.05</td>
</tr>
<tr>
<td>120</td>
<td>0.58 ± 0.09</td>
<td>0.52 ± 0.13</td>
<td>1.36 ± 0.33</td>
<td>0.54 ± 0.13</td>
</tr>
</tbody>
</table>
represents the statistical error inherent in the recording of the energy loss spectra (Fig. 2) as well as error in the normalization of the 2P transition to the elastic differential cross sections. The error in the elastic differential cross section themselves is not included.

3.1.1 Excitation of the 2P state. — The differential cross section for excitation of the 2P state at 29.2 eV, 39.2 eV and 48.2 eV is shown in figures 3, 4 and 5 respectively. Also shown are other experimental and theoretical results.

At 29.2 eV and 39.2 eV there is very good agreement between these results and the recent measurements of Truhlar et al. [17], especially when it is considered that they were obtained by a completely different method. These workers normalized the integral 2P cross section to the absolute 2P cross section which Donaldson et al. [11], obtained using an optical technique. At 48.2 eV the agreement with the results of Truhlar et al., obtained at 55 eV is good. These older results were obtained by normalization to the optical 2P cross section as measured by Jobe and St. John [8] and is somewhat lower than that obtained by Donaldson et al. [11] (see Fig. 15). Normalization of the measurements of Truhlar et al. [15], to the value of Donaldson et al. [11], would raise that differential cross section with respect to ours which is what would be expected as the integral cross section is still rising to 55 eV. However, from the general behaviour of the 2P differential cross section with increasing energy, the curve would be expected to steepen in going to 55 eV and this is not the case with the results of Truhlar et al. [15]. The measurements of Crooks [19] at 50 eV were obtained by an entirely different technique and are truly absolute measurements in that no normalization procedure was utilized. As can be seen the agreement with our results is excellent. The value obtained by Chamberlain et al. [5], at 50 eV is lower than our results but well within the error bar.

The transition to the 2P level from the ground state is the only one in the n = 2 manifold states which is optically allowed. The allowed nature of the transition implies that the electron essentially interacts with the helium atom through a long range potential...
which is proportional to $1/r^2$ to a first approximation. This long range potential involves many partial waves in the collision process which means that the differential cross section should be forward peaked. As is shown, this is in fact what is observed experimentally.

The Born approximation for calculating cross sections considers the collision interaction to be weak, represents the interaction as being that between a plane wave (electron) and the above mentioned potential ($\sim 1/r^2$). The differential cross section using the Born approximation was evaluated from the work of Kim and Inokuti [27] and the results are shown in the figures. As is seen these cross sections tend to be too large at small angles and too small at large angles. This approximation does not take into account the distortion of the incident particle from a plane wave, polarization, exchange or other short range interactions which should be important at these incident energies and which would tend to increase the scattering to large angles bringing the cross section nearer the experimental one.

Other more complex first order calculations which include electron exchange have been extensively studied by Truhlar et al. [15]. These calculations are in better agreement with experiment at small angles but still disagree both in form and magnitude at large angles.

The distorted-wave calculations of Madison and Shelton [7], while still considering the collision as a weak interaction, nevertheless, includes distortion of the incident wave as well as exchange. The agreement at 48.2 eV is very good but gets poorer as the incident energy decreases, although still an improvement on the Born approximation.

3.1.2 Excitation of the $2^3P$ state. — The differential cross section for excitation of the $2^3P$ level at 29.2 eV, 39.2 eV and 48.2 eV, along with other experimental and theoretical results are shown in figures 6, 7 and 8 respectively. Once again there is very good agreement between these results and the recent measurements of Trajmar [18] at 29.6 eV and 40.1 eV, except our angular resolutions would not allow us to observe his finer oscillations. At 48.2 eV there is also good agreement with the older measurements of Trajmar et al. [14] which were taken at 55 eV and only up to 70°. At this energy there is also good accord with the absolute measurements of Crooks [19].

Excitation of the $2^3P$ state from the ground state is spin forbidden, and can only take place under electron impact through the exchange of an incident and orbital electron. This process represents an interaction of short range. Consequently, very few partial waves contribute to the differential cross section and it can be expected to have a flat profile. This is the case, as is shown in the figures.

When applied to allowed transitions, first order calculations which include exchange are usually, of little improvement on the simpler Born approximation. Also as a rule they are less successful in calculating spin-forbidden cross sections than the Born approximation is in calculating those of allowed transitions. Mainly the exchange approximations only fair well at energies above 100 eV when exchange is low. Cartwright [28], Steelhammer [29] and Steelhammer and Lipsky [30] have recently used first-order exchange approximations to obtain $2^3P$ differential cross sections and the results of the latter authors using the
FIG. 8. — Same as figure 6 except at 48.2 eV. The results of Trajmar et al. [14] as well as the theoretical calculations were performed at 55.5 eV. The dash-dot curve represents the results of Crooks [19] at 50 eV.

Born-Oppenheimer and Ochkur approximations are shown in figures 6-8. The agreement with experiment is surprisingly good over the small angular ranges considered. In fact, the agreement between the integral cross sections is not so good. The Born-Oppenheimer approximation (Fig. 16) gives a cross section which is several times greater than that observed experimentally. The Ochkur approximation gives a better agreement but this theoretical technique is in reality a simplification of the Born-Oppenheimer approximation and on theoretical grounds should only give results comparable to those of Born-Oppenheimer at higher energies (> 100 eV). Consequently the apparent success here of this method at these low energies can be regarded as fortuitous.

3.1.3 Excitation of the $2^1S$ state. — Figures 9, 10 and 11 show the differential cross sections for excitation of the $2^1S$ state from the ground state at 29.2 eV, 39.2 eV and 48.2 eV respectively. The results at 39.2 eV are in excellent accord with those of Trajmar [18] but at 29.2 eV the agreement is less good. At 29.2 eV the minimum in our results is less deep and also the oscillations seen in the curve of Trajmar are not apparent. The angular resolution of our system depends on the settings of the analyzer optics which at 29.3 eV probably correspond to a low angular resolution which could explain these discrepancies. At 48.2 eV the general agreement with the measurements of Rice et al. [16] and Crooks [19] is good except our results show a deeper minimum. Once again varying angular resolutions of the experimental set-ups can explain these differences.

Excitation of the $2^1S$ level from the ground state is symmetry forbidden but can be excited by electron impact through a short-range monopole interaction with an exponentially decreasing form and also through a longer range interaction proportional to $1/r^4$ arising from strong polarisibility of the s orbitals. The Born approximation only takes the first of these two interactions into account. Differential cross sections were obtained using this approximation by means of the formula provided by Kim and Inokuti [27] and the results are shown in the figures. These theoretical

FIG. 9. — Differential excitation cross section of the $2^1S$ state at 29.2 eV. The present results (open circles) are joined by small dashes. The large dashed curve represents the results of Trajmar [18] at 29.6 eV. The full curves represent theoretical calculations using the Born approximation (B) from reference [27] and the polarized Born-Ochkur-Rudge approximation (POL BOR) at 34 eV [16].

FIG. 10. — Same as figure 9 except at 39.2 eV. The results of Trajmar [18] were taken at 40.1 eV. The (POL BOR) curve was obtained at 44 eV.
results bear little relation to experiments; the sharp minimum is completely unrepresented. Rice et al. [16] have adapted first order approximations to include polarization and in most cases the accord with experiment is little better than that of Born. However, in some cases a minimum was observed in their differential cross sections (see Fig.) but this was only when a value for the polarizability several times that which is physically expected was used.

The shape of the differential cross section with its sharp minimum is very remarkable and cannot be described by a single partial wave. A more likely explanation is that the direct amplitude represented by low angle scattering and the exchange scattering amplitude represented by high angle scattering interfere destructively to produce this minimum.

3.1.4 Excitation of the 2 3S state. — The differential cross sections for excitation of the 2 3S level from the ground state at 29.2 eV, 39.2 eV and 48.2 eV are shown in figures 12, 13 and 14 respectively. Once again the agreement with the recent results of Trajmar [18] at 29.6 eV and 40.1 eV is excellent except for the fact that we do not observe the minor oscillations which in this case are particularly noticeable on his curves. The older results of Trajmar et al. [14] which were only taken up to 50° are also in reasonable accord. The measurements of Crooks et al. [20] correspond well to our observations at 39.2 eV, but at 48.2 eV the agreement is less satisfactory; the minimum in their curves descends to a much lower value. The differential cross section of the 2 3S level is evolving very rapidly in this energy region and goes to virtually zero at 90° at 53 eV as the detailed study of Crooks et al. [20] shows. Consequently, this rapid evolution probably explains the difference between the two curves which takes place as the energy changes by as little as 1.8 eV. Excitation of the 2 3S level from the ground state is symmetry-and-spin-forbidden and can only be accomplished in electron impact through exchange.
FIG. 14. — Same as figure 12 except at 48.2 eV. The results of Trajmar et al. [14] and the calculations were performed at 55.5 eV. The dash-dot curve represents the results of Crooks and Rudd [20] at 50 eV.

First-order calculations were performed by Steelhammer [29] and the results using the Born-Oppenheimer and Ochkur approximations are used in the figures. In this case, theory does not have the apparent success it had for the $2^3P$ level and has no relation whatsoever to experiment.

The $2^3S$ differential cross section evolves the most rapidly of any of the $n = 2$ manifold states observed in this study. Crooks et al. [20] attribute this to the presence of a p-wave resonance centered at 53 eV with a width of 15 eV. If this is the case then first-order approximations cannot be used as they do not describe resonant behaviour. In order to obtain accurate cross sections in the presence of resonances more powerful analytical techniques will have to be used.

3.2 INTEGRAL CROSS SECTIONS. — The differential cross sections presented in the previous section were extrapolated to 180° and integrated to yield the integral cross sections. The results obtained for the four $n = 2$ states at 29.2 eV, 39.2 eV and 48.2 eV are presented in table IV along with an estimation of the error. The error value reflects the error in obtaining the differential cross sections as well as an allowance for an error in the extrapolation procedure.

3.2.1 $2^1P$ excitation cross section. — Experimental and theoretical integral cross sections for exciting the $2^1P$ level from the ground state are shown in figure 15. There is excellent concordance between these results and the recent measurements of Donaldson et al. [11], especially when it is considered that two very different experimental techniques are employed. Donaldson et al. [11] obtained the cross section after optical detection of the photons emitted when the $2^1P$ level decays to the ground state. Both of these results are somewhat higher than the observations of Jobe and St. John [8] who also used an optical technique. The latter workers show, in a more recent study [31] that radiation trapping and transfer is an important factor in determining the $2^1P$ cross section and may well have underestimated its effect in their earlier work. Two cross sections calculated by Truhlar et al. [15] using first order approximations are shown in the figure. Both give results which are too large. The cross section obtained using the post form of the Born-Ochkur-Rudge approximation and the oscillator strengths of Kim and Inokuti [27], while being a slight improvement on Born at low energies, is not as good above 50 eV. The distorted-wave calculations of Madison and Shelton [7] give cross sections much nearer the experimental observations and at 48.2 eV almost fall within the error bars. The near-threshold cross sections of Burke et al. [6] using the elaborate close-coupling method are shown and are considerably larger than the measurements of Jobe and St. John [8].

3.2.2 $2^3P$ excitation cross section. — Figure 16 shows experimental and theoretical cross sections for excitation of the $2^3P$ level from the ground state. The measurements of Trajmar [18] are slightly lower than ours, but within our combined experimental uncertainty. The optical results of Jobe and St. John [8] are even lower but the disagreement is less than in the $2^1P$ case. These workers showed that radiation trapping and transfer are less important for the $2^3P$ level than for the $2^1P$ level. Consequently, any
TABLE V

Experimental integral cross sections for excitation of the n = 2 states of helium at 29.2, 39.2 and 48.2 eV. The estimated errors are indicated.

<table>
<thead>
<tr>
<th>$E_{1}$ (eV)</th>
<th>$2^1\text{P}$</th>
<th>$2^3\text{P}$</th>
<th>$2^1\text{S}$</th>
<th>$2^3\text{S}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>29.2</td>
<td>40 ± 8</td>
<td>27.6 ± 5.4</td>
<td>24.1 ± 7.0</td>
<td>17.1 ± 5.0</td>
</tr>
<tr>
<td>39.2</td>
<td>68 ± 10</td>
<td>21.4 ± 4.2</td>
<td>21.0 ± 6.0</td>
<td>14.0 ± 12.0</td>
</tr>
<tr>
<td>48.2</td>
<td>84 ± 16</td>
<td>14.0 ± 2.8</td>
<td>19.6 ± 5.0</td>
<td>8.0 ± 12.0</td>
</tr>
</tbody>
</table>

3.2.3 2 $^1\text{S}$ excitation cross section. — Experimental and theoretical cross sections for electron impact excitation of the $2^1\text{S}$ state from the ground state are shown in figure 17. Once again there is very good agreement between these results and those of Trajmar [18] and the measurement of Crooks [19].

The earlier observations of Rice et al. [16] are much smaller and the more recent observations by Trajmar [18] of the same group can be considered to supersede them.

The calculations of Rice et al. [16], using the Born and the post form of the Born-Ochkur-Rudge approxi-
mations are displayed in the figure. The latter technique appears to give reasonable results but the more severe test of differential cross sections (see Section 2.1.3) shows this approximation to be inadequate in describing the experimental observations. The polarised Born-Ochkur-Rudge results which at least produced a valley as observed experimentally, yields an integral cross section too big; its maximum is twice that of the Born curve. The close-coupling calculations [6] show structure near threshold which is due to resonances.

3.2.4 2 $^3S$ excitation cross section. — Figure 18 shows theoretical and experimental results for electron impact excitation of the 2 $^3S$ state from the ground state. Here again the agreement between these results and those of Trajmar [18] and Crooks et al. [20] is good. The curve from threshold to 29 eV was obtained by the authors with a separate experimental set-up using the technique described in a previous paper [33]. This curve was placed on an absolute scale by normalizing the first peak to the value of $4.0 \times 10^{-18}$ cm$^2$ which was obtained by Brongersma and co-workers [34]. As can be seen the cross section is low at 29 eV but considering the experimental uncertainties inherent in this technique (which become large as the energy from threshold increases), the agreement is not unreasonable.

![Fig. 18. — Integral excitation cross section of the 2 $^3S$ state. Symbols are the same as for figure 15 except the crosses are the results of Trajmar [18]. The triangles are the results of Crooks and Rudd [20]. The dashed curve was obtained by the authors using the trapped electron technique (see text). Calculations using the Ochkur approximation (O) are shown [32].](image)

The structure in the low energy experimental cross section is faithfully described by the close coupling calculation of Burke et al. [6]. However, the cross section appears to be too large. The Ochkur approximation results of Ochkur and Bradsev [32] are the only first order calculations which can be placed on the same scale. The Born-Oppenheimer calculations of Steelhammer [29] rise to a peak value which is forty times that of the Ochkur curve.

4. Conclusion. — An electron impact spectrometer is described and its use for measuring the differentials and integral excitation cross sections of the $n = 2$ state of helium at 29.2 eV, 39.2 eV and 48.2 eV is presented.

The excellent general agreement between these differential cross sections and those of other workers is very encouraging, especially when the fact that they were made absolute by different independent methods is taken into consideration. The 2 $^1P$ integral cross section agrees well with recent optical measurements. Here the results were obtained by completely different experimental techniques and the concordance is most satisfying. The integral excitation cross sections of the other $n = 2$ states as measured by the different electron impact spectroscopic methods are in good agreement as would be expected from the agreement of their differential cross sections.

On the theoretical side the agreement is not as encouraging. First-order calculations bear very little relationship either to each other or to experiment, and it appears that more powerful analytical techniques will have to be used. This is especially so in the case of excitation of the 2 $^3S$ state where a resonance behavior dominates the excitation mechanism throughout this energy range. The distorted wave calculations of the 2 $^1P$ cross section give the best agreement yet with observations. It will be interesting to see if this technique gives as good results for the optically forbidden transitions to the other $n = 2$ states where the mechanism is through short range potentials which are more difficult to formulate.

The general agreement between the experimental cross sections obtained by widely differing techniques is particularly impressive and would tend to reinforce the validity of the values obtained. Also it demonstrates the great value of electron impact spectroscopy as a technique for obtaining cross sections.

Acknowledgments. — We wish to express our gratitude to Professor C. Magnan for continuing support and encouragement and we acknowledge gratefully the technical assistance of M. Lejards and the financial support of the « Centre National de la Recherche Scientifique (ERA 156) ». Thanks are also due to S. Trajmar and coworkers for sending us their results prior to publication and also to D. H. Madison and W. N. Shelton for performing calculations at our impact energies and communicating them to us before publication. We are also grateful to D. Andrick and A. Bitsch for sending their elastic differential cross sections in numerical form.
Here the relationship between the dispersion (transmission function width at half height) of the monochromators and the width at half height of structure observed in energy loss and constant residual energy spectra, and excitation functions is obtained. It is assumed that no relaxation occurs during the acceleration or deceleration processes, that is, the electron distribution functions are only translated with energy change and the same profile is conserved. Also no broadening due to the thermal motion of the target particles is considered.

Let $P_s(E)$ and $P_a(E)$ be the probability that an electron of energy $E$ goes through the selector and analyzer respectively.

Then the incident current yielded by the selector $I_s$ is given by

$$ I_s \propto \int f(E) P_s(E) \, dE $$

where $f(E)$ is the electron distribution function from the electron source. Here the electron source is considered « white » so that $f(E)$ is a constant.

The current collected after passing through the two monochromators is proportional to,

$$ I_x \propto \int \sigma(E) P_s(E) P_a(E) \, dE $$

where $\sigma(E)$ is the differential cross section of the observed phenomenon.

If Gaussian distributions are assumed for the transmission functions of the selector and analyzer with normalization factors $N_s$ and $N_A$ respectively, then

$$ I = N_s N_A \int_0^\infty \sigma(E) \exp \left( \frac{E - E_s}{T_s} \right)^2 \exp \left( \frac{E - E_A}{T_A} \right)^2 \, dE $$

where $E_s$ and $E_A$ are the mean selection energies of the monochromators and $T_s$ and $T_A$ are constants related to the half heights of their transmission functions $\gamma_s$ and $\gamma_A$ by the relationship

$$ \gamma = 2 \sqrt{\ln 2} \, T = 1.67 \, T. $$

The above expression can be written :

$$ I = N_s N_A \exp \left( \frac{(E_A - E_s)^2}{T_A^2 + T_s^2} \right) \times \int_0^\infty \sigma(E) \exp \left( \frac{E - E_m}{T_R} \right)^2 \, dE $$

where

$$ E_m = \frac{T_A^2 E_A + T_s^2 E_s}{T_A^2 + T_s^2} \quad \text{and} \quad T_R = \frac{T_s T_A}{\sqrt{T_s^2 + T_A^2}}. $$

In the case of an energy loss spectrum ($E_s$ constant, $E_A$ varies) or a constant residual energy spectrum ($E_s$ varies, $E_A$ constant), $\sigma(E)$ can be assumed constant over an energy range $2 \Gamma_R$ and equal to $\sigma$. Then the integral gives :

$$ I = N_s N_A \frac{\Gamma_R}{\sqrt{\pi}} \, \exp \left( \frac{(E_A - E_s)^2}{\Gamma_A^2 + \Gamma_s^2} \right) $$

and a Gaussian peak is observed with $\Gamma_R$ given by

$$ \Gamma_R^2 = \Gamma_A^2 + \Gamma_s^2 $$

where $\gamma_R$, the width at half height of an observed peak, is related to $\Gamma_R$ by

$$ \gamma_R = \frac{\Gamma_A}{\sqrt{\Gamma_A^2 + \Gamma_s^2}}. $$

Thus if $\gamma_A = \gamma_s = \gamma$ then $\gamma_R = \sqrt{2} \gamma_R$.

In the case of an excitation function the width of observed structure depends on the variation of $\sigma(E)$. If this structure in $\sigma(E)$ is very fine it can be represented by a Dirac distribution, then

$$ \sigma(E) = \delta(E - E_r) $$

where $E_r$ is the energy position of the structure. In an excitation function the difference $E_s - E_A$ is maintained fixed and only $E_m$ varies.

The integral now becomes :

$$ I = N_s N_A \exp \left( \frac{(E_A - E_s)^2}{T_A^2 + T_s^2} \right) \times \int_0^\infty \delta(E - E_r) \exp \left( \frac{E - E_m}{T_R} \right)^2 \, dE $$

$$ = N_s N_A \exp \left( \frac{(E_A - E_s)^2}{T_A^2 + T_s^2} \right) \exp \left( \frac{E_r - E_m}{T_R} \right)^2. $$

Hence, a Gaussian profile is observed with $\gamma_r$, the width at half height, given by :

$$ \gamma_r = 2 \sqrt{\ln 2} \, T_R = \frac{\gamma_s \gamma_A}{\sqrt{\gamma_s^2 + \gamma_A^2}}. $$

if

$$ \gamma_s = \gamma_A = \gamma, \quad \text{then} \quad \gamma_r = \frac{\gamma}{\sqrt{2}}. $$

The case of a resonant structure in $\sigma(E)$ with a Lorentzian profile and the effect of monochromator dispersion on the observed width has been studied and computed recently by Comer and Read [35].
APPENDIX II

Here the energy variation of the scattered electron in the laboratory system is obtained by considering total energy and momentum conservation. Capital letters are used in the centre of mass system and small letters in the laboratory system.

Energy conservation gives:
\[
\frac{1}{2} m_1 V_1^2 + \frac{1}{2} m_2 V_2^2 = E_a + \frac{1}{2} m_1 V_1'^2 + \frac{1}{2} m_2 V_2'^2 \tag{1}
\]
where subscripts 1 and 2 indicate the electron and target atom respectively, the primes indicate final velocities, and \( E_a \) is the internal energy change of the target atom.

Momentum conservation gives,
\[
V_2 = -\frac{m_1}{m_2} V_1 \quad \text{and} \quad V_2' = -\frac{m_1}{m_2} V_1'
\]
which when substituted in eq. (1) gives,
\[
V_1'^2 = V_1^2 - \frac{2\mu}{m_1} E_N \quad \text{with} \quad \mu = \frac{m_1 m_2}{m_1 + m_2}.
\]

The energy variation in the laboratory system \( \Delta E \) is,
\[
\Delta E = \frac{1}{2} m_1 (v_1'^2 - v_1^2)
\]
\[
= \frac{1}{2} m_1 ((|V_1' + v_M|^2 - |V_1 + v_M|^2)
\]
where \( v_M \) is the centre of mass velocity.

Then, letting
\[
\Delta v = v_1' - v_1 = V_1' - V_1
\]
\[
\Delta E = m_1 \Delta v \cdot v_M - \frac{\mu}{m_1} E_a
\]
or in equivalent form
\[
\Delta E = -E_a - \frac{m_1}{m_2} \left( \frac{1}{2} \frac{m_1}{m_1 + m_2} |\Delta v|^2 \right) + m_1 \Delta v \cdot v_2.
\]

APPENDIX III

Using the same notation as in Appendix I. If the incident electron distribution \( p_s(E_s, \Gamma_s, E) \) d\( E \) is broadened by the scattering and becomes
\[
p_b(E_b, \Gamma_b, E) \ dE,
\]
then flux conservation implies:
\[
\int_0^\infty p_b(E_b, \Gamma_b, E) \ dE = \int_0^\infty p_s(E_s, \Gamma_s, E) \ dE.
\]
Assuming Gaussian distributions for both the incident and scattered electrons then a relationship occurs between the normalization factors \( N_B, N_S \) and \( \Gamma_B, \Gamma_S \) such that
\[
\Gamma_B N_B = \Gamma_S N_S.
\]

The collected current is maximum for certain values of \( E_s \) and \( E_a \). For instance, in the elastic scattering case this occurs for \( E_s = E_a \). From Appendix I the current at the maximum of the distribution \( I_E \) without thermal broadening would be:
\[
I_E (E_s = E_a) = N_s N_A \sigma \Gamma \sqrt{\pi}
\]

where
\[
\Gamma = \frac{\Gamma_A \Gamma_S}{\sqrt{\Gamma_A^2 + \Gamma_S^2}}
\]
but because of broadening it is measured as:
\[
I_b (E_s = E_A) = N_B N_A \sigma \Gamma' \sqrt{\pi}
\]
where
\[
\Gamma' = \frac{\Gamma_A \Gamma_B}{\sqrt{\Gamma_A^2 + \Gamma_B^2}}
\]
which then becomes
\[
I_E = I_B \frac{N_S \Gamma_S}{N_B \Gamma_B} \sqrt{\frac{\Gamma_A^2 + \Gamma_B^2}{\Gamma_A^2 + \Gamma_S^2}} = I_B \sqrt{\frac{\Gamma_A^2 + \Gamma_B^2}{\Gamma_A^2 + \Gamma_S^2}}.
\]
But \( \Gamma_A^2 + \Gamma_B^2 = \gamma_p/1.67 \) where \( \gamma_p \) is the width at half height of the elastic peak in an energy-loss spectrum without broadening. Then similarly \( \Gamma_A^2 + \Gamma_S^2 = \gamma'/1.67 \) and \( \gamma' \) is the width with broadening. Thus
\[
I_E = I_B \frac{\gamma_p}{\gamma' P}.
\]
The same relationship holds in the inelastic case.

Bibliographie


[18] TRAJMAR, S., to be published.


