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AN ELECTRON-ATOM CROSSED BEAM
APPARATUS AND ITS FIRST APPLICATIONS

by

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Thesis submitted to the University of Stirling
for the degree of Doctor of Philosophy

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ABSTRACT

An electron-atom crossed beam apparatus has been designed and constructed. The set up uses an electron impact spectrometer in which electrons with a well defined energy are crossed with atomic target beams. The apparatus can be used for optical excitation measurements as well as for energy loss and elastic scattering experiments. Observations can be made at fixed or variable angles. Owing to the availability of independent detection channels for scattered electrons and photons it is possible to use the apparatus to make coincidence measurements.

The instrument has so far been used to study elastic scattering of electrons from atomic hydrogen and helium and for energy loss observations with helium. Further investigations have been made of the resonance structure in the excitation of first excitation levels of Ne, Ar, Kr and Xe, as well as in the 2S excitation of atomic hydrogen. 

§ These experiments are described in H. Koschmieder, Ph.D. thesis, Physics Department, University of Stirling.
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1. INTRODUCTION

Recent improvements in the design of electron guns, leading to electron monochromators, which, to some extent coincided with theoretical predictions of so-called resonances have again stimulated electron-atom collision experiments. These have led to the discovery of many narrow structures in electron-atom collision cross-sections. These structures are referred to as resonances. In a number of cases resonances have been observed experimentally but can not yet be fully described theoretically.

One particular process is especially interesting, namely electron-atomic hydrogen scattering. This process involves three particles and all the interactions between the three particles are well known, as well as the eigen­-functions of the H-atom. Therefore theory can formulate the electron-atomic hydrogen scattering processes exactly. Nevertheless it was not yet possible to obtain exact solutions of these theoretical problems. In recent years many approximations have been developed, resulting in the prediction of resonance structure in the elastic and inelastic channels. These theories can be tested by electron-atomic hydrogen scattering experiments.

The hydrogen problem is of interest to experimentalists as well. The precise knowledge of the elastic scattering resonances would supply a useful reference for experiments on other targets. Energy scales could be calibrated absolutely and furthermore it would become possible to do absolute cross-section measurements with much higher accuracy and less experimental difficulties than it has been hitherto. This requires a complete
set of elastic scattering phase-shifts to be deduced from angular distribution measurements of the elastic resonances in atomic hydrogen. Unfortunately the experimental situation, as far as atomic hydrogen scattering is concerned, is totally different from the theoretical position. Atomic hydrogen is so far one of the most difficult targets for scattering experiments.

Apart from the atomic hydrogen case it seems to be of great interest to get more information about similar features in other atomic and molecular systems, if only to stimulate theoretical work.

The growing interest in these types of features has led to the design of a crossed-beam apparatus which permits investigations of elastic and inelastic electron-atom scattering processes at fixed or variable angles. The apparatus has been set up and used for hydrogen and rare gas scattering experiments. It is possible to use the apparatus for a number of target gases, since one aim of the design was to achieve flexibility in the choice of target source.

1.1 General features of resonant scattering.

Resonances in electron-atom scattering can be explained by the formation of temporary negative ion states. The incident electron is retained by the target atom for a short time, thus forming an ion-state, which then decays. These ion states, which are analogous to the compound states in nuclear physics, distort the wave functions of the normal scattering processes and therefore affect the cross-section.
Resonance processes can be described schematically in the following way

\[ A + e \ (E_{\text{res}}) \rightarrow A^* + A + e \ (E_{\text{res}}) \]

in the case of elastic scattering. These processes interfere with the direct process

\[ A + e \ (E) \rightarrow A + e \ (E) \]

The interference between those two processes has a strong influence on the cross-section. Similar processes can occur in electron impact excitation

\[ A + e \ (E_{\text{res}}) \rightarrow A^* + A^* + e \ (E_{\text{res}} - E_n) \]

\[ \rightarrow A + h\nu \]

again interfering with the direct process for excitation. The final state of the target can be the groundstate or an excited state. The shape of the resonance can take different forms which depend on the decay mechanisms. Generally resonances show themselves as sharp anomalies in the cross-section.

One distinguishes between two basic forms of resonances - shape resonances (or open-channel or Type II resonances), and Feshbach resonances (or closed-channel or Type I resonances). The difference is in the way in which the electrons are trapped by the target. In the case of a shape resonance the electron passes close to the target atom and is trapped there by a potential barrier. The resonance decays by the electron tunnelling through the potential barrier. The energy width of the resonance is determined by the height of the potential barrier. If the electron has excited the
target and is left with little energy, then it is bound for a long time and the width of the resonance can be of the order of a few millivolts as in the case of the 10.22 eV shape resonance of atomic hydrogen.

Feshbach resonances occur when the incident electron causes an excited compound state which is energetically lower than the excited states of the target and is left with less energy than is required for tunnelling. The electron must therefore gain energy to escape. Feshbach resonances are thus very narrow, since they almost correspond to bound states. (Taylor H.S. et al 1966).

1.2 Some theoretical aspects of low energy electron-atom scattering.

Scattering processes are described by cross-sections. The cross-section for a particular process can be defined as the apparent area presented by the target atom to the incident particle. The differential cross-section $\sigma(\theta)$ is used to describe angular variations of scattering processes and is defined as the apparent target area $d\sigma$ causing an incident particle to be scattered into a solid angle $d\Omega$ between scattering angles $\theta$ and $\theta + d\theta$. The scattering angle is the angle through which the incident particle is deflected by the target:

$$\sigma(\theta) = \frac{d\sigma}{d\Omega} \text{ cm}^2$$

The total cross section

$$\sigma_{\text{tot}} = 2\pi \int_0^\pi \sigma(\theta) \sin \theta \, d\theta \text{ cm}^2$$

describes the deflection of incident particles through any angle.
Theories of electron scattering by atoms face various difficulties. The equation of motion for the system, consisting of projectile electron and target atom, is a many-body problem and cannot yet be solved exactly. One cannot distinguish between projectile and atomic electrons. Inelastic processes can occur if the electron energy is high enough to induce transitions of the target atom to its excited states.

The time-independent Schrödinger equation for the total system of target atom and projectile electron is

$$[H_A(r_j) + H_1(r_1) + V(r_1, r_2, ..., r_j) - E] \psi(r_1, ..., r_j, s_1, ..., s_j) = 0$$

(3)

$H_A(r_j)$ is the atomic Hamiltonian, $H_1(r_1)$ is the Hamiltonian of the incoming electron and $V(r_1, r_j)$ describes the interaction between incoming electron and the $i$-th target electron. Distances are measured from the nucleus, assumed to be at rest. $s_i$ is the spin coordinate of the $i$-th electron. Spin coordinates are included, in order to satisfy the Pauli exclusion principle.

The simplest target system is the hydrogen atom with only one electron. The importance of the hydrogen case is amplified by the fact that, in this scattering process, all the interactions are known and the eigenfunctions of the hydrogen atom are known exactly. It is however, even in the case of hydrogen, still very difficult to get cross-section values of reasonable accuracy by means of the different approximations. An exact solution has not yet been obtained.

For the case of atomic hydrogen, (3) reduces to

$$\left[ \frac{\hbar^2}{2m} (v_1^2 + v_2^2) + \frac{e^2}{r_1} + \frac{e^2}{r_2} - E \right] \psi(r_1, r_2) = 0$$

(4)
Index 1 refers to the projectile electron, 2 to the target electron. E is the total Energy of the System

\[ E = E_o + E_k \]  

(Eq. 5)

\( E_o \) being the energy of the atom in the ground state, \( E_k \) the kinetic energy of the projectile electron.

A standard method of describing the collision between electron and atom was suggested by H.S.W. Massey and C. B. Mohr in 1932. The wave function is expanded in terms of the unperturbed eigenfunctions of the target atom

\[ \psi(r_1, r_2) = \left( \frac{\chi_n}{\sqrt{2 \gamma}} \right)^n F_n(r_1) \]  

(Eq. 6)

Discrete states of the atom are taken into account by \( \chi_n \) and the continuum states by \( f \). The eigenfunctions \( \psi_n(r_2) \) satisfy the Schrödinger equation of the H-atom

\[ \left( \frac{\hbar^2}{2m} \frac{\partial^2}{\partial r_2^2} + \frac{e^2}{r_2} - E_n \right) \psi_n(r_2) = 0 \]  

(Eq. 7)

and are known exactly. Equations (6) and (4) result in

\[ \left( \frac{\hbar^2}{2m} \left( \frac{V_1}{r_1} + \frac{V_2}{r_2} \right) + \frac{e^2}{r_1} + \frac{e^2}{r_2} - E_n \right) \psi_n(r_2) F_n(r_1) = 0 \]  

(Eq. 8)

Putting \( k_n^2 = \left( \frac{2m}{\hbar^2} \right) (E - E_n) \) the \( E_n \) represent the energy eigenvalues, and since (7)

\[ \left( \frac{\hbar^2}{2m} \left( \frac{V_1}{r_1} + k_n^2 \right) + \frac{e^2}{r_1} - \frac{e^2}{r_1^2} \right) \psi_n(r_2) F_n(r_1) = 0 \]  

(Eq. 9)

Multiplying (8) by \( \psi_n^* \) and integrating over \( r_2 \) it follows that, since \( \int \psi_n^* \psi_m d^3r_2 = 0 \) for \( n \neq m \)

\[ (V^2 + k_n^2) F_n(r_1) = (\frac{\chi_n}{\sqrt{2 \gamma}})^n U_{nm} F_m(r_1) \]  

(Eq. 10)
where
\[ U_{nm}(r_1) = \frac{2me^2}{\hbar^2} \int_{\mathbf{r}_2} \psi_n(\mathbf{r}_2) \left( \frac{1}{r_{12}} - \frac{1}{r_1} \right) \psi_m(\mathbf{r}_2) d\mathbf{r}_2 \]  
\[ = \frac{2m}{\hbar^2} V_{nm} \]  

(11) represents the averaged interaction potential experienced by the projectile electron. Equation (10) represents a system of coupled differential equations for the expansion coefficients \( F_n(r_1) \).

The scattering process, neglecting exchange processes, requires a wavefunction with the following asymptotic form
\[
\psi(\mathbf{r}_1, \mathbf{r}_2) \approx \sum_{n=1}^{\infty} F_n(\mathbf{r}_1) \frac{e^{ikr_1}}{r_1} + \sum_{n=1}^{\infty} \psi_n(\mathbf{r}_2) \frac{f_n(\theta)}{r_1} \frac{e^{ikr_1}}{r_1} \]  
\[ = \sum_{n=1}^{\infty} F_n(\mathbf{r}_1) \frac{e^{ikr_1}}{r_1} + \sum_{n=1}^{\infty} \psi_n(\mathbf{r}_2) \frac{f_n(\theta)}{r_1} \frac{e^{ikr_1}}{r_1} \]  
\[ = \sum_{n=1}^{\infty} F_n(\mathbf{r}_1) \frac{e^{ikr_1}}{r_1} + \sum_{n=1}^{\infty} \psi_n(\mathbf{r}_2) \frac{f_n(\theta)}{r_1} \frac{e^{ikr_1}}{r_1} \]  
(12)

which means that, before the collision, the atom is in the groundstate and the projectile electron is represented by a plane wave. \( f_n(\theta) \) is the scattering amplitude. After the scattering occurs, the projectile electron is represented by a spherical wave, whereas the atom may be in an excited state. By comparing (12) and (6), the original expansion,
\[ F_n(r_1) = \frac{f_n(\theta)}{r_1} e^{ikr_1} \]  
(13)

Since the differential cross section for the scattering process is defined as
\[ \sigma_n(\theta) = |f_n(\theta)|^2, \]  
and the total cross section can be obtained by integrating over
all scattering angles

\[ \sigma = 2\pi \int \rho^2 |\psi(\theta)|^2 \sin \theta \, d\theta, \]

one can describe the scattering process completely.

Another way of solving the Schrödinger equation in order to calculate the scattering amplitudes and hence the cross sections is to expand the wavefunction in terms of Legendre Polynomials:

\[ \psi(r, \theta) = \sum_{l=0}^{\infty} A_l (k^2 \rho) \lambda_l P_l(\cos \theta) \]

This leads to the following expression for the scattering amplitude

\[ f(\theta) = \frac{1}{2\pi k} \sum_{l=0}^{\infty} \frac{2i \delta_l}{l+1} e^{i (l+1)\delta_l} P_l(\cos \theta) \]

and thus to

\[ \sigma(\theta) = |f(\theta)|^2 = \frac{1}{4k^2} \sum_{l=0}^{\infty} \frac{2i \delta_l}{l+1} e^{i (l+1)\delta_l} P_l(\cos \theta)^2 \]

\( \delta_l \) represents the phase shift of a partial wave with orbital angular momentum \( l \). If only elastic scattering occurs, then the \( \delta_l \) are real. In case of inelastic collisions \( \delta_l \) has an imaginary part describing absorption by the target and thus excitation. So far both methods are equivalent and exact in describing the solution of the scattering problem.

Equation (10) represents an infinite set of coupled differential equations, coupled by means of the averaged potential which is experienced by the projectile electron during scattering and
described by (11). Since one cannot solve this complete set numerically one has to truncate the set of states taken into account. This leads to various approximations as solutions for the truncated expansion of the wave function.

The first theoretical evidence for resonances in elastic scattering of electrons by hydrogen was indicated in a 2-state strong coupling approximation by Smith et al (1962). A very rapid increase in the cross section was caused by anomalous increases in the \(^1S\) and \(^3P\) scattering phase shifts. Using close coupling approximations, that is, more than 2 states, in the expansion of the wavefunction, Burke and Schey (1962) were able to resolve this structure in 1962. Further calculations predicted a set of structures.

Although this approach can be generalized for all atoms, it is so far only applicable for those atoms whose eigenfunctions are well enough known. Apart from Hydrogen, this is only true for Helium. Therefore, there are no theoretical calculations available which predict resonances in heavy rare gases, although it is experimentally proven that they exist.

If one knows the positions of resonances and the exact partial waves which cause these structures, it is possible to work out the line profiles which will show up in scattering experiments. For the case of atomic hydrogen, one can write the differential cross section for elastic scattering of electrons in the following form
\[ \sigma(\theta) = \frac{1}{4k^2} \left| (2l+1)(e^{-i}\theta} - 1)P_l(\cos \theta) \right|^2 \]

\[ + \frac{3}{4k^2} \left| (2l+1)(e^{-i}\theta} - 1)P_l(\cos \theta) \right|^2 \quad (16) \]

The first part of the partial wave expansion represents singlet terms, the second part triplet terms. The phase shifts \( \delta_l \) can be split up into phase shifts due to potential scattering \( \delta_l, \text{pot} \) and phase shifts due to resonance scattering \( \delta_l, \text{res} \) according to

\[ \delta_l, \text{tot} = \delta_l, \text{pot} + \delta_l, \text{res} \quad (17) \]

The resonant part is described by

\[ \delta_l, \text{res} = \frac{\pi}{2} + \arctan \frac{1}{2} \frac{\Gamma_l}{E_l - E} \quad (18) \]

Taking theoretical values for the phase shifts and the positions \( E_{ln} \) of the \(^1S\) and \(^3P\) resonances of atomic hydrogen and their energy width \( \Gamma_{ln} \), a theoretical shape for the elastic cross section, as shown in fig.1, can be calculated. This method can be used to work out individual phase shifts from experimental data by curve fitting, resulting in an explanation of the configurations involved, as well as making an absolute measurement of the elastic cross section possible. This type of experiment has been carried out for He (Andrick D. and Ehrhardt H. 1966, Gibson J.R. and Dolder K.T. 1969). Similar experiments with atomic hydrogen have not yet been published.

The whole theoretical treatment has been described
Figure 1:
Computed resonance profile for the elastic scattering resonance structure $^1S$ and $^3P$ in atomic hydrogen. The s-wave shifts used are those of C. Schwartz (1961), p and d phases are those of A. Temkin and J. C. Lamkin (1961). Energies used are 9.571eV for the $^1S$ resonance with a half width of 0.049eV, and 9.727eV for $^3P$ with a half width of 0.010eV.
in great detail by a number of authors (e.g. Massey H.S.W. and Burhop E.H.S. 1969, Smith K. 1966, etc.).

1.3 Previous experiments

Since the first resonance was observed in elastic electron-He scattering by G. J. Schulz (1963), a number of similar features have been discovered in a number of scattering processes. A full description of these experiments can be found in a recent review article by G. J. Schulz (1973).

The only e-H scattering experiments which studied resonances in the elastic channel and which have been published so far, have been carried out by G. J. Schulz (1964) a transmission experiment, and by Kleinpoppen and Raible (1965) - a crossed beam experiment, which was followed by another crossed beam experiment by McGowan et al (1965). The results were in agreement. An angular distribution measurement is still outstanding. Recently the positions of hydrogen resonances in the elastic channel have been thoroughly investigated by Sanche and Burrow (1972). Their results are shown in fig.2 and compared with theoretical results. The same type of transmission experiment was used to locate resonance structure in rare gases (Sanche L. and Schulz G.J. 1972). Some of these structures have been observed in total metastable excitation experiments (Pichanick F.M.J. and Simpson J.A. 1968), elastic scattering experiments and optical excitation measurements (Kisker E. 1972). Figures 3 and 4 show level diagrams of Neon and Argon with the experimental values for resonances obtained in transmission experiments. The transitions which have been observed in Neon and Argon during the
Figure 2:
Energy level diagram for compound states in atomic hydrogen. The diagram is reproduced in modified form from G. J. Schulz (1973) and shows the theoretical values of Burke (1968). Experimental values for the compound states below $n = 2$ are those by L. Sanche and P. D. Burrow (1972), values higher than $n = 2$ are from McGowan et al (1965, 1969).
states in H and H^-(theor. values)

n=4
12.75

n=3
12.06
12.037
11.915
11.733

n=2
10.20
10.178
10.150
10.177
10.190

RESONANCES
McGowan et al. 1965, 1969
Sanche & Burrow 1972
experim. values

1s 3s 1p 3p 1d

ENERGY (eV)

13.0
12.0
11.0
10.0
9.0

1s 3s 1p 3p 1d

12.35
12.23
12.06
11.89
11.77
11.65

10.45
10.29
10.128

3f 1s
9.738
9.558
Figure 3:

Level diagram for argon. Reproduced, slightly modified, from G. J. Schulz (1973). Transitions described later on are indicated. Experimental values as observed by L. Sanche and G. J. Schulz (1972) in a transmission experiment are shown on the right of the diagram.
Sanche, S. and Schute, R. 1972

RESONANCES OBSERVED IN TRANSMISSION (Sanche & Schute 1972)

ENERGY (eV)

11.0 12.0 13.0 14.0 15.0 15.750

1s^2 2s^2 2p^6 3s^2 3p^6 1s_0

3p^5(2P_3/2) 4s 4p 3d

3p^5(2P_1/2) 4s 4p 3d

11.546 11.623 11.723 11.828

3P_2 meta 3P_1 1P_1

-11.11 -11.28 -11.71 -11.91

-12.90 13.06 13.2 13.3 13.4

Indicated.

L. Sanche

Mission

of the
Figure 4:

Energy level diagram for neon. Taken, in a slightly modified form, from G. J. Schulz (1973). The transitions discussed later on are indicated. Energy values on the right of the diagram are those observed in transmission by L. Sanche and G. J. Schulz (1972).
RESONANCES OBSERVED IN TRANSMISSION
(Sanche and Schulz 1972)
experiments described here are also shown in these figures. Excitation measurements of the Ar resonance lines published recently (Lloyd C.R. et al 1972, McConkey J.W. et al 1973) showed no evidence of structure in the threshold region, owing to insufficient energy resolution.

2. The apparatus

In order to carry out resonance scattering experiments, some basic requirements have to be met, the most essential of which are

(a) intensive target beam source
(b) strong electron beam source
(c) electron beam of reduced energy distribution
(d) electron beam of defined energy
(e) low magnetic and electric fields in the scattering region
(f) clean system
(g) low basic pressure
(h) low contact potentials

2.1 The vacuum system

Since the apparatus is ultimately to be used for electron-atomic hydrogen scattering experiments, the actual design was based on requirements necessary for this case. Minor modifications for electron scattering from rare gases will be mentioned where necessary.
The vacuum system consists of two chambers - a target source chamber and a scattering chamber. Provisions exist for the use of a titanium sublimation pump in the scattering chamber. This additional pump was considered necessary, to reduce the molecular hydrogen background, a problem in hydrogen experiments, caused by recombination. This pump could not be used so far because its electric supplies create interfering pulses, which have not yet been suppressed.

The target source chamber is pumped by a four-stage oil diffusion pump. Pumping speed for air is 6000 l/sec. This pump is baffled by a liquid nitrogen chevron-type baffle and a freon cooled chevron baffle. The temperature of the freon baffle was kept at -30°C to -50°C. The scattering chamber is evacuated by a 3000 l/sec four-stage oil diffusion pump, again baffled by liquid nitrogen and freon baffles. Both diffusion pumps are connected in parallel to a two stage rotary pump with a pumping speed of 100 m³/h. The diffusion pumps can be separated from the main tanks by means of electro-pneumatically operated gate valves. There is a by-pass connecting each vacuum tank separately with the backing pump. This additional backing line is available through hand-operated right angle valves mounted on either tank. Figure 5 shows a schematic diagram of the vacuum system.

At the moment DC705 oil is used in the diffusion pumps and seals are of viton. An even better ultimate vacuum could be achieved using metal seals. This can be done when required. Four-stage diffusion pumps are used to prevent pressure fluctuations when large amounts of hydrogen have to be pumped (Franke H. and Bauer H. 1965). The first stage
Figure 5:

Side view of the vacuum system which was used for the experiments described later on. All dimensions are given according to isometric standards. NW gives the nominal width of the ports in mm.
of the pump acts as a booster pump.

The actual vacuum system consists of two tanks with a nominal bore 350 mm. The scattering chamber is separated from the source chamber by means of a helmet-shaped vacuum wall with provisions for mounting beam apertures of different diameter. There are sufficient ports in either tank to take components as required. Tanks and flanges have been machined from immaculate V stainless steel. Argon arc welding techniques were used to make sure that the magnetic properties of the material were not distorted. All components are held together by isometric screws and bolts made from 18/8 or 18/8/2 stainless steel.

The whole system was designed to isometric standards using metric components. This was done to allow a flexible interchange of this equipment or parts of it with other systems in the future. Sealing discs were again to isometric standards. This type of seal allows one to use a metal or non-metal vacuum seal by a simple exchange of duraluminium discs carrying the sealing material.

The main tanks of this vacuum system can be baked at moderate temperatures by heater coils wrapped around the vessels. The maximum temperature used so far was 150°C. This could be raised by using metal seals which are capable of standing up to higher temperatures. So far only viton and some Indium seals have been used.

Ultimate pressures of $2 \times 10^{-7}$ torr can be achieved in both vacuum tanks after approximately two hours. The ultimate pressure after continuous running over several days is $10^{-8}$ torr. This pressure can be maintained with the
electron gun operating and a hot hydrogen dissociator. With the hydrogen beam on, a hydrogen pressure of $7.10^{-5}$ torr in the over chamber increases the pressure in the scattering chamber to about $3.10^{-6}$ torr. This pressure increase is almost entirely due to molecular hydrogen, which is created by recombination of atoms hitting the metal parts of the vacuum system. Some background pressure will also be caused by diffusion between the two vessels of this differentially-pumped system. This is one problem which could be reduced by means of an intermediate chamber. This however would certainly reduce the target beam intensity owing to the longer beam path. It was this problem of high molecular background which led to the consideration of using a titanium sublimation pump as mentioned before.

One disadvantage of the vacuum system described here could be the use of oil diffusion pumps, possibly resulting in contamination of the electron monochromators. Although great care was taken to reduce oil backstreaming into the system by means of liquid nitrogen and freon baffles, it is not possible to completely suppress it. To minimize the effect, the electron gun system is bakeable. This should counteract an extensive build-up of insulating oil layers on the electrodes.

2.2 The oven chamber

This part of the vacuum system consists of a T-shaped vessel with a nominal internal diameter of 350 mm (see fig.5) and a length of 652 mm. Six ports with nominal widths of 50 mm are available to take auxiliary equipment. One of these ports is used for a foreline by-pass which is
normally closed by means of a hand operated right angle valve. Three other ports take bakeable ionisation gauge heads, Balzers type IMR 5. One port contains an additional Pirani gauge and a venting valve. The system can be vented with air or other appropriate gas. The oven chamber extends into the scattering chamber by means of a concentric water-cooled vessel which has an overall length of 226 mm. This allows the hydrogen dissociator to be positioned as close to the scattering region as possible. The arrangement can be seen in figure 6. The concentric vessel had interchangeable target beam apertures up to a maximum of 20 mm Ø. The normal apertures used were between 3 mm Ø and 8 mm Ø, as required.

The pump column, which is suspended from a port with nominal diameter of 350 mm, can be separated from the oven chamber by means of an electro-pneumatically operated gate valve (VAT). This chamber is evacuated by a four-stage oil diffusion pump (Leybold Heraeus). The pump is baffled with a liquid nitrogen cooled chevron baffle and a freon cooled chevron baffle. The pumping speed of the diffusion pump is 6000 l/sec for air, according to the manufacturer.

A third port with nominal bore 350 mm is used to introduce the hydrogen, or other beam source into the system.

2.3 The scattering chamber

Another T-shaped tank with nominal bore 350 mm was used to accommodate the scattering section of the apparatus. A port on top of the tank was used to take a quadrupole mass spectrometer to investigate the fractional composition of the atomic hydrogen target at the interaction region. The electron
Figure 6:

Longitudinal section of the apparatus showing the electron spectrometer and the target beam source in position. The concentric extension of the source chamber into the interaction chamber is also shown.
spectrometer was introduced into the system through a port of nominal internal diameter of 200 mm. The spectrometer was mounted on a table which also supported a mechanical chopper. This gun table was then suspended on two stainless steel rods from an NW 200 mm flange. For the 2S excitation experiment (Koschmieder H. 1974) there were two separate ports on one side of the scattering tank to take components required for this experiment.

Additional ports of internal diameter 32 mm and 50 mm were used to accommodate bakeable ionisation gauge heads, a pirani gauge and a venting line. A separate foreline by-pass was available through a hand-operated right angle valve. The arrangement of vacuum ports and the internal arrangement of important components can be seen in figures 5 and 6 respectively.

The pump column was suspended from a 250 mm diameter flange and could be separated from the scattering chamber by means of an electro-pneumatically operated gatevalve (VAT). The scattering tank was pumped with a four stage oil diffusion pump (Leybold Heraeus). This pump was baffled with a liquid nitrogen cooled chevron baffle and a freon cooled chevron baffle. The nominal pumping speed of the diffusion pump was 3000 l/sec for air, according to the manufacturer.

The entire vacuum system was suspended from a beam and could be moved with castor wheels running along the beam. The steel beam itself was mounted on a scaffolding. All parts of the system have been designed according to DIN standards which have in the meantime been adopted almost entirely as isometric standards. Only metric components are used throughout.
2.4 Gas injection system

A schematic diagram of the gas injection system is shown in figure 7. By means of several mechanical leak valves it is possible to admit a number of pure gases or gas mixtures into the system. Mixtures can be monitored either by ionisation gauges or by means of a quadrupole mass spectrometer. This gas handling system is pumped through the main vacuum system. In the case of sudden leaks or of breakdown, an electromagnetic safety valve is automatically closed to safeguard the system. This is a necessary precaution, especially for hydrogen operation.

Rare gases used in the system were from research grade cylinders obtained from outside suppliers. Ultra-pure hydrogen was generated by means of a palladium silver diffusion cell. Heated to about 350°C, this cell transmits hydrogen but is impermeable to any other gas. The hydrogen was extracted from ordinary town gas which contains about 40% hydrogen. This method avoids the use of high pressure hydrogen gas cylinders and the dangers associated with them.

2.5 The interlock system

A system as expensive and elaborate as the one described here, a system which can even be a severe safety risk must be supplied with a fully automatic control system. This is even more necessary, since some of the experiments might require extended operation of the system, sometimes without attention.

A complete shut down of the system involving all equipment is caused by water failure, steep pressure rise or
Figure 7:

Schematic diagram of the gas handling system. The electromagnetic valve is connected to an interlock system to safeguard the apparatus.
failure in the liquid nitrogen cooling system. The control system designed works in two possible sequences. In one sequence there is a 20 minute delay of this procedure to carry out necessary adjustments. The other sequence, which is used if the system is left unattended, causes an immediate shut down including electric isolation of the system. This shut down involves the isolation of the vacuum system from pumps and gas intake. Disconnection of all electric supplies to the system is caused after a preset interval and the water supply to the apparatus is closed. The cause of this failure has to be cured otherwise it is not possible to restart the apparatus. These precautions have proven to be valuable and have certainly prevented expensive damage to the system on several occasions.

3. The atomic beam source

In this chapter the production of an atomic target beam and its properties, such as intensity and directivity are discussed. The treatment is for the complicated case of atomic hydrogen. In order to produce a significant proportion of atomic hydrogen in a beam, temperatures in excess of 2500°K are required. This creates technical problems, as will be mentioned. The recombination of atoms into hydrogen molecules results in background problems which have led to the design of a modulated beam.

3.1 General considerations

Using atomic beams in a vacuum system is equivalent to the artificial introduction of a leak into the
vacuum system. The leak rate and thus the intensity of the beam will be limited by the maximum value of the background pressure which can be tolerated in the system. This pressure is mainly determined by the proper functioning of components like detectors and, in this case, by the electron beam source. In order to maintain this pressure in the system one has to continuously pump the gas intake. This means, that the intensity of the target beam is very much dependent on the pumping speed of the vacuum system.

Pumping speeds given by manufacturers are normally optimum values, reached with a particular pump when pumping air of molecular weight 28. Since diffusion processes are involved, one can work out the actual pumping speed of a diffusion pump for different gases according to (Dennis N.T.M. and Heppel T.A.):

\[
S_{\text{GAS}} = S_{\text{AIR}} \left( \frac{28}{m_{\text{GAS}}} \right)^{1/2}
\]  

(1)

\(S\) is given in \(1 \text{ sec}^{-1}\), and \(m_{\text{GAS}}\) is the molecular weight of the gas being evacuated. Considering the conductance \(C_i\) of baffles, which are in series with the diffusion pump, the effective pumping speed at the vacuum system is

\[
S_{\text{eff GAS}} = \frac{S_{\text{GAS}}}{1 + S_{\text{GAS}} \cdot \frac{C_1}{1}}
\]  

(2)

\(C_i\) is again in \(1 \text{ sec}^{-1}\). In the case of the source chamber described here, the pumping speed of the four stage diffusion pump is 6000 \(1 \text{ sec}^{-1}\) for air. Taking the total conductance \(C\) as 4600 \(1 \text{ sec}^{-1}\) one expects effective pumping speeds of

5200 \(1 \text{ sec}^{-1}\) ≤ \(S_{\text{H}_2}\) ≤ 6500 \(1 \text{ sec}^{-1}\)
A factor of between 2 and 2.5 (Leybold Heraeus) has been used as more realistic than the correction suggested by (1). This pumping speed drops, for the noble gases, to

\[
S_{Ne} = 3000 \text{ l}.\text{sec}^{-1} \\
S_{Ar} = 2200 \text{ l}.\text{sec}^{-1}
\]

These figures can be used to make estimates of the beam intensities which can be achieved with the present system. Gas leaking into a vacuum system will cause the pressure in the source chamber to rise to \( p \) Torr. If \( S \text{l}.\text{sec}^{-1} \) is the effective pumping speed for the particular gas leaked into the system, then it is possible to work out the total effusion rate of this source according to

\[
N = 3.54 \cdot 10^{19} \cdot S \cdot \text{molec}.\text{sec}^{-1}
\]

This assumes that the apparatus is working in a stationary state and the pumping speed at the source chamber is known. For a source chamber pressure of \( 5 \cdot 10^{-5} \) torr of hydrogen and using a pumping speed of \( 5.2 \cdot 10^3 \text{l}.\text{sec}^{-1} \), the total effusion is \( N = 9.2 \cdot 10^{18} \) molecules.\text{sec}^{-1}. The problem which arises is to get as many of these particles as possible into a limited target area, in order to make the target intensity as high as possible. The source configurations one has to consider are

(a) simple aperture source
(b) long channel source
(c) multicapillary source
(d) supersonic nozzle
Bearing the flexibility of the system in mind, only the first three possibilities were considered. Out of these the multicapillary source had to be ruled out for hydrogen, since a new type of heater was to be used for the dissociator. This heater was not efficient enough for this type of source. A multicapillary source has been used in previous experiments (Raible V, 1965) and has temporarily been used here for some rare gas experiments.

The use of long channel beam sources, that is sources with length $L$ cm and radius $a$ cm, where

$$L \gg a,$$

as compared to thin-walled aperture sources has proven to be advantageous. These long channel sources have a higher directivity and thus achieve higher target densities for the same gas intake. This has been investigated both experimentally and theoretically by several groups (Giordmaine J.A. and Wang T.C. 1960, Hanes G.R. 1960, Zugenmaier P. 1966). The intensity of a beam effusing from an ideal orifice source at a distance $i$ cm from the source is

$$I(\theta) = \frac{n^2 A}{4\pi i^2} \cdot \cos \theta \text{ molec.cm}^{-2} \text{ sec}^{-1}$$

A is the area of the aperture, $\theta$ is the polar angle, $n$ is the number density in the source. The mean velocity of the gas molecules in the source is given by

$$\bar{v} = \left( \frac{8kT}{\pi m} \right)^{\frac{1}{2}}$$

and the particle density is given by

$$n = \frac{p}{kT}$$
where $p$ is the source pressure, $T$ the source temperature, $k$ the Boltzmann constant and $m$ the mass of the particle. On the axis normal to the source, the beam intensity is described by

$$I(0) = \frac{n\nu A}{4\pi k^2} \text{molec.cm}^{-2}\text{sec}^{-1} \quad (8)$$

The total number of molecules emerging from the source is given by

$$N = \int_0^{\pi/2} \frac{n\nu A}{4\pi} \cos\theta d\omega \quad (9a)$$

Where $d\omega$ is a solid angle at an angle $\theta$ with respect to the normal of the aperture, $d\omega = 2\pi\sin\theta d\theta$.

$$N = \frac{n\nu A}{4} \quad (9)$$

The centre beam intensity (8) can therefore be expressed in terms of the total effusion

$$I(0) = \frac{N}{\pi k^2} \quad (10)$$

It becomes clear, that the maximum beam intensity is determined by the rate at which particles, which are no longer part of the beam, are pumped away.

In the case of long channels, these simple relations are no longer valid. Depending on the mean free path of the particles compared to the dimensions of the channel, several modes of flow have to be investigated. The importance of the source pressure plays a significant role in the beam intensity. The mean free path of molecules is given by

$$\lambda = \left(\sqrt{2\pi n_0} \theta\right)^{-1} \quad (11)$$
where $n$ is related to the source pressure according to (7). $\delta$ is the hard sphere molecular diameter. Two important cases are to be considered:

(a) Collisions between individual molecules can be neglected, $\lambda \gg L$. The molecules pass through the channel with collisions only with the walls and this is described as transparent flow. Peak intensities are $< 10^{17}$ particles sterad$^{-1}$ sec$^{-1}$. The peak intensity is proportional to the pressure behind the source.

(b) By increasing the source pressure, one reaches conditions where $\lambda < L$ but $\lambda \gg a$. This is referred to as intermediate flow conditions. This region produces centre beam intensities of (Giordmaine J.A. & Wang T.C. 1960)

$$I(0) = \frac{1}{2^{3.8.6}} \cdot \left(\frac{\pi \cdot a \cdot N}{\lambda}\right)^{\frac{3}{2}} \text{molec. sterad}^{-1} \text{sec}^{-1}$$

which means, that this intensity is no longer proportional to the total flow as in (8) but to the square root of the total flow (3). The half width of the beam, that is, the angle $\theta_{1/2}$ for which the intensity drops to half the centre beam intensity at $\theta=0$ is given by (Giordmaine and Wang)

$$\theta_{1/2} = 2^{7/4} \frac{\delta}{1.78} \cdot \left(\frac{3N}{a \cdot \nu}\right)^{\frac{1}{2}}$$

The beam expands in proportion to the square root of the total flow. The criterion for the validity of these equations to
within 1% is given (Giordmaine and Wang) by

\[ L > \frac{2.5}{a^{3/4}} \cdot a^{3/2} \left( \frac{v}{3N} \right)^{1/4} \quad (14) \]

In the present experiment, the radius of the 10 cm long tungsten tube used was 0.35 cm. Taking a pressure of 10^{-4} torr Hydrogen in the source chamber, the total effusion rate according to (3) is

\[ N = 1.8 \cdot 10^{19} \text{ molec.sec}^{-1} \]

At an operating temperature of 2800°K the centre beam intensity according to (12) works out to be

\[ I = 5.10^{18} \text{ molec.sterad}^{-1} \text{ sec}^{-1} \]

and drops at a distance of 10 cm from the source to

\[ I = 5.10^{16} \text{ molec.cm}^{-2} \text{ sec}^{-1} \]

The corresponding values for a simple aperture source are

\[ I = 2.10^{16} \text{ molec.cm}^{-2} \text{ sec}^{-1} \]

and a beam half-width of 60° compared to about 35° for the tube source. Thus a gain of about 2.5 in intensity is achieved by using a long channel source.

The beam density, at a source temperature of 2800°K, is now

\[ n = \frac{I}{V} = 6.10^{10} \text{ molec.cm}^{-3} \]

This is the actual target density at the scattering region which is about 10 cm from the source, in the case of hydrogen experiments.

In elastic scattering experiments, the limit of sensitivity for a measurement not only depends on the target
beam intensity - the signal is proportional to the intensity - but also depends on the signal created by the background gas. This of course assumes that no other signals arise for example from electrons scattered off metal surfaces, which can be a very important disadvantage. The signal to noise ratio is directly proportional to the ratio of target beam intensity to background intensity.

With the hydrogen beam on, and a pressure of \( p_1 = 10^{-4} \text{ torr} \) in the source chamber, the pressure in the scattering chamber drops to \( p_2 = 2.10^{-6} \text{ torr} \). This background pressure corresponds to a background particle density of about \( 7.10^{10} \text{ molec.cm}^{-3} \). This background is caused by a direct contribution of the target beam entering the scattering chamber through an aperture of radius \( r \) which defines a solid angle \( \Delta \Omega \). This contribution is given by

\[
N = I(0) \Delta \Omega
\]

Due to the pressure difference between the two chambers, particles diffuse through the partition aperture at a rate given by

\[
N = 3.5\cdot10^{22} \frac{(p_1-p_2)}{\sqrt{MT}} \pi r^2
\]

where \( M \) is the molecular weight of the gas considered. The background particle density is of the same magnitude as the target beam itself. This creates the problem of distinguishing between electrons scattered from the target beam and those scattered from background particles. The target beam in the present experiment was therefore modulated.
In rare gas experiments, the situation is much more favourable. The major disadvantage in atomic hydrogen scattering experiments is the large distance between the beam source and the actual scattering centre. This distance is a consequence of the high temperatures required to dissociate hydrogen. The total effusion rate in the case of Argon, based on the effective pumping speed of 2200 \( l \cdot \text{sec}^{-1} \) is, according to (3)

\[
N = 8 \cdot 10^{18} \text{ atoms} \cdot \text{sec}^{-1}
\]

This intensity can be fully utilised by moving the target beam source to within millimetres of the scattering centre. The normal distances used in the excitation measurements were between 1 cm and 2 cm.

As has been shown, the target intensity of a beam experiment strongly depends on the effective pumping speed of the pumps used and the source to interaction region distance which is to be as short as possible. Limitations on the latter are caused by the use of hot beam sources and auxiliary equipment such as mechanical choppers. In order to improve the ratio of target beam intensity to background intensity, the aperture used between source-chamber and scattering chamber should be as small as possible in order to reduce diffusion from the higher pressure vessel to the scattering chamber.

3.2 The atomic hydrogen source

Since hydrogen in its stable form is a diatomic molecule, one has to produce atomic hydrogen by dissociation. The energy required to split the molecule is 4.478 eV. Two
methods are generally used, namely electrical discharge and thermal dissociation. Atomic hydrogen, in high concentration was probably first produced in a discharge tube (R. W. Wood) which is now known as the Woods tube. The first successful thermal dissociation was achieved in 1950 (Lamb W.E. and Retherford R.C. 1950). The use of discharge methods, whether d.c. discharge or microwave was thought to be unsuitable, since the apparatus was to be used for ultraviolet excitation measurements (Koschmieder H. 1974) and discharges are strong sources of Ly$\alpha$-radiation. Only thermal dissociation has therefore been considered.

There are three methods to achieve thermal dissociation

(a) direct heated ovens (e.g. Fite W.L. et al 1958)
(b) heating by electron bombardment (e.g. Raible V. 1965)
(c) heating by radiation

The first type of dissociator is a tungsten cylinder which is heated in its central part by direct passage of current through its walls. A disadvantage of this type of furnace is mechanical instability leading to a short life-time. A further disadvantage is due to its beam properties. The oven acts like a simple aperture source which has poorer directivity compared to long channel sources. In the second type of oven this problem no longer exists. A massive tungsten pipe is bombarded by electrons with energies between 1 keV and 2 keV. This type has been used in previous experiments (Raible V. 1965). Merits of this type of furnace are high reliability, long lifetime and high stability. An electron-bombarded oven can easily be used as a multi-capillary source.
The reasons for not using this type of furnace were that, owing to the electron bombardment this type of source creates Ly_α photons, electrons and ions. They create a lot of experimental difficulties and were thought to be no longer present in a radiation heated dissociator.

3.3 Radiation heated atomic hydrogen beam source.

The hydrogen dissociator consists of a 10 cm long, thin tungsten tube. This tube is surrounded by a heater. The heat is transferred by radiation (see figure 8). This arrangement combines low ultraviolet background radiation emerging from the oven region into the scattering region with the collimation properties of a long tube. Since radiation heating is less efficient than direct heating or heating by electron bombardment, thorough provisions had to be made to prevent heat losses by radiation or conduction. Conduction was kept low by using a tube with walls as thin as possible. Radiation losses were reduced by a set of radiation shields which contain the heat in a confined volume.

The tungsten tube was rolled from 0.025 mm thick tungsten foil and has a diameter of 3.5 mm. One end of the tube was fitted around the molecular hydrogen intake and held by a ring. This sandwich arrangement produced a tight fit which prevented gas from leaking into the source chamber. The open end of the tungsten pipe was surrounded by a heater loop, which was made from tungsten sheet 0.15 mm thick and 15 mm wide. The total length of this heater ribbon was 80 mm. Both tungsten pipe and heater were heat treated at 700-1000°C in special jigs to get rid of mechanical stress.
Figure 8:

The top part shows a cross-section through the hydrogen oven. The hydrogen source is perpendicular to the plane of drawing. The ribbon heater and its suspension is shown, as well as the supports and radiation cylinders. The bottom drawing shows a longitudinal section of the hydrogen beam source.
Figure 9:

The most critical part of the hydrogen oven was the coaxial current supply line.
The part of the oven consisting of heater and tungsten pipe were then surrounded by a set of six concentric radiation cylinders made from molybdenum, and two inner shield cylinders made from tungsten. These radiation shields were separated from each other by small punchmarks. The complete set of radiation shields was contained in a stainless steel cylinder which was mounted onto two watercooled stainless steel rods.

A further watercooled support was designed as a coaxial current feedthrough. This was used to mount the heater ribbon. Technically, the most difficult problem was this heater arrangement. The final version was a circular loop with the heater current flowing in opposite directions along straight legs. Since under normal operation conditions 150A were passed through the heater, this design reduced the magnetic field created by the heater current. In order to maintain a low magnetic field along the current supply line, a special water-cooled coaxial heater support was designed. The final design of this is partly shown in fig.9. The outer section of the coaxial current feedthrough was interrupted by an insulated joint a few cm behind the connection to one side of the heater ribbon. A connection to the other end of the ribbon was made by means of a flexible lead. The two ends of the heater are insulated from each other by a mica strip and then clamped together by the two connectors in a sandwich. The insulated joint in the current feedthrough was made with low vapour pressure resin. Mechanical stability was achieved by using a concentric joint. This final version of heater and heater connector proved strong enough to withstand the
mechanical stress caused by thermal expansion when in operation and it was water- and leak-tight. Due to this assembly, the magnetic field caused by high heater currents was reduced considerably.

A fourth water-cooled support was used to mount a mu-metal shield around the oven assembly. Another mu-metal cylinder was fitted inside the oven chamber extension. This extensive mu-metal shielding in addition to the coaxial current supply reduced the magnetic field in the scattering region to less than 20 m Gauss.

The oven was a.c. heated, using a variable transformer to supply the primary side of a high power transformer. The latter had an 0-12V output with a maximum current of 300A. 1500 watt were dissipated by the 150A heater current.

One disadvantage of the present oven is the low heater efficiency. Despite the radiation shields, radiation losses are still too high. Temperatures of around 600°C have been measured at the stainless steel cylinder containing the radiation shields, even though this cylinder is water-cooled. Owing to these radiation losses it is very difficult to reach or exceed oven temperatures of 2800°C at the higher flow rates of hydrogen through the tungsten pipe. The final assembly of the hydrogen oven is shown in fig.10.

As soon as the oven was completed, an investigation of its background properties was carried out, since this was one of the reasons for designing this type of dissociator. It was found that the oven emitted a number of electrons which managed to get into the interaction region, thus interfering with electron
detection in the elastic scattering mode. These electrons can be suppressed by means of biasing voltages applied to the oven assembly, in such a way that electrons were collected by the radiation cylinders. At heater voltages larger than 10V a.c., the creation of 2S hydrogen atoms in the oven region caused some trouble with the 2S excitation measurements.

3.4 The hydrogen beam characteristics

The efficiency of a dissociation process of the type

\[ \text{H}_2 \rightarrow 2\text{H} \]

can be described, assuming thermal equilibrium of the gases concerned with the oven walls, by

\[ \frac{[\text{H}]}{[\text{H}_2]}^2 = K(T, p) \]

The equilibrium constant \( K \) is a function of the absolute temperature \( T \) and the pressure. This method was used by Lamb and Retherford (1950) to work out the degree of dissociation in their hydrogen beam.

Since the actual dissociation process is not yet well enough understood (chemisorption processes, which are influenced by the surface properties of tungsten (G. Ehrlich 1959, Joe Smith and Wade L. Fite 1962), on hot surfaces followed by evaporation are probably involved) this method was not thought to be appropriate to describe a hydrogen oven which has not been used before. It was considered essential to actually measure the dissociation which can be achieved with the furnace described in chapter 3.3. This can be done by comparing the \( \text{H}_1 \) and \( \text{H}_2 \) particle fluxes in the beam using a mass spectrometer.
The hydrogen oven in its final version.
The radiation cylinders are cut open to give a view of the dissociator arrangement. The complete assembly can be lowered and raised by means of a perbunane membrane. For rare gas experiments, the tungsten tube is replaced by a stainless steel tube and pushed through the heater section to shorten the source interaction region distance.
The dissociation fraction $D$ of a beam of diatomic molecules can be defined as

$$D = \frac{n_1}{\frac{n_1}{2} + n_2}$$

that is, by the ratio of the number of dissociated molecules $\frac{n_1}{2}$ to the total number of molecules. $n_1$ refers to atomic hydrogen and $n_2$ to molecular hydrogen. If $Q_i$ is the ionisation cross section of beam particle $i$ per unit electron current at a given electron energy, then the ion current observed is

$$S_i = Q_i \cdot \frac{n_i}{\bar{v}_i}$$

If the gas comes to equilibrium in the hydrogen furnace, the mean speed in the beam is given by

$$\bar{v}_i = \text{const.} \cdot \left(\frac{T}{m_i}\right)^{\frac{3}{2}}$$

where $m_i$ is the mass of the particle considered and $T$ the absolute temperature of the oven. This leads to

$$S_i = \text{const.} \cdot Q_i n_i \cdot m_i \cdot T^{-\frac{3}{2}}$$

and

$$S_i = A \cdot Q_1 n_i m_i^{\frac{1}{2}}$$

$A$ contains the beam geometry and other constants at a given temperature $T$. This can be used to express the fractional dissociation in the beam according to (1), remembering that $m_2 = 2 m_1$, as

$$D(T) = \left(1 + \sqrt{2} \cdot \frac{S_2}{S_1} \cdot \frac{Q_1}{Q_2}\right)^{-\frac{1}{2}}$$
\( Q_1/Q_2 \) is the known ratio of the ionisation cross sections of \( H_1 \) and \( H_2 \). This method of expressing the fractional dissociation of a hydrogen beam in terms of ion signals according to (5) has been used previously (i.e. Fite Wade L. and Brackmann R.T. 1958, Kauppila W.E. et al 1970).

Since the beam profile of a long channel source varies with the source temperature as described in chapter 3.3, another method of describing the beam is to define a fractional beam composition \( D^* \) as the ratio of the particle number \( n_1 \) of species 1 to the total number of particles in the ion formation region of the mass spectrometer:

\[
D^* = \frac{n_1}{n_1 + n_2}
\]

This leads to the following expression:

\[
D^*(T) = \left(1 + \frac{T^*}{2} \right) \frac{S_2}{S_1} \cdot \frac{Q_1}{Q_2}^{-1}
\]  \hspace{1cm} (6)

Equation (6) gives a better description of the beam composition available for scattering experiments, provided the beam is investigated at the actual scattering centre of the experiments. Both considerations (5) and (6) neglect contributions arising from dissociative ionisation of \( H_2 \) in the mass spectrometer. This process is very small (Massey H.S.W. and Burhop E.H.S. 1969) and certainly inside the uncertainty of this beam investigation.

A thorough investigation of the hydrogen beam was carried out before it was used in experiments. This presented the problem of measuring the \( H_1 \) and \( H_2 \) components of the beam against a background which mainly consisted of molecular hydrogen. A series of tests was carried out using a modulated beam. For this
purpose the electron spectrometer was removed from the gun table which remained in the system, since it carried the chopper facility and the final beam aperture. A commercial quadrupole mass spectrometer, Balzers QM 101, equipped with a cross beam electron gun was substituted for the electron spectrometer. The arrangement is shown in fig.11. This was done to measure the beam composition at the actual interaction region of the later hydrogen experiments. The cross beam ionizer used was suitable for the analysis of a beam. A mechanical chopper, which will be described in more detail in the following chapter, interrupted the hydrogen beam with a frequency of 62 Hz. This chopper was positioned inside the scattering tank in order to prevent modulated background hydrogen from reaching the scattering tank by simple diffusion from the source chamber. A photocell (later on a photomultiplier), observing the hydrogen furnace through the scattering region and chopper wheel, supplied a reference signal for the chopper frequency and phase. A lock-in phase sensitive detector PAR type HR8 was used to analyse the mass spectrometer signals. Repetitive sweeps of the mass range 1 and 2 supplied signals proportional to the actual partial densities of H\textsubscript{1} and H\textsubscript{2} in the beam, according to (2). Typical signal traces are shown in fig.12. Since the electron energy in the ionizer is fixed at 95eV, the signals observed have to be corrected for their respective ionisation cross sections, the ratio being taken to be \( Q_1/Q_2 = 0.67 \) (Fite Wade L. and Brackmann R.T. 1958).

The source temperature was measured by means of an optical pyrometer which looked along the beam axis through a viewing point in the scattering tank. Source chamber pressure as well as the pressure in the scattering tank were monitored.
Figure 11:

This schematic diagram shows the quadrupole mass spectrometer in position for measurements of the hydrogen beam composition in a modulated beam experiment.
Relative intensities of atomic and molecular hydrogen. The recorder traces were taken at different source temperatures as indicated. The source chamber pressure was $7 \times 10^{-5}$ torr.
Molecular spectra taken at different temperatures:

- $T = 1700^\circ K$
- $T = 2300^\circ K$
- $T = 2600^\circ K$

Relative intensity graph showing peaks for $H_2$ and $H$.
using ionisation gauges. The peak heights of signals $S_1$ and $S_2$ were used to work out the beam composition.

Typical values of the fractional dissociation of the beam are shown in fig.13. An extended series of dissociation measurements was carried out, at different source pressures and with new tungsten tubes and heaters, until a reliable reproducible set of the beam values was found. Then the mass spectrometer was removed from its position and kept at a different position in the beam for occasional monitoring purposes. At pressures of $7 \times 10^{-5}$ torr in the source chamber, the beam contained more than 80% atomic hydrogen at source temperatures of $2500^\circ$K.

The same arrangement can be used, to inject mixed gas beams as for example in rare gas experiments, although this possibility has not been used so far. The beam composition could again be worked out.

3.5 Target beam modulation

One of the main problems in electron-atomic hydrogen scattering is the recombination of atomic hydrogen into molecules, producing a background of molecular hydrogen. Scattering signals therefore contain a component due to electron scattering from molecular hydrogen. An additional signal component, especially in the elastic scattering mode, is caused by scattering of electrons from metal surfaces. This contribution to the elastic scattering signal can be significant.

To overcome problems of that kind the target beam is modulated. It is periodically interrupted by means of a rotating wheel with ten blades. This wheel, which is
Figure 13:

Composition of the hydrogen target beam as measured in a modulated beam experiment, using a commercial quadrupole mass-spectrometer. These measurements were repeated to establish that the performance of the hydrogen beam source was reproducible.
beam as a measurement, using a spectrometer. To establish a beam source...
made from duraluminium, is driven by a synchronous motor (AEG) which is powered by a variable frequency square wave oscillator capable of supplying 240V. This mechanical chopper arrangement is an integral part of the gun table and is therefore inside the scattering tank. The assembly is shown in fig.14 with the electron spectrometer mounted on the gun table. This position of the beam chopper was chosen to make sure that the actual target-beam which reaches the interaction centre is modulated, whereas the background gas is unmodulated. Background modulation would take place if the chopper was located in the source chamber or even in an intermediate chamber. One further advantage of this chopper arrangement is, that during the off period the background gas pressure is not influenced, since the beam is only dispersed during that time and the total gas load in the chamber remains constant. The physical layout of the modulation part of the apparatus including a schematic description of the electronics is shown in fig.14.

The correct chopper frequency is observed by interrupting a light beam which is monitored by means of a phototransistor. The light source is a normal 6.3V miniature light bulb. Power to the lamp comes from a d.c. power supply. Both lamp and transistor have been stripped of insulation in order to prevent vacuum problems arising from outgassing. The modulation signal derived in this way is then amplified and adjusted to a 1:1 mark to space ratio by means of a time comparator. To ensure that the target modulation is in phase with this modulation detector circuit, the light from the hydrogen dissociator oven is monitored by means of a photomultiplier. By comparing the two signals, phase discrepancies
Figure 14:

Beam modulation system. The electron spectrometer is shown in its final position. Parts of the rotary drive of the turntable are shown, as well as a section through the integrated gun table-chopper assembly. Electronic circuits used to derive the modulation signals are shown schematically.
can be adjusted with a phase shifter.

The modulation signal is then converted to a square wave with positive polarity for switching the external + counting input of a multiscaler. After completion of every beam on-off-cycle a + 10V pulse is derived to advance the channel of the multiscaler. These pulses can be accumulated to advance the storage channels after 1, 2, 4, 8 or 16 complete on-off cycles of the chopper. Since the channel advance is related to the electron beam energy, the modulation also controls the electron beam energy. This will be described in more detail later on.

The detection of the oven light with a photomultiplier also monitors the oven temperature and indicates temperature fluctuations. This facility might prove to be very valuable for future experiments. In the case of hydrogen dissociation measurements, the phase adjustments were made with a phase shifter incorporated in the lock-in detector, while for modulated counting an additional phase shifter was used.

4. The electron gun

In this chapter the design and operation of the electron spectrometer is discussed. Its characteristics, including energy distribution and energy calibration will also be considered.

4.1 Introduction

The energy properties of an electron beam can be described by the most probable energy $E$ and the energy spread around this mean energy. The energy spread $\Delta E$ can be defined as the energy between the half-maxima of the electron beam current.
distribution. Conventional types of electron sources do not produce electron beams having uniform energy. Furthermore, the mean energy of electrons in the beam usually differs from the applied accelerating voltages. The main contribution to the energy distribution of electrons is given by the thermal energy of electrons emitted from a thermionic cathode. The current distribution of such an emitter can be described by the Maxwell distribution

\[ \frac{I(E) \, dE}{I} = \frac{E}{kT} \cdot e^{-E/kT} \cdot d\left(\frac{E}{kT}\right) \]

normalized to the total current I. This leads to an energy spread

\[ \Delta E \approx 2.5 \, kT. \]

One therefore expects energy spreads of between 0.2 eV to 0.6 eV according to the type of cathode used. The energy at high current densities in the electron beam broadens owing to space charge effects and the distribution function is no longer Maxwellian. Differences between applied voltages and actual energies can be of the order of several volts and are a result of cathode surface conditions plus contact potentials arising from surface conditions in the electron gun.

Since this apparatus described here was to be used to investigate structures with an energy width of 0.1 eV or less, one requires an electron beam with an energy spread of the same order. Devices for reducing the thermal energy spread of electron beams are reasonably well known. A description of such electron monochromators can be found in a number of articles (i.e., Simpson J.A. 1967).
In atomic beam experiments, especially in the case of atomic hydrogen scattering experiments, where the target beam source is distant from the interaction region, it seems to be advantageous to use a ribbon-type electron beam. This should make better use of the already divergent target beam. The 127° electrostatic electron monochromator was therefore considered to be the most suitable electron source for this apparatus.

4.2 The 127° electron monochromator

This device was suggested by Hughes and Rojanski (1929), who worked out the focussing and energy selection properties of an inverse first power electrostatic field. The first selector was built by Hughes and McMillen (1929), but had a rather poor resolution owing to the use of sheet metal for the cylindrical electrodes. This original design has been improved meantime (Marmet P. et al 1961) and gives good energy resolution with reasonable current throughputs.

The electric field between two concentric cylinders of radii \( r_1 \) and \( r_2 \) \((r_1 < r_2)\) and which are at potentials \( V_1 \) and \( V_2 \) respectively is given by (see fig.15)

\[
E(r) = \frac{1}{r} \cdot \frac{V_2 - V_1}{\ln \frac{r_1}{r_2}}
\]  

Electrons injected into that field only remain on a centre trajectory \( \delta = 1/2 (r_1 + r_2) \) if

\[
\frac{m_e \cdot v^2}{R} = E(R) \cdot e
\]

and their kinetic energy will be

\[
E_{\text{kin}} = 2^{-1} e \cdot \frac{V_2 - V_1}{\ln \frac{r_1}{r_2}}
\]
Schematic description of the $127^\circ$ selector field showing the centre trajectory as well as a typical trajectory for electrons with $E < E_0$. 
\[
R = \frac{R_1 \cdot R_2}{2}
\]

\[
\frac{\bar{AB}}{\bar{AC}} = \frac{(4/3)\alpha^2 R}{(\Delta E/E)R}
\]

Diagram with labeled points A, B, C, and a vector \( \alpha \).
This is one of the operating conditions of the system. It is found that a beam entering the cylindrical field through a slit and having a small beam divergence $\alpha$ with respect to the slit normal, is focussed at an angle of $\pi/\sqrt{2} = 127^\circ 17'$. This can be seen by solving the equation of motion of an electron in this field which, in cylindrical polar coordinates, is given by

$$m(r - r_0) = \frac{q}{r} \ln \frac{r_1}{r_2}$$ (3)

This differential equation can be solved in first order approximation for the case of the entrance slit positioned on the mean trajectory, and for small angular divergence of the electron beam. In a recent calculation (Delage Y. and Carette J.D. 1971) the assumption of small $\alpha$ was dropped and this leads to an energy resolution

$$\frac{\Delta E}{E} = \frac{AR}{R} + \frac{n}{3} \alpha^2 + \beta^2 + ...$$ (4)

$\Delta E$ is the full energy width at the half maximum of the distribution curve, $E$ is the mean energy of the electrons entering the monochromator. $AR$ is the width of two identical slits positioned at either end of the $127^\circ$ field on the mean radius $R$. $\alpha$ is the aperture angle of the electron beam. The expression (4) suggests operation of the monochromator at as low energies as possible and small values of $AR$. However the influence of $\alpha$ will increasingly dominate the energy resolution of the device. In order to reduce $\alpha$, the electron beam should be formed in a conventional electron gun before injecting it
into the selector. Another adverse effect on the resolution of this type of monochromator is caused by the length of the slits. This introduces a beam divergence $\delta$ perpendicular to the plane of selection. The effect can be lowered by a pre-selector injection system.

The reason the first $127^\circ$ selector (Hughes A.L. and McMillen J.H. 1929) did not succeed was the neglect of space charge in the selector. The space charge is built up by electrons which are not transmitted because they have an unsuitable energy, as well as by the main electron beam. The maximum current one can put through a $127^\circ$ monochromator is given by (Simpson J.A. 1968)

$$I_{\text{max}} = 38.5 \cdot E^{3/2} \left( \frac{\sqrt{\gamma}}{\pi} \cdot \frac{AR}{R} \right)^2 \mu\text{A}$$

The space charge problem was solved by Marmet and Kerwin. They replaced the sheet metal cylindrical plates by high transparency grids. Behind these grids are collector plates. The effect of this modification is, that electrons not transmitted through the device owing to having an unsuitable energy or too large a beam divergence, leave the selector field and are collected by the outer collector plates. This counteracts the build up of a high space charge and leads to a higher current throughput. Furthermore it reduces the possibility that the undesired electrons could pass through the exit slit after metal reflections, thus decreasing the energy resolution.
4.3 Mechanical design of the monochromator system

The electron monochromator used in the present apparatus was designed to achieve a resolution of the order of 0.1 eV and give a well-collimated beam. The system consists of three parts, an electron gun, the 127° selector field and a lens system to accelerate, align and focus the beam emerging from the selector.

4.3.1 Electron gun

A three-electrode system was used as electron gun-cathode, anode and a final thick lens which could alternatively be used as a deflector. This facility allowed the beam to be aligned with respect to the entrance of the selector. The cathode used was a dispenser type cathode BP1A supplied by Philips. It was mounted by means of three pointed screws in the centre of a Pierce-type cathode holder. All the electrodes were mounted on three oxide ceramic rods 1.5 mm Ø and separated by means of oxide ceramic washers. The aligned system was then mounted on a small flange and inserted into a metal tube. The assembly is shown in fig.16. The metal housing used for the electron gun is necessary to prevent stray electrons from leaving this injector system. One difficulty arising here is the trapped volume inside the injector assembly. To enable a reasonable evacuation of this tube, the injector assembly ends in a baffle which leads right up to the entrance slit of the monochromator.
A standard electron gun is used as injector into the selector field to reduce the beam divergence. The third electrode can alternatively be used as a split electrode to align the beam.
4.3.2 The monochromator section

The 127° monochromator section was a modified version of Marmet and Kerwin's design. The dimensions of the system are

\[ r_{\text{outer grid}} = 18.00 \text{ mm} ; \quad r_{\text{inner grid}} = 12.00 \text{ mm} \]

\[ r_{\text{outer plate}} = 22.00 \text{ mm} ; \quad r_{\text{inner plate}} = 8.00 \text{ mm} \]

mean radius \( R = 15.00 \text{ mm} \); height of slits = 5.0 mm

The width of the slits \( \Delta R \) could be varied.

The grids had a transparency of 87% and were made from tungsten mesh. The mesh was woven from 0.018 mm \( \varnothing \) tungsten wire. The mesh size was 0.245 mm. The grids were spot welded onto frames. All electrodes were mounted onto 120° segments using 1.5 mm \( \varnothing \) oxide ceramic rods. The correct spacing between electrodes was achieved using oxide ceramic washers which slipped over the mounting rods. This arrangement is shown in fig.17. This sandwich arrangement was then held together by an outside shield which was built as a heater so that the system could be baked at temperatures up to 200°C.

The entrance and exit slits of the 120° field section were screwed onto frames which were mounted on brackets using oxide ceramic supports and spacers. These brackets were screwed to the 120° field section. Electrical connections to individual electrodes were made to pins which protruded from the top of the monochromator.

Two identical monochromators were built, one made from Immaculate V stainless steel and the second, which was gold plated, from oxygen-free copper. There were no differences in performance. All slits used in the system
Figure 17:

Vertical section through the 127° selector, showing the insulation of individual electrodes. The heater section used to bake this part of the system is cut open to show the oxide ceramic capillaries used to take the heater wire. One of these is used for a thermocouple. All insulators are hidden from the electron beam by the metal electrodes.
were made of molybdenum and spark-eroded to a knife-edge finish in order to minimize electron scattering from the edges. The complete monochromator is shown in fig.18.

4.3.3 Output lens system

The electron beam emerging the monochromator section was focussed and aligned by two thick lenses $L_1$ and $L_2$, a method first used by Andrick and Ehrhardt (1966). $L_1$ is a split lens, which could be used as a deflector to align the beam. In addition to the deflecting voltage the lens potential was adjusted to focus the beam. $L_2$ was also used to focus the beam. These two thick lenses were located in a nozzle-type housing, held in position and aligned by insulated screws as shown in fig.19. The insulating material used was either boron nitride or oxide ceramic. The electron beam emerged from the nozzle through a rectangular aperture 1.5 mm wide. There were provisions for a second aperture behind the main exit aperture.

Using this lens system, the transmitted current was a smooth function of energy. The voltages necessary to handle the beam varied according to the energy range. Typical voltages for one particular case will be given later.

4.3.4 Main beam collector

The electron beam leaving the monochromator passed through the target beam and primary electrons not undergoing scattering processes were collected. The collector allowed the intensity of the primary beam to be monitored. A 2mm Ø copper wire inside a copper tube acted as collector.
Figure 18:

Electron beam source, horizontal section, showing the electron gun, monochromator section and thick lenses $L_1$ and $L_2$. $L_1$ is a split lens and acts as deflector. $P_0$ and $P_1$ are the outer and inner collector plates. $G_0$ and $G_1$ are the selector field electrodes made from high transparency grids. $H$ is the heater element used to bake this part of the system.
Figure 19:

A vertical section through the split lens $L_1$, showing how it is assembled and the method of insulation from the housing which is kept at earth potential.
Electrons reached the collector through a slit aperture. The collector was permanently attached to the monochromator by means of a metal bar, to ensure its proper location when the scattering angle was being altered. The efficiency of this main beam collector was poor. A more sophisticated collector could not be accommodated owing to space limitations.

4.4 Analyser or scattered beam collector

A 127° system identical to the monochromator was used to energy analyse electrons scattered from the atomic beam. These electrons entered the analysing system through a slit aperture 1.5 mm wide and were decellerated and focussed onto the entrance slit of the analyser by means of two thick lenses $L_4$ and $L_3$. $L_3$ again was a split lens which enabled the electron beam to be deflected and hence aligned. Electrons transmitted through the analyser were detected by a channeltron electron multiplier. Figure 20 shows the analyser section of the electron beam system.

This arrangement of monochromator and analyser permitted measurements of electron energy distributions in both primary and scattered electron beams. Since the analyser was tunable to transmit only electrons with a defined energy, the device could be used for elastic scattering experiments as well as for energy loss spectra.

4.5 The electron spectrometer assembly

All parts of the electron beam system described so far are shown assembled in fig.21, which is drawn to scale. The components are mounted on a gun table made from
Figure 20:

A horizontal section through the analyser. $P_i$ and $P_o$ are the inner and outer collector plates. $G_i$ and $G_o$ are the selector field electrodes. $L_3$ is a split lens to align the scattered electrons relative to the entrance slit of the analyser.
Figure 21:

Electron spectrometer assembly, horizontal section. The target beam emerges perpendicular to the plane of drawing.
MONOCHROMATOR
HEATER SECTION

ELECTRON GUN HOUSING
LENS L0
ANODE
CATHODE
HEATER
SLIT
INNER COLLECTOR PLATE P1
OUTER COLLECTOR PLATE P0
OUTER GRID G0
INNER GRID G1

SPLIT LENS L1
LENS L2

PRIMARY BEAM COLLECTOR

LENS L4
SPLIT LENS L3
INNER COLLECTOR PLATE P1
OUTER COLLECTOR PLATE P0
OUTER GRID G0
INNER GRID G1

CHANNELTRON MULTIPLIER
CHANNELTRON HOUSING
10mm
Immaculate V stainless steel and supported by two stainless steel rods. These rods are screwed into the NW200 flange (see fig.5) which accommodates all the feedthroughs necessary for the electrical supply of the electron beam system. The flange also supports a universal rotary drive. A cross section through the gun table has already been shown in fig.14, which also shows the electron beam system in position.

The monochromator section is fixed to a double T-shaped bench. This bench slides on a rail fixed to a turntable which can rotate around the target beam. A bevelled gearwheel of 100mm diameter is used as turntable and is rotated by means of a precision universal rotary drive from outside the vacuum system. The angular movement of the monochromator covers the range $-90^\circ \leq \theta \leq 130^\circ$ with the analyser in position.

The analyser section is supported by a duraluminium platform which is screwed to the gun table. This platform can be moved in two directions perpendicular to one another to permit alignment of the analyser with respect to the primary electron beam direction and the atomic beam. Alignment of the monochromator-analyser system is performed with a jig which can be inserted into the final target-beam aperture which is at the centre of the gun turntable.

The entire assembly can be moved perpendicular to the target beam, since the gun table slides on its support rods which move in PTFE bushes fitted to the gun table. This alignment of the electron beam system relative to the target beam can be performed from outside the vacuum chamber with the same universal rotary drive which rotates the gun.
All connections to the electron spectrometer are made with copper wire covered in fibre glass sleeving. The leads are then screened and led to nine-pin feedthroughs which have been designed for this purpose.

4.5.1 Suppression of stray electrons

A serious problem in all experiments which monitor scattered electrons, either in the elastic or inelastic channels, is presented by electrons leaving the beam forming system before passing the final aperture. These electrons may reach the detector, thus creating a background signal. The most likely source contributing to this background is the electron gun itself. This stage of the electron beam system carries currents of up to 0.5mA. In order to reduce the escape of electrons from this stage, the electron gun is concealed in a tube as has already been mentioned in chapter 4.3.1. This arrangement has proved to be very effective.

The monochromator section is accommodated in a box which is pumped through the bottom and top support plates. The same design is used for the analyser. Electrons can only reach the detector if they pass through the exit slit of the analyser, since the channeltron multiplier is again in an earthed box leading right up to the exit slit. The number of electrons reaching the detector by completely by-passing the monochromator and analyser gives a background of the order of 10 counts per second.

A much more serious source of stray electrons is the small fraction of the primary electron beam which is not
completely suppressed by a collector. These electrons, especially in the elastic mode, reach the analyser after metal reflections and are transmitted, thus creating a significant contribution to the background signal. This was especially serious at the lower electron energies which were necessary in the case of elastic electron-hydrogen scattering. Some improvement has been achieved by coating all the metal components surrounding the target region with aquadag which in turn was covered with soot, but further improvements ought to be possible by modifying the primary beam collector. The electron count rate with the target beam switched off, is of the order of 100 counts per second in the elastic scattering mode, at a scattering angle of 90°. This count rate increases considerably for small angles.

4.6 Electrical supply of electron spectrometer

All voltages required to run the electron beam system are derived from individual power supplies. These d.c. power supplies were built by the electronic workshop to our specifications and have a high stability and low noise performance. The outputs are fully floating and screened. Fine adjustments are made possible by means of multi-turn helipots. A schematic diagram of the circuit used is shown in fig.22. The electrical supply lines to the electron spectrometer are fully screened.

Signal connections to the channeltron and primary beam collector are also fully screened. The same precaution applies to the high voltage supply to the channeltron detector.

All electrical supplies of the apparatus are earthed
Figure 22:

Schematic circuit of the electron spectrometer. All potentials are relative to one reference point in each monochromator and analyser. This reference point is biased relative to earth potential to define the electron beam energy.
REFERENCE POTENTIAL ANALYSER

- Upper plate
- Lower plate
- S
- 180 pF
- 1 MΩ
- 10 MΩ
- 3500 V
- 0 - 40 V
- 0 - 5 V
- 0 - 40 V
- 0 - 5 V
at one common point to prevent spurious signals due to earth loops. This central earth point is connected to a galvanic earth outside the laboratory.

If the spectrometer is to be used in the elastic channel, the scattering energy is determined by a staircase voltage relative to earth, derived from a multichannel analyser. This will be described in more detail in a later chapter. The same method is used for optical observations. In the energy loss mode, a fixed voltage applied to the monochromator relative to earth determines the incident energy in the primary beam, whereas the staircase voltage is used to scan the energy loss, i.e. the analyser.

4.7 Cancellation of magnetic and electric fields

In electron scattering experiments involving low energy electrons, stray magnetic or electric fields can disturb the electron beam considerably. The Lorentz force acting on the electrons simply deflects the electron beam. It is therefore necessary to suppress these fields.

The electric fields were minimized by keeping all outside parts of the electron beam system at earth potential as well as all the other components of the system which can be seen by the electron beam in the interaction region. All electrical supplies are fully screened and installed as far from the electron beam as possible. Insulators are shielded from the electron beam throughout the system in order to prevent electric fields, created by charging up of the insulators, from interfering with the electron beam.
Magnetic fields in the interaction region arise from various sources. Static magnetic fields result from the earth's field and from the residual magnetisation of steel components used in the system. Dynamic fields are caused by the a.c. supplies of the apparatus, by the motor powering the chopper wheel and, in the case of hydrogen experiments by the heavy a.c. current necessary to heat the oven.

The static magnetic field in the interaction region was reduced by a constant field of equal magnitude but of opposite direction. This field was obtained by surrounding the scattering tank with three mutually perpendicular pairs of Helmholtz coils. The scattering centre is the centre of all three sets of coils, which consisted of 50 turns of insulated copper wire wound on duraluminium formers. All Helmholtz coils were firmly attached to the scattering tank. The current for these coils was supplied by three independent constant current supplies. The static field was thereby reduced to less than 10 mGauss. A Hewlett Packard magnetic probe was used to check the field cancellation. For this purpose the system was opened and the probe positioned at the interaction centre.

Alternating magnetic fields created by the oven and chopper motor were reduced by extensive mu-metal shielding of the oven and of the chopper motor housing. The chopper motor was contained in a mild steel box to contain its magnetic field.

4.8 Performance of the electron spectrometer

The energy resolution of the electron spectrometer described was then tested and possible means of calibrating the energy scale were investigated. When studying resonance features
one must not only have an idea of the actual energy width of the electron beam used, but it is also important to position the features observed on an absolute energy scale. Calibration should be made easy, for example by the observation of some reproducible feature, since the energy scale might alter owing to variations of contact potentials.

4.8.1 Energy distribution measurements

There are several methods one could use to determine the energy distribution of an electron beam. A retarding field in front of the primary beam collector could be used, or one could observe a feature of known energy width. However a monochromator-analyser arrangement offers methods of observing energy distributions which are quicker and easier to evaluate.

If \( V_0 \) is the potential corresponding to a circular trajectory of radius \( R \) through the monochromator, the equation (2) chapter 4.2 can be rewritten as

\[
V_0 = \frac{V_2 - V_1}{\frac{2}{R} \ln R_1/R_2}
\]  

(1)

This offers the first method of observing the energy resolution of a monochromator using an analyser. The monochromator is tuned to transmit electrons with an energy equivalent to a potential \( V_0 \). The analyser is then tuned to the same energy and its potential difference \( (V_2 - V_1) \) is scanned symmetrically with respect to \( V_0 \). This method has been used in transmission to display the energy distribution on an oscilloscope so that coarse adjustments of the distribution curve could be made.
The method normally used is to scan the analyser against the monochromator which is set to transmit electrons having a certain energy. Assuming the transmission function $\sigma_m(E)$ of the monochromator is Gaussian with a width at half maximum of $\Delta E_m$ eV, where $E_m$ is the mean energy transmitted by the monochromator, then

$$\sigma_m(E) = \frac{1}{\sqrt{2\pi}\Delta E_m^2} \exp\left(-\frac{(E-E_m)^2}{2\Delta E_m^2}\right)$$

A similar profile applies to the analyser

$$\sigma_a(E) = \frac{1}{\sqrt{2\pi}\Delta E_a^2} \exp\left(-\frac{(E-E_m)^2}{2\Delta E_a^2}\right)$$

If the analyser scans the monochromator profile the resultant observed profile is given by

$$\sigma_{tot} = \frac{1}{2\pi\Delta E_m\Delta E_a} \int_{-\infty}^{\infty} \exp\left(-\frac{(E-E_m)^2}{2\Delta E_m^2}\right) \cdot \exp\left(-\frac{(E-E_a)^2}{2\Delta E_a^2}\right) \, dE$$

$$\sigma_{tot} = \text{Const.} \exp\left[-\frac{(E_m-E_a)^2}{2(\Delta E_m^2 + \Delta E_a^2)}\right]$$

This is a Gaussian distribution with a half width

$$\Delta E_{tot} = \left(\Delta E_m^2 + \Delta E_a^2\right)^{\frac{1}{2}}$$

If both analyser and monochromator are identical then

$$\Delta E_m = \frac{\Delta E_{tot}}{\sqrt{2}}$$
Since the set up described here uses mechanically identical selectors which operate with almost identical potentials, this assumption should be good enough to obtain a reasonable idea of the actual resolution of the monochromator. Using the methods described, energy distribution curves as shown in fig. 23 are observed. The second method described, scanning the analyser relative to the monochromator, has been used for measurements in transmission as well as at scattering angles other than 0° and was repeated frequently to observe possible changes in the distribution. The best resolution achieved with the present system was 50 meV with currents of the order of $10^{-10}$ A. So far the system has normally been run with resolutions of the order of 100 meV and primary currents of around $3.10^{-8}$ A, depending on the energy range. A set of typical figures for the system is given in Table I.

4.8.2 Energy calibration

The energy of an electron beam should be given by the potential difference between the cathode and the last element of the electron gun. The channel address of a multiscaler is used to derive this energy, as will be described in chapter 5. The voltage reading of every tenth channel is recorded using a digital voltmeter. This gives relative energy values, but the absolute values can be considerably different. The source of this discrepancy is the effective potential difference between the target region and the nominal energy zero and is caused by a combination of
<table>
<thead>
<tr>
<th>Electrode</th>
<th>Monochromator</th>
<th>Analyser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dimension mm</td>
<td>Voltage referred to slit</td>
</tr>
<tr>
<td>ΔR (slit)</td>
<td>variable, but in experiments descr. (0.4 x 5.0)</td>
<td>0.0</td>
</tr>
<tr>
<td>mean radius R</td>
<td>15.00</td>
<td></td>
</tr>
<tr>
<td>r\textsubscript{in} grid</td>
<td>12.00</td>
<td>+ 1.2</td>
</tr>
<tr>
<td>r\textsubscript{out} grid</td>
<td>18.00</td>
<td>- 0.5</td>
</tr>
<tr>
<td>r\textsubscript{in} plate</td>
<td>8.00</td>
<td>+ 50</td>
</tr>
<tr>
<td>r\textsubscript{out} plate</td>
<td>22.00</td>
<td>+ 50</td>
</tr>
<tr>
<td>top deflector</td>
<td>-</td>
<td>- 0.10</td>
</tr>
<tr>
<td>bottom deflector</td>
<td>-</td>
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</tr>
<tr>
<td>cathode</td>
<td>-</td>
<td>- 2.5</td>
</tr>
<tr>
<td>anode</td>
<td>-</td>
<td>+ 55.2</td>
</tr>
<tr>
<td>lens</td>
<td>-</td>
<td>+ 17.7</td>
</tr>
</tbody>
</table>
Energy distribution in the electron beam scattered elastically through 34°.
Incident beam energy 19.00 eV.
\[ E_{\text{in}} = 1900 \text{ eV} \]
\[ \Delta E = 84 \text{ meV} \]
\[ \theta = 3^\circ \]
\[ \text{He} \]

Scattering Signal

Electron Energy (eV)
(a) contact potentials, which depend on the surfaces involved, surface conditions, etc.
(b) finite energy of electrons leaving the cathode
(c) space charge effects

Introducing gases into the system can change the contact potentials. Space charge effects can be compensated for in those parts of the electron beam system where the electron energy might exceed the ionisation potential of the gas. These effects make it impossible to determine the electron energy simply by measuring the voltage between the cathode and the last element of the electron beam source. A correction must be applied which must be determined experimentally. Primary standards normally used to calibrate energy scales are known ionisation or excitation potentials. Well established resonances, which have been calibrated against these primary standards can be used as secondary calibration standards. This means that the reliability of energy calibrations is limited by the accuracy of a previous experiment. Two methods are available in the present apparatus. Energy loss spectra of electrons scattered from Helium give a calibration against the spectroscopic levels of the He-atom. This possibility has been used to check the position of the elastic He resonance. The method generally used in all of the experiments was the observation of the elastic He resonance at 19.35 ± 0.008eV (Schulz G.J. 1973).

The accuracy of the energy calibration is limited by the precision with which the position of the observed features can be positioned on the calibration curves.
Another limitation is imposed by energy drifts occurring in the time necessary to obtain calibration curves. Errors caused by the non-linearity of the ramp voltage used to scan the energy and by voltage measurements are negligible. It must however be emphasized that, since calibration was carried out with respect to a secondary standard, a recalibration of the standard could very well lead to better energy values for the features presented later on.

Having obtained an absolute energy scale there are two methods of transferring it to the energy region of interest. One is to observe the feature to be calibrated and the calibration signal in a mixture of calibrating gas and gas to be investigated. This method should be used if possible since the experimental conditions for observation of both calibration standard and feature to be calibrated are identical. The second method is to make successive runs using the different gases involved. Both methods have been described previously (i.e. Schulz G.J. (1964), Kuyatt C.E. (1965)).

5. Data collection system

As can be seen from fig.24, there are two detection channels available. Both can be used to detect scattered electrons and one can be used to detect uv-photons. The particle detector is, in either case, a channel-electron multiplier Mullard B312 BL. For photon observation one channeltron is positioned behind two high transparency grids $S_1$ and $S_2$, which can be used to suppress charged particles. The entrance cone of this detector is at earth potential and
Figure 24:

Geometry of the electron spectrometer showing the photon detector in position. $S_1$ and $S_2$ are suppressor grids to keep charged particles from entering the channeltron during uv-photon observations. The electronics used is indicated schematically.
S₂ particles photon
the voltage across the channeltron is 3400V. A second channeltron is positioned behind the analyser and is used for electron detection only. The entrance cone of this detector is kept at +10V with respect to the analyser exit. The total voltage across this channeltron is again 3400V. Individual particles are observed as discrete pulses and are transmitted through a 180 pF high voltage capacitor from the high voltage end of the channeltrons. The load resistor used was 1 MΩ in both channeltrons.

The pulses are then passed through an emitter follower, which is battery operated. This reduces the output impedance of the channeltron circuit. The pulses are then amplified by an NE4603 amplifier and an integral discriminator is used to cut off noise without affecting the actual signal. Standard pulses from the discriminator are counted by a timed scaler, or displayed on a pen recorder which records the analogue output of a ratemeter, or stored in the memory of a multiscaler. The number of pulses accumulated in a preset counting time or in a preset number of sweeps can be printed out on an electric typewriter. A schematic diagram of the main electronic components is shown in fig. 25.

For cross section measurements a multichannel analyser was used in the multiscaling mode. The system available is an 800-channel analyser (Didac 800, Intertechnique). This instrument operates in a continuous sweep mode for a preset number of sweeps. Pulses are stored in individual channels of a memory and the counting time per channel can be varied. At the end of each complete sweep, the instrument automatically restarts at the first channel.
Figure 25:

Schematic diagram of the electronics circuit. The detector can be either the electron detector or the photon detector. In case of modulated beam experiments, additional information from the chopper circuit is used to control the counting system as indicated by the sub-section.
The channel number is used to synchronise the electron beam energy with individual channels of the memory unit. For this purpose, the channel address is converted into a step function by means of a digital-to-analogue converter. This step function which has an overall amplitude of 8.0V corresponding to the full range of the 800 channels is fed into an operational amplifier. The operational amplifier outputs a negative ramp which controls the energy of the electron beam. A normal step width of 12.5 meV was used throughout the experiments to be described later. This means that a maximum energy interval of 10eV can be covered by the full range of the 800 channels. It is however possible to select small sub-groups out of the total number of channels available.

Experiments of the type described here are very sensitive to pressure fluctuations, electron beam current fluctuations and other variations of the experimental conditions. The effect of these fluctuations can be kept low by signal averaging which is achieved by continuous scanning of the signal and summing up of individual scans, hence the use of the multiscaler.

In the case of background signals created by electron scattering from targets other than the beam, the multiscaler can be used to automatically subtract the background signal. For this purpose, the beam modulation facility as described in 3.5 is used to gate the multiscaler. The circuit is indicated in fig.25. The square wave signal derived from the chopper frequency monitoring circuit is used to supply a 0 to +10V square wave necessary for switching the memory unit.
from + counting to - counting. A schematic of the signals derived from the chopper circuit is shown in fig. 26. An additional pulse sequence derived from the modulation signal takes over the function of the internal clock and adjusts the dwell-time per channel in multiples of the chopper open-closed sequences. Dwell-times equivalent to one chopper cycle and up to 16 complete chopper cycles can be preset.

6. Results

In this chapter the measurements carried out are presented and discussed. The first part shows the helium energy loss spectra which were taken to test the performance of the electron spectrometer. This is followed by the elastic scattering of electrons from Helium observing the helium resonance which was to be used as energy calibration standard. These measurements are followed by results obtained for Neon and Argon. Preliminary results for the elastic scattering of electrons from atomic hydrogen are shown at the end of this chapter.

6.1 Helium

Helium energy loss spectra were taken in order to obtain an indication of the energy shift of the electron beam. One typical curve is shown in fig. 27. The energy shift varied for different measurements but the drifts were similar to those measured against the elastic resonance in Helium. The experimental conditions are given in the caption to fig. 27.

The 19.35eV 1s(2s) 2S resonance occurring in the elastic scattering of electrons from Helium has been studied
Figure 26:

Time sequence of the modulation circuit. The chopper position as indicated by the photo-transistor is converted into a suitable square wave to gate the + counting modes of the multiscaler. A pulse derived from the modulation signal is used to drive the channel advance of the multiscaler. A counter enables the 2^n-th pulse received, n = 0,1,...,4, to be used for channel advance.
CHOPPER POSITION

0V
-10V

OPEN  CLOSED

OV

COUNTING MODE

+10V
0V

PLUS  MINUS

ELECTRON BEAM ENERGY
(EXT. CLOCK)

+10V
0V
eV

12.5 mV

TIME

THE MODULATION CIRCUIT PERMITS TO ADVANCE ONE CHANNEL AFTER COMPLETION OF 1, 2, 4, 8, 16 CHOPPER CYCLES

( 800 Steps max.)
Figure 27:

Typical energy loss spectrum in helium. Incident energy 40.00eV, source chamber pressure $1 \times 10^{-4}$ Torr. Scattering angle $45^\circ$. $2^1P$ appears at 21.22eV compared to the spectroscopic value of 21.24eV. The $2^3P$ level is not resolved and only indicated as a slight shoulder of the $2^1P$. For $n=3$ and $n=4$ energy values for the $1^1P$ levels only are shown in the diagram.
$\theta = 45^\circ$

$E_{\text{inc}} = 40.00 \text{ eV}$

Scatt. Intensity

Energy loss (eV)

23.74 23.09 21.22 20.61 19.77

3P

2P 2S 2S

3S

$\text{E}_{\text{inc}}\text{=}40.00\text{ eV}$
in great detail (Schulz G.J. 1973). It was studied with
the present apparatus at various angles. One typical curve
is shown in fig.28. The observation of this structure was
used as a calibration standard and is available as such in
future observations using the apparatus.

This structure can be seen after about 20 minutes
sampling time and can thus be easily repeated between different
observations in order to calibrate the energy-scale. The
repeated observation of this structure showed energy drifts
of the electron beam system over periods of 4 tc 5 hours
and this led to the restriction of the sampling time before
recalibration of the energy scale became necessary. These
relatively short integration times for individual runs were
the main contributions to the difficulties encountered with
the elastic scattering of electrons from atomic hydrogen in
the present set up.

6.2 Neon

The excitation of Neon was observed in the energy
region 15.0eV to 21.0eV. This leads to the excitation of the
neon states \((2p^53s)^3P_1\) with a threshold at 16.671eV and
\((2p^53s)^1P_1\) with threshold at 16.848eV. These excited states
decay to the \((2p^6)^1S_0\) groundstate by emission of two lines
743 Å and 736 Å. The combined excitation function of the two
lines was observed using an open channeltron multiplier
positioned at 90° to the incident beam direction. The detection
of scattered electrons was suppressed by means of biased grids
in front of the detector. Background count rates were of the
order of 1/sec. The counting rate depended linearly on the
Figure 28:

He elastic resonance, observed at 34°. Helium pressure $1.5 \cdot 10^{-4}$ Torr in source chamber.
pressure in the interaction region as shown in fig. 29. The linear dependence of the excitation signal on the electron beam current is shown in fig. 30. This indicates single collision conditions and ensures that resonance trapping is negligible.

Structure in the combined excitation function was observed and it is shown for one individual experimental run in fig. 31. Electron beam current variations over the energy interval considered were smooth and showed a slight increase at higher beam energies. This is caused by the lens properties of the accelerating and beam forming elements in the electron beam system. Figure 32 shows one typical example of this change of transmission current versus energy. An excitation curve resulting from the addition of the data from several experimental runs is shown in fig. 33. The observed structure has been energy calibrated in two ways. The first calibration was carried out by measuring the elastic Helium resonance and the Neon structures in successive runs, whereas the second calibration was carried out in a Neon-Helium gas mixture. In the latter case the structures observed for Helium and Neon could be directly compared under the same conditions. The energy positions of the structures observed by the two methods differed slightly. The values are listed in Table II where they are compared with structures observed in transmission experiments (Sanche, L. and Schulz G.J. 1972). The error assigned to the energy scale for either calibration is ± 0.06eV, which consists of the uncertainty in positioning the points of individual curves and of the differences between individual calibration runs.
Figure 29:

Linearity of signal versus pressure over a wide range. Beam energy 18.00eV, primary beam current $2.5 \times 10^{-9}$A.
Ne
30:10.73
E = 18.00 eV
I_{p} = 2.5 \times 10^{-9} A
Figure 30:

Linearity of signal versus beam current. Pressure was kept at $7 \cdot 10^{-5}$ Torr, incident beam energy at 18.00eV.
7.2.74
Ne $7 \times 10^{-5}$ Torr
$E = 18.00$ eV

COUNTS

$10^2$

$10^3$

$10^4$

$10^{-10} - 10^{-8}$

BEAM CURRENT (A)
Figure 31:

One individual run, showing structure in the neon excitation. Pressure $1 \cdot 10^{-5}$ Torr. 100 sweeps. Approximate collection time 2 hours.
Figure 32:

Primary beam current recorder trace, showing a smooth transmission curve which slightly increases at higher energies.
Figure 33:

Excitation cross-section of the combined 736 Å and 743 Å lines of neon near threshold. The error bars show one standard deviation. Clear structure A, C and D can be seen. B shows a slight peak followed by a dip. The energy values obtained for the structures are listed in Table II.
A clear description of the Ne⁻ state causing the structure cannot be made, although it has been suggested that more information can be obtained by comparing the structures with isoelectronic systems (Swanson, N. et al 1973) as has been done for a similar case in Krypton.

TABLE II
Position of resonances in neon (eV)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Present Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>He-calibr.</td>
</tr>
<tr>
<td></td>
<td>$§$</td>
</tr>
<tr>
<td>A</td>
<td>16.99±0.06</td>
</tr>
<tr>
<td>B</td>
<td>18.32</td>
</tr>
<tr>
<td></td>
<td>18.40</td>
</tr>
<tr>
<td>C</td>
<td>18.76</td>
</tr>
<tr>
<td>D</td>
<td>19.06</td>
</tr>
</tbody>
</table>

Position of structures observed in the combined excitation of the 736 $\AA$ and 743 $\AA$ lines of neon. Structure A has been used as sub-standard for energy calibration in He($§$) and in a He-Ne mixture ($§§$). Structure B shows a slight peak followed by a dip. All values are given in eV.
6.3 Argon

The excitation of the two lowest states of Argon has been observed in the energy range 11.0eV to 14.00eV. These are levels with configuration \((3p^54s)^3P_1\), with a threshold at 11.623eV and \((3p^54s)^1P_1\) with a threshold at 11.828. They decay to the \((3p^5)^1S_0\) groundstate by emission of two lines, 1066 Å and 1048 Å. The combined excitation of these two lines was observed using the open channeltron multiplier positioned at 90° to the incident electron beam direction. Structure can be seen, as shown in fig.34. The signal depends linearly on the target gas pressure as well as on the electron beam current as can be seen in fig.35 and fig.36. The primary beam current over the whole energy region considered is a smooth curve, slightly increasing at higher energies as shown in fig.37. Data from different experiments have been accumulated and are shown in fig.38. The energy calibration was again carried out in the two ways already described for Neon. This again resulted in two sets of slightly different energy values. The structures observed are listed in Table III, where they are compared with results of transmission experiments (Sanche L. and Schulz G.J. 1972). The calibration error again consists of the uncertainty of positioning points on individual curves and of the energy differences of individual calibration runs. A clear assignment of the structures observed cannot be made and should be left until more detailed information is available.
Figure 34:

An individual experimental run, showing structure in the argon excitation.
Pressure \(2.5 \times 10^{-5}\) Torr. 140 sweeps.
Approximate collection time 2 hours.
Figure 35:

Linearity of argon signal with pressure.
Incident beam energy 12.00eV, primary beam current $10^{-9}$ A.
Figure 36:

Linearity of argon signal with primary beam current. Argon pressure $7 \times 10^{-5}$ Torr.
Incident beam energy 12.00eV.
8.274
Ar
$7 \times 10^{-5}$ Torr
$E = 12.00$ eV

COUNTS

$10^{-10}$
$10^{-9}$
$10^{-8}$

BEAM CURRENT (A)
Figure 37:

Smooth transmission curve, slightly increasing at higher energies. The recorder trace is typical of those that have been taken during all experiments.
creasing.

This is typical of all experiments.
Figure 38:

Excitation cross-section of the combined 1048 Å and 1067 Å lines in argon near threshold. The error bars show one standard deviation. Apart from clear structure D, E, F and G, there is indication of structure around A, B, and C. The values obtained for the energy positions are listed in Table III.
## TABLE III

Position of resonances in argon (eV)

<table>
<thead>
<tr>
<th>Structure</th>
<th>Present He-calibr.</th>
<th>Experiment He-Ar calibr.</th>
<th>Transmission experiment Sanche L. &amp; Schulz G.J.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>11.68</td>
<td>11.72</td>
<td>11.71</td>
</tr>
<tr>
<td>B</td>
<td>11.80</td>
<td>11.84</td>
<td>11.91</td>
</tr>
<tr>
<td>C</td>
<td>11.93</td>
<td>11.97</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>12.68</td>
<td>12.72</td>
<td>12.89-12.92</td>
</tr>
<tr>
<td>E</td>
<td>12.74</td>
<td>12.78</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>13.05+0.06</td>
<td>13.09+0.06</td>
<td>12.95</td>
</tr>
<tr>
<td>G</td>
<td>13.30</td>
<td>13.34</td>
<td>13.33</td>
</tr>
</tbody>
</table>

The position of structures observed in the excitation of the combined 1048 $\tilde{R}$ and 1067 $\tilde{R}$ lines of argon. Sub-standard for calibration was structure F.

§ Values obtained by calibration in helium.

§§ Values obtained by calibration in a helium argon mixture.
6.4 Atomic hydrogen

The elastic scattering of electrons from atomic hydrogen close to the n=2 threshold presented problems which have only allowed preliminary results to be obtained so far. An accumulated curve resulting from the data of several experimental runs is shown in fig. 39. There is an indication of structure, which is due to the formation of a hydrogen compound state having the configuration \( (2s^2)^1S \), as has been reported in the few previous experiments which have already been mentioned in chapter 1.2.

Several difficulties have arisen which resulted in a very bad signal to background ratio which was of the order of 1:10. Although the atomic beam density is of the order of \( 10^{10} \) atoms cm\(^{-3} \), the molecular background is of the same order, thus creating a background signal which interfered with the elastic scattering signal from atomic hydrogen. Furthermore there was a high background of electrons scattered from metallic surfaces. This is a problem which is well known for slow electrons. At scattering angles of 90°, this electron background dropped to a minimum which is the reason that the preliminary results were taken at this scattering angle.

Using the modulation facility available, there are two signal channels. With the chopper open, the signal detected is

\[
S_1 = S + B
\]

where \( S \) is the scattering signal caused by the atomic beam itself, and \( B \) describes scattering caused by background gas and metal surfaces. This latter contribution is detected with the chopper closed. The actual signal is the difference between
6.4 Atomic hydrogen

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\[ S_1 = S + B \]

where S is the scattering signal caused by the atomic beam itself, and B describes scattering caused by background gas and metal surfaces. This latter contribution is detected with the chopper closed. The actual signal is the difference between
Figure 39:

Preliminary results for the elastic scattering of electrons from atomic hydrogen. Scattering angle $\theta = 90^\circ$. This curve has been obtained by accumulating several runs. An indication of structure can be seen.
the two signal channels. The statistical error of such a modulated signal is given by

$$\Delta S = \left( (\Delta S_1)^2 + (\Delta S_2)^2 \right)^{1/2}$$

and therefore by

$$\Delta S = (S + 2B)^{1/2}$$

which means that the statistical fluctuations are mainly caused by the background contribution. In order to achieve better statistics, long integration times are required. This, in turn, requires a good long-term stability of the system. The main reason this has not yet been achieved is that the energy of the electron spectrometer fluctuates within a time period which is short compared to the time necessary to get reasonable counting statistics. These energy fluctuations smear out structure and the preliminary results had to be accumulated from several short runs. The structure indicated was positioned, according to the transmission experiment of L. Sanche and P. D. Burrow (1972), at 9.558 eV. Initial calibration runs in pure helium placed the structure at somewhat higher values, around 9.6 to 9.7 eV, which is not unexpected when compared with the energy discrepancies encountered for the rare gas results presented earlier. Future results will again have to be calibrated in a gas mixture.
7. Conclusions and suggestions for further experiments

The apparatus described can be used for a wide range of investigations for example the observation of electrons that have undergone collisions as well as photons originating from decay of excitation processes caused by these collisions. The final arrangement of two independent information circuits could be coupled in a coincidence experiment to give more detailed information about the actual collision processes. However the next step should be to remeasure the rare gas excitation functions with even higher resolution and to perform angular distribution measurements. This should give information on the polarisation of the lines involved as well as more information about the structures observed.

As far as atomic hydrogen is concerned, several improvements will have to be made before satisfactory results for the elastic scattering resonances can be obtained. The most urgent improvements should be to remove the hydrogen background in the interaction region by additional pumps. This could be done by cryo-pumping the hydrogen beam, or by means of an intermediate tank between source and interaction chamber. Although the latter modification involves longer distances between target beam source and scattering region, it should result in a much better signal to noise ratio. The electron beam system requires a much improved primary beam collector. An extended collector area surrounding the whole electron beam system together with a more sophisticated collector in the primary beam direction should reduce the problem of stray electrons considerably. This should result in a much better suppression of electrons which undergo reflections from various metal surfaces.
8. Acknowledgements

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One of the pleasures throughout the planning, building and running of the system described, was to work with Mr. H. Koschmieder. I should like to thank him for his co-operation in overcoming various difficulties which both of us had to experience.

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