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LARGE ANGLE SCATTERING
IN HEAVY PARTICLE COLLISIONS
USING A COINCIDENCE TECHNIQUE

by

Chaitanya Eknath Chitnis

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

MASTER OF ARTS

APPROVED, THESIS COMMITTEE:

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December, 1985
ABSTRACT

LARGE ANGLE SCATTERING
IN HEAVY PARTICLE COLLISIONS
USING A COINCIDENCE TECHNIQUE

by

CHAITANYA EKNATH CHITnis

The study of atomic collisions is important for a full understanding of a broad range of physical phenomena. A new technique has been developed to study the scattering of keV-energy atomic beams by gas targets at large angles. It uses two microchannel-plate based position-sensitive detectors to detect both the projectile and target in coincidence after the collision. The detectors provide information about the position and time of arrival of a particle. This is used to discriminate against noise and to determine scattering cross-sections. Relative differential cross sections have been measured for He-He scattering. While oscillations are observed in the differential cross sections for the symmetric collisions, He$^4$-He$^4$ and He$^3$-He$^3$, no such oscillations are seen for the asymmetric collision, He$^3$-He$^4$. This interference effect due to nuclear symmetry is one of the many beautiful consequences of Quantum Mechanics. A simple calculation assuming a Coulomb potential between the colliding atoms compares well with the experimental data.
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CHAPTER I

INTRODUCTION

Atomic and molecular collisions are of fundamental physical interest. Elastic and inelastic differential scattering cross sections measured over a wide range of angles and energies provide information that can lead to a detailed understanding of two-body interactions. Such measurements when applied to the study of atomic interactions, are useful in determining interaction potentials and reaction mechanisms.

A clear understanding of atomic and molecular collisions is crucial for developments in a number of fields. Accurate laboratory measurements of parameters like reaction rates and scattering cross sections are needed for modeling environments ranging from planetary atmospheres to fusion reactors.\textsuperscript{1,2}

Scattering processes involving atoms, ions and molecules in the earth's atmosphere lead to local heating and the escape of atoms from the atmosphere.\textsuperscript{3,4} During geomagnetic storms, energetic (0.7–12KeV) oxygen, hydrogen and helium ions trapped in the earth's magnetic field precipitate into the atmosphere. The precipitating particles penetrate the atmosphere and interact with it through a variety of collision processes, most important of which are charge
transfer, elastic scattering and inelastic scattering.\(^6,7\) The energetic ions undergo charge transfer collisions with the thermospheric oxygen and hydrogen and precipitate as keV-energy neutrals. The kinetic energy of the precipitating neutrals is transferred to the atoms and molecules of the upper atmosphere through elastic and inelastic collisions. The important scattering processes that take place are

\[
\begin{align*}
A + B \rightarrow A' + B' \text{ (elastic and inelastic)} \\
A^+ + B \rightarrow A^+ + B' \text{ (elastic and inelastic)} \\
A^+ + B \rightarrow A + B^+ \text{ (charge transfer)}
\end{align*}
\]

In the case of an inelastic collision, the final states of A and B may not be the same as their initial states. The precipitating particles, A, are atomic oxygen, hydrogen and helium. The ambient atmospheric constituents, B, that collide with these precipitating particles are primarily atomic oxygen and hydrogen at higher altitudes while at lower altitudes helium and molecular nitrogen and oxygen are also important. The energy deposited through these collisions causes the 'local heating' of the upper atmosphere. Some of the atoms receive enough energy to escape from the earth's atmosphere. This 'splash' effect leads to a net loss of atmospheric atoms for each energetic particle that penetrates the atmosphere.

Differential cross sections (DCS's) for the scattering processes relevant to particle precipitation have not been available.
Modelers have, therefore either assumed particular forms for the cross-sections or estimated them by scaling other measurements. Heating rates and atom loss fluxes calculated by these models are very sensitive to the cross sections and scattering parameters used. It is thus important to measure the differential cross sections for the relevant collision processes over the applicable range of energies and angles.

Motivated by the need for accurate laboratory data, a program to measure DCS’s for the scattering of energetic neutrals from stable atomic and molecular gas targets was undertaken. DCS’s for the scattering of ground state atomic hydrogen, helium and oxygen with targets of O₂, N₂, H₂ and He have been measured at laboratory scattering angles between 0.08° and 5° over a projectile energy range of 500eV to 5000eV.

When a fast particle undergoes elastic scattering, it transfers some of its kinetic energy to its collision partner. Consider a fast particle, A, of mass m₁, that is elastically scattered at an angle θ in the lab frame by a particle B of mass m₂ that is initially at rest in the lab. Straightforward application of the conservation of energy and momentum theorems dictates that the amount of kinetic energy lost by particle A in an elastic scattering event is given by

\[ \Delta E(\theta) = E_1 \frac{m_1 \tan^2(\theta)}{m_2 + m_1 \tan^2(\theta)} \]
To assess the amount of energy loss as a function of scattering angle, one can compute the differential energy loss cross section \( \frac{d\sigma(\theta)}{d\theta} \): \[ \frac{d\sigma(\theta)}{d\theta} = \frac{d\sigma(E)}{d\theta} \Delta E(\theta) \]  \[ \text{1.2} \]

where \( \frac{d\sigma(\theta)}{d\theta} \) is the DCS at angle \( \theta \). Plots of \( \frac{d\sigma(\theta)}{d\theta} \) shown in Fig. 1.1 reveal the importance of energy loss through elastic scattering at large angles. \[ \text{9} \]

**FIG. 1.1 DIFFERENTIAL ENERGY LOSS CROSS SECTIONS**

For the data of Fig. 1.1 the DCS drops by 3 orders magnitude from 0.08° to 5° and fewer than 5% of the scattered particles are scattered by more than 5°. Nevertheless, the greater amount of energy lost by particles scattered at larger angles compensates for the reduction in the DCS, and the amount of energy loss by a particle in an elastic collision appears to be independent of the scattering
angle. There is just as much energy transferred to the target by collisions resulting in 1-degree scattering as there is in collisions resulting in 5-degree scattering. Scattering at larger angles thus may play an important role in the energy loss of precipitating particles. The role of inelastic processes should be more significant in large-angle scattering because a close collision has a higher probability of resulting in excitation or ionization of the colliding particles. In an ideal experiment one should distinguish between elastic and inelastic scattering and identify the inelastic process observed.

The study of scattering at large angles is clearly important if one wants to fully understand the problem of particle precipitation in the atmosphere. Large-angle scattering also promises to be a problem of fundamental physical interest. We therefore developed a technique for measuring DCS's at large angles.

The technique uses two position-sensitive detectors (PSD's) to detect both the incident and target particle in coincidence after the collision. The detectors provide information about the time and position at which a particle is detected. The position information gives the angle at which a particle is scattered. The position and timing information is used in conjunction with the conservation of momentum theorem to distinguish between signal and noise. Large-angle scattering cross sections and consequently the signal from scattering at large angles are small. However, the detectors in our experiment subtend a very large solid
angle (detecting particles scattered by $26.5^\circ$ to $57^\circ$), yielding a count rate of $\sim 1$ count/sec. The position information completely defines the directions of the final velocity vectors of the two collision partners. The conservation of momentum theorem can be used to determine the magnitude of the velocities and the kinetic energies of the two particles. Hence, the coincidence technique can in principle be used to distinguish between elastic and inelastic collisions and to determine the energy loss in inelastic scattering processes.

This thesis describes the coincidence technique developed and presents the first results obtained. The collision processes studied are

\[ \text{He}^4(3000\text{eV}) + \text{He}^4 \]
\[ \text{He}^3(3000\text{eV}) + \text{He}^3 \]
\[ \text{He}^3(3000\text{eV}) + \text{He}^4 \]
\[ \text{He}^4(1500\text{eV}) + \text{He}^4 \]
CHAPTER II

PRINCIPLES OF THE EXPERIMENT

1.) KINEMATICS OF TWO-PARTICLE COLLISIONS

Fig. 2.1 illustrates the geometry of an elastic collision in both the laboratory (LAB) and center of mass (CM) coordinate systems. In the LAB frame the incident particle, $m_1$, has an initial velocity, $\vec{u}_1$, and the target particle, $m_2$, is initially at rest. After the collision, $m_1$ and $m_2$ have velocities $\vec{v}_1$ and $\vec{v}_2$ respectively. The angle $\theta_1$ is referred to as the laboratory scattering angle and $\theta_2$ as the laboratory recoil angle. It is assumed that the two-particle interaction is described by a central-field potential in which case the scattering is axially symmetric. The velocity, $\vec{V}$, of the centre of mass in the LAB system is given by

$$\vec{V} = \frac{m_1 \vec{u}_1}{m_1 + m_2} \quad 2.1$$

Since no external forces act on the two-particle system the velocity of the centre of mass, $\vec{V}$, remains unchanged.

In the CM system (the system in which the centre of mass is at rest) the initial velocities of the incident and target particles are $\vec{u}_1'$ and $\vec{u}_2'$ respectively. In the CM system, the total
FIG. 2.1 GEOMETRY OF AN ELASTIC COLLISION
linear momentum is zero. Before the collision, the particles move
directly towards each other and after the collision they move in
exactly opposite directions. The final velocities in the CM system
are $\vec{v}_1$' and $\vec{v}_2$' and $\Theta$ is the CM scattering angle.

The conservation of momentum theorem, which holds for all
collisions, produces the equations:

$$m_1v_1\sin\theta_1 = m_2v_2\sin\theta_2 \quad 2.2$$
$$m_1v_1\cos\theta_1 + m_2v_2\cos\theta_2 = m_1u_1 \quad 2.3$$

For elastic collisions, we can also apply the conservation of energy
theorem:

$$\frac{m_1u_1^2}{2} = \frac{m_2v_1^2}{2} + \frac{m_3v_2^2}{2} \quad 2.4$$

Equations (2.1–2.4) can be used to establish a relation between the
LAB scattering angle, $\Theta_1$, and the LAB recoil angle, $\Theta_2$.

$$\tan\Theta_1 = \frac{\sin2\Theta_2}{\frac{m_1}{m_2} - \cos2\Theta_2} \quad 2.5$$

The LAB scattering angle, $\Theta_1$, is plotted in Fig. 2.2 as a function
of the LAB recoil angle for various values of the mass ratio $m_1/m_2$.\(^{12}\)

There is a discontinuity from direct backscattering ($\Theta_1^{\text{MAX}} \rightarrow \pi$),
when the incident mass, $m_1$, is smaller than the target mass, $m_2$, to a
$\Theta_1^{\text{MAX}} = \pi/2$ for equal masses. When the incident mass is the heavier
FIG 2.2 LABORATORY AND RECOIL ANGLES FOR DIFFERENT MASS RATIOS ($m_1/m_2$)
(\(m_1 > m_2\)), the maximum possible LAB scattering angle is still more restricted by

\[ \theta_1 < \theta_1^{\text{MAX}} = \sin^{-1}\left(\frac{m_2}{m_1}\right) \quad 2.6 \]

with \(\theta_1 = \theta_1^{\text{MAX}}\) occurring for \(2\theta_1 = \pi/2 - \theta_1^{\text{MAX}}\). Also for \(m_1 > m_2\) the LAB recoil angles are double valued for \(\theta_1 < \theta_1^{\text{MAX}}\). For equally massive collision partners \((m_1 = m_2)\) every collision results in the two particles separating at right angles, \(\theta_1 + \theta_2 = \pi/2\).

These features can be demonstrated graphically using Newton diagrams as shown in Figs. 2.3a-h. Since the target is initially at rest in the LAB system using Eq.2.1 we have

\[ \vec{u}_2' = -\vec{V} = -\frac{m_1 u_1}{m_1 + m_2} \quad 2.7 \]

For an elastic collision the CM velocities before and after the collision are identical.

\[ u_1' = v_1' \quad \text{and} \quad u_2' = v_2' \quad 2.8 \]

Therefore, we have for the final CM velocities

\[ v_2' = \frac{m_1 u_1}{m_1 + m_2} \quad 2.9 \]

and

\[ v_1' = u_1' = u_1 - V = \frac{m_2 u_1}{m_2 + m_2} \quad 2.10 \]
FIG. 2.3 NEWTON DIAGRAMS
From Eqs. 2.1 and 2.10 we have

\[
\frac{v_1}{v_1'} = \frac{m_1}{m_2} \quad 2.11
\]

Fig. 2.3a shows the final velocity vectors for the case \( m_1 < m_2 \).
Since the total linear momentum in the CM frame is always zero, we have

\[
m_1v_1 = m_2v_2 \quad 2.12
\]

For \( m_1 < m_2 \), using Eqs. 2.11 and 2.12 we get

\[
v < v_1' \quad 2.13
\]

and \( v_1' > v_2' \quad 2.14\)

Also, as shown in Fig. 2.3a, we have

\[
\vec{v}_1 = \vec{v}_1' + \vec{V} \quad 2.15
\]

and \( \vec{v}_2 = \vec{v}_2' + \vec{V} \quad 2.16\)

As shown in Fig. 2.3b the final velocity vectors for an inelastic collision are always smaller than for the corresponding elastic collision at the same angle \( \Theta \). When transformed into the LAB frame,
\[(\theta_1 + \theta_2)_{\text{inelastic}} < (\theta_1 + \theta_2)_{\text{elastic}}\]. Figs. 2.3c and 2.3d show the final velocity vectors for the case \(m_1 > m_2\) where \(V > v_1'\) and \(v_2' > v_1'\), and for every laboratory scattering angle, \(\theta_1\), there exist two possible laboratory recoil angles \(\theta_{2b}\) and \(\theta_{2f}\) (where \(b\) and \(f\) stand for backward and forward, respectively). The two recoil angles clearly lead to different recoil velocities \(v_{2f}\) and \(v_{2b}\). Fig. 2.3e shows the final velocity vectors in the event of an inelastic collision. For the case \(m_1 > m_2\) we also have the situation of Fig. 2.3f. Clearly, at \(\theta_1^{\text{MAX}}\), the angle between \(v_1'\) and \(v_1\) is 90°, so that

\[\sin(\theta_1^{\text{MAX}}) = \frac{v_1'}{V} = \frac{m_2}{m_1}\]

and hence

\[\theta_1^{\text{MAX}} = \sin^{-1}(\frac{m_2}{m_1})\]

For \(m_1 = m_2\) we have \(V = v_1\) and \(v_1' = v_2'\). This leads to \(\theta_1 + \theta_2 = 90°\) for elastic collisions as shown in Fig. 2.3g. In case of an inelastic collision between particles of equal mass, some energy is lost and now we must have \(v_1' < V\). Clearly now \(\theta_1 + \theta_2 < 90°\) as is shown in Fig. 2.3h.
2.) PRINCIPLES OF THE TECHNIQUE.

a.) MEASUREMENT OF RELATIVE DIFFERENTIAL CROSS-SECTIONS (RDCS'S)

The coincidence technique uses two position sensitive detectors (PSD's) to detect both the incident and target particles after the collision. Details of the experiment will be described in the next chapter. The fundamental principles are discussed here.

Fig. 2.4 shows how the PSD's are mounted with respect to the beam axis and the target cell (TC). After the collision, the incident and target particles fly out of the TC at angles $\theta_1$ and $\theta_2$ with respect to the beam axis, respectively. For symmetric collisions ($m_1=m_2$), $\theta_1+\theta_2=90^\circ$ for elastic collisions and $\theta_1+\theta_2<90^\circ$ for inelastic collisions. The PSD's are circular and each has an active area with a diameter of 2.5cm. They are mounted vertically such that both the distance from the TC to the plane of the PSD's and the distance from the center of the PSD's to the beam center is 2.5cm. With this arrangement the PSD's can detect particles scattered by $26.5^\circ$ to $57^\circ$ as shown in Fig. 2.4. However, both the particles are detected in coincidence only over the lab scattering angles from $33^\circ$ to $57^\circ$.

The PSD's provide information about the time and position (X,Y coordinates) at which particles hit the detectors. PSD 1 (upper) is used as a trigger. Detection of a particle at PSD 1 opens a gate in a timing circuit for a period of 0.5$\mu$s. If PSD 2 (lower) receives a particle within this time interval the positions of both the particles and the time difference between their arrival
FIG 2.4 PSDs, TC AND BEAM AXIS
on the PSD's is recorded. This information is stored by a computer and is used to distinguish between signal and noise, and to determine the RDCS's.

b.) NOISE DISCRIMINATION USING POSITION INFORMATION

If the target particle is initially at rest the velocity vector of the center of mass always lies along the incident beam axis. The velocity vectors of the two particles after the collision, $(v_1, v_2)$, and the velocity vector of the center of mass, $V$, lie in a plane after the collision. Hence, a line joining the positions of the two particles on the PSD's intersects the beam axis if the particles are collision partners.

In reality the target particle is not at rest but has some thermal velocity ($\sim 1.4 \times 10^3 \text{m/sec}$), which is much smaller than the velocity of the incident beam ($\sim 3.8 \times 10^5 \text{m/sec}$ for a 3keV He$^4$ beam). The maximum flight time of a particle after collision is of the order of $2.2 \times 10^{-7} \text{sec}$. The center of mass can thus be displaced from the incident beam axis by a distance, $D$, of at most 0.3mm. To check if a pair of particles represents true signal, a line joining the positions of the two particles on the PSD's is drawn. If the perpendicular distance from the beam axis to this line is less than $D$, the pair of particles is treated as real signal. Otherwise it is discarded from the analysis. Fig. 2.5 shows how the noise is identified using the position signal. Lines joining the positions of the collision partners have been drawn. Clearly, most of the lines
FIG. 2.5  NOISE ANALYSIS USING POSITION INFORMATION
pass through the beam centre and the corresponding pair of particles represents true signal.

c) NOISE DISCRIMINATION USING TIMING INFORMATION

Consider a coordinate system XYZ with its origin located at the TC, a distance L from the plane of the PSDs as shown in Fig. 2.6. The laboratory scattering and recoil angles can be determined using the position information of the two particles as follows

\[ \theta_1 = \tan^{-1} \left( \frac{x_1^2 + y_1^2}{L} \right) \] 2.19

and

\[ \theta_2 = \tan^{-1} \left( \frac{x_2^2 + y_2^2}{L} \right) \] 2.20

Since the conservation of momentum theorem holds for all collisions, Eqs. 2.2 and 2.3 are always valid, and produce the equations

\[ v_1 = \frac{u_1}{\cos \theta_1 + \sin \theta_1 \cot \theta_2} \] 2.21

and

\[ v_2 = \frac{m_2 v_1 \sin \theta_2}{m_1 \sin \theta_2} \] 2.22

where
FIG. 2.6 APPARATUS GEOMETRY
\[ u_\lambda = \left( \frac{2E}{m_\lambda} \right)^{1/3} \quad \text{(2.23)} \]

and \( E \) is the energy of the incident particle. The final velocities of the particles can be determined using Eqs. (2.19–2.23).

We can now calculate the expected time difference, \( \Delta T_{\text{CALC}} \), between the arrival of the two particles at the PSD's.

\[
\Delta T_{\text{CALC}} = \frac{L}{v_2 \cos \theta_2} - \frac{L}{v_1 \cos \theta_1} \quad \text{(2.24)}
\]

The calculated time difference is compared with the measured time difference (\( \Delta T_{\text{MEAS}} \)) for each pair of particles recorded.

\[ \text{If } \left| \frac{\Delta T_{\text{MEAS}} - \Delta T_{\text{CALC}}}{\Delta T_{\text{MEAS}}} \right| \times 100 < X \% \quad \text{(2.25)} \]

(where \( X \) is specified) we treat the two particles as signal. The largest \( \Delta T_{\text{MEAS}} \) is of the order of \( 1 \times 10^{-7} \text{ sec} \) for a 3keV He–He collision. The resolution of the timing electronics is about \( 10^{-9} \text{ sec} \). If both \( \Delta T_{\text{MEAS}} \) and \( \Delta T_{\text{CALC}} \) are less than \( 10^{-8} \text{ sec} \) then the pair of particles is treated as signal. If \( \Delta T_{\text{CALC}} \) is greater than \( 10^{-8} \) then Eq. 2.25 is used to distinguish between signal and noise. The value of \( X \) used is typically between 10 and 50 percent. In a data file, 20% of the data points are typically identified as noise and are discarded. The data that corresponds to real signal is analysed to determine the RDCS's.
d) DETERMINATION OF RDCS's FROM DATA

For symmetric collisions the surface of PSD 1 is divided into rings centered at the beam center as shown in Fig. 2.7. The \( n^{th} \) ring corresponds to the scattering angle, \( \theta_n \), and subtends an angle of around 0.5° at the TC. An array, \( S_n' \), is used to store the calculated RDCS's, where \( S_n \) is the signal in the \( n^{th} \) ring. The position information of the particle detected by PSD 1 is used to determine which ring it falls in.

The PSD's have been studied and characterized in our lab. The PSD detection efficiency is a function of the energy of the incident particle as shown in Fig. 2.8.\textsuperscript{14} The detection efficiencies of fast neutrals are not available, but it is believed that they are the same as ions of the same energy. The kinetic energies are determined for each pair of particles using Eqs.2.19-2.23. If \( f_1 \) and \( f_2 \) are the PSD efficiencies at these energies, the detection efficiency, \( f_{12} \), for the pair, is given by

\[
f_{12} = \frac{f_1 \cdot f_2}{100} \quad 2.26
\]

The array element, \( S_n' \), is incremented by \( \frac{100}{f_{12}} \) if the particle detected by PSD 1 falls in the \( n^{th} \) ring. Since only a fraction of each ring lies on the PSD surface, the signal, \( S_n' \), is scaled for the area over which particles are collected in each ring.

Fig. 2.9 shows a magnified picture of the collision geometry in the TC. Let the angles at which the particles are
FIG 2.7 SCALING FOR DETECTION AREA
FIG 2.8 PSD EFFICIENCIES FOR H(0), He+(4) AND O+(•)
FIG 2.9 COLLISION VOLUME IN THE TC
detected be $\theta_1$ and $\theta_2$. For both the particles to reach the detectors the collision must take place inside the volume, $V$, shown in Fig. 2.9. This volume, $V$, is the intersection of the conical volume with its vertex at $A$, and the cylindrical volume of the incident beam. A collision resulting in scattering at angle $\theta_1$ which takes place outside the volume $V$ is not detected since one of the particles is blocked by the exit aperture and does not reach the PSD. The collision volumes for scattering at different angles are not the same. The signal, $S_n$, in each ring is thus scaled to normalize for the different collision volumes. The normalized signal gives the RDCS as a function of the scattering angle.

e.) ASSYMETRIC COLLISIONS

This apparatus can be used to study asymmetric collisions where $\frac{m_1}{m_2} = 1$ (e.g. $\text{He}^3$-$\text{He}^4$). For $\text{He}^3$-$\text{He}^4$ scattering both the incident and target particles can be detected in coincidence for scattering angles from $38^0$ to $57^0$. The principles used to discriminate against noise in the case of symmetric collisions are also applicable for asymmetric collisions. However, it is now necessary to identify which of the pair of particles detected is the projectile ($\text{He}^3$). This is accomplished by using the timing information. We first assume that $\text{He}^3$ is detected by PSD 1 and $\text{He}^4$ by PSD 2. The expected time difference is calculated using Eqs.2.19-2.24 and compared with the measured time difference. If the percentage difference is large, our assumption is clearly wrong. We
then assume that PSD 1 detects He\textsuperscript{4} and PSD 2 detects He\textsuperscript{3}. If the calculated and measured time difference are now comparable, we have succeeded in identifying the projectile (He\textsuperscript{3}) and the target (He\textsuperscript{4}). If the percentage difference continues to be large, we treat the pair of particles as noise. For He\textsuperscript{3}-He\textsuperscript{4} collisions, PSD 1 detects He\textsuperscript{3} at scattering angles from 38\textdegree{} to 52\textdegree{}, and PSD 2 detects He\textsuperscript{3} at scattering angles from 52\textdegree{} to 57\textdegree{}. The method used to determine EDCS's in the case of symmetric collisions can be applied. However, for asymmetric collisions, the surfaces of both the PSD's must be divided into rings since the projectile is detected on both detectors.

f.) ANGULAR AND ENERGY RESOLUTION

The error in the scattering angle, \( \Theta_1 \), is caused by the finite collision length of the target cell and the position resolution of the PSD's. The collision length is \( \sim 450 \mu \) and the position resolution of the PSD's is \( \pm 60 \mu \). This gives an angular resolution of \( \sim 0.51 \textdegree{} \) for the configuration shown in Fig. 2.3.

One can find the scattering and recoil angles, \( \Theta_1 \) and \( \Theta_2 \), using the position information. Eqs. 2.21-2.23 can then be used to determine the final velocities, \( v_1 \) and \( v_2 \). The final kinetic energies are

\[
E_1 = \frac{m_1 v_1^2}{2}
\]  

2.27
and \[ E_2 = \frac{m_2 v_2}{2} \] 2.28

Since the energy of the incident beam (\(E_{\text{incident}}\)) is known we can determine the energy loss (\(\Delta E\)) in an inelastic collision.

\[ \Delta E = E_{\text{incident}} - E_1 - E_2 \] 2.29

The energy resolution is limited mainly by the angular resolution of the apparatus. Other factors that affect the energy resolution are the energy spread of the incident beam (1eV), and the thermal energy of the target particles. The energy resolution for the configuration of Fig. 2.3 is \(~55\text{eV}\). The first ionization potential of \(\text{He}^3\) is 24.6eV. With the present energy resolution it is therefore not possible to identify the various excitation processes in an inelastic collision.
CHAPTER III

EXPERIMENTAL DETAILS

1.) APPARATUS

Fig. 3.1 shows a schematic diagram of the apparatus. Ions emerging from a magnetically-confined electron impact source are accelerated and focussed by a set of cylindrical electrostatic lenses which render the beam parallel as it enters the first magnet. The beam is then momentum analyzed by a pair of 60° sector magnets. The magnetic fields of the two magnets are set so that only the desired species (He⁺) passes through. The other ions are deflected out of the beam. The momentum-analyzed ion beam passes through the charge transfer cell (CTC) containing helium gas, which neutralizes a fraction of the fast helium ions by charge transfer. Deflection plates (DP) remove residual ions from the beam emerging from the CTC. The CTC exit aperture and the target cell (TC) entrance aperture collimate the neutral helium beam. The CTC exit aperture and the TC entrance aperture have diameters of 500µ and 30µ respectively. They are separated by a distance of approximately 10cm. This limits the beam divergence to about 5 milliradians (0.3°).

The TC is approximately 450µ long and has an exit aperture of 300µ diameter. An adjustable leak valve is used to
admit gas (He\textsuperscript{3} or He\textsuperscript{4}) to the TC. The helium atoms of the fast neutral beam collide with the helium atoms in the TC. Both, the projectile and target atom fly out of the TC and are detected by two position sensitive detectors (PSD's). Fig. 2.4 shows schematically the TC and the PSD's. The PSD's are circular and each has an active area with a diameter of 2.5cm. They are mounted vertically and their centre-to-centre distance is 5cm. The distance between the exit aperture of the TC and the plane of the PSD's is 2.5cm \pm 0.01cm. With this arrangement the PSD's are symmetrically placed with respect to the unscattered neutral beam and can receive scattered particles over the angular range of 26.5° to 57°.

The PSD used in this experiment is a microchannel plate (MCP) based detector that can be used to detect both ions and neutrals. It has been studied and characterized extensively in our laboratory. A detailed discussion can be found elsewhere.\textsuperscript{14} The PSD provides information about the time and position at which a particle is detected. A timing pulse indicates the arrival of a particle. Two analog voltages proportional to the X and Y coordinates of the arrival position are also produced.

For a scattering event to be recorded, both the projectile and the target must be detected by the PSD's. PSD 1 is used as a trigger. When PSD 1 detects a particle it produces a timing pulse and a position signal. The pulse is sent to a timing circuit. Fig. 3.2 shows a circuit diagram of the timing circuit and Fig. 3.3 shows a timing diagram of the circuit. When the timing
FIG. 3.2 TIMING CIRCUIT DIAGRAM

FIG. 3.3 TIMING DIAGRAM
circuit receives a pulse from PSD 1, it opens a gate for an interval of 0.5μs and produces a STOP pulse at the end of this interval. The STOP pulse is sent to a time-to-digital converter (TDC). If PSD 2 detects a particle within this interval of 0.5μs, it sends a pulse to the timing circuit indicating the arrival of the second particle. On receiving a pulse from PSD 2, the timing circuit produces a START pulse which is sent to the TDC. The TDC measures the time interval, T, between the START and STOP pulses. As shown in Fig. 3.3 the time difference between the arrival of the two particles is given by

\[ \Delta T = (0.5\mu s - T) \]  

3.1

The position signal is produced approximately 6μs after the timing pulse. A strobe pulse, of width 4μs, is simultaneously produced indicating that the position signal is available. The position signal from the two PSD's is sent to two dual analog-to-digital converters (ADC's). The ADC's read and digitize the position information only if both the particles have been detected and both the position and timing information is available. Fig. 3.4 shows the time relationship of all the pulses and signals. The digitized position and timing information is collected and stored by a MIK-11/2 microcomputer. Fig. 3.5 shows a flowchart of the data-taking program. It reads and stores the digitized data from the TDC's and ADC's, checks for coincident signals, clears and enables the electronics for the next signal and finally saves the data on a disk.
FIG. 3.4  TIME RELATIONSHIP OF ALL PULSES AND SIGNALS.
BEGIN

CLEAR TDC AND ADC LAM REGISTERS
ENABLE TDC AND ADC LAM REGISTERS
ENABLE TDC AND ADC

TOC LAM '0'
'1'
'0'

CHECK ADC LAM 10 TIMES

CAUGHT AN EVENT
RECORD IT TO
COMPUTER MEMORY

MEMORY FULL
NO
YES

CLEAR MEMORY

SAVE DATA ON DISK

YES
REPEAT
NO

STOP

FIGURE 3.5 FLOWCHART OF DATA TAKING PROGRAM
2.) DATA ANALYSIS

This experiment records the position of arrival of both the particles that undergo a collision and the time difference between their arrival at the PSD’s. This information is used to discriminate against noise and to determine the relative differential cross-sections (RDCS’s) using the principles described earlier. Fig. 3.6 shows a flowchart of the computer program used to analyze the data. It reads the data from a disk, eliminates noise using the position and timing information in conjunction with considerations of momentum conservation, calculates the RDCS’s normalizing the signal for PSD efficiency, detection area and collision volume, plots the RDCS’s as a function of the lab scattering angle and stores the results on a disk.

The next chapter presents the first results obtained using the coincidence technique.
FIGURE 3.6 FLOWCHART OF THE DATA ANALYSIS PROGRAM
CHAPTER IV

RESULTS AND DISCUSSION

1.) RESULTS

Relative differential cross sections (RDCS's) were measured for the collisions listed in Table 4.1 below.

<table>
<thead>
<tr>
<th>No</th>
<th>PROJECTILE</th>
<th>TARGET</th>
<th>PROJECTILE ENERGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>He$^4$</td>
<td>He$^4$</td>
<td>3000eV</td>
</tr>
<tr>
<td>2</td>
<td>He$^3$</td>
<td>He$^3$</td>
<td>3000eV</td>
</tr>
<tr>
<td>3</td>
<td>He$^3$</td>
<td>He$^4$</td>
<td>3000eV</td>
</tr>
<tr>
<td>4</td>
<td>He$^4$</td>
<td>He$^4$</td>
<td>1500eV</td>
</tr>
</tbody>
</table>

Figs. 4.1-4.3 show the raw data as it was recorded on the PSD's. An interference pattern is clearly visible for the symmetric collisions, He$^4$-He$^4$ and He$^3$-He$^3$. The pattern is more prominent for He$^4$-He$^4$ than for He$^3$-He$^3$. Fig. 4.4 shows the He$^4$(3000eV)-He$^4$ data after noise filtering. Figs. 4.5 and 4.6 show the data for He$^3$(3000eV)-He$^4$ after the projectile has been identified and the noise eliminated. In Fig. 4.5, He$^3$ is detected on PSD 1.
FIG. 4.1 \( \text{He}^4(3000\text{eV})-\text{He}^4 \) RAW DATA

FIG. 4.2 \( \text{He}^3(3000\text{eV})-\text{He}^3 \) RAW DATA
FIG. 4.3  $\text{He}^3(3000\text{eV})$-$\text{He}^4$ RAW DATA

FIG. 4.4  $\text{He}^4(3000\text{eV})$-$\text{He}^4$ DATA AFTER NOISE ANALYSIS
FIG. 4.5 $\text{He}^3(3000\text{eV})-\text{He}^4$ DATA AFTER NOISE ANALYSIS
$\text{He}^3$-PSD 1 (LEFT), $\text{He}^4$-PSD 2 (RIGHT)

FIG. 4.6 $\text{He}^3(3000\text{eV})-\text{He}^4$ DATA AFTER NOISE ANALYSIS
$\text{He}^4$-PSD 1 (LEFT), $\text{He}^3$-PSD 2 (RIGHT)
(left), over the lab scattering angle range of 38° to 52°, and He⁴ is detected on PSD 2. Fig. 4.6 shows the data for which He³ is detected on PSD 2 (right), over the lab scattering angle range of 52° to 57°, and He⁴ is detected on PSD 1.

Plots of the RDCS's are shown in Figs. 4.7-4.10. The distinctive feature of these plots is the presence of oscillations for the symmetric collisions and their absence in case of the asymmetric collision. The maxima in the RDCS of He⁴(3000eV)-He⁴ are out of phase with those of He³(3000eV)-He³. While He⁴(3000eV)-He⁴ has a peak at the lab scattering angle θ₁ of 45°, He³(3000eV)-He³ has a minimum. The RDCS of He⁴(3000eV)-He⁴ has larger oscillations than He³(3000eV)-He³. Table 4.2 lists the periods of the oscillations for the collisions studied.

<table>
<thead>
<tr>
<th>No</th>
<th>PROJECTILE</th>
<th>TARGET</th>
<th>PROJECTILE ENERGY</th>
<th>PERIOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>He⁴</td>
<td>He⁴</td>
<td>3000eV</td>
<td>4.0° ±0.25°</td>
</tr>
<tr>
<td>2</td>
<td>He³</td>
<td>He³</td>
<td>3000eV</td>
<td>4.6° ±0.25°</td>
</tr>
<tr>
<td>3</td>
<td>He⁴</td>
<td>He⁴</td>
<td>1500eV</td>
<td>3.1° ±0.25°</td>
</tr>
</tbody>
</table>

2.) DISCUSSION.

a.) RESULTS FROM LITERATURE

The interference effect due to the nuclear symmetry of the collision partners has been observed in large angle scattering by
He$_4$ (3000eV) + He$_4$

![Graph showing RDCS for He$_4$ (3000eV) + He$_4$](image)

**FIG. 4.7** RDCS FOR He$_4$ (3000eV) - He$_4$
He\textsuperscript{3} (3000eV) + He\textsuperscript{3}

![Graph showing RDCS vs. LAB Angle for He\textsuperscript{3} (3000eV) + He\textsuperscript{3}](image)

FIG. 4.8 RDCS FOR He\textsuperscript{3} (3000eV) - He\textsuperscript{3}
He\(_3\) (3000eV) + He\(_4\)

FIG. 4.3 RDCS FOR He\(^3\) (3000 ev) - He\(^4\)
He\textsubscript{4} (1500 eV) + He\textsubscript{4}

FIG. 4.10 RDCS FOR He\textsuperscript{4} (1500 eV) — He\textsuperscript{4}
Siska et al. (1970,71)\textsuperscript{15,16}, Parson et al. (1972)\textsuperscript{17} and Barat et al. (1972)\textsuperscript{18} Siska et al. measured RDCS for He\textsuperscript{4}–He\textsuperscript{4} and Ne\textsuperscript{20}–Ne\textsuperscript{20} scattering at thermal energies using two supersonic nozzle atom beams crossing at right angles, with a rotatable electron bombardment mass filter detector in the plane of the beams. Their results for He\textsuperscript{4}–He\textsuperscript{4} collisions are shown in Fig. 4.11\textsuperscript{16}. Parson et al. used the same apparatus to study the symmetry oscillations in Ar–Ar scattering at thermal energies. Barat et al. measured DCS for He\textsuperscript{4}–He\textsuperscript{4} collisions in the keV energy range. Their data is shown in Fig.4.12.\textsuperscript{18} There is no other data at the projectile energies and scattering angles we have studied. Also, there are no theoretical calculations of the DCS for the collisions studied here. We have thus carried out a simple calculation of the DCS and compared the results with our measurements.

b.) CALCULATION OF DCS FROM THEORY

Fig. 4.13 shows the scattering process in the CM frame. Detector's $D_1$ and $D_2$ detect the particles at the CM scattering angles $\theta$ and $\pi - \theta$ respectively. Fig. 4.13 shows the two possible processes by which the particles can reach the detectors. If the particles A and B are distinguishable, as is true in He\textsuperscript{3}–He\textsuperscript{4} collisions, the DCS is given by

$$\sigma(\theta) = |f(\theta)|^2$$

4.1
FIG 4.11 DCS FOR He—He COLLISIONS

FIG 4.12 DCS FOR He—He COLLISIONS
FIG. 4.13 COLLISION IN CM FRAME
where $f(\phi)$ is the scattering amplitude.

In a He$^4$-He$^4$ collision the incident and target particles are identical. A He$^4$ atom can reach detector $D_2$ by either of the two processes shown in Fig. 4.13. We thus have a physical situation in which two indistinguishable routes lead to the same physical outcome. Since ground state He$^4$ atoms are spin zero particles (Bosons) the DCS may be written as

$$
\sigma(\phi) = \left| f(\phi) + f(\pi - \phi) \right|^2 \hspace{1cm} 4.2
$$

The addition of the scattering amplitudes results in the interference effect (oscillations in the RDCS) observed.

Ground state He$^3$ atoms are spin-one-half particles and so must be treated as Fermions. In a He$^3$-He$^3$ collision, if the colliding atoms have opposite spins, then they may be distinguished by a measure of their spin. There are, in this case, two distinguishable ways by which one of the He$^3$ atoms can reach detector $D_2$. The DCS is then,

$$
\sigma(\phi) = \left| f(\phi) \right|^2 + \left| f(\pi - \phi) \right|^2 \hspace{1cm} 4.3
$$

If the colliding He$^3$ atoms have parallel spins, then they are indistinguishable and the DCS is given by,

$$
\sigma(\phi) = \left| f(\phi) - f(\pi - \phi) \right|^2 \hspace{1cm} 4.4
$$
In our experiment the incident and target He\(^3\) atoms are unpolarized. The probability for any pair of He\(^3\) atoms to have identical or opposite spins is 1/2 and the DCS is therefore,

\[\sigma(\theta) = \frac{(||f(\theta)||^2 + ||f(\pi - \theta)||^2)}{2} + \frac{(||f(\theta) - f(\pi - \theta)||^2)}{2}\]  \hspace{1cm} 4.5

It is reasonable to assume that scattering at large angles results from a close collision and the interaction primarily responsible is the Coulomb interaction between the nuclei of the colliding atoms. The Coulomb potential between them can be written as

\[V(r) = \frac{Z_{\text{eff}}^2 e^2}{r}\]  \hspace{1cm} 4.6

where r is the distance of separation, and Z\(_{\text{eff}}\) is the effective nuclear charge seen by the collision partners. Classically, for a given total energy of the incident particle, and a given impact parameter, b, the CM scattering angle, \(\theta\), is precisely known. For scattering by a Coulomb potential, the relation between the impact parameter and the CM scattering angle is\(^{11}\)

\[b = a \cot \frac{\theta}{2}\]  \hspace{1cm} 4.7

where
\[ a = \frac{\text{2Z}_{\text{eff}}^3}{\mu \nu} \]

\[ \mu = \text{reduced mass of the incident and target particles} \]

\[ \nu = \text{relative velocity when incident particle is at infinity} \]

The impact parameter, \( b \), is related to the distance of closest approach, \( r_{\text{min}} \), by the relation

\[ b = r_{\text{min}} \left( 1 - \frac{r_e}{r_{\text{min}}} \right)^{2/3} \]

For a \( \text{He}^4(3000\text{eV})-\text{He}^4 \) collision resulting in a CM scattering angle of 90° (lab scattering angle of 45°), the impact parameter, \( b \), is 1.92\( \times \)10\(^{-12} \)m, and the distance of closest approach, \( r_{\text{min}} \), is 4.64\( \times \)10\(^{-12} \)m. Since the radius of the ground state helium atom is 2.65\( \times \)10\(^{-9} \)m, the nuclei in such a close encounter are within the electron cloud of the two helium atoms. For large-angle scattering in keV-energy collisions we can therefore make the plausible assertion that the Coulomb interaction between the nuclei governs the scattering process. A calculation of the DCS based on this assumption, though simplistic, can be expected to give realistic results at large angles.

N. F. Mott calculated the scattering amplitude for the Coulomb scattering of a beam of charged particles (electrons, \( \alpha \)-particles) by a bare nucleus in 1933. The Mott expression for the scattering amplitude is\(^{19,20} \)
\[ f(\phi) = \frac{-a^2}{4k \sin^2(\phi/2)} \frac{(1+ik/2)}{(1-ik/2)} \exp(-\frac{ia \log(\sin^2(\phi/2))}{2k}) \] 4.9

where \( a = \frac{2mZ_1Z_2e^2}{\hbar} \)

\[ k = \left(\frac{2mE_k}{\hbar^2}\right)^{\frac{1}{2}} \]

\( m = \) reduced mass of the projectile and target

\( E_k = \) total energy in CM frame

\( Z_1e = \) charge of projectile

and \( Z_2e = \) charge of target

We can use this expression for the scattering amplitude and our earlier results, Eqs. 4.1, 4.2 and 4.5, to calculate the DCS's. For a \( \text{He}^4 - \text{He}^4 \) collision, using Eqs. 4.2 and 4.8 we have

\[ \sigma(\phi) = \frac{a^2}{16k \sin^4(\phi/2)} \left[ 1 + \tan^4(\phi/2) + 2\tan^2(\phi/2) \cos(\frac{a \log(\tan^2(\phi/2))}{2k}) \right] \] 4.10

where \( a = \frac{2mZ^2}{\hbar^2} \)

For a \( \text{He}^3 - \text{He}^3 \) collision, using Eqs. 4.5 and 4.9 we have

\[ \sigma(\phi) = \frac{a^2}{16k \sin^4(\phi/2)} \left[ 1 + \tan^4(\phi/2) - \tan^2(\phi/2) \cos(\frac{a \log(\tan^2(\phi/2))}{2k}) \right] \] 4.11

Finally for a \( \text{He}^3 - \text{He}^4 \) collision using Eqs. 4.1 and 4.9 we have
\[ \sigma(\phi) = \frac{3}{16k \sin^4 \phi / 2} \quad 4.12 \]

Note that the interference of the scattering amplitudes in case of the symmetric collisions leads to an oscillatory term in the expression for the DCS. To convert the DCS from the CM system to the lab system we use the fact that the total cross section, \( \sigma \), must be the same in all coordinate systems. The invariance of \( \sigma \) requires that

\[ \sigma_{\text{LAB}}(\Theta_1) = \sigma_{\text{CM}}(\phi) \frac{d(\cos \phi)}{d(\cos \Theta_1)} \quad 4.13 \]

where \( \phi = \text{CM scattering angle} \) and \( \Theta_1 = \text{lab scattering angle} \)

For elastic collisions, the CM scattering angle, \( \phi \), is related to the lab scattering angle, \( \Theta_1 \), by the relation

\[ \tan \Theta_1 = \frac{m_2 \sin \phi}{m_2 \cos \phi + m_1} \quad 4.14 \]

For symmetric collisions \( \Theta_1 = \phi / 2 \). Eqs. 4.12 and 4.13 give the following relation.

\[ \sigma_{\text{LAB}}(\Theta_1) = \frac{\sigma_{\text{CM}}(\phi) \left( \frac{m_1^2 + m_2^2 + 2m_1m_2 \cos \phi}{m_2} \right)^{1/2}}{m_2 |m_1 + m_2 \cos \phi|} \quad 4.15 \]

Eqs. 4.10-4.15 were used to calculate the DCS's for the collisions studied. Different values of \( Z_{\text{eff}} \) were tried to get the best fit to
the experimental data. While $Z_{\text{eff}} = 2.0$ gave the best fit for all the collisions with 3000eV projectiles, $Z = 1.9$ gave the best fit for the $\text{He}^4(1500\text{eV})-\text{He}^4$ collision. This suggests that at lower energies the colliding atoms see a shielded nucleus and the effective charge, $Z_{\text{eff}}$, is less than the charge of the bare helium nucleus. It would be interesting to see how the effective charge varies as a function of the projectile energy.

A calculation of the DCS, assuming a Coulomb potential between the colliding helium atoms gives results which compare fairly well with the experimental data. The oscillations in the DCS of the symmetric collisions are clearly due to the nuclear symmetry of the colliding atoms. Note that the oscillatory term in Eq. 4.10 and Eq. 4.11 is not the same. This is due to the different ways in which the scattering amplitudes interfere in case of Fermions ($\text{He}^3$) and Bosons ($\text{He}^4$). As a result, the amplitude and the phase of the oscillations is different in case of $\text{He}^3-\text{He}^3$ and $\text{He}^4-\text{He}^4$ collisions. For the CM scattering angle, $\theta$, of $90^\circ$ ($\theta_\perp = 45^\circ$), while the DCS for $\text{He}^4-\text{He}^4$ has a peak, there is a minimum for $\text{He}^3-\text{He}^3$. 
CHAPTER V

CONCLUSIONS AND FUTURE WORK

Scattering at large angles in He-He collisions has been studied using a newly developed coincidence technique. Measurements of the relative differential cross-sections (RDCS's) have been presented for \( \text{He}^4-\text{He}^4 \), \( \text{He}^3-\text{He}^3 \) and \( \text{He}^3-\text{He}^4 \) collisions. Oscillations in the RDCS's, due to nuclear symmetry, were found in the symmetric collisions. The differences in the phase and amplitude of the oscillations for \( \text{He}^4-\text{He}^4 \) and \( \text{He}^3-\text{He}^3 \) were accounted for by the fact that while \( \text{He}^4 \) atoms are Bosons, \( \text{He}^3 \) atoms are Fermions. A simple calculation of the DCS, assuming a Coulomb interaction between the colliding helium atoms, gave a good fit to the experimental data.

This technique can be used to study other scattering processes. 0-0 collisions are of great importance to the ion-precipitation problem in the earth's atmosphere where energetic oxygen atoms precipitate into an atmosphere consisting primarily of atomic oxygen at higher altitudes. Differential cross-section (DCS) measurements for 0-0 collisions will thus be of great interest to atmospheric modelers. With this in mind, an atomic oxygen source has been recently developed in our laboratory to be used as a target.
source. Measurements of the DCS for O-O scattering will provide the first such results.

With some modifications to the apparatus the angular range of the technique can be increased. A more flexible assembly of the target cell (TC) and position sensitive detectors (PSD's) has been designed. One of the PSD's it uses has a larger active area (4cm diameter) than the one presently used (2.5cm diameter). The distance between the PSD's and the position of the beam with respect to the PSD's can be changed to make optimum use of the active area of the PSD's. RDCS's can now be measured for lab scattering angles from 25° to 45° for symmetric collisions. In the case of scattering at smaller angles, the recoil particle acquires very little kinetic energy. Because the efficiency of the PSD's drops drastically below 500eV, this technique cannot be used to study scattering at small angles. The flexibility of the new assembly will also allow us to study highly assymetric collisions (e.g. O-He, H-O etc.).

Since the final kinetic energies of both the collision partners can be determined, this technique can be used to study the energy loss in a collision. However, as seen in Fig. 5.1, the present energy resolution is not good enough to identify individual inelastic peaks. The resolution can be improved by decreasing the collision length in the TC and increasing the flight length (L, in Fig.2.4). The energy resolution, AE, has been calculated for different values of collision length and flight length for a 3keV beam and is shown in Table 5.1.
FIG 5.1 ENERGY LOSS SPECTRUM FOR He⁺ (3000 eV) — He⁺
### TABLE 5.1

<table>
<thead>
<tr>
<th>No.</th>
<th>COLLISION LENGTH</th>
<th>FLIGHT LENGTH</th>
<th>ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450µ</td>
<td>2.5cm</td>
<td>55eV</td>
</tr>
<tr>
<td>2</td>
<td>450µ</td>
<td>4.0cm</td>
<td>34eV</td>
</tr>
<tr>
<td>3</td>
<td>100µ</td>
<td>4.0cm</td>
<td>9eV</td>
</tr>
<tr>
<td>4</td>
<td>100µ</td>
<td>10.0cm</td>
<td>3eV</td>
</tr>
</tbody>
</table>

Absolute DCS's can be measured from 0.05° to 28° using the single PSD technique developed in our lab.\textsuperscript{9,10} The RDCS's measured using the coincidence technique can be normalized to the absolute DCS data in regions of overlap. Absolute DCS's can thus be determined over the entire scattering angle range from 0.05° to 45° for symmetric collisions.

The coincidence technique promises to be a simple yet elegant way to study scattering at large angles. Many of the experiments suggested may be performed in the near future and will provide useful and interesting data.
REFERENCES

1. A. Dalgarno, Advances in Atomic and Molecular Physics, 15, 37, (1979)


