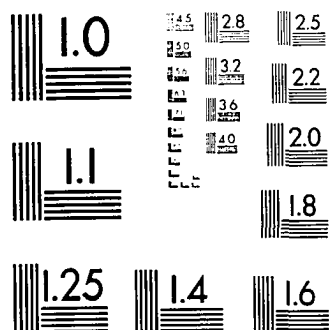


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ABSOLUTE ELASTIC ELECTRON-HELIUM AND TOTAL ELECTRONICALLY
ELASTIC ELECTRON-HYDROGEN(2) SCATTERING CROSS-SECTION
MEASUREMENTS FROM 1-19 EV

The University of Oklahoma

PH.D. 1985

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ABSOLUTE ELASTIC e^- -He AND TOTAL ELECTRONICALLY ELASTIC
 e^- -H₂ SCATTERING CROSS-SECTION MEASUREMENTS
FROM 1-19 eV

A DISSERTATION
SUBMITTED TO THE GRADUATE FACULTY
in partial fulfillment of the requirements for the
degree of
Ph.D.

By
MASSOUD MAHGEREFTEH
Norman, Oklahoma
1985

ABSOLUTE ELASTIC e^- -He AND TOTAL ELECTRONICALLY ELASTIC
 e^- -H₂ SCATTERING CROSS-SECTION MEASUREMENTS
FROM 1-19 eV
A DISSERTATION
APPROVED FOR THE DEPARTMENT OF PHYSICS

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TO
MY PARENTS
NISSAN AND TOURAN

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MM.

Abstract

Absolute e^- -He and e^- -H₂ total electronically, elastic differential cross-sections have been determined from relative scattered electron angular distribution measurements in the energy range from 2 to 19 eV in e^- -He; and 1-19 eV in e^- -H₂ by comparison to absolute e^- -He cross-section measurements. The s, p, and d phase shifts determined in work are roughly in agreement with various previous determinations. The total and momentum-transfer cross sections for e^- -He, and integrated total cross-sections for e^- -H₂ have been determined as well. In case of e^- -He, the total and momentum transfer cross sections found in this work at 2 and 5 eV are in excellent agreement with the direct measurements of Golden and Bandel and of Crompton et al., respectively. For e^- -H₂, absolute differences as large as 50% between the present results and some previous results have been found, although the agreement as to shape is quite good in many cases. The present results, for e^- -H₂, are generally in excellent agreement with recent full rovibrational laboratory-frame close-coupling calculations.

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ABSOLUTE ELASTIC e^- -He AND TOTAL ELECTRONICALLY
 e^- -H₂ SCATTERING CROSS-SECTION MEASUREMENTS
FROM 1-19 eV

CHAPTER I

INTRODUCTION

The study of the physical processes involving collisions between electrons and atoms and/or molecules is of interest in a number of fields such as plasma physics, atmospheric physics and astrophysics. These processes can be separated into two general classes: elastic and inelastic interactions. The inelastic processes are characterized by a loss of energy of the incident electrons and subsequent change in the structure of the atom. The measurement of the scattering cross section, which describes these processes, has been the subject of systematic inquiries since the 1920's. The first measurements on electron-atom collisions provided total cross sections describing the collisions, but as quantum mechanical calculations describing the collision processes began, it became obvious that total cross section measurements did not provide sufficient sensitivity to guide further theoretical works. Thus the early measurements of the angular distribution of scattered

electrons were undertaken to provide more rigorous tests of theoretical calculations.

After the initial period of study, limited attention was given, both theoretically and experimentally, to electron-atom collisions. The study of collisional processes has within the past three decades again become a vigorous experimental and theoretical area with the advent of high speed computers and advances in experimental technology such as ultra high vacuum technology and high energy resolution electron beam monochrometers and analyzers.

1-Electron Helium

In the latter years the most important problems in the physics of electron-collision processes has been the establishment of an accurate set of differential, integral and momentum-transfer cross sections for low impact electron energy. Differential cross sections (DCS) were first measured by Bullard and Massey,¹ Ramsauer and Kollath² and others initiating experiments which established the main features of electron-atom cross sections and advocated many useful theoretical work.

Absolute total cross section measurements were performed by Ramsauer,³ Ramsauer and Kollath and more recently by Golden and Bandel.⁴

Momentum transfer cross section determination was first placed on an absolute basis by Frost and Phelps⁵ and were extended to higher energies and made more precise by Crompton et al.⁶ These authors have used

various procedures to determine momentum transfer cross sections from total cross section measurements and vice versa.

The basic difficulty in measuring an accurate set of data is the determination of the parameters which relate the measured scattering intensities to the DCS. The energy and spatial distribution of the electron beam, the target density distribution, the scattering geometry, and the efficiency of the electron optics and detectors as a function of energy and angle must all be known with high precision in order to arrive at the desired cross sections.

Different techniques such as phase-shift analysis, normalization to the optical oscillator strength F , and normalization to accessible integral cross sections have been used, but each of these indirect approaches is limited to either a few atomic and molecular species or to certain impact energies and scattering angles. The method of phase-shift analysis at low energies where only the first few partial waves impose can produce reliable data for some atomic species, though this method is not reliable at energies above the inelastic threshold. Normalization to optical F values is limited by the conditions of obtaining accurate optical data for normalization, high impact energies and low scattering angles (small momentum transfer). The best technique at this time seems to be the use of an accurate set of elastic cross sections for which normalization of

relative elastic scattering measurements can be performed. Large effort has been focused on electron-helium scattering because, below the first excitation threshold, helium is one of the simplest targets to study both experimentally and theoretically.

Bederson and Kieffer⁷ in their review of low energy elastic scattering concluded that the total cross section for helium had not been determined experimentally "to better than perhaps 10-15%." More recently several measured values have become available for He DCS, such as those of McConkey and Preston⁸ (1.5 to 100 eV), Andrick and Bitsch⁹ (2 to 19 eV), Srivastava and Trajmar¹⁰ (5 to 75 eV), Williams and Willis¹¹ (0.5 to 10 eV), Williams¹² (0.5 to 20 eV), Gibson and Dolder¹³ (3.1 to 19.1 eV), Shyn¹⁴ (2 to 400 eV), Newell et al.¹⁵ (7.5 to 17.5 eV), and Register et al.¹⁶ In the limit of overlap, these measurements vary from each other in some cases by as much as 35%.

A higher accuracy had been claimed, by Crompton et al.⁶ using swarm experiment technique, for the momentum transfer cross section over a more limited energy range, but several factors are against acceptance of these cross sections, as for energies less than 3 eV, where the maximum accuracy was claimed, there are considerable discrepancies between the results of different theoretical approaches; also, since a comparison of their results lies on a knowledge of angular scattering data, a comparison of these results with those of transmission

experiments is open to question; and the limited range of the swarm derived cross section itself gives problems in making comparisons with the results of beam experiments.

Theoretical calculation of the differential elastic cross sections for slow collisions have employed a variety of techniques. Examples of calculational methods which have been investigated include the polarized orbital method of La Bahn and Callaway,^{17,18} and also Callaway et al.¹⁹. Winters et al.,²⁰ and McCarthy et al.²¹ have used close coupling techniques. Buckley and Walters²² calculated differential elastic cross section using second order Born approximation. Khare and Moiseiwitsch²³ used adiabatic polarization potential approximation. Nesbet²⁴ calculated cross sections using a variational method. Duxler et al.²⁵ used polarized orbital model. Another example of variational calculation is that of Sinfailam and Nesbet.²⁶ Yarlagadda et al.²⁷ employed many-body Green function and, Wichmann and Heiss²⁸ used close coupling approximation. O'Malley et al. calculated phase shifts using the R-matrix method.

2-Electron Hydrogen

The e-H₂ system is one of the more interesting systems in molecular collision physics both from theoretical and experimental point of view. It is simple enough to do ab-initio calculations, and experimentally the most favorable example to carry out a detailed and

quantitative investigation. These studies have served as testing ground for theoretical models and approximations. From a practical point of view these processes are of importance in thyatron switches, planetary ionosphere, and interstellar media. In general cross section measurements have been carried out for a large variety of electron impact processes.

Differential elastic cross section measurements have been carried out by Linder and Schmidt,³⁰ Sarivastava et al.,³¹ Weingartshofer et al.,³² Trajmar et al.,³³ and Shyn and Sharp.³⁴ The contribution from rotational excitation was separated from elastic scattering only in case of Linder and Schmidt,³⁰ who extrapolated their distribution to 0° and 180° for elastic and all open inelastic channels and integrated to get relative integral cross sections. The sum of the relative integral cross sections was then normalized to the total scattering cross section values of Golden et al.³⁵ Srivastava et al.³¹ normalized their data against the He elastic cross section data of McConkey and Preston,⁸ and later renormalized their data against the He elastic cross sections of Register et al.¹⁶ Shyn and Sharp³⁴ normalized their results at 10 eV against He which in turn were normalized to the theoretical calculation of LaBahn and Callaway.¹¹ In their measurements the scattered signal intensity was measured without the use of a lens system in the detector and it was assumed that no change in detector efficiency occurred with impact energy.

Weingartshofer et al.³² measured the energy dependence of the elastic DCS at 20°, 50°, and 100° scattering angles in the 11 to 13 eV impact energy range where the cross sections are influenced by sharp resonances.

Total electron scattering cross sections for H₂ have been measured by Ferch et al.,³⁶ Dalba et al.,³⁷ Jones and Bonham,³⁸ Golden et al.,³⁵ and Hofman et al.³⁹ In some cases these measurements disagree with each other by as much as a factor of two.

Elastic momentum transfer cross sections have been obtained from the swarm measurements by Crompton et al.⁴⁰ and Gibson⁴¹ and from beam measurements of Srivastava et al.³¹ and Shyn and Sharp.³⁴

The theory of e-H₂ scattering at low energies has been further worked out during the last years by several groups.⁴²⁻⁴⁸ In view of the progress in theory it is the purpose of the present work to provide more accurate and more complete experimental data, especially with respect to angular distribution measurements and determination of the absolute cross sections. Thus we have developed a pulsed-time-of-flight technique to make more precise measurements and compare to recent experimental and theoretical results. This work presents the absolute elastic e⁻-He, and total electronically elastic e⁻-H₂, differential and total integrated scattering cross section in energy range from 1 to 19 eV.

CHAPTER II

THEORY

The purpose of this section is to briefly review the theory of electron atom collisions necessary for the interpretation of electron-He(H₂) scattering data presented in this work. The connection between the experimentally measured differential cross section $\sigma(\theta)$ and the quantum mechanically calculable scattering amplitude $f(\theta)$ is

$$\sigma(\theta) = \frac{d\sigma}{d\Omega} = f(\theta)^2 \quad (1)$$

The liberal use of the excellent reviews of Mott and Massey,⁴⁹ Massey and Burhop,⁵⁰ Bates,⁵¹ Moiseiwitsch and Smith,⁵² O'Malley⁵³ Cohen-Tannoudji et al.,⁵⁴ and Golden⁵⁵ are gratefully acknowledged.

Scattering theory using the stationary state method starts with the time-independent Schrodinger equation describing the motion of an electron by a spherically symmetric, spin-independent, local potential $V(r)$ centered at the origin of coordinates is

$$\left[-\frac{1}{2} \nabla^2 + V(r) \right] \psi(r) = E \psi(r) \quad (2)$$

where in this and later equations atomic units are used.

We look for a positive-energy solution of this equation corresponding to scattering. At large distances from the origin, the wave function can be

chosen to represent a plane wave incident in the positive z direction together with outgoing spherically scattered wave,

$$\psi(r) \underset{r \rightarrow \infty}{\sim} e^{ikz} + f(\theta) \frac{e^{ikr}}{r} \quad (3)$$

where $k^2 = 2E$. This equation defines the scattering amplitude $f(\theta)$, which is a function of the polar scattering angle θ , but because of the symmetry of $V(r)$ and e^{ikz} about the incident beam direction, does not depend on the azimuthal angle ϕ .

In order to calculate the cross section we must determine the flux of particles passing through an area dS in the direction specified by θ, ϕ . This is given by

$$\mathbf{j} \cdot d\mathbf{S} = \frac{1}{2i} (\psi^* \nabla \psi - \psi \nabla \psi^*) \cdot d\mathbf{S} \quad (4)$$

Substituting the second term in equation (3) into equation (4) gives

$$\mathbf{j} \cdot d\mathbf{S} = k f(\theta)^2 d\Omega \quad (5)$$

which is the flux passing through an area $dS = r^2 d\Omega$ at a radius r .

The differential cross section $\sigma(\tau)$ is defined by

$$\frac{d\sigma}{d\Omega} = \frac{\text{scattered flux/unit solid angle}}{\text{incident flux/unit area}} \quad (6)$$

Using equation (5), we find that

$$\frac{d\sigma}{d\Omega} = f(\theta)^2 \quad (7)$$

as given in equation (1).

The total cross section in units of a_0^2 is obtained after integrating overall scattering angles:

$$\sigma_T = \int_0^{2\pi} d\phi \int_0^\pi \sin\theta d\theta f(\theta)^2 = 2\pi \int_0^\pi |f(\theta)|^2 \sin\theta d\theta \quad (8)$$

In order to determine the scattering amplitude and hence the cross section it is necessary to solve equation (2). For low-energy electron scattering this is most conveniently done by making a partial wave or angular momentum expansion and by solving the resultant radial equations. Making use of the symmetry of the wave function about the incident beam direction, we write

$$\psi(r) = \frac{1}{r} \sum_{\ell=0}^{\infty} A_{\ell}(k^2) u_{\ell}(r) P_{\ell}(\cos\theta) \quad (9)$$

where $P(\cos\theta)$ are the Legendre polynomials and the $A_{\ell}(k^2)$ will be determined below to ensure that $\psi(r)$ satisfies equation (3). In order to determine the radial wave function $u_{\ell}(r)$ we substitute equation (9) into equation (2), and premultiply by $P(\cos\theta)$ and integrate over all scattering angles θ . We find that $u_{\ell}(r)$ satisfies the equation

$$\left[\frac{d^2}{dr^2} - \frac{(\ell+1)}{r^2} - U(r) + k^2 \right] u_{\ell}(r) = 0 \quad (10)$$

where

$$U(r) = 2V(r) \quad (11)$$

For electron-atom potentials, which have an r^{-1} singularity at the origin it is found from the indicial equation for equation (10) that

$$u(r) \underset{r \rightarrow 0}{\sim} r^{\ell+1} + O(r^{\ell+2}) \quad (12)$$

or

$$u_{\ell}(r) \underset{r \rightarrow 0}{\sim} r^{-\ell} + O(r^{-\ell+1}) \quad (13)$$

Only the first solution gives a probability density that is finite at the origin for all positive values of ℓ .

The first solution is therefore the physical solution. For the potentials which vanish faster than r^{-1} as $r \rightarrow \infty$, it flows that

$$u_\ell(r) \underset{r \rightarrow \infty}{\sim} \sin(kr - \frac{1}{2} \pi + \eta_\ell) \quad (14)$$

which defines the energy-dependent real phase shift η_ℓ . It is convenient to write this asymptotic form in terms of the regular and irregular solutions of the differential equation

$$\frac{d^2}{dr^2} - \frac{(\ell+1)}{r^2} + k^2 \quad v_\ell(r) = 0 \quad (15)$$

These solutions can be related to the spherical Bessel functions as follows:

$$\begin{aligned} F_\ell(kr) &= kr j_\ell(kr) = \left(\frac{\pi kr}{2}\right)^{1/2} J_{\ell+1/2}(kr) \\ &\underset{r \rightarrow \infty}{\sim} \sin(kr - \frac{1}{2} \ell \pi) \end{aligned} \quad (16)$$

and

$$\begin{aligned} G_\ell(kr) &= -kr n_\ell(kr) = (-1)^\ell \left(\frac{\pi kr}{2}\right)^{1/2} J_{-\ell-1/2}(kr) \\ &\underset{r \rightarrow \infty}{\sim} \cos(kr - \frac{1}{2} \ell \pi) \end{aligned} \quad (17)$$

we find that

$$u_\ell(r) = kr [j_\ell(kr) \cosh \eta_\ell - n_\ell(kr) \sinh \eta_\ell] \quad r > r_0 \quad (18)$$

where r_0 is the value of r beyond which the potential term in equation (10) can be neglected.

In order to equate the asymptotic forms of equations (3) and (9) we expand the plane wave

$$e^{ikz} = \sum_{\ell=0}^{\infty} (2\ell+1) i J_\ell(kr) P_\ell(\cos\theta) \quad (19)$$

Since the second term in equation (3) only contributes to the outgoing spherical wave term in equation (9), we can determine $A_\ell(k^2)$ by equating the coefficient of the ingoing wave $\exp[-i(kr - 1/2 \ell \pi)]$ in equations (9) and

(19). Using equation (16), we find that

$$A_\ell(k^2) = \frac{1}{k} (2\ell+1) i^\ell e^{i\eta_\ell} \quad (20)$$

Substituting this expression for $A_\ell(k^2)$ into equation (9) and using equation (14) gives

$$f(\theta) = \frac{1}{2ik} \sum_{\ell=0}^{\infty} (2\ell+1) (e^{2i\eta_\ell} - 1) P_\ell(\cos\theta) \quad (21)$$

The total cross section obtained by substituting this expression for $f(\theta)$ into equation (8) is

$$\sigma_T = \frac{4\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) \sin^2 \eta_\ell \quad (22a)$$

$$= 2\pi \int_0^\pi \sigma(\theta) \sin\theta \, d\theta \quad (22b)$$

and the momentum transfer cross section

$$\sigma_{MT} = \frac{4\pi}{k^2} \sum_{\ell=0}^{\infty} (\ell+1) \sin^2 (\eta_\ell - \eta_{\ell+1}) \quad (23a)$$

$$= 2\pi \int_0^\pi \sigma(\theta) (1 - \cos\theta) \sin\theta \, d\theta \quad (23b)$$

Equations (22b) and (23b) could be integrated numerically to obtain $\sigma_T(\theta)$ and $\sigma_{MT}(\theta)$, if absolute measurements of $\sigma(\theta)$ at fixed energy (E) could be made for the full angular range 0 to π at small angular intervals. Then using equations (22a) and (23a) by use of phase shift analysis of the data should serve as a validity check. For Helium data the following properties should hold. The s-wave phase shift should be 0 or $n\pi$ at $E=0$ and should increase or decrease as E increases; but all other phase shifts should be 0 for $E=0$ and increase smoothly as E increases. If the data are not measured over the complete angular range a phase

shift analysis eliminates the errors associated with extrapolating the data to 0° and 180° .

In principle an infinite number of partial waves should be used. In practice, however, the first few partial waves usually contain the dominant terms in the total cross section, and the higher phases may be treated with acceptable accuracy in some approximate manner. Roughly speaking, they do not penetrate the inner part of the atom and so only feel the longest range part of the electron atom interaction. This is the dipole polarization potential. We tried two such approximation in this work: (i) a Born effective⁵⁷ range-theory for evaluation of the phases, and (ii) Thompson's⁸⁸ expression for the Born contribution to the scattering amplitude for all partial waves greater than some cutoff value of L .

The Born effective range formulas for electron-atom scattering phase shifts may be written

$$\tanh \eta_0 = -Ak - (\pi/3a_0)\alpha k^2 - (4/3a_0)\alpha Ak^3 n(ka_0) + O(k^3) \quad (24a)$$

$$\tanh \eta_1 = (\pi/15a_0)k^2 - A_1 k^3 + O(k^4) \quad (24b)$$

$$\tanh \eta_\ell = \pi \alpha k^2 / [(2\ell+1)(2\ell+3)] \quad (24c)$$

where a_0 is the electron Bohr radius and α is the electric polarizability of the atom. The values of $\eta(\ell > 1)$ calibrated from equation (24c) may be inaccurate for small values of ℓ but as ℓ increases the contribution to the scattering amplitude decreases and accuracy improves. Thus in a fitting procedure, the first several

values of $\eta(\ell < L)$ can be treated as variable parameters, then evaluate the higher order values of $\eta(L < \ell < L')$ from equation (24c) to fit equation (21) to the data.

However, a large number of terms may be necessary to describe the small angle scattering and the values of L' needed is energy dependent.

Thompson⁸⁸ has shown that a more satisfactory method is to sum all of the Born scattering amplitudes for $\ell > L$ analytically provided the $\ell=0$ term is excluded. Then the difference between the Born sum f_0^B and the contribution from the $\ell=0$ term f_0^B is given by

$$f_B - f_B^0 = \pi \alpha k \left(\frac{1}{3} - \frac{1}{2} \sin \frac{1}{2} \theta \right) \quad (25)$$

Then subtracting³⁴ all terms for $\ell < L$ from equation (25), thus the scattering amplitude f_B^L for $L < \ell < \infty$ can be written as

$$f_B^L = \pi \alpha k \left[\frac{1}{3} - \frac{1}{2} \sin \frac{1}{2} \theta - \sum_{\ell=1}^L \frac{P(\cos \theta)}{(2\ell+3)(2\ell-1)} \right] \quad (26)$$

so that equations (1) and (21) can be expressed as

$$f(\theta) = \frac{1}{2ik} \left[\sum_{\ell=0}^L (2\ell+1)(e^{2i\eta_\ell}-1) P_\ell(\cos \theta) + 2ik f_B^L \right] \quad (27)$$

$$\begin{aligned} \sigma(\theta) = \frac{1}{4k^2} & \left[\left(\sum_{\ell=0}^L (2\ell+1) \sin 2\eta_\ell P_\ell(\cos \theta) + 2k f_B^L \right)^2 \right. \\ & \left. + \left(\sum_{\ell=0}^L (2\ell+1)(\cos 2\eta_\ell - 1) P_\ell(\cos \theta) \right)^2 \right] \quad (28) \end{aligned}$$

CHAPTER III

APPARATUS

The experimental apparatus, shown schematically in Fig. 1a and 1b, is capable of the measurement of electron-atom (molecule) cross sections for low energy electrons. The interaction region is formed by crossed electron and atomic (molecular) beams. The apparatus consists of a fixed electron gun, a rotatable scattered-electron detector, a stationary scattered-electron detector, a double walled Faraday cup, an atomic (molecular) beam source, electrostatic and magnetic shielding and pulsed electron gun. These components are contained within a high vacuum system capable of a base pressure 1×10^{-7} Torr. These components as well as the gas handling system, the construction materials, power distribution, and the cleaning, alignment and bakeout procedure are discussed in the following sections. The associated electronics will be discussed in detail.

Vacuum System

The vacuum system, shown schematically in Fig. 1a and 1b, consists of a main vacuum chamber 18" OD and 10" high and contains the experiment. It is constructed of 300 series stainless steel and has been baked in this

work to 110°C. All demountable members are tungsten-inert-gas welded. All welds are inside, where physically possible. Two types of electrical connectors are utilized: multipin connectors which are welded on flanges and weldable MHV type high vacuum fittings made by Ceramaseal. The MHV fittings are used where necessary for their shielding characteristics. The main chamber has five ports (P1-P5) positioned 90° apart and equipped with 23 cm standard ASA flanges. These ports are allocated as follows: P1 contains the electron gun, P2 contains the Faraday cup and detectors leads, P3 and P4 connects the main chamber via gate valves to two trapped oil diffusion pumps. The top flange of the main chamber has one port (P6) to which a turbo-molecular pump can be connected. The side arms connected to ports P3 and P4 also contain two titanium sublimation pumps which can optionally be used. Port P5 is connected to another chamber in which contains the atomic-beam source so that the atomic beam is skimmed and differentially pumped by another trapped oil diffusion pump via port P6. The side arms connected to P3 and P5 each contain a high vacuum triode ionization gauge. These ion gauges allow pressure measurement of the gas in both chambers when the experiment is running; the gas pressure measurement is explained in more detail in section IV.B.

Several different types of seals are in use on the vacuum system. Varian conflat flanges use knife edge seals which seal on soft copper gaskets. Swagelock

fittings are used on some of the small tubing. Some parts of the main chamber access ports, and the diffusion pumps are sealed with aluminum wire gasket. The gaskets are made from 20 gauge (0.030" OD) dead soft aluminum wire. An amount sufficient to reach around the flange with about 8" extra is cut off the roll of wire. The ends are twisted together and the wire is carefully laid onto the sealing surface, and taped at ends away from the sealing surface to hold. The wire is then shaped into a circle to conform with the sealing surface. To complete a successful seal, uniform torque is applied to the bolts holding the mating flanges. The most widely used gasket uses Viton O-ring which is mounted on a vacuum type aluminum-O-ring. This type of seal is the easiest to use as no large torque is needed, but the bolts are tightened uniformly. All flange seals, welds and fittings are leak checked after they are installed and are leak checked at any time that the background pressure in the vacuum system shows an increase above the normal base pressure.

Three varian VHS-4 oil diffusion pumps are used to pump the system. Two of them pump the main chamber through elbows, and the other is used to differentially pump the atomic beam source. The diffusion pumps are rated at 1200 liters/sec of air below 10^{-3} Torr. Diffusion pump uses Convoil 20 pump oil and the boiler requires 300 cc of oil to fill it. The exhausts of the three diffusion pumps are pumped in parallel by a

Sargent-Welch 1397 mechanical rotary pump. Each pump has a speed of 300 liters/minute from 10^{-2} to 10^{-4} Torr. The free air displacement is 500 liters/min. A foreline valve is located between the mechanical pump and the diffusion pumps, which is electrically operated in parallel with the mechanical pump. When power to the mechanical pump is turned off, the valve (#1), Fig. 2, seals the diffusion pump exhausts, opening the mechanical pump to the atmosphere, but maintaining the diffusion pump at low pressure until the quick cool on the diffusion pump has time to cool the oil, thus avoiding oxidation of the oil and back streaming of pump oil into the high vacuum region.

The foreline pressure is measured with two thermocouple gauges. The gauges are connected to a Varian model #840 thermocouple controller. The controller contains an adjustable set point, optically activated meter relay. The meter relay is used to interlock the diffusion pump operation to an adjustable preset maximum foreline pressure. One of the thermocouple gauges measures the foreline pressure of the main chamber and the bottom chamber and the other measures the foreline pressure of the three diffusion pump exhausts through a foreline valve (#2). In start of pump down of the vacuum system, valve #2 is closed then the bottom chamber is evacuated through a hand opened valve, thus making sure that the pressure from the main chamber keeps the atomic beam skimmer in place, then the main chamber is

pumped down, also through a hand opened valve so that the thermocouple connected to this part of the forline reaches 50 mT; then the two hand opened valves are closed and valve #2 is opened.

Sorbent traps are located between the chamber and diffusion pumps to eliminate both backstreaming and creep of oil from the pump into the chambers. The trap interior consists of a center basket and a wall liner constructed of stainless steel mesh. This mesh holds the sorbent material. The center basket forms a dense baffle which provides the major protection against backstreaming oil. The wall liner restricts the creep of oil. The sorbent material (Zeolite) is a molecular sieve which has an alumina-silica base with a pore size of 10Å. One disadvantage of this type of trap compared to a liquid nitrogen trap is the amount of water absorbed into the Zeolite when the system is exposed to air. For this reason, three air operated gate valves were placed in between the chambers and elbows connected to the diffusion pumps. The gate valves are closed when it is needed to open the main chamber for maintenance and back filling the system is done using N₂.

Power Distribution

All the power lines are connected through isolation transformers to provide isolation from the main power line common ground. The power used for the experiment is 120 volts at 60 HZ. In order to protect the vacuum system and associated experimental apparatus from

interruption of power, water or the failure of equipment, an electrical interlock system is wired to turn off the rack which powers the electron gun, the power to the diffusion pumps heater and to cool the oil in the diffusion pump. The interlock wiring diagram is shown in Fig. 3.

Pulsed Electron Gun

The Pulsed Electron Gun has two distinct parts: (1) the source region and (2) the beam forming optics which also includes the pulsing element. A schematic diagram of the PEG including the electrical operation is shown in Fig. 4.

The voltages on the PEG lenses are floated off the cathode common by a high voltage isolation transformer. This technique allows operation of the lens elements to be independent of the beam energy defined by the cathode voltage. The PEG physical dimensions and a typical set of operating voltages are given in Table I.

Source Region

Two kinds of electron source were used: (a) an indirectly heated triple-oxide-coated cathode and (b) an ordinary tungsten wire; both in a Pierce configuration. Each of the above sources are outlined below.

(a) This kind of cathode is formed by an oxide coated nickel cup which is bonded to a ceramic disk about 1/2 in. OD. The cathode is manufactured by RCA and the part number is FKS623B-801R. The filament is

also made by RCA and has part numbers MCH8004D and NEB261.

The cathode activation process which reduces the oxide coating and allows the migration of the electron emitter to the surface of the cathode is accomplished by increasing the filament current in steps of about 0.05 amp at 10 to 15 minute intervals. During activation, the background pressure is monitored and care is taken that it does not exceed 5×10^{-6} Torr. Activation is accompanied by a sharp increase in background pressure with very slight increase in filament current and the emission of electrons detected by monitoring the current to the anode. The filament power is then increased by 25% for 15 minutes to ensure that the oxide coating is completely reduced. The filament power is then reduced to its activation value. At this time the gun is left for 24 hours to stabilize electrically and thermally. A typical activation schedule is given in Table II.

(b) A short length of tungsten wire 1/4 in. with 0.08" OD is shaped like V over an Exacto knife and used as the filament, the cathode power supply is then floated on one side of it.

The activation process is accomplished by increasing the current to the filament to 2 amperes for 15 minutes and then again increasing the current so that it reaches a maximum of 5 amps. Again, the gun is left for 24 hours to stabilize.

The Beam Forming Optics

The beam forming optics are comprised of the Pierce,⁵⁷ anode, 2000, pulsing element, 4000 and 5000 elements which provide four focusing regions (A-2, 2-Pulser, Pulser-4000, 4000-5000, 5000-Snout).

Either the oxide-coated cathode or the tungsten wire, is used in a Pierce configuration. The arrangement consists of the cathode, an equipotential surface (the Pierce element) at an angle of 58.5° to the axis of the electron beam in order to produce a 3° convergent beam emerging from the anode with an aperture the diameter of which is small compared to the cathode to anode spacing. The Pierce element ideally is at potential zero with respect to the cathode, but actually provision is made to adjust this potential to account for differences in geometry due to construction tolerances and assembly. By changing the voltage of the Pierce element and using the focusing properties of the anode which is set at approximately 100 volts with respect to the cathode, the electron beam emerging from the anode aperture may be made parallel by the proper choice of electrode shapes and applied voltages. What is done in principle is to use the analytical solution for parallel flow of a beam of electrons between two planes to establish the potential distribution required to produce a parallel beam with no charge in the region outside the limits of the beam.^{57,58} The Pierce element is placed between the cathode and anode.

The anode element has an aperture which defines the beam diameter. Another aperture is placed in the field free region of the 2000 element to remove divergent electrons without further limiting the beam diameter.

The pulsing element, shown schematically in Fig. 5, is used both to pulse the electrons using a 8011A Hewlett-Packard pulse generator and also as an electron lens. The pulsed beam is produced by deflecting the electron beam past the pulsing element aperture. The rise time of the electron current pulse may thus be diminished relative to the rise time of the pulse (7.5 nsec) applied to the deflecting electrode. The electron pulsewidth is proportional to the rate of change of the pulse generator voltage and is adjustable, the electron pulsewidth was ~4 nsec. For this work the pulse generator width used was about 50 nsec with a repetition rate of 5 μ sec.

The lenses were designed to provide a beam at the scattering center with an energy independent focus for a range of output energies. Minor misalignment of the cathode, and the beam can be compensated by an electrostatic quadrupole steering lens which contains two independent sets of elements (top, bottom, left and right). These sets are contained within the anode and the 4000 element. The elements of a set operate at the same voltage but different polarities. The mean potential of a set is referenced to the elements which contain it so that the center line potential through the element is constant. All the lens voltages are fixed

relative to the cathode, with the exception of the snout which is grounded.

The snout is designed with a replaceable aperture which defines the maximum possible angular divergence of the beam.

Pulse Techniques

The 8011A is operated in the back terminated mode (output impedance is 50Ω), and the pulsing lens end of the coaxial cable is also terminated in 50 ohm. This reduces reflections from the ends of the cables to a minimum and improves the timing resolution of the apparatus.

Proper termination of all coaxial lines is very important where fast rise time pulses are utilized, especially when switching electron beams since they respond very rapidly.⁵⁸ The dimensions of a coaxial line for a given characteristic impedance may be calculated from the formula

$$z_0 = (138/\sqrt{v}) \log_{10}(D/d) \quad (29)$$

where d is diameter of inner conductor, D is the inside diameter of outer conductor, and v is the dielectric constant of dielectric media between two conductors. When a transmission line is not terminated with its characteristic impedance, the pulses sent down the line will reflect off the end where the improper termination is connected. This will cause a series of reflections to be formed on the line which distorts the pulses and

changes timing information contained in the pulses.

The effect of a mismatch in terminating a transmission line is described in many references^{59,60} which consider how to determine the magnitude of the effects. One common way to test a transmission line and termination system is with a fast rise time pulser and a wide band oscilloscope, pulses are applied to one end of the terminated line and examined on the other terminated end with the fast scope. The wave form of the pulses is examined for lengthened rise and fall times or any distortion which indicates reflections. If the transit time of the pulse down the entire length of the line is long compared to the width of the pulse, a series of pulses of diminishing amplitude will be observed if a mismatch exists. The quality of the impedance match may be estimated directly from the amplitude of the reflected pulses or the distorted rise and fall times.

The 50 ohm terminator and vacuum coax for the pulsing element have been tested as outlined above using pulses from the 8011A pulse generator with a 7.5 nsec rise and fall time. The pulses were observed on a Tektronix 7904 scope with a ISI sampling unit. By comparing the wave form of the pulses before (Photo 1a) and after (Photo 1b) being applied to the pulsing element it was found that no noticeable difference in the wave forms existed on a 10 nsec/cm scale. From this test the impedance match of the pulsing element is determined to be acceptable.

Electron Gun Tuning

As no energy selection is used in the electron gun, the full Maxwellian energy distribution is characterized by the temperature and space charge conditions in the source region. These are the only means of affecting the width of the energy distribution of the electron beam. By reducing the filament power and thus reducing the cathode temperature, the width of the energy distribution is reduced. With the cathode temperature set at its activation value, the energy distribution of the electron beam increases from about 150 meV full-width-half-maximum (FWHM) to about 250 meV FWHM. The energy resolution width is not critical in the present work.

It was found that in tuning the electron gun, it was possible to find a tuning such that the electron beam angular profile was asymmetric or had very broad wings and secondary maxima. This problem was assumed to be due to electrons bouncing off the tube lenses and affecting the angular profile of the primary beam. This problem was overcome by decreasing the diameter of the snout aperture so that it was much less than the inner diameter of the snout, so that electrons that manage to bounce off the wall of the lenses have a greater probability of being collected by the snout.

The determination of the operating voltages was achieved as follows. The electrons from the source region are accelerated to the beam defining aperture, as

suggested by Kuyatt⁶¹ and then focused at the target region by the output optics. During these focusing procedures, the currents to the gun snout, Faraday cup, and Faraday cup shield as well as the scattered electron count rate are monitored. Proper focusing is achieved when the current to the gun snout is minimized, and the ratio of Faraday cup to Faraday cup shield currents is maximized. After the gun is "tuned" the angular distribution of the beam is checked. If the angular profile is asymmetric the "tuning" procedure is repeated. A sample electron beam profile is shown in Fig. 6 where the current is measured as a function of scattering angle. The signals were obtained by measuring the current received by a grid in front of the rotating detector channel plates. In general it was relatively easy to obtain electron beam profiles with FWHM of about 4°. However, in order to be successful at measuring scattering cross sections of less than about 40° it was necessary to have an electron beam profile which dropped by 4-5 orders of magnitude within 10°.

Energy Calibration

Two methods of energy calibration were used in this work. One method was to measure the energy position of the lowest ²S resonance,⁶² 19.36 eV in Helium, as determined from the voltage between cathode and interaction region, Fig. 7, Table III. The other was to measure the retarding potential necessary to prevent scattered electrons from reaching the rotating detector at a

particular accelerating voltage. The voltage position of the maximum of the measured energy distribution function was taken to be the electron energy Fig. 8, Table IV. These two procedures gave agreement at the position of $2s$ resonance to be about 0.05 eV. We would expect the energy scale to be good to about 0.1 eV at all energies.

Rotation Mechanism

The frame of the rotating detector is bolted to an aluminum base plate. An aluminum gear wheel is bolted to the underside of this base plate. The gear wheel has teeth on its inner diameter which engage the gear of a Varian 1-to-1 direct drive feed through rotation mechanism. The base plate rotates on 1/4" diameter ceramic balls held in vee grooves cut in the gear wheel and in an aluminum plate beneath it. A race is provided to ensure that the ceramic balls remain equally spaced for easy rotation. The angular position of the electron gun is determined to within 0.1° by a vernier scale on the edge of the aluminum base plate visible through a window in the vacuum wall.

Scattered-electron Detectors

As mentioned before, two scattered-electron detectors, Fig. 9, are used to measure the scattered-electron signal and a signal proportional to the product of background pressure and electron beam current. The first has an acceptance solid angle of 1.3×10^{-2} sr and is

rotatable from -60° to 120° with respect to the electron beam direction about the atomic beam axis while the second, which has an acceptance solid angle of 1.77×10^{-2} sr, is fixed and views a region along the electron beam between the output snout of the electron gun and the atomic beam.

In both of the detectors scattered electrons are collected by a Varian Type VUW-8900 series continuous dynode Channel Electron Multiplier (CEM), which is mounted in a grounded housing. A channel electron multiplier is an array of 10^4 - 10^7 miniature electron multipliers oriented parallel to one another;⁶³ typical channel diameters are in the range 10-100 μm and have length to diameter ratios between 40 and 100. Channel axes are typically normal to, or biased at a small angle (8°) to the CEM input surface. The channel matrix is usually fabricated from a lead glass,⁶⁴ treated in such a way as to optimize the secondary emission characteristics, greater than unity, of each channel and to render the channel walls semiconducting so as to allow charge replenishment from an external voltage source. Thus each channel can be considered to be a continuous dynode structure which acts as its own dynode resistor chain. Parallel electrical contact to each channel is provided by the deposition of a metallic coating, usually Nichrome or Inconel,⁶⁵ on the front and rear surfaces of CEM, which then serve as input and output electrodes, respectively. Channel electron multipliers are

non-magnetic and when properly processed, the glass exhibits useful secondary emissive and resistive characteristics.⁶⁵⁻⁶⁸ CEM typically exhibit resistance in the range of 10^9 ohms. Channel electron multipliers have excellent signal to noise capability (dark counts of less than 0.5 count/sec), stable dynode surface that can be exposed to air without degradation; low power requirements for operation, narrow gain distribution of output pulses, and fast response.

Between the ends of the multiplier a potential of a few thousand volts (2500 V) is applied. This operation is performed in a vacuum of 10^{-6} Torr or less since higher pressure operation increases background and can result in shortened life. At pressures higher than 10^{-4} Torr high voltage is not applied as arcing can occur. This usually results in a destroyed multiplier.

An electron of sufficient energy will be detected when it is incident upon the interior surface of the CEM aperture and causes the emission of at least one secondary electron. This secondary electron is accelerated by the electrostatic field within the channel until it hits the interior surface of the channel. Assuming it has accumulated enough energy from the field, more than one secondary will be released.

A diagram of a straight CEM is shown in Fig. 10. Pictured here is a simple mechanism where an incident electron produces secondary electrons. The kinematics are such that δ^2 secondary electrons are produced in the

second stage, δ^3 in the third, etc., so that the overall gain G is given by $G=\delta^n$. According to Schagen,⁶⁹ assuming that the secondary emission is normal to the channel walls,

$$G = \left(\frac{AV}{2V_0^{1/2}} \right)^{4V_0\alpha^2/V} \quad (30)$$

where V is the total channel voltage, V_0 is the initial energy of an emitted secondary electron ~ 1 eV, α is the length to diameter ratio, and A is the proportionality constant in the assumed relation $\delta=AV_c^{1/2}$, where V_c is the electron collision energy in eV, and $A\sim 0.2$. As V increases, so does δ , the secondary electron yield, since each collision then occurs at a higher energy V_c . At the same time, the number of collisions within the channel must decrease, resulting in an extremum in the G vs. V characteristic, Fig. 11. Rather than exhibiting a maximum, the curve levels off at large V ; this is due to secondary emission which is not orthogonal to the channel walls.

Eq.(30) also exhibits an extremum in α , suggesting that there is a gain for which the inevitable variations in α from channel to channel have minimal effect. From Eq.(30) and the condition $d(nG)/d\alpha=0$, we find that

$$\alpha_m = \frac{AV}{3.3 V_0^{1/2}} = \frac{V}{16.5} \quad (31)$$

and

$$G_m = \exp (0.184A^2V) = \exp (0.0074V) \quad (32)$$

where G_m and α_m are the values of G and α at the extremum.

Straight CEMs are unstable at gains in excess of 10^4 . The primary reason for this instability is the phenomenon known as ion feedback.⁷⁰ At the output end of an operating CEM a large number of electrons are traveling through the channel. In this region, there is a high probability of ionizing some of the residual gas molecules within the channel. These positive ions are accelerated toward the input. Some of these ions hit the electron wall, emitting electrons that are multiplied in the normal fashion, causing spurious output pulses not representative of the input, i.e., noise.

A method that eliminates the ion feedback instability is to add curvature to the channel.^{71,72} Curvature limits the distance that an ion can travel toward the input ends of the multiplier. Since the highest probability of generating ions exists near the output end of the channel and the distance toward the input that these ions can travel is limited, the gain of pulses due to these ions is very low in comparison to the overall gain of the device. Elimination of ion feedback allows CEMs of appropriate design to operate at gains in excess of 10^8 .⁷³⁻⁷⁵ It is this fact that allows considerable size reduction of arrays of CEMs called micro channel plates as an extension and integration of both CEM and fiber optic technology.^{76,77}

The range of input current for which the output current is linearly proportional to the input current is

an important parameter of CEM, which is called Dynamic Range and is defined as

$$\log_{10}(\text{max. linear output current}/\text{min. output current}).$$

For pulse counting techniques, as in this work, CEMs have very low bias currents, on the order of $2\mu\text{A}$ at 2500 V. Thus, the maximum linear output is about $0.2\mu\text{A}$. If one assume a dark current of 1 pA at 3×10^6 gain, the dynamic range of this pulse counting CEM is⁷⁸

$$\log_{10} \frac{2 \times 10^{-7}}{1 \times 10^{-12}} = 5.3$$

The CEMs which are manufactured during the last ten years have a considerably greater dynamic range.

As mentioned above, in this work microchannel plates are used in pulse-counting technique. The pulse-counting CEM operates at a high gain and has an output pulse height that has a characteristic amplitude, Fig. 12. Figure 13 shows pulses resulting from input signals which are clearly distinguishable from spurious noise events originating elsewhere within the pulse-counting multiplier. By using standard discriminator techniques one can effectively eliminate most noise pulses. This results in inherently higher sensitivity due to decreased noise levels in the pulse-counting system. Slight changes of the discriminator level do not result in a marked change in the observed count rate. Note, however, that noise pulses created by random events at the aperture cannot be distinguished from signal pulses; i.e., ions are in-

distinguishable from electrons, if all are incident upon the aperture.

There is an optimum voltage at which to operate a pulse-counting CEM. Figure 14 shows the output count rate observed on a counter, after discriminator, as a function of CEM voltage when the input signal is constant. The output count rate will be observed to plateau as the CEM enters saturation (point A, approximately 10^8 gain). The proper place to operate the channel is 50 to 100 V above this point, i.e., at point B. Operation at voltages above this value does not increase the gain much, but it can damage the plates. First, the life of the CEM can be unnecessarily decreased. Second, when operating at voltages far in excess of those necessary for saturation, ion feedback may occur very early in the channel, resulting in a noise pulse. CEMs operating in the saturated, pulse-counting Chevron mode produce a pulse of 10^8 electrons with pulsewidth of less than 1 nsec and rise times of less than 500 psec.⁷⁹ Figure 15 shows the gain vs. accumulated output charge of pulse-counting CEM. The initial gain drop, labeled clean-up phase, is due to gasses being desorbed from the surface of the channel. This will occur to some extent whenever the CEM is exposed to air and gasses absorbed on the surface.

As noted above, ion feedback suppression may be achieved in single channel multipliers by the single expedient of curving the channel. Such a device is

difficult to achieve in a thin (0.5 mm) microchannel plate and commonly used method of obtaining high gain space charge saturated output pulses is the MCP Chevron described by Colson et al.,⁸⁰ used in this work and which is shown schematically in Fig. 16. The plates are oriented so that the channel bias angles (typically $8^\circ/8^\circ$ or $0^\circ/15^\circ$) provide a sufficiently large directional change so as to inhibit positive ions produced at the output of the rear plate from reaching the input of the front plate, the plates are separated by a center conductor (copper) of $120\text{ }\mu\text{m}$ thick and individually operated at gains of the 10^4 range.

The high voltage leads are carried within the vacuum chamber as coax cables compatible with ultra-high vacuum operation. The shielded leads are made with #24 gauge wire for the center conductor, ceramic fish spine beads for the insulator and braided shield stripped from commercial RG-8 cable. The characteristic impedance of this vacuum coax is about 46 Ω . It should be noted that the copper braid of the coaxial shield should be sufficiently dense to properly shield the center conductor and also the shield should be continuous and unbroken along the entire length of the vacuum coax. Even relatively minor breaks can lead to "feathers" of copper braid which can cause shorts.

Faraday Cup

The electrons transmitted through the interaction region are collected by a double walled Faraday cup

shown schematically in Fig. 17. The outer wall is grounded and has an aperture of 1.0". This insures that the full beam enters the cup, even for low beam energies where space charge spreading is greatest. The inner cup is insulated and its aperture diameter is 1.3" so that full beam also enters the Faraday cup inner cup.

The maximization of the collection efficiency is accomplished by the choice of geometry, electrical operation and construction materials as discussed by Kuyatt.⁵⁹ The main problem is the emission of secondary electrons from the construction material, here copper, which has been discussed by Kuyatt⁸¹ and Meyers.⁸² The ratio of secondary emission to incident primaries for energies below 10 eV at normal incidence to a copper surface is 0.2 and as the energy of the primary electron decreases from 10 to 5 eV the secondary emission ratio for copper decreases from 0.2 to 0.07. For further decrease in the primary energy the ratio remains sensibly constant at 0.06 to 0.07, but at very low energies (< 1 eV) the secondary emission ratio increase slightly, indicating a value 0.1 as the primary energy approaches zero. The secondary electrons are emitted from the surface in a cosine distribution relative to the surface normal and suffer additional collisions with the Faraday cup walls. With these facts the FC was designed to maximize the collection efficiency. The cup was made as deep as possible. In order to direct the cosine distribution of the secondaries away from the entrance

aperture, a target, which is inclined at 50° , is placed at the back of the cup. Although the secondary yield increases with a decrease in the angle of incidence, the secondary flux over the entrance aperture is reduced by 30%.⁸³ Finally, the FC is so that the collecting surface area is 100 times greater than the aperture area. Thus, an average electron would require 100 collision before exiting the FC. The currents from the FC inner walls and target are connected in parallel to an electrometer.

Atomic Beam Source

The atomic beam source is shown schematically in Fig. 18. The atomic beam is generated by a single capillary with an inside diameter of 0.51 mm and an aspect ratio, R_A , of 100 ($R_A = \text{length/diameter}$). The capillary is silver-soldered into a 1/4" copper tube which delivers the gas. The capillary is held in place by two bushings within a copper differential pumping manifold (DPM). The capillary is positioned at the center of the DPM and 1 mm below a 0.5 mm aperture in the top of the DPM. This aperture serves as a differentially pumped skimmer which reduces the wings of the beam profile of the gas which effuses through the capillary. The edges of the skimmer were sharpened to reduce the number of gas atoms which scatter from the edges towards the scattering plane which would increase the wings of the beam profile. Measurements by Naumov⁸⁴ have shown

that the angular width, $\Delta\Theta_B$, of the directivity pattern of a capillary with aspect ratio R_A is given by

$$\Delta\Theta_B = 2 \cot^{-1} (R_A) \quad (33)$$

For the present work $\Delta\Theta_B = 1.14^\circ$. Thus, the combination of a large aspect ratio and differential skimming is expected to produce a beam of target atoms 0.51 mm in diameter in the scattering plane which is 5 mm above the skimmer.

Gas Handling System

The gas handling system is shown schematically in Fig. 18. High purity (99.995%) Helium or Hydrogen from a high pressure cylinder is introduced via a Grainville Phillips leak valve. Three bellows-operated metal sealed valves are present to direct gas flow. During the experiment valve #1 is open and valves #2 and #3 are closed. A high pressure ionization gauge together with an MKS Baratron are provided to measure the capillary driving pressure. Valve #1 can be closed to isolate the high vacuum system from the variable leak valve. Valves #2 and #3 can be opened to flood the chamber with gas.

Electric and Magnetic Shielding

The Electron Gun (EG), the scattered electron detectors (SED) and the Faraday Cup (FC) were each provided with integral grounded shields made from sheets of copper 0.04" thick. The shields were bent into proper shape and screwed directly to the grounded frames of the EG, SED and FC. Although the scattered electron

detector housing were grounded, other copper shields were provided to insure that fields from the CEM high voltage connection could not be seen from the interaction region. This was simple for the stationary electron detector as the leads were behind the integral shield and follow through a hole, behind the molypermalloy shield into the port #2 (P2). The leads to the rotating electron detector presented more of a problem. This was solved by inserting the leads into a 0.75" diameter copper tube 9" long. This tube was attached at one end to a universal pivot joint on the electron detector frame and the other end was fed through a 1" diameter hole in the magnetic shield. As the electron detector was rotated with respect to the hole, the copper tube slid in and out of the hole. The leads were made long enough to accommodate this motion. The EG leads were in port #1 away from interaction region. The EG, SED, and FC atomic beam source and copper base plate were all contained within a magnetic shield. The magnetic shield is contained within the vacuum system and is constructed of 1 mm thick molypermalloy. It was formed into a one and closed cylinder 16" in diameter and 9" in height. It was closed with a top which was tightly fitted onto the cylinder.

The magnetic shield is penetrated by several holes to facilitate the leads, the rotation gears, and to allow efficient pumping. In all cases these holes are positioned away from the electron beam and all detected

electron trajectories. The magnetic shield was degaussed commercially using hydrogen annealing. The entire chamber is also totally enclosed within two sets of square Helmholtz coils. After degaussing and adjusting the current in the Helmholtz coils, the maximum field strength in the interaction region was < 8 mG measured with a Rawson-Lush rotating coil Gauss meter.

Construction Materials

The choice of materials was determined by four criteria. (1) The material should be compatible with an ultra-high vacuum system and the bake out procedure. (2) The material should not contain any material which can damage the cathode emitting surface. (3) All materials used must be non-magnetic within the magnetic shield. (4) Any material which holds a surface charge must be shielded from the interaction region. The first criterion requires the exclusive use of metal seals and or Viton seals. The second criterion prohibits the use of brass and requires all solder joints to be silver-soldered. The third criterion excludes the use of stainless steel inside the magnetic shield. The fourth criterion limits the use of insulators and aluminum (which oxidizes readily).

All four criteria must be adhered to within the magnetic shield. All threaded stock was locally fabricated from beryllium-copper alloy. All tapped holes are relieved with bleed holes or slotted screws to provide pumping channels. The replaceable apertures are

fabricated from 0.13 mm thick molybdenum sheet. Aluminum has been used for gear wheels beneath the base plate. All other metal components have been made from oxygen-free-high-conductivity (OFHC) copper.

Assembly of Electron Gun

In order to achieve maximum current, the proper assembly of the gun's elements is required. Each element should be spaced from the preceding element about 0.04". The ceramic rods should not dig into soft copper, since this would cause the axis of the element not to be collinear with the axis of the other elements.

The Pierce element is so constructed that it shorts to the anode when the spacing on the O.D. of both elements is 0.016". Thus, if one anode to Pierce spacing at the beam line of 0.040" is desired, there should be 0.048" between the Pierce and anode elements on the outside surface. All the elements should be spaced so that there will be a no optical path from the beam line to any insulators.

Due to the heat generated by the cathode heater, the end of the gun near the cathode is at a high temperature. Thus, the mounting bolts for the elements on the end of the gun near the cathode must be tightened more than these farther away. The extra tightness of the mounting nuts at the cathode end will insure that the elements do not slip even during temperature cycling caused by turning the power to the cathode heater on and off.

After assembly of the electron gun, several checks are made to insure proper operation. Each element is checked for possible shorts to all other elements or to ground. Each element lead is checked for continuity from the element to the connector on the outside of the vacuum system. Also each connector is tested for high resistance leaks to ground which can upset sensitive electrometer readings.

Cleaning Procedures

The cleaning procedure described here has been adapted from that of Sutcliffe⁸⁵ and that of Rosebury⁸⁶ with slight modification. The copper cleaning consists basically of an acid etch and several rinses to leave the etched surface clear and free of any cleaning material. The following steps are used in cleaning. Clean the container each time solutions are renewed, with detergent and scrubbing. Rinse with tap water and finally with distilled water to get rid of all the detergent's residue.

1. Clean with abrasive pad in tap water to remove scale, oxide and grease.
2. Acetone dip-degrease.
3. Mix formic acid HCOOH 8% by volume, hydrogen peroxide H_2O_2 5% by volume, and 87% distilled water. Solution should be put in an ultrasonic cleaner. Small bubbles should form over entire surface of work. Leave in solution until surface shows a uniformly fine etch. Depending on condition of

surface, this step takes 1-5 minutes. Replace solution when it turns dark blue or a dark residue is formed on work.

4. Distilled water rinse thoroughly.
5. Methanol rinse thoroughly.
6. Distilled water rinse thoroughly.
7. Mix HCl 12% by volume and distilled water 88% by volume. Again solution should be left inside the ultrasonic cleaner for 5 minutes before use and there after. Rinse and leave work in solution 5 to 10 minutes, longer if finished pieces darken and turn red to yellow when exposed to air.
8. Distilled water rinse thoroughly.
9. Acetone (reagent grade) rinse and agitate with ultrasonic cleaner 10 to 15 minutes. Change every 3 to 4 hours of use. Keep covered at all times.
10. Repeat step 9 above.
11. Remove piece from last acetone rinse. Rinse entire piece with clean acetone from squeeze bottle, especially bolt holes, corners and residue from last acetone rinse. Immediately blot drops and pools that form in cracks, crevices, and holes with a clean KIMWIPETM towel and blow dry.
12. Cover the electron pathes with AerodagTM.
13. Store copper wrapped in KIMWIPETM in a plastic covered box.
14. Handle pieces only with chemically clean plastic gloves.

Bakeout Procedure

When the vacuum system is sealed, pump down is initiated by roughing the vessel through the diffusion pump with the mechanical pump. When the foreline pressure falls below 0.1 Torr, the gate valves are opened and through the diffusion pumps a pressure of 1×10^{-6} Torr is achieved. Depending on how long the system has been exposed to the atmosphere, this pump down is achieved in from 1 to 12 hours. In order to lower the pressure further, it is necessary to bake the system to drive off water and other gases trapped in the walls and the molecular sieve material. Heating tapes are used and power is supplied through variacs so that the temperature change can be controlled. Bake out is accomplished by first heating the main chamber and then heating the traps. The voltage to the heaters is increased until the wall temperature reaches 150°C . The system is left at 150°C for 1 to 2 days and the system pump down to 5×10^{-6} Torr. When this pressure is reached, the sorbent trap heaters are turned off. The system is then left overnight so the sorbent traps may cool completely. The pressure at this time is 10^{-7} Torr and the chamber heaters are turned off. After about six hours the pressure will be down to about 5×10^{-8} Torr and cathode activation may begin.

Mechanical Alignment Procedure

The rotating table and the rotating scattered electron detector are aligned first. The rotating table is

bolted loosely to the chamber. The electron detector is placed with its center line on the zero degree mark. The table is then rotated and adjusted until the alignment collar tool placed on the snout of the detector is concentric with a steel rod which is placed in the 0.5 mm skimmer aperture. Then the bolts are tightened. Next the electron gun is aligned by passing a steel rod through the gun snout and onto the molybdenum aperture. The gun is then adjusted until the gun steel rod completely crosses the skimmer steel rod. The stationary electron detector is placed so that the collar placed on its snout is halfway between the gun snout and the skimmer aperture and looking onto the electron beam. The height of the electron gun, and the detectors are all adjusted so that they all define one plane with respect to the skimmer. When the alignment is complete the rods and collars are removed.

CHAPTER IV

ELECTRONICS

In this experiment we have used state-of-the-art electronics. Care has been taken to ensure that the electronics do not bias the data and alter the experimental results. Experimental checks were developed to minimize any random, and systematic effects of the electronics.

Power Supplies

The power supply, in the case where the filament is made of tungsten wire is a Hewlett Packard model 6264B operated in constant current mode, and in the case of oxide-coated cathode is a Hewlett Packard model 6201B operated in constant current mode. The load and line regulator for model 6264B is $< 0.02\%$ and ripple is < 1 mvolt rms. The output is variable, 0-20 Volts at 0-20 Amp. The load and line regulation for model 6201B is $< 0.01\%$ and ripple is $< 0.02\%$ rms. The output is variable 0-20 Volts at 0-1.5 Amp.

The EG power supplies are Kepco model PAT 100-0.2 operated in constant voltage mode. The load and line regulation is $< 0.01\%$ and ripple is < 5 mVolt rms. The output is variable, 0 to 100 Volts at 0.2 Amp. Each of the outputs of these power supplies is connected to a

pair of ten-turn potentiometers for coarse and fine voltage control. These pots are arranged in pairs on the system control panel, and marked with the number of the electrode they control.

The CEM high voltage power supplies are Ortec model 456. The load and line regulation is $< 0.01\%$ and ripple is 10 mV peak-to-peak. The regulated high voltage output is 0-3 KV DC with 0 to 10 mA output current capability.

The digital electronic components are mounted in an auxiliary rack containing two Ortec model 401A modular system bins. Each bin is supplied with power by an Ortec model 402A power supply.

Pressure Measurement

The experiment is equipped with two Varian ionization gauges, and an MKS Baratron. These gauges are controlled by a Varian Ratiomatic model 843. The Varian ionization gauges indicate pressure in the range from 1×10^{-4} to 1×10^{-11} Torr. The ionization gauges are model UHV-24. The emission current is 4 mA. Both gauges are degassed by electron bombardment. The MKS Baratron has a transducer model 227, which can indicate pressure in the range from 1 to 1000 mmHg. It has an accuracy of 0.15% of reading 0.04% of reading/ $^{\circ}\text{C}$. The power supply for the MKS Baratron is model PDR-C-1B with a line input of 115/230 VAC and an output of 15 VDC at 200 mA. All pressures given in this work have implied uncertainties of 2%.

Current Measurement

The current from the FC, EG snout, or electron detector grid is measured by a Keithley model 610C electrometer capable of measuring currents in the range from 10^{-14} to 1 Amp. The accuracy of reading is 1%. Currents can be integrated for greater accuracy, if desired. All currents given in this work have implied uncertainties of 1%.

Time of Flight Circuit

The scattered electron pulses are AC coupled out of CEMs as shown in Fig. 19. The negative pulses are 20 meV deep and 20 nsec FWHM. They form the input to the time-of-flight circuit shown in Fig. 20. The pulses are fed into Ortec model 454 timing filter amplifiers (TFA) through 50 Ω terminated inputs. The gain of the TFA is variable to 250. The amplified pulses are fed into Ortec model 473A constant fraction discriminators (CFD). The CFDs were used in both constant fraction and leading edge modes. These two modes give different timing resolutions, as discussed in section IV.E. The output of a CFD are NIM-standard fast, negative logic pulse and a NIM-standard slow, positive logic pulse. The slow, positive pulse from the scattered electrons is connected to Ortec model 449 log/lin ratemeter. The electron count rate, R_e , is read from this meter with 1% accuracy. The fast, negative pulses are fed into the start of an Ortec model 467 time-to-amplitude converter

(TAC). The pulse from the trigger output of the pulse generator is used to stop the TAC. Since the scattered electrons require as much as 157 nsec at 19.0 eV to travel to the CEM, the pulses from the pulse generator must be delayed. The fast, negative pulses from the pulse generator are passed through a Lecroy model 222N Dual Gate Generator, delayed and are used to stop the TAC. Thus, if an electron which has been scattered is detected, the triggered pulse should stop the TAC 152 nsec after the electron has started it. The time range of the TAC is set at 1000 nsec and the output pulses range in amplitude from 0 to 10 Volts as a linear function of the start top time. The TAC output is fed into a Norland Linotech model 5400 1024 channel multichannel analyzer (MCA) in case of the rotating detector, and an Ortec model 7100 1024 channel multichannel analyzer. The 5400 MCA has an input range in amplitude from 0 to 8 Volts. The 7100 MCA has an input range in amplitude from 0 to 10 Volts. Both MCAs are operated as a pulse height analyzer (PHA). The amplitudes of the pulses from the TAC are converted to a time-of-flight (TOF) spectrum by the PHA, which fall into a group of about 20 channels of MCA corresponding to a range of delays Δt . This time resolution is discussed in section IV.E.

Since the TAC is started on the "slow" event and stopped on the delayed "fast" event, the result is an inverted time spectrum. This procedure can prevent the loss of data due to TAC dead time effects.

Timing Calibration

The calibration of a TAC-PHA pair can be accomplished with an Ortec model 462 time calibrator (TC). The TC generates logic signals at precise time intervals. These signals are fed into the start and stop inputs of the TAC and time spectrum is generated in the PHA. The spectrum is a series of peaks 1 channel wide. The linearity of the TAC-PHA pair is established if the number of channels between these peaks is constant. The time represented by one channel in the PHA is determined by dividing the period of TC stop signals by the number of channels between peaks in the PHA spectrum. Alternatively the period of TAC stop signals is divided by the number of channels in use in the MCA (1024) and multiplied by 0.8 (as PHA output amplitude range is 0-8 Volts). The result is the number of nanoseconds per channel, t_c ($t_c = 1.5625$ nsec/channel). The time resolution of the electronics can also be determined by attenuating the logic pulses of the TC and feeding through the TOF circuit. The FWHM of the peaks in the PHA spectrum then determines the time uncertainty of the electronics Δt . When the CFDs are set in the constant fraction or in the leading edge mode, Δt is ~2 nsec. However, this result is only valid for TC which provides uniform pulses. The FWHM of a measured TOF peak obtained with the CFDs in the constant fraction mode is typically ~9 nsec. When the CFD is operated in the leading edge mode the FWHM is typically ~12.5 nsec. The

change in the FWHM accurately gauges the improved time resolution of CFD. The increase of the FWHM from 2 nsec to 9 nsec is due to two contributions: (1) The electrons travel through the scattered electron detectors in a variety of trajectories. Assuming the energy of an electron in the detector is 19 eV, the electron's velocity is 2.58 mm/nsec. The shortest path from the collision center to the CEM is ~165 mm, so possible trajectories need vary by only 5% to impose a ~3.5 nsec uncertainty. (2) The size of the pulses from the CEMs vary from 10 meV to 20 meV. This variation leads to added time uncertainty in the CFD even when operated in the constant fraction mode.

One serious problem is seen when using constant fraction mode. There is some ringing present in the TOF spectrum. This ringing can become large for high count rates and can make data analysis difficult. The data presented here were taken usually in the leading edge mode. However, as we do not measure any parameter which is time dependent, the time resolution is not a crucial consideration.

CHAPTER V

DATA ACQUISITION

It is necessary to check several experimental variables to ensure that the measurement is done properly before data is taken. The procedure for data acquisition is followed carefully to make certain that each measurement is made under well known conditions.

Experimental Alignment

Mechanical alignment, while necessary, is insufficient to completely align the various experimental components. The operation of the electron gun requires further alignment procedure for its performance to be maximized.

Tuning of the Electron Gun

After the cathode or filament activation process is complete, the EG requires tuning to provide the desired electron beam. The lens voltages given in Table IV reflect the characteristics of a particular cathode or filament. Each time the cathode or filament is changed, slightly different values will be found. Since each voltage affects two lens elements, the trial and error technique is tiresome; but it is the only practical method of tuning the EG.

Once a electron stable beam has been achieved, the EG is tuned so that the current to the FC as well as the scattered electrons rate at a particular scattering angle, is maximized. This is achieved by using the electrostatic quadrupole steering lenses. This aligns the electron beam with the atomic beam axis.

Alignment of Electron Scattering Angle

The mechanical alignment and tuning of the EG can alter the effective angular position of the EG. To eliminate any uncertainty about the angular position of the EG, the electron beam profile is checked, prior to and after each set of measurements, to determine the position of 0° on the angle scale.

Procedure

The electron scattering rates measured by the rotating and stationary detectors vary directly with the product of current and pressure, IP. In order to maintain high gain in the CEMs, neither of the scattering rates is allowed to exceed 3×10^4 counts/sec. The count rate rises for small electron scattering angles due to large beam widths so several tunings of the gun may be necessary as a large current to FC does not necessarily mean good tuning.

After the current and pressure are set, this procedure is followed:

1. Turn the rotating detector to about 30° .
2. Check cathode voltage.
3. Using the energy calibration methods, measure

the electron beam energy and set cathode voltage accordingly.

4. Connect the rotating electron detector grid to the electrometer, and ground the FC. Rotate the detector through the electron beam. Check the beam width and determine the scale position 0° . If the beam width is too large a retuning of the gun is necessary.
5. Turn off the high voltage to the rotating electron detector.
6. Rotate the rotating electron detector to the 0° mark.
7. Reconnect the grid to its power supply and rotate the detector to a larger angle (30°).
8. Turn on the electron detector high voltage.
9. Rotate the detector to a smaller angle, in steps of 1° , being careful not to exceed the 3×10^4 count/sec (25°).
10. Record the values of the experimental parameters (current, pressure, the scale position of 0° , and the lens voltages) in the experiment log.
11. To start the data run, start both of the MCAs for a preset time which depends on the desired level of statistics.
12. When the run has stopped the data is stored as discussed in the next section. The values of the electron counts in both detectors are

written in the experimental log and the rotating detector is moved to next angle.

13. After all the chosen angles are done, the atomic beam valve is closed and the chamber is flooded to the same pressure and steps 11 and 12 are repeated.
14. When all the data are stored or written, then following procedures 1-13, a new set of data can be obtained for a different energy.

Data Transfer and Storage

In our experiment we have the capability of transferring the 1024 channels of data to a Tektronix 4051 minicomputer via the TYPE output of the MCAs. The data could be stored in files on a magnetic tape cartridge or could simply be transferred to a VAX VMS 11/780 for later analysis. Alternatively, as was done here, the data are simply written in the experiment log.

CHAPTER VI

DATA ANALYSIS

This section will provide the theoretical treatment of the data analysis and statistics as they pertain to the reported measurements. Such topics as solid angle and atomic beam density effects are considered. The evaluation of relative differential scattering cross sections is treated first since this analysis will be used in later evaluation of the absolute cross section measurements. The analysis in this section assumes that the coordinate system describing the collision geometry is defined with the origin at the scattering center and the incident beam along the +z direction. It is assumed throughout that the electron beam is uniform and parallel.

Relative Cross Section Measurements

The absolute cross section measurements reported in this work have been determined by measuring a scattered-electron signal rate from the atomic beam as a function of scattering angle using the rotating detector, $\dot{R}(E, \theta)$, as well as a scattered-electron signal rate from the background gas at each scattering angle used using the stationary detector, $\dot{S}(E, \theta)$. In addition, signal rates from both detectors were also measured with the atomic

beam off and the chamber flooded to the same background pressure as when the atomic beam was on, $\dot{R}'(E, \theta)$ and $\dot{S}'(E, \theta)$, respectively. The relative differential cross section at a particular electron energy E for scattering angles θ is determined from the following equation.

$$\sigma(E, \theta) = \frac{\dot{R}(E, \theta)}{\dot{S}(E, \theta)} - \frac{\dot{R}'(E, \theta)}{\dot{S}'(E, \theta)} \quad (34)$$

Pulses from the rotating and fixed electron detectors were used to start two time-to-amplitude converters (TAC) which were both stopped by a pulse derived from that which triggered the electron gun pulse. Each TAC was pulse-height analyzed and the resulting arrival time spectra stored. A sample time spectra from the rotating detector is shown in Fig. 21. The measurements were made for various driving pressures and were found to be independent of the driving pressure for pressures between 3 to 10 Torr (which corresponds to a background gas pressure range of about 1.5×10^{-7} to about 1×10^{-6} Torr in the chamber).

The justification for Eq. (34) with $\dot{S}$ and $\dot{S}'=1$ has been given by Andrick and Bitsch.⁹ Here a treatment using a notation similar to that of Steph et al.⁵⁶ will be given.

The general expression relating the differential scattering cross section $\sigma(E, \theta)$ and the scattered electron count rate is given by

$$\begin{aligned} \dot{N}(E, \theta) = & \frac{I_e}{e} \epsilon_e \int_{\Delta \Omega_e} \int_{\mathcal{L}_e} \rho(z) d\Omega dz \\ & \times \int_{-\infty}^{\infty} \sigma(E, \theta) F(E) d(E) + \dot{n}_e \end{aligned} \quad (35)$$

where I_e/e is the number of incident electrons per second in the electron beam, $\rho(z)$ is the target density, ϵ_e is the efficiency of the electron detector, ℓ_e is the interaction length viewed by the electron detector. $\Delta\Omega_e$ is the solid angle subtended by the electron detector at the interaction volume, $F(E)$ is the normalized energy distribution and $\dot{n}_e$ is the count rate due to electronic noise. Except for measurements in the neighborhood of a resonance, the cross section can be assumed constant over the energy integral and Eq. (35) reduces to

$$\dot{N}(E, \theta) = \frac{I_e}{e} \epsilon_e \int_{\Delta\Omega_e} \int_{\ell_e} \rho(z) \sigma(E, \theta) d\Omega dz + \dot{n}_e \quad (36)$$

In the usual case $\dot{n}_e$ can be made sufficiently small so that it can be neglected [as seen from Eq. (34), this term will drop out due to subtraction]. Assuming that the half-angle viewed by electron detector is small, in addition to the assumption that angular divergence of the incident electron beam is small Eq. (36) reduces to

$$\dot{N}(E, \theta) = \frac{I_e}{e} \epsilon_e \int_{\Delta\Omega_e} \int_{\ell_e} \rho(z) \sigma(E, \theta) d\Omega dz \quad (37)$$

Above assumptions are further discussed in next chapter. The target density is separated into the static background contribution (ρ_0) which has no z dependence and the contribution due to the atomic beam [$\rho_B(z)$] which leads to

$$\rho(z) = \rho_0 \left[\frac{\rho_B(z)}{\rho_0} + 1 \right] \quad (38)$$

Using Eq. (38) in Eq. (37), the scattered electron

signal rate at the rotating detector when the atomic beam is off, is given by

$$\dot{R}'(E, \theta) = \frac{I_e}{e} \epsilon_R \rho_0 \sigma(E, \theta) L_e \quad (39)$$

where ϵ_R is the efficiency of the rotating electron detector, and

$$L_e = \int_{\Delta\Omega_e} \int_{\ell_e} d\Omega dz \quad (40)$$

is the average path length viewed by the rotating detector. Then, when the atomic beam is on, the scattered-electron signal rate at the rotating detector is given by

$$\dot{R}(E, \theta) = \frac{I_e}{e} \epsilon_R \rho_0 \sigma(E, \theta) \left[\int_{\Delta\Omega_e} \int_{\ell_e} \frac{\rho_B}{\rho_0} d\Omega dz + L_e \right] \quad (41)$$

The stationary detector views scattering from the background gas whether or not the atomic beam is on.

Therefore, the signal rates to the stationary detector with the beam on and off, are both given by

$$\dot{S}(E, \theta) = \dot{S}'(E, \theta) = \frac{I_e}{e} \epsilon_S \rho(z) \int_{\Delta\Omega_e} \int_{\ell'_e} \sigma(E, \theta) d\Omega dz \quad (42)$$

That is, in either case we have a signal proportional to the product of electron beam current and background gas density. (The integral is a constant.)

Thus, the signals given by Eq. (42) can be used to normalize the signals given by Eq. (39) and Eq. (41) and properly account for fluctuations in the electron and atomic beam signal intensities. Subtracting the

normalized signal derived from Eq. (39) and Eq. (41) one obtains

$$\frac{R(E, \theta)}{S(E, \theta)} - \frac{R'(E, \theta)}{S'(E, \theta)} = \sigma(E, \theta) \left[\frac{\epsilon_R}{\epsilon_S} \right] \times \frac{\int_{\Delta\Omega_e} \int_{\ell_e} (\rho_B/\rho_0) d\Omega dz}{\int_{\Delta\Omega_e} \int_{\ell'_e} \sigma(E, \theta) d\Omega dz} \quad (43)$$

which is a signal proportional to the differential cross section provided that the ratio of detection efficiencies and the geometrical factors in Eq. (43) remain constant. Thus Eq. (34) may be used to measure relative differential cross sections. The measurements were made from 115° to the smallest angle used in 10° steps and then by returning to large angle in 10° steps offset by 5° . This usually resulted in about 20 points.

Absolute Cross-Section Determinations

Helium

The measured relative differential cross sections (DCS) are fitted to an analytic phase shift expansion representation of the DCS where the first several phase shifts are assumed to be unknown and the rest are represented by the Born sum (as was discussed in Chapter II). This method was first used by Steph et al.⁵⁶.

$$\sigma(\theta) = \frac{1}{4k^2} \left[\left(\sum_{\ell=0}^L (2\ell+1) \sin 2\eta_\ell P_\ell(\cos\theta) + 2kf_B^L \right)^2 + \left(\sum_{\ell=0}^L (2\ell+1)(\cos 2\eta_\ell - 1) P_\ell(\cos\theta) \right)^2 \right] \quad (28)$$

In order to keep the time necessary to perform the fitting it is expedient to make L as small as

possible.⁵⁶ Consider $\ell(\ell+1)/r^2$, the centrifugal barrier term for the ℓ th partial wave. In the absence of a scattering potential an incident electron of energy k^2 has a distant of closest approach given by

$$r = [\ell(\ell+1)]^{1/2} / k \quad (44)$$

that is where the kinetic energy is equal to the centrifugal barrier potential. If r is outside the atom then the ℓ th partial wave does not infiltrate the atom. That is, it only sees the long-range dipole potential due to the polarization of the atom and it is unaffected by the nuclear potential. For 19.6 eV electron, $k=1.2$ Bohr⁻¹. Thus $r_1=1.18$, $r_2=2.04$, and $r_3=2.89$, which are approximately obtained by setting the potential equal to zero. The presence of a potential will decrease them. A Helium atom has a size of 1.8 Bohr, thus the $\ell=3$ partial wave does not penetrate the atom and can be handled by Born approximation. Throughout the course of this work thus L is set equal to 2.

Setting $L=2$, Eq. (28) can be fitted to data by starting with a trial set of phase shifts (η_0, η_1 , and η_2) and subsequently changing these phase shifts to determine the combination leading to the best fit. The best fit to the data was determined as that fit which gave a minimum reduced chi square χ^2 defined by

$$\chi^2 = \frac{1}{N-P} \sum_{\theta_i} \left[\frac{\sigma_c^{-1}(\theta_i) - \sigma_m(\theta_i)}{\Delta \sigma_m(\theta_i)} \right]^2 \quad (45)$$

where N is the number of angles and P the number of parameters ($P=4$ in this work), σ_c and σ_m the calculated and measured DCS, $\Delta\sigma_m$ is the fractional error in σ_m , and κ is the scale factor for the relative DCS. This is done to insure that there is agreement between the measured and calculated angular distributions and also between their absolute magnitudes. This is necessary because Eq. (28) produces a curve which is an interference pattern of Legendre polynomials weighted by the terms containing the variable parameters.⁵⁶ This interference produces a curve of pronounced structure. Provided the errors are small enough so that the structure is clearly defined, the measurements may be brought to an absolute scale using parameter κ which multiplies the angular distribution measurements.

Once the DCS are determined, the total cross section σ_T and the momentum-transfer cross section σ_{MT} may be calculated,

$$\sigma_T = \frac{4\pi}{k^2} \sum_{\ell=0}^{\infty} (2\ell+1) \sin^2 \eta_{\ell} \quad (22a)$$

$$\sigma_{MT} = \frac{4\pi}{k^2} \sum_{\ell=0}^{\infty} (\ell+1) \sin^2 (\eta - \eta_{\ell+1}) \quad (23a)$$

It should be noted that the scale factors for relative differential cross sections, measured at different energies, are not independent of each other. Rather, they are related through the measured signals at different energies. This then allows the measurements to be extended upwards in energy although the type of phase

shift analysis described here is only valid for energies below the threshold of the first excited state.

Hydrogen

The relative differential cross section $d\sigma(E,\theta)/d\Omega$ at a particular electron energy E for scattering angles θ is determined from Eq. (34) as was done for Helium. Throughout these measurements the grid in front of each detector was biased so that electrons which had excited an electronic level of H_2 were not detected. The relative differential cross sections are placed on an absolute scale by comparison to measurements of absolute elastic e^- -He scattering cross sections. For this normalization, both He and H_2 relative differential cross section measurements at 90° are made at each energy studied using the same neutral-beam driving pressure (measured by the MKS Baratron), background gas pressure, electron beam current, voltages, etc. The accelerating voltage is adjusted slightly when changing gases in order to keep the electron energy the same. In the normalization process the driving pressure in the gas reservoir is sufficiently low so that the gas outflow is laminar³¹. In actual measurements the pressure in the gas reservoir is set to some value for when H_2 is flowed through the system to form the target beam. The flow of H_2 is then stopped and the system is pumped out to about 4×10^{-7} Torr pressure, this took about 10 minutes. The He gas is then let in at the same driving pressure shown by the MKS Baratron. Under such conditions, a constant

pressure in the gas reservoir together with a small rate of outflow is sufficient to give equal target beam densities for He and H_2 at the same gas reservoir pressure.

The absolute values of the differential cross sections previously determined in He at 2, 5, 12, and 19 eV at 90° together with their respective errors, are given in Table VIII. Relative measurements made at these energies in H_2 are then placed on an absolute scale by measuring the cross sections in H_2 relative to that in He at 90° for each energy. In this aspect of the work at least four determinations at each energy have been made. These relative values with their respective errors are also given in Table VIII.

The s-, p-, and d-wave phase shifts found at 2, 5, 12, and 19 eV in He have been fitted with effective range formulas to interpolate and extrapolate to the other energies given in Table VIII. The resulting phase shifts have been used to calculate the He cross sections at 90° given in Table VIII. The relative H_2 to He cross section ratios measured at 2, 5, 12, and 19 eV have been fitted with a third-order polynomial to obtain the values of this quantity given in Table VIII. The H_2 differential cross-section values at 90° given in Table VIII were obtained by multiplying the He cross sections by H_2 -to He cross section ratios at each energy. In this fashion, the relative angular distribution measurements at the other energies given in Table VIII were placed on an absolute scale.

The absolute total differential cross sections were fitted with third-order polynomials and extrapolated to 0° and 180° in such a way that the angular distribution curve followed the shape of the theoretical curve calculated by Morrison et al.⁴⁸ These fitted functions were integrated in order to obtain the integrated total cross sections $\sigma(E)$ given in Table X.

CHAPTER VII

ERROR ANALYSIS

In order to ensure that the results are free from any errors, various sources of errors have been investigated.

Discussion of Uncertainty in Fitted Parameters

As Eq. (28) is not linear in η_0 , η_1 , and η_2 thus one cannot obtain an analytic form for the errors in the best values of fitting parameters.⁵⁶ Furthermore, the errors in the phase shifts are correlated, thus complicating the problem of finding errors for total and momentum transfer cross sections. For these reasons the below criteria was chosen in order to compare the values of phase shifts arrived from this work to values obtained by other methods. In this work, all combinations of the first three phase shifts which resulted in curves lying within 5% of all but two data points were accepted. The errors in all parameters were determined as the range of the parameters in the accepted fits.

Discussion of Systematic Error

Inherent to Eq. (43) is the assumption that electron beam has uniform density and is of the same spatial extent as the gas beam. The rate of scattering events detected at a scattering angle is proportional to

$$\dot{N} \propto \int_{\ell(\theta)} \rho(z) \Delta\Omega(z, \theta) dz = J(\theta) \quad (46)$$

where the electron beam is taken to be uniform and along the z -axis ($z=0$ is the center of intersection of the electron and atomic beams) and is defined by the opening angle θ of the detector and its distance from the electron beam. $\Delta\Omega(z, \theta)$ is the solid angle a detector subtends at a given point in the scattering volume and $\rho(z)$ is the density of scattering targets at that point. If $\rho(z)$ is written as the sum of the density of the atomic beam $\rho_B(z)$ and the uniform background density ρ_0 , Eq. (46) may be written

$$J = \int_{\ell_B} \rho_B(z) \Delta\Omega(z, \theta) dz + \rho_0 \int_{\ell(\theta)} \Delta\Omega(z, \theta) dz \quad (47)$$

where ℓ_B is the width of the atomic beam. Since ℓ_B is sufficiently small (0.5 mm) the variation of $\Delta\Omega(z, \theta)$ is negligible in the first integral and may be taken outside. Thus

$$\begin{aligned} J(\theta) &= \rho_0 \Omega \left\{ \int_{\ell_B} \frac{\rho_B(z)}{\rho_0} dz + \int_{\ell(\theta)} \frac{\Delta\Omega(z, \theta)}{\Omega} dz \right\} \\ &= \rho_0 \Omega \left\{ K + L(\theta) \right\} \end{aligned} \quad (48)$$

where Ω is the solid angle subtended at $z=0$ and is independent of θ . The integral $L(\theta)$ is determined solely by properties of the detector and may be calculated exactly (Appendix A). While $\rho_B(z)$ cannot be directly determined in this experiment, the value of the integral K may be inferred from measurements of the static electron scattering rate at a given angle with the atomic

beam on $\dot{R}(E, \theta)$, and with the atomic beam off and the chamber flooded to the same back ground density $\dot{S}(E, \theta)$. The result is

$$K = \left\{ \frac{\dot{R}(E, \theta)}{\dot{S}(E, \theta)} - 1 \right\} L(\theta)$$

This measurement is made at several values of θ to ensure that K is independent of θ . Once K is determined, the integral

$$J(\theta) = \int_{\ell(\theta)} \rho(z) \Delta Q(z, \theta) dz = \rho_0 Q [K + L(\theta)] \quad (49)$$

necessary for the scattering rate can be calculated. Examples of $\Delta Q(z, \theta)$ are shown in Figs. 22-25. Note that when $\theta \neq 90^\circ$, the maximum value of ΔQ does not occur at $z=0$. If the atomic beam were large, there could be a systematic error in the position of the detector. In this work, the beam diameter was ≥ 0.50 mm. Thus, the angular position of the detectors was unaffected.

The accepted fits were calculated by varying all phase shifts for $\ell \leq L$ and κ and a grid search technique was used to determine the curves.

In the analysis of He, the errors vary between about 9% at 2 eV to 2% at 19 eV. The errors in the relative cross sections in H_2 determined in this work vary from a maximum of 8.8% at 2 eV to a minimum of about 2.8% at 12 eV. These errors have been combined to determine the errors in the H_2 absolute cross sections. The errors in the integrated total cross sections have been determined by the differences introduced into the

integrated total cross sections due to differences in the possible extrapolations.

CHAPTER VIII

RESULTS AND DISCUSSION

Helium

Samples of the differential cross-section measurements made according to the procedure outlined in Chapter VI are shown in Fig. 26-29 at 2, 5, 12, and 19 eV. The scales on the figures have been determined by the fitting procedure also described in Chapter VI, while the two dashed lines on each figure are the limits of the scale as determined in this work. The solid line on each figure is the data of Andrick and Bitsch⁹ at the level determined in this work as the best fit to their data.

The first three phase shifts as determined in this work are presented in Table V and Fig. 30-32, along with those determined in previous measurements and calculations. The present results are the results of weighted averages of different runs made over a long period of time. At each energy at least four runs have been made. The errors given here have been determined by combining the statistical errors of all the data used. The differential cross section scale has been determined to have errors of 9%, 8.3%-7.1%, 8.0%-6.0%, and 1.9%-2.1% at 2, 5, 12, and 19 eV, respectively. This is to be compared to an error which decreases from 20% to 5% in

this energy range given by Andrick and Bitsch,⁹ 5% in this energy range given by Register et al.,¹⁶ 4% given by Williams at 19.2 eV,¹² 3% given by Williams and Willis at 19.2 eV,¹¹ 5% given by McConkey and Preston at 19.1 eV,⁸ and 4% given by Gibson and Dolder at 19.1 eV.¹³

The phase shifts as determined in this work are in general agreement within the errors with the result of the previous measurements of Andrick and Bitsch,⁹ Register et al.,¹⁶ Williams,¹² and Williams and Willis,¹¹ as well as the calculations of Nesbet,²⁴ O'Malley et al.,²⁹ Yarlagadda et al.,²⁷ Callaway et al.,¹⁹ Duxler et al.,²⁵ Sinfailam and Nesbet,²⁶ and Wichmann and Heiss.²⁸

However, the p-wave phase shifts as determined in this work are slightly outside of the error bar overlap with those of Williams,¹² Nesbet,²⁴ and Duxler et al.²⁵ at 2 eV; Williams,¹² Nesbet,²⁴ Duxler et al.,²⁵ Sinfailam and Nesbet²⁶ and Callaway et al.¹⁹ at 5 eV. Williams,¹² Nesbet,²⁴ Yarlagadda et al.,²⁷ and Wichmann and Heiss²⁸ at 12 eV. Williams,¹² Nesbet,²⁴ Sinfailam and Nesbet,²⁶ Wichmann and Heiss²⁸ and Yarlagadda et al.²⁷ at 19 eV. It should be noted that the present analysis of the experimental results of Andrick and Bitsch⁹ and Register et al.¹⁶ yields lower χ^2 than given by those authors.

In Fig. 33-36 differential cross section as evaluated using Eq. (28) and the determined phase shifts are compared to the theoretical values as calculated by Nesbet.²⁴ The resulting total and momentum-transfer

cross sections are tabulated in Tables VI and VII, and shown in Fig. 37 and 38, respectively. The present result for the total cross section at 2 eV is in excellent agreement with the previous result of Golden and Bandel.⁴ It agrees with the previous result given by Andrick and Bitsch⁹ although it is near the end of the error bar. However, the present results drastically disagree with the present analysis of the 2 eV data of Andrick and Bitsch. The present results also agree with the previous results of Nesbet,²⁴ O'Malley et al.,²⁹ Kennerly and Bonham⁸⁷ and Shyn,⁸⁰ although in all of these cases the agreement is at or near the end of the present error bar. The present result for the total cross section at 5 eV is also in excellent agreement with the previous result of Golden and Bandel.⁴ In this case the result disagrees with that of Andrick and Bitsch,⁹ Nesbet,²⁴ O'Malley et al.,²⁹ and Shyn,¹⁴ while it is just at the end of the overlap of error bars with Register et al.¹⁶ and just outside of error bar overlap with Kennerly and Bonham.⁸⁷ At 12 eV the present total cross section result is several percent out side of the overlap of error bars with the previous result of Golden and Bandel⁴ and it is in better agreement with the previous results of Andrick and Bitsch.⁹ It is just outside of error overlap with Register et al.,¹⁷ Nesbet²⁴ and Shyn.¹⁴ The present total cross section result at 19 eV is in agreement with the previous result of Golden and Bandel,⁴ although it is in better agreement with the

previous results of the other measurements and calculations.

The present results for the momentum-transfer cross sections are below the previous results at 2 and 5 eV, are about the same at 12 eV, and are slightly above the previous results at 19 eV. The present momentum-transfer cross section results are in agreement with the past results within the respective errors except for the results of Nesbet²⁴ and O'Malley et al.²⁹ at 5 and 12 eV. In all cases these results are very close to error-bar overlap.

Hydrogen

Total differential cross sections measured at 1, 2, 4, 5, 6, 8, 10, 12, and 19 eV are plotted in Fig. 39-47 together with the previous experimental results of Linder and Schmidt,³⁰ Srivastava et al.,³¹ Trajmar et al.,³³ Shyn and Sharp,³⁴ and the calculations of Morrison et al..⁴⁸ The absolute total differential cross sections found in the present work are summarized in Table IX.

The measurements of Srivastava et al.³¹ (shown on the plots) have been renormalized to the He results of Register et al.¹⁶ The agreement between the present measurements and the recent full ro-vibrational laboratory frame close-coupling calculations of Morrison et al.¹⁸ is excellent over the complete energy range of overlap. In general, the present results are above those of Srivastava et al.³¹ and Trajmar et al.³³ in the

forward direction (25% at 30° and 10 eV) and in agreement with them in the backward direction. In contrast, the present results are generally in agreement with those of Shyn and Sharp³⁴ in the forward direction but below them in the backward direction (50% at 115° and 10 eV). The present results are generally higher than those of Linder and Schmidt³⁰ (25% at 10 eV) although the two sets of results are very similar in shape and become closer in absolute magnitude as one goes to lower energies.

The integrated total cross sections found in this work are presented in Table X. In Fig. 48 the integrated total cross sections found in this work are presented together with the previous direct determinations of Dalba et al.³⁷ and Jones,³⁸ the integrated total DCS measurements of Srivastava et al.³¹ Trajmar et al.,³³ and Shyn and Sharp,³⁴ as well as the calculations of Morrison et al.⁴⁸ The present results agree best with the older direct measurements of Golden et al.³⁵ the other two direct measurements, and the recent calculation shown on the plot.

In conclusion, the experimental apparatus and the measurement technique of the present work have been thoroughly analyzed for sources of systematic and random error. Where there is disagreement with previous measurements, the disagreement has been explained and resolved in favor of the present results.

Presently the electron gun is being modified and equipped with an energy monochromater with an energy resolution of 30 meV. This arrangement will allow the study of rotational and vibrational excitation of H_2 .

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TABLE I. Pulsed Electron Gun physical dimension and operating voltages.

Element	Voltage ^a (volt)	Tube Diameter (mm)	Tube Length (mm)
Anode	103.52	10.41	60.046
2000	95.20	20.70	34.8
Pulser	23.62	6.60 ¹	30.74 ¹
		15.50 ²	81.28 ²
4000	2.86	20.70	23.62
5000	4.30	20.70	24.64

¹Pulsing part
²Front part

^aVoltage measured with respect to a cathode common voltage of 19.85 volts. The current was 3 nAmp.

Cathode emitting surface area.....	15.8 mm ²
Angle of Pierce element.....	58.5
Anode aperture diameter.....	1.0 mm
2000 element aperture diameter.....	2.0 mm
Puler front aperture diameter.....	1.0 mm
Snout replacable aperture diameter.....	1.0 mm
Lens spacing.....	1.0 mm
Snout length.....	42.0 mm
Snout tube diameter.....	20.70 mm
Snout-collision center distance.....	25.40 mm

TABLE II. Cathode activation schedule.

Elapsed Time	Pressure at power change	Filament Current	Peak Pressure
(min)	(10^{-8} Torr)	(Amp)	(10^{-8} Torr)
	2.0	0.1	2
5	2.0	0.2	2
15	2.4	0.25	10
20	2.5	0.35	21
35	3.2	0.4	9
45	3.2	0.41	9
51	3.2	0.42	12
60	3.5	0.44	14
75	6.0	0.46	14
90	20.0	0.47	26
100	22.0	0.48	40
120	22.0	0.50	30
133	14.0	0.53	28
140	4.6	0.6	9
145	5.2	0.7	10
160	6.4	0.53	—

TABLE III. Sample energy calibration using ^2S resonance in He.

Cathode Voltage	Actual Energy	COUNTS
20.500	19.200	5.14
20.650	19.350	4.22
20.725	19.380	4.10
20.810	19.510	4.20
20.825	19.525	4.35
20.845	19.545	4.52
20.900	19.600	4.89

Sample energy calibration using retarding grid voltage.

Cathode voltage was 20.65 volts.

Grid Voltage	COUNTS	Grid Voltage	COUNTS
20.00	38	19.35	628
19.95	45	19.30	709
19.90	42	19.25	815
19.85	93	19.15	972
19.80	83	19.10	1068
19.75	132	19.05	1100
19.70	156	19.00	1102
19.65	226	18.90	1229
19.60	311	18.80	1310
19.55	344	17.00	1357
19.50	416	12.00	1370
19.45	473	5.00	1391
19.40	541	0.00	1417

TABLE IV. Scattered electron detector dimensions.

Scattering center to aperture.....	25.0 mm
Aperture to CEM face.....	145.0 mm
Aperture diameter(Rotating detector).....	1.6 mm
Aperture diameter(Stationary detector).....	2.4 mm
Front aperture to grid.....	24.13 mm

TABLE V.1. The first three phase shifts in radians,
at 2 eV.

η_0	η_1	η_2	Author
2.65(+0.9% -0.9%)	0.046(+13.5% -13.5%)	0.008(+27.0% -27.0%)	Present
2.62(+5.0% -5.0%)	0.052(+37.0% -37.0%)	0.006 (fixed)	Andrick and Bitsch ^a
2.52(+1.8% -1.8%)	0.066(+24.9% -18.9%)	0.009(+63.0% -62.0%)	Andrick and Bitsch ^b
2.61(+2.0% -2.0%)	0.060(+2.0% -2.0%)	0.006(+8.0% -8.0%)	Williams ^c
2.62	0.060	0.006 (fixed)	O'Malley et al. ^d
2.64	0.056	0.006 (fixed)	Nesbet ^e
2.63	0.045	0.003 (fixed)	Wichmann ^f
2.63	0.051	0.004 (fixed)	Yarlagadda et al. ^g
2.64	0.050	0.006 (fixed)	Callaway et al. ^h
2.66	0.056	0.007 (fixed)	Duxler et al. ⁱ
2.65	0.050	0.006 (fixed)	Sinfailam and Nesbet ^j

^aReference 9
^bPresent analysis
^cReference 11
^dReference 29
^eReference 24
^fReference 28
^gReference 27
^hReference 19
ⁱReference 25
^jReference 26

**TABLE V.2. The first three phase shifts in radians,
at 5 eV.**

η_0	η_1	η_2	Author
2.38(+1.1% -1.3%)	0.114(+8.6 % -10.8%)	0.016(+52.0% -53.0%)	Present
2.32(+2.0% -2.0%)	0.135(+19.0% -19.0%)	0.015 (fixed)	Andrick and Bitsch ^a
2.34(+2.0% -2.0%)	0.126(+25.0% -25.0%)	0.010(+108% -108%)	Andrick and Bitsch ^b
2.35(+10.0% -3.6%)	0.118(+44.0% -50.0%)	0.011(+108% -108%)	Register et al ^{b,k}
2.32(+2.0% -2.0%)	0.129(+2.0% -2.0%)	0.014(+8.0% -8.0%)	Williams ^c
2.33	0.114	0.015 (fixed)	O'Malley et al. ^d
2.34	0.124	0.015 (fixed)	Nesbet ^e
2.35	0.098	0.009 (fixed)	Wichmann ^f
2.35	0.119	0.009 (fixed)	Yarlagadda et al. ^g
2.36	0.121	0.016 (fixed)	Callaway et al. ^h
2.38	0.134	0.017 (fixed)	Duxler et al. ⁱ
2.37	0.123	0.014 (fixed)	Sinfailam and Nesbet ^j

- ^aReference 9
^bPresent analysis
^cReference 11
^dReference 29
^eReference 24
^fReference 28
^gReference 27
^hReference 19
ⁱReference 25
^jReference 26

TABLE V.3. The first three phase shifts in radians,
at 12 eV.

η_0	η_1	η_2	Author
2.01(+0.5% -3.2%)	0.250(+0.9% -7.9%)	0.037(+19.7% -19.4%)	Present
1.99(+3.0% -3.0%)	0.259(+12.0% -12.0%)	0.037 (fixed)	Andrick and Bitsch ^a
1.99(+2.2% -2.6%)	0.255(+9.6% -9.0%)	0.036(+36.0% -36.0%)	Andrick and Bitsch ^b
1.96(+3.6% -4.8%)	0.272(+12.0% -16.2%)	0.036(+45.0% -45.0%)	Register et al. ^{b,k}
1.97(+1.9% -1.9%)	0.242(+2.0% -2.0%)	0.037(+8.0% -8.0%)	Williams ^c
1.98	0.236	0.037 (fixed)	O'Malley et al. ^d
1.99	0.243	0.037 (fixed)	Nesbet ^e
1.97	0.196	0.022 (fixed)	Wichmann ^f
2.01	0.235	0.025 (fixed)	Yarlagadda et al. ^g
2.02	0.236	0.026 (fixed)	Callaway et al. ^h
2.09	0.255	0.041 (fixed)	Duxler et al. ⁱ
2.02	0.247	0.035 (fixed)	Sinfailam and Nesbet ^j

^aReference 9

^bPresent analysis

^cReference 11

^dReference 29

^eReference 24

^fReference 28

^gReference 27

^hReference 19

ⁱReference 25

^jReference 26

TABLE V.4. The first three phase shifts in radians,
at 19 eV.

η_0	η_1	η_2	Author
1.84(+1.9% -2.0%)	0.353(+3.2% -4.3%)	0.065(+12.9% -10.8%)	Present
1.81(+5.0% -5.0%)	0.325(+12.0% -12.0%)	0.058 (fixed)	Andrick and Bitsch ^a
1.82(+4.2% -3.4%)	0.325(+11.0% -11.2%)	0.060(+27.0% -22.0%)	Andrick and Bitsch ^b
1.82(+1.5% -1.5%)	0.305(+2.0% -2.0%)	0.056(+8.0% -8.0%)	Williams ^c
1.80	0.316	0.058 (fixed)	Nesbet ^e
1.77	0.257	0.037 (fixed)	Wichmann ^f
1.81	0.298	0.043 (fixed)	Yarlagadda et al. ^g
1.80	0.279	0.052 (fixed)	Callaway et al. ^h
1.80	0.320	0.062 (fixed)	Duxler et al. ⁱ
1.82	0.298	0.056 (fixed)	Sinfailam and Nesbet ^j

^aReference 9

^bPresent analysis

^cReference 11

^dReference 29

^eReference 24

^fReference 28

^gReference 27

^hReference 19

ⁱReference 25

^jReference 26

TABLE VI. Total cross section in A²

ENERGY (eV)	2	5	12	19
Present	5.58(+9.7% -8.9%)	4.89(+4.5% -7.5%)	4.24(+2.1% -3.2%)	3.12(+0.6% -2.1%)
Andrick and Bitsch ^a	6.20(+50.0% -50.0%)	5.64(+11.0% -11.0%)	4.15(+4.0% -4.0%)	3.19(+4.0% -4.0%)
Andrick and Bitsch ^b	8.47(+14.4% -13.3%)	5.41(+11.7% -11.2%)	4.11(+3.4% -3.5%)	3.19(+3.5% -3.4%)
Register et al. ^c		5.25(+3.0% -3.0%)	3.96(+3.0% -3.0%)	
Register et al. ^b		5.26(+19.9% -47.1%)	4.31(+4.5% -4.1%)	
Golden and Bandel ^d	5.57(+7.0% -7.0%)	4.95(+7.0% -7.0%)	3.70(+7.0% -7.0%)	2.87(+7.0% -7.0%)
Kennerly and Bonham ^e	6.01(+3.0% -2.0%)	5.25(+3.0% -2.0%)	3.96(+3.0% -2.0%)	3.11(+3.0% -2.0%)
O'Malley et al. ^f	6.00	5.58	4.25	
Nesbet ^g	6.03	5.38	4.06	3.13
Shyn ^h	5.75	5.26		

^aReference 9

^bPresent analysis

^cReference 16

^dReference 4

^eReference 87

^fReference 29

^gReference 24

^hReference 14

TABLE VII. Momentum-transfer cross section in $\text{\AA}^2$

ENERGY (eV)	2	5	12	19
Present	6.43($+10.7\%$ -9.80%)	5.84($+5.1\%$ -7.7%)	4.33($+0.8\%$ -2.7%)	2.92($+1.8\%$ -3.7%)
Andrick and Bitsch ^a	7.20($+40.0\%$ -40.0%)	6.64($+11.0\%$ -11.0%)	4.28($+3.0\%$ -3.0%)	2.86($+4.0\%$ -4.0%)
Andrick and Bitsch ^b	9.84($+15.8\%$ -14.3%)	6.40($+11.8\%$ -11.7%)	4.26($+2.7\%$ -2.9%)	2.86($+3.4\%$ -3.4%)
Register et al. ^c		6.45($+5.0\%$ -5.0%)	4.27($+5.0\%$ -5.0%)	
Register et al. ^b		6.20($+18.0\%$ -47.4%)	4.39($+3.4\%$ -3.4%)	
Crompton et al. ^d	6.98($+2.0\%$ -2.0%)	6.31($+3.0\%$ -3.4%)	4.15($+5.0\%$ -5.0%)	
O'Malley et al. ^e	6.88	6.52	4.53	
Nesbet ^f	7.00	6.32	4.21	2.85
Shyn ^g	6.74	6.12		

^aReference 9

^bPresent analysis

^cReference 16

^dReference 6

^eReference 29

^fReference 24

^gReference 14

TABLE VIII. Differential cross sections in He and H₂ from 1 to 19 eV determined in this work.

ENERGY	$\frac{d\sigma[\text{He}(90^\circ)]}{d\Omega}$	$\frac{d\sigma[\text{H}_2(90^\circ)]}{d\Omega} / \frac{d\sigma[\text{He}(90^\circ)]}{d\Omega}$	$\frac{d\sigma[\text{H}_2(90^\circ)]}{d\Omega}$	$\sigma(\text{H}_2)$
(eV)	(Å ² /sr)		(Å ² /sr)	(Å ²)
1	0.470	2.23	1.05	14.2±13%
2	0.453±9%	2.16±8.8%	0.978±12.6%	15.7±13%
4	0.408	2.01	0.820	15.1±12%
5	0.381±7.7%	1.94±6.0%	0.739±9.8%	15.2±10%
6	0.372	1.87	0.696	13.25±9%
8	0.338	1.73	0.585	11.3±8%
10	0.307	1.59	0.488	10.2±8%
12	0.279±7%	1.46±2.2%	0.407±7.3%	9.8±9%
19	0.201±2%	1.08±2.9%	0.217±3.5%	6.8±10%

TABLE IX. Elastic differential cross sections for H₂ in Å²/sr.

Scattering angle (deg)	Collision energy (eV)								
	1	2	4	5	6	8	10	12	19
20							2.99	3.53	2.84
25				2.65	2.47	2.40	2.62	3.10	2.61
30	0.498	1.30	2.12	2.54	2.40	2.26	2.31	2.66	2.26
35	0.606	1.27	1.98	2.12	1.88	1.97	2.03	2.30	1.81
40	0.594	1.24	1.73	2.04	1.78	1.76	1.79	1.91	1.38
45	0.798	1.08	1.49	1.78	1.66	1.58	1.55	1.76	1.12
50	0.756	1.02	1.30	1.67	1.05	1.33	1.24	1.40	0.910
55	0.773	0.913	1.24	1.36	1.29	1.24	1.15	1.26	0.785
60	0.786	0.838	1.11	1.30	1.22	1.11	1.04	0.994	0.630
65	0.855	0.802	1.05	1.10	1.03	0.991	0.909	0.847	0.507
70	0.864	0.799	1.02	0.997	0.963	0.886	0.779	0.710	0.393
75	0.955	0.842	0.890	0.919	0.866	0.719	0.657	0.610	0.319
80	0.971	0.893	0.849	0.910	0.806	0.694	0.577	0.540	0.256
85	1.18	0.883	0.843	0.786	0.773	0.627	0.532	0.485	0.226
90	1.05	0.978	0.820	0.739	0.696	0.585	0.488	0.407	0.217
95	1.18	0.985	0.812	0.726	0.623	0.509	0.410	0.354	0.170
100	1.19	1.00	0.784	0.758	0.634	0.475	0.378	0.315	0.144
105	1.31	1.09	0.777	0.775	0.638	0.441	0.342	0.295	0.126
110	1.36	1.19	0.858	0.786	0.641	0.440	0.309	0.259	0.122
115	1.40	1.25	0.910	0.799	0.659	0.414	0.295	0.260	0.122

TABLE X. Integrated cross sections in H_2 in A^2

Author	Collision energy (eV)								
	1	2	4	5	6	8	10	12	19
Peresent	14.192	15.675	15.077	15.190	13.250	11.250	10.244	9.8	7.37
Morrison et al. ^a	13.588	15.873	15.822	15.290	13.821	11.823	10.147	8.897	
Srivastava et al. ^b				13.7			8.27		
Shyn and Sharp ^c				15.9			11.29		
Dalba et al. ^d	14.00	16.16	15.79		14.23	12.35	10.78		
Jones ^e	13.29	15.59	15.64	15.17	14.12	12.15	10.54	9.262	
Golden et al. ^f	13.0	15.0	14.9	13.9	12.7	10.8	9.3	8.2	

^aReference 48^bReference 31^cReference 34^dReference 37^eReference 38^fReference 35

TABLE XI. Elastic differential cross sections for He
in $\text{\AA}^2/\text{sr}$.

Scattering angle	Collision energy (eV)				
	(deg)	2	5	12	19
0		0.190	0.201	0.552	0.758
5		0.175	0.196	0.509	0.753
10		0.186	0.195	0.469	0.679
15		0.198	0.196	0.433	0.611
20		0.211	0.199	0.401	0.548
25		0.225	0.203	0.372	0.492
30		0.240	0.209	0.347	0.441
35		0.255	0.217	0.325	0.396
40		0.272	0.226	0.307	0.357
45		0.289	0.236	0.292	0.322
50		0.306	0.248	0.280	0.293
55		0.324	0.262	0.271	0.269
60		0.343	0.276	0.266	0.248
65		0.362	0.292	0.262	0.232
70		0.380	0.309	0.262	0.220
75		0.399	0.326	0.263	0.211
80		0.417	0.344	0.267	0.205
85		0.435	0.363	0.272	0.202
90		0.453	0.382	0.279	0.201
95		0.470	0.401	0.288	0.202
100		0.486	0.420	0.298	0.204
105		0.501	0.439	0.308	0.208
110		0.516	0.457	0.319	0.212
115		0.529	0.475	0.331	0.218
120		0.542	0.492	0.343	0.223
125		0.553	0.509	0.355	0.229
130		0.564	0.524	0.366	0.235
135		0.573	0.539	0.378	0.241
140		0.581	0.552	0.388	0.246
145		0.588	0.564	0.398	0.251
150		0.594	0.574	0.406	0.255
155		0.599	0.584	0.414	0.259
160		0.603	0.591	0.421	0.262
165		0.607	0.597	0.426	0.265
170		0.609	0.601	0.429	0.266
175		0.610	0.604	0.432	0.267
180		0.614	0.608	0.446	0.264

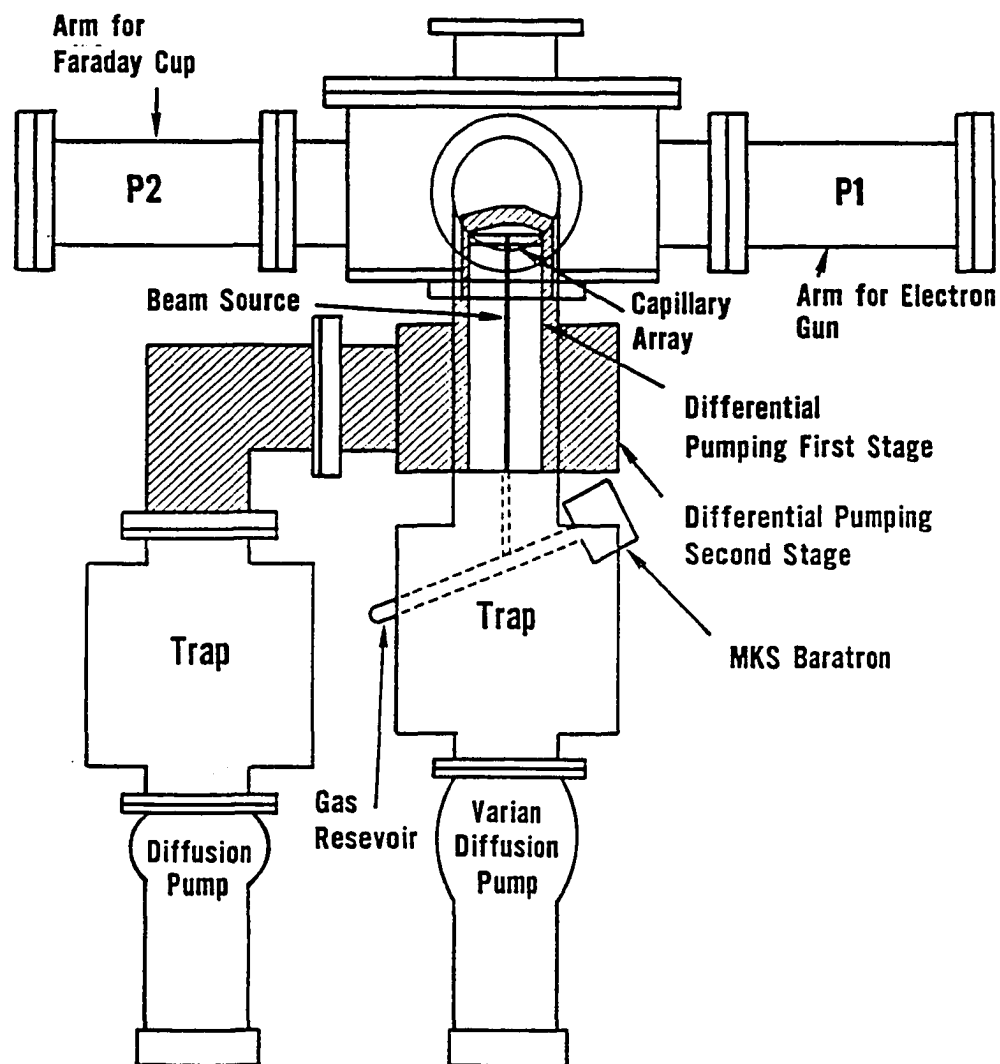


Fig.1a. Schematic diagram of the ultra-high vacuum system.

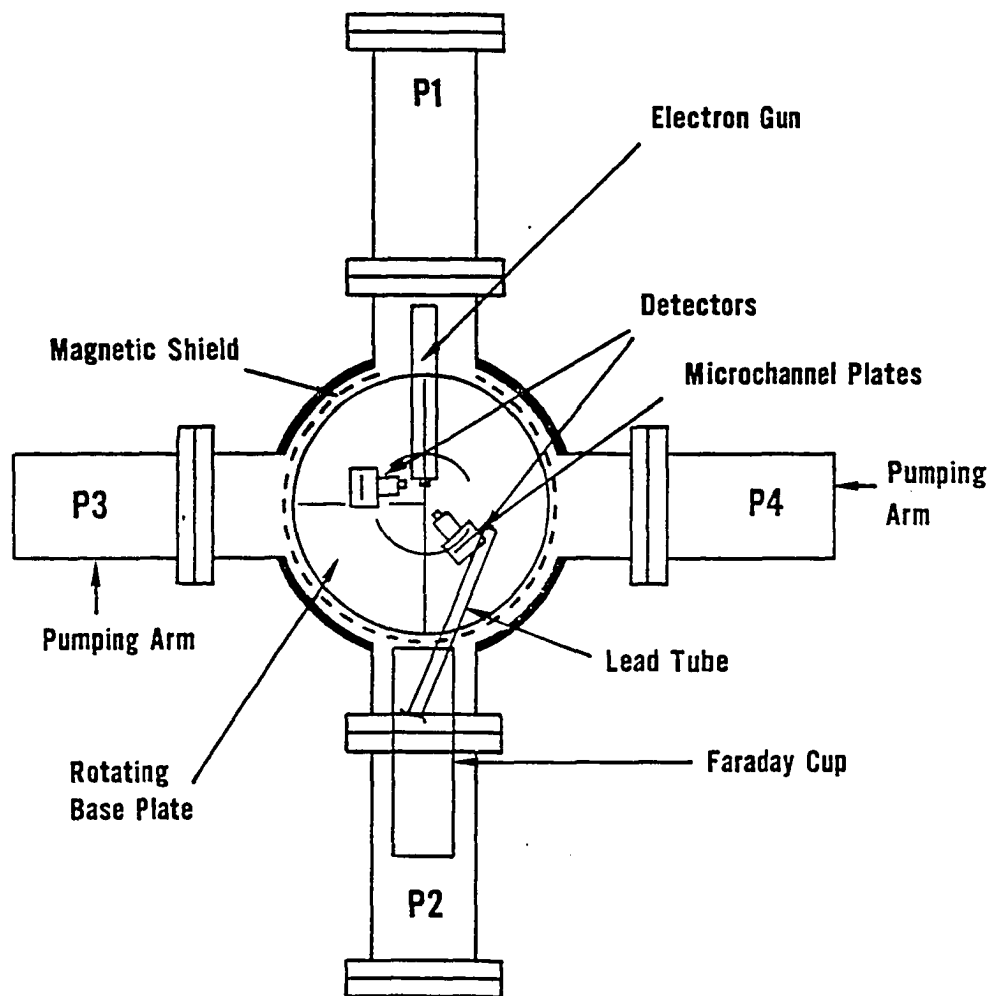


Fig.1b. Schematic diagram of the ultra-high vacuum system. Figure shows various components inside the top chamber.

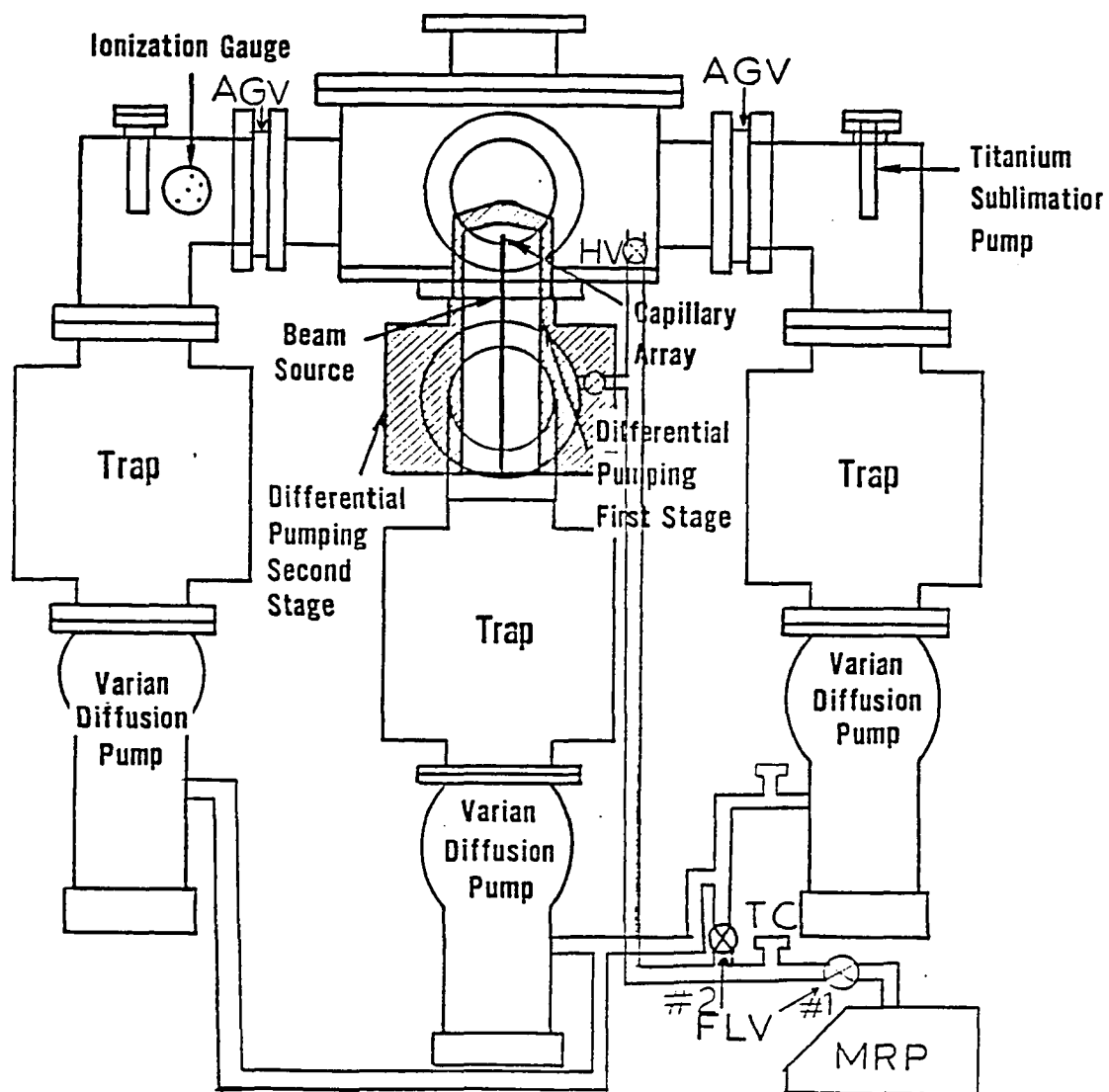


Fig.2. Schematic diagram of the ultra-high vacuum system. FLV, Foreline valve. MRP, Mechanical rotary pump. TC, Thermo-Couple. AGV, Air operated gate valve.

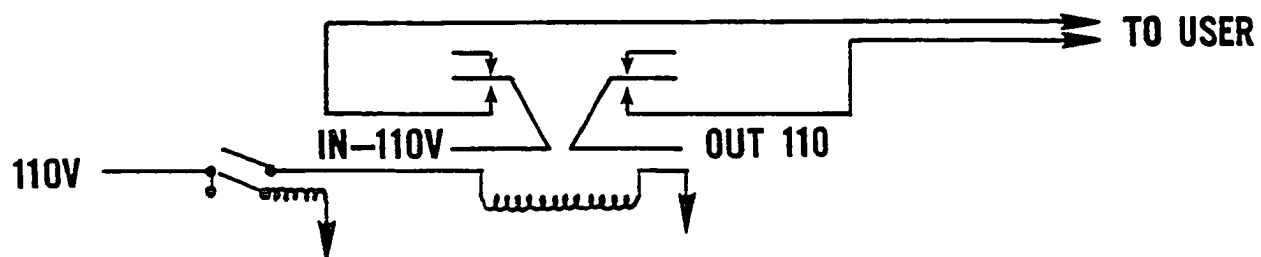


Fig.3. Interlock wiring sample diagram.

Fig.4. Schematic diagram of the Pulsed Electron Gun and its electrical operation.

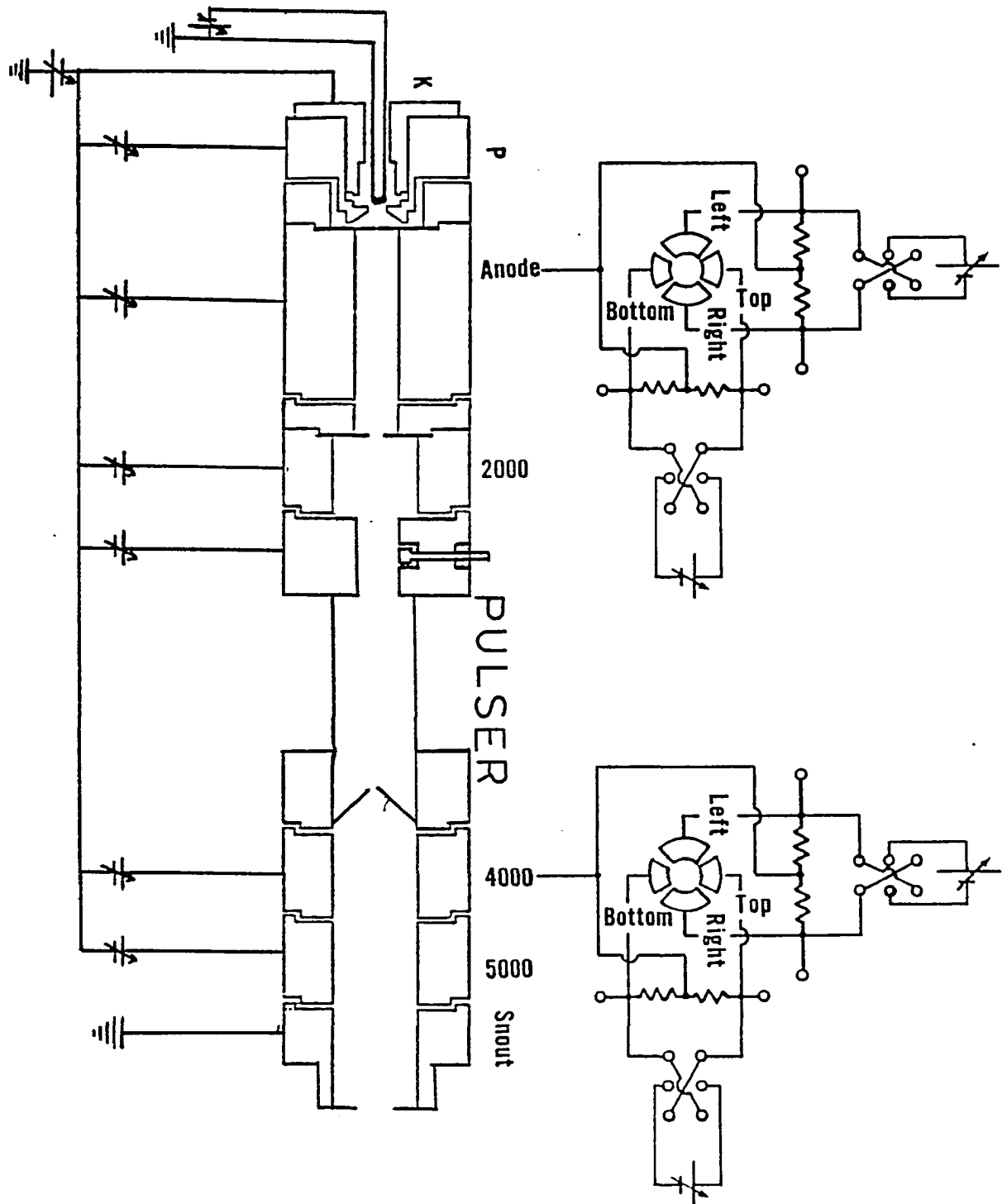
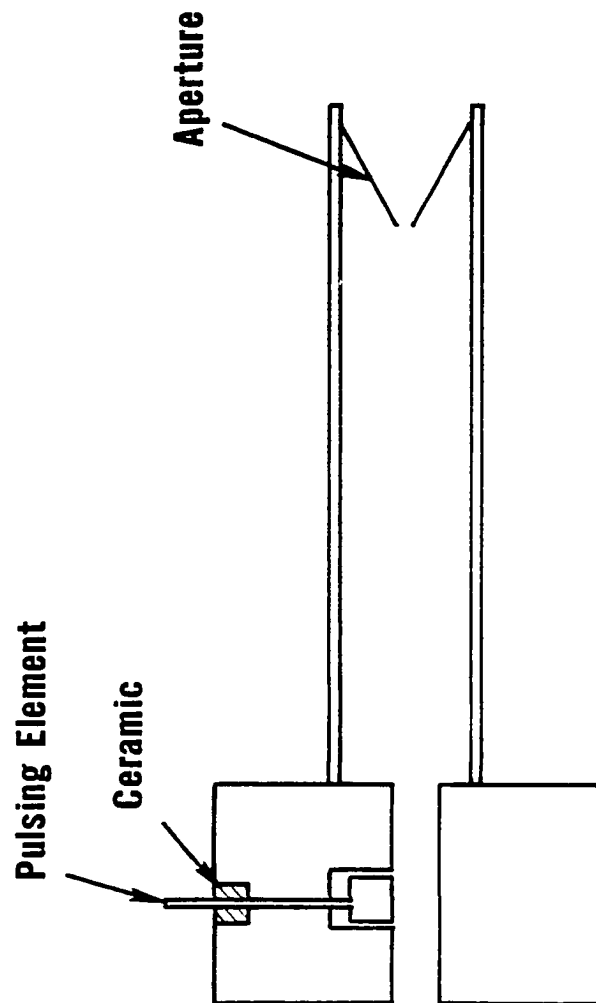


Fig.5. Schematic diagram of the pulsing lens.



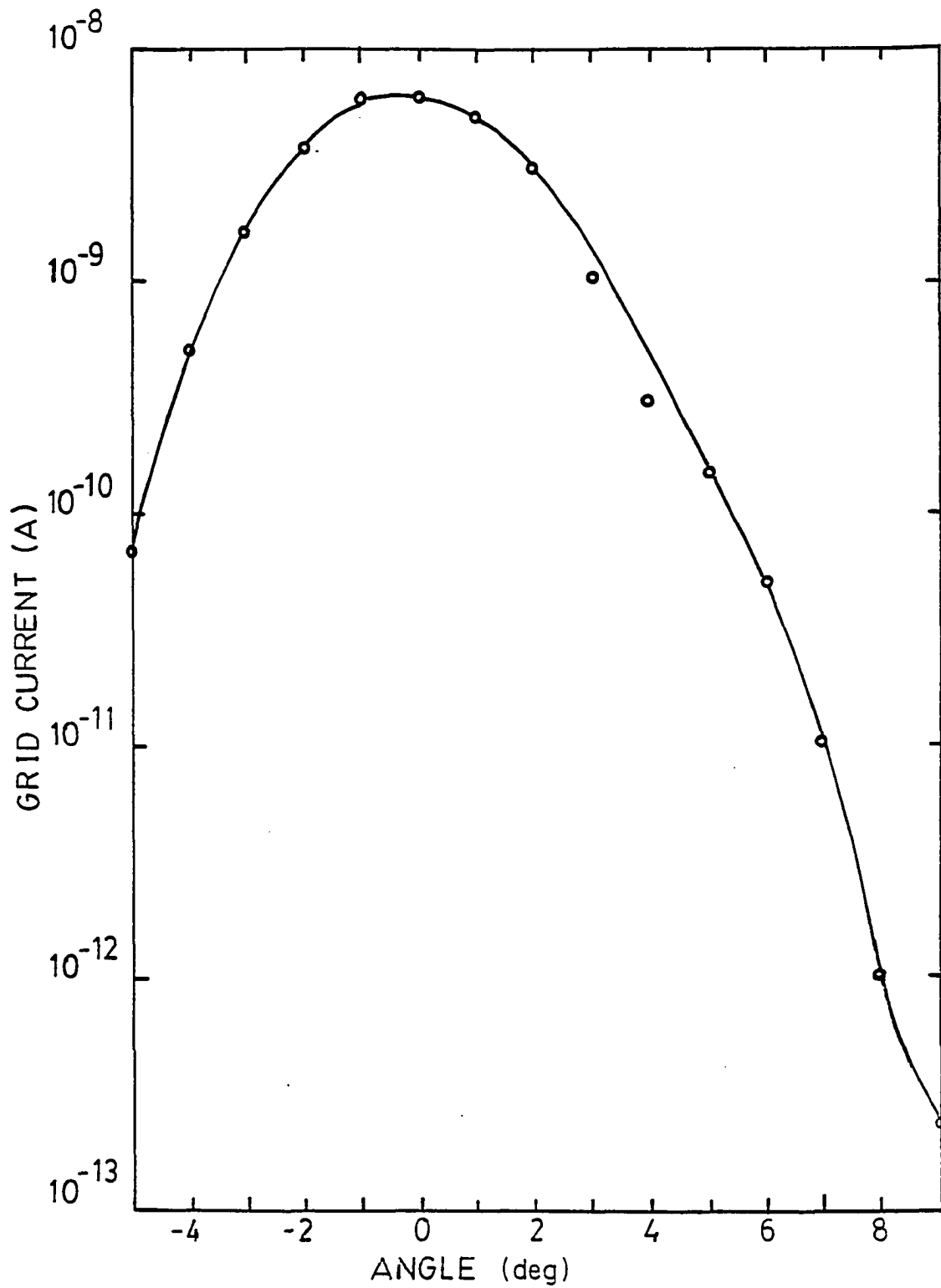


Fig.6. Electron beam profile as viewed by the scattered electron detector.

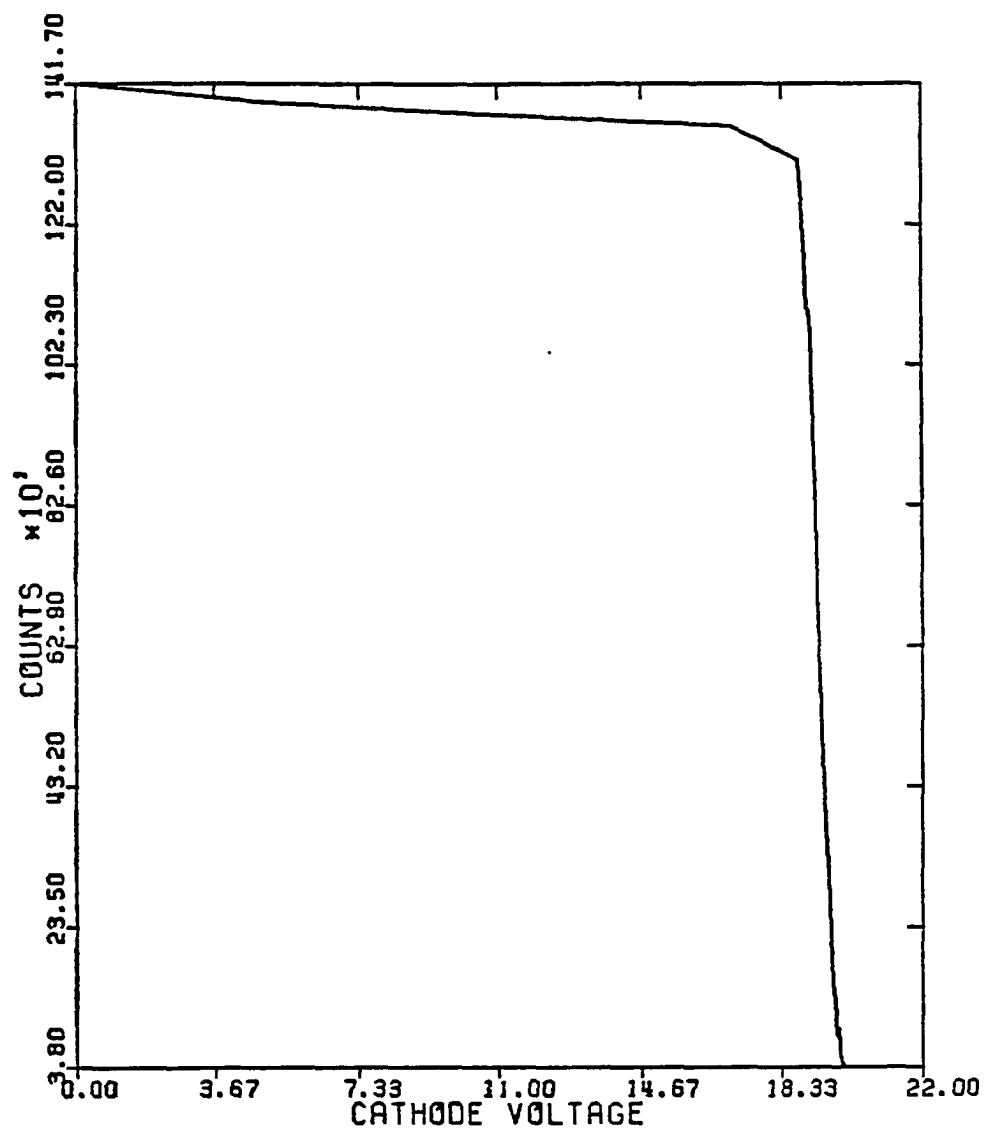


Fig.7. Sample energy calibration using ^2S resonance in He.

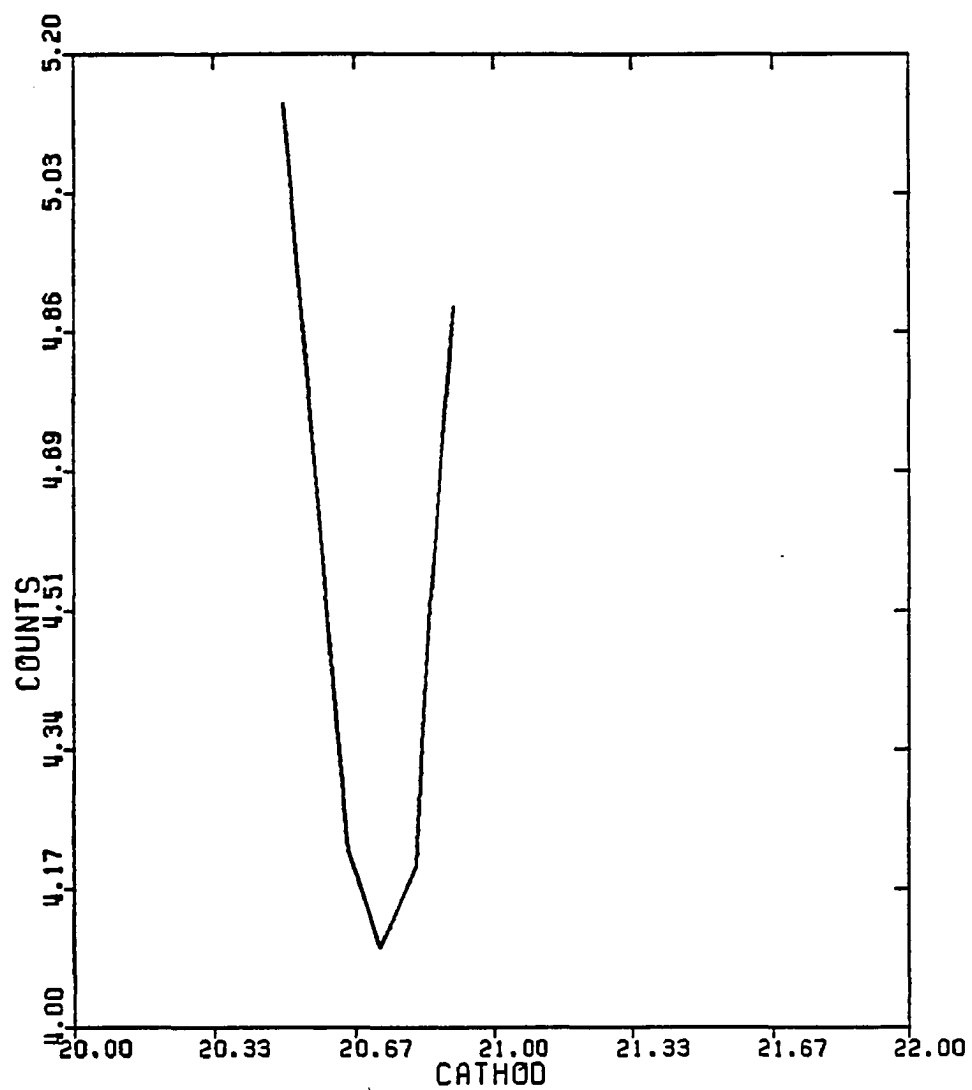


Fig.8. Sample energy calibration using retarding grid voltage.

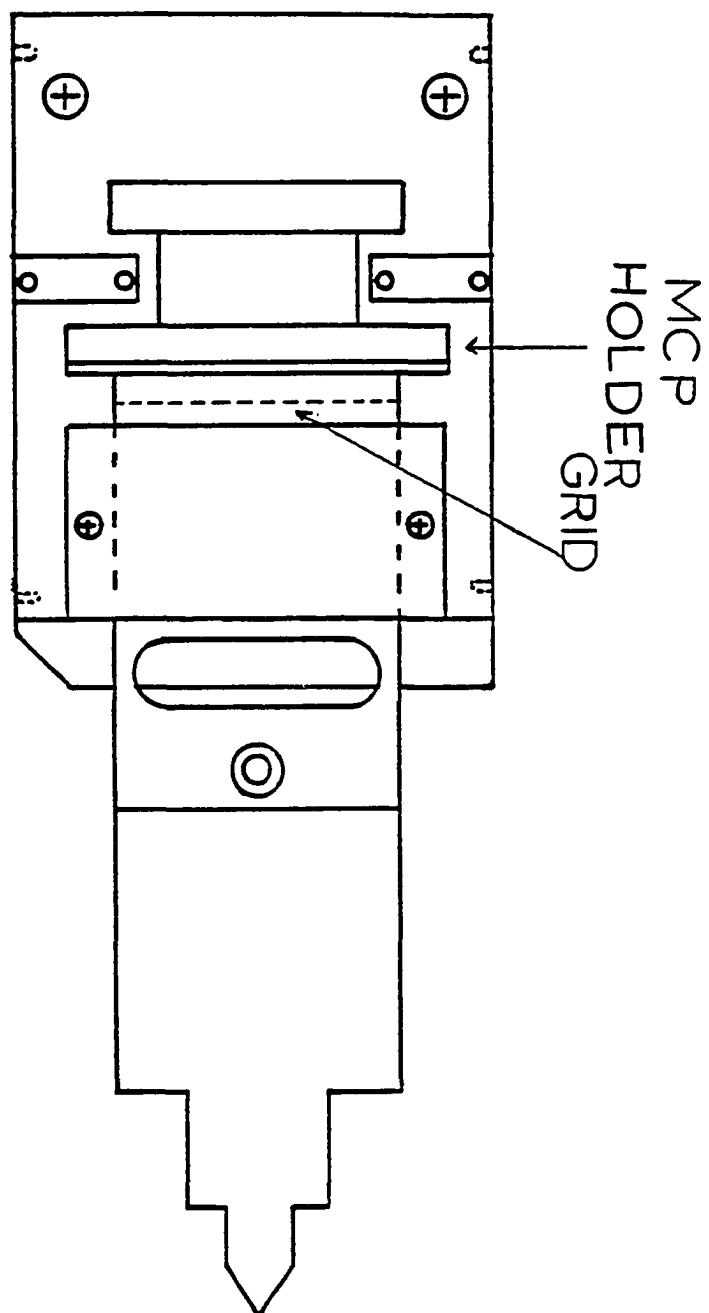


Fig.9. Schematic diagram of the scattered electron detector.

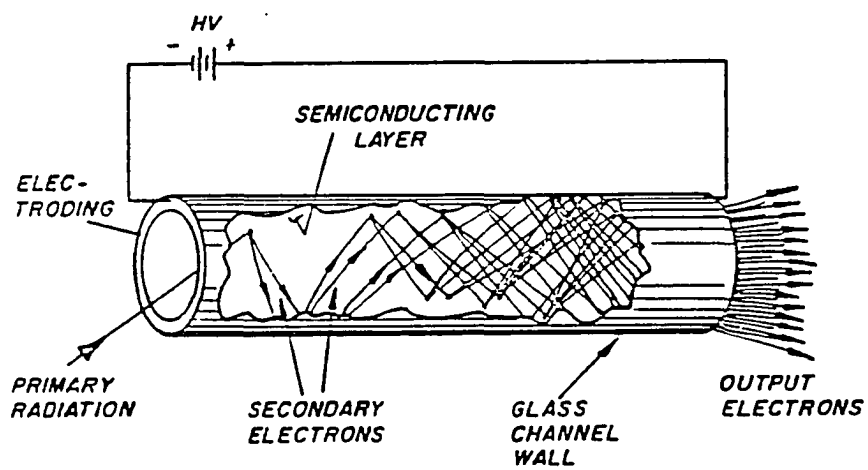


Fig.10. A straight channel electron multiplier.

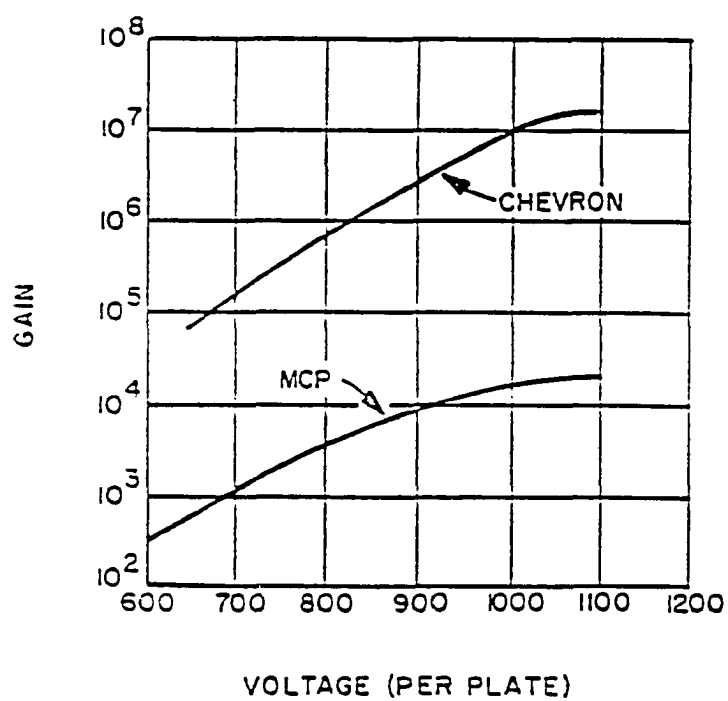


Fig.11. Gain vs voltage characteristic for a straight channel MCP and a Chevron.

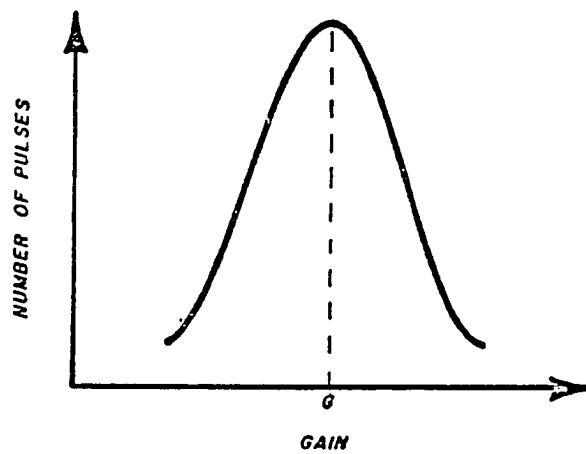


Fig.12. Pulse height distribution for a pulse-counting CEM.

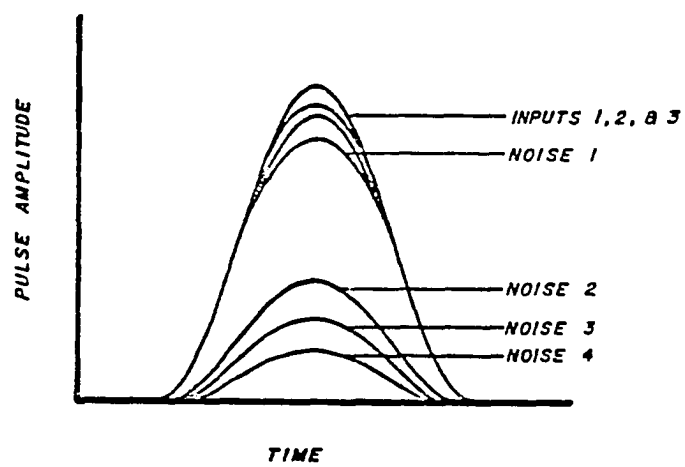


Fig.13. Pulse-counting CEM.

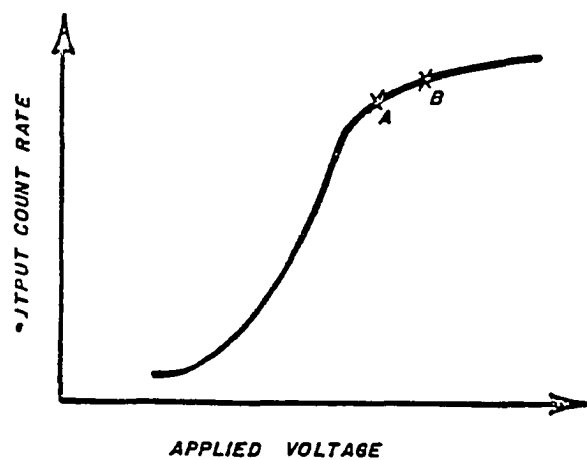


Fig.14. Observed output count rate with constant input vs voltage applied to CEM.

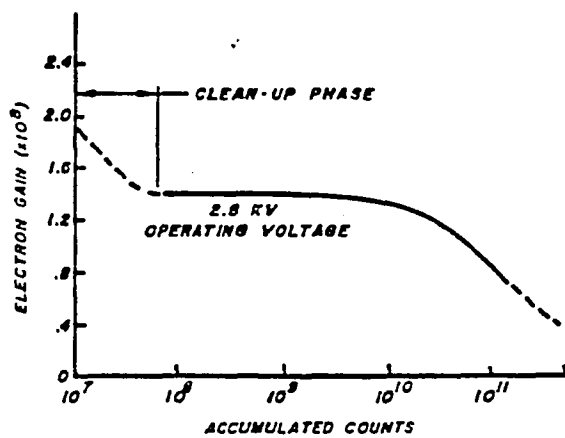


Fig.15. Gain as a function of accumulated counts.

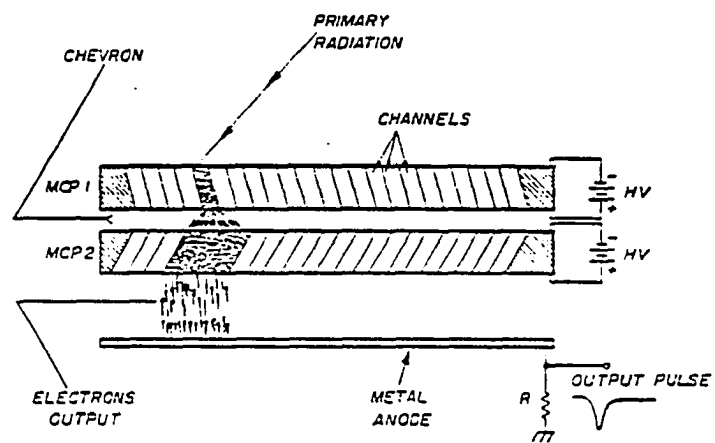


Fig.16. Chevron operation.

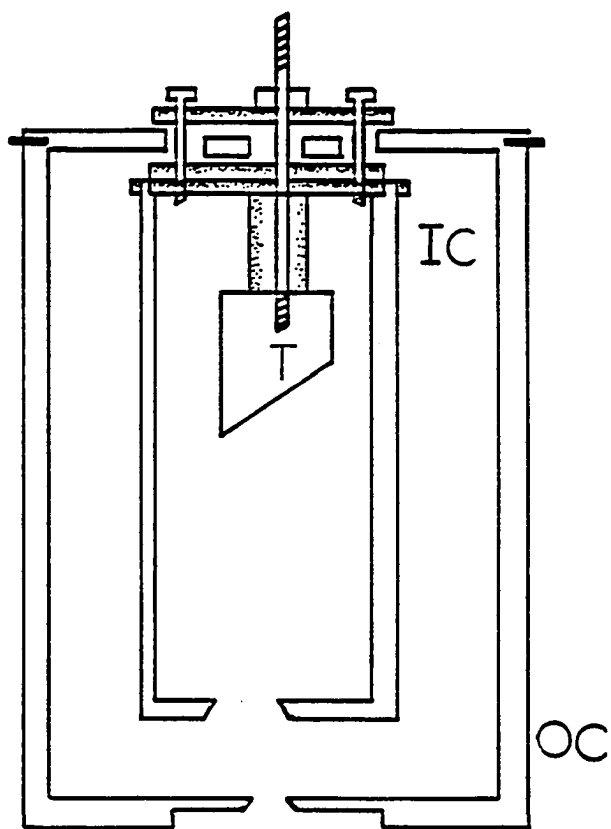


Fig.17. Schematic diagram of the Faraday cup. OC, outer cup; IC, inner cup; T, target (to deflect electron away from the entrance aperture).

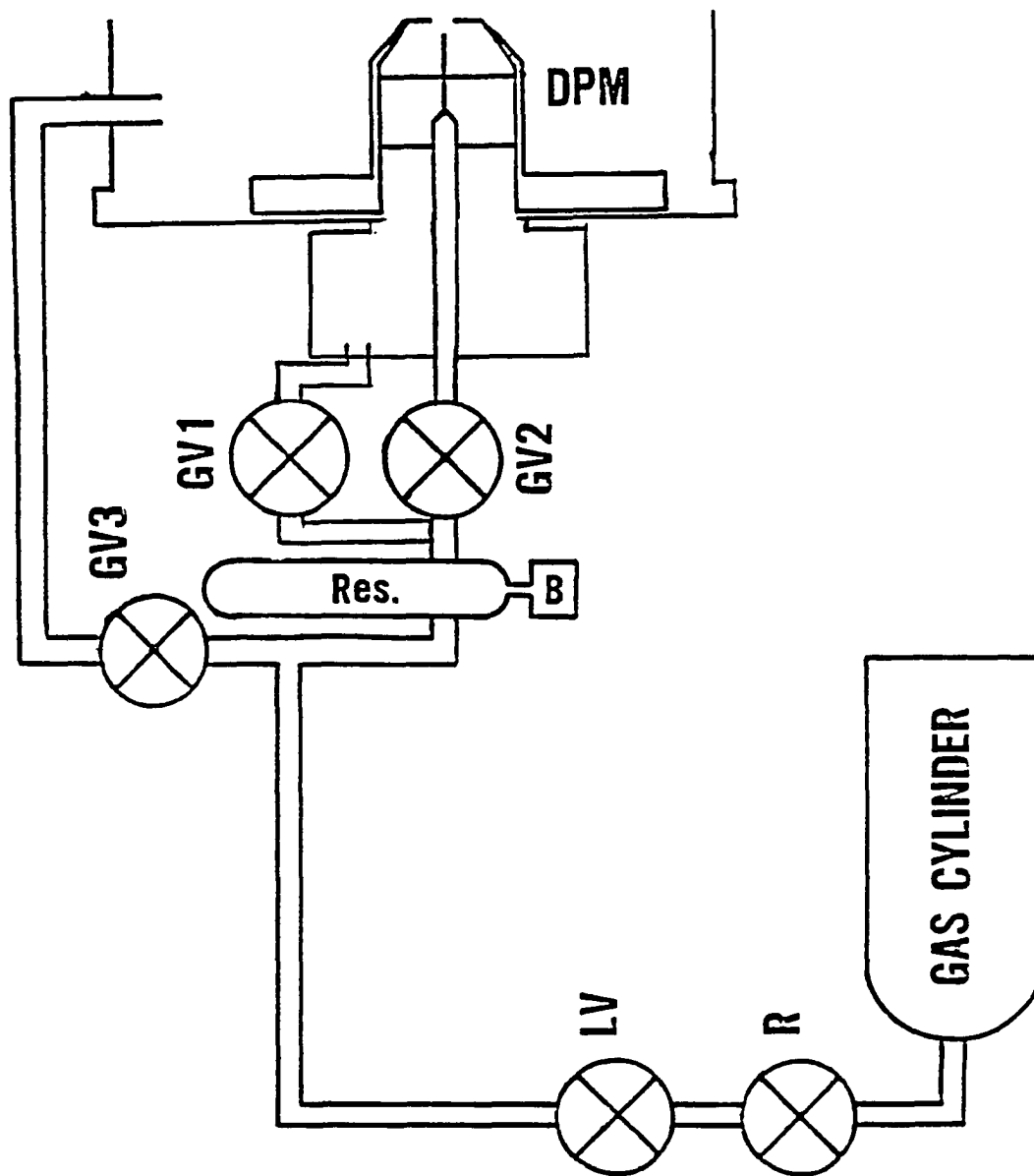


Fig.18. The gas handling system and the atomic beam source are combined. R, regulator; LV, leak valve; GV, gate valve; DPM, differential pumping manifold which contains the capillary atomic beam source; B, the MKS Baratron; Res. gas reservoir. The capillary is held and aligned by spider bushings.

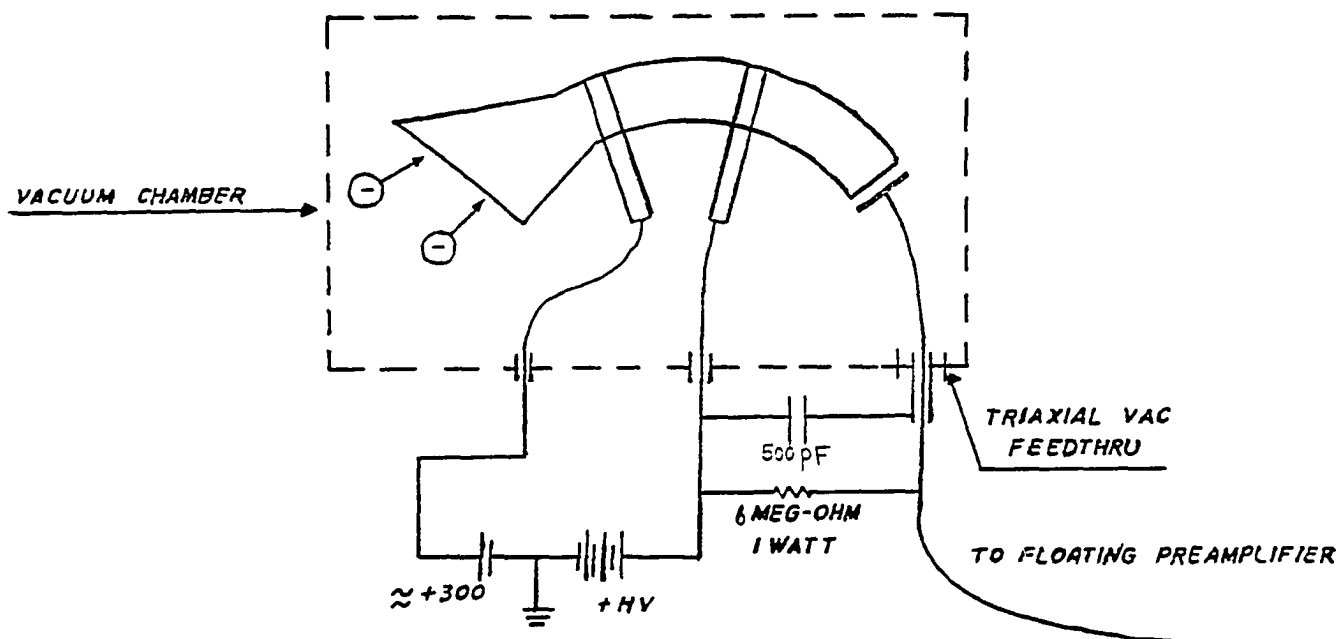


Fig.19. Electrical connection for pulse counting operation.

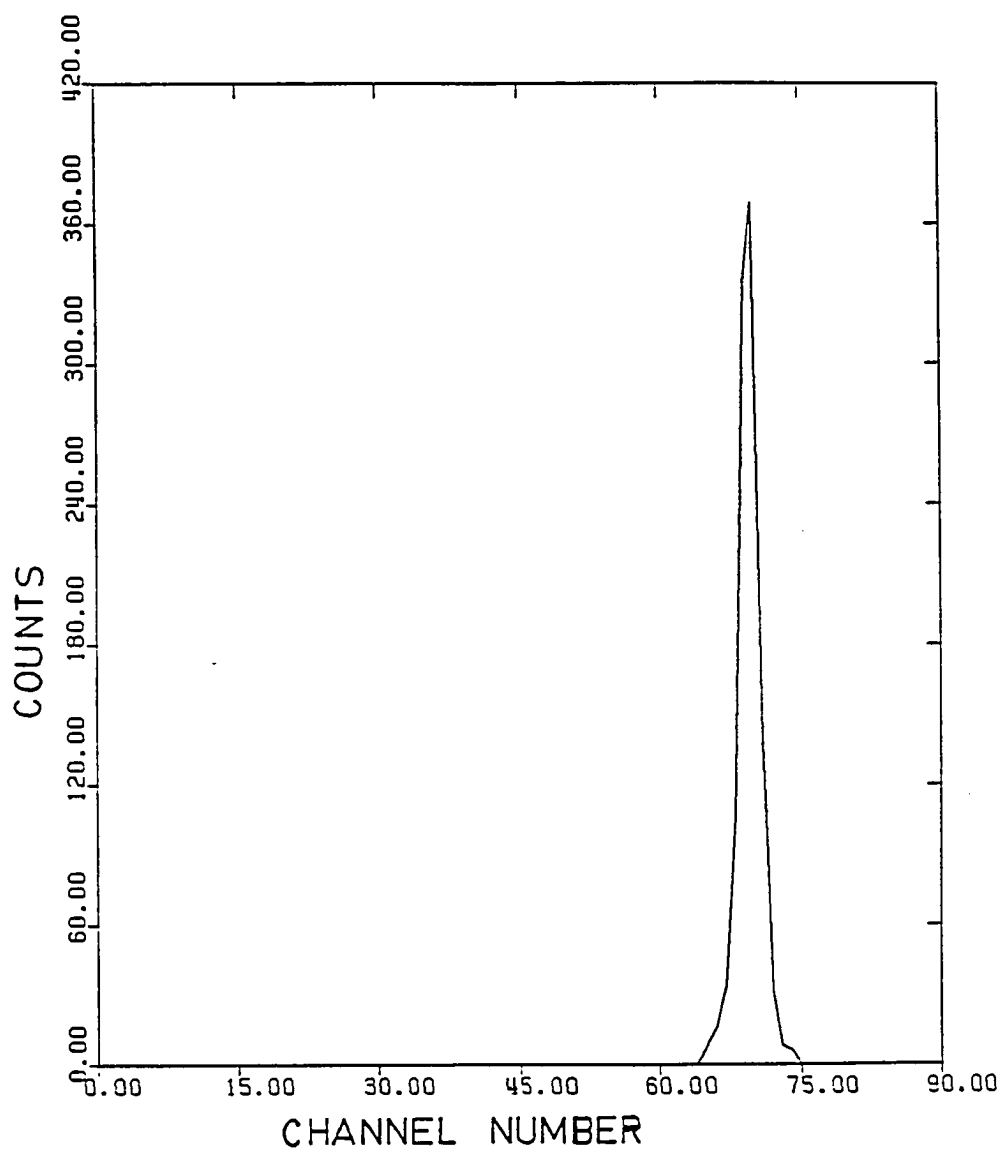


Fig.21. A sample 10-sec time spectrum from the rotating detector for scattering at 90. (Time scale increases from right to left.)

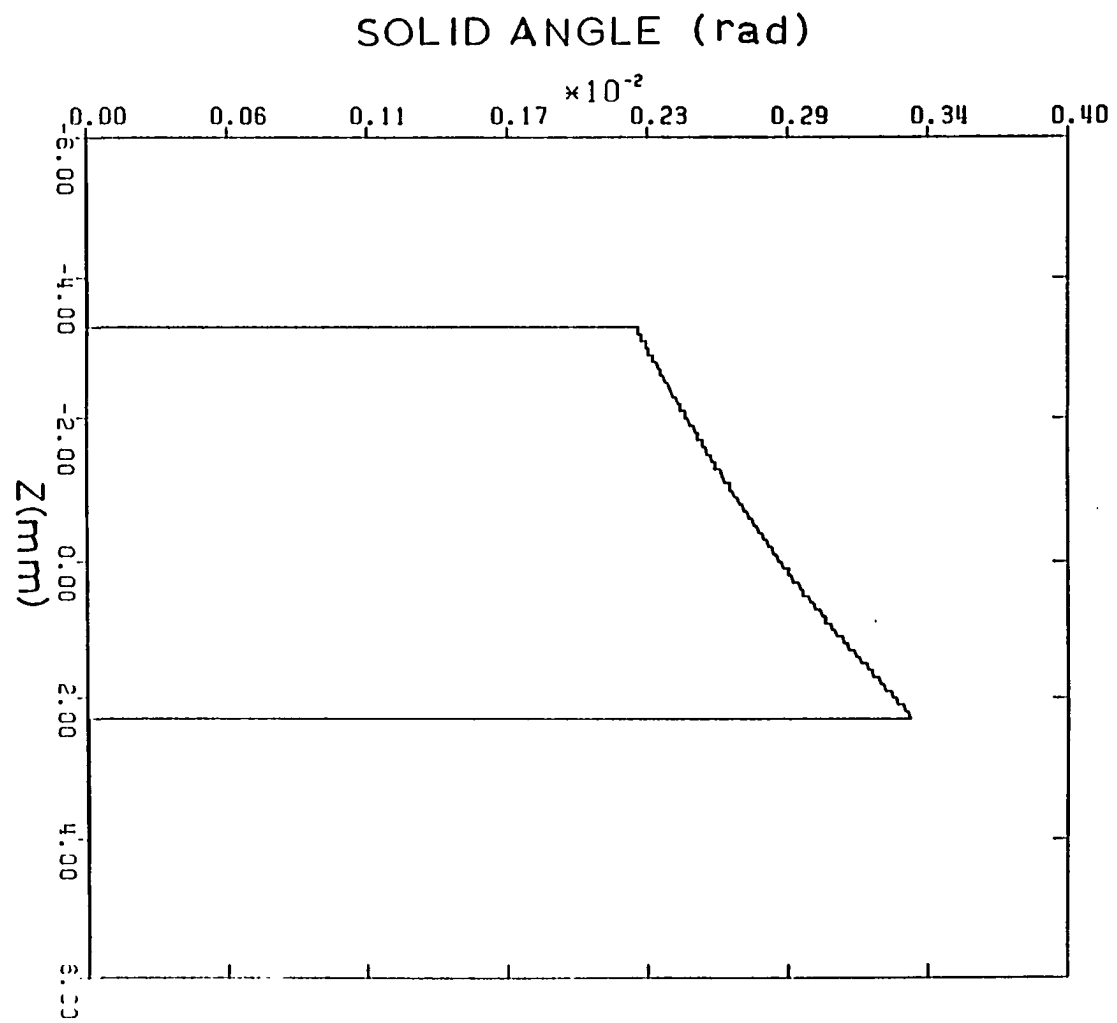


Fig.22. $\Delta\Omega(Z,20)$

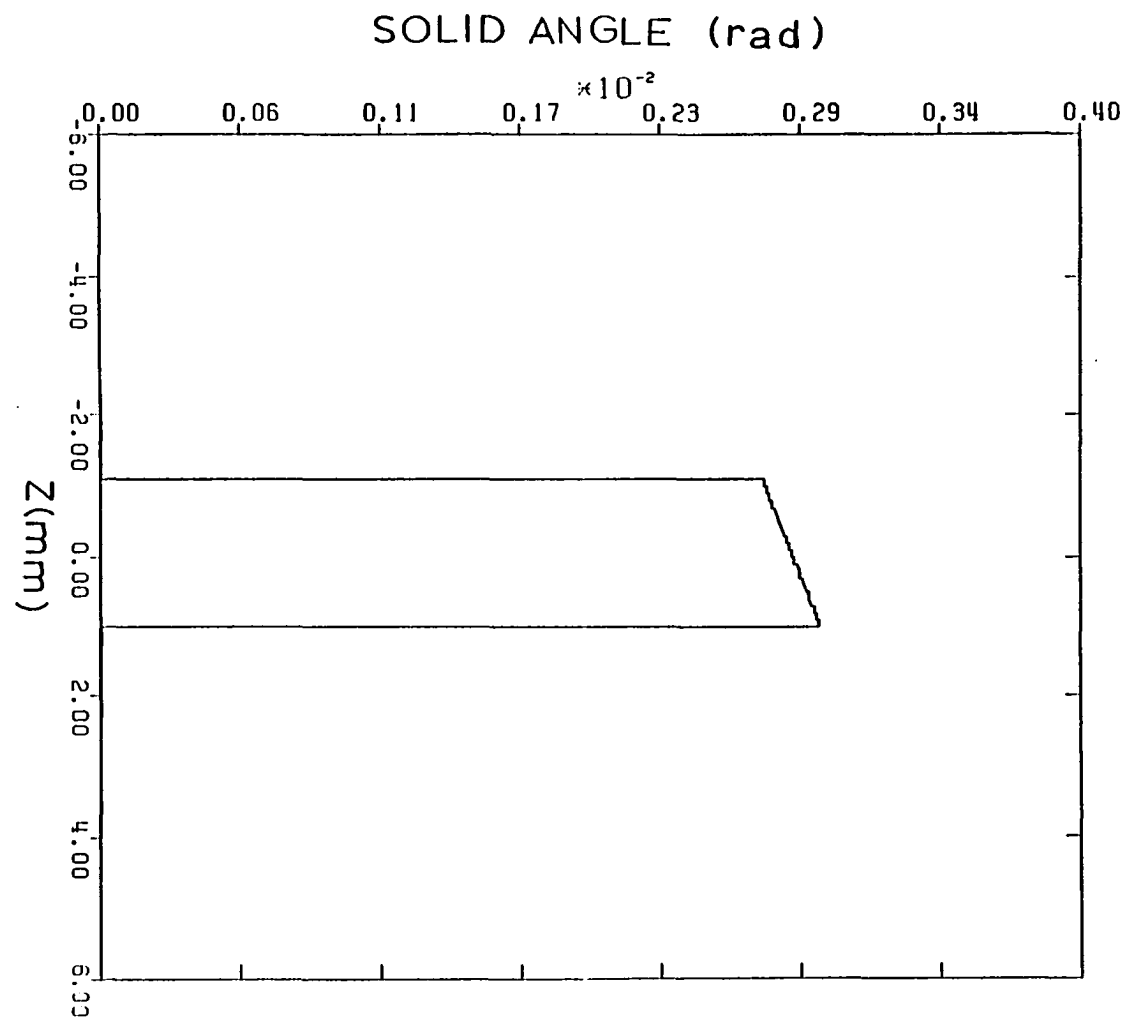


Fig.23. $\Delta\Omega(z, 60)$

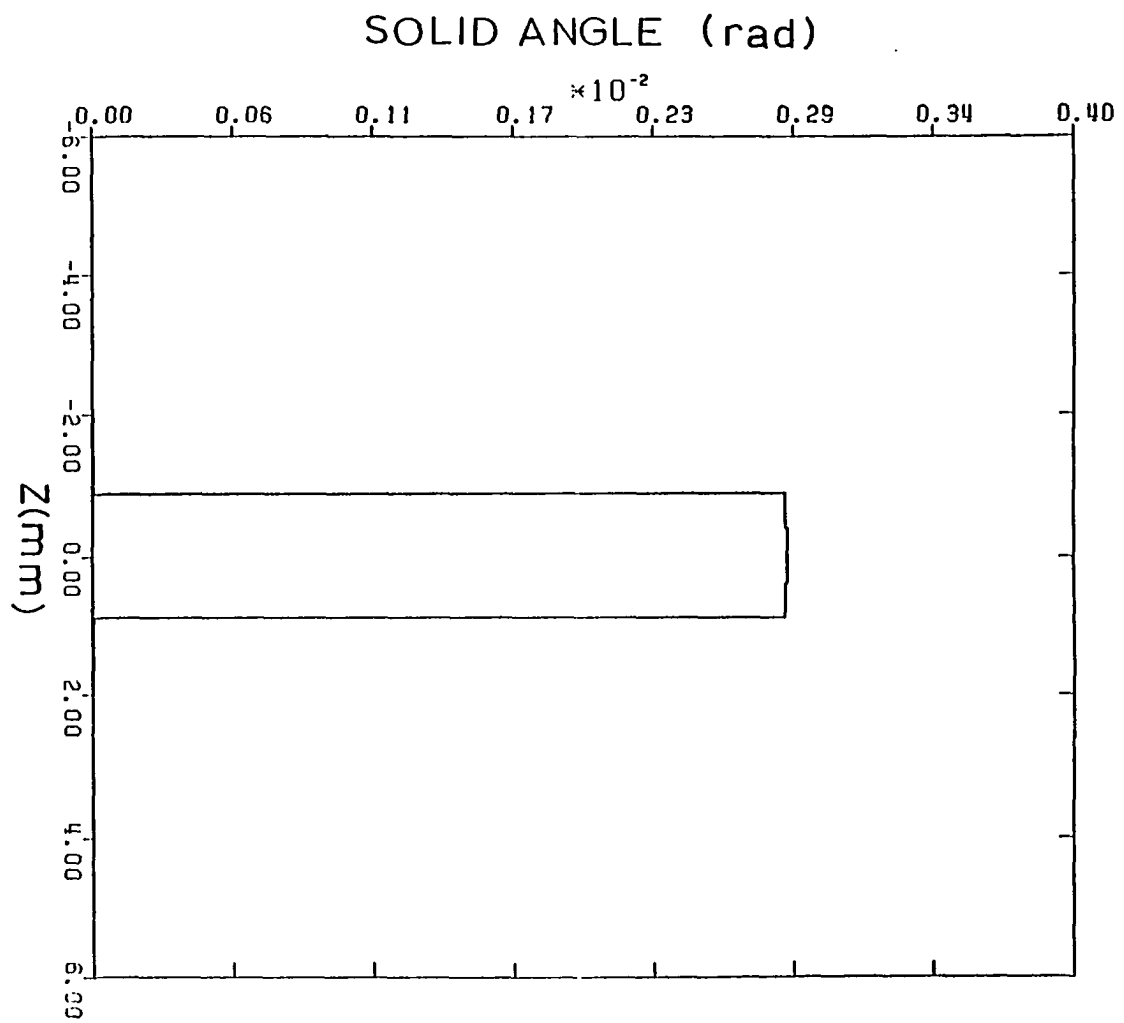


Fig.24. $\Delta\Omega(z,90)$

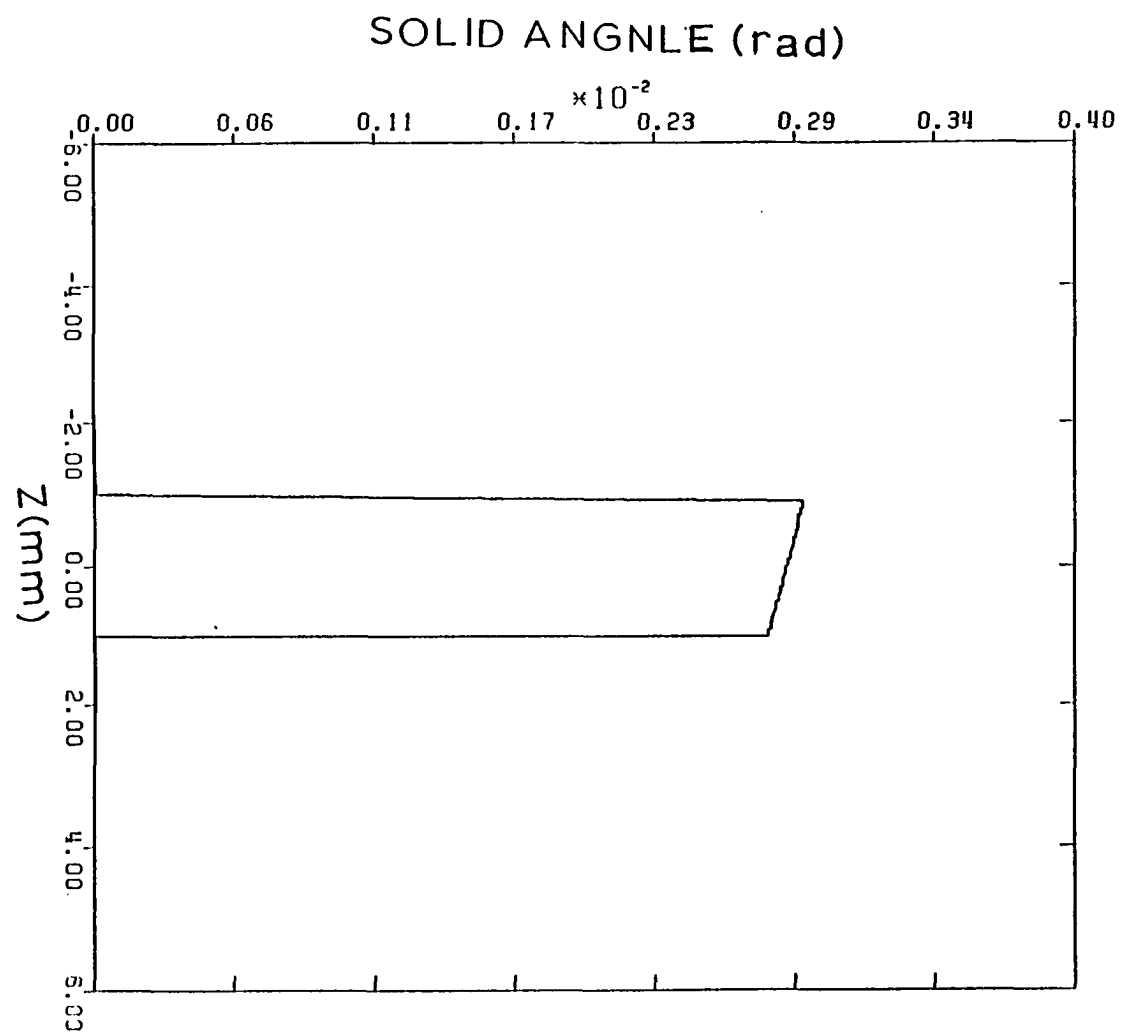


Fig.25. $\Delta\theta(z,20)$

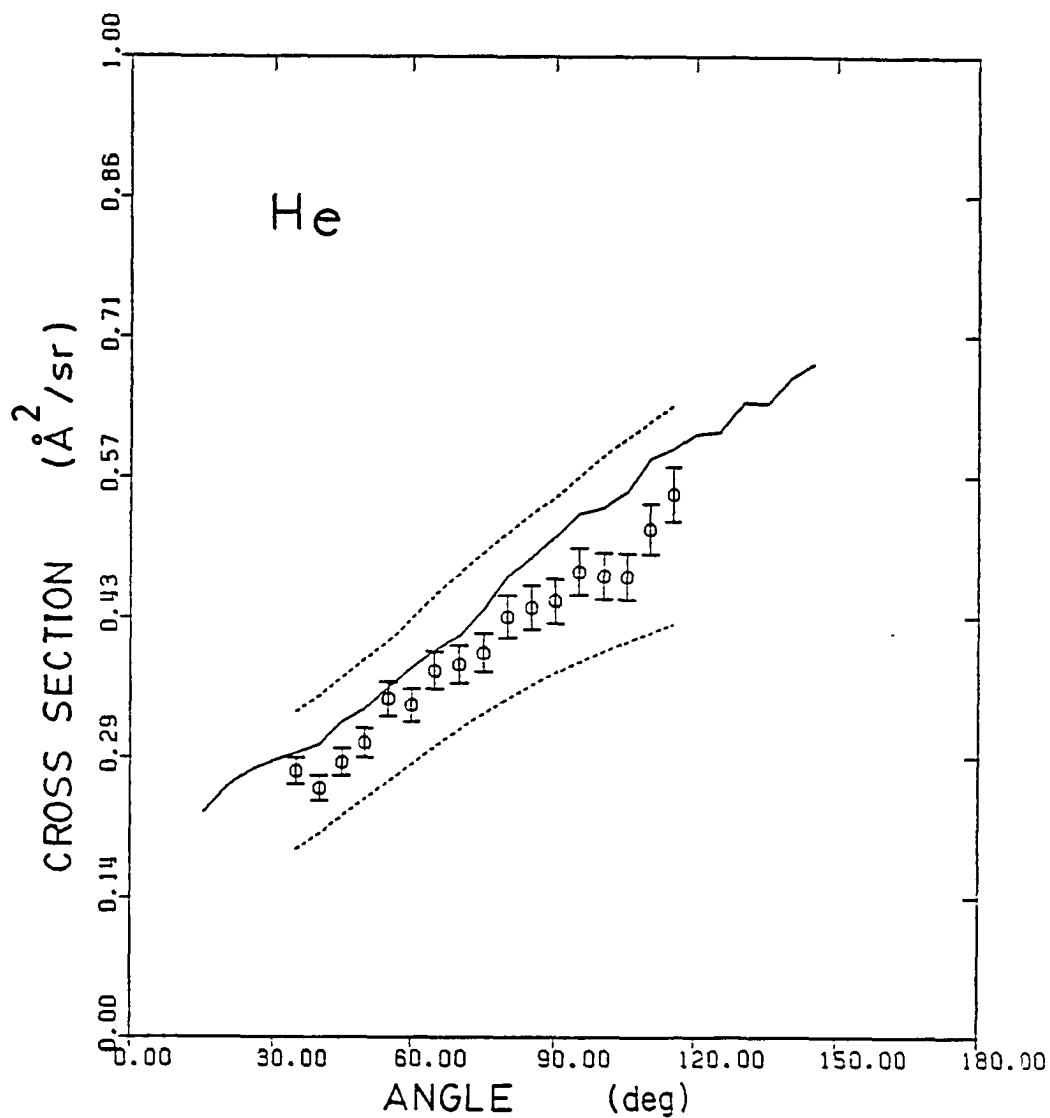


Fig.26. Sample differential cross-section measurement at 2 eV. Data are at level determined as the "best fit" to the data while the dashed lines are the limits of the scale as determined in this work. Solid line is the data of Andrick and Bitsch (Ref.9) placed at the level determined in this work.

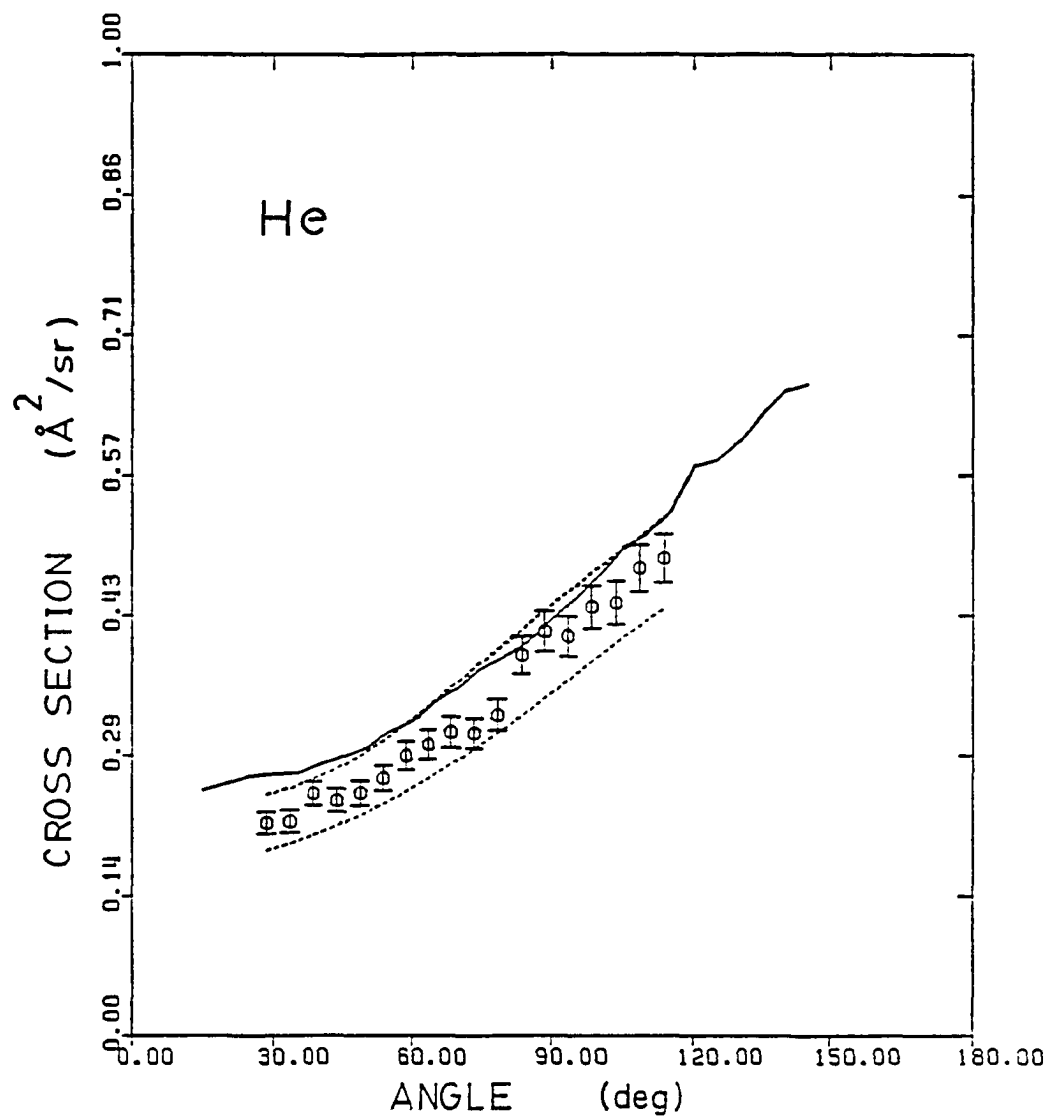


Fig.27. Sample differential cross-section measurement at 5 eV. Data are at level determined as the "best fit" to the data while the dashed lines are the limits of the scale as determined in this work. Solid line is the data of Andrick and Bitsch (Ref.9) placed at the level determined in this work.

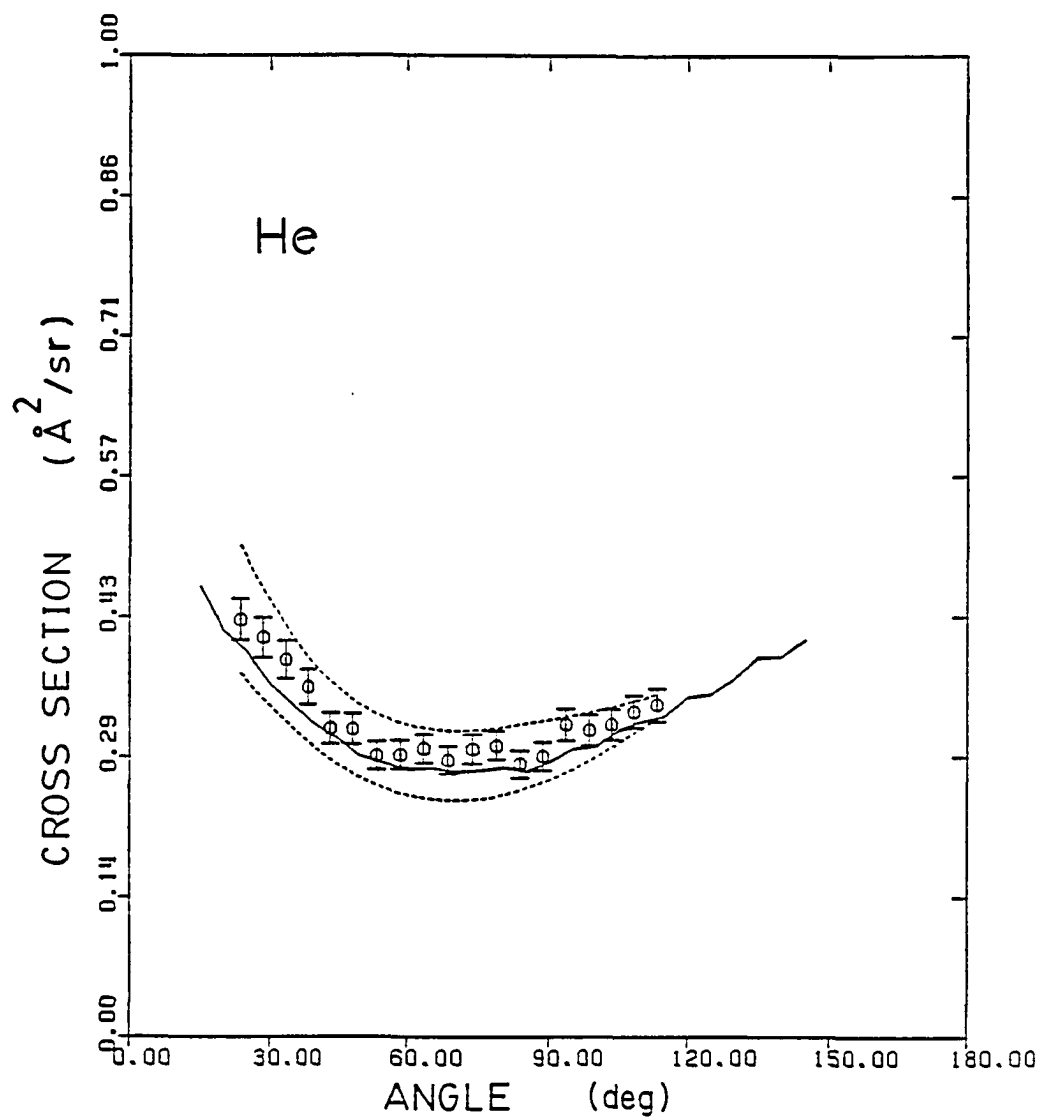


Fig.28. Sample differential cross-section measurement at 12 eV. Data are at level determined as the "best fit" to the data while the dashed lines are the limits of the scale as determined in this work. Solid line is the data of Andrick and Bitsch (Ref.9) placed at the level determined in this work.

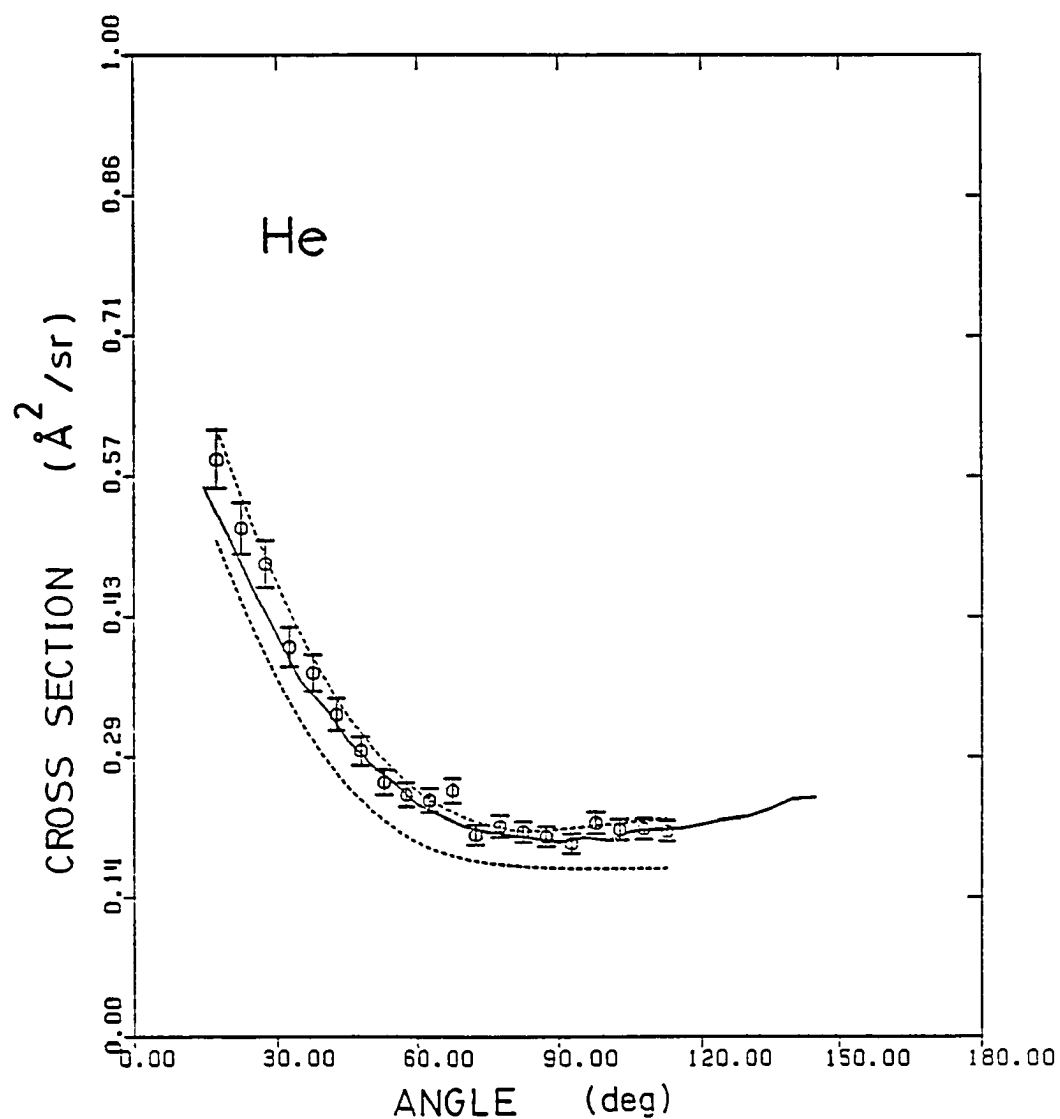


Fig.29. Sample differential cross-section measurement at 19 eV. Data are at level determined as the "best fit" to the data while the dashed lines are the limits of the scale as determined in this work. Solid line is the data of Andrick and Bitsch (Ref.9) placed at the level determined in this work.

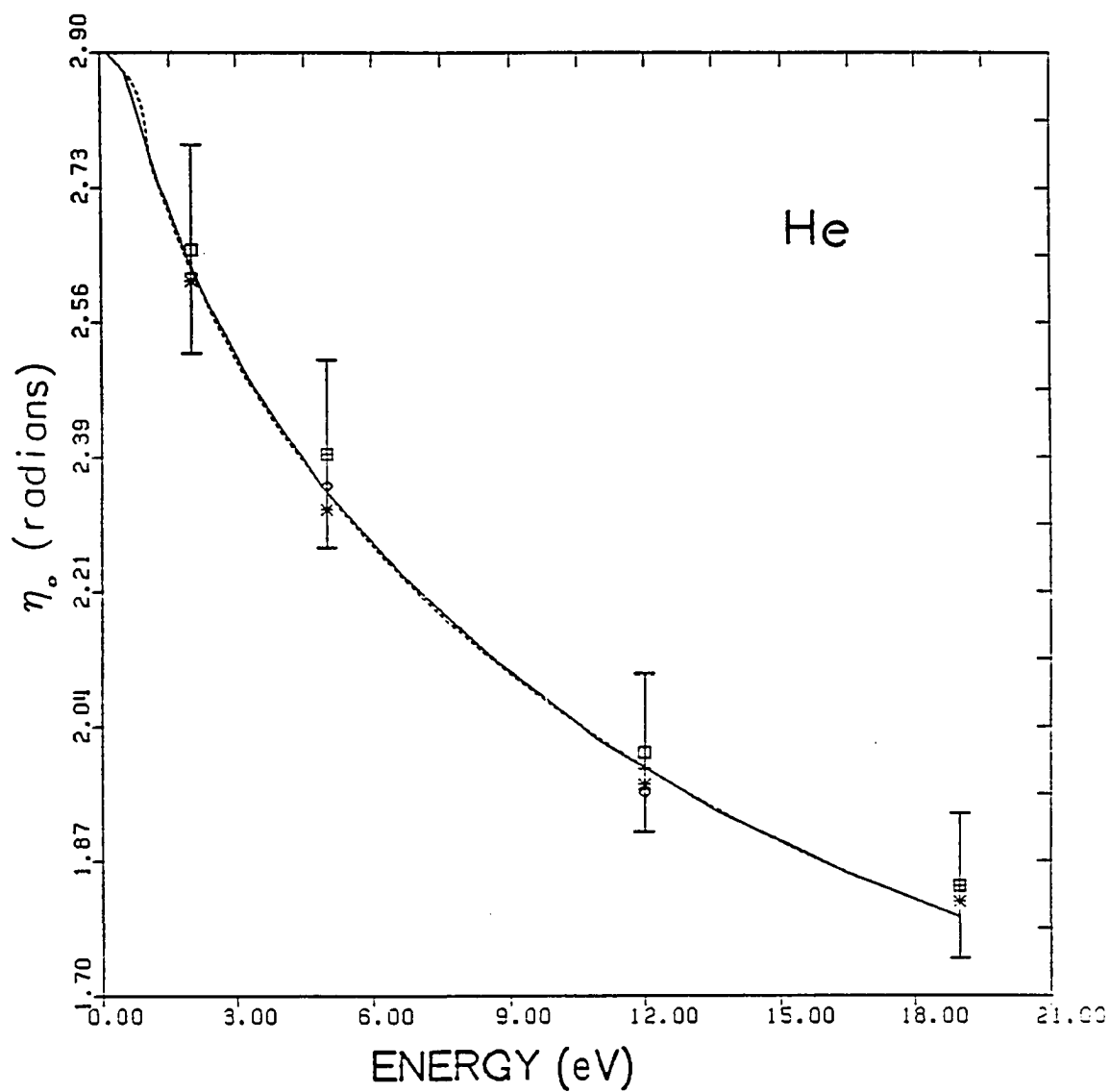


Fig.30. The S-wave phase shift vs Electron energy. $\square$, present results; + , Andrick and Bitsch; Williams; $\diamond$, Register et al.. —, Nesbet; -----, O'Mally et al..

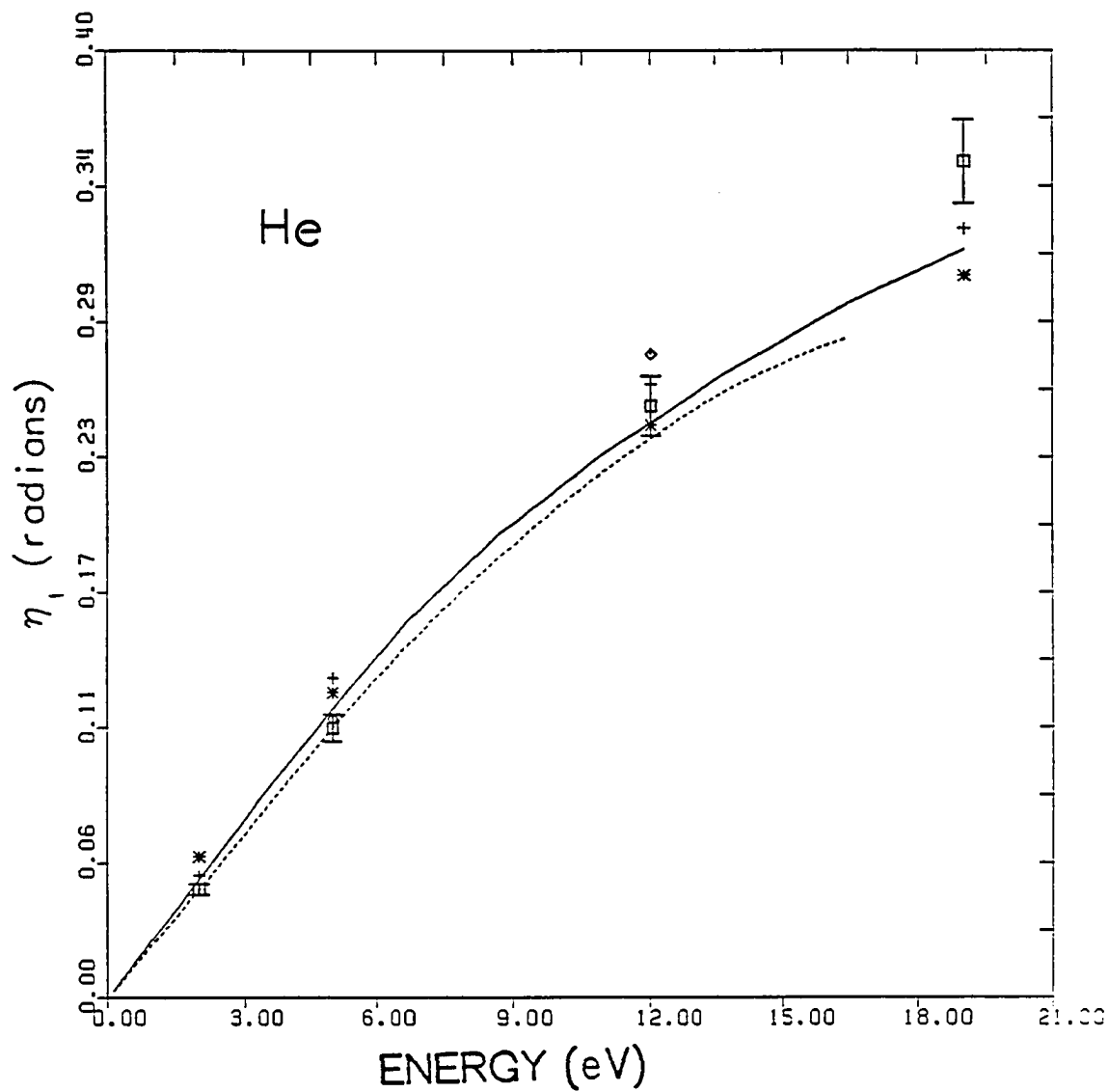


Fig.31. The P-wave phase shift vs Electron energy. $\square$, present results; + , Andrick and Bitsch; * , Williams; $\diamond$, Register et al.. —, Nesbet; -----, O'Mally et al..

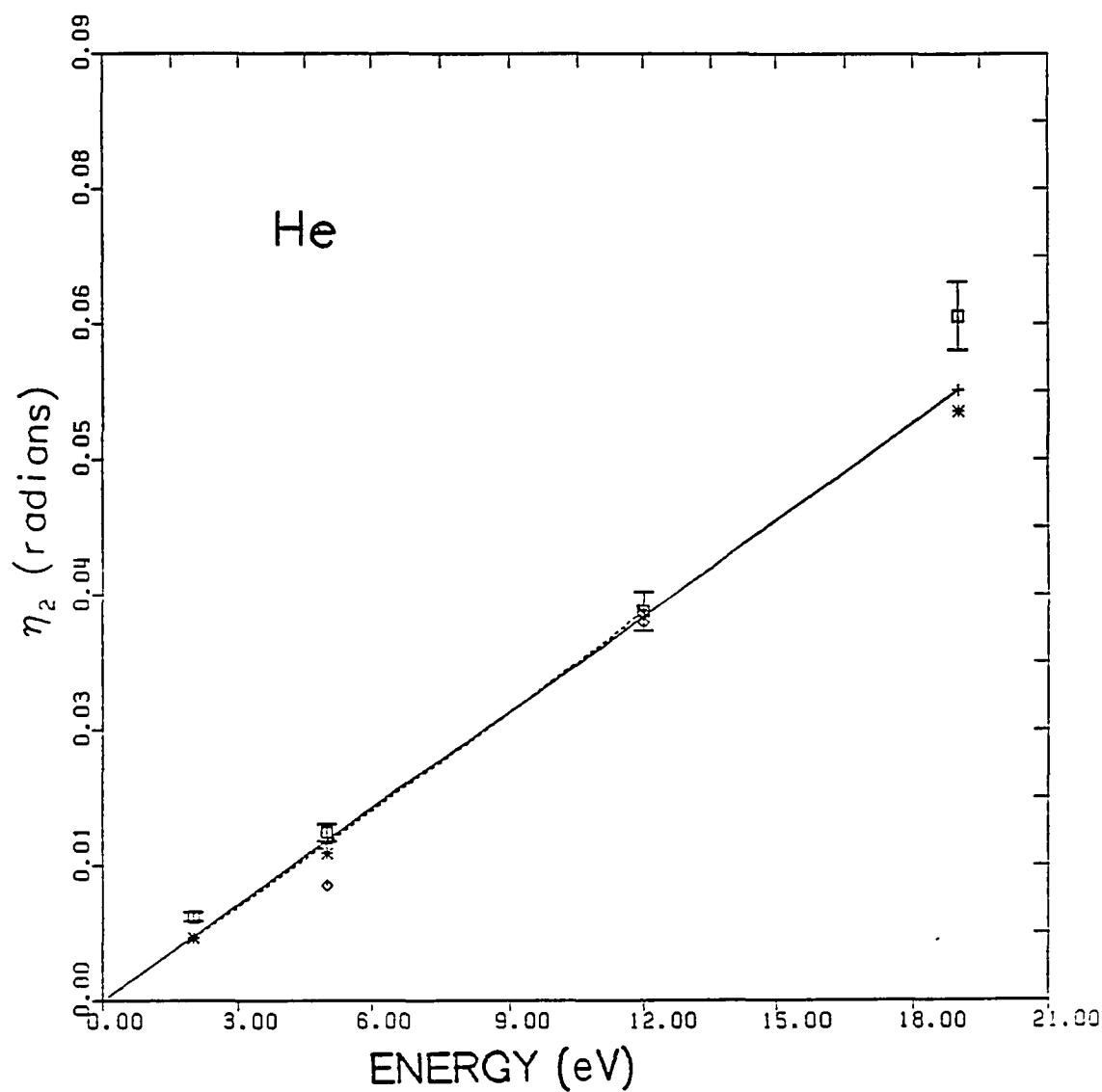


Fig.32. The D-wave phase shift vs Electron energy. □ , present results; + , Andrick and Bitsch; Williams; ◇ , Register et al.. —, Nesbet; -----, O'Mally et al..

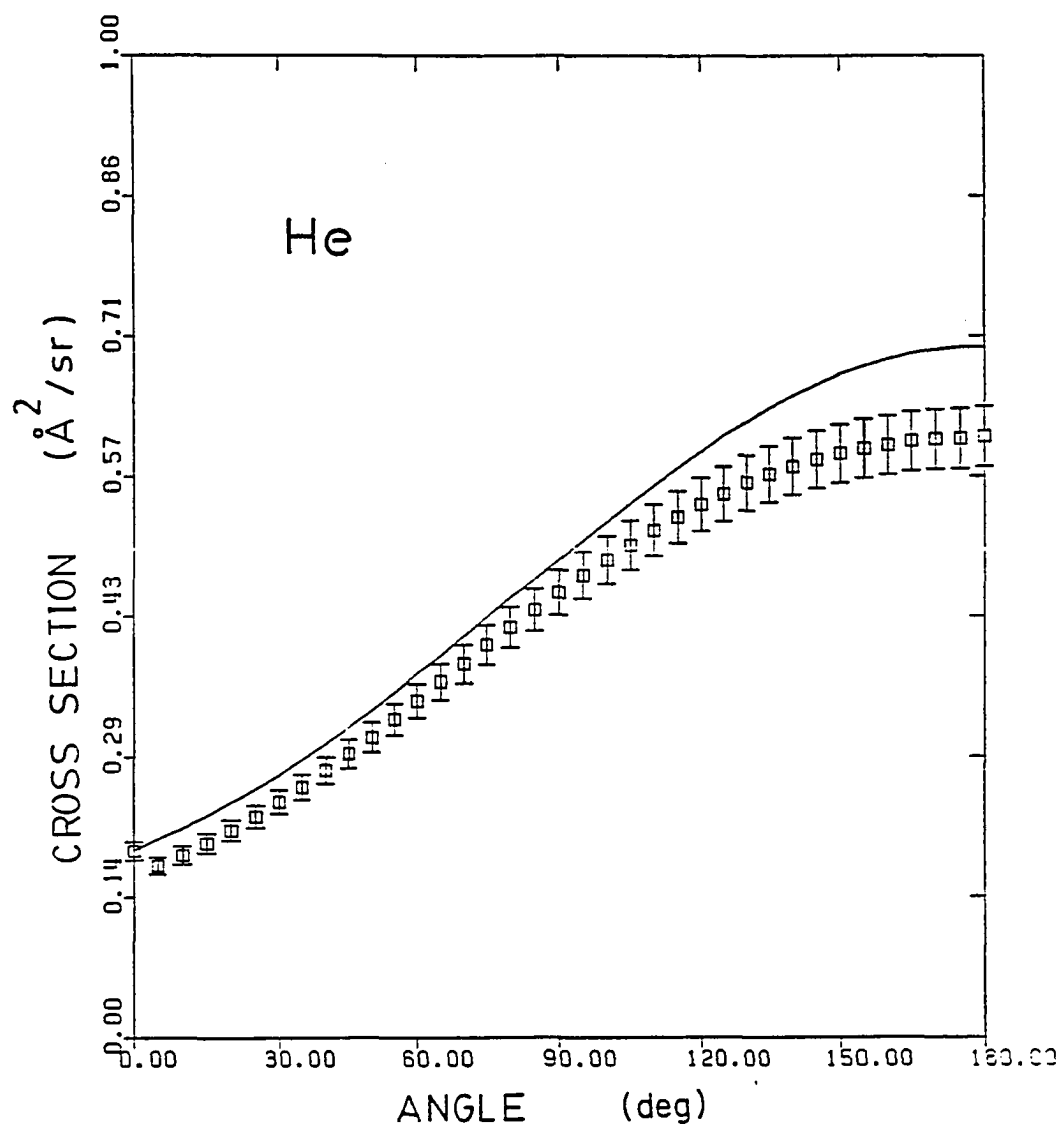


Fig.33. Differential cross section at 2eV evaluated using the determined phase shifts. $\square$, Present results; —, Nesbet.

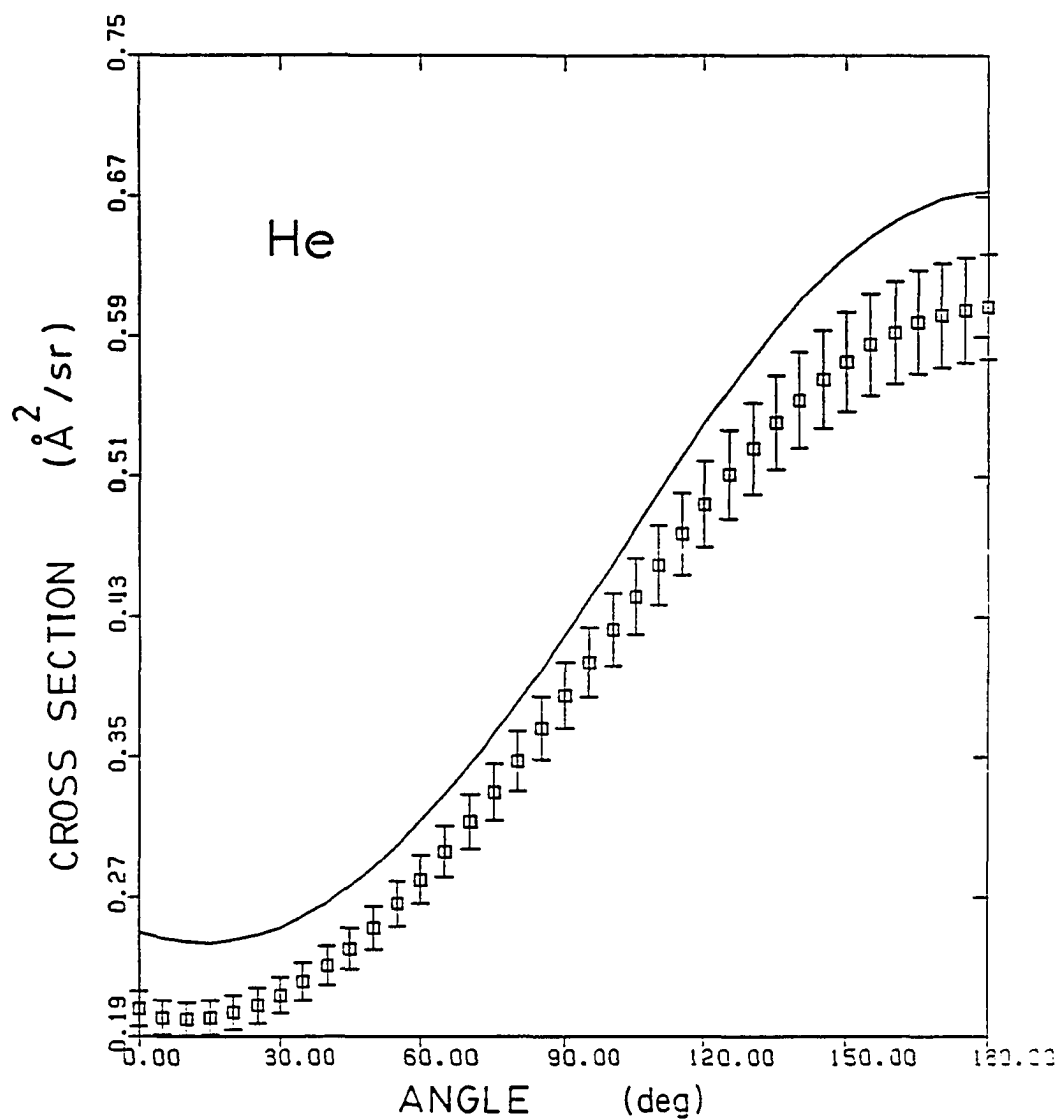


Fig.34. Differential cross section at 5eV evaluated using the determined phase shifts. $\square$, Present results; —, Nesbet.

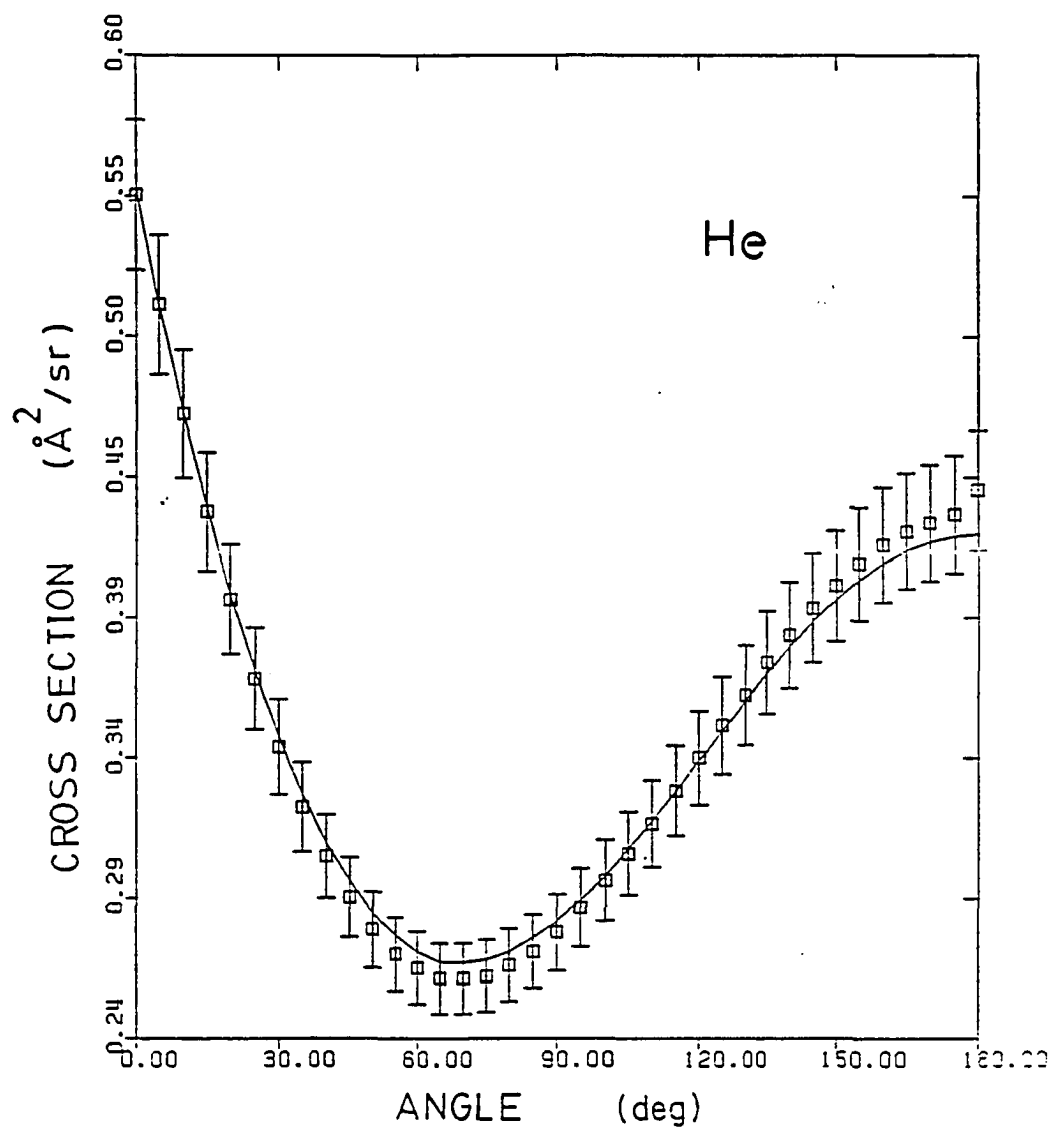


Fig.35. Differential cross section at 12eV evaluated using the determined phase shifts. $\square$, Present results; —, Nesbet.

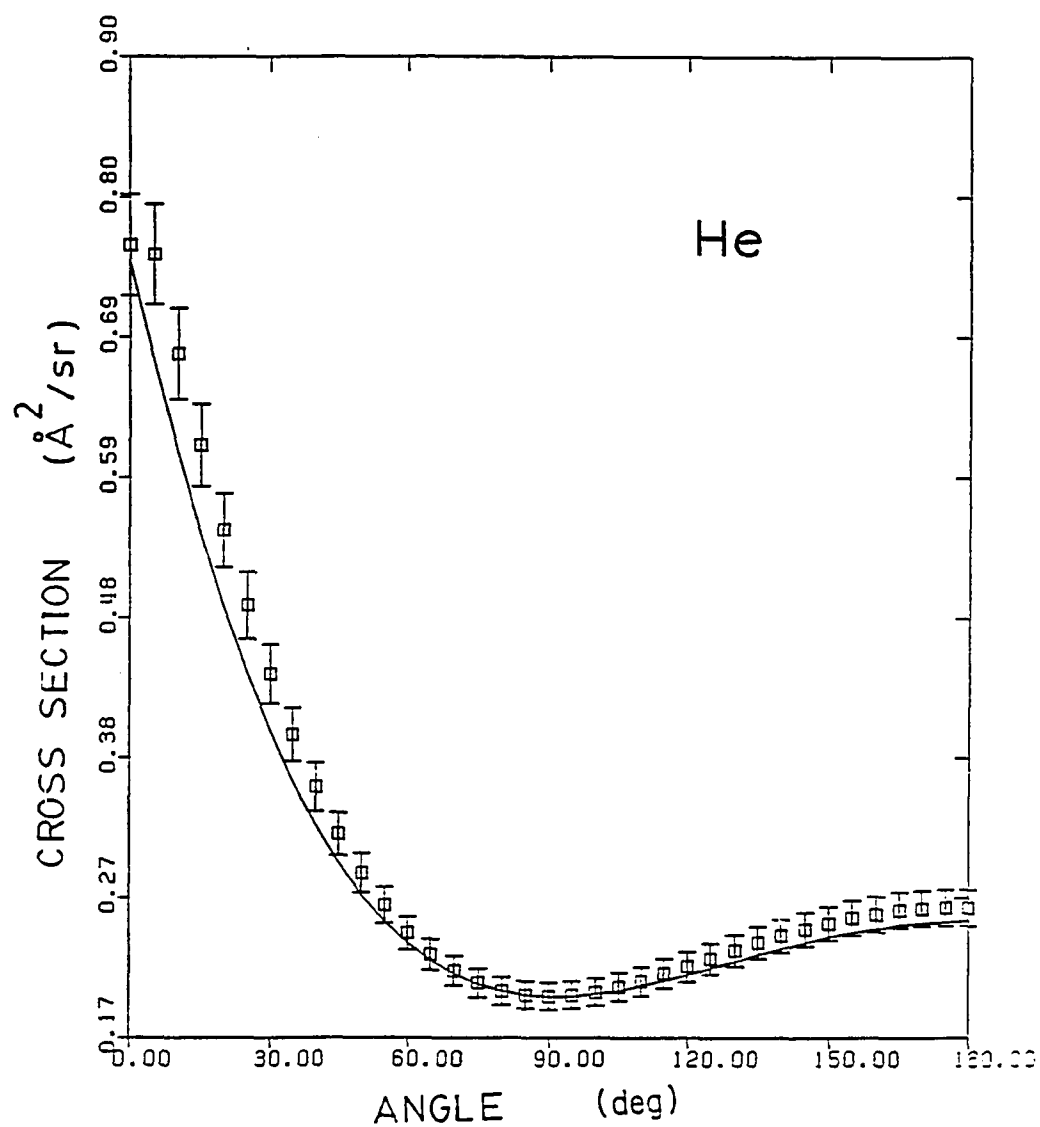


Fig.36. Differential cross section at 19eV evaluated using the determined phase shifts. $\square$, Present results; —, Nesbet.

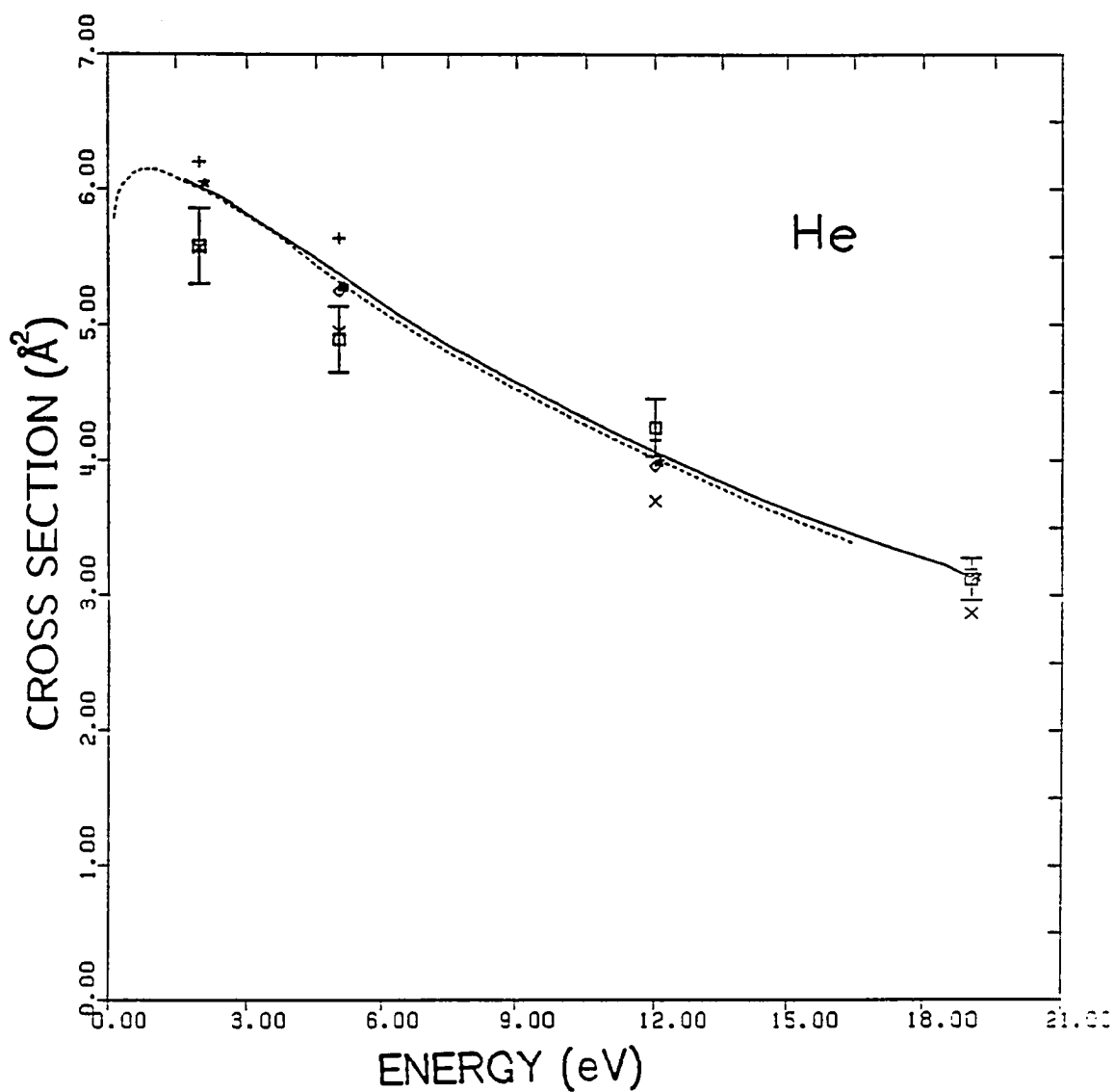


Fig.37. Total cross section in He. , Present results; +, Andrick and Bitsch; , Register et al.; x, Golden and Bandel; , Kennerly and Bonham; -----, O'Malley et al.; ———, Nesbet.

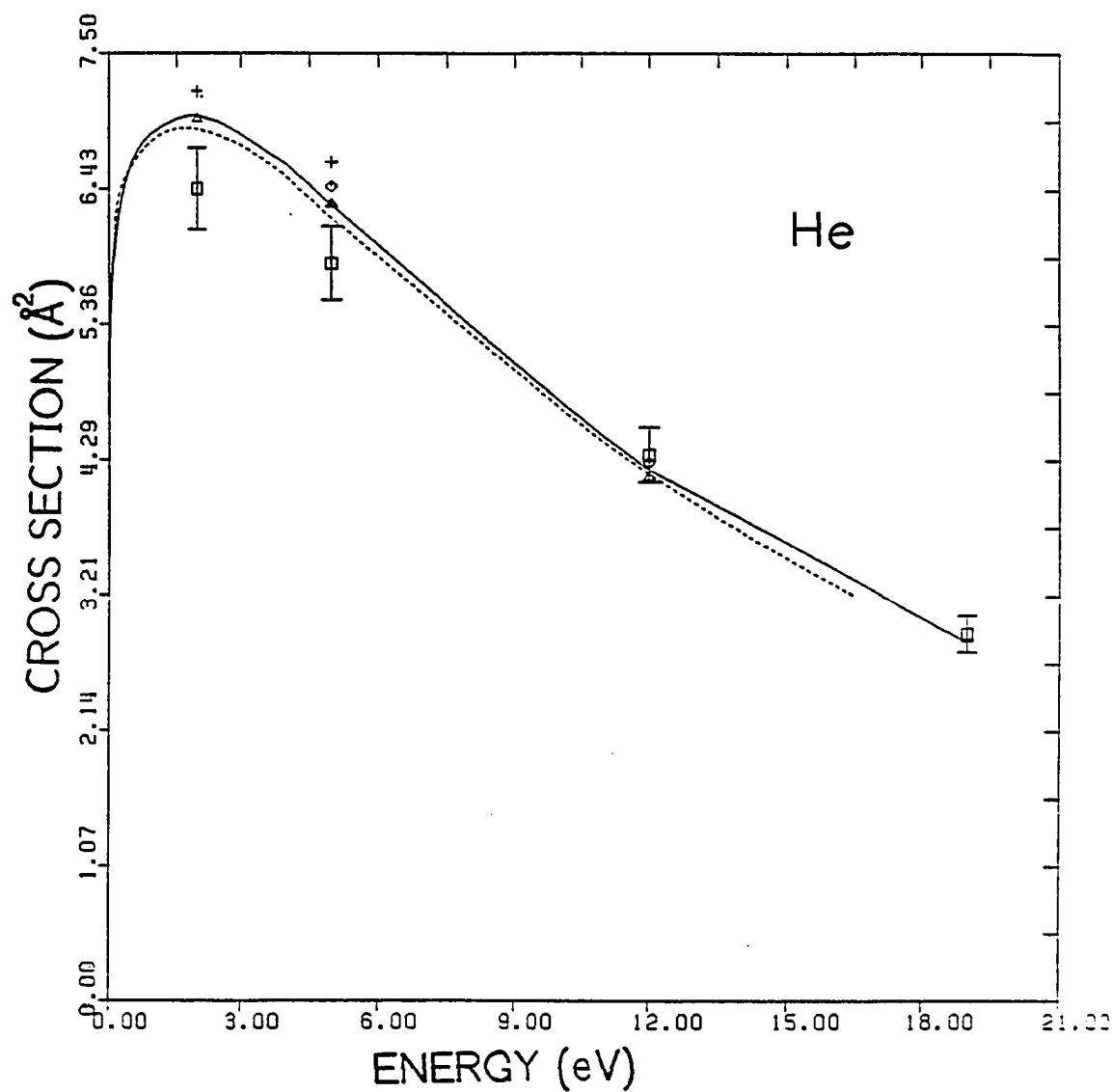


Fig.38. Momentum transfer cross section in He. , Present results; +, Andrick and Bitsch; , Register et al.; , Crompton et al.; -----, O'Malley et al.; ———, Nesbet.

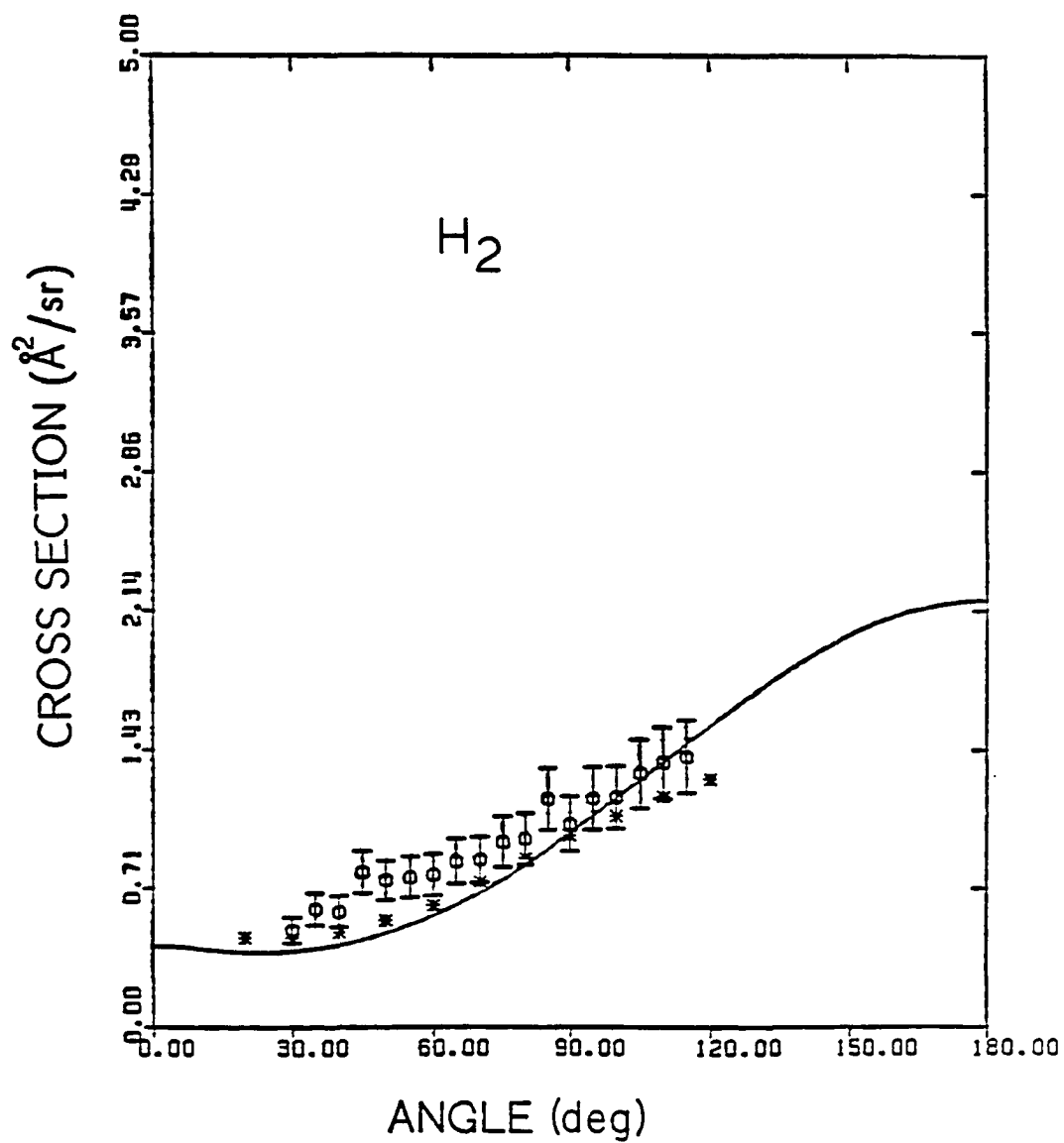


Fig.39. Differential cross section at 1 eV. $\circ$, present results; —, Morrison et al.; *, Linder and Schmidt.

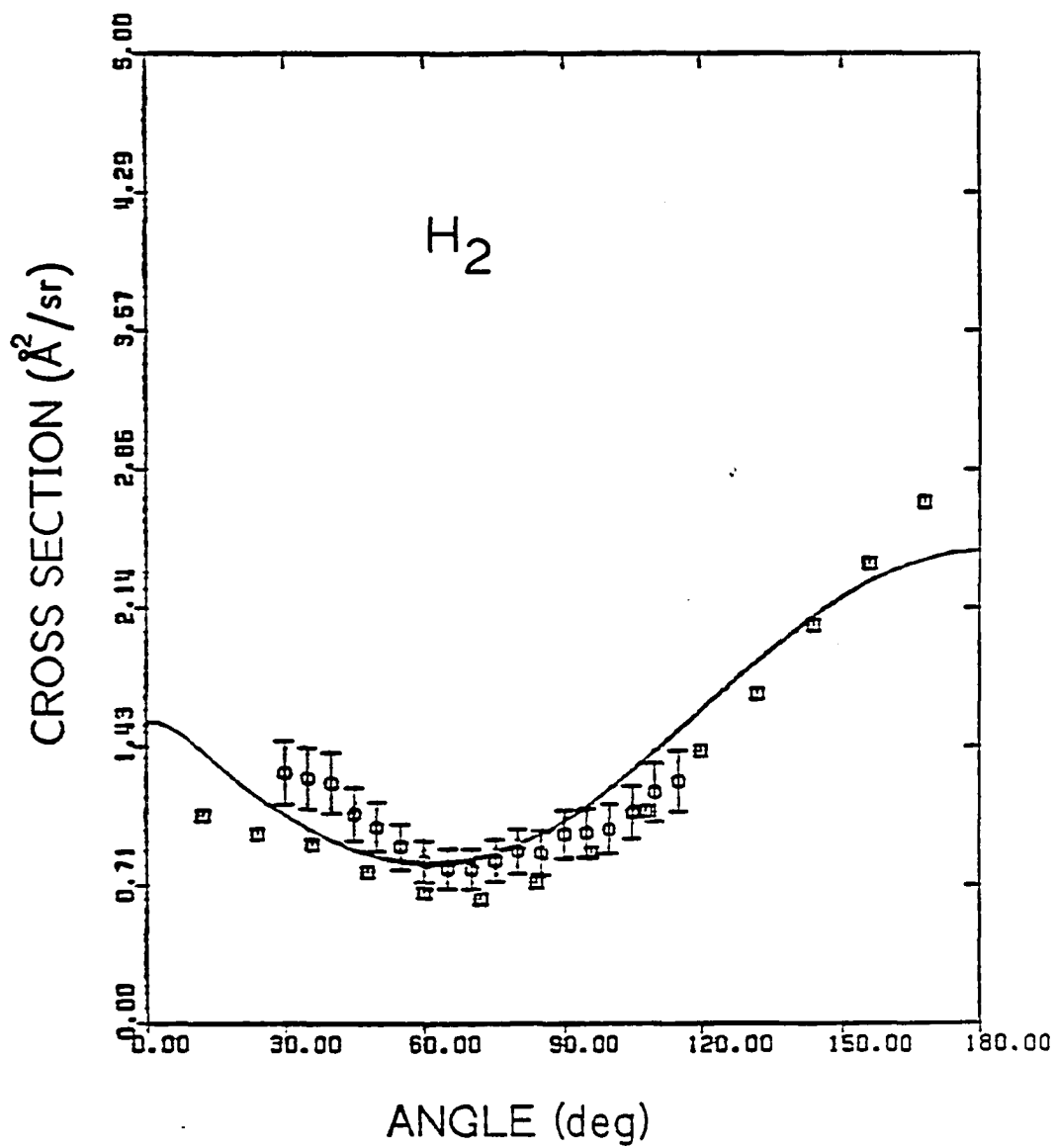


Fig.40. Differential cross section at 2 eV. $\circ$, present results; —, Morrison et al.; $\square$, Shyn and Sharp.

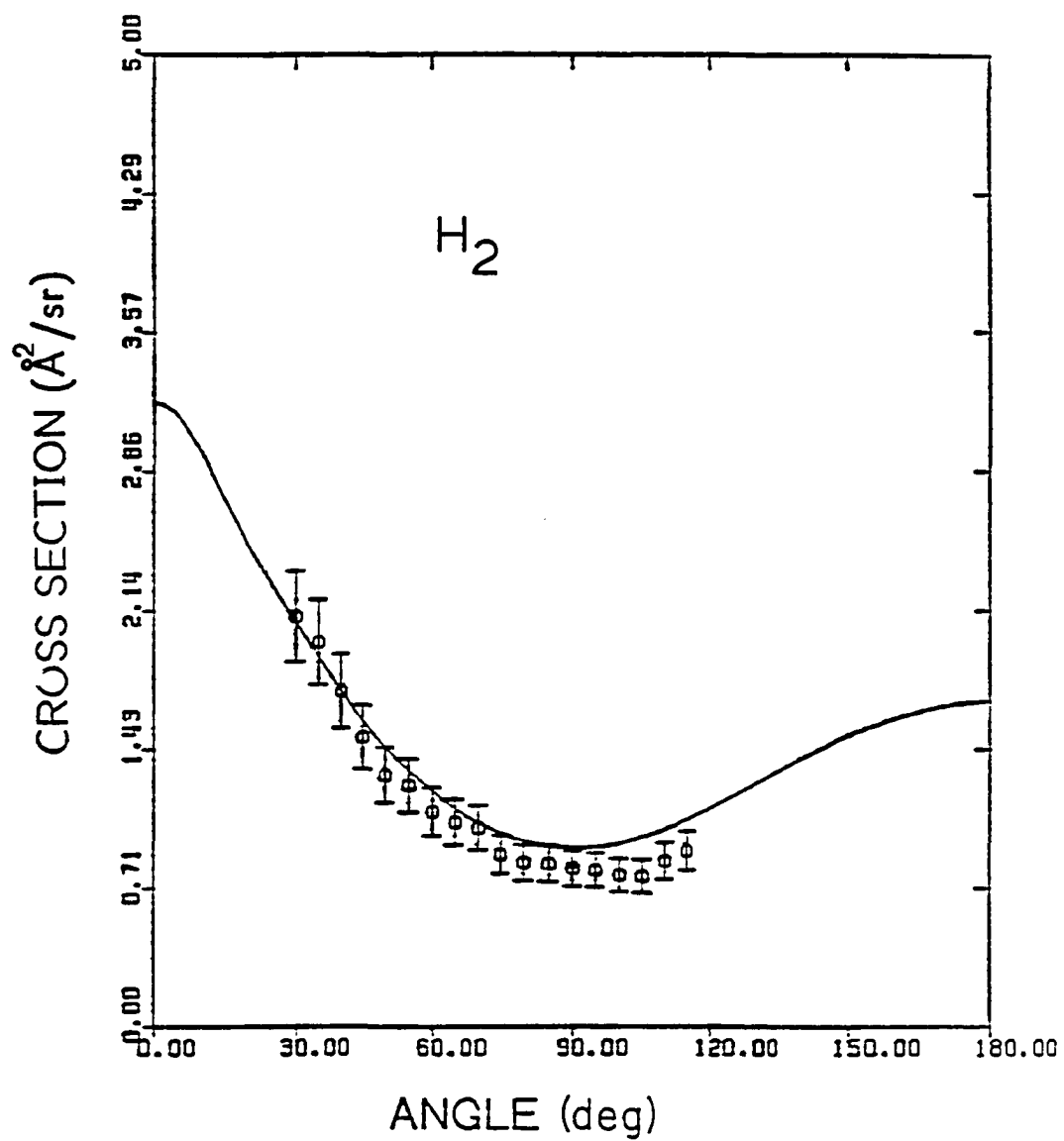


Fig.41. Differential cross section at 4 eV. $\circ$, present results; —, Morrison et al..

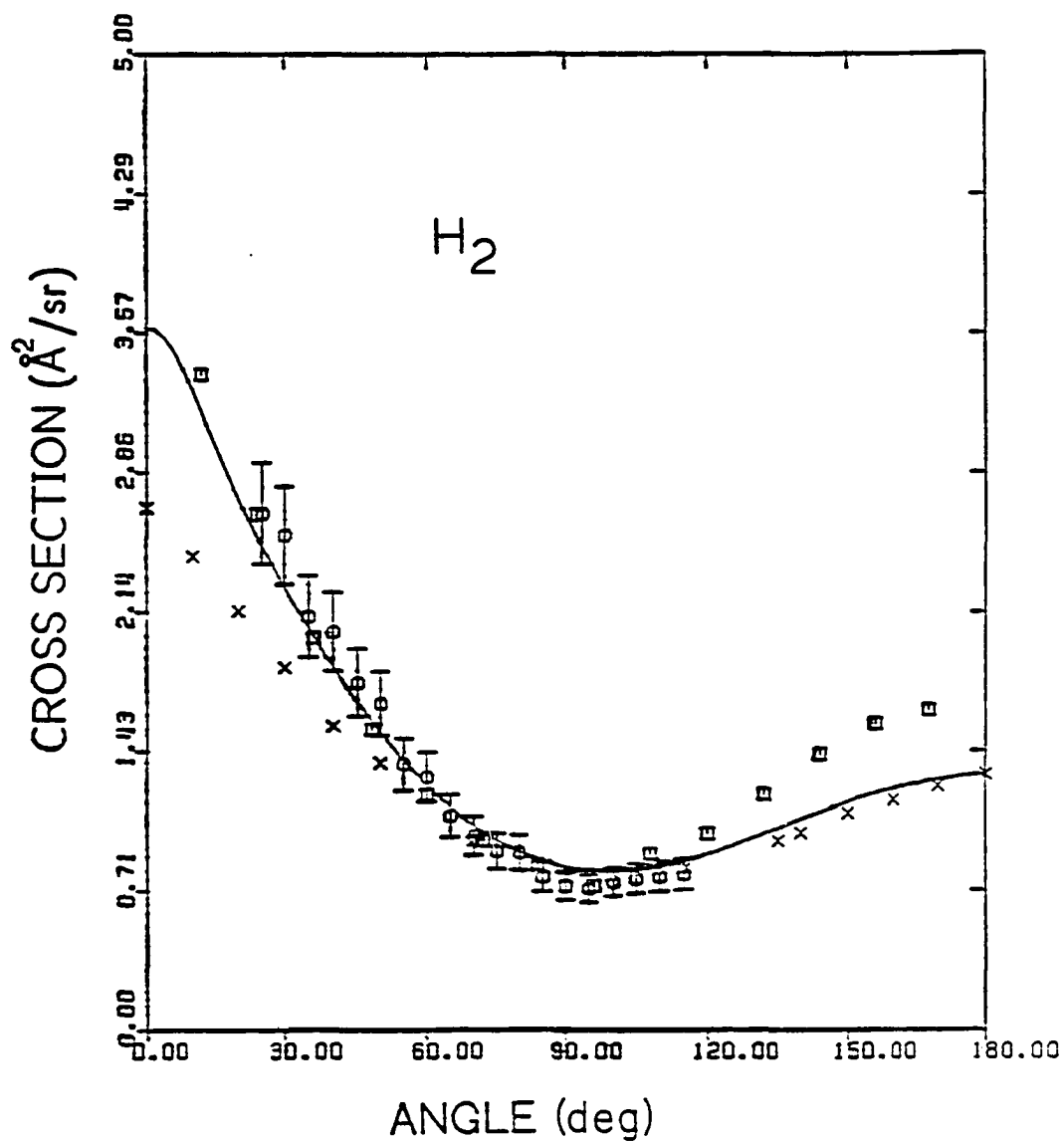


Fig.42. Differential cross section at 5 eV. $\circ$, present results; —, Morrison et al.; $\times$, Srivastava et al and Trajmar et al.; $\square$, Shyn and Sharp.

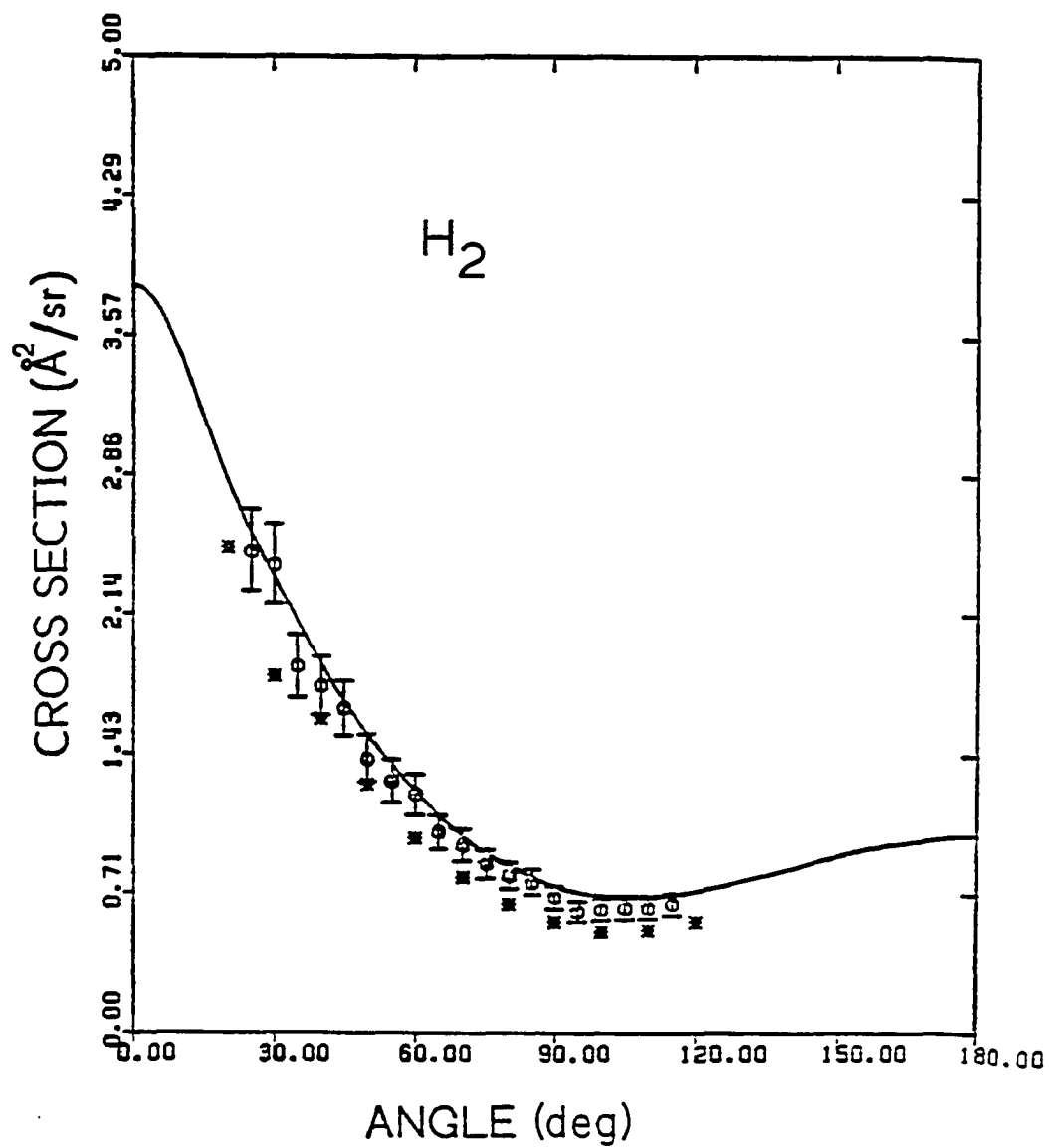


Fig.43. Differential cross section at 6 eV. $\circ$, present results; —, Morrison et al.; * , Linder and Schmidt.

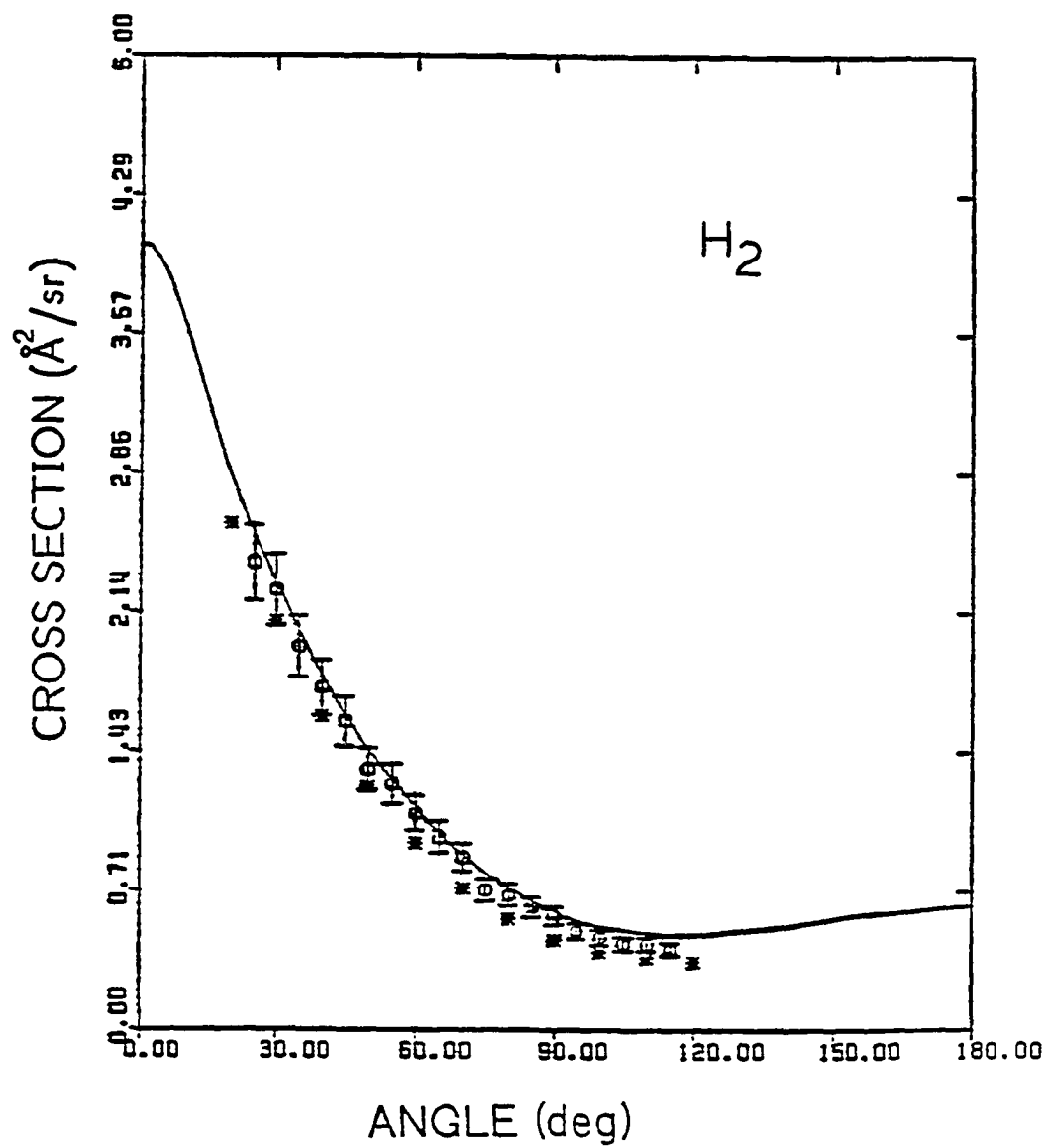


Fig.44. Differential cross section at 8 eV. $\circ$, present results; —, Morrison et al.; * , Linder and Schmidt.

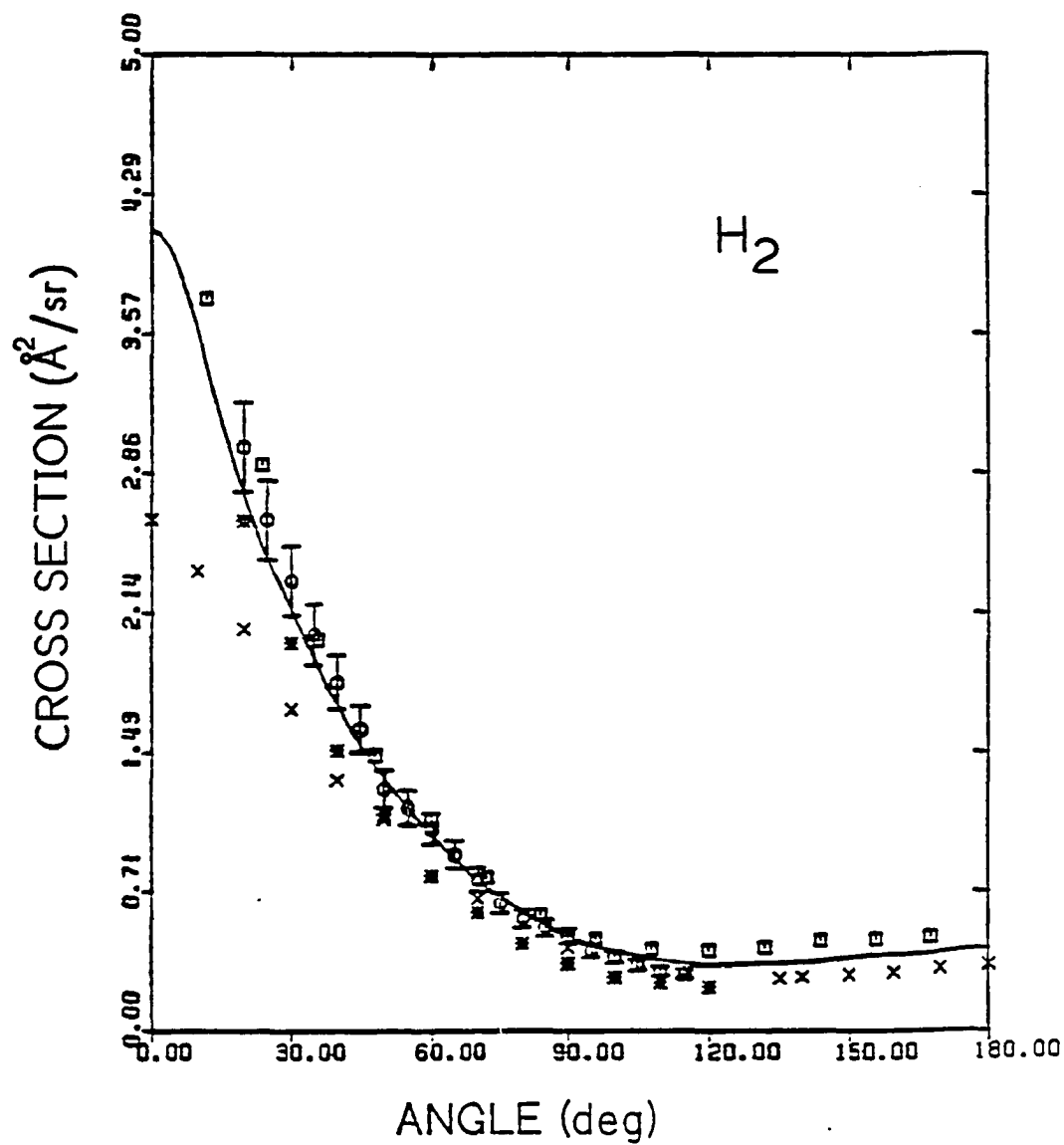


Fig.45. Differential cross section at 10 eV. $\circ$, present results; —, Morrison et al.; $\times$, Srivastava et al. and Trajmar et al.; $\square$, Shyn and Sharp; , Linder and Schmidt.

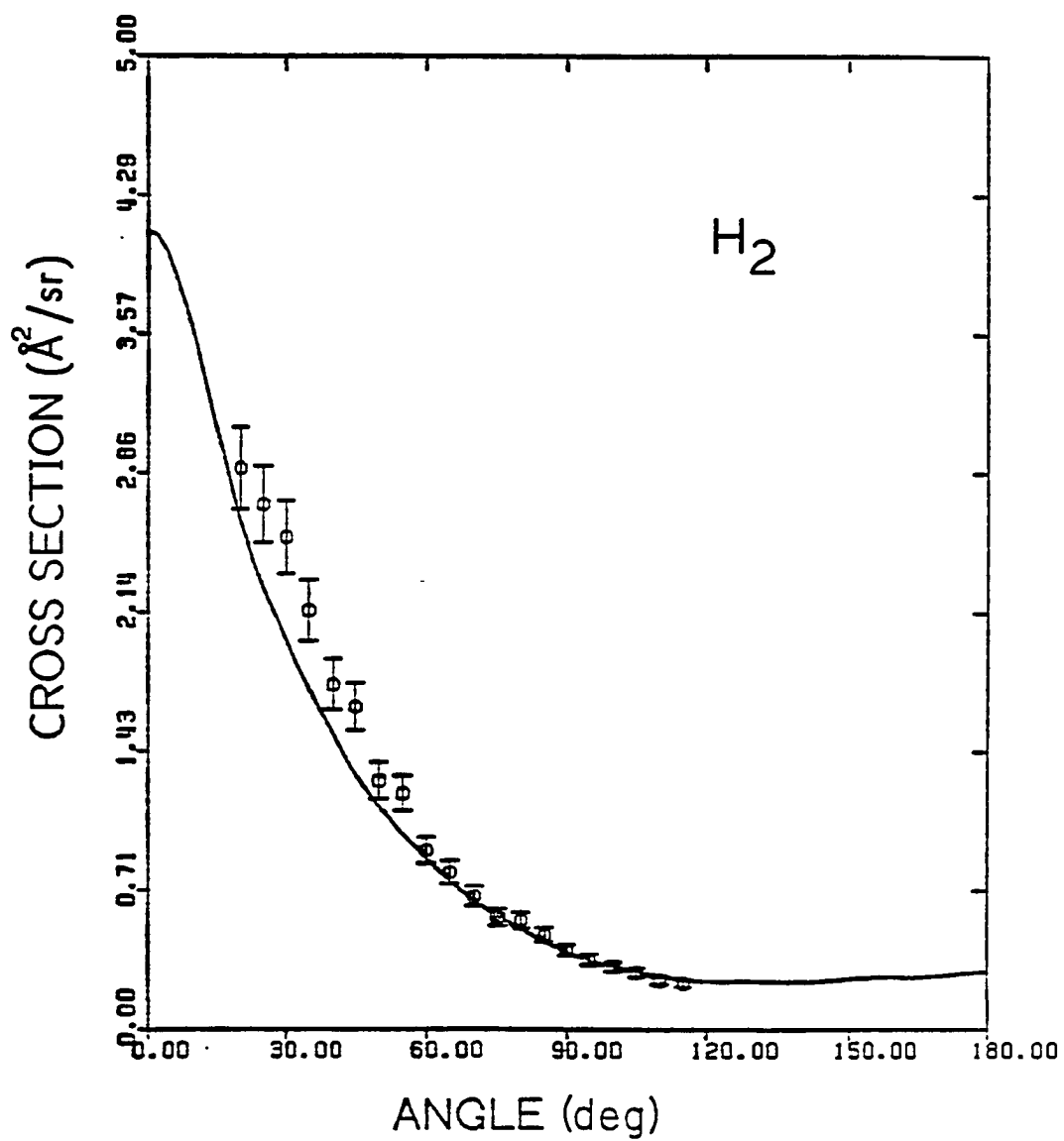


Fig.46. Differential cross section at 12 eV. $\circ$, present results; —, Morrison et al.

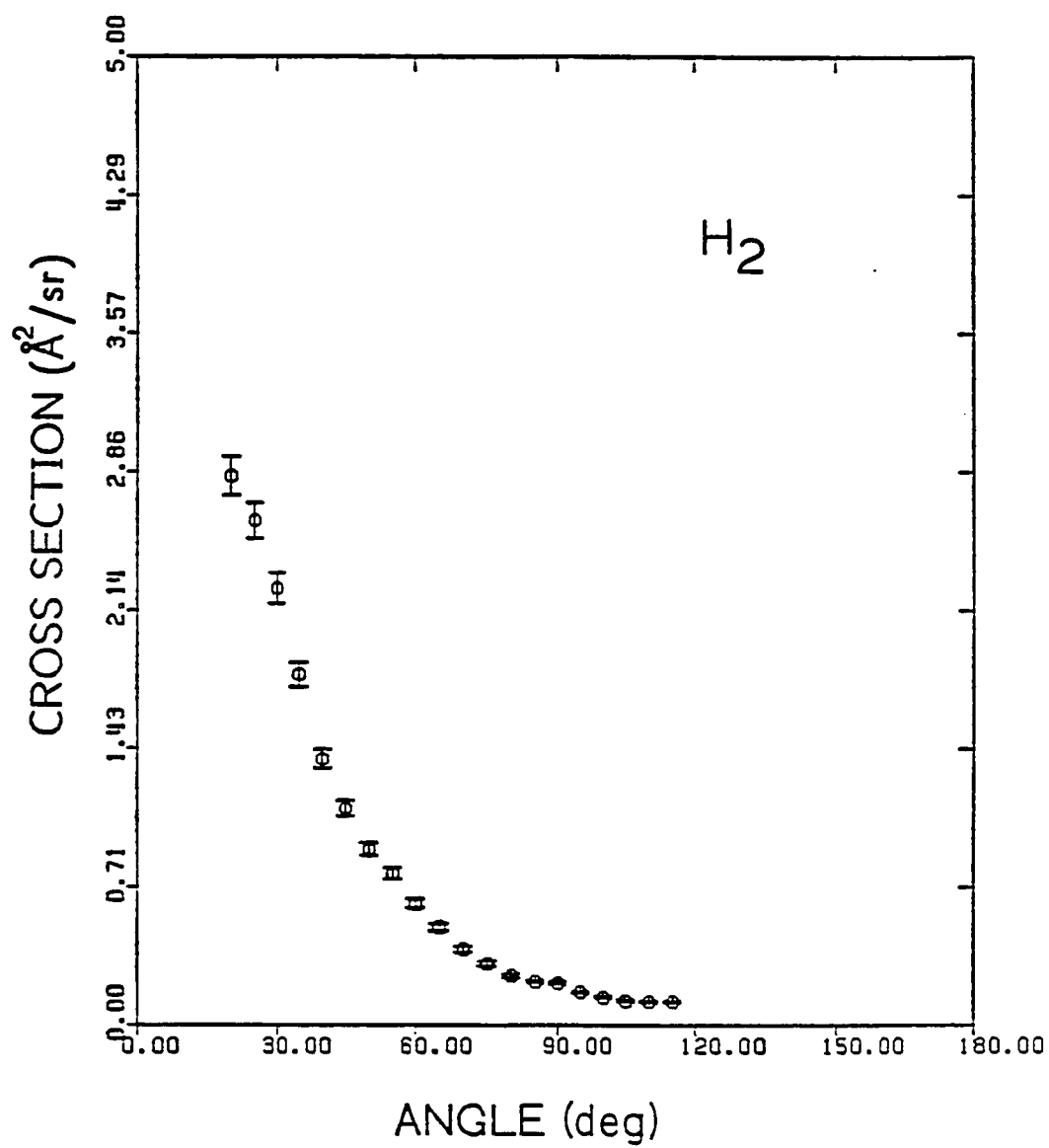


Fig.47. Differential cross section at 19 eV. ○ , present results.

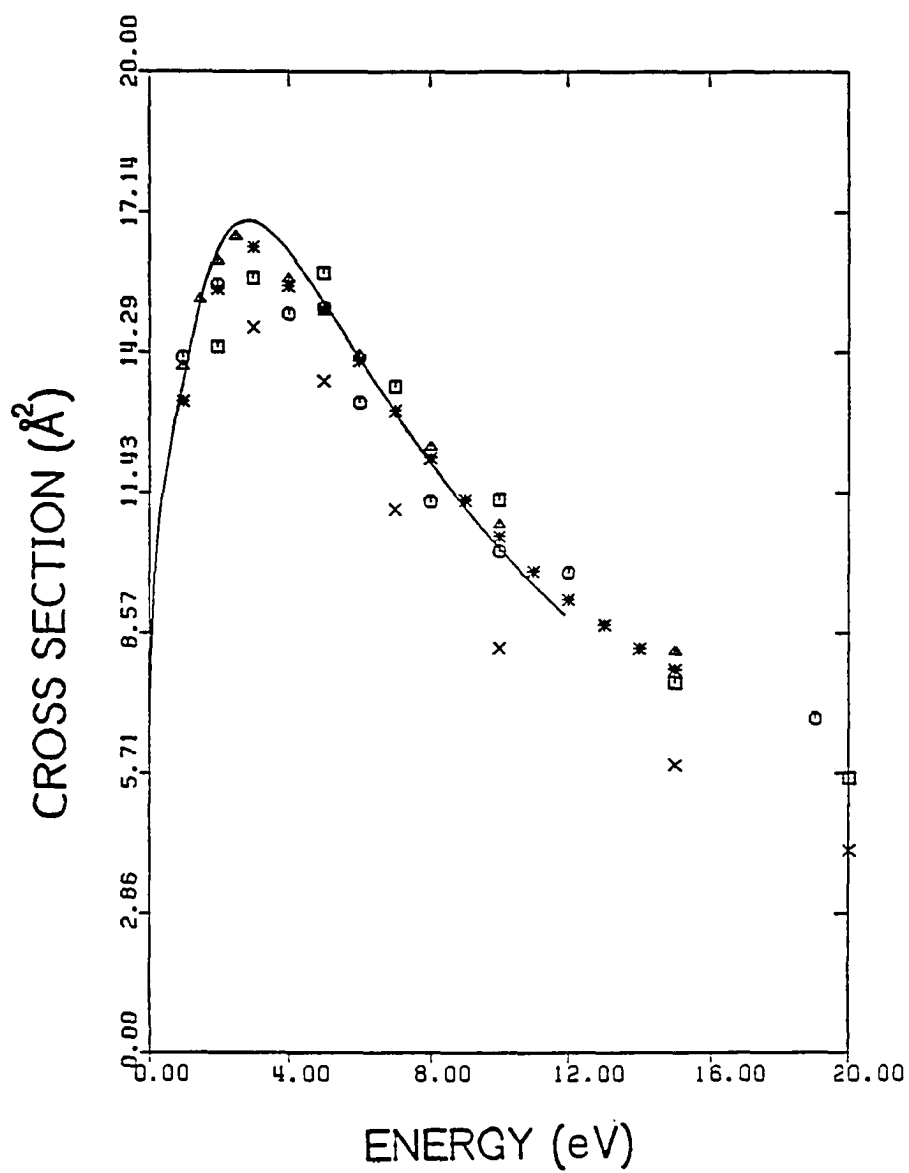


Fig.48. Integrated total cross section in H_2 . $\circ$, present results; —, Morrison et al.; $\times$, Srivastava et al. and Trajmar et al.; $\square$, Shyn and Sharp; $\triangle$, Dalba et al.; $*$, Jones.

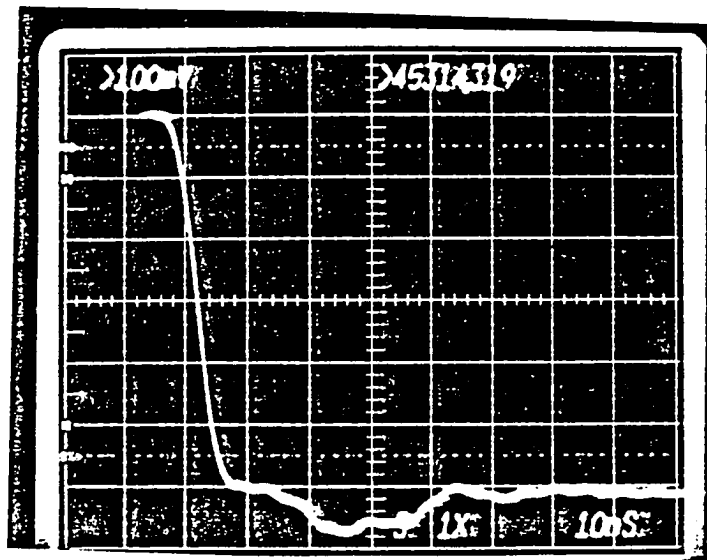


Photo 1a. Wave form of the pulse generator prior to the pulsing lens.

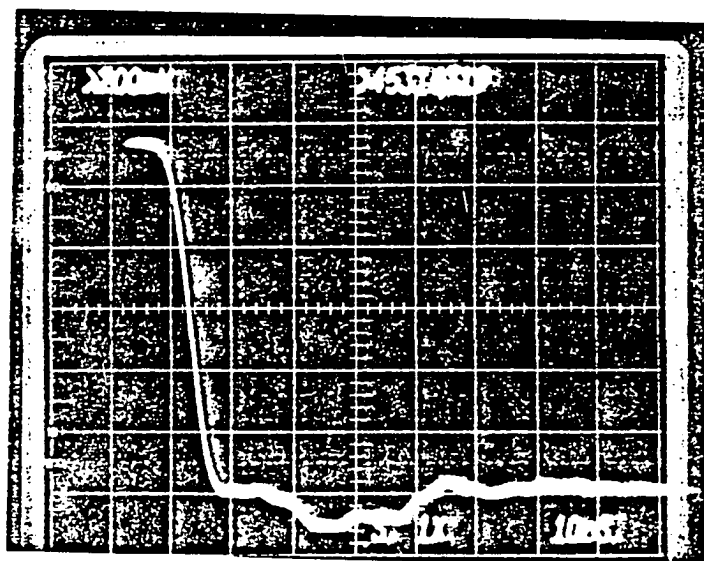


Photo 1b. Wave form of the pulses after the pulsing lens.

APPENDIX A

SOLID ANGLE CALCULATION

The defining geometry for the calculation is assumed to be two circular coplanar aperture of radius R_1 and R_2 in a field free region. Allowance for non-uniform target particle densities can be easily accommodated if the density distribution is known.

There are two approximations used in the derivation of $d\Omega(z)$. It is assumed that the incident beam is one-dimensional and that the solid angle integral can, to a good approximation, be written as

$$\int \frac{R \cdot da}{R^3} = \frac{A \cos \delta}{R^2} \quad (A1)$$

where R is the distance from the point on the beam axis to center of mass of the aperture area and δ is the angle between R and the normal to the surface A . For the stationary detector where this approximation might be suspect due to the large aperture diameter, the error is less than 1%. The calculation of the solid angle subtended by the aperture system at the point z shown in Fig. A1 proceeds by assuming that an effective area of the rear aperture can be projected onto the plane of the front aperture using Eq. (A1). The area common to both Apertures (A') is evaluated and the location of the center of mass of the common area (x') is found. The

distance from z to x' is found and the solid angle $\Delta\Omega(z)$ is evaluated.

The radius of the rear aperture (R'_2) projected on the plane of the front aperture is given by

$$R'_2 = R_2 (D'_4/D_4) \quad (A2)$$

where D_4 and D'_4 are defined in Figs. A1 and A2 and D_4 is given by

$$D_4 = [(D_1 + D_2)^2 + z^2 - 2(D_1 + D_2) z \cos\theta]^{1/2} \quad (A3)$$

where θ is defined in Fig. A1. The distance between the centers of the two circles (t) is given by

$$t = D_2 \tan\phi \quad (A4)$$

where

$$\phi = \cos^{-1} \left(\frac{D_2^2 + D_4^2 - D_3^2}{2D_2D_4} \right) \quad (A5)$$

The common area of the two circles is given by

$$A' = R'_2{}^2 \cos^{-1}(t'/R'_2) + R'_1{}^2 \cos^{-1}(x_0/R_1) - x_0(R_1^2 - x_0^2)^{1/2} - t' [(R'_2)^2 - (t')^2]^{1/2} \quad (A6)$$

and the center of mass of the common area is given by

$$x' = t[R'_2{}^2 \cos^{-1}(t'/R'_2) - t' [(R'_2)^2 - (t')^2]^{1/2}] \quad (A7)$$

where x_0 is defined in Fig. A2. x_0 and t' are given by

$$x_0 = (R_1^2 + t^2 - R'_2{}^2)/2t$$

$$t' = t - x_0$$

the distance (D_5) from x' to z is given by

$$D_5 = D_3^2 + (x')^2 + 2D_3x' \sin\beta \quad (A7)$$

where

$$\beta = \cos^{-1} \left(\frac{D_1^2 + D_3^2 - z^2}{2D_1D_3} \right)$$

The solid angle $\Delta\Omega(z)$ is evaluated using

$$\Delta\Omega(z) = \frac{A'}{(D_5)^2} \cos\delta \quad (A8)$$

where $\delta = \sin^{-1} \frac{(z - x')}{D'_4} \sin\theta$

The integration of the length solid angle product

$$\int_{\ell} \int_{\Delta\Omega} d\Omega(z) dz \quad (A9)$$

over the viewed interaction length (ℓ) is calculated using Simpson's rule. The calculated results for the electron detector geometry agree to better than 1% with the usual ($\ell/\sin\theta$) approximation for angles $\theta > 10^\circ$.

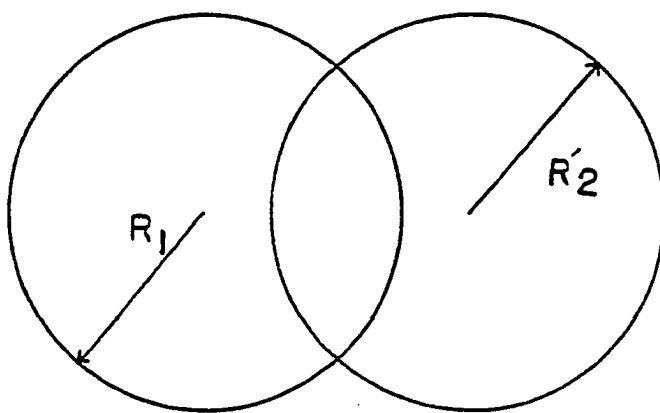
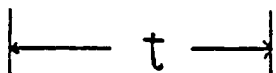
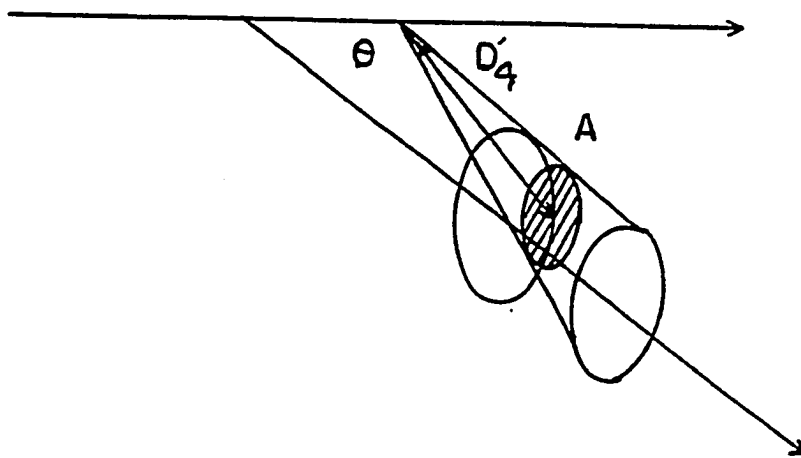


Fig A2. Solid angle calculation geometry

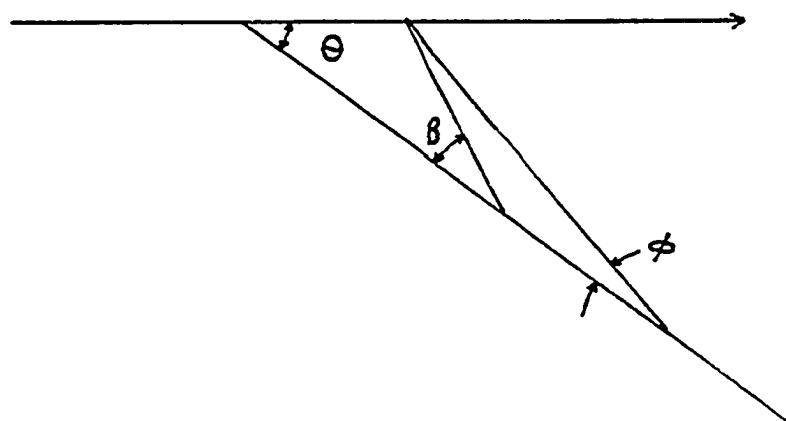
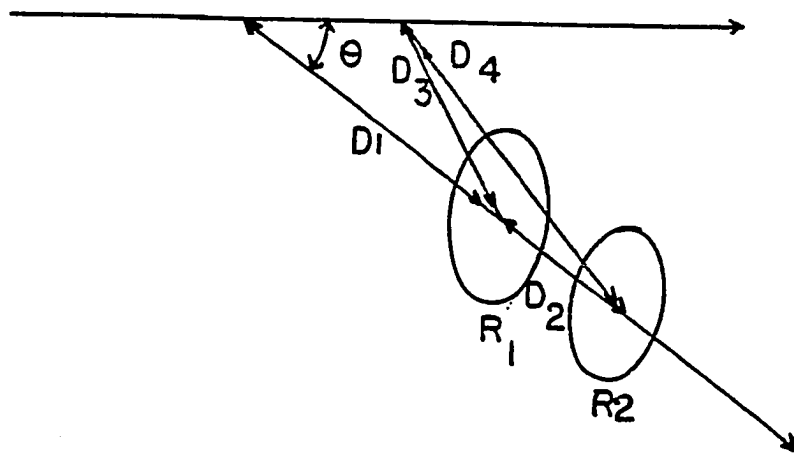


Fig A1. Solid angle calculation geometry