N89-21744

1988

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

The Measurement of Angular Differential Cross Sections at the SSL Atomic Scattering Facility

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Date:	August 12, 1988
Contract No.:	NGT 01-002-099 The University of Alabama

The Measurement of Angular Differential Cross Sections at the SSL Atomic Scattering Facility

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ABSTRACT

This report covers the design of the SSL Atomic Scattering Facility (ASF) located at NASA/Marshall Space Flight Center as well as some of the initial experiments to be performed with it. The goal is to develop an apparatus capable of measuring angular differential cross sections (ADCS) for the scattering of 2 - 14 eV atomic oxygen from various gaseous targets. At present little is known about atomic oxygen scattering with kinetic energies of a few eV. This apparatus is designed to increase our understanding of collisions in this energy region.

Atomic oxygen scattering processes are of vital interest to NASA because the space shuttle as well as other low earth orbit satellites will be subjected to a flux of 5 eV atomic oxygen on the ram surfaces while in orbit. The primary experiments will involve the measurements of ADCS for atomic oxygen scattering from gaseous targets (in particular, molecular nitrogen). These, as well as the related initial experiments involving thermal He scattering from N_2 and O_2 targets will be described.

ACKNOWLEDGEMENTS

I would like to extend my thanks and appreciation to Dr. Marsha Torr for her support and enthusiam for this project. Thanks and recognition also go to Dr. Charles Keffer and Dr. Glynn Germany for their guidance and discussions about the project. The majority of the design of the apparatus is due to their efforts.

I have enjoyed being part of the 1988 Summer Faculty Program and warm thanks are extended to Dr. Michael Freeman and Ms. Ernestine Cothran for their supervision. Finally, special thanks are extended to my wife, Barbara, and sons for their understanding.

INTRODUCTION

The Atomic Scattering Facility (ASF) is being constructed to perform experiments that will give us a better understanding of the atomic and molecular processes occurring in the altitude region of 200 - 500 km. As is shown in Figure 1, the primary species at this altitude is neutral atomic oxygen. Lesser amounts of N_2, O_2, and He are also present. Because the shuttle and other satellites operate in low earth orbit (LEO), it is of timely importance to understand these atomic scattering systems. The orbital velocity of the spacecraft at this altitude is approximately 8 km/s and from this reference frame, the spacecraft would be experiencing a flux of neutral atomic oxygen with 5 eV kinetic energy impinging on the ram surfaces.

The experiments, for which the ASF is designed, pose a number of experimental and theoretical challenges. All of the collisional partners are multi-electron and with the exception of helium, are of open shell configuration. This adds to the theoretical complexity of understanding the collision. Experimentally, the production and detection of few eV atomic oxygen is non-trivial. Interpreting the scattering is complicated by the need for crossed beams as well as accounting for the possibility of the incident atomic oxygen beam being in a mixture of the ground state $O(^3P)$ and the long-lived metastable state $O(^1D)$. However, when fully analyzed, angular differential cross sections (ADCS) have been used to understand more fully the potential energy surface governing the scattering. The acquisition of these data, for which this facility is designed, promises to have wide-ranging usefulness from both basic physics as well as engineering standpoints.

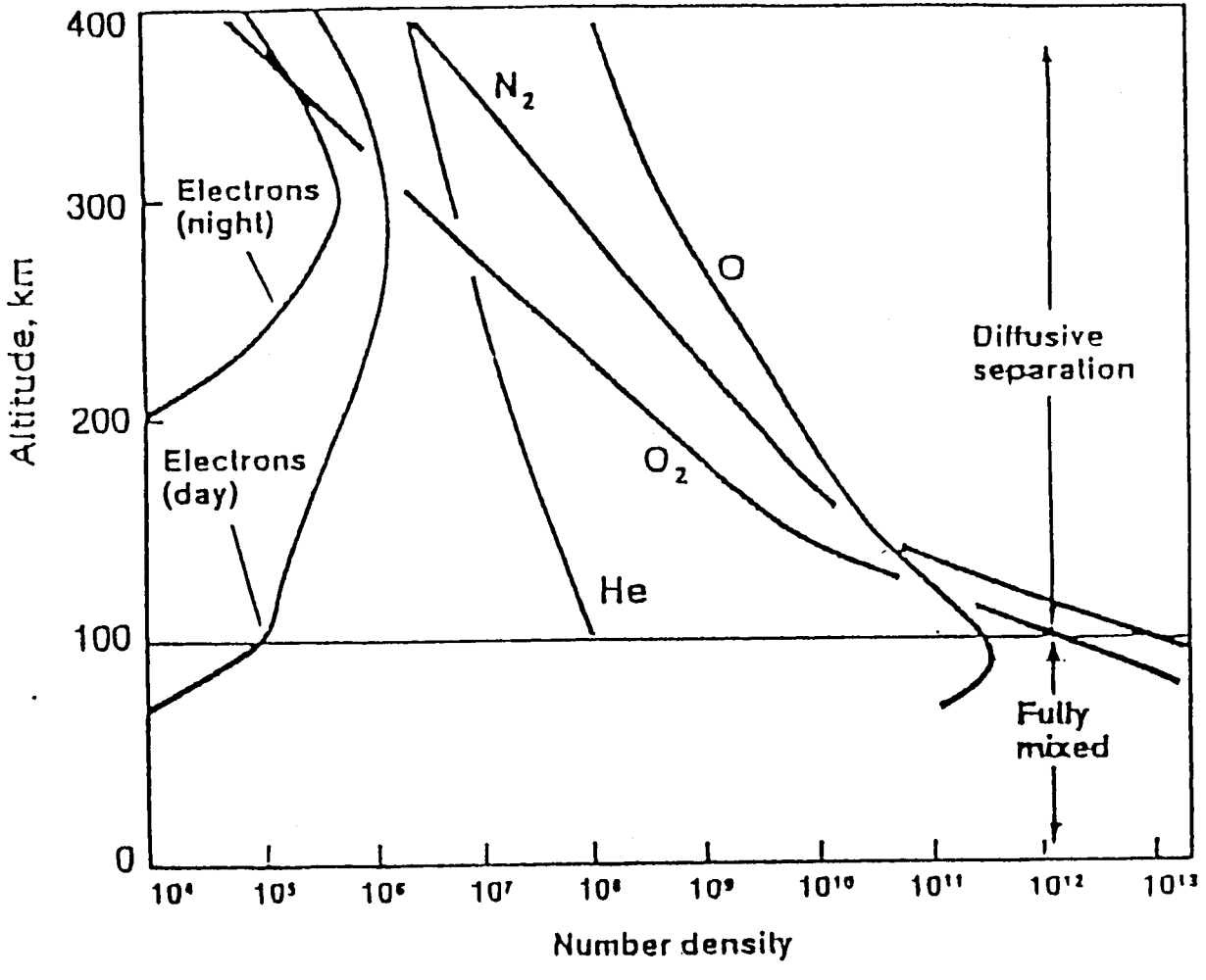

Figure 1. The number density (number/cm^3) of several of the major species of elements constituting the atmosphere as a function of altitude. Low earth orbit (LEO) where the shuttle typically operates, is in the region of 300 km. The graph is from Ref. 1.

OBJECTIVES

This summer, I was involved in the following tasks:

1) To assist in the general design and construction of the Atomic Scattering Facility.

2) To outline the measureable variables necessary for the acquisition and analysis of angular differential cross section (ADCS) measurements.

3) To explore the possibility of normalizing the relative ADCS to an absolute measurement or calculation.

APPARATUS

The Atomic Scattering Facility (ASF) is designed to be able to obtain angular differential cross sections (ADCS) for neutral atom (or molecule) scattering from thermal neutral atoms or molecules. A schematic overview of ASF is shown in Figure 2, whereas a side view illustrating the placement of the major pieces of the apparatus is given in Figure 3. Ultra-high vacuum techniques have been applied in the general design of the facility. For example, the main vacuum chamber as well as most of the components are fabricated from 304 stainless steel. The projectile source, target jet, main chamber, and mass spectrometer are all differentially pumped to isolate the effects that gas loads will have on the other components. The base pressure in the main chamber is estimated to remain in the 10^{-6} to 10^{-7} Torr region while both the projectile source and target jet are operating, whereas the base pressure in the mass spectrometer will be in the 10^{-8} to 10^{-9} Torr region.

The initial major experiment guiding the construction of this apparatus is the measurement of ADCS for 5 eV atomic oxygen scattering from thermal molecular nitrogen. One of the distinguishing (and challenging) features of this apparatus is the production of the 5 eV atomic oxygen beam. The experimental arrangement that was chosen for this source of "fast" atomic oxygen follows a design[2] by Physical Sciences, Inc.[3] Essentially, molecular oxygen is admitted into an expansion cone, as is shown in Figure 4, by a high-speed, pulsed nozzle valve. When a sufficient amount of molecular oxygen has been released to fill the space between the valve and the skimmer, a laser pulse from a 15 Joule CO_2 laser is focused at the throat of the nozzle. During the pulse, the thermal expansion of the gas accelerates the recombining atomic oxygen to eV kinetic energies. By varying the laser power and oxygen densities, the kinetic energy of atomic oxygen can be varied in the region of 2 - 14 eV. The E_{FWHM} of the atomic oxygen beam is estimated to be approx. 2 eV for a 5 eV nominal kinetic energy beam. The estimated incident flux directed on the target is 10^{12} to 10^{13} atoms/second.

The principal method of producing the N_2 target is by directing a thermal beam of molecular nitrogen into the center of the main vacuum chamber by a high speed, pulsed nozzle valve similar to that used with the oxygen source. The atomic oxygen beam and the thermal molecular nitrogen

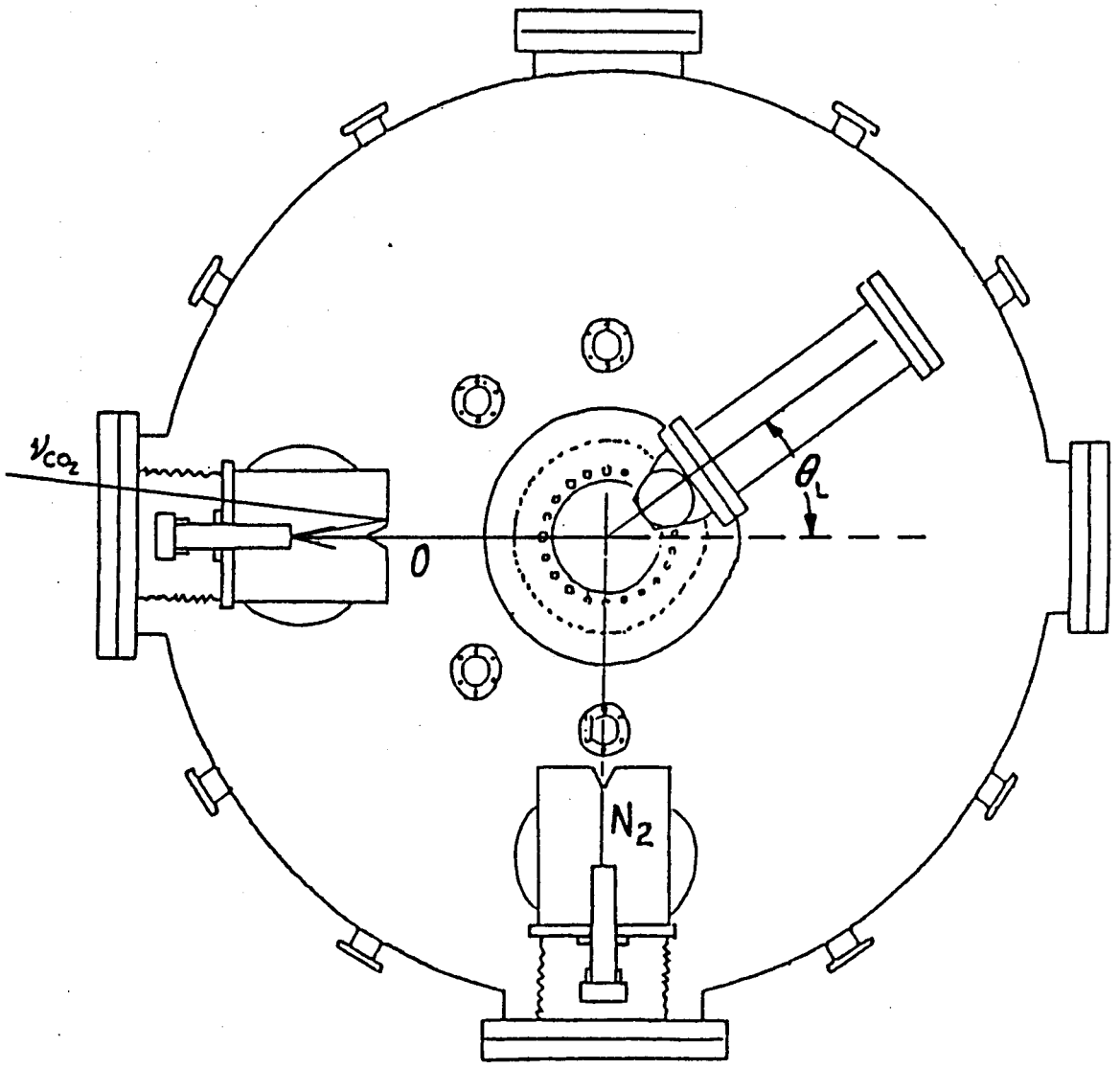

Figure 2. A schematic drawing of the overview of the experimental arrangement. Fast atomic oxygen is produced by a laser-generated plasma. The target species is directed to collide with the oxygen beam at the center of rotation of the mass spectrometer. The angle that the mass spectrometer makes with the oxygen beam is defined as the laboratory scattering angle, θ_L.

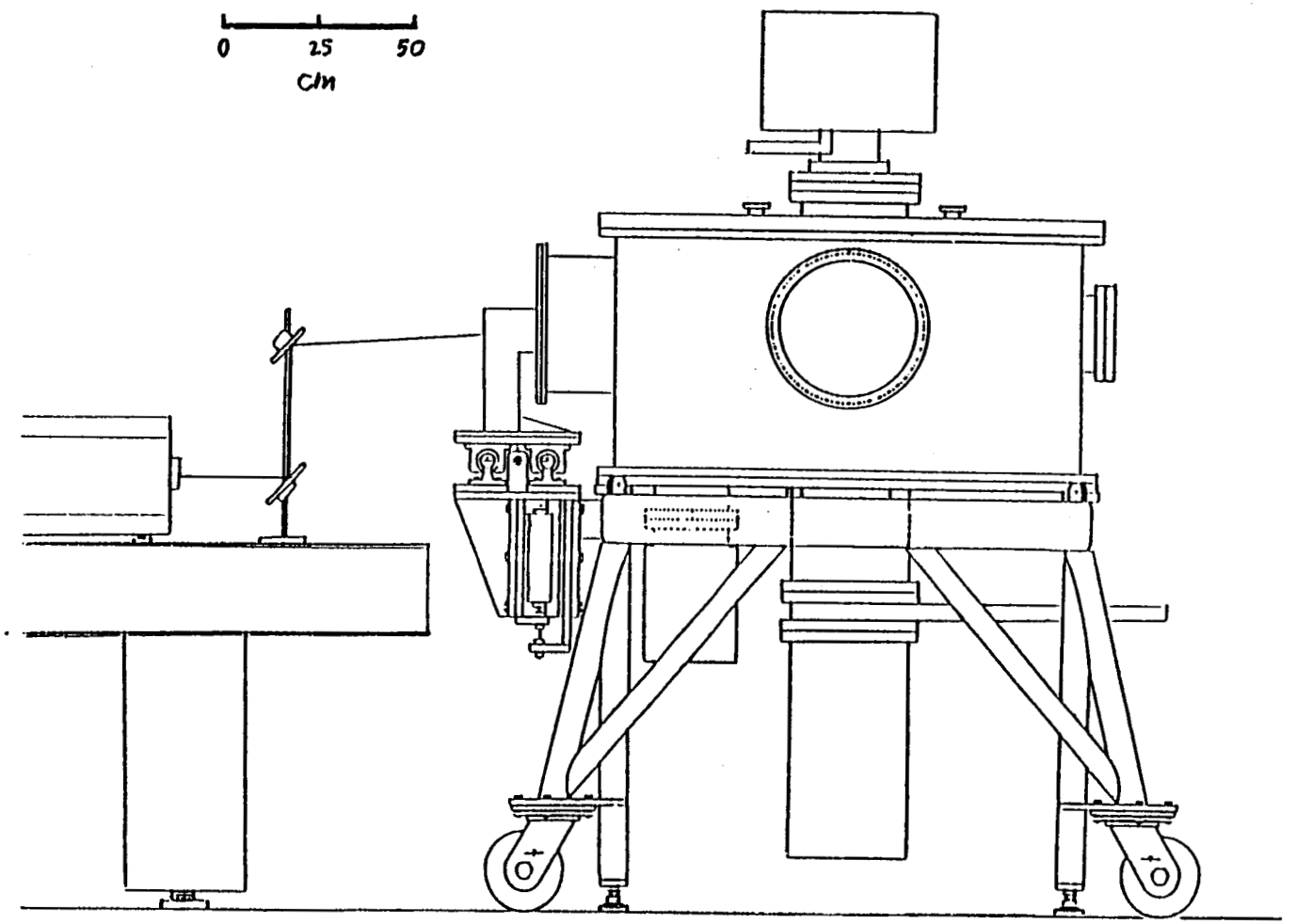

Figure 3. A schematic drawing of the major components of the SSL Atomic Scattering Facility. The CO_2 laser is located on an optical bench next to the main vacuum chamber. The scale gives an indication of the size of the facility.

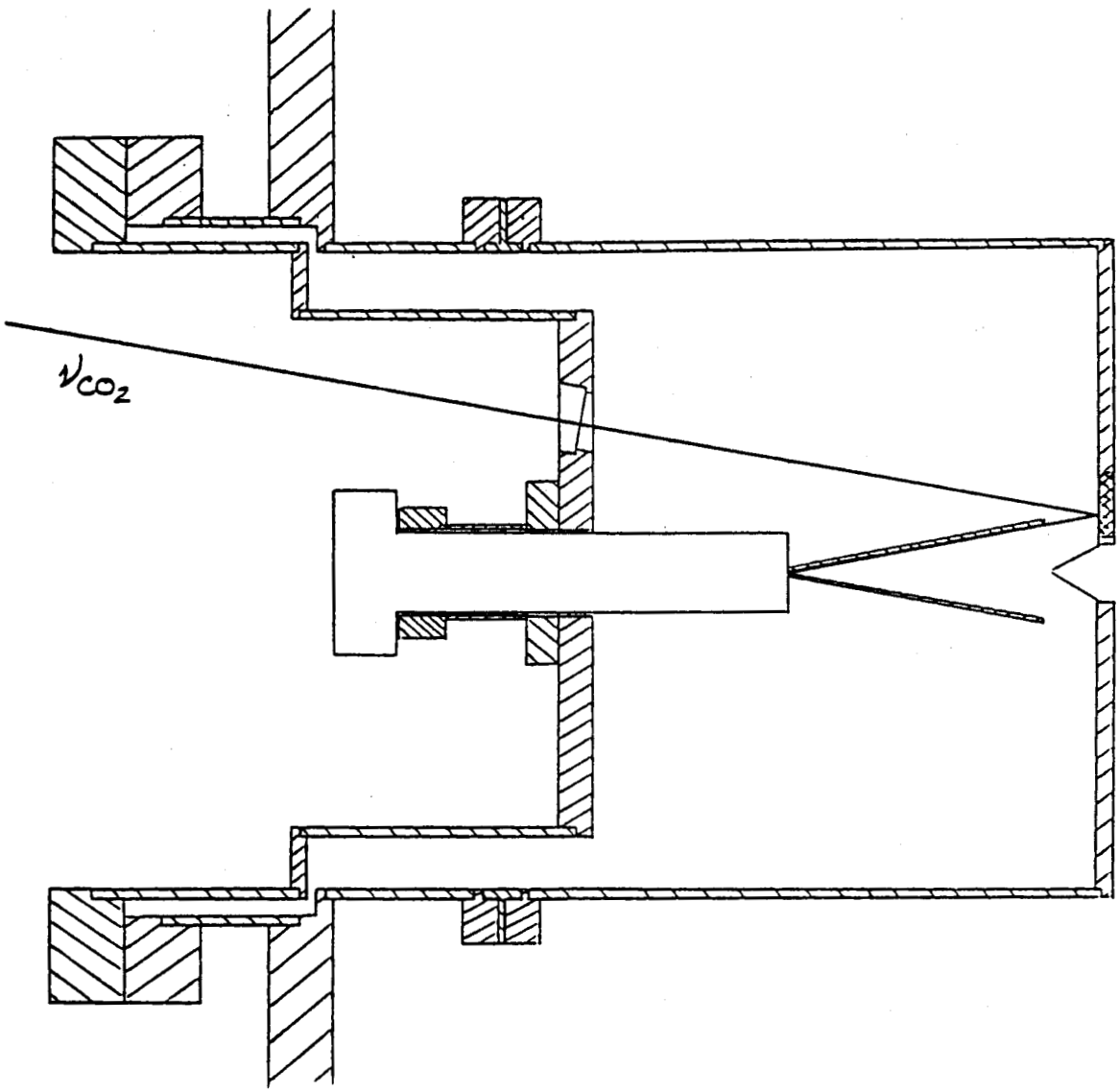

Figure 4. The schematic design of the fast atomic oxygen source. The laser light enters the differentially pumped housing through a vacuum window and is reflected by a mirror into the throat of the pulsed nozzle valve. The skimmer ensures a highly collimated beam.

beam intersect at right angles at the center of rotation of the mass spectrometer. This orientation reduces the effects that the spreads in the kinetic energies of the two beams have on the possible angular structure in the differential cross sections.

The scattered particles are detected by a mass spectrometer manufactured by Extrel Corp.[4] It is differentially pumped by an ion pump, thereby maintaining a vacuum of approximately 10^{-9} Torr. The angle at which the mass spectrometer is located relative to the incident atomic oxygen beam is defined as the laboratory scattering angle. Rotation of the mass spectrometer is made possible by its mounting on a high vacuum rotation stage. The plane of rotation is the plane formed by the two intersecting particle beams, and the angular range of the system is limited only by the differential pumping housings of the devices. This ranges from 0 - 60 degrees on one side to 0 - 140 degrees on the other side. As a further check for the internal consistancy of the data, the mass spectrometer assembly can be mounted on a port on the side of the main vacuum chamber and rotated perpendicular to the scattering plane. In this case, the angular range will be limited to only small angles.

The data acquisition electronics are shown in Figure 5, and the timing sequences for the various instruments are shown in Figure 6. In Figure 6, the baseline for each instrument represents an "off" state and raised step represents the "on" or activated state. The pulsed operation is necessary due to the use of a pulsed laser in the production of atomic oxygen and helps reduce the gas load on the system. The timing of the various components is dictated by the kinematics of that particular experiment. The O_2 pulse length is related to the time required to fill the cone region shown in Figure 4, whereas the target pulse length is to produce quasi-static number density conditions when the atomic oxygen beam arrives at the interaction region. The target is assumed to have the lesser velocity, so its pulse will initiate a data sequence. The O_2 pulse is delayed (t_o = 350 μs) to allow for the different velocities of the two beams and the laser delay (t_1 = 100 μs) is to allow for the expansion of O_2 into the cone region. The counter is gated to help reduce the background signals.

Bailey and Mullen[5] have examined the effects that thermal motion of the target have on the observed ADCS. In their study, the target configuration was varied to be: a room-temperature (300 K) static gas cell, a static gas cell at 77 K, or a beam intersecting the projectile beam at 90

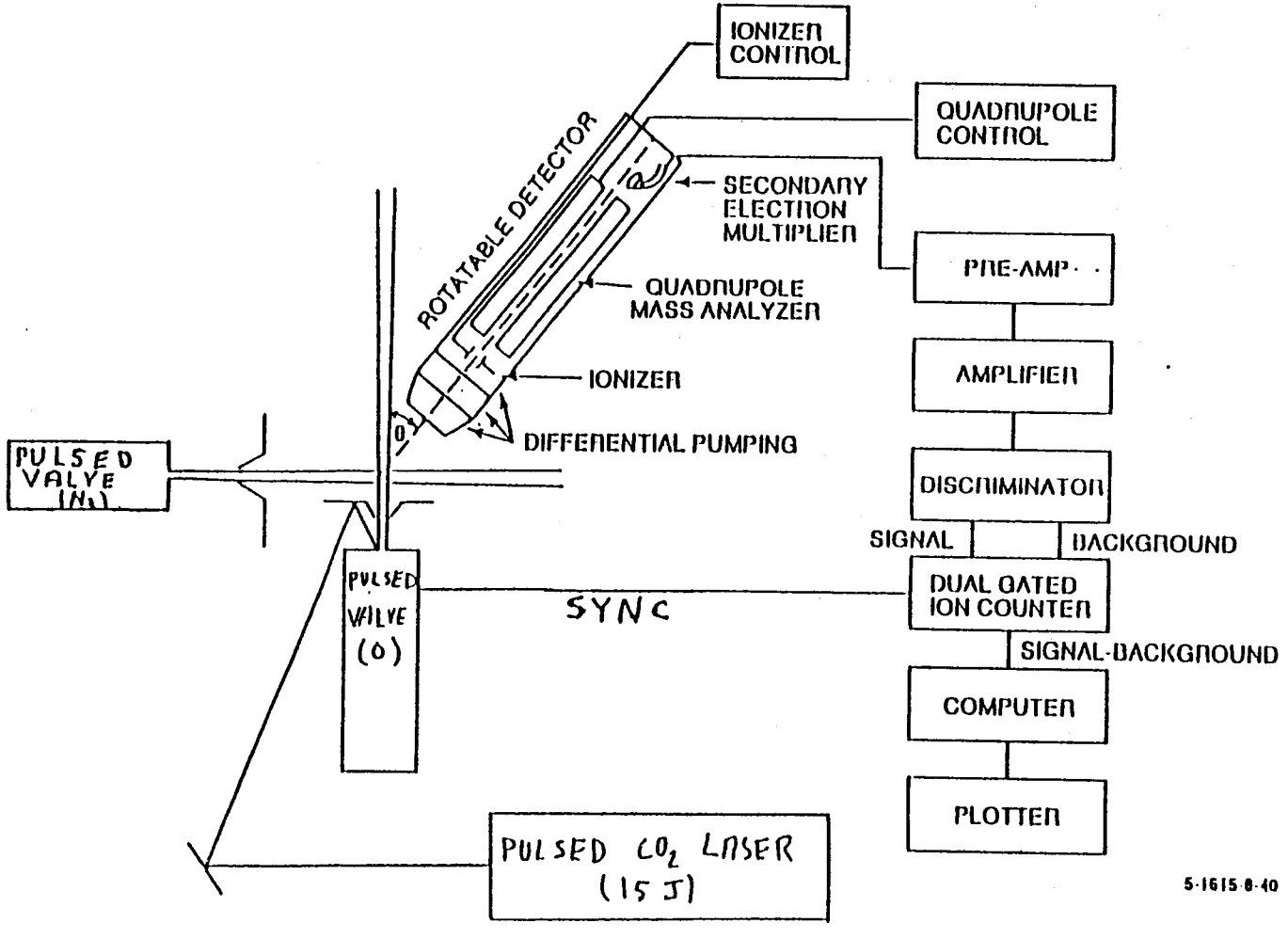

Figure 5. A scematic drawing of the electronics necessary for the data acquisition system.

TIMING DIAGRAM

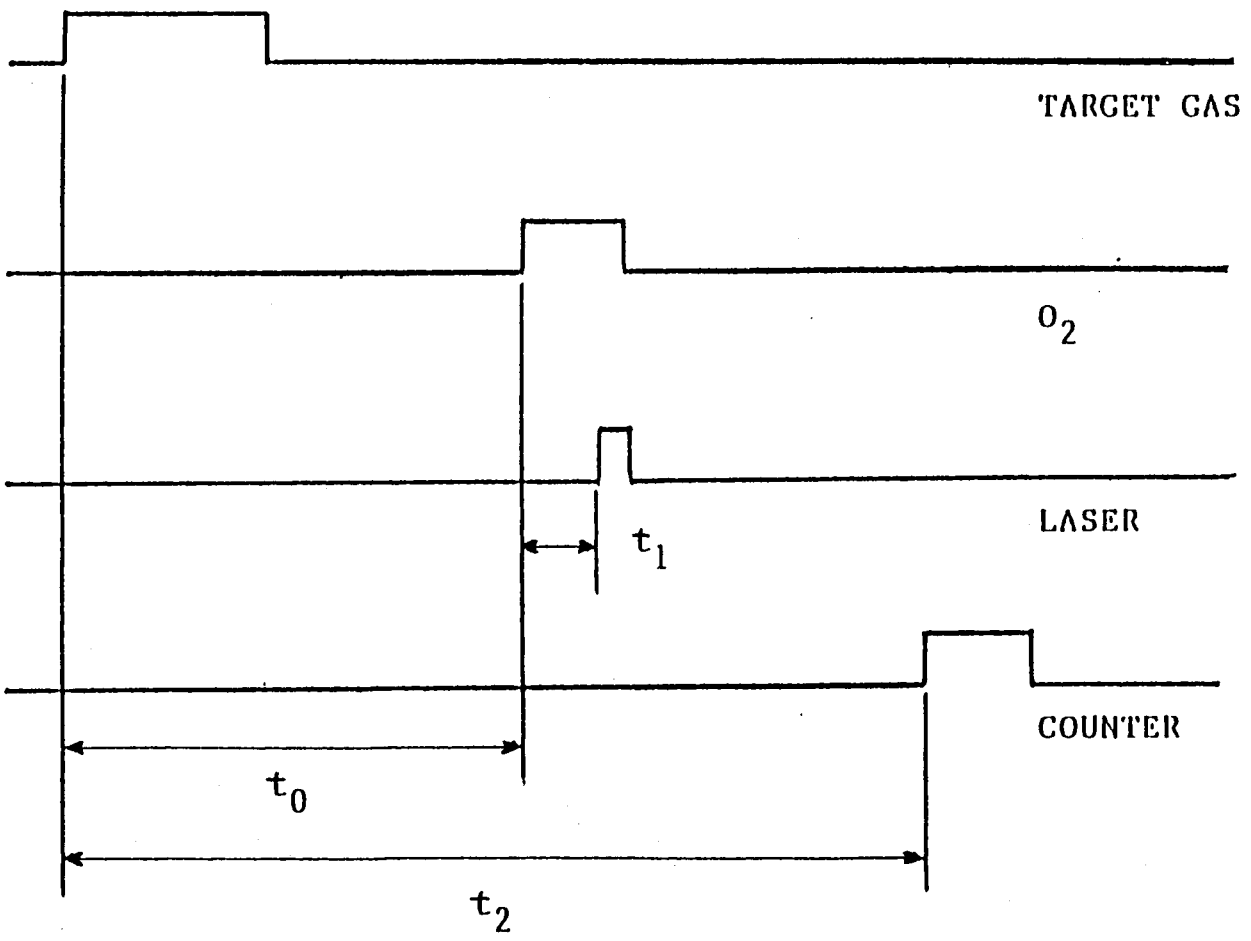

Figure 6. The timing diagram for the various events neccesary for the ADCS measurements.

degrees. Their results indicated that the room-temperature gas cell had the greatest effect on averaging over possible angular structure in the ADCS, whereas the crossed beam configuration had the least effect. Because of this, it was decided to use the crossed beam configuration for the majority of the measurements and possibly use the static gas cell only for normalization of the relative measurements.

DIFFERENTIAL CROSS SECTION MEASUREMENTS

There are several different ways to express the variables necessary for angular differential cross section (ADCS) measurements. Following the notation of Park and coworkers,[6-8] an apparent differential cross section is given by:

$$\frac{ds}{d\Omega}(\theta, E) = \frac{I(\theta)}{I_o \, n \, l \, \Delta\Omega} \qquad (1)$$

where $I(\theta)$ is the scattered signal measured at the lab scattering angle θ_L, I_o is the total integrated current (see the discussion in Refs. 6-8 whether this should be incident or elastic), n is the target number density, l is the interaction path length, and $\Delta\Omega$ is the solid angle subtended by the detector. In our case, the target beam is produced by a free jet expansion technique and thus nl is not known precisely. Because of this, the ADCS will be reported as relative measurements. A scale factor can, at a later time, normalize these relative measurements to produce absolute ADCS. Because both the source and target are crossed beams, and the mass spectrometer rotates in the plane formed by these two beams, nl will also have an angular dependency that must be accounted for. The term "apparent" ADCS ($ds/d\Omega$) is used in Equation 1 because several apparatus effects must be removed from the data before "true" angular differential cross sections ($d\sigma/d\Omega$) can be obtained. There are several methods that have been employed to arrive at $d\sigma/d\Omega$, and the reader is referred to one of the references.[6-10] For the remainder of this report, it is assumed that "true" ADCSs (either relative or absolute) have been obtained unless stated otherwise.

The kinetic energy of the scattered projectile will change depending on the angle of deflection it occurs during the collision. This kinematic energy loss is the result of the transfer of kinetic energy from the projectile to the recoiling target. Table I shows the various energies and angles in the laboratory reference frame of the collisional partners. Because the detection efficiency of the mass spectrometer is energy dependent and the scattered projectile energy changes significantly as a function of scattering angle, the data will have to be adjusted to account for this variation. A preliminary analysis of this kinetic energy loss was conducted by the approximation that the thermal N_2 beam is at rest. This approximation was used in the data shown in Table I. A more realistic model will

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Table I

Kinematic Scattering Program — T. J. Kvale — 09 August 1988
Eprojectile(eV) = 5.0000 Etarget(eV) = 0.0000
Mprojectile(amu) = 16.00 Mtarget(amu) = 28.00
Target Angle(deg) = 0.000
Internal state excitation energy (eV) = 0.0000

Scattering Angle(deg)	Escat(eV)	Recoil Angle(deg)	Erecoil(eV)
0.000	5.0000	180.000	0.0000
5.000	4.9783	273.927	0.0217
10.000	4.9137	277.847	0.0863
15.000	4.8080	281.753	0.1920
20.000	4.6638	285.635	0.3362
25.000	4.4849	289.487	0.5151
30.000	4.2759	293.301	0.7241
35.000	4.0418	297.066	0.9582
40.000	3.7884	300.775	1.2116
45.000	3.5216	304.416	1.4784
50.000	3.2473	307.980	1.7527
55.000	2.9716	311.455	2.0284
60.000	2.6996	314.831	2.3004
65.000	2.4364	318.095	2.5636
70.000	2.1860	321.239	2.8140
75.000	1.9516	324.251	3.0484
80.000	1.7357	327.123	3.2643
85.000	1.5395	329.849	3.4605
90.000	1.3636	332.425	3.6364
95.000	1.2079	334.849	3.7921
100.000	1.0713	337.123	3.9287
105.000	0.9528	339.251	4.0472
110.000	0.8506	341.239	4.1494
115.000	0.7632	343.095	4.2368
120.000	0.6888	344.831	4.3112
125.000	0.6258	346.455	4.3742
130.000	0.5726	347.980	4.4274
135.000	0.5280	349.416	4.4720
140.000	0.4908	350.775	4.5092
145.000	0.4601	352.066	4.5399
150.000	0.4349	353.301	4.5651
155.000	0.4146	354.487	4.5854
160.000	0.3987	355.635	4.6013
165.000	0.3868	356.753	4.6132
170.000	0.3784	357.847	4.6216
175.000	0.3735	358.927	4.6265
180.000	0.3719	360.000	4.6281

account for the thermal velocity of the target. Work is in progress on the modifications to the computer code to incorporate this condition.

There are a variety of methods that have been employed to obtain absolute angular differential cross sections (ADCS). Included in this report is only a brief introduction and the reader is referred to the references for more complete descriptions. An exhaustive review of all the work devoted to it is beyond the scope of this report.

1) The direct measurement of all parameters required for ADCS.[6-8,10]

   This requires that all the parameters in Eq. 1 are known exactly. This has been applied to experiments in the keV impact energy region with success. In these experiments, the scattered beam is treated identical to the incident beam, thereby cancelling the effect that the detector efficiency has on the measured currents $I(\theta)$ and I_o in Eq. 1. Also, n, l, and $\Delta\Omega$ are geometrically defined or measured. In the proposed experiment, these measurements would be difficult and accounting for the kinematic energy loss by an increase in the projectile energy would vary significantly that energy.

2. Normalize to previous absolute work.[11-13]

   Essentially, this would place a multiplicative factor in Eq. 1 and would account for the uncertainty in the exact value of nl. Experimentally, the relative ADCS could be normalized to other (or the same) targets under similar experimental conditions. A second option would be to integrate the relative ADCS to obtain total cross sections (TCS) and then normalize the TCS to absolute TCS. The third method of normalization involves normalizing the relative ADCS (or TCS) to a reliable theoretical calculation. The fact that the atomic oxygen source may produce a mixture of $O(^3P)$ and $O(^1D)$ states, as well as the inability of this apparatus to distinguish ro-vibrationally inelastic scattering complicates this last approach.

RELATED WORK

Although ADCS for 5 eV atomic oxygen scattering from molecular nitrogen have not been reported, an indication for it can be obtained from the keV scattering data using the classical approximation.[10,14,15] The basic tenets of this approximation involve the role that the impact parameter b plays in the scattering. For small angle scattering, the product of impact energy times the scattering angle can be expanded in a series in b,

$$\tau(E\theta) = E\theta = \tau_0(b) + E^{-1}\tau_1(b) + \ldots \quad (2)$$

The reduced differential cross section can also be expanded in a series of τ,

$$\rho(\theta,E) = \theta\sin\theta\frac{d\sigma}{d\Omega} = \rho_0(\tau) + E^{-1}\rho_1(\tau) + \ldots \quad (3)$$

If it is valid to truncate both series with the first term, then it is a straightforward task to use the higher energy keV data to predict what the 5 eV ADCS will look like.[15-17] This approach was taken by K. Smith[17] and his results are shown in Figure 7.

A preliminary series of experiments can be performed prior to the O + N_2 experiment which use thermal helium as the projectile rather than atomic oxygen. This will provide the opportunity to compare with previous measurements. The work by Keil et al.[18] have the possibility of detecting scattering both in the scattering plane and a right angles to it. The work by Beneventi et al.[19] is a later, high resolution study, and their results are shown in Figure 8. This series of experiments will require only minimal modifications to the experimental procedure and will be useful both as a check against systematic errors and as an extension of their work.

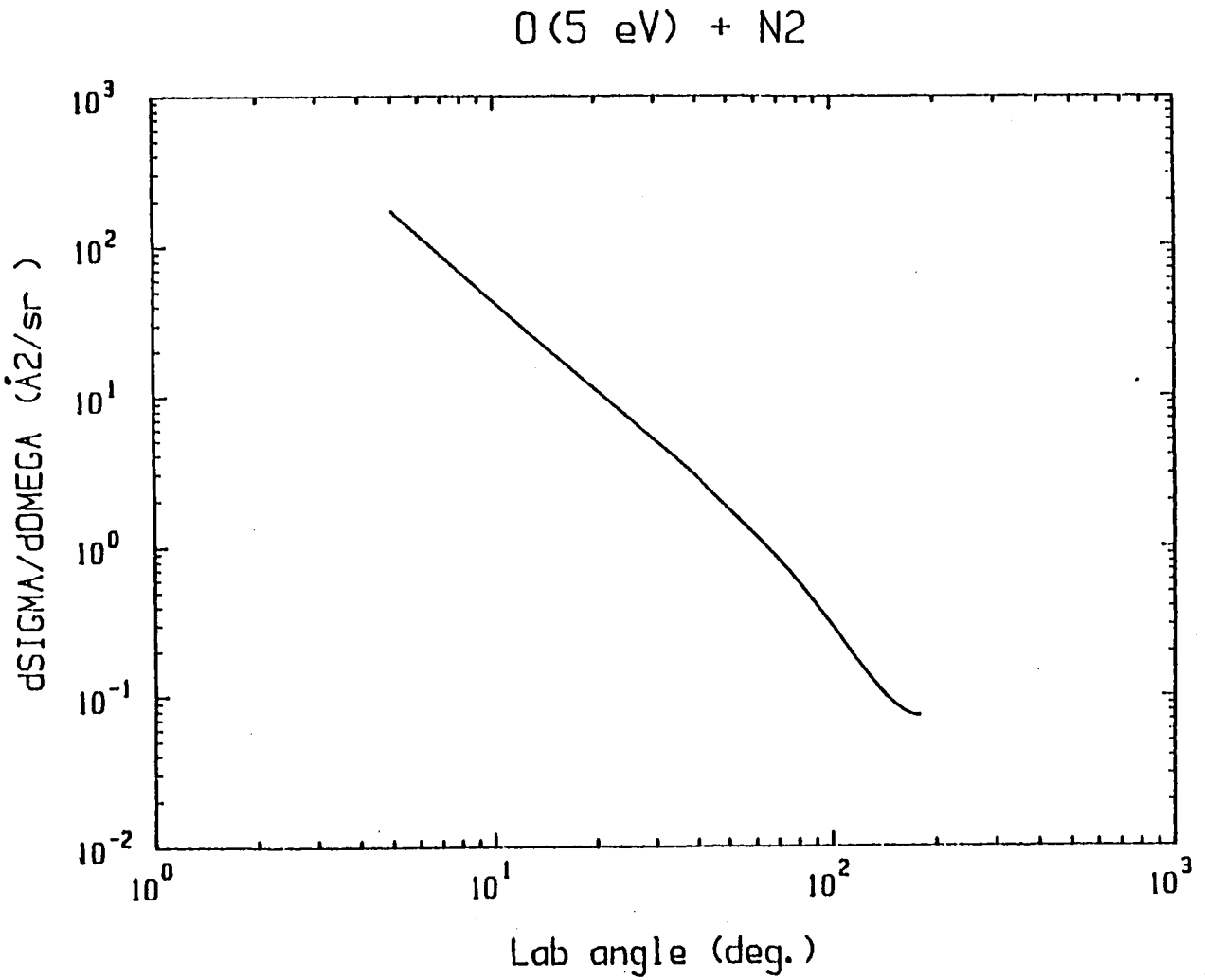

Figure 7. The prediction of O(5 eV) + N_2 angular differential cross sections from Ref. 17.

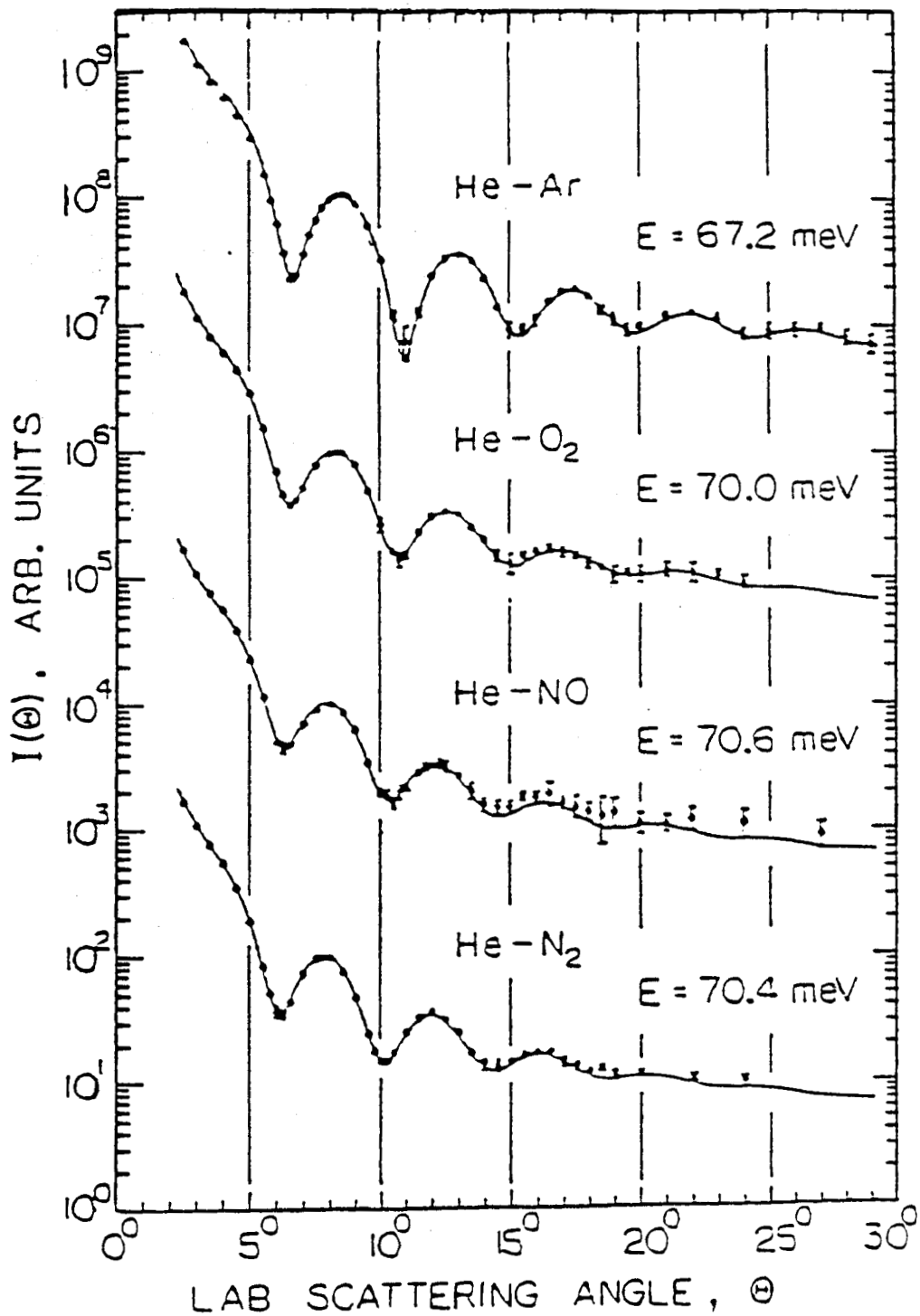

Figure 8. Thermal energy helium scattering from various targets. Graph is from Ref. 18.

CONCLUSION AND RECOMMENDATIONS

This report contained only a brief introduction to the SSL Atomic Scattering Facility (ASF). The design of it is in an advanced stage, and components are being acquired. The parameters required for the measurement of angular differential cross sections (ADCS) have been outlined and their implementation in this apparatus was discussed. In addition, several methods that have been used on other experiments to arrive at absolute differential cross sections were listed. The angular dependence of the ADCS will give an indication as to which method would be best suited for this experiment.

Some of the experimental tasks include the preliminary thermal He + (N_2, O_2) relative ADCS measurements. This is useful to provide a check against systematic errors in the new facility. Two independent measurements by other groups will provide an opportunity for comparison. The output and operating variables of the atomic oxygen source need to the characterized. The large energy spread and the mixture of atomic oxygen states (^3P and ^1D) present in the incident beam will complicate the understanding of the scattering. The functional shape of the relative ADCS will indicate the most desireable method of normalization. Once the preliminary and O + N_2 experiments have been completed, a whole range of other experiments involving other targets will be possible.

The SSL Atomic Scattering Facility is designed to address some uncertainties in our knowledge of few eV atomic oxygen scattering. This is a difficult impact energy region to study experimentally due to the complexity of producing intense few eV neutral atomic oxygen beams. Also, few theoretical calculations are available in this energy region for neutral atomic oxygen impact. For these reasons, this apparatus should make a significant contribution to the understanding of neutral atomic oxygen interaction with various atoms or molecules in the few eV impact energy region.

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