The H+ and Ho sbombardment of O2 in the 10-120 kev range
by Edward Andrew Teppo

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE in Physics
Montana State University

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ABSTRACT

A study has been made of the relative emission cross sections of hydrogen atoms and protons incident on oxygen in the 10-120 kev range. The results for Lyman alpha emission were compared to those of nitrogen. At 1304 A, the hydrogen atom and proton were shown to have nearly the same excitation cross section. Numerous atomic oxygen lines were seen indicating excitation was present to some dissociative states of the molecule.

Theoretical calculations were limited to the Born approximation largely because of the uncertainty in the wave function of the electronic energy levels.

INTRODUCTION

In the past thirty years great progress has been made in particle accelerators and, hence, in ion-atom collisions. As a result, scientists have learned a great deal about the colliding particles and their interaction in a collision. The evaluation of collision cross sections is a valuable aid in this interpretation. Experimental methods are the most feasible means of studying these cross sections.

The study of the physics of the upper atmosphere has increased rapidly since 1958. Cosmic radiation, which consists largely of energetic protons, is constantly incident upon our upper atmosphere. Fortunately this radiation is largely absorbed there. But such absorption processes are not well understood. Research is being done toward this interpretation through analysis of the aurora.

Since the major components of the atmosphere are nitrogen and oxygen and the proton accelerator is readily available, scientists can do the equivalent of space physics in the laboratory. Their capabilities are limited by their apparatus. Commonly, general studies of collision processes are not possible; only particular processes are studied in great detail.

Several cross section studies have been made in oxygen which show some similarities to results obtained in this study. The similarities lie in the shape of the cross section curves obtained.

Unfortunately the theoretical calculations of such cross sections are unreliable. In general, they have been "re-done" until they agree

appropriately with experimental results. Many of the theoretical calculations made have originated from consistencies found in experimental results. As a result, such calculations done in this study are unavoidably minimal.

THEORY

Atomic Collisions

The encounter of a projectile with a target gas may lead to elastic, inelastic and radiative collisions. In an elastic collision, there is no change in the internal energy of the colliding particles; in an inelastic collision some of the translational energy of the projectile is transferred to internal energy of the molecule. Inelastic collisions may lead to the emission of electromagnetic radiation. In extreme cases, the projectile may be captured by the molecule and an ion or excited state is produced.

Collisions are normally described by the following notation:[1] "1" refers to a singly charged positive ion; "0" refers to a neutral atom or molecule; "'" refers to an excited state; "e" refers to an electron; a "/" separates the initial and final products of the collision; and "( )" refers to two or more particles bound to a system. Using this notation, the most pertinent collisions in this study include

i)	10/01	Charge transfer
ii)	10/10'	Excitation
iii)	00/0'0	Excitation
iv)	10/1'0	Excitation

Other processes include

v)	10/11e	Ionization
vi)	1(00)/100	Dissociation

Ionizing collisions where an electron is taken from the projectile are referred to as stripping, e.g.,

$$H^{o} + O_2 \longrightarrow H^{+} + O_2 + e$$

The measurement of Lyman alpha radiation (1216 A) by a similar interaction implies only the excitation process

$$H^{o} + O_2 \longrightarrow H^{o}(2p) + O_2$$

which requires less energy.

The charge transfer cross section implies the evaluation of interactions like

$$H^{+} + O_2 \longrightarrow H^{o} + O_2^{+}$$

The measurement of Lyman alpha radiation demands an interaction such as

$$H^{+} + O_2 \longrightarrow H^{o}(2p) + O_2^{+}$$

i.e., besides the transfer of an electron from an oxygen molecule to a proton, the electron must be excited to the lowest-lying excited state of the atom. This process then requires more energy than the charge transfer process. Therefore an attempt at making exact comparisons in the results found at 1216 A and those of stripping and charge transfer should be avoided.

If, during a collision between two systems of particles, one or more particles are exchanged between them, the process is known as a rearrangement collision. It is energetically possible that 10/20e (ionization) and 00/10e (ionization by rearrangement) occur. Double excitation becomes quite probable at high energies.

Cross Sections

Let n_i denote the number of atoms excited to the state i. Then[2]

$$\frac{dn_i}{dt} = NIQ_i + \sum_{k>i} A_{ki} n_k - \sum_{j<i} A_{ij} n_j$$

is the time rate of change of the number of atoms excited to state i. The terms contribute as direct excitation to state i, cascading from upper k to state i, and the decay of state i to the state j, respectively.

Assuming only direct excitation, then

$$Q_i = n_{ij}(L)/NIL$$

denotes the excitation cross section to the state i, where $n_{ij}(L)$ represents a number density of photons emitted from such a transition, I is a measure of the incident beam flux, N is the gas density (proportional to the pressure), and L is the observed path length of interaction.

To enable the experimenter to do absolute cross section measurements, the quantum yield (current of the detector per incoming photon per second) and the value of L must be calculable. Such measurements have been done by several experimenters for ion-atom and atom-atom collisions.[3,4] These calculations enable others to do relative cross section measurements by comparative techniques.

Some emission cross sections have recently been shown to have several maxima as function of energy.[5] The oscillatory behavior in the cross sections extend almost to the threshold energy. This result contradicts the adiabatic approximation which assumes a gradual decrease

in the cross section below a maximum characteristic of the relative velocity of the projectile and the interacting electron-orbital. Since threshold energies are normally in the ev range, the present study did not reveal this characteristic.

The Massey criterion predicts a characteristic interaction distance $\underline{a}$ at a maximum in the cross section given by the equation

$$\frac{a}{v} \cdot \frac{\Delta E}{h} \simeq 1$$

where ΔE is the difference in internal energy between the two states of the system and $\underline{v}$ is the relative velocity of the colliding particles. Recent studies indicate that the levels involved in the collision approach each other in energy as R, the internuclear separation, decreases, i.e., they approach a pseudo-crossing. Only if the optically allowed excited states are widely separated from the initial state of the compound system are the molecular interactions negligible and hence, the probability of excitation small at low energies.(6)

Experimental results imply a strong velocity dependence of the projectile and the interacting electron at high energies. Such analogies may then be applied to an equivalent velocity electron in proton cross section measurements.

Theoretical Calculations

The study of cross sections of atomic and molecular processes are of great value in providing information about how constituents in an

interaction behave. The experimental work in all but the simplest atoms and molecules forms the basis of our understanding in collision processes. Since the many-body problem cannot be solved exactly, theoreticians can make only approximate calculations in the interpretation of such processes. These approximations are indeed necessary to make these calculations feasible. Yet the numerical values obtained are at the expense of unreliability of results.

In molecular physics or quantum chemistry, numerous methods of estimating wave functions have been introduced since the advent of quantum mechanics. At present, the best wave functions (those which agree best with experiment) have been found by using self-consistent field theory. Other interpretations have produced the Hartree-Fock calculations, the method of Roothaan, the distorted wave approximation, the Heitler-London theory, molecular orbital theory, and the valence bond theory by the chemist. These methods have met with varying degrees of success. Computer programs have been written for the approximate interpretation of atomic and molecular collisions incorporating the above theories, occasionally in concert. The calculation of electronic energy levels by such methods have yielded some very satisfactory results. However, these methods have not necessarily given reliable matrix elements as needed in the evaluation of transition probabilities.

Theoretical calculations for atomic collisions have been carried out using the impact parameter method[7] and by the wave treatment.[8] Such calculations have been largely restricted to H, H^+, He and He^+.

Theoretical Born cross sections have been done using an ion as the incident projectile. These calculations have shown that a typical cross section at high energies should vary as $E^{-1} \ln E$ for optically allowed transitions. Its validity for protons has been questioned below 200 kev.

Recently Born cross sections have been done for atom-atom collisions[9] due to Ochkur's contribution.[10] Unreliable wave functions do not allow such an evaluation in this experiment. The Born cross sections for electrons for optically allowed transitions is given to a first approximation by

$$Q = \frac{4\pi m^2 e^4}{k^2 h^4} |Z_{on}|^2 \ln \frac{2mv^2}{E_n - E_o}$$

The interaction between ions (or atoms) and molecules does not allow such a calculation.[1] It is not expected then that the Born approximation is reliable in the evaluation of cross sections for atom-molecule collisions.

The Oxygen Molecule

See Table I.[11]

The $^3\Sigma_g^-$ ground state of the oxygen molecule is paramagnetic. Unlike most ions, the O_2^+ ion has a larger dissociation energy and more bonding electrons than does O_2.

The electronic configuration of the oxygen molecule in atomic orbital theory is

$$1s^2 2s^2 2p_x^2 2p_y 2p_z$$

or equivalently in molecular orbital theory.

$$KK(\sigma_g 2s)^2(\sigma_u 2s)^2(\sigma_g 2p)^2(\pi_u 2p)^4(\pi_g 2p)^2$$

Both atomic orbital and molecular orbital theory have been used with limited success in the molecular interpretation of oxygen.

Since the oxygen molecule does not have a closed-shell configuration, its theoretical description is extremely difficult. Some unique contributions to the atomic orbital description have simplified electronic energy level designations a great deal. Yet the complexities in large part still remain.[12,13]

THE EXPERIMENT AND APPARATUS

Apparatus Description

See Figure 1. The protons were produced in a rf-driven ion cell[14] by introducing hydrogen gas into the system by means of a palladium leak. Initial pumping of the polyethylene line and trapping with liquid air reduced the possibility of water vapor entering the system.

Once ions were produced, the extraction, focusing and solenoid voltages were adjusted in unison with the high voltage to accelerate the ions down the accelerator. Additional focusing by an electrostatic quadrupole lens reduced the beam divergence prior to its entrance into the mass-analyzing magnet.

The beam contained approximately 10% undesirable ions; the mass analyzer allowed their removal by their smaller e/m ratio. The production of hydrogen atoms was also present in the beam and corrections due to their presence were necessary.

The composite beam, after passing through an aperture at A, entered the exchange cell which was used to produce a much higher density of hydrogen atoms in the beam. This was done by introducing hydrogen gas into the cell by means of a variable leak. At 50 Kev, approximately one-half of the particles coming out of the exchange cell were neutral.

With the high density of hydrogen atoms in the beam, the charged particles were then removed by electrostatic deflection. To insure that no charged particles were entering the interaction region, varying the deflection potential produced no noticeable change in the current at the Faraday cage.

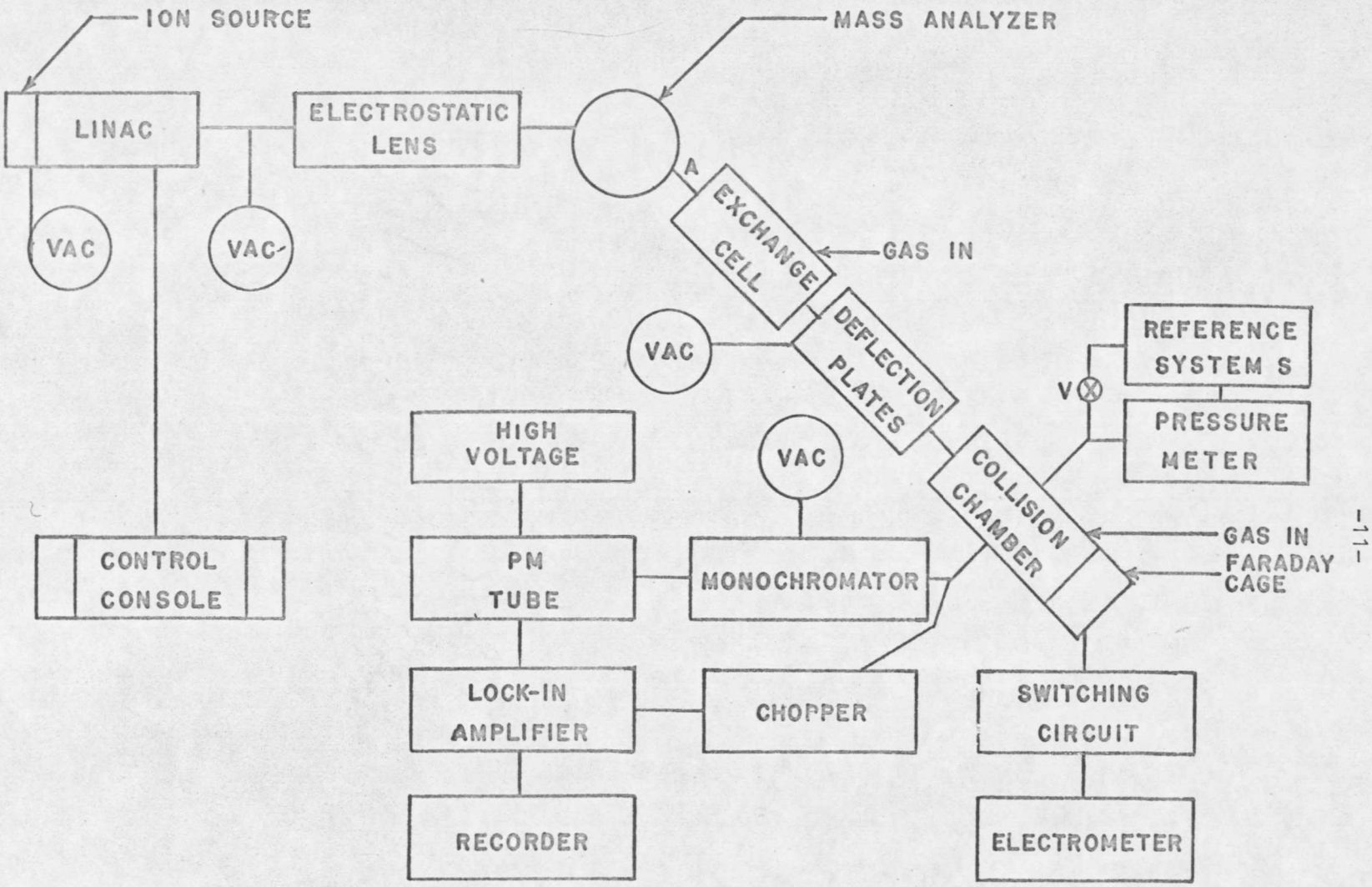


FIG. I THE APPARATUS

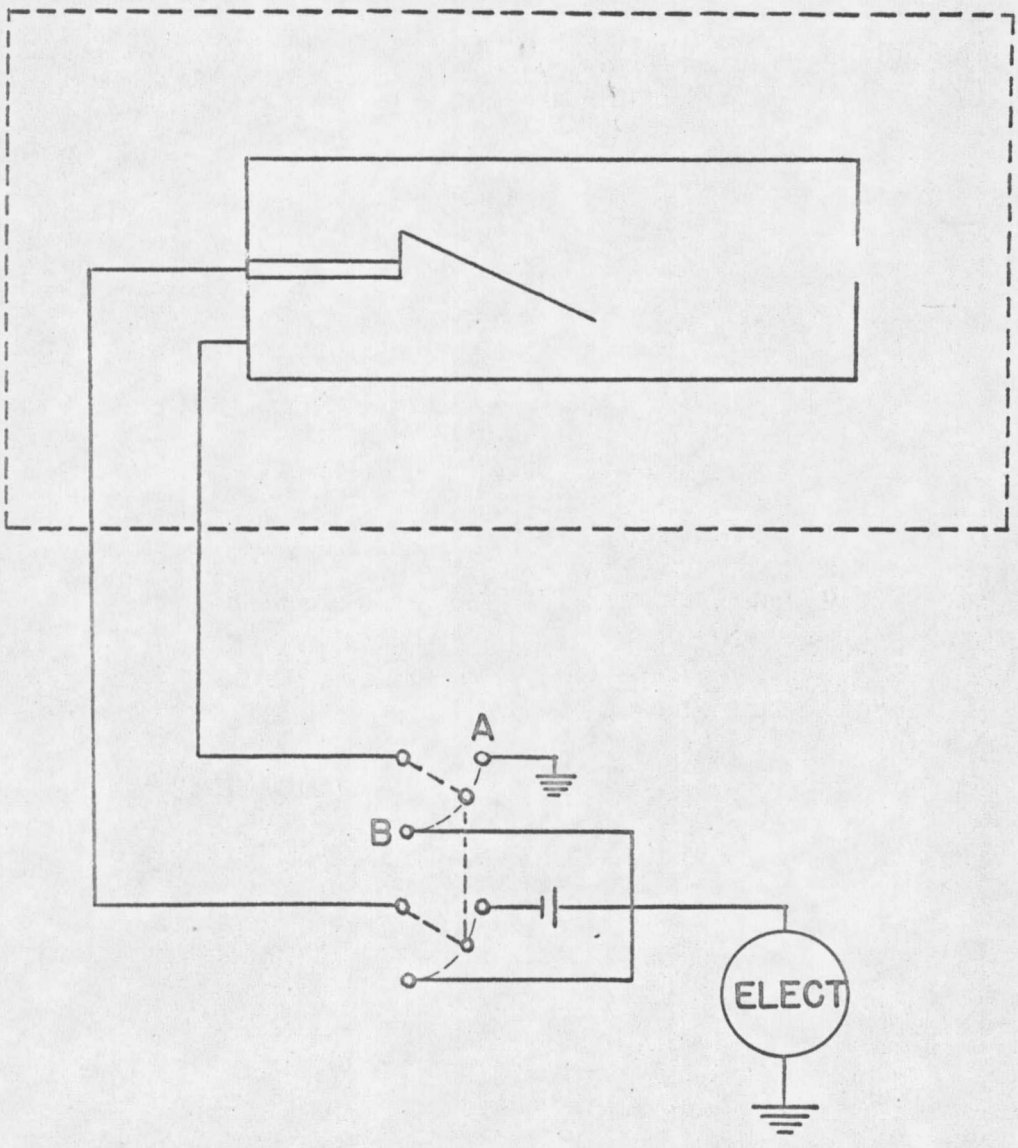
The gas used in the interaction region was introduced with a variable leak. A reference system S incorporated with a pressure meter (MKS Baratron, Type 77) was used to measure the pressure in the interaction region. By initially setting the pressure difference as null with V open, accurate pressure measurements were assured. The pressure change over a single run was negligible.

The detection system consisted of a Faraday cage with emitter and collector. See Figure 2. When particles entered the detector and struck the Mo emitter, the net current into the cup was easily measured. Corrections were necessary for the production of secondary electrons in the detector. However, by calibrating the secondary electron production efficiency as a function of energy, the number of secondary electrons produced per incident ion could be found. Stier and Barnett[15] have obtained the relative rate of secondary electron production of hydrogen atoms and protons as a function of energy in oxygen gas.

The cup potential was varied to be sure that no secondary electrons were escaping from the Faraday cage. The total current detected at the cup in position A in Figure 2 is

$$i_t = N'i_+ + Ni_o + i_+ .$$

By including the deflection voltage only the Ni_o term contributes to i_t. Therefore these two readings give the values of i_t and Ni_o. In position B, the entire Faraday cage is at the same potential and the current indicated is that of protons. We can therefore calculate N', the efficiency of secondary electron production for protons. The secondary



DETECTION SYSTEM

FIG. 2

electron production efficiency for hydrogen atoms from that for protons since their ratio is known from the results of Stier and Barnett. Intermediate points were taken but were not included in Figure 3. The true hydrogen atom and proton current must then include this correction. The net effect was to increase the cross sections at higher energies by approximately 20%.

The monochromator was mounted with its slits perpendicular to the projectile beam in the interaction region. The dispersion of the monochromator was 53.3 A/mm. The monochromator was blazed at approximately 1500 A. Sodium salicylate was used on the quartz window of the photomultiplier tube.

The EMI 9558 QB photomultiplier tube was operated at 1700 volts negative. To reduce the noise level, a liquid air-cooled Cu strip was wrapped around its base. The PM tube itself was at high potential on the outside to prevent stray field gradients across the tube boundary.

A 400 c/s Time Corporation tuning fork chopper was placed between the interaction chamber and the monochromator slit. The output signal of the photomultiplier tube was amplified with a PAR JB-4 Lock-in Amplifier. Its output was then chart-recorded.

Beam Production

The four vacuum systems were cold-trapped and diffusion-pumped. The hydrogen line was pumped and cold-trapped as well. By turning on the console power, the palladium leak allowed the diffusion of hydrogen gas into the ion cell. The Cockroft-Walton accelerator is a 10-step equi-

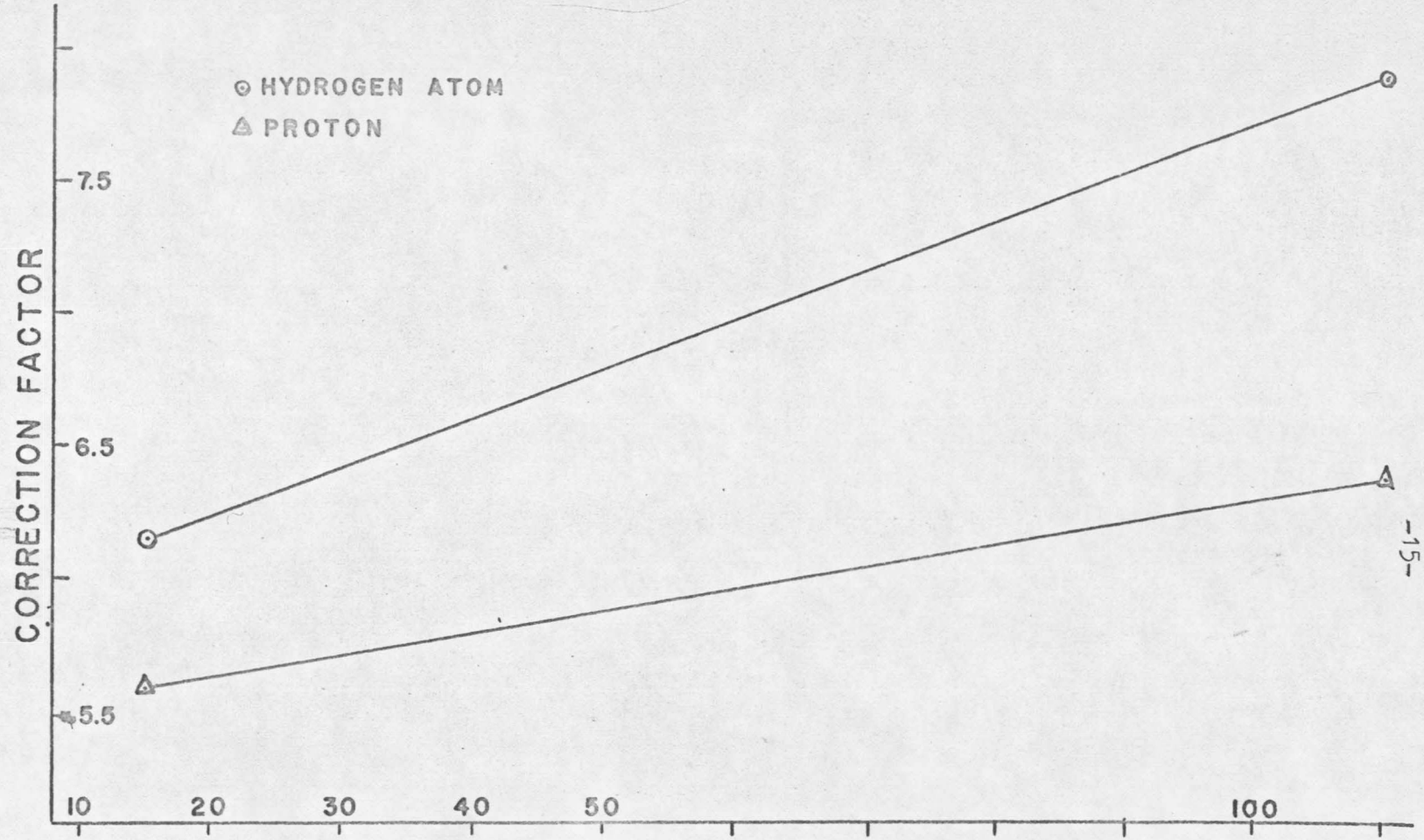


FIG. 3 ELECTRON PRODUCTION CORRECTION FACTOR AS A FUNCTION OF ENERGY (KEV)

potential divider. The potential was measured across a resistance near the last stage and represented the total resistance in a ratio of $1:10^5$.

The initial focusing of the beam into the detector was done by using the mass analyzer. Care must be taken to avoid beam reflection from the wave guide and possible use of the incorrect beam component. The electrostatic lens potential, as well as those of extraction and focusing, was increased approximately linearly with the proton energy. The hydrogen leak rate becomes important at the extremes of energy attainable.

MEASUREMENTS AND RESULTS

Initial Measurements

The feasibility of measuring the cross section for a particular emission process is limited by the transition probability and more directly by the light output from such a transition. Initially, then, scanning the spectra is necessary. When suitably intense band systems or line spectra are observed, the study of the relative cross section for hydrogen atoms and protons is possible. The initial scan was done at relatively high pressure and slit width so that all pertinent transitions were readily seen.

The largest spectral lines were seen at 1216 A (2p-1s) and 1304 A ($^3S-^3P$). See Figures 4-7. The bands and line spectra seen in the 3900 A to 6000 A region are very similar to those of Hughes and Ng.[16] Scanning the spectra at several energies showed that the intensities of the transitions decreased with the projectile energy but no new spectral features were evident. The presence of numerous atomic oxygen lines was not surprising. The excitation of the oxygen molecule was partly (perhaps largely) to dissociative states of the electronic energy levels. The dissociation into excited oxygen atoms could produce such transitions. No significant spectral features were seen in the region from 1350 A to 3700 A.

Low gas pressures insure single particle interactions. The linearity of light intensity as a function of the pressure is used to indicate this characteristic. If secondary processes were not negligible, the shape of the curve would become quadratic. A typical plot of linearity vs. pressure at fixed energy is given in Figure 8.

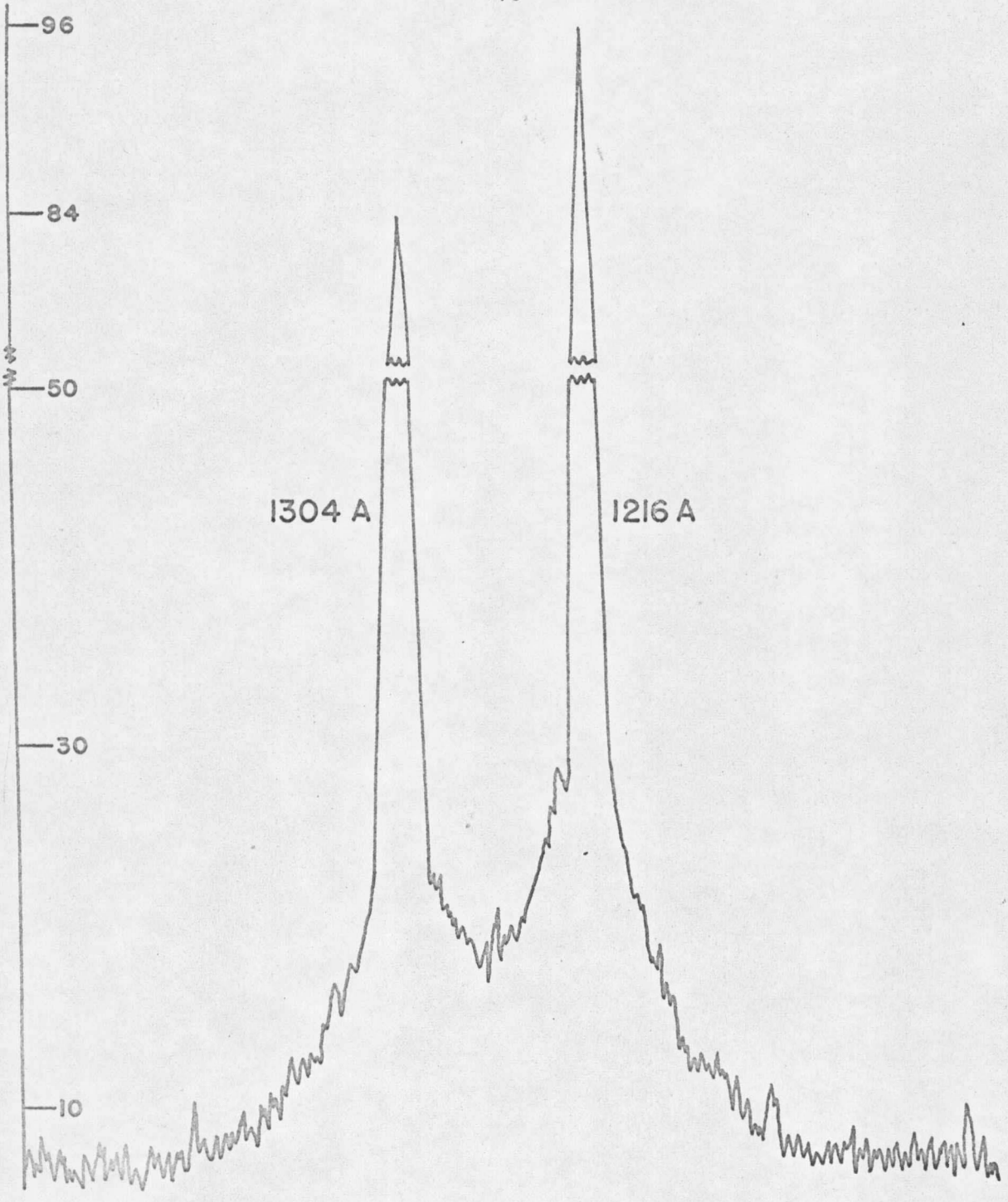


FIG. 4 RELATIVE INTENSITY AT 1216 A AND 1304 A (50 KEV)

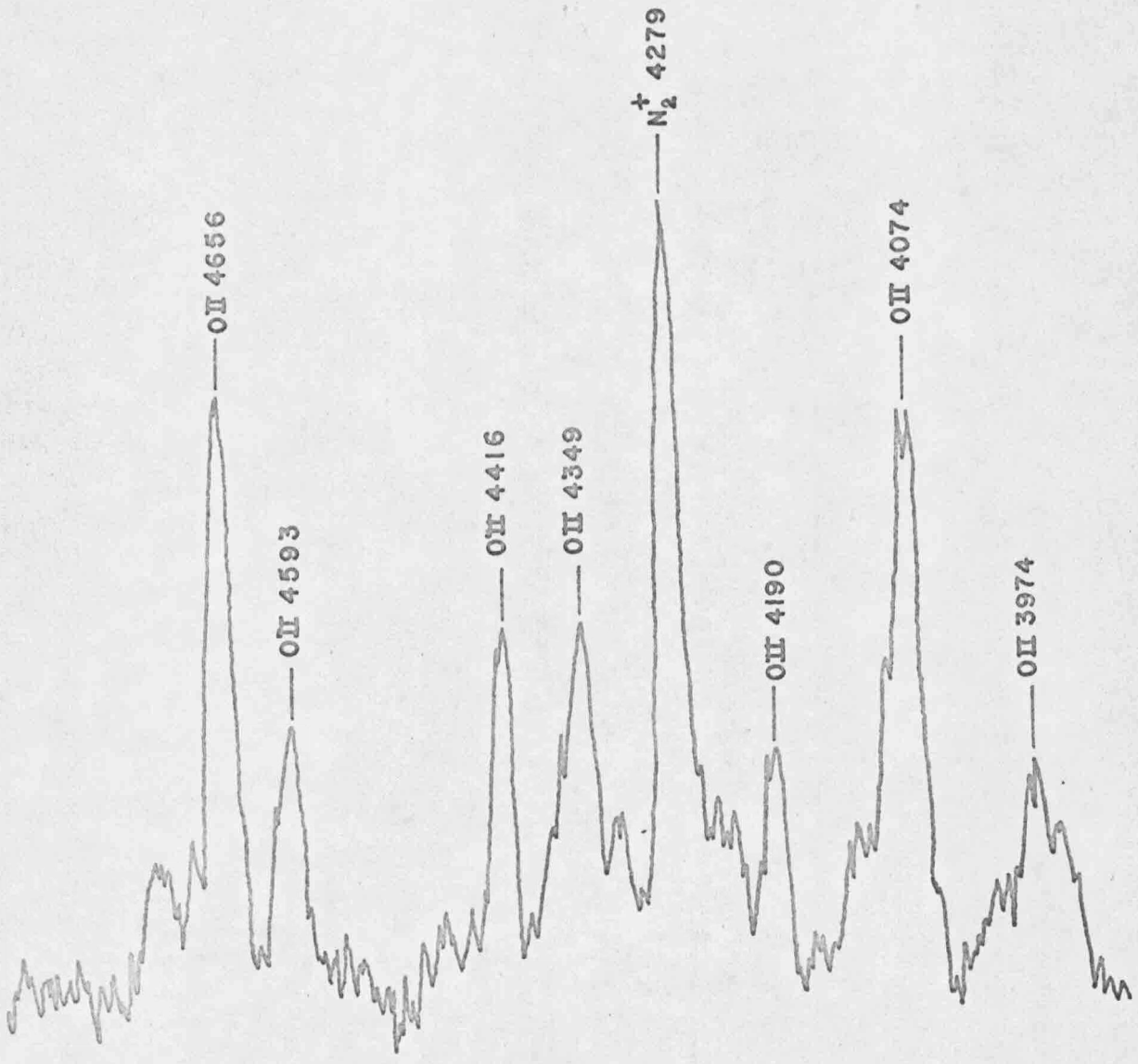


FIG. 5 SPECTRAL SCAN FROM 3900A TO 5000A IN OXYGEN AT 50 KEV

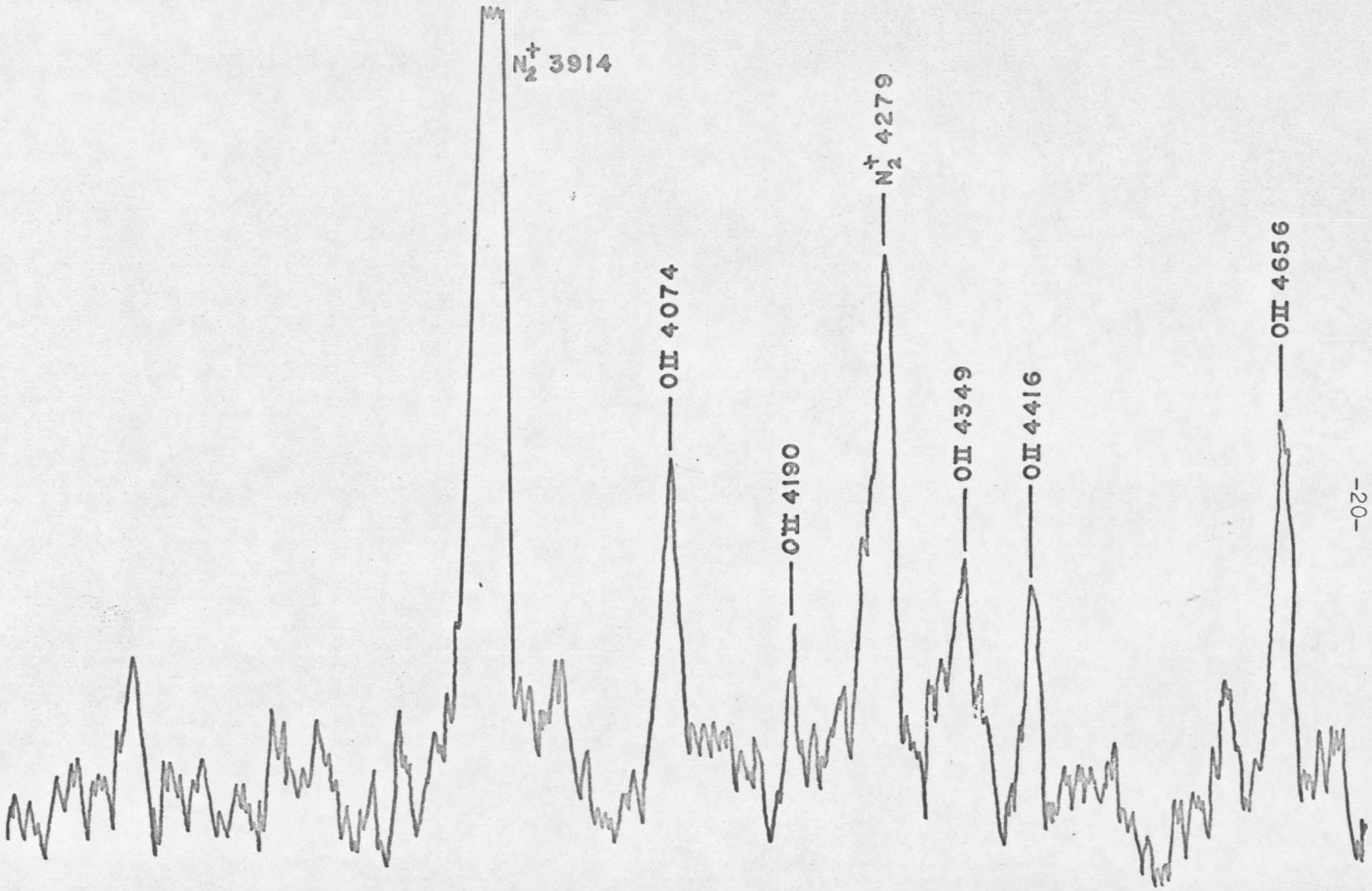


FIG. 6 SPECTRAL SCAN FROM 3600A TO 4700A IN OXYGEN AT 80 KEV

$^4\Sigma_g^- \longrightarrow {}^4\Pi_u$

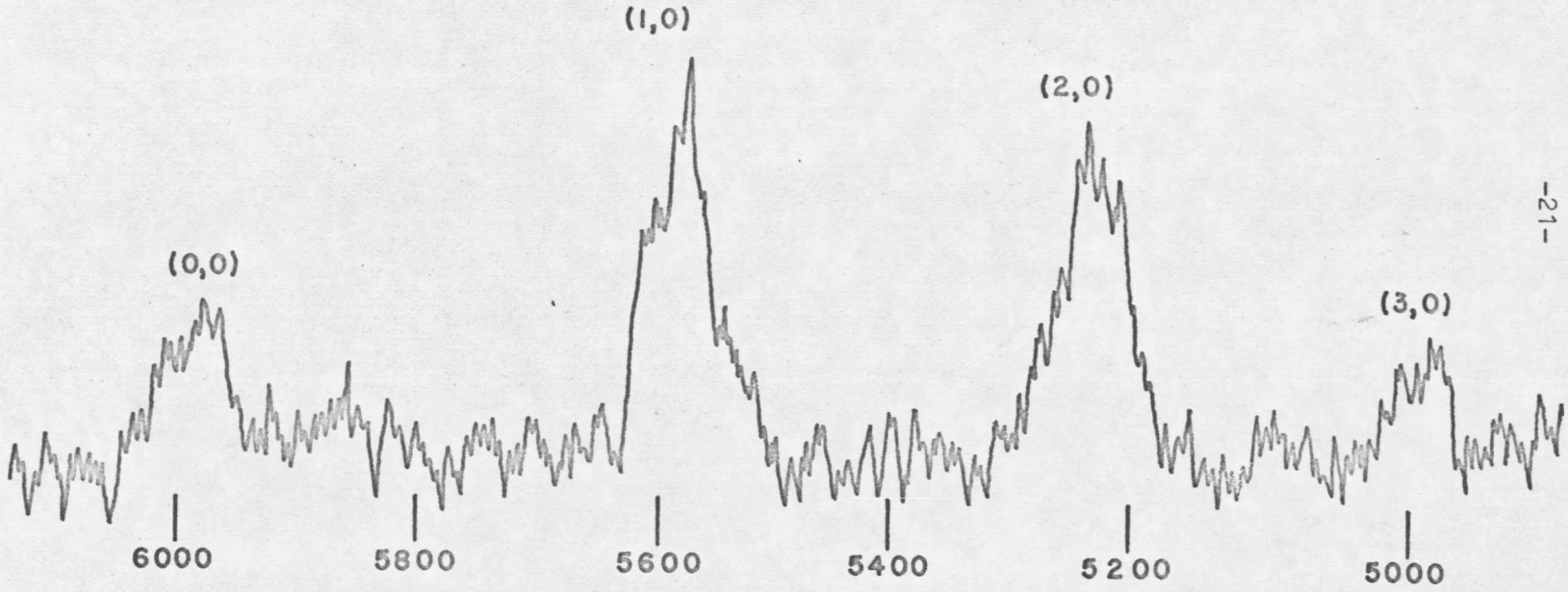


FIG. 7 SPECTRAL SCAN OF O_2^+ BANDS AT 50KEV

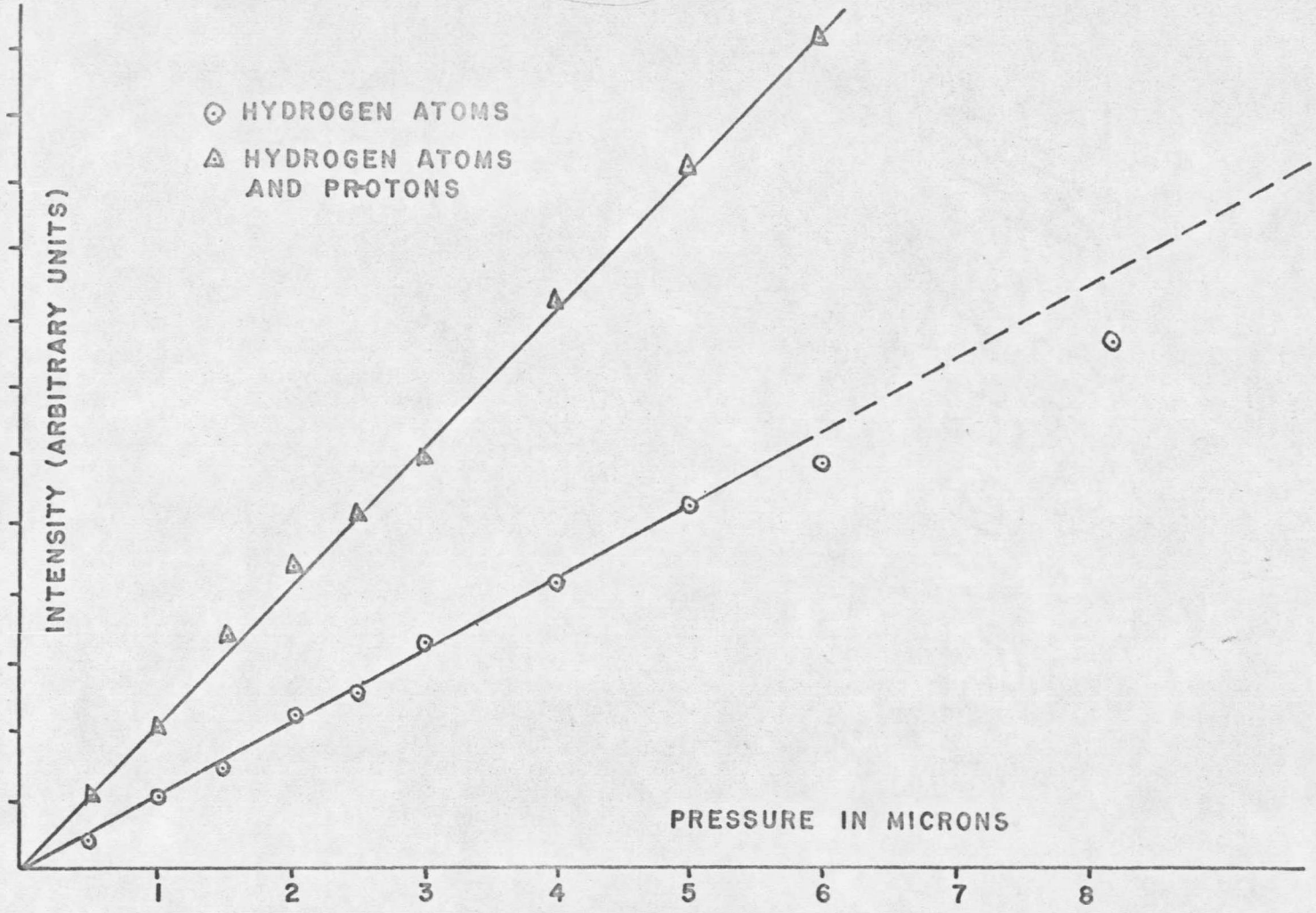


FIG. 8 LINEARITY VS. PRESSURE FOR LYMAN ALPHA AT 50 KEV

When hydrogen gas was introduced into the exchange cell, a different background correction was necessary.

Measurements at 1216 A

Analysis of Results

The pressure linearity measurements were also done at 1216 A to insure that the secondary processes were negligible. The light intensity was much smaller for hydrogen atoms (as was the beam current) and the statistical error was correspondingly larger. These cross sections are given in Figure 9. The results of this collision for nitrogen have recently been done.[17] The following comparisons were made: (1) results for protons on N_2 and O_2 at 50 kev; and (2) hydrogen atom results were compared to proton results on O_2.

A slight lowering of the neutral cross section was initially found near 50 kev. By making several runs in this region, this lowering did not reappear. The statistical accuracy of the results allow this lowering but the structure itself was not resolvable.

Constancy of the Lyman alpha cross section for hydrogen atoms above 40 kev has not been interpreted absolutely as yet. It is of interest that Dahlberg found a similar results in N_2.

In the lower portion of the cross section curve, its shape is very much like that of charge transfer while at high energy it is similar to that of stripping. Consider the following interactions:

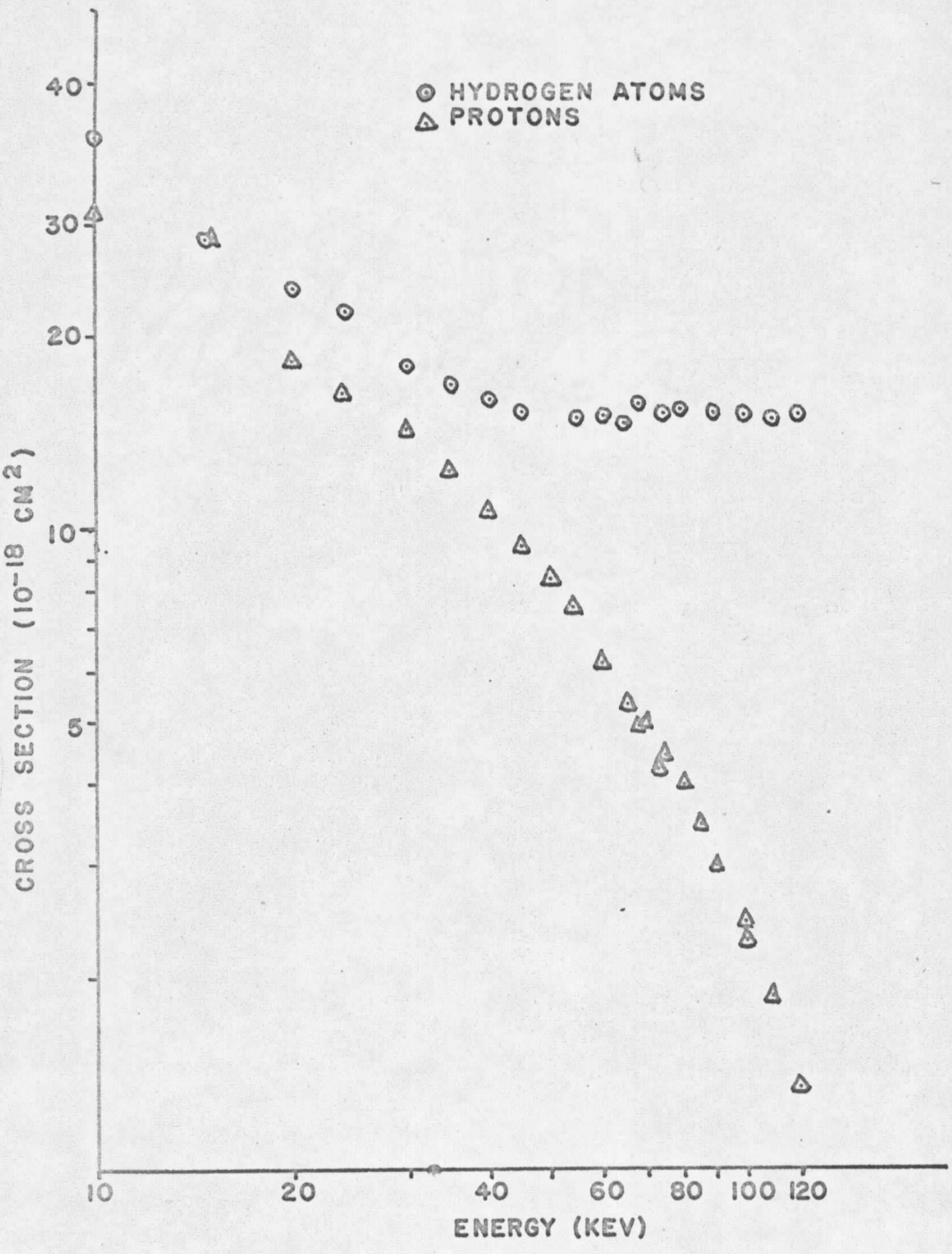


FIG. 9 LYMAN ALPHA CROSS SECTIONS IN OXYGEN

i)
$$H^{o} + O_2 \longrightarrow H^{+} + O_2^{*} + e$$
$$H^{+} + O_2 \longrightarrow H^{o}(2p) + O_2^{+}$$

and that of

ii)
$$H^{o} + O_2 \longrightarrow H^{o}(2p) + O_2^{*}$$

Case i) corresponds to a mechanism which behaves like a charge transfer process. At low projectile energies, the proton may attract an electron so that a hydrogen atom is formed. But as the projectile energy increases, the interaction time does not readily allow such a dual interaction and then case ii), direct excitation, dominates. The later case is similar to a stripping process. Yet not enough energy transfer occurs to allow complete removal of an electron. If i) and ii) are competitive processes, then the character of the curve seems very reasonable, i.e., characteristic of charge transfer at low energy and stripping at high energy. The net result on a neutral cross section curve would then be that of a superposition of charge transfer and stripping. The magnitudes of the Lyman alpha processes are smaller than the stripping process by approximately a factor of 10.

The results of Allison[18] show a very constant stripping cross section from 40-120 kev. Stier and Barnett obtain a very similar result. Their H^{o} cross sections are slightly smaller for oxygen than for nitrogen. The author's Lyman alpha results were slightly smaller than those of nitrogen. This implies then that the transition probability to the 2p

state are in a common ratio of the total transition probability.

In measurements of Lyman alpha from protons on nitrogen, the effect of the 1200 A triplet and 1243 A doublet lines in nitrogen demands that the slits be sufficiently small to prevent their contribution in 1216 A measurements. By alternately using nitrogen and oxygen and allowing sufficient time for the removal of residual gas, the excitation cross section for Lyman alpha for protons in oxygen can be found. To insure that the effects of the residual gas were negligible, the nitrogen and oxygen cross sections were done in both orders and averaged over eight readings.

Theoretical Calculations

A plot of QE vs. ln E is given in Figure 10. The high energy region for hydrogen atoms is nearly linear with positive slope. By substitution of the experimental cross section and the evaluation of the slope, the Born cross section gives

$$|Z_{on}| = 9.0 \text{ A}$$

The diameter of the oxygen molecule is 3.43 A.[19] As was stated earlier, this result can be applied directly only to electrons as the incident projectile. Although the projectile is neutral, the linear dependence at high energy supports the expected results for Born cross sections. A typical interaction distance for an exchange process is 7 A. Surprisingly then, this calculation gives similar results even though the projectile was neutral.

Hasted has suggested that other forms of the interaction potential

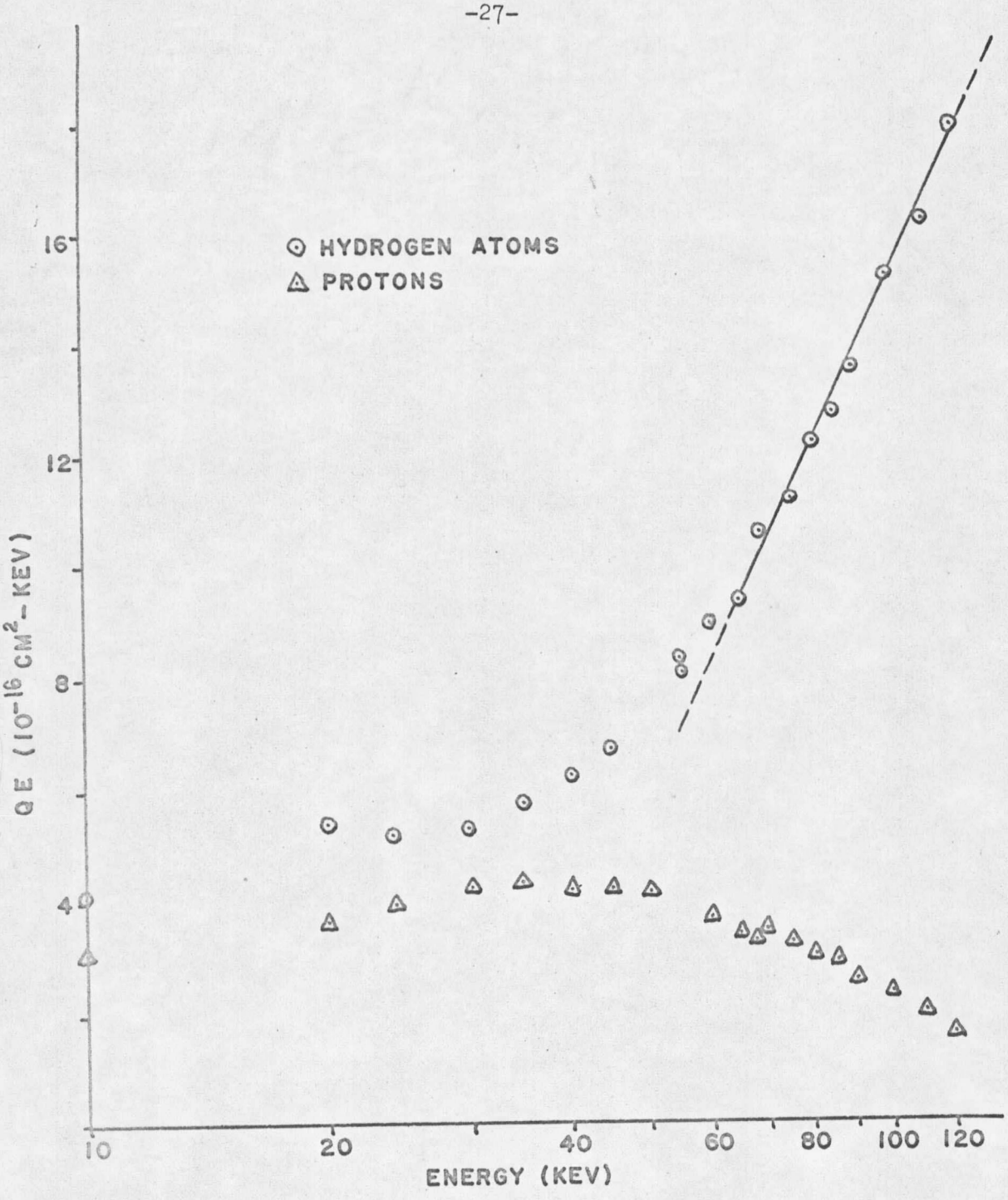


FIG. 10 QE VS. LN E AT LYMAN ALPHA

depend upon the charge and mass of the colliding particles.

Measurements at 1304 A

Analysis of Results

This spectral line actually consists of a triplet transition of wavelengths 1302 A, 1304 A, and 1306 A in atomic oxygen. A reasonably strong line was expected at 1357 A but was not observed. A much weaker line at 1217 A (in atomic oxygen) then was not expected to contribute to the results for 1216 A in hydrogen.

Since this line intensity was considerably smaller than those for hydrogen atoms at 1216 A, averaging techniques were necessary. Both curves (see Figure 11) were averaged over several independent runs. Since varied pressures and slit widths were used, conversion factors were necessary to average these independent runs. The readings were corrected to N_2 values in the 50-70 kev range where the current was the largest.

The resulting cross sections of the triplet oxygen transition were compared to those of protons at 1216 A on oxygen. These corresponding readings were done simultaneously to insure the correctness of their relative magnitude.

Unfortunately the possibility of cascading from upper levels of oxygen to the ^3S state was not considered. Although the ^3S-^3P transition has one of the largest transition probabilities in the oxygen atom, the author is uncertain as to how much of this cross section was produced by cascading. In general, cascading from levels for n greater than 3 is

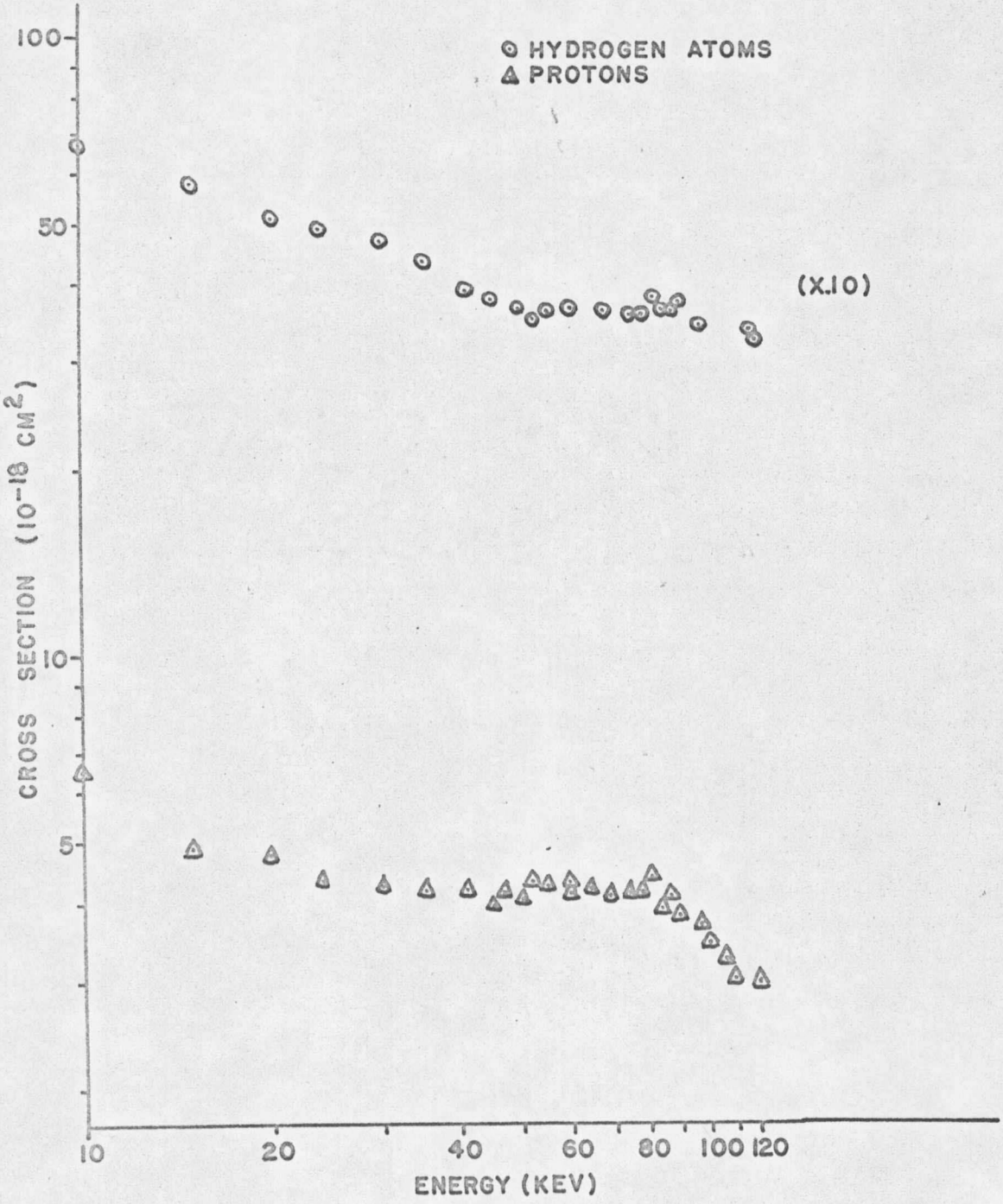


FIG. II CROSS SECTIONS AT 1304 A

negligible.

Theoretical Calculations

A plot of QE vs. ln E is given in Figure 12. The proton curve is uncertain at high energies. Yet the linearity of the hydrogen atom curve is quite evident. Using the experimental value for the cross section, the author found

$$\left| Z_{on} \right| = 3.7 \text{ A}$$

The collision is expected to be closer in the case of 1304 A triplet transitions as more energy is necessary. Again the complete validity of such a calculation is debatable. Yet the result is appropriate for such a collision product.

Theoretical calculations for such a transition are indeed difficult since the relevant wave functions are very poorly known. Seemingly elementary excited states, such as H_2^+, do not have well-defined wave functions. Until the theoretical calculations are improved, much more experimental evidence must be accumulated so that the validity of the results are assured.

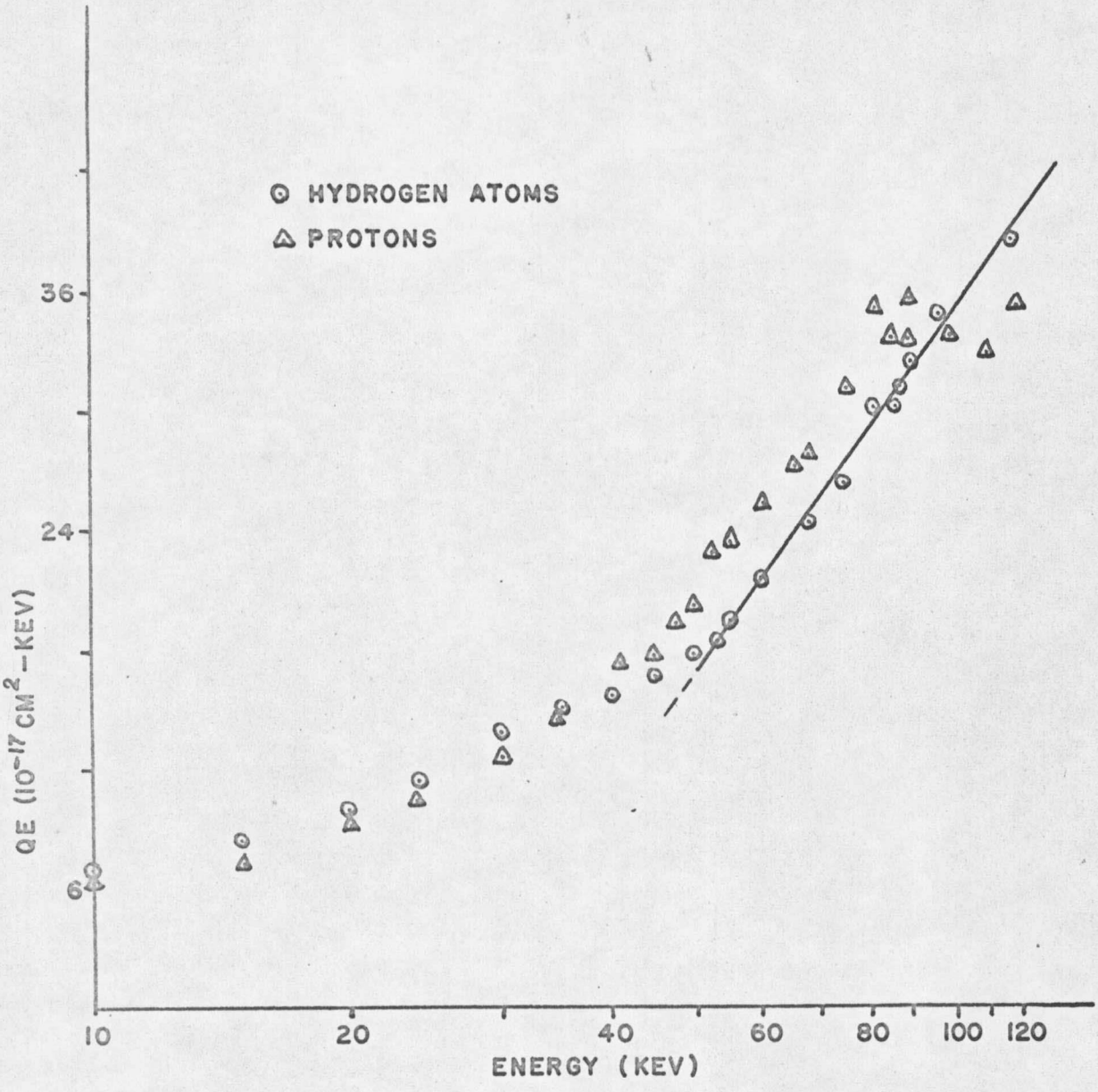


FIG. 12 QE VS. LN E AT 1304 A

ACCURACY OF RESULTS

As was stated earlier, the best statistics were near the middle of the energy range considered. Let S be the signal output on a relative scale and let S' be its total variation about S. The ratio S'/S should then provide an indication of the error in the cross sections.

See Table II. The results are for independent unrelated runs at 1216 A and 1304 A. Other errors would include the accelerating potential, current, pressure, and secondary electron production measurements.

A conservative estimate of the error for the overall results would be approximately 15-20%. This value is in keeping with the accuracy of results on similar experiments done by other experimenters.

CONCLUSIONS

The cross sections of hydrogen atoms and protons for producing the 1304 A triplet oxygen transition are nearly equal, i.e., each projectile is equally capable of dissociating molecular oxygen and exciting the oxygen atom to its lowest-lying excited state. Yet the possibility remains for contribution to this cross section due to cascading from higher excited states of the atom.

The cross sections at 1216 A show that the hydrogen atom and the proton excitation of the oxygen behave similarly at low energies. The shape of the proton cross section curve is typical of a charge exchange process.

The shape of the hydrogen atom curve is characteristic of competitive processes over the entire range studied. Such a mechanism well describes the curve obtained.

The Lyman alpha results for oxygen were found to be slightly smaller than those of nitrogen. This result is appropriate since the charge transfer and stripping cross sections are slightly smaller in oxygen compared to nitrogen.

The Born approximation formula for electrons was found to give quite satisfactory results for the interaction distance even though such calculations have not been shown to be valid. The result implies the neutral projectile appears as a charged particle to the target gas.

TABLES

TABLE I.

CHARACTERISTICS OF THE OXYGEN MOLECULE AND ITS MAJOR IONS
(ALL ENERGIES REFER TO THE LOWEST VIBRATIONAL STATE)

ELECTRONIC STATE	R_e(A)	ENERGY (ev)	DISSOCIATION PRODUCTS	OBSERVED TRANSITIONS	DISSOCIATION ENERGY
O_2^-: X $^2\pi_g^-$	1.28	-0.45	$O(^3P) + O^-(^2P_o)$		Unstable
O_2: X $^3\Sigma_g^-$	1.22	0.00	$O(^3P) + O(^3P)$	a,A,b,B,c,C	5.2 ev
O_2: a $^1\Delta_g$	1.23	+0.88	$O(^3P) + O(^3P)$		4.12 ev
O_2: b $^1\Sigma_g^+$	1.23	+1.50	$O(^3P) + O(^3P)$	X,a	3.97 ev
O_2: C $^3\pi_u$	1.48	+4.20	$O(^3P) + O(^3P)$		1.00 ev
O_2: A $^3\Sigma_u^+$	1.54	+4.35	$O(^3P) + O(^3P)$	X,b	0.85 ev
O_2: c $^1\Sigma_u^-$	1.62	+4.40	$O(^3P) + O(^3P)$		0.80 ev
O_2^+: X $^2\pi_g$	1.17	+12.0	$O(^3P) + O^+(^4S^o)$		6.70 ev
O_2^+: a $^4\pi_u$	1.38	+16.0	$O(^3P) + O^+(^4S^o)$		2.70 ev
O_2^+: A $^2\pi_u$	1.42	+16.8	$O(^3P) + O^+(^4S^o)$		1.9 ev
O_2^+: b $^4\Sigma_g^-$	1.32	+18.1	$O(^1D) + O^+(^4S^o)$	a	2.6 ev
O_2^+: $^2\Sigma_g^-$	1.34	+20.2	$O(^3P) + O^+(^2D^o)$		1.7 ev

TABLE II.

TYPICAL PARAMETERS INDICATING THE STATISTICAL ACCURACY OF THE EXPERIMENTAL RESULTS

1217 A			1307A		
ENERGY	H^0	H^+	ENERGY	H^0	H^+
30	S = 50 S' = 4 S'/S = 8%	S = 86 S' = 3 S'/S = 3.6%	30	S = 20 S' = 3 S'/S = 15%	S = 43 S' = 3 S'/S = 7%
60	S = 100 S' = 6 S'/S = 6%	S = 168 S' = 7 S'/S = 4.2%	60	S = 26 S' = 2 S'/S = 7.7%	S = 24 S' = 5 S'/S = 6%
100	S = 83 S' = 6 S'/S = 7.2%	S = 52 S' = 5 S'/S = 9.6%	100	S = 10 S' = 2 S'/S = 20%	S = 39 S' = 3 S'/S = 7.7%

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